Composite or elementary?
Probing the nature of the Higgs

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Rencontres de Moriond, 14.03.13
QCD Lagrangian in the limit $m_u, m_d \to 0$

$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

$s \ll \Lambda_{QCD}$ pions interact weakly $\to$ effective description

$$U \to g_L U g_R^\dagger, \quad U = e^{i \pi \sigma^a / f_\pi}, \quad \mathcal{L}^{(2)} = \frac{f^2}{4} \text{Tr} \left\{ D^\mu U^\dagger D_\mu U \right\}$$
QCD inspired

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\]

SM Higgs sector

\[
\mathcal{G} = SU(2)_L \times SU(2)_R \quad \to \quad \mathcal{H} = SU(2)_C
\]

\[
\phi = \begin{pmatrix} H^0 & H^+ \\ -H^- & H^0 \end{pmatrix}, \quad \phi \to g_L \phi g_R^\dagger
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EW symmetry broken

$$\phi = (v + h(x)) e^{i\frac{\pi^a(x) \sigma^a}{v}} = (v + h(x)) U$$

$$\text{Tr} \left\{ D_\mu \phi^\dagger D_\mu \phi \right\} = \frac{1}{2} \partial^\mu h \partial_\mu h + \frac{(v + h)^2}{4} \text{Tr} \left\{ D^\mu U^\dagger D_\mu U \right\}$$
Strong electroweak symmetry breaking

electroweak symmetry broken by new strong interactions

composite Higgs - PG boson
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composite Higgs - PG boson

- \( SO(5)/SO(4) \rightarrow 4\pi \rightarrow H \)
  Minimal Composite Higgs Model
  Agashe, Contino, Pomarol '04

- \( SO(6)/SO(5) \rightarrow 5\pi \rightarrow H, a \)
- \( SU(4)/Sp(4, C) \rightarrow 5\pi \rightarrow H, s \)
  Next MCHM
  Gripaios, Pomarol, Riva, Serra '09
  Chacko, Batra '08

- \( SO(6)/SO(4) \times SO(2) \rightarrow 8\pi \rightarrow H_1 + H_2 \)
  Minimal Composite Two Higgs Doublets
  Mrazek, Pomarol, Rattazzi, Serra, Wulzer '11
Signatures of composite Higgs

- modified Higgs couplings

$$\xi = \left(\frac{v}{f_\pi}\right)^2$$
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Minimal Composite Higgs Model

$$SO(5) \rightarrow SO(4) \sim SU(2)_L \times SU(2)_R$$

$$\mathcal{L}^{(2)} = \frac{1}{2} \partial_\mu h \partial^\mu h + \frac{v^2}{4} \left( 1 + 2a \frac{h}{v} + b \frac{h^2}{v^2} + \ldots \right) \text{Tr} \left\{ D^\mu U D_\mu U^\dagger \right\}$$

$$a = \sqrt{1 - \xi}, \quad b = 1 - 2\xi.$$
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- modified Higgs couplings

\[ \xi = \left( \frac{v}{f_\pi} \right)^2 \]

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\[ a = \sqrt{1 - \xi}, \quad b = 1 - 2\xi. \]

→ small values of \( \xi \) preferred, \( \xi \lesssim 0.3 \)
Signatures of composite Higgs

indirect (electroweak precision, flavor) and direct effects

- spin-1/2 resonances
- **spin-1 resonances**

Contino, Pappadopulo, Marzocca, Rattazzi
Panico, Wulzer
De Curtis, Redi, Tesi
...

→ analogue of $\rho$ of QCD
→ KK modes from extra dimension
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Goal

- provide a simple, general and self-consistent effective framework to study properties of spin-1 resonances
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**Guideline: QCD**
Effective description of spin-1 resonances

global symmetry breaking $G \rightarrow H$

Spin-1 resonances

'hidden local symmetry' $\rightarrow$ modify the symmetry breaking pattern $G \times H$

SM electroweak $SU(2)_L \times U(1)_Y$ group sits in $G$

gauge bosons of $H$ local $\rightarrow$ 'vector' resonances $S \rightarrow g S h^\dagger$, $g \in G$, $h \in H$ local, $\langle S \rangle = 1$.

