Higgsless Simplified

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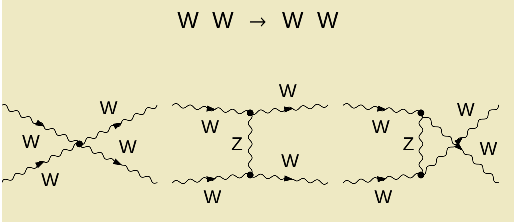
based on *AA, C. Grojean, A. Kaminska, S. Pokorski, A. Weiler*, **1108.1183**
see paper for other references and credits

Outline

1. Introduction: Higgsless theories
2. Model: a simplified model for Higgsless theories
3. Unitarity constraints: the parameter space of the simplified model
4. Phenomenology: Tevatron constraints and the predictions for the LHC
5. Summary

Who broke electroweak symmetry?

- One of the questions to be addressed by the LHC is the nature of electroweak symmetry breaking
- More quantitatively, the question is what stops the growth of the scattering amplitudes of W and Z



- In the SM (without Higgs) the tree-level amplitude for longitudinally polarized W's and Z's grows with energy, $\mathcal{M} \sim s/v^2$
- Unitarity requires $\mathrm{Re}\,\mathcal{M}^J < 1/2$ for all partial waves. Perturbative unitarity is lost at TeV
- Something else must enter at this scale!

Options for Electroweak Symmetry Breaking

3 basic possibilities. Unitarity saved by

- Non-perturbative effects (no concrete framework so far)
- Weakly Coupled: fundamental scalar coupled to WW and ZZ, otherwise knowns as *the Higgs*
- Strongly Coupled: composite vectors coupled to electroweak gauge bosons, otherwise known as *Higgsless*
- ...or a combination of the previous two, otherwise known as *composite Higgs*

In the following focus on Higgsless

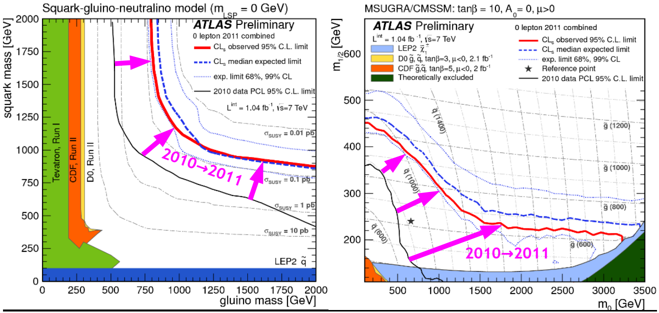
Several approaches to Higgsless theories

- Top-down approach: work out asymptotically safe 4D gauge theories that break EW symmetry in IR
  - Most ambitious: one deals with a complete and consistent model
  - Most difficult: safe to assume we haven't pinpointed all phenomenologically distinct possibilities
- Effective approach: start with 5D theory, 3-site deconstruction, etc
  - A concrete, well-defined framework for computations, grasps broad-brush features of realistic theories
  - But again some distinct phenomenology can be missed
- Chiral Lagrangian approach: low-energy degrees of freedom plus p^2 expansion
  - Successful in describing low-energy QCD phenomenology
  - Given low-energy symmetries, allows one to systematically explore most general dynamics

Simplified Philosophy

Currently 2 complementary approaches to collider phenomenology

- Full-fledged models, e.g the MSSM, to study the richness of possible collider signatures predicted by *motivated* models of new physics
- Simplified models, e.g gluino + neutralino, to explore relevant signatures of new physics within a simple effective theory containing a small number of degrees of freedom



Simplified Model for Higgsless Theories

- Focus on basic, indispensable degrees of freedom
- In this minimal setting, understanding the most general kinematics
- Convenient characterization of the parameter space, limits, future LHC reach, etc
- In any case, technicolor scale may well be pretty large, and few degrees of freedom may be available

A Simplified Model for Higgsless Theories

Agents for unitarizing WW scattering

Possibilities can be classified by representations under Lorentz and Custodial symmetry

	$SU(2)_C$ Singlet	$SU(2)_C$ Triplet
Lorentz Scalar	✓	✗
Lorentz Vector	✗	✓
Lorentz Tensor	✓	✗

