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Use of Effective Field Theories at the LHC

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Disclaimer

- This is not a standard review
- The goal is to trigger further questions/discussion
- I will shamelessly use examples from my own work (not necessarily the best, definitely not the only ones, but the ones I know best)
- Results and techniques are common to all physics, including Higgs, even if BEH does not appear explicitly

Outline

- EFTs: bottom-up approach
  - Use vs interpretation of EFTs at the LHC (and others)
    - Parametrization of experimental observables
    - Limit extraction
    - Interpretation: validity, dimension-8, how precise are the bounds obtained
- EFTs: top-down approach
  - UV/IR tree-level dictionary
  - UV/IR one-loop dictionary: automated matching
  - How to make a one-loop calculation in (top-down) EFTs

Effective theories: bottom-up

- Effective Lagrangians: model-independent description of new physics in the presence of a mass gap
- Bottom-up approach to EFTs: Map experimental (pseudo) observables to the Wilson coefficients in the effective Lagrangian to obtain all the experimental information in a model independent way
- Basis? Which basis?
  - All complete independent bases are equivalent
  - Some are more convenient than others for certain purposes (flat directions more explicit, …)
  - Some are valid only under certain assumptions (flavor alignment, …)

Effective theories: bottom-up

- Truly global fit to new physics now possible (EWPD plus LHC data -Higgs and otherwise-)

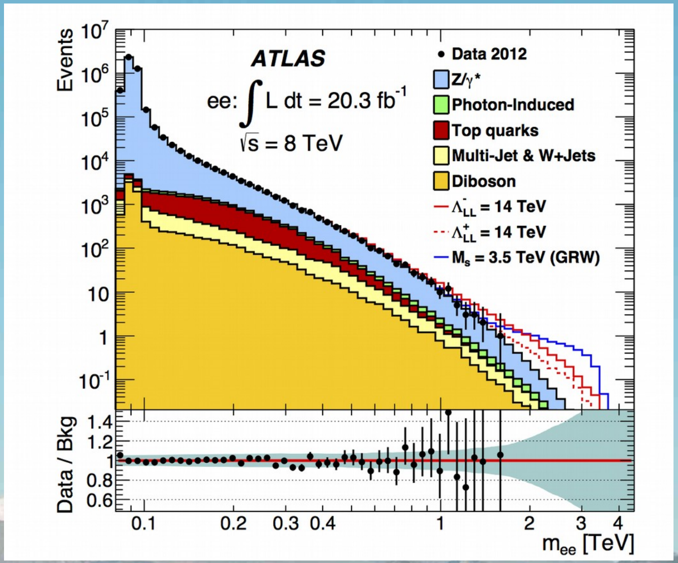
Ciuchini, Franco, Mishima, Silvestrini ('13); Blas, Chala, J.S. ('13, '15); Pomarol, Riva ('14); Falkowski, Riva ('15); Buckley, Englert, Ferrando, Miller, Moore, Russell, White ('15); Berthirer, Trott ('15), ...

- Efforts to extend to NLO already on the way

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

- The use of EFTs at the LHC is not that different from LEP but the interpretation can be very different
  - On-shell SM particle production: Z-pole, Higgs/top production, ...
  - Looking at tails: LEP2, HH-production, contact interaction searches, ...

- Use of EFTs at the LHC (or any other experiment):
  - Classify all operators that contribute to a specific observable (educated assumptions might be needed to reduce # of dof)
  - Compute the simplest yet most general parameterization of the corresponding observable (brute force can also work)
  - Compare with experimental data and extract limits
  - Analyze range of validity of the results
- I will illustrate this process in dilepton searches at the LHC



