# **THE OTHER HIGGSES, AT RESONANCE, IN THE LEE-WICK EXTENSION OF THE STANDARD MODEL**

**ARXIV:1108.3765, JHEP10 (2011) 145 (IN COLLABORATION WITH ROMAN ZWICKY)**

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# OUTLINE

- The Lee-Wick Standard Model
- Higgs boson pair production
- Top quark pair production
- Conclusions

# LEE-WICK STANDARD MODEL (LWSM)

### B.Grinstein, D.O'Connel, M.B.Wise (2007)

Based on ideas by Lee and Wick (1969,1970)

#### A TOY MODEL this section and the section and self-interaction and the self-interaction and property ˆ

(A) HD formalism: **B. Grinstein, D. O'Connel, M.B. Wise (2007)**

$$
\mathcal{L}_{hd} = \frac{1}{2} \partial_{\mu} \hat{\phi} \partial^{\mu} \hat{\phi} - \frac{1}{2M^2} (\partial^2 \hat{\phi})^2 - \frac{1}{2} m^2 \hat{\phi}^2 - \frac{1}{3!} g \hat{\phi}^3.
$$
  
Propagator:  $\hat{D}(p) = i(p^2 - p^4/M^2 - m^2)^{-1}$   
2 poles:  $p^2 = m^2, M^2$   
(B) AF formalism:  $\hat{\phi} = \phi - \tilde{\phi}$   
 $\mathcal{L} = \frac{1}{2} \partial_{\mu} \phi \partial^{\mu} \phi - \frac{1}{2} \partial_{\mu} \tilde{\phi} \partial^{\mu} \tilde{\phi} + \frac{1}{2} M^2 \tilde{\phi}^2 - \frac{1}{2} m^2 (\phi - \tilde{\phi})^2 - \frac{1}{3!} g (\phi - \tilde{\phi})^3$   
Wrong sign kinetic and mass term M.  
The two formulations are equivalent. Use EoM.

A TOY MODEL  $\Delta$  T.O.V. MC

**B. Grinstein, D. O'Connel, M.B. Wise (2007)**  $\blacksquare$ 



$$
D(p) = \frac{i}{p^2 - m^2} \qquad ; \qquad \tilde{D}(p) = \frac{-i}{p^2 - M^2}
$$

$$
\Sigma(0) = ig \int \frac{d^4 p}{(2\pi)^4} \frac{i}{p^2 - m^2} - ig \int \frac{d^4 p}{(2\pi)^4} \frac{i}{p^2 - M^2}
$$

$$
= ig \int \frac{d^4 p}{(2\pi)^4} \frac{i(m^2 - M^2)}{(p^2 - m^2)(p^2 - M^2)}
$$

uduratic divergence is cancelled<br>Pulauratic divergence !s cancelled Quadratic divergence is cancelled leading to a logarithmic divergence.

#### A TOY MODEL A TOY MODEL is calculated bubble standard bubble sum for the propagator. The self- energy  $\Delta$  to  $\Gamma$  ordinary  $\Delta$  is the same as for an ordinary  $\Delta$ particle. The only difference is that each LW scalar propagator comes with an additional minus sign, compared with  $\triangle$  TOY MODE <sup>=</sup> <sup>−</sup><sup>i</sup>

**B. Grinstein, D. O'Connel, M.B. Wise (2007)**<br>B. Grinstein, D. O'Connel, M.B. Wise (2007)

$$
\begin{aligned} D_{\tilde{\phi}}(p) &= \frac{-i}{p^2 - M^2} + \frac{-i}{p^2 - M^2} \left( -i \Sigma(p^2) \right) \frac{-i}{p^2 - M^2} + \ldots \\ &= \frac{-i}{p^2 - M^2 + \Sigma(p^2)} . \end{aligned}
$$

$$
D_{\tilde{\phi}}(p)=\frac{-i}{p^2-M^2-iM\Gamma}, \qquad \qquad \Gamma=\frac{g^2}{32\pi M}\sqrt{1-\frac{4m^2}{M^2}}.
$$

 $P_{\rm eff}$   $I_{\rm tot}$  decreases in the integral  $I_{\rm eff}$ N resonance ha:<br>- $\Lambda$  IM/ resonance has a probability  $\Gamma d\tau$  of decaying in the interval  $d\tau$ A LW resonance has a probability  $\Gamma dt$ of decaying in the interval  $-dt$  .

 $\frac{1}{2}$ Is this a problem? Shall we debate this issue further or proceed? Maximum of procedure.  $t_{\rm e}$  the resonance decayed by following the paths of the particles of the point the point the point the point they are point th we have a letter and the flip in the sign of the sign of the sign of the sign of the resonance appears to the resonance and  $\alpha$ Is this a problem? Shall we debate this issue further or proceed?

# LWSM: SUMMARY

•For each SM field add a higher derivative (HD) term.

•Auxiliary fields (AF) can be introduced to cast the theory in terms of interactions with mass dimension no greater than 4.

