# An Effective Theory for Higgs Compositeness

### Jay Hubisz Syracuse University 2/27/2011



WIP - Bellazzini, Csáki, JH, Serra, Terning

**Perspectives on Higgs physics** By G. L. Kane

### Why I would be very sad if a Higgs boson were discovered<sup>\*†</sup>

Howard Georgi Lyman Laboratory of Physics Harvard University Cambridge, MA 02138

#### Abstract

I explain the difference between the Higgs mechanism and the Higgs, discuss various options for spontaneous  $SU(2) \times U(1)$  symmetry breaking and quark and lepton mass generation, and speculate about chiral gauge theories.



10

Data 2011,  $\sqrt{s}$  = 7 TeV,  $\int$  Ldt = 4.8 fb ∫ Data

mH=130 GeV, 1xSM

**ATLAS Preliminary** 

- ATLAS + CMS have excesses in  $\gamma\gamma$ 6 ATI AC LONA I CIVI 30 n vv  $\bullet$   $\bullet$
- Backed up by collections of 4l events Backed up by collecti
- Slight excesses in CMS low res. channels  $\frac{1}{2}$
- "Smells" right  $\bullet$  "Smells" right (b), *<sup>H</sup>* <sup>→</sup> *ZZ*(∗) <sup>→</sup> !+!−!+!<sup>−</sup> in the entire mass range (c), and the *<sup>H</sup>* <sup>→</sup> *WW*(∗) <sup>→</sup> !+ν!−<sup>ν</sup> (d) channels.

I ((II)



600

700

800

## Consistent with other fundamental laws:

#### **Pauli's Other Exclusion Principle**

As I am currently stretched between continents, I ponder over the differences between the US and Europe. Apart from the taste of food and the size of humans, there seems to be a fundamental difference at the level of particle physics. Let's have a closer look at the time and place of discoveries of elementary particles:

- · Tau neutrino, 2000, Fermilab, United States
- · Top quark, 1995, Fermilab, United States
- · W and Z bosons, 1983, CERN, Switzerland
- · Gluon, 1979, DESY, Germany
- · Bottom quark, 1977, Fermilab, United States
- · Tau, 1975, SLAC, United States
- Charm quark, 1974, SLAC/Brookhaven, United States
- Up, down, and strange quarks, 1968, SLAC, United States
- · Muon neutrino, 1962, Brookhaven, United States
- · Electron neutrino, 1956, Los Alamos, United States
- · Muon, 1936, Caltech, United States
- Photon, 1905, Patent Office in Bern, Switzerland
- Electron...let's skip that one for simplicity...

This can be summarized as Pauli's other exclusion principle:

Fermions are discovered in the US, whereas bosons are discovered in Europe.

### Resonaances - Falkowski



### Naturalness and a Composite Higgs

- Higgs not necessarily a fundamental scalar
	- composite at the TeV/few-TeV scale
- Composite models 'natural' in sense that the loops that correct the higgs mass are cut off at a much lower scale (little hierarchy often remains)
- models which combine these ideas address LH prob
	- Little Higgs, composite SUSY, ...
- motivates a simplified model approach to CH
	- what are generic signatures/constraints?

## Unitarity

- The principle of unitarity in EWSB provides the strongest justification for the LHC program
- The Higgs (or cousins) had to be there



Amplitude grows with energy - non-perturbative for E>>M SM: Fixed by including higgs contributions (gauge invariance forces a 'sum-rule')

#### Gaugephobic Higgs **T** pin <sup>µ</sup> = (E, 0, 0, ± !E<sup>2</sup> <sup>−</sup> <sup>M</sup><sup>2</sup> the Higgs exchange diagrams into account. <sup>µ</sup> = (E, ± !E<sup>2</sup> <sup>−</sup> <sup>M</sup><sup>2</sup> <sup>n</sup> sin θ, 0, ± !E<sup>2</sup> <sup>−</sup> <sup>M</sup><sup>2</sup> 1100 k  $\blacktriangleleft$ nnk. (3.4)

#### Assuming A(4) = 0 we get  $\bullet$  is in the interval of  $\bullet$ Limit of decoupled Higgs

**TECC** 

 $\mathcal{F}_{\mathcal{A}}$  , the four diagrams contributing at tree level to the elastic scattering and elastic scattering amplitude and  $\mathcal{A}$ 

