5. Fingerprints of Heavy Scales

- **Electroweak Resonance Effective Theory**
- **Integration of Heavy States**
- **Short-Distance Constraints**
- **Low-Energy Constants**
- **Outlook**

Higher-Order Goldstone Interactions

$$\mathcal{L}_{\rm EW}^{(4)}\Big|_{\rm Bosonic} \;=\; \sum_i \mathcal{F}_i(h/v)\,\mathcal{O}_i \qquad\qquad \mathcal{F}_i(h/v) \;=\; \sum_{n=0} \mathcal{F}_{i,n}\left(\frac{h}{v}\right)^n$$

Appelquist-Bernard, Longhitano, Buchalla et al, Alonso et al, Pich et al...

$\mathcal{O}(p^4)$ $\mathcal{P}$-even bosonic operators

A.P., Rosell, Santos, Sanz-Cillero

$\mathcal{O}_1 = \frac{1}{4}\langle f_+^{\mu\nu} f_{+\,\mu\nu} - f_-^{\mu\nu} f_{-\,\mu\nu}\rangle$	$\mathcal{O}_6 = \frac{1}{v^2}(\partial_\mu h)(\partial^\mu h)\langle u_\nu u^\nu\rangle$
$\mathcal{O}_2 = \frac{1}{2}\langle f_+^{\mu\nu} f_{+\,\mu\nu} + f_-^{\mu\nu} f_{-\,\mu\nu}\rangle$	$\mathcal{O}_7 = \frac{1}{v^2}(\partial_\mu h)(\partial_\nu h)\langle u^\mu u^\nu\rangle$
$\mathcal{O}_3 = \frac{i}{2}\langle f_+^{\mu\nu}[u_\mu, u_\nu]\rangle$	$\mathcal{O}_8 = \frac{1}{v^4}(\partial_\mu h)(\partial^\mu h)(\partial_\nu h)(\partial^\nu h)$
$\mathcal{O}_4 = \langle u_\mu u_\nu\rangle\langle u^\mu u^\nu\rangle$	$\mathcal{O}_9 = \frac{1}{v}(\partial_\mu h)\langle f_-^{\mu\nu} u_\nu\rangle$
$\mathcal{O}_5 = \langle u_\mu u^\mu\rangle^2$	

$$U \;=\; u^2 \;=\; \exp\left\{\tfrac{i}{v}\,\vec{\sigma}\,\vec{\varphi}\right\} \quad , \quad u_\mu \;\equiv\; i\,u\,(D_\mu U)^\dagger u \;=\; u_\mu^\dagger \quad , \quad f_\pm^{\mu\nu} \;=\; u^\dagger\,\hat{W}^{\mu\nu}u \pm u\,\hat{B}^{\mu\nu}u^\dagger$$

Custodial symmetry assumed

EW Resonance Effective Theory

- **Towers of heavy states are usually present in strongly-coupled models of EWSB: Technicolour, Walking TC. . .**

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1. Build $\mathcal{L}_{\rm eff}(\varphi_i, R_k)$ with the lightest R_k coupled to the φ_i
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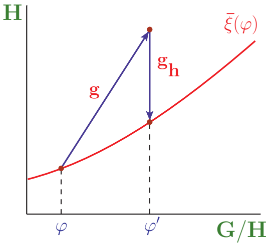
This program works in QCD: RχT (Ecker–Gasser–Leutwyler–Pich–de Rafael)

Good dynamical understanding at large N_C

Coset Space Coordinates: $G \equiv SU(2)_L \otimes SU(2)_R \;\to\; H \equiv SU(2)_V$



$$\bar{\xi}(\varphi) \;\equiv\; (\xi_L(\varphi), \xi_R(\varphi)) \in\; G$$

$$\xi_L(\varphi) \;\xrightarrow{G}\; g_L\, \xi_L(\varphi)\, g_h^\dagger(\varphi, g)$$

$$\xi_R(\varphi) \;\xrightarrow{G}\; g_R\, \xi_R(\varphi)\, g_h^\dagger(\varphi, g)$$

$$\mathbf{U}(\varphi) \;\equiv\; \xi_L(\varphi)\, \xi_R^\dagger(\varphi) \;\xrightarrow{G}\; g_L\, \mathbf{U}(\varphi)\, g_R^\dagger$$

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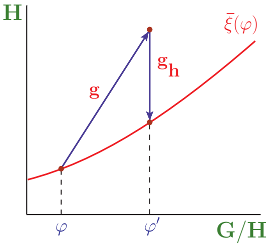