• The AFs are interpreted as LW partner states and have the wrong-sign propagator (aka Pauli-Villars regulators).

• The LWSM solves the hierarchy problem: the extra minus sign in the loop diagrams come from the LW field propagators. No need for opposite spin statistics!

•Unitarity is preserved, provided that the LW fields do no appear as asymptotic states in the S-matrix.

•Causality is preserved at the the macroscopic level (where we live). However, there can be violations of causality at the microscopic level.

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 $W$  shall discuss the Higgs and Yukawa sectors directly in the auxiliary field formalism and  $\alpha$ refer the interested reader to [1] for the connection with the higher derivative formalism. refer the interested reader to [1] for the connection with the higher derivative formalism. refer the interested reader to [1] for the connection with the higher derivative formalism. refer the interested reader to [1] for the connection with the higher derivative formalism. LWSM

#### Higgs Sector (AF formalism) The Lagrangian of the Higgs sector in the Higgs sector in the auxiliary field formalism assumes the following formalism assumes the following formalism assumes the following formalism assumes the following formalism assume  $Hijas$  Sector ( $\Delta F$  formalism) (*D*<sup>ˆ</sup> *<sup>µ</sup>H*) (*D*ˆ*µH*˜ ) *†* (*D*ˆ *<sup>µ</sup>H*˜ ) + *M*<sup>2</sup> *<sup>H</sup>H*˜ *† <sup>H</sup>*˜ *<sup>V</sup>* (*<sup>H</sup> <sup>H</sup>*˜ ) *,* (2.1)

 ${\cal L} = (\hat D_\mu H)^\dagger (\hat D^\mu H) - (\hat D_\mu \tilde H)^\dagger (\hat D^\mu \tilde H) + M_H^2 \tilde H^\dagger \tilde H - V(H-\tilde H)$ ˆ *<sup>µ</sup>H*) (*<sup>D</sup>* ˆ *<sup>µ</sup>H*˜ ) *<sup>H</sup>H*˜ *† <sup>H</sup>*˜ *<sup>V</sup>* (*<sup>H</sup> <sup>H</sup>*˜ ) *,* (2.1)  $(\mathcal{L} \mu^{H})$   $(\mathcal{L} \mu^{H})$   $(\mathcal{L} \mu^{H})$   $(H)$   $H$ <sup>*H*</sup> $H$ <sup> $H$ </sup> *µ* (*D <sup>H</sup>*˜ *<sup>V</sup>* (*<sup>H</sup> <sup>H</sup>*˜ ) *,* (2.1)  $\hat{L} = (\hat{D} \cdot H)^{\dagger} (\hat{D}^{\mu} H) - (\hat{D} \cdot \tilde{H})^{\dagger} (\hat{D}^{\mu} \tilde{H}) + M_{\mathcal{I} \mathcal{I}}^2 \tilde{H}^{\dagger} \tilde{H} - V(H - \tilde{H})$  $\mathcal{L} = (D_{\mu}H)^{\dagger}(D^{\dagger}H) = (D_{\mu}H)^{\dagger}(D^{\dagger}H) + M_{H}H^{\dagger}H^{\dagger}H = V(H - H)$  $\mathcal{L} = (\hat{D}_{\mu}H)^{\dagger}(\hat{D}^{\mu}H) - (\hat{D}_{\mu}\tilde{H})^{\dagger}(\hat{D}^{\mu}\tilde{H}) + M_{H}^{2}\tilde{H}^{\dagger}\tilde{H} - V(H - \tilde{H})$ fields and  $\left( -\mu^{2} \right)$   $\left( -\mu^{2} \right)$ 

 $\hat{D}_{\mu} = \partial_{\mu} + i(\mathbf{A}_{\mu} + \tilde{\mathbf{A}}_{\mu})$   $\mathbf{A}_{\mu} = qA_{\mu}^{a}T^{a} + q_{2}W_{\mu}^{a}T^{a} + q_{1}B_{\mu}Y$ */*4(*H†<sup>H</sup> v*2*/*2)2. The mass *<sup>M</sup><sup>H</sup>* is the mass scale of the higher derivative LW mass scale.  $\hat{D}_{\mu} \; = \; \partial_{\mu} \, + \, i ({\bf A}_{\mu} + \tilde{\bf A}_{\mu}) \hspace{0.5cm} {\bf A}_{\mu} \; = \; g A_{\mu}^{a} T^{a} \, + \, g_{2} W_{\mu}^{a} T^{a} \, + \, g_{1} B_{\mu} \, Y$ fields and analogously for the LW gauge boson for A˜ *<sup>µ</sup>*. The Higgs potential is *V* (*H*) =  $\hat{p}$   $\hat{p$  $D_{\mu} = O_{\mu} + i(A_{\mu} + A_{\mu})$   $A_{\mu} - g_{A_{\mu}} - g_{2}v_{\mu} + g_{1}v_{\mu}$  $\hat{D}_{\mu} = \partial_{\mu} + i(\mathbf{A}_{\mu} + \tilde{\mathbf{A}}_{\mu})$  $\sum_{i=1}^{n}$ particularly the contract of t

$$
H^{\top} = [0, (v + h_0) / \sqrt{2}], \quad \tilde{H}^{\top} = [\tilde{h}_+, (\tilde{h}_0 + i\tilde{p}_0) / \sqrt{2}]
$$

