Lee-Wick Higgs sector at colliders

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Based on:

- E. Alvarez, E. Coluccio, J.Z: **arXiv 1004.3496** (sent to PRD)

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Outline

- LWSM
- LW Higgs sector
- Collider bounds
- Conclusions

Motivation

- LWSM is a novel (07') solution to the hierarchy pbm.
- Higgs sector (@ tree level): 2 free parameters.
- Current constraints: only indirect bounds, obtained from B-meson mixing, $b \to X_S\gamma, Z \to b\bar{b}$.

Carone, Primulando, Phys. Rev. D80, 055020 (2009)

- This talk:
  - collider constraints from LEP and Tevatron.
  - exclusion projections from LHC Run I.

Lee-Wick Standard Model

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

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

A toy model

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

A) HD formulation:

$$\mathcal{L}_{HD} = \frac{1}{2}\partial_\mu\hat{\phi}\partial^\mu\hat{\phi} - \frac{1}{2M^2}\left(\partial^2\hat{\phi}\right)^2 - \frac{1}{2}m^2\hat{\phi}^2 - \frac{1}{4}g\hat{\phi}^4 \qquad (m \ll M)$$

Propagator: $\hat{D}(p) = i\left(p^2 - p^4/M^2 - m^2\right)^{-1} \longrightarrow 2 \text{ poles: } p^2 = m^2, M^2$

B) LW formulation: $\hat{\phi} = \phi - \tilde{\phi}$

$$\mathcal{L}_{LW} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}\partial_\mu\tilde{\phi}\partial^\mu\tilde{\phi} - \frac{1}{2}M^2\tilde{\phi}^2 - \frac{1}{2}m^2(\phi - \tilde{\phi})^2 - \frac{1}{4}g(\phi - \tilde{\phi})^4$$

ϕ has a partner $\tilde{\phi}$ with wrong sign kinetic term and mass scale M.

The two formulations are equivalent : $\mathcal{L}_{LW} + \text{int. out } \tilde{\phi} = \mathcal{L}_{HD}$

LWSM: main features

- Technicalities aside: replicate the toy model for each SM field.

- In short: PV regulators correspond to actual physical fields.

- The LWSM solves the hierarchy problem *à la SUSY*: the extra minus sign in the loop diagrams come from the LW fields propagators, rather than from the opposite statistics.

- Unitarity is preserved, provided that the LW fields do not appear as "out" states in the S-matrix (i.e: they have to be unstable).

- Causality is preserved at the macroscopic level, however it can occur at the microscopic level, testeable at the LHC through displaced vertexes (Alvarez, Schat, Da Rold, Szynkman, JHEP 0910, 023 (2009)).

Related work in LW theories

- LWSM: Lee, Wick, Nucl. Phys B9 (1969) 209, Phys. Rev. D2, 1033 (1970); Grinstein, O'Connell, Wise, Phys. Rev. D77, 025012 (2008)
- Unitarity: Grinstein, O' Connell, Wise, Phys. Rev. D77, 065010 (2008), Phys. Rev. D79,105019 (2009)
- Renormalizability: Grinstein, O' Connell, Phys. Rev. D78, 105005 (2008); Chivukula, Farzinnia, Foadi, Simmons, Phys. Rev. D82, 035015 (2010); Espinosa, Grinstein, arXiv:1101.5538
- EW constraints: Carone, Lebed, Phys. Lett B668, 221 (2008); Alvarez, Schat, Da Rold, Szynkman JHEP 0804, 026 (2008); Underwood, Zwicky, Phys. Rev. D79, 035016 (2009); Chivukula, Farzinnia, Foadi, Simmons, Phys. Rev. D81, 095015 (2010)
- Higgs sector constraints: Carone, Primulando, Phys. Rev. D80, 055020 (2009)
- FCNC: Dulaney, Wise, Phys. Lett, B 658, 230 (2008)
- Gravity: Wu, Zhong, Phys. Lett. B 659, 694 (2008)
- Neutrino masses: Espinosa, Grinstein, O'Connell, Wise, Phys. Rev. D 77, 085002 (2008)
- $H \to \gamma\gamma$: Krauss, Underwood, Zwicky, Phys. Rev. D 77, 015012 (2008), Cacciapaglia, Deandrea, Llodra-Perez, JHEP 0906, 054 (2009)
- Higher derivatives: Carone, Lebed, JHEP 0901, 043 (2009).
- Unification: Carone, Phys. Lett. B 677, 306 (2009)
- High temperature: Fornal, Grinstein, Wise, Phys. Lett B 74, 330 (2009)
- LHC phenomenology: Rizzo, JHEP 0706, 070 (2007), JHEP 0801, 042 (2008)
- Acausality behaviour: Alvarez, Schat, Da Rold, Szynkman, JHEP 0910, 023 (2009)