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Canonical choice: $\xi_L(\varphi) = \xi_R^\dagger(\varphi) \equiv \mathbf{u}(\varphi) \;\xrightarrow{G}\; g_L\, \mathbf{u}(\varphi)\, g_h^\dagger(\varphi, g) \;=\; g_h(\varphi, g)\, \mathbf{u}(\varphi)\, g_R^\dagger$

$$\mathbf{U}(\varphi) \;=\; \mathbf{u}(\varphi)^2 \;=\; \exp\left\{ \frac{i}{v}\, \vec\sigma\, \vec\varphi \right\}$$

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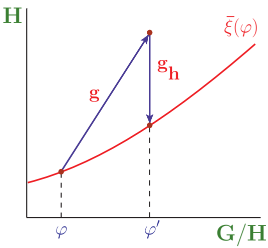

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$SU(2)_V$ triplets: $\quad \mathbf{X} \;\equiv\; \frac{1}{2}\, \sigma^a\, \mathbf{X}^a \;\xrightarrow{G}\; \mathbf{g_h}(\varphi, \mathbf{g})\;\; \mathbf{X}\;\; \mathbf{g_h^\dagger}(\varphi, \mathbf{g})$

$$\nabla_\mu X \;=\; \partial_\mu X + [\,\Gamma_\mu, X\,] \quad , \quad \Gamma_\mu \;=\; \frac{1}{2}\left\{ u^\dagger (\partial_\mu - i\,\hat W_\mu)\, u \;+\; u\, (\partial_\mu - i\,\hat B_\mu)\, u^\dagger \right\}$$

$$u_\mu \;\equiv\; i\, u\, D_\mu U^\dagger\, u \;=\; u_\mu^\dagger \quad , \quad f_\pm^{\mu\nu} \;=\; u^\dagger\, \hat W^{\mu\nu}\, u \pm u\, \hat B^{\mu\nu}\, u^\dagger$$

LO Resonance EW Lagrangian:

A.P., Rosell, Santos, Sanz-Cillero

$$\mathcal{L}_{\rm eff} \; = \; \mathcal{L}_{\rm EWET} \; + \; \sum_R \mathcal{L}_R \; + \; \sum_{R,R'} \mathcal{L}_{RR'} \; + \; \cdots$$

Heavy Triplets: $\mathbf{V}(1^{--})\,,\;\mathbf{A}(1^{++})\,,\;\mathbf{P}(1^{++})$; **Heavy Singlet:** $\mathbf{S_1}(0^{++})$

$$\sum_R \mathcal{L}_R \; = \; \frac{v}{2}\,\kappa_W\; h\,\langle u^\mu u_\mu\rangle \; + \; \frac{F_V}{2\sqrt{2}}\,\langle V_{\mu\nu}\, f_+^{\mu\nu}\rangle \; + \; \frac{i\, G_V}{2\sqrt{2}}\,\langle V_{\mu\nu}\; [u^\mu u^\nu]\rangle$$

$$+ \; \frac{F_A}{2\sqrt{2}}\,\langle A_{\mu\nu} f_-^{\mu\nu}\rangle \; + \; \sqrt{2}\;\lambda_1^{hA}\;\partial_\mu h\,\langle A^{\mu\nu}\, u_\nu\rangle$$

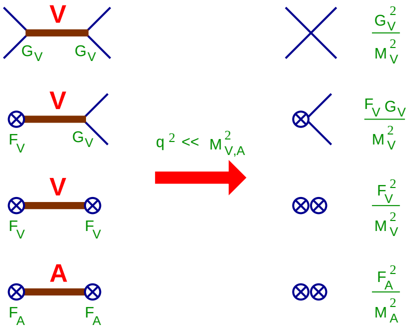
$$+ \; \frac{d_P}{v}\;\partial_\mu h\,\langle P\; u^\mu\rangle \; + \; \frac{c_d}{\sqrt{2}}\; S_1\;\langle u^\mu u_\mu\rangle \; + \; \lambda_{hS_1}\; v\; h^2\; S_1$$

$$U \; = \; u^2 \; = \; \exp\left\{\tfrac{i}{v}\,\vec{\sigma}\,\vec{\varphi}\right\} \quad , \quad u_\mu \;\equiv\; i\, u\,(D_\mu U)^\dagger u \; = \; u_\mu^\dagger \quad , \quad f_\pm^{\mu\nu} \; = \; u^\dagger\,\hat{W}^{\mu\nu}\, u \pm u\,\hat{B}^{\mu\nu}\, u^\dagger$$

Antisymmetric $V_{\mu\nu}$ and $A_{\mu\nu}$ fields (better UV properties):

$$\mathcal{L}_{\rm Kin} \; = \; -\frac{1}{2}\sum_{R=V,A}\langle\nabla^\lambda R_{\lambda\mu}\nabla_\nu R^{\nu\mu} - \frac{1}{2}\, M_R^2\, R_{\mu\nu} R^{\mu\nu}\rangle$$

