Oblique S and T parameters at one-loop and heavy resonances

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CPAN
Ingenio 2010

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

4) Phenomenology

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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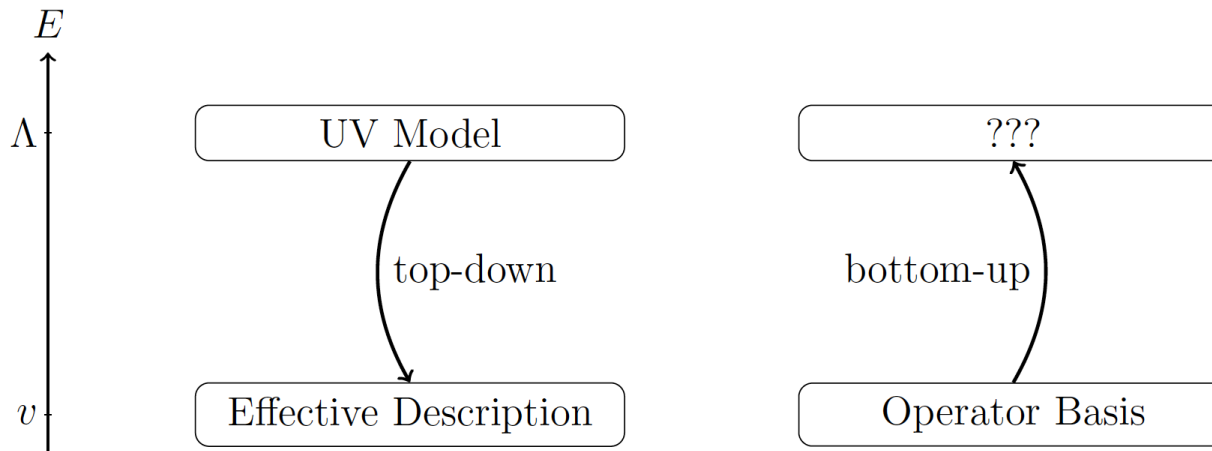

Diagram by C. Krause [PhD thesis, 2016]

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

  - 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)
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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$SU(2)_R$➡️$SU(2)_{L+R}$.

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

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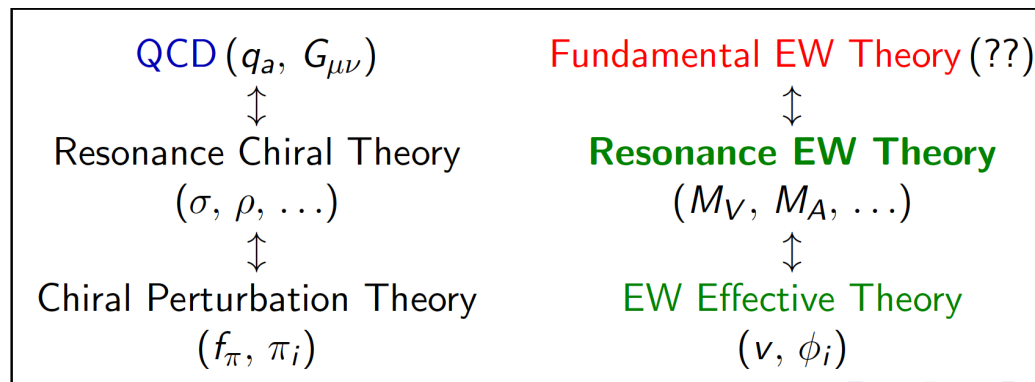$$(f_\pi,\,\pi_i) \qquad\qquad\qquad (v,\,\phi_i)$$

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) + BSM resonances (V,A). The inclusion of fermions ψ is the next step in the project.

✓ *Chiral* power counting*

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

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

Finite pieces from loops
(amplitude dependent)

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

**LO
(tree)**

**NLO
(tree)**

suppression

~1/M² + ...

