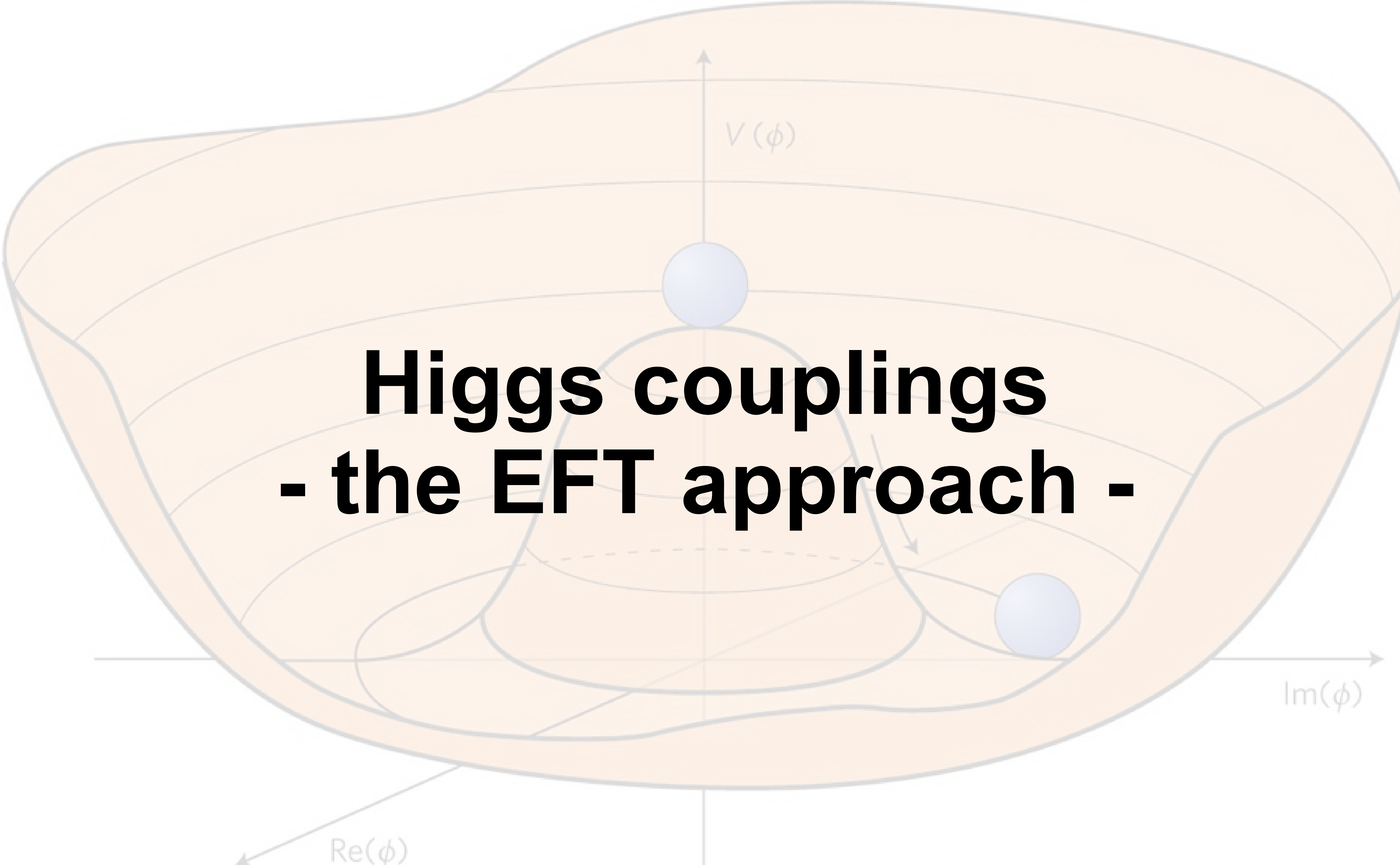
Higgs couplings
- the EFT approach -



Michael Duehrssen
HiggsTools, Freiburg

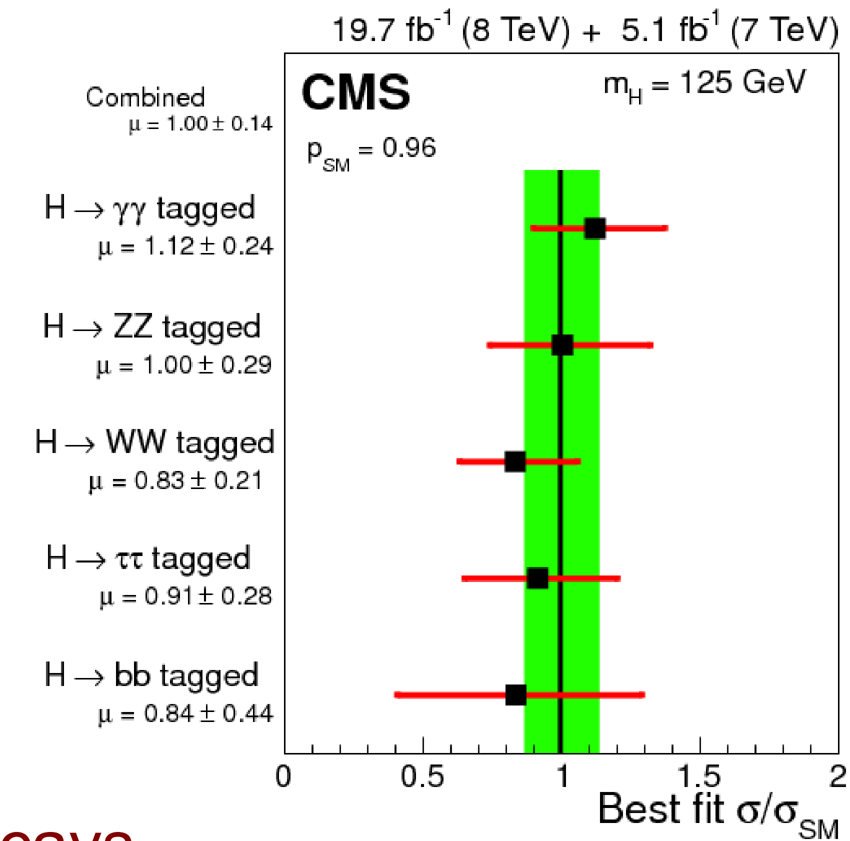
15.04.2015

Reminder: Higgs couplings, 1st try - signal strength -

In 2011 and 2012, ATLAS and CMS started to report Higgs results in terms of the signal strength $\mu=\sigma/\sigma_{SM}$

Pro:

- For discovery: one number to measure the separation from the background hypothesis $\mu=0$
- Very convenient to implement as a scale factor on the SM cross sections with $\mu=1$ as SM hypothesis
- Close to the experiment and tells already a lot about what is observed



Con:

- Depending on which μ is reported, it mixes and sums production and/or decays
- Assumes SM production and decay kinematics
- Very hard to relate to specific Higgs properties

Reminder: Higgs couplings, 2nd try
- κ-framework -

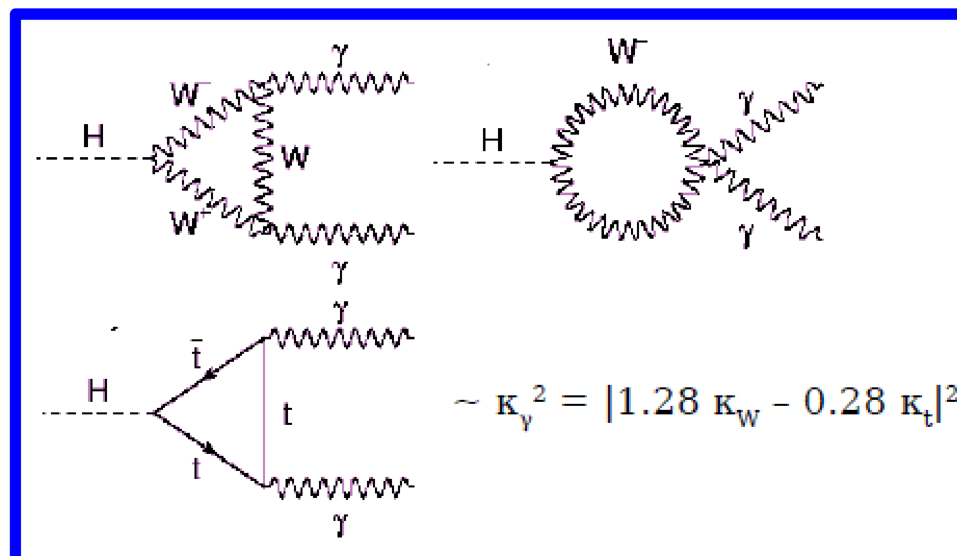
- **The coupling strength g of the Higgs to other SM particles is the most characteristic footprint. It scales with the mass:**

Fermions: $g_F = \kappa_F \frac{\sqrt{2} m_F}{v}$ **Gauge bosons:** $g_V = \kappa_V \frac{2 m_V^2}{v}$

- **Encode deviations from SM with coupling scale factors κ_i**
  - **Production:** $\sigma_i \sim \kappa_i^2 \sigma_i^{SM}$
  - **Decay:** $\Gamma_i \sim \kappa_i^2 \Gamma_i^{SM}$
  - **Total width:** $\Gamma_H = \Sigma_i \ \kappa_i^2 \Gamma_i^{SM}$
  - **SM: by definition for all $\kappa_i = 1$**
  - **Interference in H→γγ, gg→H, ...:**
    → some sensitivity to sign of κ_i

Example:

$$\frac{\sigma \cdot \mathrm{B}\,(gg \to H \to \gamma\gamma)}{\sigma_{\mathrm{SM}}(gg \to H) \cdot \mathrm{B}_{\mathrm{SM}}(H \to \gamma\gamma)} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$



