Top-quark pair production as a probe of light top-philic scalars and anomalous Higgs interactions

Mainly Based on:

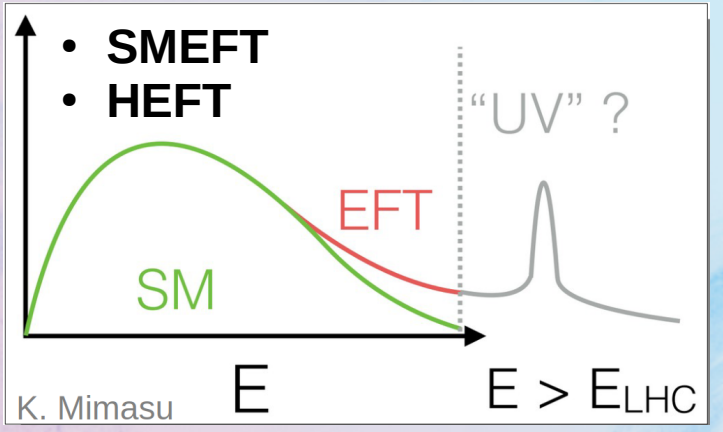
[Maltoni, Pagani, ST 2406.06694, JHEP 09 (2024) 098]

Simone Tentori

New Physics, which one?

Direct Searches

Indirect Searches



m_{NP}

Light Physics Searches:
- Specific approaches
- Cover part of UV models
- Small number of parameters

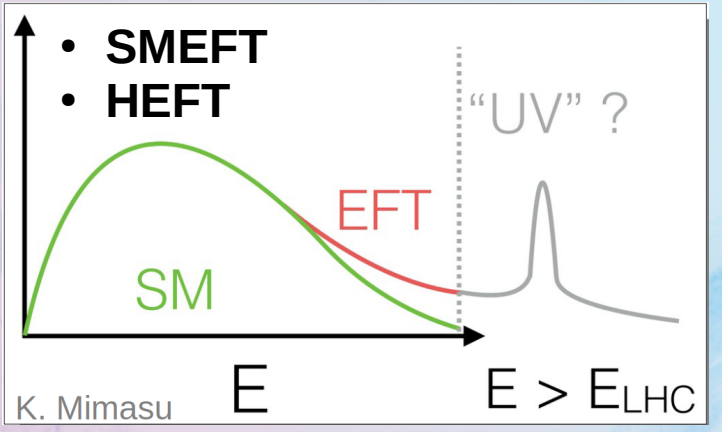
EFT approaches:
- Systematic approaches
- Cover large class of UV models
- Many parameters

New Physics, which one?

Direct Searches

THIS TALK!

Indirect Searches



m_{NP}

Light Physics Searches:
- Specific approaches
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EFT approaches:
- Systematic approaches
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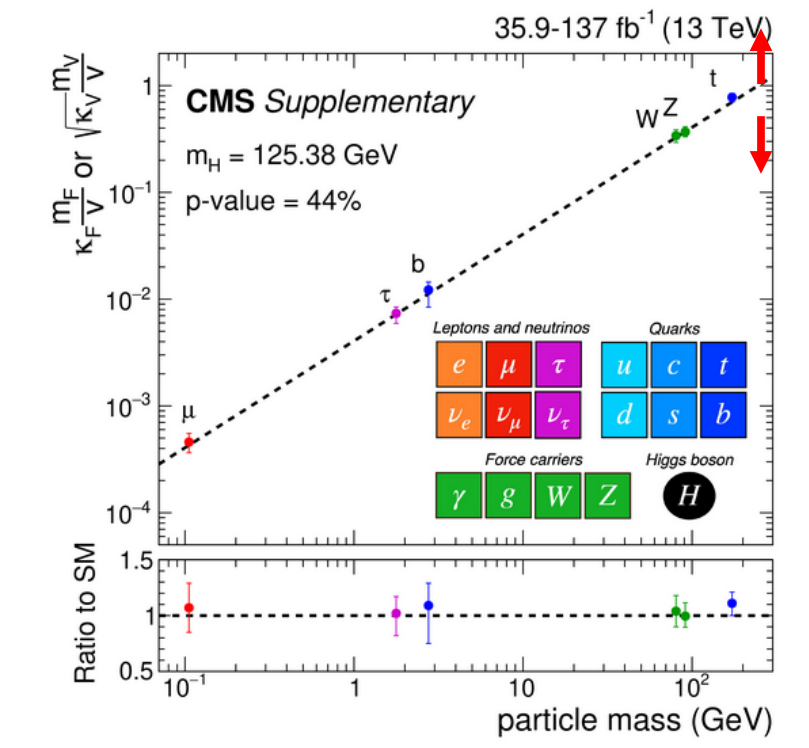
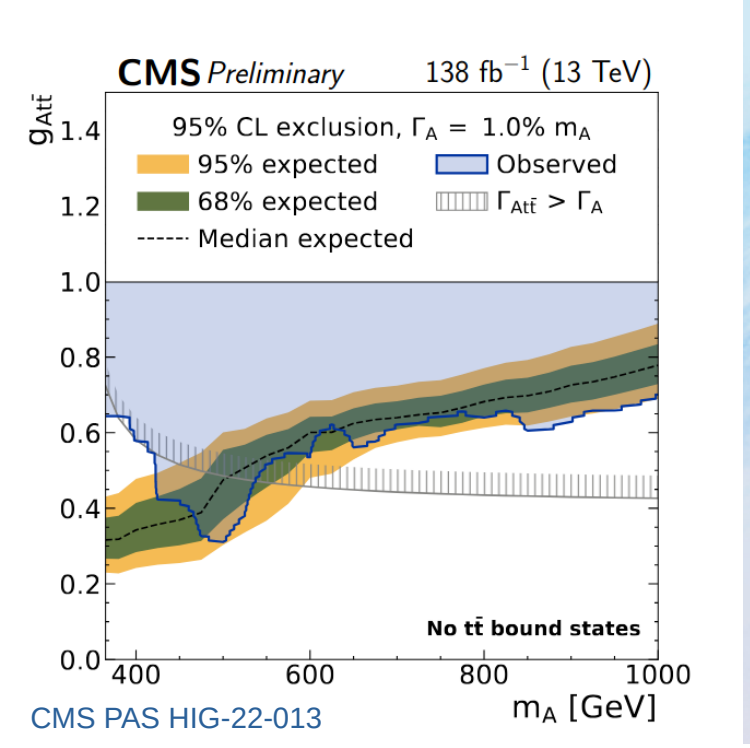
- Many parameters

New Physics, where to look?

- **Deviation in SM parameters**



- **New States**



CMS PAS HIG-22-013

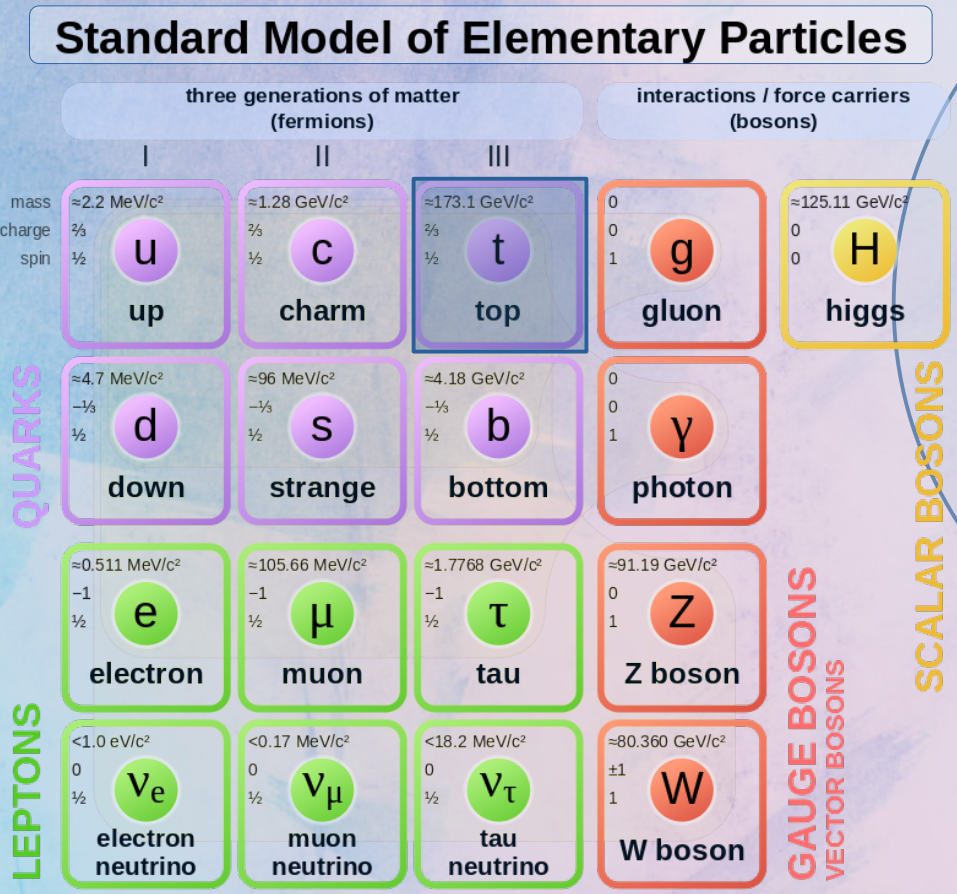
Top quark

NP Portal:

- Heaviest quark
- Models with mass hierarchical couplings

Accessible Differential Kinematical Distributions

- Invariant mass
- Top trasverse momentum
- Rapidity difference



Lot of statistics

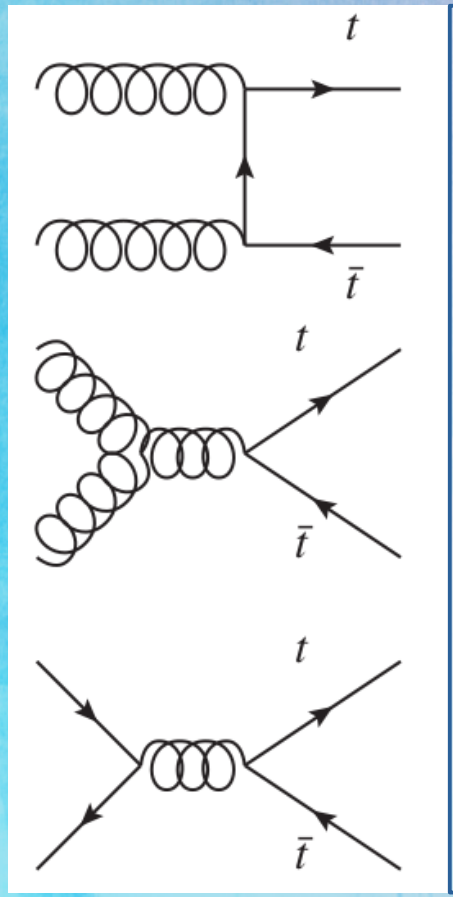
$t\bar{t}$ number of events:

- Run1: $2.7^{1}+3.8^{2}$ mln
- Run2: 152^{3} mln
- Run3: 251^{4} mln
- HL-LHC[5]: 3.1 bln

$\sigma_{t\bar{t}}$= 1:179.6 pb 2:256pb 3:833.9pb 4,5:926pb
NNLO-NNLL Top++v2.0

Simone Tentori

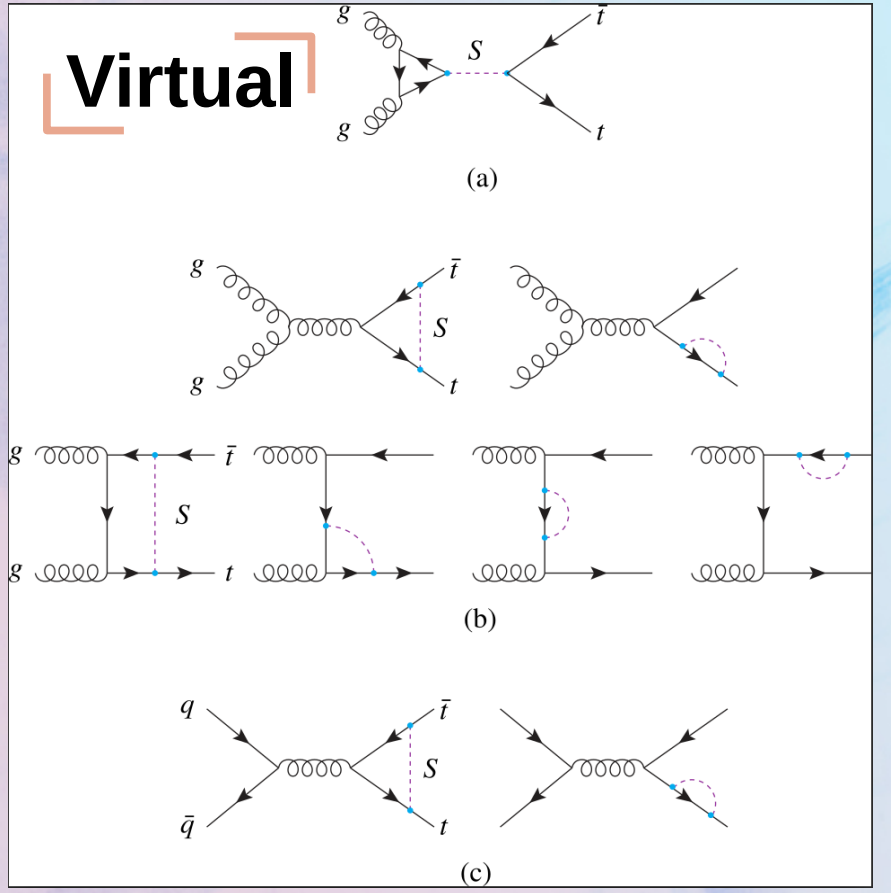
Which processes?



