XL International Meeting on Fundamental Physics
Benasque May 24-June 03, 2012

AKA WM2012

Higgs (Theory)

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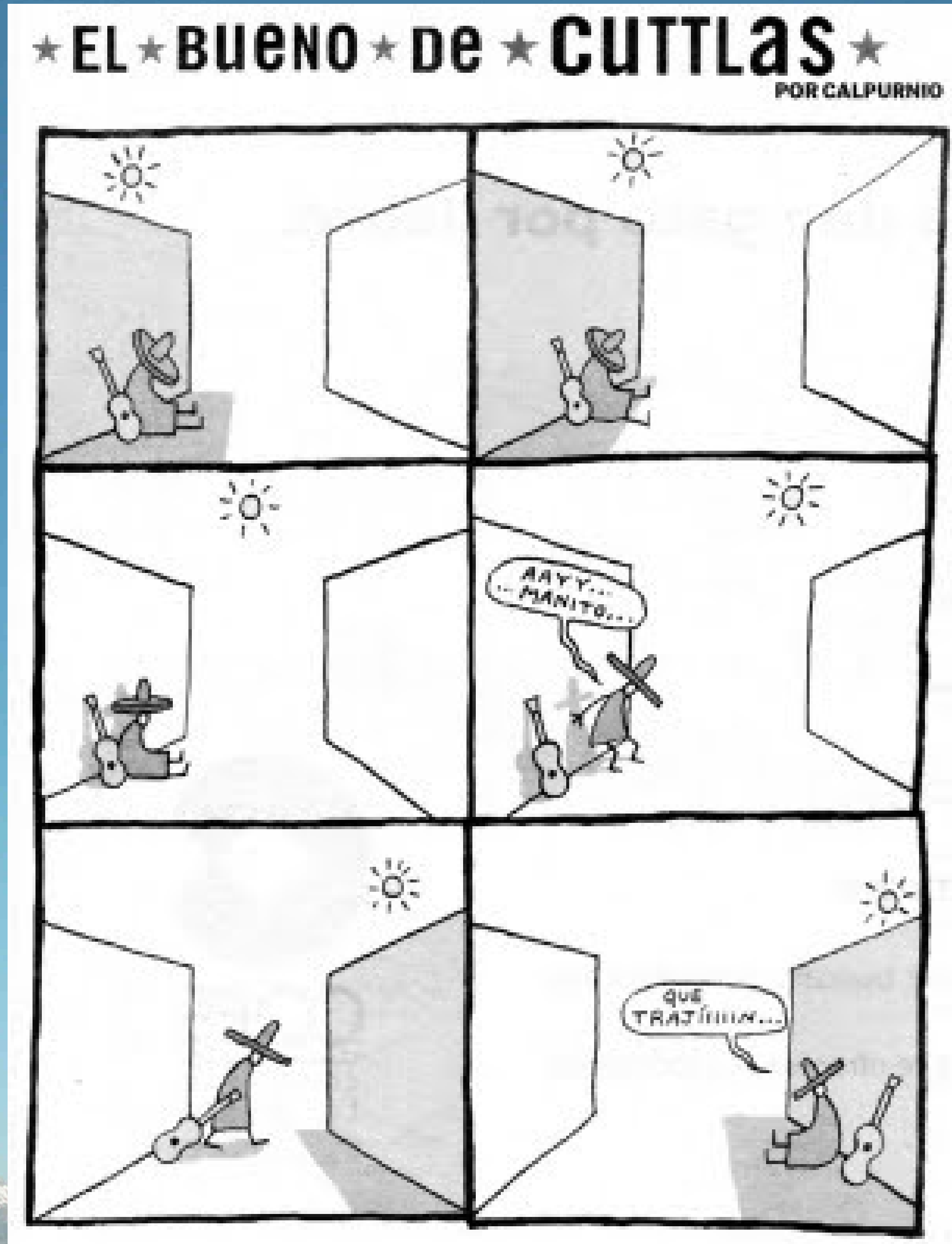
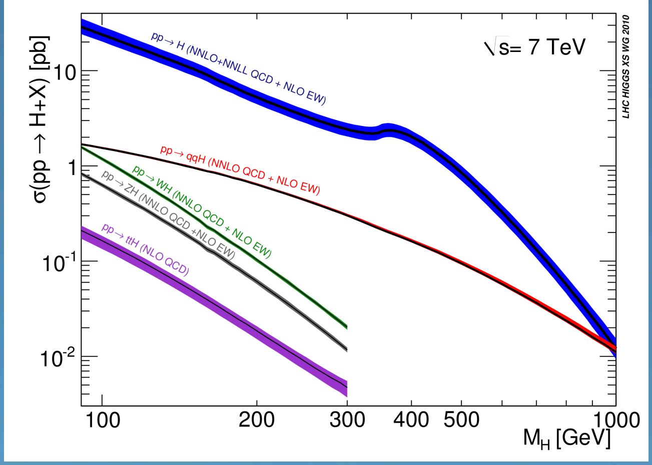
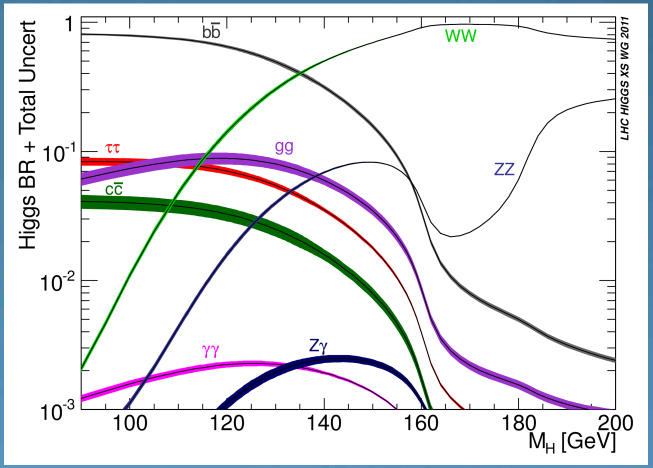
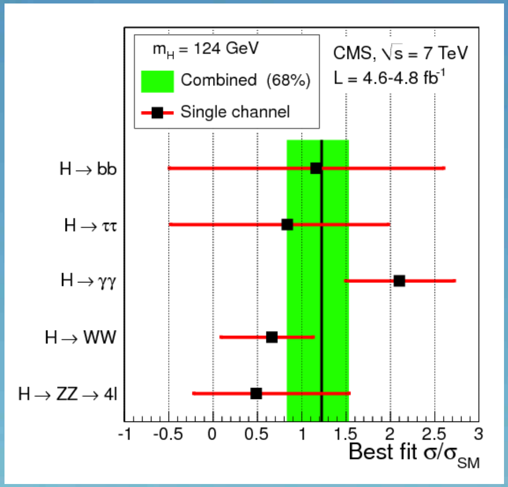