*.* (2.2)

$$
\langle h_0 \rangle = v \; , \quad \langle \tilde{h}_0 \rangle = 0
$$

In the unitary gauge the two doublets are

In the unitary gauge the two doublets are

$$
\mathcal{L}_{\rm mass} = -\frac{\lambda}{4}v^2(h_0 - \tilde{h}_0)^2 + \frac{M_H^2}{2}(\tilde{h}_0\tilde{h}_0 + \tilde{p}_0\tilde{p}_0 + 2\tilde{h}_+\tilde{h}_-)
$$

#### Higgs field by *h*0. With (2.2) the mass Lagrangian assumes the following form: *M*<sup>2</sup> <sup>h</sup>*h*0<sup>i</sup> <sup>=</sup> *v ,* <sup>h</sup>*h*˜0<sup>i</sup> = 0 *.* (2.3) LWSM

Higgs Sector <sup>2</sup> (*h*˜0*h*˜<sup>0</sup> + ˜*p*0*p*˜<sup>0</sup> + 2*h*˜+*h*˜)*.* (2.4) we have the mixing scalar and its LW–partner. The neutral CP-event of the neutral CP-even mixing scalar and its L  $\int$ <sup>2</sup>  $\cdot$ <sup>2</sup> (*h*˜0*h*˜<sup>0</sup> + ˜*p*0*p*˜<sup>0</sup> + 2*h*˜+*h*˜)*.* (2.4)

Symplectic rotation:

$$
\text{etc. rotation:} \qquad \begin{pmatrix} h \\ \tilde{h} \end{pmatrix} = \begin{pmatrix} \cosh \phi_h & \sinh \phi_h \\ \sinh \phi_h & \cosh \phi_h \end{pmatrix} \begin{pmatrix} h_{\text{phys}} \\ \tilde{h}_{\text{phys}} \end{pmatrix}
$$

Mass eigenvalues:<br>Mass seigenvalues:



## LWSM

Higgs Sector

Few in terms of the physical masses the following relations and the physical masses the following relations are useful and the physical masses the physical masses the physical masses the following relations are useful and Mixing angle:

$$
\lambda v^2 = \frac{2m_{h_0, \text{phys}}^2}{(1 + r_{h_0}^2)}, \qquad \qquad r_{h_0} \equiv \frac{m_{h_0, \text{phys}}}{m_{\tilde{h}_0, \text{phys}}},
$$

$$
s_H = \cosh \phi_h = \frac{1}{(1 - r_{h_0}^4)^{1/2}} ,
$$
  

$$
s_{H-\tilde{H}} = \cosh \phi_h - \sinh \phi_h = \frac{1 + r_{h_0}^2}{(1 - r_{h_0}^4)^{1/2}}
$$

#### In order to discuss the Yukawa terms, it is helpful to first discuss the fermions. We shall LWSM<br>IN ONST closely follow ref. [26]. However, we choose a slightly dividend basis for the fermions and re- $\sim$ closely follow ref. [26]. However, we choose a slightly dividend basis for the fermions and re----------------

#### Yukawa Interactions (in auxiliary field formalism) fer the reader to appendix C where  $\alpha$  method is outlined how the hyperbolic diagonalization  $\alpha$ can be performed using the performance of the personal standard to the periodicity of the standard tools. Yukawa Interactions (i The kinetic term of the kinetic term of the AF Lagrangian is given by: *L LARER LACLIONS* (*III dUXIIIdI y lieid l* **Exercise be performed using standard to the performance of the perfor** The kinetic term of the kinetic term of the AF Lagrangian is given by:

$$
\mathcal{L} = \overline{\Psi^t} i \eta_3 \hat{\mathcal{P}} \Psi^t - \overline{\Psi_R^t} \mathcal{M}_t \eta_3 \Psi_L^t - \overline{\Psi_L^t} \eta_3 \mathcal{M}^\dagger \Psi_R^t
$$

$$
\Psi_L^{t\top} = (T_L, \tilde{t}'_L, \tilde{T}_L), \qquad \Psi_R^{t\top} = (t_R, \tilde{t}_R, \tilde{T}'_R)
$$