LW Higgs sector

LW Higgs sector (I)

$$\mathcal{L}_{Higgs} \;=\; (D_\mu H)^\dagger D^\mu H - (D_\mu \tilde{H})^\dagger D^\mu \tilde{H} + M^2 \tilde{H}^\dagger \tilde{H} - V(H - \tilde{H})$$

Explicit mass term for the LW Higgs doublet

where $V(X) = -\frac{m^2}{2} X^\dagger X + \frac{\lambda}{4}(X^\dagger X)^2$

$$\mathcal{L}_{Yuk} \;=\; \left(g_u^{ij} \bar{u}_R^i (H - \tilde{H}) \epsilon Q_L^j - g_d^{ij} \bar{d}_R^i (H^\dagger - \tilde{H}^\dagger) Q_L^j - g_e^{ij} \bar{e}_R^i (H^\dagger - \tilde{H}^\dagger) L_L^j + \text{h.c.} \right)$$

Unitary gauge: $H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}, \quad \tilde{H} = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\,\tilde{h}^+ \\ \tilde{h} + i\tilde{P} \end{pmatrix}$

no VEV for the LW Higgs doublet!

Spectrum: 2 CP-even ($h, \tilde{h}$), 1 CP-odd ($\tilde{P}$) , a charged pair $\tilde{h}^\pm$

$$\mathcal{L}_{mass} \;=\; -\frac{\lambda}{4} v^2 (h - \tilde{h})^2 + \frac{M^2}{2} \left(\tilde{h}\tilde{h} + \tilde{P}\tilde{P} + 2\tilde{h}^+ \tilde{h}^- \right)$$

LW Higgs sector (II)

CP-even bosons can be diagonalized by a symplectic rotation

$$\begin{pmatrix} h \\ \tilde{h} \end{pmatrix} = \begin{pmatrix} \cosh\theta & \sinh\theta \\ \sinh\theta & \cosh\theta \end{pmatrix} \begin{pmatrix} h_0 \\ \tilde{h}_0 \end{pmatrix}$$

Mass eigenvalues: $m^2_{h_0,\tilde{h}_0} = \frac{M^2}{2}(1 \mp \sqrt{1 - \frac{4m^2}{M^2}})$

Mixing angle: $\cosh\theta = \frac{1}{(1-r^4)^{1/2}}\,, \quad \sinh\theta = \frac{-r^2}{(1-r^4)^{1/2}}\,, \quad r \equiv \frac{m_{h_0}}{m_{\tilde{h}_0}}$

Sum rule: $m^2_{h_0} + m^2_{\tilde{h}_0} = m^2_{\tilde{P}} = m^2_{\tilde{h}^\pm} = M^2$

Tree level couplings

Couplings to gauge bosons: $g_{h_0 VV} = \cosh\theta\,, \qquad g_{\tilde{h}_0 VV} = \sinh\theta$

One gauge boson - Two Higgs bosons:

$$g_{h_0 \tilde{P} Z} = g_{h_0 \tilde{h}^{\pm} W^{\mp}} = -\sinh\theta\,, \qquad g_{\tilde{h}_0 \tilde{P} Z} = g_{\tilde{h}_0 \tilde{h}^{\pm} W^{\mp}} = -\cosh\theta$$

