Exotic scalars and the Higgs to gamma - gamma rate

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Second MCTP Spring Symposium on Higgs Boson Physics

Ann Arbor,

April 16th 2012

Outline

1. Introduction: status of the Higgs searches with (5+5)fb^{-1}

As last December/Moriond

2.The Higgs portal and the Higgs phenomenology

- The several scalar representations
- Effects in the Higgs to gamma-gamma rate
- Possibility of hiding a heavy Higgs

3.Direct searches of exotic scalars

- Current LHC bounds on extra scalars

4. Conclusions

Based on:

„Exploring the Higgs portal with 10fb^{-1} at the LHC "

B. Batell, S. Gori, L.T. Wang arXiv: 1112.5180

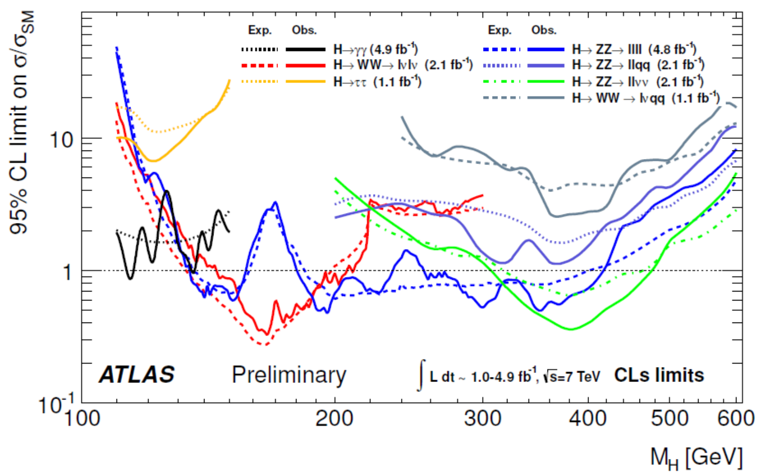
Where is the Higgs? (1)

Where is it NOT ? (at least a SM Higgs ...)

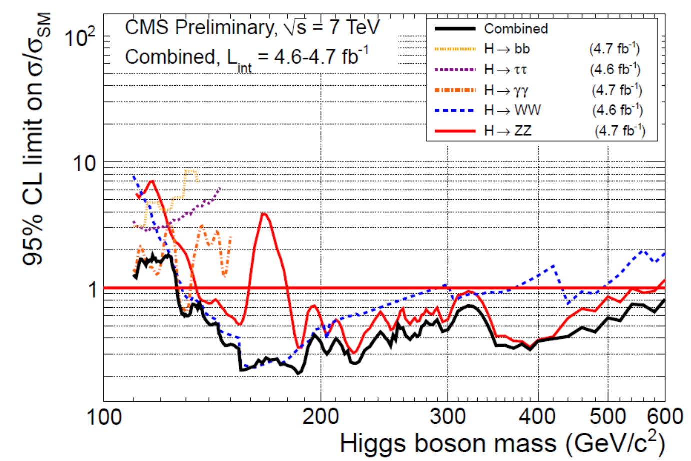
ATLAS

CMS

ATLAS-CONF-2011-163

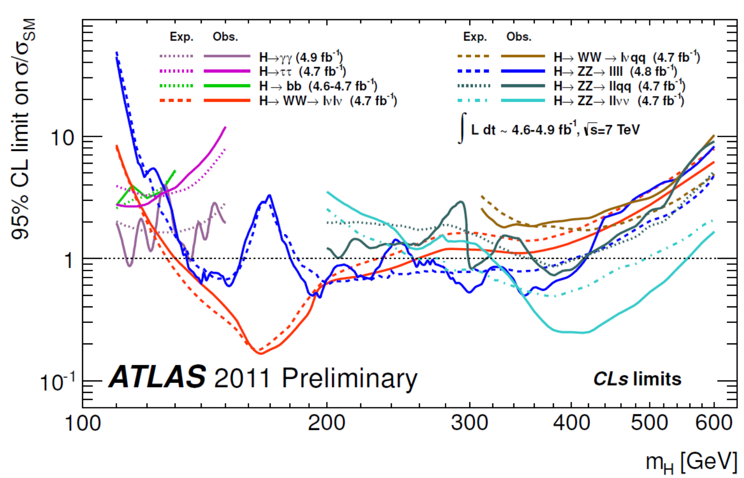


December

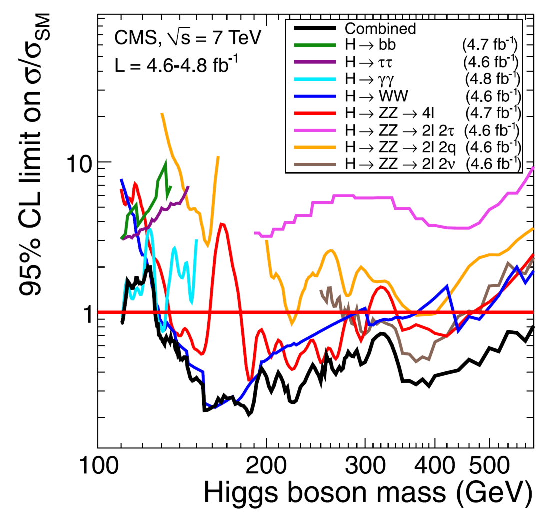


CMS-HIG-11-032

ATLAS-CONF-2012-019



Moriond



CERN-PH-EP-2012-023

Exclusion: 129–539 GeV at 95% CL

Exclusion: 127–600 GeV at 95% CL

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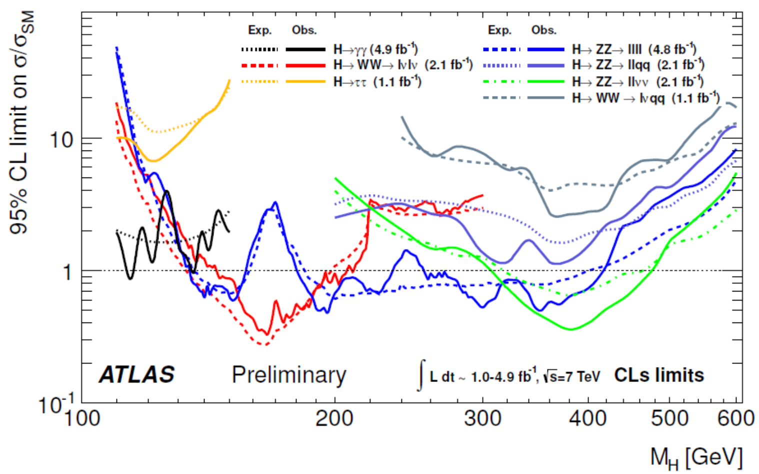

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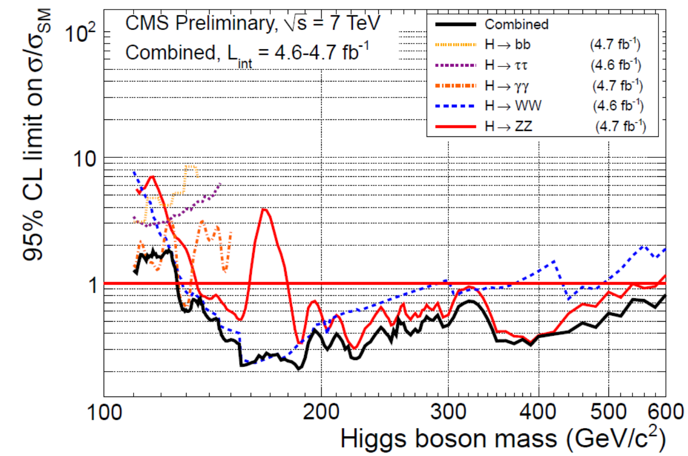

CMS-HIG-11-032

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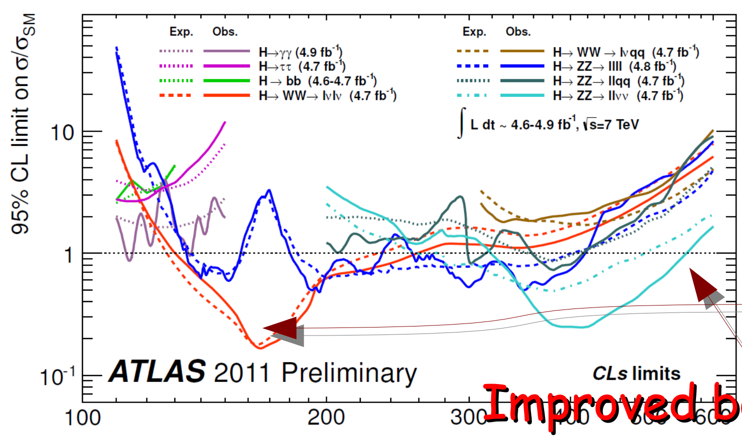
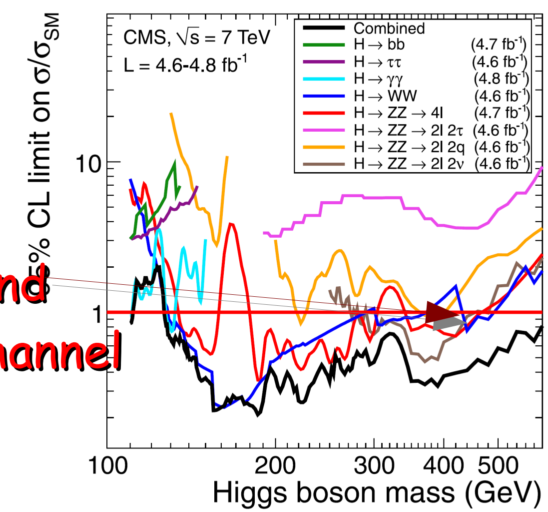


Moriond



CERN-PH-EP-2012-023

Improved bound on the WW channel

Improved bound on the ZZ channel

Exclusion: 129–539 GeV at 95% CL

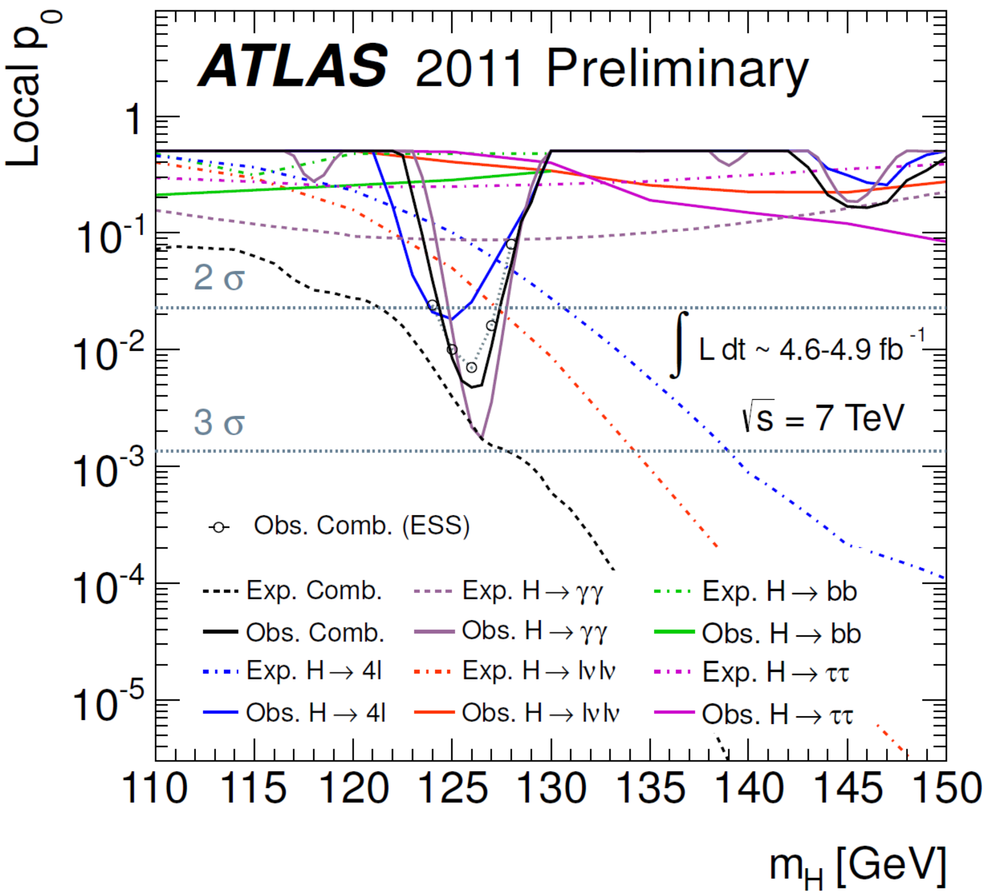
Exclusion: 127–600 GeV at 95% CL

Where is the Higgs? (2)

