Higgs 2023
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Electroweak strongly-coupled scenarios, heavy resonances and oblique parameters

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Work in progress
PRD 102 (**2020**) 035012 [arXiv: 2004.02827]
JHEP 05 (**2019**) 092 [arXiv: 1810.10544]
JHEP 04 (**2017**) 012 [arXiv: 1609.06659]
PRD 93 (**2016**) 055041 [arXiv: 1510.03114]
JHEP 01 (**2014**) 157 [arXiv: 1310.3121]
PRL 110 (**2013**) 181801 [arXiv: 1212.6769]
JHEP 08 (**2012**) 106 [arXiv: 1206.3454]

OUTLINE

1) Motivation

2) The effective resonance Lagrangian

3) Oblique Electroweak Observables: S and T at NLO

4) Phenomenology

5) Conclusions

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2) The effective resonance Lagrangian

3) Oblique Electroweak Observables: S and T at NLO

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5) Conclusions

Bottom-up approach

1. Motivation

- The Standard Model (SM) provides an extremely succesful description of the electroweak and strong interactions.

- A key feature is the particular mechanism adopted to break the electroweak gauge symmetry to the electroweak subgroup, $SU(2)_L \times U(1)_Y \rightarrow U(1)_{QED}$, so that the W and Z bosons become massive. The LHC discovered a new particle around 125 GeV*.

  ➔ Higgs Physics

- Up to now all searches for New Physics have given negative results: Higgs couplings compatible with the SM and no new states. Therefore, we can use EFTs because it seems there is a large mass gap.

  ➔ Effective Field Theories

* CMS and ATLAS Collaborations.

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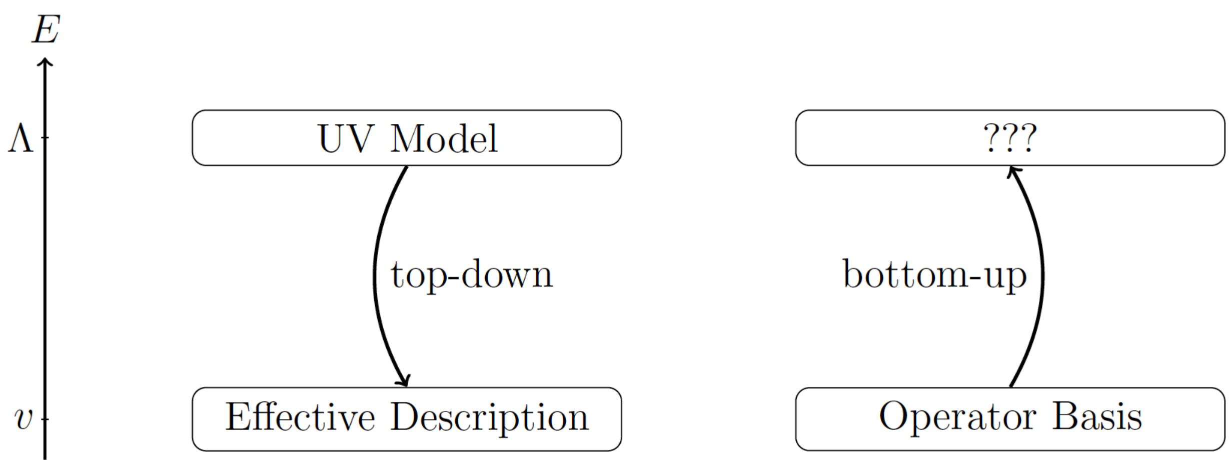
Effective Field Theories



Explained in many talks.

Diagram by C. Krause [PhD thesis, 2016]

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- Depending on the nature of the EWSB we have two possibilities for these EFTs (or something in between):

See, for instance, Sutherland's and Building's talks.

  - The decoupling (linear) EFT: SMEFT
    - SM-Higgs (forming a doublet with the EW Goldstones, as in the SM)
    - Weakly coupled
    - LO: SM
    - Expansion in canonical dimensions
  - The more general non-decoupling (non-linear) EFT: EWET, HEFT, EWChL
    - Non-SM Higgs (being a scalar singlet)
    - Strongly coupled
    - LO: Higgsless SM + scalar h + 3 GB (chiral Lagrangian)
    - Expansion in loops or chiral dimensions
    - Some composite Higgs models can be described within the EWET.

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What do we want to do?

S and T at NLO → Inclusion of BSM resonances in the effective Lagrangian in order to calculate S and T at NLO in terms of resonance parameters.

Short-distance constraints → Short-distance contraints are fundamental because we understand the resonance Lagrangian as an interpolation between low- and high energies and in order to reduce the number of resonance parameters.

Phenomenology → Following a typical bottom-up approach, what values for resonance masses are compatible with phenomenology?

