SMEFT-Tools 2022

14-16 September 2022
University of Zürich
Europe/Zurich timezone

Introductory talk

José Santiago

FTAE High Energy Theory

Universidad de Granada

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Motivational talk ???

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What's interesting in (SM)EFT

Very personal view!!!

José Santiago

FTAE High Energy Theory

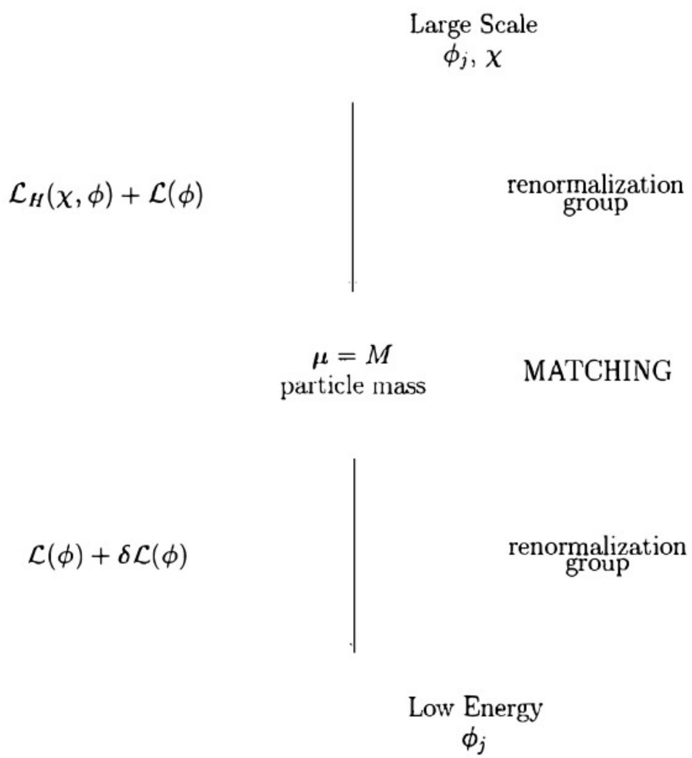
ugr Universidad de Granada

Outline

- The effective way beyond the Standard Model.
- IR/UV dictionaries to connect theory and experiment.
  - Towards the next IR/UV dictionaries.
- Automated matching (and much more) with Matchmakereft.
- Recent developments:
  - On-shell matching.
  - Generation of arbitrary models.
  - Renormalization and matching or general theories.
- Closing the gap ... with experiment.
- Conclusions and outlook.

EFTs are essential!

- Effective field theory is an essential tool to study physics across scales



EFTs are essential!

- Effective field theory is an essential tool to study physics across scales.

Annu. Rev. Nucl. Part. Sci. 1993. 43:209–52

EFFECTIVE FIELD THEORY[1]

Howard Georgi

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

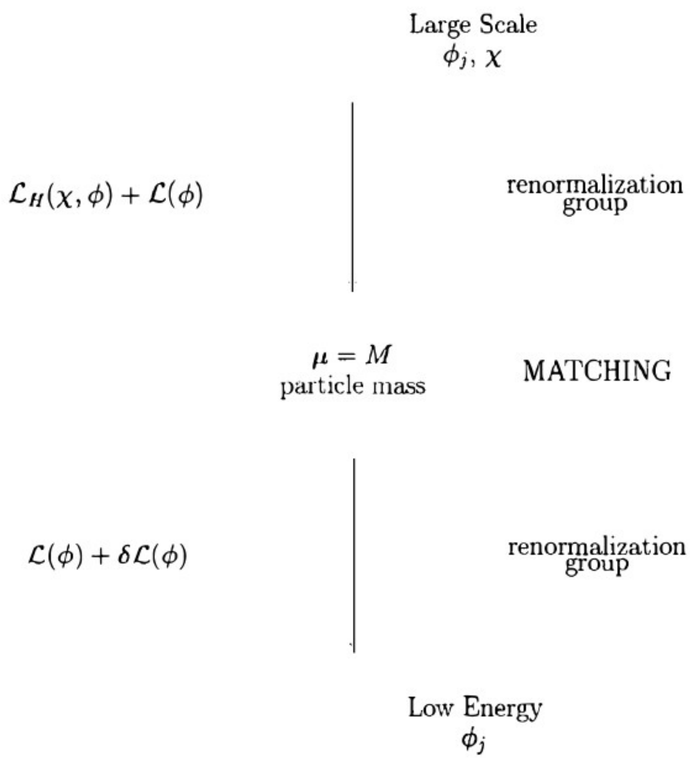
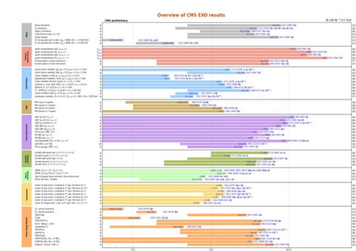


Figure 4 The general form of a matching calculation.

Told you so (many years ago)

- Why are we so interested now?
  - Experiment:
    - It seems like a mass gap is actually present!



  - Tools:
    - We now have tools that allow us to make calculations that were impossible until recently.