(heavier states)

NLO (1-loop)

**Typical loop
suppression**

~ ⁄(16π²v²)

(non-linearity)

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

* Weinberg '79
* Appelquist and Bernand '80
* Longhitano '80 '81
* Manohar, and Georgi '84
* Gasser and Leutwyler '84 '85
* Hirn and Stern '05
* Alonso et al. '12
* Buchalla, Catá and Krause '13
* Brivio et al. '13
* Delgado et al. '14
* Pich, IR, Santos and Sanz-Cillero '16 '17
* Krause, Pich, IR, Santos and Sanz-Cillero '19

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LO (tree)

NLO (tree)

NLO (1-loop)

Typical tree suppression ~1/M² +... (heavier states)

Typical loop suppression ~ ⁄/(16π²v²) (non-linearity)

Typical order-by-order renormalization

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

* Weinberg '79
* Appelquist and Bernand '80   * Hirn and Stern '05
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* Gasser and Leutwyler '84 '85   * Brivio et al. '13   * Krause, Pich, IR, Santos and Sanz-Cillero '19

✓ The Lagrangian reads:

$$\Delta\mathcal{L}_{\mathrm{RT}} = \quad \frac{v^2}{4}\left(1 + \frac{2\kappa_W}{v}h\right)\langle\, u_\mu u^\mu\,\rangle_2$$

$$+\,\langle\, V^1_{3\,\mu\nu}\left(\frac{F_V}{2\sqrt{2}}f^{\mu\nu}_+ + \frac{iG_V}{2\sqrt{2}}[u^\mu, u^\nu] + \frac{\widetilde{F}_V}{2\sqrt{2}}f^{\mu\nu}_- + \frac{\widetilde{\lambda}^{hV}_1}{\sqrt{2}}\left[(\partial^\mu h)u^\nu - (\partial^\nu h)u^\mu\right]\right)\,\rangle_2$$

$$+\,\langle\, A^1_{3\,\mu\nu}\left(\frac{F_A}{2\sqrt{2}}f^{\mu\nu}_- + \frac{\lambda^{hA}_1}{\sqrt{2}}\left[(\partial^\mu h)u^\nu - (\partial^\nu h)u^\mu\right] + \frac{\widetilde{F}_A}{2\sqrt{2}}f^{\mu\nu}_+ + \frac{i\widetilde{G}_A}{2\sqrt{2}}[u^\mu, u^\nu]\right)\,\rangle_2\,.$$

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✓ Including resonance masses, we have 10 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 $\left(G_V, \widetilde{G}_A, \lambda^{hA}_1, \widetilde{\lambda}^{hV}_1\right)$ in terms of the remaining parameters:

$$\frac{G_V}{F_A} = -\frac{\widetilde{G}_A}{\widetilde{F}_V} = \frac{\lambda^{hA}_1 v}{\kappa_W F_V} = -\frac{\widetilde{\lambda}^{hV}_1 v}{\kappa_W \widetilde{F}_A} = \frac{v^2}{F_V F_A - \widetilde{F}_V \widetilde{F}_A}$$

   ✓ 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)

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

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

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

✓ T parameter*: custodial symmetry breaking

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

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

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

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

    ✓ $\rho_S(t)$ and $\rho_T(t)$ are the spectral functions of the $W^3 B$ 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 ($\phi\phi$, $h\phi$) and in general we take as working assumptions $M_A > M_V$ and $\widetilde{F}^2_{V,A} < F^2_{V,A}$.

- ✓ LO result ($T_{\text{LO}}=0$):

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

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

- ✓ NLO result including 1st and 2nd WSR:

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

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

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

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

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

$$\Delta T_{\text{NLO}}^{\text{P-odd}} = \frac{3}{16\pi\cos^2\theta_W}\left[2\kappa_W^2\frac{\widetilde{F}_A}{F_A} - 2\frac{\widetilde{F}_V}{F_V} + 2\left(\frac{\widetilde{F}_V}{F_V}M_V^2 - \kappa_W^2 M_A^2\frac{\widetilde{F}_A}{F_A}\right)\frac{\log\frac{M_A^2}{M_V^2}}{M_A^2-M_V^2}\right.$$
$$+ 3\left(\left(\frac{\widetilde{F}_V^2}{F_V^2}-\kappa_W^2\frac{\widetilde{F}_A^2}{F_A^2}\right)(M_A^2+M_V^2) + 2\frac{\widetilde{F}_V\widetilde{F}_A}{F_V F_A}(M_V^2-\kappa_W^2 M_A^2)\right)\frac{\log\frac{M_A^2}{M_V^2}}{M_A^2-M_V^2}$$
$$\left.+ 6\left(\kappa_W^2\frac{\widetilde{F}_A^2}{F_A^2} - \frac{\widetilde{F}_V^2}{F_V^2} - (1-\kappa_W^2)\frac{\widetilde{F}_V\widetilde{F}_A}{F_V F_A}\right)\right] + \mathcal{O}\left(\frac{\widetilde{F}_{V,A}^3}{F_{V,A}^3}\right)$$

$\Delta S_{\text{NLO}}^{\text{P-even}}$ and $\Delta T_{\text{NLO}}^{\text{P-even}}$ correspond to Pich, IR and Sanz-Cillero '13 '14
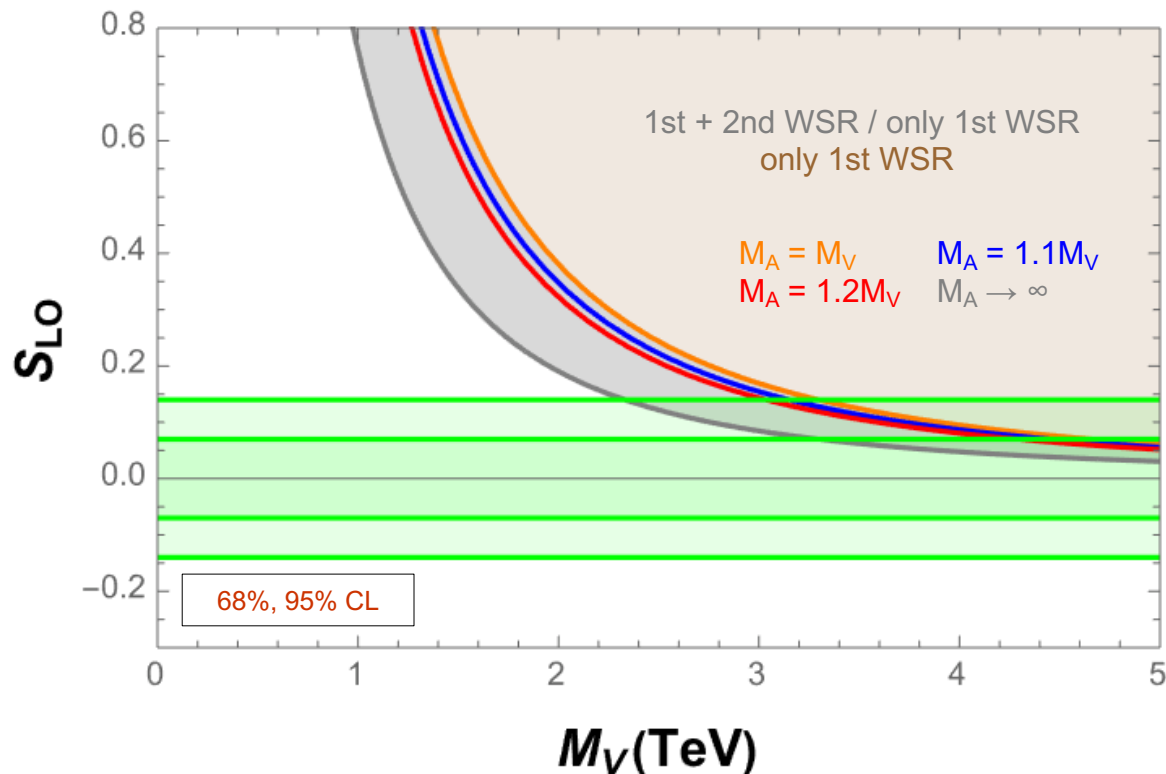
Expansion in $\frac{\widetilde{F}_{V,A}}{F_{V,A}}$.