- Not all possibilities allow the coupling to W and Z that does not violate the custodial symmetry. For ✗ entries large couplings excluded by constraints from T parameter
- Singlet is equivalent to the SM Higgs. Tensor leads to $\mathcal{M} \sim s^2$.
- That leaves vector triplet as the simplest non-trivial possibility

The model: SM sector

Minimal set-up describing the SM gauge sector includes (fermions later)

- Standard Model gauge bosons L^a_μ, B_μ
- 3 Goldstone bosons π who become the longitudinal polarizations of the W and Z bosons
- Approximate $SU(2)_C$ custodial symmetry

Nonlinear sigma model with $SU(2)_L \times SU(2)_R / SU(2)_C$ global symmetry whose $SU(2)_L \times U(1)_Y$ subgroup is weakly gauged by the SM gauge bosons

$$U = e^{i\sigma^a \pi^a(x)/v} \qquad U \to g_L U g_R^\dagger$$

The model: resonance sector

Now add

- A triplet of massive vector bosons called the ρ_μ mesons

Severals way to introduce ρ, as in ChPT for QCD:

- Tensor formalism, $V_{\mu\nu} \to h^\dagger V_{\mu\nu} h$
- Vector formalism, $V_\mu \to h^\dagger V_\mu h$
- Hidden gauge formalism: $V_\mu \to i h^\dagger \partial_\mu h + h^\dagger V_\mu h$

where h is the $SU(2)_C$ transformation.
All of those equivalent when higher order operators are included

Hidden gauge formalism

1. Rewrite $U = \xi_L \xi_R^\dagger$ where new fields transform as

$$\xi_L \to \quad g_L \xi_L h^\dagger \quad \xi_R \to \quad g_R \xi_R h^\dagger$$

2. New "hidden" global symmetry $SU(2)_h$. The number of Goldstones doubled

$$\xi_L = e^{\;i\pi^a\sigma^a/2v} e^{-iG^a\sigma^a/2v\sqrt{\alpha}} \qquad \xi_R = e^{-i\pi^a\sigma^a/2v} e^{-iG^a\sigma^a/2v\sqrt{\alpha}}$$

3. ρ introduced as the gauge field of $SU(2)_h$

$$D_\mu \xi_L = \partial_\mu \xi_L - i\frac{g}{2} L_\mu^a \sigma^a \xi_L + i\frac{g_\rho}{2}\xi_L \rho_\mu^a \sigma^a$$

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

Surplus Goldstones G eaten by ρ

Parity exchanges $L \leftrightarrow R$. Define adjoints of $SU(2)_h$

$$V_\mu^\pm = \xi_L^\dagger D_\mu \xi_L \pm \xi_R^\dagger D_\mu \xi_R \qquad V_\mu^\pm \to h V_\mu^\pm h^\dagger$$

At lowest order, most general parity conserving lagrangian

$$-\frac{v^2}{4} \mathrm{Tr} \left\{ \alpha V_\mu^+ V_\mu^+ + V_\mu^- V_\mu^- \right\},$$

$+$ kinetic term for the gauge fields

- 3 parameters g, g', v fixed by the W and Z mass and the cubic gauge coupling
- 2 new parameter α and g_ρ related to
  - resonance mass $m_\rho^2 \approx \alpha g_\rho^2 v^2$
  - resonance couplings to longitudinal SM gauge bosons, $g_{\rho\pi\pi} \epsilon^{abc} \pi^a \partial_\mu \pi^b \rho_\mu^c$, $g_{\rho\pi\pi} = \alpha g_\rho / 2$
- $\alpha = 1$, or $g_{\rho\pi\pi} = g_\rho/2$ corresponds to "3-site deconstruction" (with only "local" link kinetic terms). $\alpha = 2$, or $g_{\rho\pi\pi} = g_\rho$ is the KSFR relation; for this value SM gauge bosons do not couple directly to π.

