Renormalisation group running effects in $pp \to t\bar{t}h$ in the SMEFT

(based on Eur.Phys.J.C 84 (2024) 4, 403 with R. Gröber)

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Introduction

- The **Standard Model** (**SM**): a great successes, but it must be extended (baryon asymmetry, dark matter. . .)
- Many **New Physics** (**NP**) theories have been proposed, but no clear experimental indication.
- **Effective Field Theories** (**EFTs**) offer a powerful and pragmatic approach to the search for NP with minimal UV assumptions.
- This talk focuses on Standard Model Effective Field Theory (**SMEFT**).

The SMEFT

- Parametrise heavy NP effects with a tower of gauge/Lorentz invariant operators:

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_{\mathfrak{D}_i > 4} \frac{C_i}{\Lambda^{\mathfrak{D}_i - 4}} \mathcal{O}_i,$$

$$O_i \sim \partial^{n_d^i} \phi^{n_\phi^i} A^{n_A^i} \psi^{n_\psi^i}, \qquad \mathfrak{D}_i = n_d^i + n_\phi^i + n_A^i + \frac{3}{2} n_\psi^i.$$

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- ϕ, A, ψ: SM fields.
- Gauge group: $\mathrm{SU}(3)_\mathrm{C} \otimes \mathrm{SU}(2)_\mathrm{W} \otimes \mathrm{U}(1)_\mathrm{Y}$.

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- ϕ, A, ψ: SM fields.
- Gauge group: $\mathrm{SU}(3)_\mathrm{C} \otimes \mathrm{SU}(2)_\mathrm{W} \otimes \mathrm{U}(1)_\mathrm{Y}$.
- Dominant effect in collider physics at $\mathfrak{D} = 6$ (**Warsaw basis, 2499 operators**, [Grzadkowski,Iskrzynski,Misiak,Rosiek,'10]).

SMEFT: how should we use it?

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- Intro
- Running effects
- $pp \to \bar{t}th$ @LHC
- Conclusions
- Backup

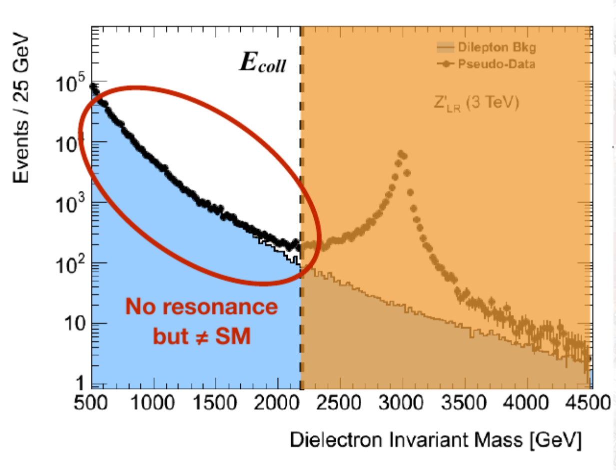

Figure: Courtesy of P. Azzi.

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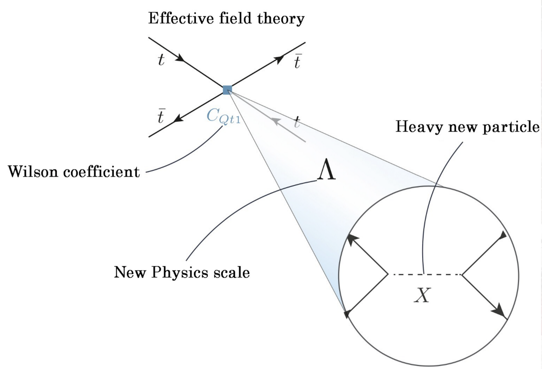

Figure: courtesy of L. Alasfar

- Information on UV mediator from IR dynamics: see [Altmannshofer, Gori, Lehmann, Zuo,'23]

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- Renormalization procedure induces energy-dependent parameters.
- Crucial ingredient to connect different energy scales (e.g.: matching scale Λ, experiment $\sim v \ll \Lambda$).

