HEFT 2017
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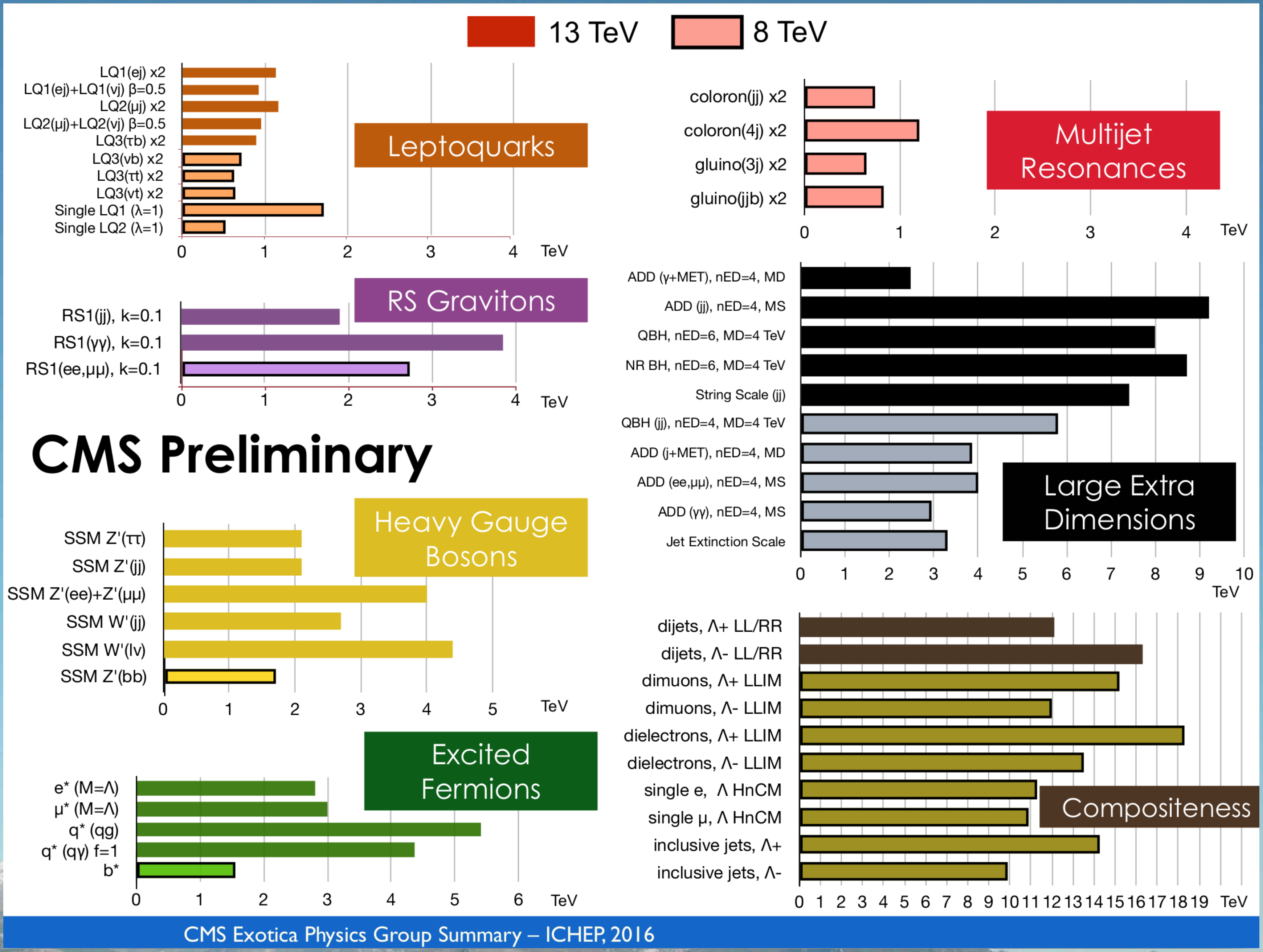
Automated one-loop matching with Match Maker

José Santiago

Based on: C. Anastasiou, A. Carmona, A. Lazopoulos, J.S. (to appear)

After the discovery of the Higgs, the LHC has turned into New Physics search mode

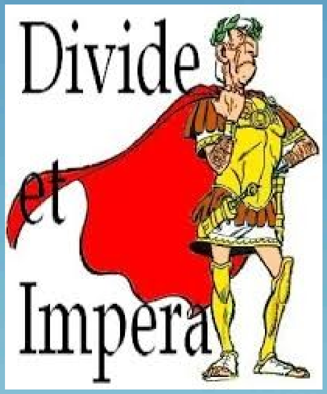


Given the absence (so far) of direct evidence of NP and the huge number of different searches, what is the best strategy to use these data?