- Dilepton searches at the LHC

J Blas, M. Chala, J.S., PRD (13) + to appear

  - Classify operators that contribute to the process

$$
\begin{aligned}
\mathcal{O}_{lq}^{(1)} &= (\bar{l}\gamma^\mu l)(\bar{q}\gamma_\mu q), & \mathcal{O}_{lq}^{(3)} &= (\bar{l}\sigma_I\gamma^\mu l)(\bar{q}\sigma_I\gamma_\mu q), \\
\mathcal{O}_{eu} &= (\bar{e}\gamma^\mu e)(\bar{u}\gamma_\mu u), & \mathcal{O}_{ed} &= (\bar{e}\gamma^\mu e)(\bar{d}\gamma_\mu d), \\
\mathcal{O}_{lu} &= (\bar{l}\gamma^\mu l)(\bar{u}\gamma_\mu u), & \mathcal{O}_{ld} &= (\bar{l}\gamma^\mu l)(\bar{d}\gamma_\mu d), \\
\mathcal{O}_{qe} &= (\bar{q}\gamma^\mu q)(\bar{e}\gamma_\mu e), & \mathcal{O}_{qde} &= (\bar{l}e)(\bar{d}q), \\
\mathcal{O}_{lq\epsilon} &= (\bar{l}e)\epsilon(\bar{q}^T u), & \mathcal{O}_{ql\epsilon} &= (\bar{q}e)\epsilon(\bar{l}^T u),
\end{aligned}
$$

Do not interfere with SM plus are very constrained by pion decay

Other operators (vertex corrections) strongly constrained by Z-pole observables

- Dilepton searches at the LHC
  - Compute the Master Equation (most general contribution)

$$
\begin{aligned}
48\pi \frac{d\sigma}{d\hat{t}}(\bar{u}u \to \ell^+\ell^-) &= \left[\left|\mathcal{A}^{\rm SM}_{u_L\ell_R} + \frac{\alpha_{qe}}{\Lambda^2}\right|^2 + \left|\mathcal{A}^{\rm SM}_{u_R\ell_L} + \frac{\alpha_{lu}}{\Lambda^2}\right|^2 + \frac{1}{2\Lambda^4}\left[|\alpha_{ql\epsilon}|^2 + {\rm Re}(\alpha_{lq\epsilon}\alpha^*_{ql\epsilon})\right]\right]\frac{\hat{t}^2}{\hat{s}^2} \\
&+ \left[\left|\mathcal{A}^{\rm SM}_{u_L\ell_L} + \frac{\alpha^{(1)}_{lq} - \alpha^{(3)}_{lq}}{\Lambda^2}\right|^2 + \left|\mathcal{A}^{\rm SM}_{u_R\ell_R} + \frac{\alpha_{eu}}{\Lambda^2}\right|^2 - \frac{1}{2\Lambda^4}{\rm Re}(\alpha_{lq\epsilon}\alpha^*_{ql\epsilon})\right]\frac{\hat{u}^2}{\hat{s}^2} \\
&+ \frac{1}{2\Lambda^4}\left[|\alpha_{lq\epsilon}|^2 + {\rm Re}(\alpha_{lq\epsilon}\alpha^*_{ql\epsilon})\right], \\
48\pi \frac{d\sigma}{d\hat{t}}(\bar{d}d \to \ell^+\ell^-) &= \left[\left|\mathcal{A}^{\rm SM}_{d_L\ell_R} + \frac{\alpha_{qe}}{\Lambda^2}\right|^2 + \left|\mathcal{A}^{\rm SM}_{d_R\ell_L} + \frac{\alpha_{ld}}{\Lambda^2}\right|^2\right]\frac{\hat{t}^2}{\hat{s}^2} \\
&+ \left[\left|\mathcal{A}^{\rm SM}_{d_L\ell_L} + \frac{\alpha^{(1)}_{lq} + \alpha^{(3)}_{lq}}{\Lambda^2}\right|^2 + \left|\mathcal{A}^{\rm SM}_{d_R\ell_R} + \frac{\alpha_{ed}}{\Lambda^2}\right|^2\right]\frac{\hat{u}^2}{\hat{s}^2} + \frac{|\alpha_{qde}|^2}{2\Lambda^4},
\end{aligned}
$$