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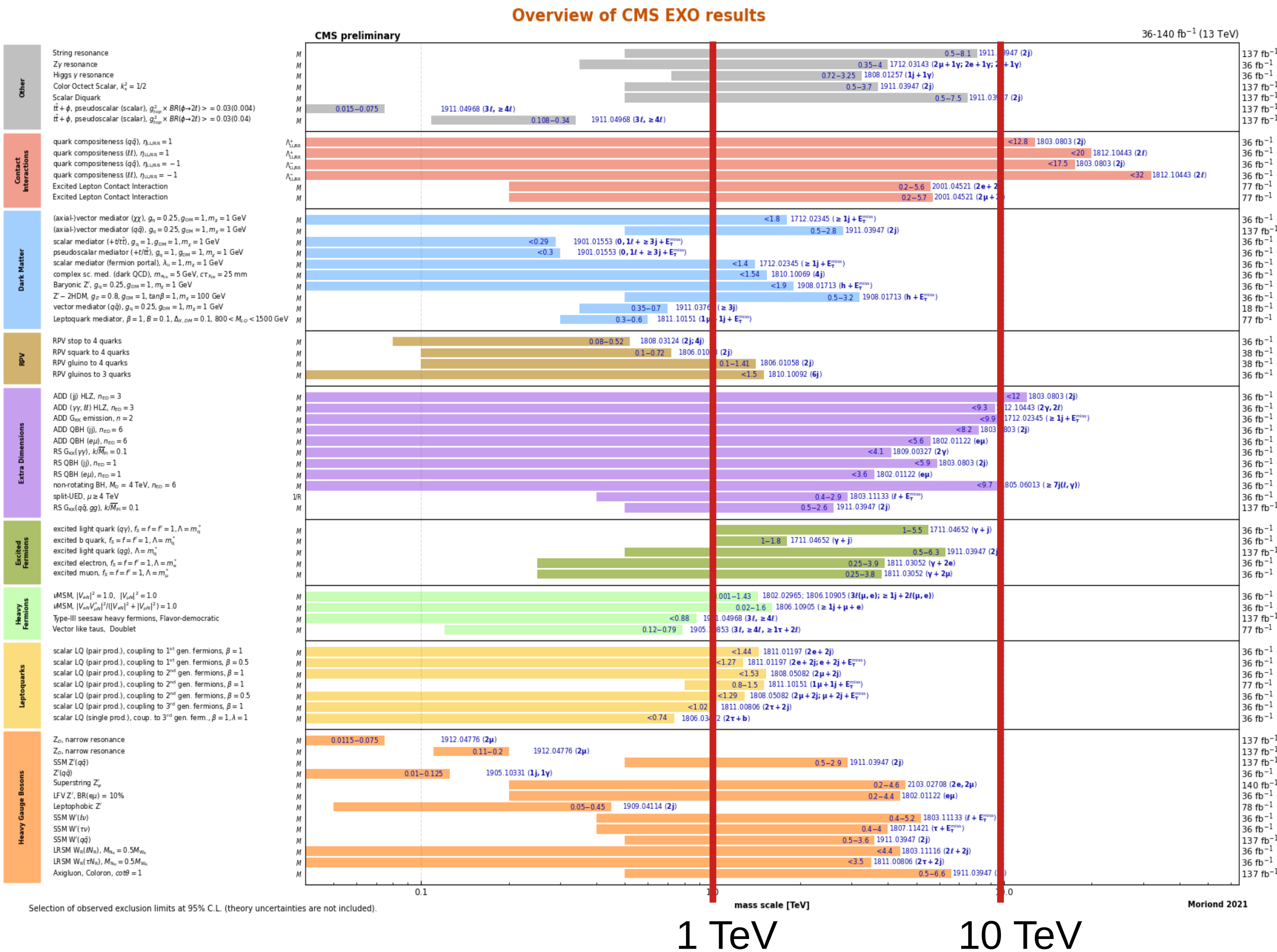
What is experiment telling us?

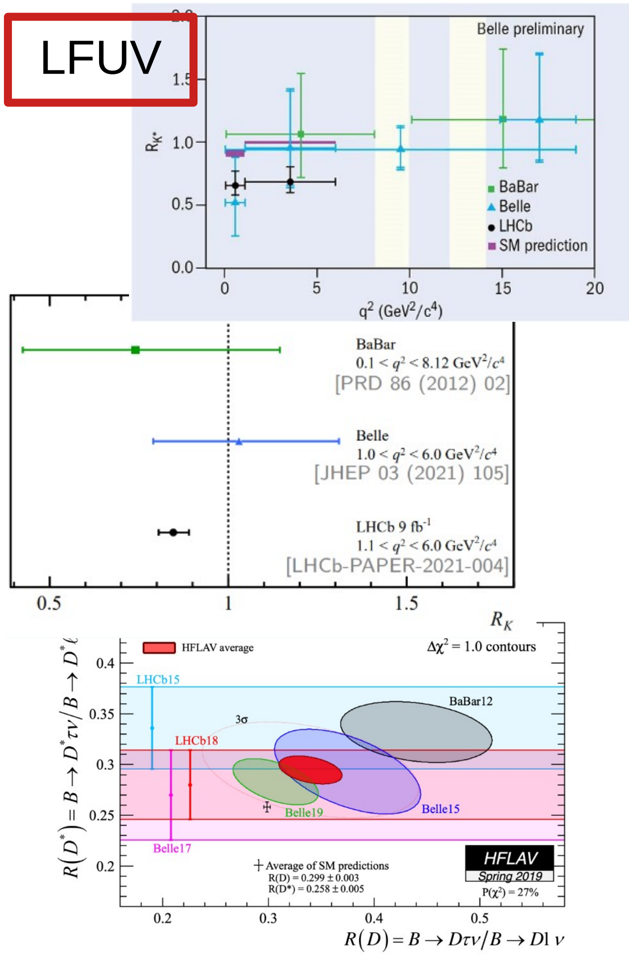


Turning all the stones! NP seems to be relatively heavy.