★ EL ★ BUENO ★ DE ★ CUTTLAS ★
POR CALPURNIO
AAYY... ...MANITO...
QUE TRAJÍIIIN...

SM Higgs





Naturalness



Flavor

SUSY

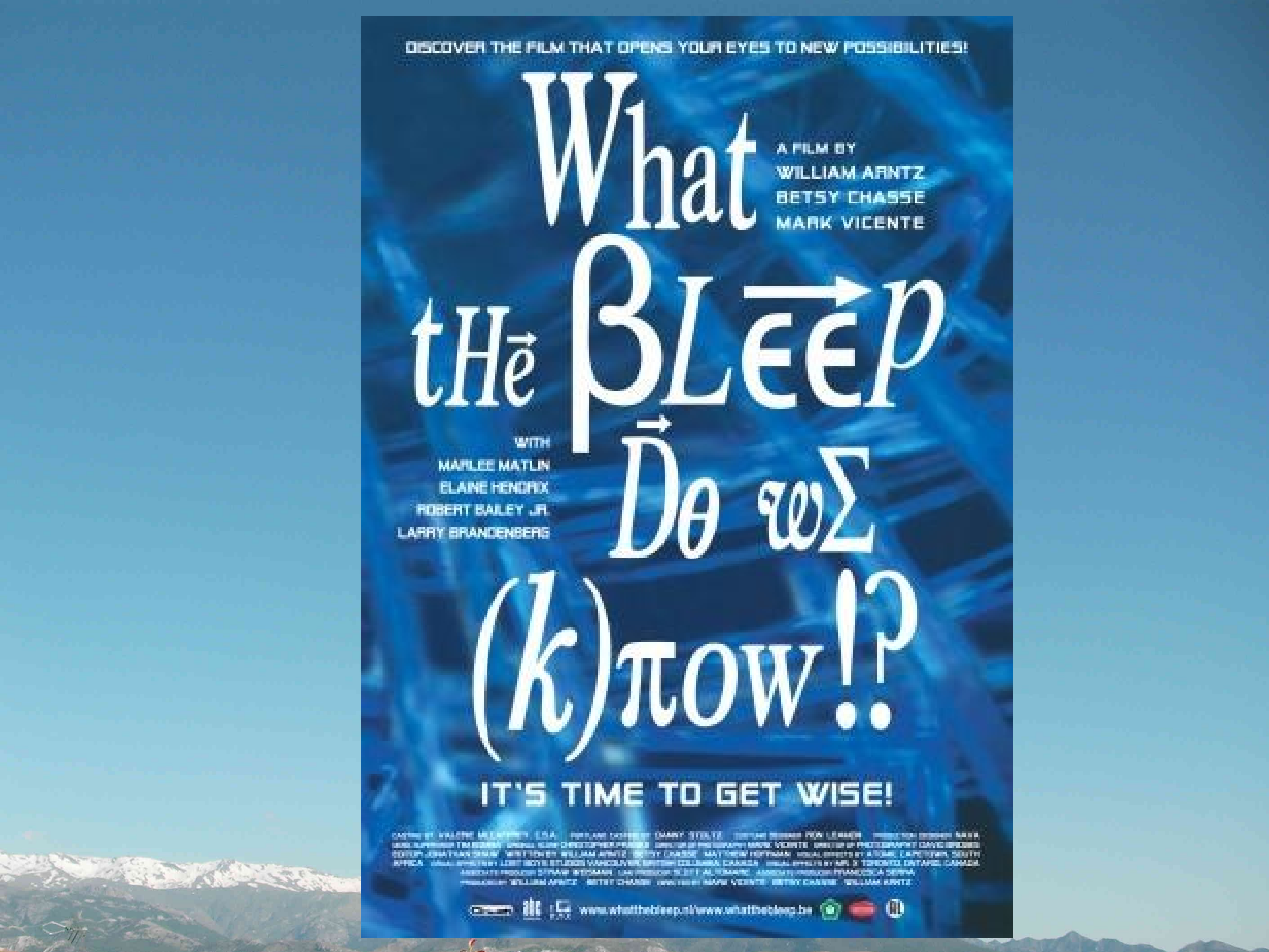
Composite H

No Higgs

??????

Outline

- What do we know about the Higgs?
  - Pre-LHC
  - At the dawn of LHC era
- Implications for BSM
  - 2HDM (SUSY)
  - Reinterpretation of SM Higgs searches
  - Don't forget non-minimal models
  - New old channels
  - Higgs portal
- Outlook