Effective theories: Split the problem in two (in a smart way)

- Top-down: compute Wilson coefficients in terms of UV parameters

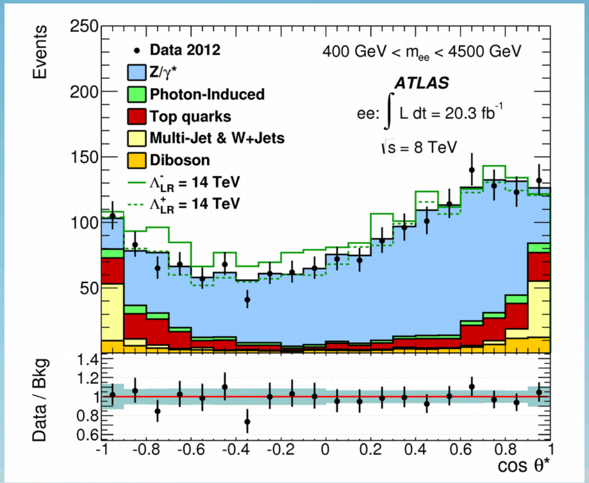
$$\mathcal{L} = \mathcal{L}_4 + \sum_{d>4} \sum_{i_d} \frac{c_{i_d}}{\Lambda^{d-4}} \mathcal{O}_{i_d}$$



- Bottom-up: Map experimental (pseudo) observables to Wilson coefficients

Effective theories (bottom-up):

- General description of new physics with minimal theoretical input (in the presence of a mass gap)
- Classify physical behaviour in universality classes
- Map experimental (pseudo) observables to Wilson coefficients



$$\mathcal{L}_6 = \alpha^{(1)}_{lq}(\bar{l}\gamma^\mu l)(\bar{q}\gamma_\mu q) + \ldots$$

Effective theories (bottom-up):

- General description of new physics with minimal theoretical input (in the presence of a mass gap)
- Classify physical behaviour in universality classes
- Map experimental (pseudo) observables to Wilson coefficients
- Global fit: use this map to encode all experimental information in constraints on Wilson coefficients

Ciuchini, Franco, Mishima, Silvestrini ('13); Blas, Chala, J.S. ('13, '15); Pomarol, Riva ('14); Falkowski, Riva ('15); Buckley, Englert, Ferrando, Miller, Moore, Russell, White ('15-’17); Berthier, Trott (‘15), Blas, Ciuchini, Franco, Mishima, Pierini, Reina, Silvestrini (‘16), ...

Effective theories (top-down):

- In order to extract information on UV physics we need to match specific models to the EFT
- Map UV model parameters to Wilson coefficients

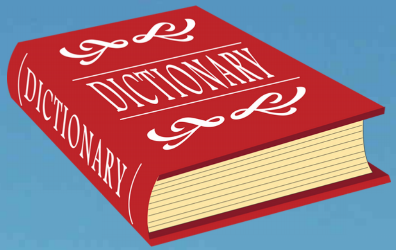
$$\mathcal{L}_{NP} = \mathcal{L}_{SM} + \bar{\Psi}(i\not{D} - M)\Psi - \lambda' \bar{\Psi}\phi\psi + \ldots$$

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i \alpha_i \mathcal{O}_i$$

- Can be (in principle) performed at an arbitrary order in loops and operator dimension
- Can be done:
  - Via functional methods
  - Diagramatically: MatchMaker

Henning, Lu, Murayama ('14-'16); Drodz, Ellis, Quevillon, You ('15-'16); Fuentes-Martin, Portoles, Ruiz-Femenia ('16); Zhang ('16); ...

