Hiding a Heavy Higgs Boson

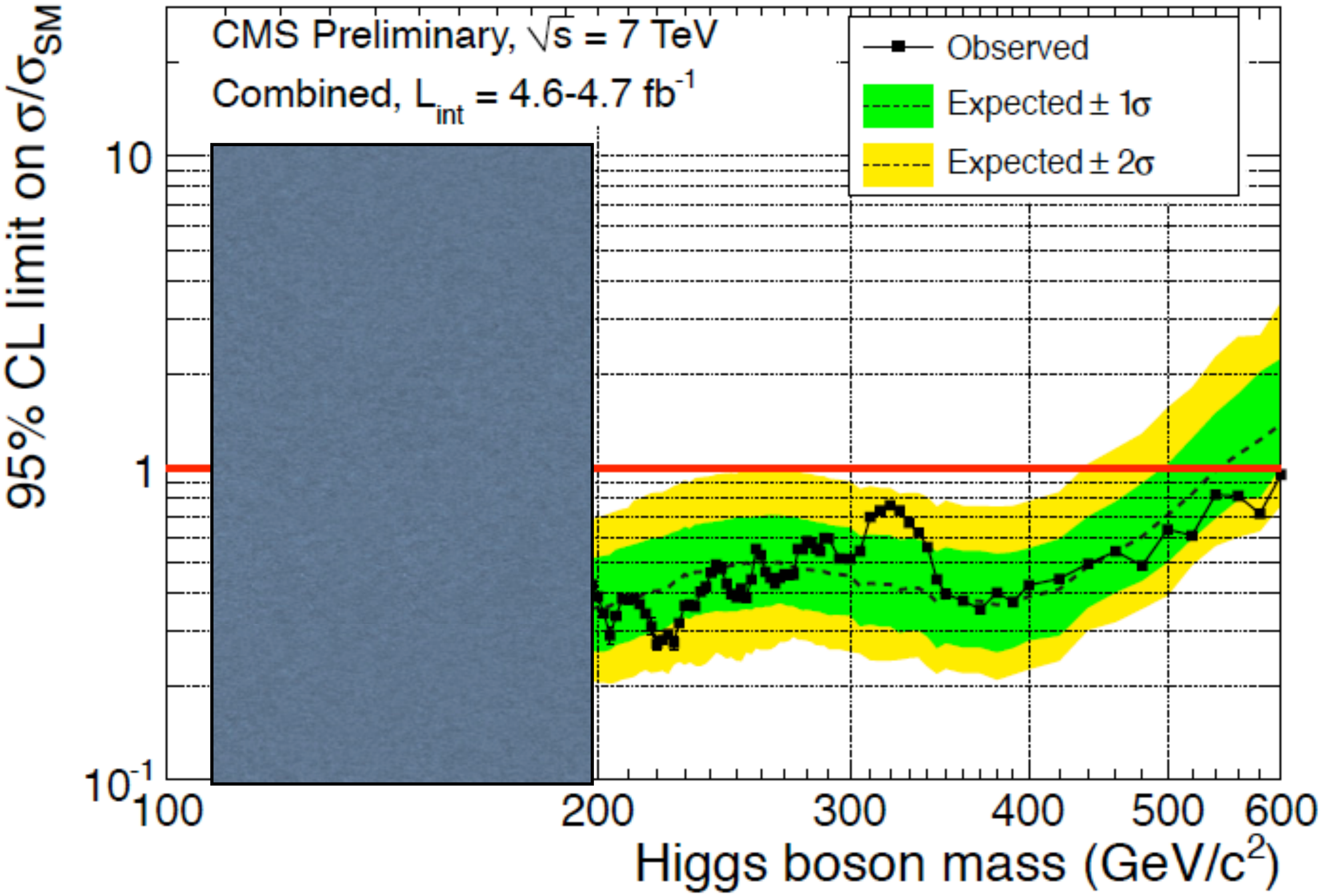
Yang Bai

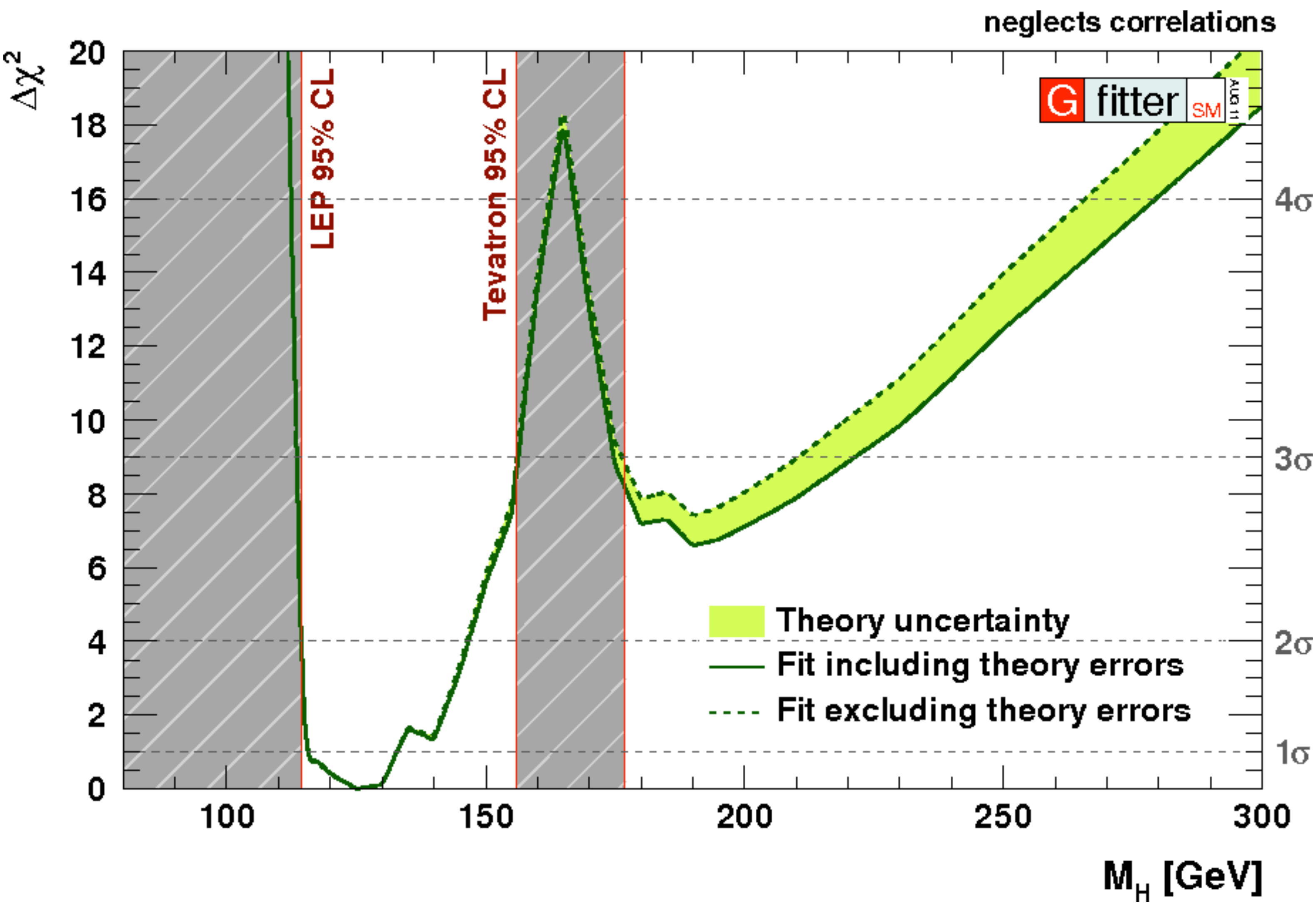
Theoretical Physics Group, SLAC

TRIUMF Workshop on LHC Results
Dec. 15, 2011

with JiJi Fan and JoAnne L. Hewett

arXiv:1112.1964


CMS Preliminary, √s = 7 TeV
Combined, L_int = 4.6-4.7 fb^-1
Observed
Expected ± 1σ
Expected ± 2σ
95% CL limit on σ/σ_SM
10
1
10^-1
100
200
300
400
500
600
Higgs boson mass (GeV/c^2)

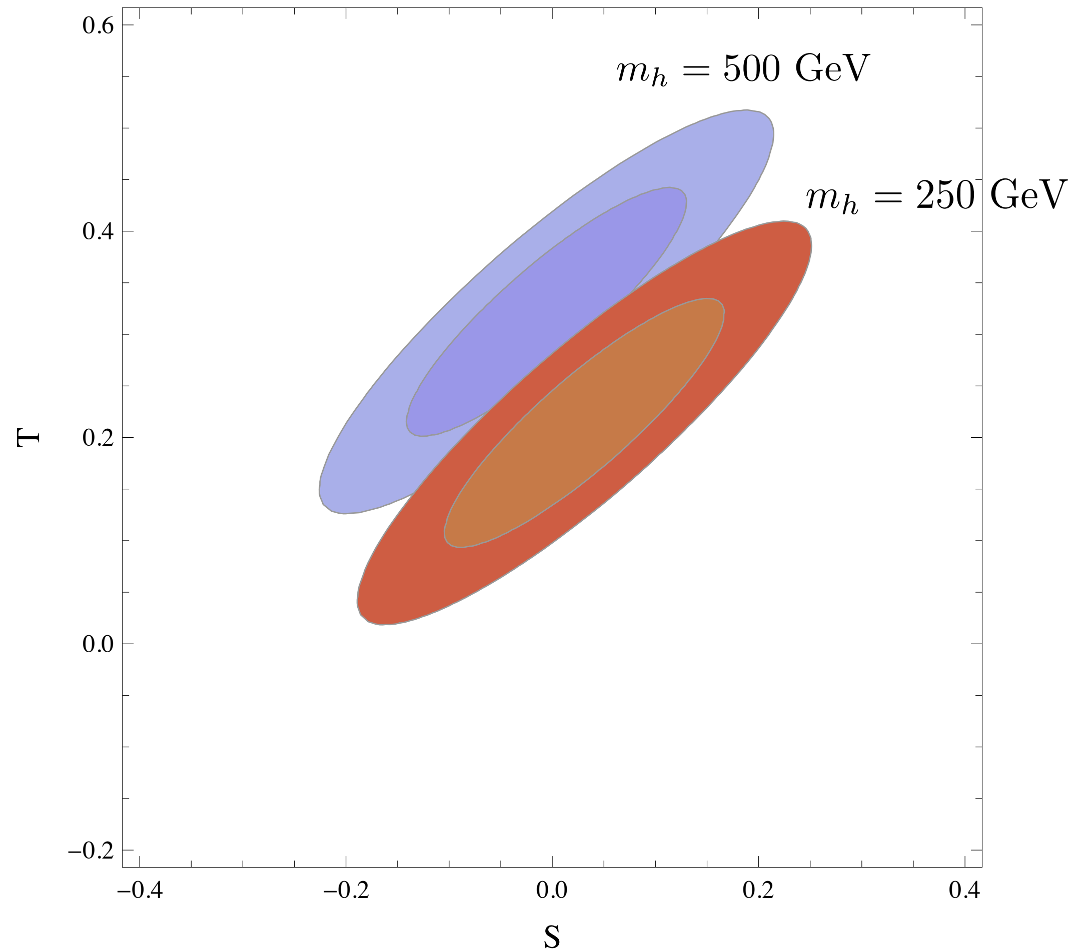


A heavy Higgs boson with a mass above 200 GeV is not consistent with electroweak precision observables

