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Testing Composite Higgs models with Vector Boson Scattering at LHC

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Composite Higgs Models with partial compositeness

EW sector:

$$G \to H \supset SU(2)_L \times SU(2)_R$$

Minimal Cosets: $SU(4)/Sp(4) \quad SU(4)^2/SU(4) \quad SU(5)/SO(5)$

$\langle\psi\psi\rangle \sim h,\ \pi$

Higgs boson emerges as a pseudo-Nambu-Goldstone boson (pNGB)

$\langle\psi\chi\psi\rangle, \langle\chi\psi\chi\rangle \sim T$

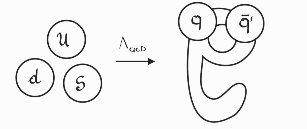
Top partners appears as bound states of three hyperfermions

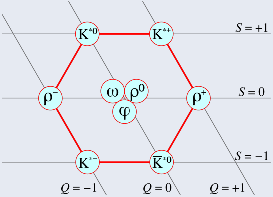
Composite Higgs models with partial compositeness

$\langle \psi \sigma_\mu \psi \rangle \sim \mathcal{V}_\mu, \mathcal{A}_\mu$

QCD

- $SU(3)_L \otimes SU(3)_R \to SU(3)_D$

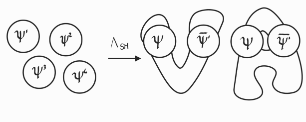




Composite Higgs

- $G \to H$

  Ex.: $SU(4)/Sp(4)$



$\mathcal{A}_\mu$		$\mathcal{V}_\mu$	
$\mathrm{SU}(2)_D$	name	$\mathrm{SU}(2)_D$	name
3	a_μ	3	$\hat{r}_\mu$
1	$\hat{y}_{1\mu}$	1	$\hat{x}_{1\mu}$
1	$\hat{y}_{2\mu}$	3	$v_{1\mu}$
		3	$v_{2\mu}$

Composite Higgs models with partial compositeness

$\langle\psi\psi\rangle \sim \mathcal{V}_\mu, \mathcal{A}_\mu$

Spin-1 resonances mix with each other

$$r^+, r^0 \text{gauge eigenstates} \quad R^+, R^0 \text{mass eigenstates}$$

$$R^+ = \left(W_\mu^+, V_{1\mu}^+, \dots\right) \quad R^0 = \left(A_\mu, Z_\mu, V_{1\mu}^0, V_{2\mu}^0, \dots\right)$$

$$r^+ = \mathcal{C}R^+ \quad r^0 = \mathcal{N}R^0 \quad \mathcal{C}, \mathcal{N} \text{ mixing matrices}$$

Mass mixing induces fermion couplings

Charged and neutral currents of SM get modified:

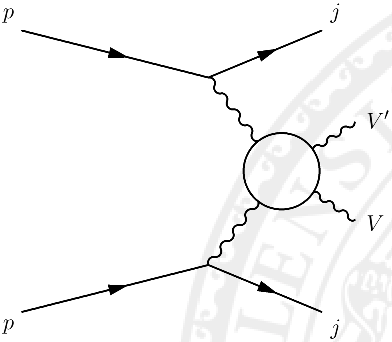
$$\mathcal{L}_{CC} = \frac{\hat{g}}{\sqrt{2}} \sum_{ij} \bar{q}_i \gamma^\mu \tilde{W}_\mu^+ P_L (V_{CKM})^{i,j} q_j = \frac{\hat{g}}{\sqrt{2}} \sum_{i,j,m} \mathcal{C}_{1m} \bar{q}_i \gamma^\mu R_{m,\mu}^+ P_L (V_{CKM})^{ij} q_j$$

VBS

VBS

What is VBS?

Vector Boson Scattering (VBS) is an interaction of the kind VV'$\rightarrow$ VV', where V designates the electroweak bosons of the SM, i.e. V = W, Z, γ



$$V, V' = W^{\pm}, Z, \gamma$$

Why VBS?

