Catching Heavy Vector Triplets with the SMEFT:

from one-loop matching to phenomenology

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arXiv:2108.01094

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Tilman Plehn (Heidelberg University); Wolfgang Kilian (University of Siegen);
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We constrain new physics along two axes: measurements and models

Constraints on
new physics

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Single measurement → Constraints on new physics → All relevant measurements

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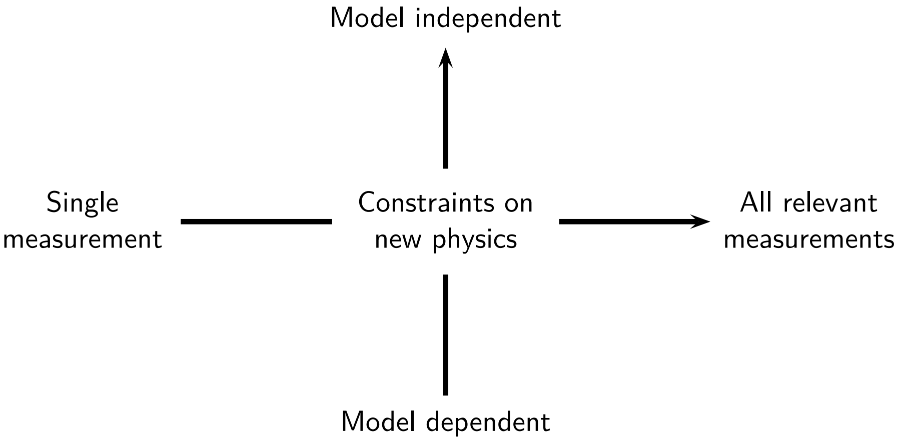

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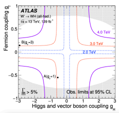

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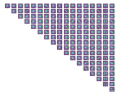
Global SMEFT Fits



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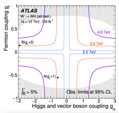

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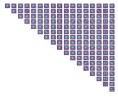

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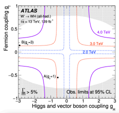

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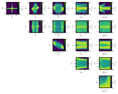

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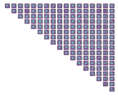

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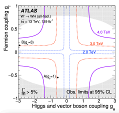

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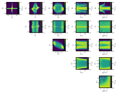

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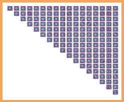

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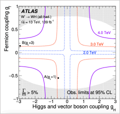

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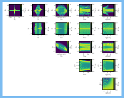

Model dependent

Heavy Vector Triplet

Today's Agenda

1. Ingredients
2. Results
3. Conclusions and Outlook

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- Measurements: **Higgs, Gauge and Electroweak Precision**

Our model space corresponds to parameters of the Heavy Vector Triplet model...

$$
\begin{aligned}
\mathcal{L}_{HVT} &= \mathcal{L}_{SM} - \frac{1}{4}\widetilde{V}^{\mu\nu A}\widetilde{V}^{A}_{\mu\nu} + \frac{\widetilde{m}_V^2}{2}\widetilde{V}^{\mu A}\widetilde{V}^{A}_{\mu} - \frac{\widetilde{g}_M}{2}\widetilde{V}^{\mu\nu A}\widetilde{W}^{A}_{\mu\nu} \\
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[Low, Rattazzi, Vichi: 0907.5413 | del Aguila, de Blas, Perez-Victoria: 1005.3998 | Pappadopulo, Thamm, Torre, Wulzer: 1402.4431 | Biekoetter, Knochel, Kraemer, Liu, Riva: 1406.7320 | Brehmer, Freitas, Lopez-Val, Plehn: 1510.03443]

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5 UV model parameters + mass

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... and an additional nuisance parameter from the matching at 1-loop!

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Low and high kinematic measurements in the Higgs, Gauge and EWP sectors are included

- **Low kinematics constrain non-kinematically enhanced operators** [Butter et al.: 1604.03105 | Biekötter, Corbett, Plehn: 1812.07587]

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  - Higgs measurements at LHC (275)
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  - Electroweak Precision Observables at LEP (14)

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- **High kinematics constrain kinematically enhanced operators**
  - VH resonance searches by ATLAS: 1712.06518 and **2007.05293**
  - VV resonance search by ATLAS: **2004.14636**

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Varying the matching scale introduces (large) theoretical uncertainties

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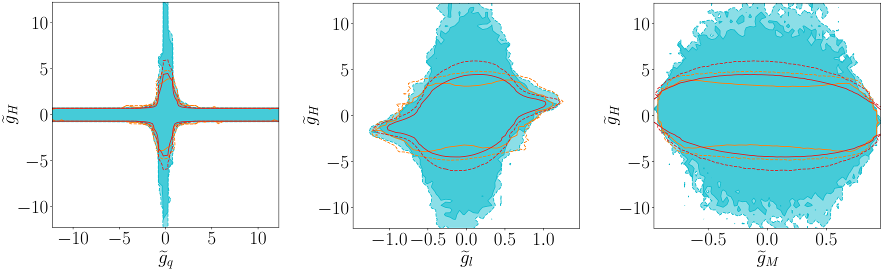
Changes to this matching scale affect the bounds on $\widetilde{g}_H$!



