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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The University of Manchester

Birmingham Particle Physics Seminars

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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

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

(A) HD formalism:

$$\mathcal{L}_{\rm hd} = \frac{1}{2}\partial_\mu\hat\phi\partial^\mu\hat\phi - \frac{1}{2M^2}(\partial^2\hat\phi)^2 - \frac{1}{2}m^2\hat\phi^2 - \frac{1}{3!}g\hat\phi^3$$

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

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

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

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

Quadratic divergence is cancelled leading to a logarithmic divergence.

A TOY MODEL

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

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

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

A LW resonance has a probability Γdt of decaying in the interval $-dt$.

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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LWSM

Higgs Sector (AF formalism)

$$\mathcal{L} = (\hat{D}_\mu H)^\dagger (\hat{D}^\mu H) - (\hat{D}_\mu \tilde{H})^\dagger (\hat{D}^\mu \tilde{H}) + M_H^2 \tilde{H}^\dagger \tilde{H} - V(H - \tilde{H})$$

$$\hat{D}_\mu \;=\; \partial_\mu + i(\mathbf{A}_\mu + \tilde{\mathbf{A}}_\mu) \qquad \mathbf{A}_\mu \;=\; g A_\mu^a T^a + g_2 W_\mu^a T^a + g_1 B_\mu Y$$

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

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

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

LWSM

Higgs Sector

Symplectic rotation:

$$\begin{pmatrix} h \\ \tilde{h} \end{pmatrix} = \begin{pmatrix} \cosh\phi_h & \sinh\phi_h \\ \sinh\phi_h & \cosh\phi_h \end{pmatrix} \begin{pmatrix} h_{\mathrm{phys}} \\ \tilde{h}_{\mathrm{phys}} \end{pmatrix}$$

Mass eigenvalues:

	h_0	$\tilde{h}_0$	$\tilde{p}_0$	$h_\pm$
CP	even	even	odd	none
$\frac{m^2_{\mathrm{phys}}}{M_H^2}$	$\frac{1}{2}\left(1 - \sqrt{1 - 2v^2\lambda/M_H^2}\right)$	$\frac{1}{2}\left(1 + \sqrt{1 - 2v^2\lambda/M_H^2}\right)$	1	1

LWSM

Higgs Sector

Mixing angle:

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

$$\begin{aligned} s_H &= \cosh\phi_h = \frac{1}{(1-r^4_{h_0})^{1/2}}\,, \\ s_{H\text{–}\tilde{H}} &= \cosh\phi_h - \sinh\phi_h = \frac{1+r^2_{h_0}}{(1-r^4_{h_0})^{1/2}} \end{aligned}$$

LWSM

Yukawa Interactions (in auxiliary field formalism)

$$\mathcal{L} = \overline{\Psi^t} i\eta_3 \hat{\not{D}} \Psi^t - \overline{\Psi^t_R} \mathcal{M}_t \eta_3 \Psi^t_L - \overline{\Psi^t_L} \eta_3 \mathcal{M}^\dagger \Psi^t_R$$

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

SU(2) doublet: $Q_L = (T_L, B_L)^\top$

$$\mathcal{M}_t \eta_3 = \begin{pmatrix} m_t & 0 & -m_t \\ -m_t & -M_u & m_t \\ 0 & 0 & -M_Q \end{pmatrix}\,, \qquad \eta_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

LWSM

Diagonalization of mass matrices

$$\Psi_{L(R),\mathrm{phys}} = \eta_3 S^\dagger_{L(R)} \eta_3 \Psi_{L(R)}\,, \qquad \mathcal{M}_{t,\mathrm{phys}}\eta_3 = S^\dagger_R \mathcal{M}_t \eta_3 S_L\,,$$

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

Higgs-quark vertices

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

$$g_t = \begin{pmatrix} m_t & 0 & -m_t \\ -m_t & 0 & m_t \\ 0 & 0 & 0 \end{pmatrix}, \quad g_{t,\mathrm{phys}} = S^\dagger_R g_t S_L$$

LWSM

LW gauge bosons are massive and mix:

$$\begin{aligned}\mathcal{L}_{2g} = & - \frac{1}{2}\mathrm{Tr}\left(B_{\mu\nu}B^{\mu\nu} - \tilde{B}_{\mu\nu}\tilde{B}^{\mu\nu} + W_{\mu\nu}W^{\mu\nu} - \tilde{W}_{\mu\nu}\tilde{W}^{\mu\nu}\right) \\ & - \frac{1}{2}({M_1}^2\tilde{B}_\mu\tilde{B}^\mu + {M_2}^2\tilde{W}^a_\mu\tilde{W}^\mu_a) + \frac{g_2^2v^2}{8}(W^{1,2}_\mu + \tilde{W}^{1,2}_\mu)^2 \\ & + \frac{v^2}{8}(g_1B_\mu + g_1\tilde{B}_\mu + g_2W^3_\mu + g_2\tilde{W}^3_\mu)^2\end{aligned}$$

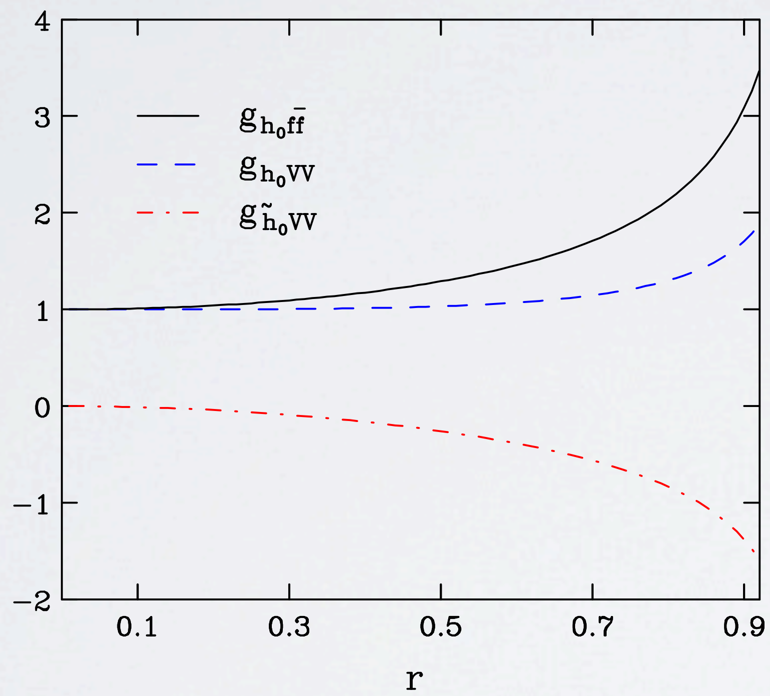
Gauge interactions:

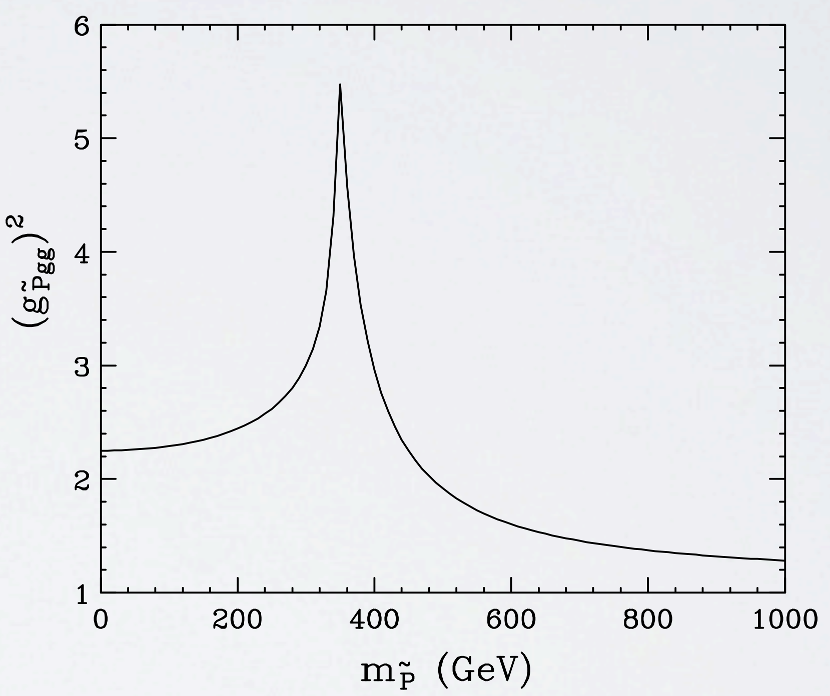
$$\begin{aligned}\mathcal{L}_{int} = & - \sum_{\psi=q_L,u_R,d_R}[g_1\bar{\psi}(\not{B} + \tilde{\not{B}})\psi + g_2\bar{\psi}(\not{W} + \tilde{\not{W}})\psi] \\ & + \sum_{\psi=q,u,d}\left[g_1\bar{\tilde{\psi}}(\not{B} + \tilde{\not{B}})\tilde{\psi} + g_2\bar{\tilde{\psi}}(\not{W} + \tilde{\not{W}})\tilde{\psi}\right].\end{aligned}$$

LWSM

Couplings to gauges bosons and fermions

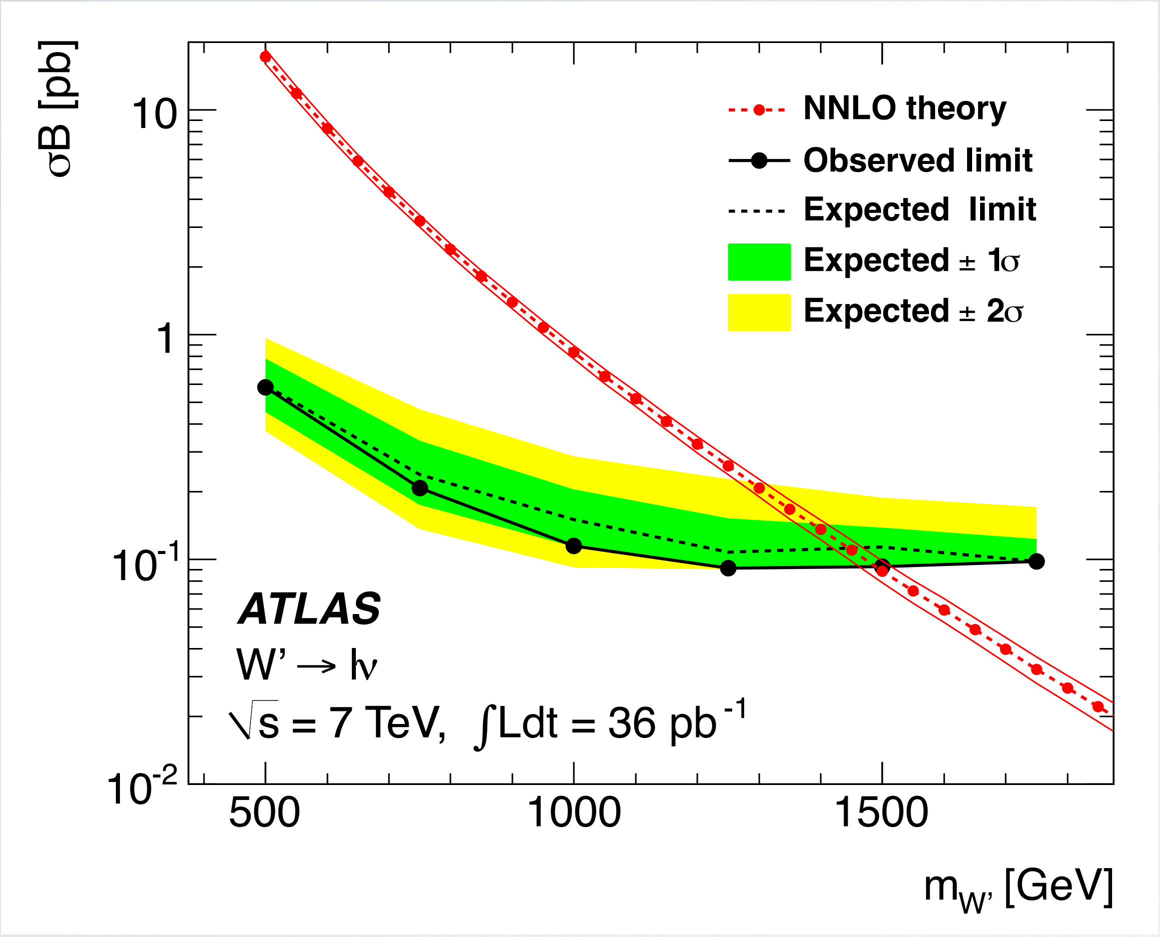
E. Alvarez, E. Coluccio, J.Zurita: **arXiv 1004.3496**



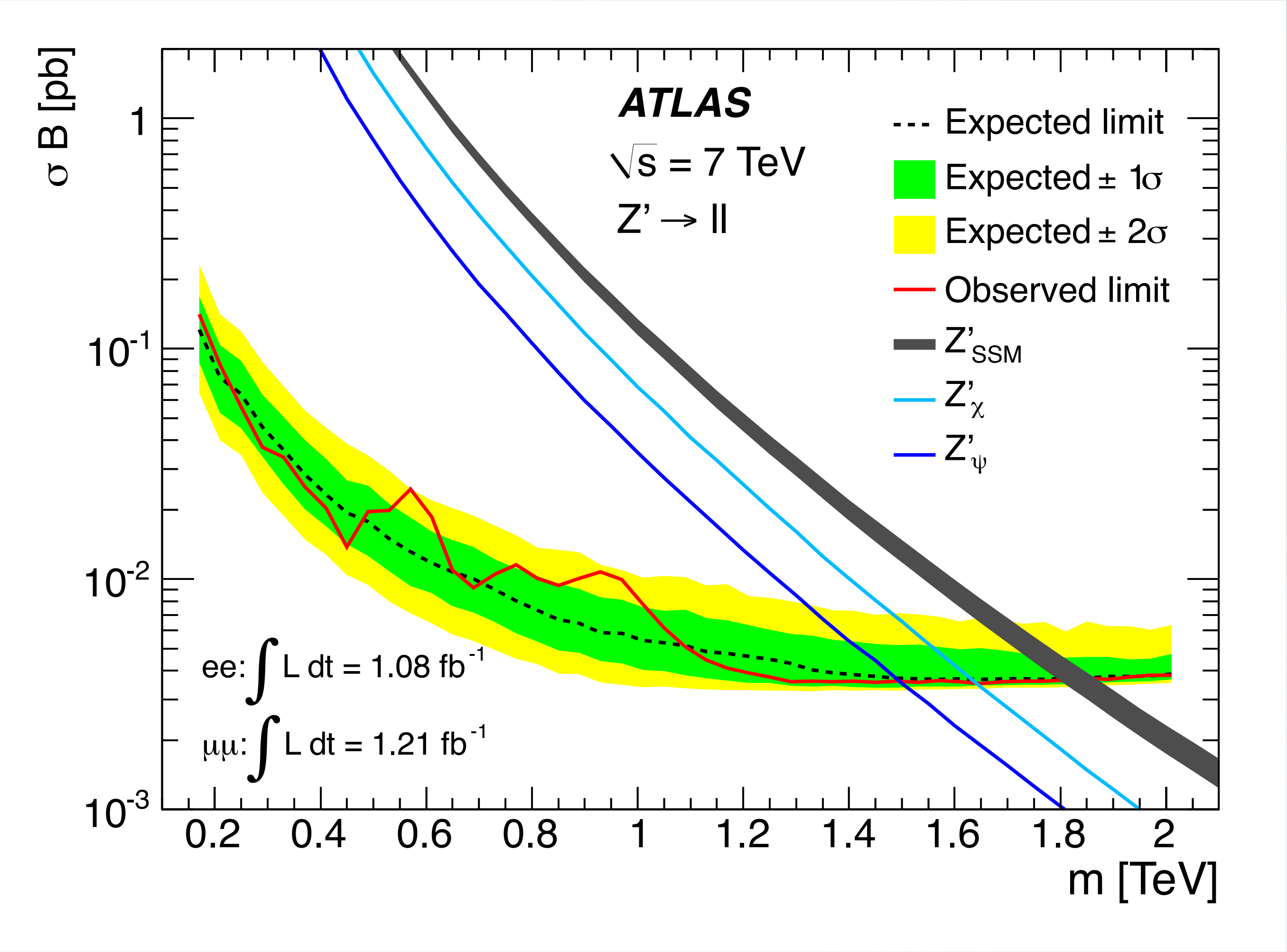


$$g_{h_0 f\bar{f}} = -g_{\tilde{h}_0 f\bar{f}} = \cosh\theta - \sinh\theta = \frac{1+r^2}{\sqrt{1-r^4}}\,, \qquad g_{\tilde{P}f\bar{f}} = -1 \qquad g^2_{\tilde{P}gg} = \frac{\sigma(gg\to\tilde{P})}{\sigma^{SM}(gg\to H)} = |\frac{g_{\tilde{P}t\bar{t}}\,F^{\tilde{P}}_{1/2}(\beta^t_{\tilde{P}})}{F_{1/2}(\beta^t_{\tilde{P}})}|^2$$