Unitarity with only vectors: C∴ E,p⊥ C, P⊥ C, P gauge resonances terminate growth of amplitudes via KK-mode sum rule PICU I 11885 Sauge Tesonances terminate growth of amplitudes via and a model grow as E4, and the and the amplitude could grow as E4, and the amplitude then  $\overline{a}$  $\overline{\phantom{a}}$   $\overline{\$ s auge resultances terminate  $\sigma$  arounth of tors:  $\overline{K}$   $K$ -mode sum rule k of amplitudes via coupling between the KK modes. In the KK modes with the CHC modes with extra dimensions theories with extra dimensions the CHC modes. In the CHC modes with the CHC modes with the CHC modes with the CHC modes with the CHC m



t channel exchange





u channel exchange

 $\mathcal{A}=A^{(4)}\frac{E^4}{M^4}$  $M_n^4$  $+ A^{(2)} \frac{E^2}{\sqrt{2}}$  $M_n^2$  $+A^{(0)}+O$  $\sqrt{M_n^2}$  $E^2$  $\setminus$ among the coupling of the various KK modes is satisfied:  $+A^{(2)}\frac{1}{M^2}+A^{(0)}+O\left(\frac{n}{F^2}\right)$ k  $\mathcal{A}(4)$   $\mathcal{L}$  $\overline{4}$  $\begin{bmatrix} 1 & \Lambda(2) & \end{bmatrix}$   $\begin{bmatrix} L^{\mathsf{T}} & \mathsf{T} & \end{bmatrix}$  $=$   $\frac{1}{2}$  $\frac{1}{l}$  $\overline{\phantom{a}}$ 

 $\mathbf{1}$ 

exchange  
\n
$$
A^{(2)} = \frac{i}{M_n^2} \left( 4g_{nnnn} M_n^2 - 3 \sum_k g_{nnk}^2 M_k^2 \right) \left( f^{ace} f^{bde} - \sin^2 \frac{\theta}{2} f^{abe} f^{cde} \right)
$$
\n
$$
(n) \int_{0}^{C} c \qquad g_{nnnn} M_n^2 = \frac{3}{4} \sum_k g_{nnk}^2 M_k^2
$$

k

#### ruie  $\overline{\phantom{0}}$  $\mathcal{L}_{\mathcal{A}_{q^-}}$  sum rule automatic auge  $\bullet$ dyariance) l (5D gauge invariance)  $A$ mazingly, higher dimensional gauge invariance will ensure that both of these summarizations  $\mathcal{A}$  $\sum_{i=1}^N$  is the sum rule via the complete functions of the  $\sum_{i=1}^N$  $\sqrt{ }$ age mival land  $\mathcal{L}$

review: Csaki, JH, Meade and only depend on the amplitude on the state on the state on the state on the state o

and overall kinematic factor multiplied by an overall expression of the couplings. Assuming  $\mathcal{A}$ 

### Simplified model for LHC unitarity

WIP: Bellazzini, Csáki, JH, Serra, Terning

- Unitarity sum-rule only partially saturated by Higgs exchange diagrams - suppressed couplings
- one set of vector resonances  $(\rho's)$  completes saturation of the electroweak GB sum-rules
	- non-linear realization of custodial coset:
		- $\bullet$  SU(2)L x SU(2)R/SU(2)c a-la hidden local symmetry Cassalbuoni, Curtis, Dominici, Gatto '87 Falkowski, Grojean, Kaminska, Pokorski, Weiler '11
		- $\rho$ 's come as triplet of SU(2) $<$

#### The Goldstones space *G/H*. In order to deal with fields defined up to *g*(*x*) ⇠ *g*(*x*)*h*(*x*) we can use the standard on non-linear realizations of symmetries [1]. We summarize here the CCWZ method. *U*(⇧) = *e<sup>i</sup>*⇧*a*ˆ*<sup>T</sup> <sup>a</sup>*<sup>ˆ</sup> *g*0*U*(⇧) = *U*(⇧<sup>0</sup> )*h*(⇧*, g*0) (1.1) where  $\overline{\phantom{a}}$  **h**  $\overline{\phantom{a}}$   $\overline{\phantom{$ that defines the parametrization of the coset. The action of the group *G* on the coset *U*(⇧) = *e<sup>i</sup>*⇧*a*ˆ*<sup>T</sup> <sup>a</sup>*<sup>ˆ</sup> *g*0*U*(⇧) = *U*(⇧<sup>0</sup> )*h*(⇧*, g*0) (1.1)