$L \ni v$

$\text{Tr} \{ D_\mu S D^\mu S^\dagger \}$

'vector' resonances most relevant for phenomenology
Effective description of spin-1 resonances

Global symmetry breaking $G \rightarrow H$

Spin-1 resonances
  - ’hidden local symmetry’
Effective description of spin-1 resonances

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Spin-1 resonances
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$$G \times H_{\text{local}} \rightarrow H$$

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- gauge bosons of $H_{\text{local}}$ $\rightarrow$ 'vector' resonances
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Global symmetry breaking $G \rightarrow H$

Spin-1 resonances
- 'hidden local symmetry'
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$$G \times H_{local} \rightarrow H$$

SM electroweak $SU(2)_L \times U(1)_Y$ group sits in $G$

gauge bosons of $H_{local} \rightarrow 'vector'~resonances$

$$S \rightarrow g\, S\, h^\dagger, \quad g \in G, \ h \in H_{local}, \quad \langle S \rangle = 1.$$  

$$\mathcal{L} \ni v_1^2 \text{Tr} \left\{ D_\mu SD^\mu S^\dagger \right\}$$

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Spin-1 resonances
- general features for small $\xi$, small $g/g_\rho$

- eigenstates - mixture of SM and 'hidden gauge' fields
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- general features for small $\xi$, small $g/g_\rho$

- eigenstates - mixture of SM and 'hidden gauge' fields
  at leading order in $g/g_\rho$
- heavy spin-1 eigenstates ↔ 'hidden gauge' $\rho^\mu$ fields
- light eigenstates ↔ SM $A, W, Z$ fields
- mixing $\sim g, g'/g_\rho$ → interactions!
Spin-1 resonances
- general features for small $\xi$, small $g/g_\rho$

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- ’pairing up’ of $SU(2)$ subgroups

\[ SU(2)_L \quad SU(2)_{h_L} \quad SU(2)_{h_R} \quad SU(2)_R \]
Spin-1 resonances
- general features for small \(\xi\), small \(g/g_\rho\)

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- mixing \(\sim g, g'/g_\rho \rightarrow\) interactions!

- 'pairing up' of \(SU(2)\) subgroups

  \[
  \begin{array}{c}
  \text{SU}(2)_L \quad \text{SU}(2)_{hL} \quad \text{SU}(2)_{hR} \quad \text{SU}(2)_R \\
  \end{array}
  \]

- 3 free parameters: \(\xi, g_\rho, g_{\rho\pi\pi}\)

  \[
  g_{\rho\pi\pi} \epsilon^{abc} \pi^a \partial_\mu \pi^b \rho^c_\mu - g_\rho \epsilon^{abc} \partial_\mu \rho^a_\nu \rho^b_\mu \rho^c_\nu
  \]
SO(5) → SO(4) ∼ SU(2)_L × SU(2)_R

- heavy spin-1 eigenstates ↔ ˜ρ^μ_L, ˜ρ^μ_R
\[ \text{heavy spin-1 eigenstates} \leftrightarrow \tilde{\rho}_L^\mu, \tilde{\rho}_R^\mu \]

- SM gauge fields

\[
\begin{align*}
W^\pm_\mu & \approx \tilde{W}^\pm_\mu - \frac{\sqrt{2}}{2} \sqrt{2 - \xi} \frac{g}{g_\rho} \tilde{\rho}^\pm_\mu \\
Z_\mu & \approx \tilde{Z}_\mu - \frac{\sqrt{2 - \xi}}{\sqrt{2}} \frac{g^2 - g'{}^2}{g_\rho \sqrt{g^2 + g'{}^2}} \tilde{\rho}^0_\mu - \frac{2\sqrt{2 - 2\xi}}{(2 - \xi)^{3/2}} \frac{g'{}^2}{g_\rho \sqrt{g^2 + g'{}^2}} \tilde{\rho}^0_\mu \\
A_\mu & \approx \tilde{A}_\mu - \sqrt{\frac{2}{2 - \xi}} \frac{e}{g_\rho} \tilde{\rho}_L^\mu + \sqrt{\frac{2 - 2\xi}{2 - \xi}} \frac{e}{g_\rho} \tilde{\rho}_R^\mu
\end{align*}
\]
\[ SO(5) \rightarrow SO(4) \sim SU(2)_L \times SU(2)_R \]

- heavy spin-1 eigenstates \( \leftrightarrow \tilde{\rho}^\mu_L, \tilde{\rho}^\mu_R \)
- SM gauge fields

\[ W^\pm_\mu \approx \tilde{W}^\pm_\mu - \frac{\sqrt{2}}{2} \sqrt{2 - \xi} \frac{g}{g_\rho} \tilde{\rho}^\pm_\mu \]

\[ Z_\mu \approx \tilde{Z}_\mu - \frac{\sqrt{2 - \xi}}{\sqrt{2}} \frac{g^2 - g'^2}{g_\rho \sqrt{g^2 + g'^2}} \tilde{\rho}^0_\mu - \frac{2 \sqrt{2 - 2\xi}}{(2 - \xi)^{3/2}} \frac{g'^2}{g_\rho \sqrt{g^2 + g'^2}} \tilde{\rho}^0_R \]

\[ A_\mu \approx \tilde{A}_\mu - \sqrt{\frac{2}{2 - \xi}} \frac{e}{g_\rho} \tilde{\rho}^\mu_L + \sqrt{\frac{2 - 2\xi}{2 - \xi}} e \frac{g_\rho}{g_\rho} \tilde{\rho}^\mu_R \]

assumption: couplings of \( \tilde{\rho} \) eigenstates with SM fermions arise only via their admixture in SM \( W^\pm_\mu, Z_\mu \) and \( A_\mu \)

