Strong electroweak symmetry breaking

Anna Kamińska

A.Falkowski, C.Grojean, AK, S.Pokorski, A.Weiler

Institute of Theoretical Physics

This research project has been supported by a Marie Curie Early Initial Training Network Fellowship of the European Community's Seventh Framework Programme under contract number (PITN-GA-2008-237920-UNILHC)

Rencontres de Moriond EW 2012
Electroweak symmetry breaking sector

Three Goldstone bosons → $W_L$, $Z_L$

Custodial $SU(2)_C$ → $ho = M_W^2 \approx 1$

Unitarization of $WW$ scattering amplitudes

Anna Kamińska

Strong electroweak symmetry breaking
Electroweak symmetry breaking sector?
Electroweak symmetry breaking sector? Needed

- three Goldstone bosons $\rightarrow W_L, Z_L$
Electroweak symmetry breaking sector? Needed

- three Goldstone bosons $\rightarrow W_L, Z_L$
- custodial $SU(2)_C \rightarrow \rho = \frac{M_W^2}{M_Z^2 \cos^2 \theta_W} \approx 1$
Electroweak symmetry breaking sector? Needed

- three Goldstone bosons $\rightarrow W_L, Z_L$
- custodial $SU(2)_C \rightarrow \rho = \frac{M_W^2}{M_Z^2 \cos^2 \theta_W} \approx 1$
- unitarization of $WW$ scattering amplitudes
Standard Model scalar sector

EW symmetry breaking sector $\supset$ scalar doublet $H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$
Standard Model scalar sector

EW symmetry breaking sector ⊇ scalar doublet $H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$

global symmetries

$$\mathcal{G} = SU(2)_L \times SU(2)_R \quad \rightarrow \quad \mathcal{H} = SU(2)_C$$
Standard Model scalar sector

EW symmetry breaking sector $\supset$ scalar doublet $H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$

global symmetries

$$\mathcal{G} = SU(2)_L \times SU(2)_R \quad \rightarrow \quad \mathcal{H} = SU(2)_C$$

$$\phi \rightarrow g_L \phi g^\dagger_R$$

$$\phi = \begin{pmatrix} H^0 \\ -H^- \\ H^0 \end{pmatrix} = e^{i \frac{\pi a T a}{v}} \begin{pmatrix} v + h & 0 \\ 0 & v + h \end{pmatrix}$$

$$\mathcal{L}_{SB} = \frac{1}{2} \text{tr} \left[ D_\mu \phi^\dagger D_\mu \phi \right] - \frac{1}{2} \lambda \left( \frac{1}{2} \text{Tr}[\phi^\dagger \phi] - v^2 \right)^2$$
scattering amplitudes for longitudinally polarized W and Z (using the Goldstone boson equivalence theorem)

with the Scalar exchange

\[ M(s, t, u) = \frac{s}{v^2} - \frac{s}{v^2} \frac{s}{s - m_h^2} \]

in the SM without the Scalar exchange

\[ M(s, t, u) = \frac{s}{v^2} \]

perturbative unitarity lost $\sim 1.5 \text{ TeV}$
Strong electroweak symmetry breaking

EW breaking by new strong interactions

Motivation: strong dynamics is realized in Nature
Strong electroweak symmetry breaking

**EW breaking by new strong interactions**

Motivation: strong dynamics is realized in Nature

Can we provide an effective low-energy perturbative description?

- CHPT

(QCD: approximate $SU(2)_L \times SU(2)_R \rightarrow SU(2)_V \leftrightarrow$ pions)

What is the nature of the Goldstone bosons which provide $W^\pm_L$, $Z_L$?

- $\pi^a$ are composite fields
Strong electroweak symmetry breaking

How is perturbative unitarity restored?
How is perturbative unitarity restored?

- resonances
How is perturbative unitarity restored?

- resonances

**spin-1 resonances**

- Motivation: QCD
  → vector meson dominance
How is perturbative unitarity restored?

- resonances

spin-1 resonances

- Motivation: QCD
  → vector meson dominance
- technicolor, deconstruction
### Strong electroweak symmetry breaking

How is perturbative unitarity restored?

- resonances

<table>
<thead>
<tr>
<th>spin-1 resonances</th>
<th>scalar resonance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motivation: QCD</td>
<td>PG composite scalar</td>
</tr>
<tr>
<td>→ vector meson</td>
<td></td>
</tr>
<tr>
<td>dominance</td>
<td></td>
</tr>
<tr>
<td>technicolor, deconstruction</td>
<td></td>
</tr>
</tbody>
</table>
# Strong electroweak symmetry breaking

How is perturbative unitarity restored?

