HiggsTools 2nd annual meeting
Granada, April 2016

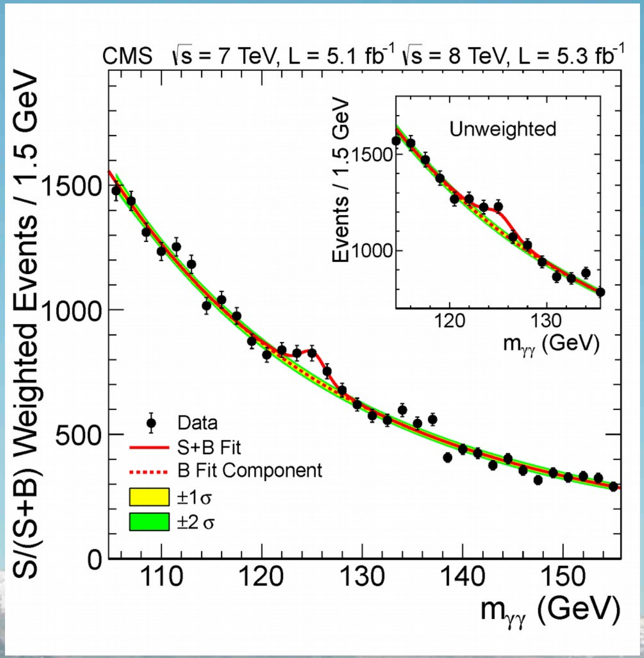
Tools for Effective Field Theory Calculations
(EFT from the top down)

Jose Santiago

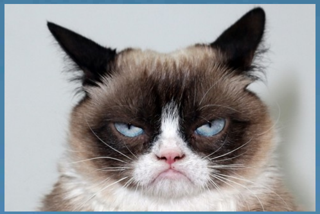
Based on: J. Blas, M. Chala, M. Perez-Victoria, J.S. [1412.8480]
F. del Aguila, Z. Kunszt, J.S. [1602.00126]
C. Anastasiou, A. Lazopoulos, J.S. (in progress)

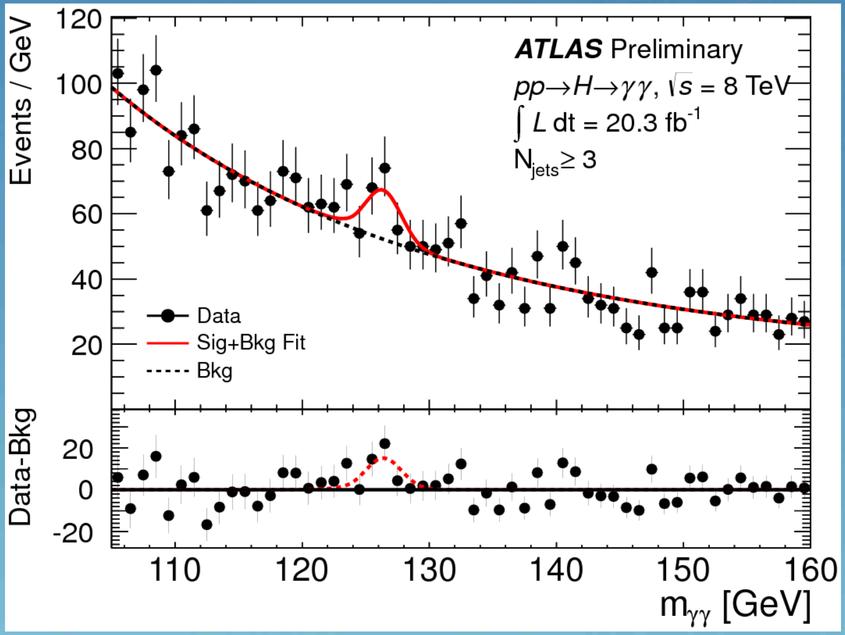
The LHC is a discovery machine

And sure enough we got our discovery!