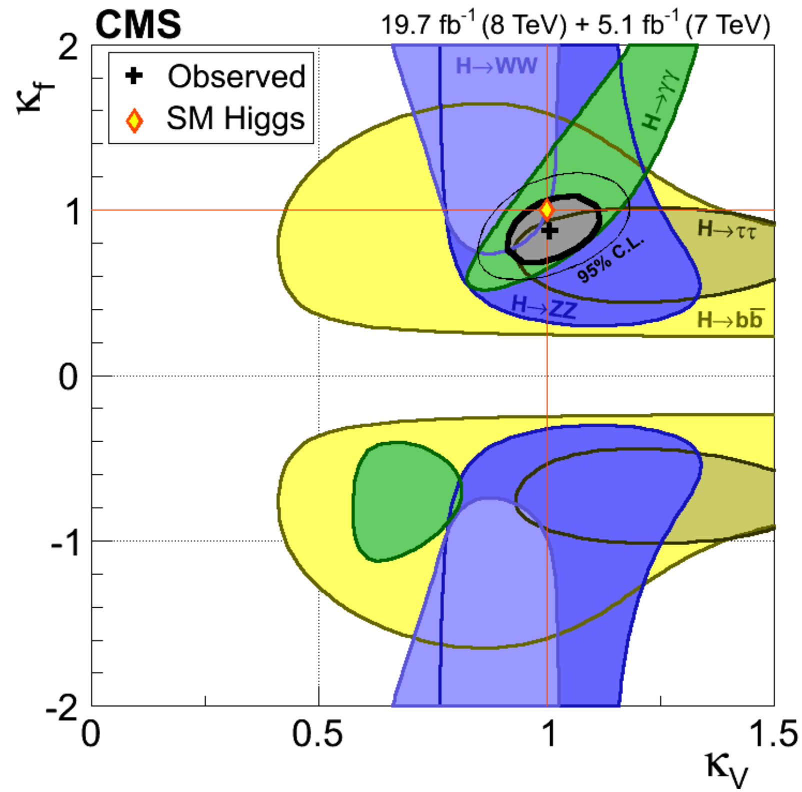
- **Benchmarks:**
  - Models with different degrees of freedom to search for deviations from the SM in many directions

Reminder: Higgs couplings, 2nd try
- κ-framework -

The κ-framework was designed to look at the (effective) tree level couplings of the Higgs boson (leading order motivated)

Pro:

- Intuitive: $\Gamma(H\to WW)$ scales with κ_W^2, $\sigma(gg\to H)$ scales with κ_g^2
- Also allows for more complex cases: loop contributions to $H\to\gamma\gamma$ or $gg\to H$
- "Correctly" relates coupling information between production and decay
- SM hypothesis for all $\kappa_i = 1$



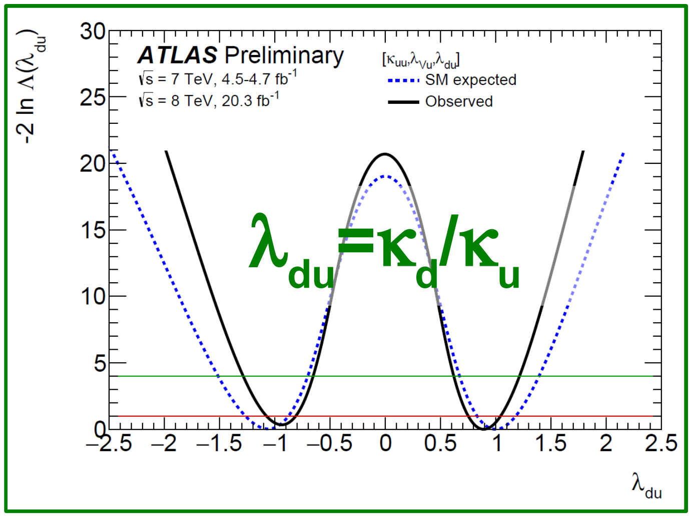
Con:

- Still assumes SM production and decay kinematics
- Not very consistent from the theory perspective: all SM corrections @NLO EW are scaled by κ_i. Trust results with <10% precision?

  → not really a measurement, only κ_i=1 is well defined

Reminder: Higgs couplings, 2nd try
- κ-framework -

However, still a very good tool to look for deviations from the SM hypothesis and no issues when used for this purpose!



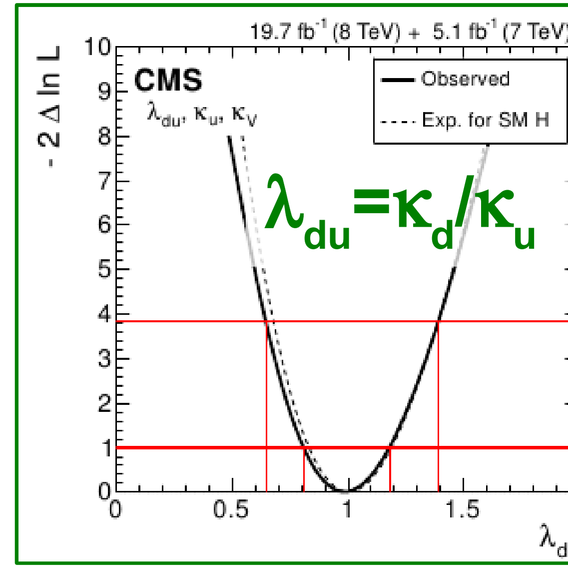
2HDM motivated: ratios of couplings in the fermion sector

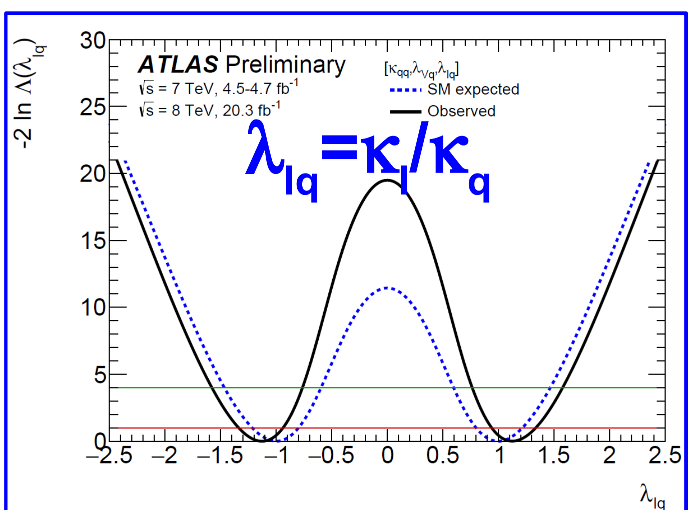
- **between down- and up-type fermions**

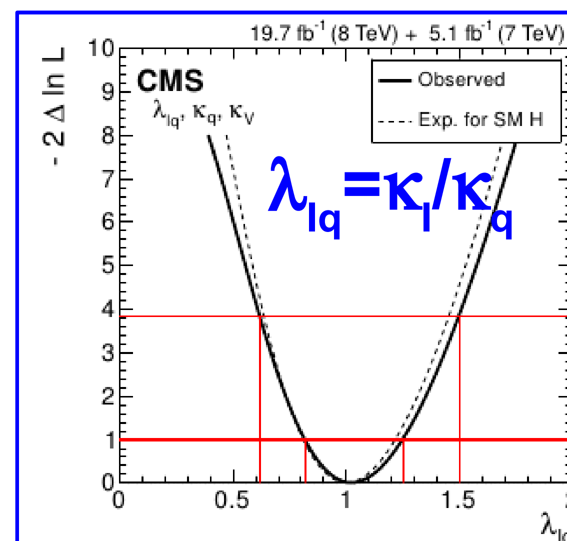
and

- **between leptons and quarks**

For both: very good agreement to the SM expectation!







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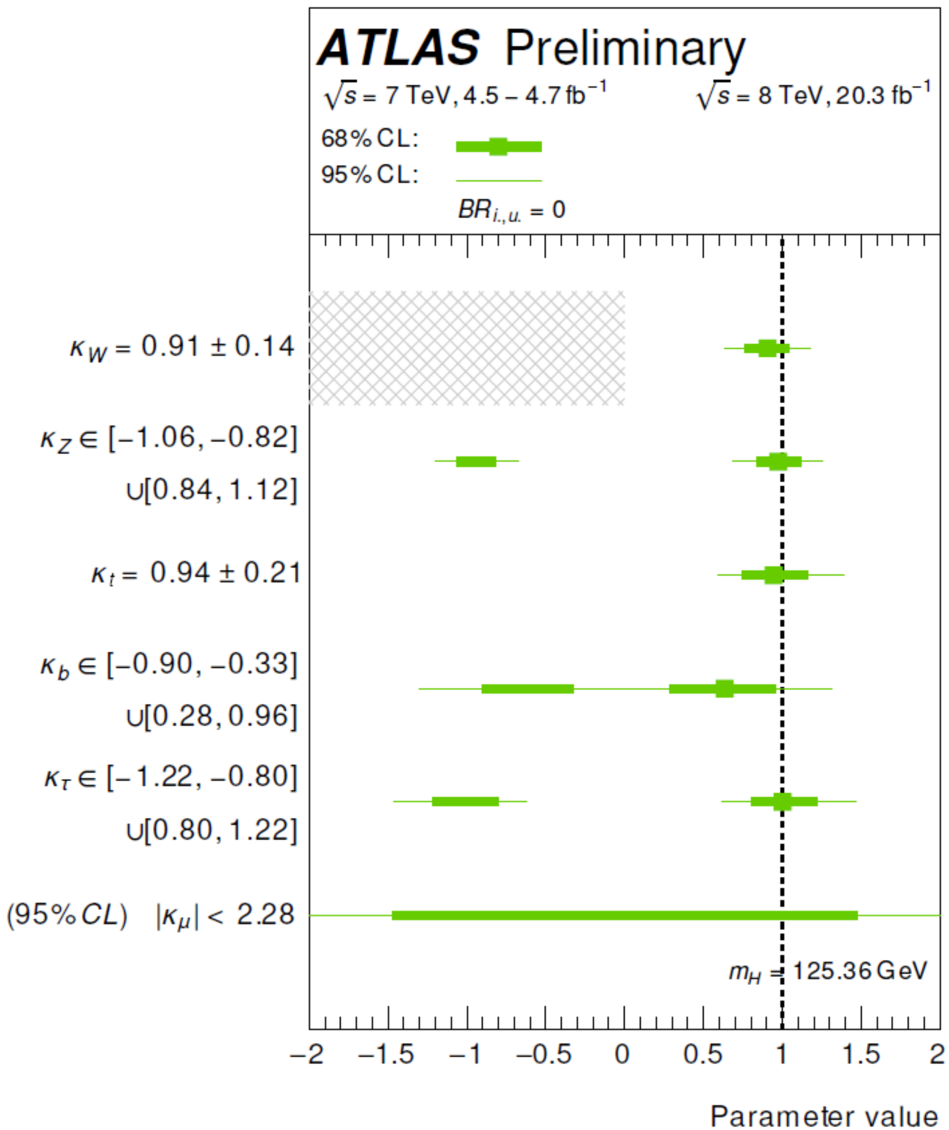