Hints for a light Higgs at ~125 GeV

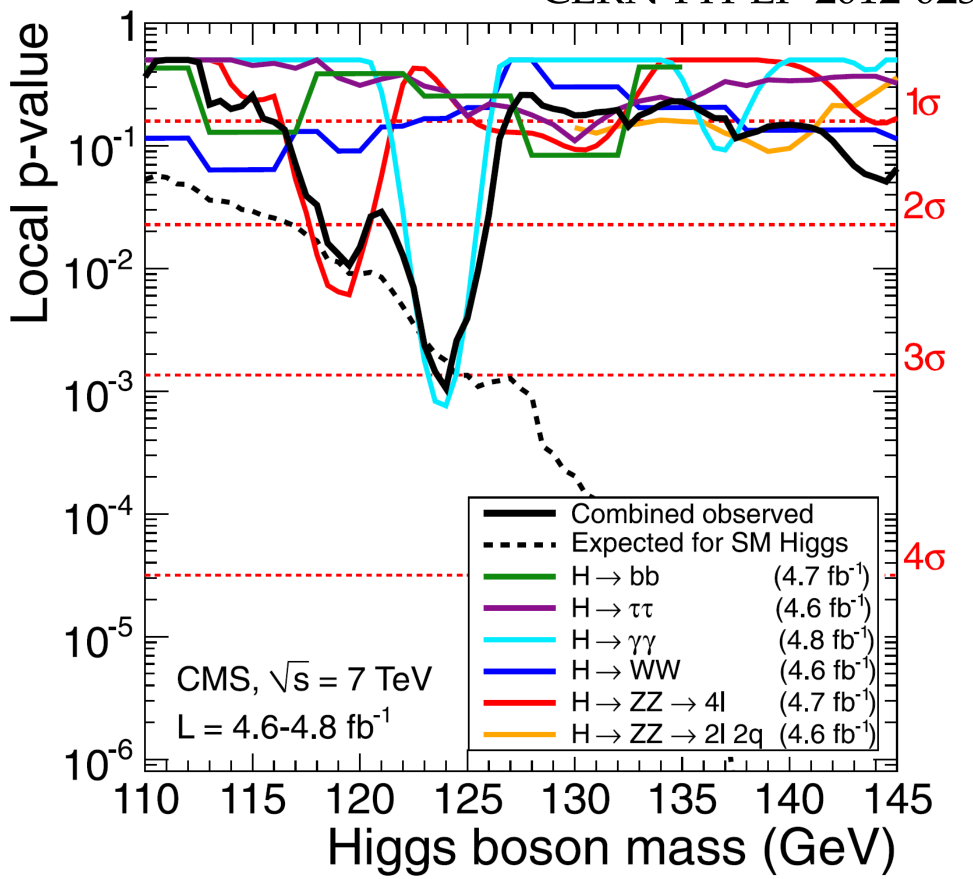
ATLAS

ATLAS-CONF-2012-019



CMS

CERN-PH-EP-2012-023

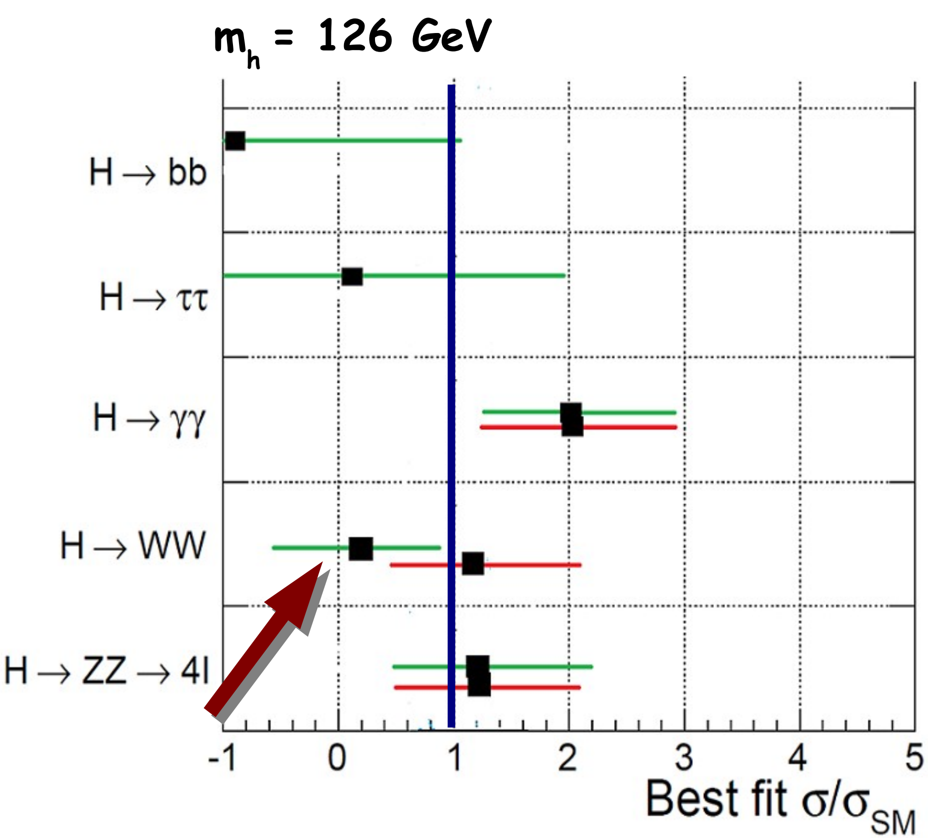


Not yet significant but still...

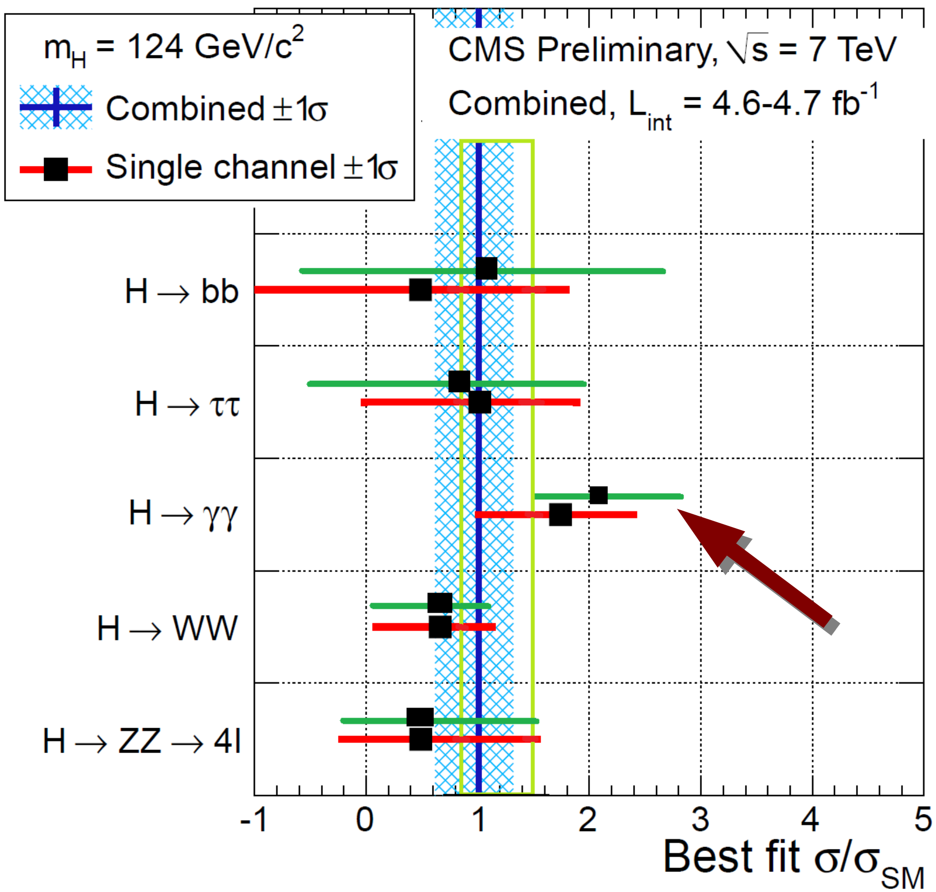
Where is the Higgs? (2)

Hints for a light Higgs at ~125 GeV

ATLAS



CMS



Results of
1. last December
2. Moriond

Possible reactions...

ATLAS & CMS results

Take the signal seriously

This is a statistical fluctuation

Evidence for a SM Higgs boson

Evidence for a Higgs with enhanced gamma-gamma rate

Higgsless theories
&
theories with heavy Higgs
are still viable

Study of the implications for new physics scenarios

The Higgs portal

- The hierarchy problem suggests the existence of new particles at the TeV scale that couple with the Higgs

How?

- An easy way: $\mathcal{L} \supset \lambda H^\dagger H \mathcal{O}_{NP}$

Lorentz invariant gauge singlet

- $\mathcal{O}_{NP}$ can be made of NP states carrying SU(3) x $SU(2)_L$ x $U(1)_Y$ quantum numbers
- Many specific examples, including Higgs-partner coupling in natural theories

Manohar, Wise, 2006
Hur, Jung, Ko, Lee, 2007
Low, Vichi, 2010
Bai, Fan, Hewett, 2011
Dobrescu, Kribs, Martin, 2011

- Possible couplings:
  - Fermion $\frac{\lambda}{\Lambda} H^\dagger H \bar{F} F$
  - Vector $\frac{\lambda}{\Lambda^2} H^\dagger H F^{\mu\nu} F_{\mu\nu}$
  - Scalar $\lambda H^\dagger H S^\dagger S$

Need low cut-off to have large effect

$\lambda H^\dagger H A^\mu A_\mu$ Introduces mixing between SM and new gauge boson

Exotic scalars

- Interactions of the type

$$\mathcal{L} \supset -\lambda|S|^2 H^\dagger H - m_0^2|S|^2 + \lambda_S|S|^4 + (\mathcal{L}_{\text{fermion}})$$

Very much dependent on the gauge representation of S

- Free parameters
  - **λ** coupling constant of the Higgs portal
  - **Mass** of the scalar **S** ($m_s^2 = m_0^2 + \lambda v^2$)
  - **Mass** of the **Higgs** boson m_h
- We impose that
  - Potential is bounded from below: $\lambda_S > 0,\ \lambda > -2\sqrt{\lambda_H \lambda_S}$
  - S does not participate to EWSB $-\frac{\lambda v^2 + m_0^2}{\lambda_S} < 0$ → No mixing between S and H
  - The $SU(2)_L$ components of S are approximately degenerate in mass
  - Perturbativity up to (2-3)TeV at least: $|\lambda| < 4$

