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Viable strongly-coupled scenarios with a light Higgs-like boson

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A. Pich, I. Rosell and JJ SC, PRL 110 (2013) 181801; in preparation.

1.- Oblique parameters **S & T**

2.- **$SU(2)_L \otimes SU(2)_R$ effective Lagrangian** w/ Higgs + NGB's **+ Resonances**

3.- Π_{30} and Σ_π spectral functions **at LO and NLO**, i.e., up to 1 loop

4.- We demand **a good UV behaviour + Dispersive** calculation for S & T

5.- **Phenomenology** with 2 WSR's or just the 1^{st} WSR

Oblique EWPO's

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

$$\mathcal{L}_{\text{vac-pol}} = -\frac{1}{2} W^3_\mu \Pi^{\mu\nu}_{33}(q^2) W^3_\nu - \frac{1}{2} B_\mu \Pi^{\mu\nu}_{00}(q^2) B_\nu - W^3_\mu \Pi^{\mu\nu}_{30}(q^2) B_\nu - W^+_\mu \Pi^{\mu\nu}_{WW}(q^2) W^-_\nu ,$$

with the subtracted definition,

$$\Pi_{30}(q^2) = q^2 \, \widetilde{\Pi}_{30}(q^2) + \frac{g^2 \tan\theta_W}{4} v^2$$

$$\mathbf{e_1} = \frac{\mathbf{1}}{\mathbf{m_W^2}} \Big(\mathbf{\Pi_{33}(0) - \Pi_{WW}(0)} \Big) \stackrel{**}{=} \frac{\mathbf{Z^{(+)}}}{\mathbf{Z^{(0)}}} - \mathbf{1}$$

$$\mathbf{e_3} = \frac{\mathbf{1}}{\tan\theta_\mathbf{W}} \widetilde{\mathbf{\Pi}}_{\mathbf{30}}(\mathbf{0})$$

$$\varepsilon_1^{\rm SM} \approx -\frac{3g'^2}{32\pi^2} \log\frac{M_H}{M_Z} + {\rm const}, \qquad \varepsilon_3^{\rm SM} \approx \frac{g^2}{96\pi^2} \log\frac{M_H}{M_Z} + {\rm const}'$$

$$T = \frac{4\pi}{g'^2 \cos^2\theta_W} (e_1 - e_1^{\rm SM})$$

$$S = \frac{16\pi}{g^2} \left(e_3 - e_3^{\rm SM}\right),$$

We find that

strongly-coupled models **are**

perfectly allowed

* Peskin and Takeuchi '92.

** Barbieri et al.'93

\+ Gfitter
\+ LEP EWWG
\+ Zfitter

$SU(2)_L \otimes SU(2)_R$ / $SU(2)_{L+R}$ Resonance Theory

$$\mathcal{L} = \mathcal{L}_{\rm EW}^{(2)} + \mathcal{L}_{\rm GF} + \mathcal{L}_V + \mathcal{L}_A + \mathcal{L}_{VV}^{\rm kin} + \mathcal{L}_{AA}^{\rm kin} + \ldots$$

w/ field content: $SU(2)_L \otimes SU(2)_R / SU(2)_{L+R}$ EW Goldstones + SM gauge bosons

\+ lightest V and A resonances -triplets- *(antisym. tensor formalism)*

\+ one $SU(2)_L \otimes SU(2)_R$ singlet scalar S_1 with m_{S1}=126 GeV

•Relevant resonance Lagrangian (x), (+), *

$$\mathcal{L} = \left\{ \frac{v^2}{4} + \omega \frac{v}{2} S_1 \right\} \langle u_\mu u^\mu \rangle$$ ← S + π sector

$$+ \frac{F_V}{2\sqrt{2}} \langle V_{\mu\nu} f_+^{\mu\nu} \rangle + \frac{i\, G_V}{2\sqrt{2}} \langle V_{\mu\nu} [u^\mu, u^\nu] \rangle$$ ← V + π sector

$$+ \frac{F_A}{2\sqrt{2}} \langle A_{\mu\nu} f_-^{\mu\nu} \rangle + \sqrt{2} \lambda_1^{SA} \partial_\mu S_1 \langle A^{\mu\nu} u_\nu \rangle$$ ← A+S+π sector

$$\omega = \mathbf{a} = \kappa_{\mathbf{W}} = \kappa_{\mathbf{Z}} = \begin{cases} 1 & \textbf{SM} \\ \sqrt{1 - v^2/f^2} & \textbf{MCHM} \\ v/f & \textbf{Dilaton} \end{cases}$$

We will have 7 resonance parameters:

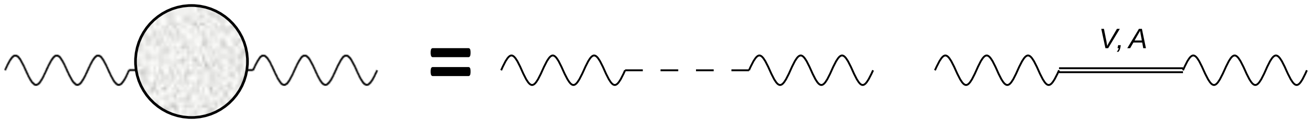
F_V, G_V, F_A, ω, λ_1^{SA}, M_V and M_A

The high-energy constraints will be crucial

(x) Ecker et al. '89
(x) EoM simplifications: Xiao, SC '07
(x) EoM simplifications: Georgi '91
(+) Appelquist '80
(+) Longhitano '81, '81
(+) Dobado,Espriu,Herrero '91
* Pich, Rosell, SC '13

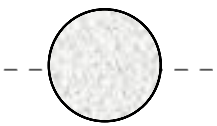
S and T *at LO*

➔ *W³B correlator* * *(transverse in Landau gauge)*



$$\Pi_{30}(s)|_{\rm LO} = \frac{g^2 \tan\theta_W}{4}\, s \left(\frac{v^2}{s} + \frac{F_V^2}{M_V^2 - s} - \frac{F_A^2}{M_A^2 - s} \right)$$

➔ *NGB self-energies* *



= 0

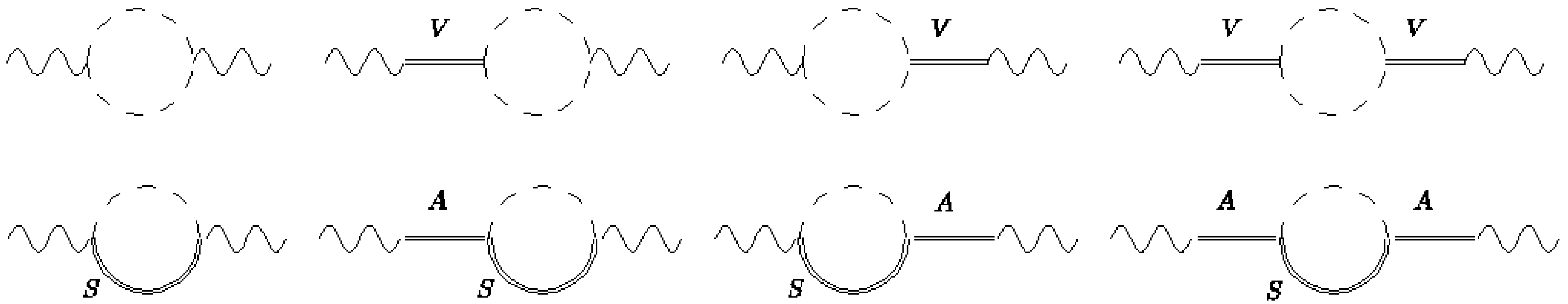
$$\Sigma(s)^{(0)} - \Sigma(s)^{(+)} = 0$$

$$S_{\rm LO} = 4\pi \left(\frac{F_V^2}{M_V^2} - \frac{F_A^2}{M_A^2} \right) , \qquad T_{\rm LO} = 0$$