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Similarities to Chiral Symmetry Breaking in QCD

i) Custodial symmetry: The Lagrangian is approximately invariant under global $SU(2)_L$ x $SU(2)_R$ transformations. Electroweak Symmetry Breaking (EWSB) turns to be $SU(2)_L x SU(2)_R \rightarrow SU(2)_{L+R}$.

ii) Similar to the Chiral Symmetry Breaking (ChSB) occurring in QCD, *i.e.*, similar to the "pion" Lagrangian of Chiral Perturbation Theory (ChPT)*^, by replacing f_π by $v=1/\sqrt{(2G_F)}=246$ GeV. Rescaling naïvely we expect resonances at the TeV scale.

* Weinberg '79
* Gasser and Leutwyler '84 '85
* Bijnens et al. '99 '00

** Ecker et al. '89
** Cirigliano et al. '06

^Dobado, Espriu and Herrero '91
^Espriu and Herrero '92
^Herrero and Ruiz-Morales '94

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Similarities to Chiral Symmetry Breaking in QCD

QCD $(q_a,\ G_{\mu\nu})$	Fundamental EW Theory (??)
$\updownarrow$	$\updownarrow$
Resonance Chiral Theory $(\sigma,\ \rho,\ \ldots)$	**Resonance EW Theory** $(M_V,\ M_A,\ \ldots)$
$\updownarrow$	$\updownarrow$
Chiral Perturbation Theory $(f_\pi,\ \pi_i)$	EW Effective Theory $(v,\ \phi_i)$

Diagram by J. Santos [VIII CPAN days, 2016]

2. The effective resonance Lagrangian

✓ Custodial symmetry

✓ Degrees of freedom: bosons χ (EW goldstones, gauge bosons, h) + fermions ψ + BSM resonances (V,A).

✓ *Chiral* power counting*

$$\frac{\chi}{v} \sim \mathcal{O}\left(p^0\right) \qquad \frac{\psi}{v} \sim \mathcal{O}\left(p\right) \qquad \partial_\mu,\, m \sim \mathcal{O}(p) \qquad \mathcal{T} \sim \mathcal{O}(p) \qquad g,\, g' \sim \mathcal{O}(p)$$

✓ Inclusion of odd-parity operators, not considered in Pich, IR, Santos and Sanz-Cillero '13 '14.

Finite pieces from loops (amplitude dependent)

$$\mathcal{M}(2\to 2) \approx \frac{p^2}{v^2}\left[1 + \left(\frac{c_k^r\, p^2}{v^2} - \frac{\Gamma_k\, p^2}{16\pi^2 v^2}\ln\frac{p}{\mu} + \ldots\right) + \mathcal{O}(p^4)\right]$$

LO (tree)

NLO (tree) **suppression** **$\sim 1/M^2$ + …** **(heavier states)**

NLO (1-loop) **Typical loop suppression** **$\sim 1/(16\pi^2 v^2)$** **(non-linearity)**

Diagram by J.J. Sanz-Cillero [HEP 2017]

* Weinberg '79
* Appelquist and Bernand '80
* Longhitano '80 '81
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* Hirn and Stern '05
* Alonso et al. '12
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* Krause, Pich, IR, Santos and Sanz-Cillero '19

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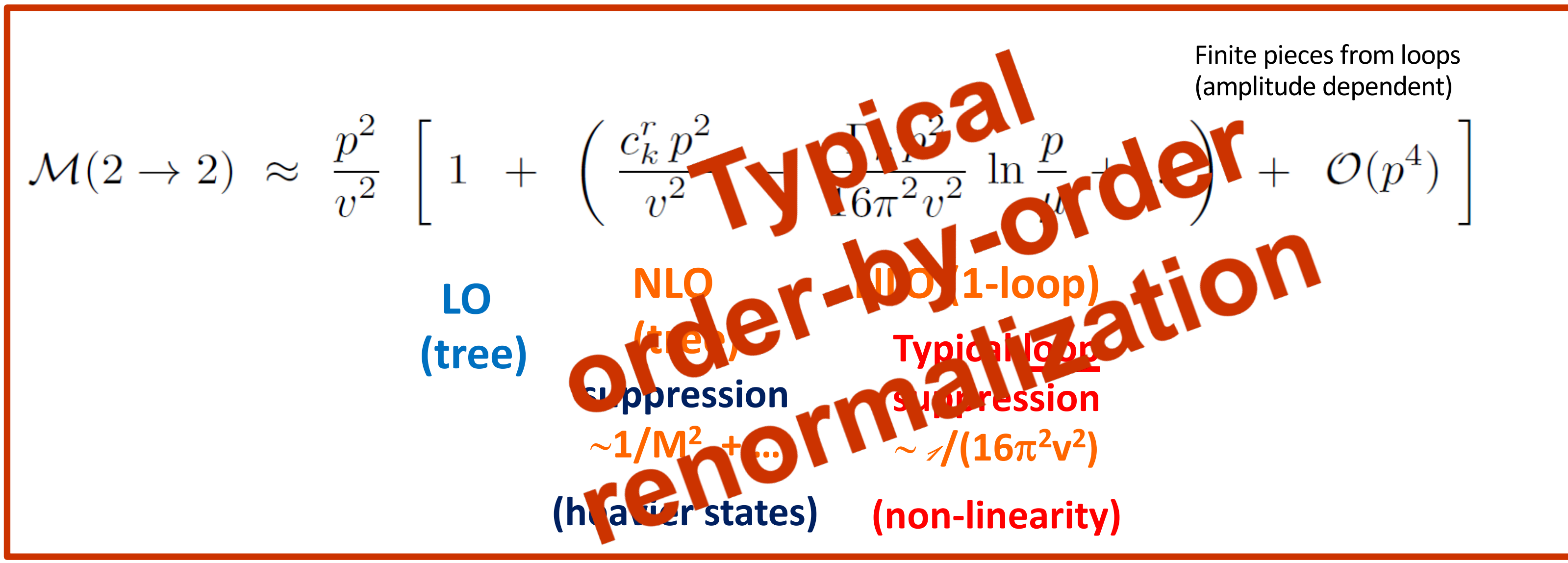