We can use any of the 2 parameters to characterize the parameter space: $(g_\rho, g_{\rho\pi\pi})$, $(m_\rho, g_{\rho\pi\pi})$, (g_ρ, α), etc

Lagrangian with parity breaking

Customarily assumed strong sector respects parity. If it's not the case, the lowest resonance may have parity breaking interactions,

$$\frac{v^2}{4(1-\beta^2)}\mathrm{Tr}\left\{\alpha \mathrm{V}_\mu^+ \mathrm{V}_\mu^+ + \mathrm{V}_\mu^- \mathrm{V}_\mu^- - 2\sqrt{\alpha}\beta \mathrm{V}_\mu^- \mathrm{V}_\mu^+\right\}$$

where $\beta \in [0,1)$. Most prominent effect is ρ coupling to 3 Goldstone bosons

$$g_{\rho\pi\pi}\epsilon^{abc}\pi^a\partial_\mu\pi^b\rho_\mu^c + \frac{g_{\rho\pi^3}}{3v}\left(\rho_\mu^a\pi^a\partial_\mu\pi^b\pi^b - \rho_\mu^a\partial_\mu\pi^a\pi^b\pi^b\right)$$

$$m_\rho^2 = \frac{\alpha g_\rho^2 v^2}{1-\beta^2} \quad g_{\rho\pi\pi} = \frac{\alpha-\beta^2}{2(1-\beta^2)}g_\rho \quad g_{\rho\pi^3} = \beta\frac{\alpha-\beta^2}{\sqrt{\alpha}(1-\beta^2)}g_\rho$$

The widths for the 2- and 3- body decay

$$\Gamma(\rho\to 2\pi) = \frac{g_{\rho\pi\pi}^2 m_\rho}{48\pi} \qquad \Gamma(\rho\to 3\pi) = \frac{3g_{\rho\pi^3}^2 m_\rho^3}{4096\pi^3 v^2}$$

Later I'll show that branching fraction for 3-body can be up to 30 percent in allowed parameter space

Unitarity Constraints and Parameter Space

Unitarity of the S-matrix implies the relation for the scattering amplitudes

$$\mathrm{Im}\,\mathcal{M}_{\alpha\beta} = \sum_{\gamma} \mathcal{M}_{\alpha\gamma}\sigma_\gamma \mathcal{M}^*_{\beta\gamma}$$

where $\sigma_\alpha^2 = (1 - m_1^2/s - m_2^2/s)^2 - 4m_1^2 m_2^2/s^2$ for $s > (m_1 + m_2)^2$, and $\sigma_\alpha = 0$ otherwise. For one initial and one final state available, the amplitude must lie on the Argand circle,

$$\sigma_\alpha \left(\mathrm{Re}\,\mathcal{M}_{\alpha\alpha}\right)^2 + \sigma_\alpha \left(\mathrm{Im}\,\mathcal{M}_{\alpha\alpha} - \frac{1}{2\sigma_\alpha}\right)^2 = \frac{1}{4\sigma_\alpha}$$

which implies

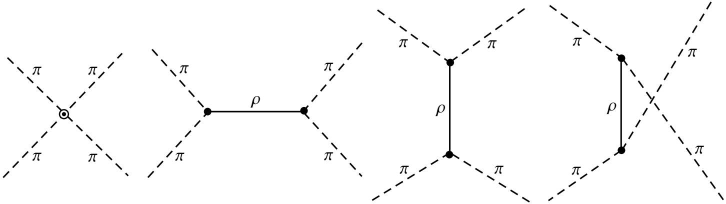
$$|\mathrm{Re}\,\mathcal{M}_{\alpha\alpha}| \leq 1/2\sigma_\alpha$$

Projecting into partial waves,

$$\mathcal{M}^J_{\alpha\beta}(s) = \frac{1}{32\pi} \int_{-1}^{1} d(\cos\theta) \mathcal{M}_{\alpha\beta} P_J(\cos\theta)$$

the same condition for each partial wave. Typically, s-wave gives the strongest bound.