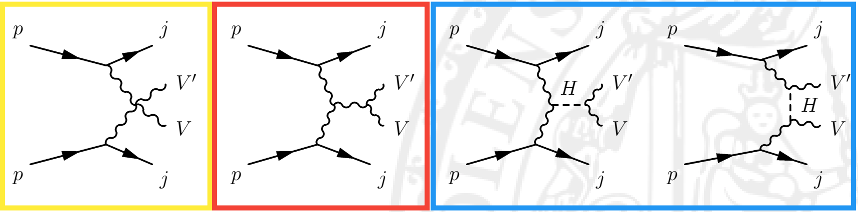
- Test of the SM for its sensitivity to gauge boson self-couplings.
- A direct probe of the triple and quartic gauge boson couplings.
- Understanding fundamental interactions and the SM gauge structure.
- Probe new physics processes at multi-TeV energy scales. A window to new physics processes.

New vertices

- We start with the simplest coset $SU(4)/Sp(4)$

$\mathcal{A}_\mu$			$\mathcal{V}_\mu$		
$\mathrm{SU}(2)^2$	$\mathrm{SU}(2)_D$	name	$\mathrm{SU}(2)^2$	$\mathrm{SU}(2)_D$	name
(2,2)	3	a_μ	(2,2)	3	$\hat{r}_\mu$
	1	$\hat{y}_{1\mu}$		1	$\hat{x}_{1\mu}$
(1,1)	1	$\hat{y}_{2\mu}$	(3,1)+(1,3)	3	$v_{1\mu}$
				3	$v_{2\mu}$

- New vertices contribute to the VBS



  - Quartic Gauge Coupling (QGC)
  - Double Triple Gauge Coupling (TGC)
  - Higgs exchange in s- and t- channel (HC)

$W^+W^+ \to W^+W^+$

- Due to its distinctive signature and low background, the same-sign $W^+W^+ \to W^+W^+$ process is the "golden" channel of VBS processes. Using MadGraph5

$$pp \to W^+W^+jj$$

- We let the W decay leptonically (MadSpin) and the quarks shower (pythia8):

$$pp \to W^+W^+jj \to l_i^+\nu_{l,i}l_k^+\nu_{l,k}jj$$

Cuts

An experimental cut refers to a kinematic or selection cut applied to simulated events to mimic the conditions of a real particle physics experiment and reduce background.

Requirement	SR	Low-m_{jj} CR	WZ CR
Leading and subleading lepton p_T	> 27 GeV		
Electron $\|\eta\|$	< 2.47 (1.37 in ee), excluding $1.37 \leq \|\eta\| \leq 1.52$		
Muon $\|\eta\|$	< 2.5		
Leading (subleading) jet p_T	> 65 (35) GeV		
Additional jet p_T	> 25 GeV		
Jet $\|\eta\|$	< 4.5		
$m_{\ell\ell}$	> 20 GeV		
E_T^{miss}	> 30 GeV		
Charge misid. $Z \to ee$ veto	$\|m_{ee} - m_Z\| > 15$ GeV		–
b-jet veto	$N_{b\text{-jet}} = 0$, $p_T^{b\text{-jet}} > 20$ GeV, $\|\eta^{b\text{-jet}}\| < 2.5$		
$N_{\text{veto leptons}}$	= 0	= 0	= 1 , $p_T > 15$ GeV
$m_{\ell\ell\ell}$	–	–	> 106 GeV
m_{jj}	> 500 GeV	$200 < m_{jj} < 500$ GeV	> 200 GeV
$\|\Delta y_{jj}\|$	> 2		

from Atlas arXiv:2312.00420v2

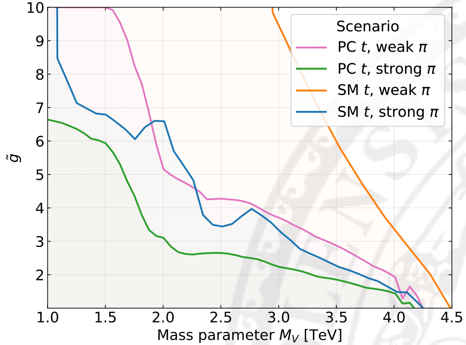
p_{Tj} $\Longrightarrow$ Removes soft jets (background).
VBS jets are mostly hard (t-channel exchange).