LW Gauge bosons at the LHC

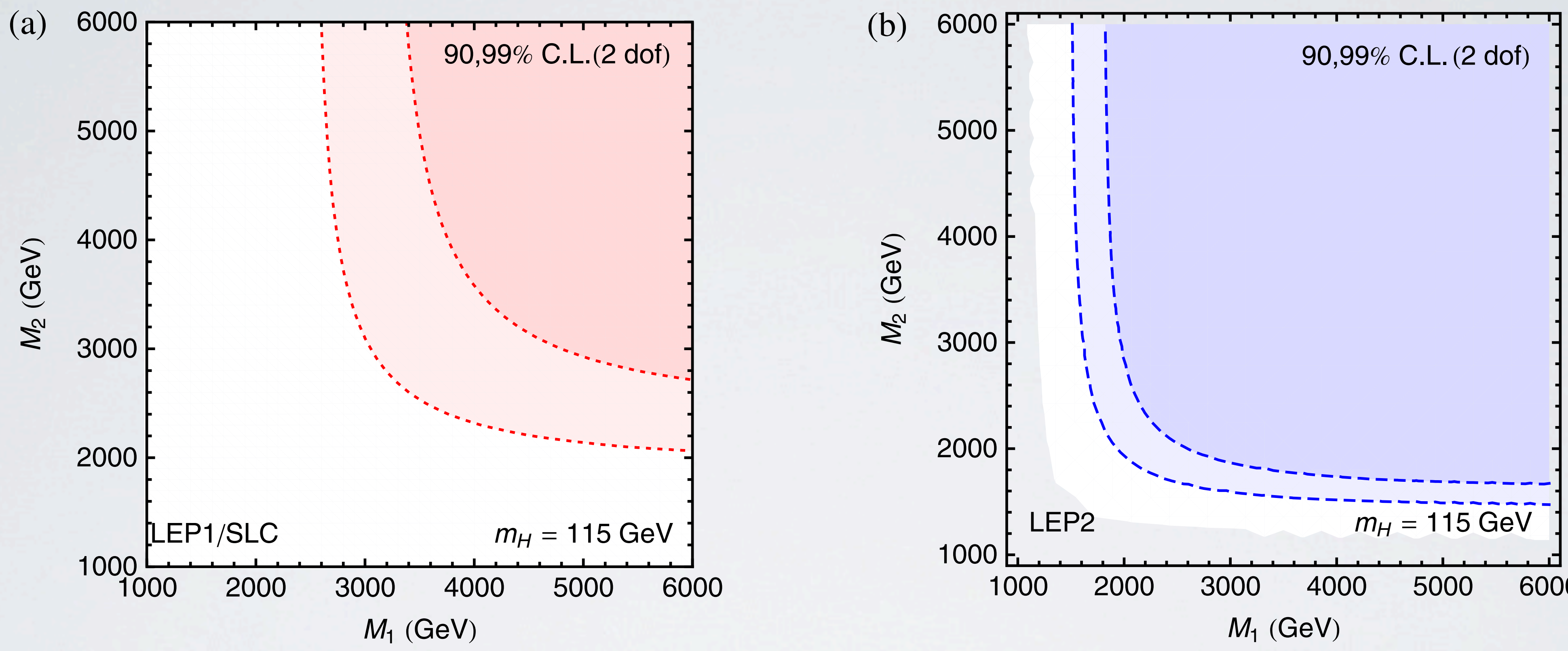


ArXiv:1103.1391



ArXiv:1108.1582

Electroweak Precision Constraints

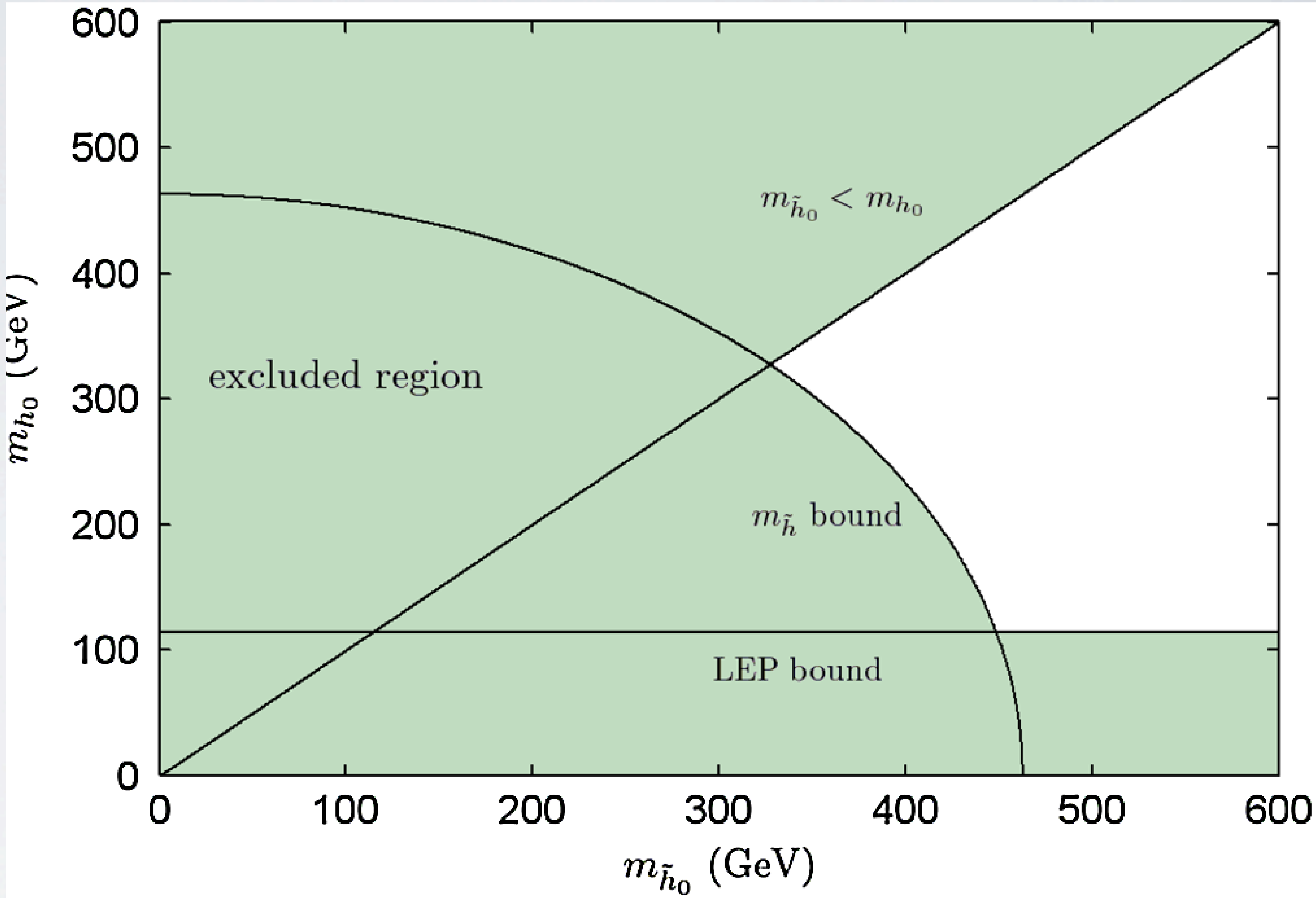


T.E.J. Underwood and R. Zwicky (2009)

LWSM HIGGS CONSTRAINTS

C.D. Carone and R. Primulando (2009)

$$B \to X_s \gamma$$



$$m^2_{h_0} + m^2_{\tilde{h}_0} = m^2_{\tilde{p}_0} = m^2_{\tilde{h}^\pm} > (463\ \mathrm{GeV})^2$$

Electroweak Precision Constraints

R.S. Chivukula, A. Farzinnia, R. Foadi, and E.H.Simmons (2010)

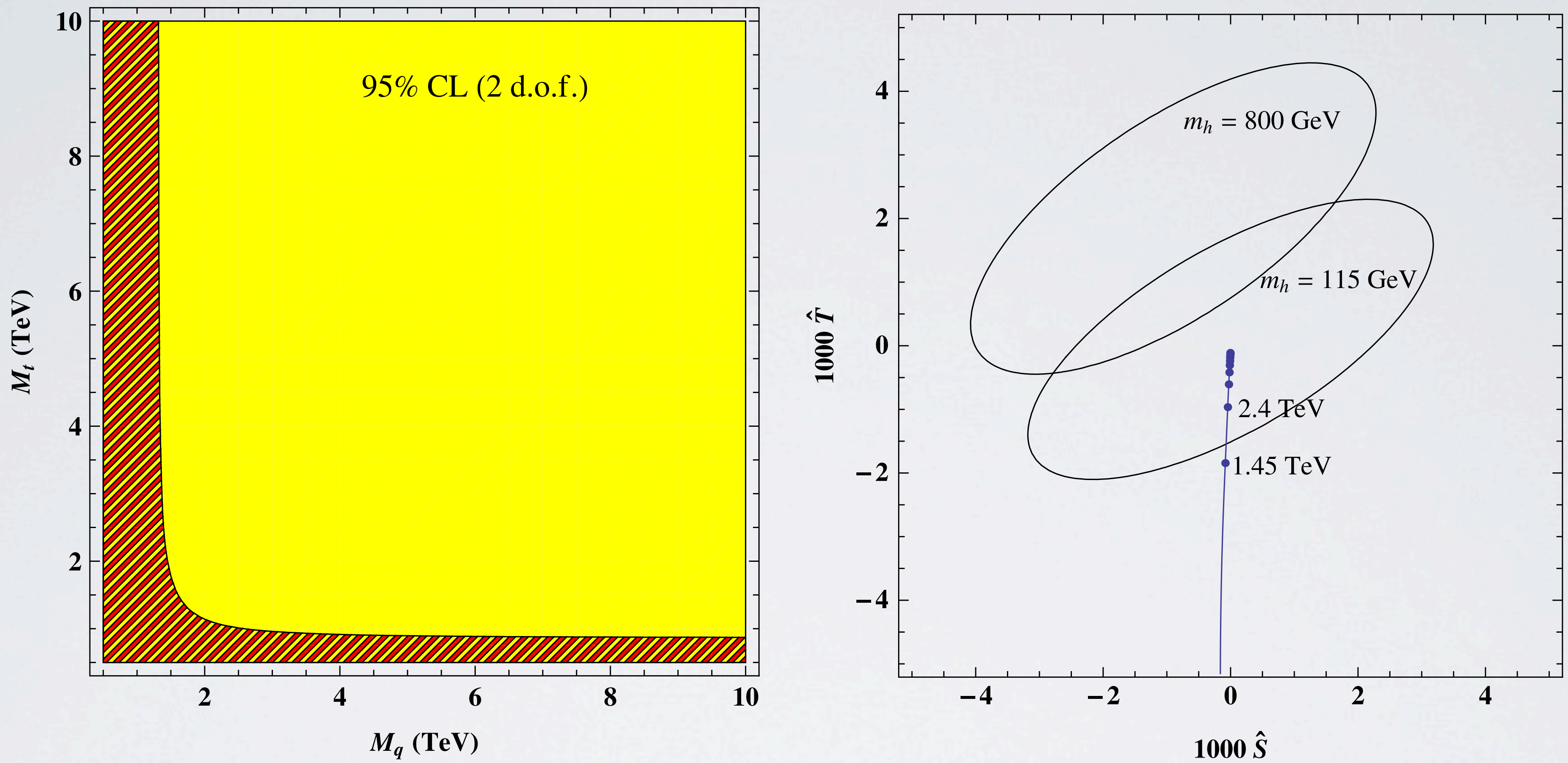
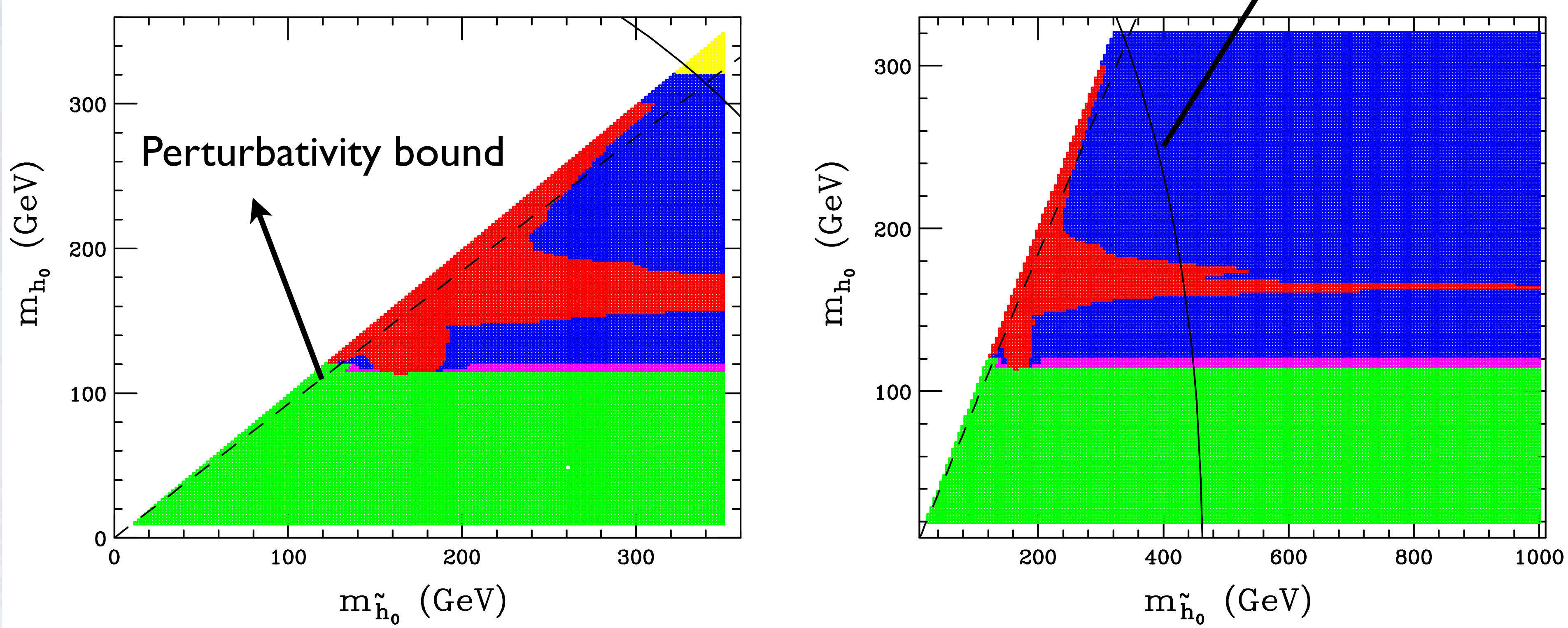


FIG. 6 (color online). Left: 95% C.L. exclusion plots for the LW fermion masses M_q and M_t. These bounds come almost entirely from the experimental constraints on $\hat{T}$. For a light Higgs the striped region to the left of the curve is excluded, while a heavy Higgs is completely excluded. Right: 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 $< M_q <$ 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.

