Strong Higgs Production at CLIC

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Planck 2012
Warsaw, 30 May 2012

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to appear soon and also based on arXiv:1202.5940

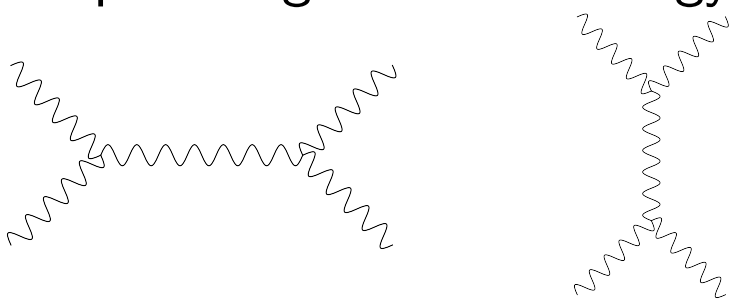
Outline

Perturbative Unitarity Violation in the SM

- Scattering of longitudinally polarized W in terms of NG bosons $\Sigma = e^{\frac{i}{v}\sigma^a\chi^a}$

$$\mathcal{L} = \frac{v^2}{4}\mathrm{Tr}\left[(D_\mu\Sigma)^\dagger (D^\mu\Sigma)\right]$$

- Amplitude grows with energy

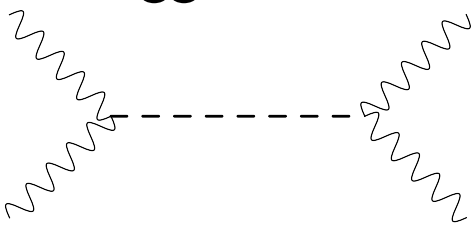


$$\mathcal{A}(V_L^+V_L^- \to V_L^+V_L^-) \sim \frac{s+t}{v^2}$$

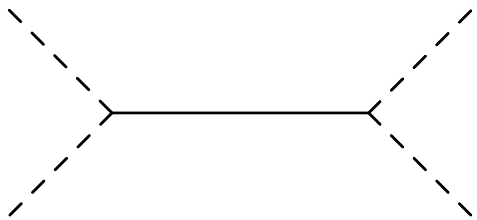
- Perturbative unitarity violated at $4\pi v \sim 3$ TeV
  $\Rightarrow$ expect new degrees of freedom

Higgs as a composite Nambu-Goldstone-Boson

Weak Dynamics:
Higgs Boson

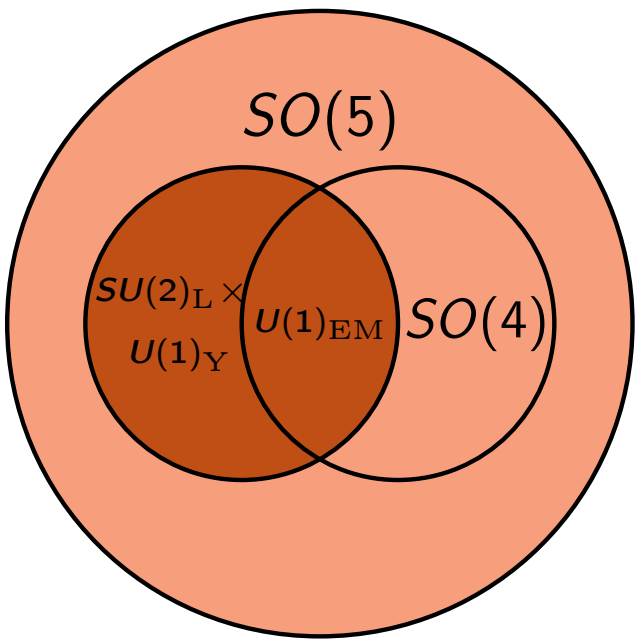


Strong Dynamics:
Non-perturbative Interactions



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 $\xi = \frac{v^2}{f^2} = \frac{\text{weak scale}^2}{\text{strong scale}^2}$

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

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

The ILC and CLIC

	International **L**inear **C**ollider **ILC**	**C**ompact **L**inear **C**ollider **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: $\mathcal{A}(V_L^+ V_L^- \to V_L^+ V_L^-) \sim (s+t)/v^2$
- Process: $e^+e^- \to W^+W^-\nu\bar{\nu}$
- 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	53.4	11.5	6.52	0.64
3	12.73	2.45	0.69	0.02
5	5.29	0.69	0.23	0.007

for $L = 1\,\text{ab}^{-1}$, $m_h = 120$ 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