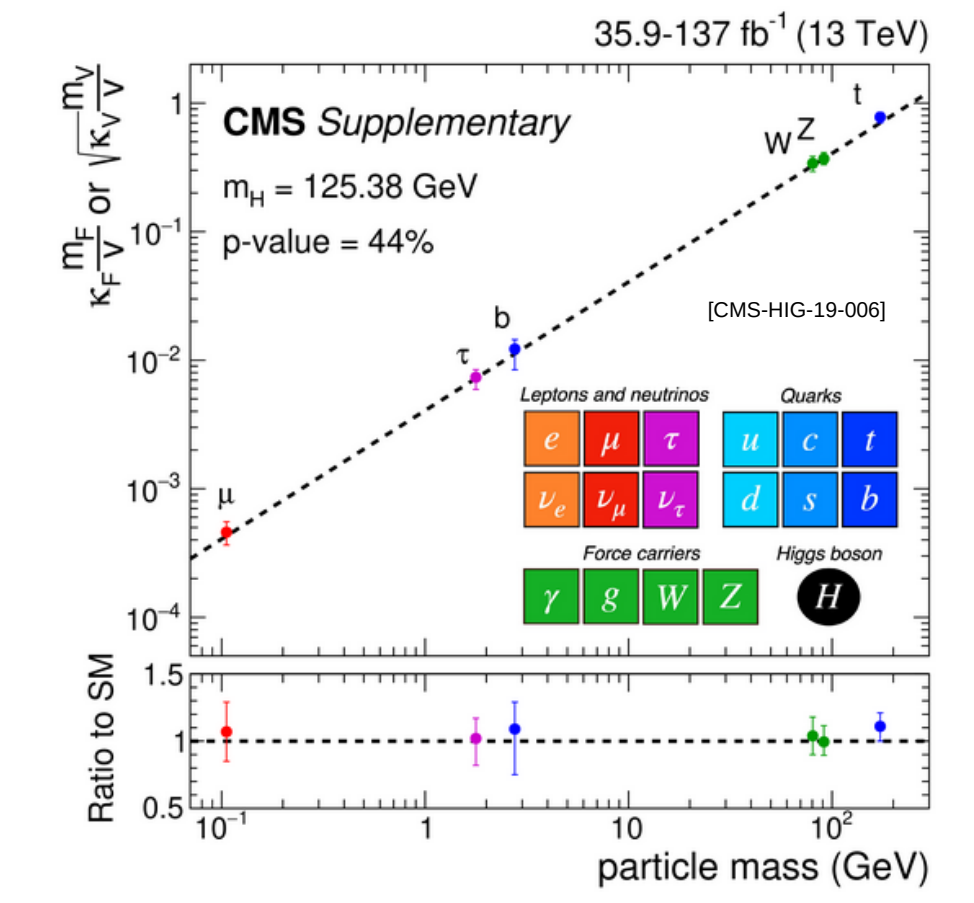
SM:

- **NNLOQCD**
- **NLOEW**

Virtual



The SM Higgs



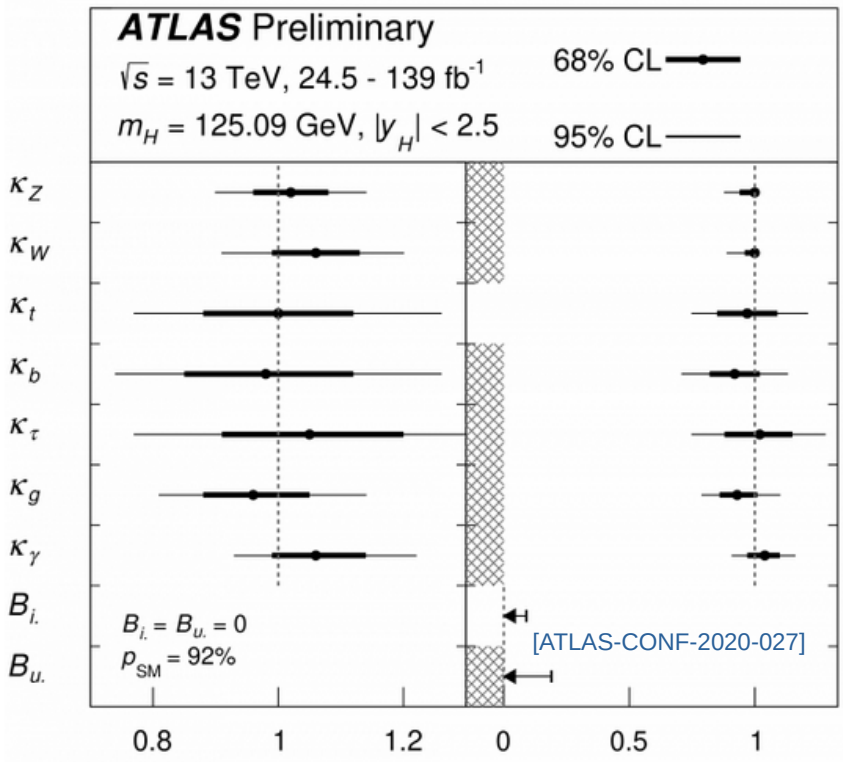
- Higgs-fermion couplings in SM uniquely depend on:
  - m_f
  - Higgs vev (v)

$$y_f = \frac{\sqrt{2} m_f}{v}$$

- NP can modifies SM couplings in many ways

Anomalous Higgs coupling

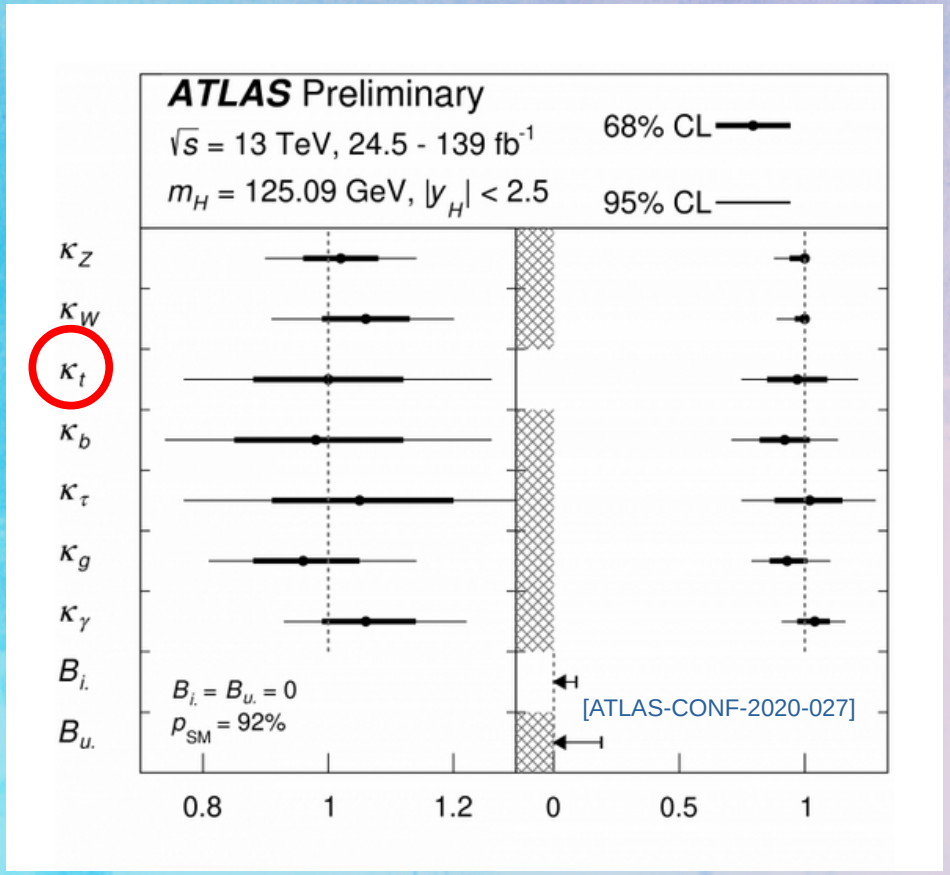
The Kappa Framework



- Dress SM cross-section and partial decay width with scale factor κ

$$\sigma(i \to H \to f) = \sigma^{i}_{\mathrm{SM}} \mathrm{Br}_{\mathrm{SM}} \cdot \left(\frac{\kappa_i^2 \kappa_f^2}{k_H^2} \right)$$

The Kappa Framework



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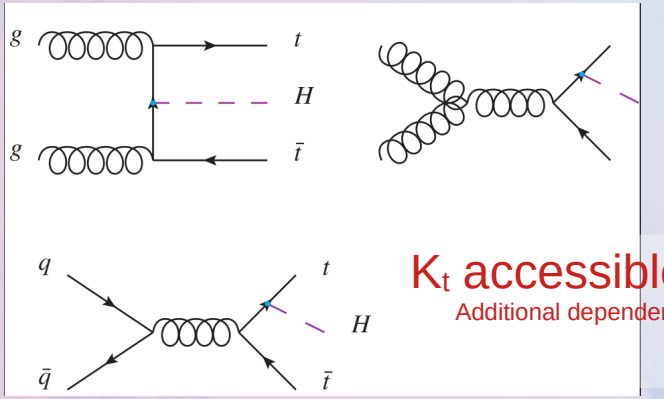


K_t accessible in ttH

Additional dependencies in H decay

Higgs-Top modified couplings

$$\mathcal{L}_H = -\frac{1}{\sqrt{2}}\bar{t}\left[y_t + i\tilde{y}_t\gamma_5\right]tH$$

CP-EVEN y_t CP-ODD $\tilde{y}_t\gamma_5$

$$\begin{cases} \kappa_t = \dfrac{y_t}{y_t^{\mathrm{SM}}}, \\ \tilde{\kappa}_t = \dfrac{\tilde{y}_t}{y_t^{\mathrm{SM}}} \end{cases}$$

SM:

- K_t=1 (y_t=m_t/v)
- $\widetilde{K_t}$=0.

$$\sigma_{H,NP} = (\kappa_t^2 - 1)\overline{\sigma}_{\kappa_t} + \tilde{\kappa}_t^2\overline{\sigma}_{\tilde{\kappa}_t}$$

y_t from $t\bar{t}$: Experiments

Measurement of the top quark Yukawa coupling from $t\bar{t}$ kinematic distributions in the lepton+jets final state in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

total of 55 bins in $M_{t\bar{t}}$, $|\Delta y_{t\bar{t}}|$, and the number of reconstructed jets. The measured value of Y_t is $1.07^{+0.34}_{-0.43}$, compared to an expected value of $1.00^{+0.35}_{-0.48}$. The observed upper limit on Y_t is 1.67 at 95% confidence level (CL), with an expected value of 1.62.

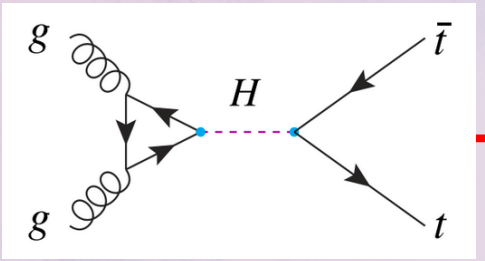
Measurement of the top quark Yukawa coupling from $t\bar{t}$ kinematic distributions in the dilepton final state in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

antiquark are sensitive to the value of Y_t. The measurement yields a best fit value of $Y_t = 1.16^{+0.24}_{-0.35}$, bounding $Y_t < 1.54$ at a 95% confidence level.

