



CEU

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

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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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**Bottom-up  
approach**

# 1. Motivation

- The **Standard Model** (SM) provides an extremely successful 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.

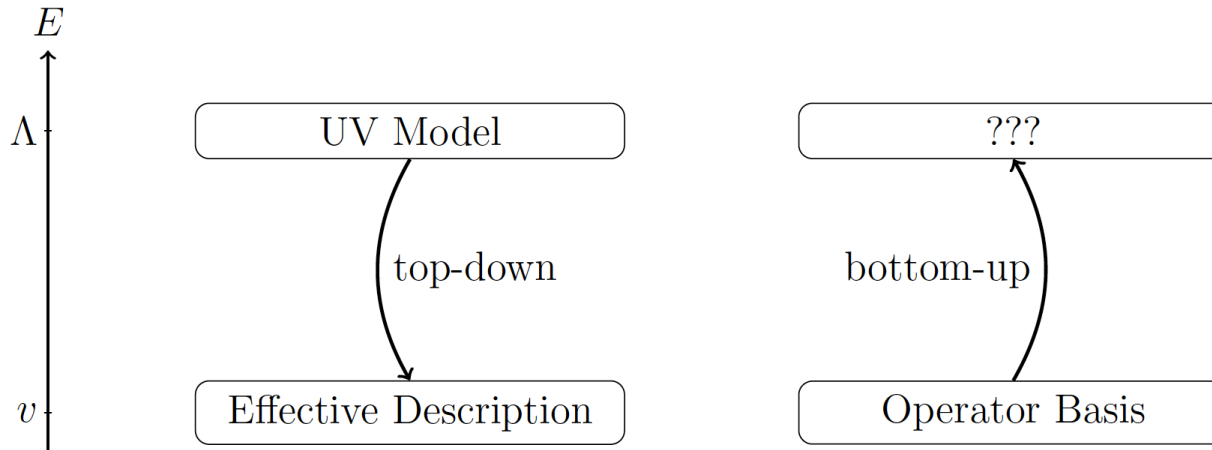


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Higgs Physics

Effective Field Theories



\* [CMS](#) and [ATLAS](#) Collaborations.

[Diagram by C. Krause \[PhD thesis, 2016\]](#)

- 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)
    - Expansion in **loops or chiral dimensions**
    - Some **composite Higgs models** can be described within the EWET.

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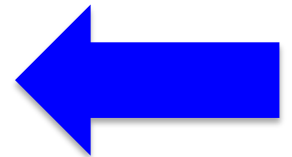
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See also  
Domènec's talk

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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 constraints** 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**?

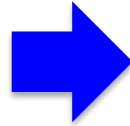
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## Similarities to Chiral Symmetry Breaking in QCD

- i) **Custodial symmetry**: The Lagrangian is approximately invariant under global  $SU(2)_L \times SU(2)_R$  transformations. **Electroweak Symmetry Breaking** (EWSB) turns to be  $SU(2)_L \times SU(2)_R \rightarrow SU(2)_{L+R}$ .
- ii) Similar to the **Chiral Symmetry Breaking** (ChSB) occurring in **QCD**, *i.e.*, similar to the “pion” Lagrangian of **Chiral Perturbation Theory** (ChPT)<sup>\*</sup>, by replacing  $f_\pi$  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](#)

<sup>^</sup>[Dobado, Espriu and Herrero '91](#)

<sup>^</sup>[Espriu and Herrero '92](#)

<sup>^</sup>[Herrero and Ruiz-Morales '94](#)