 $Q_L = (T_L, B_L)$ is noteworthy that a chiral fermion necessitates two chiral fermions which in turn form a  $SU(2)$  doublet:  $Q_L = (T_L, B_L)^\top$ massive Dirac fermion. This becomes explicit in the basis chosen above the basis chosen above the basis chosen  $\mathcal{S} \cup (\angle)$  doublet.  $\mathcal{Q}L = (IL, DL)$ 

massive Dirac fermion. This becomes explicit in this becomes explicit in the basis chosen above the basis chos<br>This becomes explicit in the basis chosen above the basis chosen above the basis chosen above the basis chosen

is noteworthy that a chiral fermion necessitates two chiral fermions which in turn form a

$$
\mathcal{M}_{t}\eta_{3}=\begin{pmatrix}m_{t} & 0 & -m_{t}\\-m_{t} & -M_{u} & m_{t}\\0 & 0 & -M_{Q}\end{pmatrix}\;,\qquad \eta_{3}=\begin{pmatrix}1 & 0 & 0\\0 & -1 & 0\\0 & 0 & -1\end{pmatrix}
$$

#### *m<sup>t</sup> M<sup>u</sup> m<sup>t</sup>* **1**  $\mathsf{L} \mathsf{V} \mathsf{V}$ . CA *,* ⌘<sup>3</sup> <sup>=</sup> *m<sup>t</sup>* 0 *m<sup>t</sup>* 0 0 *M<sup>Q</sup>* which dividends from the one in from the one in from the one in from that all physical masses remain unchanged<br>That all physical masses remain unchanged that all physical masses remain unchanged that all physical masses r  $LVV$ LWSM

#### Diagonalization of mass matrices  $\Sigma_{\text{in}}$   $\sigma$ under change of basis. The mass matrix is diagonalized by symplectic rotations *S<sup>L</sup>* and under change of basis. The mass matrix is diagonalized by symplectic rotations *S<sup>L</sup>* and Diagonalization of mass matrices under change of basis. The mass matrix is diagonalized by symplectic rotations *S<sup>L</sup>* and

$$
\Psi_{L(R),\text{phys}} = \eta_3 S_{L(R)}^\dagger \eta_3 \Psi_{L(R)} , \qquad \mathcal{M}_{t,\text{phys}} \eta_3 = S_R^\dagger \mathcal{M}_t \eta_3 S_L \ ,
$$

$$
S_L \eta_3 S_L^{\dagger} = \eta_3 \quad \text{and} \quad S_R \eta_3 S_R^{\dagger} = \eta_3
$$

Now we may turn to the Yukawa sector for which we only write down the neutral Higgs Higgs-quark vertices and which we only write down the neutral Higgs-quark vertices

$$
\mathcal{L} = -\frac{1}{v}(h_0 - \tilde{h}_0) \left( \overline{\Psi_R^t} g_t \Psi_L^t + \overline{\Psi_L^t} g_t^\dagger \Psi_R^t \right) - \frac{1}{v} (-i\tilde{p}_0) \left( \overline{\Psi_R^t} g_t \Psi_L^t - \overline{\Psi_L^t} g_t^\dagger \Psi_R^t \right)
$$

$$
g_t = \begin{pmatrix} m_t & 0 & -m_t \\ -m_t & 0 & m_t \\ 0 & 0 & 0 \end{pmatrix}, \quad g_{t, \text{phys}} = S_R^\dagger g_t S_L
$$

## LWSM

LW-gauge bosons are mass LW gauge bosons are massive and mix:

$$
\mathcal{L}_{2g} = -\frac{1}{2} \text{Tr} \left( B_{\mu\nu} B^{\mu\nu} - \tilde{B}_{\mu\nu} \tilde{B}^{\mu\nu} + W_{\mu\nu} W^{\mu\nu} - \tilde{W}_{\mu\nu} \tilde{W}^{\mu\nu} \right) \n- \frac{1}{2} (M_1^2 \tilde{B}_{\mu} \tilde{B}^{\mu} + M_2^2 \tilde{W}_{\mu}^a \tilde{W}_{a}^{\mu}) + \frac{g_2^2 v^2}{8} (W_{\mu}^{1,2} + \tilde{W}_{\mu}^{1,2})^2 \n+ \frac{v^2}{8} (g_1 B_{\mu} + g_1 \tilde{B}_{\mu} + g_2 W_{\mu}^3 + g_2 \tilde{W}_{\mu}^3)^2
$$

Gauge interactions:

$$
\mathcal{L}_{int} = - \sum_{\psi=q_L, u_R, d_R} [g_1 \bar{\psi} (\cancel{B} + \widetilde{\cancel{B}}) \psi + g_2 \bar{\psi} (W + \widetilde{W}) \psi] \n+ \sum_{\psi=q, u, d} \left[ g_1 \bar{\widetilde{\psi}} (\cancel{B} + \widetilde{\cancel{B}}) \tilde{\psi} + g_2 \bar{\widetilde{\psi}} (W + \widetilde{W}) \tilde{\psi} \right].
$$

LWSM As a first step it is interesting to plot (Fig. 1a) the relative couplings *g<sup>h</sup>*0*V V , gh*˜0*V V* and *3. The loop-mediated e*↵*ective couplings*