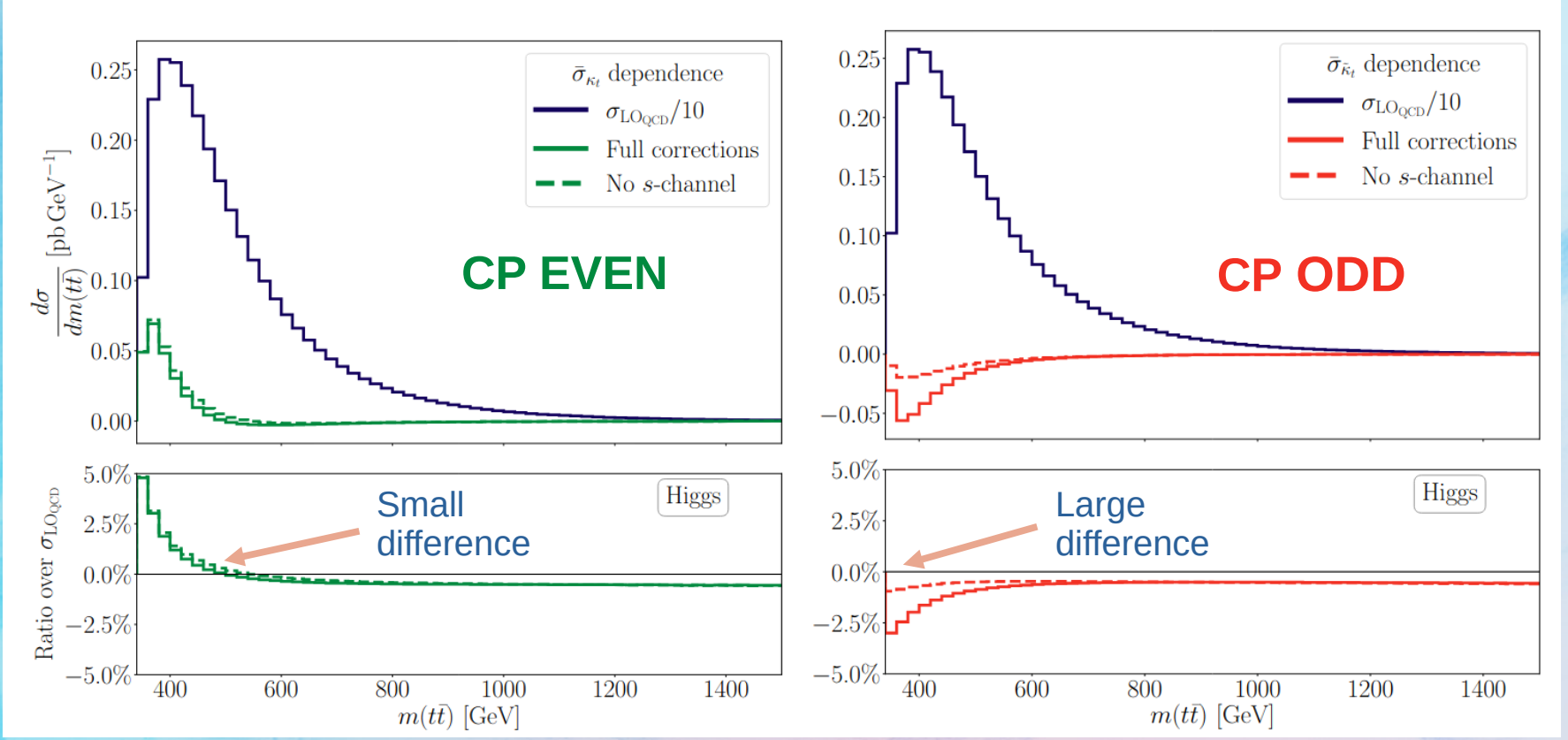
Theory prediction:

- HATHOR (Aliev et al. '10)
- Complemented with CP-odd Higgs interaction from [2104.04277]

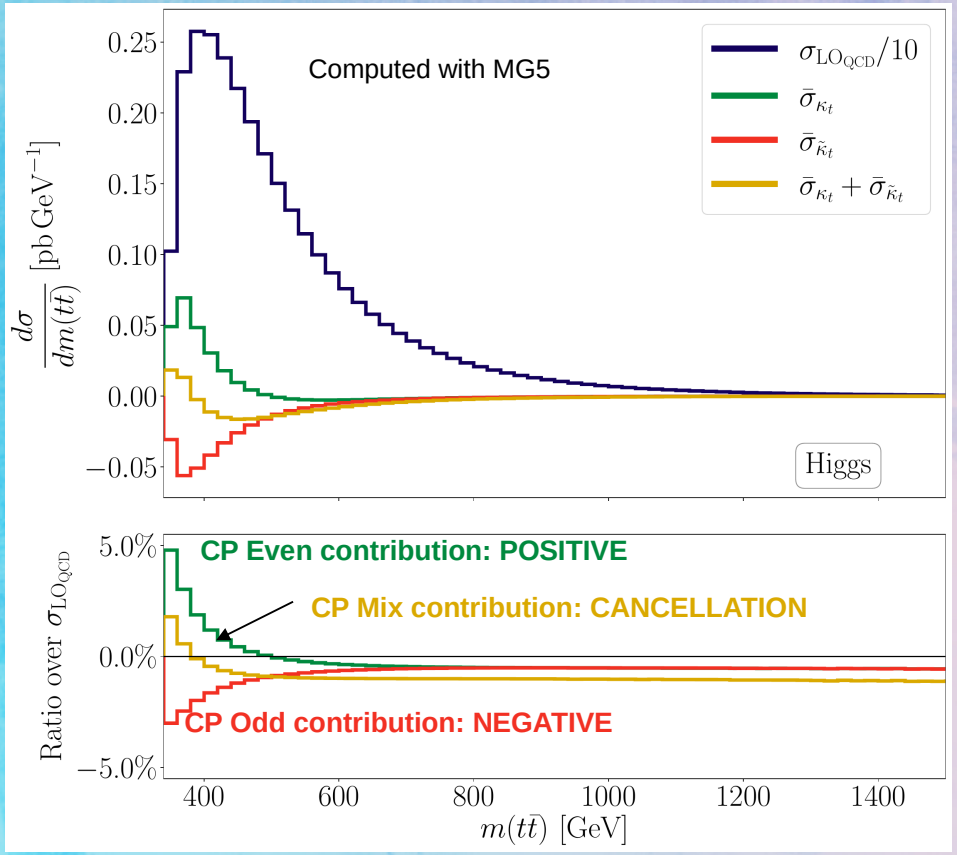


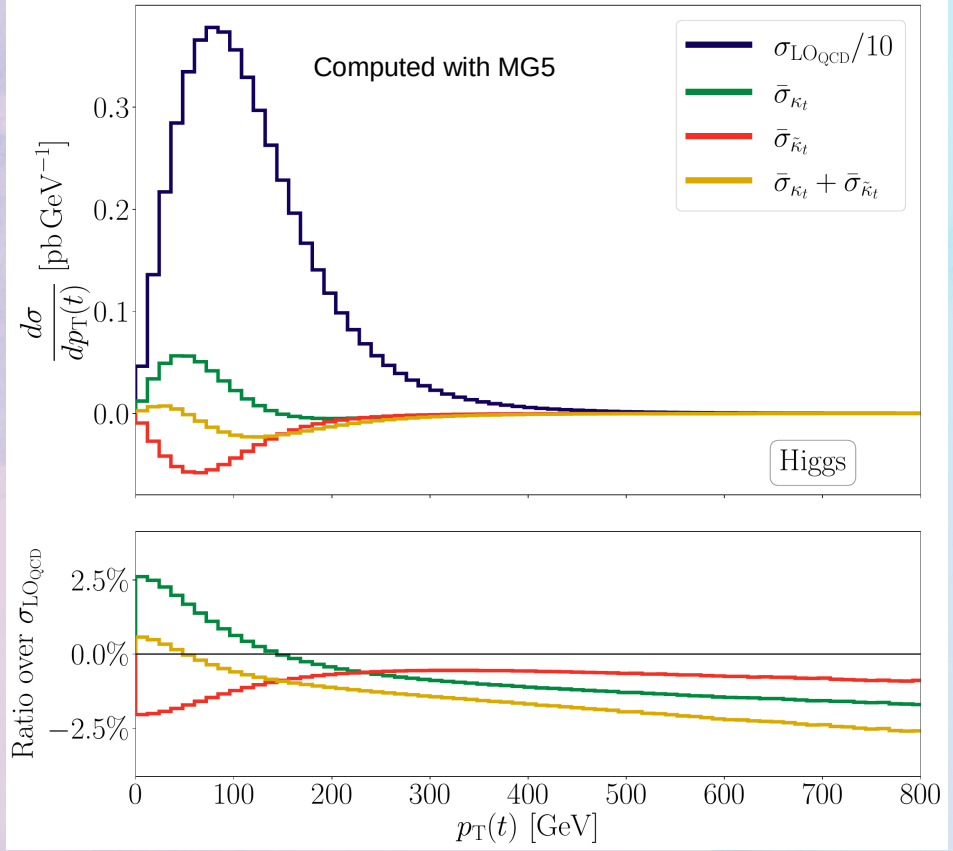
→ Omitted in the theoretical calculation

S-channel contribution



Distributions





Fit: 1 parameter CP Even

FIT INFO:
- Data: SM
- Baseline: SM without Higgs
- Errors and Bins: [CMS: 1803.08856]

$$\mathcal{L} = \mathcal{L}_{\text{SM, no Higgs}} - \frac{y_t}{\sqrt{2}}\bar{t}tH$$

	κ_t $^{+1\sigma,\,2\sigma,\,3\sigma}_{-1\sigma,\,2\sigma,\,3\sigma}$	$\tilde{\kappa}_t$ $^{+1\sigma,\,2\sigma,\,3\sigma}_{-1\sigma,\,2\sigma,\,3\sigma}$
SM_{mult} LHC	$1.00^{+0.28,\,0.52,\,0.72}_{-0.41,\,1.0,\,1.0}$	$0.0^{+0.59,\,1.05,\,1.43}_{-0.59,\,1.06,\,1.44}$

By Construction **By “Magic”**

Fit: 1 parameter CP Odd

FIT INFO:
- Data: SM (CP Odd Higgs)
- Baseline: SM without Higgs
- Errors and Bins: [CMS: 1803.08856]

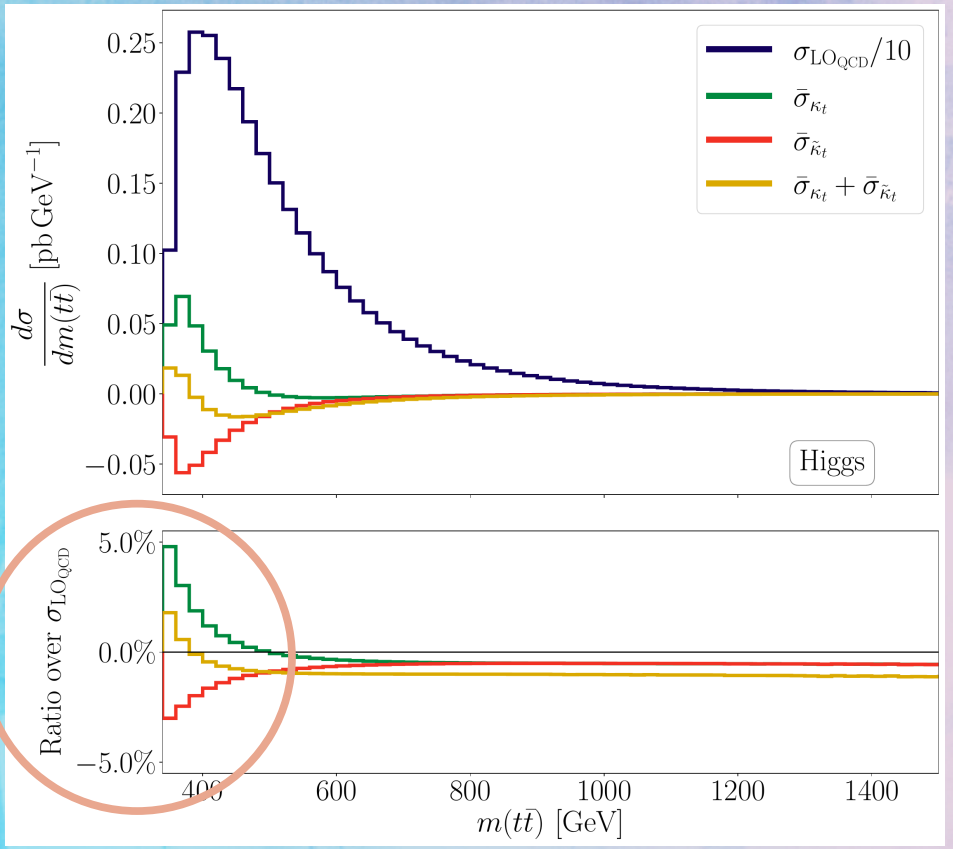
$$\mathcal{L} = \mathcal{L}_{\text{SM, no Higgs}} - \frac{y_t}{\sqrt{2}} \bar{t} \gamma_5 t H$$

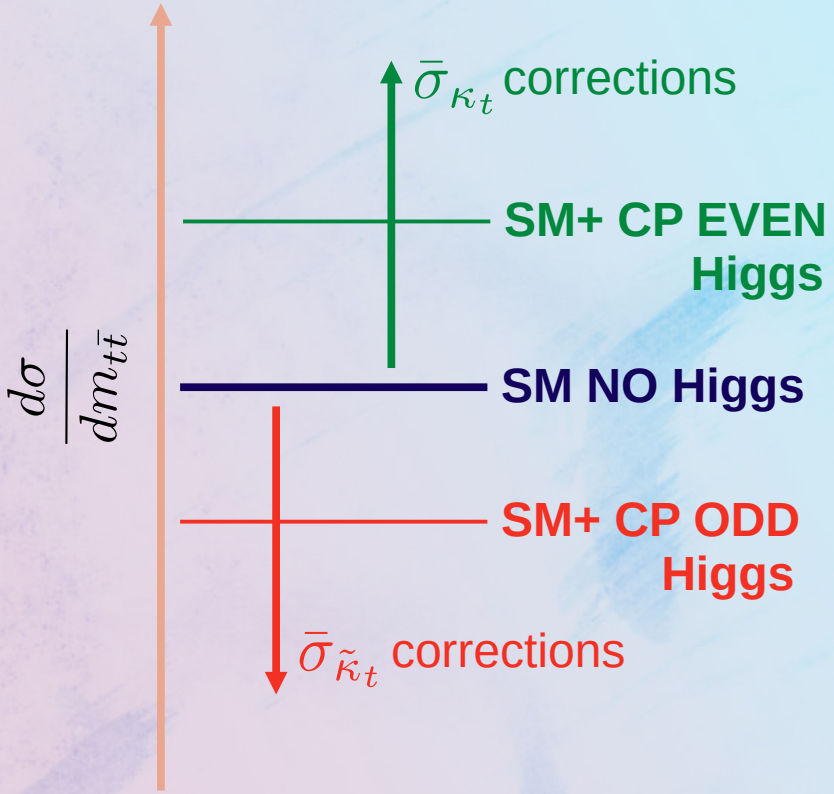
	$\kappa_t {}^{+1\sigma, 2\sigma, 3\sigma}_{-1\sigma, 2\sigma, 3\sigma}$	$\tilde{\kappa}_t {}^{+1\sigma, 2\sigma, 3\sigma}_{-1\sigma, 2\sigma, 3\sigma}$
SM_{mult} LHC	$0.00^{+0.55, 0.93, 1.22}_{-0.55, 0.93, 1.22}$	$1.0^{+0.44, 0.78, 1.06}_{-1.00, 1.00, 1.00}$