Scalar representations

Model	Couplings	Signatures
$(1,1,1)$	LL	$(\ell^-\ell^+)(\ell^-\ell^+), \ell^-\ell^+ + \not{E}_T$
$(1,1,2)$	$e_R e_R$	$(\ell^-\ell^+)(\ell^-\ell^+)$
$(1,2,\frac{1}{2})$	$\bar{u}_R Q$	$(jj)(jj), (tj)(\bar{t}j), (bj)(\bar{b}j), (t\bar{b})(\bar{t}b), (t\bar{t})(t\bar{t})$
	$\bar{Q} d_R$	$(jj)(jj), (tj)(\bar{t}j), (bj)(\bar{b}j), (t\bar{b})(\bar{t}b), (b\bar{b})(b\bar{b})$
	$\bar{L} e_R$	$(\ell^-\ell^+)(\ell^-\ell^+), \ell^-\ell^+ + \not{E}_T$
$(1,3,1)$	LL	$(\ell^-\ell^+)(\ell^-\ell^+), \ell^-\ell^+ + \not{E}_T$
$(3,1,-\frac{1}{3})$	QQ, $u_R d_R$	$(jj)(jj)$, $(tj)(\bar{t}j)$, $(bj)(\bar{b}j)$, $(tb)(\bar{t}\,\bar{b})$
	$\bar{Q}\bar{L}$	$(\ell^- j)(\ell^+ j), (\ell^- t)(\ell^+\bar{t}), 2j + \not{E}_T, b\bar{b} + \not{E}_T$
	$\bar{u}_R \bar{e}_R$	$(\ell^- j)(\ell^+ j), (\ell^- t)(\ell^+\bar{t})$
$(3,1,\frac{2}{3})$	$d_R d_R$	$(jj)(jj), (bj)(\bar{b}j)$
$(3,1,-\frac{4}{3})$	$u_R u_R$	$(jj)(jj), (tj)(\bar{t}j)$
	$\bar{d}_R \bar{e}_R$	$(\ell^- j)(\ell^+ j), (\ell^- b)(\ell^+\bar{b})$
$(6,1,\frac{1}{3})$	$\bar{Q}\bar{Q}$	$(jj)(jj)$, $(tj)(\bar{t}j)$, $(bj)(\bar{b}j)$
	$\bar{u}_R \bar{d}_R$	$(jj)(jj)$, $(tj)(\bar{t}j)$, $(bj)(\bar{b}j)$, $(tb)(\bar{t}\,\bar{b})$
$(6,1,-\frac{2}{3})$	$\bar{d}_R \bar{d}_R$	$(jj)(jj), (bj)(\bar{b}j), (bb)(\bar{b}\bar{b})$
$(6,1,\frac{4}{3})$	$\bar{u}_R \bar{u}_R$	$(jj)(jj), (tj)(\bar{t}j), (tt)(\bar{t}\bar{t})$
$(8,1,0)$	loop decay	$(jj)(jj)$
$(3,2,\frac{1}{6})$	$\bar{d}_R L$	$(\ell^- j)(\ell^+ j), (\ell^-\bar{b})(\ell^+ b), 2j + \not{E}_T, b\bar{b} + \not{E}_T$
$(3,2,\frac{7}{6})$	$\bar{u}_R L$	$(\ell^- j)(\ell^+ j), (\ell^-\bar{t})(\ell^+ t), 2j + \not{E}_T, t\bar{t} + \not{E}_T$
	$\bar{Q} e_R$	$(\ell^- j)(\ell^+ j), (\ell^-\bar{t})(\ell^+ t), (\ell^-\bar{b})(\ell^+ b)$
$(8,2,\frac{1}{2})$	$\bar{u}_R Q$	$(jj)(jj), (tj)(\bar{t}j), (bj)(\bar{b}j), (t\bar{b})(\bar{t}b), (t\bar{t})(t\bar{t})$
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$(8,3,0)$	loop decay	$(W^+ j)(W^- j), (\gamma j)(\gamma j), (Zj)(Zj), (\gamma j)(Zj)$

Simplifying assumption:

Choice of Y to allow simple renormalizable couplings to SM fields

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$(1,1,1)$	LL	$(\ell^-\ell^+)(\ell^-\ell^+), \ell^-\ell^+ + \not{E}_T$
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	QQ, $u_R d_R$	$(jj)(jj), (tj)(\bar{t}j), (bj)(\bar{b}j), (tb)(\bar{t}\bar{b})$
[illegible]	[illegible]	[illegible]
[illegible]	QQ	[illegible]
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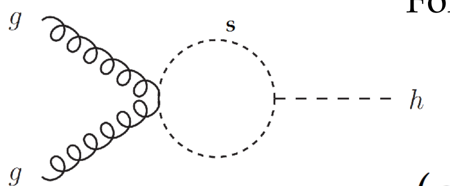
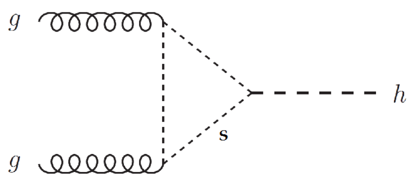
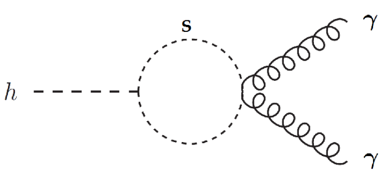
See Bonciani, G. Degrassi, and A. Vicini, 2007 & Boughezal, Petriello, 2010
For the NNLO computation for the 8 representation

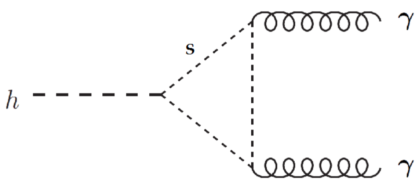




$$\frac{\sigma(gg\to h)}{\sigma(gg\to h)_{\rm SM}} \sim \frac{\Gamma(h\to gg)}{\Gamma(h\to gg)_{\rm SM}} = \left| 1 + Kc\frac{\lambda\, C(r) A_0(\tau_S)\frac{v^2}{m_S^2}}{\sum_f A_{1/2}(\tau_f)}\right|^2$$



$$\frac{\Gamma(h\to\gamma\gamma)}{\Gamma(h\to\gamma\gamma)_{\rm SM}} = \left| 1 - \sum_i \frac{\lambda\, d(r) Q_{S_i}^2 A_0(\tau_S)\frac{v^2}{2m_S^2}}{A_1(\tau_W) - \sum_f N_f Q_f^2 A_{1/2}(\tau_f)}\right|^2$$



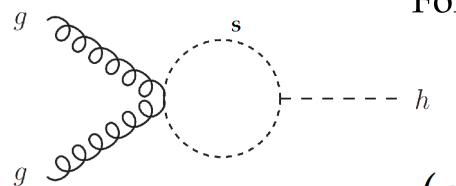
W boson contribution in the SM

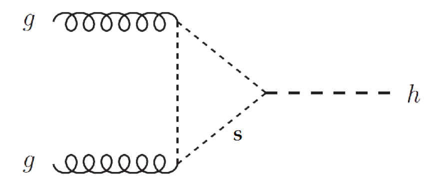
Quark contributions in the SM

- Under the assumption that the modifications are small, negligible effects on the branching ratios to other final states (the Higgs total width is unchanged)

Modification of the Higgs phenomenology

See Bonciani, G. Degrassi, and A. Vicini, 2007 & Boughezal, Petriello, 2010
For the NNLO computation for the 8 representation





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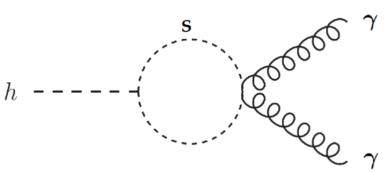

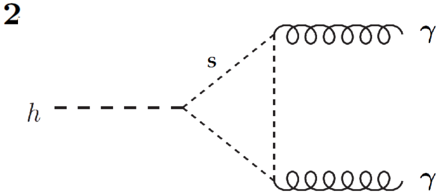

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W boson contribution in the SM

Quark contributions in the SM

- Under the assumption that the modifications are small, negligible effects on the branching ratios to other final states (the Higgs total width is unchanged)

Note: $\lambda>0$ implies a positive NP contribution to the production cross section and a negative NP contribution in the branching ratio to two photons, and viceversa

Two interpretations

What are the implications of

1. A light Higgs at (124-126) GeV

„Moriond best fit values“

$$\mu_i = \frac{\sigma_i^{\rm best}}{\sigma_i^{\rm SM}}$$

	$\gamma\gamma$	ZZ	WW	$\tau\tau$	bb
ATLAS	1.96 ± 0.86	1.19 ± 1.18	0.17 ± 0.65	0.14 ± 0.84	-0.82 ± 1.16
CMS	2.1 ± 0.62	0.48 ± 1.1	0.67 ± 0.57	0.84 ± 1.32	1.7 ± 1.65

Chi square, assuming a Gaussian form in R:

$$\chi^2 = \sum_i \frac{(R_i - \mu_i)^2}{\tilde{\sigma}_i^2} < \#$$

It depends on the number of degrees of freedom and on the C.L.

2. A hidden heavy Higgs

$$\tilde{\mu}_i^{\rm NP} = \frac{\sigma_i}{\sigma_i^{\rm bound}}$$

at the 95% C.L., combination of both experiments

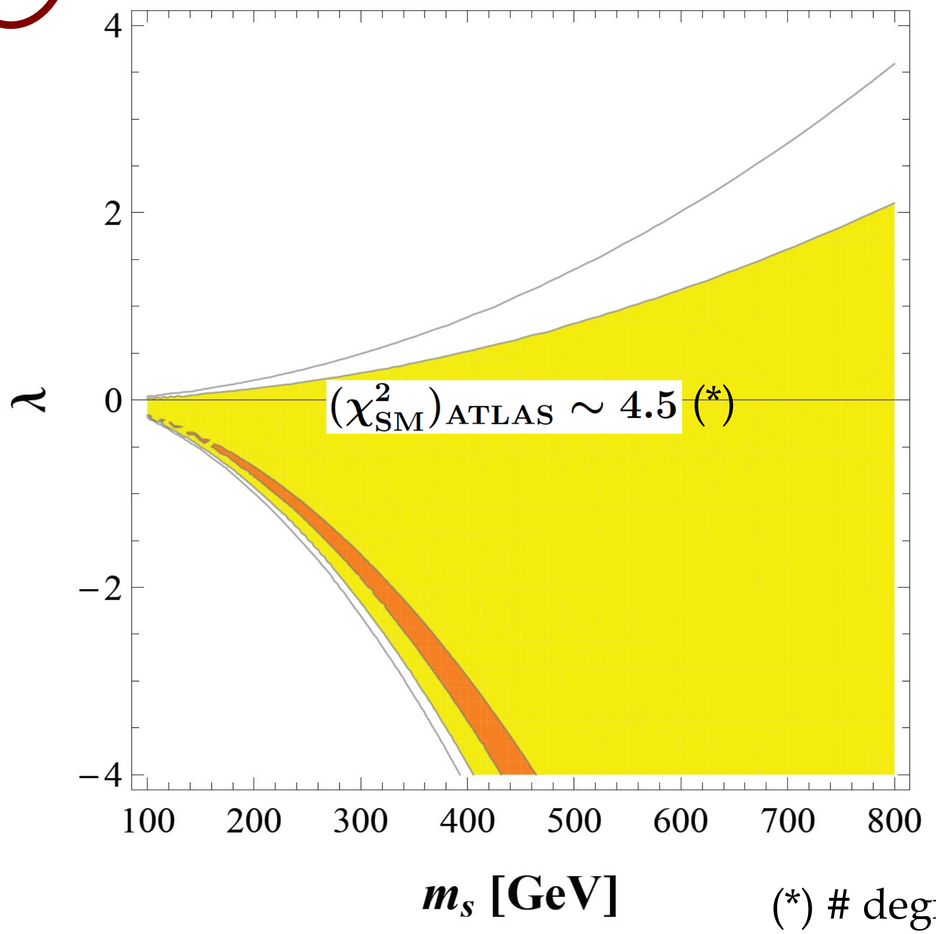
$$\tilde{\mu}_{\rm comb} = 1/\sqrt{\sum_i \frac{1}{(\tilde{\mu}_i^{\rm NP})^2}} < 1$$