DISCOVER THE FILM THAT OPENS YOUR EYES TO NEW POSSIBILITIES!
What tHē βLEEP Đθ wΣ (k)πow!?
A FILM BY
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MARLEE MATLIN
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IT'S TIME TO GET WISE!
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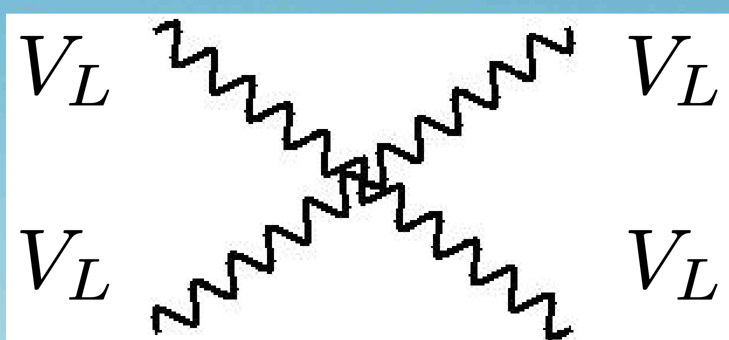
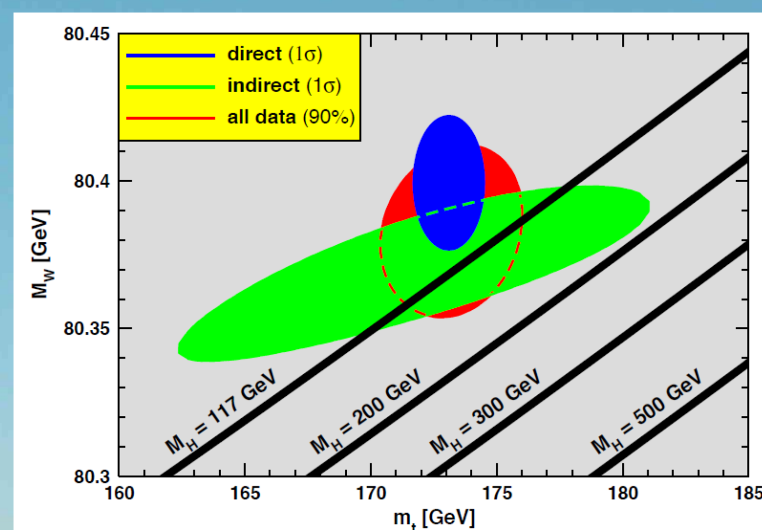
What do we know? (pre-LHC)

- The EW symmetry is spontaneously broken (3 would-be Goldstone bosons)
- Such theory (SM $\ominus$ Higgs):
  - Becomes strongly coupled at ~ 1 TeV
  - Is inconsistent with EW precision data