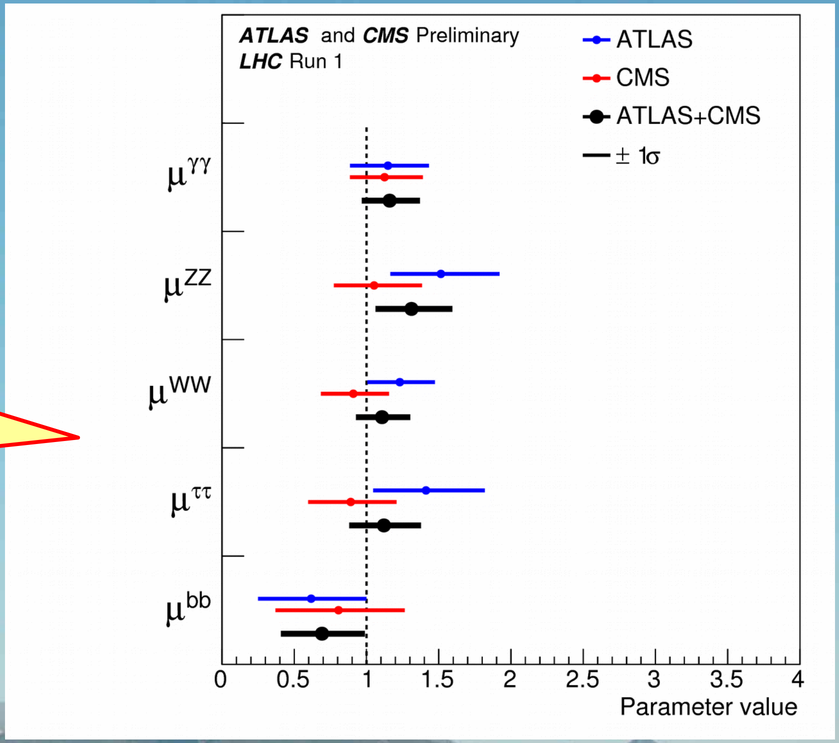


… but the sweet taste from this great triumph might not last long



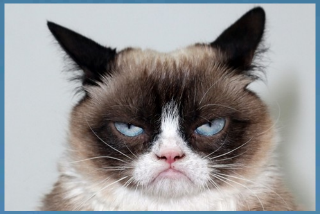


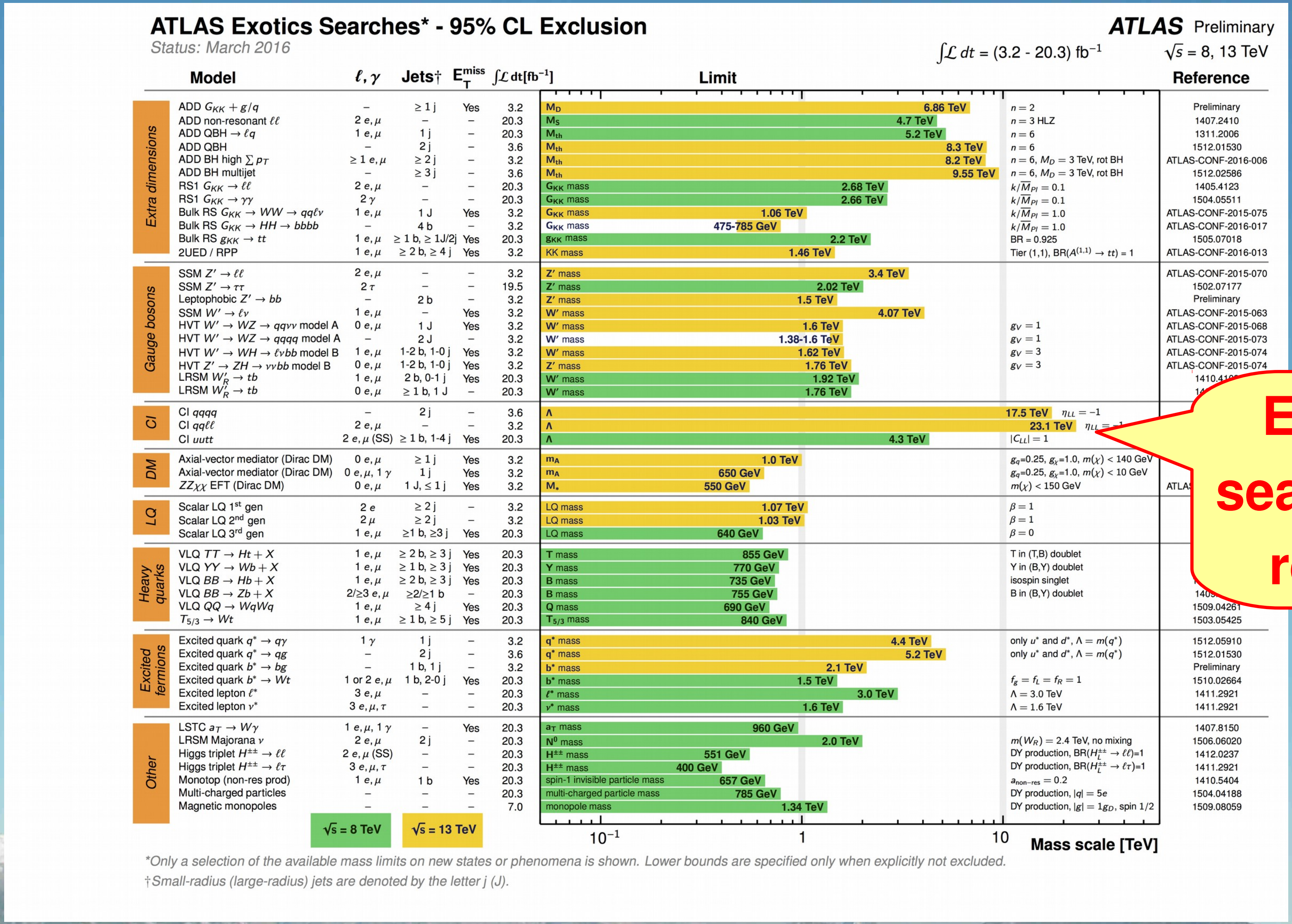
The Higgs mass is where we expected



The Higgs couplings are compatible with the SM ones

… but the sweet taste from this great triumph might not last long





Exhaustive NP searches with null results (so far)

Effective theories: bottom-up

- Effective Lagrangians: model-independent description of new physics in the presence of a mass gap
- Truly global fit to new physics now possible (EWPD plus LHC data -Higgs and otherwise-)

  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); Berthirer, Trott ('15), ...
- Map experimental (pseudo)observables to the Wilson coefficients in the effective Lagrangian to obtain all the experimental information in a model independent way
- Efforts to extend to NLO already on the way (see Passarino and Gomez-Ambrosio's talk)

  Ghezzi, Gomez-Ambrosio, Passarino, Uccirati ('15), Hartmann, Trott ('15), David, Passarino ('15), Boggia, Gomez-Ambrosio, Passarino ('16) ...

Effective theories: top-down

- A complementary approach is to consider specific UV completions
  - Correlations among Wilson coefficients in specific models (eventually observable in data)
  - Give up model-independence? Not if all models considered

$$\mathcal{L}(\phi, \Phi)$$

Matching

E

$$\mathcal{L}_{\rm eff}(\phi, \mu = M_\Phi)$$

RGE

$$\mathcal{L}_{\rm eff}(\phi, \mu = E_{exp})$$

  - Goal: Generate a UV/IR dictionary (map all possible UV completions of the SM to the Wilson coefficients of the SM effective Lagrangian)