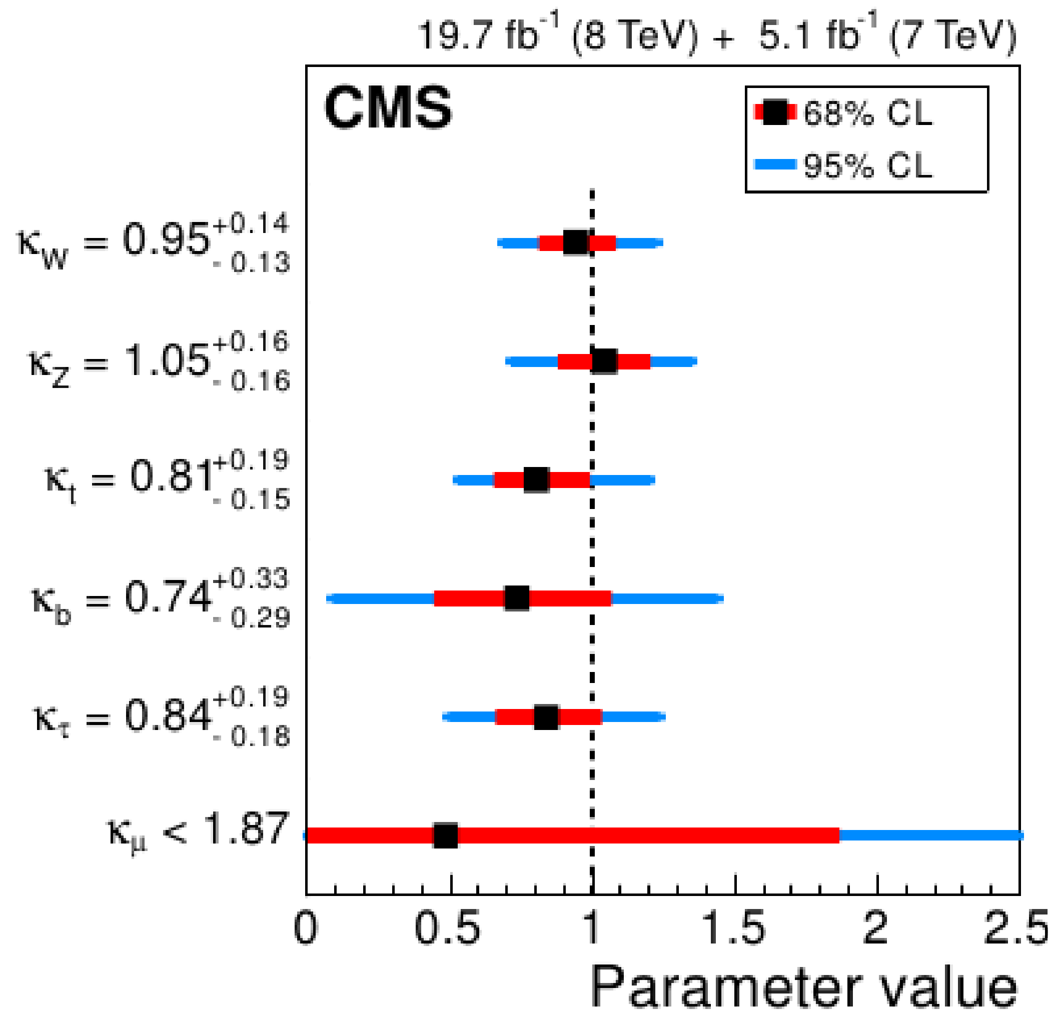

Reminder: Higgs couplings, 2nd try
- κ-framework -

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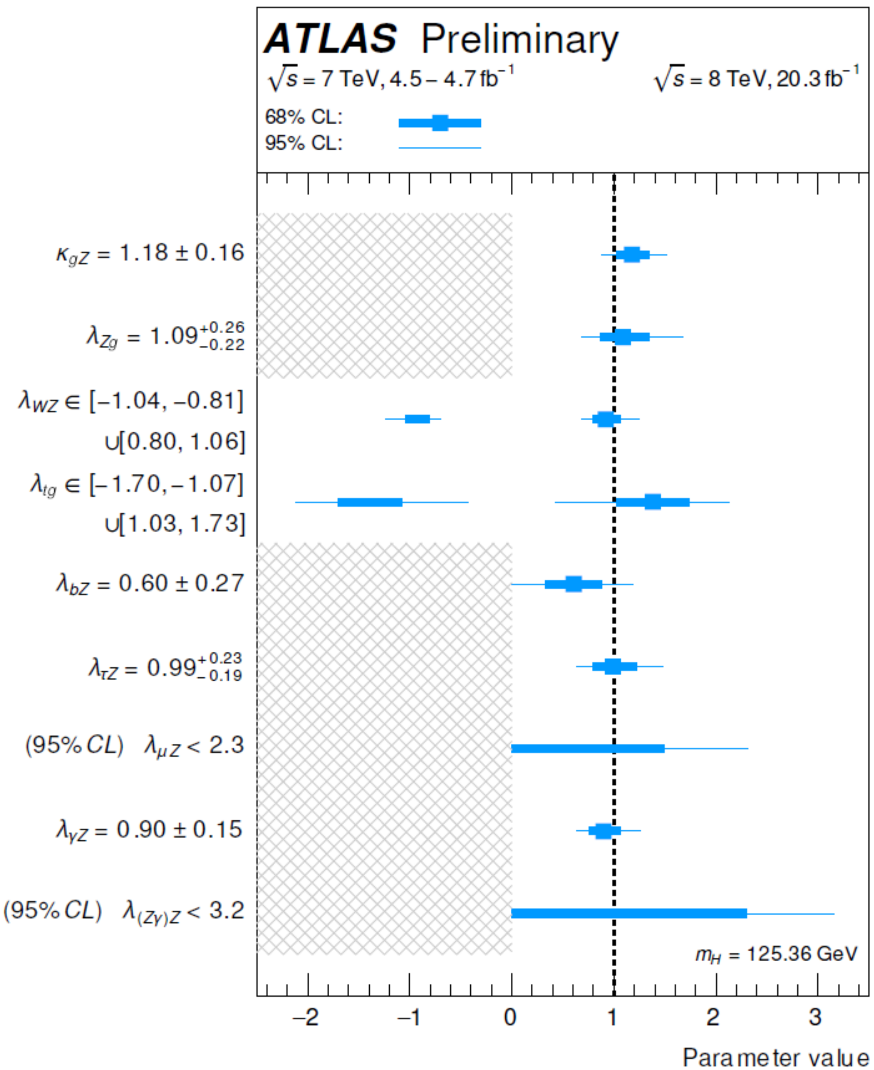
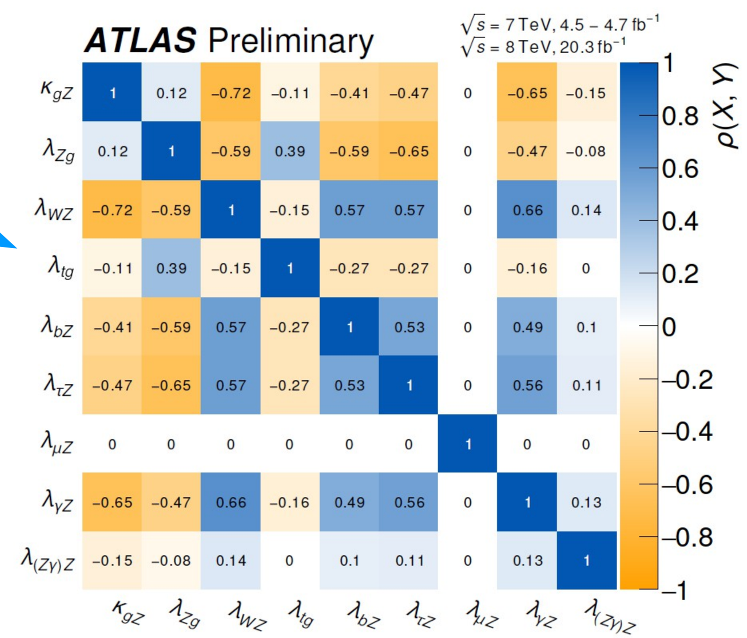


Most general fit within the κ-framework:

- **No assumption on particle content in gg→H, H→γγ, H→Zγ loops**
- **No assumptions on BSM Higgs decay modes or total width**

Correlation matrix



Higgs couplings, 3rd try - what do we actually want? -

Wish list:

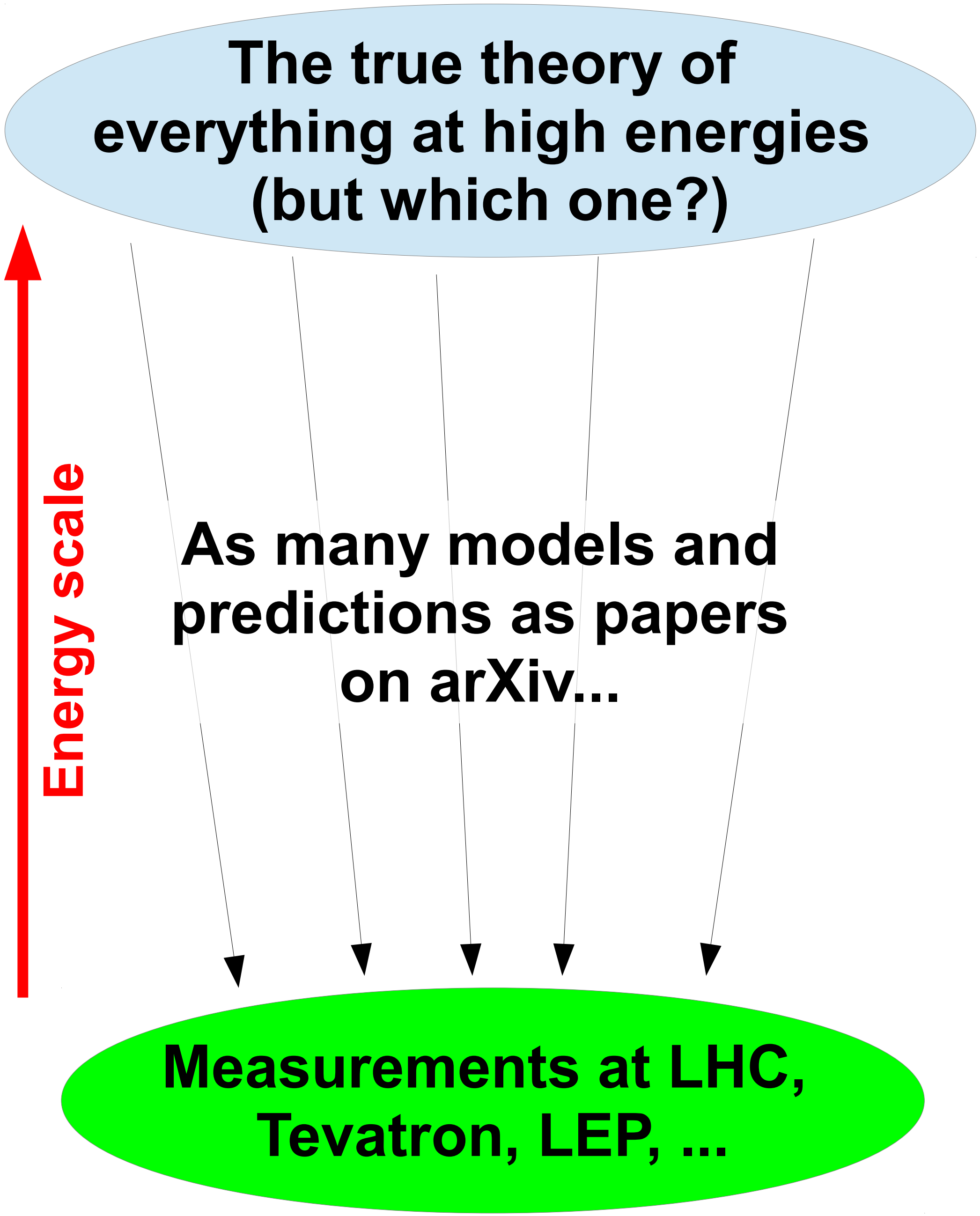
- Merge Higgs coupling measurements and measurements of kinematic distributions (currently done as CP-measurements)
  → No longer need to assume SM kinematics!
- Allows to consistently calculate beyond leading order
  → make a measurement, not just a search for deviations
- Allows to combine with other LHC measurements (e.g. aTGC) and non-LHC measurements (LEP EW precision observables)

Answer from theory:

$$\mathcal{L}_{eff} = \mathcal{L}_{\rm SM}^{(4)} + \sum_i \frac{1}{\Lambda^{d_i-4}} c_i \mathcal{O}_i$$

- Use an effective field theory (EFT)
  - Describes BSM interactions in a very general way and naturally predicts both effects on rates and kinematic distributions
  - Allows higher order calculation and global fits (not just Higgs)
- Comes with a price tag: assumes new physics is heavy!
  - Not predictive beyond (some unknown) cut off scale

what you get when you ask an experimentalist to talk about EFT...



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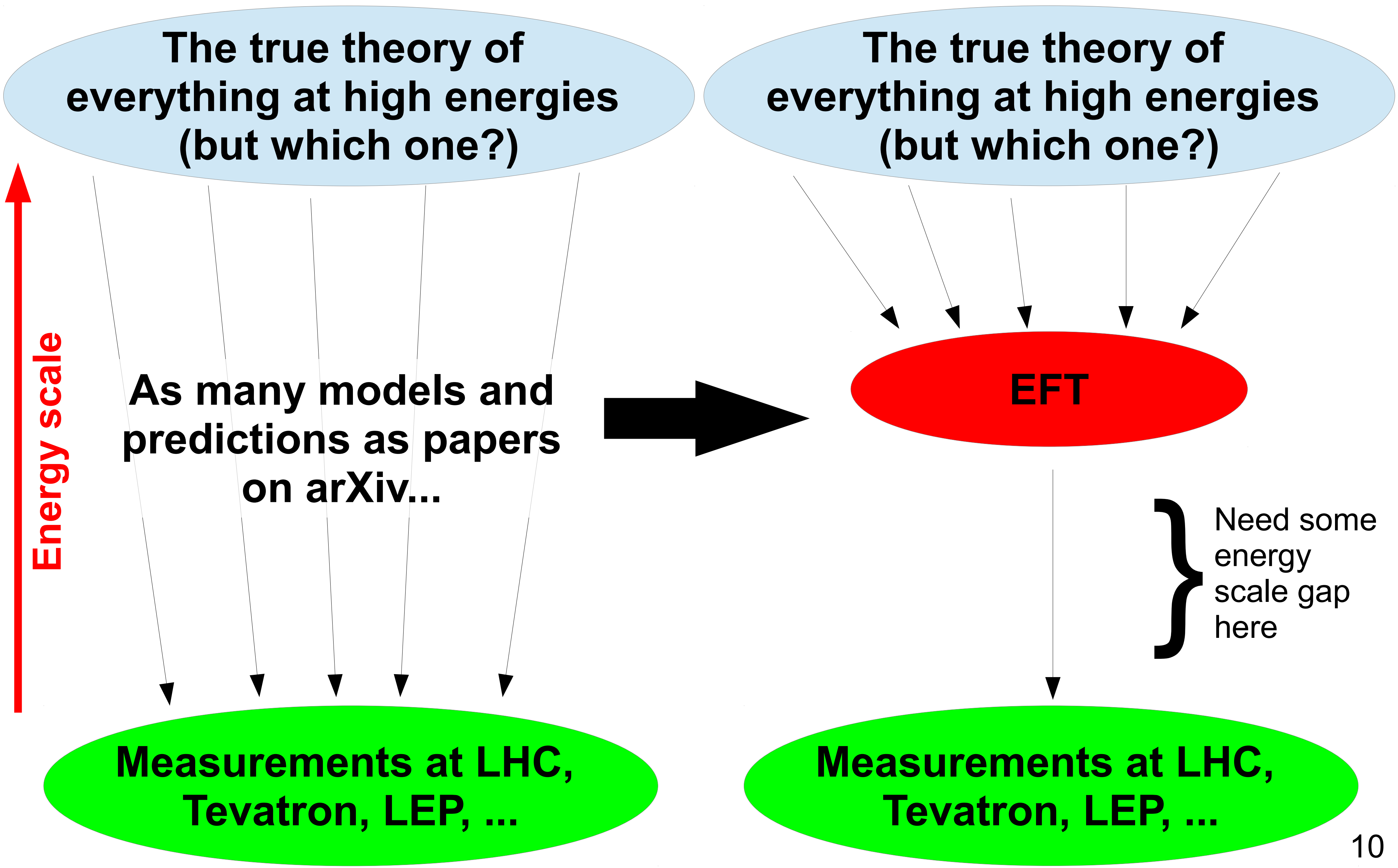