$$\mathcal{A}^{\rm SM}_{\psi\phi} = \frac{e^2 Q_\psi Q_\phi}{\hat{s}} + \frac{g_\psi g_\phi}{\hat{s} - m_Z^2 + {\rm i} m_Z \Gamma_Z}$$

$$\sim \frac{e^2 Q_\psi Q_\phi + g_\psi g_\phi}{\hat{s}}$$

- Dilepton searches at the LHC
  - Compute the Master Equation (most general contribution)

$$\sigma \;=\; \sigma^{\rm SM} + \frac{1}{\Lambda^2}\sum_{q=u,d}\big[\underbrace{F_1^q A_1^q}_{\sim t^2} + \underbrace{F_2^q A_2^q}_{\sim u^2}\big] + \frac{1}{\Lambda^4}\sum_{q=u,d}\big[\underbrace{G_1^q B_1^q}_{\sim t^2} + \underbrace{G_2^q B_2^q}_{\sim u^2} + \underbrace{G_3^q B_3^q}_{\sim s^2}\big]$$

$$\begin{aligned}
A_1^u &= [e^2 Q_u Q_e + g_{u_L} g_{e_L}](\alpha_{lq}^{(1)} - \alpha_{lq}^{(3)}) + [e^2 Q_u Q_e + g_{u_R} g_{e_R}]\alpha_{eu},\\
A_2^u &= [e^2 Q_u Q_e + g_{u_L} g_{e_R}]\alpha_{qe} + [e^2 Q_u Q_e + g_{u_R} g_{e_L}]\alpha_{lu},\\
A_1^d &= [e^2 Q_d Q_e + g_{d_L} g_{e_L}](\alpha_{lq}^{(1)} + \alpha_{lq}^{(3)}) + [e^2 Q_d Q_e + g_{d_R} g_{e_R}]\alpha_{ed},\\
A_2^d &= [e^2 Q_d Q_e + g_{d_L} g_{e_R}]\alpha_{qe} + [e^2 Q_d Q_e + g_{d_R} g_{e_L}]\alpha_{ld},\\
B_1^u &= 4(\alpha_{lq}^{(1)} - \alpha_{lq}^{(3)})^2 + 4\alpha_{eu}^2 - 2{\rm Re}(\alpha_{lq\epsilon}\alpha_{ql\epsilon}^*),\\
B_2^u &= 4\alpha_{qe}^2 + 4\alpha_{lu}^2 + 2|\alpha_{ql\epsilon}|^2 + 2{\rm Re}(\alpha_{lq\epsilon}\alpha_{ql\epsilon}^*),\\
B_3^u &= 2|\alpha_{lq\epsilon}|^2 + 2{\rm Re}(\alpha_{lq\epsilon}\alpha_{ql\epsilon}^*),\\
B_1^d &= 4(\alpha_{lq}^{(1)} + \alpha_{lq}^{(3)})^2 + 4\alpha_{ed}^2,\\
B_2^d &= 4\alpha_{qe}^2 + 4\alpha_{ld}^2,\\
B_3^d &= 2|\alpha_{qde}|^2.
\end{aligned}$$

- Dilepton searches at the LHC
  - Complementarity of LHC and LEP measurements

	LHC	EWPT
$\mathcal{O}_{lq}^{(1)}$	$[-0.032, 0.073]$	$[-0.012, 0.055]$
$\mathcal{O}_{lq}^{(3)}$	$[-0.106, 0.019]$	$[-0.006, 0.012]$
$\mathcal{O}_{eu}$	$[-0.032, 0.102]$	$[-0.097, 0.017]$
$\mathcal{O}_{ed}$	$[-0.107, 0.068]$	$[-0.077, 0.040]$
$\mathcal{O}_{lu}$	$[-0.043, 0.079]$	$[-0.041, 0.095]$
$\mathcal{O}_{ld}$	$[-0.096, 0.076]$	$[-0.021, 0.106]$
$\mathcal{O}_{qe}$	$[-0.040, 0.058]$	$[-0.055, 0.011]$

