# ALP effects in top-pair production

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LHC TOP WG meeting, 30 Nov 2023

Radboud University
Nikhef

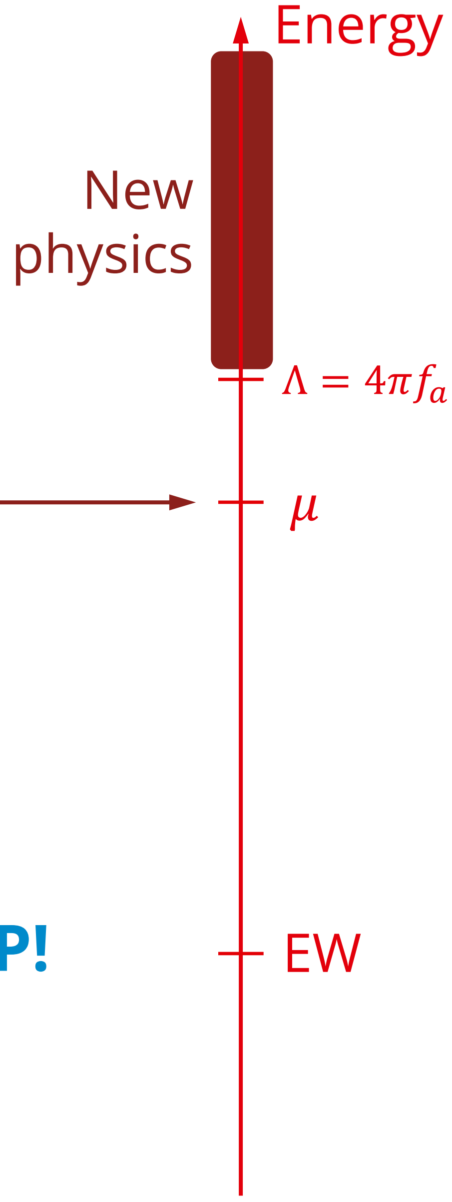
Georgi, Kaplan, and Randall (1986)

# AXION-LIKE PARTICLE (ALP)

- Generalization of the axion (a pseudo-scalar)

$$\mathcal{L}_{\text{eff}}(\mu) \supset \frac{1}{2}\partial_\mu a\, \partial^\mu a - \frac{m_a^2}{2}a^2 - \sum_q m_q c_{qq}\frac{a}{f_a}\bar{q}i\gamma^5 q + \tilde{c}_{GG}\frac{a}{f_a}\frac{\alpha_s}{4\pi}G^A_{\mu\nu}\tilde{G}^{A,\mu\nu}$$

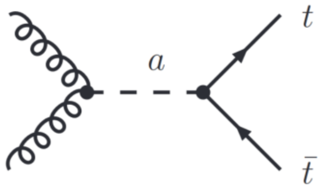

**top is most sensitive to ALP!**



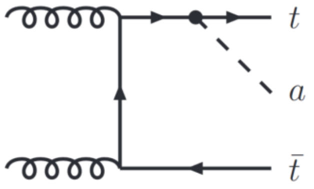
# ALP EFFECTS IN TOP-PAIR PRODUCTION

Leading contributions

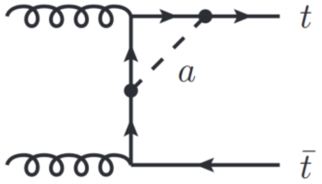
Tree-level




Real ALP radiation



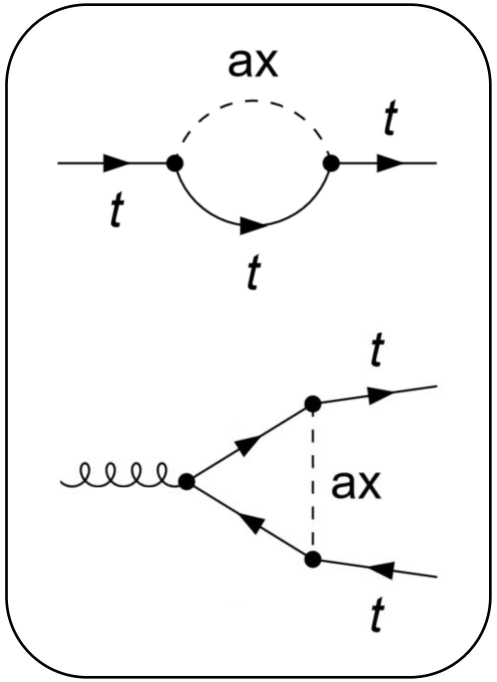

Virtual corrections



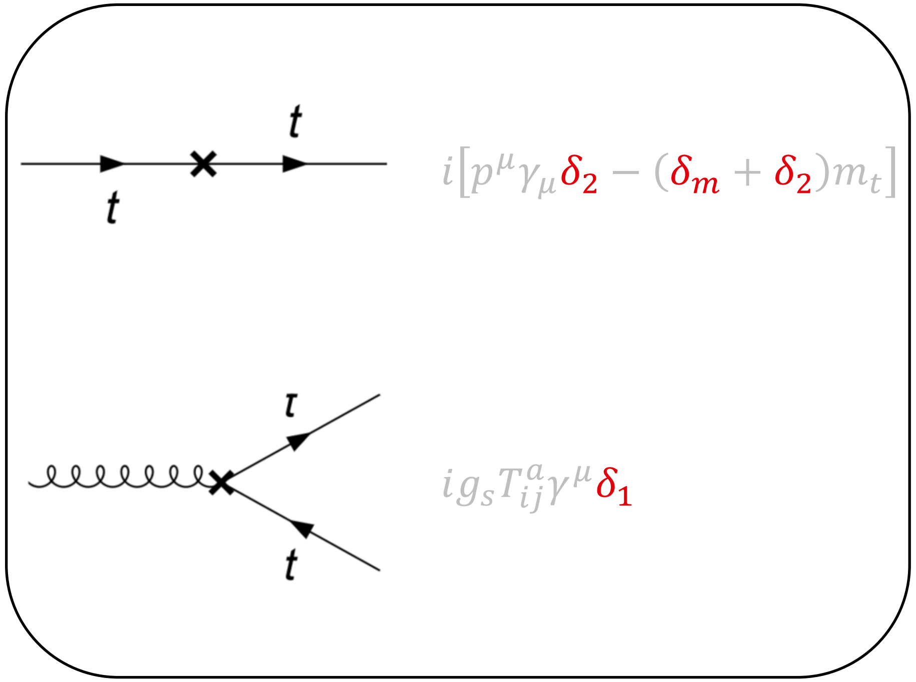

→ Need renormalization

# RENORMALIZATION (SIMPLIFIED)

$$\mathcal{L}_{\text{eff}}(\mu) \supset Z_2 \bar{t} i \partial_\mu \gamma^\mu t - Z_2 Z_m m_t \bar{t} t + Z_1 g_s G_\mu^a \bar{t} \gamma^\mu T^a t$$



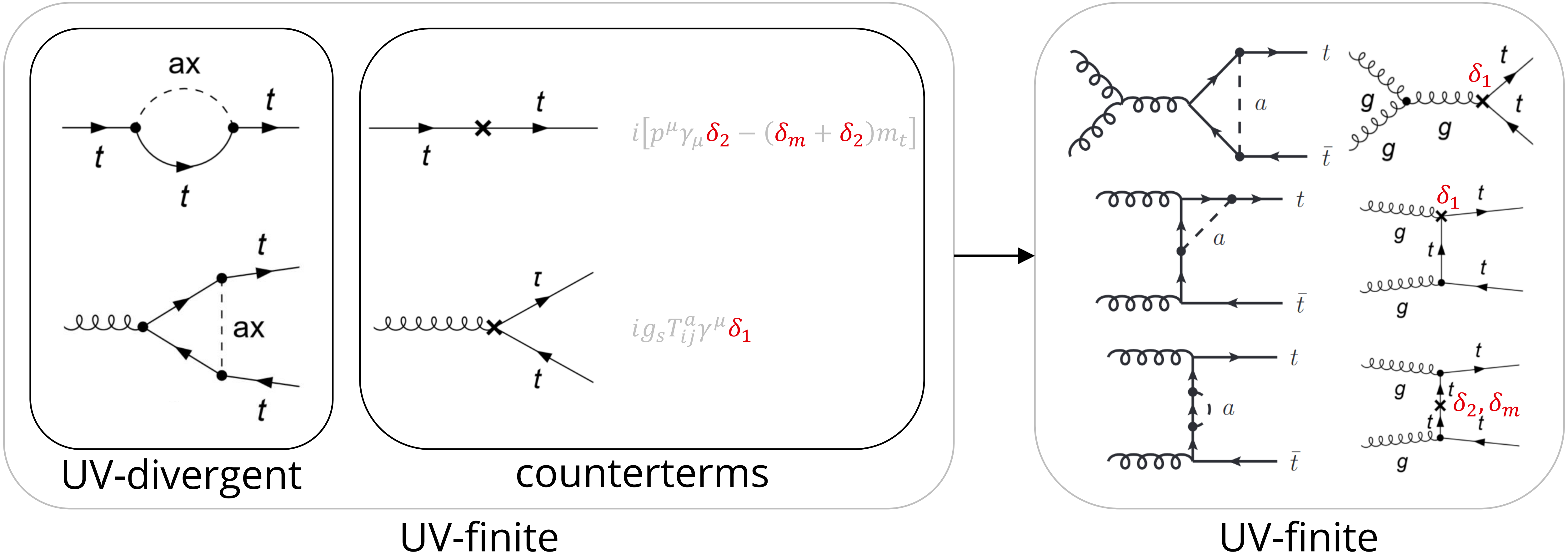

UV-divergent




counterterms

# RENORMALIZATION (SIMPLIFIED)

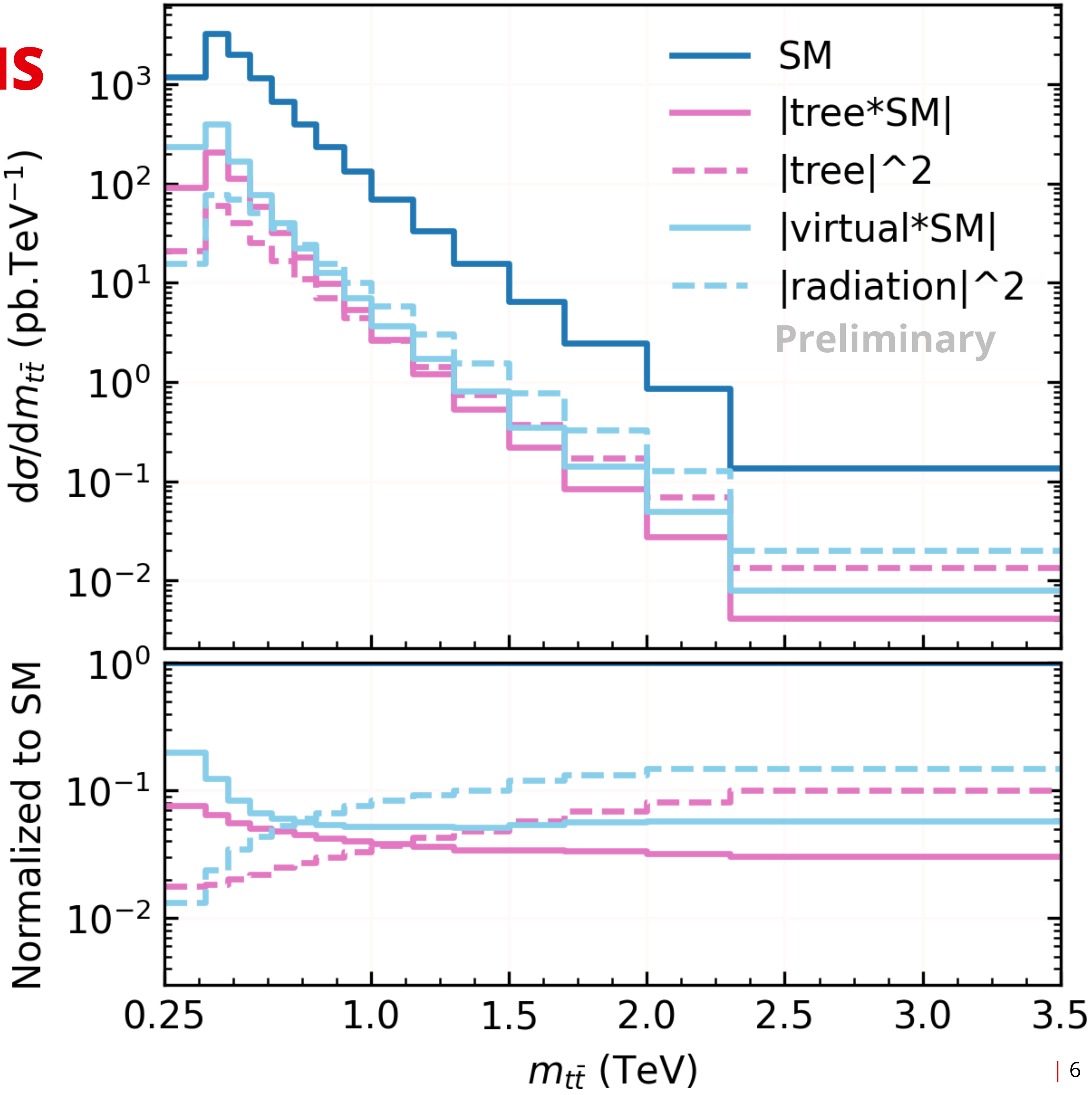
$$\mathcal{L}_{\text{eff}}(\mu) \supset Z_2 \bar{t} i \partial_\mu \gamma^\mu t - Z_2 Z_m m_t \bar{t} t + Z_1 g_s G^a_\mu \bar{t} \gamma^\mu T^a t$$