#### auplings to gauges bosons and formio production with gauge bosons and/or heavy quarks, bottom fusion) are always larger that mediated e↵ective couplings of Lee-Wick Higgs bosons to two gluons, two photons, and a Couplings to gauges bosons and fermions



 $\int \cosh \theta - \sinh \theta = \frac{1+r^2}{\sqrt{1-r^4}}, \qquad g_{\tilde{P}f\bar{f}} = -1 \qquad g_{\tilde{P}gg}^2 = \frac{\sigma(gg\to \tilde{P})}{\sigma^{SM}(gg\to H)} = |\frac{g_{\tilde{P}t\bar{t}}F_{1f}^P}{F_{1fg}(g)}|$  $\frac{\sigma(s)g}{\sigma^{SM}(gg \to H)} =$  $g_{\tilde{P} t\bar{t}}\,F^{\tilde{P}}_{1/2}(\beta^t_{\tilde{P}})$  $\overline{F_{1/2}(\beta_{\tilde{P}}^t)}$  |  $g_{h_0f\bar{f}}=-g_{\tilde{h}_0f\bar{f}}=\cosh\theta-\sinh\theta=\frac{1+r^2}{\sqrt{1-r^4}}\,,\qquad g_{\tilde{P}f\bar{f}}=-1\qquad\quad g_{\tilde{P}g_{\tilde{q}}}^2=\frac{\sigma(gg\to\tilde{P})}{-\hbox{SM}\left(\cos\to H\right)}=|\frac{g_{\tilde{P}t\bar{t}}\,F_{1/2}^P(\beta_{\tilde{P}}^t)}{\hbox{F}}|^2$  $\frac{1}{\sqrt{1-r^4}}$ ,  $g_{\tilde{P}f\bar{f}} = -1$   $g_{\tilde{P}gg}^2 = \frac{c}{\sigma^5}$ 

#### LW Gauge bosons at the LHC )S(  $\frac{1}{2}$  +  $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$



ArXiv:1108.1582 and the combination of these (bottom). The solid lines show the observed limits with all uncertainties. The expected limit is indicated with

### Electroweak Precision Constraints



R. Zwicky (2009)  $\sim$  and  $\sim$   $\sim$   $\sim$   $\sim$   $\sim$   $\sim$  $Indonu$ FIG. 2 (color online). The M<sup>1</sup> vs M<sup>2</sup> plane showing the results  $\alpha$ icky (2009) T.E.J. Underwood and R. Zwicky (2009)

# LWSM HIGGS CONSTRAINTS



$$
m_{h_0}^2 + m_{\tilde{h}_0}^2 = m_{\tilde{p}_0}^2 = m_{\tilde{h}^\pm}^2 > (463 \text{ GeV})^2
$$

#### Electroweak Precision Constraints Cision Constratives





FIG. 6 (color online). Left: 95% C.L. exclusion plots for the LW fermion masses  $M_q$  and  $M_t$ . These bounds come almost entirely from the experimental constraints on  $\hat{T}$ . For a light Higgs the striped region to the left of the curve is excluded, while a heavy Higgs is completely excluded. Right: 95% C.L. ellipses in the  $(\hat{S}, \hat{T})$  plane, and the LW prediction for degenerate masses,  $M_q = M_t$ . The parametric plot is for 0.5 TeV  $\lt M_q \lt 10$  TeV and the dots are equally spaced in mass. The lower bound on  $M_q$  is approximately 1.5 TeV for a light Higgs.

A heavy light Higgs boson is disfavored.

# Current collider bounds s



Tuesday, May 10, 2011 and the control of t

# LIGHT HIGGS BOSON AT THE LHC



 $\mathcal{L} = 1, 5, 10$  fb<sup>-1</sup>: end of 2011, end of 2012, optimistic  $h_0 \to WW:$   $m_{h_0} \geq 130/125/120$  GeV

Other Higgs bosons and channels are out of LHC Run I reach.

# LIGHT HIGGS BOSON AT THE LHC



 $E.VVENTS and J.ZUrl (ZU11)$ E. Weihs and J. Zurita (2011)

The minimal LWSM can be ruled out by searching for the light Higgs boson at the LHC.