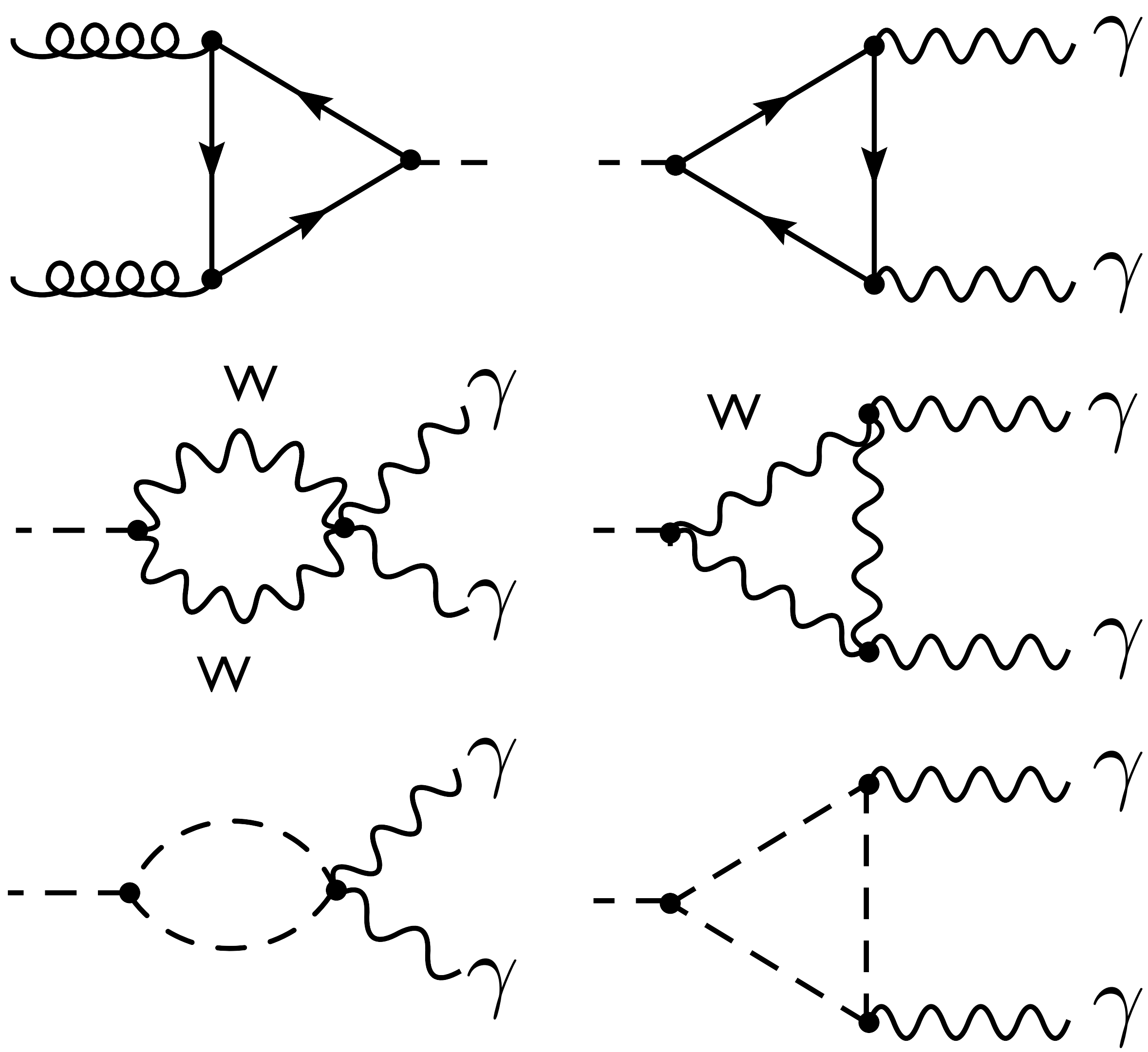
Neutral Yukawa couplings: $g_{h_0 f\bar{f}} = -g_{\tilde{h}_0 f\bar{f}} = \cosh\theta - \sinh\theta = \frac{1+r^2}{\sqrt{1-r^4}}\,, \qquad g_{\tilde{P} f\bar{f}} = -1$

Charged Yukawa couplings:

$$\mathcal{L}_{\tilde{h}^{\pm} f\bar{f}} = \frac{\sqrt{2}}{v}\left[\tilde{h}^{+}\left(\bar{u}_R M_u V d_L - \bar{u}_L M_d V d_R\right) + \tilde{h}^{-}\left(-\bar{d}_R V^{\dagger} M_d u_L + \bar{d}_L V^{\dagger} M_u u_R\right)\right]$$

Gauge couplings sum rule: $g^2_{h_0 VV} - g^2_{\tilde{h}_0 VV} = 1$ ⇨ Both effective couplings can be larger than one, if $r \gtrsim 0.8$:) ⇨ Those values are excluded :(