Resonance Exchange



Pich, Rosell, Santos, Sanz-Cillero

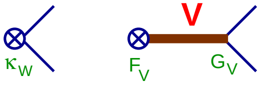
$$\mathcal{F}_1 = \frac{F_A^2}{4M_A^2} - \frac{F_V^2}{4M_V^2} \quad , \quad \mathcal{F}_2 = -\frac{F_A^2}{8M_A^2} - \frac{F_V^2}{8M_V^2} \quad , \quad \mathcal{F}_3 = -\frac{F_V G_V}{2M_V^2}$$

$$\mathcal{F}_4 = \frac{G_V^2}{4M_V^2} \quad , \quad \mathcal{F}_5 = \frac{c_d^2}{4M_{S_1}^2} - \frac{G_V^2}{4M_V^2} \quad , \quad \mathcal{F}_6 = -\frac{(\lambda_1^{hA})^2 v^2}{M_A^2}$$

$$\mathcal{F}_7 = \frac{d_P^2}{2M_P^2} + \frac{(\lambda_1^{hA})^2 v^2}{M_A^2} \quad , \quad \mathcal{F}_8 = 0 \quad , \quad \mathcal{F}_9 = -\frac{F_A \lambda_1^{hA} v}{M_A^2}$$

Short-Distance Constraints

- **Vector Form Factor:** $\langle \varphi(p_1)\varphi(p_2)|J_V^\mu|0\rangle = (p_1 - p_2)^\mu\, \mathbb{F}^V_{\varphi\varphi}(s)$



$$\mathbb{F}^V_{\varphi\varphi}(s) = 1 + \frac{F_V\, G_V}{v^2}\, \frac{s}{M_V^2 - s}$$

$$\lim_{s\to\infty} \mathbb{F}^V_{\varphi\varphi}(s) = 0 \quad \longrightarrow \quad \boxed{F_V\, G_V = v^2}$$

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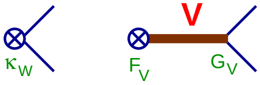

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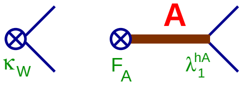
- **Axial Form Factor:**

$$\langle h(p_1)\varphi(p_2)|J_A^\mu|0\rangle \;=\; (p_1-p_2)^\mu\,\mathbb{F}^A_{h\varphi}(s)$$



$$\mathbb{F}^A_{h\varphi}(s) \;=\; \kappa_W\left(1 \;+\; \frac{F_A\,\lambda_1^{hA}}{\kappa_W\,v}\,\frac{s}{M_A^2-s}\right)$$

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Weinberg Sum Rules

Chiral Symmetry:

$$\Pi_{LR}^{\mu\nu}(q) \,\equiv\, \int d^4x \; \mathrm{e}^{iqx} \,\langle 0|\, T\big(J_L^\mu(x)\, J_R^\nu(0)^\dagger\big)|0\rangle \,=\, \left(-g^{\mu\nu} q^2 + q^\mu q^\nu\right)\, \Pi_{LR}(q^2) \,=\, 0$$

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OPE: $\Pi^{\mu\nu}_{LR}(q) \neq 0$ only through **order parameters of EWSB**
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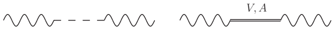
→

$$\frac{1}{\pi}\int_0^\infty ds\; [\mathrm{Im}\Pi_{VV}(s) - \mathrm{Im}\Pi_{AA}(s)] = v^2 \qquad (1^{\mathrm{st}}\ \mathrm{WSR})$$

$$\frac{1}{\pi}\int_0^\infty ds\; s\; [\mathrm{Im}\Pi_{VV}(s) - \mathrm{Im}\Pi_{AA}(s)] = 0 \qquad (2^{\mathrm{nd}}\ \mathrm{WSR})$$

• WSRs @ LO:

$$\Pi_{LR}(s) = \frac{v^2}{s} + \frac{F_V^2}{M_V^2 - s} - \frac{F_A^2}{M_A^2 - s}$$



- **1st WSR:** $F_V^2 - F_A^2 = v^2$
- **2nd WSR:** $F_V^2\, M_V^2 - F_A^2\, M_A^2 = 0$

$$\Longrightarrow \quad F_V^2 = v^2\, \frac{M_A^2}{M_A^2 - M_V^2} \quad , \quad F_A^2 = v^2\, \frac{M_V^2}{M_A^2 - M_V^2} \quad , \quad M_A > M_V$$

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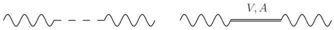

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- **WSRs @ NLO:**

$$\kappa_W \equiv \frac{g_{hWW}}{g_{hWW}^{\mathrm{SM}}} = \frac{M_V^2}{M_A^2}$$

A.P., Rosell, Sanz-Cillero

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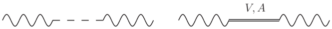

