Tools for di-Higgs searches and interpretations

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Overview

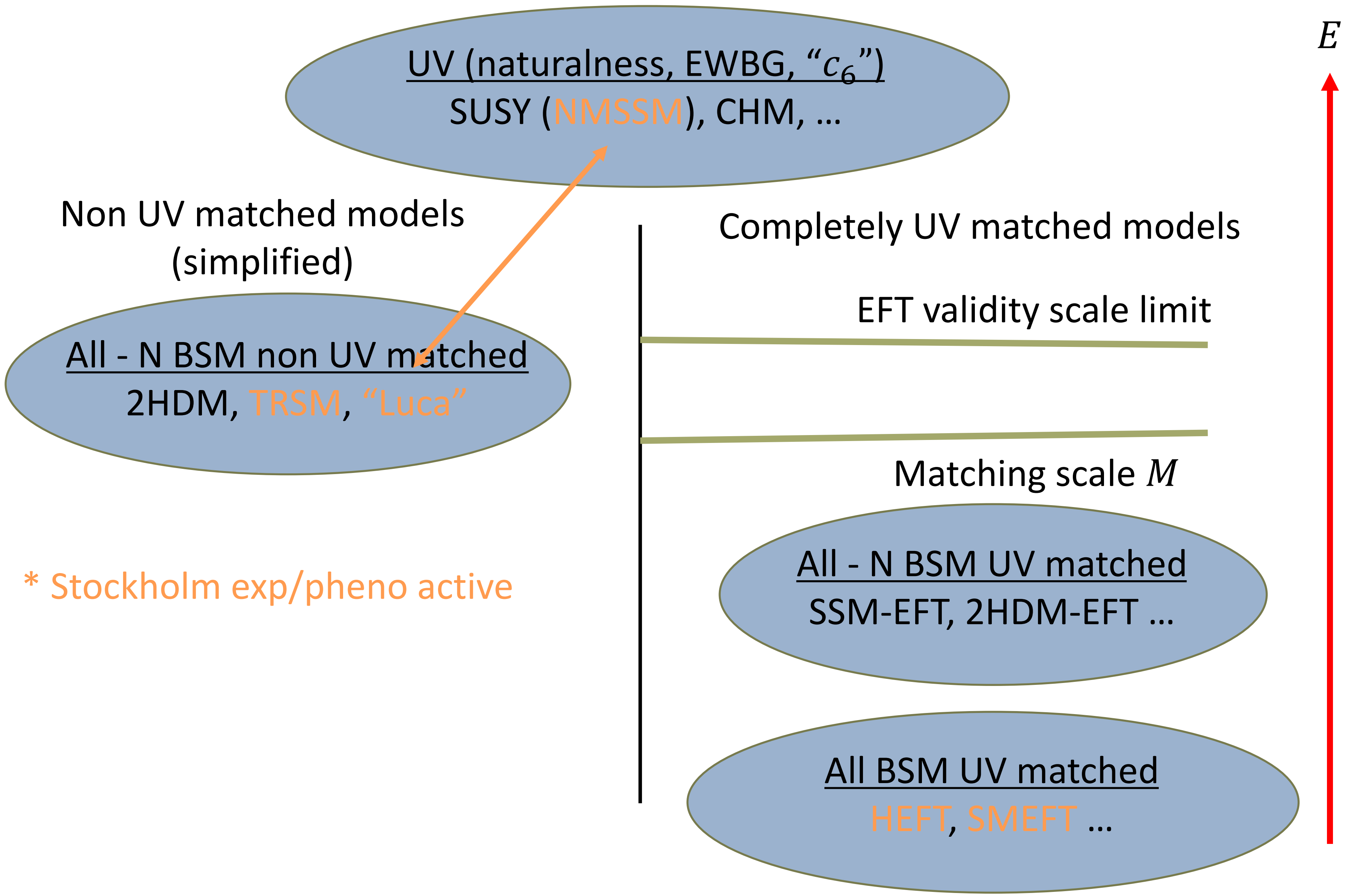
- What to measure in di-Higgs and model dependence
- Models and energy scale validity
- SM field content (UV matched) models: HEFT and SMEFT
- Examples of tools for di-Higgs EFTs
- SM + additional field content (non UV matched) models
- Examples of tools for di-Higgs simplified models
- Future developments

What to measure in di-Higgs?