$|\Delta y|$ $\Longrightarrow$ Ensures jets are within the measurable region.
VBS jets are often forward-backward

m_{jj} $\Longrightarrow$ high-mjj due to energetic forward-backward jets.
Background processes (QCD) have lower-mjj, suppressed

Parameter Space

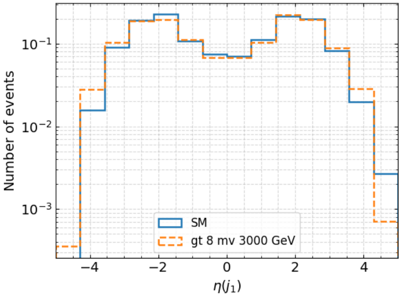
- M_V = mass parameter;
- $\tilde{g}$ = gauge coupling of the spin-1 resonances

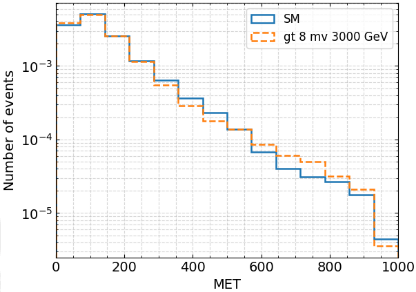


10.1007/JHEP04(2025)160

Results

Using MadAnalysis5





What's next?

- Understanding why there is this cancellation
- Study polarized SM bosons,
- Study other VBS processes

Vielen Dank

Hidden symmetries approach

Consider two sectors:

$$
\begin{array}{ccccccc}
SU(2)_L \otimes U(1)_Y \subset & G_0 & \otimes & G_1 & & & \\
 & \downarrow & & \downarrow & & & 1) \\
 & H_0 & \otimes & H_1 & & & \\
 & \searrow & & \swarrow & & & 2) \\
SU(2)_L \otimes U(1)_Y \subset & & H_d & & & & \\
\downarrow & & & & & & 3) \\
U(1)_{em} & & & & & &
\end{array}
$$

where:

- G_0 is partly gauged by SM,
- G_1 is fully gauged by the heavy resonances

[1] D. Franzosi et all arXiv:1605.01363v3 [hep-ph] 7 Nov 2016

Why Partial Compositeness is Natural?[1]

Technicolor

$$\mathcal{L}_{int}[\Lambda_{UV}] = \frac{\lambda_{t_L}}{\Lambda_{UV}^{d_L-1}}\bar{q}_L\mathcal{O}_S^L t_R + \frac{\lambda_{t_R}}{\Lambda_{UV}^{d_R-1}}\bar{q}_L\mathcal{O}_S^R b_R$$

Partial compositenesss

$$\mathcal{L}_{int}[\Lambda_{UV}] = \frac{\lambda_{t_L}}{\Lambda_{UV}^{d_L-\frac{5}{2}}}\bar{q}_L\mathcal{O}_F^L + \frac{\lambda_{t_R}}{\Lambda_{UV}^{d_R-\frac{5}{2}}}\bar{t}_R\mathcal{O}_F^R$$

$d_{R/L}$ are the dimensions of $\mathcal{O}_{F/S}^{R/L}$.
Let's call $s = \{1, \frac{5}{2}\}$

$$\lambda_{t_L}[m_*] \simeq \lambda_{t_L}\left(\frac{m_*}{\Lambda_{UV}}\right)^{d_L-s} \quad \lambda_{t_R}[m_*] \simeq \lambda_{t_R}\left(\frac{m_*}{\Lambda_{UV}}\right)^{d_R-s}$$

To generate a large enough top Yukawa $y_t \sim \lambda_{t_L}\lambda_{t_R}/g^*$ we need $s \sim d_{L/R}$

- if $S \sim 1$ (Technicolor):
  the only possible theory is the one with a free scalar $\implies$ NP
- if $S \sim \frac{5}{2}$ (PC):
  No problem occurs. $\mathcal{O}_F^{R/L}$ contain Fermions (Top partners)

[1] G. Panico and A. Wulzer arXiv:1506.01961

Scheme

To construct top-partners, as trilinears of new UV hyperfermions, carrying both color and EW quantum numbers, we need models with hyperfermions in two inequivalent irreducible representations $\{\psi, \chi\}$ and two different breaking sectors for color and EW breaking.