- The two programs (bottom-up and top-down) can be developed independently
- When put together they provide a dictionary between experimental observables and NP models



$$\mathcal{L}_{NP} = \mathcal{L}_{SM} + \bar{\Psi}(i\not{D} - M)\Psi - \lambda' \bar{\Psi}\phi\psi + \ldots$$

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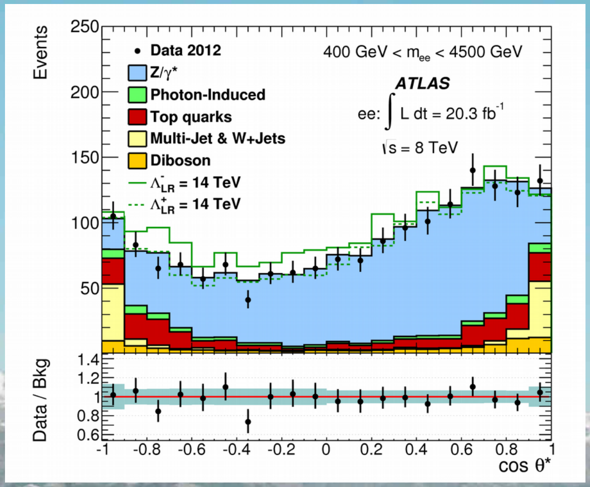

- The tree level (dim 6) dictionary is almost complete: tree-level, dimension 6 new physics effects have been completelly classified and computed

  New quarks: Aguila, Perez-Victoria, J.S. (‘00);
  New leptons: Aguila, Blas, Perez-Victoria (‘08),
  New vectors: Aguila, Blas, Perez-Victoria (‘10);
  New scalars: Blas, Chala, Perez-Victoria, J.S (‘15);
  Mixed contributions: Blas, Criado, Perez-Victoria, J.S. (to appear)

- We can automatically infer which NP can generate large effects and all their possible correlations (due to accidental symmetries and properties of UV models)
- Some effects can only be generated at the loop level (dipole moments, ...). Others can be potentially tree level but are only generated at loop level in specific models (T parameter in models with VLQ, …). The dictionary should be extended to one-loop in these cases.

MatchMaker: automated matching in effective theories

Anastasiou, Carmona, Lazopoulos, J.S.

- Automated tool to perform tree-level and one-loop matching of arbitrary theories into arbitrary effective Lagrangians
- Written in python (easy to install via pip, cross-platform). Uses well tested tools (QGRAF, FORM, Mathematica)
- Flexible (from full matching to specific operators), fully automated and general
- Off-shell matching with (initially) massless particles in the effective theory (e.g. unbroken phase of the SM)

MatchMaker: automated matching in effective theories

Input card

UFO model → MM model → Compute and dress relevant amplitudes

QGRAF

MatchMaker

Bonus: (re)calculation of RGEs and basis translation

FORM

Evaluate amplitudes (momentum expansion, tensor reduction, Dirac algebra, partial fractioning, IBP ids, ...)