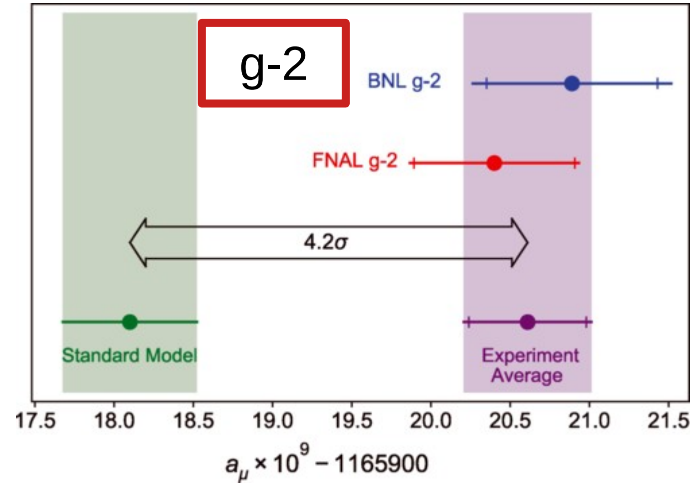
What is experiment telling us?

We got ourselves new (low-energy) anomalies!

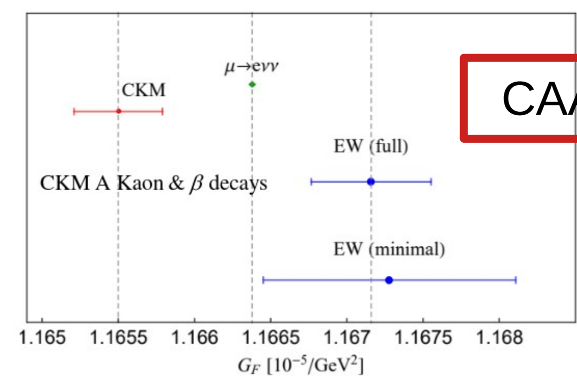
LFUV



g-2

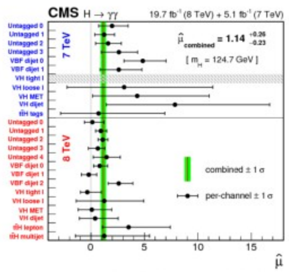


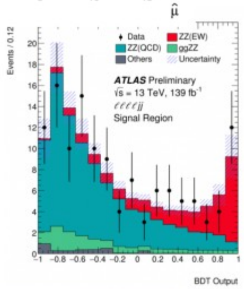
CAA

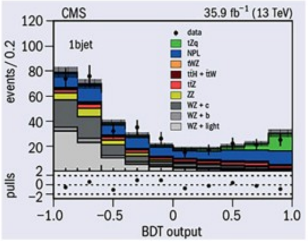


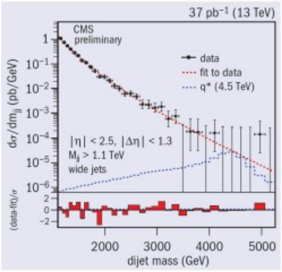
This calls for theory interpretation!

Connecting theory and experiment

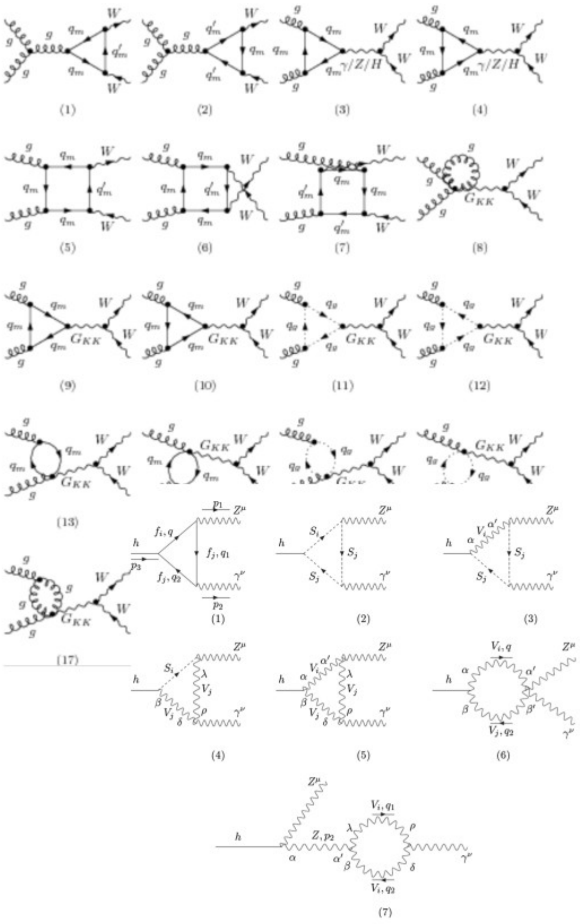


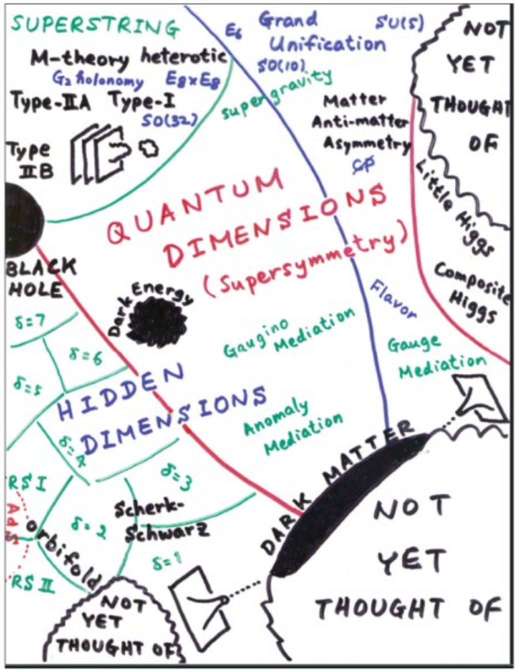






Getting implications of experimental data on new physics models is highly non trivial!