Unitarity of Electroweak gauge boson scattering



Scattering amplitudes for longitudinally polarized W and Z, or, equivalently, for the Goldstone bosons π eaten by W and Z are given by

$$\mathcal{M}(\pi^a\pi^b \to \pi^c\pi^d) = \delta^{ab}\delta^{cd}M(s,t,u) + \delta^{ac}\delta^{bd}M(t,u,s) + \delta^{ad}\delta^{bc}M(u,s,t)$$

$$M(s,t,u) = \frac{s}{v^2} - g^2_{\rho\pi\pi}\left(\frac{s-u}{t-m_\rho^2} + \frac{s-t}{u-m_\rho^2} + 3\frac{s}{m_\rho^2}\right)$$

S-wave amplitude

$$\mathcal{M}^0(\pi^a\pi^b \to \pi^c\pi^d) = \left[\delta^{ab}\delta^{cd} - \frac{1}{2}\delta^{ac}\delta^{bd} - \frac{1}{2}\delta^{ad}\delta^{bc}\right]\mathcal{M}^0_{\pi\pi\to\pi\pi}(s)$$

$$\mathcal{M}^0_{\pi\pi\to\pi\pi}(s) = \frac{1}{16\pi}\left[\frac{s}{v^2} - \frac{3g_{\rho\pi\pi}}{2g_\rho}\frac{s}{v^2} - 2g^2_{\rho\pi\pi} + 4g^2_{\rho\pi\pi}\left(1+\frac{m_\rho^2}{2s}\right)\log\left(1+\frac{s}{m_\rho^2}\right)\right]$$

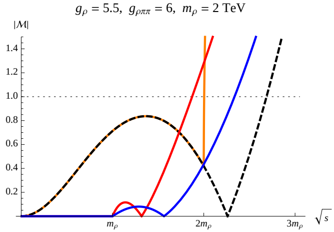
Unitarity Condition

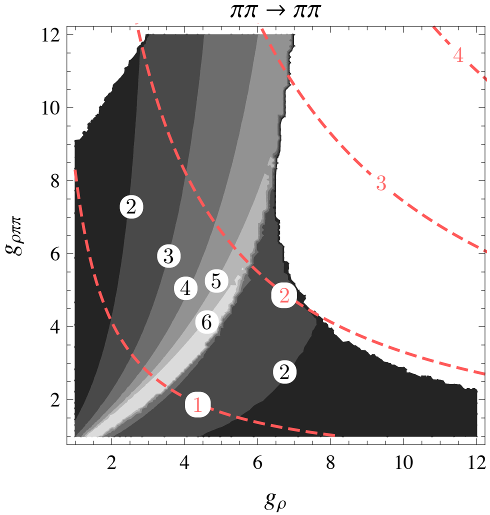
$$|\mathcal{M}^0_{\pi\pi\to\pi\pi}(s)| \leq 1$$

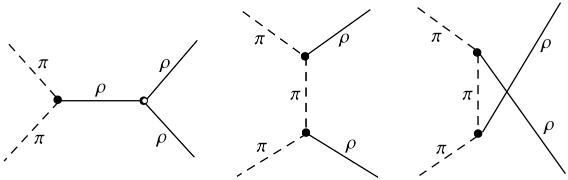
- Amplitude grows with energy as

$$\sim \frac{s}{v^2}\left(1 - \frac{3}{2}\frac{g_{\rho\pi\pi}}{g_\rho}\right)$$

- Maximum cutoff Λ allowed by unitarity is determined by the lowest solution $|\mathcal{M}^0_{\pi\pi\to\pi\pi}(\Lambda^2)| = 1$
- For $g_{\rho\pi\pi} \approx 2g_\rho/3$ the quadratic growth is tamed, $\mathcal{M} \sim \log s$, and the cutoff can be high $\Lambda \gg m_\rho$
- Actually, it is often better to take $g_{\rho\pi\pi} \approx g_\rho$, as then the negative quadratic contribution cancels against the positive logarithmic one,




$\pi\pi \to \pi\pi$
$g_{\rho\pi\pi}$
g_ρ
2
3
4
5
6
2
1
2
3
4



Another, independent unitarity condition

$$|\mathcal{M}_{IE}| \equiv |\mathcal{M}^0_{\pi\pi\to\pi\pi}| + \theta(s - 4m_\rho^2)\sqrt{1 - 4m_\rho^2/s}\,\frac{|\mathcal{M}^0_{\pi\pi\to\rho\rho}|^2}{|\mathcal{M}^0_{\pi\pi\to\pi\pi}|} \leq 1$$