Outline

- UV/IR tree-level dictionary
- UV/IR one-loop dictionary
  - Effective Lagrangian at one loop: functional methods and matching
  - Matchmaker: automated one-loop matching in effective theories
  - Spin-offs
- Conclusions and outlook

Tree-level dictionary (non-mixed contributions)

New Quarks:
F. Aguila, M. Perez-Victoria, J.S., JHEP (00)

$Q^{(m)}$	U	D	$\begin{pmatrix} U \\ D \end{pmatrix}$	$\begin{pmatrix} X \\ U \end{pmatrix}$	$\begin{pmatrix} D \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ U \\ D \end{pmatrix}$	$\begin{pmatrix} U \\ D \\ Y \end{pmatrix}$
isospin	0	0	$1/2$	$1/2$	$1/2$	1	1
hypercharge	$2/3$	$-1/3$	$1/6$	$7/6$	$-5/6$	$2/3$	$-1/3$

New Leptons:
F. Aguila, J. Blas, M. Perez-Victoria, PRD (08)

Leptons	N	E	$\begin{pmatrix} N \\ E^- \end{pmatrix}$	$\begin{pmatrix} E^- \\ E^{--} \end{pmatrix}$	$\begin{pmatrix} E^+ \\ N \\ E^- \end{pmatrix}$	$\begin{pmatrix} N \\ E^- \\ E^{--} \end{pmatrix}$
Notation			Δ_1	Δ_3	Σ_0	Σ_1
$SU(2)_L \otimes U(1)_Y$	1_0	1_{-1}	$2_{-(1/2)}$	$2_{-(3/2)}$	3_0	3_{-1}
Spinor	Dirac or Majorana	Dirac	Dirac	Dirac	Dirac or Majorana	Dirac

New Vectors:
F. Aguila, J. Blas, M. Perez-Victoria, JHEP (10)

Vector	$\mathcal{B}_\mu$	$\mathcal{B}^1_\mu$	$\mathcal{W}_\mu$	$\mathcal{W}^1_\mu$	$\mathcal{G}_\mu$	$\mathcal{G}^1_\mu$	$\mathcal{H}_\mu$	$\mathcal{L}_\mu$
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,\mathrm{Adj})_0$	$(1,\mathrm{Adj})_1$	$(\mathrm{Adj},1)_0$	$(\mathrm{Adj},1)_1$	$(\mathrm{Adj},\mathrm{Adj})_0$	$(1,2)_{-\frac{3}{2}}$
Vector	$\mathcal{U}^2_\mu$	$\mathcal{U}^5_\mu$	$\mathcal{Q}^1_\mu$	$\mathcal{Q}^5_\mu$	$\mathcal{X}_\mu$	$\mathcal{Y}^1_\mu$	$\mathcal{Y}^5_\mu$	
Irrep	$(3,1)_{\frac{2}{3}}$	$(3,1)_{\frac{5}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,\mathrm{Adj})_{\frac{2}{3}}$	$(\bar{6},2)_{\frac{1}{6}}$	$(\bar{6},2)_{-\frac{5}{6}}$	

New Scalars:
J. Blas, M. Chala, M. Perez-Victoria, J.S., JHEP (15)

Colorless Scalars	$\mathcal{S}$	$\mathcal{S}_1$	$\mathcal{S}_2$	φ	Ξ_0	Ξ_1	Θ_1	Θ_3
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,1)_2$	$(1,2)_{\frac{1}{2}}$	$(1,3)_0$	$(1,3)_1$	$(1,4)_{\frac{1}{2}}$	$(1,4)_{\frac{3}{2}}$

Colored Scalars	ω_1	ω_2	ω_4	Π_1	Π_7	ζ
Irrep	$(3,1)_{-\frac{1}{3}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{4}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$