Tree level matching

1-loop level matching for $Q = 4$ TeV

1-loop level matching for $Q \in [0.5, 4]$ TeV

[Other paper considering Q: Dawson, Giardino, Homiller: 2102.02823]

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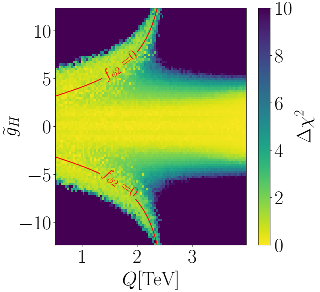

Flower due to tree-loop cancellation in $f_{\phi,2}, f_t, f_b, f_\tau$

Physical mass: $m_V = \frac{\widetilde{m}_V}{\sqrt{1-\widetilde{g}_M^2}} = 4\text{TeV}$

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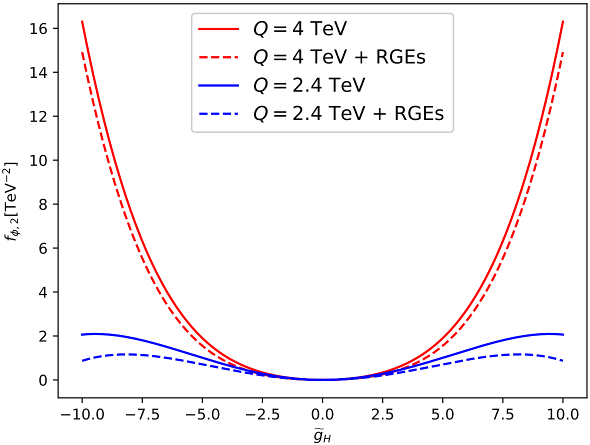
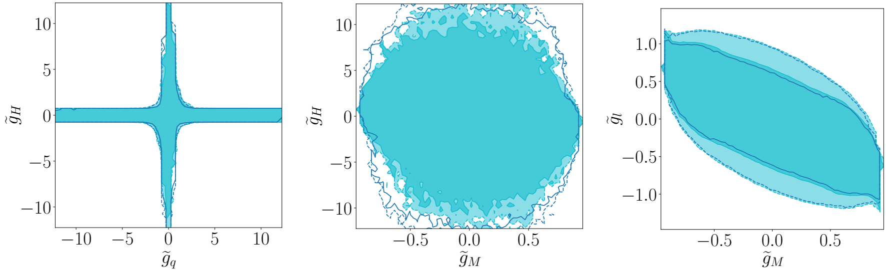
RGEs for SMEFT parameters do not compensate for this tree-loop cancellation



RGEs for HVT parameters are not yet available in the literature.

For the HVT model, the greatest constraints come from EWPOs and not heavy resonance searches with high kinematic reach

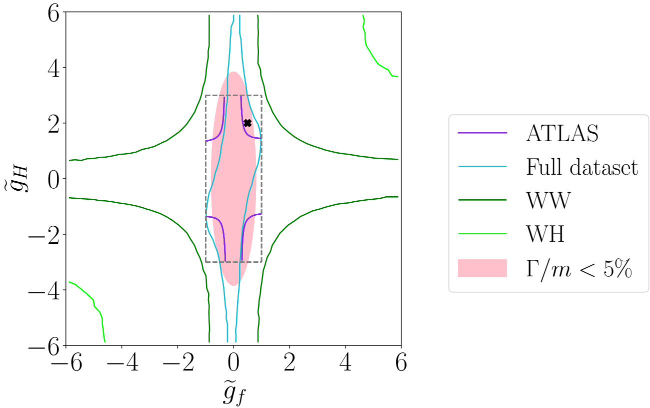


Heavy resonances searches included

Heavy resonances searches excluded

[ATLAS Collaboration: 1712.06518, 2004.14636, 2007.05293]