- The scale dependence of the coefficients is encoded in the **Renormalization Group Equations (RGEs)** (1-loop):

$$\mu \frac{dC_i(\mu)}{d\mu} = \frac{1}{16\pi^2} \Gamma_{ij}(\mu) C_j(\mu).$$

- $\Gamma_{ij}(\mu)$: **Anomalous Dimension Matrix (ADM)**.

Structure of ADM in the SMEFT

- $\Gamma_{ij}(\mu)$: known at 1-loop [(Alonso),Jenkins,Manohar,Trott,'13].

- $\Gamma_{ij}(\mu)$ depends on μ through the couplings:

$$\Gamma_{ij}(\mu) = g_1^2(\mu)\Gamma_{ij}^{(g_1^2)} + g_2^2(\mu)\Gamma_{ij}^{(g_2^2)} + \ldots$$

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- Exactly solvable with only one coupling (typically g_s^2, $\Gamma_{ij}(\mu) = g_s^2(\mu)\Gamma_{ij}^{(g_s^2)}$, [Maltoni,Vryonidou,Zhang,'16], [Battaglia,Grazzini,Spira,Wiesemann'21]).

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- $\Gamma^{(g_i)}$ do not commute: **analytical solution is impossible**.

Solving the RGEs I

① **Approximate solution** (first leading log):

$$C_i(\mu_F) = C_i(\mu_I) + \Gamma_{ij}(\mu_I) C_j(\mu_I) \frac{\log\left(\mu_F/\mu_I\right)}{16\pi^2}.$$

- Neglects dependence on μ of Γ.
- Ok only if $\Gamma_{ij}(\mu_I) C_j(\mu_I) \frac{\log\left(\mu_F/\mu_I\right)}{16\pi^2} \ll 1$

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2. **Numeric solution**:

- More precise.
- Slow! Problem for extensive phenomenological analyses.

Solving the RGEs II

- Example: a Monte Carlo analysis in an hadronic collider:
  - $\hat{s} = x_1 x_2 E^2_{\text{collider}}$: different for each event.
  - $C_i(\mu = \Lambda) \xrightarrow[\text{RG flow}]{} C_i(\mu \sim \sqrt{\hat{s}})$ for each event.
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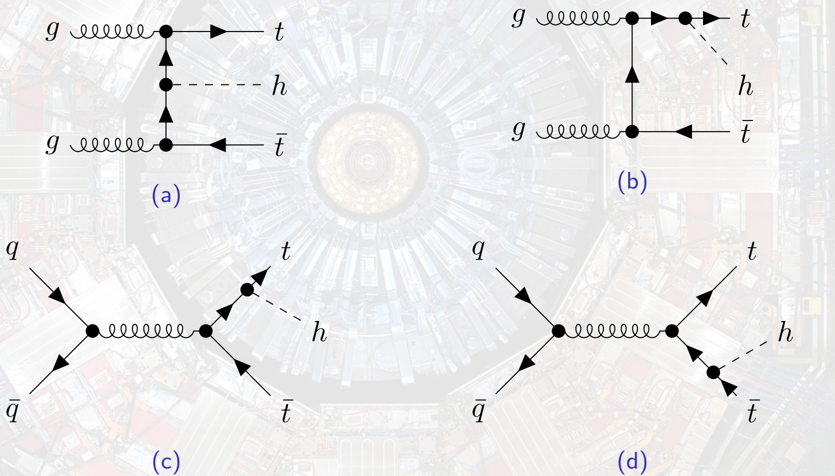
  - Can be optimized (grid).
- State of the art:
  - `DsixTools` ([Fuentes-Martin,Ruiz-Femenia,Vicente,Virto,'20], `Mathematica`).
  - `wilson` ([Aebischer, Kumar, Straub,'18], `python`) SMEFT running ported from `DsixTools`.

RGESolver [S.D.N.,Silvestrini,'22]

- A C++ library that performs RG evolution of SMEFT coefficients.
- General flavour structure (assuming L, B conservation, 2499 operators).
- Tested against DsixTools.
- High time efficiency: (numeric running: $\mathcal{O}(0.1\,s)$ vs $\mathcal{O}(10\,s)$ (DsixTools)).
- Flavour back-rotation implemented.
- Inclusion in HEPfit ([De Blas et. al.,'19]) in progress!