EW Sector breaking: ψ

The three minimal cosets, preserving custodial symmetry, $G \to H \subset G_{CS}$, are:

- $SU(5)/SO(5)$;
- $SU(4)/Sp(4)$;
- $SU(4) \otimes SU(4)'/SU(4)_D$.

Color Sector breaking: χ

The three minimal cosets, preserving the color group $G \to H \subset G_{QCD}$, are:

- $SU(6)/SO(6)$;
- $SU(6)/Sp(6)$;
- $SU(3) \otimes SU(3)'/SU(3)_D$.

Models

G_{HC}	ψ	χ	Restrictions	$-q_\chi/q_\psi$	Y_χ	Non Conformal	Model Name
	Real	Real	SU(5)/SO(5) × SU(6)/SO(6)				
$SO(N_{\mathrm{HC}})$	$5\times\mathbf{S}_2$	$6\times\mathbf{F}$	$N_{\mathrm{HC}}\geq 55$	$\frac{5(N_{\mathrm{HC}}+2)}{6}$	1/3	/	
$SO(N_{\mathrm{HC}})$	$5\times\mathbf{Ad}$	$6\times\mathbf{F}$	$N_{\mathrm{HC}}\geq 15$	$\frac{5(N_{\mathrm{HC}}-2)}{6}$	1/3	/	
$SO(N_{\mathrm{HC}})$	$5\times\mathbf{F}$	$6\times\mathbf{Spin}$	$N_{\mathrm{HC}}=7,9$	$\frac{5}{6},\frac{5}{12}$	1/3	$N_{\mathrm{HC}}=7,9$	M1, M2
$SO(N_{\mathrm{HC}})$	$5\times\mathbf{Spin}$	$6\times\mathbf{F}$	$N_{\mathrm{HC}}=7,9$	$\frac{5}{6},\frac{5}{3}$	2/3	$N_{\mathrm{HC}}=7,9$	M3, M4
	Real	Pseudo-Real	SU(5)/SO(5) × SU(6)/Sp(6)				
$Sp(2N_{\mathrm{HC}})$	$5\times\mathbf{Ad}$	$6\times\mathbf{F}$	$2N_{\mathrm{HC}}\geq 12$	$\frac{5(N_{\mathrm{HC}}+1)}{3}$	1/3	/	
$Sp(2N_{\mathrm{HC}})$	$5\times\mathbf{A}_2$	$6\times\mathbf{F}$	$2N_{\mathrm{HC}}\geq 4$	$\frac{5(N_{\mathrm{HC}}-1)}{3}$	1/3	$2N_{\mathrm{HC}}=4$	M5
$SO(N_{\mathrm{HC}})$	$5\times\mathbf{F}$	$6\times\mathbf{Spin}$	$N_{\mathrm{HC}}=11,13$	$\frac{5}{24},\frac{5}{48}$	1/3	/	
	Real	Complex	SU(5)/SO(5) × SU(3)^2/SU(3)				
$SU(N_{\mathrm{HC}})$	$5\times\mathbf{A}_2$	$3\times(\mathbf{F},\overline{\mathbf{F}})$	$N_{\mathrm{HC}}=4$	$\frac{5}{3}$	1/3	$N_{\mathrm{HC}}=4$	M6
$SO(N_{\mathrm{HC}})$	$5\times\mathbf{F}$	$3\times(\mathbf{Spin},\overline{\mathbf{Spin}})$	$N_{\mathrm{HC}}=10,14$	$\frac{5}{12},\frac{5}{48}$	1/3	$N_{\mathrm{HC}}=10$	M7
	Pseudo-Real	Real	SU(4)/Sp(4) × SU(6)/SO(6)				
$Sp(2N_{\mathrm{HC}})$	$4\times\mathbf{F}$	$6\times\mathbf{A}_2$	$2N_{\mathrm{HC}}\leq 36$	$\frac{1}{3(N_{\mathrm{HC}}-1)}$	2/3	$2N_{\mathrm{HC}}=4$	M8
$SO(N_{\mathrm{HC}})$	$4\times\mathbf{Spin}$	$6\times\mathbf{F}$	$N_{\mathrm{HC}}=11,13$	$\frac{8}{3},\frac{16}{3}$	2/3	$N_{\mathrm{HC}}=11$	M9
	Complex	Real	SU(4)^2/SU(4) × SU(6)/SO(6)				
$SO(N_{\mathrm{HC}})$	$4\times(\mathbf{Spin},\overline{\mathbf{Spin}})$	$6\times\mathbf{F}$	$N_{\mathrm{HC}}=10$	$\frac{8}{3}$	2/3	$N_{\mathrm{HC}}=10$	M10
$SU(N_{\mathrm{HC}})$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$6\times\mathbf{A}_2$	$N_{\mathrm{HC}}=4$	$\frac{2}{3}$	2/3	$N_{\mathrm{HC}}=4$	M11
	Complex	Complex	SU(4)^2/SU(4) × SU(3)^2/SU(3)				
$SU(N_{\mathrm{HC}})$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$3\times(\mathbf{A}_2,\overline{\mathbf{A}}_2)$	$N_{\mathrm{HC}}\geq 5$	$\frac{4}{3(N_{\mathrm{HC}}-2)}$	2/3	$N_{\mathrm{HC}}=5$	M12
$SU(N_{\mathrm{HC}})$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$3\times(\mathbf{S}_2,\overline{\mathbf{S}}_2)$	$N_{\mathrm{HC}}\geq 5$	$\frac{4}{3(N_{\mathrm{HC}}+2)}$	2/3	/	
$SU(N_{\mathrm{HC}})$	$4\times(\mathbf{A}_2,\overline{\mathbf{A}}_2)$	$3\times(\mathbf{F},\overline{\mathbf{F}})$	$N_{\mathrm{HC}}=5$	4	2/3	/	