# INDIVIDUAL CONTRIBUTIONS

SM: PRD 104 (2021) 092013

$$\frac{c_{tt}(\Lambda)}{f_a} = 20\ \mathrm{TeV}^{-1}\,;\, c_{GG}(\Lambda) = 0\,;\, m_a = 10\ \mathrm{GeV}$$



# INDIVIDUAL CONTRIBUTIONS

SM: PRD 104 (2021) 092013

Virtual ALP and tree-level interferences with SM are negative

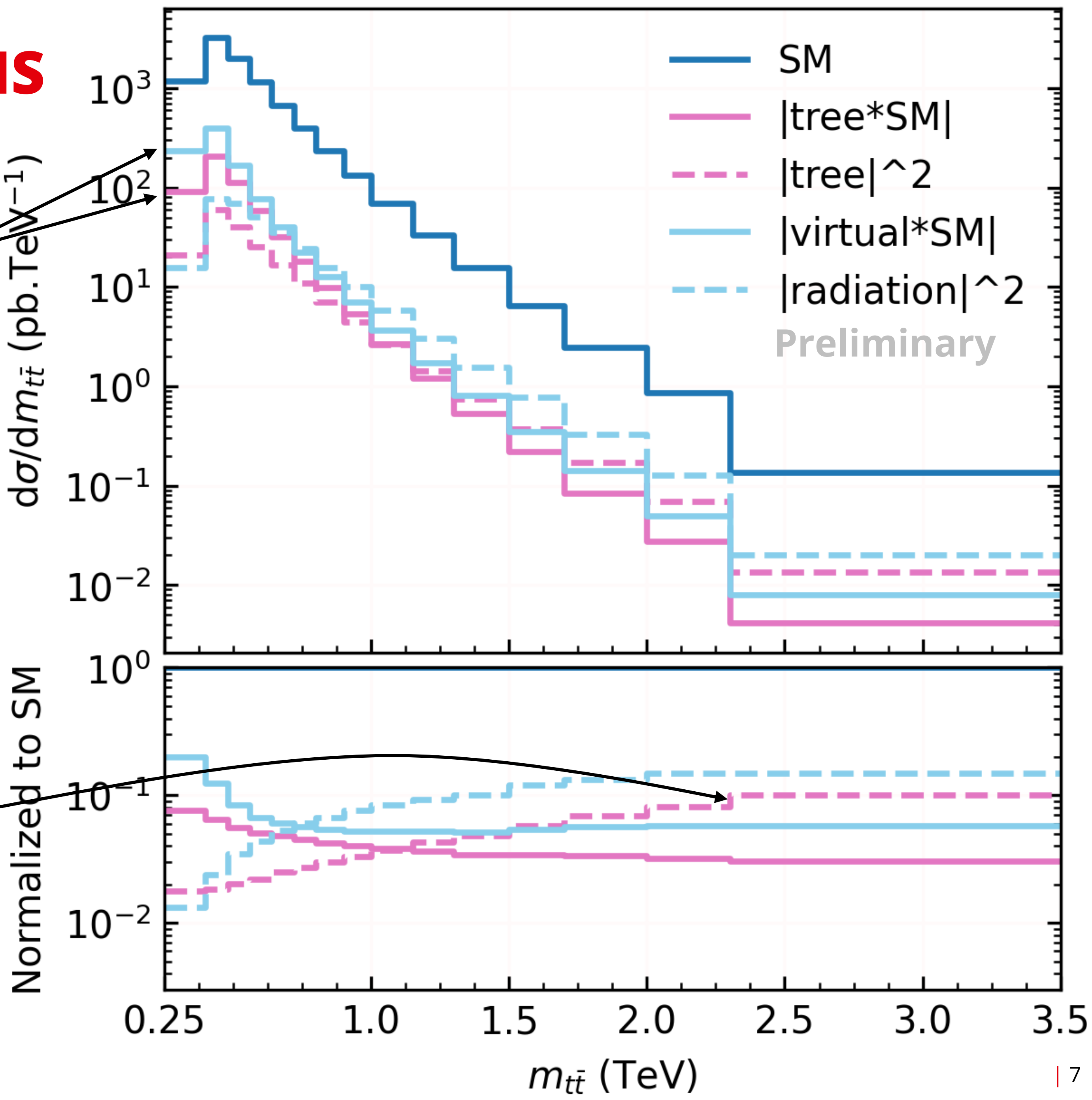
$$c_{GG} = \tilde{c}_{GG} - \frac{1}{2} c_{tt}$$

$$\frac{c_{tt}(\Lambda)}{f_a} = 20\ \mathrm{TeV}^{-1}\,;\, c_{GG}(\Lambda) = 0\,;\, m_a = 10\ \mathrm{GeV}$$