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

- Extremely challenging due to large QCD background in $pp \to hhjj$
  [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 $e^+e^- \to Zhh$
- Define

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

- Statistical errors $(\Delta\delta_b, \Delta\delta_{d3})$

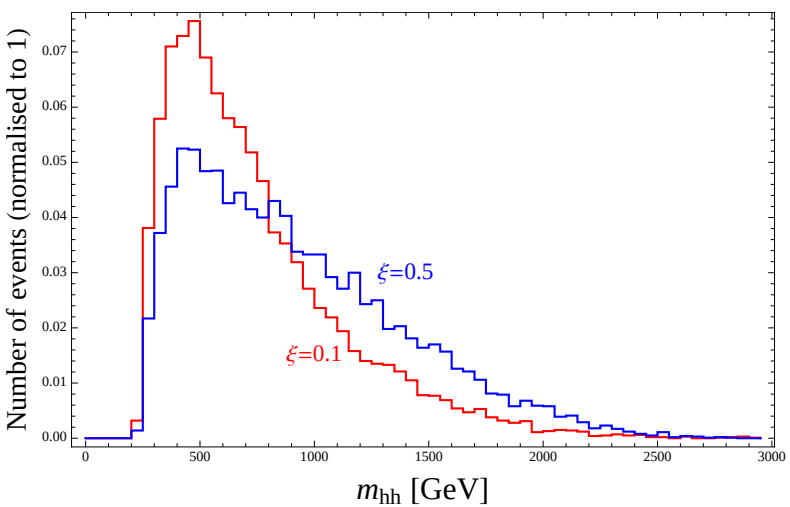
δ_b	δ_{d_3} 0	0.1	0.5
0.01	(0.27, 0.48)	(0.27, 0.49)	(0.26, 0.48)
0.05	(0.27, 0.48)	(0.28, 0.49)	(0.26, 0.47)
0.1	(0.27, 0.49)	(0.28, 0.49)	(0.27, 0.49)
0.5	(0.26, 0.47)	(0.27, 0.49)	(0.28, 0.52)

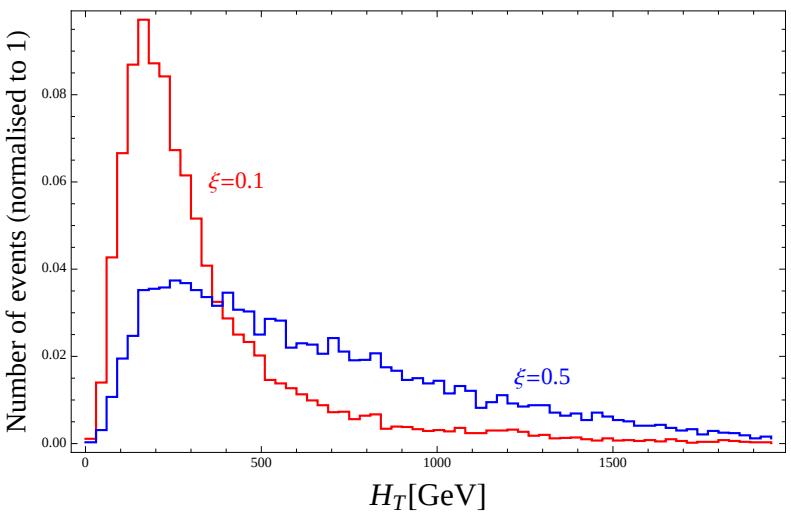
for $\sqrt{s} = 500$ GeV, $L = 1\,\text{ab}^{-1}$, $m_h = 120$ GeV

- Sensitive to large values of δ_b only

Double Higgs Production at CLIC

- Dominant process: $e^+e^- \to W^+W^-\nu\bar{\nu} \to hh\nu\bar{\nu}$
- Cut on m_{hh} and H_T to disentangle b and d_3
- Distributions for $\sqrt{s} = 3$ TeV, $m_h = 120$ GeV