Motivation

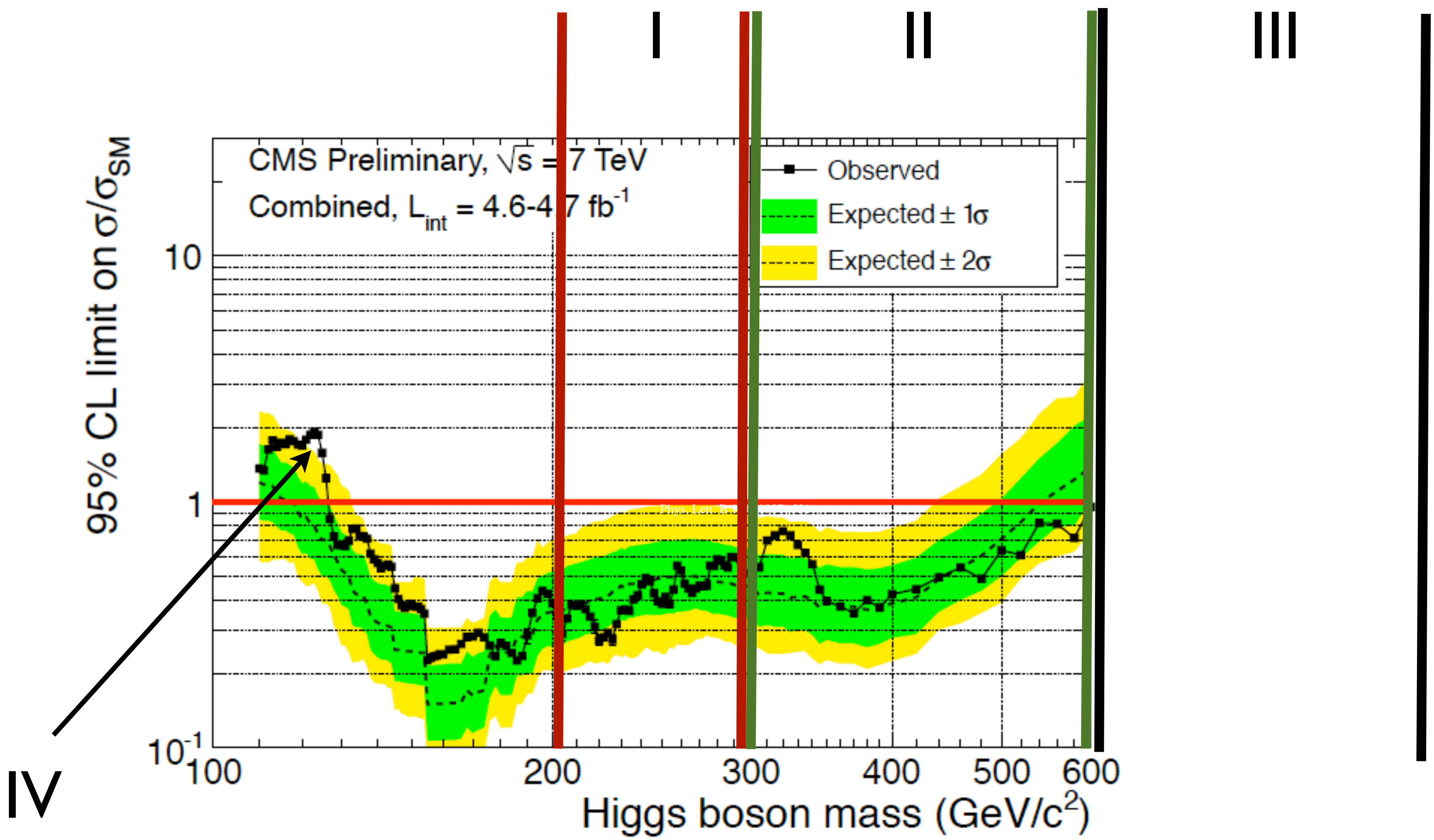
Introduce a new particle to simultaneously make a heavy Higgs boson consistent with both the indirect constraints and the direct null searches

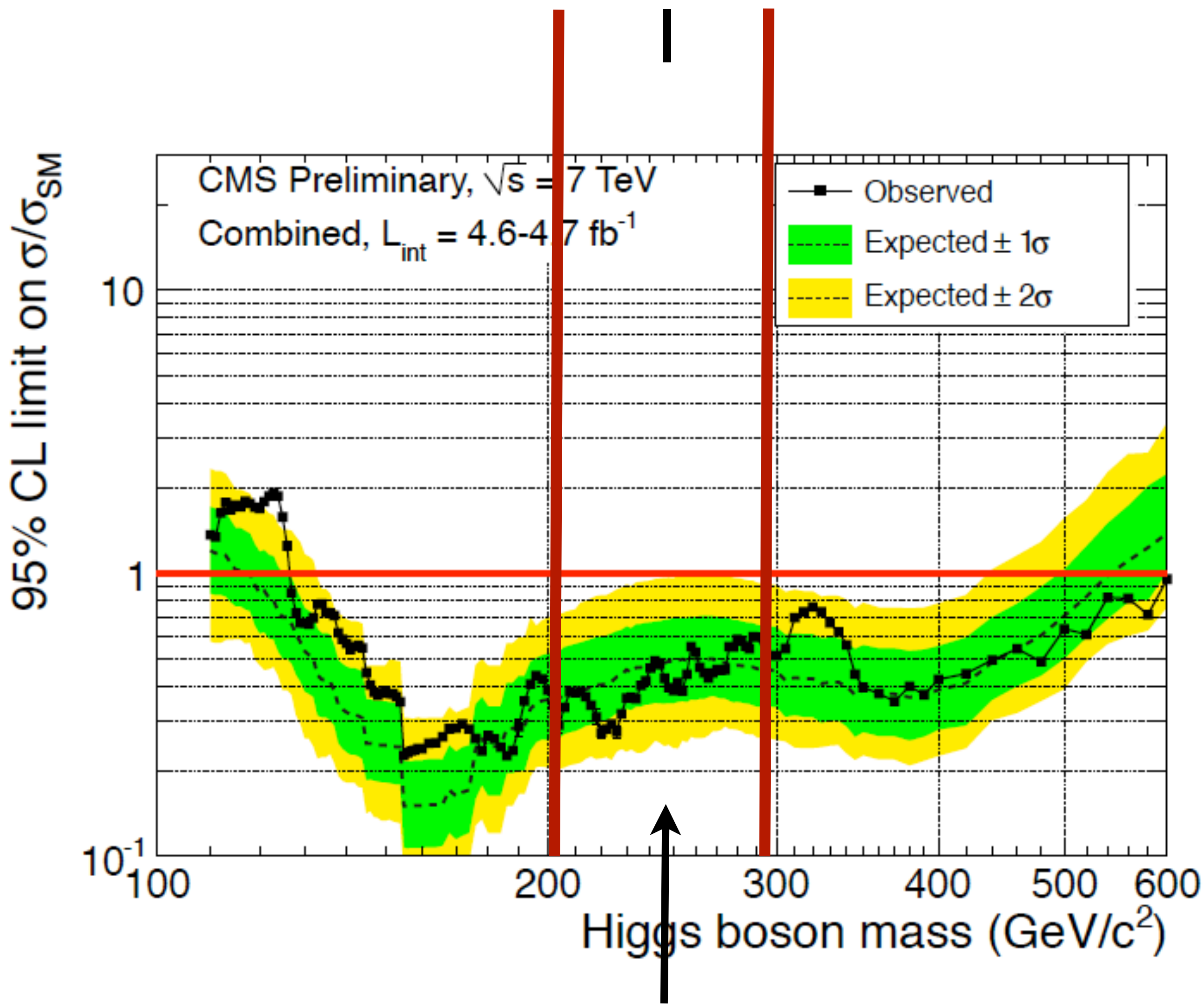
See what the implications are at the LHC and how to look for these new particles



New physics should have a positive contribution to T and a negative contribution to S

Outline


I
II
III
IV
CMS Preliminary, √s = 7 TeV
Combined, L_int = 4.6-4.7 fb^-1
Observed
Expected ± 1σ
Expected ± 2σ
95% CL limit on σ/σ_SM
10
1
10^-1
100
200
300
400
500
600
Higgs boson mass (GeV/c^2)



Color singlet; weak double or triplet scalar

Higgs decays into the new particle

Color Singlet and weak doublet

$$V = -\mu_1^2|H|^2 + \mu_2^2|\Phi|^2 + \lambda_1|H|^4 + \lambda_2|\Phi|^4 + \lambda_3|H|^2|\Phi|^2 + \lambda_4|H^\dagger\Phi|^2 + \frac{\lambda_5}{2}\left[(H^\dagger\Phi)^2 + h.c.\right].$$

$$\Phi = (\phi^+,\ \phi^0)^T \quad (1,2)_{1/2}$$

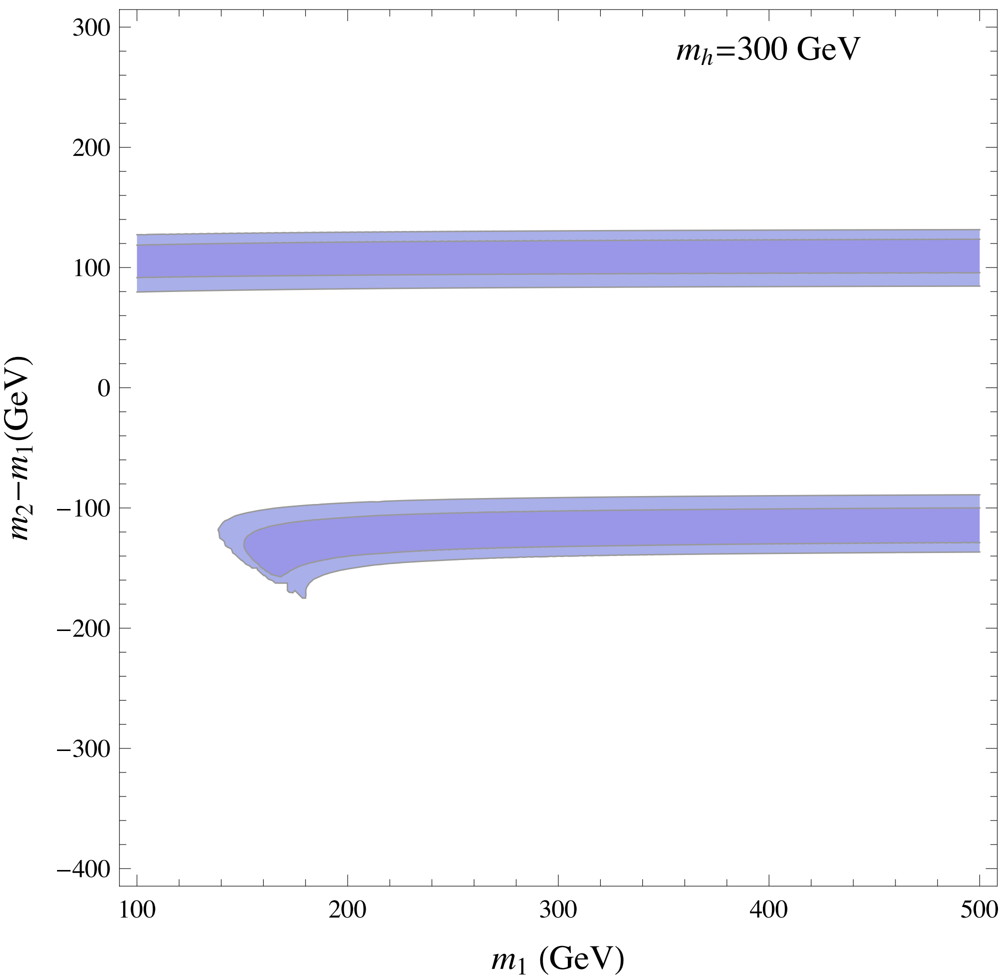
$$\lambda_{1,2} > 0; \quad \lambda_3,\ \lambda_3 + \lambda_4 - |\lambda_5| > -2\sqrt{\lambda_1\lambda_2}$$

$$\delta \equiv m_1 - m_2 = \sqrt{m_2^2 + \lambda_4\, v_{\rm EW}^2} - m_2$$

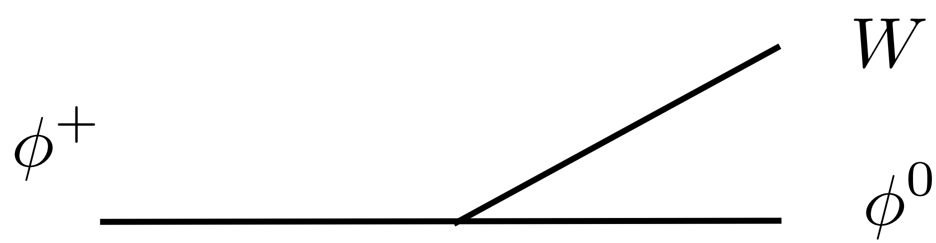
$$\Delta T = \frac{1}{8\pi s_W^2 M_W^2}\left[\frac{m_1^2 + m_2^2}{2} - \frac{m_1^2 m_2^2}{m_1^2 - m_2^2}\ln\left(\frac{m_1^2}{m_2^2}\right)\right]$$