Loop induced effective couplings



$$g_{Xgg} = g_{Xf\bar{f}} \qquad X = h_0, \tilde{h}_0, \tilde{P}$$

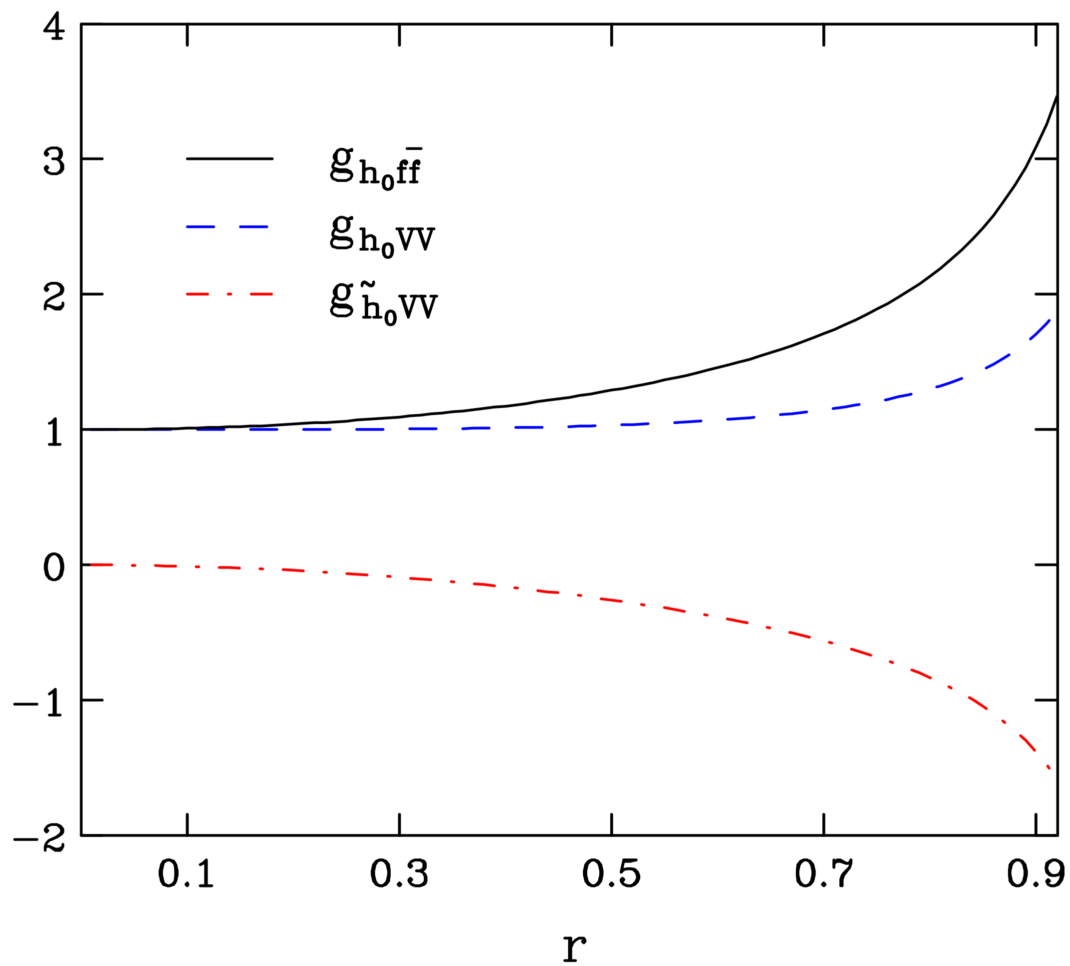
No need to deal with very large bottom Yukawa: all of the Yukawa couplings are enhanced by EXACTLY the same factor.