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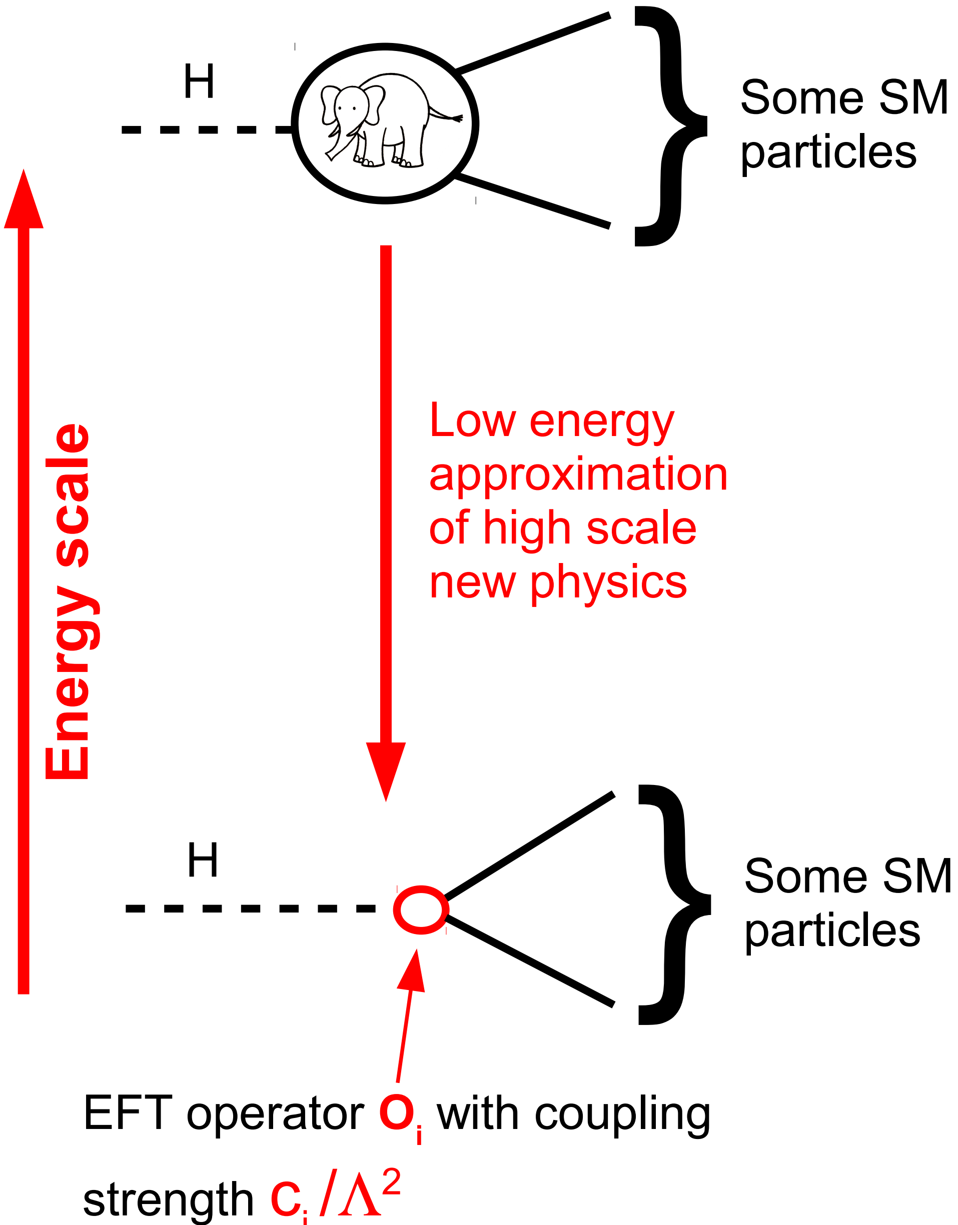
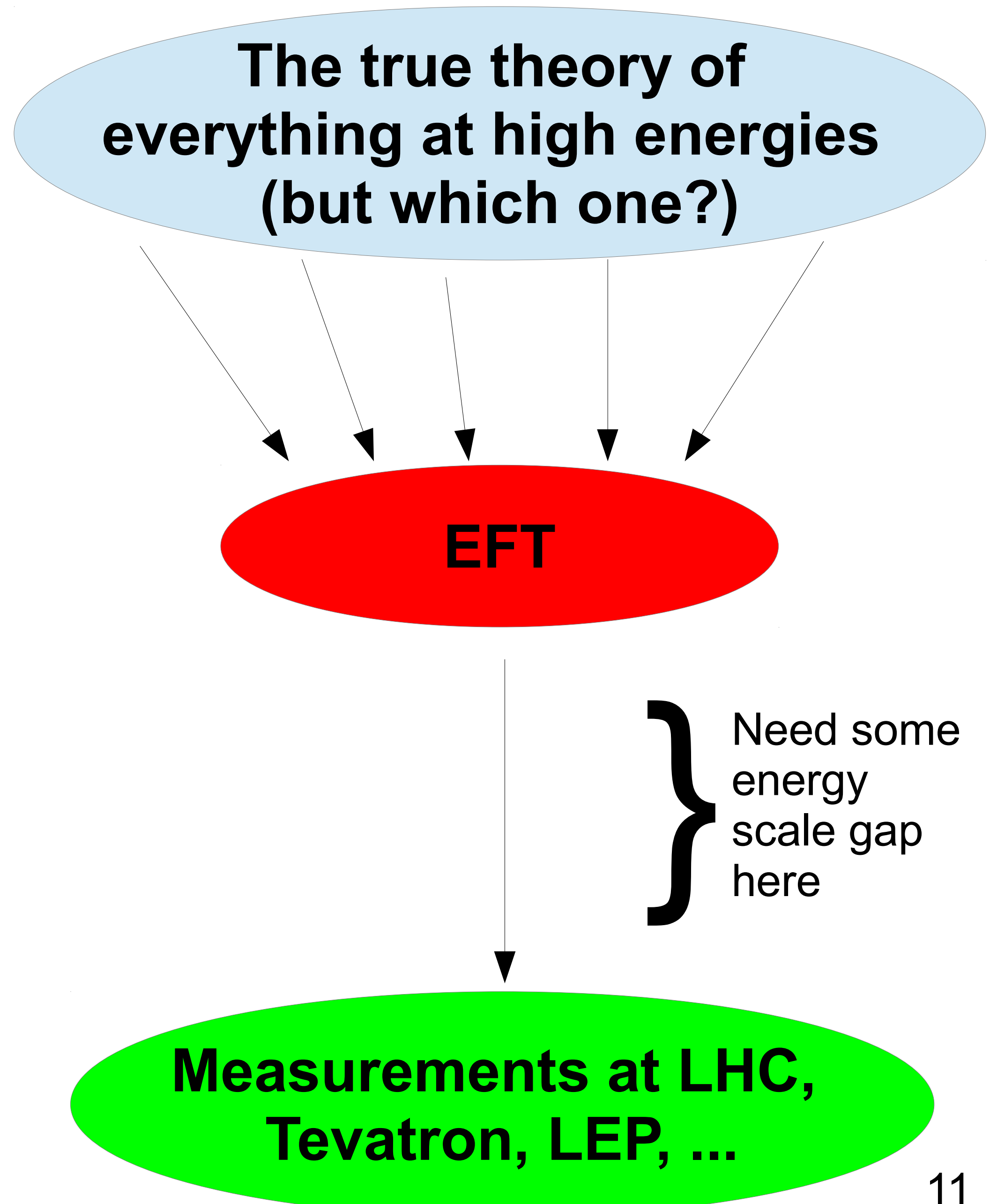




EFT basis

Many discussions of EFT basis:

- So far only the leading extension to the SM is considered: dimension 6 operators
- As long as a complete basis set is implemented, all EFT basis choices are equivalent. Still some variants:
  - 59 operators for one fermion family (so e=μ=τ)
  - 2499 operators for three fermion families...
- In development: convenient “Higgs-basis” in LHC XS WG2

Φ^6 and $\Phi^4 D^2$	$\psi^2\Phi^3$	X^3
$\mathcal{O}_{\Phi} = (\Phi^\dagger\Phi)^3$	$\mathcal{O}_{e\Phi} = (\Phi^\dagger\Phi)(\bar{l}\,\Gamma_e e\Phi)$	$\mathcal{O}_G = f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$\mathcal{O}_{\Phi\Box} = (\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi)$	$\mathcal{O}_{u\Phi} = (\Phi^\dagger\Phi)(\bar{q}\,\Gamma_u u\widetilde{\Phi})$	$\mathcal{O}_{\widetilde{G}} = f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$\mathcal{O}_{\Phi D} = (\Phi^\dagger D^\mu\Phi)^*(\Phi^\dagger D_\mu\Phi)$	$\mathcal{O}_{d\Phi} = (\Phi^\dagger\Phi)(\bar{q}\,\Gamma_d d\Phi)$	$\mathcal{O}_W = \varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
		$\mathcal{O}_{\widetilde{W}} = \varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$X^2\Phi^2$	$\psi^2 X\Phi$	$\psi^2\Phi^2 D$
$\mathcal{O}_{\Phi G} = (\Phi^\dagger\Phi) G_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{uG} = (\bar{q}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_u u\widetilde{\Phi}) G_{\mu\nu}^A$	$\mathcal{O}_{\Phi l}^{(1)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{l}\gamma^\mu l)$
$\mathcal{O}_{\Phi\widetilde{G}} = (\Phi^\dagger\Phi)\widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{dG} = (\bar{q}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_d d\Phi) G_{\mu\nu}^A$	$\mathcal{O}_{\Phi l}^{(3)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu^I\Phi)(\bar{l}\gamma^\mu\tau^I l)$
$\mathcal{O}_{\Phi W} = (\Phi^\dagger\Phi) W_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{eW} = (\bar{l}\sigma^{\mu\nu}\Gamma_e e\tau^I\Phi) W_{\mu\nu}^I$	$\mathcal{O}_{\Phi e} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{e}\gamma^\mu e)$
$\mathcal{O}_{\Phi\widetilde{W}} = (\Phi^\dagger\Phi)\widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{uW} = (\bar{q}\sigma^{\mu\nu}\Gamma_u u\tau^I\widetilde{\Phi}) W_{\mu\nu}^I$	$\mathcal{O}_{\Phi q}^{(1)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{q}\gamma^\mu q)$
$\mathcal{O}_{\Phi B} = (\Phi^\dagger\Phi) B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{dW} = (\bar{q}\sigma^{\mu\nu}\Gamma_d d\tau^I\Phi) W_{\mu\nu}^I$	$\mathcal{O}_{\Phi q}^{(3)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu^I\Phi)(\bar{q}\gamma^\mu\tau^I q)$
$\mathcal{O}_{\Phi\widetilde{B}} = (\Phi^\dagger\Phi)\widetilde{B}_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{eB} = (\bar{l}\sigma^{\mu\nu}\Gamma_e e\Phi) B_{\mu\nu}$	$\mathcal{O}_{\Phi u} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{u}\gamma^\mu u)$
$\mathcal{O}_{\Phi WB} = (\Phi^\dagger\tau^I\Phi) W_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{uB} = (\bar{q}\sigma^{\mu\nu}\Gamma_u u\widetilde{\Phi}) B_{\mu\nu}$	$\mathcal{O}_{\Phi d} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{d}\gamma^\mu d)$
$\mathcal{O}_{\Phi\widetilde{W}B} = (\Phi^\dagger\tau^I\Phi)\widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{dB} = (\bar{q}\sigma^{\mu\nu}\Gamma_d d\Phi) B_{\mu\nu}$	$\mathcal{O}_{\Phi ud} = i(\widetilde{\Phi}^\dagger D_\mu\Phi)(\bar{u}\gamma^\mu\Gamma_{ud} d)$

Example of operators involving the Higgs or Gauge fields

EFT basis

Many discussions of EFT basis:

- So far only the leading extension to the SM is considered: dimension 6 operators
- As long as a complete basis set is implemented, all EFT basis choices are equivalent. Still some variants:
  - 59 operators for one fermion family (so $e=\mu=\tau$)
  - 2499 operators for three fermion families...