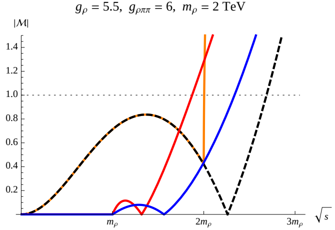
Unitarity constraints from inelastic processe

Amplitude

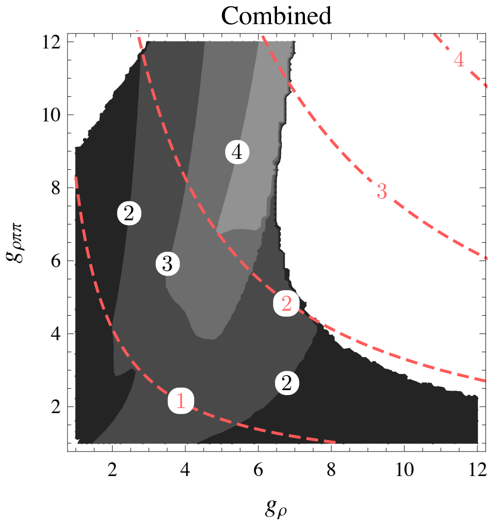
$$\mathcal{M}^0(\pi^a\pi^b \to \rho_L^c\rho_L^d) = \left[\delta^{ab}\delta^{cd} - \frac{1}{2}\delta^{ac}\delta^{bd} - \frac{1}{2}\delta^{ad}\delta^{bc}\right]\mathcal{M}^0_{\pi\pi\to\rho\rho}(s)$$

$$\mathcal{M}^0_{\pi\pi\to\rho\rho}(s) \approx \frac{g^2_{\rho\pi\pi}}{16\pi}\left(\frac{s}{m_\rho^2} - 2\right)$$

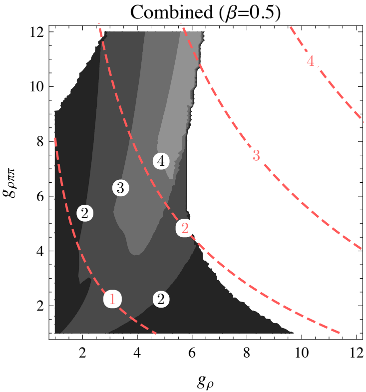
- Amplitude for inelastic ρ-pair production grows linearly with s,
- The coefficient of the $\mathcal{O}(s)$ term is always positive
- For large $g_{\rho\pi\pi}$ inelastic amplitude often provides the most stringent unitarity constraint
- Yet another constraint is provided by considering the $\rho\pi \to \rho\pi$ scattering



Parameter space after all unitarity constraints



Contour plots of the maximum cut-off scale Λ overlaid it with contours of constant m_ρ (dashed).



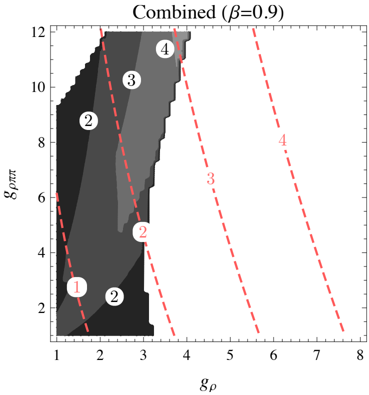
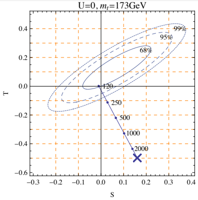


Figure: Contour plots of the maximum cut-off scale for $\beta = 0.5$ (left) and $\beta = 0.9$ (right) overlaid it with contours of constant m_ρ (dashed).