New Physics scale $\Lambda = 4\pi f_a$

Energy enhancement in |tree-level|^2

$$\sigma_{|\mathrm{ALP}|^2}(s) \sim \frac{1}{s}\frac{m_t^2 s}{f_a^4}$$



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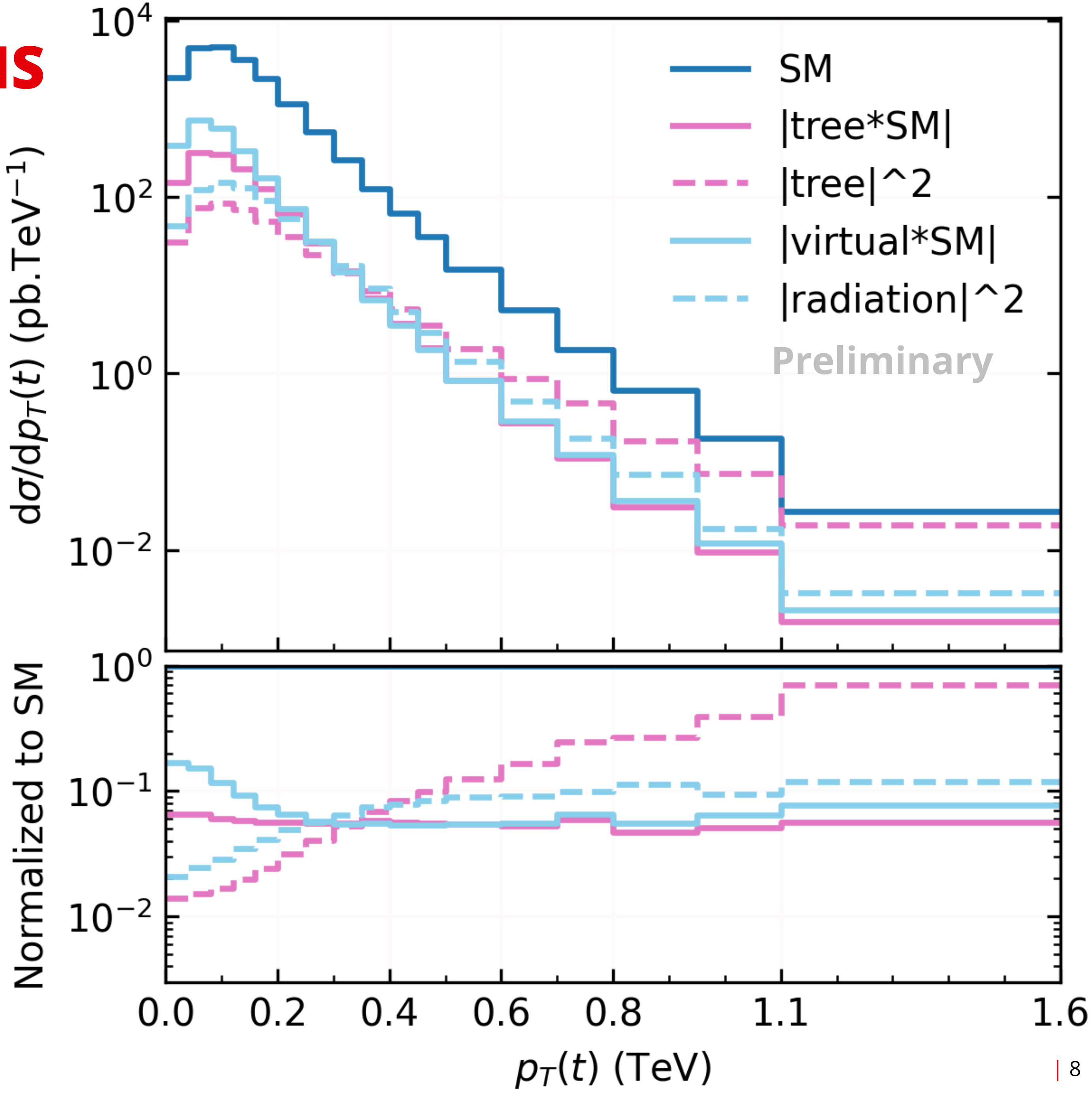
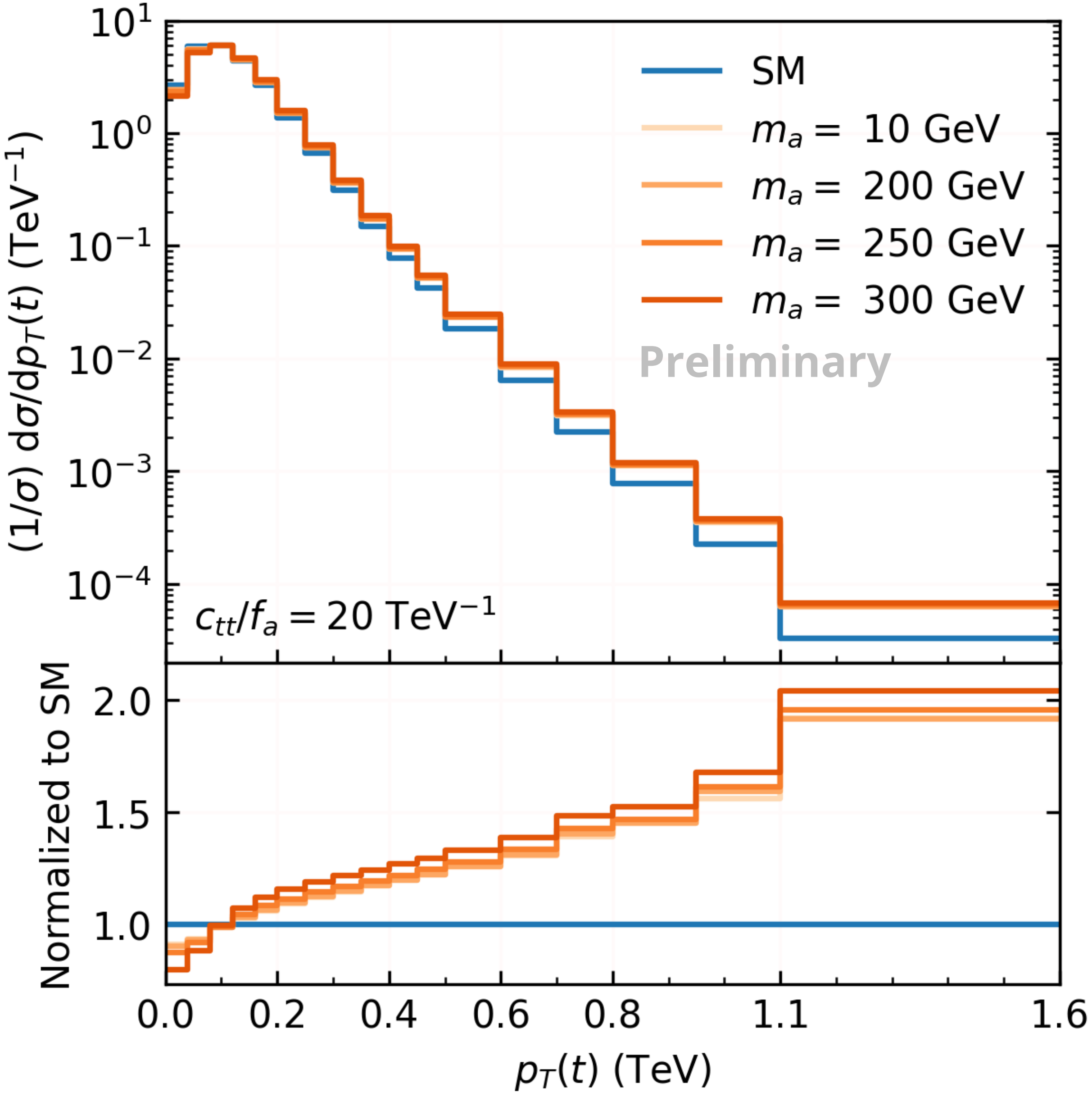
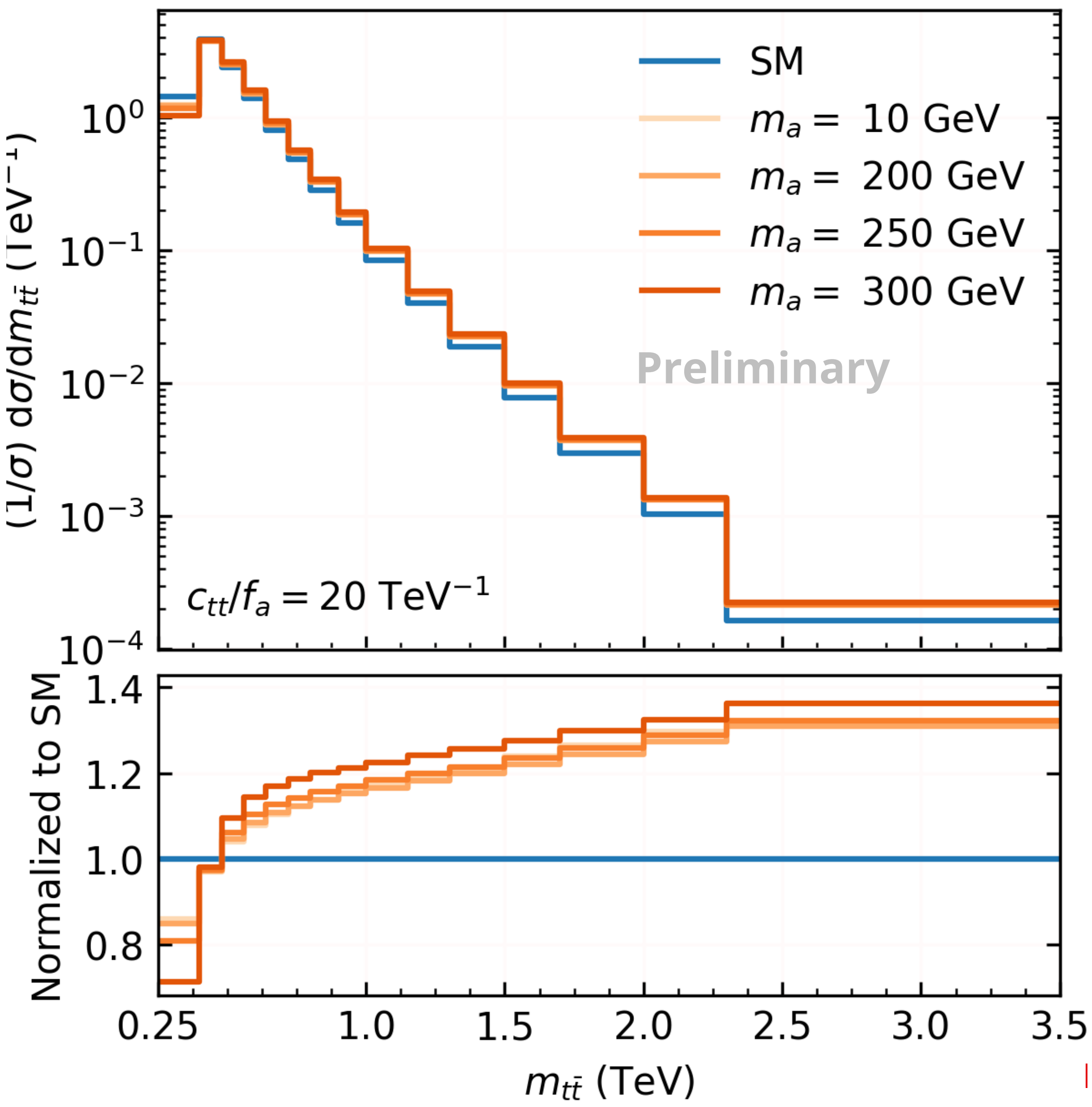


# ALP MASS DEPENDENCE

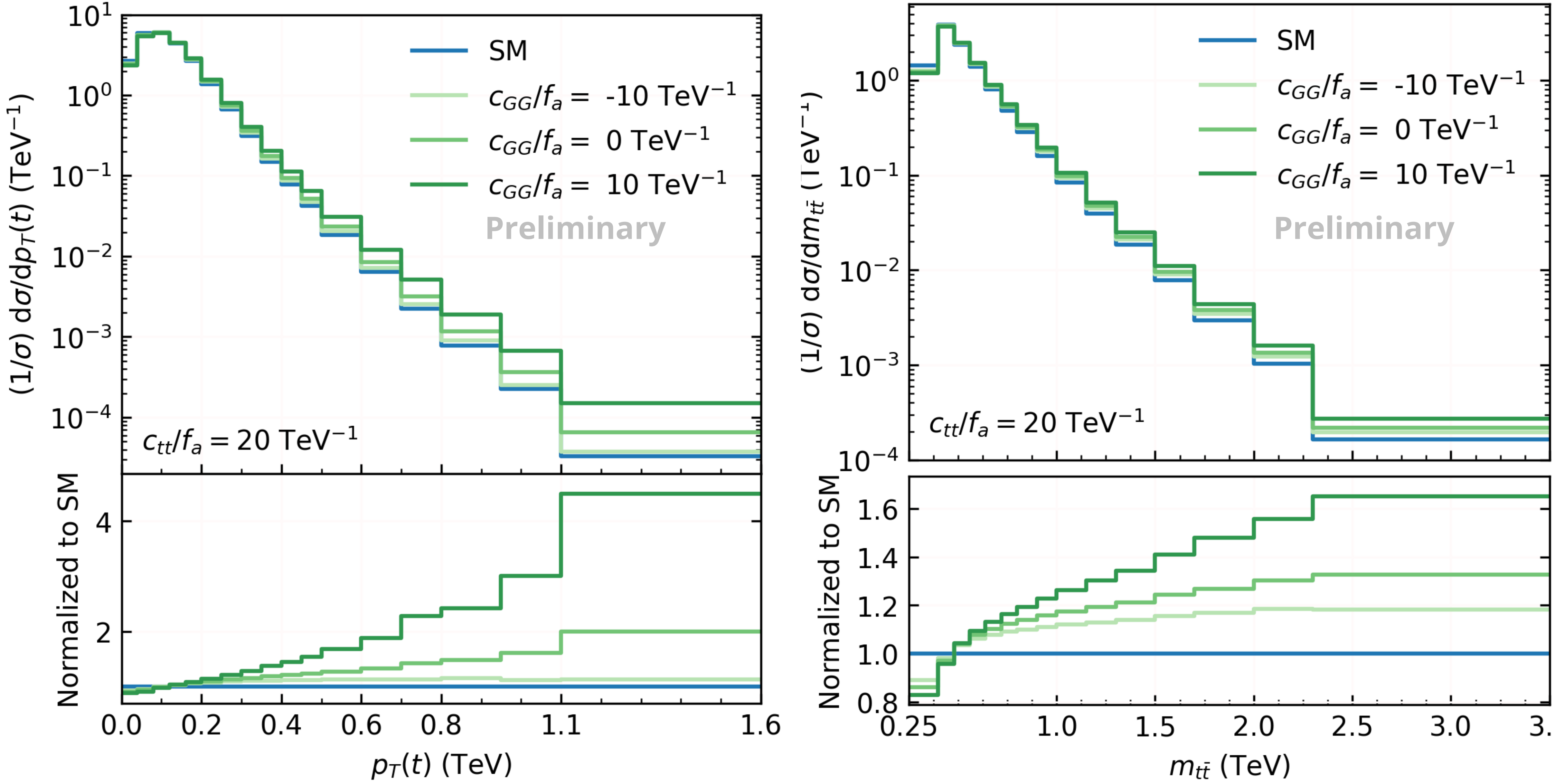
$$\frac{c_{tt}(\Lambda)}{f_a} = 20\ \mathrm{TeV}^{-1}\,;\, c_{GG}(\Lambda) = 0$$