- As these might be too many operators too handle in analysis, several proposals exist to reduce number of operators:
  - Based on power counting and estimations of the size of the involved terms → this needs additional assumptions!
  - Concentrate on operators involving the Higgs, e.g. SILH gives 12 CP even, 4 CP odd operators

- However, usually the value of one operator has no meaning. Only a complete (sub-)set of operators is physical unless symmetries allow a reduction.

Beyond EFT basis considerations

Are there tools for EFT calculations/simulations?

Yes, many already exist:

- FeynRules models
- MadGraph5/aMC@NLO
- eHDECAY
- HAWK (anomalous couplings)
- VBFNLO (anomalous couplings)
- Rosetta: translation tool between different (sub-)basis sets

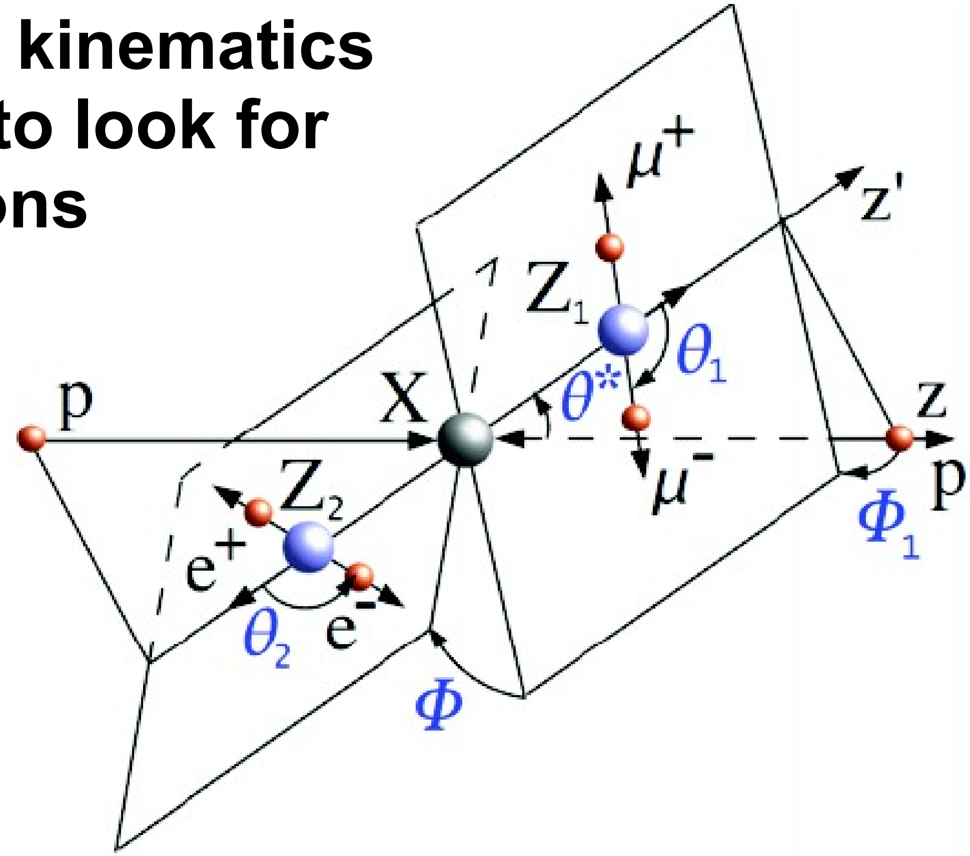
Are there EFT based experimental Higgs analysis?

Not so many (yet)...

- EFT allows consistent interpretation of measurements. But not mandatory for analysis to report EFT operators as results
  - Fiducial measurements are perfect inputs to EFT fits
  - One can give the κ-fits an EFT interpretation (within limits).
- ATLAS and CMS have made CP-analysis of the $H \rightarrow VV$ decay kinematics using an EFT (equivalent) approach.

CP measurements in H→VV decays

- **Both experiments use the decay kinematics in the H→VV→4fermion system to look for deviations from the SM predictions**
- **ATLAS uses (part of) the Higgs characterization model**



$$\mathcal{L}_0^V = \Big\{ c_\alpha \kappa_{\rm SM} \big[\tfrac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W_\mu^+ W^{-\mu}\big]$$

$$- \frac{1}{4}\big[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma}\, A_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma}\, A_{\mu\nu} \widetilde{A}^{\mu\nu}$$

$$- \frac{1}{2}\big[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma}\, Z_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma}\, Z_{\mu\nu} \widetilde{A}^{\mu\nu}$$

$$- \frac{1}{4}\big[c_\alpha \kappa_{Hgg} g_{Hgg}\, G^a_{\mu\nu} G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg}\, G^a_{\mu\nu} \widetilde{G}^{a,\mu\nu}$$

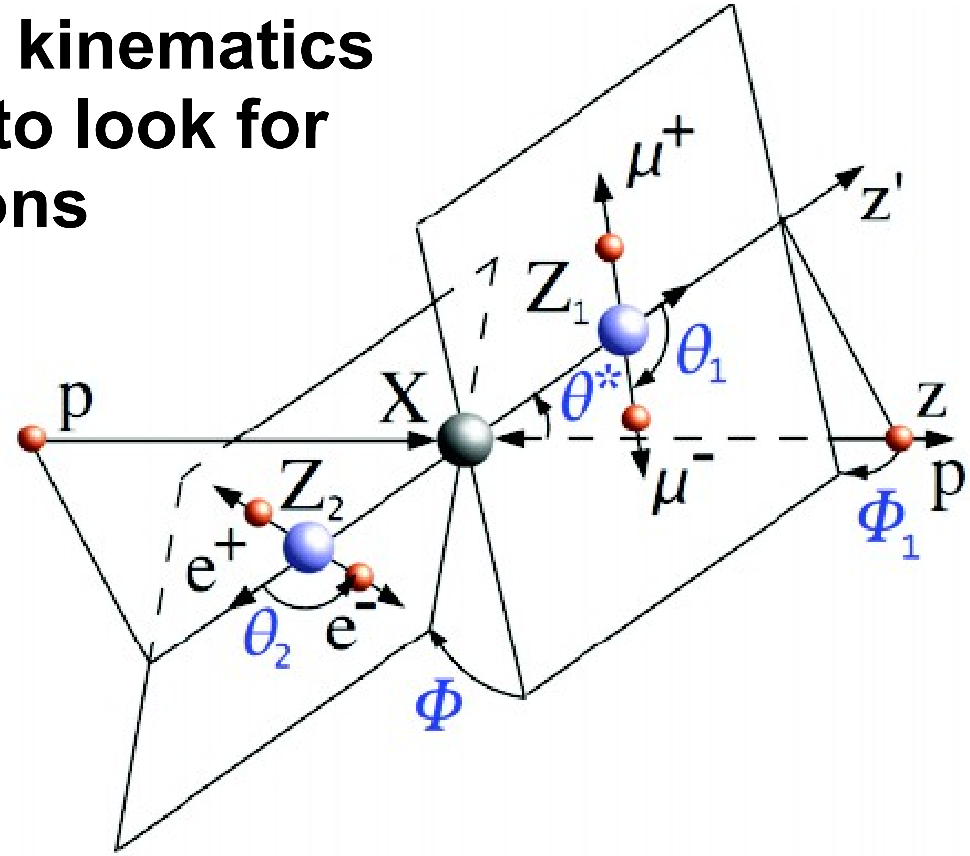
$$- \frac{1}{4}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HZZ}\, Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ}\, Z_{\mu\nu} \widetilde{Z}^{\mu\nu}\big]$$

$$- \frac{1}{2}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HWW}\, W^+_{\mu\nu} W^{-\mu\nu} + s_\alpha \kappa_{AWW}\, W^+_{\mu\nu} \widetilde{W}^{-\mu\nu}\big]$$

$$- \frac{1}{\Lambda} c_\alpha \big[\kappa_{H\partial\gamma}\, Z_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + \big(\kappa_{H\partial W}\, W_\nu^+ \partial_\mu W^{-\mu\nu} + h.c.\big)\big]\Big\} X_0$$