#### LIGHT HIGGS BOSON AT THE LHC ON AT THE I HC -1 Ldt = 1.0-4.9 fb ∫ **19**

CMS PAS HIG-11-032 ATL-CONF-2011-163  $\overline{a}$ Signal strengthening **ATLAS** Preliminary 2011 Data 1 Local p-value Local p-value Local P-Value **ATLAS** Preliminary **Contact Fiture 2011** Data 2011 Data 1 1σ ±1 oct = 7 minutes = 7 minute  $10^{-1}$  $\ddot{\cdot}$  $10^{-1}$  $0^{-2}$  $\overline{2}$ 2σ  $10^{-2}$ ]? -<br>-- $10^{-2}$  $\overline{a}$  $10^{-3}$ Observed 2σ .... Expected CMS Preliminary,  $\sqrt{s}$  = 7 TeV  $\sqrt{s}$  $10^{-4}$ 3σ -<br>F- $10^{-3}$  $10^{-5}$  $Ldt = 1.0 - 4.9$  fb<sup>-1</sup> **Combined** 3σ  $H \to bb$  (4.7 fb<sup>-1</sup>)  $\cdot$ (4 7 fh  $\vdash$  1.  $4.6$  fb  $(4.7 f b)$  $10^{6}$ Interpretation requires look- $10^{-4}$  $\sqrt{s}$  = 7 TeV<br>= 50  $4.6<sub>b</sub>$  $\frac{1}{1}$   $\rightarrow$  YVVV elsewhere effect correction  $H \rightarrow ZZ \rightarrow 4$ l (4.7 fb<sup>-1</sup>)  $(4.7 \text{ fb})$  $10^{-7}$ <u>1 → ZZ → 2l 2q(4.6 fb</u>  $4σ$ , <u>1 H + γ (+ H + y (+ H + y (+ H + + (+ H</u> 110 115 120 125 130 135 140 145 150 155 160 Interpretation requires look-110 115 120 125 130 135 140 145 150 45 150 155 110  $\frac{120}{2}$   $\frac{120}{20}$   $\frac{130}{130}$   $\frac{130}{130}$   $\frac{130}{130}$   $\frac{130}{130}$   $\frac{130}{130}$  $-1$   $-1$   $-1$   $-1$  $\rm\dot{M}_H$  [GeV]  $(b)$ 110 115 120 125 130 135 140 145 150 155 160 2022 boson mass (Gev/color) 2.5 2.5  $\overline{\phantom{a}}$ SM Signal strength  $C_{\text{M}}$ C Dreliminary, s  $\sim$  7 TeV  $\vec{p}$   $\vec{p}$   $\vec{p}$  **ATLAS** Preliminary  $\vec{p}$  2011 Data  $\vec{p}$  $5 -$  CMS Preliminary,  $\sqrt{s} = 7$  TeV σ / σ2.5 2 **← Best fit** 2 SM  $\begin{array}{c} \n\frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\ \n\frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\ \n\frac{1}{2} & \frac{1}{2} & \frac{1}{2} \n\end{array}$  Ldt = 1.0-4.9 fb<sup>-1</sup> Best fit Combined,  $L_{int} = 4.6-4.7$  fb<sup>-1</sup> σ / σ $\begin{array}{ccc} \hline \end{array}$   $\begin{array$ 1.5  $\overline{\phantom{a}}$  ±1 σ 2 Best fit  $\frac{1}{2}$  dashed  $\frac{1}{2}$  indicate the *p-values*  $\sqrt{2}$   $\sqrt{3}$  and  $\sqrt{3}$  and  $\sqrt{3}$  $\equiv$ 1 1.5 0.5 1  $\Omega$  $0.5$ -0.5  $\overline{0}$ -1 -0.5 -1.5 110 115 120 125 130 135 140 145 150 155 160 110 115 120 125 130 135 140 145 150 155 160 -1 -2

 $20$  Higgs boson mass (GeV/ $c^2$ )

(b)

110 115 120 125 130 135 140 145 150

2σ

3σ

4σ

 $M_H$  [GeV]

#### A Higher Derivative LWSM  $\Delta$  real scalar field in  $\Delta$  real scalar field in  $\Delta$  /Ch  $\Delta$ a straightforward way to one of a complex scalar Hˆ that transforms in the fundamental A Higher Derivative LWSM

C.D. Carone and R. F. Lebed (2008) C.D. Carone and R. E. Lebed (2008) ebed (2008)

$$
\mathcal{L}_{HD} = \hat{D}_{\mu}\hat{H}^{\dagger}\hat{D}^{\mu}\hat{H} - m_{H}^{2}\hat{H}^{\dagger}\hat{H} - \frac{1}{M_{1}^{2}}\hat{H}^{\dagger}(\hat{D}_{\mu}\hat{D}^{\mu})^{2}\hat{H} - \frac{1}{M_{2}^{4}}\hat{H}^{\dagger}(\hat{D}_{\mu}\hat{D}^{\mu})^{3}\hat{H} + \mathcal{L}_{int}(\hat{H})
$$

$$
\mathcal{L} = -H^{(1)\dagger}(\hat{D}_{\mu}\hat{D}^{\mu} + m_{1}^{2})H^{(1)} + H^{(2)\dagger}(\hat{D}_{\mu}\hat{D}^{\mu} + m_{2}^{2})H^{(2)}
$$

$$
-H^{(3)\dagger}(\hat{D}_{\mu}\hat{D}^{\mu} + m_{3}^{2})H^{(3)} + \mathcal{L}_{int}(\hat{H}) ,
$$

$$
H^{(1)} = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v+h_{1}) \end{pmatrix}, H^{(2)} = \begin{pmatrix} h_{2}^{\dagger} \\ \frac{1}{\sqrt{2}}(h_{2} + iP_{2}) \end{pmatrix}, H^{(3)} = \begin{pmatrix} h_{3}^{\dagger} \\ \frac{1}{\sqrt{2}}(h_{3} + iP_{3}) \end{pmatrix}
$$

t model with 3 Higgs doublet model with one negative norm state and

two positive norm states.<br>The auxiliary field of the fundamental representation in the fundamental representation. And the fundamental representation. The fundamental representation of the fundamental representation. Again re riegative from it state and Melleave this for further study and focus on the minimal LWSM.<br>two positive norm states.