Colored Scalars	Ω_1	Ω_2	Ω_4	Υ	Φ
Irrep	$(6,1)_{\frac{1}{3}}$	$(6,1)_{-\frac{2}{3}}$	$(6,1)_{\frac{4}{3}}$	$(6,3)_{\frac{1}{3}}$	$(8,2)_{\frac{1}{2}}$

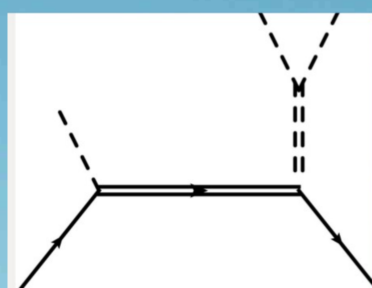
Tree-level dictionary (mixed contributions)

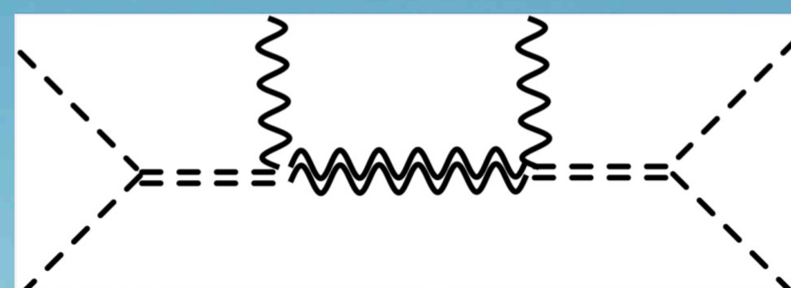
Mixed contributions: J. Blas, M. Chala, J.C. Criado, M. Perez-Victoria, J.S., to appear soon

- Dimensionful couplings imply that particles with different spins can simultaneously contribute to $\mathcal{L}_6$ at tree level

$$\kappa \phi_1 \phi_2 \phi_3 + \kappa' V^\mu D_\mu \phi + \kappa'' V^\mu V'_\mu \phi + \ldots$$

- We are currently classifying and computing all possible contributions





- Only a subset of the representations in the previous list contributes

One-loop UV/IR dictionary

- Many contributions to the effective Lagrangian can be only generated at the quantum level
- Even contributions that can potentially arise at tree-level only appear at loop level in specific models
- The dictionary should be extended to one loop if we want to account for these cases
- The number of possibilities increases dramatically: automation seems compulsory

Functional methods and matching

- An interesting attempt has been recently made using functional methods Henning, Lu, Murayama ('14); Gaillard ('86); Cheyette ('86)
- There has been a great deal of developments in the last year: Henning, Lu, Murayama ('14); Drozd, Ellis, Quevillon, You ('15)
  - Initial attemps were not complete in the case of linear couplings to heavy states F. Aguila, Z. Kunszt, J.S. ('16)
  - The missing terms are local and can only be recovered by matching, which can be performed diagramatically Anastasiou, Lazopoulos, J.S. or by functional methods Henning, Lu, Murayama ('16); Ellis, Quevillon, You, Zhang ('16)

MatchMaker: automated matching in effective theories

C. Anastasiou, A. Lazopoulos, J.S., in progress

- We are developing an automated tool to perform tree-level and one-loop matching of arbitrary theories into arbitrary effective Lagrangians
- Based on standard, well-tested tools (FeynRules, QGRAF, FORM, Mathematica, Python)
- Flexible (from full matching to specific operators), fully automated and general
- Unified treatment (effective theory just another model)
- Off-shell matching with (initially) massless particles in the effective theory (e.g. unbroken phase of the SM)

MatchMaker: automated matching in effective theories

C. Anastasiou, A. Lazopoulos, J.S., in progress

- Model Implementation: FeynRules. Feynman rules are automatically computed and the QGRAF model written.
- A Python engine runs QGRAF to generate Feynman diagrams and compute the amplitudes. Amplitudes are automatically manipulated with FORM.
- The FORM code performs the corresponding Dirac algebra, momentum expansion, partial fractioning, ibp identities, …, to obtain the amplitude in a useful form
- The FORM output is fed into Mathematica to perform the actual matching