- resonances

<table>
<thead>
<tr>
<th>spin-1 resonances</th>
<th>scalar resonance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motivation: QCD</td>
<td>PG composite scalar</td>
</tr>
<tr>
<td>→ vector meson dominance</td>
<td></td>
</tr>
<tr>
<td>technicolor, deconstruction</td>
<td></td>
</tr>
</tbody>
</table>

spin-1 resonances - distinctive feature of strong electroweak symmetry breaking models
Assume: lightest set of resonances - of spin-1 resonances, vector meson dominance
approximate $SU(2)_C$

Goal: concentrate on the vector boson sector

Goal: provide a simple, general and self-consistent effective framework to study electroweak symmetry breaking by strong dynamics

$\rightarrow$ perfect laboratory for studying spin-1 resonances
Assume:

- lightest set of resonances - of spin-1 resonances, vector meson dominance
- approximate $SU(2)_C$ custodial symmetry
Assume:

- lightest set of resonances - of spin-1 resonances, vector meson dominance
- approximate $SU(2)_C$ custodial symmetry

Goal: concentrate on the vector boson sector
Goal: provide a simple, general and self-consistent effective framework to study electroweak symmetry breaking by strong dynamics
Strong electroweak symmetry breaking

spin-1 resonances

A.Falkowski, C.Grojean, AK, S.Pokorski, A.Weiler

Assume:
- lightest set of resonances - of spin-1 resonances, vector meson dominance
- approximate $SU(2)_C$ custodial symmetry

Goal: concentrate on the vector boson sector
Goal: provide a simple, general and self-consistent effective framework to study electroweak symmetry breaking by strong dynamics

→ perfect laboratory for studying spin-1 resonances
Introducing spin-1 resonances

\[ U^{SU(2)_L \times SU(2)_R} \rightarrow g_L U g_R^\dagger, \quad U = e^{i\sigma \cdot \pi(x)/v} \]

\[ \mathcal{L}_{\text{CHPT}}^{(2)} = \frac{v^2}{4} \text{Tr} \left\{ D_\mu U^\dagger D^\mu U \right\}, \quad D_\mu U = \partial_\mu U - ig' \frac{1}{2} B_\mu \sigma^3 U + ig \frac{1}{2} U \sigma^a W^a_\mu \]
Introducing spin-1 resonances

\[ U \xrightarrow{SU(2)_L \times SU(2)_R} g_L U g_R^\dagger, \quad U = e^{i\sigma \cdot \pi(x)/v} \]

\[ \mathcal{L}_{\text{CHPT}}^{(2)} = \frac{V^2}{4} \text{Tr} \left\{ D_\mu U^\dagger D^\mu U \right\}, \quad D_\mu U = \partial_\mu U - i \frac{g'}{2} B_\mu \sigma^3 U + i \frac{g}{2} U \sigma^a W^a_\mu \]

spin-1 resonances ↔ gauge bosons of a "hidden" local symmetry \( SU(2)_h \)

\[ U = \xi_L \xi_R^\dagger, \quad \xi_{L,R} \rightarrow g_{L,R} \xi_{L,R} h^\dagger \]

\[ D_\mu \xi_L = \partial_\mu \xi_L - i \frac{g}{2} W^a_\mu \sigma^a \xi_L + i \frac{g_\rho}{2} \xi_L \rho^a_\mu \sigma^a \]

\[ D_\mu \xi_R = \partial_\mu \xi_R - i \frac{g'}{2} B_\mu \sigma^3 \xi_R + i \frac{g_\rho}{2} \xi_R \rho^a_\mu \sigma^a \]

"hidden" gauge coupling \( g_\rho \gg g, g' \)
Introducing spin-1 resonances

\[ U \xrightarrow{SU(2)_L \times SU(2)_R} g_L U g_R^\dagger, \quad U = e^{i\sigma \cdot \pi(x)/v} \]

\[ \mathcal{L}^{(2)}_{\text{CHPT}} = \frac{V^2}{4} \text{Tr} \left\{ D_\mu U^\dagger D^\mu U \right\}, \quad D_\mu U = \partial_\mu U - i\frac{g'}{2} B_\mu \sigma^3 U + i\frac{g}{2} U \sigma^a W^a_\mu \]