Every *g* 2 *G* in a neighborhood of the identity can be written in this convenient form *g* = Symmetry spontaneously broken at  $t = v_{ew}$ Symmetry spontaneously broken at f = v<sub>ew</sub>

**Element of coset G/H:**  $U(\Pi) = e^{i\Pi^{\hat{a}}T^{\hat{a}}}$ **Element of coset G/H:**  $U(\Pi) = e^{i \Pi^{\alpha} T^{\alpha}}$ U<sup>(</sup>∪) *U*(**0**) ! *U*(∴0) that is a non-linear transformation of  $\mathcal{L}^{(1)}$ 

 $-iU^{-1}\partial_{\mu}U = \Pi_{\mu}^{\hat{a}}T^{\hat{a}} + E_{\mu}^{a}T^{a} \equiv \Pi_{\mu} + E_{\mu}$ **that is a contract of the Lie algebra we can provide a consequence we can proper we can proper along the broken**  $\Pi_{\mu} \rightarrow h(\Pi, g_0) \Pi_{\mu} h^{-1}(\Pi, g_0)$  $U$   $\mu$ <sup>*U*</sup> (11, 90)</sub>  $\Pi_{\mu} \rightarrow h(\Pi, g_0) \Pi_{\mu} h^{-1}(\Pi, g_0)$ <br> $E_{\mu} \rightarrow h(\Pi, g_0) E_{\mu} h^{-1}(\Pi, g_0) = i h(\Pi, g_0) \partial h^{-1}(\Pi, g_0)$  $E_{\mu} \rightarrow h(11, g_0)E_{\mu}h$  (11, *g*<sub>0</sub>)  $=$   $\mu\mu(11, g_0)$ *on* (1 (a)  $\frac{1}{2}$ ,  $\frac{1}{2}$ ,  $\frac{1}{2}$ which transform in this way to be a strategy of  $\mathcal{C}$  $E_{\mu} \rightarrow h(\Pi, g_0) E_{\mu} h^{-1}(\Pi, g_0) - ih(\Pi, g_0) \partial h^{-1}(\Pi, g_0)$ . Under transformation go in G:

 $\Pi_\mu$  transforms linearly  $\mathbf{r}_\mu$  $\boldsymbol{y}$  is the gauge in (⇧*, g*0) (1.4) it is not an independent degree of  $F$  franch  $E_{\mu}$  transforms like gauge field

#### The Goldstones We can also introduce a covariant derivative r*<sup>µ</sup>* = @*<sup>µ</sup> iEµ*. Note that the vector field ⇧*<sup>µ</sup>* transforms linearly whereas *E<sup>µ</sup>* like a "gauge field" but the fact that With all these covariant variables we can now easily define *G*-symmetric actions on *G/H*. For it is not an independent degree of freedom o<br>Independent degree of freedom of

Build action that is invariant under G: @*µU*] ⇧*<sup>a</sup>*<sup>ˆ</sup>

$$
\mathcal{L}_{\Pi}^{(2)} = \frac{f^2}{2} \text{Tr}[\Pi_{\mu} \Pi^{\mu}]
$$
 Goldstone kinetic terms

Goldstone kinetic terms

 $\overline{A}$  and  $\overline{B}$   $\overline{B}$   $\overline{B}$  are respectively to  $\overline{B}$  and  $\overline{B}$  and  $\overline{B}$   $\overline{B}$ The lagrand is suite of singlet under *H* is very singlet under *H* is very signified with  $\frac{1}{2}$ With all these covariable constants we can now  $\overline{A}$ Add inggs interactions (singlet couplings). Add Higgs interactions (singlet couplings):

$$
\mathcal{L}^{(h)} = \frac{1}{2}(\partial h)^2 + V(h) + \frac{f^2}{2}(2a_h \frac{h}{f} + b_h \frac{h^2}{f^2}) \text{Tr}[\Pi_\mu \Pi^\mu]
$$
  
free parameters

 $\mathbf{r}$  $a_h$  sets h $m \pi$  coupling - unitarity saturated for  $a_h = 1$ 