By "Magic"

By Construction

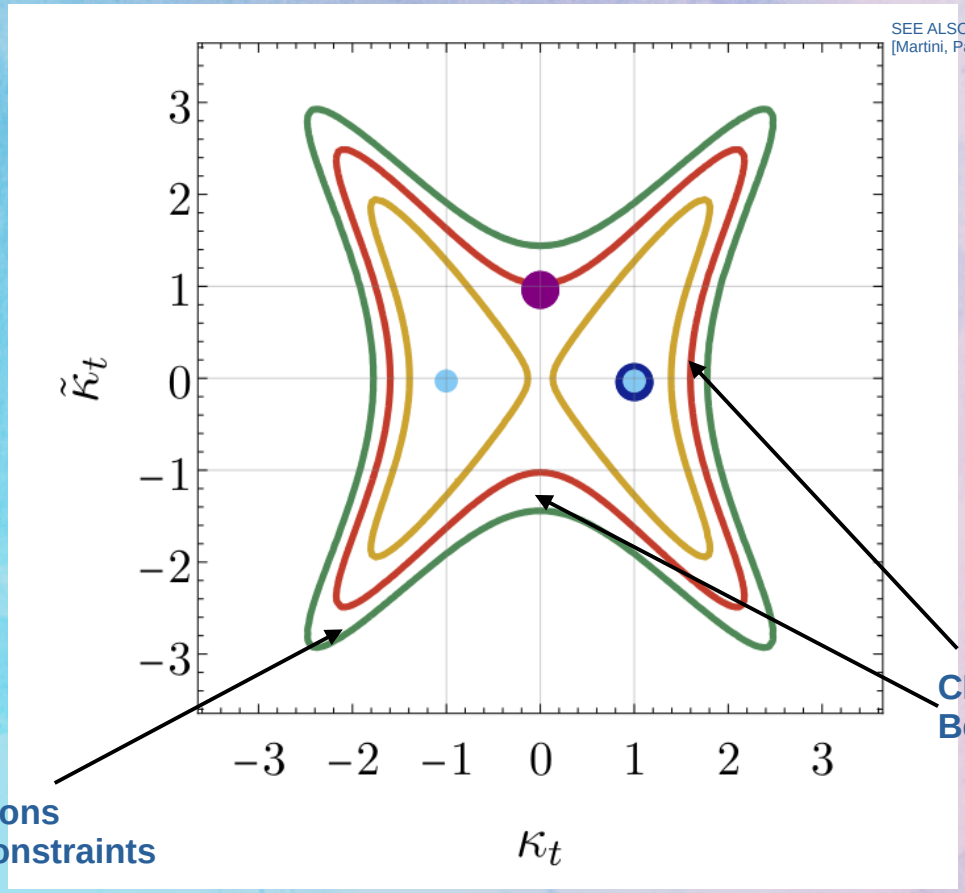
Fit: CP Even or CP Odd

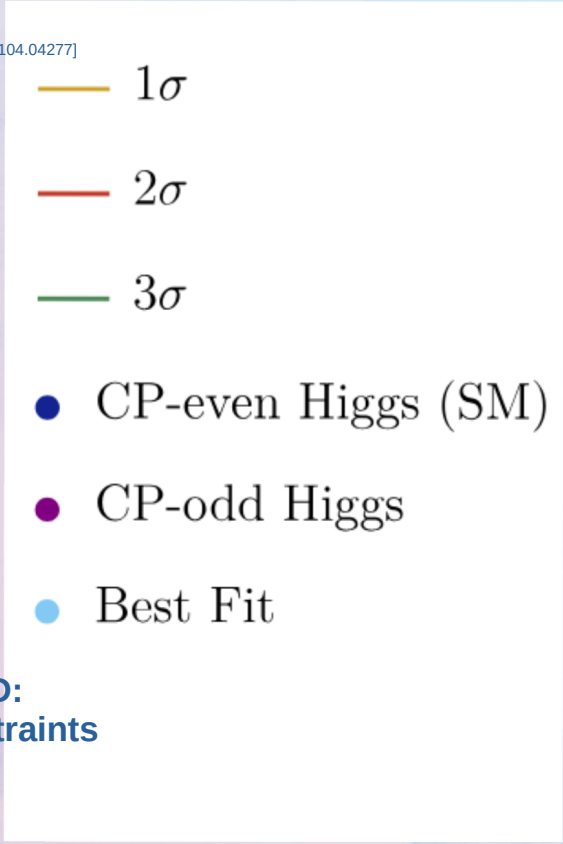




Fit: 2 parameters

SEE ALSO:
[Martini, Pan, Schulze and Xiao, 2104.04277]

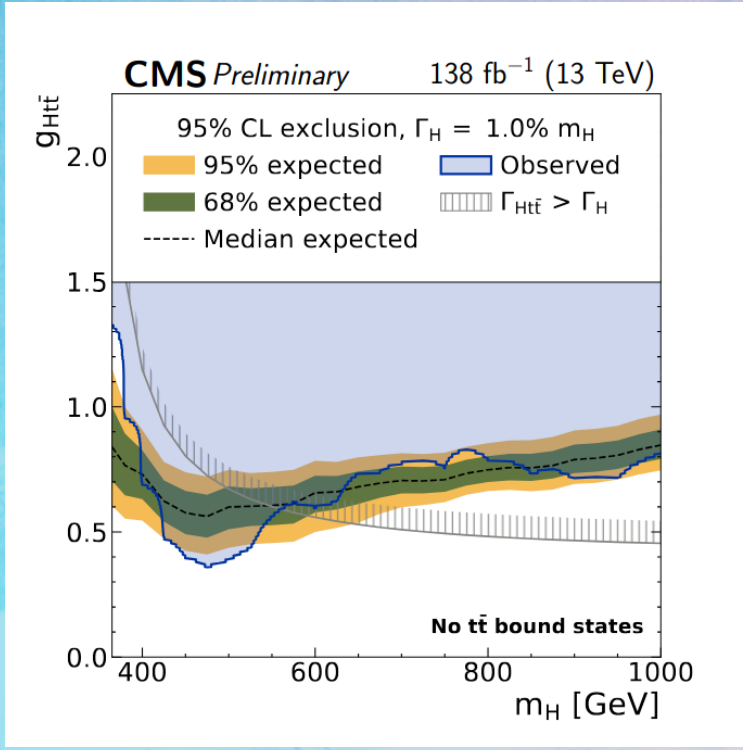


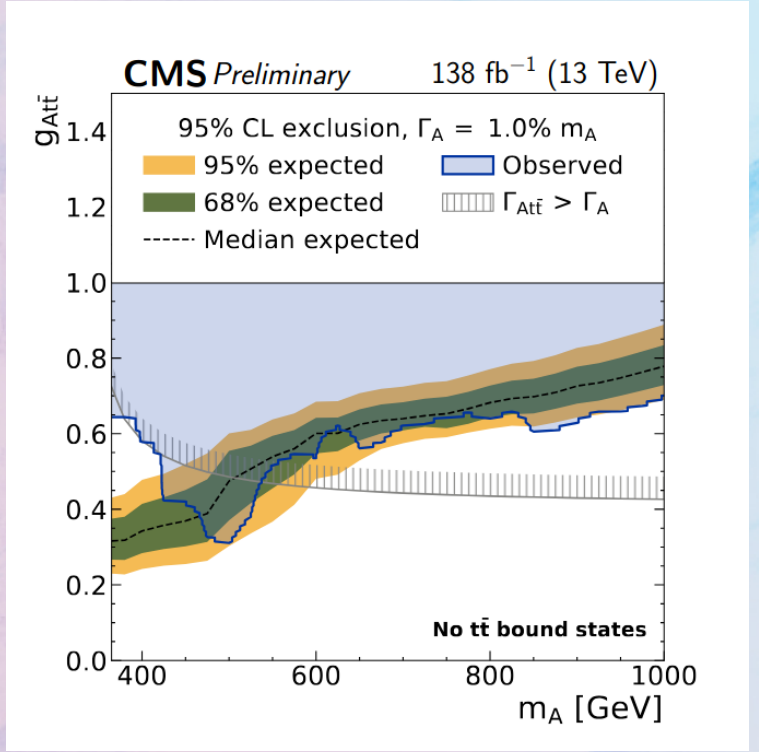


CP MIX:
Cancellations
weaken constraints

CP DEFINED:
Better constraints

Top-philic Scalar and Psuedoscalars





The Model

$$\mathcal{L}_{NP} = -\bar{t}(c_t + i\tilde{c}_t\gamma_5)tS$$

CP-EVEN

CP-ODD

Generic Scalar State

Induced corrections to top-pair production

$$\sigma_{NP} = \bar{\sigma}_{c_t} c_t^2 + \bar{\sigma}_{\tilde{c}_t} \tilde{c}_t^2 + \bar{\sigma}_{c_t \tilde{c}_t} c_t \tilde{c}_t$$

The Model

$$\mathcal{L}_{NP} = -\bar{t}(c_t + i\tilde{c}_t\gamma_5)tS$$

CP-EVEN

CP-ODD

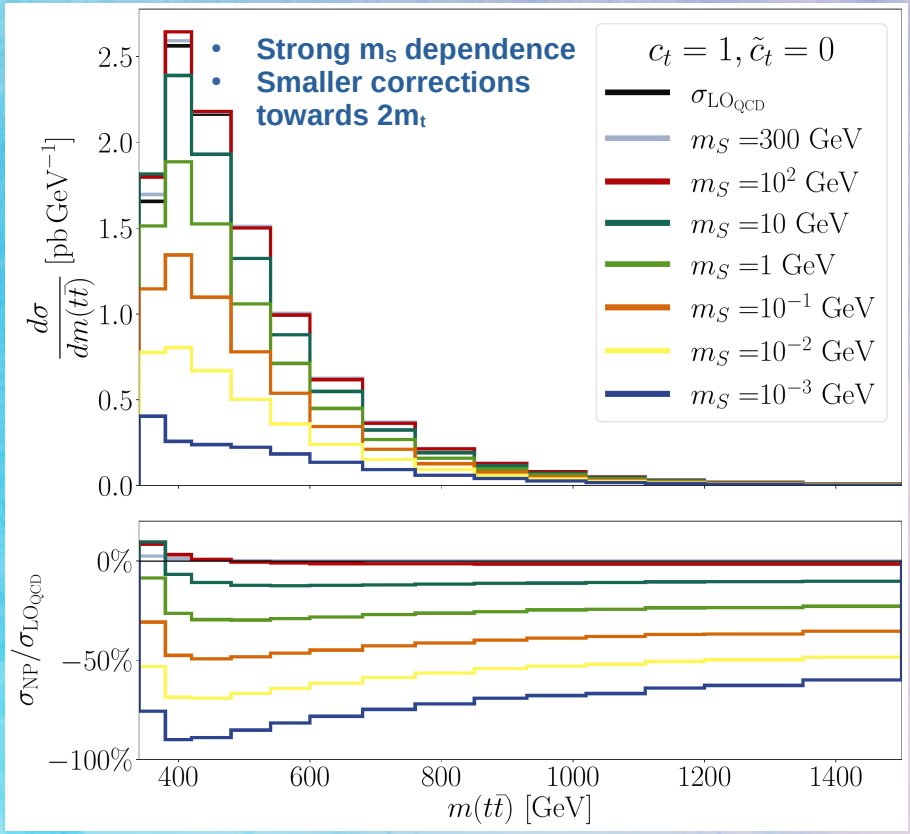
Generic Scalar State

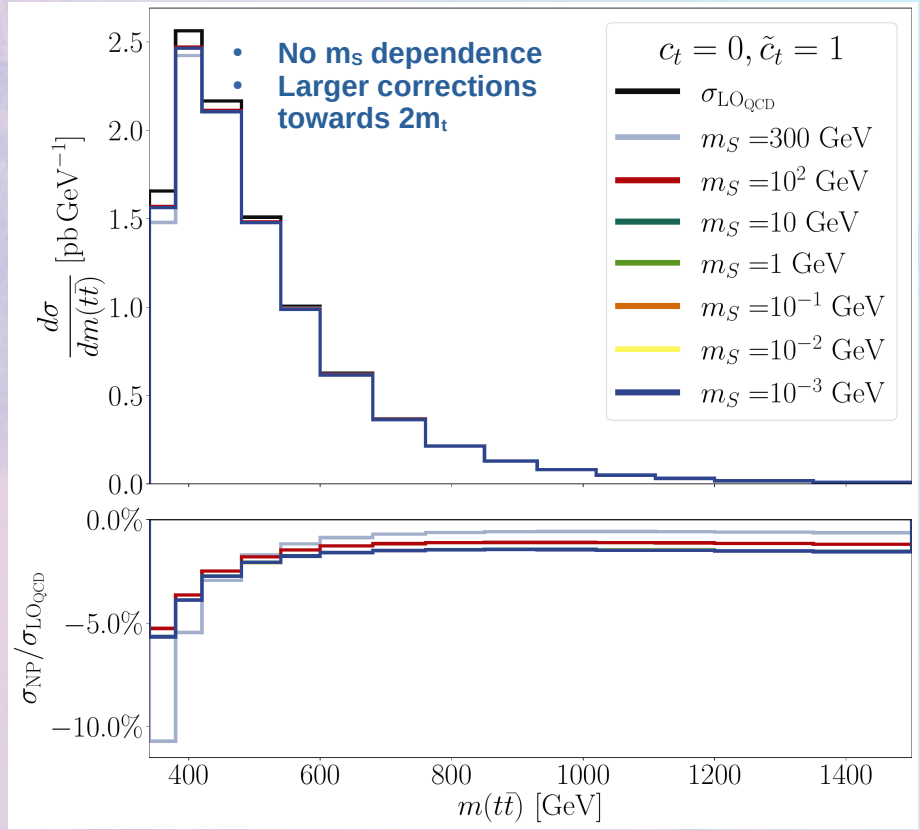
Induced corrections to top-pair production