LWSM HIGGS CONSTRAINTS

E. Alvarez, E. Coluccio, J.Zurita: **arXiv 1004.3496**

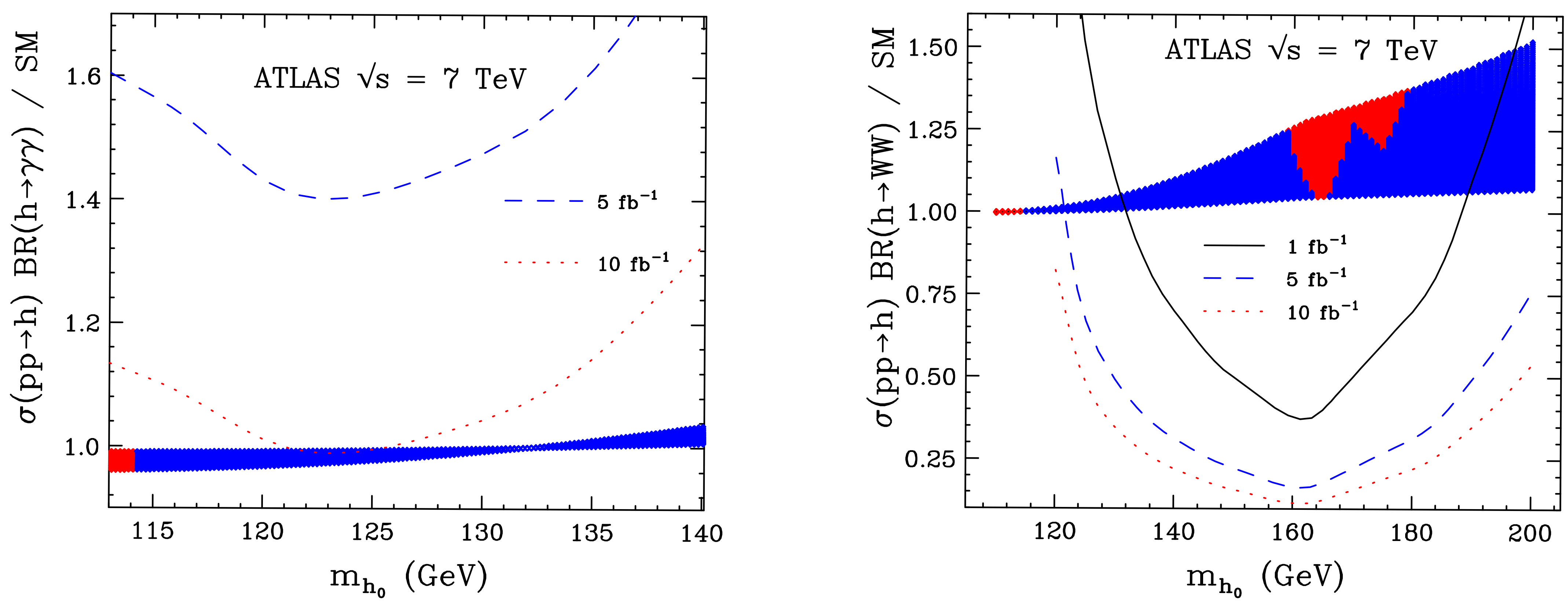


- Excluded by LEP
- Excluded by Tevatron
- None analysis apply
- "LEP reach"
- Currently allowed

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

LIGHT HIGGS BOSON AT THE LHC

E. Alvarez, E. Coluccio, J.Zurita: **arXiv 1004.3496**

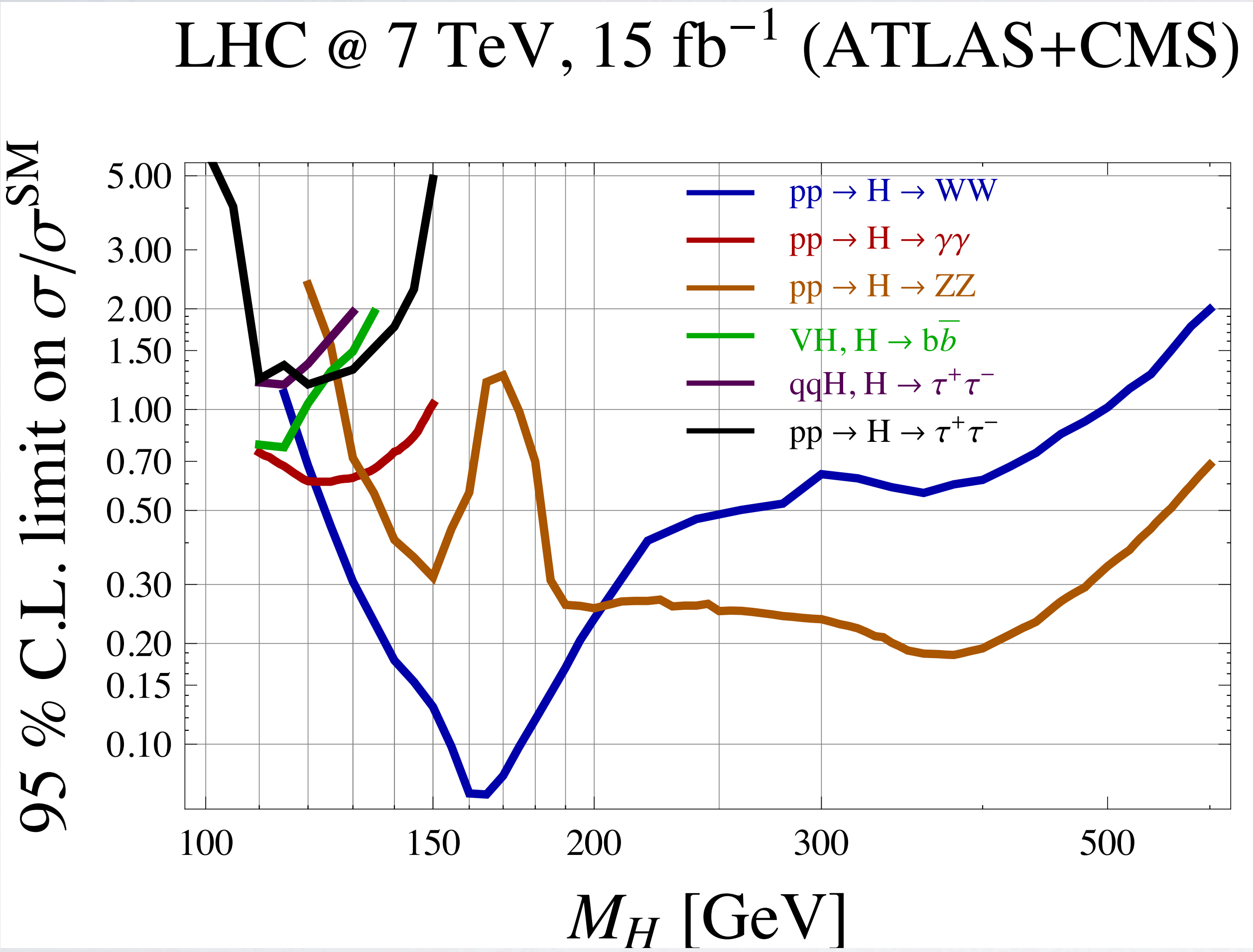


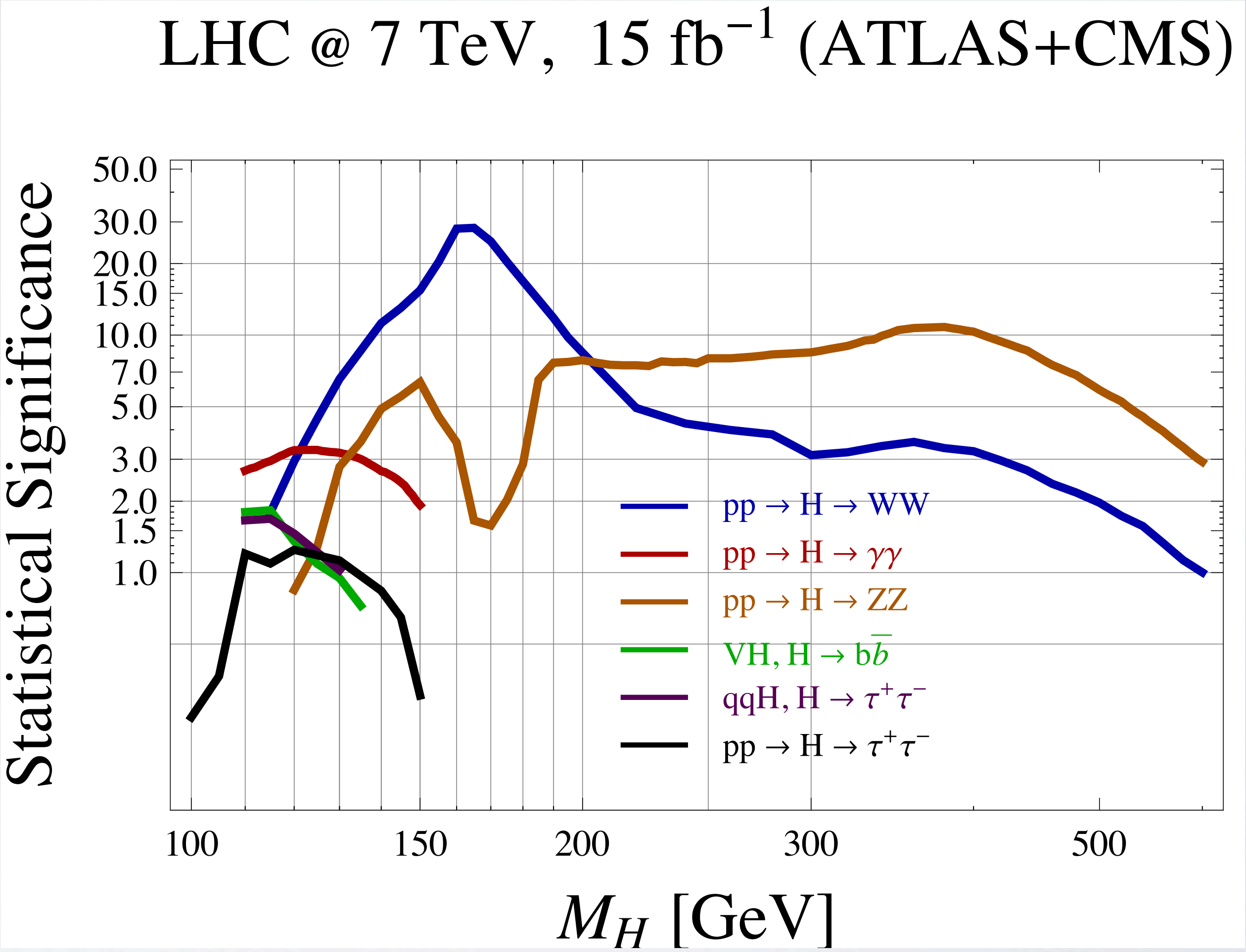
$\mathcal{L} = 1, 5, 10 \text{ fb}^{-1}$: end of 2011, end of 2012, optimistic

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

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

LIGHT HIGGS BOSON AT THE LHC





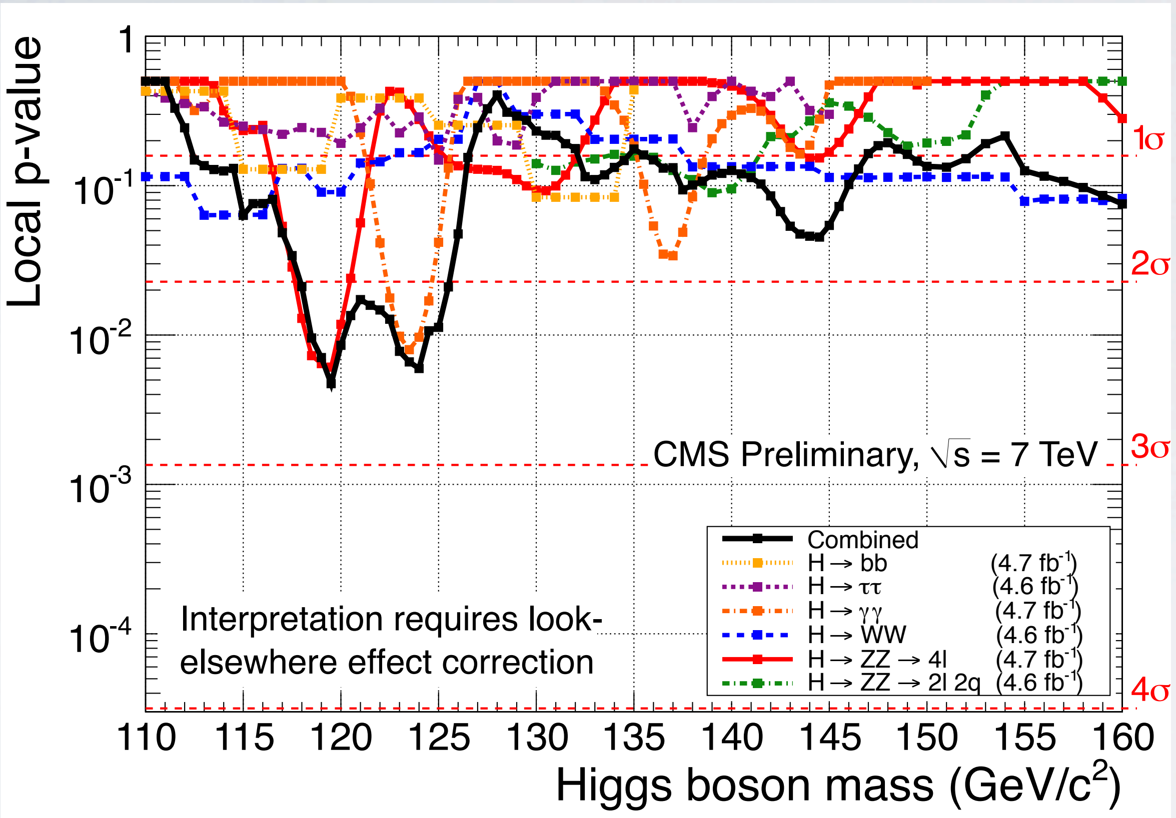
E. Weihs and J. Zurita (2011)