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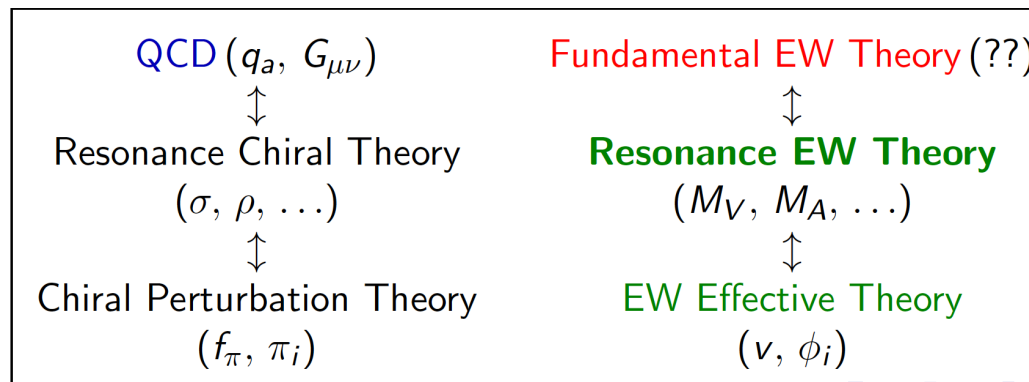


Diagram by J. Santos [VIII CPAN days, 2016]

## 2. The effective resonance Lagrangian

✓ Custodial symmetry

✓ Degrees of freedom: bosons  $\chi$  (EW goldstones, gauge bosons, h) + BSM resonances (V,A). The inclusion of fermions  $\psi$  is the next step in the project.

✓ Chiral power counting\*

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

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

Finite pieces from loops  
(amplitude dependent)

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

<b>LO</b>	<b>NLO</b>	<b>NLO (1-loop)</b>
<b>(tree)</b>	<b>(tree)</b>	<b>Typical loop</b>
	<b>suppression</b>	<b>suppression</b>
	$\sim 1/M^2 + \dots$	$\sim 1/(16\pi^2 v^2)$
	<b>(heavier states)</b>	<b>(non-linearity)</b>

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

\* Weinberg '79

\* Appelquist and Bernard '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)  
suppression  
 $\sim 1/M^2 + \dots$   
(heavy states)
(1-loop)  
Typical loop  
suppression  
 $\sim 1/(16\pi^2 v^2)$   
(non-linearity)

Typical order-by-order renormalization

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

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\* Krause, Pich, IR, Santos and Sanz-Cillero '19



✓ The Lagrangian reads:

$$\begin{aligned}
\Delta\mathcal{L}_{\text{RT}} = & \frac{v^2}{4} \left( 1 + \frac{2\kappa_W}{v} h \right) \langle u_\mu u^\mu \rangle_2 \\
& + \langle V_{3\mu\nu}^1 \left( \frac{F_V}{2\sqrt{2}} f_+^{\mu\nu} + \frac{iG_V}{2\sqrt{2}} [u^\mu, u^\nu] + \frac{\tilde{F}_V}{2\sqrt{2}} f_-^{\mu\nu} + \frac{\tilde{\lambda}_1^{hV}}{\sqrt{2}} [(\partial^\mu h)u^\nu - (\partial^\nu h)u^\mu] \right) \rangle_2 \\
& + \langle A_{3\mu\nu}^1 \left( \frac{F_A}{2\sqrt{2}} f_-^{\mu\nu} + \frac{\lambda_1^{hA}}{\sqrt{2}} [(\partial^\mu h)u^\nu - (\partial^\nu h)u^\mu] + \frac{\tilde{F}_A}{2\sqrt{2}} f_+^{\mu\nu} + \frac{i\tilde{G}_A}{2\sqrt{2}} [u^\mu, u^\nu] \right) \rangle_2 .
\end{aligned}$$

- ✓ The **Lagrangian** reads:

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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  $(G_V, \tilde{G}_A, \lambda_1^{hA}, \tilde{\lambda}_1^{hV})$  in terms of the remaining parameters:

$$\frac{G_V}{F_A} = -\frac{\tilde{G}_A}{\tilde{F}_V} = \frac{\lambda_1^{hA} v}{\kappa_W F_V} = -\frac{\tilde{\lambda}_1^{hV} v}{\kappa_W \tilde{F}_A} = \frac{v^2}{F_V F_A - \tilde{F}_V \tilde{F}_A}$$

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

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

### 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  $Q^2=0$ .

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

- ✓ **T parameter\***: custodial symmetry breaking

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

- ✓ 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  $W^3B$  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** ( $\phi\phi$ ,  $h\phi$ ) and in general we take as working assumptions  $M_A > M_V$  and  $\tilde{F}_{V,A}^2 < F_{V,A}^2$ .