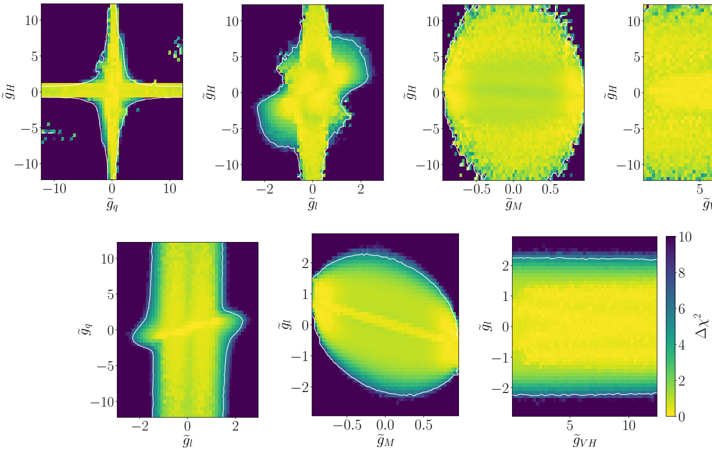
Direct searches constraints are stronger than constraints set through a SMEFT fit with the same analysis



95CL limits, physical mass: $m_V = \frac{\tilde{m}_V}{\sqrt{1-\tilde{g}_M^2}} = 4\text{TeV}$.

[ATLAS Collaboration: 2007.05293]

But SMEFT limits reach beyond the range of direct searches and constrain more parameters at once



We get constraints for $m_V = \frac{\widetilde{m}_V}{\sqrt{1-\widetilde{g}_M^2}} = 8$TeV, where direct resonance searches don't exist. And we fit in the full 5 parameter model space.

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- The full SMEFT constraints are comparable to the constraints from direct searches for heavy resonances in $\widetilde{g}_H$, and stronger in $\widetilde{g}_f$, thanks to the EWPOs.

- The full SMEFT results also set constraints on all relevant UV model parameters at once and in regions beyond the reach of direct searches.

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What is your preferred model?

The SFitter framework samples the likelihood function for a chosen model space

[Lafaye, Plehn, Zerwas: hep-ph/0404282]

- What we compute: **likelihood function**

$$\mathcal{L}(M) = \mathcal{L}(D|M) = p(D|M)$$

- How we scan the parameter space: **Markov chains**

- How we measure the goodness of fit: **likelihood ratio** (statistical test)

$$\frac{\mathcal{L}(D|M_1)}{\mathcal{L}(D|M_2)}$$

We match the model onto the SMEFT

The matching procedure ensures that **all matrix element in the SMEFT and the HVT are equal** at $\mu = Q$.

[Appelquist, Carazzone: 10.1103/PhysRevD.11.2856 | Weinberg: 10.1103/PhysRevD.19.1277]

$$\Rightarrow \quad \frac{c_i}{\Lambda^2}\left(\widetilde{g}_M, \widetilde{g}_H, \widetilde{g}_l, \widetilde{g}_q, \widetilde{g}_{VH}, \widetilde{m}_V, Q\right)$$

Matching is done at 1-loop using the functional matching formalism.

[Benjamin Summ, 2103.02487 or 2108.01094, GIT REPOSITORY]

We focus on specific SMEFT sectors

Standard **M**odel **E**ffective **F**ield **T**heory:

- Assume new physics is **heavier than SM** (no new light particles).
- Take the **symmetries and particle content** of the SM.
- **Higher order operators** mediating **new interactions** are classified in an **expansion in 1/Λ**:

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM}^{d\leq 4} + \frac{1}{\Lambda} c\, \mathcal{O}^{d=5} + \boxed{\frac{1}{\Lambda^2} \sum c_i\, \mathcal{O}_i^{d=6}} + \ldots$$

↑ 59 operators, too many...

Focus on Higgs, Gauge and Electroweak Precision sectors
⇒ 17 operators / Wilson coefficients

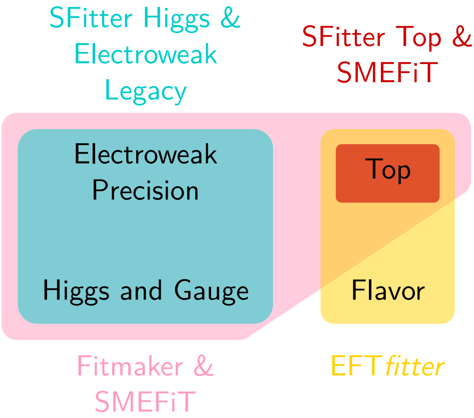
We use the HISZ basis

Not generated by matching

[Hagiwara, Ishihara, Szalapski, Zeppenfeld: 10.1016/0370-2693(92)90031-X]