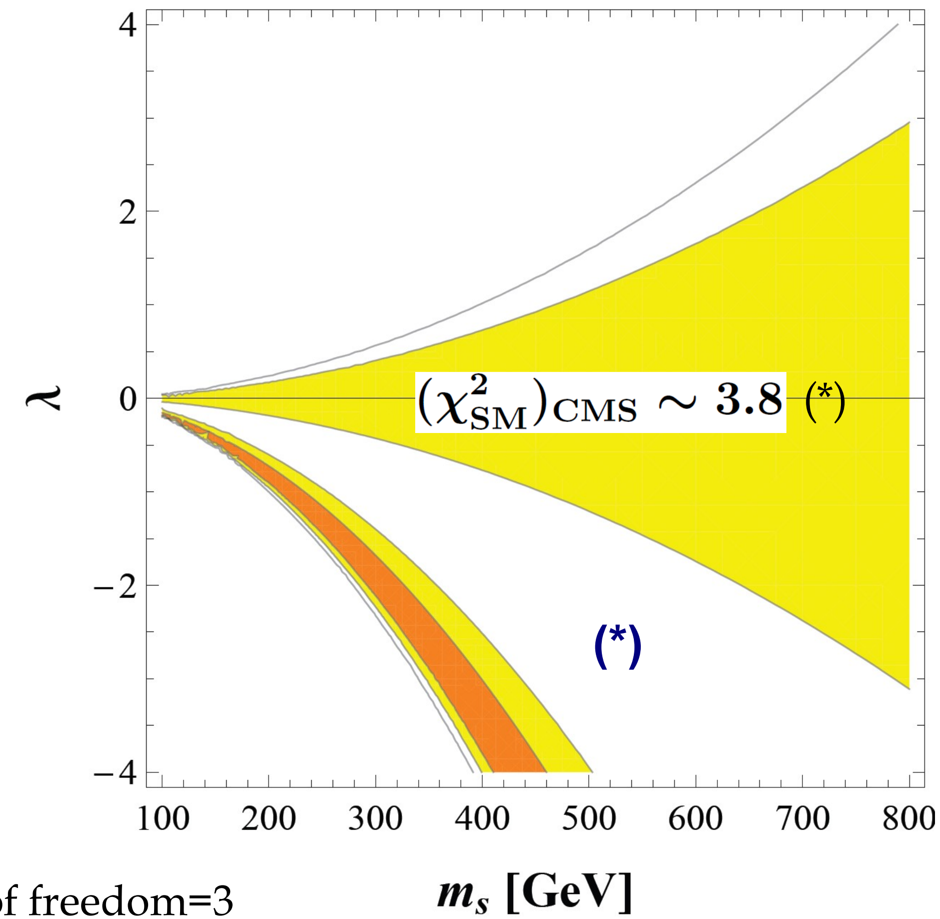
Suppression of its gluon gluon production cross section

A light Higgs boson signal: colored scalars

1.

ATLAS **(8,2,1/2)** **CMS**





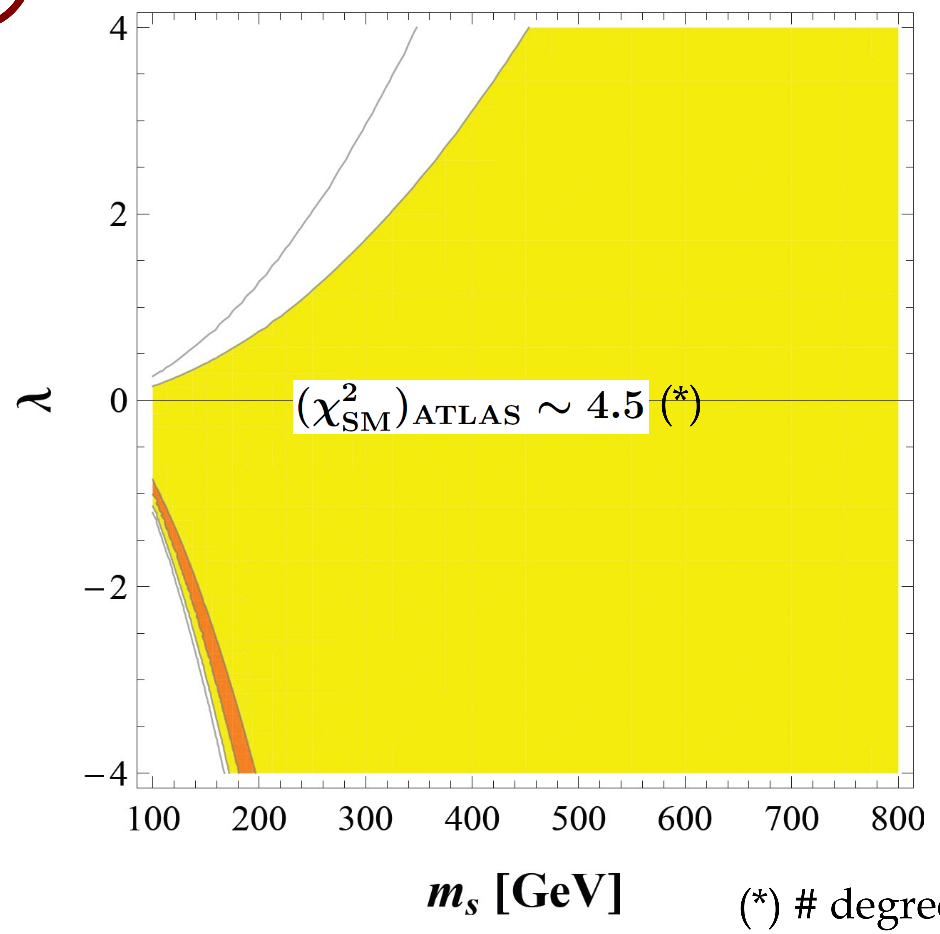
(*) # degrees of freedom=3

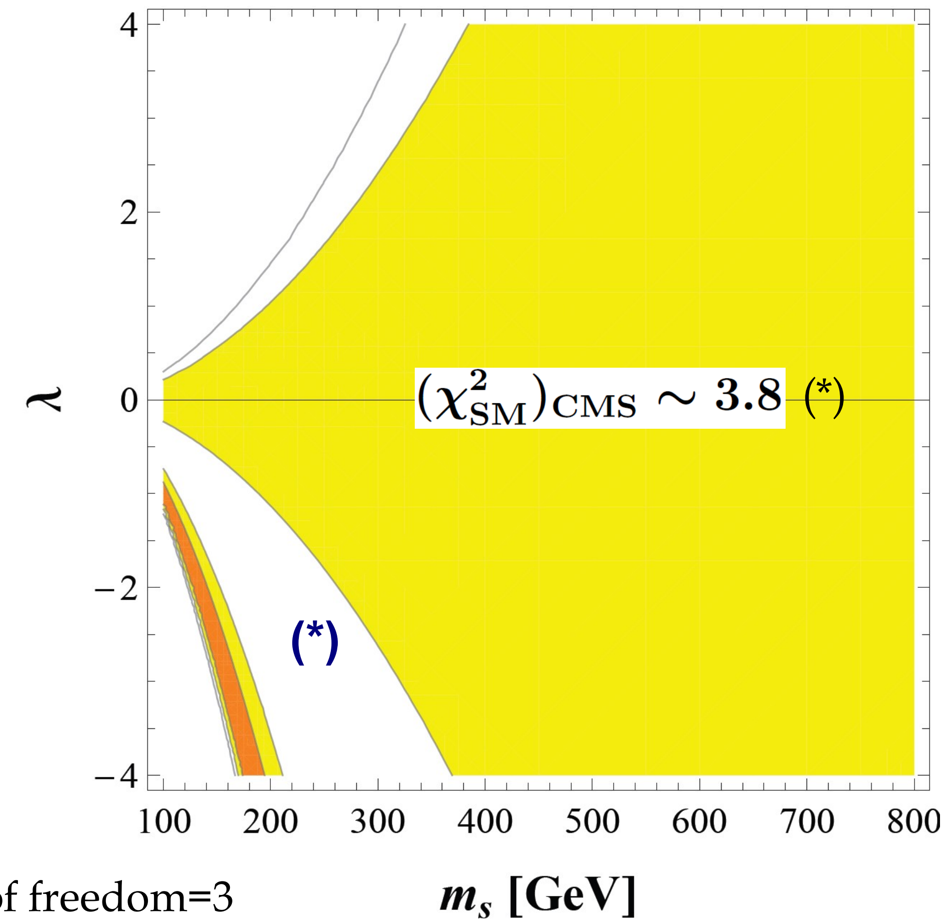
1σ 2σ

- A strong suppression of the gg fusion is not producing a good fit of the CMS data **(*)**
- Enhancement of the gg fusion is rather constrained

A light Higgs boson signal: colored scalars

1. ATLAS (3,2,1/6) CMS





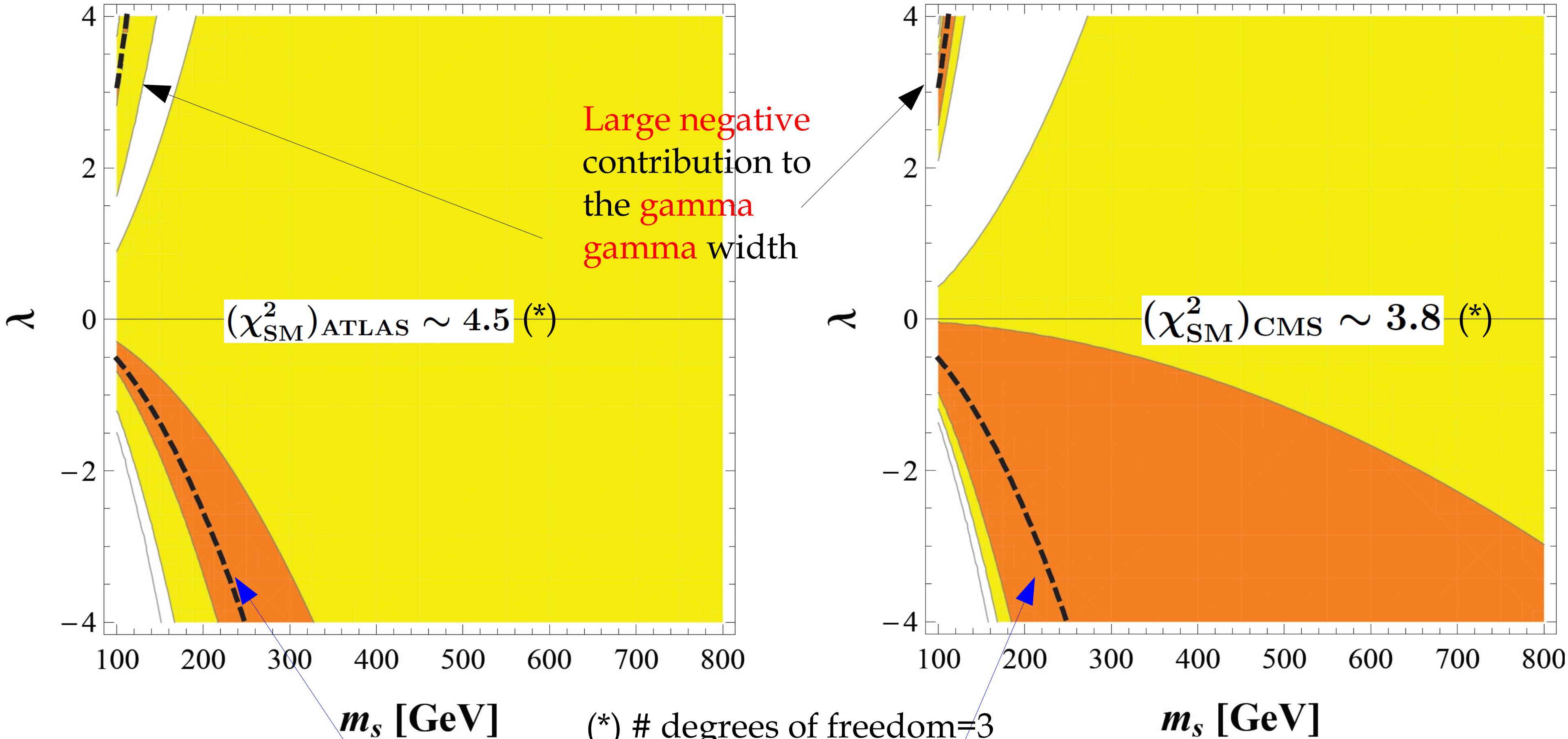
(*) # degrees of freedom=3

1σ 2σ

- A strong suppression of the gg fusion is not producing a good fit of the CMS data (*)
- Enhancement of the gg fusion is rather constrained