First a reminder of some basics to set the scene:

1. **There is no such thing as a model independent measurement: even "just" unfolding the data means one have to assume a model for the background subtraction.**
2. **I.e. all measurement are model dependent: either the measurements are direct model parameters, or else cross-sections from data with associated (hidden) model assumptions.**
3. **The Devils advocate: A discovery means SM rejected with 5σ using data, no BSM is involved in this! So what do we need BSM for?**
4. **A BSM model is essential to guide the measurement. Neyman - Pearson proves that the searched alternative model is needed for the most powerful test. Everything else is suboptimal.**
5. **Bottomline: what model do you assume in the measurement?**

Di-Higgs models and energy scale validity



No light dof BSM models ≡ SM dof EFT at low E

- **As a consequence of requiring a gauge invariant L with masses and applying the Appelquist-Carazzone theorem, there are two fundamentally <u>different</u> valid EFT cases: SMEFT that preserves the H doublet symmetry , and HEFT that does not (actually HEFT\SMEFT).**
- **HEFT will by construction violate unitary at $O(4\pi v) \sim$ 3 TeV, but up to that point has a more powerful expansion. E.g. a larger set of valid model overlap to e.g. a non decoupling 2HDM.**
- **One very important task is to test the SM H doublet symmetry. This can be done by comparing the fit consistency of HEFT vs SMEFT in sensitive scenarios (e.g. HH VBF), or possibly GW cosmology.**
- **A big advantage of SMEFT, besides not being limited in energy scale, is that single H and HH are related and can benefit from combinations.**

Standard model EFT for HH: the SM H doublet case

- State-of-the art SMEFT HH is implemented in POWHEG BOX as "ggHH_SMEFT" at NLO QCD (recently bug fixed virtual 2-loop).
- Full NLO QCD including finite top mass. Variations of top mass scheme is the leading theory uncertainty.
- Expanding around vev, after field redefinitions and in unitary gauge:

$$\mathcal{L}_{\rm SMEFT} \supset -\left(\frac{m_t}{v}\left(1+v^2\frac{C_{H,\rm kin}}{\Lambda^2}\right)-\frac{v^2}{\sqrt{2}}\frac{C_{tH}}{\Lambda^2}\right) h\,\bar{t}\,t - \left(m_t\frac{C_{H,\rm kin}}{\Lambda^2}-\frac{3v}{2\sqrt{2}}\frac{C_{tH}}{\Lambda^2}\right) h^2\,\bar{t}\,t + \\ -\left(\frac{m_h^2}{2v}\left(1+3v^2\frac{C_{H,\rm kin}}{\Lambda^2}\right)-v^3\frac{C_H}{\Lambda^2}\right) h^3 + \frac{C_{HG}}{\Lambda^2}\left(v\,h+\frac{1}{2}\,h^2\right) G^a_{\mu\nu}G^{a,\mu\nu}$$

$$C_{H,\rm kin} := C_{H,\Box} - \frac{1}{4}C_{HD}$$

arXiv:2204.13045

- In new version remaining dim6 operators (mass dep. now understood)

$$\begin{aligned}
&+ g_s\bar{t}\,\gamma^\mu T^a\,t\,G^a_\mu + \frac{C_{tG}}{\Lambda^2}\sqrt{2}\,(h+v)\,\left(\bar{t}\,\sigma^{\mu\nu}T^a\,t\,G^a_{\mu\nu}\right)\\
&+ \frac{C^{(1)}_{Qt}}{\Lambda^2}\bar{t}_L\gamma^\mu t_L\bar{t}_R\gamma_\mu t_R + \frac{C^{(8)}_{Qt}}{\Lambda^2}\bar{t}_L\gamma^\mu T^a t_L\bar{t}_R\gamma_\mu T^a t_R\\
&+ \frac{C^{(1)}_{QQ}}{\Lambda^2}\bar{t}_L\gamma^\mu t_L\bar{t}_L\gamma_\mu t_L + \frac{C^{(8)}_{QQ}}{\Lambda^2}\bar{t}_L\gamma^\mu T^a t_L\bar{t}_L\gamma_\mu T^a t_L\\
&+ \frac{C_{tt}}{\Lambda^2}\bar{t}_R\gamma^\mu t_R\bar{t}_R\gamma_\mu t_R\ ,
\end{aligned}$$

arXiv:2309.10525v1

SM dof EFT for HH: the singlet H case (HEFT)