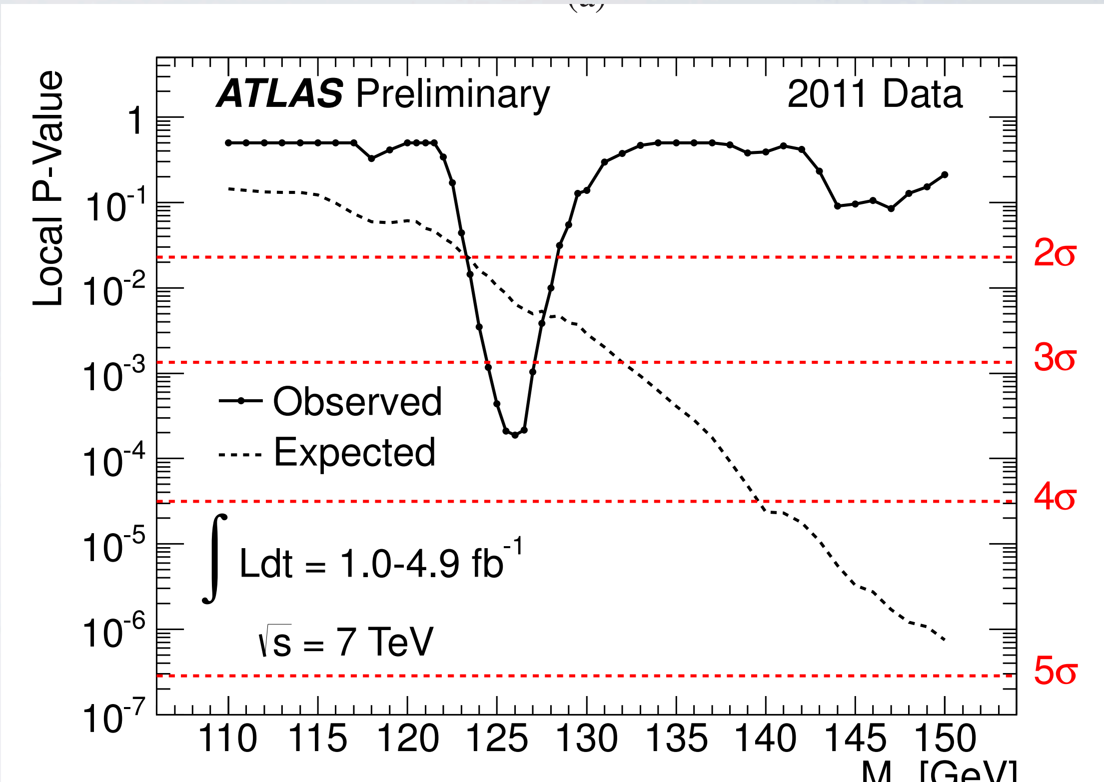
The minimal LWSM can be ruled out by searching for the light Higgs boson at the LHC.

LIGHT HIGGS BOSON AT THE LHC

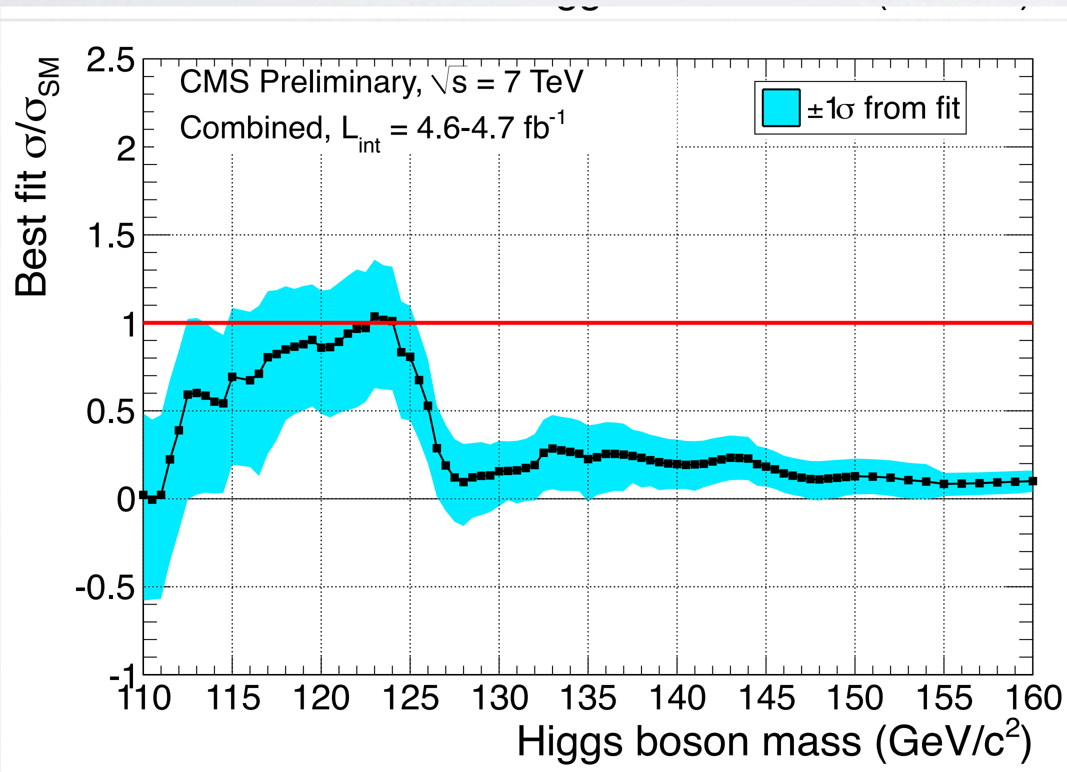
CMS PAS HIG-11-032

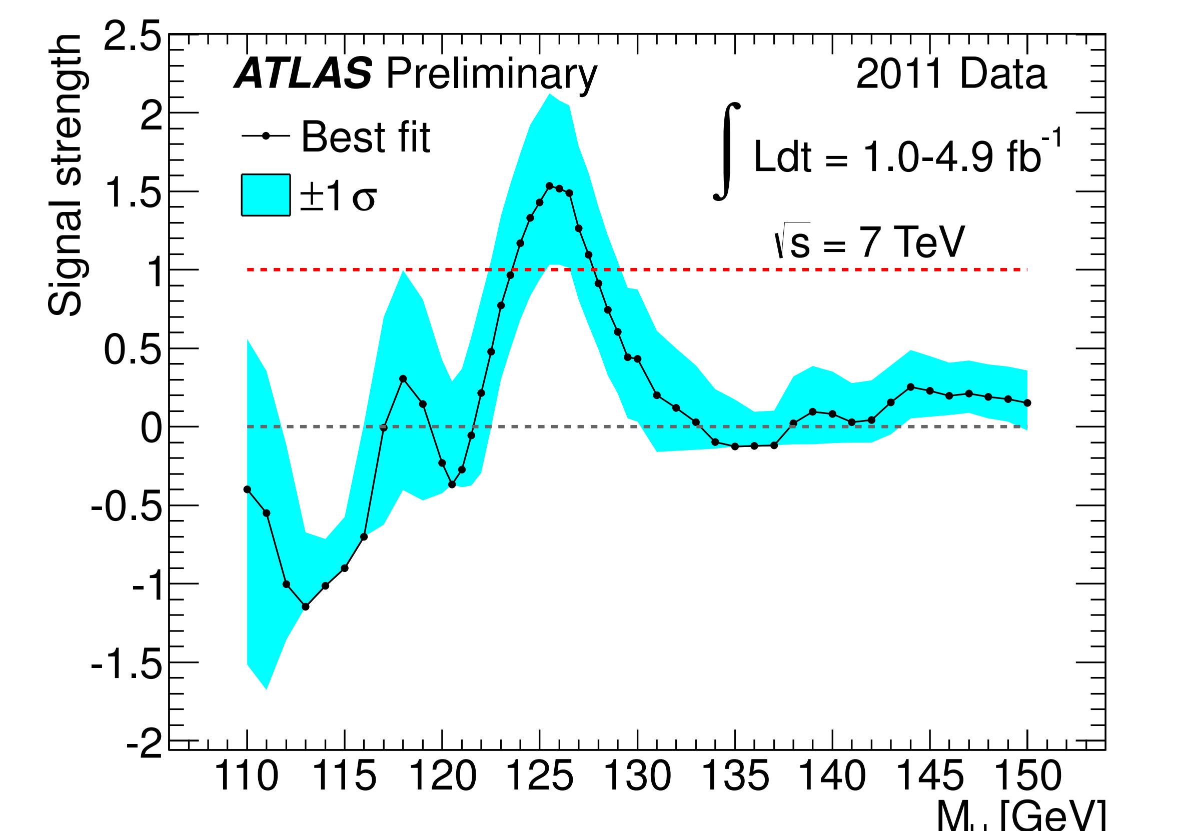
ATL-CONF-2011-163





(b)





(b)

A Higher Derivative LWSM

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

$$\mathcal{L}_{\rm HD} = \hat{D}_\mu \hat{H}^\dagger \hat{D}^\mu \hat{H} - m_H^2 \hat{H}^\dagger \hat{H} - \frac{1}{M_1^2}\hat{H}^\dagger (\hat{D}_\mu \hat{D}^\mu)^2 \hat{H} - \frac{1}{M_2^4}\hat{H}^\dagger (\hat{D}_\mu \hat{D}^\mu)^3 \hat{H} + \mathcal{L}_{\rm int}(\hat{H})$$

$$\begin{aligned} \mathcal{L} \; = & \; -H^{(1)\dagger}(\hat{D}_\mu \hat{D}^\mu + m_1^2)H^{(1)} + H^{(2)\dagger}(\hat{D}_\mu \hat{D}^\mu + m_2^2)H^{(2)} \\ & -H^{(3)\dagger}(\hat{D}_\mu \hat{D}^\mu + m_3^2)H^{(3)} + \mathcal{L}_{\rm int}(\hat{H}) \;\; , \end{aligned}$$

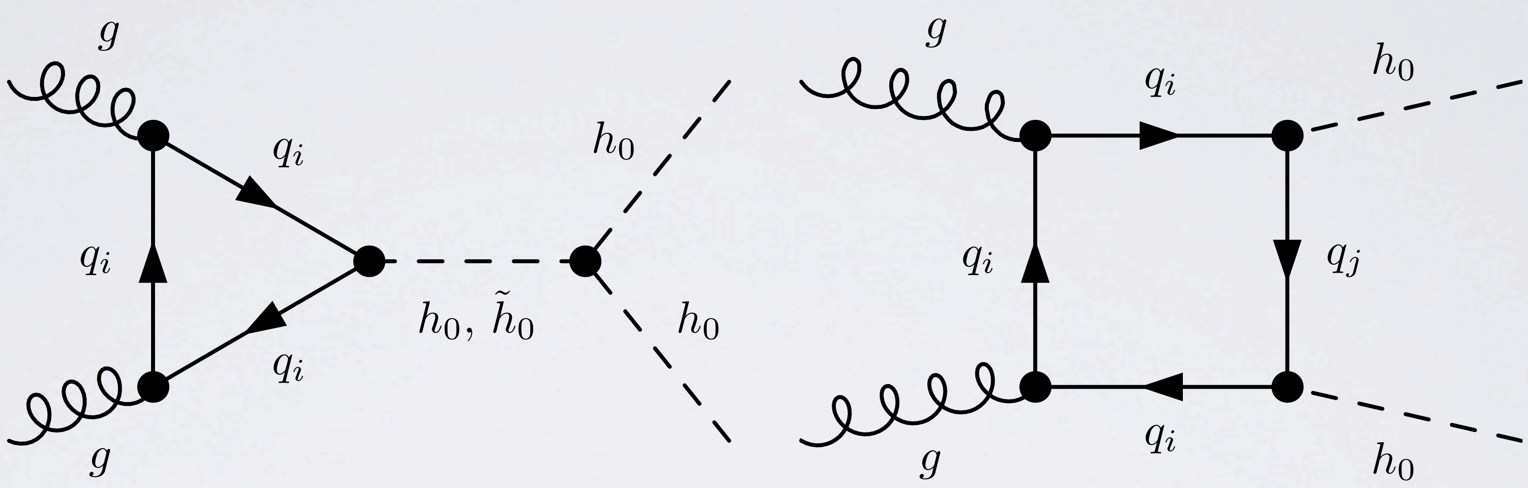
$$H^{(1)} = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v + h_1) \end{pmatrix}, \quad H^{(2)} = \begin{pmatrix} h_2^+ \\ \frac{1}{\sqrt{2}}(h_2 + iP_2) \end{pmatrix}, \quad H^{(3)} = \begin{pmatrix} h_3^+ \\ \frac{1}{\sqrt{2}}(h_3 + iP_3) \end{pmatrix}$$

3 Higgs doublet model with one negative norm state and two positive norm states.

We leave this for further study and focus on the minimal LWSM.