4. Phenomenology

S = 0.00 ± 0.07 *
T = 0.05 ± 0.06 *

✓ Oblique electroweak observables** (S and T).

✓ Short-distance constraints.

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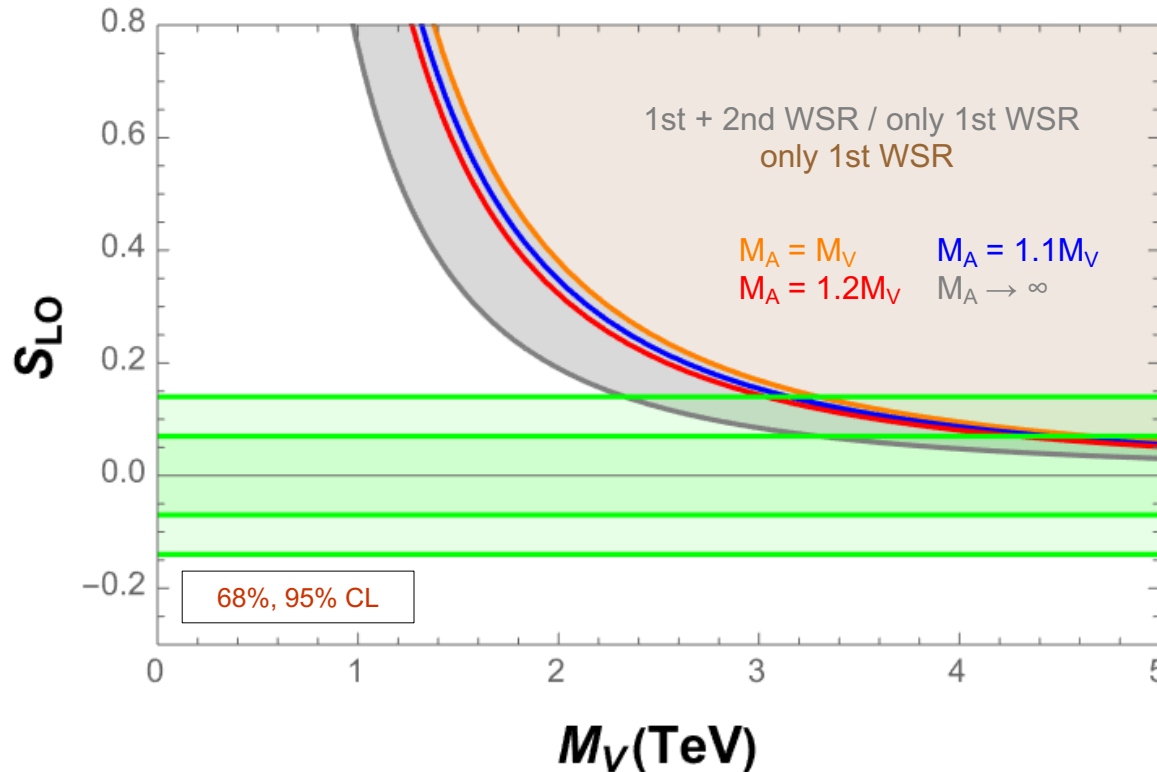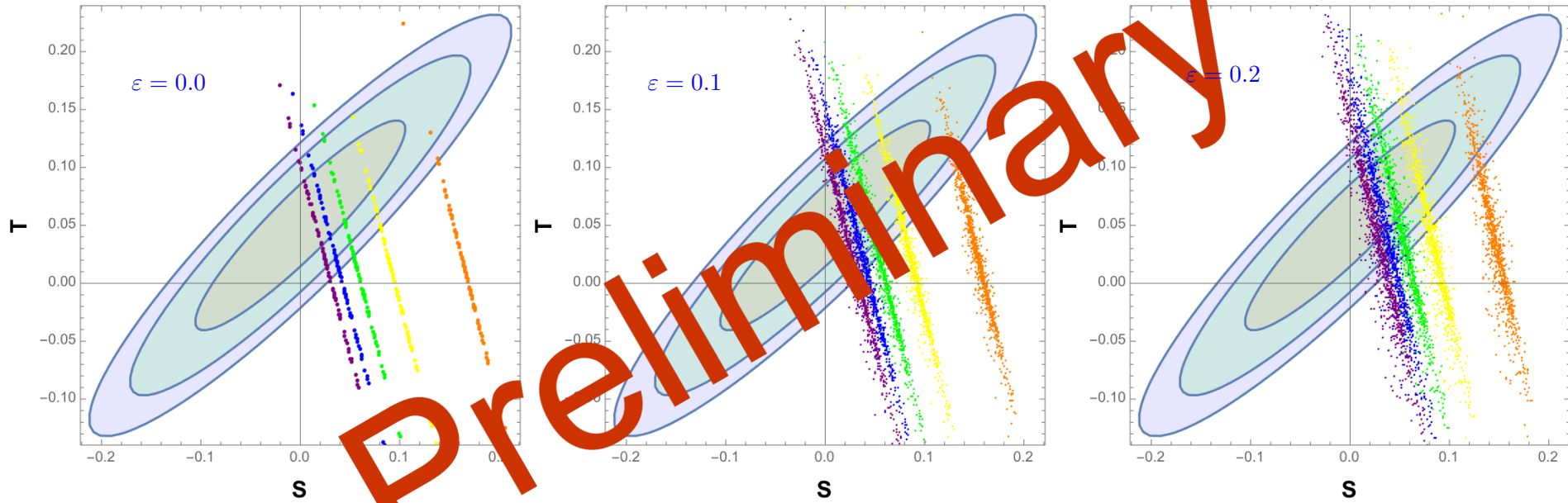
i) LO results