~~$\mathcal{O}_{GG} = \phi^\dagger \phi G^a_{\mu\nu} G^{a\mu\nu}$~~	$\mathcal{O}_{BW} = \phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \phi$
$\mathcal{O}_{BB} = \phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \phi$	$\mathcal{O}_{WW} = \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi$
$\mathcal{O}_{B} = (D_\mu \phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \phi)$	$\mathcal{O}_{W} = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \phi)$
$\mathcal{O}_{WWW} = \mathrm{Tr}\left(\hat{W}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}_\rho{}^\mu\right)$	
$\mathcal{O}_{\phi 1} = (D_\mu \phi)^\dagger \phi \phi^\dagger (D^\mu \phi)$	$\mathcal{O}_{\phi 2} = \frac{1}{2} \partial^\mu \left(\phi^\dagger \phi\right) \partial_\mu \left(\phi^\dagger \phi\right)$
$\mathcal{O}_{b} = \left(\phi^\dagger \phi\right) \bar{q}_3 \phi d_3$	$\mathcal{O}_{\tau} = \left(\phi^\dagger \phi\right) \bar{l}_3 \phi e_3$
$\mathcal{O}_{t} = \left(\phi^\dagger \phi\right) \bar{q}_3 \widetilde{\phi} u_3$	
$\mathcal{O}_{LLLL} = \left(\bar{l}_1 \gamma_\mu l_2\right) \left(\bar{l}_2 \gamma^\mu l_1\right)$	$\mathcal{O}_{\phi e} = \left(\phi^\dagger i \overleftrightarrow{D}_\mu \phi\right) \left(\bar{e}_i \gamma^\mu e_j\right) \delta^{ij}$
$\mathcal{O}_{\phi d} = \left(\phi^\dagger i \overleftrightarrow{D}_\mu \phi\right) \left(\bar{d}_i \gamma^\mu d_j\right) \delta^{ij}$	$\mathcal{O}_{\phi u} = \left(\phi^\dagger i \overleftrightarrow{D}_\mu \phi\right) \left(\bar{u}_i \gamma^\mu u_j\right) \delta^{ij}$
$\mathcal{O}^{(1)}_{\phi Q} = \left(\phi^\dagger i \overleftrightarrow{D}_\mu \phi\right) \left(\bar{q}_i \gamma^\mu q_j\right) \delta^{ij}$	$\mathcal{O}^{(3)}_{\phi Q} = \left(\phi^\dagger i \overleftrightarrow{D}^A_\mu \phi\right) \left(\bar{q}_i \gamma^\mu t^A q_j\right) \delta^{ij}$

Different groups focus on different sectors



Obstacle to joining fits:
more operators ⇒ more CPU time.

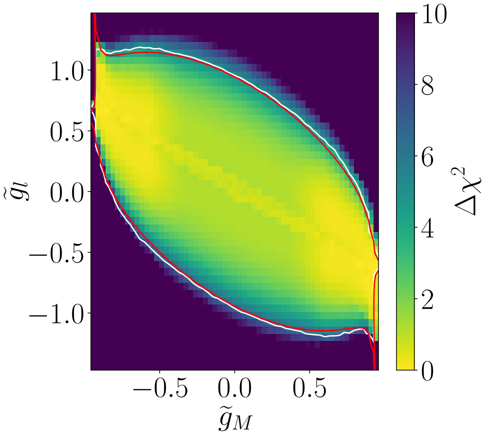
Solution:
Bayesian approach (work in progress)

SFitter Higgs & Electroweak Legacy: 1812.07587, 2108.04828, 1812.01009, 1604.03105 | SFitterTop: 1910.03606 | SMEFiT: 1901.05965 , 2105.00006 | Fitmaker: 2012.02779 | EFT*fitter*: arXiv:2012.10456

For each measurement, we include a careful uncertainty treatment

- Consider uncertainties on signal and background measurements, SM predictions, and SMEFT Monte Carlo predictions.
- Assign to each uncertainty the correct probability distribution: **gaussian, flat, or poissonian**.
- Decide which uncertainties to **correlate** or **uncorrelate**.

Limits on $(\widetilde{g}_M, \widetilde{g}_l)$ are given by $f_{LLLL} = C_{ll,1221}$



$f_{LLLL}/\Lambda^2 = -0.014, +0.017 \text{TeV}^{-2}$

(2σ interval derived from a 2D fit of f_{LLLL} and f_{BW})

What would be useful for theorists implementing diboson resonance searches in SMEFT fits

- Clear uncertainties breakdown (table)
- Invariant mass distributions on HEPData
- Way to reproduce one background and the SM signal from MC simulations (Madgraph+Pythia+Delphes) up to a k-factor:
  - either cut based analysis
  - or ANN publicly available?
  - or unfolding?