- Dilepton searches at the LHC
  - The interpretation of the results in terms of EFT is NOT the same at LHC and LEP (different precision and energies probed)
  - When can we trust the EFT description of LHC data? Depends on the value of the actual bound and the energies probed by experimental data
    - Power-counting rules to estimate range of validity
    - Compute and report bounds as a function of energy probed
    - Are we sensitive to dimension-8 operators?
    - How precise is the actual bound? We've checked a couple of examples
      - t-channel scalar: $\omega_1 \sim (3,1)_{-\frac{1}{3}}$
      - s-channel vector: $\mathcal{B}_\mu \sim (1,1)_0$
  - For simplicity we use only the ATLAS analysis [arxiv:1407.2410] and couplings only to e_R and u_R $\quad 1.2 \leq M_{ee}/\mathrm{TeV} \leq 3$

$$-0.021\ \mathrm{TeV}^{-2} \leq \frac{\alpha_{eu}}{\Lambda^2} \leq 0.097\ \mathrm{TeV}^{-2}$$

- Dimension 6 vs dimension 8:
  - Safe to neglect dimension 8 operators if contributions proportional to Λ^{-4} are negligible

$$\sigma \sim |\mathcal{A}_{\rm SM}|^2 + \frac{\mathcal{A}_{\rm SM}\mathcal{A}_6}{\Lambda^2} + \frac{|\mathcal{A}_6|^2 + \mathcal{A}_{\rm SM}\mathcal{A}_8}{\Lambda^4} + \ldots$$

$$N = 8.7 + 2.3 + 0.7 \qquad \frac{\alpha_{eu}}{\Lambda^2} = -0.021\ \mathrm{TeV}^{-2}$$

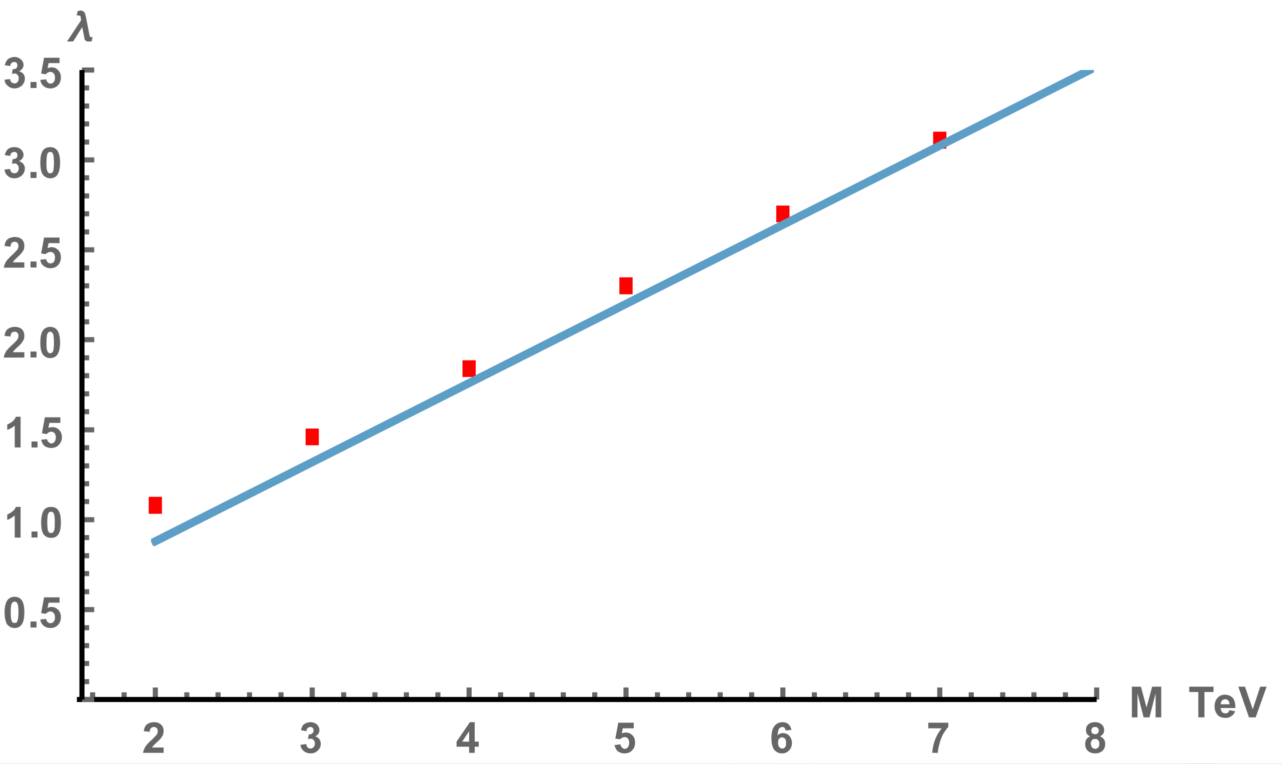
$$N = 8.7 - 10.5 + 15.2 \qquad \frac{\alpha_{eu}}{\Lambda^2} = 0.097\ \mathrm{TeV}^{-2}$$