✓ **LO** result ( $T_{LO}=0$ ):

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

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

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

$$\begin{aligned}
 S_{NLO} &= 4\pi v^2 \left( \frac{1}{M_V^2} + \frac{1}{M_A^2} \right) + \Delta S_{NLO}^{P\text{-even}} + \Delta S_{NLO}^{P\text{-odd}} \\
 \Delta S_{NLO}^{P\text{-even}} &= \frac{1}{12\pi} \left[ (1 - \kappa_W^2) \left( \log \frac{M_V^2}{m_h^2} - \frac{11}{6} \right) + \kappa_W^2 \left( \frac{M_A^2}{M_V^2} - 1 \right) \log \frac{M_A^2}{M_V^2} \right] \\
 \Delta S_{NLO}^{P\text{-odd}} &= \frac{1}{12\pi} \left( \frac{\tilde{F}_V^2}{F_V^2} + 2\kappa_W^2 \frac{\tilde{F}_V \tilde{F}_A}{F_V F_A} - \kappa_W^2 \frac{\tilde{F}_A^2}{F_A^2} \right) \left( \frac{M_A^2}{M_V^2} - 1 \right) \log \frac{M_A^2}{M_V^2} + \mathcal{O}\left(\frac{\tilde{F}_{V,A}^4}{F_{V,A}^4}\right) \\
 T_{NLO} &= \Delta T_{NLO}^{P\text{-even}} + \Delta T_{NLO}^{P\text{-odd}} \\
 \Delta T_{NLO}^{P\text{-even}} &= \frac{3}{16\pi \cos^2 \theta_W} \left[ (1 - \kappa_W^2) \left( 1 - \log \frac{M_V^2}{m_h^2} \right) + \kappa_W^2 \log \frac{M_A^2}{M_V^2} \right] \\
 \Delta T_{NLO}^{P\text{-odd}} &= \frac{3}{16\pi \cos^2 \theta_W} \left\{ 2\kappa_W^2 \frac{\tilde{F}_A}{F_A} - 2\frac{\tilde{F}_V}{F_V} + \frac{M_V^2}{M_A^2 - M_V^2} \log \frac{M_A^2}{M_V^2} \left( 2\frac{\tilde{F}_V}{F_V} - 2\kappa_W^2 \frac{M_A^2}{M_V^2} \frac{\tilde{F}_A}{F_A} \right) \right. \\
 &\quad \left. + \frac{M_V^2}{M_A^2 - M_V^2} \log \frac{M_A^2}{M_V^2} \left[ \left( \kappa_W^2 \frac{\tilde{F}_A^2}{F_A^2} - \frac{\tilde{F}_V^2}{F_V^2} \right) \left( 1 + \frac{M_A^2}{M_V^2} \right) + 2\frac{\tilde{F}_V \tilde{F}_A}{F_V F_A} \left( \kappa_W^2 \frac{M_A^2}{M_V^2} - 1 \right) \right] \right. \\
 &\quad \left. + 2 \left( \frac{\tilde{F}_V^2}{F_V^2} - \kappa_W^2 \frac{\tilde{F}_A^2}{F_A^2} + (1 - \kappa_W^2) \frac{\tilde{F}_V \tilde{F}_A}{F_V F_A} \right) \right\} + \mathcal{O}\left(\frac{\tilde{F}_{V,A}^3}{F_{V,A}^3}\right)
 \end{aligned}$$