Literature:

- A. Belyaev, G. Cacciapaglia, H. Cai, G.Ferretti, T. Flacke, A. Parolini, H. Serodio arXiv:1610.06591v3 [hep-ph] 3 Dec 2017
- G. Ferretti arXiv:1604.06467v2 [hep-ph] 8 Jun 2016
- G. Cacciapaglia, A. Deandrea, M. Kunkel, W. Porod arXiv:2404.02198v1 [hep-ph] 2 Apr 2024

We are interested in EW Spin-1 resonances.

Particle content and models

coset/particles	pNGBs			$\mathcal{A}_\mu$			$\mathcal{V}_\mu$		
	$SU(2)^2$	$SU(2)_D$	name	$SU(2)^2$	$SU(2)_D$	name	$SU(2)^2$	$SU(2)_D$	name
SU(4)/Sp(4)	(2,2)	3	φ	(2,2)	3	a_μ	(2,2)	3	$\hat{r}_\mu$
		1	H		1	$\hat{y}_{1\mu}$		1	$\hat{x}_{1\mu}$
in M8-M9	(1,1)	1	η	(1,1)	1	$\hat{y}_{2\mu}$	(3,1)+(1,3)	3	$v_{1\mu}$
								3	$v_{2\mu}$
SU(5)/SO(5)	(2,2)	3	φ	(2,2)	3	a_μ	(2,2)	3	$\hat{r}_\mu$
		1	H		1	$\hat{y}_{1\mu}$		1	$\hat{x}_{1\mu}$
in M1-M7	(1,1)	1	η	(1,1)	1	$\hat{y}_{2\mu}$	(3,1)+(1,3)	3	$v_{1\mu}$
	(3,3)	5	η_5	(3,3)	5	$\hat{a}_{5\mu}$		3	$v_{2\mu}$
		3	η_3		3	$\hat{a}_{3\mu}$			
		1	η_1		1	$\hat{a}_{1\mu}$			
$SU(4)^2/SU(4)$	(2,2)	3	φ	(2,2)	3	a_μ	(2,2)	3	$\hat{r}_\mu$
		1	H		1	$\hat{y}_{1\mu}$		1	$\hat{x}_{1\mu}$
in M10-M12	(2,2)	3	ϕ_1	(2,2)	3	$\hat{a}_\mu$	(2,2)	3	r_μ
		1	ϕ_2		1	$\hat{y}_{3\mu}$		1	$\hat{x}_{3\mu}$
	(1,1)	1	η	(1,1)	1	$\hat{y}_{2\mu}$	(1,1)	1	$\hat{x}_{2\mu}$
	(3,1)+(1,3)	3	η_1	(3,1)+(1,3)	3	$b_{1\mu}$	(3,1)+(1,3)	3	$v_{1\mu}$
		3	η_2		3	$b_{2\mu}$		3	$v_{2\mu}$