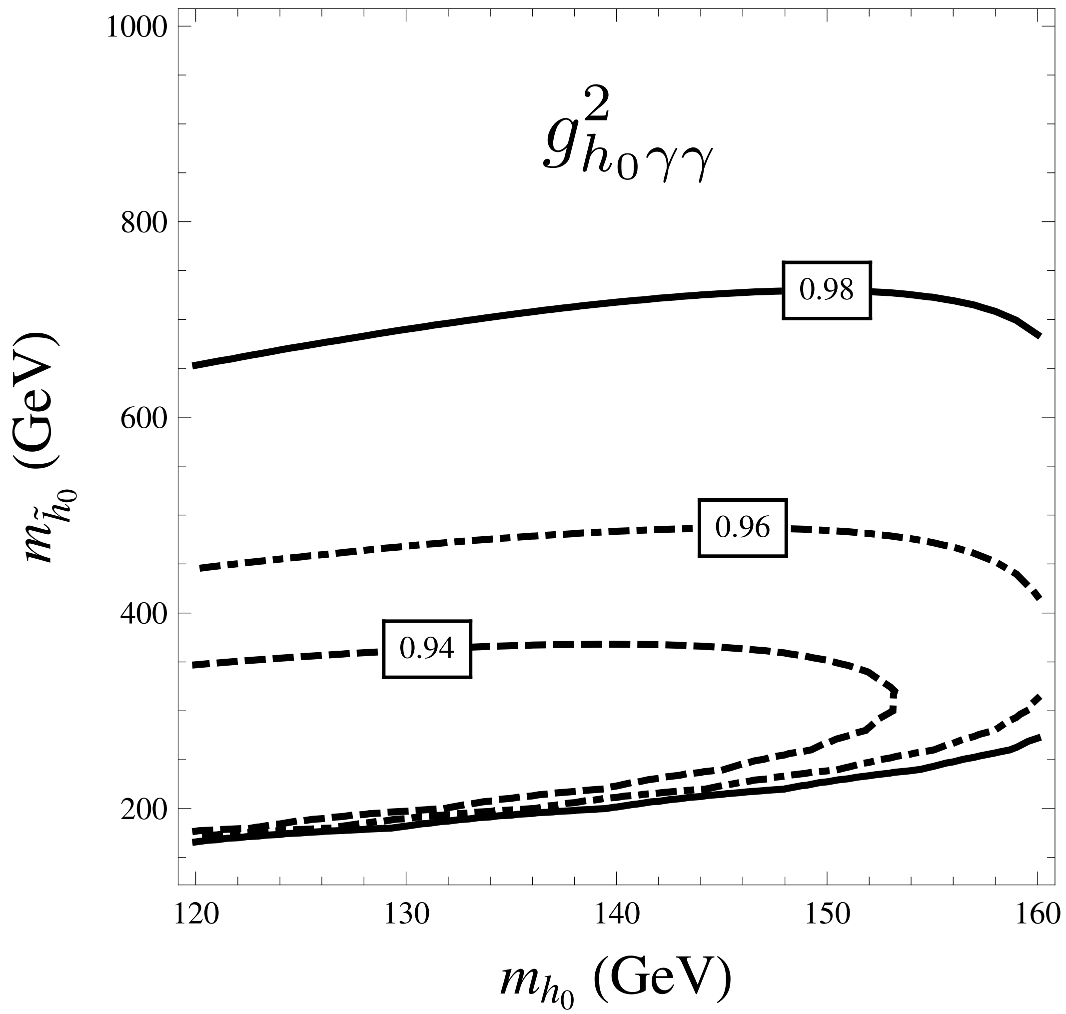
The diphoton channel is more complicated: one has to consider not only top quarks in the loop, but also W's (second row), Goldstone bosons and charged Higgs bosons (third row).

Krauss, Underwood, Zwicky, Phys. Rev. D 77, 015012 (2008)

$$g_{x\gamma\gamma} = \frac{g_{xt\bar{t}} N_c Q_t^2 F^x_{1/2}(\beta^t_x) + g_{xVV} F_1(\beta^W_x) + \frac{g_{x\tilde{h}^+\tilde{h}^-}}{2m_W^2/v} \frac{m_W^2}{m_{\tilde{h}^\pm}^2} F_0(\beta^{h^\pm}_x)}{N_c Q_t^2 F_{1/2}(\beta^t_x) + F_1(\beta^W_x)}$$