* PDG '22
** Peskin and Takeuchi '92

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i) LO results

$M_V \gtrsim 2$ TeV

* PDG '22
** Peskin and Takeuchi '92

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ii) NLO results

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

- ✓ 1st and 2nd WSR

- ✓ $\kappa_W = 1.01 \pm 0.06$ *

- ✓ $\dfrac{\widetilde{F}_{V,A}}{F_{V,A}} = 0.00 \pm 0.33$

- ✓ $M_V = \{\ 2,\ 3,\ 4,\ 5,\ 6,\ 7\ \}$ TeV.

- ✓ $M_A = M_V\,(1+\varepsilon)$

* de Blas, Eberhardt and Krause '18

ii) NLO results

Results in terms of only M_V, M_A, κ_W and $\dfrac{\widetilde{F}_{V,A}}{F_{V,A}}$
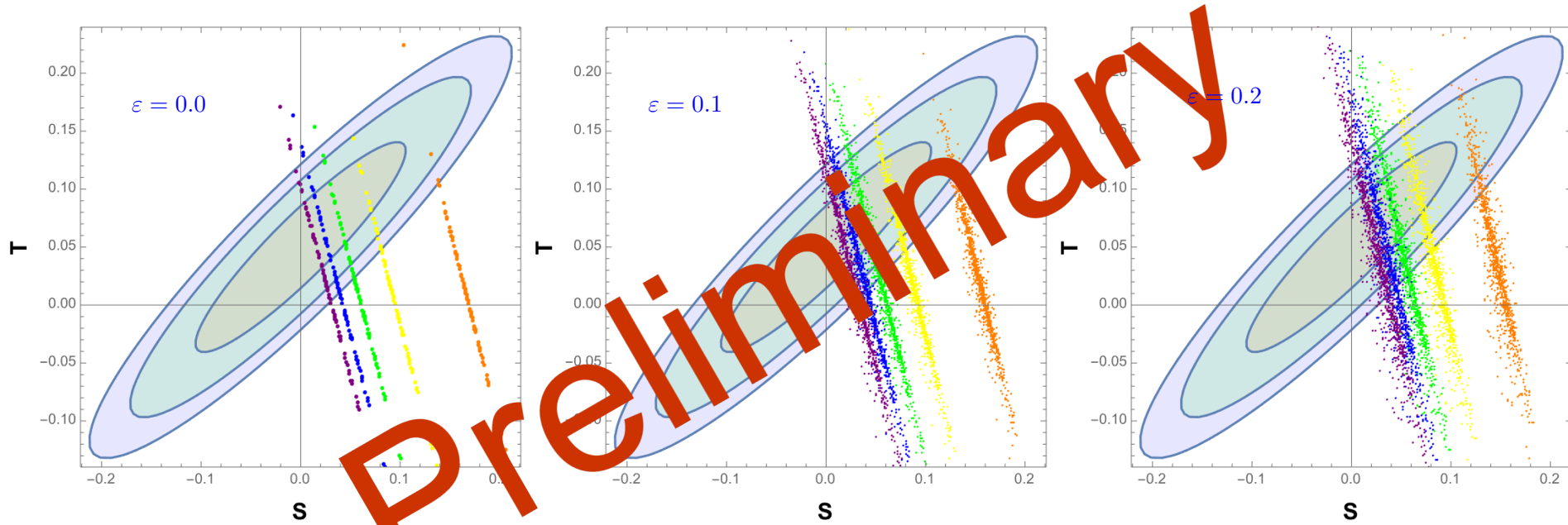
- ✓ 1st and 2nd WSR
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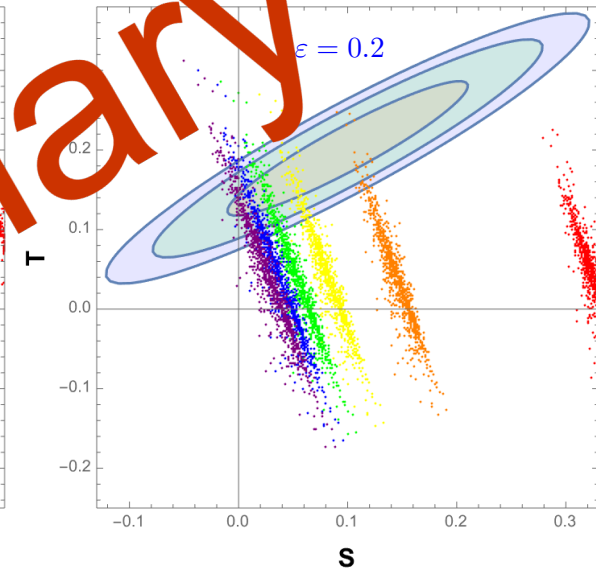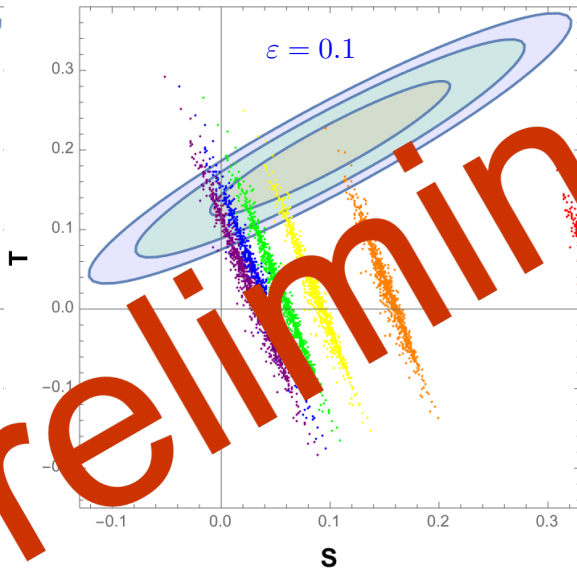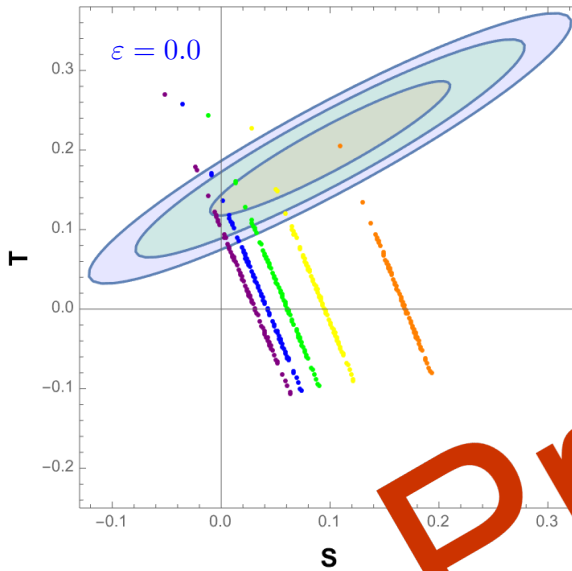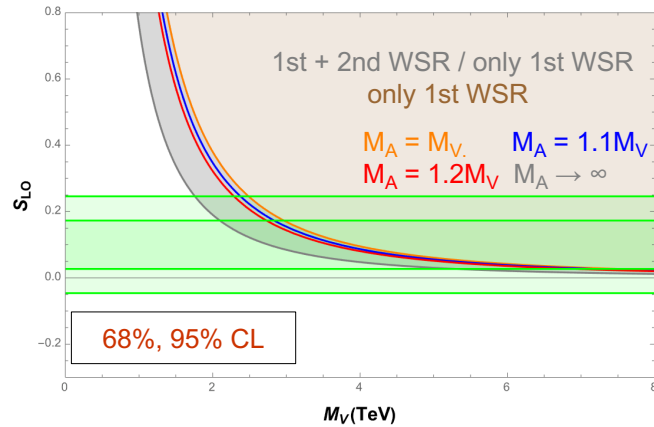- ✓ $M_V = \{\ 2,\ 3,\ 4,\ 5,\ 6,\ 7\ \}$ TeV.
- ✓ $M_A = M_V (1+\varepsilon)$