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✓ The Lagrangian reads:

$$\Delta\mathcal{L}_{\rm RT} = \frac{v^2}{4}\left(1+\frac{2\kappa_W}{v}h\right)\langle\, u_\mu u^\mu\,\rangle_2$$
$$+\ \langle\, V^1_{3\,\mu\nu}\left(\frac{F_V}{2\sqrt{2}}f_+^{\mu\nu}+\frac{iG_V}{2\sqrt{2}}[u^\mu,u^\nu]+\frac{\widetilde{F}_V}{2\sqrt{2}}f_-^{\mu\nu}+\frac{\widetilde{\lambda}_1^{hV}}{\sqrt{2}}\left[(\partial^\mu h)u^\nu-(\partial^\nu h)u^\mu\right]+C_0^{V_3^1}J_T^{\mu\nu}\right)\rangle_2$$
$$+\ \langle\, A^1_{3\,\mu\nu}\left(\frac{F_A}{2\sqrt{2}}f_-^{\mu\nu}+\frac{\lambda_1^{hA}}{\sqrt{2}}\left[(\partial^\mu h)u^\nu-(\partial^\nu h)u^\mu\right]+\frac{\widetilde{F}_A}{2\sqrt{2}}f_+^{\mu\nu}+\frac{i\widetilde{G}_A}{2\sqrt{2}}[u^\mu,u^\nu]+\widetilde{C}_0^{A_3^1}J_T^{\mu\nu}\right)\rangle_2\,.$$

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- Including resonance masses, we have 12 resonance parameters. This number can be reduced by using short-distance information, but in contrast to the QCD case, we ignore the underlying dynamical theory (BSM).

  - Vanishing form factors at high energies allow us to determine $\left(G_V\,,\widetilde{G}_A\,,\lambda_1^{hA}\,,\widetilde{\lambda}_1^{hV}\,,C_0^{V_3^1}\,,\widetilde{C}_0^{A_3^1}\right)$ in terms of the remaining parameters:

$$\frac{G_V}{F_A} = -\frac{\widetilde{G}_A}{\widetilde{F}_V} = \frac{\lambda_1^{hA}v}{\kappa_W F_V} = -\frac{\widetilde{\lambda}_1^{hV}v}{\kappa_W\widetilde{F}_A} = \frac{v^2}{F_VF_A-\widetilde{F}_V\widetilde{F}_A}\,, \qquad C_0^{V_3^1} = \widetilde{C}_0^{A_3^1} = 0\,.$$

  - Weinberg sum rules (WSRs) at LO and at NLO.