ZERO

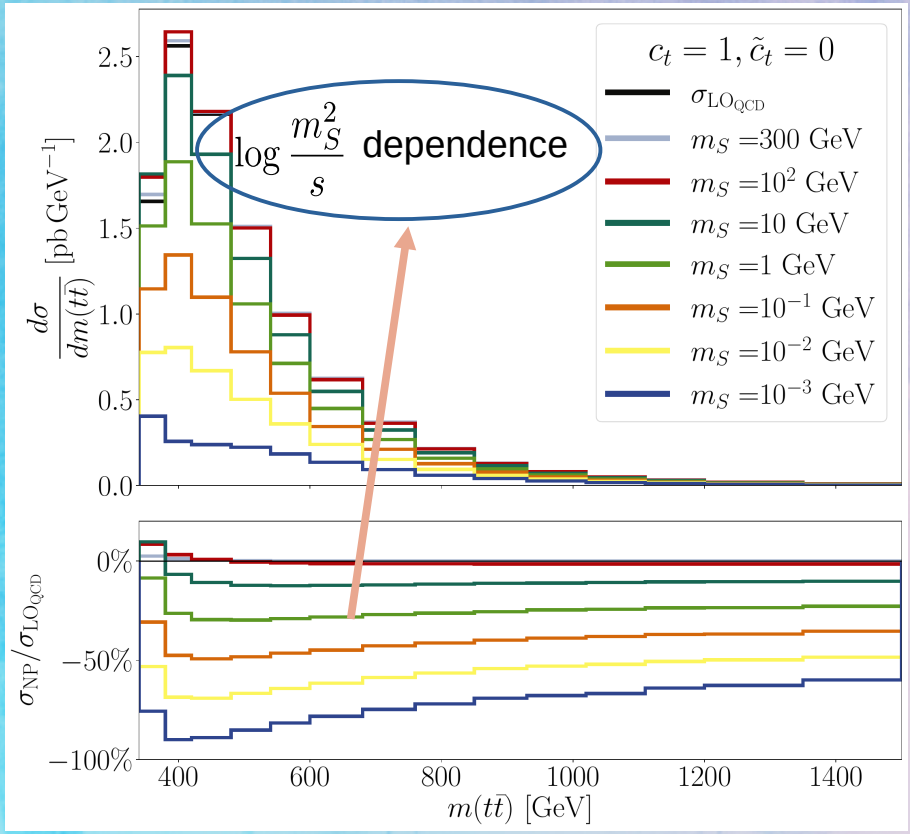
$$\sigma_{NP} = \bar{\sigma}_{c_t} c_t^2 + \bar{\sigma}_{\tilde{c}_t} \tilde{c}_t^2 + \bar{\sigma}_{c_t \tilde{c}_t} c_t \tilde{c}_t$$