$\Delta S_{NLO}^{P\text{-even}}$  and  $\Delta T_{NLO}^{P\text{-even}}$  correspond to Pich, IR and Sanz-Cillero '13 '14

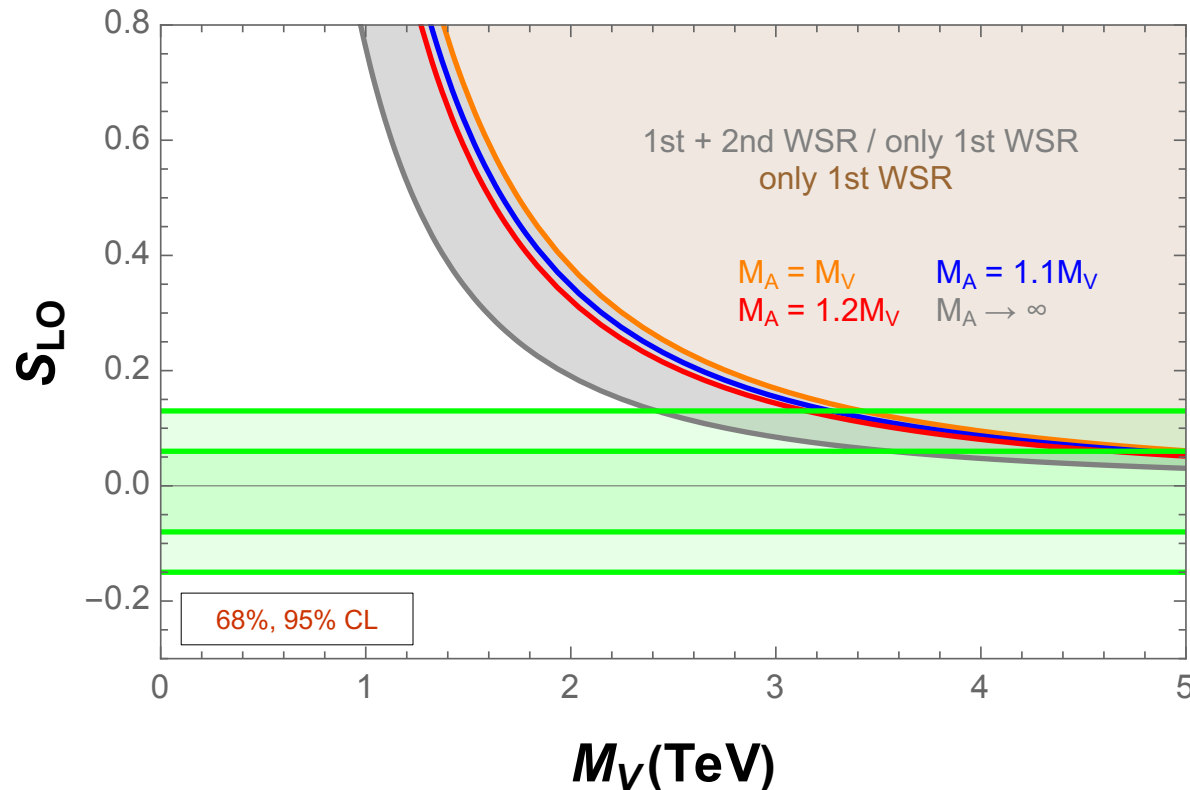
Expansion in  $\frac{\tilde{F}_{V,A}}{F_{V,A}}$ .