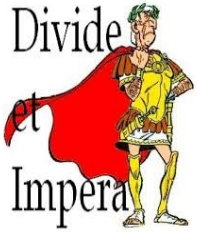




We need a more efficient approach!!

Effective Field Theories!

The effective way beyond the SM



EFTs allow for an efficient two-step comparison between theory and experiment:

Bottom-up: model-independent parametrization of experimental data in the form of global fits.

- Small number of models (EFTs).
- Observables computed just once.

Top-down: model discrimination (matching).

- Has to be done on a model-by-model basis.
- Can be automated and fully classified.

Top-down: connecting NP to EFTs

- The top-down approach consists on matching specific NP models to the EFT: computing the EFT Wilson coefficients in terms of the parameters of the NP model.
- We sacrifice model independence in favor of model discrimination (physics) and model completeness.
  - Power counting makes the problem of classifying the models that contribute at a certain order solvable.
  - Computer techniques allow us to automate the matching calculations.
- IR/UV dictionaries tell us all possible models that can contribute to a specific experimental observable at certain order in the EFT expansion: A new, alternative guiding principle beyond naturalness.

IR/UV dictionaries

- The leading IR/UV dictionary (tree-level, dimension 6 SMEFT) was computed a few years ago. [Blas, Criado, Pérez-Victoria, Santiago '18]
- Complete list of all possible models that contribute to experiment at tree-level and dim 6 (and their contributions).
- Tree-level and dimension 6 is not enough for current experimental precision. Going beyond requires automation.
- Significant progress in the last few years in the automation of matching calculations up to one loop.
  - Functional methods
    - CoDex [Bakshi, Chakrabortty, Kumar, Patra '18]
    - MATCHETE [Fuentes-Martín, König, Pagès, Thomsen, Wilsch]
  - Diagrammatic methods
    - MEFT [Carmona, Lazopoulos, Olgoso, Santiago '21]

Automated matching with MME

Matchmakereft: automated tree-level and one-loop matching

Adrián Carmona[a,b], Achilleas Lazopoulos[b], Pablo Olgoso[a] and José Santiago[a]

A. Lazopoulos' talk

https://ftae.ugr.es/matchmakereft/

Matchmakereft: automated tree-level and one-loop matching

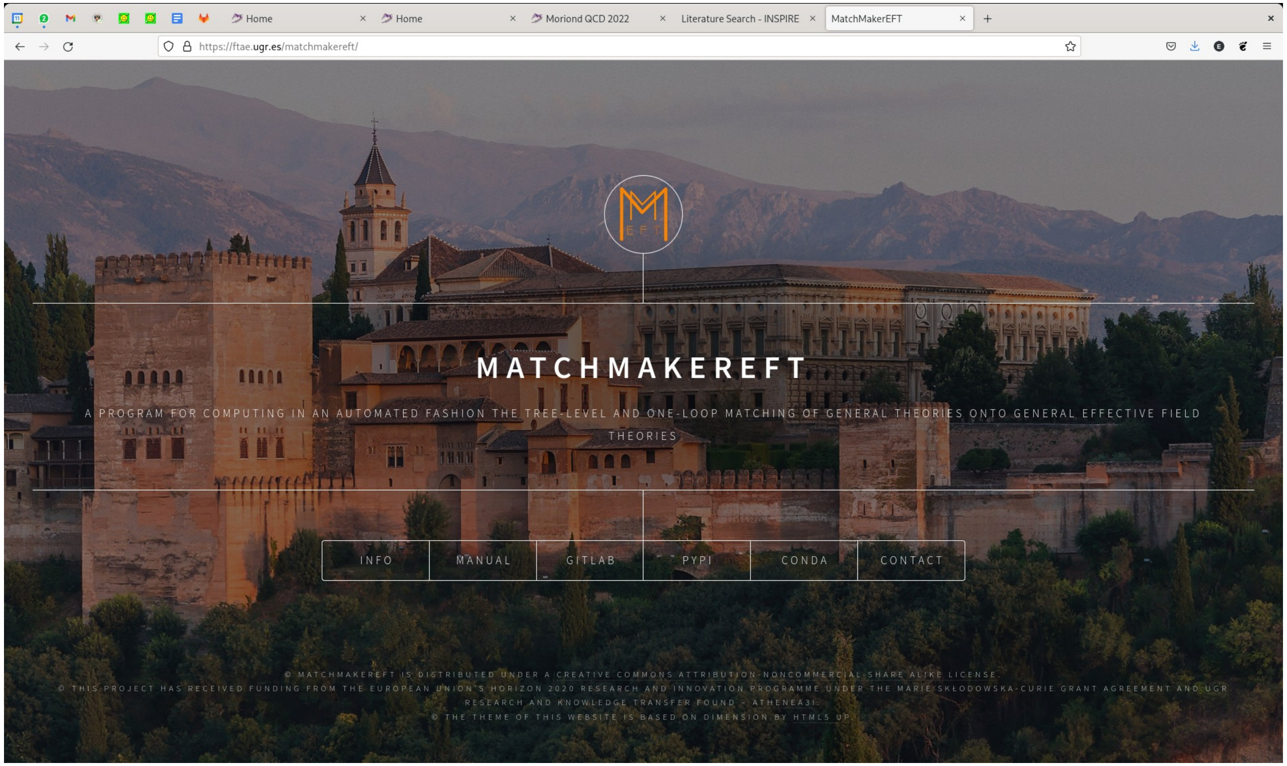
Adrián Carmona[a,b], Achilleas Lazopoulos[b], Pablo Olgoso[a] and José Santiago[a]