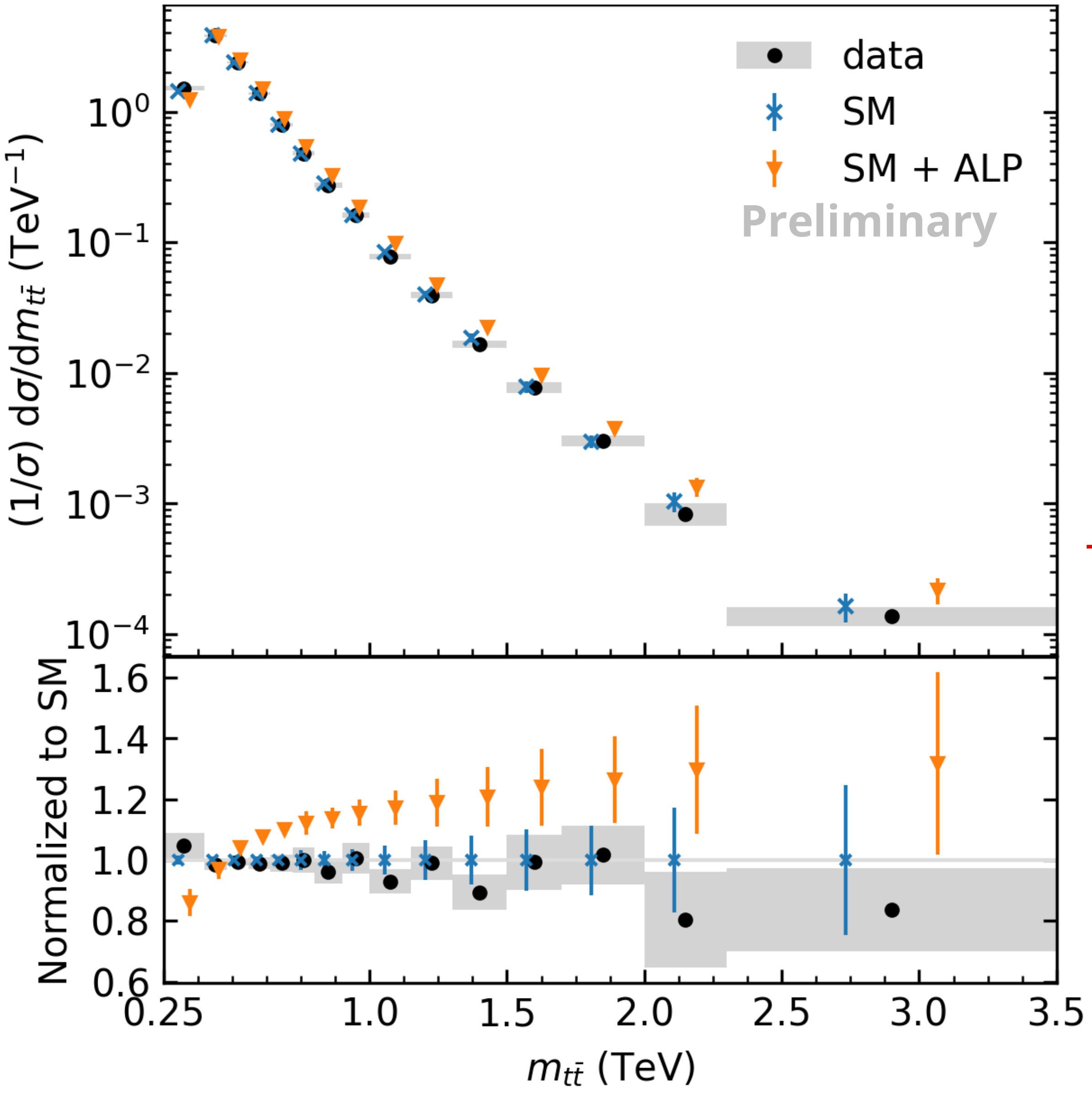
# $c_{GG}(\Lambda)$ DEPENDENCE

$$\frac{c_{tt}(\Lambda)}{f_a} = 20\ \text{TeV}^{-1}\ ; m_a = 10\ \text{GeV}$$



$$\frac{c_{tt}(\Lambda)}{f_a} = 20\ \mathrm{TeV}^{-1}\,;\, c_{GG}(\Lambda) = 0\,;\, m_a = 10\ \mathrm{GeV}$$

Data: PRD 104 (2021) 092013
ALP uncertainty: 10%



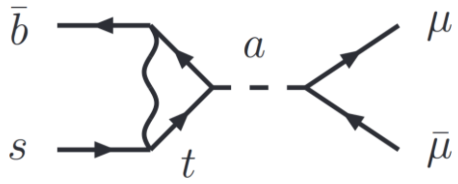

Fit to CMS data →

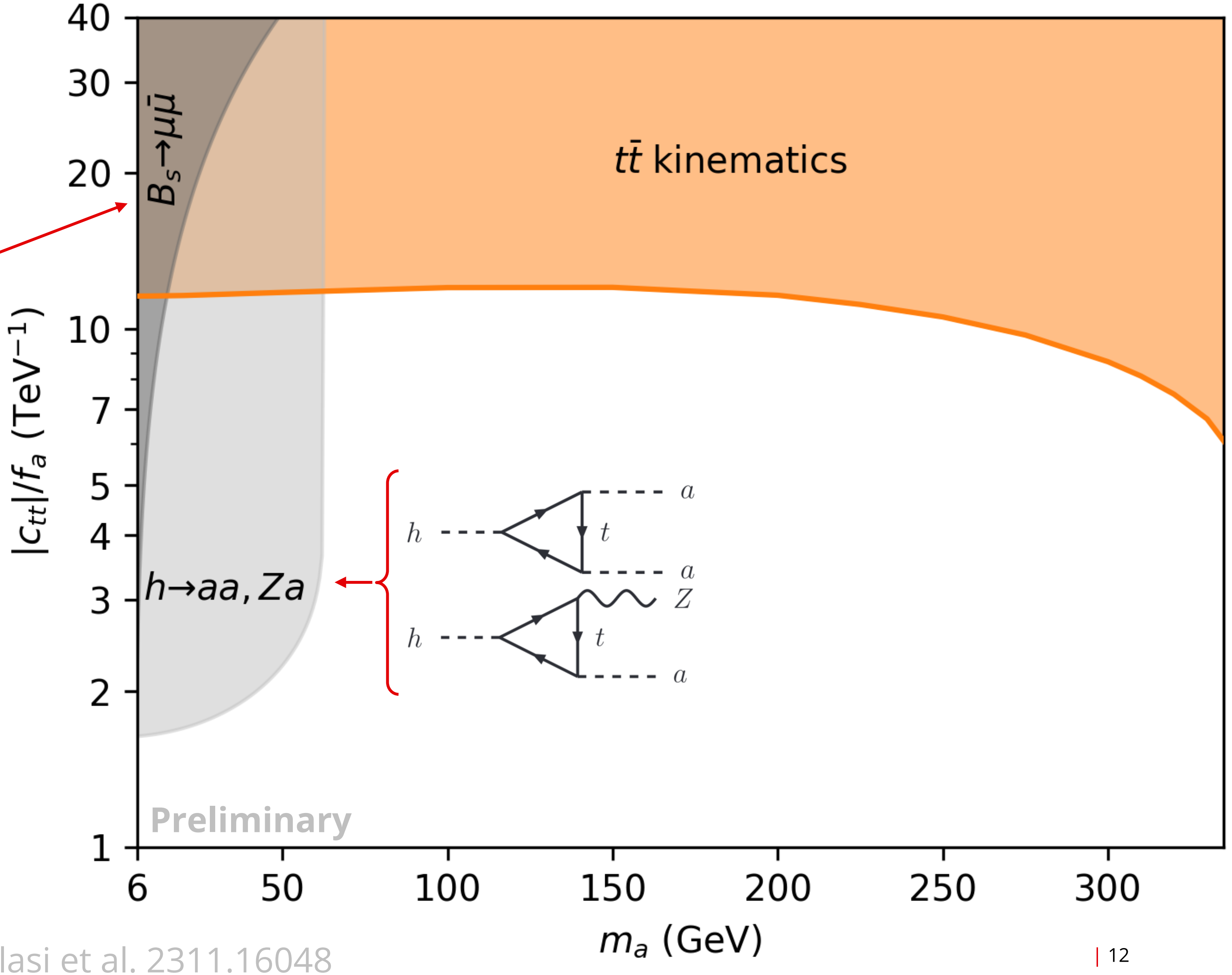
$$\left|\frac{c_{tt}(\Lambda)}{f_a}\right| \leq 11.1\ \mathrm{TeV}^{-1}$$

(95% C.L.)

# BOUNDS ON $c_{tt}$

$c_{GG}(\Lambda) = 0$



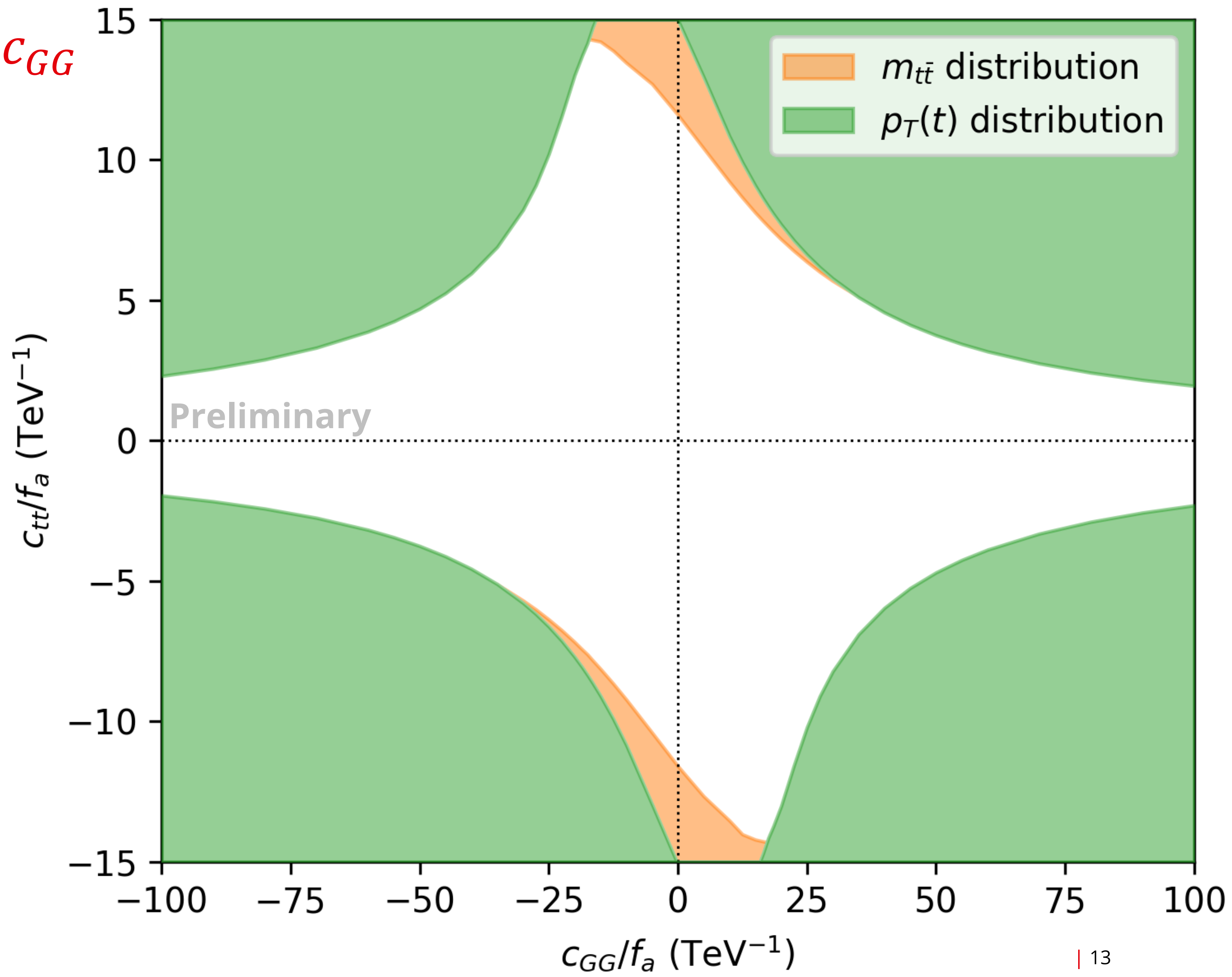




Shaded = excluded at 95% C.L.

Ref:
Bauer et al. (2021),
PDG (2023),
CMS-BPH-21-006,
DESY-14-026
t-tbar, four-top, ALP resonances: Blasi et al. 2311.16048

# BOUNDS ON $c_{tt}$ AND $c_{GG}$

$m_a = 10$ GeV



# Conclusions

- Among the SM fermions, **top is most sensitive to ALPs**.
- We constrain the ALP-top coupling using top kinematic distributions.
- $\left|\frac{c_{tt}}{f_a}\right| \leq 11 \text{ TeV}^{-1}$ (for $m_a \lesssim 200$ GeV and $c_{GG} = 0$)
- ALP effect is stronger as $m_a$ approaches $2m_t$.
- The sensitivity to the ALP-top coupling strongly depends on the ALP-gluon coupling.