Spin-1 resonances ↔ gauge bosons of a "hidden" local symmetry \( SU(2)_h \)

\[ U = \xi_L \xi_R^\dagger, \quad \xi_{L,R} \rightarrow g_{L,R} \xi_{L,R} h^\dagger \]

\[ D_\mu \xi_L = \partial_\mu \xi_L - i\frac{g}{2} W^a_\mu \sigma^a \xi_L + i\frac{g_\rho}{2} \xi_L \rho^a_\mu \sigma^a \]

\[ D_\mu \xi_R = \partial_\mu \xi_R - i\frac{g'}{2} B_\mu \sigma^3 \xi_R + i\frac{g_\rho}{2} \xi_R \rho^a_\mu \sigma^a \]

"Hidden" gauge coupling \( g_\rho \gg g, g' \)

**Goldstone bosons**

\[ \xi_L = e^{i\pi^a \sigma^a / 2}, \quad \xi_R = e^{-i\pi^a \sigma^a / 2} \]
Building the effective Lagrangian

**building blocks**

objects transforming as adjoints of $SU(2)_h$ with well defined $R \leftrightarrow L$ parity

$$V^{\pm}_\mu = -i \left( \xi_L^\dagger D_\mu \xi_L \pm \xi_R^\dagger D_\mu \xi_R \right)$$
Building the effective Lagrangian

**building blocks**

objects transforming as adjoints of $SU(2)_h$ with well defined $R \leftrightarrow L$ parity

$$V^\pm_\mu = -i \left( \xi_L^\dagger D_\mu \xi_L \pm \xi_R^\dagger D_\mu \xi_R \right)$$

most general (parity preserving) Lagrangian at the leading order in the derivative expansion

$$\mathcal{L} \supset -\frac{v^2}{4} \text{Tr} \left\{ \alpha V^+_\mu V^+_\mu + V^-_\mu V^-_\mu \right\} + \mathcal{L}_{\text{kinetic}}$$
Building the effective Lagrangian

**building blocks**

objects transforming as adjoints of $SU(2)_h$ with well defined $R \leftrightarrow L$ parity

$$V_{\mu}^{\pm} = -i \left( \xi_L^\dagger D_\mu \xi_L \pm \xi_R^\dagger D_\mu \xi_R \right)$$

most general (parity preserving) Lagrangian at the leading order in the derivative expansion

$$\mathcal{L} \supset -\frac{v^2}{4} \text{Tr} \left\{ \alpha V_\mu^+ V_\mu^+ + V_\mu^- V_\mu^- \right\} + \mathcal{L}_{\text{kinetic}}$$

- technicolor $\leftrightarrow \alpha \approx 2$
- deconstruction $\leftrightarrow \alpha = 1$

Anna Kamińska
Strong electroweak symmetry breaking
Study perturbative unitarity and check:
- up to which energy is this minimal setup self-consistent?
- what is the allowed resonance mass and its couplings?
Strong electroweak symmetry breaking

Study perturbative unitarity and check:
- up to which energy is this minimal setup self-consistent?
- what is the allowed resonance mass and its couplings?

Collider phenomenology of such a minimal setup?
Perturbative unitarity region

\[ g_{\rho\pi\pi} = \frac{\alpha}{2} g_{\rho}, \quad m_{\rho}^2 = 2 g_{\rho\pi\pi} g_{\rho} v^2 \]
Maximal cutoff

The upper bound on the resonance mass $\sim 3 \text{ TeV}$ light resonances not so efficient in unitarizing a crucial role played by $\pi\pi \rightarrow \pi\pi$ and $\pi\rho \rightarrow \pi\rho$.

Anna Kamińska

Strong electroweak symmetry breaking
Maximal cutoff

- the upper bound on the resonance mass $\sim 3$ TeV
- light resonances not so efficient in unitarizing
- a crucial role played by $\pi\pi \rightarrow \rho\rho$
Find couplings of resonances to matter fields
→ assume that the SM quarks and leptons are fundamental, couplings to resonances only via mixing of the latter with the SM gauge bosons

\[
\begin{align*}
W^\pm_\mu & \rightarrow W^\pm_\mu - \frac{g}{2g_\rho} \rho^\pm_\mu \\
Z_\mu & \rightarrow Z_\mu - \frac{g^2 - g'^2}{2g_\rho \sqrt{g^2 + g'^2}} \rho^0_\mu \\
A_\mu & \rightarrow A_\mu - \frac{e}{2g_\rho} \rho^0_\mu 
\end{align*}
\]

\[(1)\]
### Phenomenology

#### Decays

\[
\text{Br}(\rho^\pm \rightarrow e^\pm \nu) \approx 2\text{Br}(\rho^0 \rightarrow e^+ e^-) \approx \frac{16m_W^4}{m_{\rho}^4}
\]

which is strongly suppressed in the interesting parameter space (for \(m_\rho \gg 2m_W\))
Decays