Effective couplings





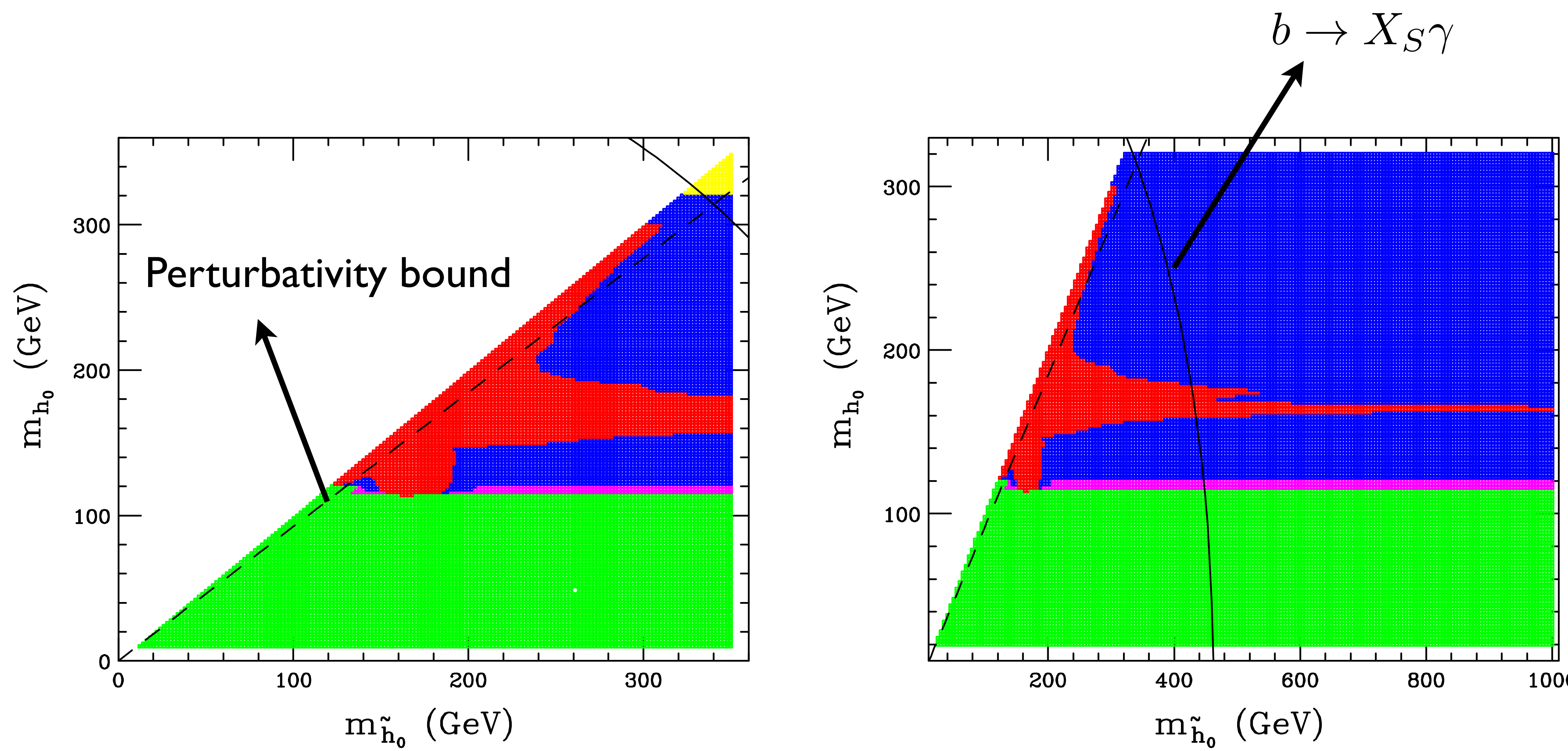
$g^2_{h_0 f\bar{f}} = g^2_{h_0 gg} > g^2_{h_0 VV} > g^2_{\tilde{h}_0 VV}$

- h_0: all prod. XS > SM
- $BR(h_0 \to f\bar{f}/gg) > \mathrm{SM}$, $BR(h_0 \to VV) < \mathrm{SM}$

$g^2_{h_0\gamma\gamma}$ deviates from the SM, at most, 7 %.