## HIGGS BOSON PAIR PRODUCT

 $pp \rightarrow h_0 h_0$ 



(a)

(b) We shall parametrize the *gg* ! *h*0*h*<sup>0</sup> matrix element as follows:

Figure 1. (a) Triangle graphs for *q* = (*t,t,*˜ *T , b,* ˜ ˜*b, B*˜) and (b) one out of six box graphs for  $\mathcal{M}(gg \to h_0 h_0) = \frac{1}{32 \pi^2} \delta^{ab} \frac{g^2}{v^2}$  $\sqrt{2}$  $\mathcal{A}_0P_0 + \mathcal{A}_2P_2$  $\setminus$  $\mu\nu$  $e(p_1)_{a}^{\mu}e(p_2)_{b}^{\nu}$ *<sup>b</sup> ,* (3.1)

r details see  $\Omega$ **For details see our Appendix!** The vertices and 1/4/2011 in order to give simple results for the amplitudes. For details see our Appendix!

## HIGGS BOSON PAIR PRODUCTION



 $\mathbf{F}_{\mathbf{a}}$  is section (in fb) with the LWSM (solid lines) and  $\mathbf{F}_{\mathbf{a}}$  is defined and  $\mathbf{F}_{\mathbf{a}}$  is defined by *Total cross section* 

 $-11$  $d =$ 600 7 TeV 0.5 600 14 TeV

## HIGGS BOSON PAIR PRODUCTION



respectively versus the mass of the mass of the *h*  $\overline{P}$ Figure 16. The cross section of *pp* ! *<sup>h</sup>*0*h*<sup>0</sup> via gluon fusion at the LHC for <sup>p</sup>*<sup>s</sup>* = 7*/*14 TeV

 $\sigma$  (fb)





*g*  $\frac{1}{2}$  **h**  $\frac{1}{2}$  **d**  $\frac{1}{$ 

Total cross section

# HIGGS BOSON PAIR PRODUCTION



Figure 8. Contour plot of the total cross section (in fb) for *gg* ! *<sup>h</sup>*0*h*<sup>0</sup> ! *<sup>b</sup>*¯*b* (  $mn \to h_0 h_0 \to b\bar{h}\gamma\gamma$  $pp \rightarrow h_0 h_0 \rightarrow b\bar{b}\gamma\gamma$ 

# HIGGS BOSON PAIR PRODUCTION

 $pp \rightarrow h_0 h_0 \rightarrow b b \gamma \gamma$ 

• Cut I: Two isolated photons. •Cut 2: Two kt jets. • Cut 3: At least one b-tagged jet. • Cut 4:  $|M_{\gamma\gamma} - m_{h_0}| \leq 2$  GeV • Cut 5:  $|M_{bj} - m_{h_0}| \leq 20$  GeV • Cut 6:  $|M_{bj\gamma\gamma} - m_{\tilde{h}_0}| \leq \delta m_{\tilde{h}_0}$ 

Cuts inspired by radion studies performed by ATLAS and CMS. A more detailed description of cuts is in our paper.



### HIGGS BOSON PAIR PRODUCTION Benchmark *mh*<sup>0</sup> (GeV) *mh*˜<sup>0</sup> (GeV) *mh*˜<sup>0</sup> (GeV)



cut 5c 0*.*221 0*.*213 0*.*174 0*.*242 0*.*234 0*.*274

 $pp \rightarrow h_0 h_0 \rightarrow b\bar{b}\gamma\gamma$  $\mathcal{L} \mathcal{L} \mathcal{$ 



#### HIGGS BOSON PAIR PRODUCTION *pp* ! *<sup>h</sup>*0*h*<sup>0</sup> ! *b*¯*<sup>b</sup>* (a) (b) (c) gen(fb) 11*.*2 0*.*964 0*.*195



cut 6b 0*.*136 0*.*0567 0*.*129 0*.*138 0*.*165 0*.*130

Table 4. Cross sections (in fb) for *<sup>h</sup>*0*<sup>Z</sup>* ! *b*¯*<sup>b</sup>* before selection and after selection for benchmark