    - 1st WSR. Vanishing of the 1/s term of $\Pi_{VV}(s)-\Pi_{AA}(s)$: $\left(F_V^2-\widetilde{F}_V^2\right)-\left(F_A^2-\widetilde{F}_A^2\right) = v^2$
    - 2nd WSR. Vanishing of the 1/s² term of $\Pi_{VV}(s)-\Pi_{AA}(s)$: $\left(F_V^2-\widetilde{F}_V^2\right)M_V^2-\left(F_A^2-\widetilde{F}_A^2\right)M_A^2 = 0$

3. Oblique Electroweak Observables: S and T at NLO

- ✓ Universal oblique corrections via the EW boson self-energies (transverse in the Landau gauge)

$$\mathcal{L}_{\rm v.p.} \doteq -\frac{1}{2} W^3_\mu \, \Pi^{\mu\nu}_{33}(q^2) W^3_\nu - \frac{1}{2} B_\mu \, \Pi^{\mu\nu}_{00}(q^2) B_\nu - W^3_\mu \, \Pi^{\mu\nu}_{30}(q^2) B_\nu - W^+_\mu \, \Pi^{\mu\nu}_{WW}(q^2) W^-_\nu$$

- ✓ S parameter*: new physics in the difference between the Z self-energies at $Q^2=M_Z^2$ and $Q^2=0$.

$$e_3 = \frac{g}{g'} \, \widetilde{\Pi}_{30}(0) \,, \qquad \Pi_{30}(q^2) = q^2 \, \widetilde{\Pi}_{30}(q^2) + \frac{g^2 \tan\theta_W}{4} \, v^2 \,, \qquad S = \frac{16\pi}{g^2} \left(e_3 - e_3^{\rm SM} \right) .$$

- ✓ T parameter*: custodial symmetry breaking

$$e_1 = \frac{\Pi_{33}(0) - \Pi_{WW}(0)}{M_W^2} \overset{**}{=} \frac{Z^{(+)}}{Z^{(-)}} - 1 \qquad T = \frac{4\pi}{g'^2 \cos^2\theta_W} \left(e_1 - e_1^{\rm SM} \right)$$

- ✓ We follow the useful dispersive representation introduced by Peskin and Takeuchi* for S and a dispersion relation for T (checked for the lowest cuts):

$$S = \frac{16\pi}{g^2 \tan\theta_W} \int_0^\infty \frac{{\rm d}t}{t} \left(\rho_S(t) - \rho_S(t)^{\rm SM} \right)$$

$$T = \frac{16\pi}{g'^2 \cos^2\theta_W} \int_0^\infty \frac{{\rm d}t}{t^2} \left(\rho_T(t) - \rho_T(t)^{\rm SM} \right)$$

  - ✓ $\rho_S(t)$ and $\rho_T(t)$ are the spectral functions of the W^3B and of the difference of the neutral and charged Goldstone boson self-energies, respectively.
  - ✓ They need to be well-behaved at short-distances to get the convergence of the integral.
  - ✓ S and T parameters are defined for a reference value for the SM Higgs mass.

* Peskin and Takeuchi '92
** Barbieri et al. '93

- We consider only the lightest two-particle absorptive cuts ($\phi\phi$, $h\phi$, $\psi\bar{\psi}$) and in general we take as working assumptions $M_A > M_V$ and $\widetilde{F}^2_{V,A} < F^2_{V,A}$.

- LO result (T_{LO}=0):

  - With 1st and 2nd WSR: $S_{LO} = \frac{4\pi v^2}{M_V^2}\left(1+\frac{M_V^2}{M_A^2}\right) \longrightarrow \frac{4\pi v^2}{M_V^2} < S_{LO} < \frac{8\pi v^2}{M_V^2}$

  - With only the 1st WSR: $S_{LO} > \frac{4\pi v^2}{M_V^2}$

- NLO result with 1st and 2nd WSR:

$$S_{NLO} = 4\pi v^2\left(\frac{1}{M_V^{r\,2}}+\frac{1}{M_A^{r\,2}}\right) + \Delta S_{NLO}^{P-even} + \Delta S_{NLO}^{P-odd}$$

$$\Delta S_{NLO}^{P-even} = \frac{1}{12\pi}\left[(1-\kappa_W^2)\left(\log\frac{M_V^2}{m_h^2}-\frac{11}{6}\right)+\kappa_W^2\left(\frac{M_A^2}{M_V^2}-1\right)\log\frac{M_A^2}{M_V^2}\right]$$

$$\Delta S_{NLO}^{P-odd} = \frac{1}{12\pi}\left(\frac{\widetilde{F}_V^2}{F_V^2}+2\kappa_W^2\frac{\widetilde{F}_V\widetilde{F}_A}{F_VF_A}-\kappa_W^2\frac{\widetilde{F}_A^2}{F_A^2}\right)\left(\frac{M_A^2}{M_V^2}-1\right)\log\frac{M_A^2}{M_V^2}+\mathcal{O}\left(\frac{\widetilde{F}^4_{V,A}}{F^4_{V,A}}\right)$$