HIGGS BOSON PAIR PRODUCTION

$$pp \to h_0 h_0$$

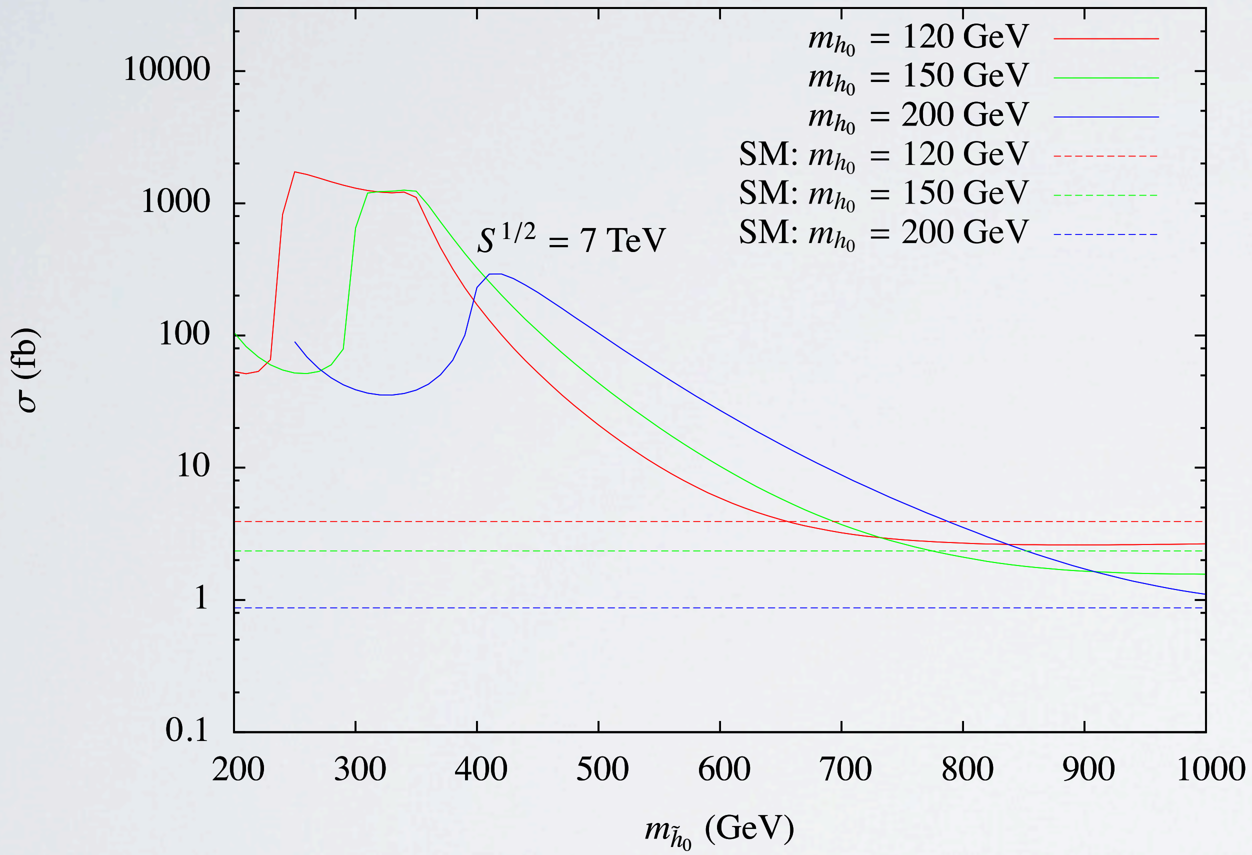


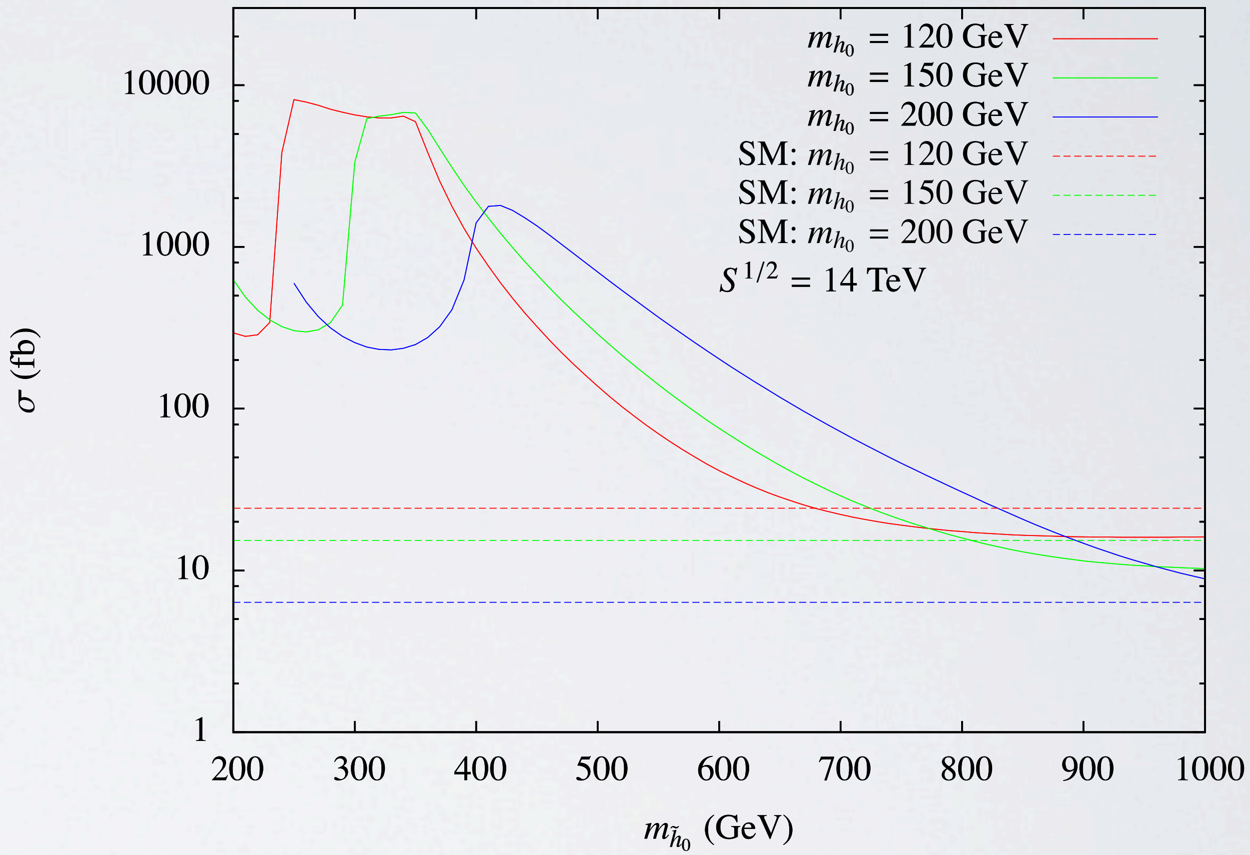
(a) (b)

$$\mathcal{M}(gg \to h_0 h_0) = \frac{1}{32\pi^2}\delta^{ab}\frac{g^2}{v^2}\Big(\mathcal{A}_0 P_0 + \mathcal{A}_2 P_2\Big)_{\mu\nu} e(p_1)^\mu_a \, e(p_2)^\nu_b$$

For details see our Appendix!