$M_V \gtrsim 3$ TeV

* de Blas, Eberhardt and Krause '18

What if we consider the new value of M_W from CDF*?

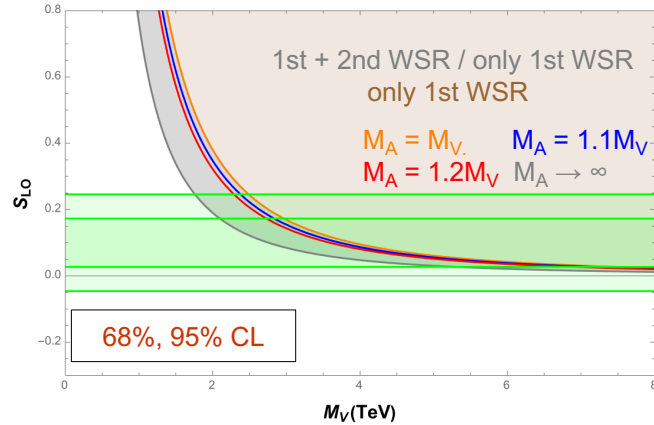$$S = 0.100 \pm 0.073 \text{ **}$$
$$T = 0.202 \pm 0.056 \text{ **}$$

Figure top: plot of S_{LO} vs M_V(TeV) with labels:
- 1st + 2nd WSR / only 1st WSR
- only 1st WSR
- $M_A = M_V$ (orange), $M_A = 1.1 M_V$ (blue)
- $M_A = 1.2 M_V$ (red), $M_A \to \infty$ (gray)
- 68%, 95% CL

Bottom figures: T vs S scatter plots for $\varepsilon = 0.0$, $\varepsilon = 0.1$, $\varepsilon = 0.2$

$M_V = \{ 2, 3, 4, 5, 6, 7 \}$ TeV

$M_A = M_V (1 + \varepsilon)$

* CDF '22
** de Blas et al. '22

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$S = 0.100 \pm 0.073$ **
$T = 0.202 \pm 0.056$ **

1st + 2nd WSR / only 1st WSR
only 1st WSR

$M_A = M_V$ $M_A = 1.1 M_V$
$M_A = 1.2 M_V$ $M_A \to \infty$

68%, 95% CL

Similar conclusions,
but high M_V is disfavored:
$3 \lesssim M_V \lesssim 7$ TeV.