 $pp \rightarrow h_0 h_0 \rightarrow b b \gamma \gamma$ 



## HIGGS BOSON PAIR PRODUCTION



 $pp \rightarrow h_0 h_0 \rightarrow b b \gamma \gamma$ 



INTERFERENCE EFFECTS IN TOP PAIR PRODUCTION The interference e $\frac{1}{2}$  , which is where  $\frac{1}{2}$  , which is  $\frac{1}{2}$  $gg\to K\to tt$  density discussed in the following form  $gg$  $\frac{d\hat{\sigma}}{ds}(gg \to \bar{t}t)|_{\text{interface}} = -|c(s)|\text{Re}\left[\frac{l_{\Delta}}{s - m_{B}^{2} + 1}\right]$  $s - m_R^2 + i m_R \Gamma_R$  $\overline{1}$  $=-|\tilde{c}(s)|\left((s-m_R^2)\mathrm{Re}[l_\Delta] + m_R\Gamma_R\mathrm{Im}[l_\Delta]\right)$  *,* (4.1)  $gg \to R \to \bar{t}t$ D.Dicus, A. Strange, and S. Willenbrock

 $\frac{1}{2}$ ,  $\frac{1}{2}$  ( $\frac{1}{2}$ ) decreasing the invariant mass of the two standard mass of the two states in  $l_{\Delta} = l_{\Delta} (s/4m_t^2)$  loop triangle function

peak-dip structure to destruction to destruction to destruction to destruction to destruction to the structure in loop-function does not change the case is a scalar or the case where the resonance is a scalar or the reso 2. For a scalar or pseudo-scalar resonance this pattern does not change. 1. If there is no loop function there will be a peak-dip.

#### INTERFERENCE EFFECTS IN TOP PAIR PRODUCTION  $I$  in itedeed and change the constant of the resonance in the resonance is a scalar oriented in the resona a pseudoscalar function in a pseudoscalar function and imaginary part of the loop function are positive. The lo loop-function does not change this pattern in the case where the resonance is a scalar or SERENCE EFFECTS IN TOP PAIR PRODUCTION

$$
gg\to R\to \bar{t}t
$$

$$
\frac{d\hat{\sigma}}{ds}(gg \to \bar{t}t)|_{\text{LW-interference}} = -|c(s)| \text{Re}\left[\frac{-l_{\Delta}(s/4m_t^2)}{(s - m_R^2) - im_R\Gamma_R}\right]
$$

$$
= -|\tilde{c}(s)|\left(-(s - m_R^2)\text{Re}[l_{\Delta}] + m_R\Gamma_R\text{Im}[l_{\Delta}]\right)
$$
Sign-flip in the LW

case

propagator and the width,

$$
\mathcal{M}_R^2 = m_R^2 + \frac{\text{Im}[l_\triangle]}{\text{Re}[l_\triangle]} m_R \Gamma_R
$$

Exp peak su acture 2. The peak structure 2. The dip-peak structure is a unique feature is a unique feature feature feature is a unique feature Dip-peak structure<br>
Dip-peak structure

### INTERFERENCE EFFECTS IN TOP PAIR PRODUCTION



Figure 2. The company of the cross section (and the cross of a the cross of the cross of the cross of the company of Usual resonance Lee-Wick type resonance

### Top pair invariant mass spectrum



# CONCLUSIONS

- LW Gauge bosons and LW fermions are constrained to be in the few TeV range by EWPO and dilepton searches while the LW Higgs could be below a TeV.
- We have computed the total cross section for double Higgs boson pair production.
- Additionally, we have investigated a search at the a 14 TeV LHC using the di-photon plus di-jet channel. For LW Higgs boson masses of 300 GeV a 5 sigma discovery can be made with 20 1/fb of integrated luminosity.
- We have investigated top pair production in the LWSM. For LW Higgs boson masses above the top pair production threshold, the branching fraction of the LW Higgs boson decaying top pairs dominates. Hence, the top pair channel dominates over the double Higgs boson channel.

### Higgs boson decays



 $Br_{h_0}$ 

### Higgs to two photons



Figure 4: The relative change in the cross-section times decay rate for the full process  $gg \rightarrow$  $h_0\to\gamma\gamma$  in the LWSM, expressed as  $|\kappa_{gg}|^2|\kappa_{\gamma\gamma}|^2-1$ , plotted as a function of  $m_{h_0,\mathrm{phys}}.$  Lee-Wick mass scales are such that  $M_Q = M_u = m_{\tilde{h}, \text{phys}} = m_{\tilde{h} + \text{,phys}} = m_{\tilde{W}, \text{phys}} \equiv \tilde{M}$ 

#### F.Krauss, T.E.J Underwood, R. Zwicky: **arXiv 0709.4054** F.Krauss, T.E.J Underwood, R. Zwicky: **arxiv U709.4054**

enhancement of the total Higgs width in the LWSM. This enhancement almost cancels with the LWSM. This enhancement almost cancels with the LWSM. This endamic cancels with the LWSM. This endamic cancels with the LWSM. This e