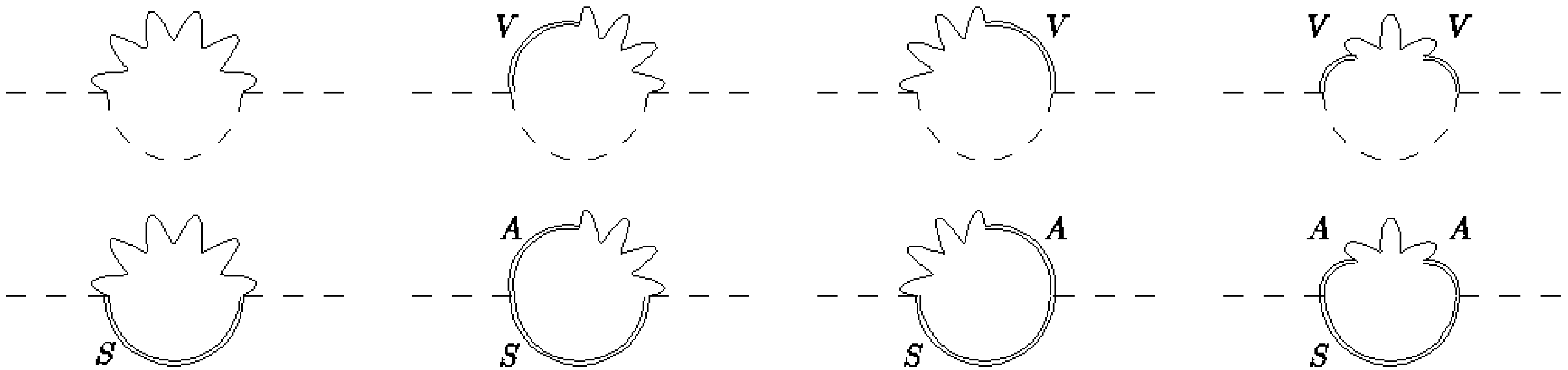
* Peskin and Takeuchi '92.

S and T *at NLO*

➔ *W^3B correlator**



➔ *NGB self-energy **

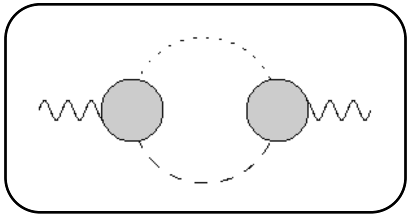


* Barbieri et al.'08
* Cata and Kamenik '10
* Orgogozo, Rychkov '11, '12

High-energy constraints + *Dispersion relations*

➔ *W^3B correlator* ⟶ **S-parameter sum-rule** (+)

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

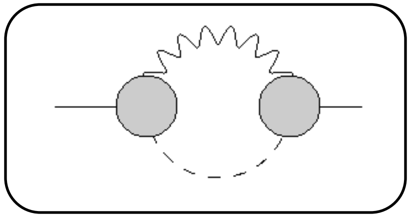


$$\rho_{\bf S}({\bf s}) = \frac{1}{\pi} {\rm Im}\widetilde{\bf \Pi}_{\bf 30}({\bf s}) \quad \begin{cases} \rho_S|_{\pi\pi} = \dfrac{gg'\,\theta(s)}{192\pi}\left(1+\dfrac{F_V G_V}{v^2}\dfrac{s}{M_V^2-s}\right)^2 \overset{\rm VFF+\,WSR}{\longrightarrow} \dfrac{gg'\,\theta(s)}{192\pi}\left(\dfrac{M_V^2}{M_V^2-s}\right)^2 \\ \rho_S|_{S\pi} = -\dfrac{gg'\,\omega^2\,\sigma_{S\pi}^3\theta(s-m_S^2)}{192\pi}\left(1+\dfrac{F_A\lambda_1^{SA}}{\omega w}\dfrac{s}{M_A^2-s}\right)^2 \overset{\rm VFF+\,WSR}{\longrightarrow} -\dfrac{gg'\,\omega^2\,\sigma_{S\pi}^3\theta(s-m_S^2)}{192\pi}\left(\dfrac{M_A^2}{M_A^2-s}\right)^2 \end{cases}$$

➔ *NGB self-energies* ⟶ **Convergent dispersion relation for T** (x)

for the lightest absorptive diagrams with $B\pi$ + BS

$$T = \frac{4}{g'^2 \cos^2\theta_W} \int_0^\infty \frac{dt}{t^2} \left[\rho_T(t) - \rho_T(t)^{\rm SM} \right]$$



*

$$\rho_{\bf T}({\bf s}) = \frac{1}{\pi} {\rm Im}[{\bf \Sigma}({\bf s})^{(0)} - {\bf \Sigma}({\bf s})^{(+)}] \quad \begin{cases} \rho_{\bf T}({\bf s})|_{{\bf B}\pi} \overset{{\bf s}\to\infty}{\longrightarrow} -\dfrac{{\bf 3g'^2 s}}{{\bf 64}\pi^{\bf 2}}\left({\bf 1}-\dfrac{{\bf F_V G_V}}{{\bf v^2}}\right)^{\bf 2} + \mathcal{O}({\bf s^0}) \\ \rho_{\bf T}({\bf s})|_{{\bf BS_1}} \overset{{\bf s}\to\infty}{\longrightarrow} \dfrac{{\bf 3g'^2}\omega^{\bf 2}{\bf s}}{{\bf 64}\pi^{\bf 2}}\left({\bf 1}-\dfrac{{\bf F_A}\lambda_{\bf 1}^{\bf SA}}{\omega{\bf v}}\right)^{\bf 2} + \mathcal{O}({\bf s^0}) \end{cases}$$

+ Peskin ,Takeuchi '92

x Pich,Rosell,SC '13

* Orgogozo,Rychkov '11

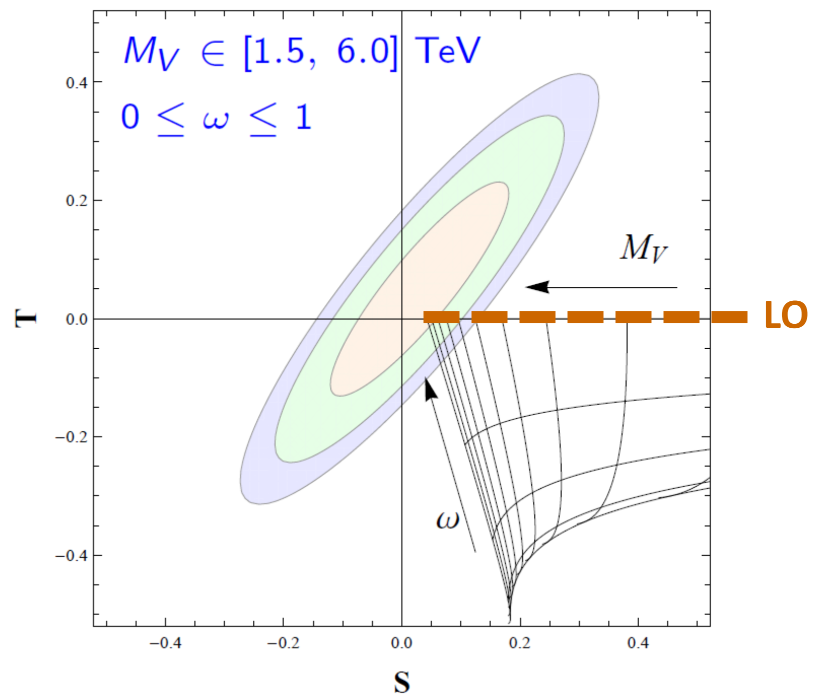
NLO results: 1st and 2nd WSRs in Π_{30}

$$T = \frac{3}{16\pi\cos^2\theta_W}\left[1+\log\frac{m_H^2}{M_V^2} - \omega^2\left(1+\log\frac{m_S^2}{M_A^2}\right)\right]$$