Double Higgs Production at CLIC

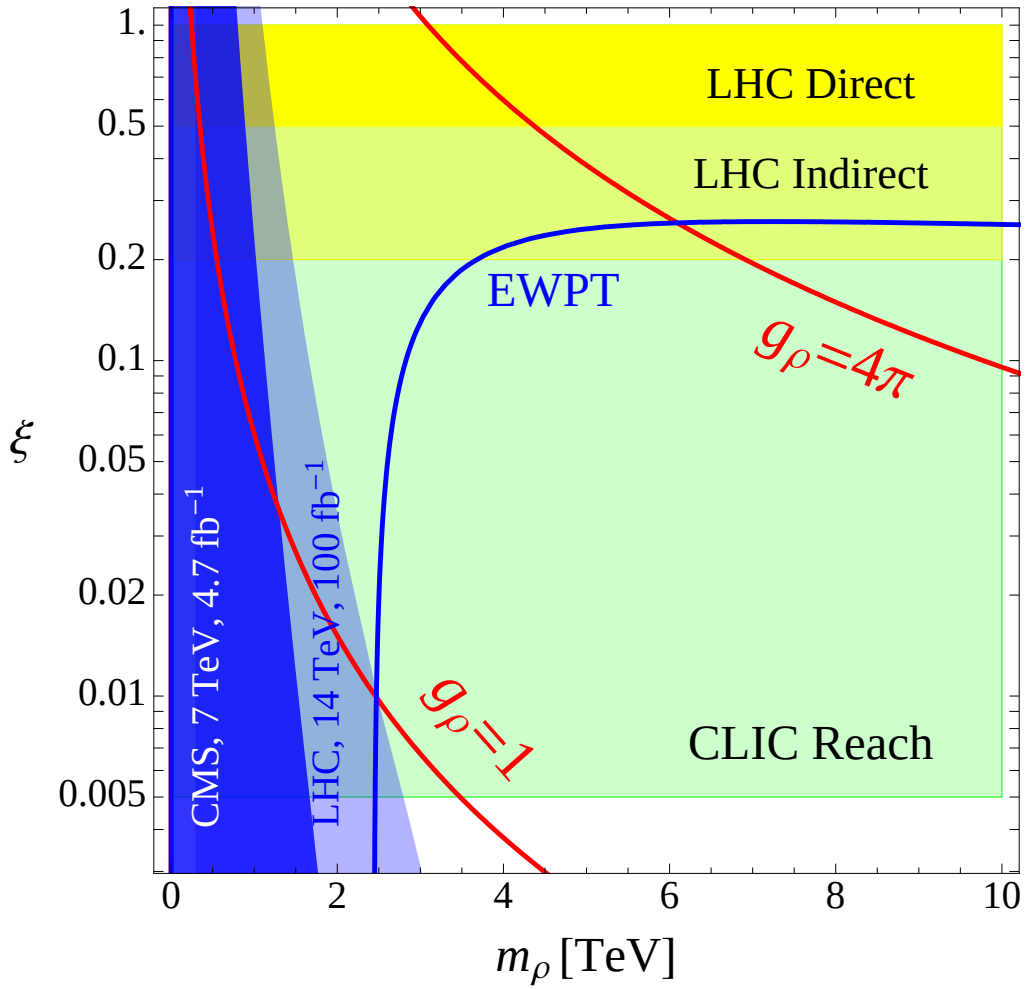
- Statistical errors $(\Delta\delta_b, \Delta\delta_{d3})$

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	(0.008, 0.06)	(0.008, 0.05)	(0.008, 0.04)
0.1	(0.007, 0.05)	(0.007, 0.05)	(0.007, 0.04)
0.5	(0.006, 0.04)	(0.006, 0.04)	(0.006, 0.04)

for $\sqrt{s} = 3$ TeV, $L = 1\,\text{ab}^{-1}$, $m_h = 120$ GeV

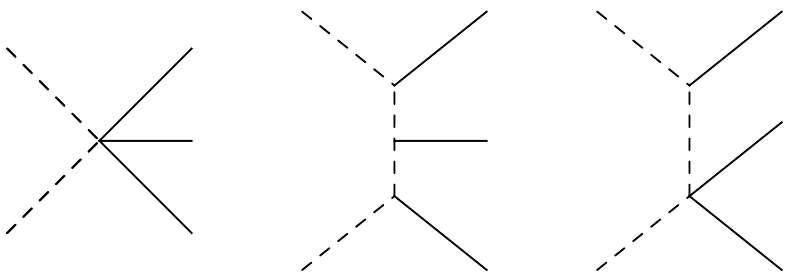
- Sensitive to b with $1 - 2$ % precision
- Sensitive to d_3 with 10 % precision
  $\Rightarrow$ sensitive to ξ up to 0.01
  $\Rightarrow$ sensitive to compositeness scale up to 30 TeV