(plot stolen from Cata,Kamenik [1010.2226])

Integrating out the ρ-mesons contributes to the S parameter at the tree level,

$$\Delta S = \frac{4\pi}{g_\rho^2}$$

large, unless g_ρ is near the perturbativity limit. Some ways to cope with it:

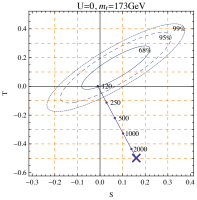
- Allow an axial resonance to cancel part of S,
- Allow $\mathcal{O}(p^4)$ operator

$$-\frac{\epsilon}{16g_\rho}\mathrm{Tr}\left\{[\mathrm{g}\xi_\mathrm{L}^\dagger \mathrm{L}_{\mu\nu}\xi_\mathrm{L} + \mathrm{g}'\xi_\mathrm{R}^\dagger \mathrm{R}_{\mu\nu}\xi_\mathrm{R}]\rho_{\mu\nu}\right\}$$

  who contributes $\Delta S = 4\pi\epsilon/g_\rho^2$.
- Allow parity breaking that contributes as

$$\Delta S = \frac{4\pi}{g_\rho^2}\left(1 - \frac{\beta^2}{\alpha}\right)$$

Electroweak Precision Observables: T parameter



T parameter zero at tree level. At one loop

$$\Delta T \sim -\frac{3}{8\pi \cos^2\theta_W}\left(1-\frac{3\alpha}{4}+\frac{\alpha^2}{4}\right)\log\Lambda$$

For $\alpha < 3$ less negative than in the SM without Higgs, good. But always negative, bad. For $\epsilon \neq 0$ also quadratically divergent contributions to T that can have any sign.

Phenomenology of Resonances

Mixing between SM and heavy resonances

In the "flavor" basis $(W^\pm, \rho^\pm)$ mass matrix not diagonal

$$v^2 \begin{pmatrix} (1+\alpha)g^2/4 & -\alpha g g_\rho/2 \\ -\alpha g g_\rho/2 & \alpha g_\rho^2 \end{pmatrix}$$

For $g_\rho \gg g$ hierarchical eigenvalues

$$m_\rho^2 \approx \alpha g_\rho^2 v^2 \qquad m_W^2 \approx \frac{g^2 v^2}{4}$$

The rotation to mass eigenstates

$$W^\pm \to \cos\theta W^\pm - \sin\theta \rho^\pm \qquad \rho^\pm \to \sin\theta W^\pm + \cos\theta \rho^\pm \quad \sin\theta \approx \frac{g}{2g_\rho}$$

Couplings of a single resonance to the SM

Robust coupling: Cubic gauge couplings from mixing

$$-\frac{g^2}{4g_\rho}[W^+W^-\rho^0]-\frac{g\sqrt{g^2+g'^2}}{4g_\rho}[W^-Z\rho^+]-\frac{g\sqrt{g^2+g'^2}}{4g_\rho}[W^+Z\rho^-]$$

Less Robust: *if* all SM quarks and leptons are fundamental (the couple to resonances only via the mixing)

$$-\frac{g^2}{2\sqrt{2}g_\rho}\rho_\mu^\pm \bar{f}_L\gamma_\mu T^\pm f_L-\frac{1}{2g_\rho}\rho_\mu^0\bar{f}\gamma_\mu\left((g^2-g'^2)T^3+g'^2Q\right)f$$

Caveat: in concrete models one expects top quark to have a large composite component, and therefore a larger coupling to resonances. Ignored here, but in concrete models the branching fraction to top quarks can be significant or even dominant

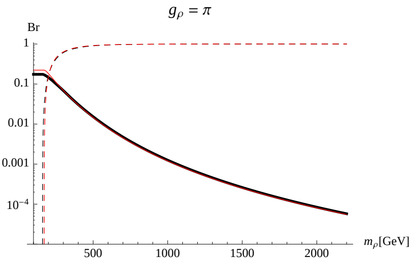
Resonance decays

Decays to SM gauge bosons dominated by decays to longitudinal polarization

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

Decays to VV effectively have no $1/g_\rho$ suppression! Decays to SM fermions suppressed

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

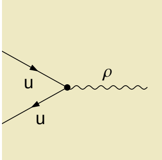


- For $m_\rho \sim$ TeV leptonic branching is less than 10^{-3}.
- At LHC or Tevatron heavy ρ meson show up as resonances in the WW and WZ channels

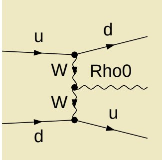
Production of resonances in hadron colliders

