

STRONG HIGGS PRODUCTION AT CLIC

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to appear soon and also based on arXiv:1202.5940

OUTLINE

1 MOTIVATION

- For a Strongly Coupled Sector
- For the ILC and CLIC

2 PHENOMENOLOGY

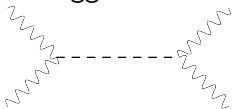
- WW scattering: probing a
- Double Higgs Production: probing b and d_3
- Triple Higgs Production: probing the coset space

3 CONCLUSION AND OUTLOOK

HIGGS AS A COMPOSITE NAMBU-GOLDSTONE-BOSON

Weak Dynamics:

Higgs Boson



Strong Dynamics:

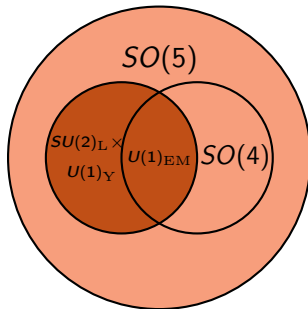
Non-perturbative Interactions



Interpolation: **Strongly interacting light Higgs**

[Giudice, Grojean, Pomarol, Rattazzi 07]

- Higgs - bound state of strongly interacting sector
- Minimal Coset: $SO(5)/SO(4)$
 \Rightarrow 4 NG-bosons
 3 eaten, 1 Higgs
- Breaking scale f



ANOMALOUS HIGGS COUPLINGS

- Higgs potential at one-loop in weak gauge coupling \Rightarrow
 $\langle H \rangle = v$ controlled by small explicit breaking of $SO(5)$

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - V(h) + \left(m_W^2 W_\mu^+ W^{\mu-} + \frac{m_Z^2}{2} Z_\mu Z^\mu \right) \left[1 + 2a \frac{h}{v} + b \frac{h^2}{v^2} + b_3 \frac{h^3}{v^3} + \dots \right]$$

$$V(h) = \frac{1}{2} m_h^2 h^2 + d_3 \left(\frac{m_h^2}{2v} \right) h^3 + \dots$$

- Couplings in terms of $\xi = \frac{v^2}{f^2} = \frac{\text{weak scale}^2}{\text{strong scale}^2}$

$$a = \sqrt{1 - \xi} \quad b = 1 - 2\xi \quad b_3 = -\frac{4}{3}\xi\sqrt{1 - \xi} \quad d_3 = \sqrt{1 - \xi}$$

- SM: $\xi = 0 \Rightarrow a = b = d_3 = 1, b_3 = 0$

HIGGS PRECISION MEASUREMENTS

- Elementary or composite Higgs?
 - If $\sigma(W^+W^- \rightarrow hh)$ grows with s
 measure deviations from $a = b = 1$: δ_{hh}
 lower bound on strong coupling: $g_\rho > \sqrt{\delta_{hh}} \frac{E}{v}$
- In $SU(2)$ doublet?
 - Measure precise relation between a and b in single and double Higgs production:
 $2a^2 - b = 1$
- NG-boson?
 - Triple Higgs production:
 suppressed if NG-boson due to $\pi \rightarrow -\pi$ symmetry

THE ILC AND CLIC

	International Linear Collider ILC	Compact Linear Collider CLIC
Collisions	e^+e^- linear collider	
\sqrt{s} [TeV]	0.5	3 and 5
Luminosity [$cm^{-2}s^{-1}$]	2×10^{34}	0.8×10^{35}
Site length [km]	31	33
Assume negligible SM background, full Higgs reconstruction		

WW SCATTERING AT CLIC

- Scattering of longitudinal components:
 $\mathcal{A}(V_L^+ V_L^- \rightarrow V_L^+ V_L^-) \sim (s + t)/v^2$
- Process: $e^+ e^- \rightarrow W^+ W^- \nu \bar{\nu}$
- p_T -cut to optimize analysis
- Statistical relative error $\Delta\xi/\xi$

\sqrt{s} [TeV]	ξ			
	0.01	0.05	0.1	0.7
0.5	32	7	4	0.47
3	8.0	1.3	0.51	0.02
5	1.19	0.39	0.34	0.006

for $L = 1 \text{ ab}^{-1}$, $m_h = 125 \text{ GeV}$

- LHC with 14 TeV, 300 fb^{-1} : sensitive to $\xi \geq 0.5$
 [Contino, Grojean, Moretti, Piccinini, Rattazzi '10]

DOUBLE HIGGS PRODUCTION AT THE LHC

- Directly sensitive to ξ

$$\mathcal{A}(V_L V_L \rightarrow hh) = \frac{s}{v^2} (b - a^2) + \frac{(3ad_3 - 2a^2) m_h^2}{4M_W^2} + \dots$$

- Extremely challenging due to large QCD background in

$$pp \rightarrow hhjj$$

[Contino, Grojean, Moretti, Piccinini, Rattazzi '10]

- Visible signal only for $\xi \sim 1$
- No sensitivity to quadratic, b , and trilinear, d_3 , coupling

DOUBLE HIGGS PRODUCTION AT THE ILC

- Relevant process: Higgsstrahlung $e^+e^- \rightarrow Zh h$
- Define

$$\delta_b \equiv 1 - \frac{b}{a^2}, \quad \delta_{d_3} \equiv 1 - \frac{d_3}{a}.$$

- Statistical errors ($\Delta\delta_b, \Delta\delta_{d_3}$)