LO

$$S = \boxed{4\pi v^2\left(\frac{1}{M_V^2}+\frac{1}{M_A^2}\right)} + \frac{1}{12\pi}\left[\log\frac{M_V^2}{m_H^2} - \frac{11}{6} + \frac{M_V^2}{M_A^2}\log\frac{M_A^2}{M_V^2} - \frac{M_V^4}{M_A^4}\left(\log\frac{M_A^2}{m_S^2}-\frac{11}{6}\right)\right],$$

[terms $O(m_S^2/M^2_{V,A})$ neglected]



✓ 1st and 2nd WSRs at LO and NLO + ππ-VFF:

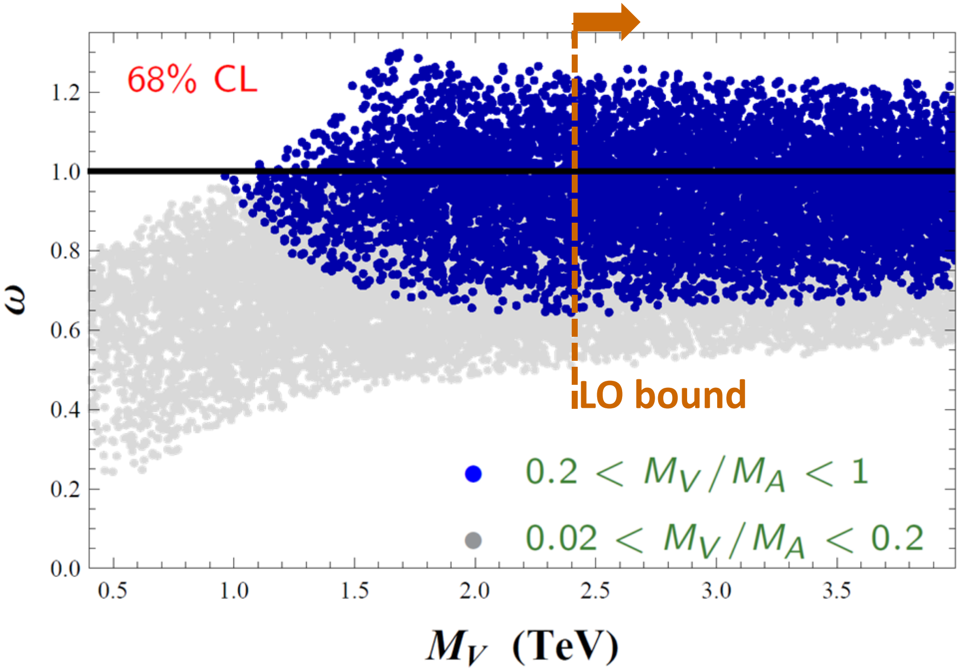
→ 2nd WSR: $0 < \omega = M_V^2/M_A^2 < 1$

At NLO with the 1st and 2nd WSRs

$M_V > 5.4$ TeV, $\omega > 0.97$ at 68% CL

Small splitting M_V/M_A

NLO Results: Only 1st WSRs in Π_{30}



At NLO with only 1st WSRs

M_V > 1 TeV, **$\omega \in$ (0.6 , 1.3)** at 68% CL

for moderate splitting $0.2 < M_V/M_A < 1$

$\omega \equiv g_{SWW}/g_{HWW}^{SM}$ **very different from the SM requires large (unnatural) mass splitings**

$$T = \frac{3}{16\pi \cos^2\theta_W}\left[1 + \log\frac{m_H^2}{M_V^2} - \omega^2\left(1 + \log\frac{m_S^2}{M_A^2}\right)\right]$$

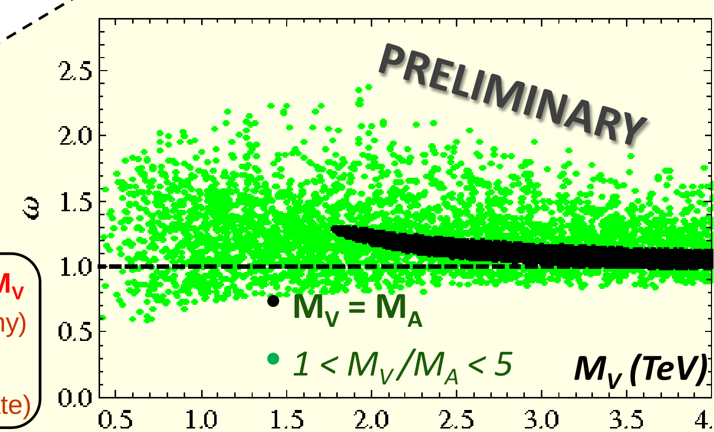
$$S \geq \underbrace{\frac{4\pi v^2}{M_V^2}}_{\text{LO}} + \frac{1}{12\pi}\left[\log\frac{M_V^2}{m_H^2} - \frac{11}{6} - \omega^2\left(\log\frac{M_A^2}{m_S^2} - \frac{17}{6} + \frac{M_A^2}{M_V^2}\right)\right]$$

S lower-bound for **$M_A > M_V$**
(normal hierarchy)

PRELIMINARY

S upper-bound for **$M_A < M_V$**
(inverted hierarchy)

S identity for **$M_A = M_V$**
(degenerate)



Conclusions

✓ **Framework:** - Oblique parameters S & T

- $SU(2)_L \otimes SU(2)_R$ / $SU(2)_{L+R}$ Lagrangian w/ Higgs + NGB's + Resonances
- High-energy constraints + 1 loop dispersive calculation

✓ **1st + 2nd WSR's:** Tiny splitting *(68% CL)* $0.97 < (M_V/M_A)^2 = \omega < 1$, $M_V > 5.4$ TeV

✓ ***Only* 1st WSR:** For a moderate mass splitting $M_A \sim M_V$, $\omega \sim 1$, $M_V > 1$ TeV

✓ **FINAL CONCLUSIONS:**

- Resonances perfectly allowed by S & T at $M_R \sim 4\pi v \approx 3$ TeV
- Resonances perfectly compatible with LHC $\omega = a = \kappa_W \approx 1$
- Only some slight issues below TeV *(large splitting, inv. hierarchy…)*
- Conclusions applicable to more specific models *(e.g. SO(5)/SO(4) MCHM)*

BACKUP SLIDES

•Does this exclude strongly-coupled EWSB models?

-Not yet

❑ <u>THEORETICALLY:</u> **NOT YET**

-E.g., the σ-meson in the LσM in QCD doesn't imply the absence of other hadrons

(although here the σ has completely different properties!!)