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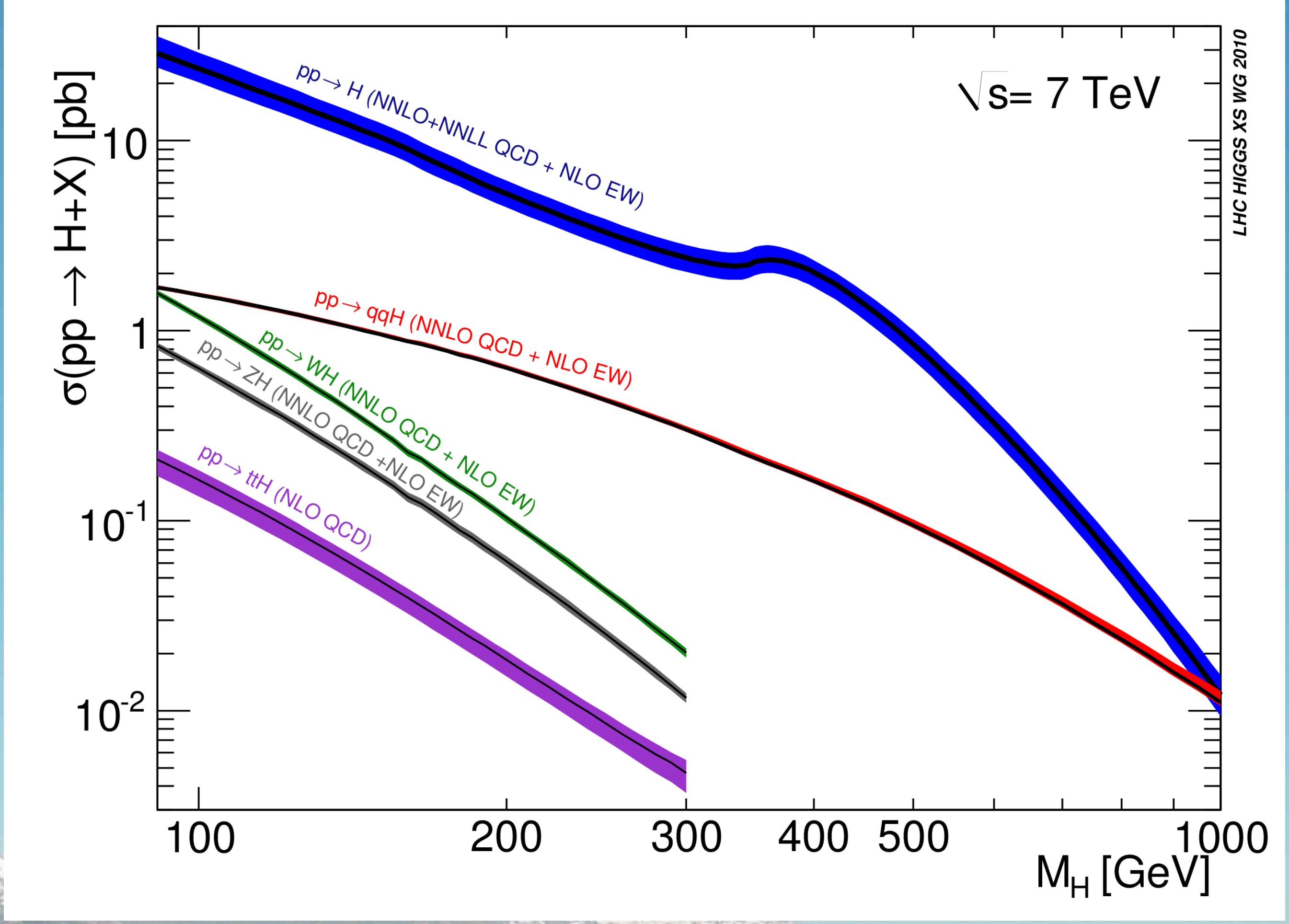
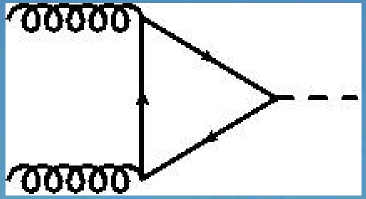
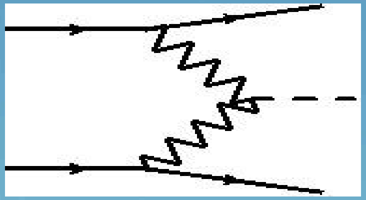
- The EW symmetry is spontaneously broken (3 would-be Goldstone bosons)
- Such theory (SM $\ominus$ Higgs):
  - Becomes strongly coupled at ~ 1 TeV
  - Is inconsistent with EW precision data
- SM Higgs fixes both problems but:
  - Must be $114.4\ \mathrm{GeV} \leq m_H \leq 149\ \mathrm{GeV}$
  - Is not natural (and does not explain flavor, DM, ...)
- More natural solutions can also fix these problems and explain other features

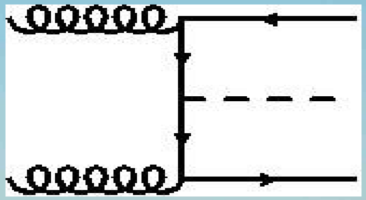
What do we know? (theory)