Collider Bounds

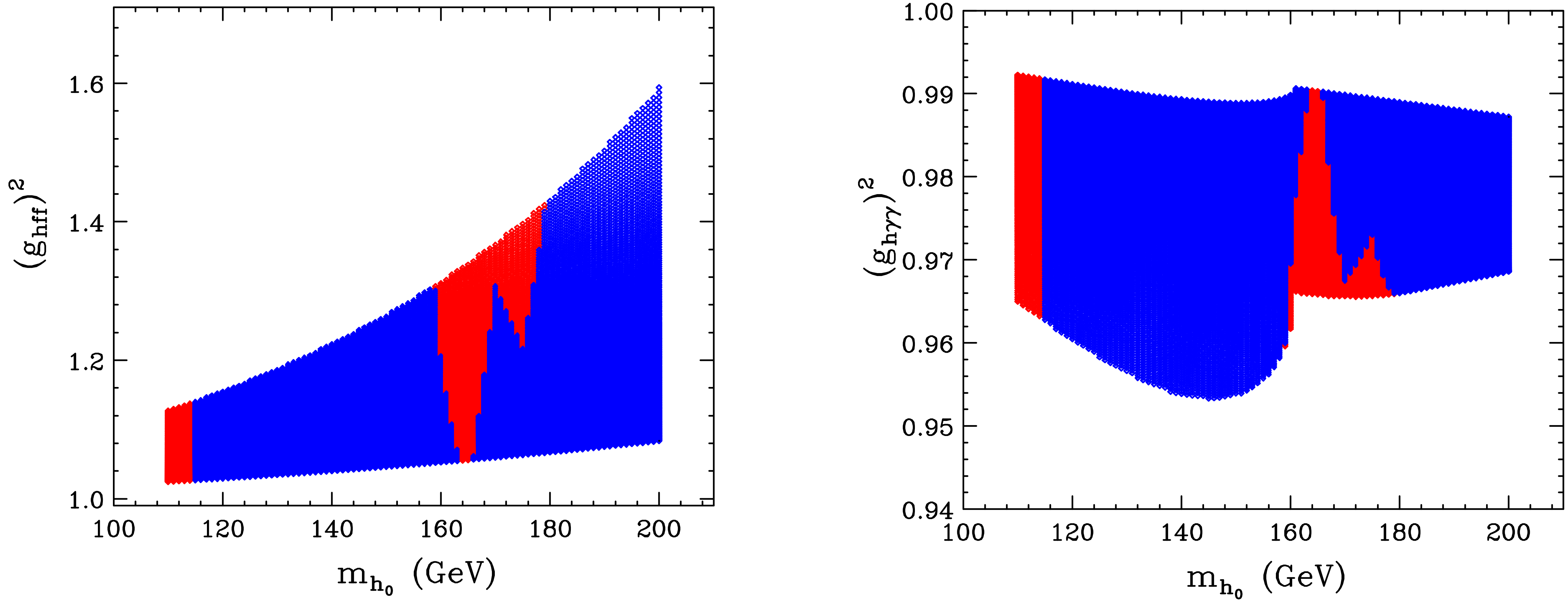
Current collider bounds



- Excluded by LEP
- Excluded by Tevatron
- None analysis apply
- "LEP reach"
- Currently allowed

HiggsBounds 2.1.1: P. Bechtle, O. Brein, S. Heinemeyer, G. Weiglein, K. E. Williams (2008-2011)