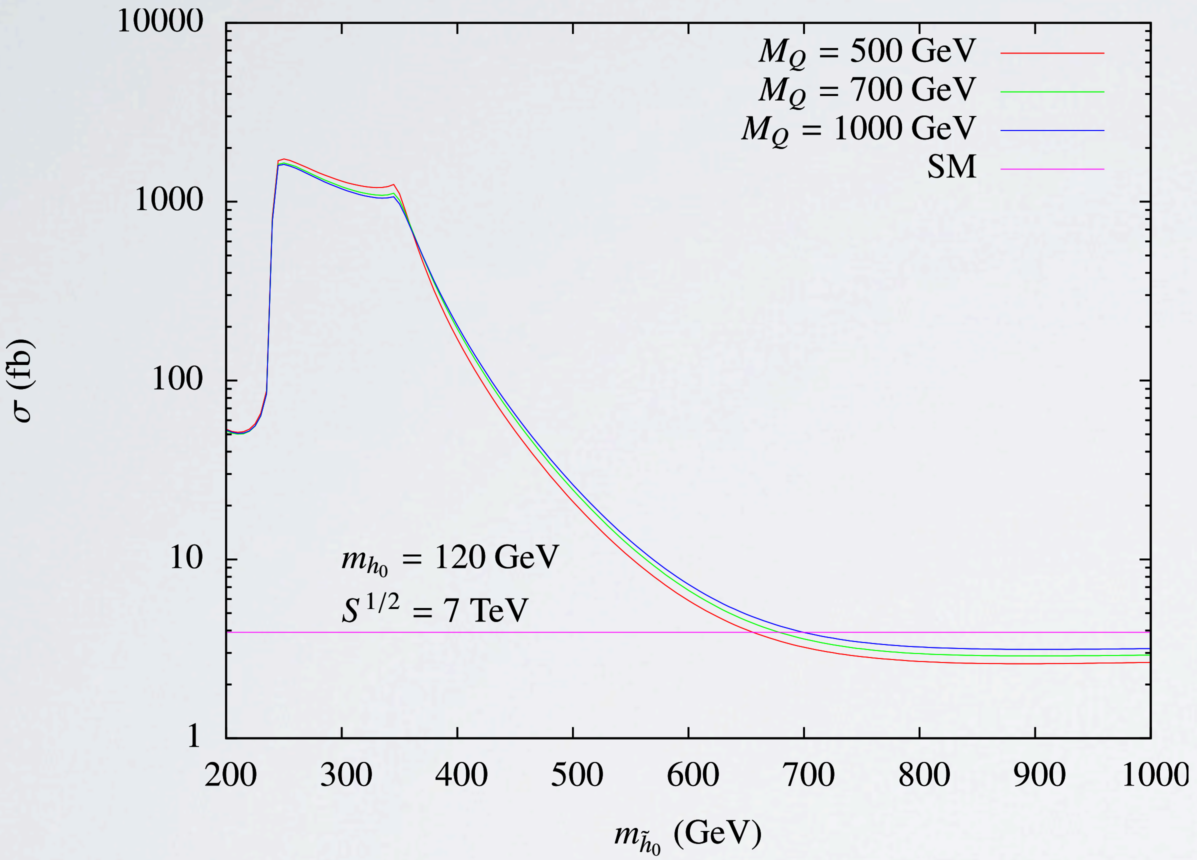
HIGGS BOSON PAIR PRODUCTION

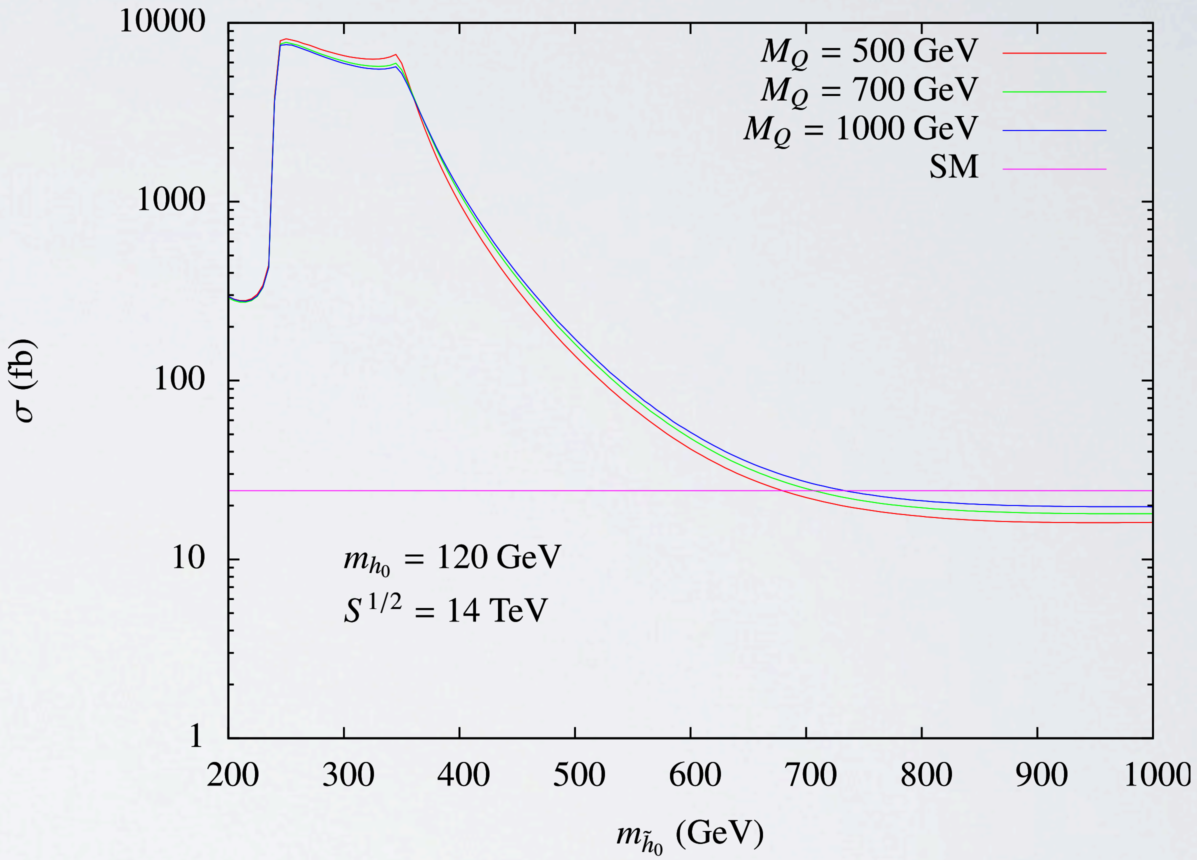




Total cross section

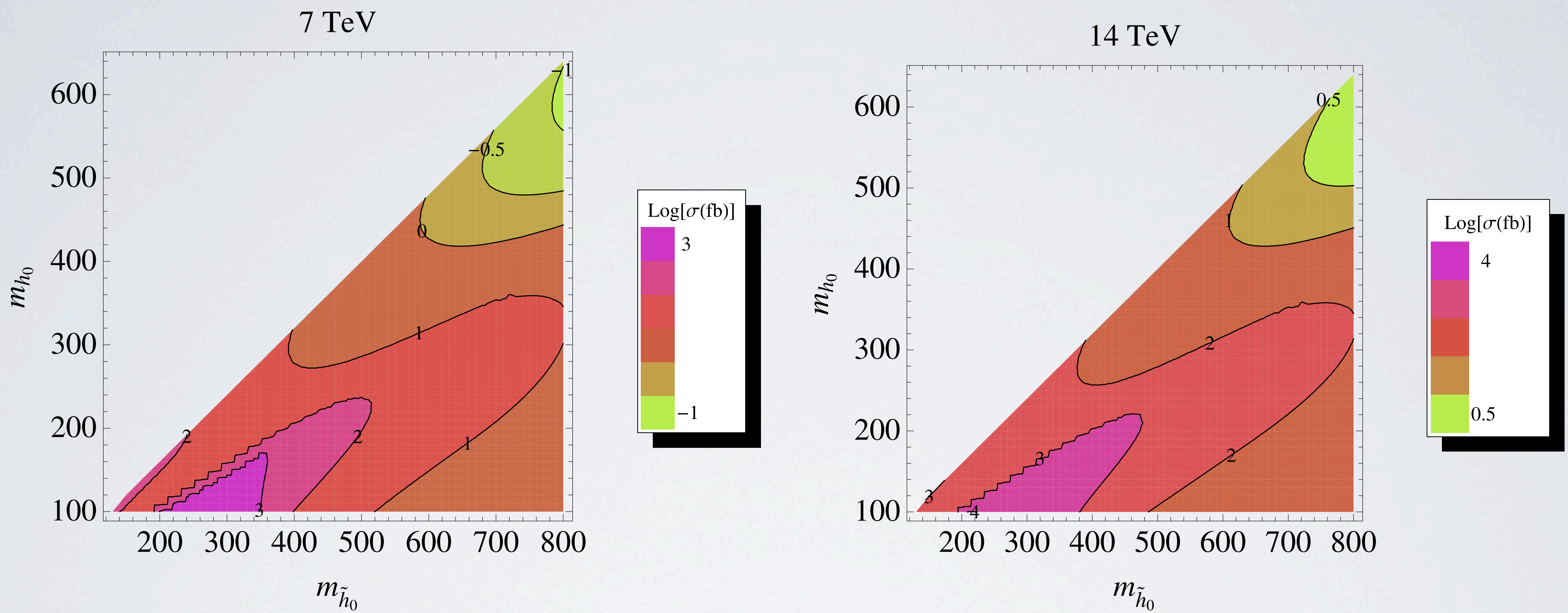
HIGGS BOSON PAIR PRODUCTION





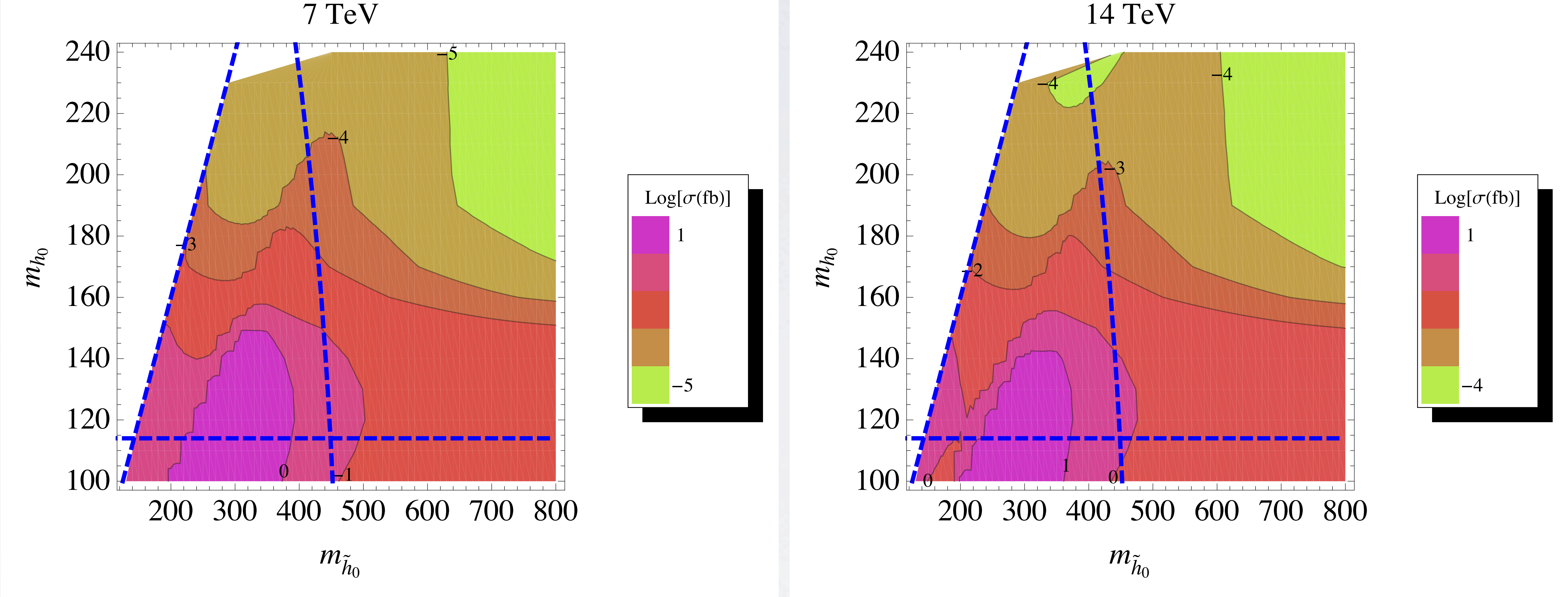
Total cross section

HIGGS BOSON PAIR PRODUCTION



Total cross section

HIGGS BOSON PAIR PRODUCTION



$$pp \to h_0 h_0 \to b\bar{b}\gamma\gamma$$

HIGGS BOSON PAIR PRODUCTION

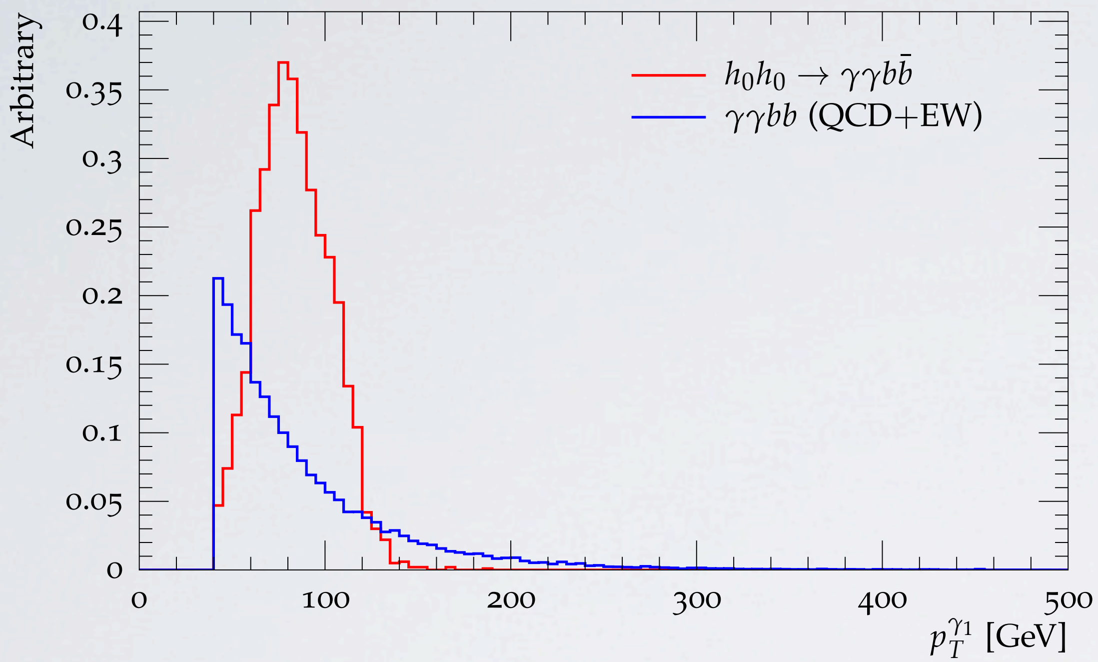
$$pp \to h_0 h_0 \to b\bar{b}\gamma\gamma$$

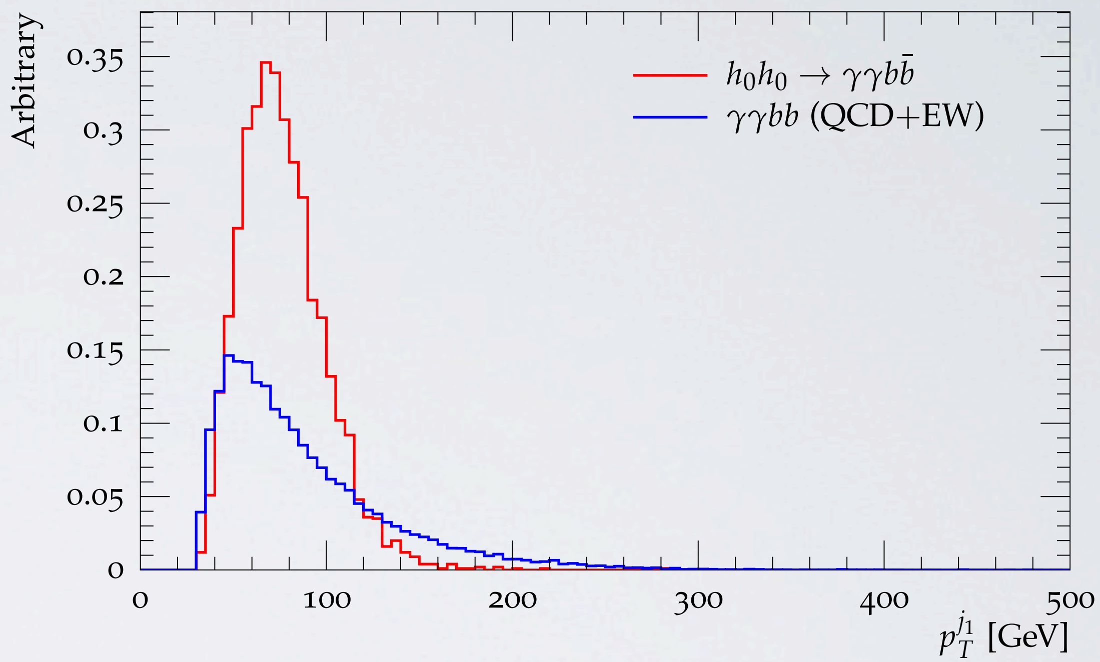
- Cut 1: Two isolated photons.
- Cut 2: Two kt jets.
- Cut 3: At least one b-tagged jet.
- Cut 4: $|M_{\gamma\gamma} - m_{h_0}| \leq 2$ GeV
- Cut 5: $|M_{bj} - m_{h_0}| \leq 20$ GeV
- Cut 6: $|M_{bj\gamma\gamma} - m_{\tilde{h}_0}| \leq \delta m_{\tilde{h}_0}$

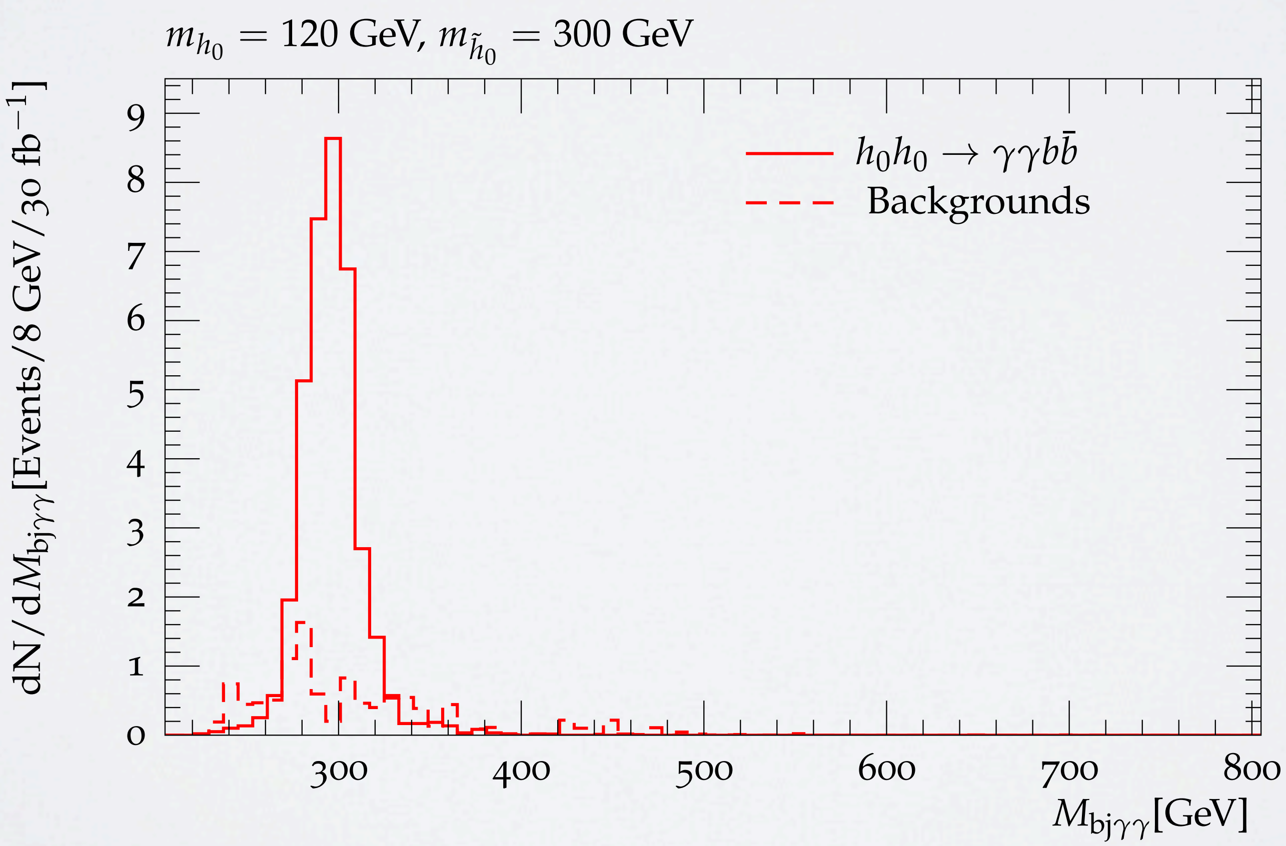
Cuts inspired by radion studies performed by ATLAS and CMS.
A more detailed description of cuts is in our paper.

HIGGS BOSON PAIR PRODUCTION

$$pp \to h_0 h_0 \to b\bar{b}\gamma\gamma$$







HIGGS BOSON PAIR PRODUCTION

Benchmark	m_{h_0}(GeV)	$m_{\tilde{h}_0}$(GeV)	$\delta m_{\tilde{h}_0}$(GeV)
(a)	120	300	40
(b)	130	445	45
(c)	130	550	50

$$pp \to h_0 h_0 \to b\bar{b}\gamma\gamma$$

	QCD+EW:	$\gamma\gamma jj$	$\gamma\gamma bb$	$\gamma\gamma cc$	$\gamma\gamma bc$	$\gamma\gamma bj$	$\gamma\gamma cj$
	σ_{gen}(pb)	23.2	0.176	1.56	0.0840	0.519	6.26
	cut 1	0.390	0.370	0.306	0.295	0.344	0.354
	cut 2	0.363	0.358	0.386	0.435	0.406	0.366
	cut 3	0.0526	0.795	0.116	0.516	0.460	0.0920
	cut 4a	0.0212	0.0233	0.0247	0.0217	0.0240	0.0200
	cut 5a	0.249	0.229	0.232	0.242	0.264	0.203
	cut 6a	0.604	0.547	0.713	0.534	0.471	0.627
	ϵ_{tot}	2.37×10^{-5}	3.07×10^{-4}	5.60×10^{-5}	1.85×10^{-4}	1.93×10^{-4}	3.03×10^{-5}
(a)	σ_{eff}(fb)	0.550	0.0527	0.0873	0.0156	0.100	0.190
	cut 4b	0.0150	0.0202	0.0139	0.0167	0.0221	0.0191
	cut 5b	0.221	0.213	0.174	0.242	0.234	0.276
	cut 6b	0.136	0.0567	0.129	0.138	0.165	0.130
	ϵ_{tot}	3.37×10^{-6}	2.56×10^{-5}	6.14×10^{-6}	3.67×10^{-5}	5.46×10^{-5}	8.06×10^{-6}
(b)	σ_{eff}(fb)	0.0782	0.00431	0.00959	0.00309	0.0283	0.0505
	cut 4c	0.0150	0.0213	0.0199	0.0167	0.0221	0.0191
	cut 5c	0.221	0.213	0.174	0.242	0.234	0.274
	cut 6c	0.00723	0.0337	0.00289	0.0164	0.0303.	0.0.0122
	ϵ_{tot}	1.79×10^{-7}	1.52×10^{-5}	1.38×10^{-8}	4.36×10^{-6}	1.00×10^{-5}	7.58×10^{-7}
(c)	σ_{eff}(fb)	0.00414	0.00261	2.15×10^{-5}	0.000366	0.00521	0.00475

HIGGS BOSON PAIR PRODUCTION

Benchmark	m_{h_0}(GeV)	$m_{\tilde{h}_0}$(GeV)	$\delta m_{\tilde{h}_0}$(GeV)
(a)	120	300	40
(b)	130	445	45
(c)	130	550	50

$$pp \to h_0 h_0 \to b\bar{b}\gamma\gamma$$

$pp \to h_0 Z \to \gamma\gamma b\bar{b}$	(a) $m_{h_0} = 120$ GeV, $m_{\tilde{h}_0} = 300$ GeV
$\sigma_{\rm gen}$(fb)	32.3
cut 1	0.745
cut 2	0.489
cut 3	0.772
cut 4	0.999
cut 5	0.184
cut 6	0.422
$\epsilon_{\rm tot}$	0.0218
$\sigma_{\rm eff}$(fb)	0.703

$pp \to h_0 h_0 \to \gamma\gamma b\bar{b}$	(a)	(b)	(c)
$\sigma_{\rm gen}$(fb)	11.2	0.964	0.195
cut 1	0.594	0.675	0.693
cut 2	0.414	0.405	0.391
cut 3	0.734	0.760	0.748
cut 4	0.999	0.999	0.999
cut 5	0.601	0.567	0.586
cut 6	0.966	0.823	0.725
$\epsilon_{\rm tot}$	0.105	0.097	0.0861
$\sigma_{\rm eff}$(fb)	1.18	0.0935	0.0168