A light Higgs boson signal: colored neutral

1. ATLAS **(1,1,2)** CMS



(*) # degrees of freedom=3

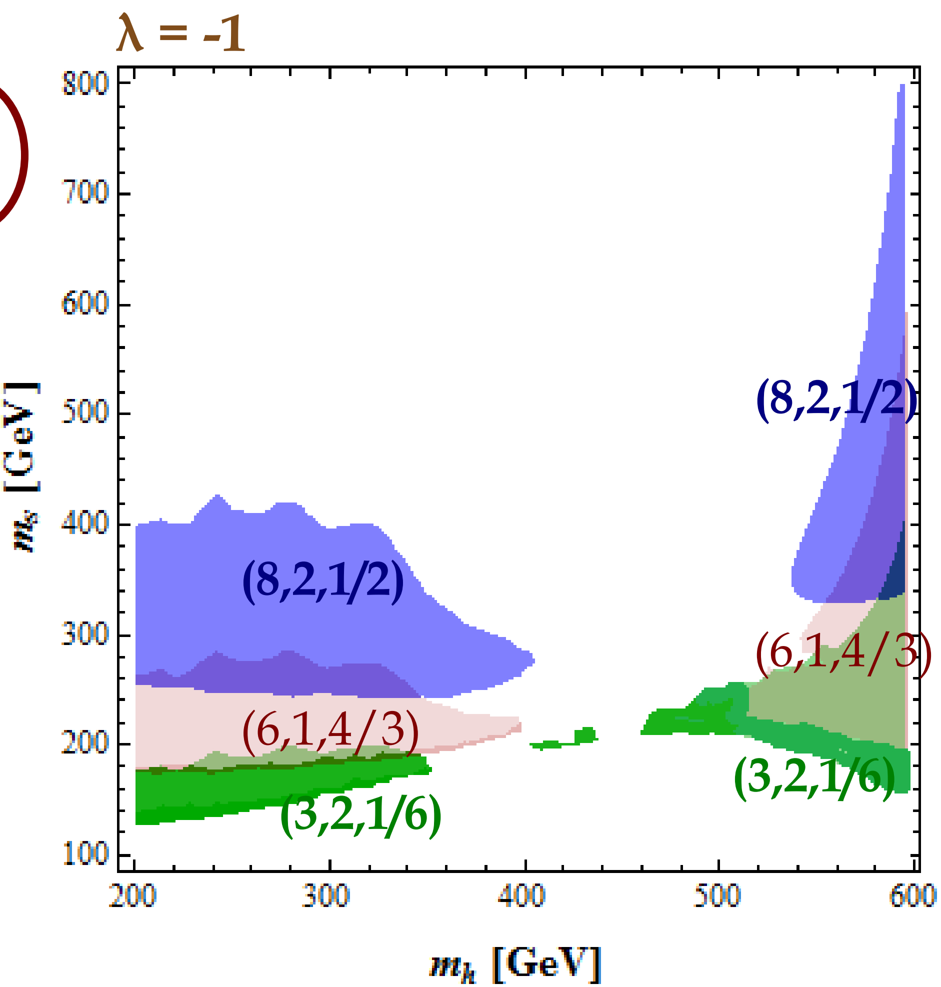
The gamma-gamma rate is enhanced by a factor of 2

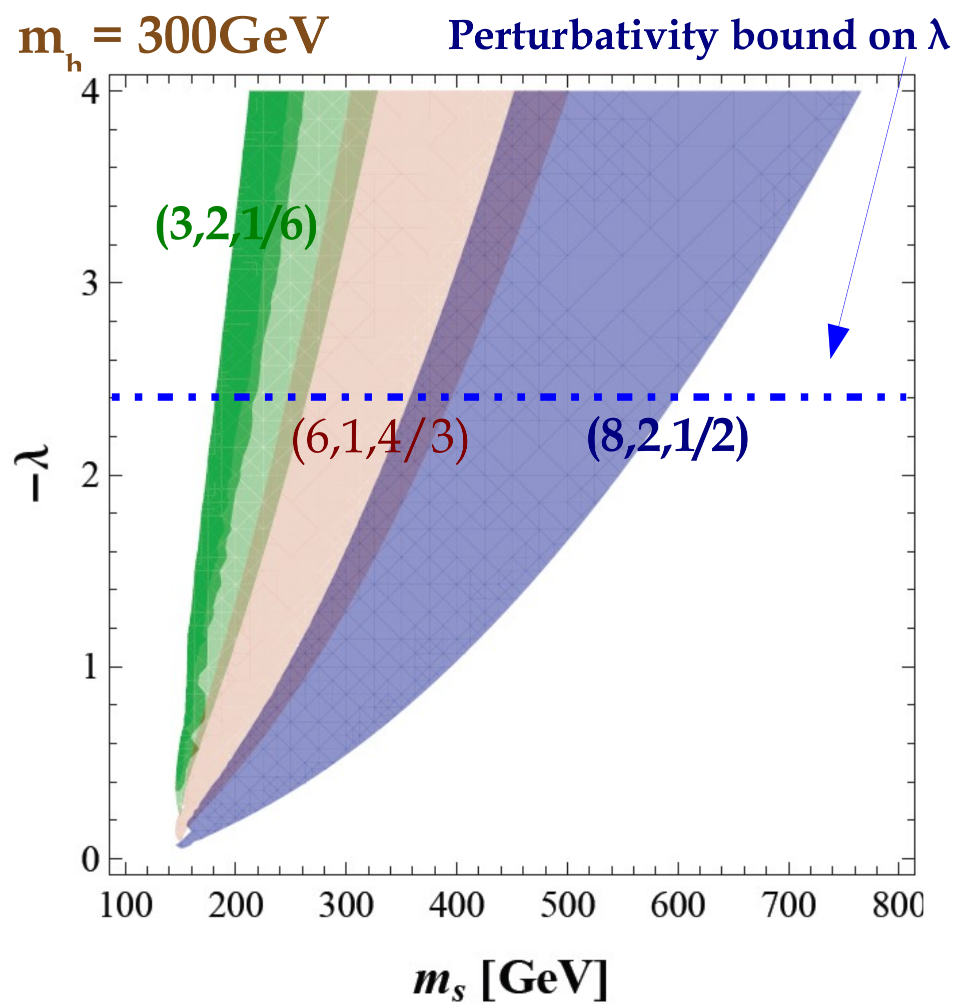
1σ 2σ

Both ATLAS and CMS prefer <u>λ<0</u> → enhancement of the gamma-gamma rate

A hidden heavy Higgs

2.





The triplet representation should be rather light to hide „efficiently" a heavy Higgs

Already been excluded by direct searches? See later...

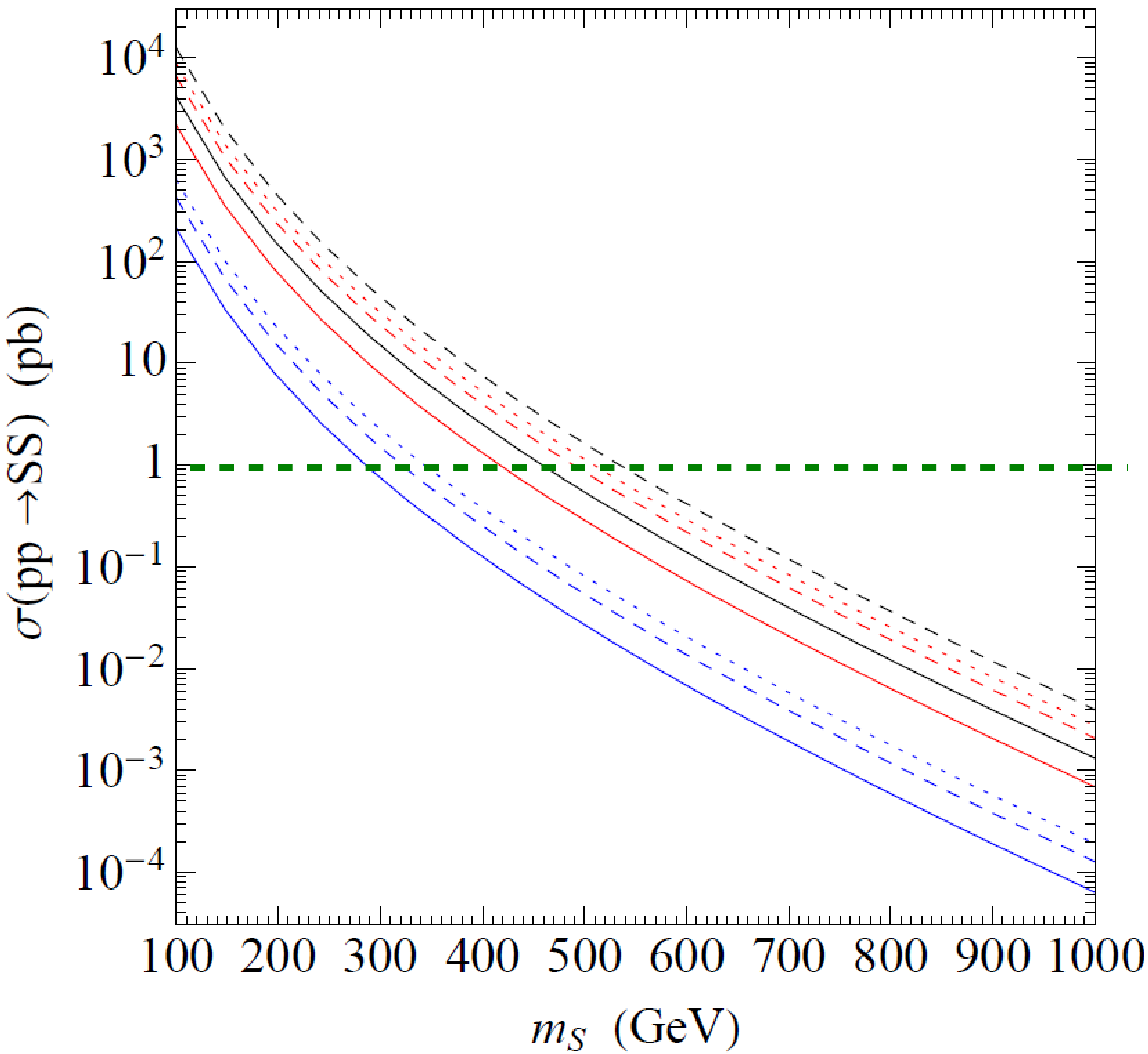
Complementary searches

- Higgs phenomenology are consistent with (possible even favor) lighter exotic scalars
- These states can be searched for at the LHC
- Complementary to the measurement of the Higgs phenomenology
- QCD pair production $pp \to SS^{(*)}$ with sizable rates even at the 7 TeV LHC

Note: single production of these scalars through gluon gluon fusion can have similar rates only for very heavy (m_s>1TeV) scalars

Gresham, Wise, 2007

Production of the new scalars



Copiously pair produced at the 7TeV LHC

$$pp \to SS^{(*)}$$

$SU(3)_c$ triplet

$SU(3)_c$ sextet

$SU(3)_c$ octet

10^4 events at $10fb^{-1}$

$SU(2)_L$ singlet

$SU(2)_L$ doublet

$SU(2)_L$ triplet

Decay modes

$$\mathcal{L} \supset -\lambda |S|^2 H^\dagger H - m_0^2 |S|^2 + \lambda_S |S|^4 + (\mathcal{L}_{\text{fermion}})$$

Decays mediated by the renormalizable couplings

$$\mathcal{L}_{\text{fermion}} \supset \eta_{ij} S \bar{\psi}^i_{1\text{SM}} \psi^j_{2\text{SM}} + h.c.$$