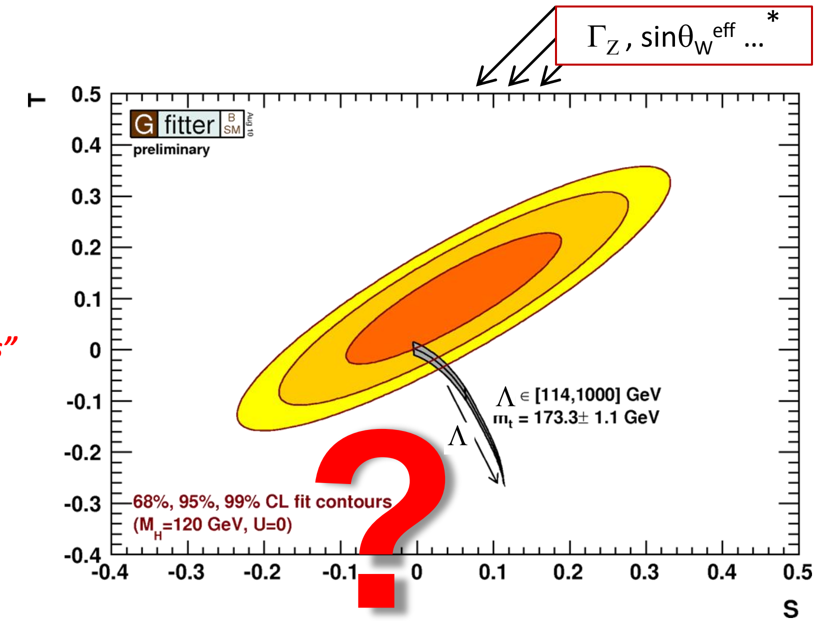
❑ <u>EXPERIMENTALLY:</u> **NOT YET**

- ***The EWPO Oblique Parameters***

don't exclude them at all

-Dangerous naïve cut-offs at some $\Lambda^{\text{"phys"}}$

$$S \approx \frac{1}{12\pi}\ln\frac{\Lambda^2}{m^2_{H,ref}}\,,$$
$$T \approx -\frac{3}{16\pi\cos^2\theta_W}\ln\frac{\Lambda^2}{m^2_{H,ref}}$$



-We will see that, more precisely,

$$S \approx \#\frac{4\pi v^2}{\Lambda^2} + \frac{1}{12\pi}\ln\frac{\#\Lambda^2}{m^2_{H,ref}}\,,$$
$$T \approx -\frac{3}{16\pi\cos^2\theta_W}\ln\frac{\#\Lambda^2}{m^2_{H,ref}}$$

* Peskin,Takeuchi '92

What? One-loop calculation of the oblique (S,T)-parameters in strongly-coupled EWSB *, **

Why? Origin of mass generation? strongly-coupled models?

How? Effective approach

a) EWSB: $SU(2)_L \times SU(2)_R \rightarrow SU(2)_{L+R}$: similar to ChSB in QCD→ ChPT ***

b) Strongly-coupled models: Resonances like in QCD→ RChT (+)

c) General Lagrangian + EoM + short-distance cond. (+)

d) Just the lightest two-particle absorptive cuts.

+

Dispersive representation for S *
+
Dispersion relation for T (for the lightest cuts) (x)

← $\pi\pi$ + $S\pi$

← $B\pi$ + BS

(impact of heavier channels neglected (x))

* Peskin,Takeuchi '92

(x) Pich, Rosell, SC '12, '13

** Gfitter
** LEP EWWG
** Zfitter

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

(+) Ecker et al. '89
(+) Cirigliano et al. '06
(+) Pich, Rosell, SC '08

ii) EWSB similar to Chiral Symmetry Breaking (ChSB) in QCD:

$SU(2)_L \times SU(2)_R \rightarrow SU(2)_{L+R}$

- At low energies, same EFT pion Lagrangian, Chiral Perturbation Theory (ChPT)**

$$\mathcal{L} = \frac{\mathbf{v^2}}{\mathbf{4}} \langle \mathbf{D_\mu U^\dagger D^\mu U} \rangle + \mathcal{O}(\mathbf{p^4/\Lambda^2})$$

$$U(\varphi) = \exp\{i\vec{\sigma}\,\vec{\varphi}/v\}$$

$$\mathbf{U}(\pi) \longrightarrow \mathbf{g_L}\,\mathbf{U}(\pi)\,\mathbf{g_R^\dagger}$$

- E.g., in the SM

$$\mathcal{L}^{\rm SM} = \frac{\mathbf{1}}{\mathbf{2}} \langle \mathbf{D_\mu \Sigma^\dagger D^\mu \Sigma} \rangle - \frac{\lambda}{\mathbf{16}} (\langle \mathbf{\Sigma^\dagger \Sigma} \rangle - \mathbf{v^2})^2 \quad \xrightarrow{\mathbf{p \ll m_H}} \quad \mathcal{L} = \frac{\mathbf{v^2}}{\mathbf{4}} \langle \mathbf{D_\mu U^\dagger D^\mu U} \rangle + \mathcal{O}(\mathbf{p^4/v^2})$$

$$\Sigma(x) = \frac{1}{\sqrt{2}} [v + H(x)]\; U(\varphi(x))$$

$$\Sigma \xrightarrow{G} g_L\, \Sigma\, g_R^\dagger, \qquad g_{L,R} \in {\rm SU}(2)_{L,R}$$

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

** Appelquist, Bernard '80
** Longhitano '80 '81
** Dobado,Espriu,Herrero '91
** Espriu,Matias '95 …

iii) EFT for the Goldstones (SM gauge symmetry non-linearly realized)

+

Lighest resonances from strongly-coupled models *

✓ Similar to Resonance Chiral Theory (RChT) in QCD **

✓ Energy scales?

The most naive rescaling	F_π=0.090 GeV	→	v=0.246 TeV
from QCD to EW scale yields:	$\Lambda_{\chi PT}=4\pi F_\pi \approx 1.2$ GeV	→	$\Lambda_{EW}=4\pi v \approx 3.1$ TeV
	M_ρ=0.770 GeV	→	M_{V1}=2.1 TeV
	M_{a1}=1.260 GeV	→	M_{A1}=3.4 TeV
	///////////////////////////	→	m_S= 0.126 TeV !!

*Matsuzaki et al. '07
*Barbieri et al. '08
*Catà, Kamenik '11
*Orgogozo, Rychkov '11, '12

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

• Field content of the theory:

$SU(2)_L \otimes SU(2)_R / SU(2)_{L+R}$ EW Goldstones + SM gauge bosons

+ lightest V and A resonances *(antisym. tensor formalism)*

+ one $SU(2)_L \otimes SU(2)_R$ singlet scalar S_1

• $SU(2)_L \otimes SU(2)_R$ transformation properties:

$$u(\varphi) \longrightarrow g_L\, u(\varphi)\, h^\dagger(\varphi,g) = h(\varphi,g)\, u(\varphi)\, g_R^\dagger$$

$$\hat{W}^\mu \to g_L\, \hat{W}^\mu g_L^\dagger + i\, g_L\, \partial^\mu g_L^\dagger\,, \qquad \hat{B}^\mu \to g_R\, \hat{B}^\mu g_R^\dagger + i\, g_R\, \partial^\mu g_R^\dagger$$

$$R \longrightarrow h(\varphi,g)\, R\, h^\dagger(\varphi,g)\,, \qquad R_1 \longrightarrow R_1$$

NOTATION:

$$U = u^2 = \exp\{i\vec{\sigma}\vec{\pi}/v\}$$

$$f_\pm^{\mu\nu} = u^\dagger\, \hat{W}^{\mu\nu} u \pm u\, \hat{B}^{\mu\nu} u^\dagger \qquad \hat{W}^\mu = -g\, \frac{\vec{\sigma}}{2}\, \vec{W}^\mu\,, \qquad \hat{B}^\mu = -g'\, \frac{\sigma_3}{2}\, B^\mu$$

$$\hat{W}^{\mu\nu} = \partial^\mu \hat{W}^\nu - \partial^\nu \hat{W}^\mu - i\, [\hat{W}^\mu, \hat{W}^\nu]\,, \qquad \hat{B}^{\mu\nu} = \partial^\mu \hat{B}^\nu - \partial^\nu \hat{B}^\mu - i\, [\hat{B}^\mu, \hat{B}^\nu]\,,$$

$$u^\mu = i\, u\, D^\mu U^\dagger\, u = -i\, u^\dagger D^\mu U\, u^\dagger = u^{\mu\dagger}\,, \qquad D^\mu U = \partial^\mu U - i\, \hat{W}^\mu U + i\, U\, \hat{B}^\mu\,.$$

1.) Estimation of the **S-parameter** in strongly-coupled EW models:

Equivalent to the determination of $L_{10}(\mu)-L_{10}(\mu_{ref})$ in ChPT/RChT * ← **S-parameter**

❖ New physics in the difference between the Z self-energies at $Q^2=M_Z^2$ and $Q^2=0$.