$$\Delta S = -\frac{Y}{6\pi}\ln\left(\frac{m_2^2}{m_1^2}\right)$$

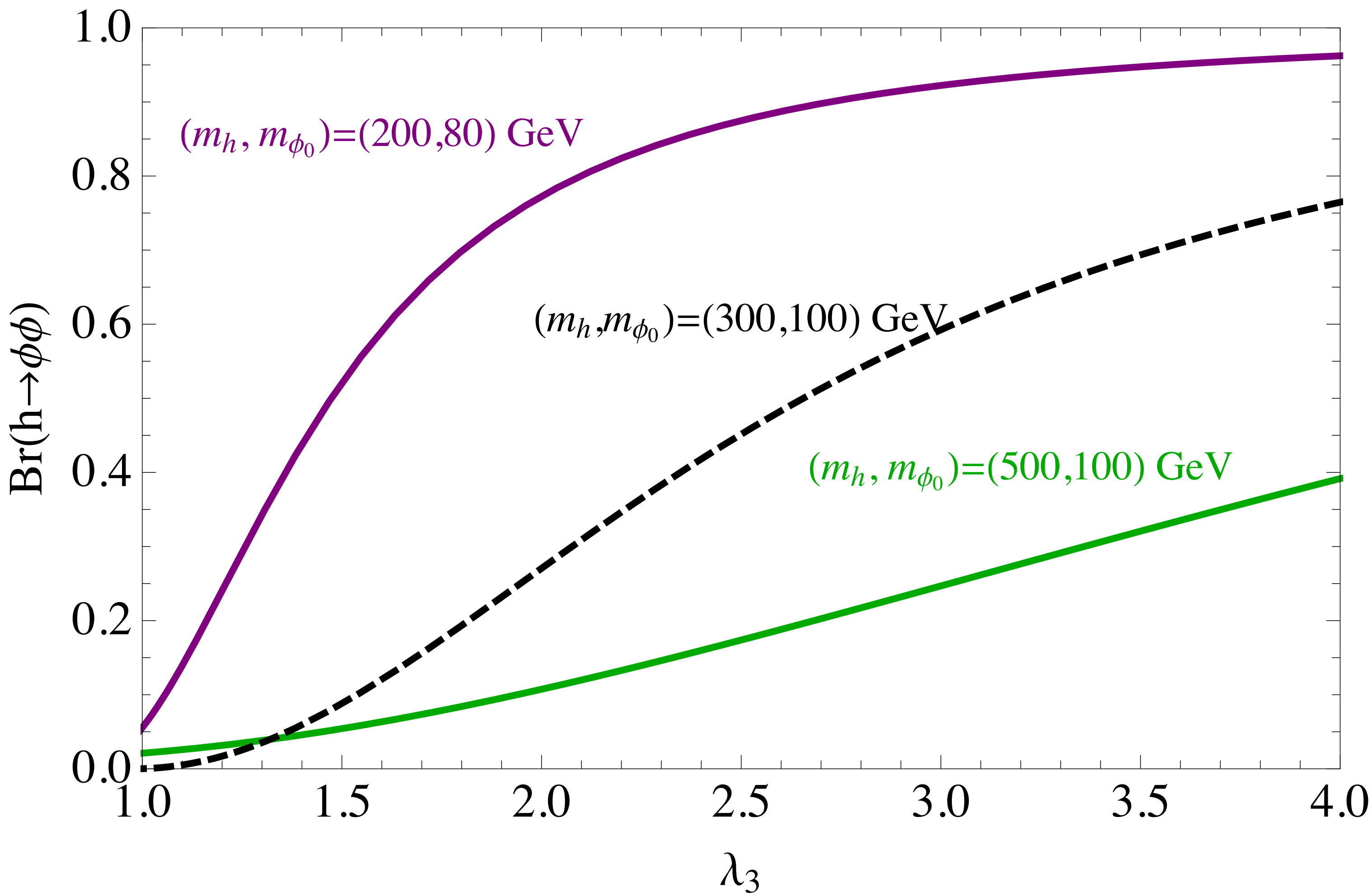
Barbieri, Hall, Rychkov,
hep-ph/0603188



m_h=300 GeV
300
200
100
0
−100
−200
−300
−400
m_2-m_1(GeV)
100
200
300
400
500
m_1 (GeV)



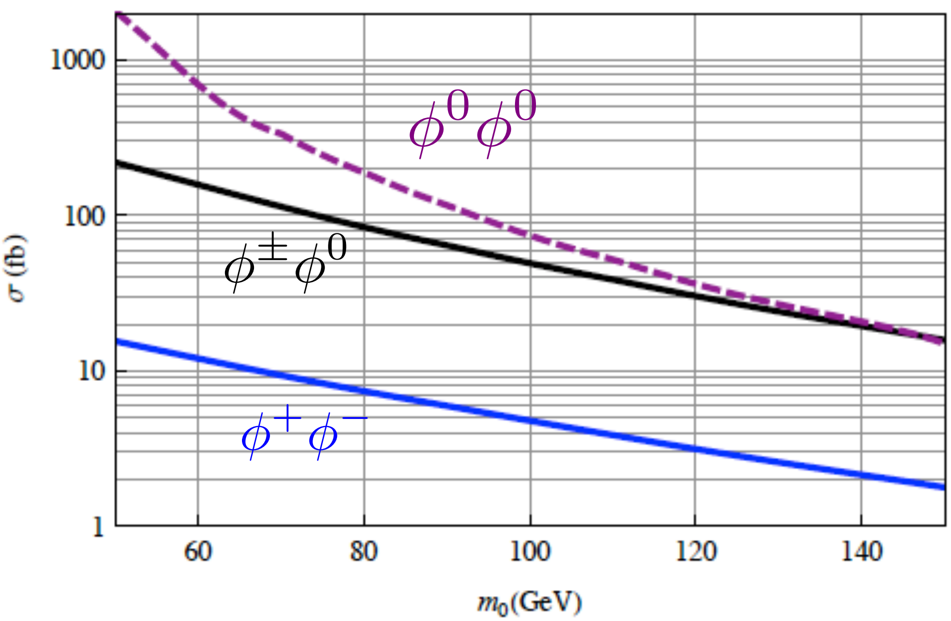
W
ϕ^+
ϕ^0



so the Higgs could be hided by the new decay channel

ϕ_0 is stable at the collider scale

- Dark matter: need to split the real and imaginary parts to forbid elastic scattering by the Z boson exchange
- Z boson decay: the mass should be above Mz/2
- Mono-photon constraints from LEP: Mz/2 is allowed



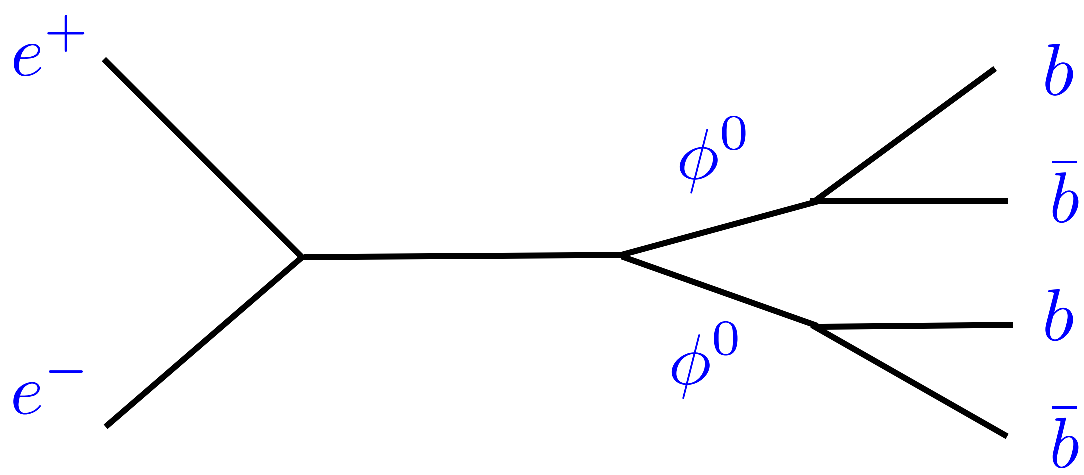
$$m_{\phi^+} - m_{\phi^0} = 100 \text{ GeV}$$

OS+MET does not constrain the parameter space

ϕ_0 decays into two fermions

$$\lambda_d \overline{Q}_L \Phi d_R + \lambda_u \overline{Q}_L \tilde{\Phi} u_R + \lambda_\ell \overline{L}_L \Phi e_R$$

- For the neutral scalar below twice of top quark, the main decay channel is into two bottom quarks

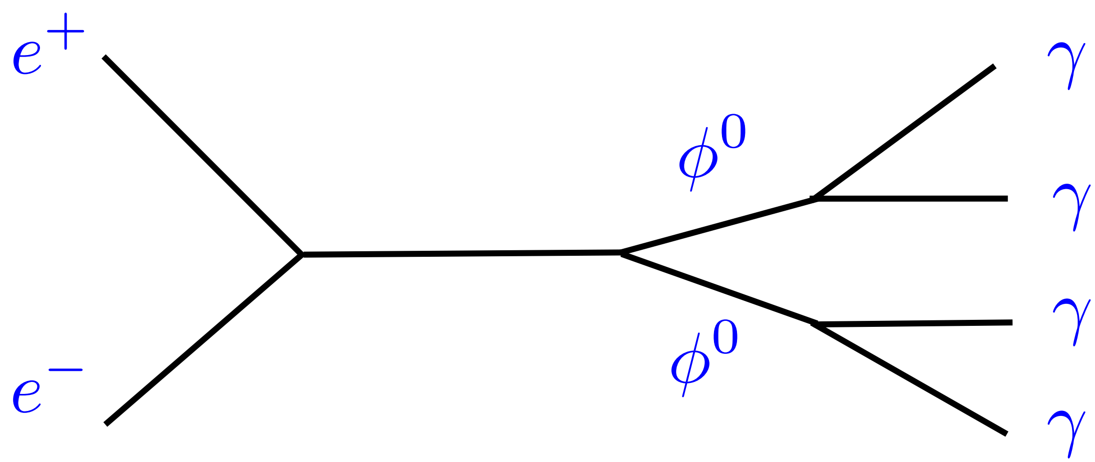


- DELPHI constrains the neutral scalar above 90 GeV

ϕ_0 decays into two gauge bosons

$$\frac{c_g(\Phi^\dagger H)G_A^{\mu\nu}G^A_{\mu\nu}}{\Lambda^2}+\frac{c_w(\Phi^\dagger H)W_a^{\mu\nu}W^a_{\mu\nu}}{\Lambda^2}+\frac{c_b(\Phi^\dagger H)B^{\mu\nu}B_{\mu\nu}}{\Lambda^2}+\frac{c_{wb}(\Phi^\dagger\sigma^a H)W^a_{\mu\nu}B^{\mu\nu}}{\Lambda^2}$$

- For the case that the neutral scalar decays into two photons



- LEPII constrains the neutral scalar above 90 GeV

What shall we look for?

	Relevant final states	Possible signals
ϕ_0 stable	MET, W + MET, W^+W^-+MET	mono-jet+MET, jets+MET, 1 l+MET
$\phi_0 \to 2b/g$'s	4 j, $W + 4j$, $W^+W^- + 4j$	4 j, W+j's, OS+MET, 1 l + b jets + MET
$\phi_0 \to 2\gamma/\gamma + Z$	nW's + mZ's + $l\gamma$'s	SS, multi-leptons, multi-photons, multi-jets

Table 1: A sample of collider signals from producing doublet Φ at hadron collider.

Where is the Higgs hided?

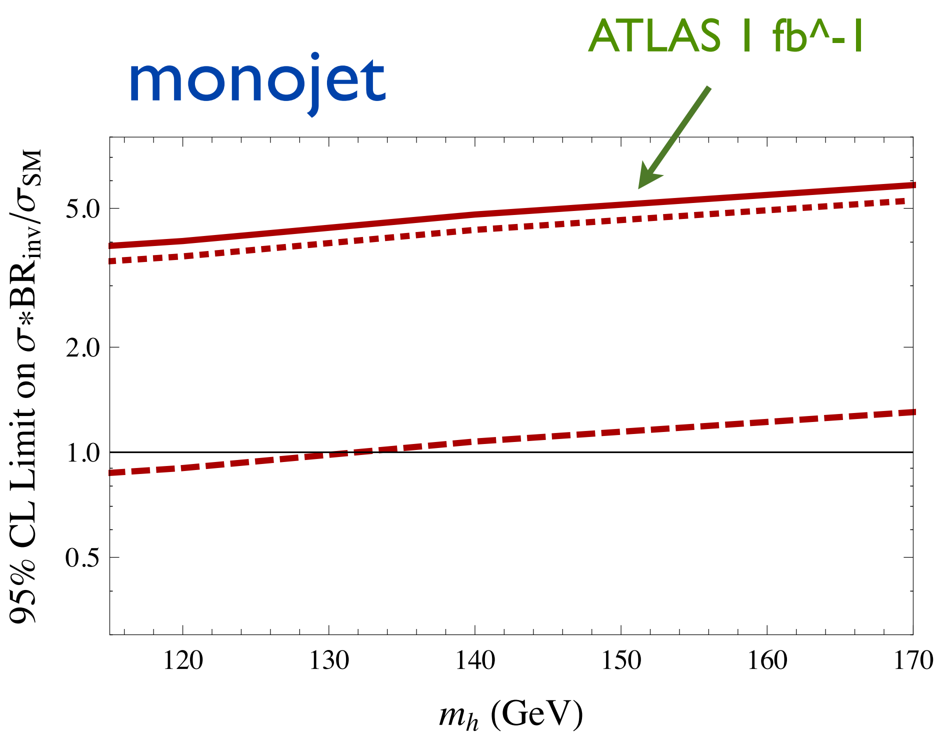
$$h \to \phi_0\phi_0 \to \text{missing } E_T$$