#### The ρ's current gives rise, via the exchange of longitudinal  $\mathcal{L}_{\mathcal{A}}$  is the exchange of longitudinal  $\mathcal{L}_{\mathcal{A}}$ *<sup>µ</sup>*, to non-renormalizable operators suppresed  $h \cap \Omega'$ because non-renormalizable terms should be weighted by the cuto↵ scale ⇤ *m*⇢ where the EFT

With  $E_{\mu}$ , can write down invariant action that includes additional gauge fields transforming under SU(2)c  $\Delta b$  is  $\Gamma$  and with down. In print of a step that includes **SOMALL COUPLINGS AS (***M*) to some power interesting power. The  $\mu$ , the  $\mu$ 

$$
\mathcal{L}_{\rho}^{(2)} = -\frac{1}{4g_{\rho}^2} \rho_{\mu\nu}^a \rho_{\mu\nu}^a + \frac{a_{\rho}^2 f^2}{2} (\rho_{\mu}^a - E_{\mu}^a(\Pi))^2
$$

Generates a ρ mass:  $m_\rho = a_\rho g_\rho f$ 

#### $\sigma_0$  sets self-interactions of  $\rho$ 's  $g\rho$  sets sen-interactions of  $\rho$ s  $a_\rho$  sets mass, interactions with goldstones, and adds alredy diagonalized the mass matrix.  $\bullet$  is equivalent to the lagrangian symmetry considered in the hidden local symmetry  $\bullet$ The leading order in the singlet under in the singlet under the singlet under the singlet under  $\theta$  is very simple  $\theta$ gρ sets self-interactions of ρ's aρ sets mass, interactions with goldstones, and adds goldstone self-interactions

*SU*(*N<sup>f</sup> Nc*) [9] . *<sup>L</sup>*(*h*) <sup>=</sup> 5 s couplings 1 <sup>2</sup> (2*a<sup>h</sup> h*  $\left| \right.$  *H*iggs couplings to *p*'s:  $\left| \right.$   $\mathcal{L}_{\rm h\rho} =$ 

**Higgs couplings to p's:** 
$$
\left(\mathcal{L}_{h\rho} = \frac{f^2}{2} (2c_h \frac{h}{f} + d_h \frac{h^2}{f^2}) (\rho^a_\mu - E^a_\mu)^2 \right)
$$

### SM Gauge Bosons Rotating to the physical basis where the masses are diagonal we can get the ⇢*WW*- and ⇢*±W*⌥*Z*coupling which might be important for the VBF production channel. At the lowest order in

Gauging SU(2)<sup>L</sup>xU(1)<sup>x</sup>: gauge fields in  $\Pi_{\mu}$  and  $E_{\mu}$ .  $\overline{G}$ 2*g*⇢ l<sub>u</sub> and  $E_{\mu}$ .



 $\overline{C}$ SU(2)<sub>C</sub> insures against large T-parameter *<u>sures</u>* a  $\overline{a}$   $\overline{b}$ ns  $\overline{4}$ ⇢*<sup>±</sup>* !⇢*<sup>±</sup>* <sup>+</sup> *<sup>g</sup>*<sup>2</sup> 2*g*⇢  $P^a P^a P^a A^b$ 

 $\psi_{\overline{a}}\rho^0$  explicit pVV couplings: after diagonalization, have  $\frac{1}{2}$  : *g*⇢ *<sup>A</sup> <sup>g</sup>*<sup>2</sup>  $\frac{1}{2}$ **j** *Z* (4.25)

$$
\rho \sqrt{g_1 + g_2}
$$
\n
$$
\rho^0
$$
\n
$$
g_0^2 - g_1^2 - g_2^2
$$
\n
$$
g_{\rho WZ} = -\left(\frac{g_2}{4g_\rho}\right) \sqrt{g_1^2 + g_2^2} = -\left(\frac{g_1^2 + g_2^2}{4g_{2\rho}}\right) g_{WWZ}^{SM}
$$

 $Z \bigcup_{\mathbf{z} \in \mathbb{R}^n} z^{\mathbf{z}}$ where we have suppressed the index  $\sim$  ph" (with the index  $\sim$ participates in unitarization of VBS *g*  $\bullet$  (4.28) **c**  $\bullet$  (4.28) **c**  $\bullet$  (4.28) **c**  $\bullet$ p*g*<sup>2</sup> <sup>1</sup> + *g*<sup>2</sup>  $2.70c$ order of the coupling to  $\overline{a}$ 