❖ Notice the **running with reference scale μ_{ref}**

➔ Only recovered if the $\pi\pi$ loop included

➔ Tree-level ambiguity on the μ_{ref} running

2.) Estimation of the **T-parameter** in strongly-coupled EW models:

Equivalent to the determination of $F_{\pi^+}^2 - F_{\pi^0}^2$ in ChPT/RChT ← **T-parameter**

❖ It parametrizes the Custodial symmetry breaking

❖ Again, **running with reference scale μ_{ref}:** *$B\pi$ loop; tree-level ambiguity on μ_{ref}*

* Pich,, Rosell, SC ’08

S-parameter sum-rule *

✓ In this work, dispersive representation introduced by Peskin and Takeuchi*.

$$S = \frac{16}{g^2 \tan\theta_W} \int_0^\infty \frac{\mathrm{dt}}{t} \left(\mathrm{Im}\widetilde{\Pi}_{30}(t) - \mathrm{Im}\widetilde{\Pi}_{30}(t)^{\mathrm{SM}} \right)$$

$$= \int_0^\infty \frac{\mathrm{dt}}{t} \left(\frac{16}{g^2 \tan\theta_W} \mathrm{Im}\widetilde{\Pi}_{30}(t) - \frac{1}{12\pi} \left[1 - \left(1 - \frac{m_{H,ref}^2}{t} \right)^3 \theta(t - m_{H,ref}^2) \right] \right)$$

→ The convergence of the integral requires $\rho_{\mathbf{S}}(\mathbf{t}) \equiv \frac{1}{\pi} \mathrm{Im}\widetilde{\mathbf{\Pi}}_{\mathbf{30}}(\mathbf{t}) \overset{\mathbf{t}\to\infty}{\longrightarrow} \mathbf{0}$

→ S-parameter defined for an arbitrary reference value $m_{H,ref}$

→ Higher threshold cuts in $\mathrm{Im}\Pi_{30}$ will be suppressed in the dispersive integral

→ At tree-level: $S_{\mathrm{LO}} = 4\pi \left(\frac{F_V^2}{M_V^2} - \frac{F_A^2}{M_A^2} \right)$

* Peskin and Takeuchi '92.

- We will have 7 resonance parameters: F_V, G_V, F_A, ω, λ_1^{SA}, M_V and M_A.
- The number of unknown couplings can be reduced by using short-distance information.
- In contrast with the QCD case, we ignore the underlying dynamical theory.

i) Weinberg Sum Rules (WSR)*

$$\Pi_{30}(s) = \frac{g^2 \tan\theta_W}{4}\, s\, [\Pi_{VV}(s) - \Pi_{AA}(s)]$$

1ST WSR:

$$\left| \mathbf{s} \times \widetilde{\mathbf{\Pi}}_{\mathbf{30}}(\mathbf{s}) \right| \xrightarrow{\mathbf{s}\to\infty} \mathbf{0} \quad \Longrightarrow \quad \int_0^\infty \mathbf{dt}\ \rho_{\mathbf{S}}(\mathbf{t}) = \frac{\mathbf{g^2 v^2} \tan\theta_{\mathbf{W}}}{\mathbf{4}}$$

2ND WSR:

$$\left| \mathbf{s^2} \times \widetilde{\mathbf{\Pi}}_{\mathbf{30}}(\mathbf{s}) \right| \xrightarrow{\mathbf{s}\to\infty} \mathbf{0} \quad \Longrightarrow \quad \int_0^\infty \mathbf{dt}\ \mathbf{t}\ \rho_{\mathbf{S}}(\mathbf{t}) = \mathbf{0}$$

* Weinberg'67
* Bernard et al.'75.

i.i) LO

$$F_V^2 - F_A^2 = v^2$$
$$F_V^2 M_V^2 - F_A^2 M_A^2 = 0$$

(1 / 2 constraints)

i.ii) Imaginary NLO

$$\mathrm{Im}\Pi_{V-A}(s) \sim \mathcal{O}\left(\frac{1}{s^{\Delta/2}}\right)$$

(1 / 2 constraints)

i.iii) Real NLO: fixing of $F_{V,A}^r$ or lower bounds**

$$F_V^{r\,2} - F_A^{r\,2} = v^2\,(1 + \delta^{(1)}_{\rm NLO})$$
$$F_V^{r\,2} M_V^{r\,2} - F_A^{r\,2} M_A^{r\,2} = v^2 M_V^{r\,2} \delta^{(2)}_{\rm NLO}$$

(constraints on $F_{V,A}^r$)

- ✓ Once-subtract. dispersive relation from tree+1-loop spectral function:
  ππ, Sπ … (higher cuts suppressed) $\Pi_{30}(s) = \Pi_{30}(0) + \frac{s}{\pi}\int_0^\infty \frac{\mathrm{d}t}{t\,(t-s)} \mathrm{Im}\Pi_{30}(t)$
- ✓ F_R^r and M_R^r are *renormalized* couplings which define the resonance poles at the one-loop level.

$$\Pi_{30}(s)|_{\rm NLO} = \frac{g^2\tan\theta_W}{4}\, s\left(\frac{v^2}{s} + \frac{F_V^{r\,2}}{M_V^{r\,2}-s} - \frac{F_A^{r\,2}}{M_A^{r\,2}-s} + \overline{\Pi}(s)\right)$$

* Weinberg'67
* Bernard et al.'75.
** Pich, Rosell, SC '08

ii) Additional short-distance constraints

ii.i) ππ Vector Form Factor**

$$\frac{F_V G_V}{v^2} = 1$$

+ NO HIGHER DERIV. OPERATORS for W,B→ππ

ii.ii) Sπ Axial-vector Form Factor**

(equivalent to VFF + vanishing $\rho_S(t)$ at $t \to \infty$)

$$\frac{F_A \lambda_1^{SA}}{\omega v} = 1$$

+ NO HIGHER DERIV. OPERATORS for W,B→Sπ

ii.iii) $W_L W_L \to W_L W_L$ scattering*

*(NOT CONSIDERED HERE, studied in a previous work***)*

[$\omega > 0$ + WSRs + VFF] ➔ $M_V/M_A > 0.8$

$$\frac{3G_V^2}{v^2} + \omega^2 = 1$$

* Bagger et al.'94
* Barbieri et al.'08
* Guo, Zheng, SC '07
* Pich, Rosell, SC '11

** Ecker et al.'89

*** Pich, Rosell, SC '12

1^{st} + 2^{nd} WSR determination:

- ✓ 7 parameters (only lowest cuts $\pi\pi$+Sπ): M_V, M_A, F_V, F_A & G_V, ω, λ_1^{SA}
- ✓ 2 + 2 + 1 constraints: F_V, F_A & M_A, ($F_V G_V$), ($F_A \lambda_1^{SA}$) $\Longrightarrow$ 2 free parameters: M_V, ω

Only 1^{st} WSR lower bound for M_V<M_A:

- ✓ 6 parameters (only lowest cuts $\pi\pi$+Sπ / Bπ+BS): M_V, M_A, F_V & ($F_V G_V$), ω, ($F_A \lambda_1^{SA}$)
- ✓ 1 + 1 + 1 constraints: F_V & ($F_V G_V$), ($F_A \lambda_1^{SA}$) $\Longrightarrow$ 3 free parameters: M_V, M_A, ω

S = 0.03 ± 0.10 * ($m_{H,ref}$=0.126 TeV)

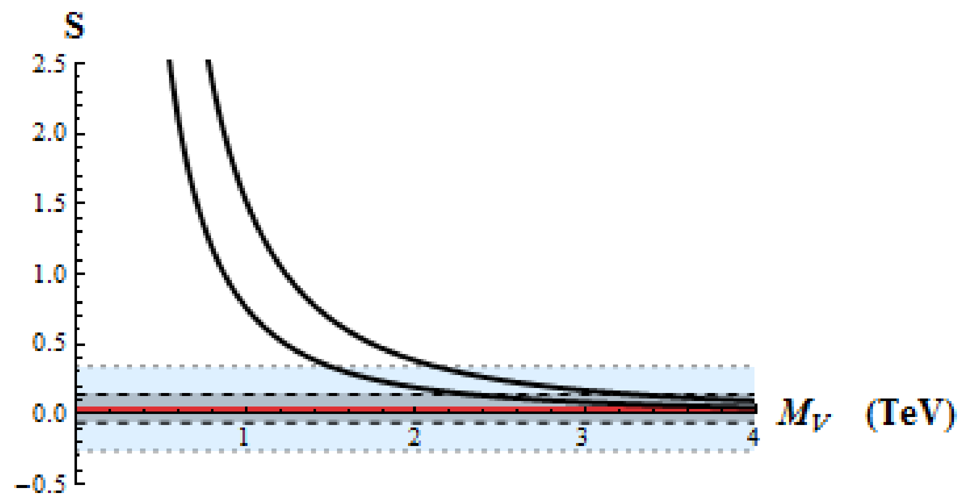
i) LO results

i.i) 1st and 2nd WSRs **

$$S_{\rm LO} = \frac{4\pi v^2}{M_V^2}\left(1+\frac{M_V^2}{M_A^2}\right)$$

$$\frac{4\pi v^2}{M_V^2} < S_{\rm LO} < \frac{8\pi v^2}{M_V^2}$$

$$S_{\rm LO} = 4\pi\left(\frac{F_V^2}{M_V^2}-\frac{F_A^2}{M_A^2}\right), \qquad T_{\rm LO}=0$$



i.ii) Only 1st WSR *** (lower bound for $M_A>M_V$)

$$S_{\rm LO} = 4\pi\left\{\frac{v^2}{M_V^2}+F_A^2\left(\frac{1}{M_V^2}-\frac{1}{M_A^2}\right)\right\}$$

$$S_{\rm LO} > \frac{4\pi v^2}{M_V^2}$$

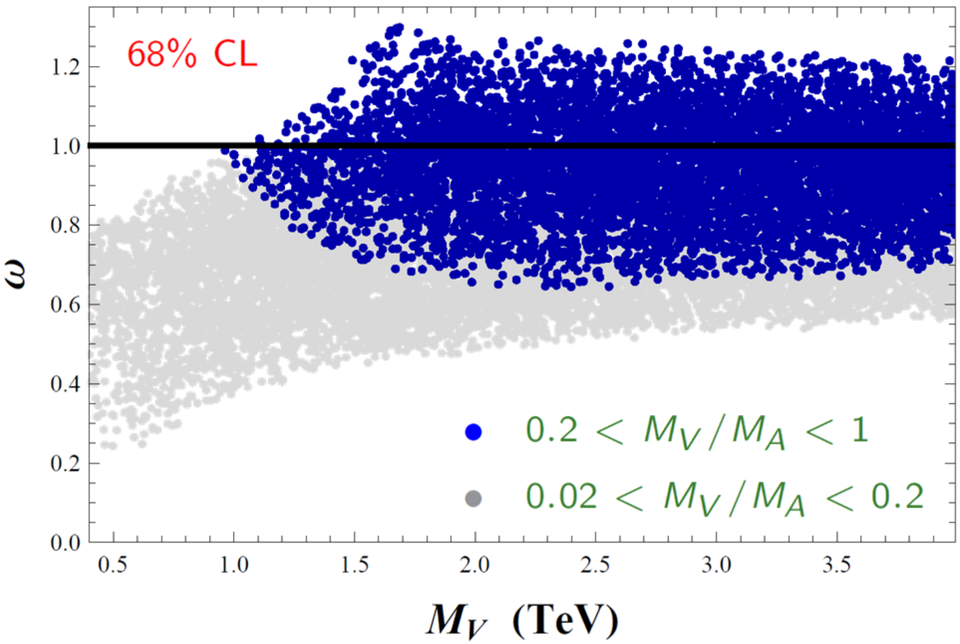
At LO M_V > 2.4 TeV at 68% CL

(M_V> 3.6 TeV if T_{LO}=0 also considered)

* Gfitter
* LEP EWWG
* Zfitter

** Peskin and Takeuchi '92.

*** Pich, Rosell, SC '12



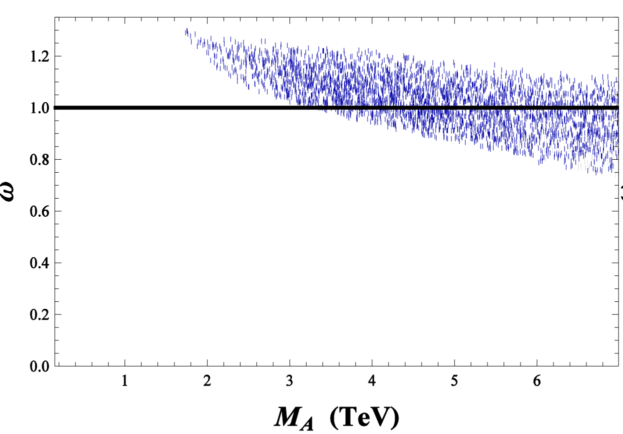
At NLO with only 1st WSRs

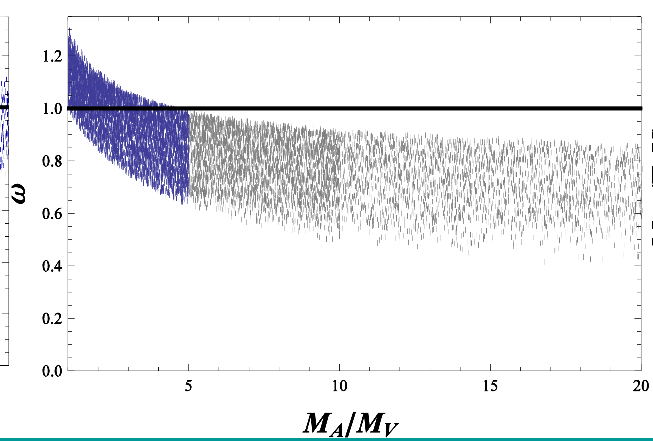
$M_V > 1$ TeV, $\omega - 1 \in (-0.36, +0.30)$ at 68% CL