HIGGS BOSON PAIR PRODUCTION

Benchmark	m_{h_0}(GeV)	$m_{\tilde{h}_0}$(GeV)	$\delta m_{\tilde{h}_0}$(GeV)
(a)	120	300	40
(b)	130	445	45
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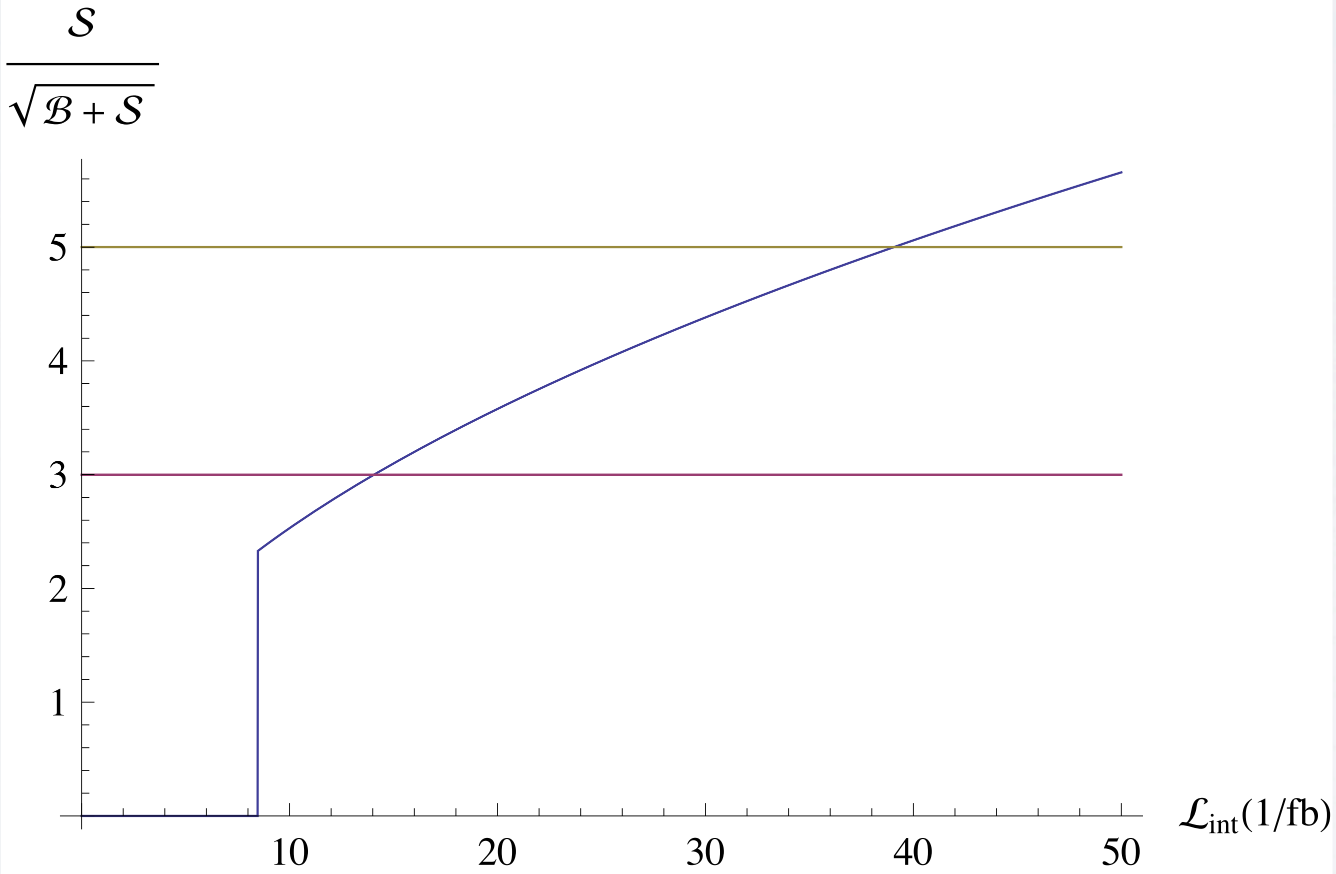
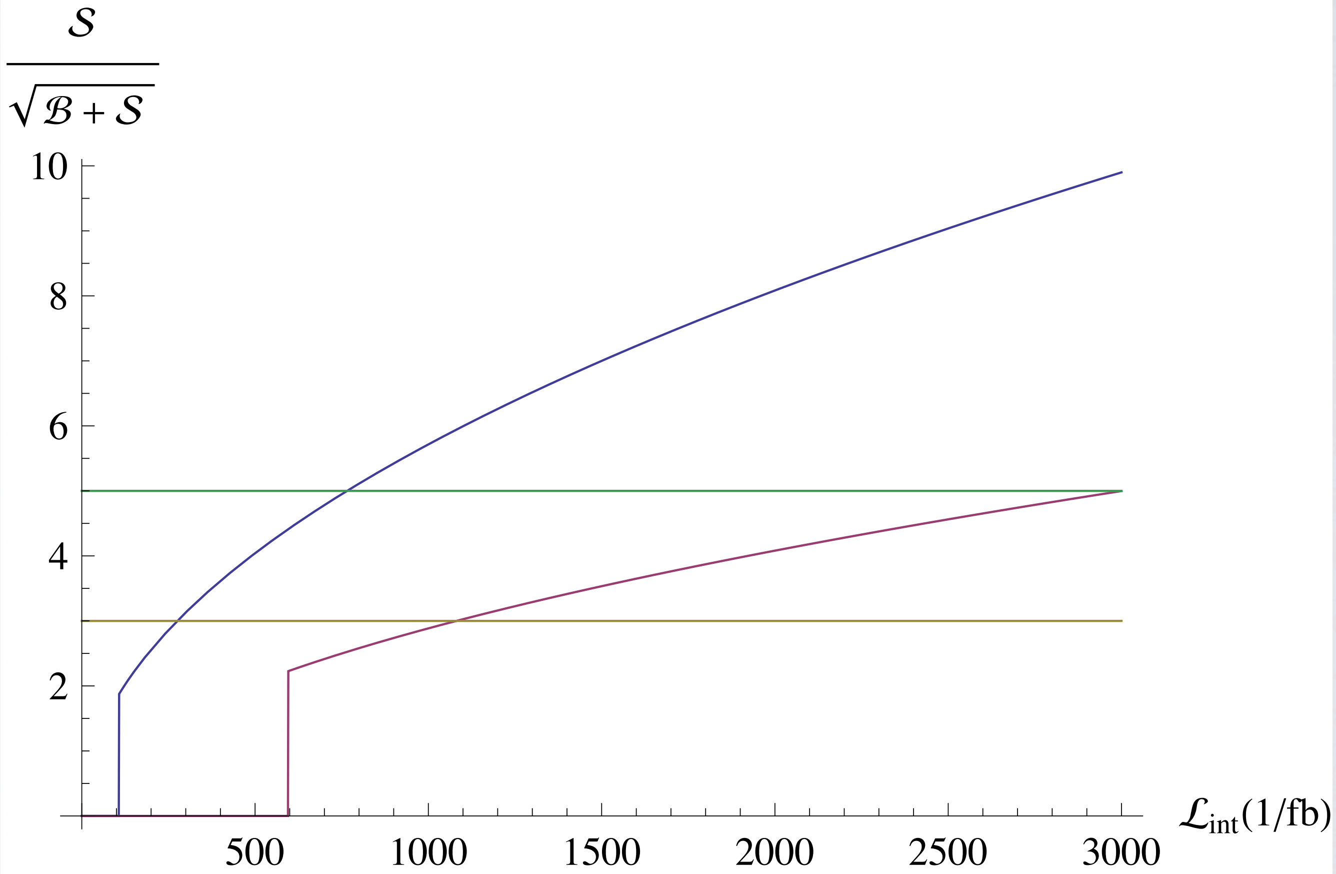
$$pp \to h_0 h_0 \to b\bar{b}\gamma\gamma$$





INTERFERENCE EFFECTS IN TOP PAIR PRODUCTION

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

D.Dicus, A. Strange, and S. Willenbrock

$$\frac{d\hat{\sigma}}{ds}(gg \to \bar{t}t)|_{\text{interference}} = -|c(s)|\text{Re}\left[\frac{l_\triangle}{s - m_R^2 + im_R\Gamma_R}\right]$$
$$= -|\tilde{c}(s)|\left((s - m_R^2)\text{Re}[l_\triangle] + m_R\Gamma_R\text{Im}[l_\triangle]\right)$$

$l_\triangle = l_\triangle(s/4m_t^2)$ loop triangle function

1. If there is no loop function there will be a peak-dip.
2. For a scalar or pseudo-scalar resonance this pattern does not change.

INTERFERENCE EFFECTS IN TOP PAIR PRODUCTION

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

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

$$= -|\tilde{c}(s)|\left(-(s-m_R^2)\mathrm{Re}[l_{\triangle}] + m_R\Gamma_R\mathrm{Im}[l_{\triangle}]\right)$$

Sign-flip in the LW case

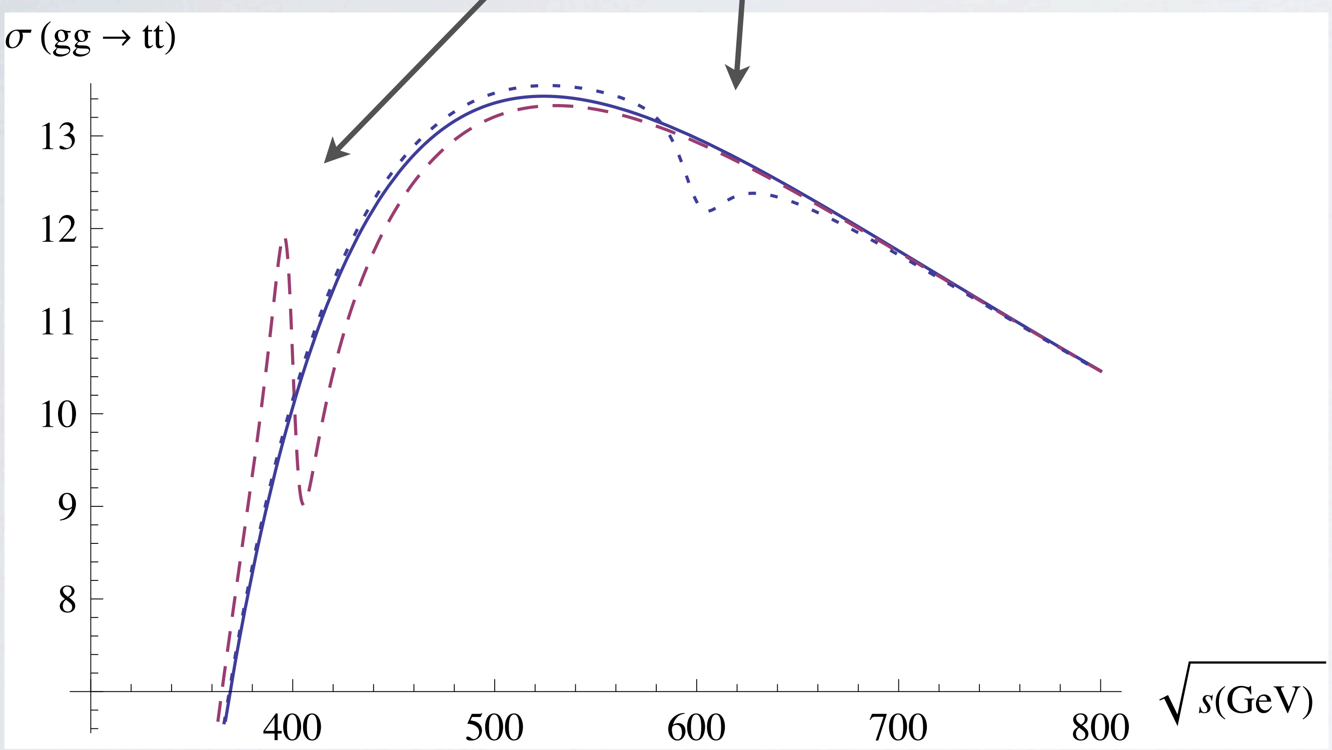
$$\mathcal{M}_R^2 = m_R^2 + \frac{\mathrm{Im}[l_{\triangle}]}{\mathrm{Re}[l_{\triangle}]} m_R\Gamma_R$$