P-even results correspond to Pich, IR and Sanz-Cillero '13 '14

$$T_{NLO} = \Delta T_{NLO}^{P-even} + \Delta T_{NLO}^{P-odd}$$

$$\Delta T_{NLO}^{P-even} = \frac{3}{16\pi\cos^2\theta_W}\left[(1-\kappa_W^2)\left(1-\log\frac{M_V^2}{m_h^2}\right)+\kappa_W^2\log\frac{M_A^2}{M_V^2}\right]$$

$$\Delta T_{NLO}^{P-odd} = \frac{3}{16\pi\cos^2\theta_W}\left\{2\kappa_W^2\frac{\widetilde{F}_A}{F_A}-2\frac{\widetilde{F}_V}{F_V}+\frac{M_V^2}{M_A^2-M_V^2}\log\frac{M_A^2}{M_V^2}\left(2\frac{\widetilde{F}_V}{F_V}-2\kappa_W^2\frac{M_A^2}{M_V^2}\frac{\widetilde{F}_A}{F_A}\right)\right.$$
$$+\frac{M_V^2}{M_A^2-M_V^2}\log\frac{M_A^2}{M_V^2}\left[\left(\kappa_W^2\frac{\widetilde{F}_A^2}{F_A^2}-\frac{\widetilde{F}_V^2}{F_V^2}\right)\left(1+\frac{M_A^2}{M_V^2}\right)+2\frac{\widetilde{F}_V\widetilde{F}_A}{F_VF_A}\left(\kappa_W^2\frac{M_A^2}{M_V^2}-1\right)\right]$$
$$\left.+2\left(\frac{\widetilde{F}_V^2}{F_V^2}-\kappa_W^2\frac{\widetilde{F}_A^2}{F_A^2}+(1-\kappa_W^2)\frac{\widetilde{F}_V\widetilde{F}_A}{F_VF_A}\right)\right\}+\mathcal{O}\left(\frac{\widetilde{F}^3_{V,A}}{F^3_{V,A}}\right)$$

Expansion in $\frac{\widetilde{F}_{V,A}}{F_{V,A}}$.

Preliminary

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  - ✓ With only the 1st WSR: $S_{\rm LO} > \frac{4\pi v^2}{M_V^2}$

- ✓ NLO result with only the 1st WSR:

$$S_{\rm NLO} > \frac{4\pi v^2}{M_V^{r\,2}} + \Delta\widetilde{S}_{\rm NLO}^{\rm P-even} + \Delta\widetilde{S}_{\rm NLO}^{\rm P-odd}$$

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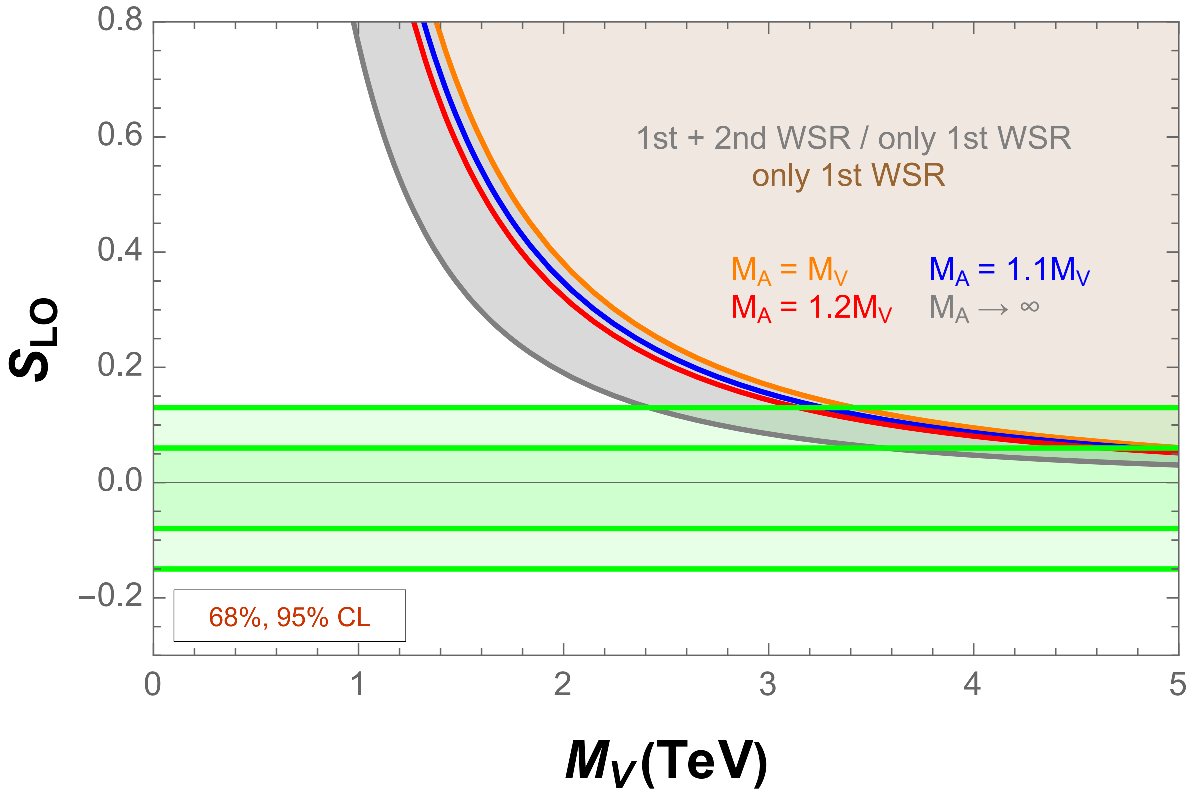
Expansion in $\frac{\widetilde{F}_{V,A}}{F_{V,A}}$.