[a] *CAFPE and Departamento de Física Teórica y del Cosmos, Universidad de Granada, Campus de Fuentenueva, E–18071 Granada, Spain*

[b] *Institute for Theoretical Physics, ETZ Zürich, 8093 Zürich, Switzerland*

Abstract

We introduce `matchmakereft`, a fully automated tool to compute the tree-level and one-loop matching of arbitrary models onto arbitrary effective theories. `Matchmakereft` performs an off-shell matching, using diagrammatic methods and the BFM when gauge theories are involved. The large redundancy inherent to the off-shell matching together with explicit gauge invariance offers a significant number of non-trivial checks of the results provided. These results are given in the physical basis but several intermediate results, including the matching in the Green basis before and after canonical normalization, are given for flexibility and the possibility of further cross-checks. As a non-trivial example we provide the complete matching in the Warsaw basis up to one loop of an extension of the Standard Model with a charge −1 vector-like lepton singlet. `Matchmakereft` has been built with generality, flexibility and efficiency in mind. These ingredients allow `matchmakereft` to have many applications beyond the matching between models and effective theories. Some of these applications include the one-loop renormalization of arbitrary theories (including the calculation of the one-loop renormalization group equations for arbitrary theories); the translation between different Green bases for a fixed effective theory or the check of (off-shell) linear independence of the operators in an effective theory. All these applications are performed in a fully automated way by `matchmakereft`.



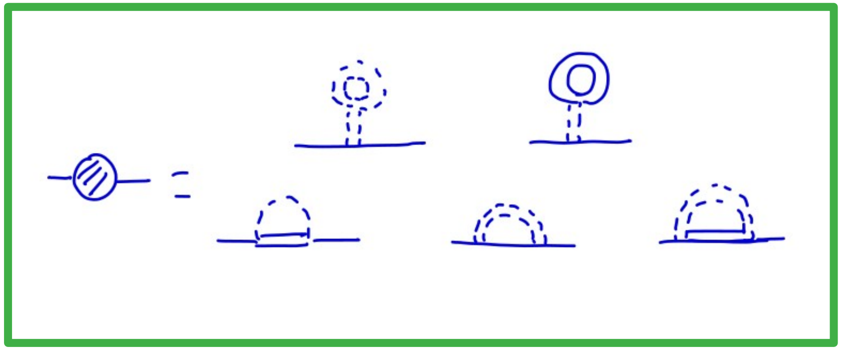
Towards the next IR/UV dictionaries

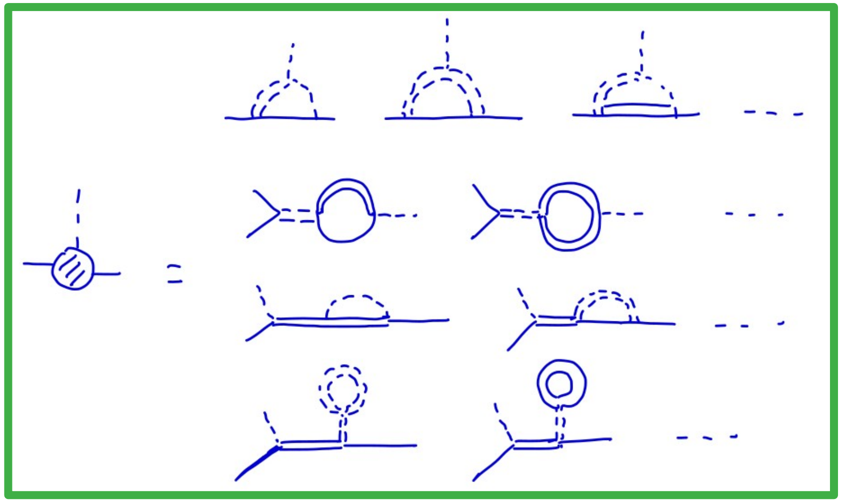
- These tools will allow us to go beyond the current IR/UV dictionary at tree-level and dimension 6. Such extensions have severe challenges that will have to be dealt with:
  - 1-loop, dimension 6:
    - Number of models can be classified but it is no longer finite.
    - Expressions become large, difficult to provide the results in print.
  - Tree level, dimension 8:
    - The number of operators is very large (from ~80 at dim 6 to ~ 1000 at dim 8).
    - The number of models is finite but also very large.
- It is likely that the next order dictionaries will have to be provided in electronic form. We are working on developing the best way for storing and using these results [with J.C. Criado].