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A.P., Rosell, Sanz-Cillero

1st WSR likely valid also in gauge theories with non-trivial UV fixed points

2nd WSR questionable (not valid) in walking (conformal) TC scenarios

Appelquist–Sannino, Orgogozo–Rychkov

Short-distance constraints bring sharper predictions

Pich, Rosell, Santos, Sanz-Cillero

$$\mathcal{F}_1 = \frac{F_A^2}{4M_A^2} - \frac{F_V^2}{4M_V^2} = -\frac{v^2}{4}\left(\frac{1}{M_V^2} + \frac{1}{M_A^2}\right)$$

$$\mathcal{F}_2 = -\frac{F_A^2}{8M_A^2} - \frac{F_V^2}{8M_V^2} = -\frac{v^2(M_V^4+M_A^4)}{8M_V^2 M_A^2(M_A^2-M_V^2)}$$

$$\mathcal{F}_3 = -\frac{F_V G_V}{2M_V^2} = -\frac{v^2}{2M_V^2}$$

$$\mathcal{F}_4 = \frac{G_V^2}{4M_V^2} = \frac{(M_A^2-M_V^2)v^2}{4M_V^2 M_A^2}$$

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$$\mathcal{F}_6 = -\frac{(\lambda_1^{hA})^2 v^2}{M_A^2} = -\frac{M_V^2(M_A^2-M_V^2)v^2}{M_A^6}$$

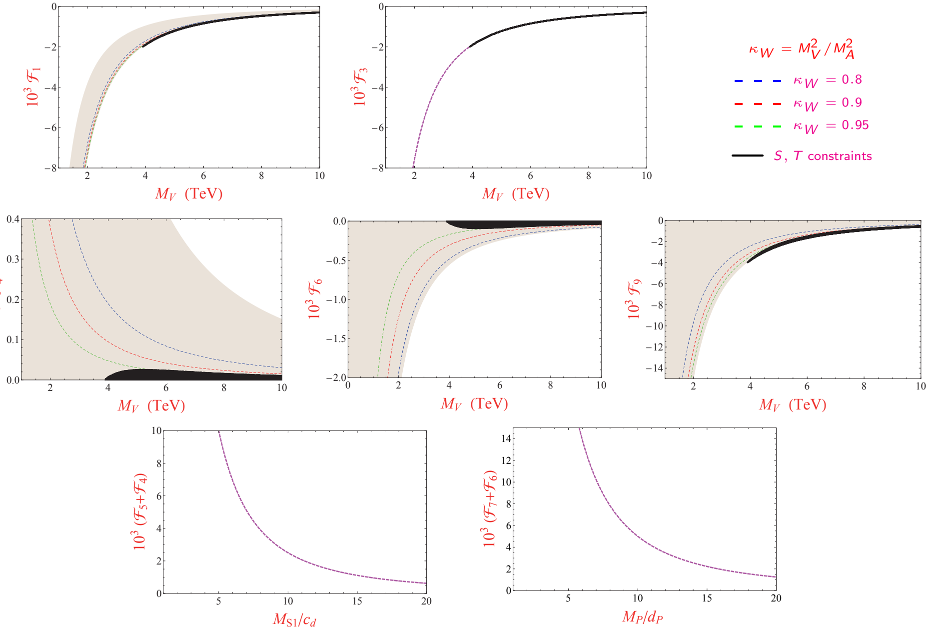
$$\mathcal{F}_7 = \frac{d_P^2}{2M_P^2} + \frac{(\lambda_1^{hA})^2 v^2}{M_A^2} = \frac{d_P^2}{2M_P^2} + \frac{M_V^2(M_A^2-M_V^2)v^2}{M_A^6}$$

$$\mathcal{F}_8 = 0$$

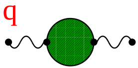
$$\mathcal{F}_9 = -\frac{F_A \lambda_1^{hA} v}{M_A^2} = -\frac{M_V^2 v^2}{M_A^4}$$

Asymptotically-Free Theories

A.P., Rosell, Santos, Sanz-Cillero, arXiv:1510.03114



Gauge Boson Self-Energies: S, T



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

Landau gauge $(\xi = 0)$**:** $\quad \Pi^{\mu\nu}_{ij}(q^2) = \left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right) \Pi_{ij}(q^2)$

There is no mixing with the Goldstones

$$S \equiv \frac{16\pi}{g^2}\left(e_3 - e_3^{\mathrm{SM}}\right) = 0.05 \pm 0.11$$

$$T \equiv \frac{4\pi}{g^2 \sin^2\theta_W}\left(e_1 - e_1^{\mathrm{SM}}\right) = 0.09 \pm 0.13$$

$$e_3 = \frac{g}{g'}\, \widetilde{\Pi}_{30}(0)$$

$$e_1 = \frac{\Pi_{33}(0) - \Pi_{WW}(0)}{M_W^2}$$

$$\Pi_{30}(q^2) = \frac{g^2 \tan\theta_W}{4}\, s\, \left[\Pi_{VV}(s) - \Pi_{AA}(s)\right] = q^2\, \widetilde{\Pi}_{30}(q^2) + \frac{g^2 \tan\theta_W}{4}\, v^2$$