4. Phenomenology

S = -0.01 ± 0.07 *
T = 0.04 ± 0.06 *

- ✓ Oblique electroweak observables** (S and T).
- ✓ Short-distance constraints.
- ✓ Assumptions: lightest two-particle absorptive cuts, $M_A > M_V$ and $\widetilde{F}^2_{V,A} < F^2_{V,A}$.

i) LO results



* PDG '22
** Peskin and Takeuchi '92

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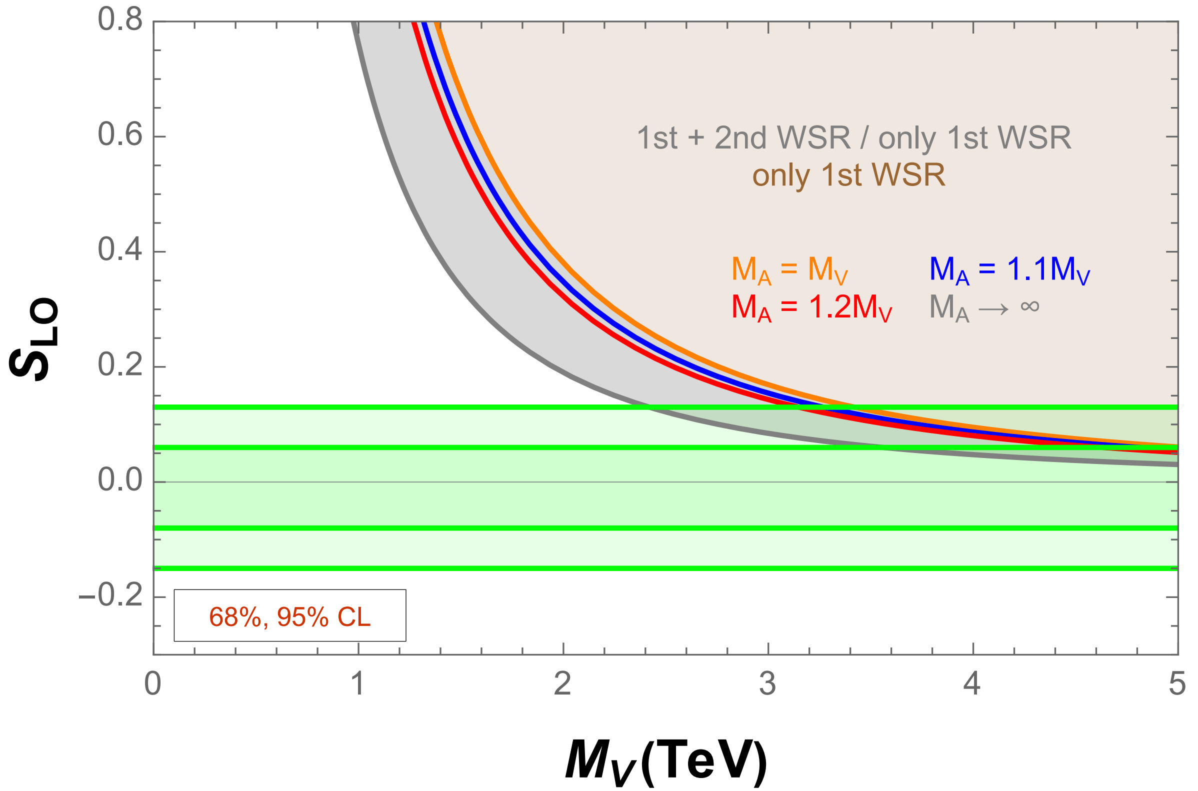