MatchMaker: automated matching in effective theories

C. Anastasiou, A. Lazopoulos, J.S., in progress

- Some issues we have to deal with:
  - Generation of redundant and evanescent operators
  - Treatment of γ_5
- Cross-checks:
  - Gauge invariance
  - Cancellations of IR divergencies
  - Comparison with known examples

MatchMaker: automated matching in effective theories

C. Anastasiou, A. Lazopoulos, J.S., in progress

- Status:
  - First version: SM effective Lagrangian
    - Bosonic operators: finished
    - Two-fermion operators: almost finished
    - Four-fermion operators: in progress
- Expected time-line:
    - First complete version: spring 2016
    - First public version: summer 2016
    - Second version with extended matching: end 2016

MatchMaker: automated matching in effective theories

C. Anastasiou, A. Lazopoulos, J.S., in progress

- Bonus:
  - As a by-product of our method we will obtain an independent calculation of the:
    - SM effective Lagrangian RGE, from the UV divergencies of the effective theory calculation (which can be related to the IR divergencies of the full theory side calculation)
    - Translation between arbitrary operator bases

MatchMaker: automated matching in effective theories

C. Anastasiou, A. Lazopoulos, J.S., in progress

F. Aguila, Z. Kunszt, J.S., 1602.00126

- Sample result: T parameter from charge 2/3 vector-like quark singlet

$$\mathcal{L}_T = \overline{T}(\mathrm{i}\not{D} - M)T - \left[\lambda_T\ \overline{q_L}\tilde{\phi}T_R + \mathrm{h.c.}\right]$$

  - Computed in the physical basis (full model)

$$\Delta\hat{\mathrm{T}} = \frac{N_C}{32\pi^2}\frac{v^2}{M^2}\left[|\lambda_T|^4 + 2\lambda_t^2|\lambda_T|^2\left(\log\frac{M^2}{m_t^2} - 1\right)\right]$$

M. Carena, E. Ponton, J.S., C. Wagner ph/0607106

  - Computed in an EFT approach (3 steps)
    - Matching at M
    - Running to m_t
    - Matching at m_t

MatchMaker: automated matching in effective theories

C. Anastasiou, A. Lazopoulos, J.S., in progress
F. Aguila, Z. Kunszt, J.S., 1602.00126

- Sample result: T parameter from charge 2/3 vector-like quark singlet
  - Matching at M: off-shell (3 independent operators)

$$\mathcal{O}_1 = |\phi^\dagger D_\mu \phi|^2 \qquad \mathcal{O}_2 = \phi^\dagger \phi \partial^2 \phi^\dagger \phi \qquad \mathcal{R} = \phi^\dagger \phi \phi^\dagger D^2 \phi$$

  - Compute $\langle H_1 H_1^* H_2 H_2^* \rangle$ in full and effective theories

$$\alpha_1^{(1l)} = \frac{N_C|\lambda_T|^2}{16\pi^2 M^2}\left(\frac{1}{2}\lambda_t^2 - \frac{1}{2}|\lambda_T|^2\right),$$

$$\alpha_2^{(1l)} = \frac{N_C|\lambda_T|^2}{16\pi^2 M^2}\left(\frac{3}{2}\lambda_t^2 - \frac{1}{3}|\lambda_T|^2\right),$$

$$\alpha_{\mathcal{R}}^{(1l)} = \frac{N_C|\lambda_T|^2}{16\pi^2 M^2}\left(-\frac{1}{2}\lambda_t^2 + \frac{1}{2}|\lambda_T|^2\right),$$

$$\Delta\hat{T} = -v^2\alpha_1$$

$$\Delta\hat{\mathrm{T}} = \frac{N_C}{32\pi^2}\frac{v^2}{M^2}\left[|\lambda_T|^4 + 2\lambda_t^2|\lambda_T|^2\left(\log\frac{M^2}{m_t^2} - 1\right)\right]$$