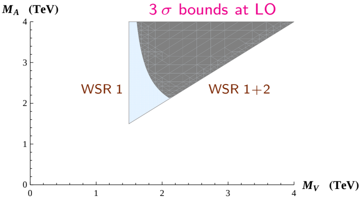
$\mathbf{e^{SM}_{1,3}}$ **defined at** $\mathbf{M_h = 125\ GeV}$

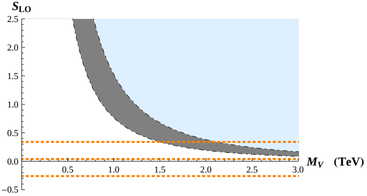
Gauge Boson Self-Energies @ LO

A.P., Rosell, Sanz-Cillero

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

- **1st + 2nd WSR:** $\quad S_{\rm LO} \,=\, \frac{4\pi v^2}{M_V^2} \left(1 + \frac{M_V^2}{M_A^2} \right)$
- **1st WSR ($M_A > M_V$):** $\quad S_{\rm LO} \,=\, 4\pi \left\{ \frac{v^2}{M_V^2} + F_A^2 \left(\frac{1}{M_V^2} - \frac{1}{M_A^2} \right) \right\} \,>\, \frac{4\pi v^2}{M_V^2} \,>\, \frac{4\pi v^2}{M_A^2}$



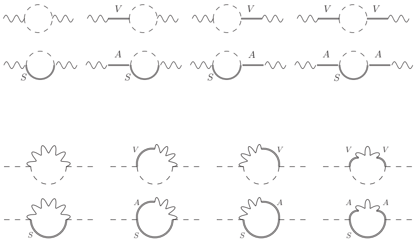


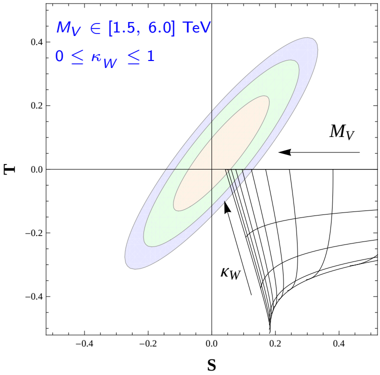
Sensitive to vector and axial states ➡ $\mathbf{M_A > M_V > 1.5\ TeV}$

Gauge Boson Self-Energies @ NLO

Sensitive to the light scalar h(125)

AP, Rosell, Sanz-Cillero





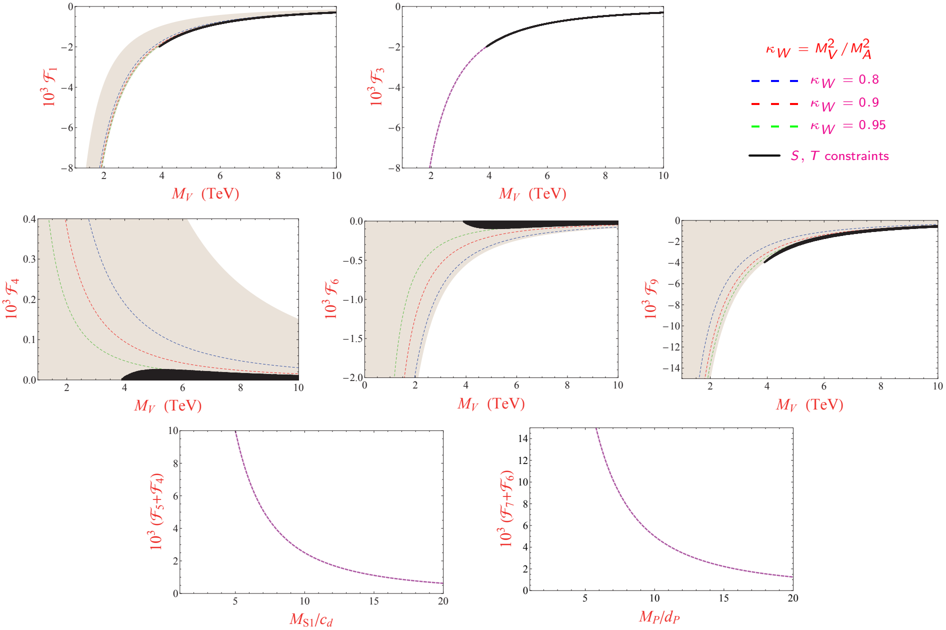
$$\kappa_W \equiv \frac{g_{SWW}}{g_{HWW}^{SM}} = \frac{M_V^2}{M_A^2} \in [0.94,\ 1]$$