$pp \to \bar{t}th$@LHC (SM)

- Tree-level in the SM:



$pp \to \bar{t}th$@LHC (SMEFT) I

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- Some operators induce a rescaling of the SM vertices.
- $\mathcal{O}_{t\phi} = (\phi^\dagger\phi)\,\bar{Q}_L\phi t_R$ rescales the top Yukawa coupling:

$$\mathcal{O}_{t\phi} \xrightarrow[\text{S.S.B.}]{} \frac{v^2}{2}\frac{h}{\sqrt{2}}\bar{t}t + \ldots, \qquad g_{t\bar{t}h} = \underbrace{-i\frac{m_t}{v}}_{\text{SM}} + \underbrace{i\frac{v^2}{\sqrt{2}}C_{t\phi}}_{\text{SMEFT}} .$$

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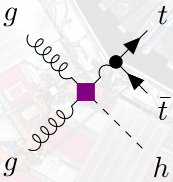
- Some operators induce new interaction vertices!



$$\mathcal{O}_{\phi G} = (\phi^\dagger \phi) G^A_{\mu\nu} G^{A\mu\nu}$$

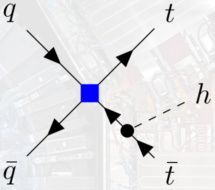
- New couplings:

$$ggh,\ gghh,\ gggh....$$

$pp \to \bar{t}th$@LHC (SMEFT) II

$$\mathcal{O}_{uu}^{1133} = (\bar{q}\gamma^{\mu}\mathbb{P}_R q)\,(\bar{t}\gamma_{\mu}\mathbb{P}_R t)$$

- New coupling: $\bar{q}q\bar{t}t$.



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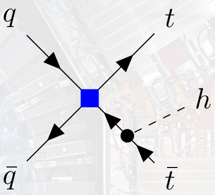
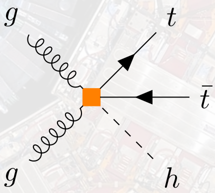


$$\mathcal{O}_{tG} = (\bar{Q}_L\sigma^{\mu\nu}T_A t_R)\,\tilde{\phi}G^{A}_{\mu\nu}$$

- New couplings:

  $\bar{t}tgg,\ \bar{t}tgh,\ \bar{t}tggh.$

- Modifies $\bar{t}tg$.



Dynamical vs Fixed scale I

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- RGEs connect different energy scales: $\Lambda = \mathcal{O}(\mathrm{TeV}) \to \mu_{\mathrm{R}}$.
- How to choose μ_{R}?

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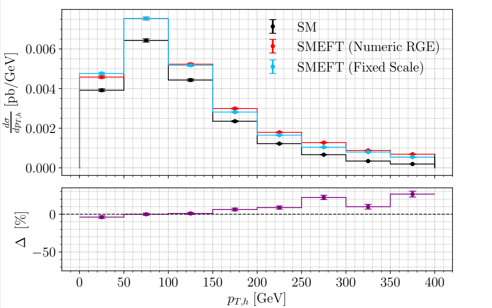
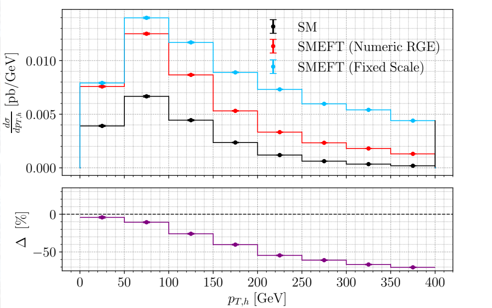
- RGEs connect different energy scales: $\Lambda = \mathcal{O}(\text{TeV}) \to \mu_\text{R}$.
- How to choose μ_R?

- We set some Wilson coefficients at the scale $\Lambda = 2\,\text{TeV}$ (inside the bounds in [Ethier et al.,'21]) and test their impact on differential distributions.
- New bounds in [Celada et al.,'24].
- We compare two different choices:
  - Fixed scale: $\mu_\text{R} = m_t$ (same for all the events).
  - Dynamical scale: $\mu_\text{R} = (p_{T,h} + p_{T,t} + p_{T,\bar{t}})/2$ (changes event by event).