  - The sign of the interference is important (quartic terms can be necessary to stabilize)
  - There can be exceptions (vanishing SM contribution, ...)

- How precise are the bounds?

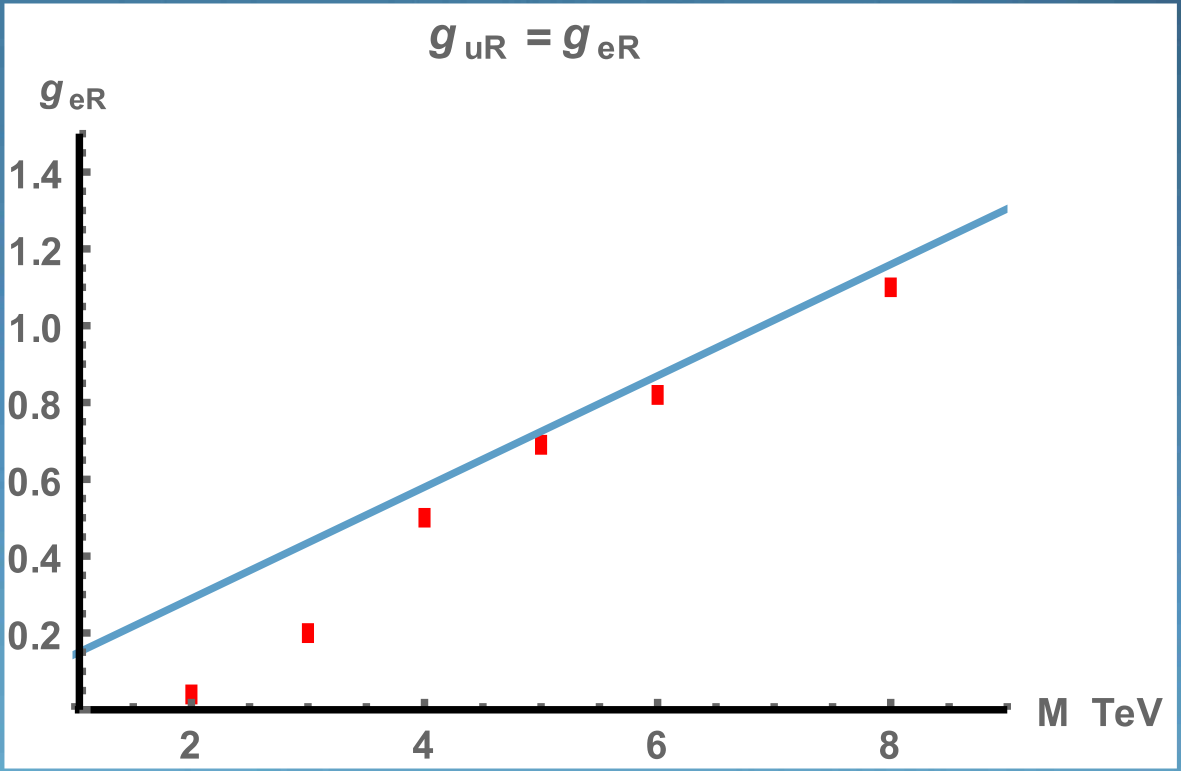
$$\omega_1 \sim (3,1)_{-\frac{1}{3}}$$

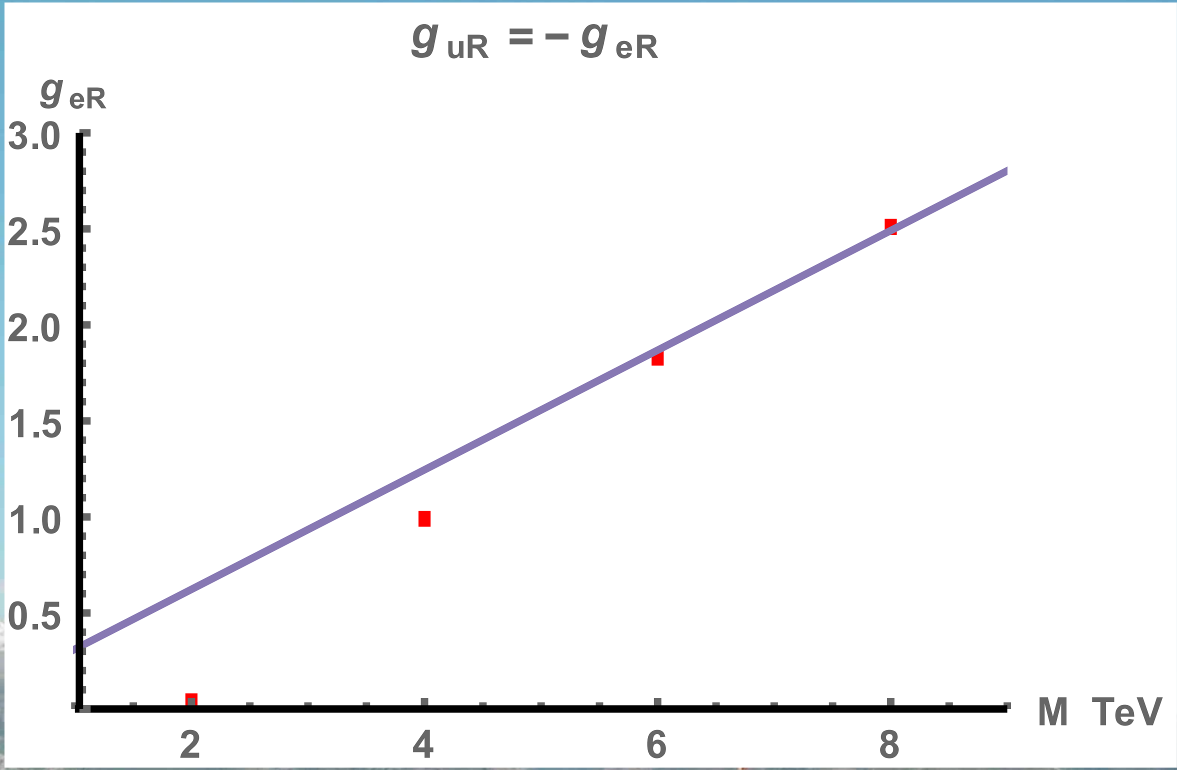
$$\alpha_{eu} > 0$$



- How precise are the bounds?

$$\mathcal{B}_\mu \sim (1,1)_0$$





Summary of part 1

- Bottom-up approach to EFTs at the LHC:
  - Use of EFTs similar to other experiments, interpretation (and range of validity) can be quite different
  - If quartic terms are not negligible we are in principle sensitive to dimension-8 operators
  - Still, corresponding bounds can be quite accurate, even for low masses of new particles
  - It's useful to report bounds as a function of the scales probed (limits using smaller number of bins might be less stringent but more robust)
  - LHC can be competitive with EWPT on common observables (but attention must be paid to the difference in the interpretations)