20 possible final states

If η_{ij} are generic O(1) couplings, large FCNCs are induced, however

1. One can impose the Minimal Flavor Violation (**MFV**) principle
2. One can impose that η_{ij} are **small**

} Work for the future

1.
- Only the representation (8, 2, 1/2) can have MFV coupling — Manohar, Wise, 2006
- Multi b or multi top final state searches

2.
- Lifetime of a real scalar decaying to two (relatively light) fermions:

$$c\tau \sim 0.5\text{mm} \left(\frac{10^{-7}}{\eta}\right)^2$$

- If $\eta \geq 10^{-7}$ the decay is prompt in the detector

LHC direct searches

- In most cases, no dedicated S searches
- We estimate the bounds based on similar final state searches
- Assumption:

  The scalar decays 100% in one of the possible final states

  → If several decay modes are open the constraints would be less stringent

- We compare the LO cross section with the LHC excluded rate

  (this is an estimation, the kinematic may be different for example)

However, since rate falls very fast with mass,
a factor of 2 error on the constraint of rate only translate into
10-20% error on the constraint of mass

$$\sigma \sim \frac{1}{m^{(6-8)}}$$

LHC direct searches

- In most cases, no dedicated S searches
- We estimate the bounds based on similar final state searches
- Assumption:

  The scalar decays 100% in one of the possible final states

  → If several decay modes are open the constraints would be less stringent

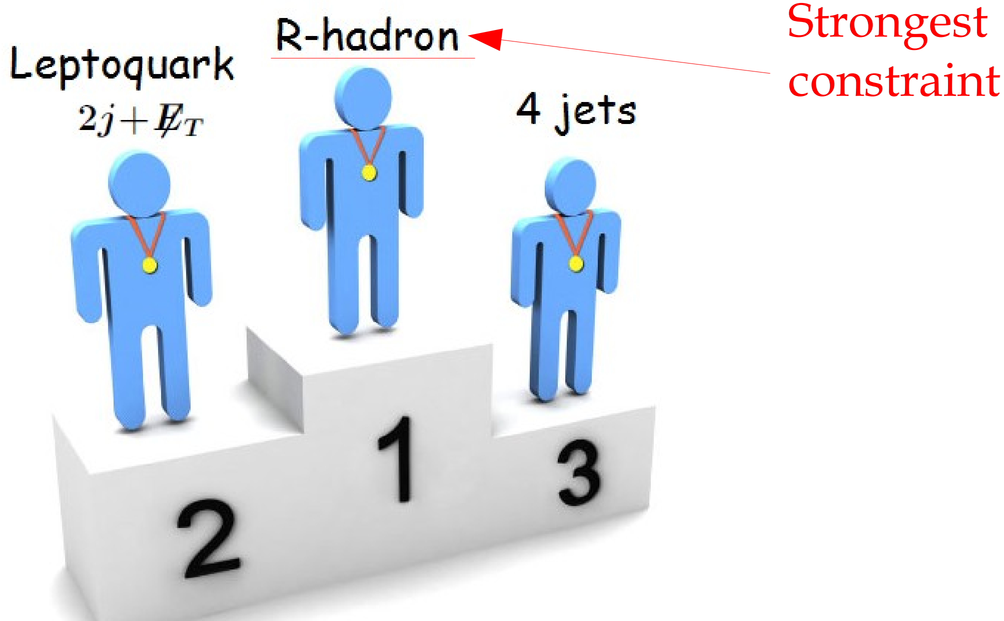
- We compare the LO cross section with the LHC excluded rate

  (this is an estimation, the kinematic may be different for example)

However, since rate falls very fast with mass, a factor of 2 error on the constraint of rate only translate into 10-20% error on the constraint of mass

$$\sigma \sim \frac{1}{m^{(6-8)}}$$

Several LHC searches:



R-hadron searches

R-hadron = long lived charged and hadronizing particle

(CMS-PAS-EXO-11-022)

L = 1.09 fb^{-1}

If η is particularly small...

- Present limit on sgluons: M > 900 GeV

  We deduce the bounds for the color octets:

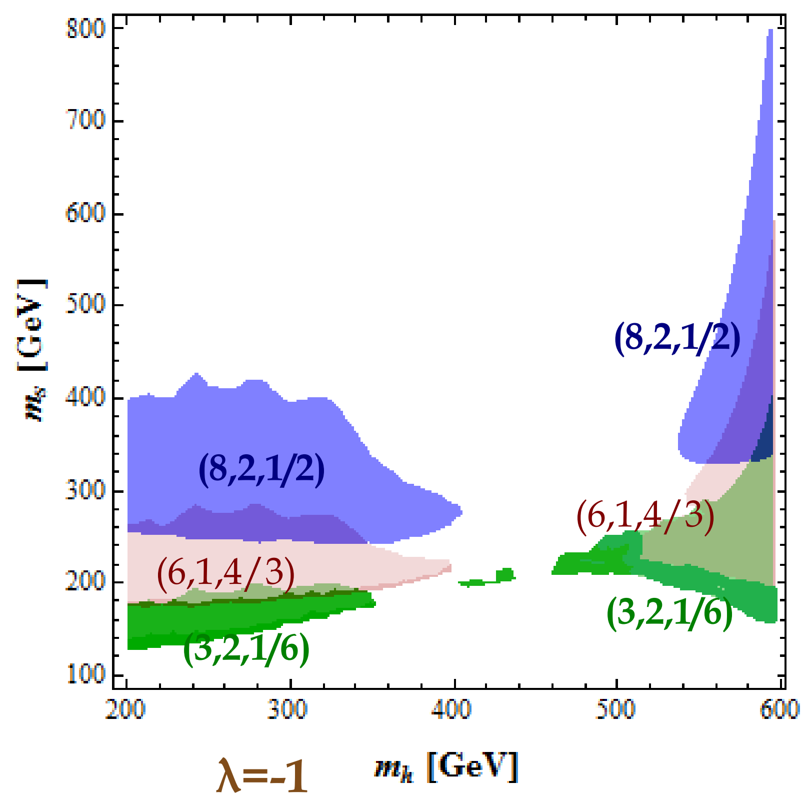
$$(8,1,0) \quad \to \quad m_S \gtrsim 800\text{GeV},$$
$$(8,2,Y) \quad \to \quad m_S \gtrsim 1000\text{GeV}$$

- Present limit on scalar tops: M > 620 GeV

  We deduce the bounds for the color triplets:

$$(3,1,0) \quad \to \quad m_S \gtrsim 600\text{GeV},$$
$$(3,2,Y) \quad \to \quad m_S \gtrsim 700\text{GeV}$$

Reminder:



Very difficult to hide a Higgs if the scalars are long lived ⟶ $\eta \gtrsim 10^{-7}$

Leptoquarks and 2j+missing energy searches

Only for color triplets:

- $2j + \not{E}_T$: similar to Susy searches

$L = 1.04\ fb^{-1}$ ATLAS collaboration: arXiv:1109.6572.
$L = 1.14\ fb^{-1}$ CMS collaboration: arXiv:1109.2352.

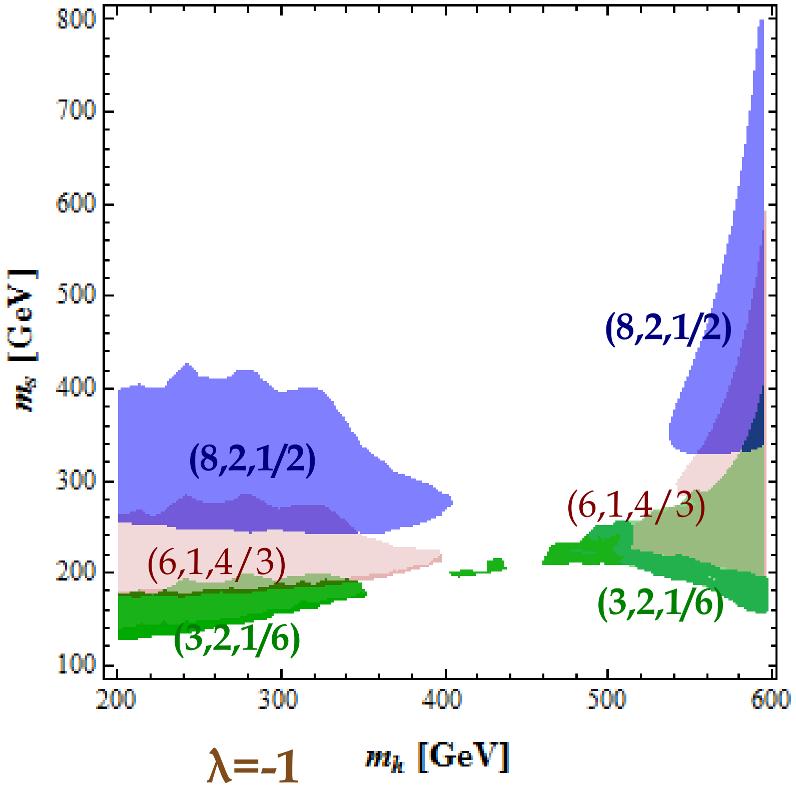
In the limit $m_{\tilde{g}} \to \infty,\ m_{\rm LSP} \to 0$, $M_{\rm squark} > 800$ GeV

We deduce the bounds for the color triplets:

$$(3,1,0) \;\to\; m_S \gtrsim 550\text{GeV},$$
$$(3,2,Y) \;\to\; m_S \gtrsim 650\text{GeV}$$

- $SU(2)_L$ gauge invariance requires that this final state co-exists with a lepto-quark-like $(\ell^- j)(\ell^+ j)$ final states

Reminder:



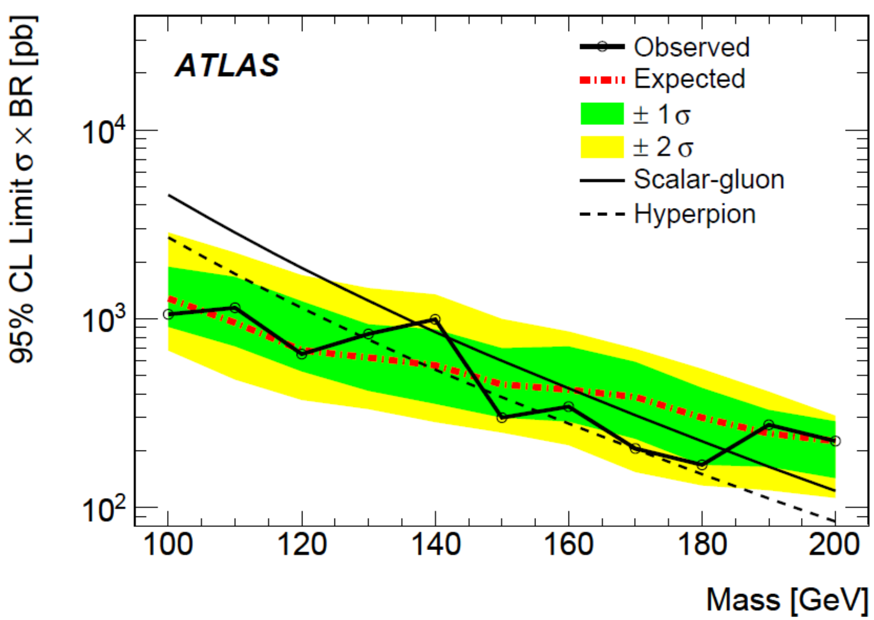
$L = 1.03\ fb^{-1}$ ATLAS collaboration: 1112.4828
$L = 1.8\ fb^{-1}$ CMS PAS EXO-11-030

$m_S > 650$ GeV (for first generation lepto-quarks)