J.C. Criado’s talk

Towards the next IR/UV dictionaries

- We are working on the one-loop, dimension-6 IR/UV dictionary [with G. Guedes and P. Olgoso]. see also [Cepedello, Esser, Hirsch, Sanz 2207.13714]
  - We have started with operators that cannot be generated at tree level in weakly-coupled extensions $[X^3, X^2\phi^2, \psi^2 X\phi]$, with heavy scalars and fermions [heavy vectors currently under study with J. Fuentes-Martín, P. Olgoso, A.E. Thomsen] and renormalizable interactions.
    - Extend the SMEFT with heavy fields in arbitrary gauge configurations.
    - Just need 2 and 3 point functions (plus gauge boson insertions).





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        - Extend the SMEFT with heavy fields in arbitrary gauge configurations.
        - Just need 2 and 3 point functions (plus gauge boson insertions).
        - Perform the matching with MME using the kinematics but leave gauge directions general [MME is very well suited for this task: matching from EFT, gauge numerics replaced only at the end of the calculation].

Towards the next IR/UV dictionaries

- We are working on the one-loop, dimension-6 IR/UV dictionary [with G. Guedes and P. Olgoso].
  - We have started with operators that cannot be generated at tree level in weakly-coupled extensions $[X^3, X^2\phi^2, \psi^2 X\phi]$, with heavy scalars and fermions [heavy vectors currently under study with J. Fuentes-Martín, P. Olgoso, A.E. Thomsen] and renormalizable interactions.
    - Extend the SMEFT with heavy fields in arbitrary gauge configurations.
    - Just need 2 and 3 point functions (plus gauge boson insertions).
    - Perform the matching with MME using the kinematics but leave gauge directions general.
    - Result for specific models can be obtained doing a simple group-theoretical calculation [we use GroupMath by R. Fonseca].
    - Currently we have functions to:
      - Provide the results (Green and Physical bases) for arbitrary spectra.
      - Write Lagrangian (including numerical values of group theory functions).

More than (finite) matching

- Matchmakereft can do more than just finite matching:
  - Compute one-loop RGEs of arbitrary EFTs:
    - Cross-check important calculations (SMEFT/LEFT RGEs)
    - RGEs at higher orders (dim-8) or new EFTs (alp-SMEFT/alp-LEFT)

      Chala, Guedes, Ramos, Santiago ‘20 (ALPs RGEs)
      Chala, Guedes, Ramos, Santiago ‘21 (Dim 8 SMEFT RGEs I)
      Bakshi, Chala, Díaz-Carmona, Guedes ‘22 (Dim 8 SMEFT RGEs II)

  - Check off-shell (in)dependence of a list of operators using the rank of the kinematic tensor of amplitudes, based on method developed in

    Chala, Díaz-Carmona, Guedes ‘21 (Green basis dim 8)

  - Non-trivial (higher-dimension) finite matching also useful for other interesting physics

    Chala, Santiago ‘21 (Positivity bounds dim 8)

M. Chala’s talk

Automated matching with MME

- Long term goal: automatically integrate over arbitrary thresholds

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EFFECTIVE FIELD THEORY[1]

Howard Georgi

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

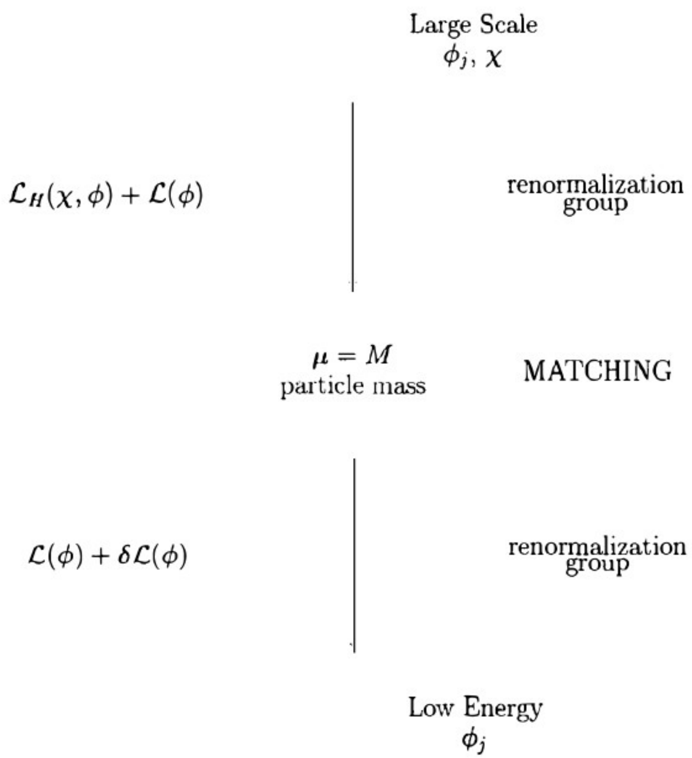


Figure 4 The general form of a matching calculation.

- Current bottlenecks are:
  - Model generation
  - Reduction to physical basis
- We are working on both fronts:
  - Interplay with Sym2Int (with R. Fonseca) to automatically generate models.
  - On-shell matching (with M. Chala) to automatically reduce to the physical basis.

The long-sought dream of a fully automated tool for the calculation of experimental observables in arbitrary theories is finally within reach!