Effective theories: top-down

- A complementary approach is to consider specific UV completions
  - Correlations among Wilson coefficients in specific models (eventually observable in data)
  - Validity of EFT can be explicitly checked
  - Give up model-independence? Not if we can classify all UV models that contribute

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

Matching

E

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

RGE

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

- The goal is to generate a UV/IR dictionary: map all possible SM UV completions to the Wilson coefficients of the SM effective Lagrangian at certain order in mass dimension and loops

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	$(6,1)_{\frac{1}{3}}$	$(6,1)_{-\frac{2}{3}}$	$(6,1)_{\frac{4}{3}}$	$(6,3)_{\frac{1}{3}}$	$(8,2)_{\frac{1}{2}}$

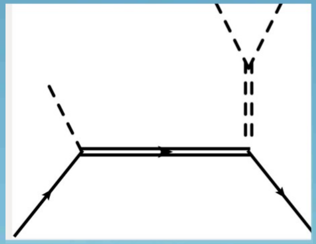
Tree-level dictionary (mixed contributions)

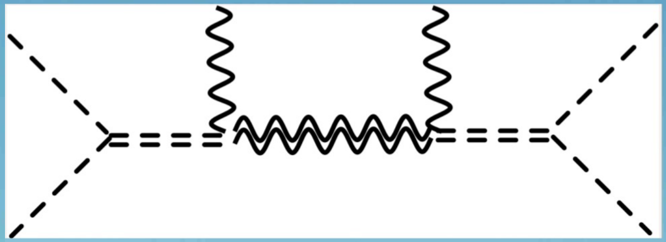
Mixed contributions: J. Blas, M. Chala, J.C. Criado, M. Perez-Victoria, J.S., to appear soon

- 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

- With this, the tree-level, dimension 6 UV/IR dictionary is complete: we can map arbitrary UV extensions to the SM EFT

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 one-loop dictionary would allow a consistent combination with EWPT and low energy experiments
- 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, Carmona, Lazopoulos, J.S.
    - by functional methods Henning, Lu, Murayama ('16); Ellis, Quevillon, You, Zhang ('16)

Leading one-loop corrections

- One-loop corrections have log-enhanced and finite terms
  - Log-enhanced are typically larger and can be computed from RGEs (already available). They can give important constraints on otherwise unprobed operators

    $$(\alpha_{lq}^{(3)})_{lltt} \in [-0.07, 0.29]\ \mathrm{TeV}^{-2}$$ Blas, Chala, J.S. ('16)