$M_A \approx M_V > 4$ TeV (95% CL)

$1^{st} + 2^{nd}$ WSRs

Asymptotically-Free Theories

A.P., Rosell, Santos, Sanz-Cillero, arXiv:1510.03114



Ongoing work:

A.P., Rosell, Santos, Sanz-Cillero, arXiv:1609.06659
C. Krause, A.P., Rosell, Santos, Sanz-Cillero

- CP-odd operators ✓
- Couplings with SM fermions ✓
- Equivalence of different spin–1 field formalisms ✓

  Proca, Hidden-Gauge, Antisymmetric
- Short-distance constraints

  Green functions, additional states, . . .
- Heavy fermion fields
- Coloured heavy fields ✓
- Flavour dynamics
- . . .

OUTLOOK

- **Effective Field Theory: powerful low-energy tool**

- **Mass Gap:** $E, m_{light} \ll \Lambda_{NP}$

- **Assumption: relevant symmetries (breakings) & light fields**

- **Most general $\mathcal{L}_{eff}(\phi_{light})$ allowed by symmetry**

- **Short-distance dynamics encoded in LECs**

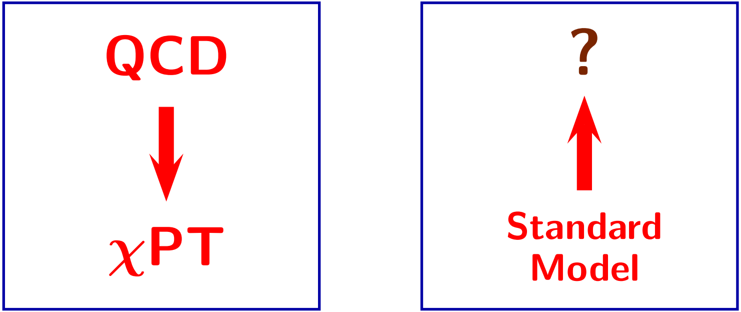
- **LECs constrained phenomenologically**

- **Goal: get hints on the underlying fundamental dynamics**

$\Longrightarrow$ **New Physics**

Learning from QCD experience. EW problem more difficult

Fundamental Underlying Theory unknown



Additional dynamical input (fresh ideas!) needed


Backup Slides

Proca Spin–1 Fields: $\hat{R}^\mu = \hat{V}^\mu, \hat{A}^\mu$

$$\mathcal{L}_{\hat{R}} = -\frac{1}{4}\langle \hat{R}_{\mu\nu}\hat{R}^{\mu\nu} - 2\, M_R^2\, \hat{R}_\mu \hat{R}^\mu \rangle + \underbrace{\langle \hat{R}_{\mu\nu}\, \hat{\chi}^{\mu\nu}_{\hat{R}} \rangle}_{\mathcal{O}(p^3)}$$

$$\hat{\chi}^{\mu\nu}_{\hat{V}} = \frac{f_{\hat{V}}}{2\sqrt{2}}\, f_+^{\mu\nu} + \frac{i\, g_{\hat{V}}}{2\sqrt{2}}\, [u^\mu, u^\nu] \qquad , \qquad \hat{\chi}^{\mu\nu}_{\hat{A}} = \frac{f_{\hat{A}}}{2\sqrt{2}}\, f_-^{\mu\nu} + \frac{\lambda_1^{h\hat{A}}}{\sqrt{2}}\, \left[(\partial^\mu h)\, u^\nu - (\partial^\nu h)\, u^\mu \right]$$

$$\rightarrow \qquad \Delta\mathcal{L}_{\hat{R}}^{\mathcal{O}(p^4)} = 0 \qquad \rightarrow \qquad \Delta\mathcal{F}_i^{(P)} = 0$$

Proca Spin–1 Fields: $\hat{R}^\mu = \hat{V}^\mu, \hat{A}^\mu$

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$$\longrightarrow \quad \Delta\mathcal{L}_{\hat{R}}^{\mathcal{O}(p^4)} = 0 \quad \longrightarrow \quad \Delta\mathcal{F}_i^{(P)} = 0$$