On-shell matching

M. Chala's talk

- Off-shell matching is very efficient:
  - Small(ish) number of diagrams (1lPI).
  - Hard region contribution directly local, many cross-checks.
- But requires the construction and reduction of a Green basis.
- On-shell matching can be done in terms of a Physical basis but:
  - There are many diagrams contributing (light bridges have to be included).
  - There is a delicate cancellation of non-local contributions between UV and EFT that is non-trivial to follow analytically.
- Our solution:
  - We rely on QGRAF (very efficient even for a large number of diagrams).
  - We do kinematics numerically (trivial cancellation of non-local terms).
  - We stick to tree level.

On-shell matching

- Tree level on-shell matching of the Green basis to the physical basis provides a simple reduction (which has to be done only once, for the EFT at the end of the chain of EFTs across thresholds), including higher order terms.
- Simplest example: a real scalar to dimension 8 (Z2 symmetric)

$$\mathcal{L}_{IR} = -\frac{1}{2}s(\partial^2 + m^2)s - \lambda s^4 + \alpha_{61}s^6 + \alpha_{81}s^8 + \alpha_{82}s^2(\partial_\mu\partial_\nu s)^2$$

$$\mathcal{L}_{UV} = -\frac{1}{2}s(\partial^2 + m^2)s - \lambda s^4 + \alpha_{61}s^6 + \beta_{61}(\partial^2 s)^2 + \beta_{62}s^3\partial^2 s$$
$$+\alpha_{81}s^8 + \alpha_{82}s^2(\partial_\mu\partial_\nu s)^2 + \beta_{81}s\partial^2\partial^2\partial^2 s + \beta_{82}s^3\partial^2\partial^2 s$$
$$+\beta_{83}s^2(\partial^2 s)^2 + \beta_{84}s^5\partial^2 s$$

On-shell matching

- Simplest example: a real scalar to dimension 8 (Z2 symmetric)
    - Corrections to the 2-point function have to be carefully included in the UV theory

$$m_{\text{phys}}^2 = m^2 - 2\beta_{61} m^4 + 2(\beta_{81} + 4\beta_{61}^2) m^6 + \dots$$

$$\sqrt{Z} = 1 - 2\beta_{12} m^2 + (3\beta_{81} + 10\beta_{61}^2) m^4 + \dots$$

-
    - Connected, amputated amplitudes have to be computed with full propagators, $\sqrt{Z}$ factors and $p_i^2 = m_{\text{phys}}^2$

$$\alpha_{61} \to \alpha_{61} + 16\lambda^2\beta_{61} - 4\lambda\beta_{62} + m^2 \Big[-\frac{304}{5}\lambda^4\beta_{81} + \frac{65}{5}\lambda\beta_{82} + 8\lambda\beta_{83} - \beta_{84} - 12\alpha_{61}\beta_{61} - \frac{1728}{5}\lambda^2\beta_{61}^2 - \frac{22}{5}\beta_{62}^2 + \frac{512}{5}\lambda\beta_{61}\beta_{62} \Big]$$

$$\alpha_{81} \to \alpha_{81} - \frac{576}{2}\lambda^3\beta_{81} + 6\alpha_{61}\beta_{62} + \dots$$

Automatic basis generation

- Producing a Green basis is non-trivial.

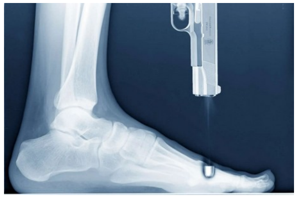
  [Buchmuller, Wyller '86]
  [Grzadkowski, Iskrzynski, Misiak, Rosiek 1008.4884]
  [Gherardi, Marzocca, Venturini 2003.12525]

  SMEFT at dim 6

  R. Fonseca's talk

- Tools can help us do that in an automated (and error-free) way.

- Why not do the calculation once and for all? [with R. Fonseca].



  - Write down a generic EFT up to dimension 6 [with Sym2Int].
  - Compute its RGEs [using Matchmakereft].
  - The result is valid for arbitrary EFTs (only the group theory remains to be done).

- The next step is to compute the finite matching [with R. Fonseca, G. Guedes and P. Olgoso].

RGEs of general EFTs

Preliminary!

- Build the most general EFT using Sym2Int.

$$\mathscr{L}_{d\leq 4} = -\frac{1}{4}(a_{KF})_{AB}F^A_{\mu\nu}F^{B\,\mu\nu} + \frac{1}{2}(a_{K\phi})_{ab}D_\mu\phi_a D^\mu\phi_b + (a_{K\psi})_{ij}\bar{\psi}_i \mathrm{i}\not{D}\psi_j - \frac{1}{2}\Big[(m_f)_{ij}\psi_i^T C\psi_j + \mathrm{h.c.}\Big]$$
$$-\frac{1}{2}(m^2_\phi)_{ab}\phi_a\phi_b - \frac{1}{2}\Big[Y_{ija}\psi_i^T C\psi_j + \mathrm{h.c.}\Big]\phi_a - \frac{\kappa_{abc}}{3!}\phi_a\phi_b\phi_c - \frac{\lambda_{abcd}}{4!}\phi_a\phi_b\phi_c\phi_d,$$