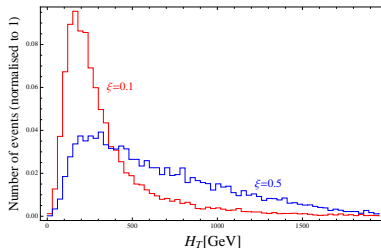
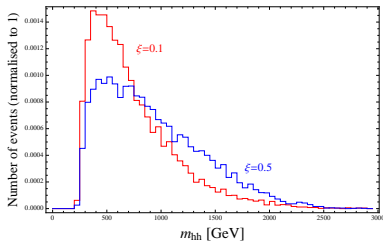
δ_b	δ_{d_3}		
	0	0.1	0.5
0.01	(0.28, 0.48)	(0.29, 0.49)	(0.30, 0.53)
0.05	(0.29, 0.49)	(0.29, 0.50)	(0.32, 0.56)
0.1	(0.29, 0.49)	(0.30, 0.51)	(0.33, 0.57)
0.5	(0.34, 0.58)	(0.36, 0.61)	(0.40, 0.70)

for $\sqrt{s} = 500$ GeV, $L = 1 \text{ ab}^{-1}$, $m_h = 125$ GeV

- Sensitive to large values of δ_b only

DOUBLE HIGGS PRODUCTION AT CLIC

- Dominant process: $e^+e^- \rightarrow W^+W^-\nu\bar{\nu} \rightarrow hh\nu\bar{\nu}$
- Cut on m_{hh} and H_T to disentangle b and d_3
- Distributions for $\sqrt{s} = 3$ TeV, $m_h = 125$ GeV



DOUBLE HIGGS PRODUCTION AT CLIC

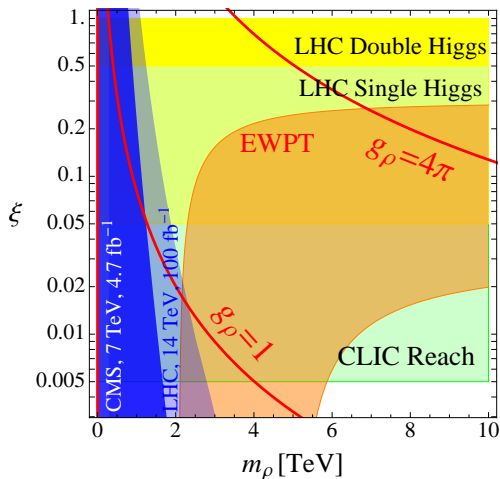
- Statistical errors ($\Delta\delta_b, \Delta\delta_{d_3}$)

δ_b	δ_{d_3}		
	0	0.1	0.5
0.01	(0.01, 0.06)	(0.01, 0.06)	(0.009, 0.05)
0.05	(0.098, 0.06)	(0.008, 0.05)	(0.007, 0.04)
0.1	(0.008, 0.06)	(0.007, 0.05)	(0.007, 0.04)
0.5	(0.006, 0.04)	(0.006, 0.04)	(0.006, 0.04)

for $\sqrt{s} = 3 \text{ TeV}$, $L = 1 \text{ ab}^{-1}$, $m_h = 125 \text{ GeV}$

- Sensitive to b with 1 – 2 % precision
- Sensitive to d_3 with 10 % precision
 - \Rightarrow sensitive to ξ up to 0.01
 - \Rightarrow sensitive to compositeness scale up to 30 TeV

SUMMARY: CONSTRAINTS AND PROSPECTS

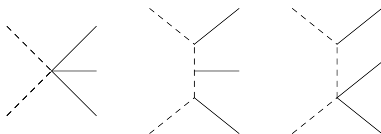


DISCRETE SYMMETRY IN SYMMETRIC COSET MODEL

- Symmetric coset \Rightarrow discrete symmetry between NG bosons:

$$\pi^{\hat{a}} \rightarrow -\pi^{\hat{a}}$$

- Process with odd number of NG-bosons forbidden
- WW scattering:

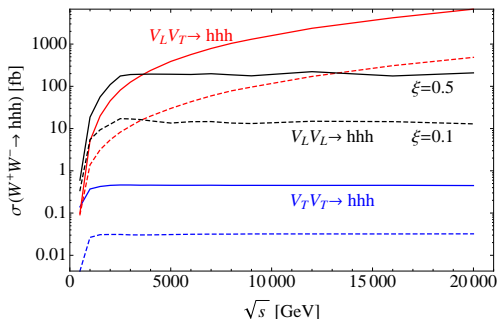


$$\mathcal{A}(V_L V_L \rightarrow hhh) = \frac{is}{v^3} (4ab - 4a^3 - 3b_3) = 0$$

- Distinct feature to distinguish symmetric and asymmetric coset

Polarisation	Amplitude for	
	NG-boson	SILH
$LL \rightarrow hhh$	$g^2 v / f^2$	$E^2 v / f^4$

TRIPLE HIGGS PRODUCTION AT CLIC



- Higgs as NGB:
 $V_L V_T \rightarrow hhh$
dominates
- Effective SILH:
 $V_L V_L \rightarrow hhh$
dominates

\sqrt{s} [TeV]	ξ				
	0	0.05	0.1	0.2	0.24
NGB	0.32	0.46	0.71	1.47	1.82
SILH	0.32	0.71	0.87	7.56	16.27

CONCLUSION AND OUTLOOK

- CLIC - unique machine to probe strong and composite nature of the Higgs
 - Precision measurements
 - **WW -scattering:** sensitive to a
 - **Double Higgs production:** sensitive to anomalous couplings b and d_3
 - ⇒ compositeness scale up to 30 TeV
 - **Triple Higgs production:** distinguish between Higgs as a NGB and SILH
 - ⇒ insight into underlying dynamics