#### Couplings to light fermions *g*⇢  $\alpha$   $\lim$ 1 light  $\int$

mixing also generates couplings to non-composite fermions:

$$
\mathcal{L}_{\rho-current}^{(element.)} = -\frac{g_2^2}{2\sqrt{2}g_\rho}\rho_\mu^\pm\bar{\psi}\gamma^\mu T^\mp\psi + \rho_\mu^0\bar{\psi}\left[\frac{(g_1^2-g_2^2)}{2g_\rho}T^3 - \frac{g_1^2}{2g_\rho}Q\right]\gamma^\mu\psi
$$

light quark coupling - Drell Yan production

**Couple with strength** 
$$
g_{\rho\bar{f}f} = g_{\rm SM} \left( a_{\rho} \frac{m_W}{m_{\rho}} \right)
$$

6 Heavy fermions may be composite carry charge under  $SU(2)_C$ couple strongly

### The Model - Summary

1 assume the gauge unbroken global SU(2)<sub>C</sub> SU(2)*<sup>R</sup>* ! SU(2)*<sup>C</sup>* with characteristic scale *v* ' 246 GeV. The residual SU(2)*<sup>C</sup>* custodial symmetry

*µ*,

 $\int$ 

is introduced in order to avoid *O*(1) contributions to the *T*b-parameter. Besides the NGBs eaten by  $\alpha$  is ρ 'gauge coupling' a<sub>ρ</sub> fixes ρ mass ah controls suppression of higgs couplings  $\mathcal{L}$  =  $v^2$  $\frac{v^2}{2}(\Pi_{\mu}^{\hat{a}})^2-\frac{1}{4}$ 4  $(\rho^a_{\mu\nu})^2 + a_\rho^2$  $v^2$ 2  $(g_{\rho}\rho_{\mu}^{a}-E_{\mu}^{a}% )_{\mu}$  $\mathcal{E}$  $+$ 1 2  $(\partial_{\mu}h)^{2} + V(h) + \frac{v^{2}}{2}$ 2  $\sqrt{2}$ 2*a<sup>h</sup> h*  $\overline{v}$  $+ b_h$  $h<sup>2</sup>$  $v^2$ ◆  $(\Pi_{\mu}^{\hat{a}})^{2} +$  $v^2$ 2  $\overline{1}$ 2*c<sup>h</sup> h*  $\overline{v}$  $+ d_h$  $h<sup>2</sup>$  $v^2$  $\bigg)$  $g_{\rho}\rho^{a}_{\mu}-E^{a}_{\mu}$  $\mathcal{E}$  $+$   $O(p^4)$  $)$  $\frac{1}{2}$ C(2)<sup>L</sup>/<sub>C</sub> and the SU(2)<sup>C</sup>/<sub>C</sub> and hat the SU(2)<sup>*C*</sup>)<sup>*R*</sup>/ **Parity 19** (Suitstones eater by vv,  $\angle$ ) Scattering of a set of the field of fermines *<sup>W</sup>* is well described  $\frac{1}{2}$   $\$  $\sim$ **2**<br>2010 -<br>2011 values for soffield <sup>2</sup> (@*µ*⇡*<sup>a</sup>*<sup>ˆ</sup> Sufficient to consider π scattering for unitarity (goldstones eaten by W, Z) Electroweak bosons mix with ρ's couple to SM gauge fields/fermions Specific models predict values for some/all parameters

6*v*<sup>2</sup>

4

### Unitarization *<sup>d</sup>*(cos ✓)*M*↵(cos ✓) *<sup>t</sup>* <sup>=</sup> *<sup>s</sup>* (1 cos ✓) *<sup>u</sup>* <sup>=</sup> *<sup>s</sup>*

Couplings and masses must satisfy sum rules to ensure perturbative W/Z scattering  $\frac{1}{\sqrt{2}}$ 