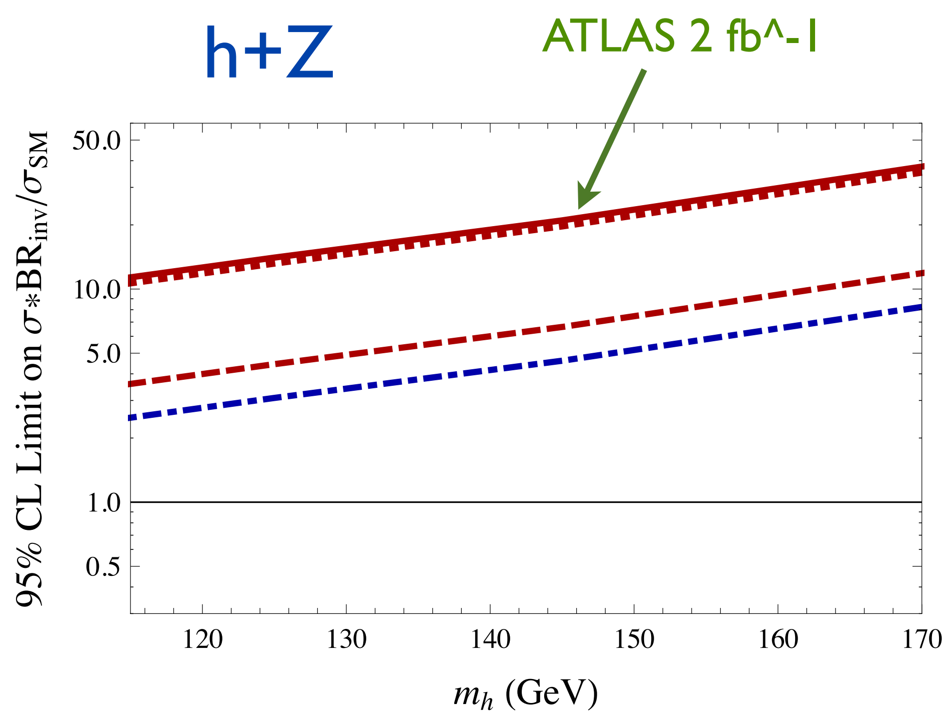
$$h \to \phi_0\phi_0 \to 4b, 4g$$

$$h \to \phi_0\phi_0 \to 4\gamma, 2Z + 2\gamma$$

Invisible Higgs decay

to appear,
YB, Draper, Shelton



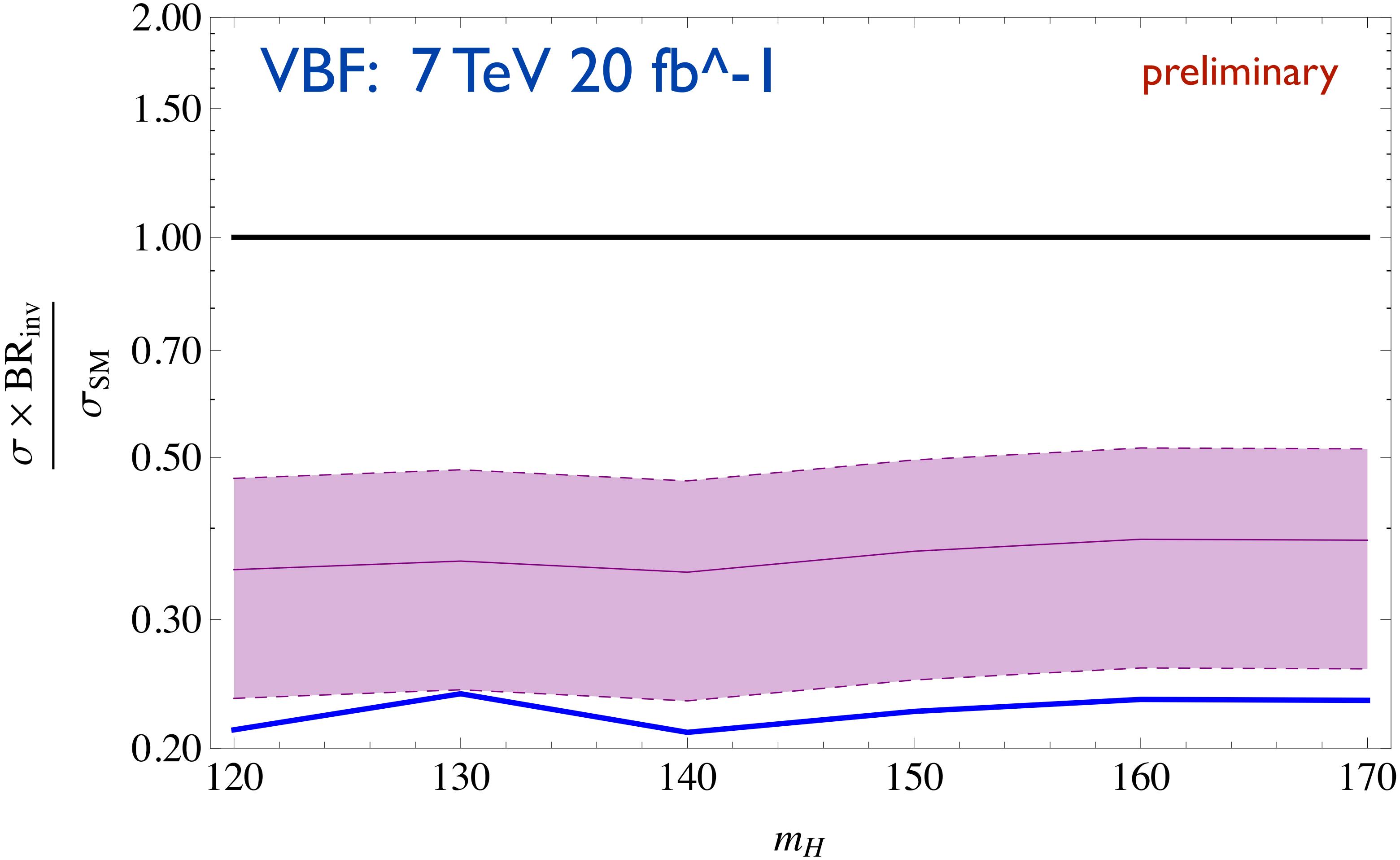


see Roni Harnik's talk for the dark matter interpretation

Invisible Higgs decay

to appear,
YB, Draper, Shelton

see early study at 14 TeV: Davoudiasl, Han, Logan; hep-ph/0412269



Color Singlet and weak triplet

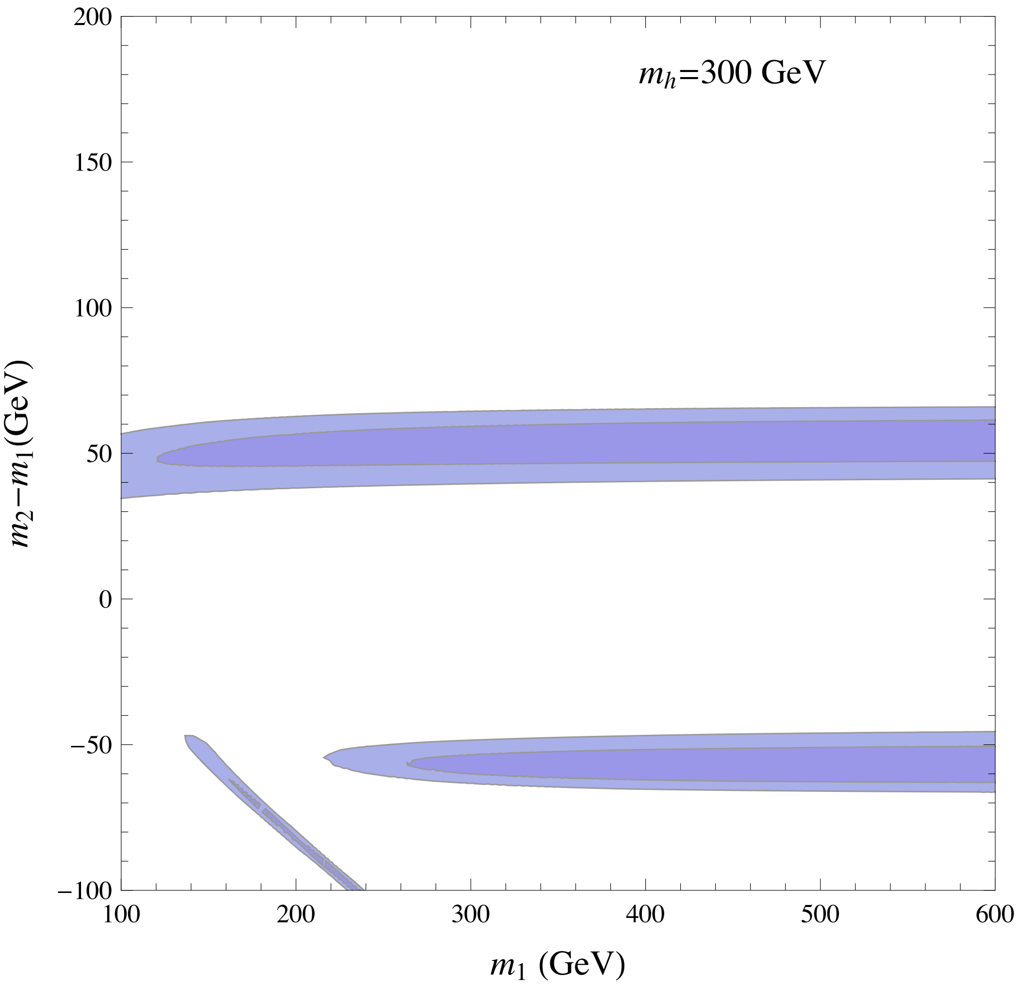
$$V = \mu_1 |H|^2 + \mu_2 |\Phi|^2 + \lambda_1 |H|^4 + \lambda_2 |\Phi|^4 + \lambda_3 |H|^2 |\Phi|^2 + \lambda_4 (\Phi^\dagger t^a \Phi)^2 + \lambda_5 (H^\dagger \tau_a H)(\Phi^\dagger t^a \Phi)$$

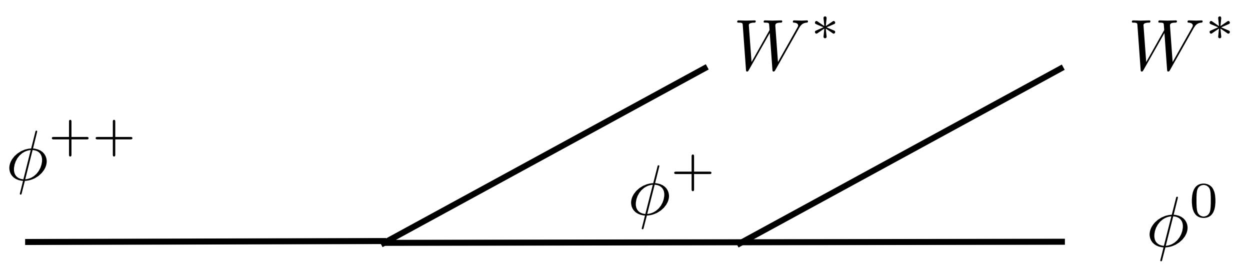
$$\Phi = (\phi^{++},\, \phi^{+},\, \phi^{0})^T \qquad (1,3)_1$$