Dynamical vs Fixed scale II

- Sizeable/important effect for large coefficients $(\sim 1\,\mathrm{TeV}^{-2}/\sim 100\,\mathrm{TeV}^{-2})$.
- Numeric running in both cases!

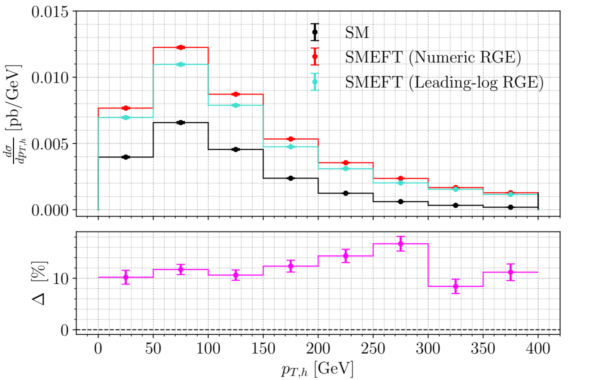




Conservative scenario: $C_{4t} \sim 1\,\mathrm{TeV}^{-2}$. Extreme scenario: $C_{4t} \sim 100\,\mathrm{TeV}^{-2}$.

Numeric vs. 1LL

- Small ($< 5\%$, not shown)/sizeable effect for large coefficients ($\sim 1\,\mathrm{TeV}^{-2}/\sim 100\,\mathrm{TeV}^{-2}$).
- Numeric running: $\simeq 20\,\mathrm{mins}$, 1LL running : $\simeq 40\,\mathrm{s}$, $\mu_\mathrm{R} = \mu_\mathrm{F} = (p_{T,h} + p_{T,t} + p_{T,\bar{t}})/2$ (dyn. ren. scale).



g_s vs y_t I

- $g_{ht\bar{t}} = \frac{m_t}{v}\left(1 - \frac{v^2}{\sqrt{2}} C_{t\phi}\right)$ is the effective Higgs-top coupling.

$$\beta_{t\phi} \propto y_t^3 \left(C_{Qt}^{(1)} + \frac{4}{3} C_{Qt}^{(8)} \right),$$

$$\mathcal{O}_{Qt}^{(1,8)} = (\bar{Q}_L \gamma^\mu (T^A) Q_L)\, (\bar{t}_R \gamma_\mu (T^A) t_R)\,.$$

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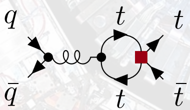
- $C_{Qt}^{(8)}$ contributes via penguin diagrams to the running of operators (such as $\mathcal{O}_{uu}^{33ii}$, $i = 1, 2$) entering at tree-level.
- $C_{Qt}^{(1)}$ **does not!** We can compare g_s vs y_t running effects



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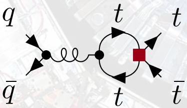

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- We set $C_{Qt}^{(1,8)} \neq 0$ individually in such a way they contribute (almost) in the same way to the Yukawa-induced running.

g_s vs y_t II

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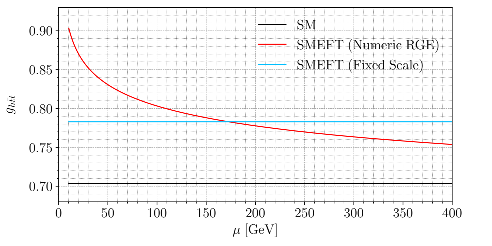
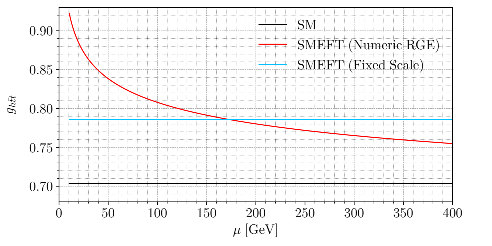