# Thank you for listening!

# BACKUP SLIDES

# FITTING METHOD

Höcker et al. (2001); Charles et al. (2017 )

## RFit

Minimize the log-likelihood function

$$\chi^2(c_{tt}) = \vec{\chi}_d^T C^{-1} \vec{\chi}_d$$

Experimental covariance matrix

$\chi_{d,i} = |\mathrm{data_i} - \mathrm{prediction_i}|$

1. For each value of $c_{tt}$
   1. Let all $\mathrm{prediction_i}$ vary within their theoretical uncertainty range
   2. Find $\chi^2_{\min}(c_{tt})$, the minimum of $\chi^2(c_{tt})$ w.r.t all possible values of $\mathrm{prediction_i}$
2. Find $\chi^2_{\min} = \min\limits_{c_{tt}} \chi^2_{\min}(c_{tt})$
3. A value of $c_{tt}$ is excluded at 95% C.L. if $\Delta\chi^2(c_{tt}) = \chi^2_{\min}(c_{tt}) - \chi^2_{\min} \geq 3.84$.
   (For $c_{GG}$-$c_{tt}$ fit, we assume 2 d.o.f)
4. Best bound of all distributions is selected

RESULTS

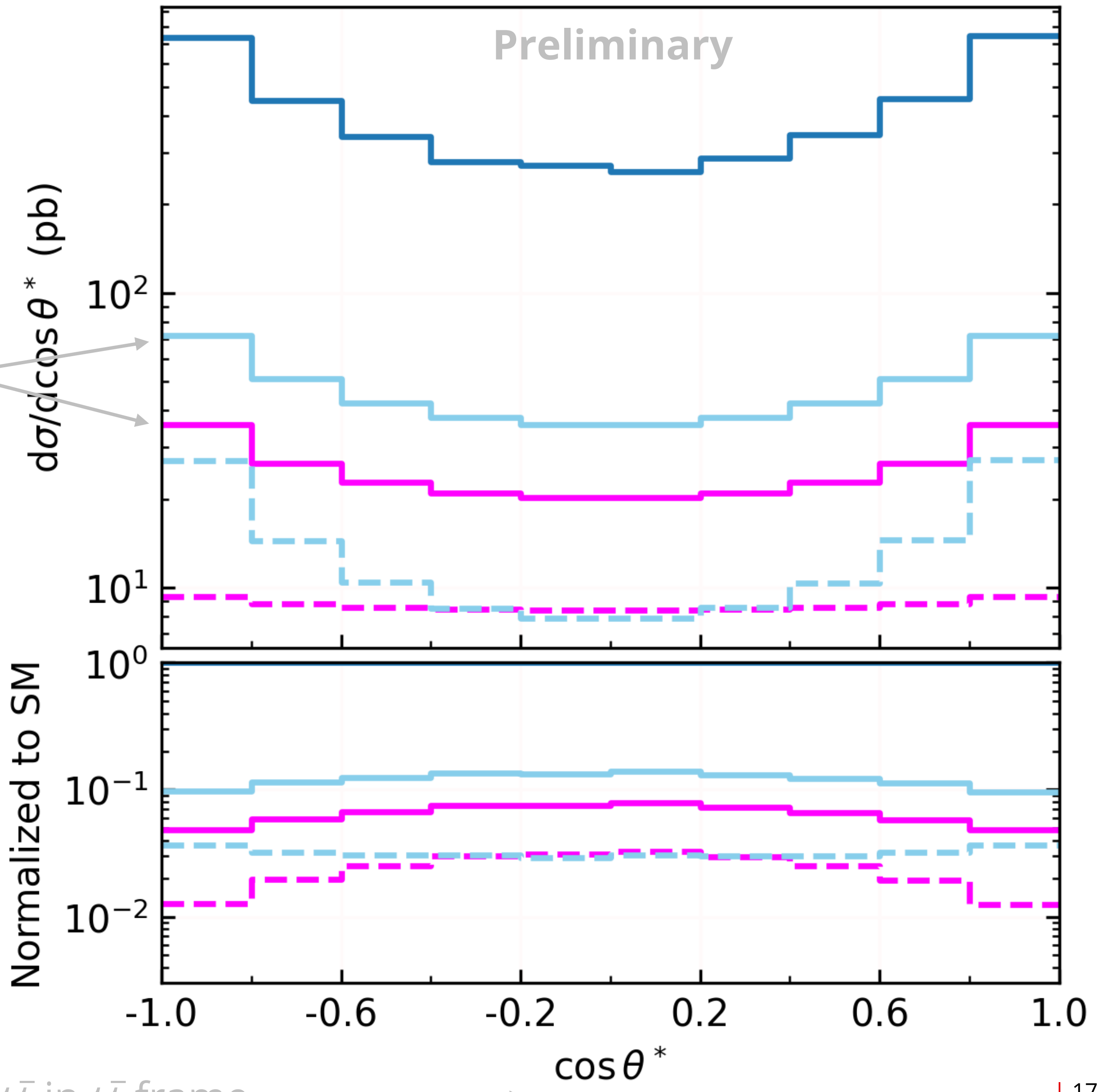
# INDIVIDUAL CONTRIBUTIONS

SM: PRD 104 (2021) 092013

Virtual ALP and tree-level interferences with SM are negative

$$\frac{c_{tt}(\Lambda)}{f_a} = 20\ \text{TeV}^{-1}\,;\, c_{GG}(\Lambda) = 0\,;\, m_a = 10\ \text{GeV}$$

New Physics scale $\Lambda = 4\pi f_a$




Angle between top and $t\bar{t}$ in $t\bar{t}$ frame

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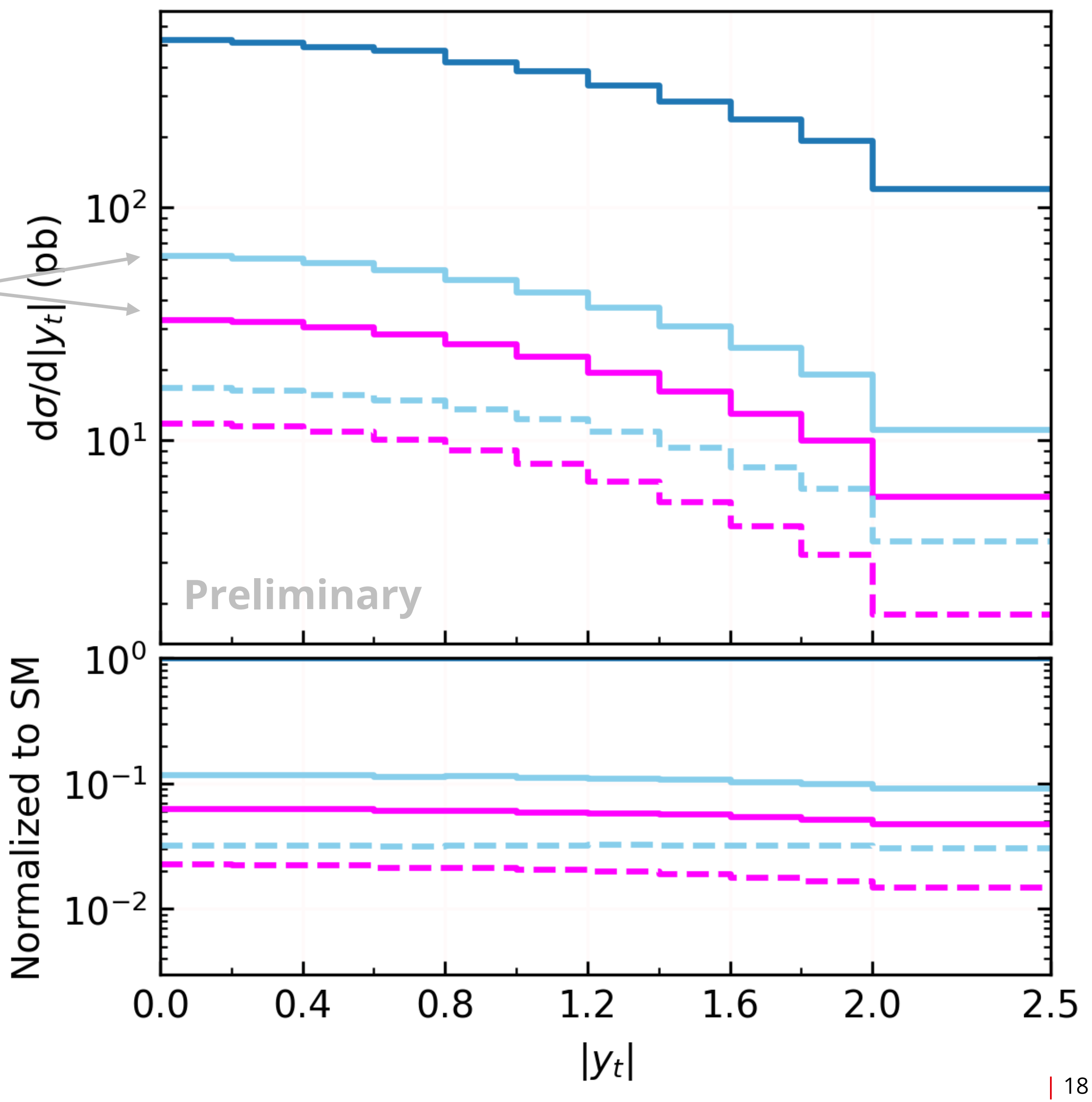