$$m_3^2 = m_1^2 + 2\Delta^2\,, \quad \text{and} \quad m_2^2 = m_1^2 + \Delta^2$$

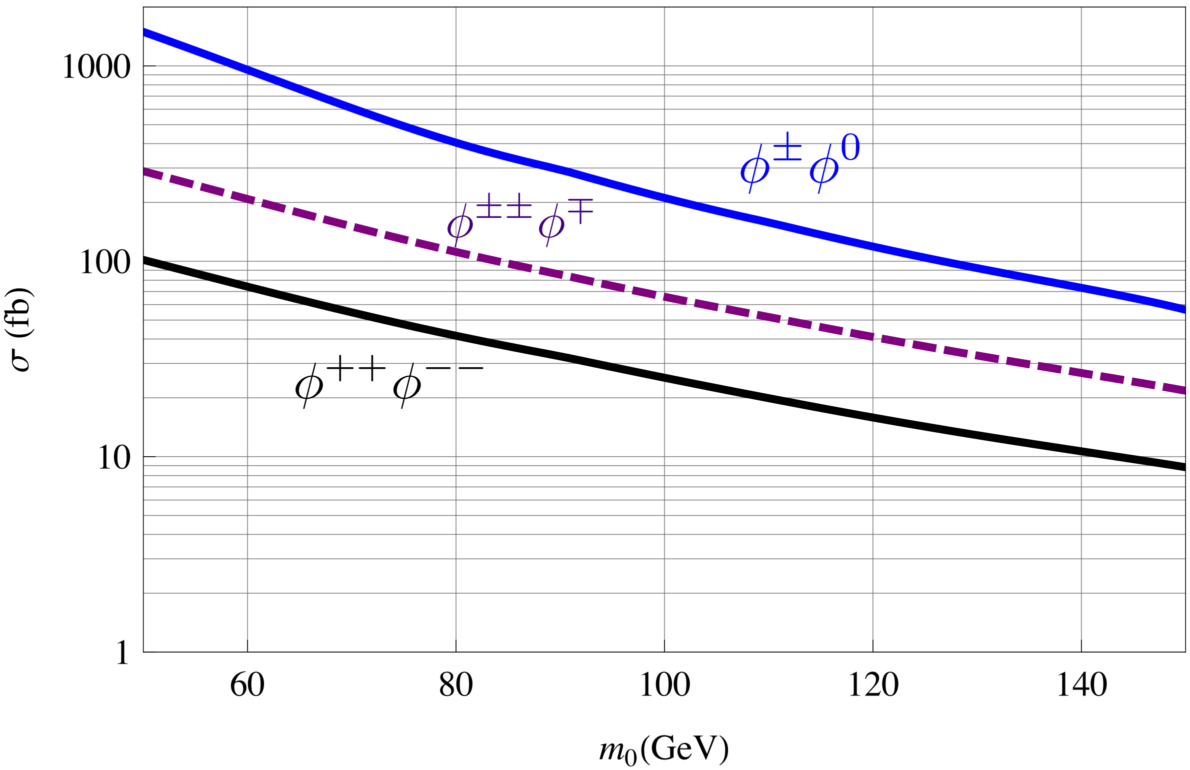
$$T = \frac{(m_1^2+\Delta^2)\left\{\Delta^2\left[1-\ln\left(\frac{m_1^2+2\Delta^2}{m_1^2+\Delta^2}\right)\right] - m_1^2\,\tanh^{-1}\left(\frac{\Delta^2}{m_1^2+\Delta^2}\right)\right\}}{2\pi s_W^2 M_W^2 \Delta^2}$$

$$S = -\frac{Y}{3\pi}\ln\left(\frac{m_3^2}{m_1^2}\right)$$





same-sign leptons

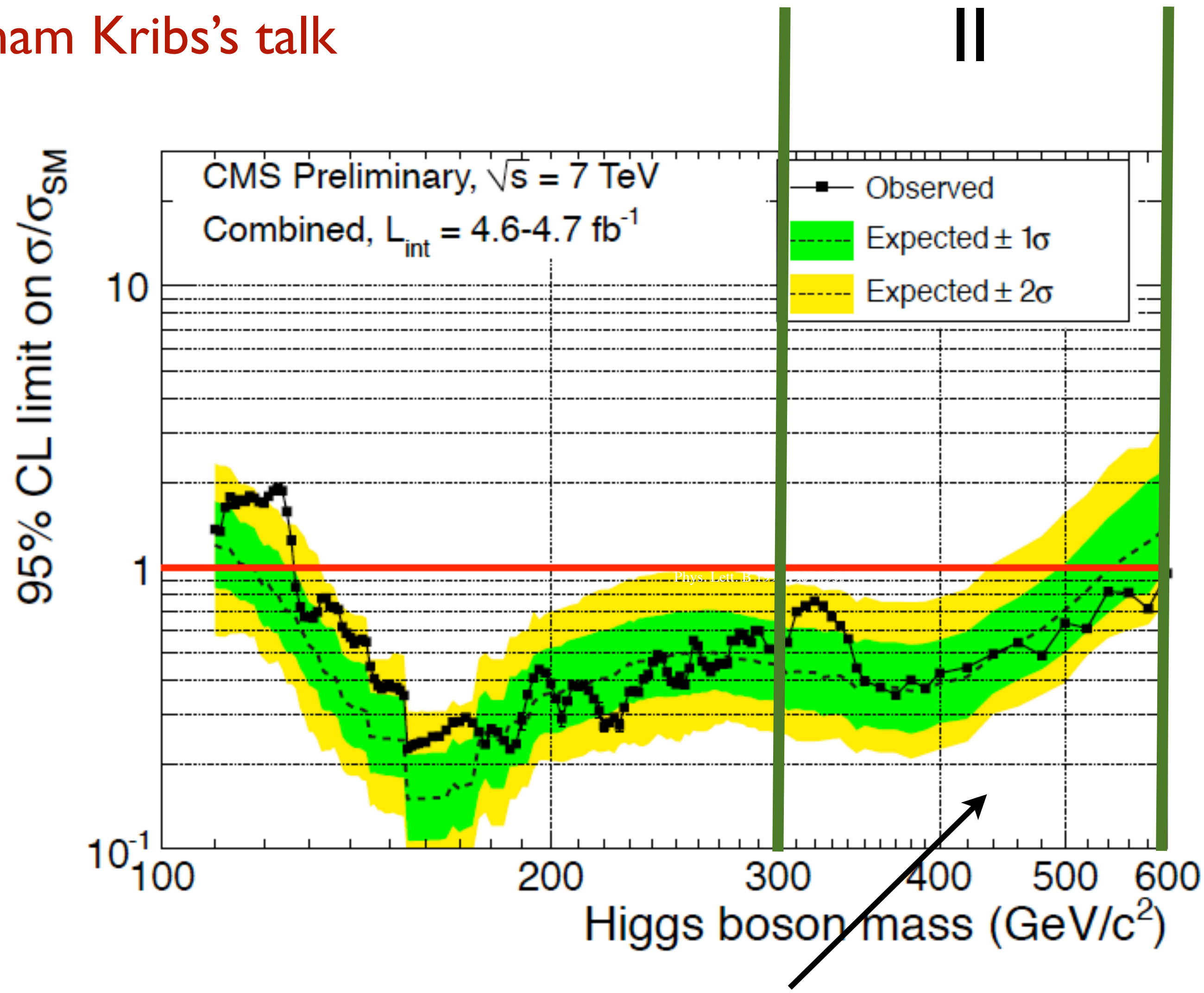


$m_{\phi^+} - m_{\phi^0} = 50$ GeV

	Relevant final states	Possible signals
ϕ_0 stable	MET, nW's + MET,	mono-jet+MET, OS+MET, SS+MET, multi-leptons, multi-jets
$\phi_0 \to 2b/g$'s	4 j, W's+ $4j$,	OS+MET, SS+MET, multi-leptons, multi-jets
$\phi_0 \to 2\gamma/\gamma + Z$	nW's + mZ's + $l\gamma$'s	multi-photons, OS+MET, SS+MET, multi-leptons, multi-jets

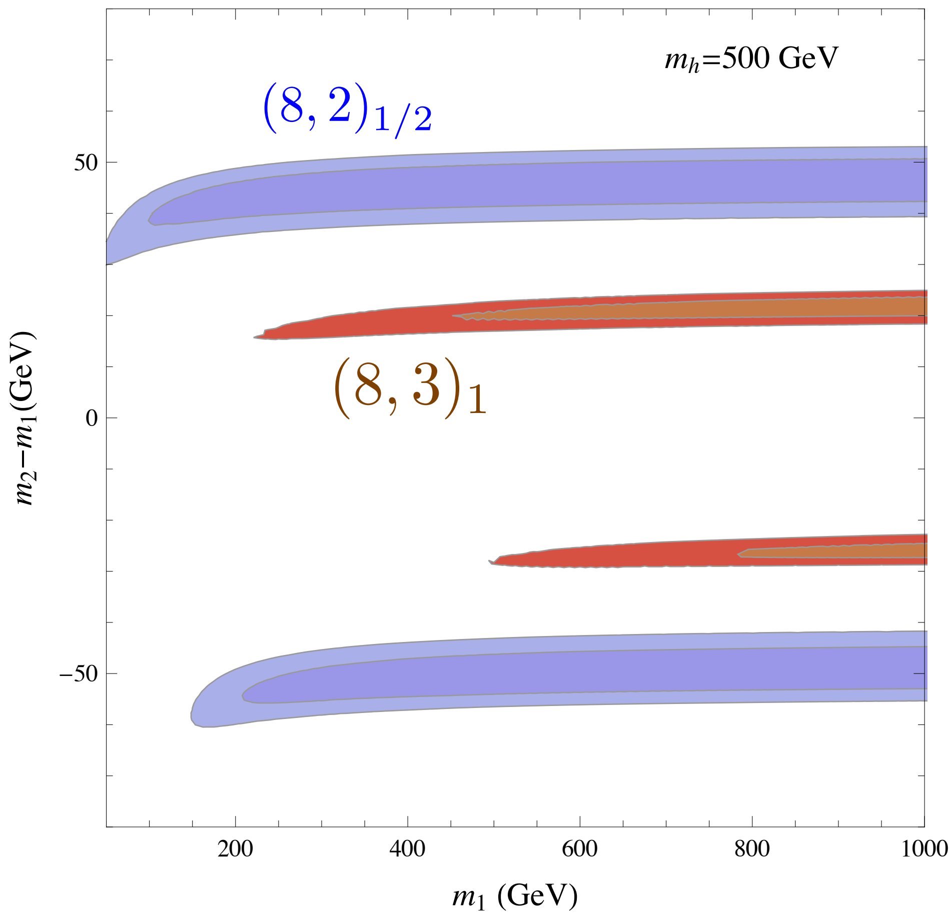
the current SS dilepton searches are not sensitive

See Graham Kribs's talk

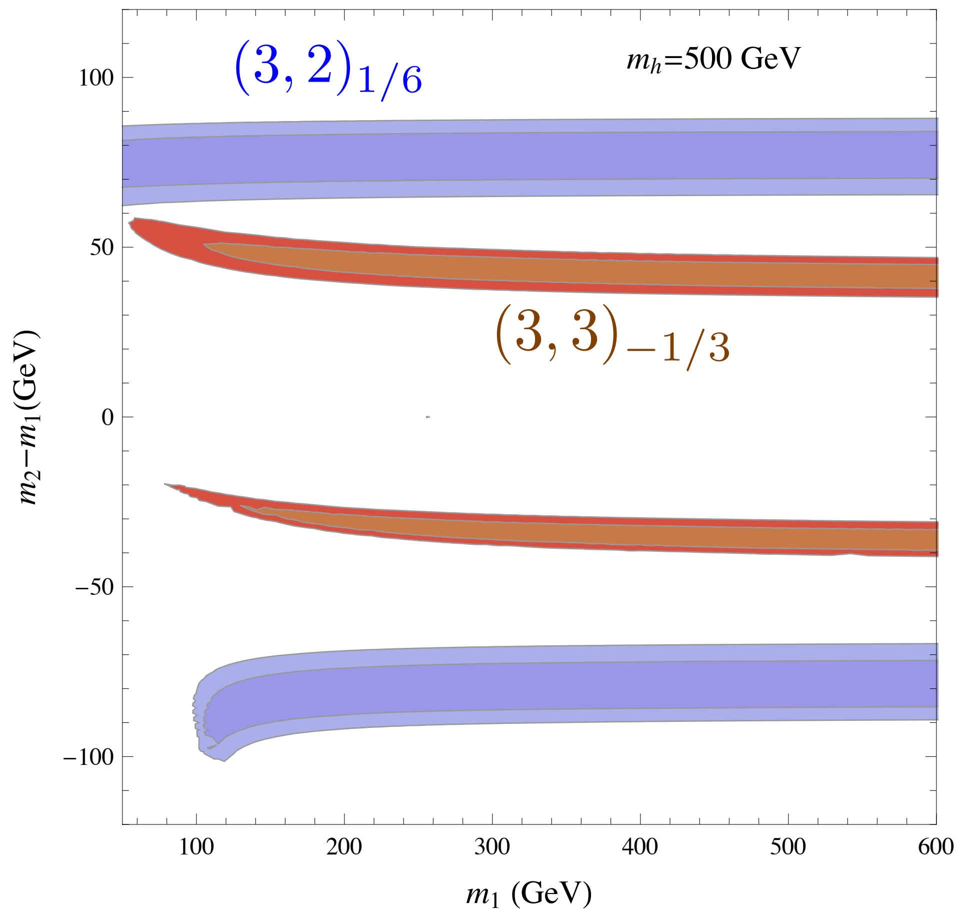


Color octet or triplet; weak double or triplet scalar reduce the Higgs production from gluon fusion