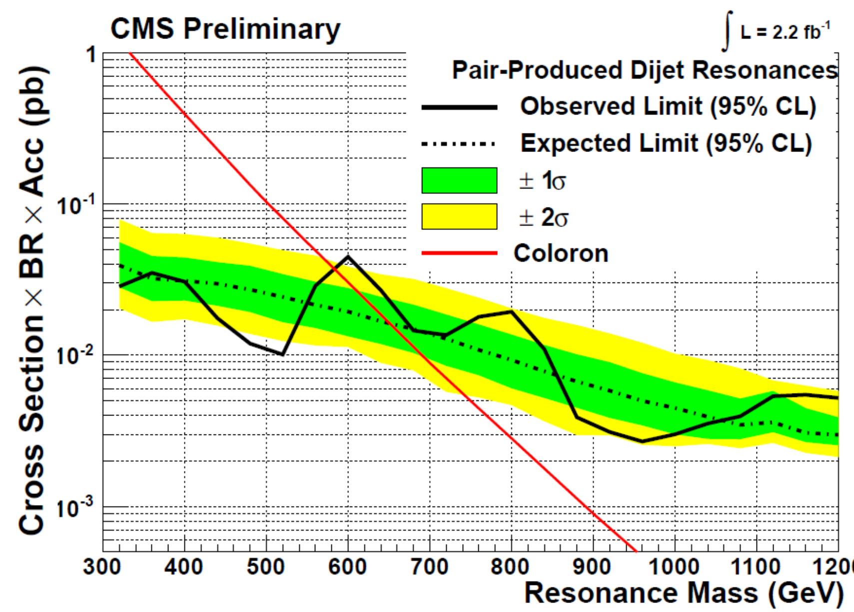
4 jet searches

A very common final state (both for triplets, sextets and octets)

A rather difficult channel because of the large QCD background



$L = 34\ pb^{-1}$ ATLAS collaboration: arXiv:1110.2693

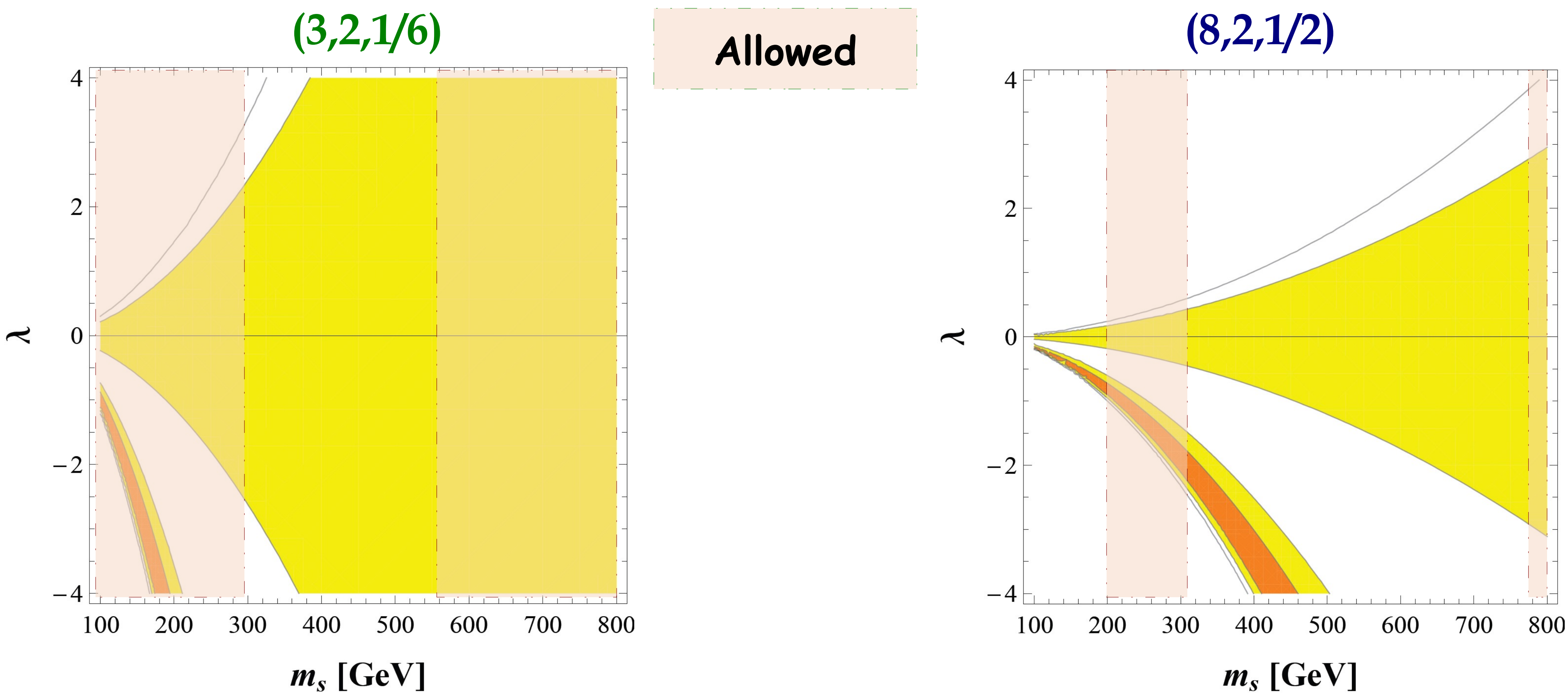


$L = 2.2\ fb^{-1}$ CMS PAS EXO-11-016 (last January public note)

New

Interplay with the Higgs phenomenology

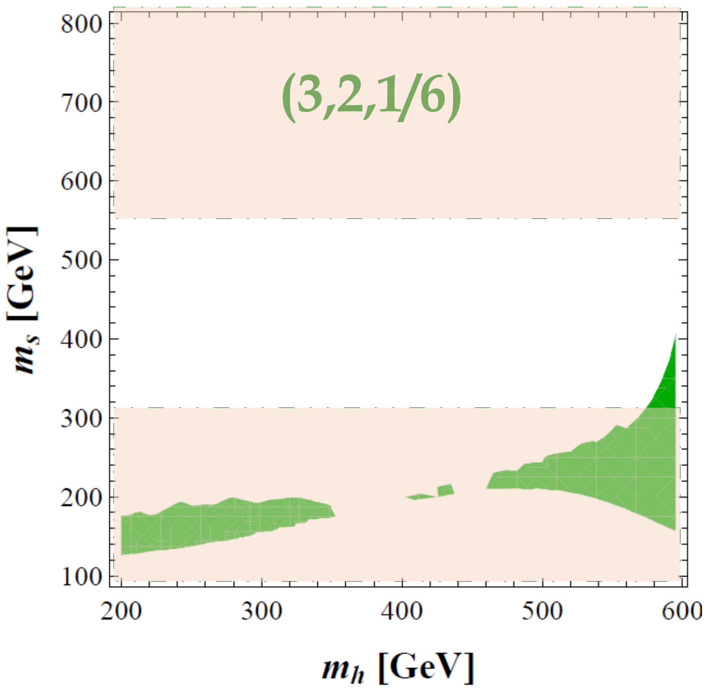
If the exotic scalars are decaying exclusively to 2 jets:



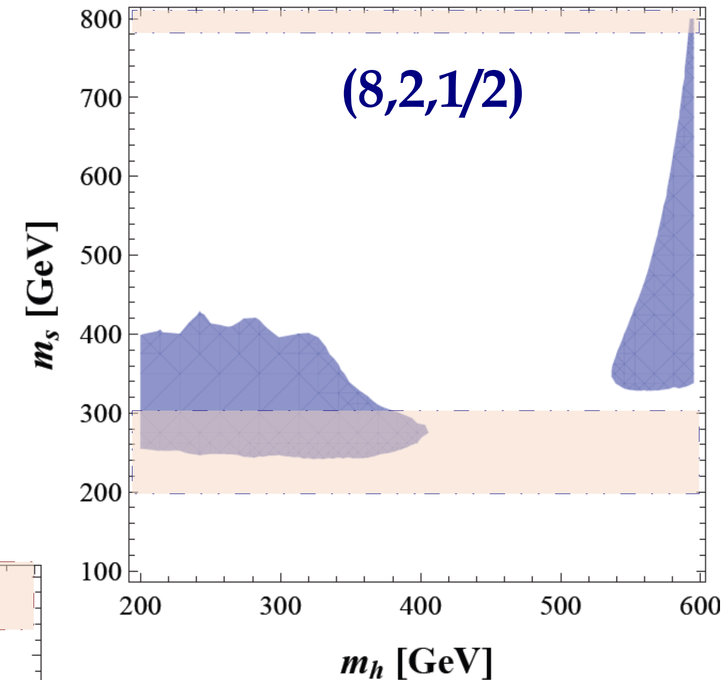
CMS fit for a light Higgs (m_h~125 GeV)

Interplay with the Higgs phenomenology

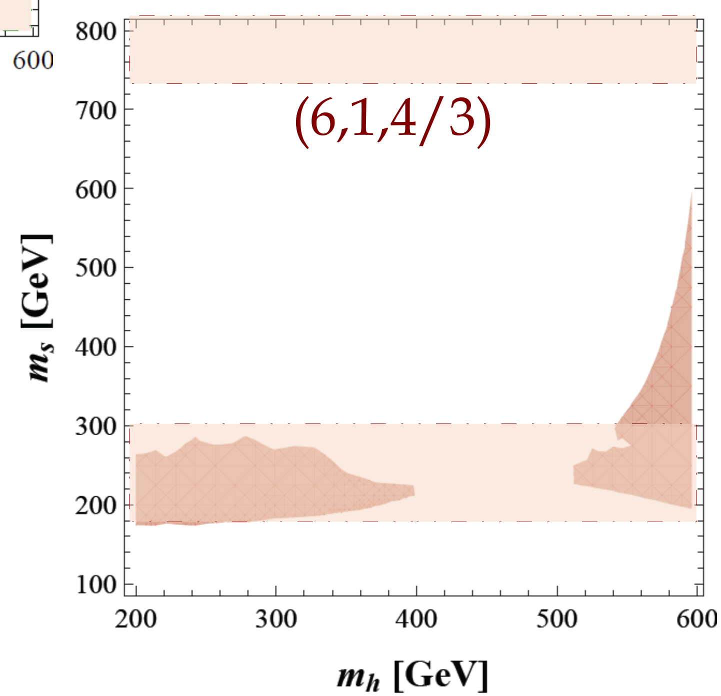
If the exotic scalars are decaying exclusively to 2 jets:



Allowed



Heavy hidden Higgs



Conclusions

- 2012 is going to be the year for the Higgs:
  - Confirm a light Higgs signal, or
  - Rule out SM-like weakly coupled Higgs.

- Rich implications for NP particles interacting with the Higgs (Higgs portal)

$$\lambda H^\dagger H \mathcal{O}_{\rm NP}$$

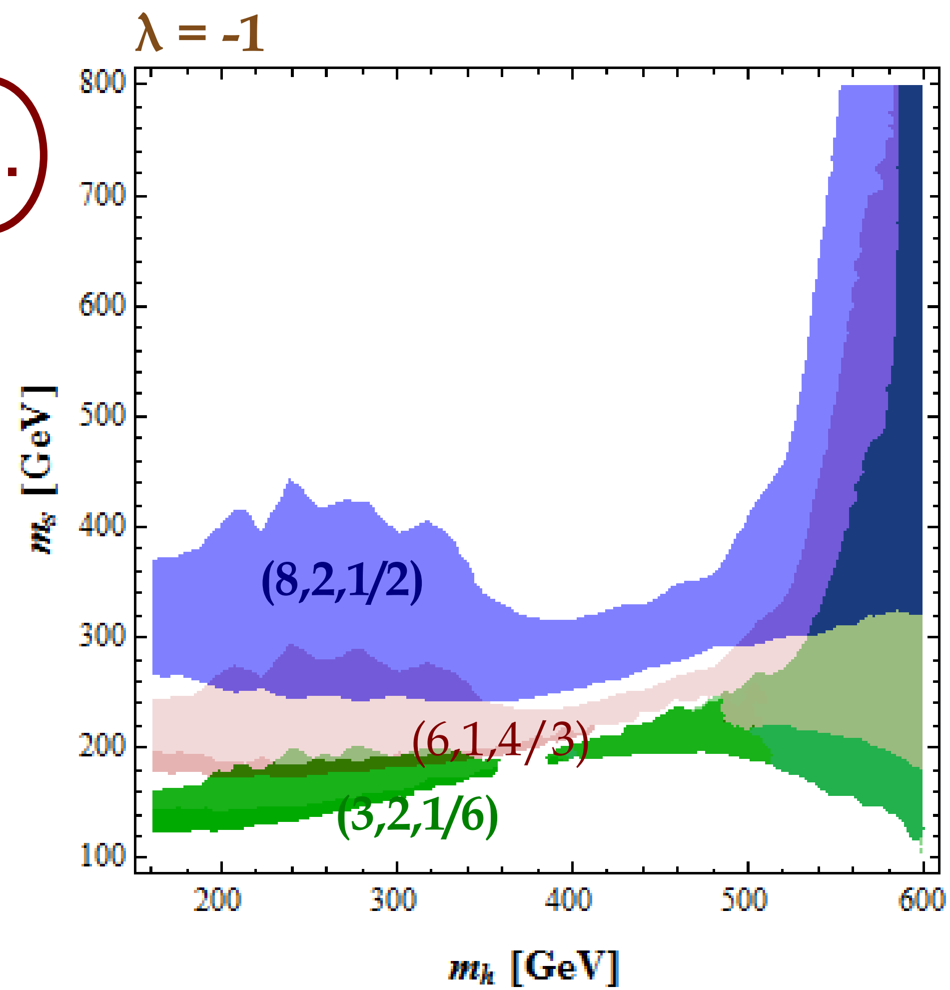
  - Already with 10 fb^{-1}, direct searches of colored scalars are close to mass scales needed to hide a heavy Higgs.