MatchMaker: automated matching in effective theories

C. Anastasiou, A. Lazopoulos, J.S., in progress

F. Aguila, Z. Kunszt, J.S., 1602.00126

- Sample result: T parameter from charge 2/3 vector-like quark singlet

  (Alonso), Jenkins, Manohar, Trott ('13);
  Elias-Mir , Espinosa, Masso, Pomarol ('13)

  - Running to m_t: tree-level operators relevant $\Delta\hat{T} = -v^2\alpha_1$

$$16\pi^2 \frac{\mathrm{d}\,\alpha_1}{\mathrm{d}\log\mu} = 8N_C\lambda_t^2\alpha_{\phi q}^{(1)} + \dots\ ,$$

$$\Delta\hat{\mathrm{T}} = \frac{N_C}{32\pi^2}\frac{v^2}{M^2}\left[|\lambda_T|^4 + 2\lambda_t^2|\lambda_T|^2\left(\log\frac{M^2}{m_t^2} - 1\right)\right]$$

$$\mathcal{O}_{\phi q}^{(1)} = \mathrm{i}\phi^\dagger D_\mu\phi\bar{q}\gamma^\mu q \qquad \alpha_{\phi q}^{(1)} = \frac{|\lambda_T|^2}{4M^2}$$

$$\begin{aligned}\alpha_1(m_t) &= \alpha_1(M) - \frac{N_C\lambda_t^2\alpha_{\phi q}^{(1)}(M)}{2\pi^2}\log\left(\frac{M}{m_t}\right)\\ &= \frac{N_C}{32\pi^2M^2}\left[\lambda_t^2|\lambda_T|^2 - |\lambda_T|^4 - 2\lambda_t^2|\lambda_T|^2\log\left(\frac{M^2}{m_t^2}\right)\right].\end{aligned}$$

MatchMaker: automated matching in effective theories

C. Anastasiou, A. Lazopoulos, J.S., in progress
F. Aguila, Z. Kunszt, J.S., 1602.00126

- Sample result: T parameter from charge 2/3 vector-like quark singlet
  - Matching at m_t: top contribution with anomalous tree-level couplings

$$g_{W_3 t_L t_L} = g^{\rm SM}_{W_3 t_L t_L}[1 - 2v^2(\alpha^{(1)}_{\phi q} - \alpha^{(3)}_{\phi q})] = g^{\rm SM}_{W_3 t_L t_L}\left(1 - \frac{|\lambda_T|^2 v^2}{M^2}\right),$$

$$g_{W_1 t_L b_L} = g^{\rm SM}_{W_1 t_L b_L}[1 + 2v^2 \alpha^{(3)}_{\phi q}] = g^{\rm SM}_{W_1 t_L b_L}\left(1 - \frac{|\lambda_T|^2 v^2}{2M^2}\right).$$

$$\hat{T}(m_t^+) = \frac{N_C}{32\pi^2}\lambda_t^2\left(1 - \frac{|\lambda_T|^2 v^2}{M^2}\right) = \hat{T}_{\rm SM} + \Delta\hat{T}_{\rm SM}$$

$$\Delta\hat{T}(m_t^-) = -v^2\alpha_1(m_t) + \Delta\hat{T}(m_t^+) = \frac{N_C}{32\pi^2}\frac{v^2}{M^2}\left[|\lambda_T|^4 + 2\lambda_t^2|\lambda_T|^2\left(\log\frac{M^2}{m_t^2} - 1\right)\right]$$

- Summary:
  - The goal is to complete the UV/IR dictionary: direct map between UV theories and experimental observables
  - The tree level dictionary is complete
  - Automated calculation of one-loop (and tree-level) matching conditions is well advanced
  - MatchMaker: General, fully automated and flexible code to match arbitrary models to arbitrary effective Lagrangians
  - 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