$$\mathscr{L}_5^{\mathrm{phys}} = \Big[\frac{1}{2}\big(a^{(5)}_{\psi F}\big)_{Aij}\psi_i^T C\sigma^{\mu\nu}\psi_j F^A_{\mu\nu} + \frac{1}{4}\big(a^{(5)}_{\psi\phi^2}\big)_{ijab}\psi_i^T C\psi_j\phi_a\phi_b + \mathrm{h.c.}\Big]$$
$$+\frac{1}{2}\big(a^{(5)}_{\phi F}\big)_{ABa}F^{A\,\mu\nu}F^B_{\mu\nu}\phi_a + \frac{1}{2}\big(a^{(5)}_{\phi\widetilde{F}}\big)_{ABa}F^{A\,\mu\nu}\widetilde{F}^B_{\mu\nu}\phi_a + \frac{1}{5!}\big(a^{(5)}_{\phi}\big)_{abcde}\phi_a\phi_b\phi_c\phi_d\phi_e,$$
$$\mathscr{L}_5^{\mathrm{red}} = \frac{1}{2}\big(r^{(5)}_{\phi\Box}\big)_{abc}(D_\mu D^\mu\phi_a)\phi_b\phi_c + \Big[\frac{1}{2}\big(r^{(5)}_{\psi}\big)_{ij}(D_\mu\psi_i)^T C D^\mu\psi_j + \big(r^{(5)}_{\psi\phi}\big)_{ija}\bar{\psi}_i\mathrm{i}\not{D}\psi_j\phi_a + \mathrm{h.c.}\Big],$$

- Compute its beta functions using MME.

$$\big(\dot{a}^{(5)}_{\phi\widetilde{F}}\big)_{ABa} = -2g^2\theta^C_{ab}\theta^C_{bc}\big(a^{(5)}_{\phi\widetilde{F}}\big)_{ABc} - 2g^2\Big\{\Big[\frac{11}{6}f^{CDB}f^{CDE} - \frac{1}{12}\theta^B_{bc}\theta^E_{cb} - \frac{1}{3}t^B_{ij}t^E_{ji}\Big]\big(a^{(5)}_{\phi\widetilde{F}}\big)_{AEa} + (A\leftrightarrow B)\Big\}$$
$$+2\mathrm{i}g\Big[\big(a^{(5)}_{\psi F}\big)_{Aij}t^B_{jk}\bar{Y}^a_{ki} - [\big(a^{(5)}_{\psi F}\big)_{Aij}]^* t^B_{kj}Y^a_{ki} + (A\leftrightarrow B)\Big] + \frac{1}{2}\big(a^{(5)}_{\phi\widetilde{F}}\big)_{ABc}\mathrm{Tr}[Y^c\bar{Y}^a + Y^a\bar{Y}^c],$$
$$\big(\dot{a}^{(5)}_{\phi}\big)_{abcde} = \sum_{\mathrm{perm}}\Big\{\frac{1}{12}\big(a^{(5)}_{\phi}\big)_{abcfg}\lambda_{defg} - \frac{1}{12}g^2\big(a^{(5)}_{\phi}\big)_{abcdf}\theta^A_{fg}\theta^A_{ge} + \frac{1}{6}g^2\big(a^{(5)}_{\phi}\big)_{abcfg}\theta^A_{df}\theta^A_{eg}$$
$$+\frac{1}{48}\big(a^{(5)}_{\phi}\big)_{abcdf}\mathrm{Tr}[Y^e\bar{Y}^f + Y^f\bar{Y}^e] - \Big[\big(a^{(5)}_{\psi\phi^2}\big)_{ijab}\bar{Y}^c_{ik}\bar{Y}^d_{jl}Y^e_{kl} + [\big(a^{(5)}_{\psi\phi^2}\big)_{ijab}]^* Y^c_{ik}Y^d_{jl}\bar{Y}^e_{kl}\Big]$$
$$+\frac{1}{12}\lambda_{fcde}\Big[\big(a^{(5)}_{\psi\phi^2}\big)_{ijab}\bar{Y}^f_{ij} + [\big(a^{(5)}_{\psi\phi^2}\big)_{ijab}]^* Y^f_{ij}\Big]\Big\}.$$

Closing the gap … with experiment

- To do physics we need to connect with the bottom-up approach.
- Several interfaces are being developed to make the connection with experiment:
  - We are working on a general WCxf format interface [this will simplify the usage of global fit programs].
  - Also an interface to DsixTools is being developed and tested [thanks to A. Vicente] to take advantage of fully analytic calculations.
  - The complete chain, from UV model down to comparison with experimental data, is being tested by using HEPfit [see J. de Blas' talk].
- Obtaining all phenomenological implications of a specific model up to one-loop and dim. 6 order will be soon straight-forward.

Developing new features in MME

- If you need a new feature in Matchmakereft contact (any of) the authors and suggest it. Ideally come with a physics case that can be worked out together while we develop the new feature.
- Examples:
  - On-shell matching [with M. Chala].
  - Flavour indices for massive particles [with R. Fonseca].
  - Spin-2 particle support [with I. Kamines and A. Maline]. Physics case: use AI to find “good models” of new physics.
  - Other (non-Lorentz-invariant?) more exotic types of EFTs.
  - ...

Conclusions and outlook

- Tools are allowing us to study physics in a way that seemed impossible until recently.
- The effective approach is well supported by experimental data and extremely powerful:
  - IR/UV dictionaries allow us to study new physics in a systematic and comprehensive way.
  - Automated generation of models, on-shell matching, automated finite matching and RGE calculation, global likelihoods, ... all make the dream of a one-keystroke calculation of phenomenological implications of any new physics model feasible.
- The way ahead: renormalization and matching of arbitrary (effective) theories.
  - Do all calculations for a generic gauge configuration.
  - Results for specific models require just a simple group-theoretical calculation.

The (effective) future is brilliant, full of tools, interesting physics and many new properties to learn.

I'm looking forward to it (and in the meantime to your talks!)