CP measurements in H→VV decays

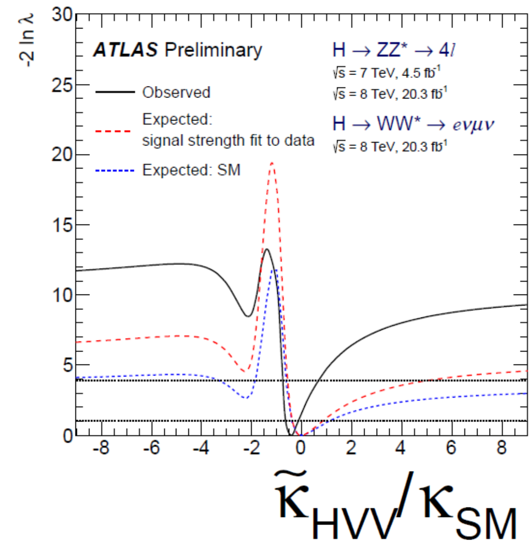
- **Both experiments use the decay kinematics in the H→VV→4fermion system to look for deviations from the SM predictions**
- **CMS uses anomalous couplings that map to an equivalent effective Lagrangian**



$$
\begin{aligned}
L(\mathrm{HVV}) \sim\; & a_1 \frac{m_Z^2}{2} \mathrm{H} Z^\mu Z_\mu + \frac{1}{(\Lambda_1)^2} m_Z^2 \mathrm{H} Z_\mu \Box Z^\mu - \frac{1}{2} a_2 \mathrm{H} Z^{\mu\nu} Z_{\mu\nu} - \frac{1}{2} a_3 \mathrm{H} Z^{\mu\nu} \tilde{Z}_{\mu\nu} \\
& + a_1^{WW} \frac{m_W^2}{2} \mathrm{H} W^\mu W_\mu + \frac{1}{(\Lambda_1^{WW})^2} m_W^2 \mathrm{H} W_\mu \Box W^\mu - \frac{1}{2} a_2^{WW} \mathrm{H} W^{\mu\nu} W_{\mu\nu} - \frac{1}{2} a_3^{WW} \mathrm{H} W^{\mu\nu} \tilde{W}_{\mu\nu} \\
& + \frac{1}{\left(\Lambda_1^{Z\gamma}\right)^2} m_Z^2 \mathrm{H} Z_\mu \partial_\nu F^{\mu\nu} - a_2^{Z\gamma} \mathrm{H} F^{\mu\nu} Z_{\mu\nu} - a_3^{Z\gamma} \mathrm{H} F^{\mu\nu} \tilde{Z}_{\mu\nu} - \frac{1}{2} a_2^{\gamma\gamma} \mathrm{H} F^{\mu\nu} F_{\mu\nu} - \frac{1}{2} a_3^{\gamma\gamma} \mathrm{H} F^{\mu\nu} \tilde{F}_{\mu\nu},
\end{aligned}
$$

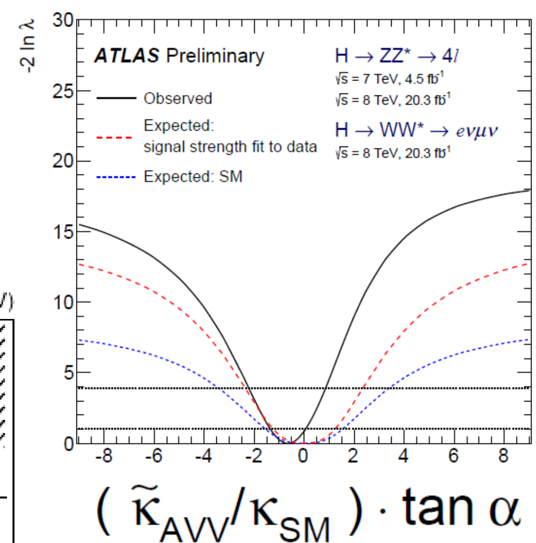
CP measurements in H→VV decays

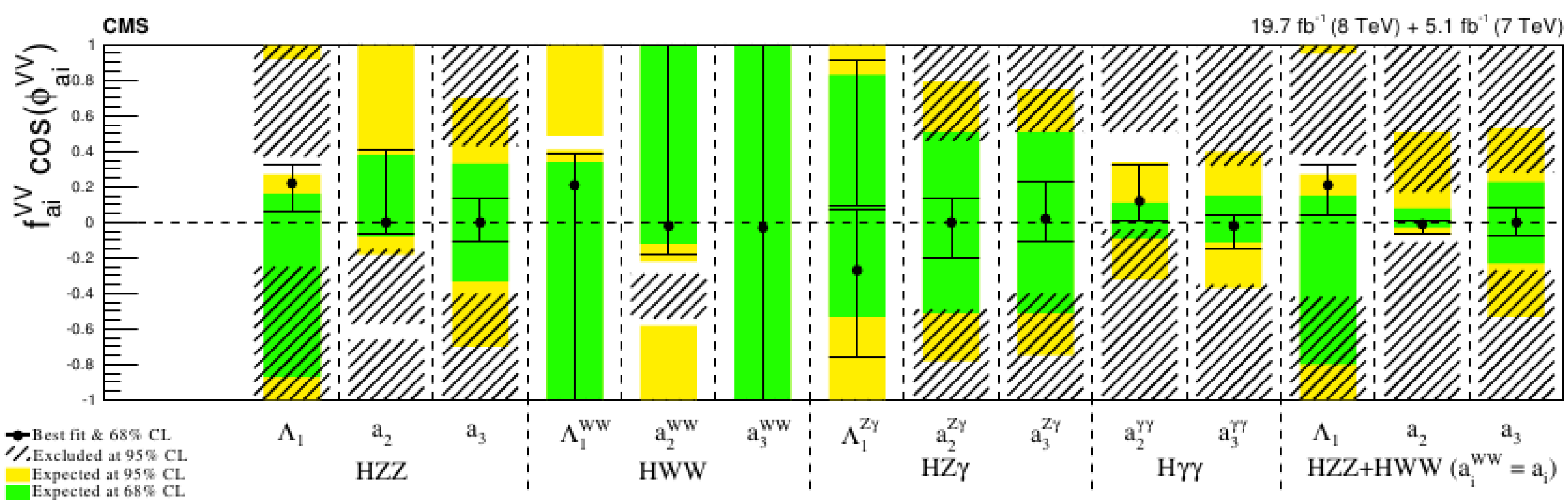
- Both experiments don't use the event rate
  → considerably simplifies analysis
  → but potential of EFT analysis is not exploited
- Both experiments don't have a simultaneous measurement of all EFT operators



Why not? It's complicated!

- To measure n EFT operators from the same events, one wants a n-dim observable. With interference terms ~2n-dim would be better.
- Worse, the Higgs signal model needs to reflect all (correlated) changes of all n EFT operators





Observables in EFT measurements

To measure n EFT operators from the same events, one wants a n-dim observable. With interference terms ~2n-dim would be better.

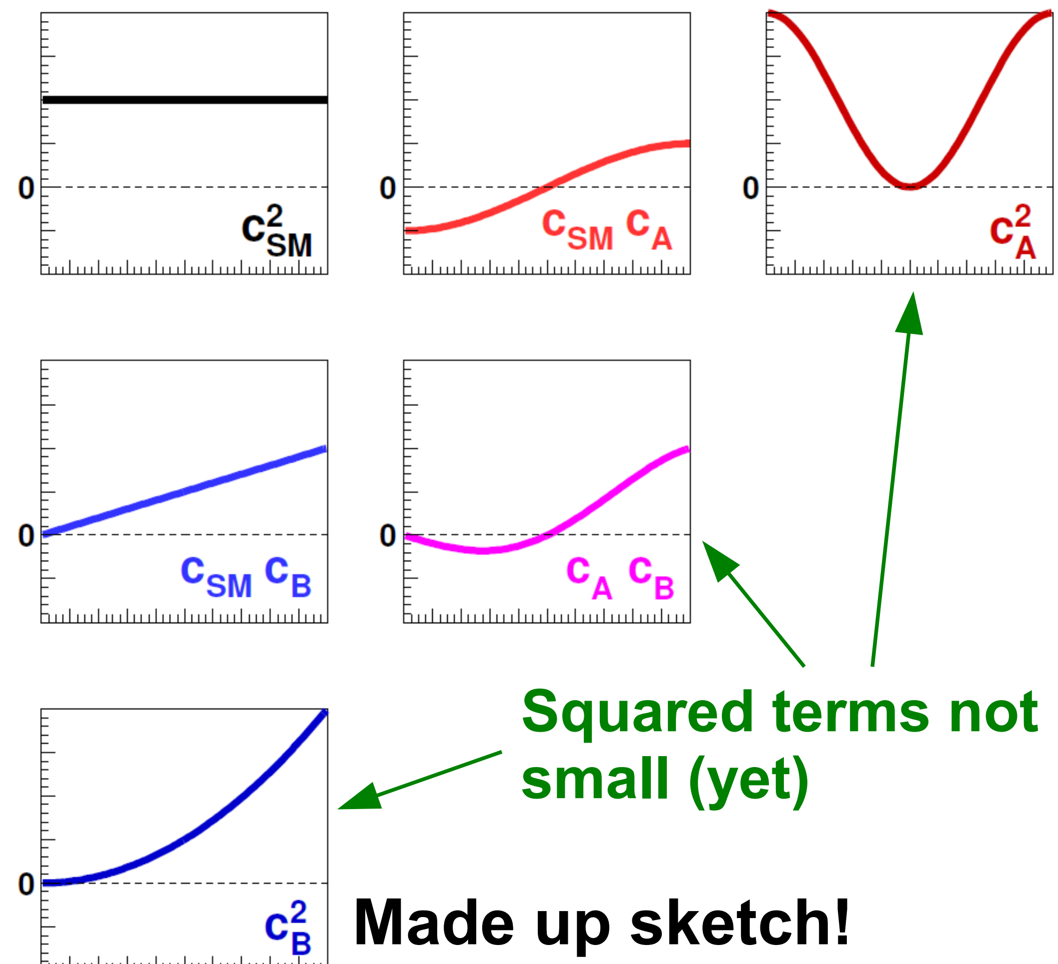
- Example: consider three operators: SM, BSM CP-odd, BSM CP-even
- Observables in something like $H \rightarrow VV$ decays:
  - Rate (partial decay width) measures the sum of these three operators
  - Angle 1 measures the BSM CP-even admixture
  - Angle 2 measures the BSM CP-odd admixture
  - Its all in the same events, so statistical correlations require to compare data and MC with a 3-dim histogram
  - Actually, interference terms are also important and look different. This requires another 2-3 observables (angles or similar), so up to a 6-dim histogram

- What if we don't manage (e.g. limited MC stats). Is that serious?
  - Actually no
  - It just means the analysis is not optimal and doesn't make maximal use of all the information in the data
  - But with still limited data stats the gain from each extra dimension should get marginal rather quickly

Signal model in EFT measurements

The Higgs signal model needs to reflect all (correlated) changes of all n EFT operators

- Because the acceptance needs to be modeled correctly and usually several EFT operators contribute to the same observable, this is true even if only a few observables are used
- Toy example of 1 observable (some angle), 3 operators: SM, operator A, operator B contributing to H→VV→4fermion
- Expect up to 6 terms in the matrix element square and correspondingly 6 fundamental distributions (building blocks)
- Will need ~$n^2/2$ building blocks for the general case of n operators
- Taking the HC EFT Lagrangian and the most general case of H→2l2ν with all interferences its n>10. Painful, but still ~ doable.