## 4. Phenomenology

$$S = -0.01 \pm 0.07^*$$
$$T = 0.04 \pm 0.06^*$$

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

### i) LO results



\* PDG '22

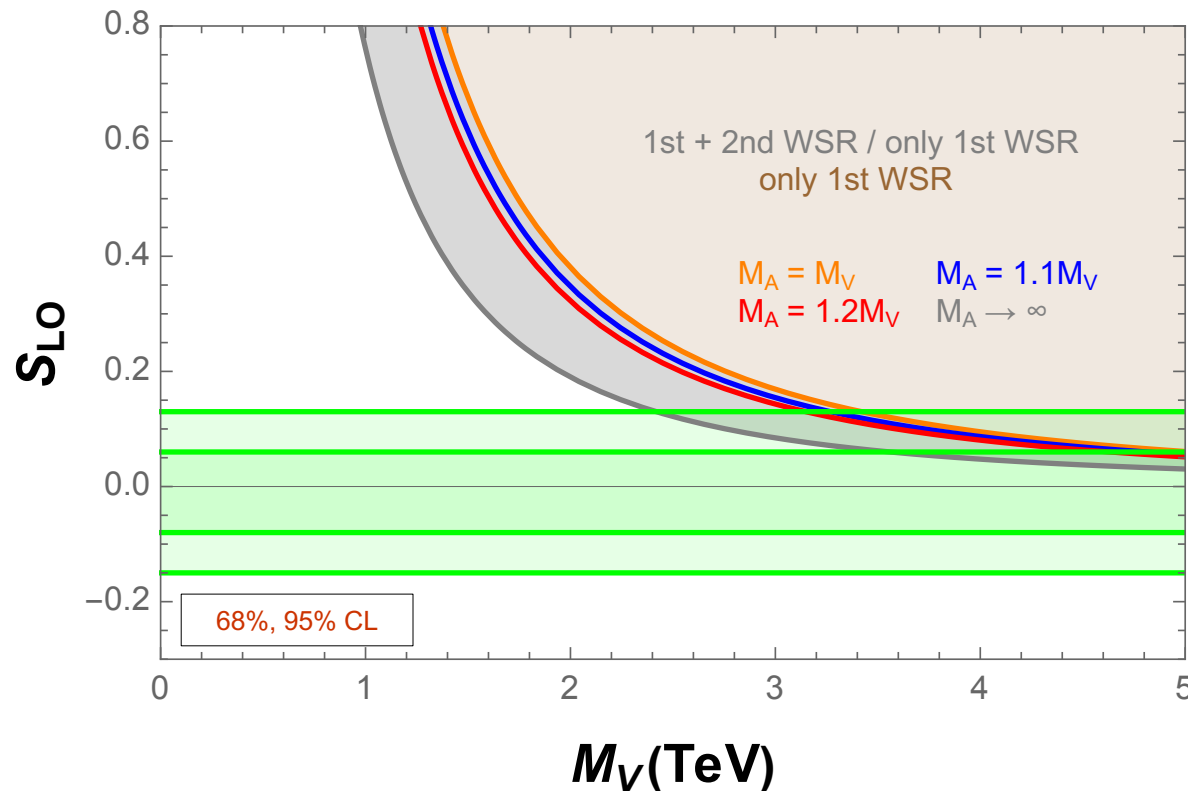
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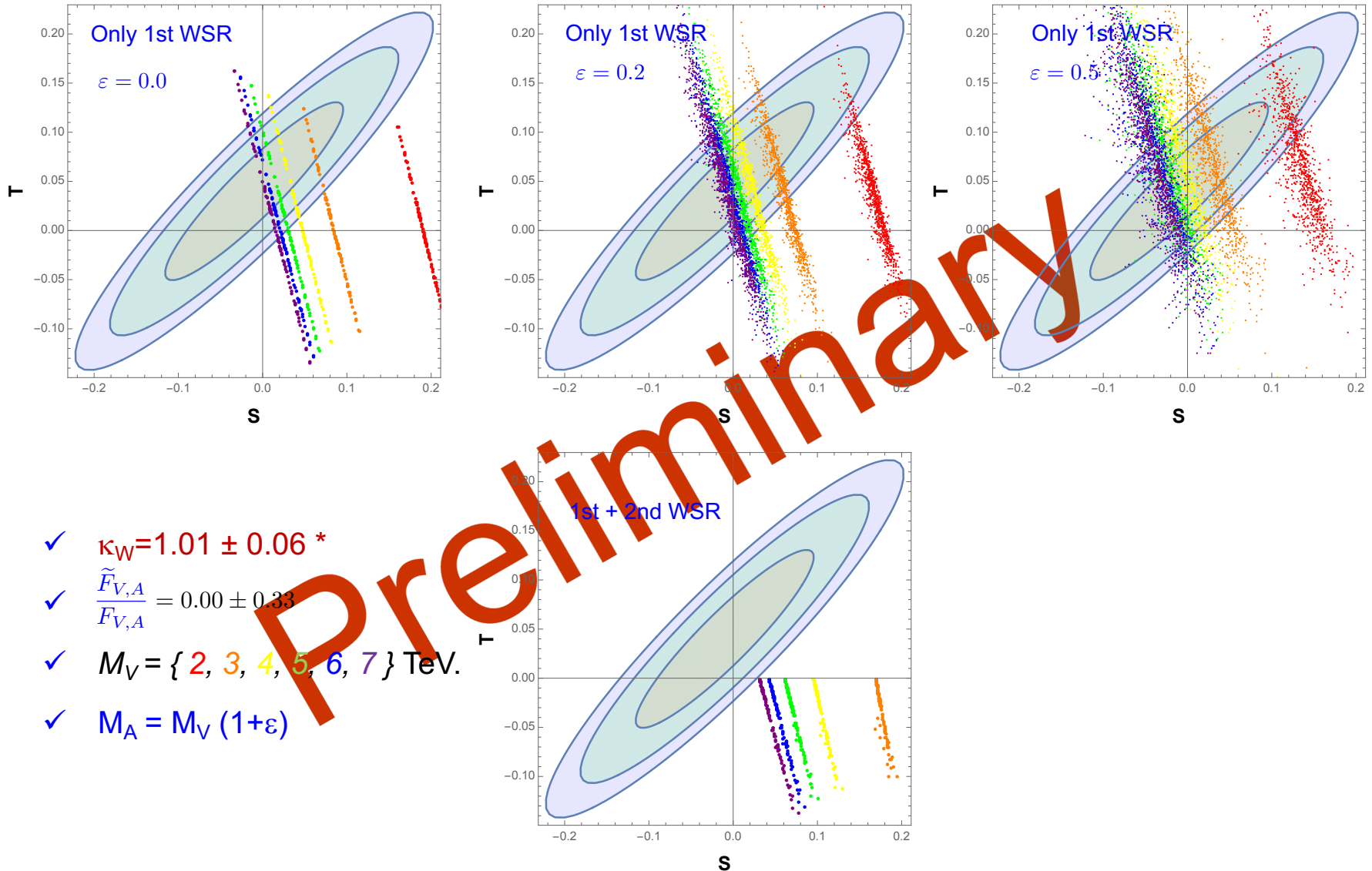
$$M_V \gtrsim 2 \text{ TeV}$$