3 main production channels:

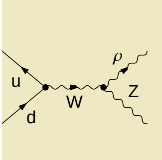
1. Drell-Yan: $q\,\bar{q} \to \rho$



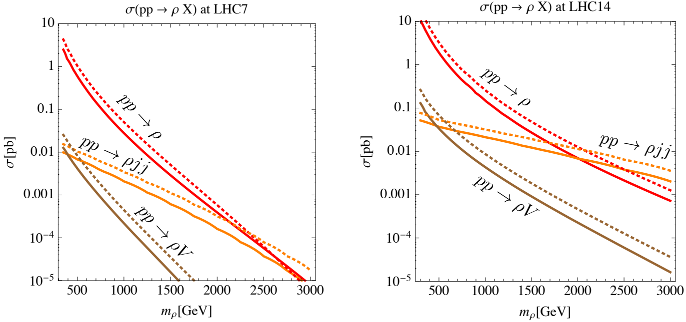
2. Vector Boson Fusion: $q\,q \to \rho\,q\,q$



3. Rho-Strahlung: $q\,\bar{q} \to \rho\,V$



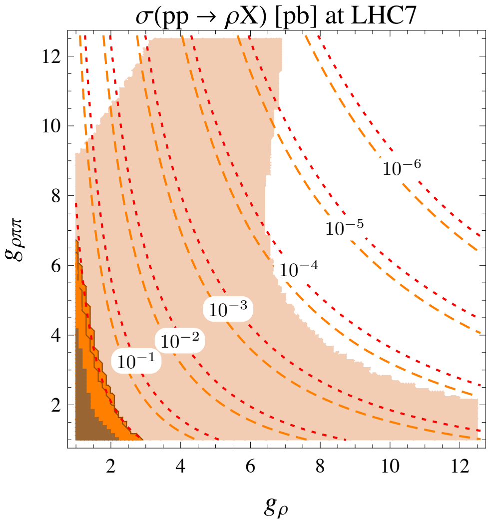
- Drell-Yan dominates for relatively light ρ
- VBF is important for very heavy ρ



- Best limits on WW and WZ resonances currently from D0 [1011.6278]
- No corresponding analysis from the LHC yet
- LHC limits on leptonic Z' and W' are not competitive because of the small leptonic branching fraction

Contour of ρ production cross section at the LHC at $\sqrt{s} = 7\,TeV$

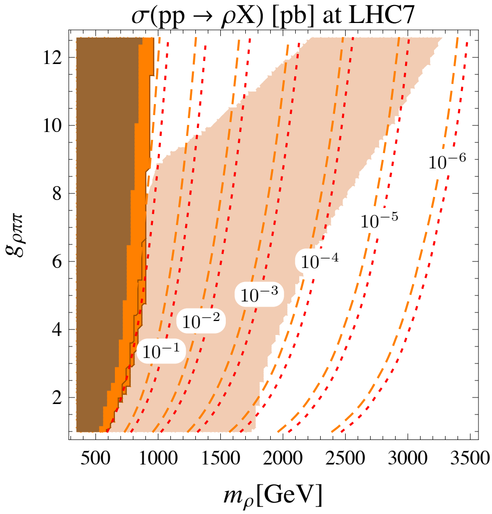
Orange dashed line: ρ_0, Red dashed line $\rho_\pm$



Peach: allowed by unitarity, Orange: Excluded by Tevatron, Brown: Excluded by LHC

Contour of ρ production cross section at the LHC at $\sqrt{s} = 7\,TeV$

Orange dashed line: ρ_0, Red dashed line $\rho_\pm$



Peach: allowed by unitarity, Orange: Excluded by Tevatron, Brown: Excluded by LHC

Take Away Points

- The full theory of electroweak symmetry breaking may well turn out to be very complicated...
- ... but it may pay off to take a simplified approach to isolate relevant collider signatures and understand the full kinematic parameter space
- Parameter space for Higgsless electroweak symmetry breaking will be open for a while; even in the simplest model the resonance masses as heavy as 2-3 TeV are possible
- Still a lot to do for the LHC, unless they find the Higgs of course :-)