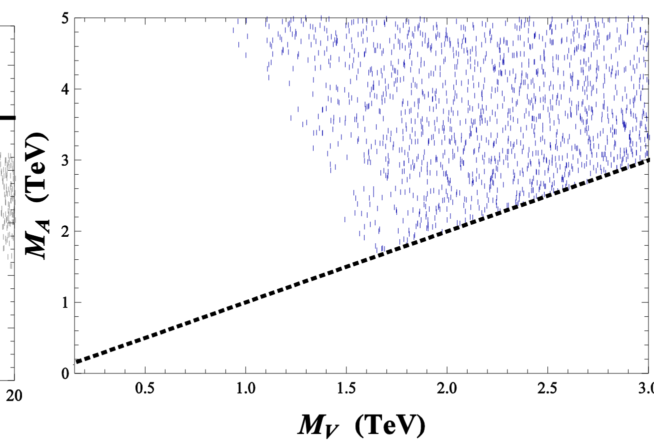
for moderate splitting $0.2 < M_V/M_A < 1$

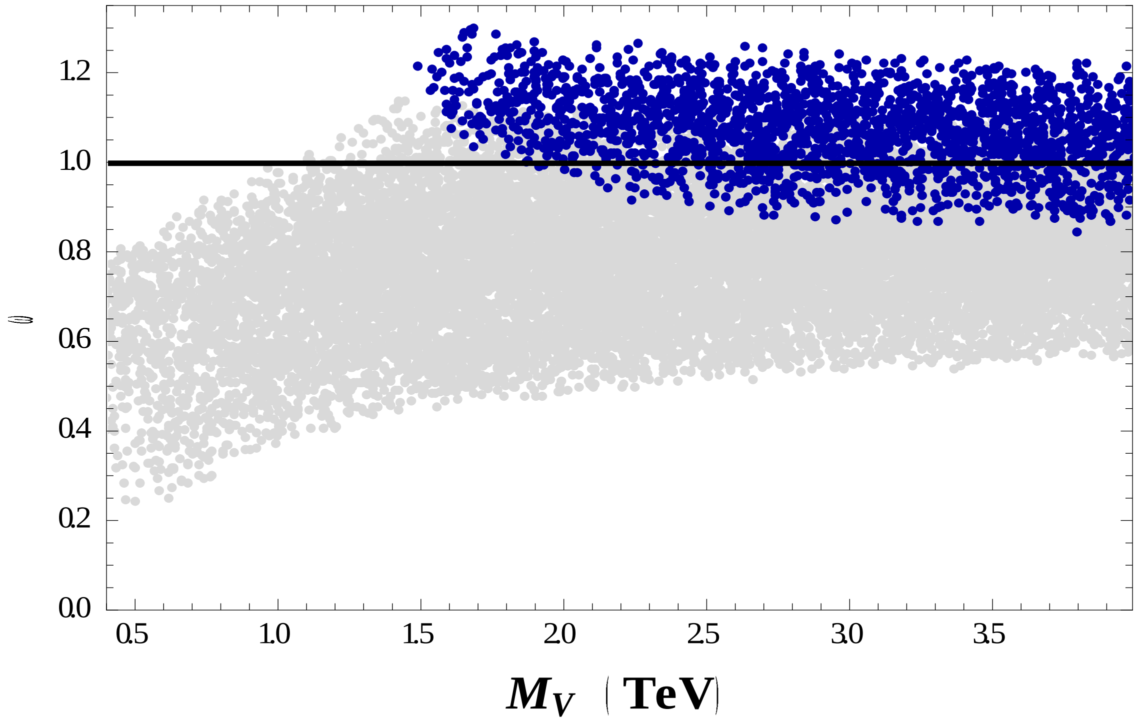
$\omega \equiv g_{sWW}/g_{HWW}^{SM}$ **very different from the SM requires large (unnatural) mass splitings**