\* PDG '22

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## ii) NLO results

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

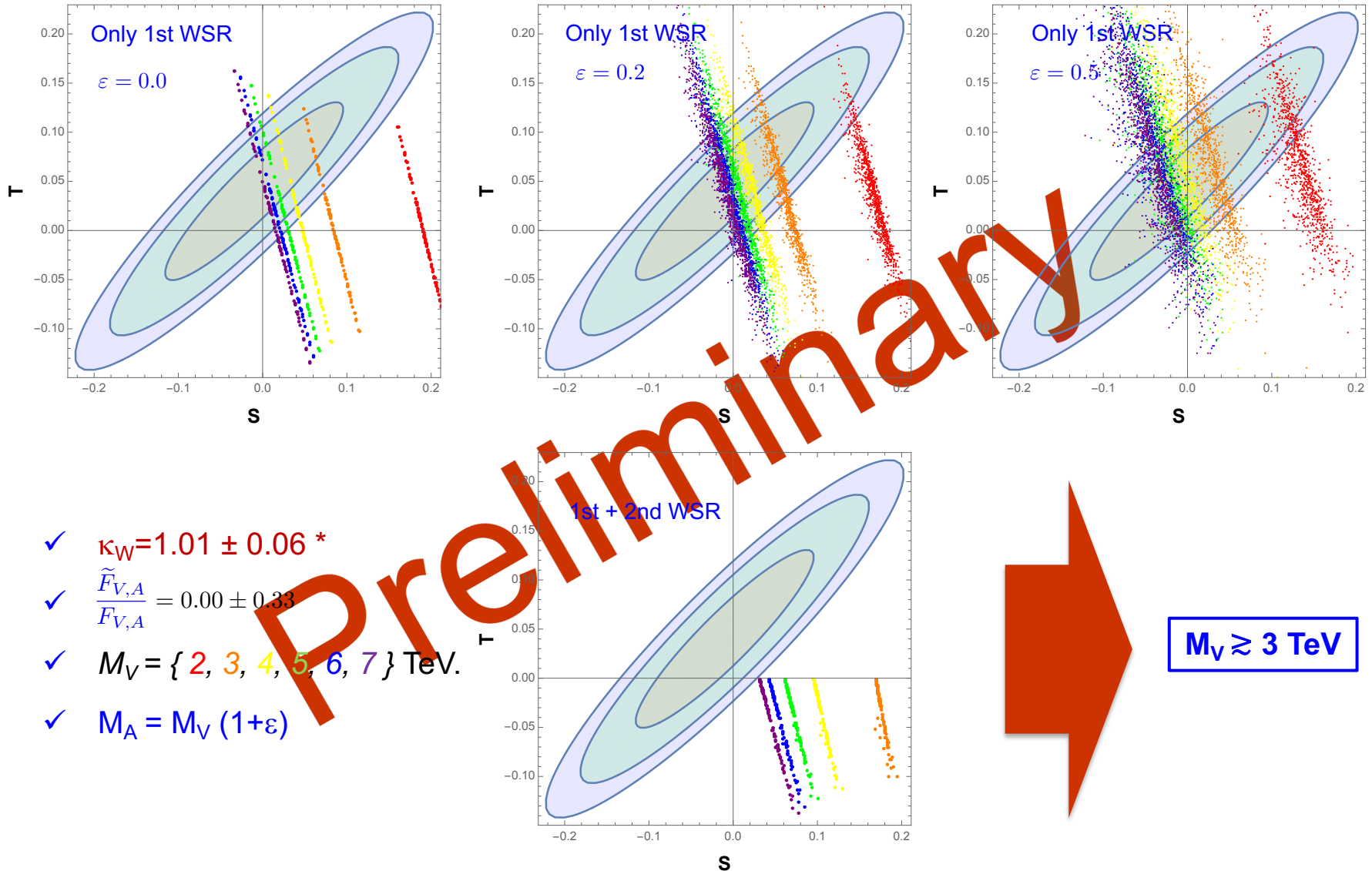


- ✓  $\kappa_W = 1.01 \pm 0.06$  \*
- ✓  $\frac{\tilde{F}_{V,A}}{F_{V,A}} = 0.00 \pm 0.33$
- ✓  $M_V = \{2, 3, 4, 5, 6, 7\}$  TeV.
- ✓  $M_A = M_V (1 + \varepsilon)$

\* de Blas, Eberhardt and Krause '18

## ii) NLO results

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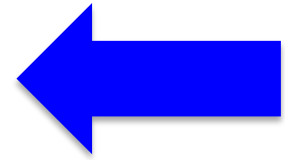


\* de Blas, Eberhardt and Krause '18



## 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  $\tilde{F}_{V,A}^2 < F_{V,A}^2$ .
  - ✓ Results in terms of only  $M_V$ ,  $M_A$ ,  $\kappa_W$  and  $\frac{\tilde{F}_{V,A}}{F_{V,A}}$ .



**Room for these BSM scenarios and  $M_V \gtrsim 3 \text{ TeV}$ .**