Fit to EWPO's



m_h=500 GeV
$(8,2)_{1/2}$
$(8,3)_1$
50
0
−50
200
400
600
800
1000
m_2-m_1(GeV)
m_1 (GeV)



m_h=500 GeV
$(3,2)_{1/6}$
$(3,3)_{-1/3}$
100
50
0
−50
−100
100
200
300
400
500
600
m_2-m_1(GeV)
m_1 (GeV)

Modifying the production cross section

$$\mathcal{L}^{eff} = -C_g \frac{h}{v} \frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} \qquad -\lambda_2 H^\dagger H \mathrm{Tr}[\mathrm{S}^2]$$

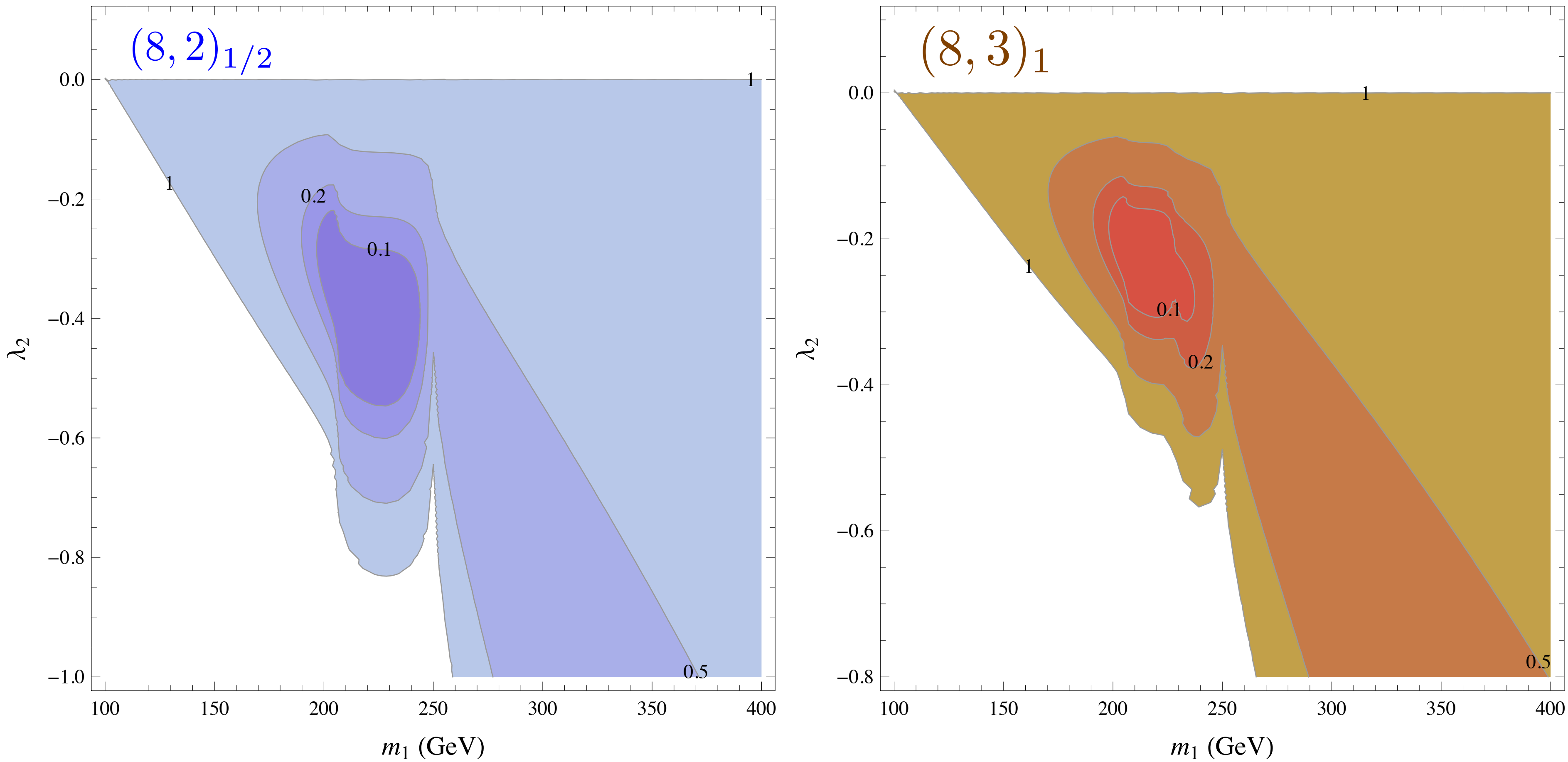
$$C_g = -\frac{\alpha_s}{3\,\pi}\left[\frac{3}{4} A^h_{1/2}(\tau_t)\right] - \frac{\lambda_2\,\alpha_s\,v^2}{8\,\pi\,m_S^2}\left[3 A^h_0(\tau_S)\right]$$

In the heavy quark or scalar limit $\quad -g_s^2 \lambda_{\mathbb{O}} \mathrm{Tr}\left[S^2\right]^2$

$$C_g = -\frac{\alpha_s}{3\,\pi} - \frac{11\,\alpha_s^2}{12\,\pi^2} - \frac{\lambda_2\,\alpha_s\,v^2}{8\,\pi\,m_S^2} - \frac{\lambda_2\,\alpha_s^2\,v^2}{16\,\pi^2\,m_S^2}\left(\frac{33}{2} + 5\,\lambda_{\mathbb{O}}\right)$$

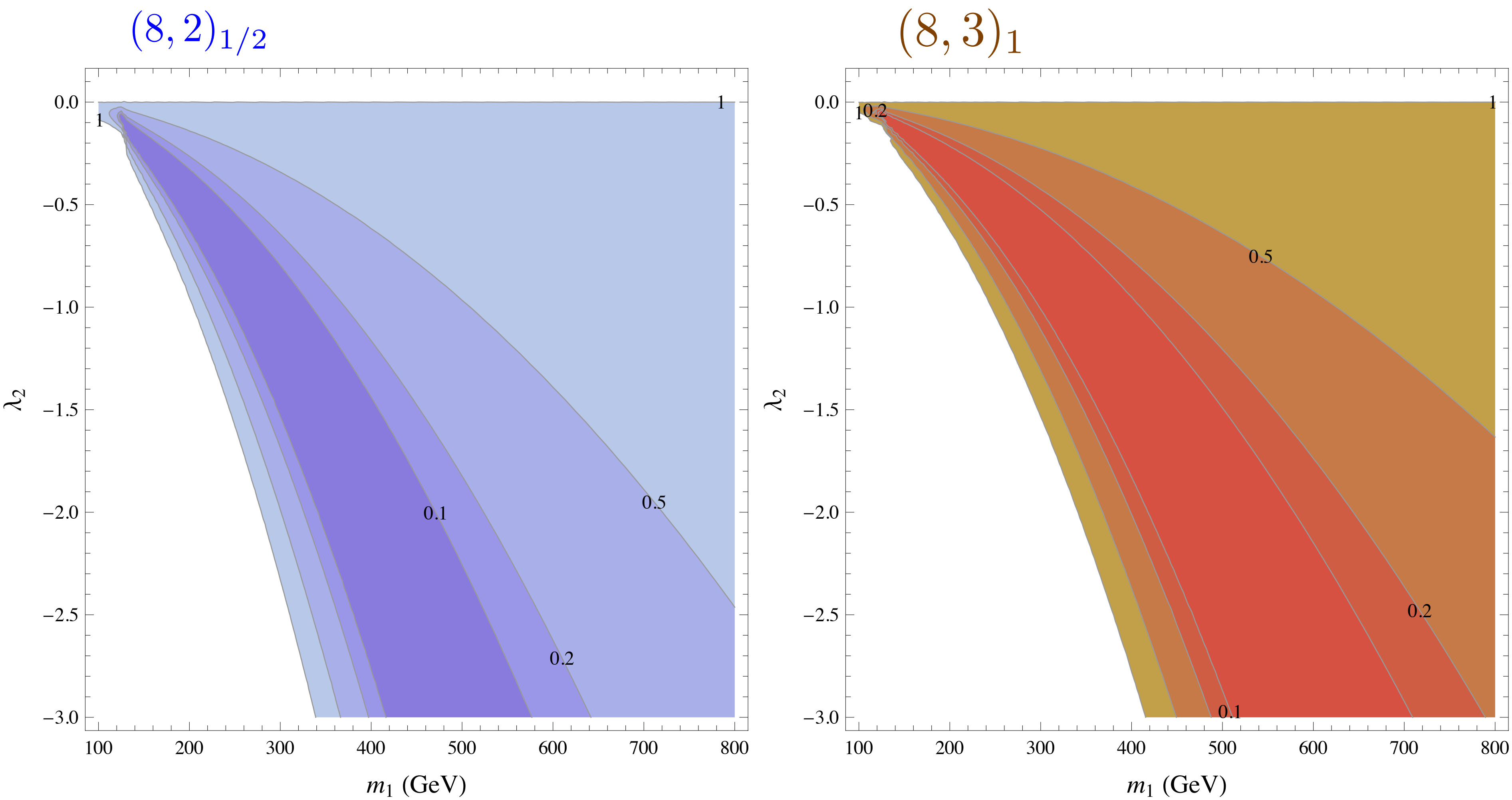
Boughezal and Petriello: 1003.2046

mh=500 GeV



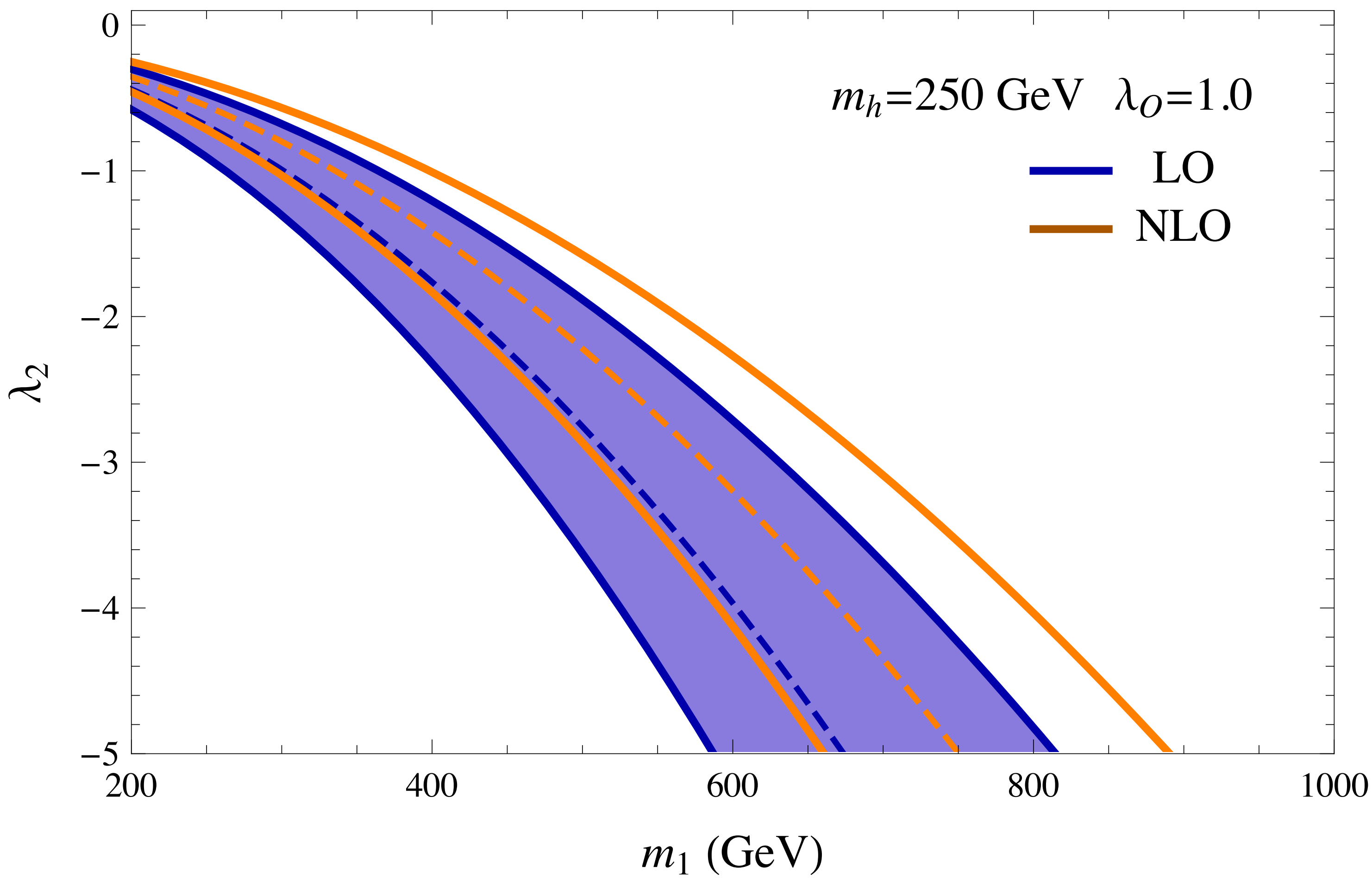
Predict both the new scalar mass and the coupling