- coupling of \( \rho \) to two fermions enhanced for small \( \xi \)
**SO(5) → SO(4) ~ SU(2)_L × SU(2)_R**

- heavy spin-1 eigenstates ↔ \( \tilde{\rho}^\mu_L, \tilde{\rho}^\mu_R \)
- SM gauge fields

\[
W^\pm_\mu \approx \tilde{W}^\pm_\mu - \frac{\sqrt{2}}{2} \frac{g}{g_\rho} \tilde{\rho}^\pm_\mu
\]

\[
Z_\mu \approx \tilde{Z}_\mu - \frac{\sqrt{2 - \xi}}{\sqrt{2}} \frac{g^2 - g^\prime_2}{g_\rho \sqrt{g^2 + g'^2}} \tilde{\rho}^0_\mu - \frac{2\sqrt{2 - 2\xi}}{(2 - \xi)^{3/2}} \frac{g'^2}{g_\rho \sqrt{g^2 + g'^2}} \tilde{\rho}^0_\mu
\]

\[
A_\mu \approx \tilde{A}_\mu - \sqrt{2 - \xi} \frac{e}{g_\rho} \tilde{\rho}^0_\mu + \sqrt{2 - 2\xi} \frac{e}{g_\rho} \tilde{\rho}^0_\mu
\]

assumption: couplings of \( \tilde{\rho} \) eigenstates with SM fermions arise only via their admixture in SM \( W^\pm_\mu, Z_\mu \) and \( A_\mu \).

- coupling of \( \rho \) to two fermions enhanced for small \( \xi \)
- coupling of \( \rho \) to two SM gauge bosons suppressed

\[
g_{\rho\pi\pi} = \xi \frac{m^2_\rho}{2g_\rho v^2} = \frac{m^2_\rho}{2g_\rho f^2_\pi}.
\]
Production and decays

- production dominated by Drell-Yan $q\bar{q} \rightarrow \rho$

for a specific value of $\xi = 0.2$ and $g_\rho = 4$
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- production dominated by Drell-Yan $q\bar{q} \rightarrow \rho$

for a specific value of

$\xi = 0.2$ and $g_\rho = 4$

- decays mainly to $hZ$ and $WW$, but $ll$ non-negligible

for a specific value of

$\xi = 0.2$ and $g_\rho = 4$

$\Gamma(\rho \rightarrow WW) \sim m_\rho g_\rho^2 \pi\pi$
Direct searches

most sensitive: CMS search for dilepton resonances

\[ m_\rho^2 \approx \frac{2g_\rho g_{\rho\pi\pi} v^2}{\xi} \]
Conclusions

- signatures of composite Higgs - modified Higgs couplings, effects of resonances
- general effective framework for spin-1 resonances → phenomenology
- at small $\xi$ - the spin-1 resonance coupling to two SM gauge bosons is suppressed, the coupling to two fermions is enhanced
- resonances mainly Drell-Yan produced
- exclusion limits from searches for dilepton resonances, diboson resonances, dijet mass spectra, ...
- the LHC is already probing the parameter space of spin-1 resonances allowed by electroweak precision tests
Perturbative unitarity constraints

without spin-1 resonances  \( \mathcal{M}^0_{WW \rightarrow WW}(s) \sim \frac{1}{16\pi} \frac{\xi s}{\nu^2} = \frac{1}{16\pi} \frac{s}{f_\pi^2} \)
Perturbative unitarity constraints

without spin-1 resonances \( M_{WW\rightarrow WW}^{0}(s) \sim \frac{1}{16\pi} \frac{\xi s}{\sqrt{\xi}} \approx \frac{1}{16\pi} \frac{s}{f_{\pi}^{2}} \)

→ perturbative unitarity violation at \( \Lambda \sim 1.3 \text{ TeV}/\sqrt{\xi} \)

\[ \xi = 0.2 \]

add \( \rho_{L} \) and \( \rho_{R} \) resonances, inelastic channels included

\[ m_{\rho}^{2} \approx \frac{2g_{\rho}g_{\rho\pi\pi}v^{2}}{\xi} \]
Comparison with indirect constraints

most constraining: prediction for $\hat{S} = \frac{g^2}{16\pi} S$
assume: saturation of Weinberg sum rules

$\xi = 0.2$

$\xi = 0.07$