MATHEMATICA

Perform the actual matching

Redundancies

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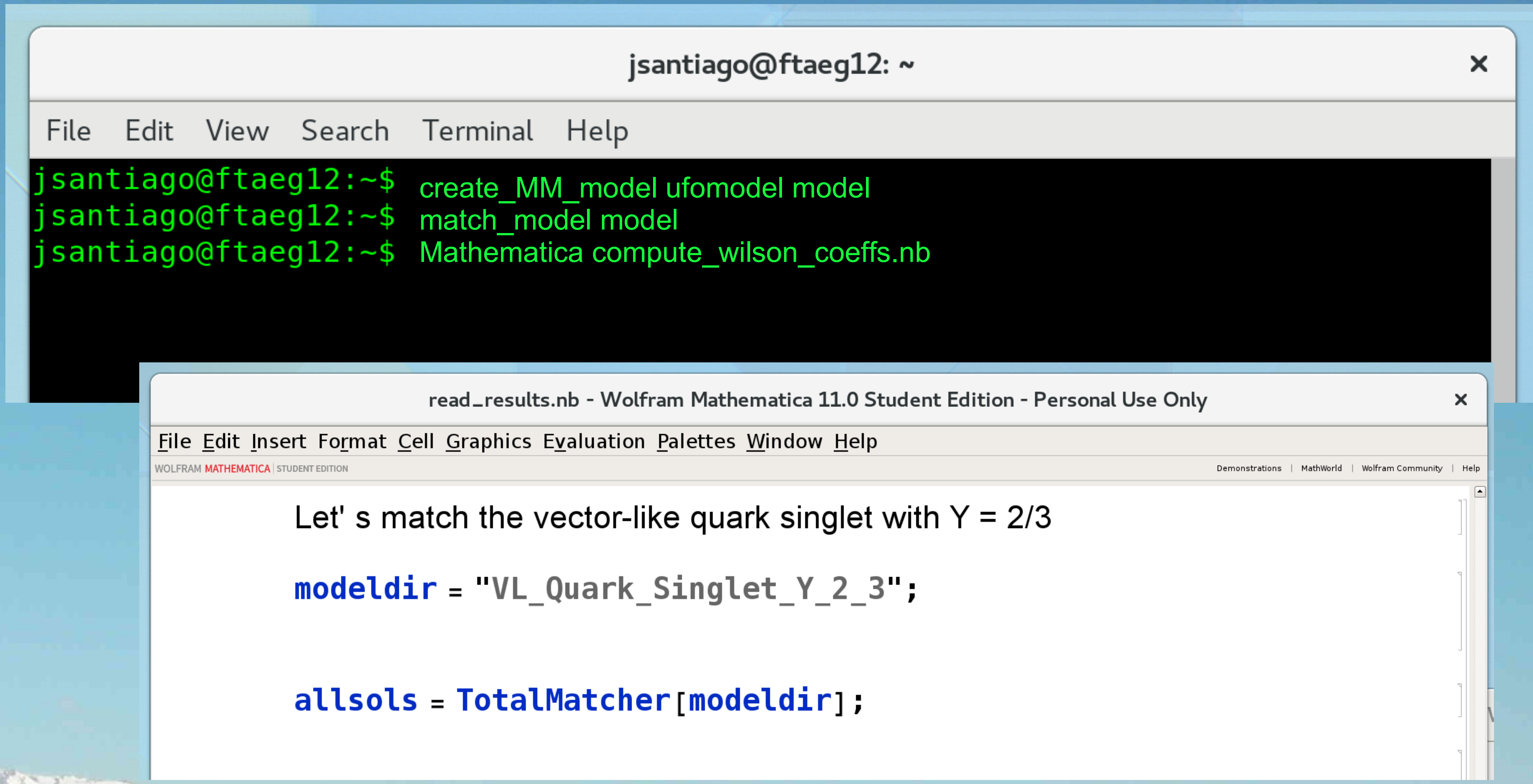
- Features of current version:
  - Matching to SMEFT fully automated (including L4)



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  - Matching to SMEFT fully automated (including L4)
  - Basis-independent results: generate all redundant and evanescent operators. A specific basis is chosen by the user via external file (default Warsaw basis)

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Sample result: One-loop Wilson coeffs for CP preserving bosonic operators when integrating out a vector-like quark with Y=2/3.

$$\Big\{\text{alpha01} \to -\frac{\text{lamprime3 lamprime3bar Nc}\left(\text{lamprime3 lamprime3bar} - \text{ytop ytopbar} + 2\,\text{ytop ytopbar Log}\left[\frac{\text{MHT}^2}{\text{mu}^2}\right]\right)}{32\,\text{MHT}^2\,\pi^2},$$

$$\text{alpha010} \to -\frac{\text{g1 gw lamprime3 lamprime3bar Nc}}{192\,\text{MHT}^2\,\pi^2},\ \text{alpha012} \to -\frac{i\,\text{gs}^3}{2880\,\text{MHT}^2\,\pi^2},\ \text{alpha014} \to 0,$$

$$\text{alpha02} \to -\frac{\text{lamprime3 lamprime3bar Nc}\left(2\,\text{lamprime3 lamprime3bar} - 9\,\text{ytop ytopbar} + 6\,\text{ytop ytopbar Log}\left[\frac{\text{MHT}^2}{\text{mu}^2}\right]\right)}{96\,\text{MHT}^2\,\pi^2},$$

$$\text{alpha04} \to \frac{\text{gs}^2\,\text{lamprime3 lamprime3bar dd}[\text{a97},\text{a99}]}{96\,\text{MHT}^2\,\pi^2\,\text{dd}[\text{i97},\text{i99}]},$$