mh=250 GeV



only predict a combination of the coupling and the scalar mass

Uncertainties



Collider signatures

$$pp \to \mathbb{O}_2^0 \mathbb{O}_2^{0\,*} \to 4b\,,4g\,,2g+2\gamma\,,2g+2Z$$

$$pp \to \mathbb{O}_2^+ \mathbb{O}_2^- \to W^{+\,*} + W^{-\,*} + (4b\,,4g\,,2g+2\gamma\,,2g+2Z)$$

constrained by OS lepton searches

$$pp \to \mathbb{O}_3^{++} \mathbb{O}_3^{--} \to 2W^{+\,*} + 2W^{-\,*} + (4b\,,4g\,,2g+2\gamma\,,2g+2Z)$$

constrained by SS lepton searches

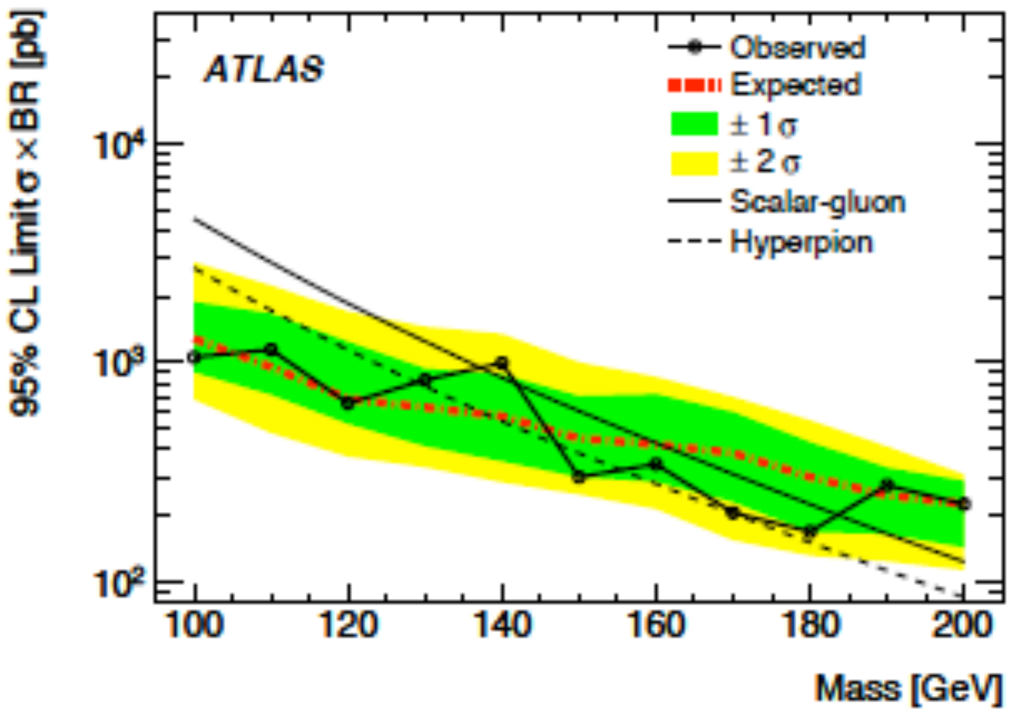
$$pp \to \mathbb{T}_2^{-1/3} \mathbb{T}_2^{+1/3} \to 4j$$

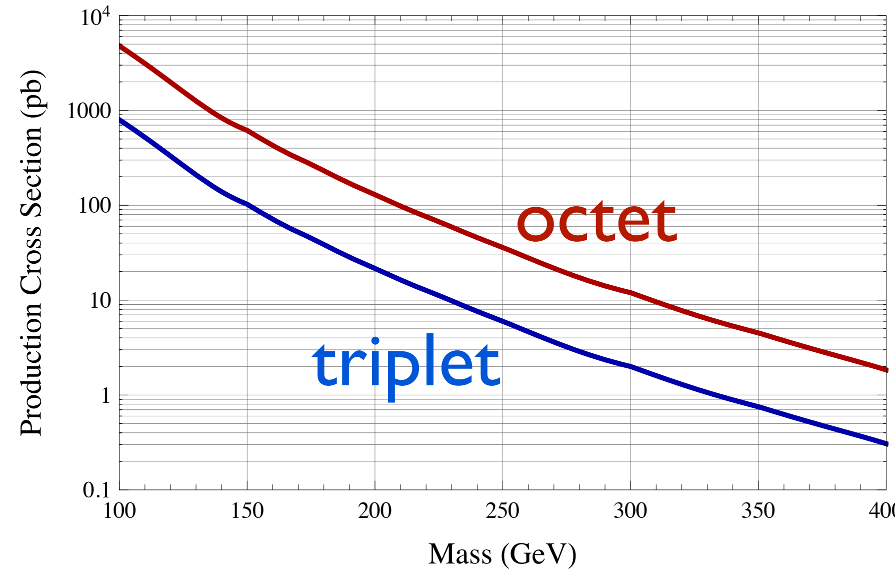
$$pp \to \mathbb{T}_2^{2/3} \mathbb{T}_2^{-2/3} \to W^{+\,*} + W^{-\,*} + 4j$$

$$pp \to \mathbb{T}_3^{2/3} \mathbb{T}_3^{-2/3} \to 2W^{+\,*} + 2W^{-\,*} + 4j$$

constrained by SS lepton searches

Four jet final state

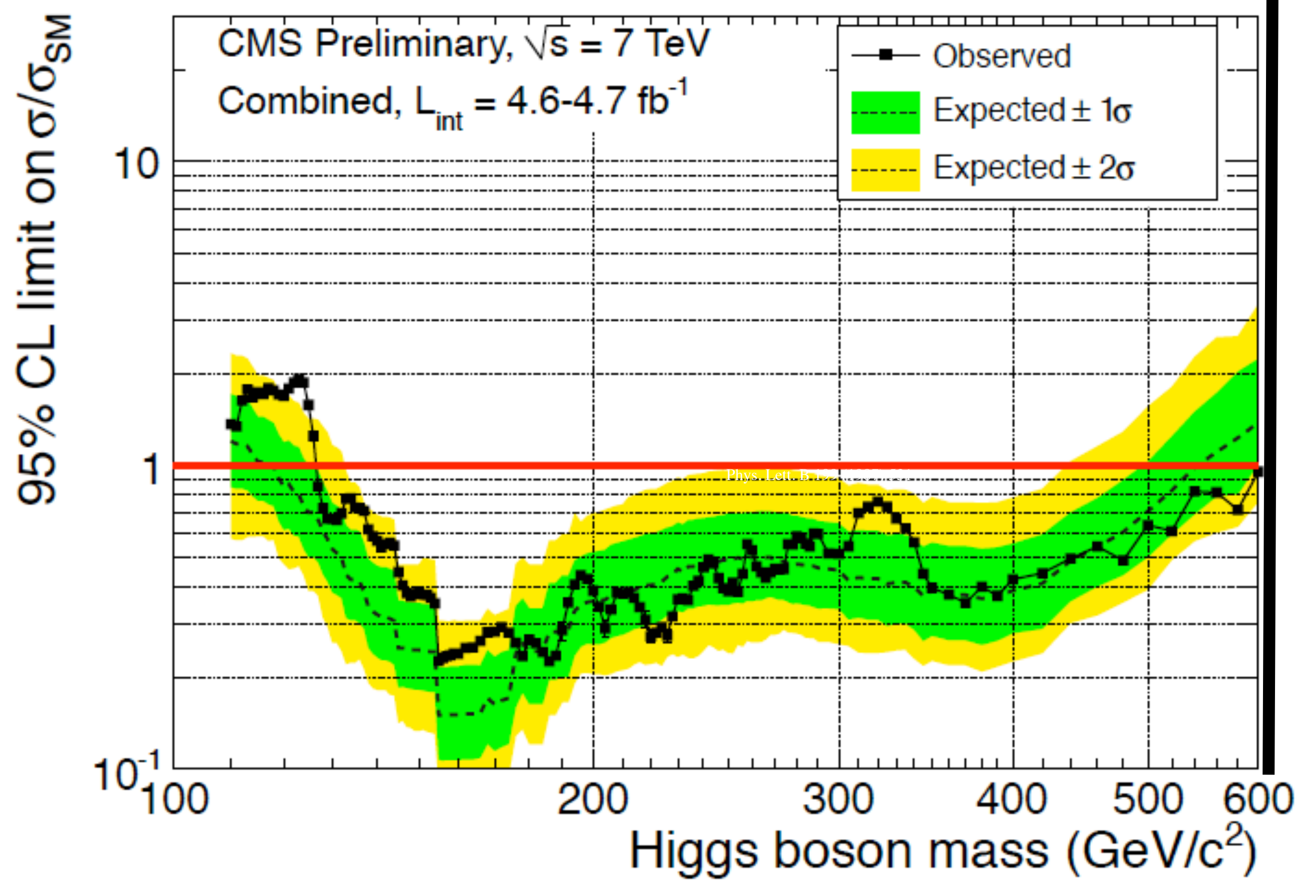




color-triplet and weak double is still allowed

Lesson: keep searching for resonances in four-jet final state; don't immediately jump to higher masses; constraining on the production cross section is also important

III

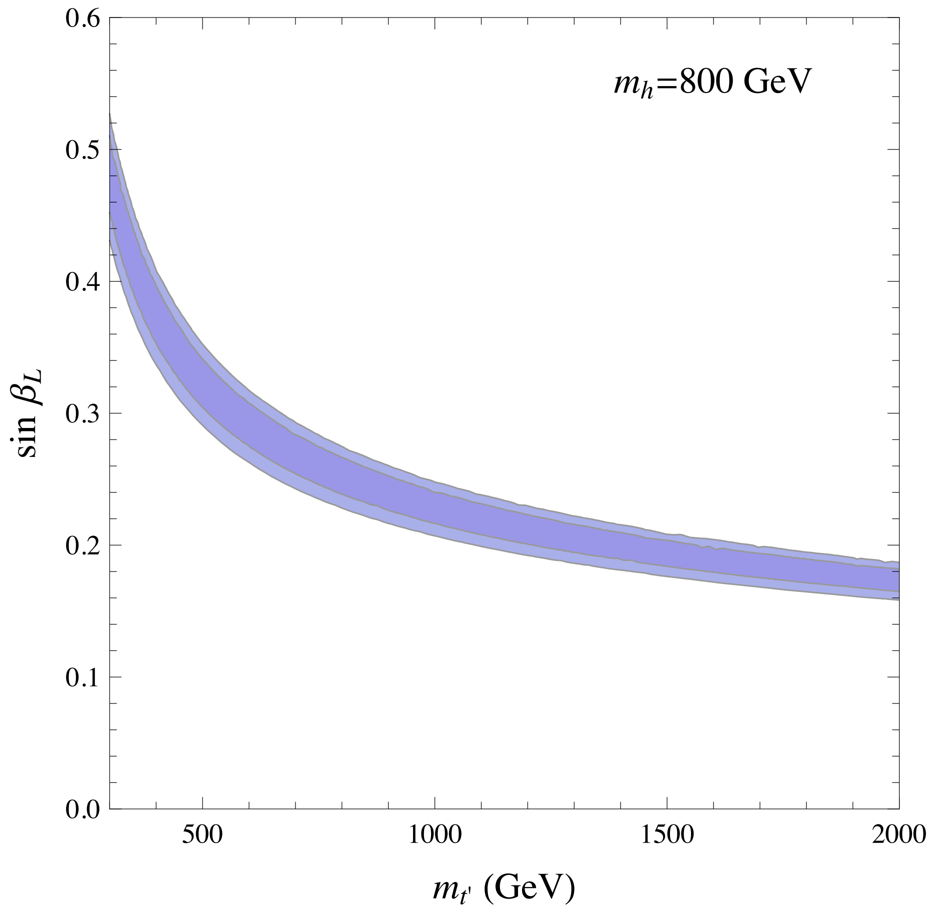


No Higgs boson

Additional vector-like fermion

Dobrescu and Hill: top seesaw

$$\lambda_1 \tilde{H} \overline{Q}_L t_R + \lambda_2 \tilde{H} \overline{Q}_L \chi_R + \mu \overline{\chi}_L \chi_R + h.c.$$