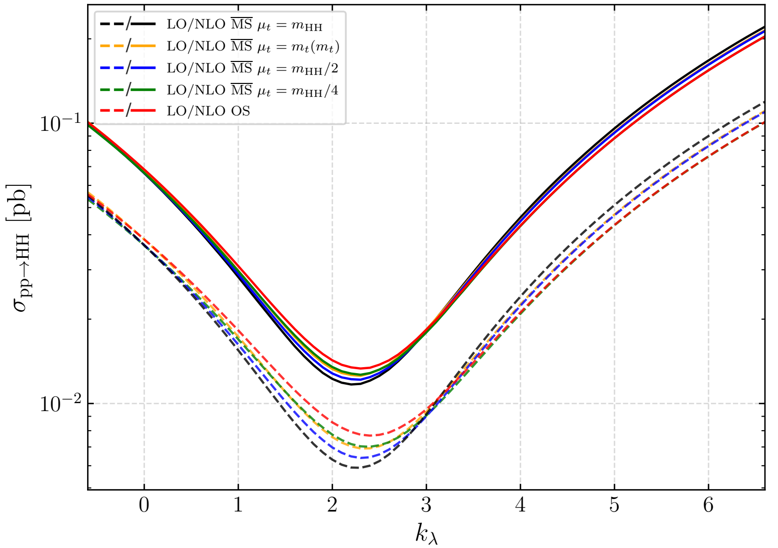
- **State-of-the art HEFT HH is implemented in POWHEG BOX as "ggHH" at NLO QCD (also recently bug fixed virtual 2-loop).**
- **Full NLO QCD including finite top mass. Variations of top mass scheme is the leading theory uncertainty.**
- **Extended Lagrangian:**

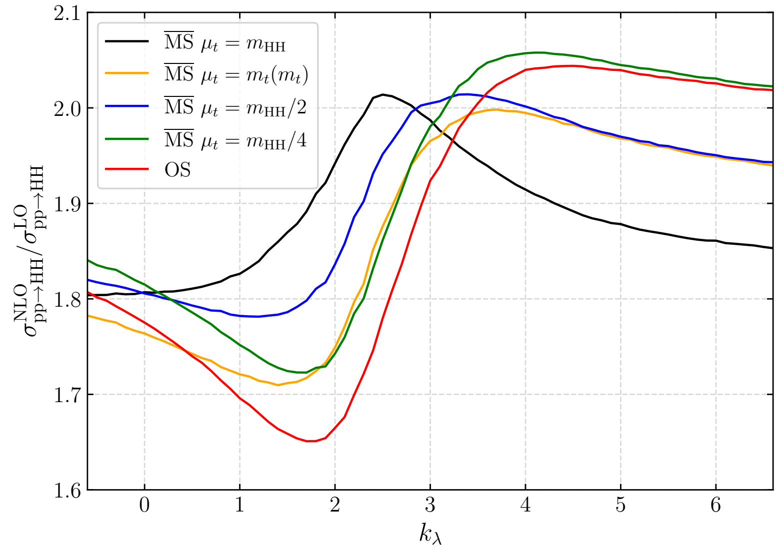
$$\mathcal{L} \supset -m_t \left(c_t \frac{h}{v} + c_{tt} \frac{h^2}{v^2} \right) \bar{t}\, t - c_{hhh} \frac{m_h^2}{2v} h^3 + \frac{\alpha_s}{8\pi} \left(c_{ggh} \frac{h}{v} + c_{gghh} \frac{h^2}{v^2} \right) G^a_{\mu\nu} G^{a,\mu\nu}$$