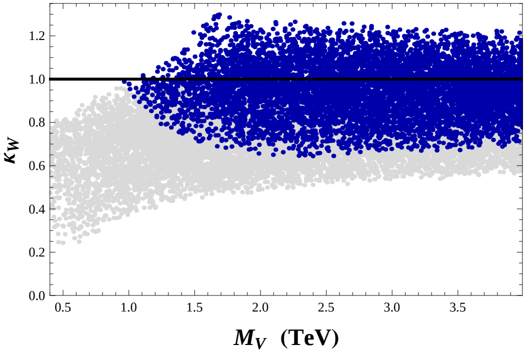
But there are also terms without $\hat{R}^\mu$: $\quad \mathcal{L}^{(4,P/A)}_{\text{non-}R} = \sum_{i=1}^{9} \mathcal{F}_i^{\mathrm{SDP/A}}\, \mathcal{O}_i$

$$\mathbb{F}^{\mathcal{V}}_{\varphi\varphi}(s) = \begin{cases} 1 + \frac{F_V\, G_V}{v^2}\, \frac{s}{M_V^2 - s} - 2\,\mathcal{F}_3^{\mathrm{SDA}}\, \frac{s}{v^2} & \text{(SDET-A)} \\ 1 + \frac{f_{\hat{V}}\, g_{\hat{V}}}{v^2}\, \frac{s^2}{M_V^2 - s} - 2\,\mathcal{F}_3^{\mathrm{SDP}}\, \frac{s}{v^2} & \text{(SDET-P)} \end{cases}$$

High-energy behaviour $\longrightarrow \quad \mathcal{F}_3^{\mathrm{SDA}} = 0 \quad , \quad \mathcal{F}_3^{\mathrm{SDP}} = -\frac{f_{\hat{V}}\, g_{\hat{V}}}{2} \equiv -\frac{F_V\, G_V}{2 M_V^2}$

Gauge Boson Self-Energies @ NLO

Weaker assumptions: 1^{st} WSR only , $M_A > M_V > 0.4$ TeV



AP, Rosell, Sanz-Cillero

- $0.2 < \frac{M_V}{M_A} < 1$
- $0.02 < \frac{M_V}{M_A} < 0.2$

$\kappa_W \equiv g_{SWW} / g^{SM}_{HWW}$ very different from one

requires large (unnatural) mass splittings

Resonance Contributions to Bosonic LECs

A.P., Rosell, Santos, Sanz-Cillero
1609.06659

i	$\mathcal{F}_i$	$\widetilde{\mathcal{F}}_i$
1	$-\frac{F_V^2-\widetilde{F}_V^2}{4M_V^2}+\frac{F_A^2-\widetilde{F}_A^2}{4M_A^2}$	$-\frac{\widetilde{F}_V G_V}{2M_V^2}-\frac{F_A\widetilde{G}_A}{2M_A^2}$
2	$-\frac{F_V^2+\widetilde{F}_V^2}{8M_V^2}-\frac{F_A^2+\widetilde{F}_A^2}{8M_A^2}$	$-\frac{F_V\widetilde{F}_V}{4M_V^2}-\frac{F_A\widetilde{F}_A}{4M_A^2}$
3	$-\frac{F_V G_V}{2M_V^2}-\frac{\widetilde{F}_A\widetilde{G}_A}{2M_A^2}$	$-\frac{F_V\widetilde{\lambda}_1^{hV}v}{M_V^2}-\frac{\widetilde{F}_A\lambda_1^{hA}v}{M_A^2}$
4	$\frac{G_V^2}{4M_V^2}+\frac{\widetilde{G}_A^2}{4M_A^2}$	—
5	$\frac{c_d^2}{4M_{S_1}^2}-\frac{G_V^2}{4M_V^2}-\frac{\widetilde{G}_A^2}{4M_A^2}$	—
6	$-\frac{\widetilde{\lambda}_1^{hV\,2}v^2}{M_V^2}-\frac{\lambda_1^{hA\,2}v^2}{M_A^2}$	—
7	$\frac{d_P^2}{2M_P^2}+\frac{\lambda_1^{hA\,2}v^2}{M_A^2}+\frac{\widetilde{\lambda}_1^{hV\,2}v^2}{M_V^2}$	—
8	0	—
9	$-\frac{F_A\lambda_1^{hA}v}{M_A^2}-\frac{\widetilde{F}_V\widetilde{\lambda}_1^{hV}v}{M_V^2}$	—
10	$-\frac{(\widetilde{c}_T^{\hat{V}_1})^2}{2M_{V_1}^2}-\frac{(c_T^{\hat{A}_1})^2}{2M_{A_1}^2}$	—
11	$-\frac{F_{V_1}^2}{M_{V_1}^2}-\frac{\widetilde{F}_{A_1}^2}{M_{A_1}^2}$	—