 $\mathcal{M}(\pi^+\pi^-\rightarrow\pi^+\pi^-)=\frac{1}{32}$  $32\pi$ *s f* 2  $\left(1-a_h^2-\hat{a}_\rho^2\right)$  $\overline{ }$  $-\frac{1}{48\pi}$  $48\pi f^2$  $\left[ m_{\rho}^2 \hat{a}_{\rho}^2 (1 - 2 \log[s/m_{\rho}^2]) + 3 m_h a_h^2 (2 m_h - i \Gamma_h) \right]$ (7.11)  $\hat{\sigma}^2 = \frac{3}{2} \hat{a}^2$  Cum Pulse  $\hat{a}^2$ *a*2 *<sup>h</sup>* + ˆ*a*<sup>2</sup>  $\frac{1}{2}$ Log growth remains Assuming this sum rule we can now plot the allowed region by unitarity condition *|M*<sup>0</sup>*| <* 1 We limit m<sub>ρ</sub> by requiring perturbative scattering up Assuming a certain Higgs coupling to SM gauge boson we can derive the upper limit for the to a few TeV (LHC unitarity)  $\mathbf{f}_{\mathbf{t}}(\mathbf{t}) = \mathbf{f}_{\mathbf{t}}(\mathbf{t})$  on the new resonance must appear below a given mass scale as shown in the new resonance must appear below a given mass scale as shown in the new resonance must appear below a given Sum Rule:  $a_h^2 +$ 3 4  $\hat{a}^2_\rho \equiv \frac{3}{4} a^2_\rho$  **Sum Rule:**  $a^2_h + \frac{3}{4} a^2_\rho = 1$ 3 4  $a_\rho^2$ include inelastic channels

<sup>9</sup>up to the symmetry factor for identical particles and an overall (*i*)*<sup>N</sup>* where *<sup>N</sup>* is the number of Goldstone

### Parameters

Unitarity sum-rule fixes  $a_{\rho}$  in terms of  $a_{h}$ 

VB Mass matrix set by  $g_{\rho}$ ,  $a_{\rho}$ , and f=246 GeV

Mixing with SM gauge fields determines most interesting phenomenology

**effectively have a 2-parameter model**

We parameterize in terms of  $a_h$  and  $m_\rho$ 

#### Turn that Higgs bound up-side down!  $M_h$  [GeV] 2000 3000 1500  $M_V$ <sup>max</sup> [Gev] 150 200 300 500  $M_H$  [GeV] 1.00 0.50 2.00 0.30 1.50 0.70  $\sigma/\sigma_{\text{SM}}$ Exercise: Higgs is at mass  $m_H$ , but with suppressed overall couplings Comb. CMS What is max allowed ρ mass? Saturate s-growth sum-rule

100 200 300 400 500 600

## The unitarity constraint

Pink regions forbidden for different values of effective cutoff

As Higgs couplings reduced, ρ's must come in earlier to unitarize scattering



## Vector Production

- Vector Boson Fusion
	- Pro: model independent (unitarity)
	- Con: cross section small, signal challenging
- Drell-Yan
	- most models have mixing with SMW's, Z
	- coupling to light quarks (but small)
	- Pro: potentially large (enough) <sup>σ</sup>
	- Con: model dependent production

## Vector decays

- The *p*'s are composite strongly interacting states
	- prefer to decay to other composites
	- massive degrees of freedom typically have larger degrees of compositeness

$$
\rho^0 \rightarrow W^+W^- \rightarrow \rho^{\pm} \rightarrow W^{\pm}Z
$$
  

$$
\rightarrow \bar{t}t \rightarrow \bar{b}t
$$
  

$$
\rightarrow \bar{b}b
$$

decays to light fermions typically suppressed

decays to 3rd gen fermions present challenging final states resonances in di-boson spectrum (leptonic) best bet



# Modeling the  $\rho^0$



Z' with suppressed coupling to light quarks

High mass Higgs search restricts values of  $\lambda^2$  Br( $\rho^0 \rightarrow W W$ ) Seems hard - Higgs search is very optimized for SM

#### Docent Dounda on Recent Bounds on Z' bosons



[O.J.P. Eboli,](http://inspirehep.net/author/Eboli%2C%20O.J.P.?recid=1079743&ln=en) [J. Gonzalez-Fraile,](http://inspirehep.net/author/Gonzalez-Fraile%2C%20J.?recid=1079743&ln=en) [M.C. Gonzalez-Garcia.](http://inspirehep.net/author/Gonzalez-Garcia%2C%20M.C.?recid=1079743&ln=en)  $\ddotsc$  .  $\ddotsc$ 

 $\alpha$ 

Finally in Fig. 5 weeks the exclusion constraints of the exclusion constraints of the exclusion constraints of