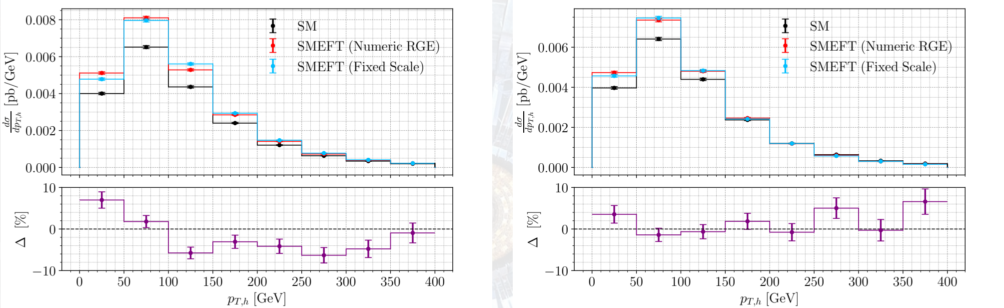
$$C^{(1)}_{Qt}(\Lambda) = \frac{4}{3} \times 20\,/\text{TeV}^2.$$

$$C^{(8)}_{Qt}(\Lambda) = 20\,/\text{TeV}^2.$$

$$\beta_{t\phi} \propto y_t^3 \left(C^{(1)}_{Qt} + \frac{4}{3} C^{(8)}_{Qt} \right)$$

- Same behaviour in $g_{h\bar{t}t}$ for both operators!

g_s vs y_t III



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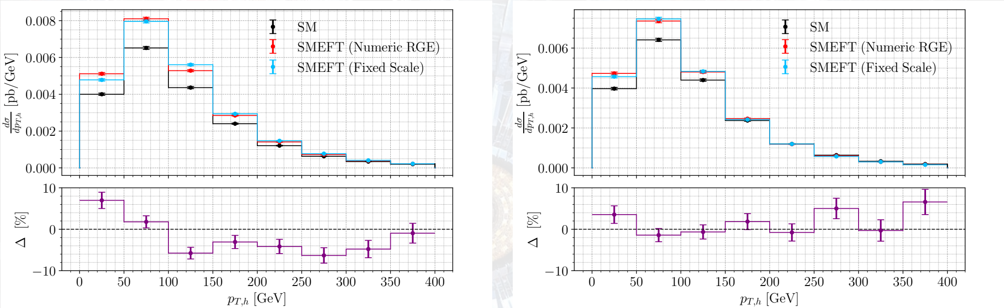

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$$\beta_{t\phi} \propto y_t^3 \left(C^{(1)}_{Qt} + \frac{4}{3} C^{(8)}_{Qt} \right)$$

- The difference betwen fixed and dynamical scale shows the importance of running effects.
- $\Delta \neq 0$ for $C^{(1)}_{Qt}$ $\rightarrow$ Top Yukawa contributions are important!

Conclusions

- Running effects are a crucial ingredient for precision physics in the next future.
- Sizable differences can arise when employing a dynamical renormalisation scale vs a fixed renormalization scale.
- In presence of large Wilson coefficients, the leading-log solution of the RGEs shows sizeable differences w.r.t. the numeric integration.
- Yukawa contributions can be as important as strong ones in some cases.

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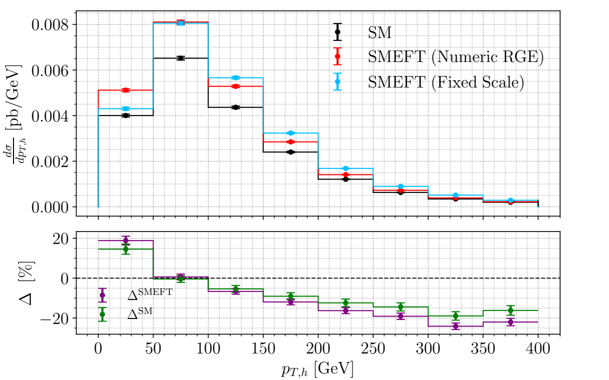
Thank you for your attention!