Wess-Zumino-Witten (WZW) term (arXiv:2202.00037v2 [hep-ph])

$$\mathcal{L}_{anom} = \alpha A \qquad \text{A - HC Anomaly}$$

$$\mathcal{L}_{anom} = \frac{e^2 dim(\psi)}{46\pi^2 f} \sum_{\substack{i=pNGBs \\ A,B=\gamma,Z,W}} K^i_{A,B} F^A_{\mu\nu} F^{\mu\nu}_B \pi^i$$

Coset	π_i	$K^i_{\gamma\gamma}$	$K^i_{\gamma Z}$	K^i_{ZZ}	K^i_{WW}	$K^i_{\gamma W}$	K^i_{ZW}	$K^i_{W^-W^-}$
$\frac{SU(4)}{Sp(4)}$	η	0	$\frac{3c_\theta}{s_W c_W}$	$\frac{3c_{2W}c_\theta}{2s_W^2 c_W^2}$	$\frac{3c_\theta}{s_W^2}$	–	–	–
	χ_5^0	$-2\sqrt{3}$	$-\frac{4\sqrt{3}c_{2W}}{s_{2W}}$	$\frac{(1-3c_{4W}+2c_{2\theta})}{\sqrt{3}s_{2W}^2}$	$\frac{s_\theta^2}{\sqrt{3}s_W^2}$	–	–	–
	χ_1^0	$\sqrt{6}$	$\frac{2\sqrt{6}c_{2W}}{s_{2W}}$	$\frac{(1+6c_{4W}-7c_{2\theta})}{2\sqrt{6}s_{2W}^2}$	$\frac{7}{2\sqrt{6}}\frac{s_\theta^2}{s_W^2}$	–	–	–
	η	$3\sqrt{\frac{2}{5}}$	$\sqrt{\frac{2}{5}}\frac{6c_{2W}}{s_{2W}}$	$\frac{3(3c_\theta^2+c_{4W})}{4\sqrt{10}c_W^2 s_W^2}$	$\frac{3(3c_{2\theta}+5)}{4\sqrt{10}s_W^2}$	–	–	–
$\frac{SU(5)}{SO(5)}$	χ_3^+	–	–	–	–	$-\frac{3c_\theta}{s_W}$	$\frac{3c_\theta}{c_W}$	–
	χ_5^+	–	–	–	–	$\frac{3i}{s_W}$	$\frac{i(3c_{2W}-c_{2\theta}-2)}{2c_W s_W^2}$	–
	χ_5^{++}	–	–	–	–	–	–	$-\frac{s_\theta^2}{\sqrt{2}s_W^2}$
$\frac{SU(4)_l \times SU(4)_r}{SU(4)_d}$	η	0	$\frac{3c_\theta}{s_W c_W}$	$\frac{3c_{2W}c_\theta}{2s_W^2 c_W^2}$	$\frac{3c_\theta}{s_W^2}$	–	–	–

Partial Compositeness

In models with PC the mixing between the top quark and the top partners induce an additional contribution to this coupling of the form

$$\mathcal{L}_{\mathrm{PC}} = \bar{t}\left(\not{V}_1^0 + \not{V}_2^0\right)\left(g_{t,L}P_L + g_{t,R}P_R\right)t + \bar{b}\left(\not{V}_1^0 + \not{V}_2^0\right)\left(g_{b,L}P_L\right)b + g_{tb,L}\bar{t}\not{V}_1^+ P_L b\,.$$