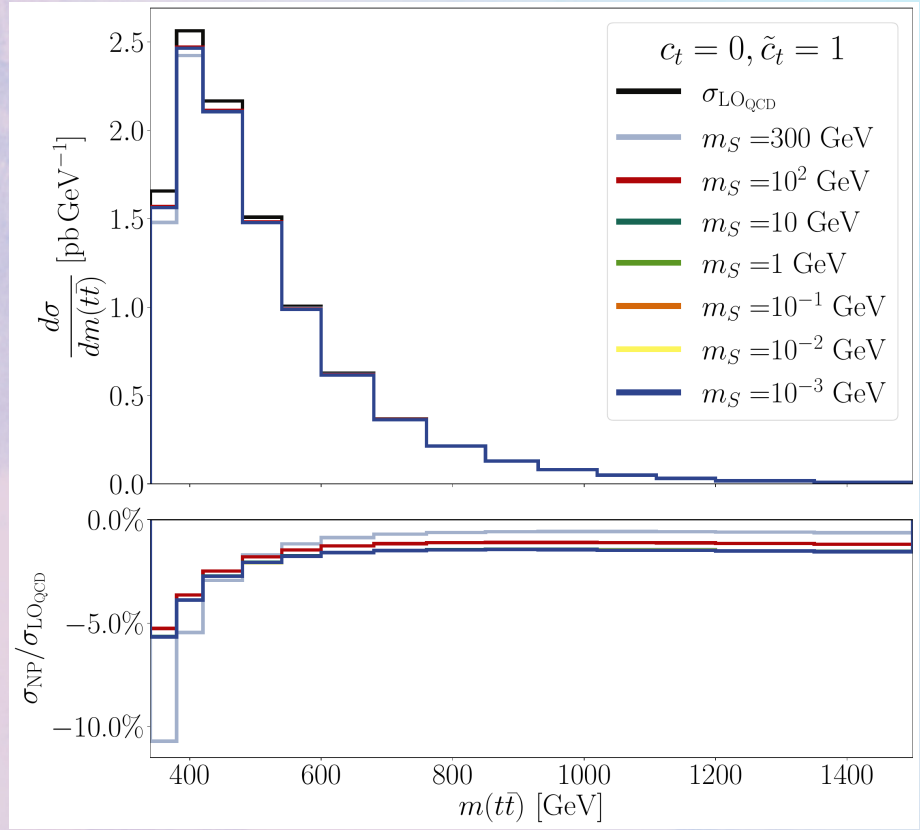
Purely Virtual Corrections



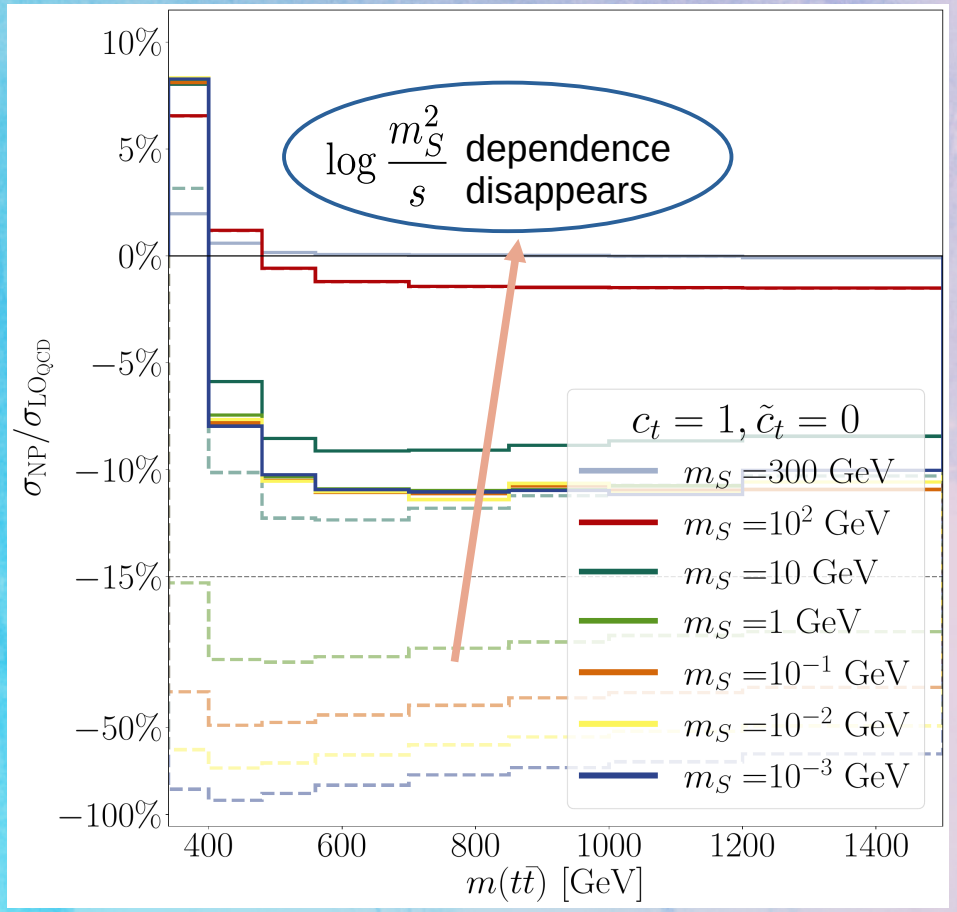


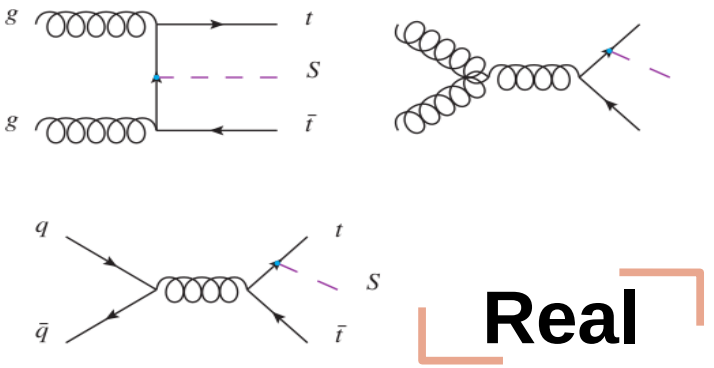
Purely Virtual Corrections



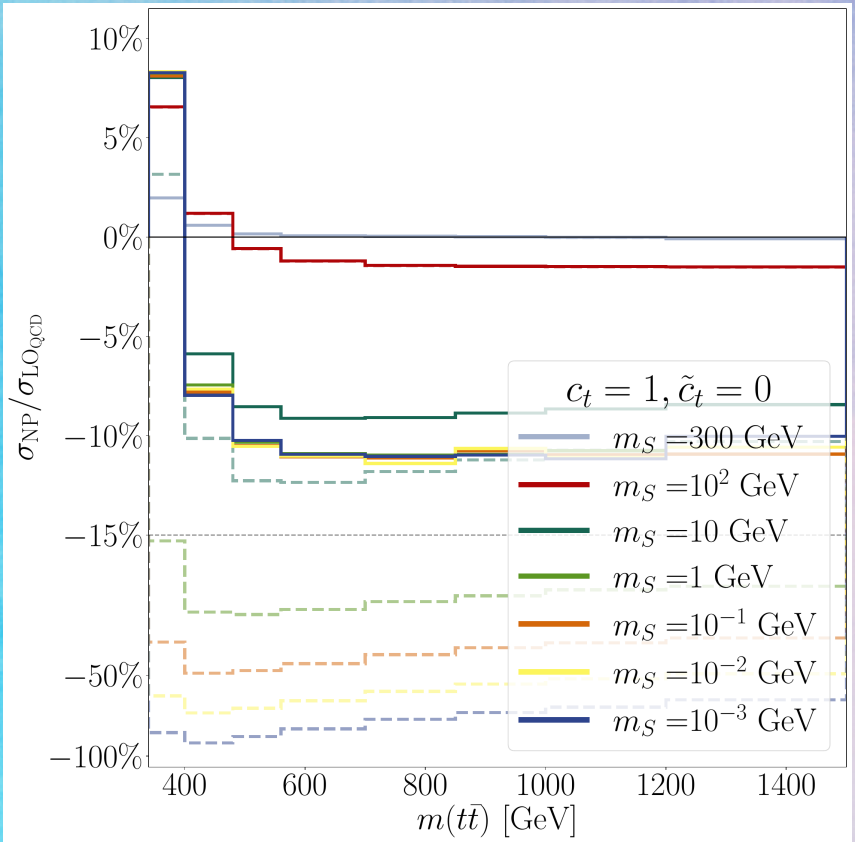


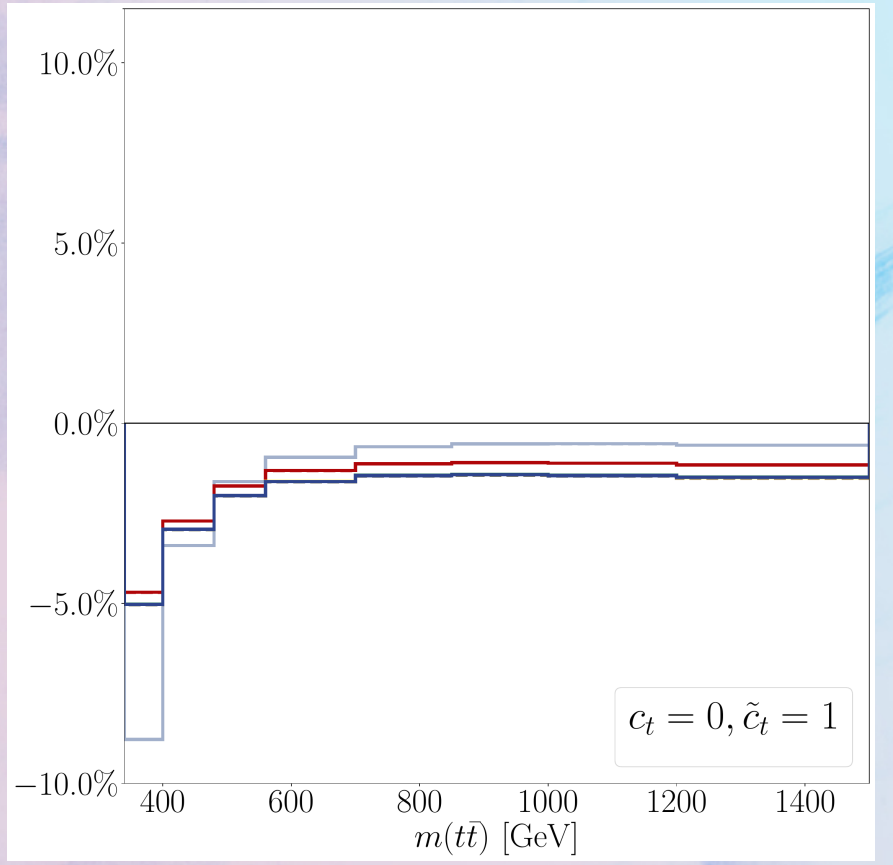
Adding the real



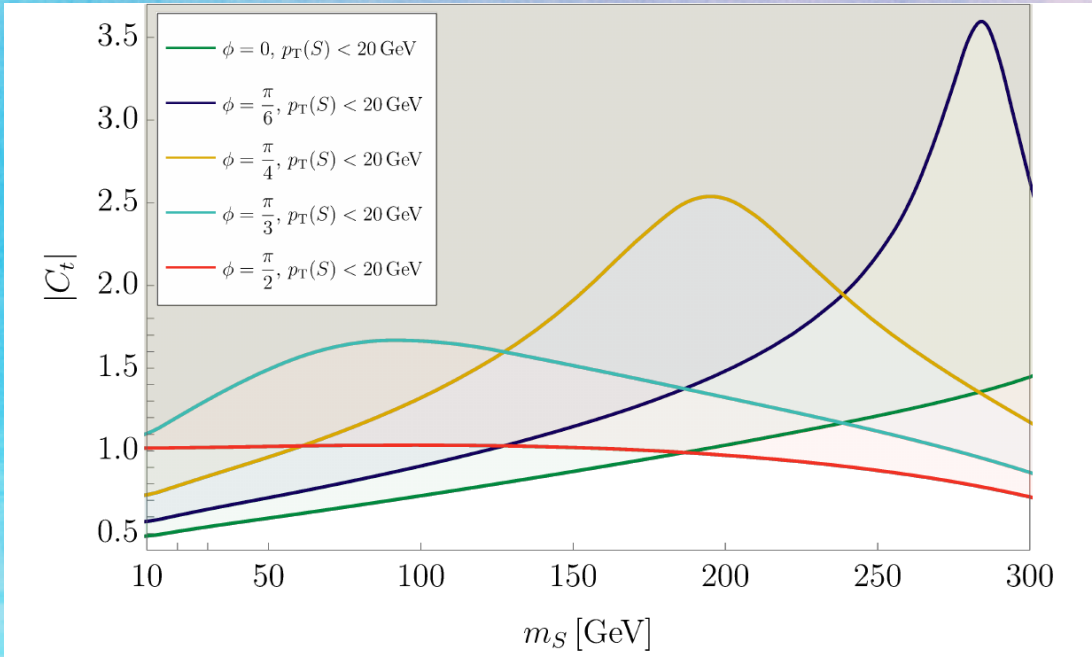


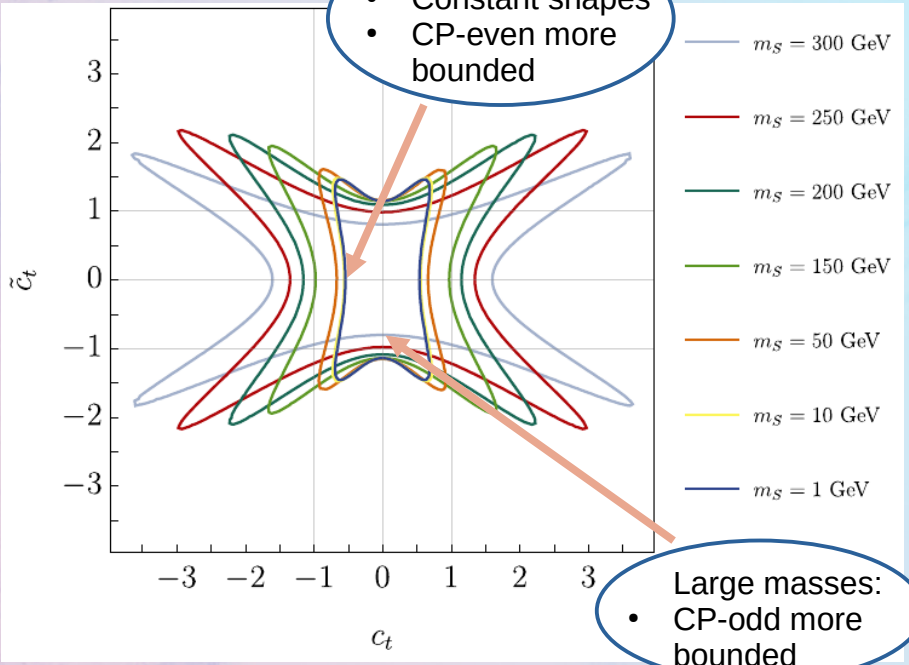
Adding the real





Mixing the couplings





Small masses:
- Constant shapes
- CP-even more bounded

Large masses:
- CP-odd more bounded

BONUS: Toponium or Pseudoscalar?

Search for heavy pseudoscalar and scalar bosons decaying to top quark pairs in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

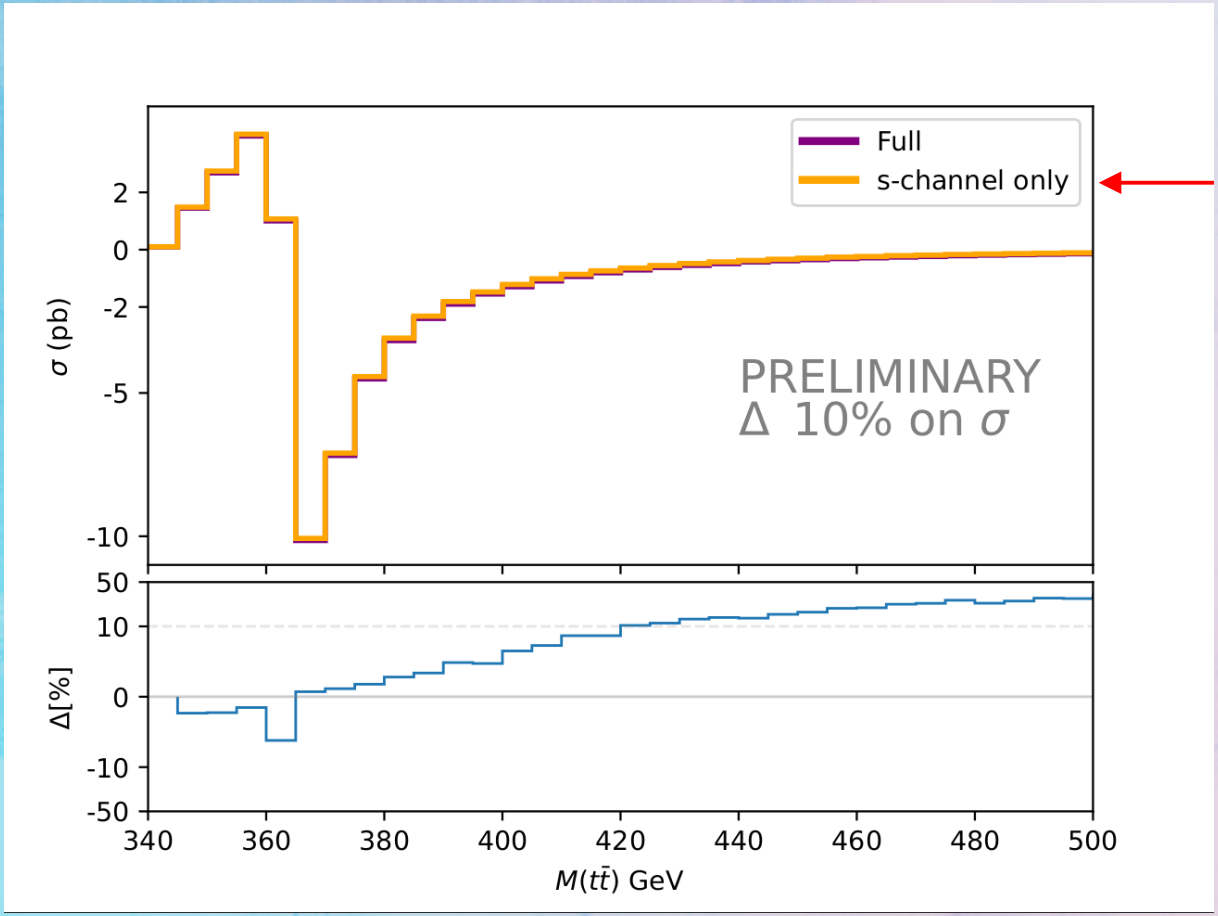
The CMS Collaboration

CMS PAS HIG-22-013

BONUS:
Toponium or Pseudoscalar?

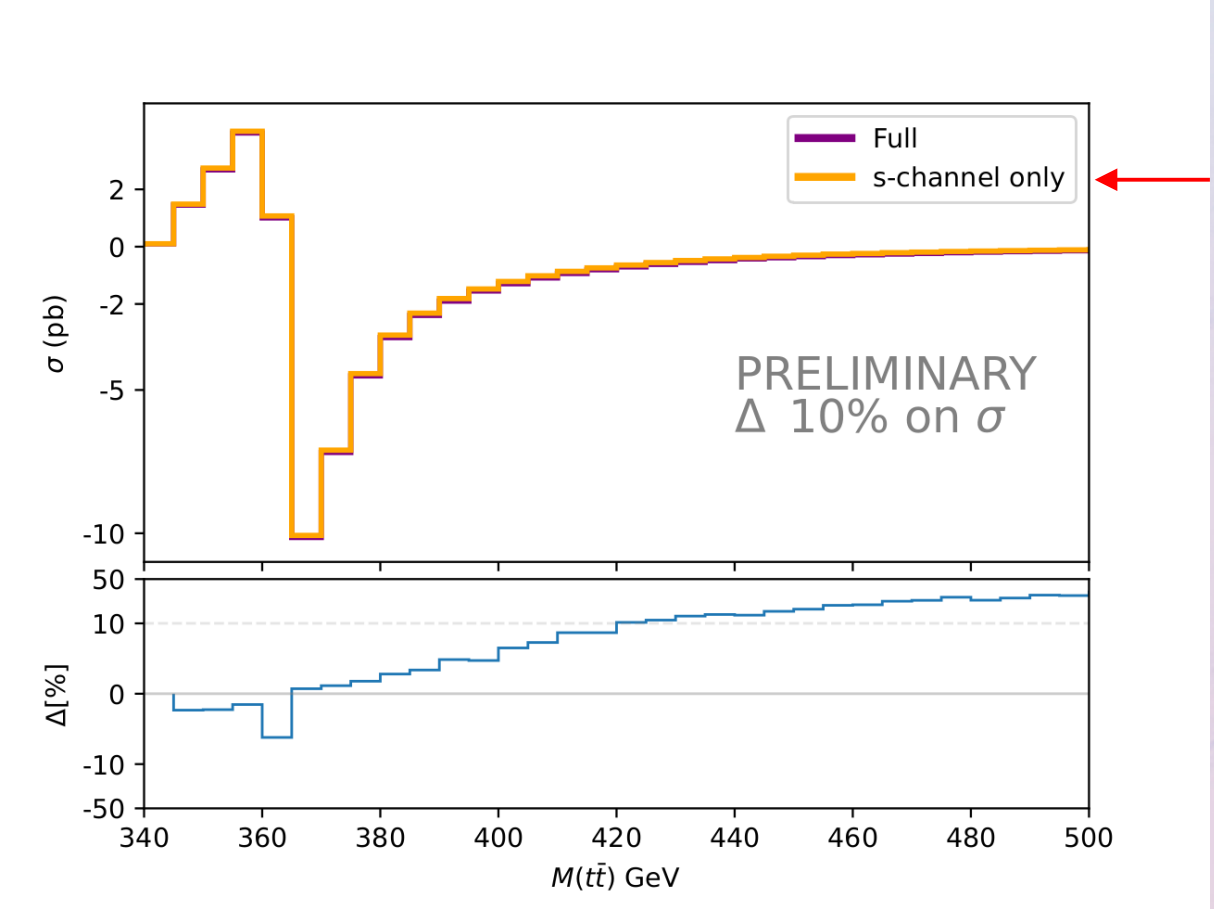
- **Excess in the threshold region**
- **Pseudoscalar hypothesis favored over Scalar**
- **Toponium (η_t) or New Pseudoscalar solve the tension**

Pseudoscalar full virtual corrections



CMS PAS HIG-22-013

Pseudoscalar full virtual corrections



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Full virtual corrections could help disentangle toponium VS pseudoscalar?