LHC analysis

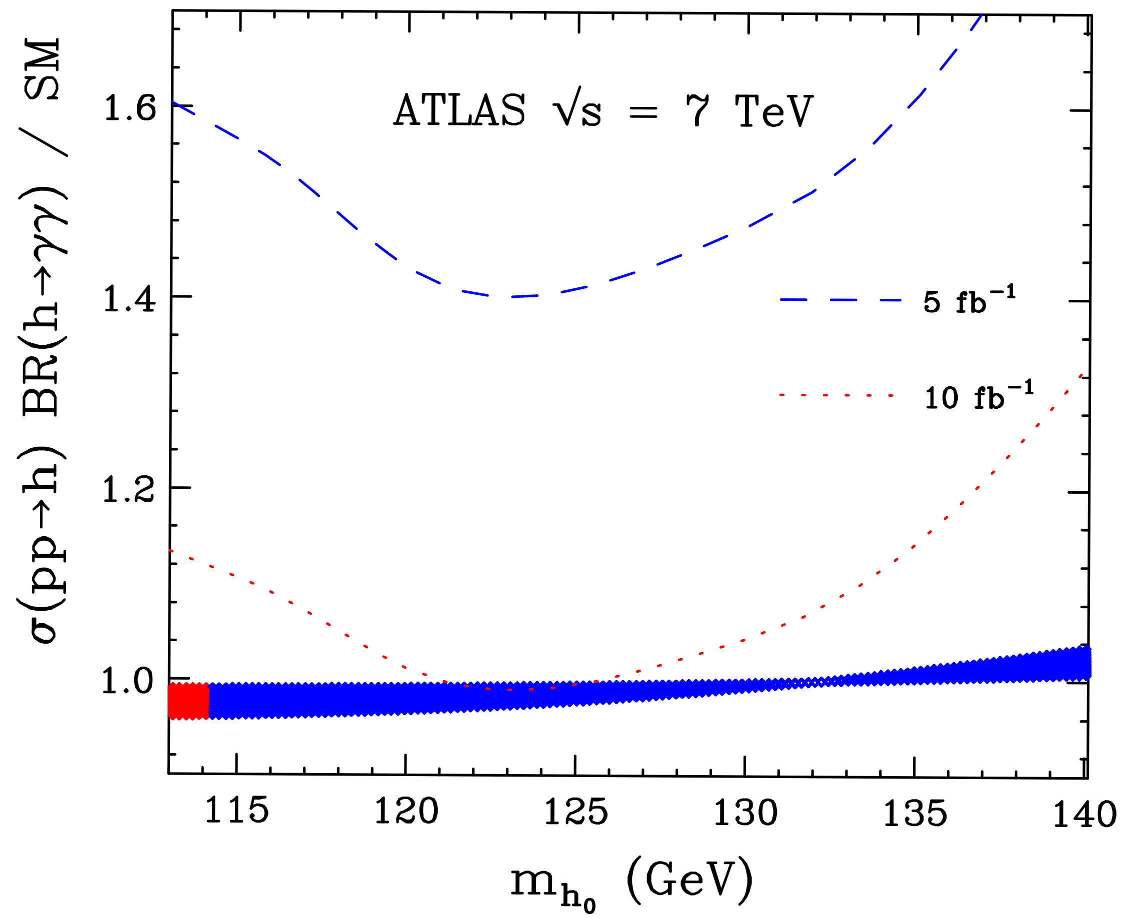


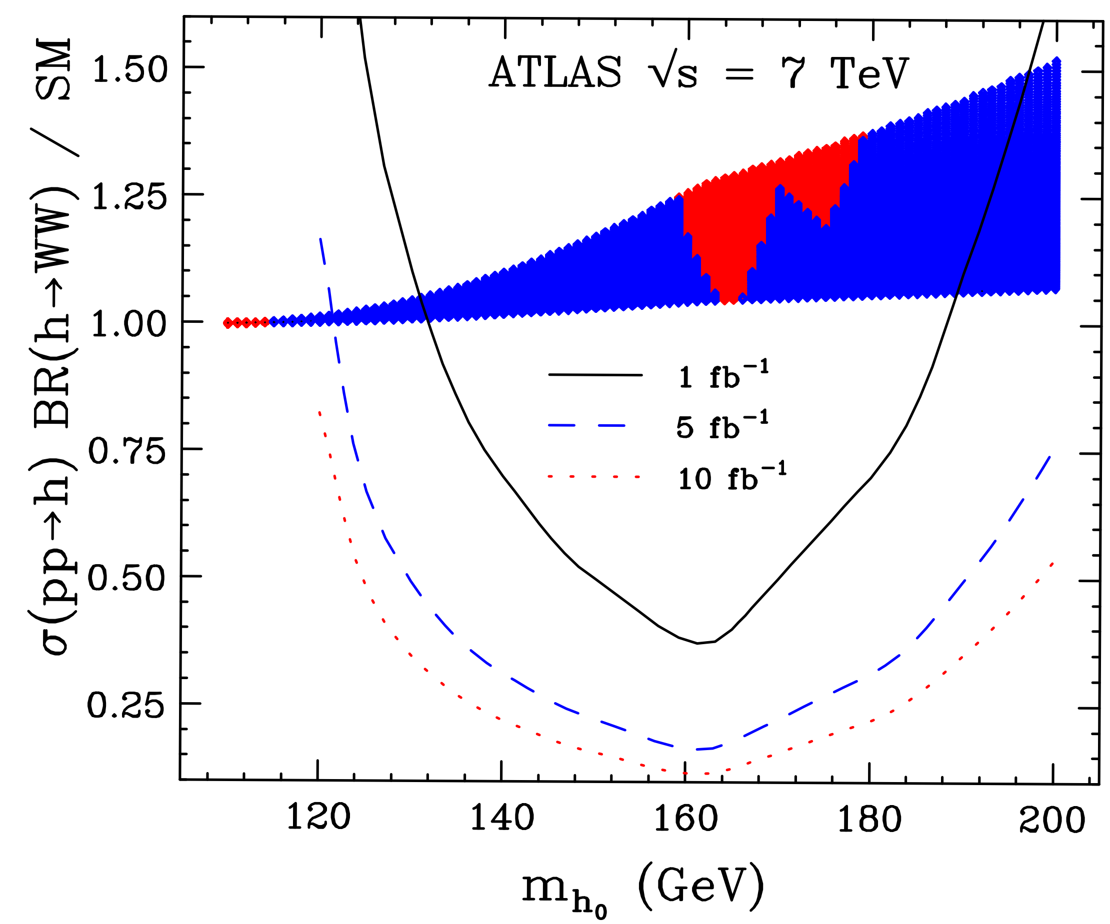
■ Excluded by LEP / Tevatron ■ Currently allowed

- Scanned mass range: $110 \text{ GeV} \leq \mathrm{m}_{\mathrm{h}_0} \leq 200 \text{ GeV}$

- Perturbativity and $b \to X_S\gamma$ exclusions are also applied.

LW @ LHC Run I





$\mathcal{L} = 1, 5, 10 \text{ fb}^{-1}$: end of 2011, end of 2012, optimistic

$h_0 \to WW: \quad m_{h_0} \geq 130/125/120 \text{ GeV}$

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

Conclusions

- We have studied the collider bounds on the Higgs sector of the LW SM.
- This work complements the $b \to X_S \gamma$ constraints.
- Tevatron current data constraints a minor portion of the parameter space.
- Lightest Higgs in the reach of LHC Run I only in the $h_0 \to WW$ channel.

Thanks!

Backup slides

Constraints on parameter space

$M_{\tilde{B},\tilde{W}} \geq 3-4\ \mathrm{TeV}$	EWPD
$M_{\tilde{Q}} \geq 3\ \mathrm{TeV}$	EWPD
$M_{\tilde{l}} \geq 100\ \mathrm{GeV}$	Direct Search
$M_{\tilde{h}} \geq 463\ \mathrm{GeV}$	$b \to X_S \gamma$