$\varepsilon = 0.0$ $\varepsilon = 0.1$ $\varepsilon = 0.2$

$M_V = \{\, 2,\ 3,\ 4,\ 5,\ 6,\ 7\,\}$ TeV

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** de Blas et al. '22

Oblique S and T parameters at one-loop and heavy resonances, I. Rosell
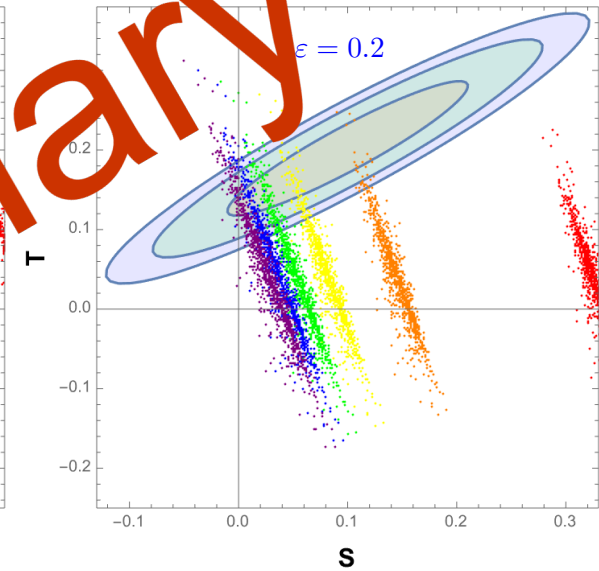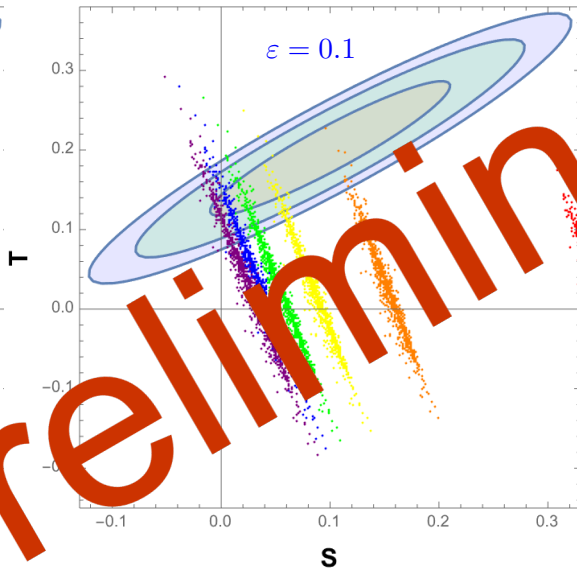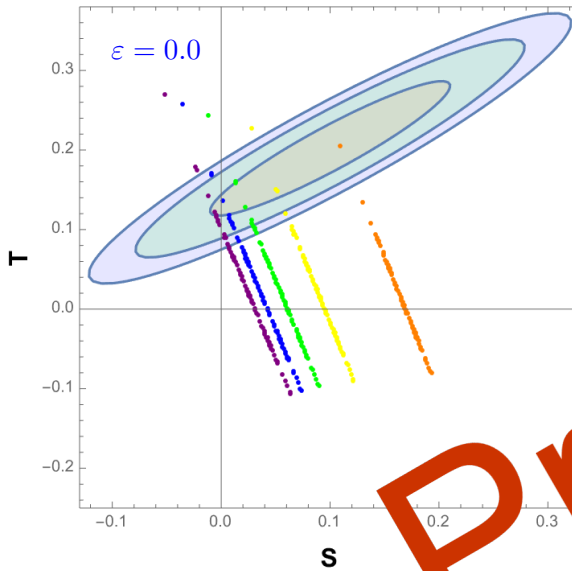
4. Conclusions

✓ 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 $\widetilde{F}_{V,A}^2 < F_{V,A}^2$.

  ✓ Results in terms of only M_V, M_A, κ_W and $\dfrac{\widetilde{F}_{V,A}}{F_{V,A}}$.
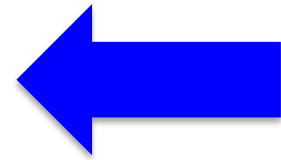
Room for these BSM scenarios and $M_V \gtrsim$ 3 TeV.