Backup

Impact of SM running of g_s

- $g_s = g_s(m_t)$ in the fixed case scenario (instead of $g_s = g_s(\mu_F) = g_s((p_{T,h} + p_{T,t} + p_{T,\bar{t}})/2)$ in the SM@1 loop).

$$C_{Qt}^{(1)} = 20\,\text{TeV}^{-2}.$$



$p_{T,h}$ vs μ_F

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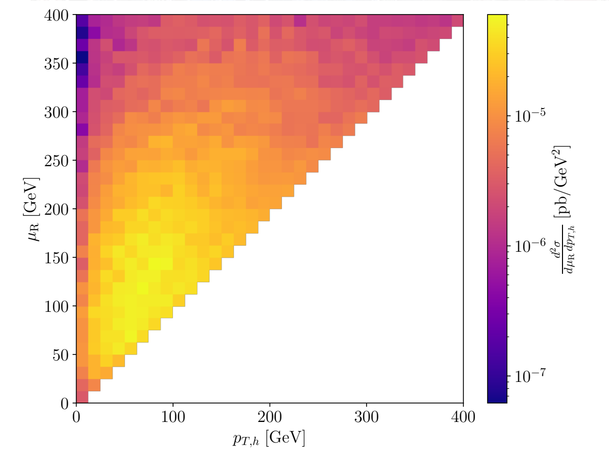

Back-rotation effects

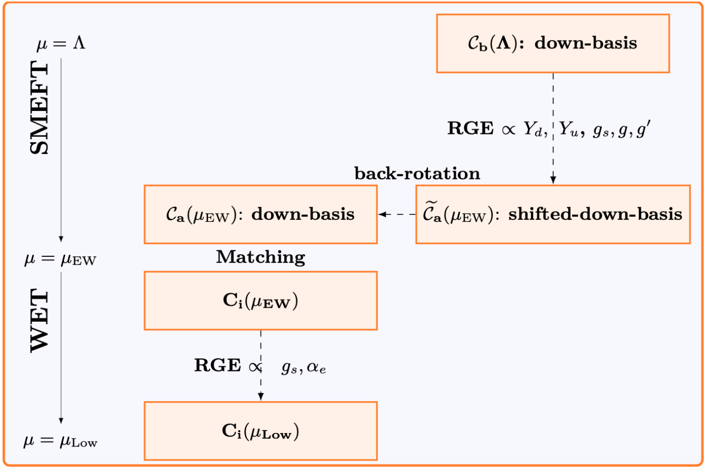

Figure: from ([Aebischer,Kumar,'20])

Running, logs, divergent parts I

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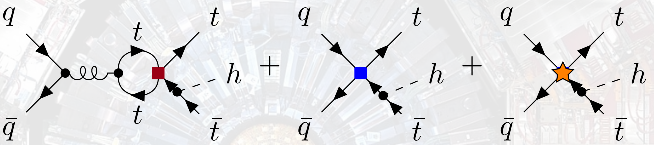
$i\mathcal{M} \propto$



$$\sim C_{4\mathrm{t}}(\mu_\mathrm{R})\frac{g_s^2}{16\pi^2}\left(A + B\left(\cancel{\frac{1}{\epsilon}} + \log\frac{\mu_\mathrm{R}^2}{m_t^2}\right)\right) + C_{2\mathrm{t}2\mathrm{q}}(\mu_\mathrm{R}) - \cancel{\delta_{2\mathrm{t}2\mathrm{q}}}.$$

Running, logs, divergent parts I

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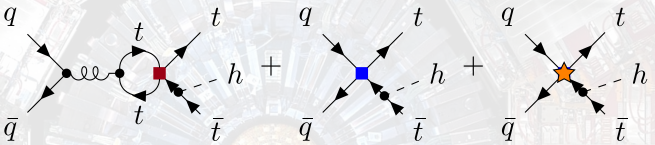

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- Divergences determine the ADM: $\delta_{2\mathrm{t}2\mathrm{q}} = -\frac{\Gamma_{2\mathrm{t}2\mathrm{q},4\mathrm{t}}}{32\pi^2\epsilon}C_{4\mathrm{t}}$

Running, logs, divergent parts I

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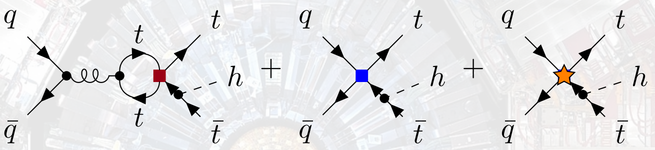