Resonance Contributions to Two-Fermion LECs

i	$\mathcal{F}_i^{\psi^2}$	$\widetilde{\mathcal{F}}_i^{\psi^2}$
1	$\dfrac{c_d\, c_1^{S_1}}{2M_{S_1}^2}$	$-\dfrac{\widetilde{F}_V\, C_0^V}{\sqrt{2}M_V^2} - \dfrac{F_A\, \widetilde{C}_0^A}{\sqrt{2}M_A^2}$
2	$-\dfrac{G_V\, C_0^V}{\sqrt{2}M_V^2} - \dfrac{\widetilde{G}_A\, \widetilde{C}_0^A}{\sqrt{2}M_A^2}$	$-\dfrac{2\sqrt{2}v\widetilde{\lambda}_1^{hV}\, C_0^V}{M_V^2} - \dfrac{2\sqrt{2}v\lambda_1^{hA}\, \widetilde{C}_0^A}{M_A^2}$
3	$-\dfrac{F_V\, C_0^V}{\sqrt{2}M_V^2} - \dfrac{\widetilde{F}_A\, \widetilde{C}_0^A}{\sqrt{2}M_A^2}$	$-\dfrac{\widetilde{c}_{\mathcal{T}}^{\hat{V}_1}\, c_1^{\hat{V}_1}}{\sqrt{2}M_{V_1}^2} - \dfrac{c_{\mathcal{T}}^{\hat{A}_1}\, \widetilde{c}_1^{\hat{A}_1}}{\sqrt{2}M_{A_1}^2}$
4	$-\dfrac{\sqrt{2}F_{V_1}\, C_0^{V_1}}{M_{V_1}^2} - \dfrac{\sqrt{2}\widetilde{F}_{A_1}\, \widetilde{C}_0^{A_1}}{M_{A_1}^2}$	—
5	$\dfrac{d_P\, c_1^P}{M_P^2}$	—
6	$-\dfrac{\widetilde{c}_{\mathcal{T}}^{\hat{V}_1}\, \widetilde{c}_1^{\hat{V}_1}}{\sqrt{2}M_{V_1}^2} - \dfrac{c_{\mathcal{T}}^{\hat{A}_1}\, c_1^{\hat{A}_1}}{\sqrt{2}M_{A_1}^2}$	—
7	0	—

Resonance Contributions to Four-Fermion LECs

i	$\mathcal{F}_i^{\psi^4}$	$\widetilde{\mathcal{F}}_i^{\psi^4}$
1	$\frac{(c_1^S)^2}{2M_S^2}$	$-\frac{c_1^{\hat{V}}\widetilde{c}_1^{\hat{V}}}{M_V^2}-\frac{c_1^{\hat{A}}\widetilde{c}_1^{\hat{A}}}{M_A^2}$
2	$\frac{(c_1^P)^2}{2M_P^2}$	$\frac{c_1^{\hat{V}}\widetilde{c}_1^{\hat{V}}}{2M_V^2}+\frac{c_1^{\hat{A}}\widetilde{c}_1^{\hat{A}}}{2M_A^2}-\frac{c_1^{\hat{V}_1}\widetilde{c}_1^{\hat{V}_1}}{2M_{V_1}^2}-\frac{c_1^{\hat{A}_1}\widetilde{c}_1^{\hat{A}_1}}{2M_{A_1}^2}$
3	$-\frac{(c_1^S)^2}{4M_S^2}+\frac{(c_1^{S_1})^2}{4M_{S_1}^2}$	—
4	$-\frac{(c_1^P)^2}{4M_P^2}+\frac{(c_1^{P_1})^2}{4M_{P_1}^2}$	—
5	$-\frac{(c_1^{\hat{V}})^2}{2M_V^2}-\frac{(\widetilde{c}_1^{\hat{A}})^2}{2M_A^2}$	—
6	$-\frac{(\widetilde{c}_1^{\hat{V}})^2}{2M_V^2}-\frac{(c_1^{\hat{A}})^2}{2M_A^2}$	—
7	$\frac{(c_1^{\hat{V}})^2}{4M_V^2}+\frac{(\widetilde{c}_1^{\hat{A}})^2}{4M_A^2}-\frac{(c_1^{\hat{V}_1})^2}{4M_{V_1}^2}-\frac{(\widetilde{c}_1^{\hat{A}_1})^2}{4M_{A_1}^2}$	—
8	$\frac{(\widetilde{c}_1^{\hat{V}})^2}{4M_V^2}+\frac{(c_1^{\hat{A}})^2}{4M_A^2}-\frac{(\widetilde{c}_1^{\hat{V}_1})^2}{4M_{V_1}^2}-\frac{(c_1^{\hat{A}_1})^2}{4M_{A_1}^2}$	—
9	$-\frac{(C_0^V)^2}{M_V^2}-\frac{(\widetilde{C}_0^A)^2}{M_A^2}$	—
10	$\frac{(C_0^V)^2}{2M_V^2}-\frac{(C_0^{V_1})^2}{2M_{V_1}^2}+\frac{(\widetilde{C}_0^A)^2}{2M_A^2}-\frac{(\widetilde{C}_0^{A_1})^2}{2M_{A_1}^2}$	—