Here we have assumed:

$$\mathbf{SM}\,\boldsymbol{t}: \quad g_{t,L/R} = g^{\mathrm{SM}}_{Ztt,L/R}, \qquad g_{b,L} = g^{\mathrm{SM}}_{Zbb,L}, \qquad g_{tb,L} = g^{\mathrm{SM}}_{Wtb}\,, \quad (1)$$

$$\mathbf{PC}\,\boldsymbol{t}: \quad g_{t,L} = \frac{1}{\sqrt{10}}\,,\; g_{t,R} = \frac{3}{\sqrt{10}}\,, \qquad g_{b,L} = \frac{1}{\sqrt{10}}\,, \qquad g_{tb,L} = \frac{1}{\sqrt{5}}\,, \quad (2)$$

gVpipi

The Lagrangian gives rise to couplings of the spin-1 resonances to two pNGB. On the one hand, they have their origin from direct couplings of the pNGB to the spin-1 resonances before taking into account any mixing with SM vector bosons:

$$\frac{f_1^2}{4}\,\mathrm{Tr}\, d_{1,\mu} d_1^\mu + \frac{f_K^2}{4}\mathrm{Tr}\Big(e_{1\mu}e_1^\mu - 2e_{0\mu}e_1^\mu\Big) + \frac{r f_1^2}{2}\,\mathrm{Tr}\, d_{0,\mu} d_1^\mu \supset \frac{i}{2} g_{V\pi\pi}\cdot \mathrm{Tr}\left(\mathcal{V}_\mu\left[\tilde{\Pi}_P, \partial_\mu \tilde{\Pi}_P\right]\right) \tag{3}$$

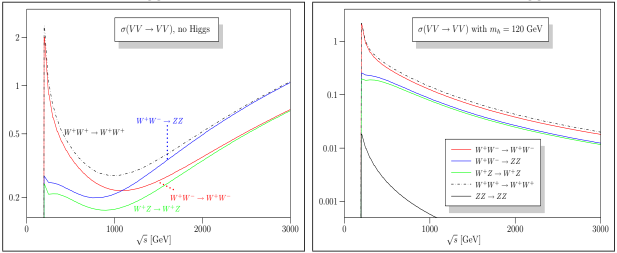
where we defined the Vector-pNGB-pNGB coupling constant

$$g_{V\pi\pi} = \frac{\tilde{g} f_K^2 (r^2-1)}{f_\pi^2}\,. \tag{4}$$

Unitarity

$QGC + TGC \sim s \implies$ Unitarity violation = loss of conservation of probability
$QGC + TGC + HC \sim \frac{1}{s} \implies$ cancellation by the Higgs boson in the s and t channels.

SM without a Higgs boson SM with a 120 GeV Higgs boson

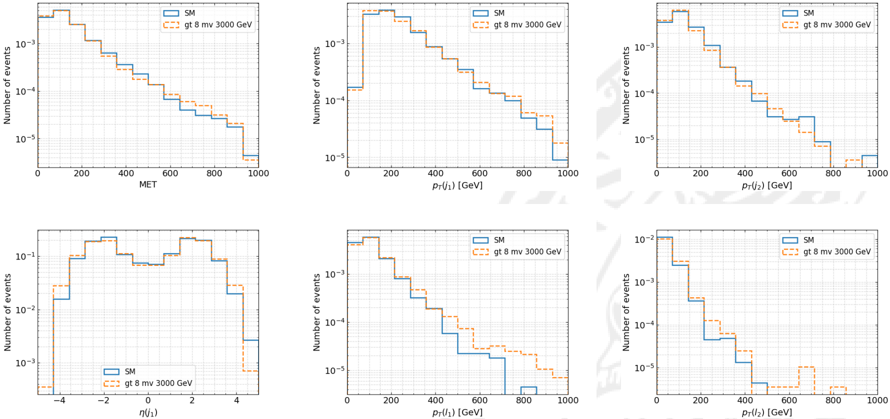


from arXiv:0806.4145

If the Higgs boson's couplings to weak bosons deviate from SM predictions, cancellations may not be as effective and the scattering amplitude may increase with energy.
A consistent theory requires a Higgs boson with $m_H < 1TeV$ or new Physics at the TeV scale

Results

Using MadAnalysis5



Results $\tilde{g} = 2$