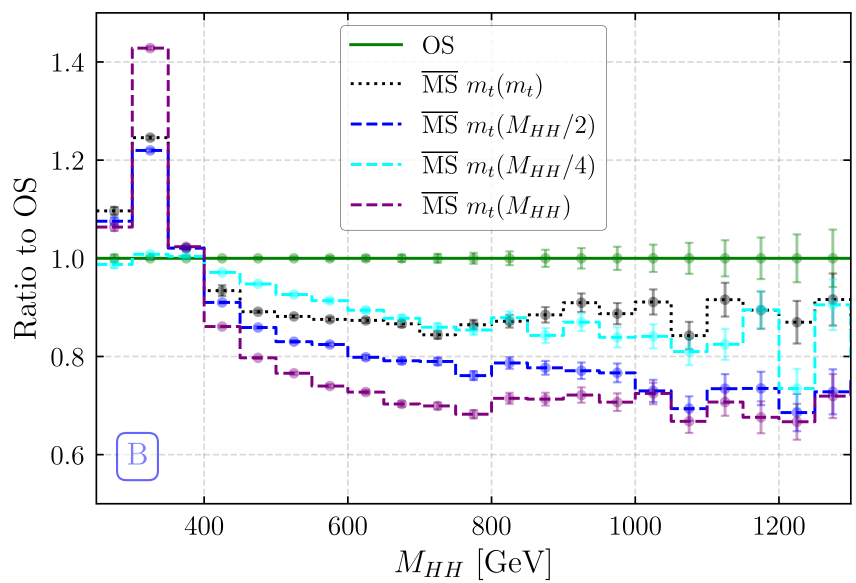
arXiv:1806.05162

- **Most striking is that htt (hgg) not related to hhtt (hhgg). In case of significant difference measured it can be tested!**
- **Mass scale breakdown around $O(4\pi v) \sim$ 3 TeV still far away for many still open scenarios so not a major problem.**
- **More effective expansion ordering than SMEFT (in loops).**

Watch out for the top mass dependence uncertainty!