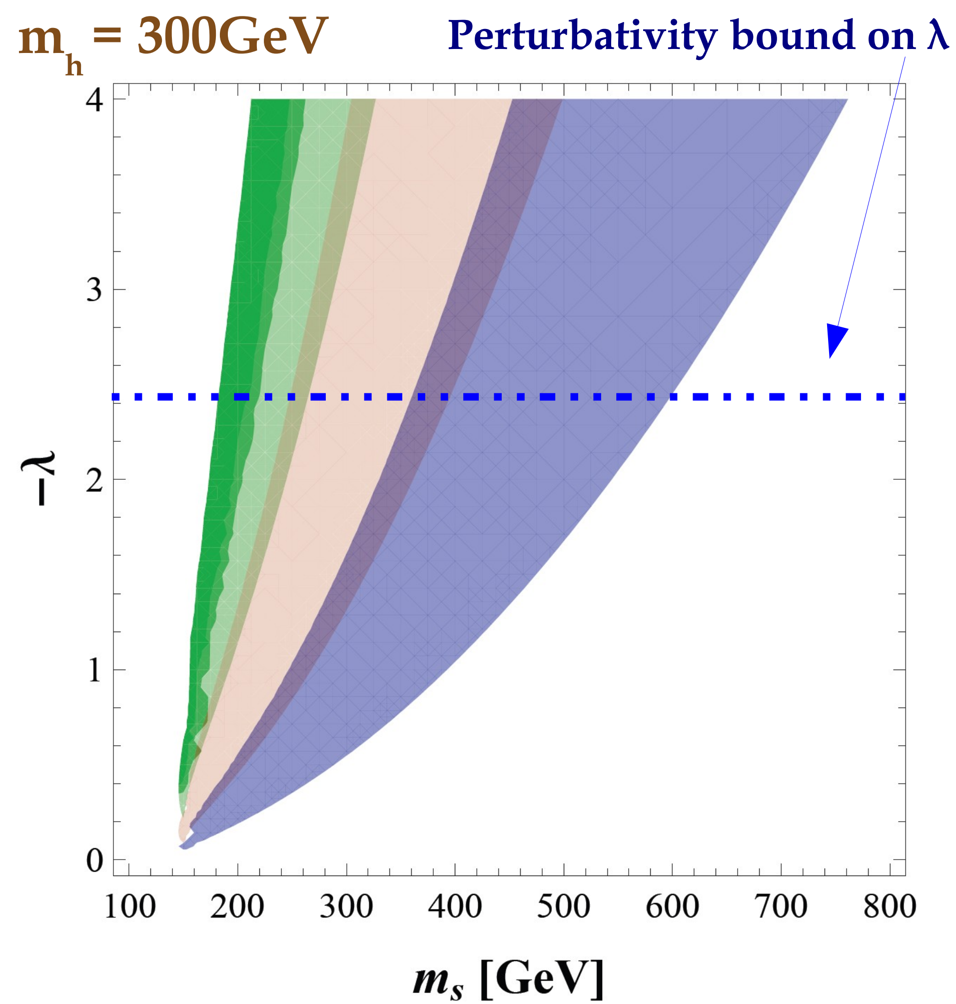
- Complementarity between exotic scalar searches and Higgs phenomenology
  - If deviations from SM-like Higgs are observed, the light exotic matter coupling through the Higgs portal will provide a promising and experimentally testable explanation.

Most exciting scenario!

A hidden heavy Higgs (as last December)

2.





Now the bounds on m_h > 350 GeV

are more stringent especially because of the ZZ channel

Coupling with SM fermions, an example

Example: color octet $(\mathbf{8}, \mathbf{2}, \frac{\mathbf{1}}{\mathbf{2}})$

$$S_a^b = \begin{pmatrix} S_+ \\ S_0 \end{pmatrix}_a^b$$

1. It interacts with $\bar{u}_R Q$

$$\mathcal{L}_{\text{fermion}} \supset \eta_{ij} (\bar{u}_R^{\alpha})^{ai} (u_{L\alpha})_b^j (S_0)_a^b - \eta_{ij} (\bar{u}_R^{\alpha})^{ai} (d_{L\alpha})_b^j (S_+)_a^b + \text{h.c.}$$

This Lagrangian mediates the decays $S_0 \to u^i \bar{u}^j,\ S_+ \to u^i \bar{d}^j$

With LHC signatures from SS$^{(*)}$ production:

$$(jj)(jj), (tj)(\bar{t}j), (bj)(\bar{b}j), (t\bar{b})(\bar{t}b), (t\bar{t})(t\bar{t})$$

a,b,c,... $SU(3)_c$ indices
i,j,k,... flavor indices
α,β,γ,... Lorentz indices

2. It interacts with $\bar{Q} d_R$

$$\mathcal{L}_{\text{fermion}} \supset \eta_{ij} (\bar{u}_{L\dot{\alpha}})^{ai} (d_R^{\dot{\alpha}})_b^j (S_+)_a^b + \eta_{ij} (\bar{d}_{L\dot{\alpha}})^{ai} (d_R^{\dot{\alpha}})_b^j (S_0)_a^b + \text{h.c.}$$

This Lagrangian mediates the decays $S_0 \to d^i \bar{d}^j,\ S_+ \to u^i \bar{d}^j$

With LHC signatures from SS$^{(*)}$ production:

$$(jj)(jj), (tj)(\bar{t}j), (bj)(\bar{b}j), (t\bar{b})(\bar{t}b), (b\bar{b})(b\bar{b})$$

Some of these signatures are already pretty constrained by the LHC!

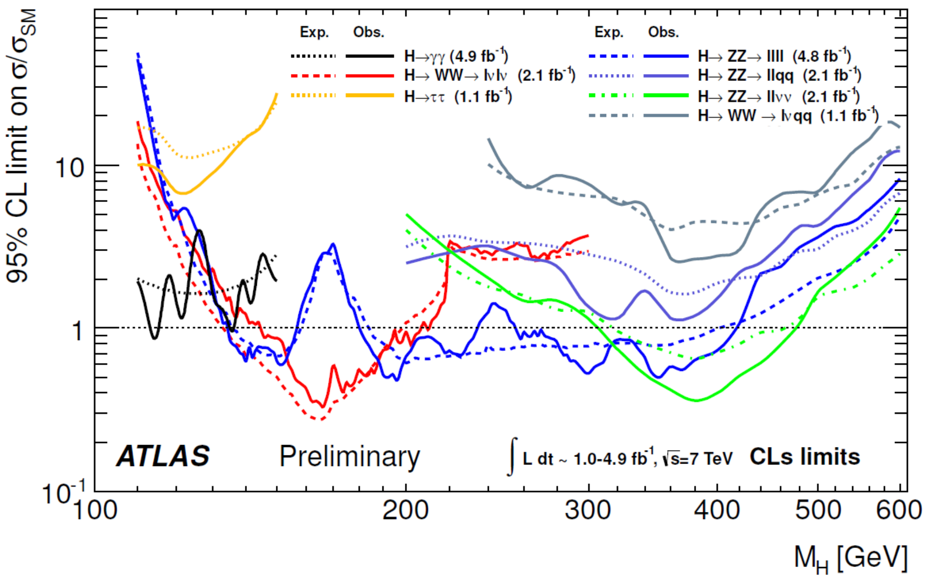
A heavy SM Higgs in trouble (2)

ATLAS-CONF-2011-163

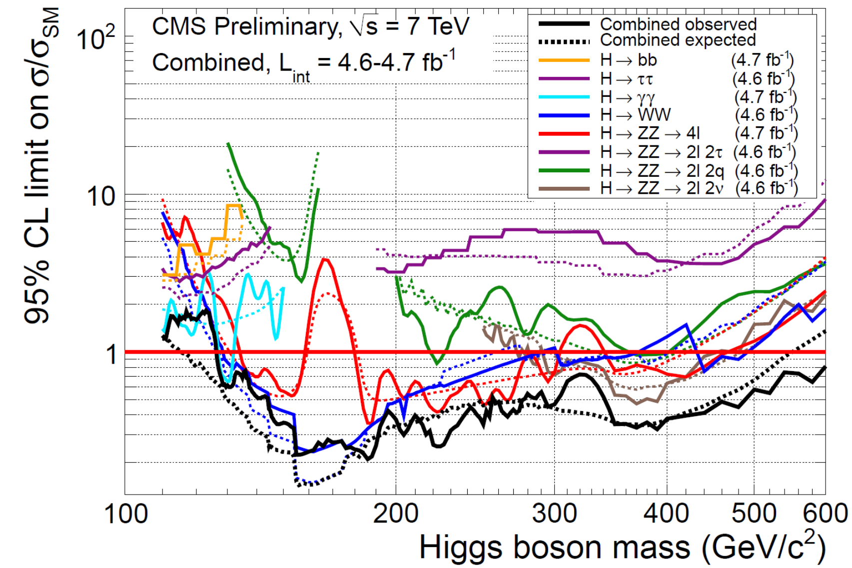
Last December results

CMS PAS HIG-11-032

ATLAS



CMS



$$\begin{aligned}
h &\to ZZ^* \to \ell^+\ell^-\ell^+\ell^- && 4.8\text{fb}^{-1}\\
h &\to \gamma\gamma && 4.9\text{fb}^{-1}\\
h &\to WW^* \to \ell^+\nu\ell^-\bar\nu && 2.1\text{fb}^{-1}\\
h &\to ZZ \to \ell^+\ell^-\nu\bar\nu && 2.1\text{fb}^{-1}\\
h &\to ZZ \to \ell^+\ell^- q\bar q && 2.1\text{fb}^{-1}\\
h &\to \tau\tau && 1.04\text{fb}^{-1}\\
h &\to WW \to \ell^+\ell^- q\bar q && 1.04\text{fb}^{-1}
\end{aligned}$$

All channels are updated with full luminosity (4.6-4.7 fb^{-1})

$$\begin{aligned}
h &\to ZZ^* \to \ell^+\ell^-\ell^+\ell\\
h &\to \gamma\gamma\\
h &\to WW^* \to \ell^+\nu\ell^-\bar\nu\\
h &\to ZZ \to \ell^+\ell^-\nu\bar\nu\\
h &\to ZZ \to \ell^+\ell^- q\bar q\\
h &\to \tau\tau\\
h &\to bb\\
h &\to ZZ^* \to \ell^+\ell^-\tau^-\tau^+
\end{aligned}$$

At high mass, main relevant channels are WW and ZZ.
They are giving strong constraints for mh ≥ 150GeV