Made up sketch! Not a real example

Signal model in EFT measurements

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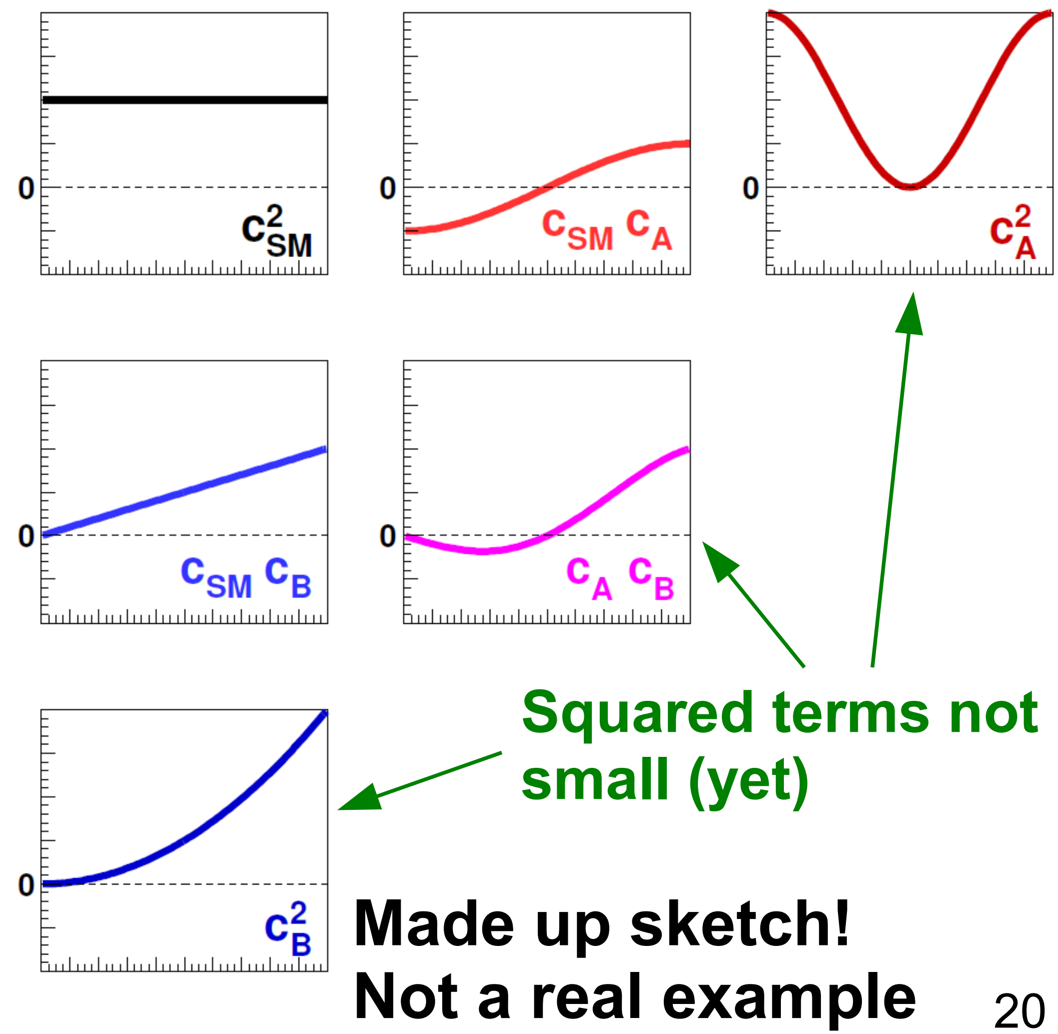

Signal model in EFT measurements

The Higgs signal model needs to reflect all (correlated) changes of all n EFT operators

- Lets look at the bigger picture

$$(\sigma^*BR)(\Omega) = \sigma_P(\Omega)\ \Gamma_D(\Omega)\ /\ \Gamma_H$$

Model of total width. Always just a number

All observables Ω

Kinematic model of production

Kinematic model of decay

- $\sigma_P(\Omega)$ depends on n_P EFT operators. So will need ~$n_P^2/2$ building blocks for the kinematic model. Think of VBF with all W and Z operators
- $\Gamma_D(\Omega)$ depends on n_D EFT operators. So will need ~$n_D^2/2$ building blocks for the kinematic model. Think of H→VV with all V related EFT operators
- Production and decay do not factorize trivially → need $n_P^2 * n_D^2/4$ building blocks? Only rough guess, as some operators are in common.
- Γ_H essentially depends on all EFT operators entering Higgs in any way. Fortunately its just a number and factorizes complete!

Signal model in EFT measurements

The Higgs signal model needs to reflect all (correlated) changes of all n EFT operators

- Lets look at the bigger picture

$$(\sigma^{*}BR)(\Omega) = \sigma_P(\Omega)\, \Gamma_D(\Omega) \,/\, \Gamma_H$$

All observables Ω

Kinematic model of production

Kinematic model of decay

Model of total width. Always just a number

- Approximately $n_P^2 * n_D^2/4$ building blocks sounds bad. Fortunately, there is room to be smart before using brute force.
- If EFT operators contributing to a building block enter both in production and decay the result could be too small to be relevant
- If dim(Ω) is small, many building blocks could end up to be very similar
  - Especially true if operators contribute only to the total (next slides)

→ Full EFT analysis should eventually be possible. But for the start expect limited number of EFT operators in measurements

Examples where POs could help

Pseudo-observables (POs) have many nice properties. In this context they help to isolate the theory interpretation from the measurement which can reduce the complexity a lot.

Example:

- Total width Γ_H: basically depends on all EFT operators. Even in "pure" bosonic processes like VBF $H \to VV$ all fermion operators will enter in the rate through Γ_H.

  → Solution: experiments treat Γ_H as PO. Instead of reporting results on Wilson coefficients c_i, they report $c_i/(\Gamma_H)^{1/4}$. Anybody with a BSM theory who wants to compare to the measurement, can re-interpret the measurement in the complete EFT by plugging in the right value(s) for Γ_H.

Examples where POs could help

Pseudo-observables (POs) have many nice properties. In this context they help to isolate the theory interpretation from the measurement which can reduce the complexity a lot.

Example:

- Decay $H\to\gamma\gamma$: current EFT models have the SM loop (but with fixed SM W and top couplings!) and a contact term. But dependence on fermion and gauge boson interactions are possible (and wanted) → many operators enter $H\to\gamma\gamma$
  → Experimentally: its a back-to-back decay in the rest frame. Ignoring photon polarization, the only measured information is $\Gamma(H\to\gamma\gamma)$
  → Use $\Gamma(H\to\gamma\gamma)$ or $BR(H\to\gamma\gamma)$ as PO instead in the measurement. For example, report measured Wilson coefficients from the production side as $c_i * (BR(H\to\gamma\gamma))^{1/2}$.

Examples where POs could help

Pseudo-observables (POs) have many nice properties. In this context they help to isolate the theory interpretation from the measurement which can reduce the complexity a lot.

Examples:

- Decay $H \to ff$: ignoring CP-odd contributions that could show up in $\tau\tau$, there is again only information on $\Gamma(H \to ff)$
- Similar case for $\sigma(gg \to H)$, ignoring for now the very high p_T tail which is not accessible (yet)
- Shameless advertising: also in VBF, VH, $H \to VV$ POs help, but more work needed as these cases are more complex

BUT

- For a consistent interpretation of a measurement within a bigger context one will still re-express all measured POs by the corresponding EFT expressions. This is the strength of EFT!

Signal model in EFT measurements

Final disclaimer

EFT is not only HIGGS

- EFT operators can modify what we usually call SM backgrounds
- EFT operators can change the interpretation of the measurements that define the SM parameters

→ Ultimately a full EFT measurement would treat all processes as signal and take EFT effects into account everywhere...

EFT validity

- For a dim-6 EFT model coefficients c_i/Λ^2 appear:

$$\mathcal{L}_{eff} = \mathcal{L}_{\rm SM}^{(4)} + \sum_i \frac{1}{\Lambda^{d_i-4}} c_i \mathcal{O}_i$$

- Beyond some energy scale M_{cut}~Λ the dim-6 EFT expansion looses validity
  - No reason to exclude dim-8, -10, ... operators
  - EFT theory is no longer predictive
  - Hence predictions for the phase space with $E>>M_{cut}$ should not be compared to data
- Unfortunately, we don't know M_{cut}
- Also no general BSM theory available for $E>>M_{cut}$
- Best suggestion so far: bin/categorize experimental measurements in some observable related to M_{cut}
  - Examples: m(VH), p_T(1^{st} tag jet) in VBF, p_T(H) in gg→H

Summary

- Higgs coupling measurements using EFT promise to improve on two key deficits of previous frameworks:
  - Consistently include kinematic deviations from the SM
  - Allow higher order calculations and true measurements

- EFT analysis are complex
  - Best to have many observables in each analysis
  - Signal model has many degrees of freedom

- Pseudo-observables can help to factorize some of the complexity between the measurement and the EFT interpretation of the same measurement

- The validity range of the EFT and how to include in measurements in some general way is an open issue.