- $\text{Br}(\rho^\pm \rightarrow e^\pm \nu) \approx 2\text{Br}(\rho^0 \rightarrow e^+ e^-) \approx \frac{16m_W^4}{m_\rho^4}$
  - which is strongly suppressed in the interesting parameter space (for $m_\rho \gg 2m_W$)

- $\Gamma(\rho^0 \rightarrow W^+ W^-) \approx \Gamma(\rho^\pm \rightarrow ZW^\pm) \approx \frac{m_\rho g^2_{\rho \pi \pi}}{48\pi} = \frac{m_\rho^5}{192\pi g^2_{\rho \pi} v^4}$
Decays

\[ \text{Br}(\rho^\pm \to e^\pm \nu) \approx 2 \text{Br}(\rho^0 \to e^+ e^-) \approx \frac{16 m_W^4}{m_\rho^4} \]

which is strongly suppressed in the interesting parameter space (for \( m_\rho \gg 2m_W \))

\[ \Gamma(\rho^0 \to W^+ W^-) \approx \Gamma(\rho^\pm \to Z W^\pm) \approx \frac{m_\rho g_{\rho \pi}^2}{48\pi} = \frac{m_\rho^5}{192\pi g_{\rho \pi}^2 v^4} \]

Production

- Drell-Yan \((q\bar{q} \to \rho) \leadsto pp \to \rho\)
- Vector boson fusion \((VV \to \rho) \leadsto pp \to \rho jj\)
- \(\rho\)-strahlung \((V \to \rho V) \leadsto pp \to \rho V\)
Collider phenomenology

Cross section for the production of a single neutral (solid) and charged (dashed) resonance at the LHC

\[ \sigma(pp \to \rho \, X) \text{ at LHC7} \]

\[ \sigma(pp \to \rho \, X) \text{ at LHC14} \]
Contours of the total cross section for the inclusive production of $\rho^0$, $\rho^\pm$ (solid, dashed) at the LHC; (purple) - CMS search for WZ resonant production exclusions.
Contours of the total cross section for the inclusive production of $\rho^0$, $\rho^\pm$ (solid, dashed) at the LHC; (purple) - CMS search for WZ resonant production exclusions.

- if the resonances are heavy and strongly coupled they might escape any direct detection at the LHC
Strong electroweak symmetry breaking

- Scalar resonance
  - PG composite scalar

Agashe, Contino, Pomarol '04

SU(4)/Sp(4,C) → 5π → H

Gripaios, Pomarol, Riva, Serra '09

SO(6)/SO(5) → 8π → H

Mrazek, Pomarol, Rattazzi, Serra, Wulzer '11

L⊃vLv + \frac{\lambda_2 v}{2} + ...
Strong electroweak symmetry breaking

**scalar resonance**

- PG composite scalar

- $SO(5)/SO(4) \rightarrow 4\pi \rightarrow H$
  
  Agashe, Contino, Pomarol '04

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

- $SO(6)/SO(4) \times SO(2) \rightarrow 8\pi \rightarrow H_1 + H_2$

  Mrazek, Pomarol, Rattazzi, Serra, Wulzer '11

\[
\mathcal{L} \supset \frac{v^2}{4} \left( 1 + 2a \frac{h}{v} + b \frac{h^2}{v^2} + \ldots \right) \text{Tr} \left( D_\mu U^\dagger D^\mu U \right)
\]
Conclusions

- we have studied the physics of spin-1 resonances connected with strong EW symmetry breaking in a simple, general effective framework built using tools known from QCD (CHPT, “hidden gauge”)
- considering perturbative unitarity in a simple, general setup with spin-1 resonances constrains the allowed resonance mass and couplings
- a crucial role is played by inelastic scattering effects - a heavy $\rho$ meson (2.5-3) TeV is more efficient in prolonging perturbative unitarity than a light resonance ($\sim$2 TeV)
- if the resonances are heavy ($m_\rho \geq 2$ TeV) and strongly coupled they might escape any direct detection at the LHC
- it is interesting to use such effective frameworks to study strong EW symmetry breaking with a light composite scalar resonance