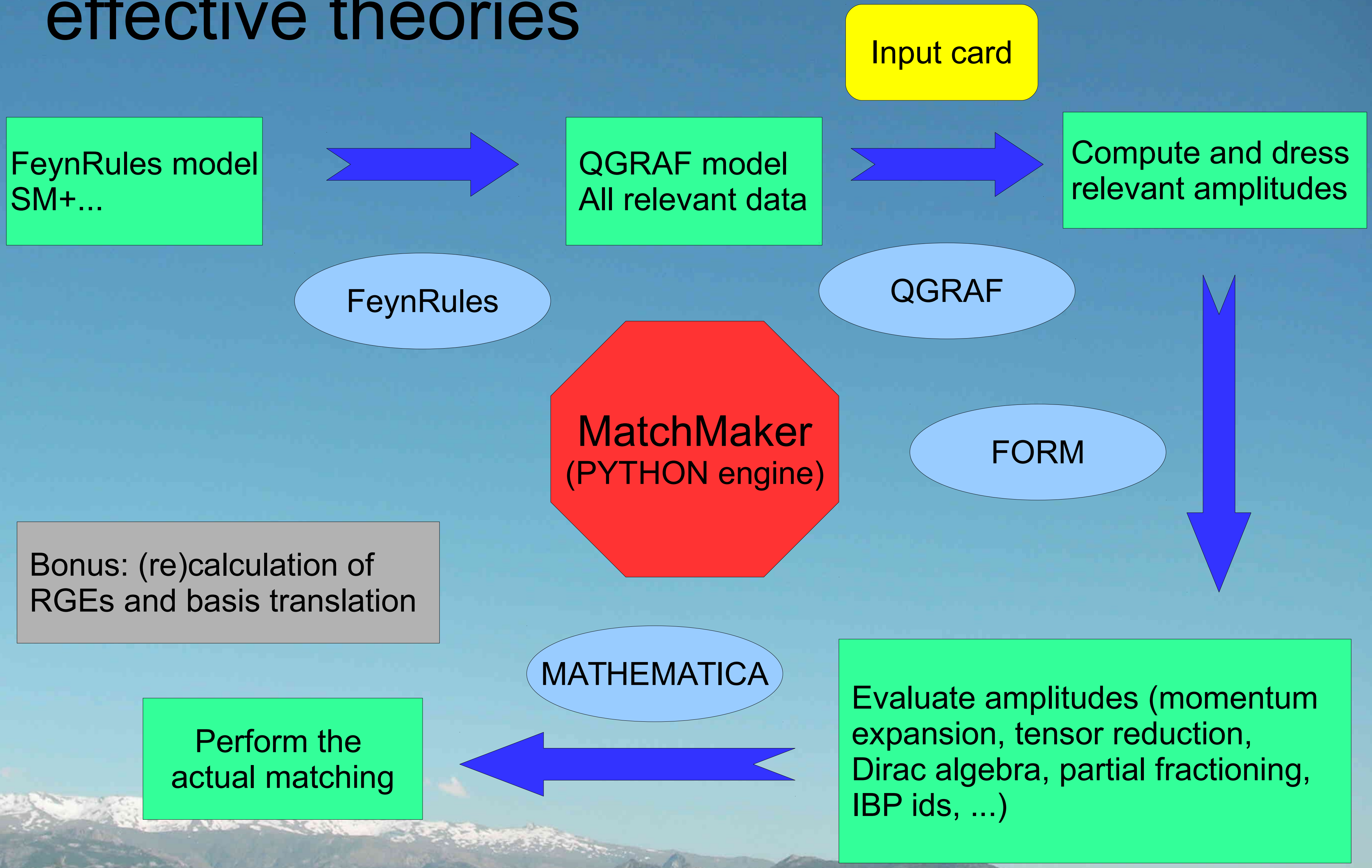
  - Finite terms can still be sizeable and will be fully computable soon

MatchMaker: automated matching in effective theories

Anastasiou, Carmona, 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



How to use EFTs (from the top-down) at one loop

F. Aguila, Z. Kunszt, J.S., ('16)

- 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)

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

Carena, Ponton, J.S., Wagner ('06)

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

How to use EFTs (from the top-down) at one loop

- 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

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

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

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

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

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

How to use EFTs (from the top-down) at one loop

- Sample result: T parameter from charge 2/3 vector-like quark singlet (Alonso), Jenkins, Manohar, Trott ('13); Elias-Miró, Espinosa, Masso, Pomarol ('13); Elias-Miró, Grojean, Gupta, Marzocca ('13)
  - Running to m_t: tree-level operators relevant

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

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

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

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

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

How to use EFTs (from the top-down) at one loop

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

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

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

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

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

$3.5\ (M = 1\ \text{TeV})$

Summary of part 2

- Top-down approach to EFTs at the LHC:
  - Specific UV completions can give further info: new correlations, control over range of validity, …
  - It can be complete: UV/IR dictionary
    - Finished at tree level and dimension 6
    - At one loop it needs automation: MatchMaker
  - Consistent one-loop calculation in (top-down) EFT:
    - Matching at high scale
    - Running down to EW scale
    - Matching at top/W/Z/H mass
    - Further running if low energy experiment

Sometimes I feel like playing football

The I remember we're never more than 4 and forget about it

We're trying to organize a football game.
If you are interested tell Roberto