BACKUP PLOTS

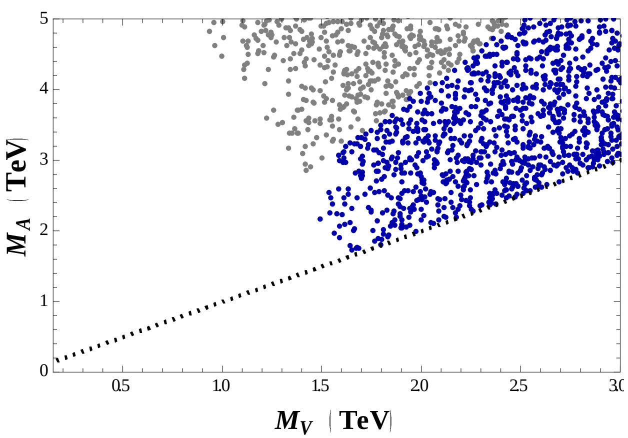


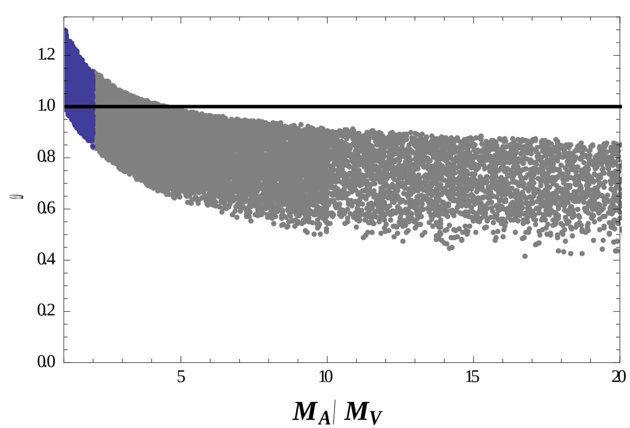


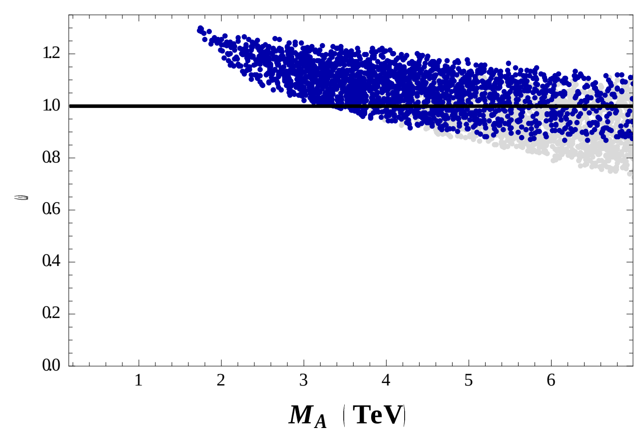


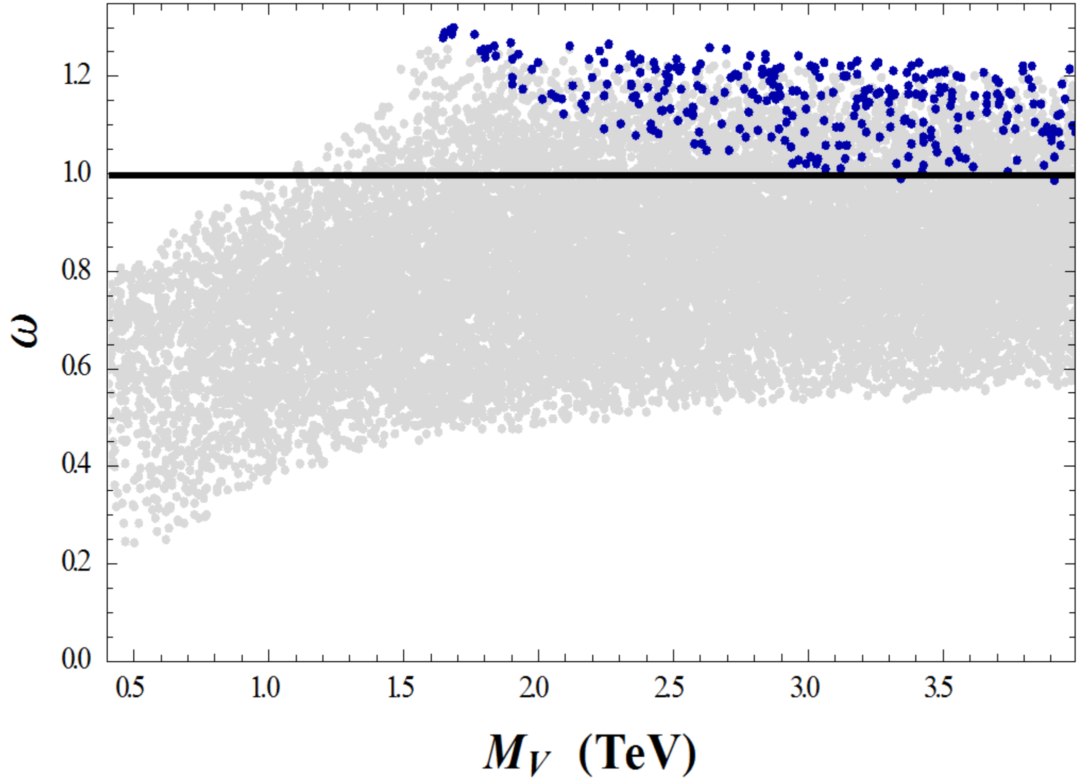


- **0.5 < M_V/M_A < 1**
- **0.02< M_V/M_A < 0.5**

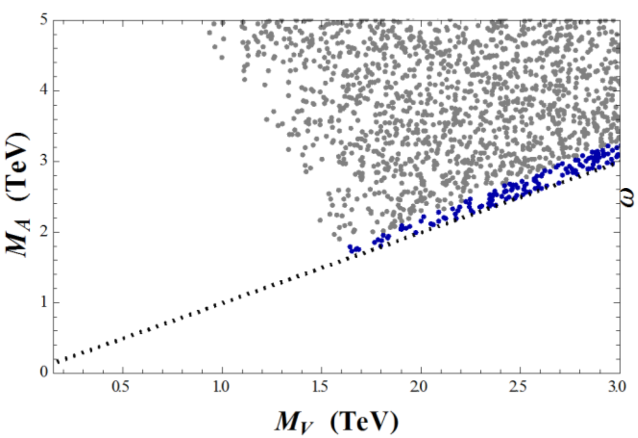


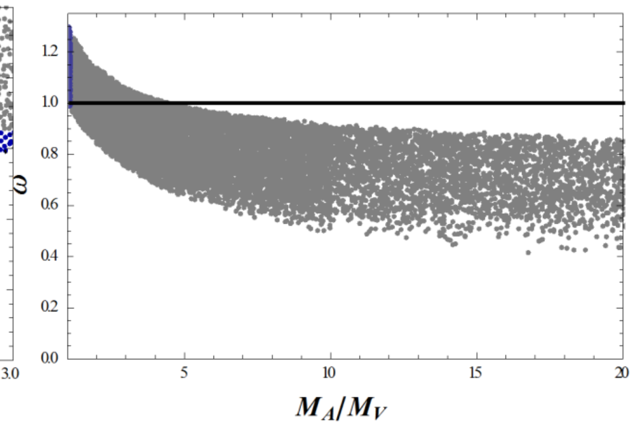


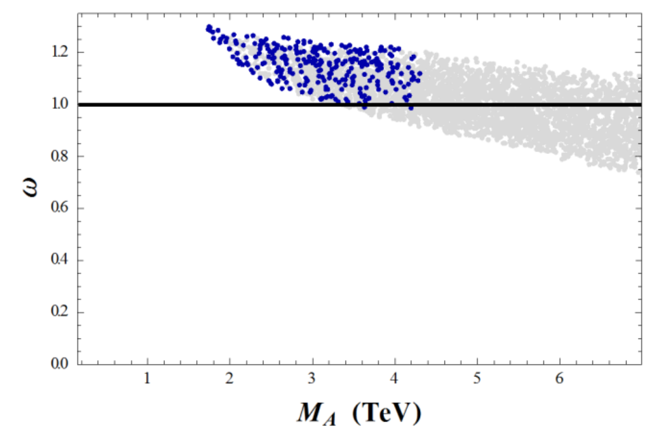




- $0.9 < M_V/M_A < 1$
- $0.02 < M_V/M_A < 0.9$







Further comments:

✓ $1 < M_A/M_V < 2$ yields **$M_V > 1.5$ TeV**, **$\omega - 1 \in [-0.16, +0.30]$**

✓ The limit $\omega \to 0$ only reached for $M_V/M_A \to 0$

$\omega = 0$ incompatible with data *(independently of whether 1st+2nd WSR's or just 1st WSR)*

✓ Calculation valid for particular models with this symmetry:

E.g., in SO(5)/SO(4) with $\omega = \cos\theta < 1$ *

EW scale → $v = 0.25$ GeV , $4\pi v = 3$ TeV

$\omega = 0.6$ → $f = 0.31$ TeV , $4\pi f = 4$ TeV

$\omega = 0.97$ → $f = 1$ TeV , $4\pi f = 13$ TeV

* Agashe,Contino,Pomarol '05
* Barbieri et al '12
* Marzocca,Serone,Shu '12 ...

S = 0.03 ± 0.10 * ($m_{H,ref}$=0.126 TeV)

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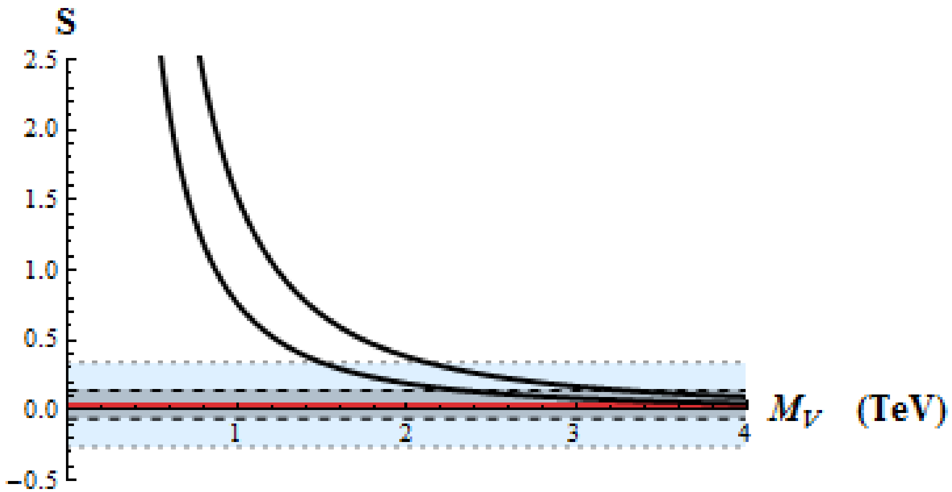
$$S_{\rm LO} = 4\pi\left(\frac{F_V^2}{M_V^2}-\frac{F_A^2}{M_A^2}\right)\,, \qquad T_{\rm LO}=0$$



i.ii) Only 1st WSR *** (lower bound for M_A>M_V)

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