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$$C_{2\mathrm{t}2\mathrm{q}}(\mu_\mathrm{R}) = C_{2\mathrm{t}2\mathrm{q}}(\Lambda) + C_{4\mathrm{t}}(\mu_\mathrm{R})\frac{g_s^2}{16\pi^2}\log\frac{\Lambda^2}{\mu_\mathrm{R}^2} \qquad \text{(1LL)}$$

$$C_{4\mathrm{t}}(\mu_\mathrm{R}) \simeq C_{4\mathrm{t}}(\Lambda) + \ldots$$

Running, logs, divergent parts II

S. Di Noi

- If we neglect the finite term (A) and we assume that $\mu_{\mathrm{R}} \sim v \sim m_t$, we can include loop effects without any computation!

$$
\begin{aligned}
i\mathcal{M} &\propto C_{4\mathrm{t}}(\Lambda)\frac{g_s^2}{16\pi^2}\left(A + B\left(\log\frac{m_t^2}{\mu_{\mathrm{R}}^2} + \log\frac{\mu_{\mathrm{R}}^2}{\Lambda^2}\right)\right) + C_{2\mathrm{t}2\mathrm{q}}(\Lambda) \\
&\simeq C_{4\mathrm{t}}(\Lambda)\frac{g_s^2}{16\pi^2} B \log\frac{\mu_{\mathrm{R}}^2}{\Lambda^2} + C_{2\mathrm{t}2\mathrm{q}}(\Lambda)
\end{aligned}
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$$\simeq C_{4\mathrm{t}}(\Lambda)\frac{g_s^2}{16\pi^2}B\log\frac{\mu_{\mathrm{R}}^2}{\Lambda^2} + C_{2\mathrm{t}2\mathrm{q}}(\Lambda)$$

- In some cases, finite terms can be phenomenologically relevant! [Alasfar,de Blas,Gröber,'22] .
- Not interesting in our case: **the focus is on running effects!**

Is the SMEFT general enough?

- The SMEFT assumes a SM-like Higgs boson:

$$(\tilde{\varphi}, \varphi) = \frac{v+h}{\sqrt{2}} \cdot U, \qquad U = \exp\left(i\frac{\pi^I \tau^I}{v}\right).$$

- The Higgs EFT (HEFT) instead assumes a more general scenario: U and h are treated separately.
- SM$\subset$SMEFT$\subset$HEFT.
- Less correlations between coefficients in HEFT: (e.g., in SMEFT $g_{5h} = v g_{6h}$ but not in HEFT).
- Measure correlation$\to$ insights about EW SSB.
- More about this topic in [Brivio,Trott,'17].

Sum over external polarizations in QCD

- Ex: 2 external gauge bosons, $\mathcal{M} = \epsilon^{\mu_1}(p_1)\epsilon^{\mu_2}(p_2)\mathcal{M}_{\mu_1\mu_2}$.
- **Ward identity**: $p_1^{\mu_1}\mathcal{M}_{\mu_1\mu_2} = p_2^{\mu_2}\mathcal{M}_{\mu_1\mu_2} = 0$ ("each photon is independent").
- In QED (abelian), we can use:

$$\sum_{\text{Pol}} \epsilon_\mu(p)\epsilon_\nu(p)^* = -g_{\mu\nu} + \cancel{\frac{n_\mu p_\nu}{(n\cdot p)}} + \cancel{\frac{p_\mu n_\nu}{(n\cdot p)}} - \cancel{\frac{p_\mu p_\nu}{(n\cdot p)^2}}.$$

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- ~~**Ward identity**~~ $\to$ **Slavnov-Taylor identity**: $p_1^{\mu_1}\epsilon^{\mu_2}(p_2)\mathcal{M}_{\mu_1\mu_2} = \epsilon^{\mu_1}(p_1)p_2^{\mu_2}\mathcal{M}_{\mu_1\mu_2} = 0$.
- Weaker than QED: all the particles must be on-shell.
- Terms $\propto p_1, p_2$ cannot be dropped.
- If we do, we must compensate subtracting (incoherently) MEs with external ghosts ([Malmquist,Kachelrieß,'21]).