Conclusions

Thanks for the attention

NP Virtual Corrections to top-pair production

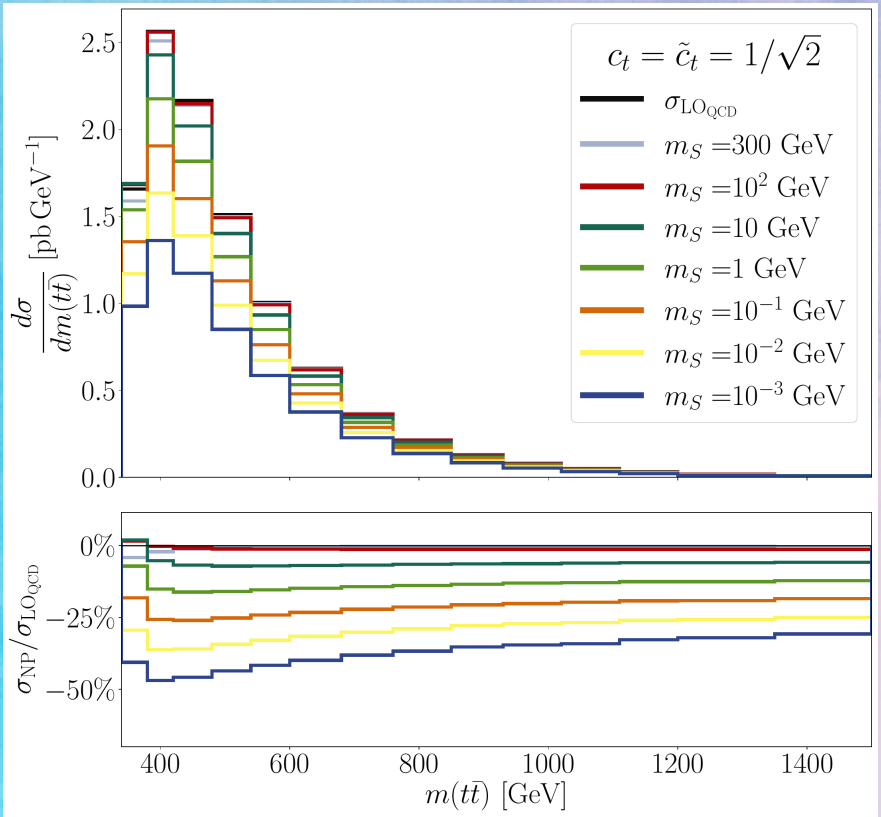
- **Powerful tool to constrain NP**
  - No specific decay assumptions
- **Can unveil elseway elusive particles**
  - ALP
  - Additional Scalars
- **Can be use to fit SM parameters**
  - Higgs anomalous couplings
  - Higgs top Yukawa
- **MG5 UFO implementation**

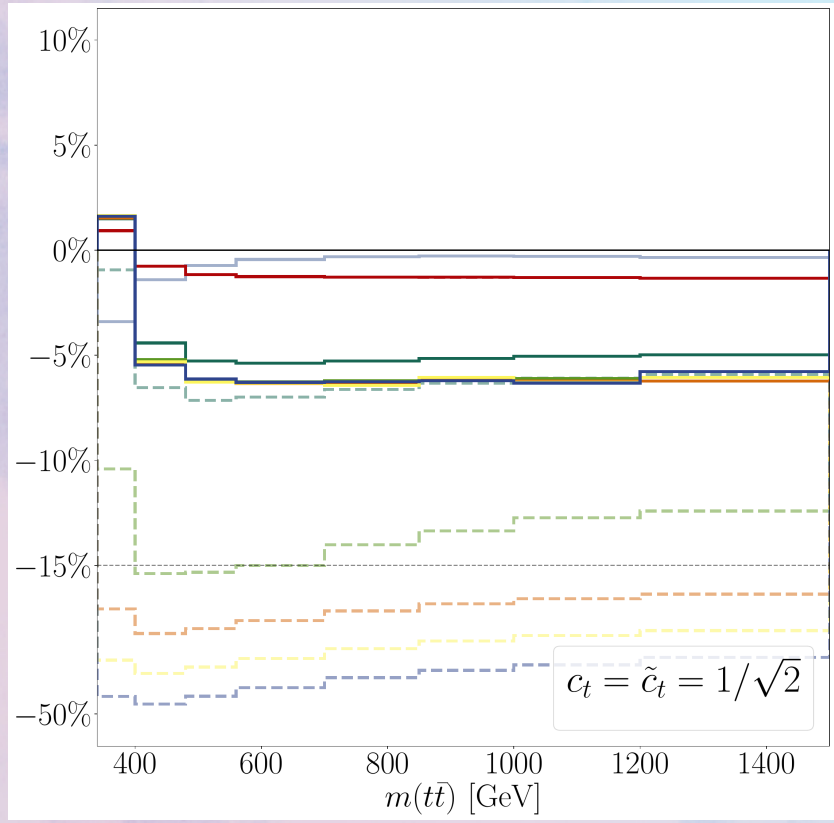
For the future:

- FCC-ee y_t
- Top decay CP information

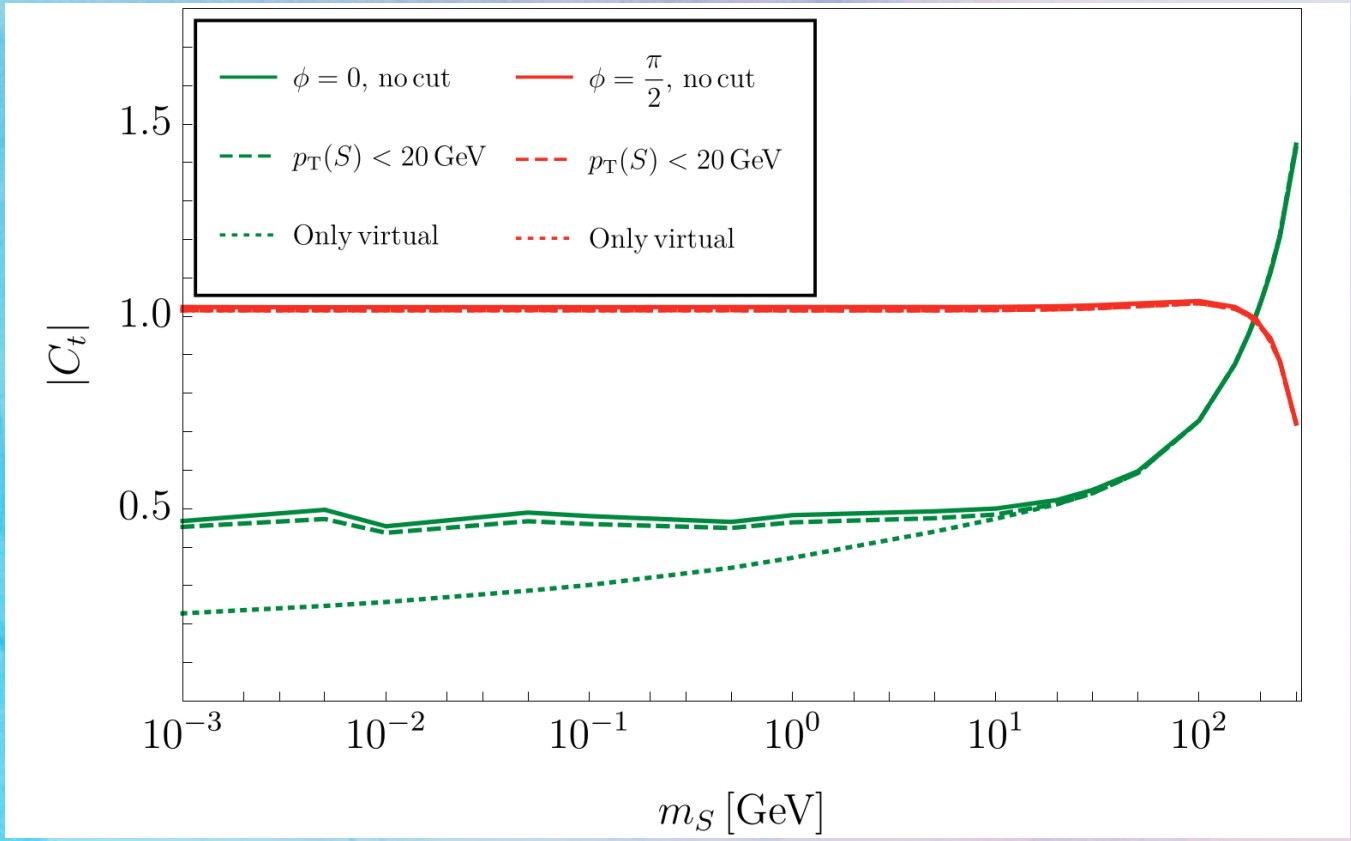
Backup

Mixing the CP





Transverse momentum sensitivity



$$C_t| = \sqrt{c_t^2 + \tilde{c}_t^2}$$

$$\phi = \arctan \frac{\tilde{c}_t}{c_t}$$

FIT INFO:
- Data: SM
- Theory: SM+S(NP)
- Errors and Bins: [CMS: 1803.08856]

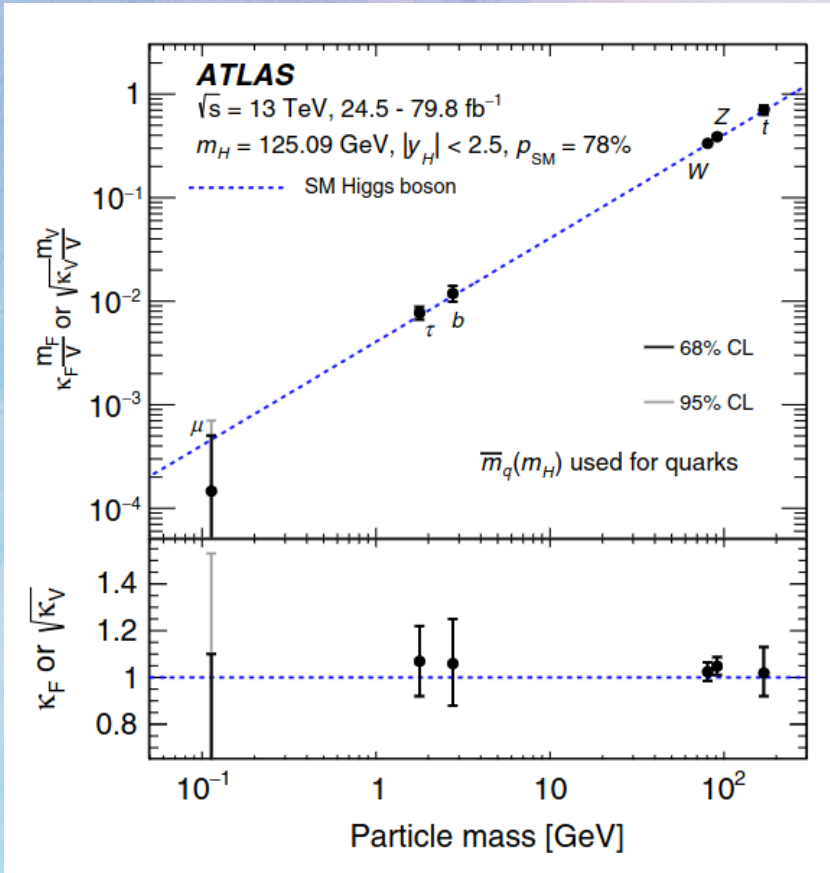
SMEFT Relations

$$\mathcal{L}^{\text{dim}=6}_{\text{SMEFT, top}-\text{Higgs}} \equiv \mathcal{L}_{\text{SM}} + \frac{C^{u\Phi}_{tt}}{\Lambda^2}\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)\overline{\psi}_{Q_{3,L}}\tilde{\Phi}\psi_{t,R} + \text{h.c.}\,,$$

$$\kappa_t = 1 - \frac{v^2}{\Lambda^2}\frac{\Re(C^{u\Phi}_{tt})}{y_t^{\text{SM}}}\,,$$

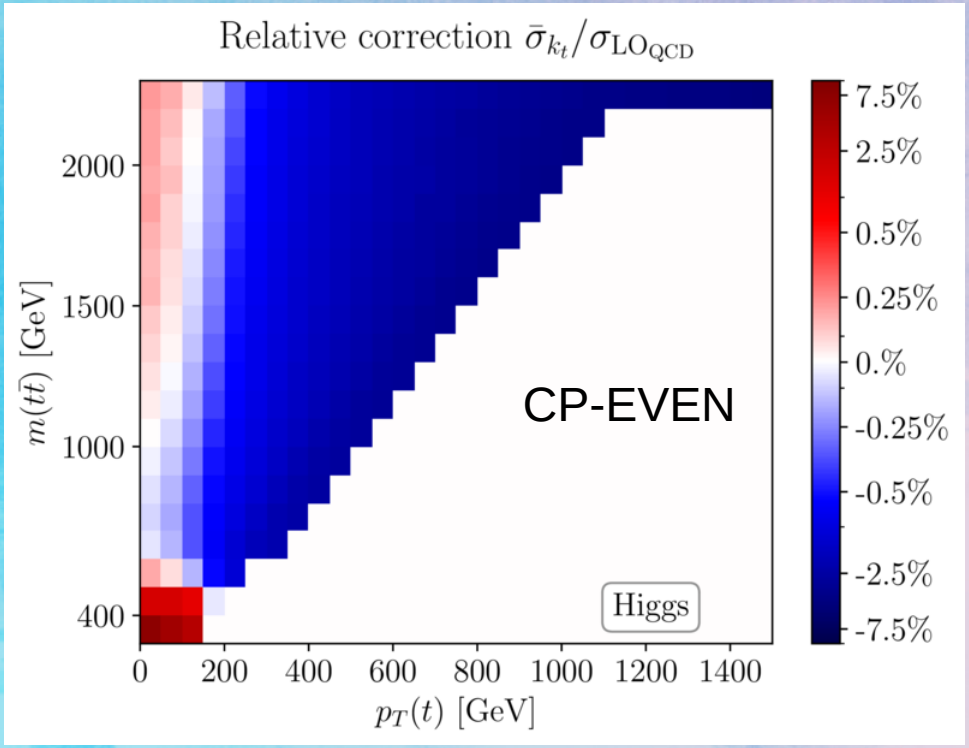
$$\tilde{\kappa}_t = -\frac{v^2}{\Lambda^2}\frac{\Im(C^{u\Phi}_{tt})}{y_t^{\text{SM}}}\,.$$