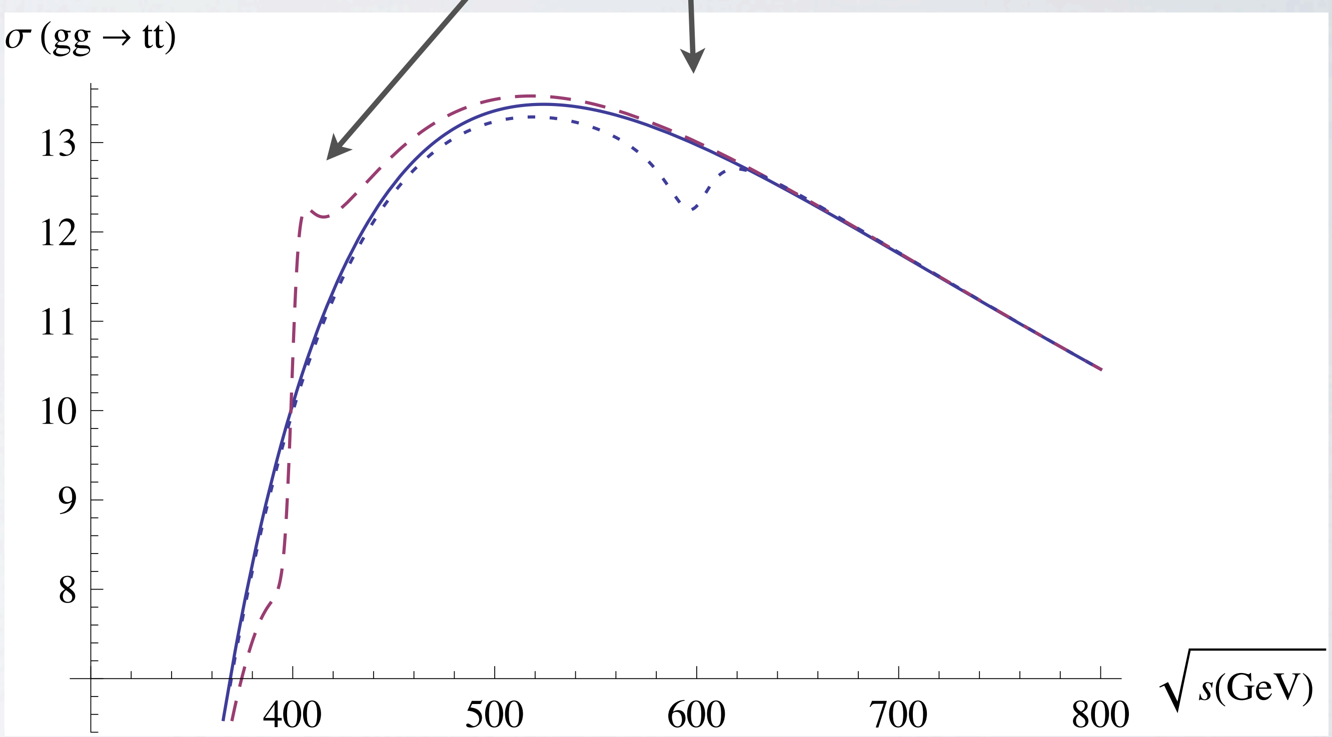
Dip-peak structure

INTERFERENCE EFFECTS IN TOP PAIR PRODUCTION

Peak-dip

Dip-peak

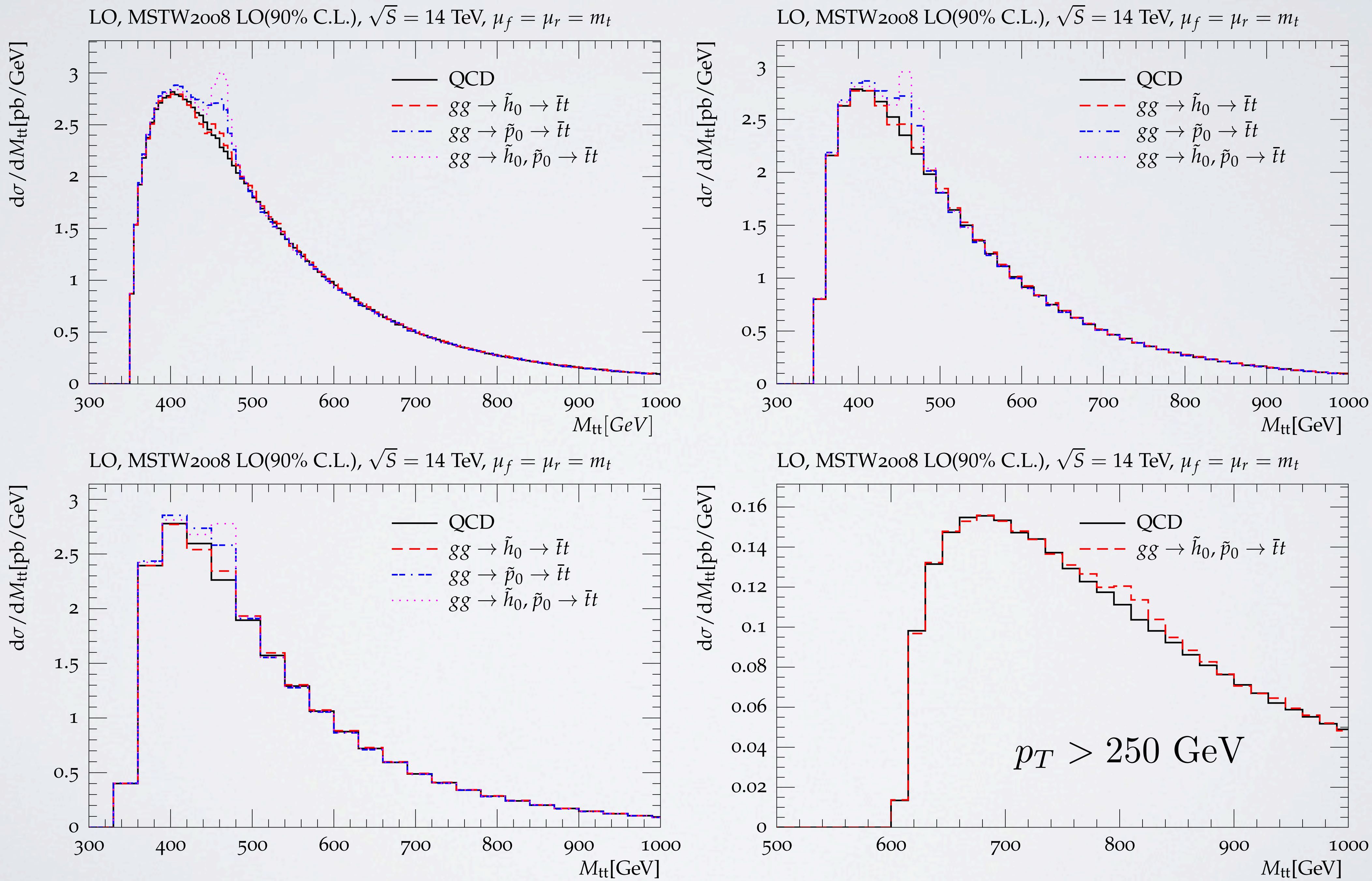




Usual resonance

Lee-Wick type resonance

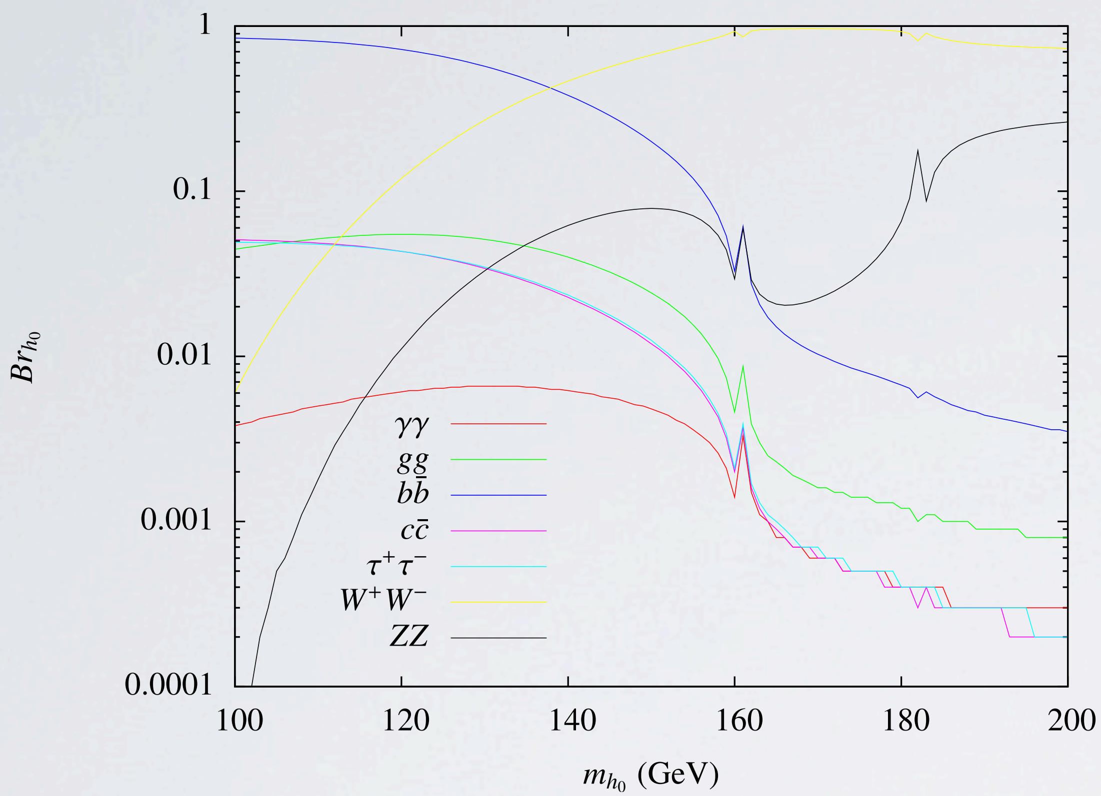
Top pair invariant mass spectrum

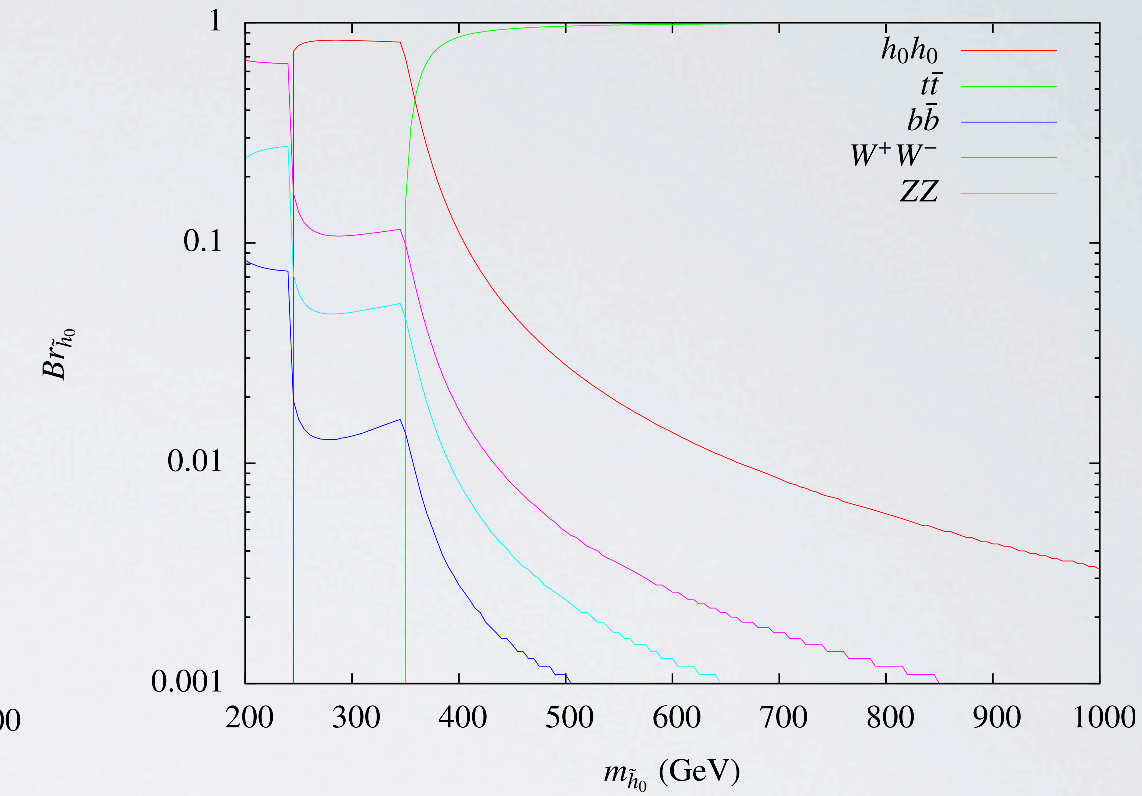


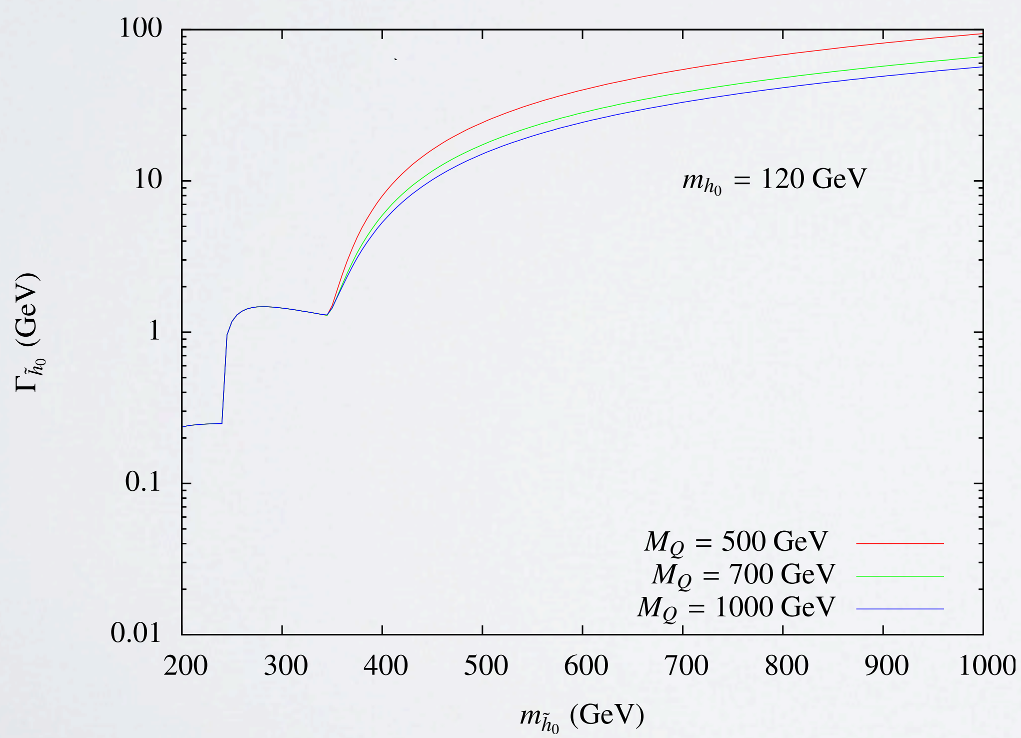
CONCLUSIONS

- LW Gauge bosons and LW fermions are constrained to be in the few TeV range by EWPO and di-lepton 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







Higgs to two photons

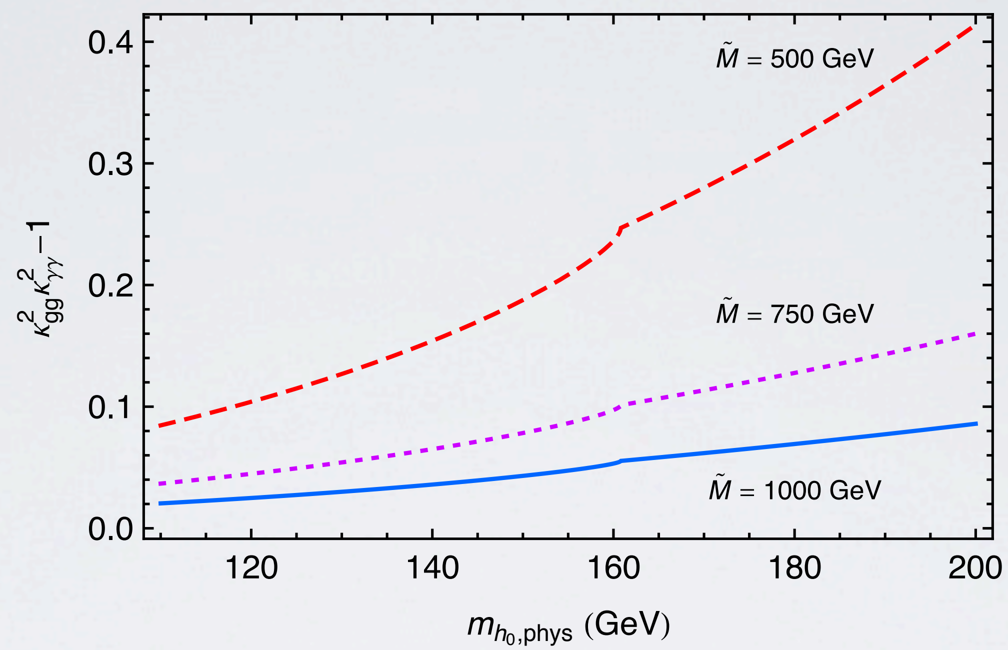


Figure 4: *The relative change in the cross-section times decay rate for the full process* $gg \to h_0 \to \gamma\gamma$ *in the LWSM, expressed as* $|\kappa_{gg}|^2|\kappa_{\gamma\gamma}|^2 - 1$*, plotted as a function of* $m_{h_0,\mathrm{phys}}$*. Lee-Wick mass scales are such that* $M_Q = M_u = m_{\tilde{h},\mathrm{phys}}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

F.Krauss, T.E.J Underwood, R. Zwicky: **arXiv 0709.4054**