RESULTS

# ALP MASS DEPENDENCE

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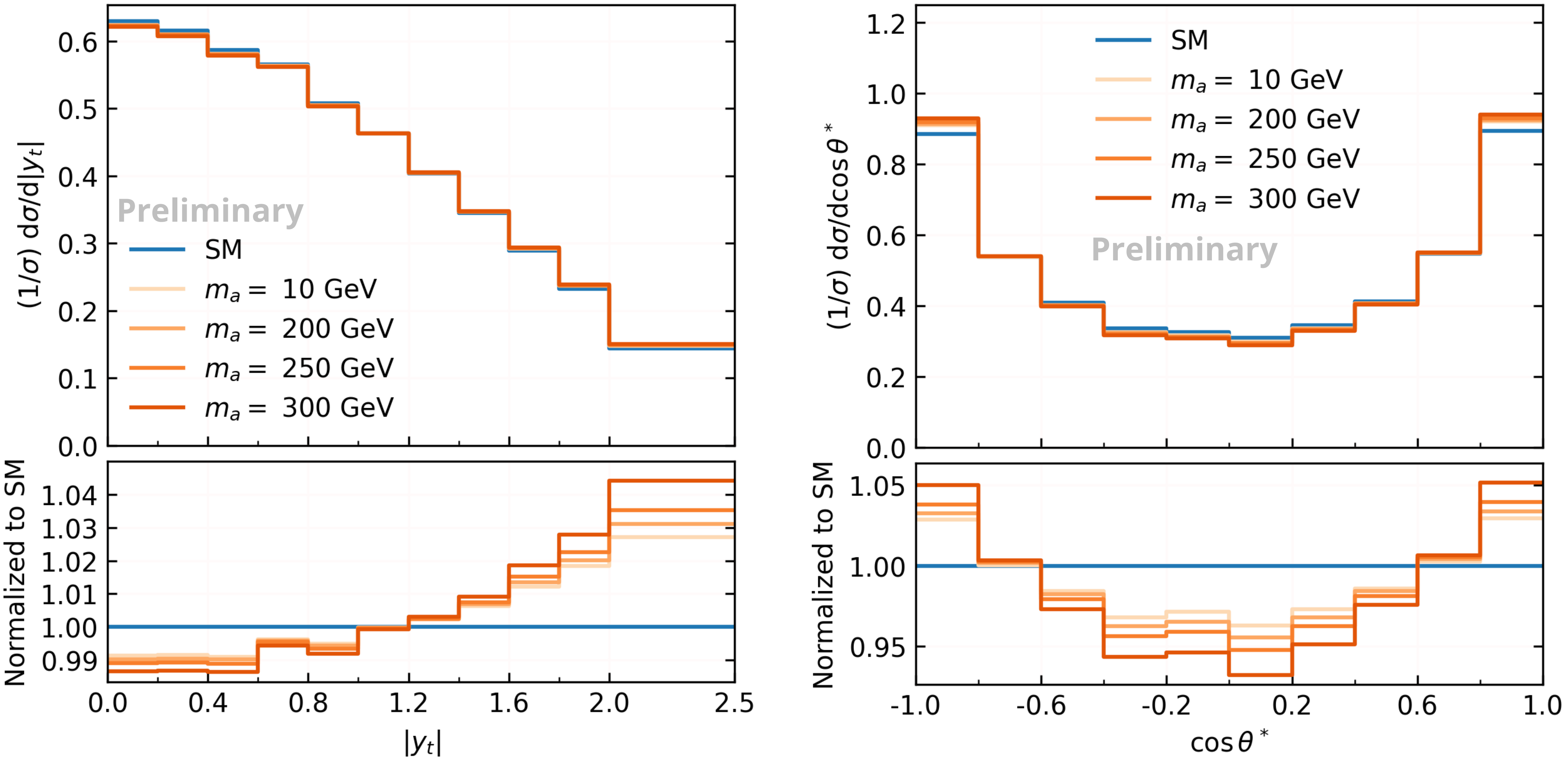
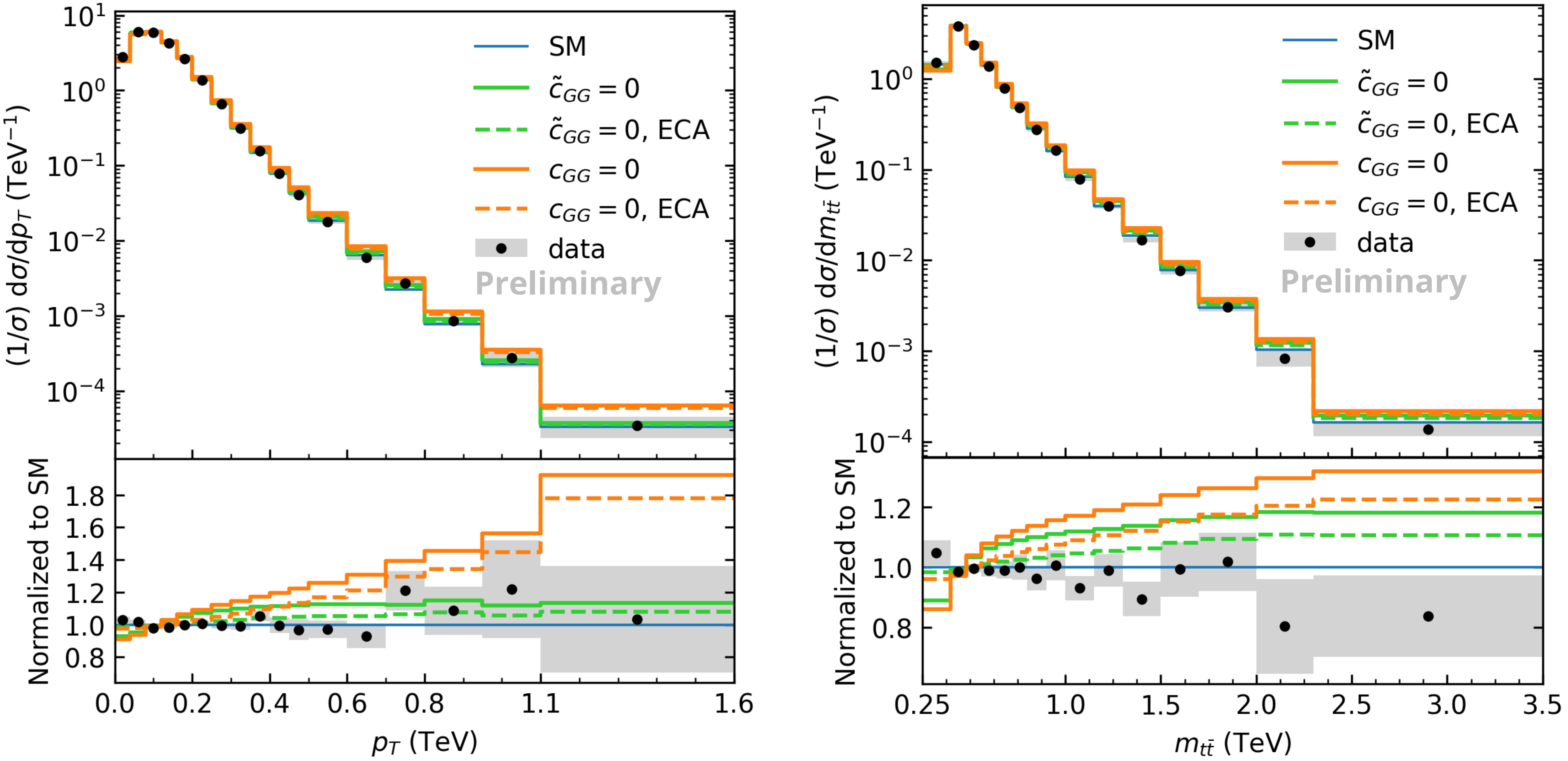


RESULTS

# EFFECTIVE COUPLING APPROXIMATION

$$\frac{c_{tt}(\Lambda)}{f_a} = 20\ \mathrm{TeV}^{-1}\,;\, m_a = 10\ \mathrm{GeV}$$



Data: PRD 104 (2021) 092013
ALP uncertainty: 10%

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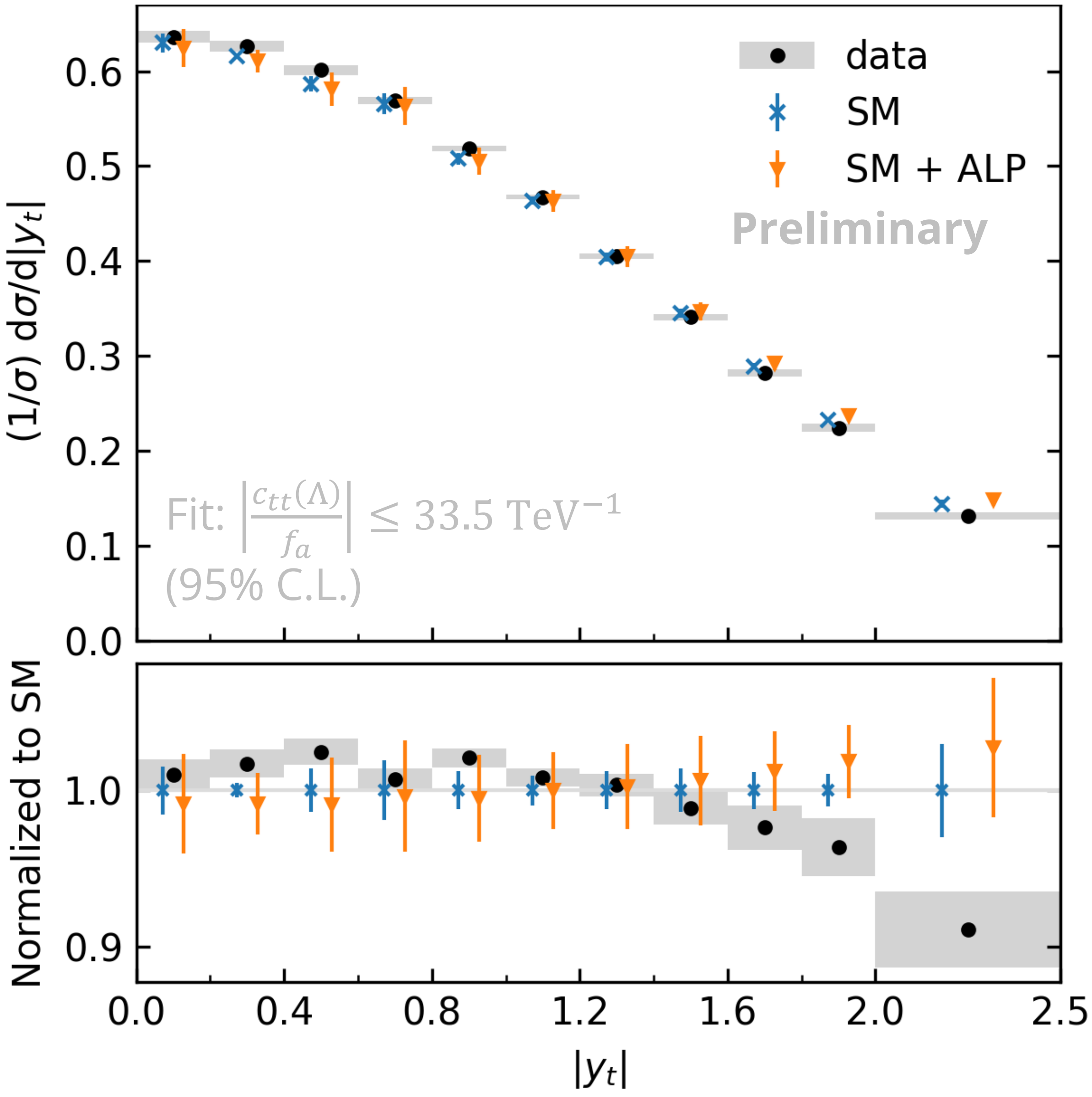