$M_V \gtrsim 2$ TeV

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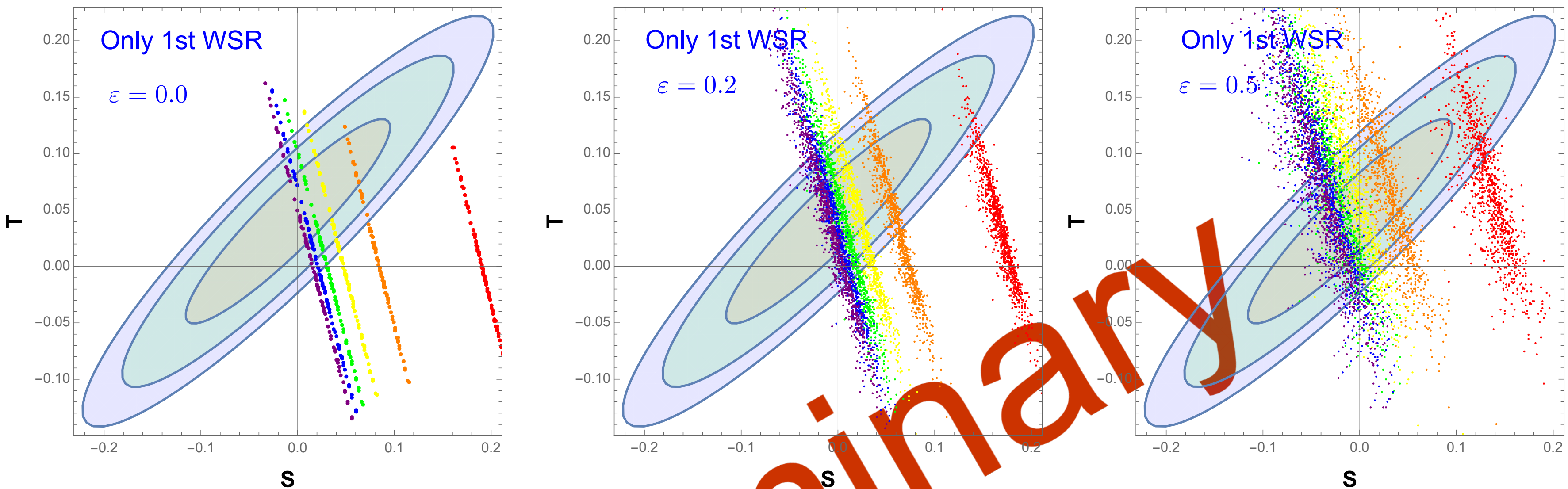
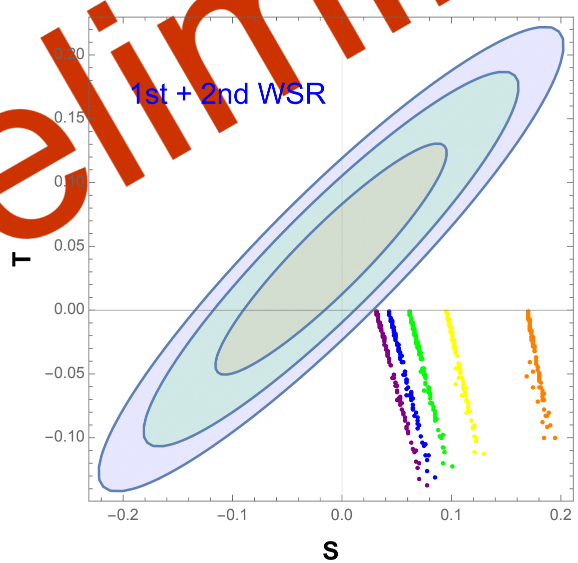
ii) NLO results

Results in terms of only M_V, M_A (only 1st WSR), κ_W and $\frac{\widetilde{F}_{V,A}}{F_{V,A}}$.



Preliminary

- ✓ κ_W=1.01 ± 0.06 *
- ✓ $\frac{\widetilde{F}_{V,A}}{F_{V,A}} = 0.00 \pm 0.33$
- ✓ M_V = { 2, 3, 4, 5, 6, 7 } TeV.
- ✓ $M_A = M_V (1+\varepsilon)$