Summary: Constraints and Prospects



Discrete Symmetry in symmetric coset model

- Symmetric coset $\Rightarrow$ discrete symmetry between NG bosons: $\pi^{\hat{a}} \to -\pi^{\hat{a}}$
- Process with odd number of NG-bosons forbidden
- WW scattering:

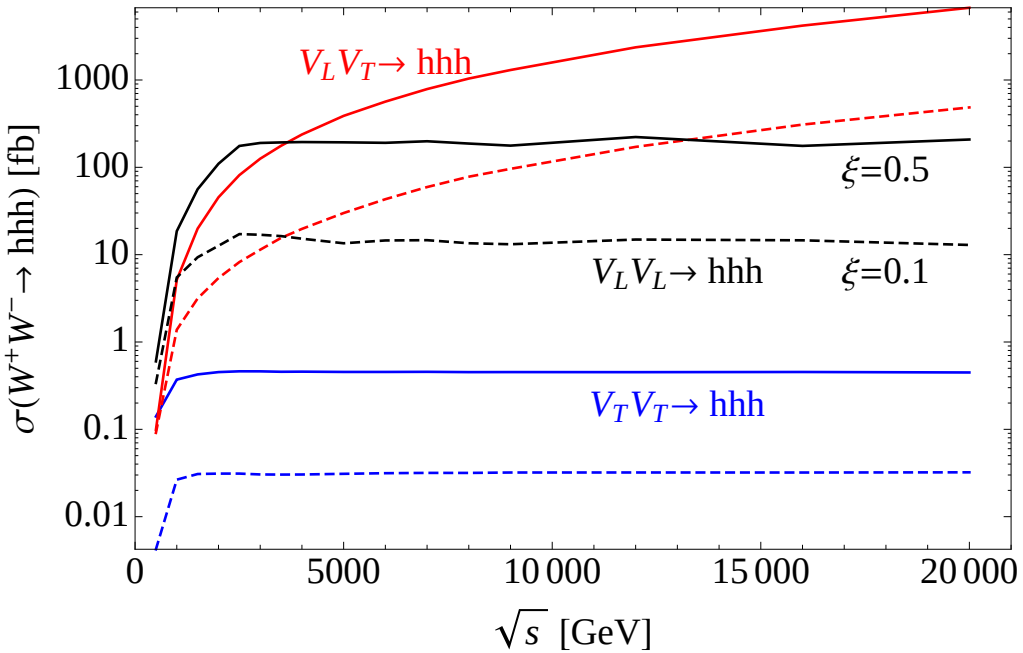


$$\mathcal{A}(V_L V_L \to hhh) = \frac{is}{v^3}\left(4ab - 4a^3 - 3b_3\right) = 0$$

- Distinct feature to distinguish symmetric and asymmetric coset

Polarisation	Amplitude for	
	symmetric coset	asymmetric coset
$LL \to hhh$	$g^2 v/f^2$	$E^2 v/f^4$

Triple Higgs Production at CLIC



- **Symmetric** coset: $V_L V_T \to hhh$ dominates
- **Asymmetric** coset: $V_L V_L \to hhh$ dominates

	coset	ξ 0.01	0.05	0.1	0.7
cross section [ab]	✓	0.38	0.50	0.76	4.65
	X	2064			

Conclusion and Outlook

- CLIC - unique machine to probe strong and composite nature of the Higgs
  - *WW*-**scattering:** sensitive to a
  - **Double Higgs production:** sensitive to anomalous couplings b and d_3
    $\Rightarrow$ compositeness scale up to 30 TeV
  - **Triple Higgs production:** distinguish between symmetric and asymmetric coset
    $\Rightarrow$ insight into underlying dynamics

- Still to do:
  - Build CLIC!