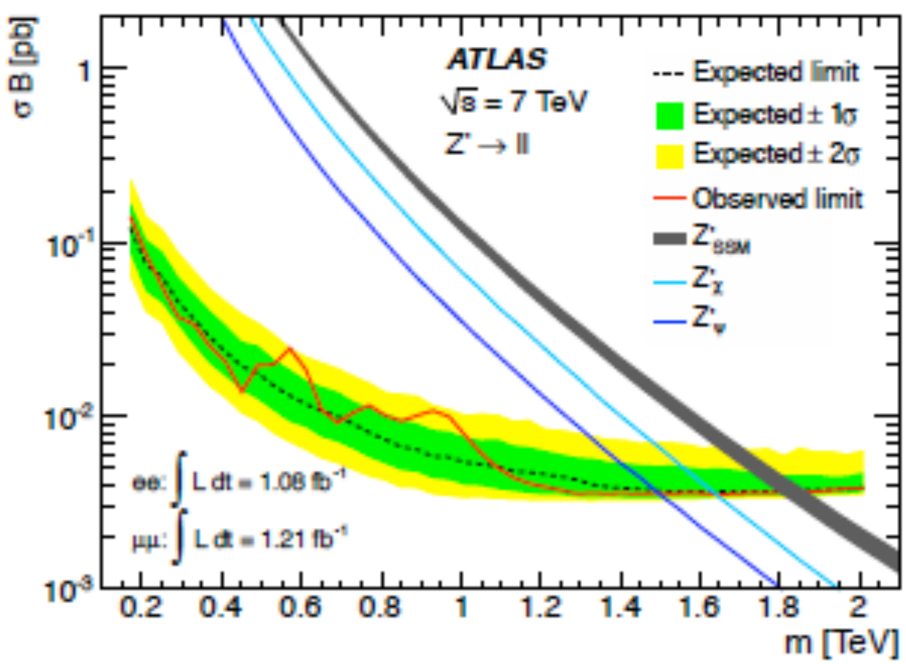
no real prediction for the t' mass;

Additional vector gauge boson Z'

Holdom: 1991
Peskin and Wells: 2001

$$\mathcal{M}^2 = \begin{pmatrix} m^2 & \gamma M_Z^2 \\ \gamma M_Z^2 & M^2 \end{pmatrix} \qquad \alpha T = \delta = \gamma^2 \frac{M_Z^2}{M^2}$$

$$\delta = (3.1 \pm 0.3) \times 10^{-3}\,, \qquad \text{or} \qquad \frac{\gamma M_Z}{M} = 0.055 \pm 0.002$$



Z' explanation is excluded unless it is leptophobic

Non-linearly realized EWSB

Grojean, Skiba, Terning: 2006

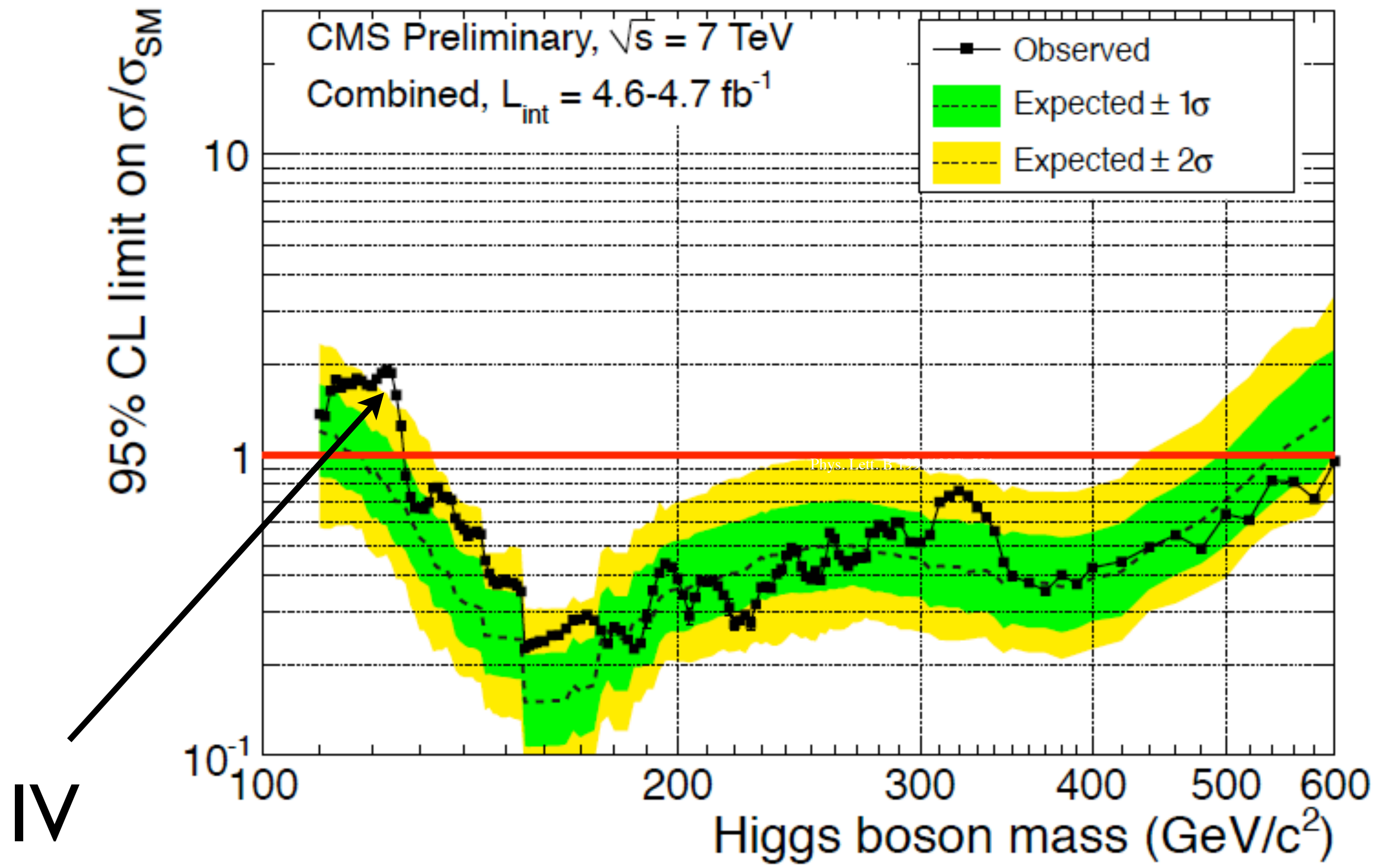
$$-16\pi\,\mathcal{O}_S + g^2(\mathcal{O}_q^1 + \mathcal{O}_\ell^1) = \mathcal{O}_{3V}$$

$$\mathcal{O}_S = -\frac{1}{32\pi} g g' B^{\mu\nu} \mathrm{Tr}(W_{\mu\nu} T)$$

$$\mathcal{O}_f^1 = i \bar{f}_L \gamma^\mu V_\mu f_L$$

$$\mathcal{O}_{3V} = i g\, \mathrm{Tr}\left(W^{\mu\nu}\left[V_\mu, V_\nu\right]\right)$$

Measure the triple gauge boson coupling more precisely



Last complain from a technicolor person:

"It is a discovery of techni-dilaton"

see Barath Coleppa's talk

Grinstein, Goldberger, Skiba; Phys.Rev.Lett, 100 (2008)

The general couplings of dilaton to SM particles are

$$\mathcal{L} \supset \frac{\sigma}{f}\left[2\, M_W^2\, W^{\mu+}\, W_{\mu-} + M_Z^2\, Z^\mu\, Z_\mu - \sum_\psi m_\psi\, \bar{\psi}\, \psi\, - \frac{\alpha_{em}\, b_{em}}{8\,\pi}\, F_{\mu\nu}F^{\mu\nu} - \frac{\alpha_s\, b_{QCD}}{8\,\pi}\, G_{a\mu\nu}G^{a\mu\nu}\right]$$

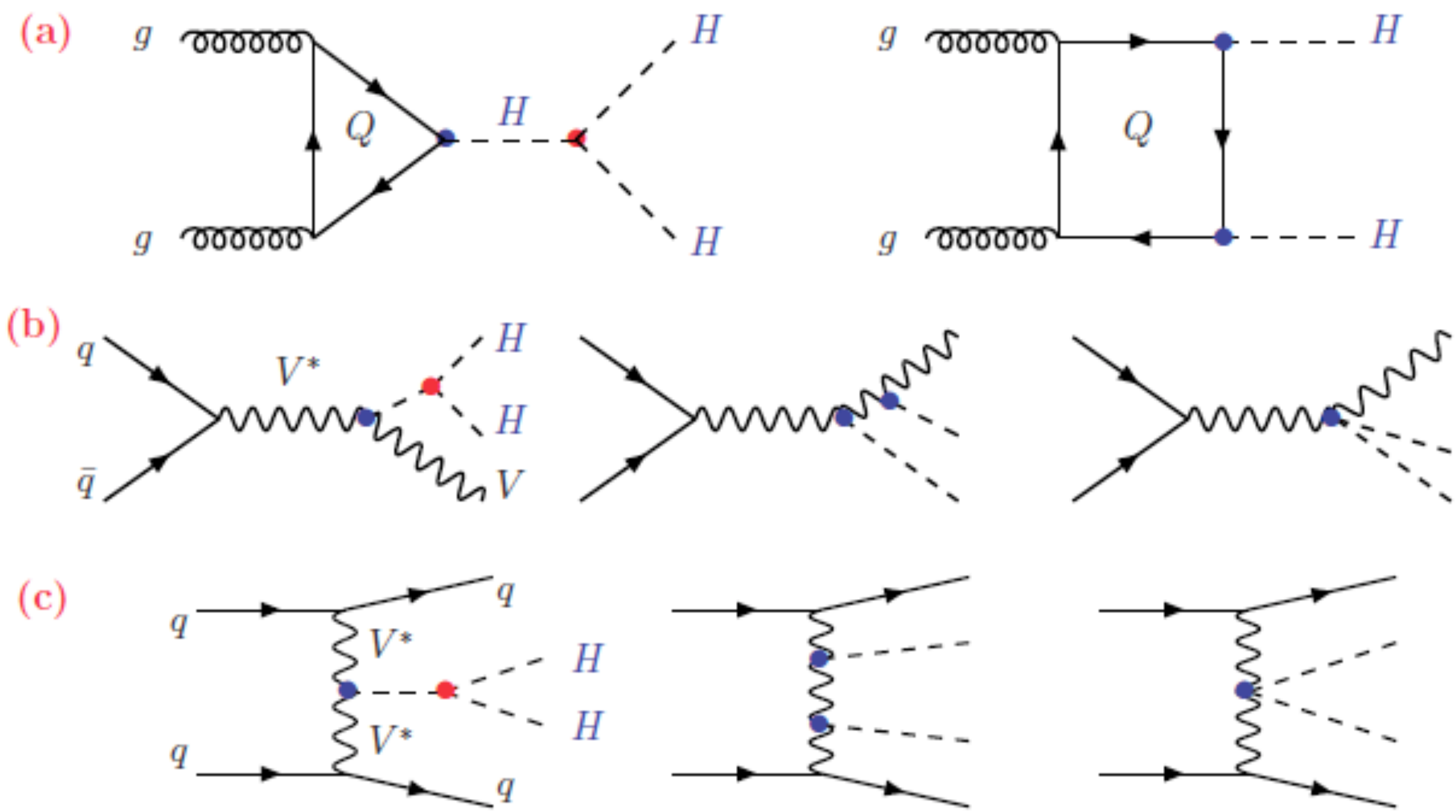
For the SM Higgs:

$$-\mathcal{L} = -\frac{1}{2}\partial_\mu h \partial^\mu h + \frac{1}{2}M_h^2 h^2 + \frac{M_h^2}{2\,v}\, h^3 + \frac{M_h^2}{8v^2}\, h^4$$

For the dilaton in WTC, with the explicitly breaking of CFT coming from a marginal operator:

$$-\mathcal{L} = -\frac{1}{2}\partial_\mu \sigma \partial^\mu \sigma + \frac{1}{2}M_\sigma^2 \sigma^2 + \frac{5\, M_\sigma^2}{6\, v}\, \sigma^3 + \cdots$$

From Barger, Han, Langacker, McElrath, Zerwas, hep-ph/0301097 at linear collider



14 TeV LHC physics

Conclusion

- If the SM Higgs is excluded, one needs to check a few scenarios considered here to hide a heavy Higgs
- For 200 < mh < 300 GeV, the Higgs could be hided from decaying into a pair of a new scalar
- For 250 < mh < 600 GeV, the Higgs production cross section from gluon fusion could be reduced by additional colored scalars in the loop
- For 600 GeV < mh (or no Higgs), wait for surprises like t', leptophobic Z', deviation of triple gauge boson couplings or new resonances from strong dynamics

Thanks