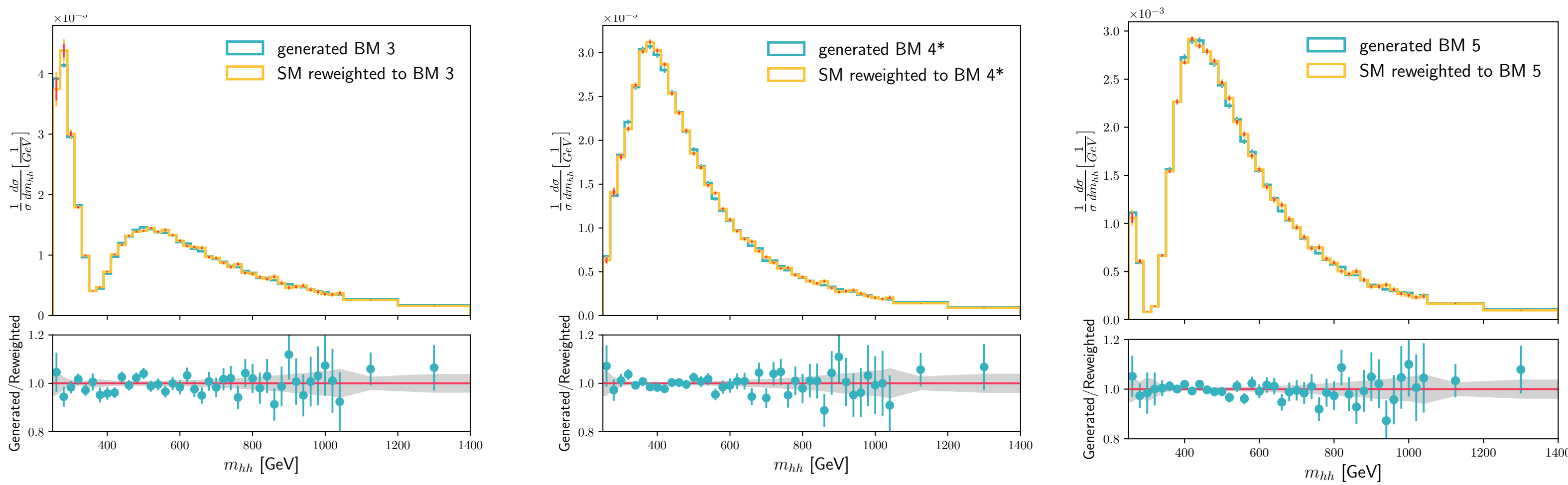




arXiv:2309.10525

EFT event re-weighting

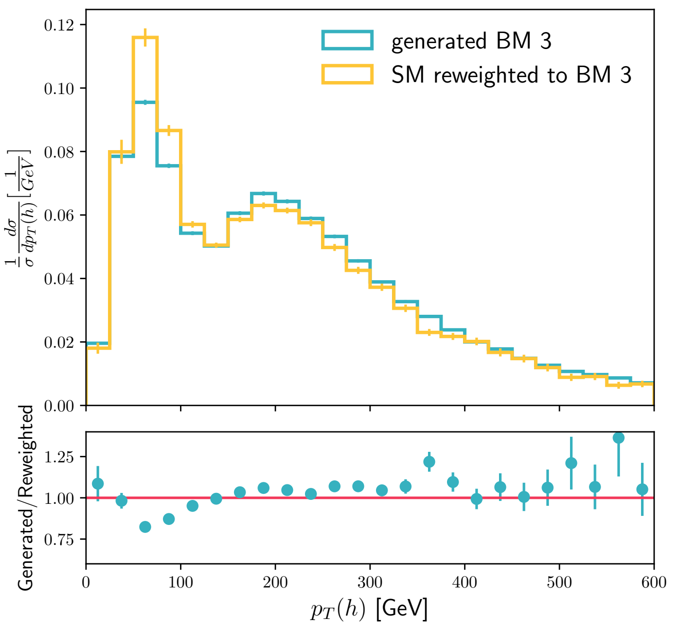
- **A very nice property of EFTs is that they allow for re-weighting since no new particles are created.**
- **As long as the density is known at each phase-space point and non-zero, events can be re-weighted. This allows also for fully differential analyses, even un-binned versions, given just the SM detector simulated sample.**
- **Examples of a few reweighted HEFT binned benchmark points in m_{hh}**



arXiv:2304.01968

EFT event re-weighting, limitations

- **In the heavy quark expansion the matrix elements depends only on shat at low energy. For higher energies and jet radiation this breaks down and must be included as an uncertainty. Also the POWHEG Sudakov factor distorts the simple picture.**
- **Will look into reducing these effect, but for now they are clearly visble:**



arXiv:2304.01968

Allowing for light BSM: Luca + Harry simplified library

- When there are light dof BSM, SM dof EFT will not work. Either build new EFT with SM+light BSM or just add light BSM without integrating out and matching assuming the rest of UV decoupled: the Luka + Harry library.
- Will not say much since next talk is by Luca, but you can e.g. add different scalars and then expand in couplings (for fixed masses). Covers full coupling parameter space. E.g. a model with extra stops effectivly contains SUSY with low mass stops.
- The current tool development concentrates on allowing for interpolated masses and requires several generated mass points.
- A proof of concept with fixed masses given MSSM and NMSSM benchmarks with sizable c_6 in shown in