 $\Box$  Deally positive  $\blacksquare$  neally integrated in the form Wededicated di\_hoso strangulated di-DOSOI  $\mathbf{d}$ : and  $\mathbf{d}$ : hose possible alcal The sensitivity reach when a non-zero observation for ance search res dedicated di-hoson resor for the process (1) while in a cone ∆R  $\sim$  0.2 around the muon, the summary the muon, the summary the summary the summary the summary to Really requires dedicated di-boson resonance search

## Modeling charged ρ's



W' with suppressed coupling to fermions

Search for W'/techni-rho limits  $\lambda^2$  Br( $\rho^0 \rightarrow WW$ )

### Limits on charged ρ's

Implemented model in Madgraph



 $m_p$ 



 $M_V$  [GeV]

## Higgs to γγ in composite models

• Higgs couplings in composite models are modified  $\sqrt{2}$ !

$$
\lambda_i = \lambda_i^{\rm SM} \left( 1 + c \left( \frac{v}{f} \right)^2 \right)
$$

- f is related to scale of compositeness
	- decay constant in higgs as PGB
- Of primary interest are hWW, htt, hbb couplings

# Unitarity arguments

- in composite models, higgs couplings are generally suppressed
	- otherwise sum rules supersaturated
	- hard to get negative contribution
		- exception: Falkowski, Rychkov, Urbano (2012)
	- best bet for increase in signal is decrease in hbb coupling, or new charged fields



### Enhancement in γγ Assume EWSB by strong dynamics, with the global symmetry breaking pattern *G* ! *H* = SU(2)*L*⇥ SU(2)*<sup>R</sup>* ! SU(2)*<sup>C</sup>* with characteristic scale *v* ' 246 GeV. The residual SU(2)*<sup>C</sup>* custodial symmetry

• Charged *p*'s may contribute in hγγ triangle **W** WARREST WAS LIGHT (2011) SPIN-1 VECTOR IN THE PRESENCE OF SPINSIPS IN THE ADDRESS OF SPINSIPS 3 OF SUCKER IN THE ADDRESS OF SUCKER IN THE SUCKER IN THE ADDRESS OF SUCKER IN THE SUCKER IN THE SUCKER IN THE SUCKER IN THE

and a light scalar singlet 1 of SU(2)*C*, *h*. The Lagrangian for such a system is given by,

$$
\mathcal{L} = \frac{v^2}{2} (\Pi_{\mu}^{\hat{a}})^2 - \frac{1}{4} (\rho_{\mu\nu}^a)^2 + a_\rho^2 \frac{v^2}{2} (g_\rho \rho_\mu^a - E_\mu^a)^2 \n+ \frac{1}{2} (\partial_\mu h)^2 + V(h) + \frac{v^2}{2} (2a_h \frac{h}{v} + b_h \frac{h^2}{v^2}) (\Pi_\mu^{\hat{a}})^2 + \frac{v^2}{2} (2c_h \frac{h}{v} + d_h \frac{h^2}{v^2}) (g_\rho \rho_\mu^a - E_\mu^a)^2 \n+ O(p^4)
$$

| This coupling is arb. from perspective of low energy EFT |

Parity *PLR* (SU(2)*<sup>L</sup>* \$ SU(2)*R*) has been assumed in the couplings of ⇢ and *h*.

✓

Scattering of longitudinal massive gauge bosons *W<sup>L</sup>* at high energies *E*<sup>2</sup> *m*<sup>2</sup> by *W<sup>L</sup>* ' ⇡. The relevant interactions following from Eq. (1) are Vanishes in Higgs as PGB

*<sup>W</sup>* is well described

i

Can compensate for reduction in gg coupling common in composite models ⇡<sup>4</sup> : <sup>1</sup> <sup>3</sup>*a*<sup>2</sup> *<u>Ictior</u>* (@*µ*⇡*<sup>a</sup>*<sup>ˆ</sup> ⇡ ) <sup>2</sup> (@*µ*⇡*<sup>a</sup>*<sup>ˆ</sup> ⇡*a*ˆ ) *a*2 ⇢*g*⇢  $\overline{a}$  $\overline{\Gamma}$  $\overline{a}$  *bosite* **models** 

◆ 1

h



### Conclusions

- A simplified model approach to Higgs compositeness - new VB's in representation of  $SU(2)_C$
- new vector masses bounded from above (unitarity) and below (LHC)
- Can manage increase in h signal, even with suppressed couplings (new triangle diagrams)
- Upcoming experimental searches for di-boson resonances will be extremely valuable