$$\text{alpha06} \to \frac{\text{gw}^2\,\text{lamprime3 lamprime3bar Nc}}{384\,\text{MHT}^2\,\pi^2},\ \text{alpha08} \to \frac{5\,\text{g1}^2\,\text{lamprime3 lamprime3bar Nc}}{3456\,\text{MHT}^2\,\pi^2},$$

$$\text{alphaR1} \to \frac{\text{lamprime3 lamprime3bar Nc}\left(\text{lamprime3 lamprime3bar} - \text{ytop ytopbar} + 2\,\text{ytop ytopbar Log}\left[\frac{\text{MHT}^2}{\text{mu}^2}\right]\right)}{32\,\text{MHT}^2\,\pi^2},$$

$$\text{alphaR1bar} \to \frac{\text{lamprime3 lamprime3bar Nc}\left(\text{lamprime3 lamprime3bar} - \text{ytop ytopbar} + 2\,\text{ytop ytopbar Log}\left[\frac{\text{MHT}^2}{\text{mu}^2}\right]\right)}{32\,\text{MHT}^2\,\pi^2},$$

$$\text{alphaR2} \to \frac{\text{lamprime3 lamprime3bar Nc}}{48\,\text{MHT}^2\,\pi^2},\ \text{alphaR3} \to \frac{\text{g1 lamprime3 lamprime3bar Nc}\left(-7 + 2\,\text{Log}\left[\frac{\text{MHT}^2}{\text{mu}^2}\right]\right)}{576\,\text{MHT}^2\,\pi^2},$$

$$\text{alphaR4} \to -\frac{\text{gw lamprime3 lamprime3bar Nc}\left(-5 + 6\,\text{Log}\left[\frac{\text{MHT}^2}{\text{mu}^2}\right]\right)}{576\,\text{MHT}^2\,\pi^2},\ \text{alphaR5} \to -\frac{\text{gs}^2}{240\,\text{MHT}^2\,\pi^2},\ \text{alphaR6} \to 0,\ \text{alphaR7} \to -\frac{\text{g1}^2\,\text{Nc}}{270\,\text{MHT}^2\,\pi^2}\Big\}$$

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Sample result: One-loop Wilson coeffs for 2 fermion, 3 scalar operators when integrating out a vector-like quark with Y=2/3.

{alpha0171x1 → 0, alpha0171x1bar → 0, alpha0171x2 → 0, alpha0171x2bar → 0,
alpha0171x3 → 0, alpha0171x3bar → 0, alpha0172x1 → 0, alpha0172x1bar → 0,
alpha0172x2 → 0, alpha0172x2bar → 0, alpha0172x3 → 0, alpha0172x3bar → 0,
alpha0173x1 → 0, alpha0173x1bar → 0, alpha0173x2 → 0, alpha0173x2bar → 0,

$$\text{alpha0173x3} \to -\frac{\text{lamprime3 lamprime3bar ytop}\left(-\text{g1}^2 - 6\,\text{lam} + 3\left(\text{g1}^2 + 2\,\text{lam}\right)\text{Log}\left[\frac{\text{MHT}^2}{\text{mu}^2}\right]\right)}{48\,\text{MHT}^2\,\pi^2},$$

$$\text{alpha0173x3bar} \to -\frac{\text{lamprime3 lamprime3bar ytopbar}\left(-\text{g1}^2 - 6\,\text{lam} + 3\left(\text{g1}^2 + 2\,\text{lam}\right)\text{Log}\left[\frac{\text{MHT}^2}{\text{mu}^2}\right]\right)}{48\,\text{MHT}^2\,\pi^2},$$

alpha0181x1 → 0, alpha0181x1bar → 0, alpha0181x2 → 0, alpha0181x2bar → 0,
alpha0181x3 → 0, alpha0181x3bar → 0, alpha0182x1 → 0, alpha0182x1bar → 0,
alpha0182x2 → 0, alpha0182x2bar → 0, alpha0182x3 → 0, alpha0182x3bar → 0, alpha0183x1 → 0,
alpha0183x1bar → 0, alpha0183x2 → 0, alpha0183x2bar → 0, alpha0183x3 → 0, alpha0183x3bar → 0}

$$\mathcal{O}_{17} = \phi^\dagger \phi \bar{q} u \tilde{\phi}$$

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Sample result: One-loop Wilson coeffs for LLLL 4-fermion operators when integrating out a vector-like quark with Y=2/3.