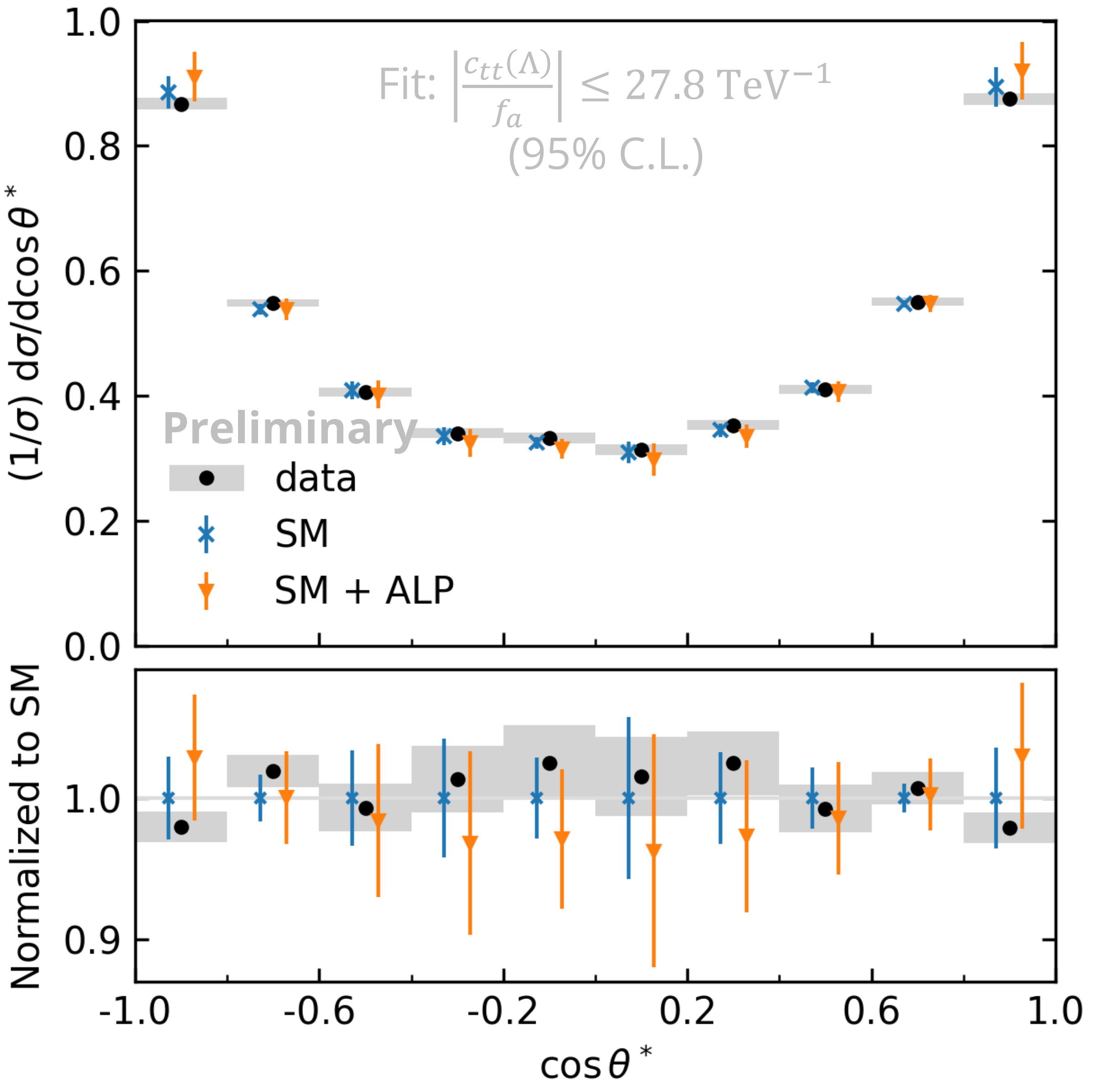

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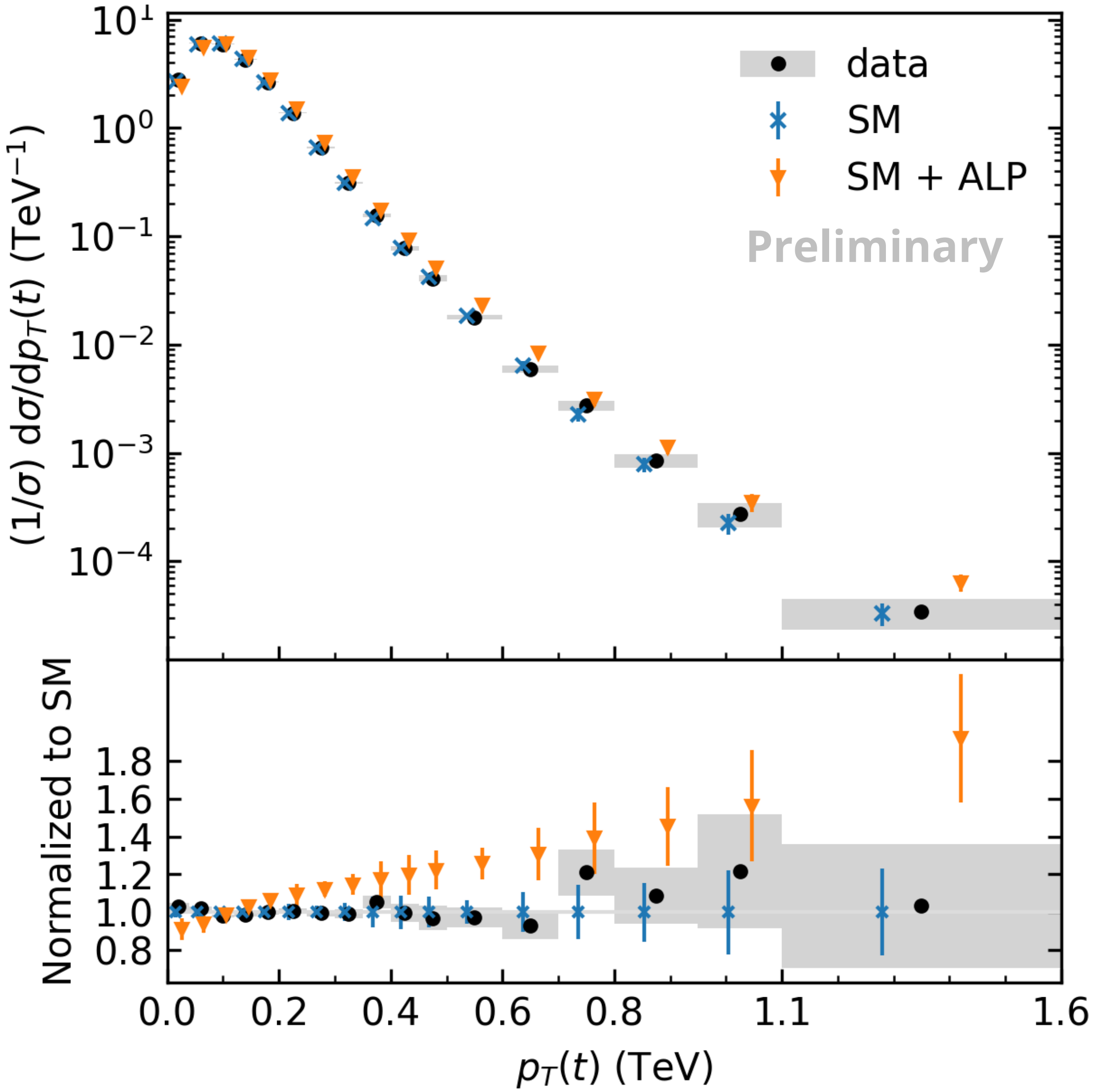
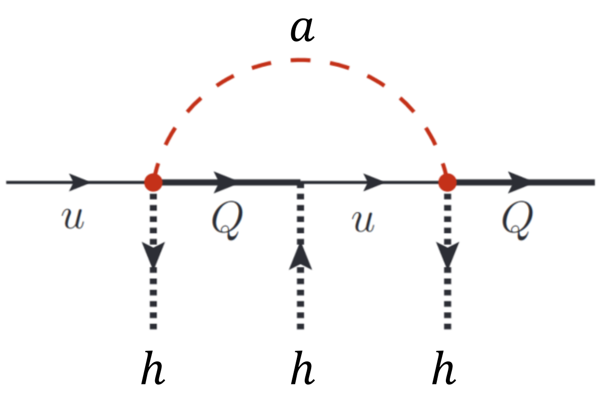



Fit: $\left|\frac{c_{tt}(\Lambda)}{f_a}\right| \leq 14.1\ \text{TeV}^{-1}$
(95% C.L.)

DISCUSSIONS

# RENORMALIZATION REVISITED

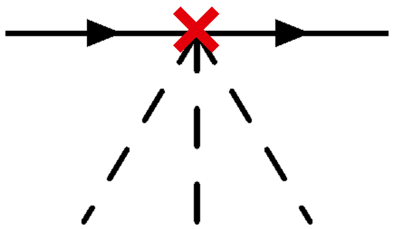



UV-diverges

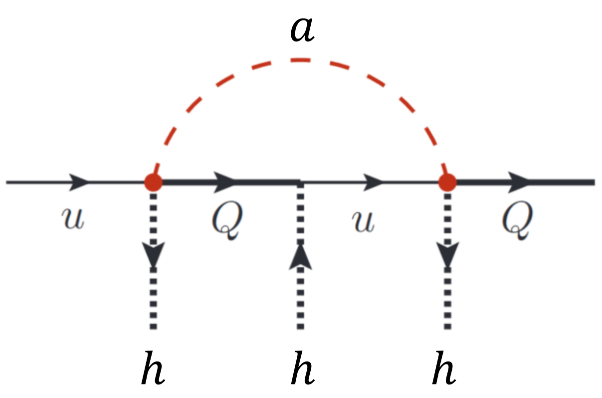
In the SM, no counterterm of the form $HHHQu$

⇒ need SMEFT counterterms

For example, from $H^\dagger H(\bar{Q}Hu) + \mathrm{h.c.}$



# RENORMALIZATION REVISITED

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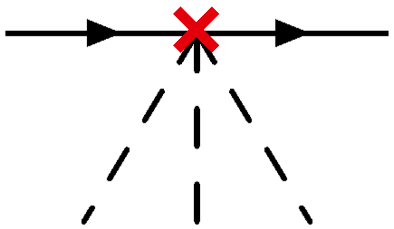
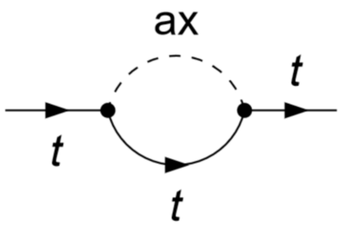
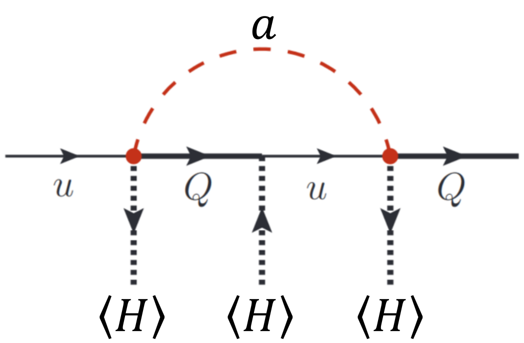


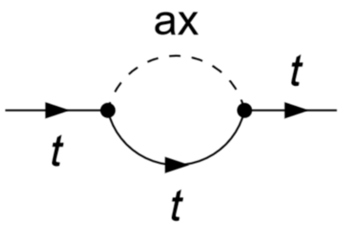
But, 



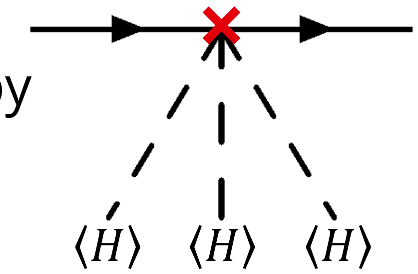

⊃



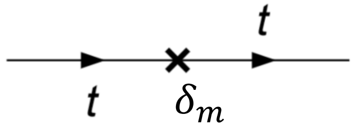

⇒




is renormalized by




⇒

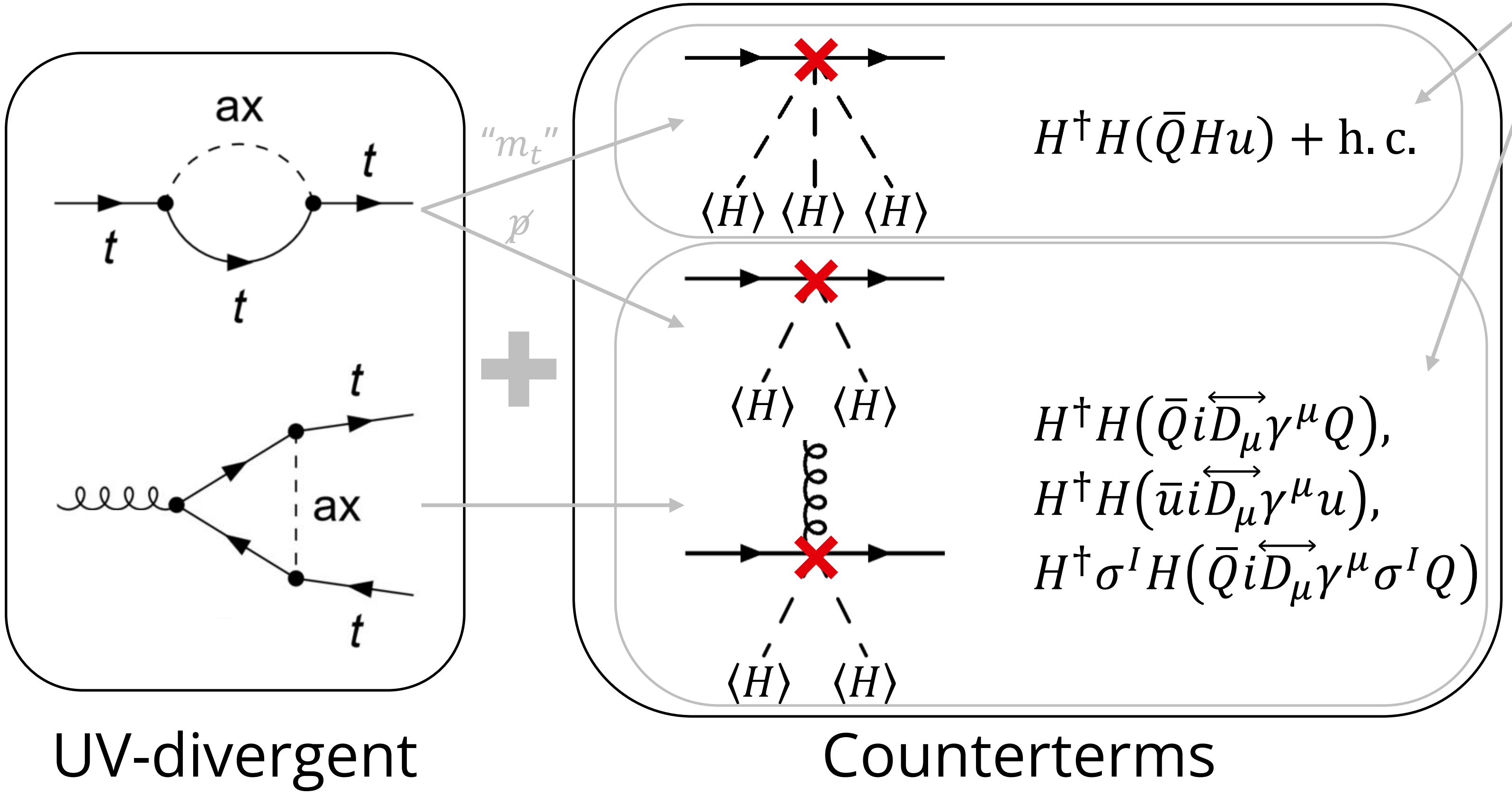



is not needed

# RENORMALIZATION REVISITED

## The complete story

Dim-6 operators




All divergences are cured

$\delta_1, \delta_2, \delta_m$ are not needed

# RENORMALIZATION IN THE WARSAW BASIS?

$$H^\dagger H(\bar{Q}Hu) + \text{h.c.},$$
$$H^\dagger H(\bar{Q}i\overleftrightarrow{D}_\mu\gamma^\mu Q),$$
$$H^\dagger H(\bar{u}i\overleftrightarrow{D}_\mu\gamma^\mu u),$$
$$H^\dagger\sigma^I H(\bar{Q}i\overleftrightarrow{D}_\mu\gamma^\mu\sigma^I Q)$$