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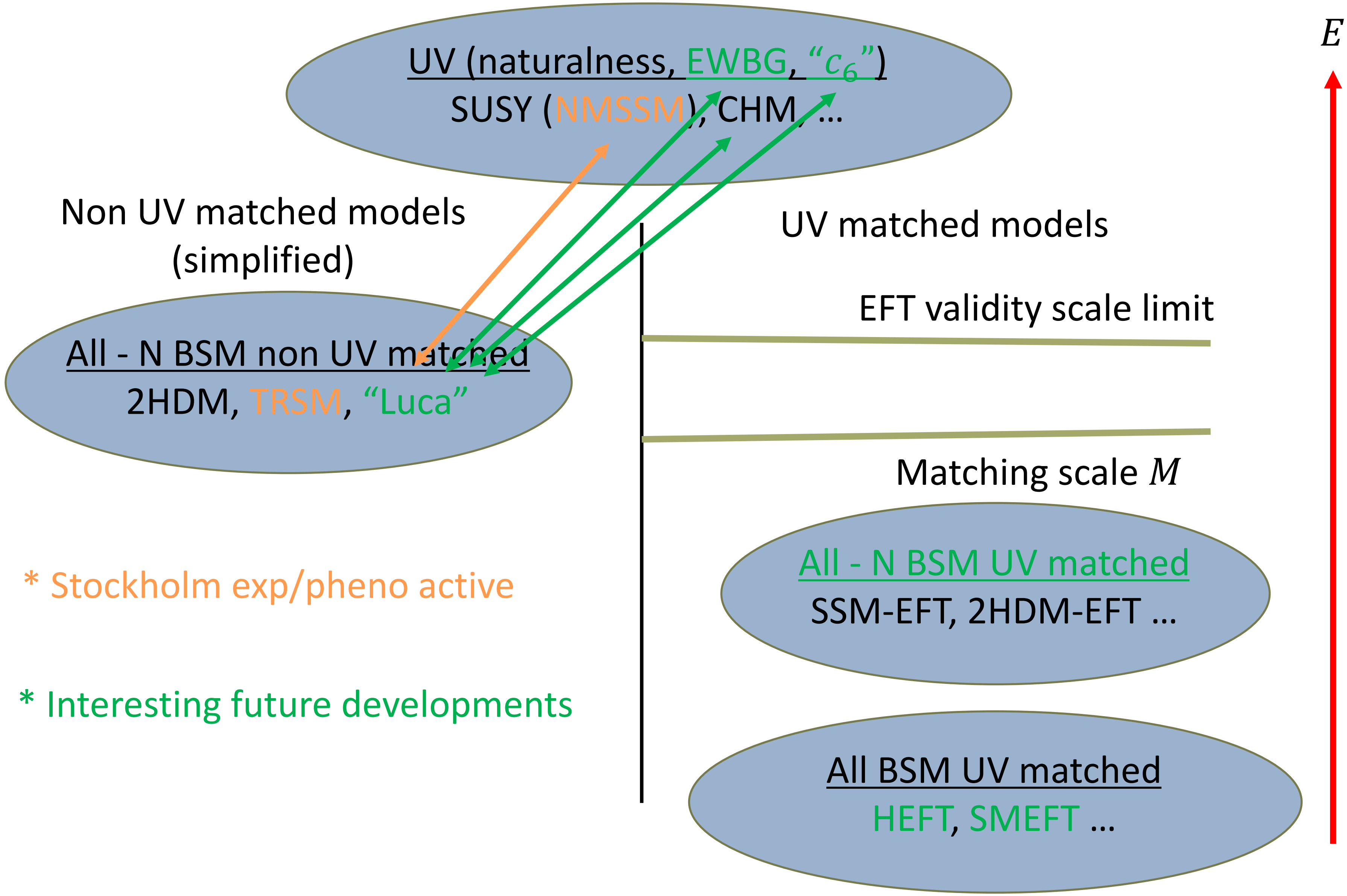
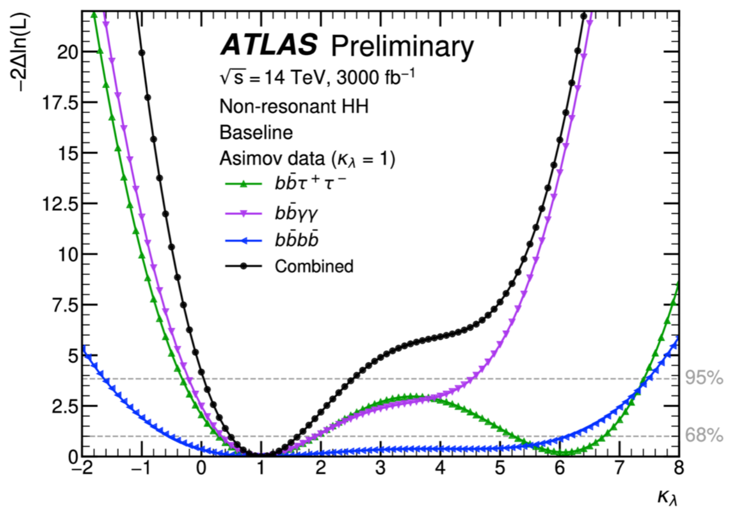
Di-Higgs future developments?



Finally a reminder of HL-LHC projections

- **With only c_6 floating there are projections available for HL-LHC.**
- **We must be very lucky to see deviations at HL-LHC and should focus on models with large c_6 effects.**



Uncertainty scenario	κ_λ 68% CI	κ_λ 95% CI
No syst. unc.	[0.7, 1.4]	[0.3, 1.9]
Baseline	[0.5, 1.6]	[0.0, 2.5]
Theoretical unc. halved	[0.3, 2.2]	[−0.3, 5.5]
Run 2 syst. unc.	[0.1, 2.4]	[−0.6, 5.6]

Conclusions

- **Effective field theories will remain as powerful "UV agnostic" tools to search for new physics at HL-LHC.**
- **EFTs is an ongoing development area progressing step by step along with the increasing precision of the data. E.g. EW loops are beginning to be at the same level as QCD for distributions.**
- **Models with new scalars are important for EWBG, and c_6 in general. Need to learn how use them as efficient tools.**