$$\{\text{alphaE423x3x3x3} \to 0,\ \text{alphaE433x3x3x3} \to 0,\ \text{alphaE473x3x3x3} \to 0,$$

$$\text{alphaE483x3x3x3} \to 0,\ \text{alphaF243x3x3x3} \to 0,\ \text{alphaF253x3x3x3} \to 0,\ \text{alphaO493x3x3x3} \to$$

$$-\frac{\text{lamprime3 lamprime3bar}\left(\text{lamprime3 lamprime3bar} - 3\,\text{ytop ytopbar} + 2\,\text{ytop ytopbar Log}\left[\frac{\text{MHT}^2}{\text{mu}^2}\right]\right)}{256\,\text{MHT}^2\,\pi^2},$$

$$\text{alphaO503x3x3x3} \to$$

$$-\frac{\text{lamprime3 lamprime3bar}\left(\text{lamprime3 lamprime3bar} - 3\,\text{ytop ytopbar} + 2\,\text{ytop ytopbar Log}\left[\frac{\text{MHT}^2}{\text{mu}^2}\right]\right)}{256\,\text{MHT}^2\,\pi^2}\}$$

$$\mathcal{O}_{49} = (\bar{q}\gamma^{\mu}q)(\bar{q}\gamma_{\mu}q)$$

$$\mathcal{O}_{50} = (\bar{q}\sigma^{I}\gamma^{\mu}q)(\bar{q}\sigma^{I}\gamma_{\mu}q)$$

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- Features of current version:
  - Matching to SMEFT fully automated (including L4)
  - Basis-independent results: generate all redundant and evanescent operators. A specific basis is chosen by the user via external file (default Warsaw basis)
  - Consistent one-loop (but not NLO in RG-improved perturbation theory) result

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Eliminating redundancy: One-loop contribution to the T-parameter when integrating out a vector-like quark with Y=2/3.

$$\text{al01} \to \text{alpha01} - 2\,\text{alphaR3}\,\text{g1} + \text{alphaR7}\,\text{g1}^2$$

$$\text{al01} \to -\frac{\text{g1}^4\,\text{Nc}}{270\,\text{MHT}^2\,\pi^2} - \frac{\text{g1}^2\,\text{lamprime3}\,\text{lamprime3bar}\,\text{Nc}\left(-7 + 2\,\text{Log}\left[\frac{\text{MHT}^2}{\text{mu}^2}\right]\right)}{288\,\text{MHT}^2\,\pi^2} - \frac{\text{lamprime3}\,\text{lamprime3bar}\,\text{Nc}\left(\text{lamprime3}\,\text{lamprime3bar} - \text{ytop}\,\text{ytopbar} + 2\,\text{ytop}\,\text{ytopbar}\,\text{Log}\left[\frac{\text{MHT}^2}{\text{mu}^2}\right]\right)}{32\,\text{MHT}^2\,\pi^2}$$

$$\mathcal{O}_1 = |\phi^\dagger D_\mu \phi|^2$$

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  - Basis-independent results: generate all redundant and evanescent operators. A specific basis is chosen by the user via external file (default Warsaw basis)
  - Consistent one-loop (but not NLO in RG-improved perturbation theory) result
- Status of current version:
  - All necessary steps are essentially finished
  - We are currently in the process of testing and tidying up (output formatting, error messages, ...)

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- Cross-checks
  - Complete off-shell kinematic structure matched
  - Gauge invariance
  - Comparison with known results
  - Cancellation of IR divergencies
- Issues/features left for future releases:
  - We still have some issues with gamma5
  - Majorana particles not implemented yet
  - Massive light particles will be implemented in a future release
  - Some features of SMEFT still hard-coded

- Summary:
  - Effective Lagrangians allow us to encode relevant experimental information in a concise, efficient, unbiased way
  - The translation of this experimental information to NP models requires matching
  - Tree-level dictionary (Exp. Observables ⟺ NP models) soon to be completed
  - Matchmaker: General, fully automated and flexible code to match arbitrary models to arbitrary effective Lagrangians at tree and one-loop levels
  - The ultimate goal is to use the code to classify and compute the complete one-loop dictionary between UV completions and the SM effective Lagrangian


Thank you!