Green basis

Redundant

Field transformation

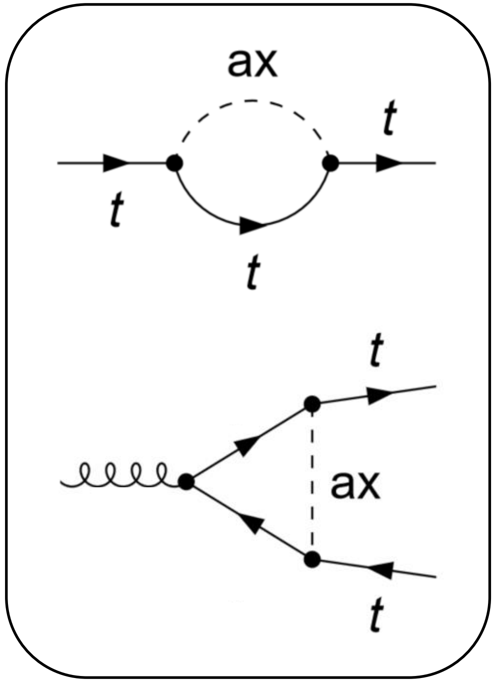
$$Q \to Q - \tilde{C}_{Hq}^{(1)} Q(H^\dagger H) - \tilde{C}_{Hq}^{(3)} \sigma^I Q(H^\dagger\sigma^I H)$$
$$u \to u - \tilde{C}_{Hu} u(H^\dagger H)$$

$$H^\dagger H(\bar{Q}Hu) + \text{h.c.}$$

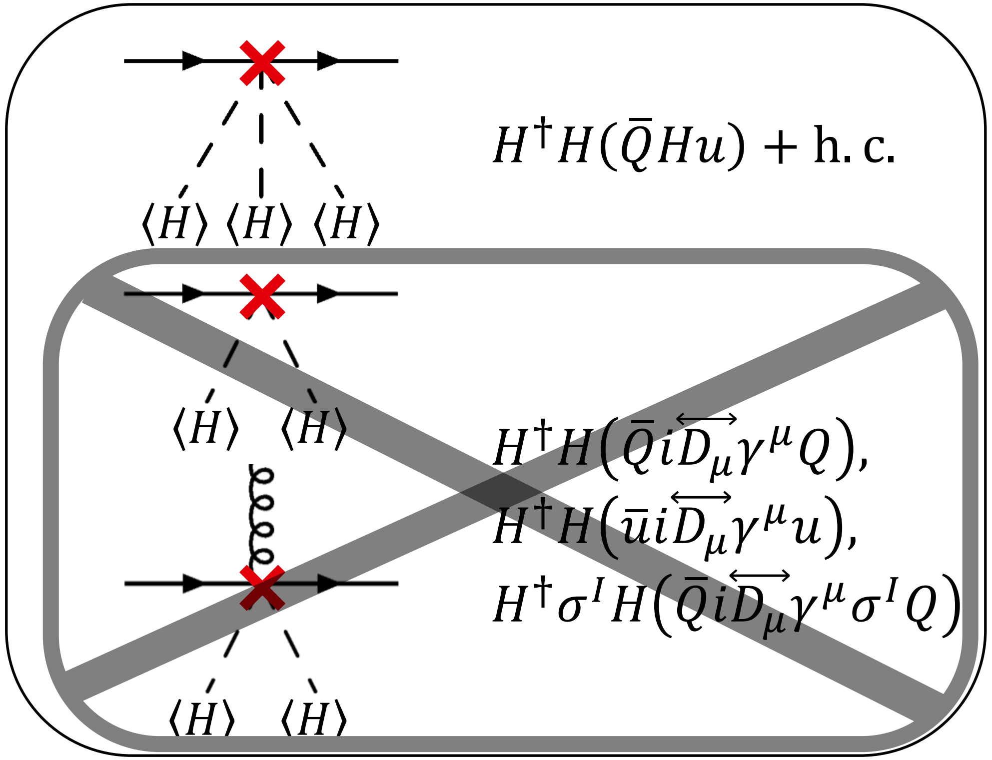
**Warsaw basis**

Simple

# RENORMALIZATION IN THE WARSAW BASIS?




UV-divergent




Counterterms

Without these operators, how do we cancel the divergences?

# RENORMALIZATION IN THE WARSAW BASIS?

Kallosh and Tyutin (1973)

$$H^\dagger H(\bar{Q}Hu) + \text{h.c.},$$
$$H^\dagger H\left(\bar{Q}i\overleftrightarrow{D}_\mu\gamma^\mu Q\right),$$
$$H^\dagger H\left(\bar{u}i\overleftrightarrow{D}_\mu\gamma^\mu u\right),$$
$$H^\dagger\sigma^I H\left(\bar{Q}i\overleftrightarrow{D}_\mu\gamma^\mu\sigma^I Q\right)$$

**Green basis**

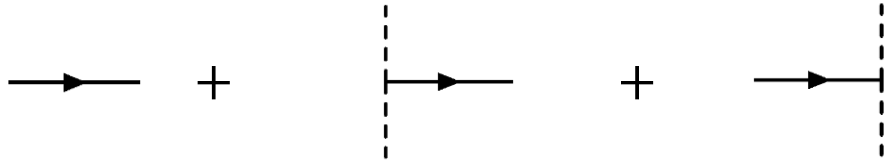
$$Q \to Q - \tilde{C}^{(1)}_{Hq}Q\left(H^\dagger H\right) - \tilde{C}^{(3)}_{Hq}\sigma^I Q\left(H^\dagger\sigma^I H\right)$$
$$u \to u - \tilde{C}_{Hu}u\left(H^\dagger H\right)$$

$$H^\dagger H(\bar{Q}Hu) + \text{h.c.}$$

**Warsaw basis**

$$\langle\bar{u}u\rangle_G$$

$$\langle\bar{u}u\rangle_W + \tilde{C}_{Hu}\left\langle H^\dagger H\bar{u}u\right\rangle_W + \tilde{C}_{Hu}\left\langle\bar{u}uH^\dagger H\right\rangle_W$$



Kallosh and Tyutin (1973)

DISCUSSIONS

# RENORMALIZATION IN THE WARSAW BASIS?

$$H^\dagger H(\bar{Q}Hu) + \text{h.c.},$$
$$H^\dagger H(\bar{Q}i\overleftrightarrow{D}_\mu\gamma^\mu Q),$$
$$H^\dagger H(\bar{u}i\overleftrightarrow{D}_\mu\gamma^\mu u),$$
$$H^\dagger\sigma^I H(\bar{Q}i\overleftrightarrow{D}_\mu\gamma^\mu\sigma^I Q)$$

**Green basis**

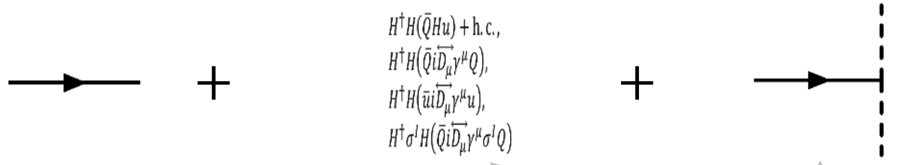
$$Q \to Q - \tilde{C}^{(1)}_{Hq}Q(H^\dagger H) - \tilde{C}^{(3)}_{Hq}\sigma^I Q(H^\dagger\sigma^I H)$$
$$u \to u - \tilde{C}_{Hu}u(H^\dagger H)$$

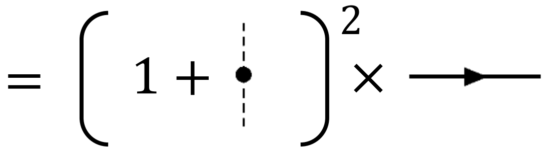
$$H^\dagger H(\bar{Q}Hu) + \text{h.c.}$$

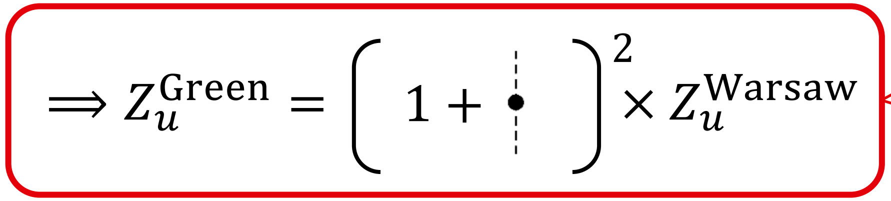
**Warsaw basis**

$$\langle\bar{u}u\rangle_G$$

$$\langle\bar{u}u\rangle_W + \tilde{C}_{Hu}\langle H^\dagger H\bar{u}u\rangle_W + \tilde{C}_{Hu}\langle\bar{u}uH^\dagger H\rangle_W$$



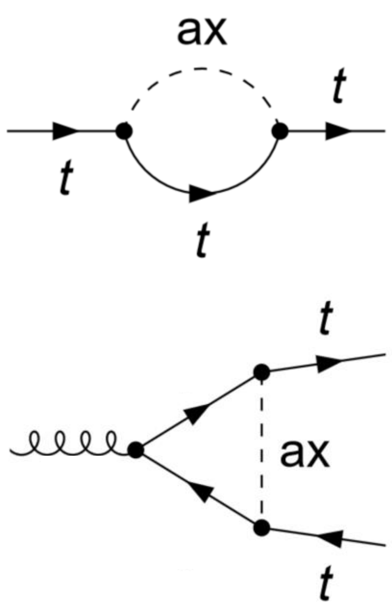




We need $Z_u$, or

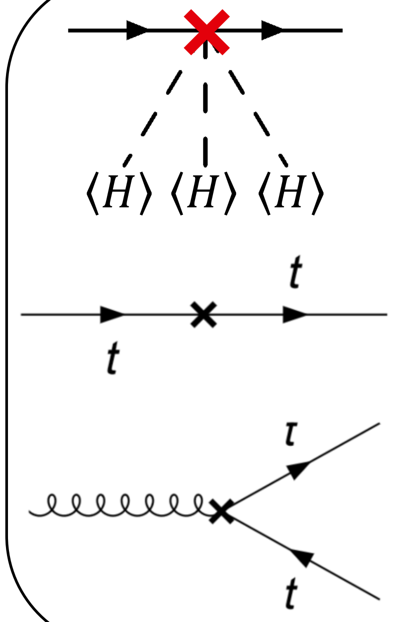
We need to include reducible diagrams

# RENORMALIZATION IN THE WARSAW BASIS

$$\mathcal{L}_{\text{eff}}(\mu) \supset Z_2 \bar{t} i \partial_\mu \gamma^\mu t - Z_2 m_t \bar{t} t + Z_2 g_s G_\mu^a \bar{t} \gamma^\mu T^a t + \left( C_{uH}^{(0)} H^\dagger H (\bar{Q} H u) + \text{h.c.} \right)$$




UV-divergent




$i \frac{v^2}{2\sqrt{2}} \delta C_{uH}$

$i(p^\mu \gamma_\mu \delta_2 - \delta_2 m_t)$

$i g_s T_{ij}^a \gamma^\mu \delta_2$

counterterms

All divergences are cured