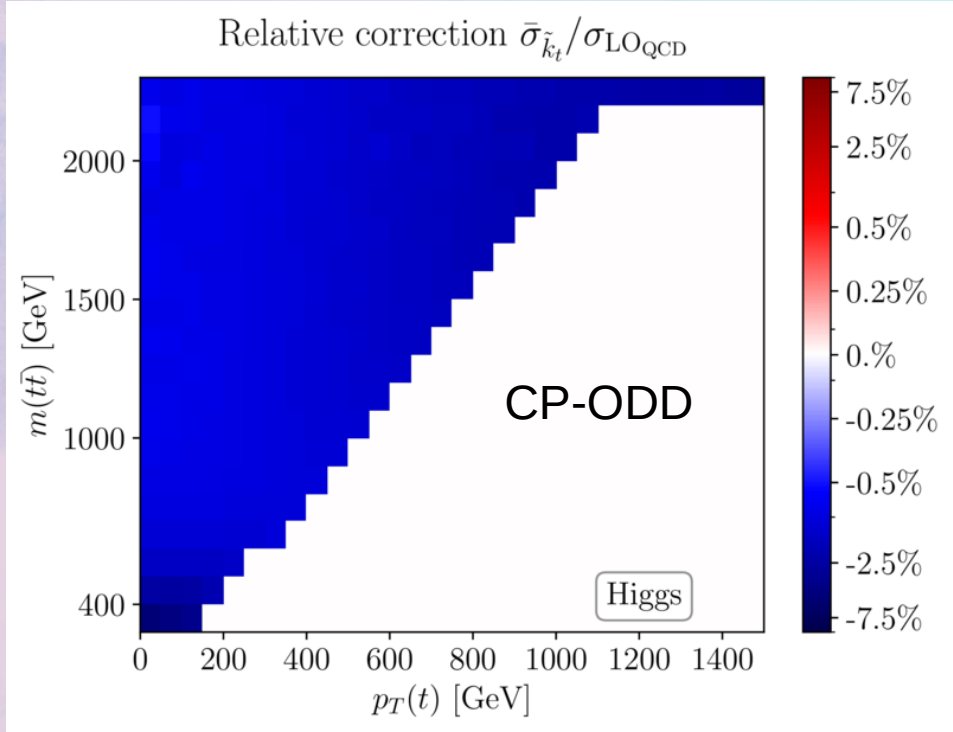
Higgs couplings state



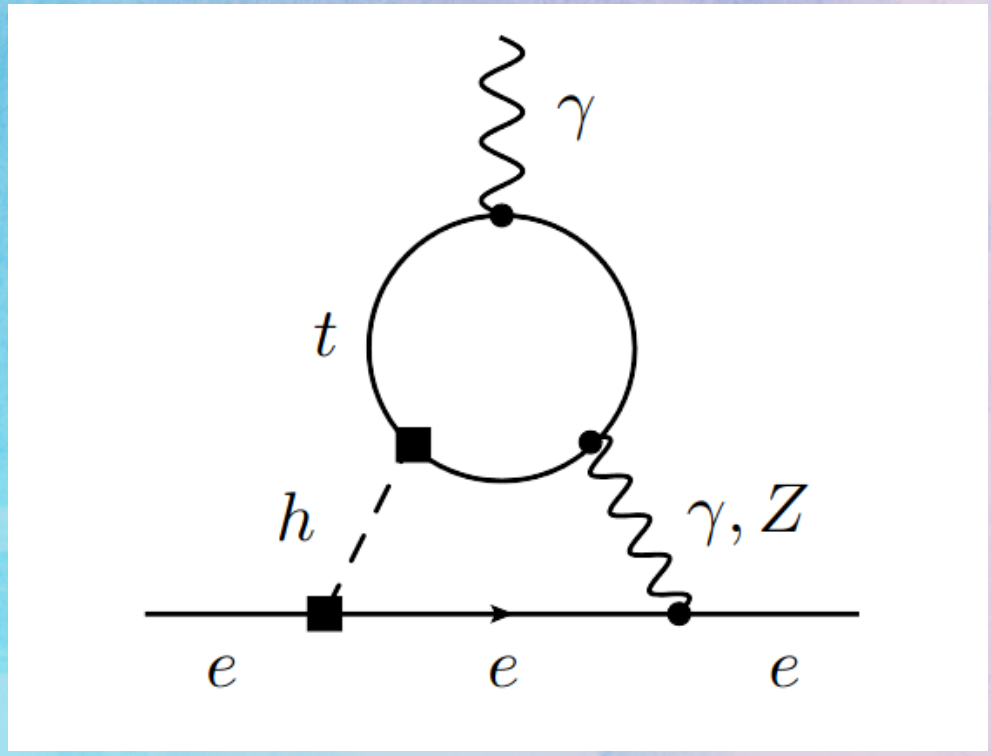
[ATLAS: 1909.02845]

Double differential





Indirect Searches: electron EDM



Brod, Haisch, Zupan: [1310.1385]

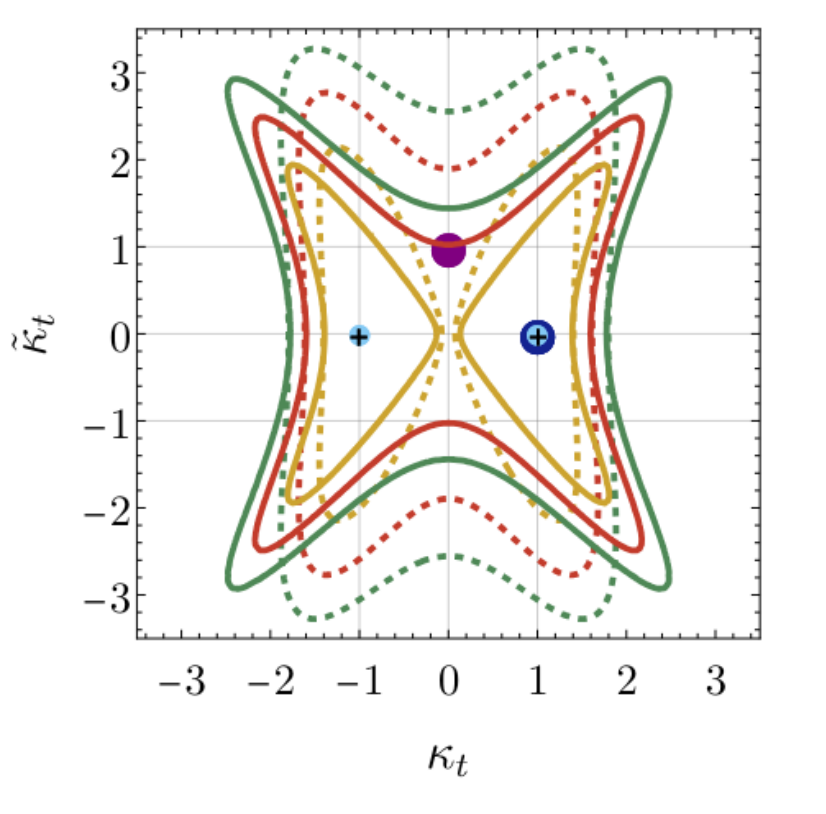
Extremely precise measurement:

- $|\widetilde{k_t}|<0.01$

Additional assumption:

- **Higgs couples to SM electron**
- $|\widetilde{k_e}|=0$, $|k_e|=1$
- **Possible One Loop NP effects**

Fit comparison



— Full corrections

--- No s-channel

— 1σ bound

— 2σ bound

— 3σ bound

• CP-even Higgs (SM)

• CP-odd Higgs

• Best Fit

+ Best Fit: no s-channel

The view from the ALPs

$$\mathcal{L} = \frac{c_t}{2}\frac{\partial_\mu a}{f_a}\bar{t}\gamma^\mu\gamma^5 t$$

Equations of motion

SEE ALSO:
[Esser. Madigan, Sanz, Ubiali, 2303.17634]
[Vu Phan, Westhoff, 2312.00872]
[Rygaard, Niedziela, Schäfer, Bruggisser, Alimena, Westhoff, Blekman, 2306.08686]
[Blasi, Maltoni, Mariotti, Mimasu, Pagani, **ST** 2311.16048]

ALP = Pseudoscalar term + Contact term → **Naturally supressed diphoton decay**

$$\mathcal{L}_{\text{equiv.}} = -ic_t\frac{m_t}{f_a}a\bar{t}\gamma_5 t + c_t\frac{\alpha_S}{8\pi}\frac{a}{f_a}G\tilde{G} + \text{E.W.terms}$$

TOP-ALP vs Pseudoscalar

$$a \to gg(\gamma\gamma)$$

Blasi, Maltoni, Mariotti, Mimasu, Pagani, **ST** [23XX.XXXX]
Bauer, Neubert, Thamm [1708.00443]

$$\Gamma \propto \left[1 + 2m_t^2 C(p,q,m_t)\right]^2$$

Only contact interaction

Only Pseudoscalar

$2m_t > m_a$

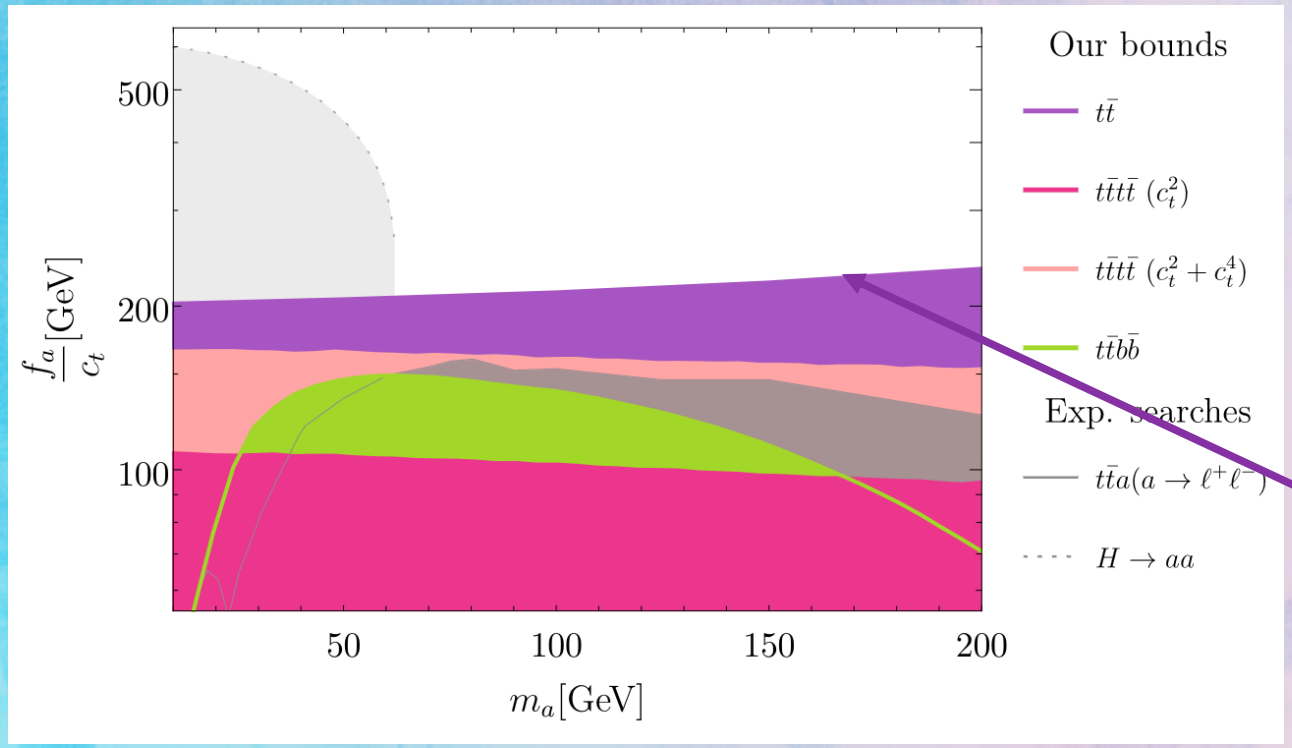
$$\Gamma \propto \left[1 + 2m_t^2\left(-\frac{1}{2m_t^2} - \frac{m_a^2}{24m_t^4}\right)\right]^2$$

Cancellation between contact interaction and pseudoscalar!

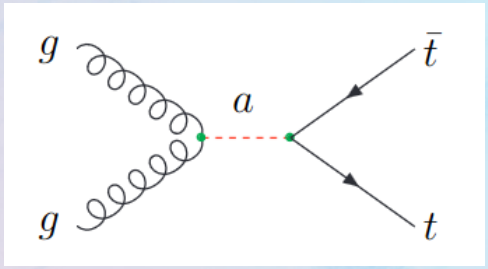
$$\Gamma \propto \frac{m_a^4}{144 m_t^4}$$

Super-suppressed w.r.t. single terms

Bounds on Axion Like Particles (ALP) couplings



One additional diagram:



Purple Line:
-Virtual corrections to $t\bar{t}$ production

BEST BOUND!!

[Blasi, Maltoni, Mariotti, Mimasu, Pagani, **ST** 2311.16048]

ALP: PT Comparison