* de Blas, Eberhardt and Krause '18

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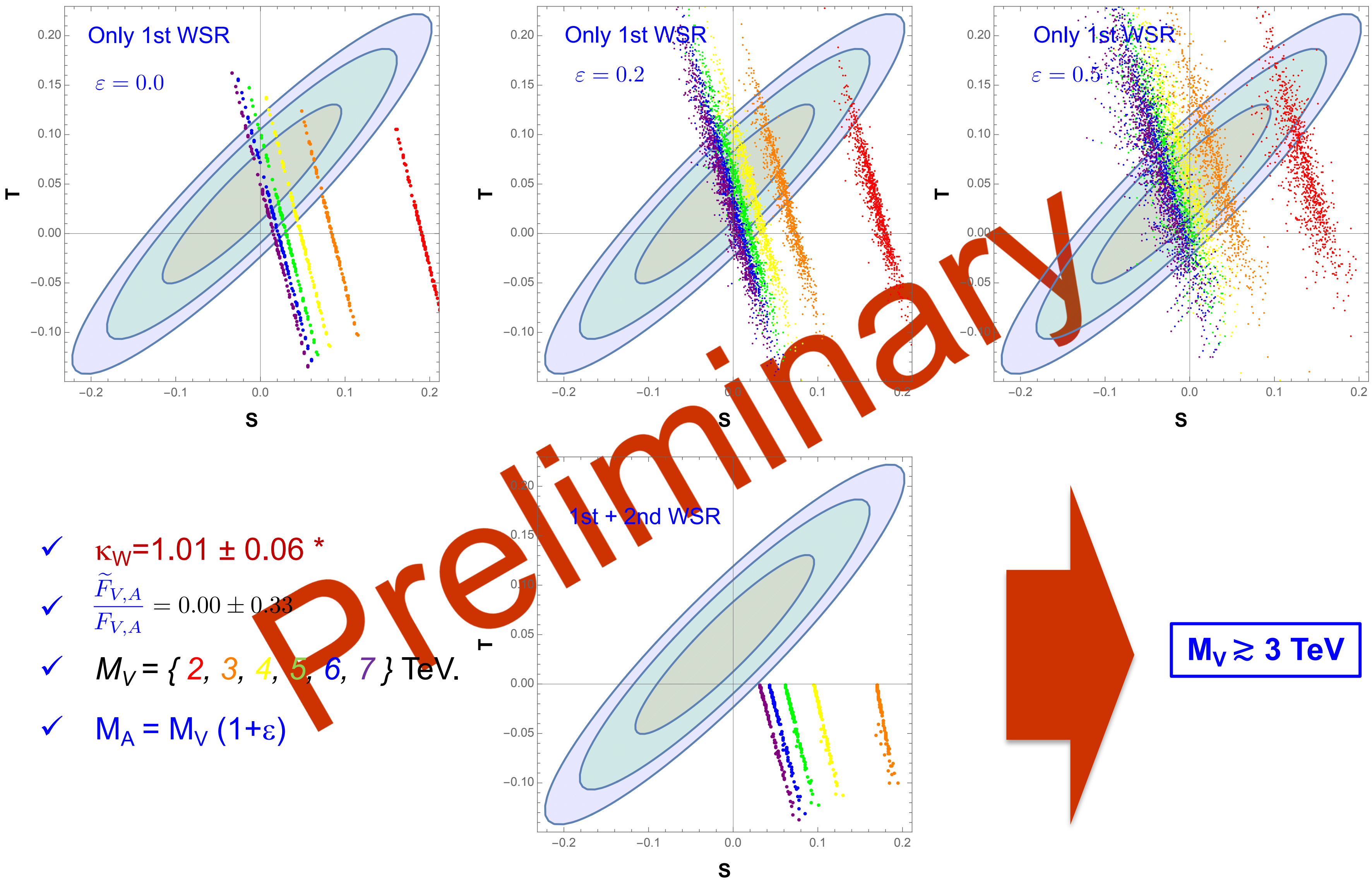

- ✓ κ_W=1.01 ± 0.06 *
- ✓ $\frac{\widetilde{F}_{V,A}}{F_{V,A}} = 0.00 \pm 0.33$
- ✓ M_V = { 2, 3, 4, 5, 6, 7 } TeV.
- ✓ $M_A = M_V\,(1+\varepsilon)$

$M_V \gtrsim 3$ TeV

* de Blas, Eberhardt and Krause '18

4. Conclusions

- ✓ Up to now all searches for New Physics have given negative results: Higgs couplings compatible with the SM and no new states. Therefore we can use EFTs because we have a mass gap.

- ✓ As a consequence of the mass gap, bottom-up EFTs are appropriate to search for BSM. Depending on the nature of the EWSB we have two possibilities:

  - ✓ Decoupling (linear) EFT: SMEFT
    - ✓ SM-Higgs and weakly coupled
    - ✓ Expansion in canonical dimensions

  - ✓ Non-decoupling (non-linear) EFT: EWET (HEFT or EWChL)
    - ✓ Non-SM Higgs and strongly coupled
    - ✓ Expansion in loops or chiral dimensions

- ✓ Phenomenology: S and T at NLO

  - ✓ Short-distance constraints: WSRs and well-behaved form factors at high energies.

  - ✓ Assumptions: lightest two-particle absorptive cuts, $M_A \gtrsim M_V$ and $\widetilde{F}^2_{V,A} < F^2_{V,A}$.

  - ✓ Results in terms of only M_V, M_A, κ_W and $\frac{\widetilde{F}_{V,A}}{F_{V,A}}$.

Room for these BSM scenarios and $M_V \gtrsim 3$ TeV.

Why?
How?
What?