- Production cross section and decays well known









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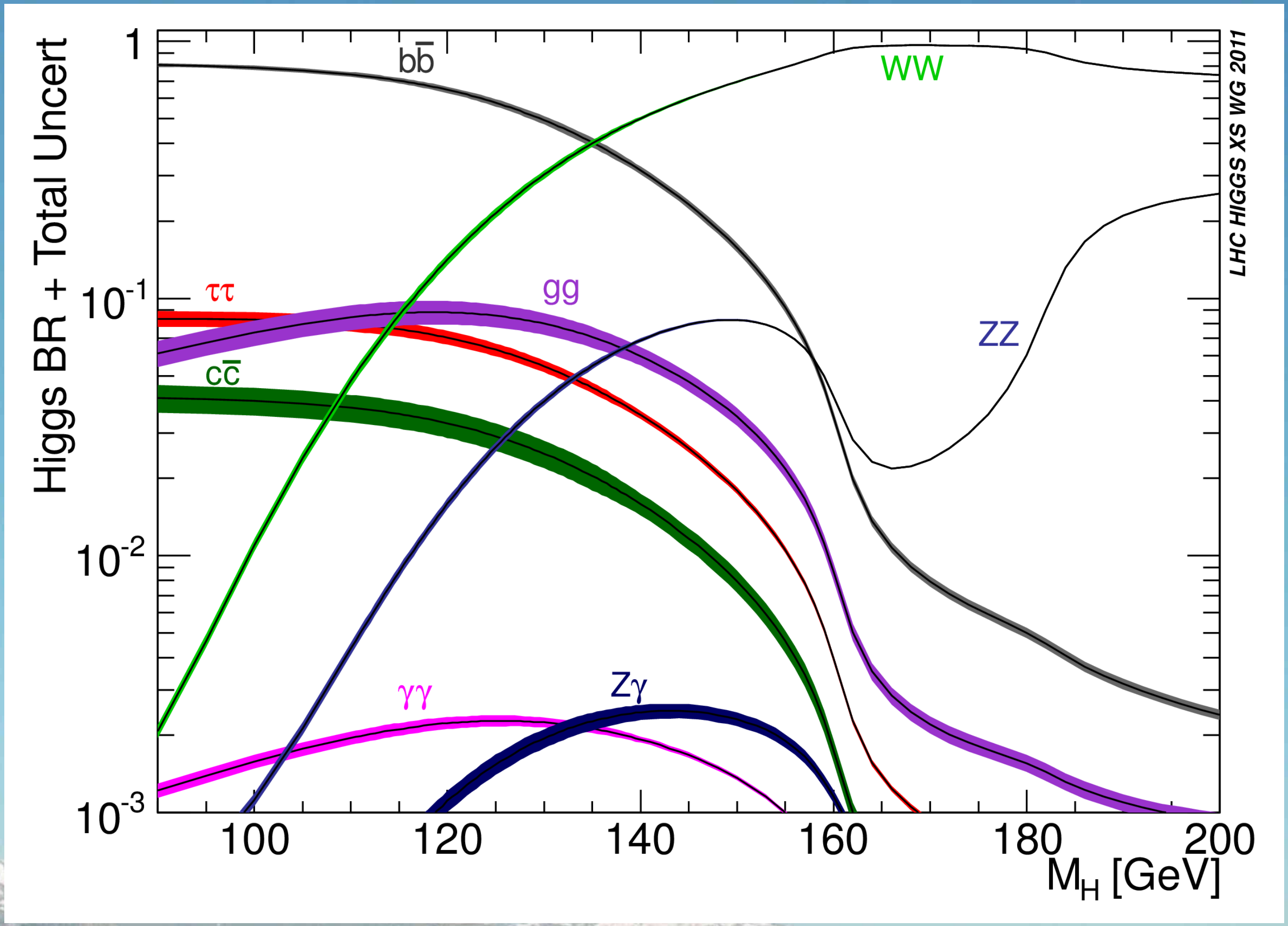
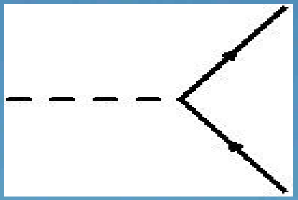
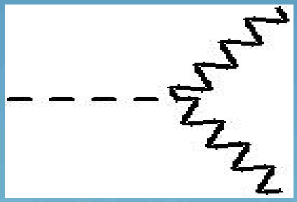
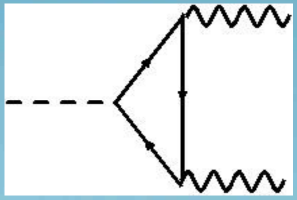
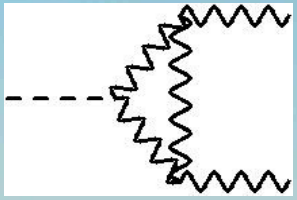










What do we know? (theory)

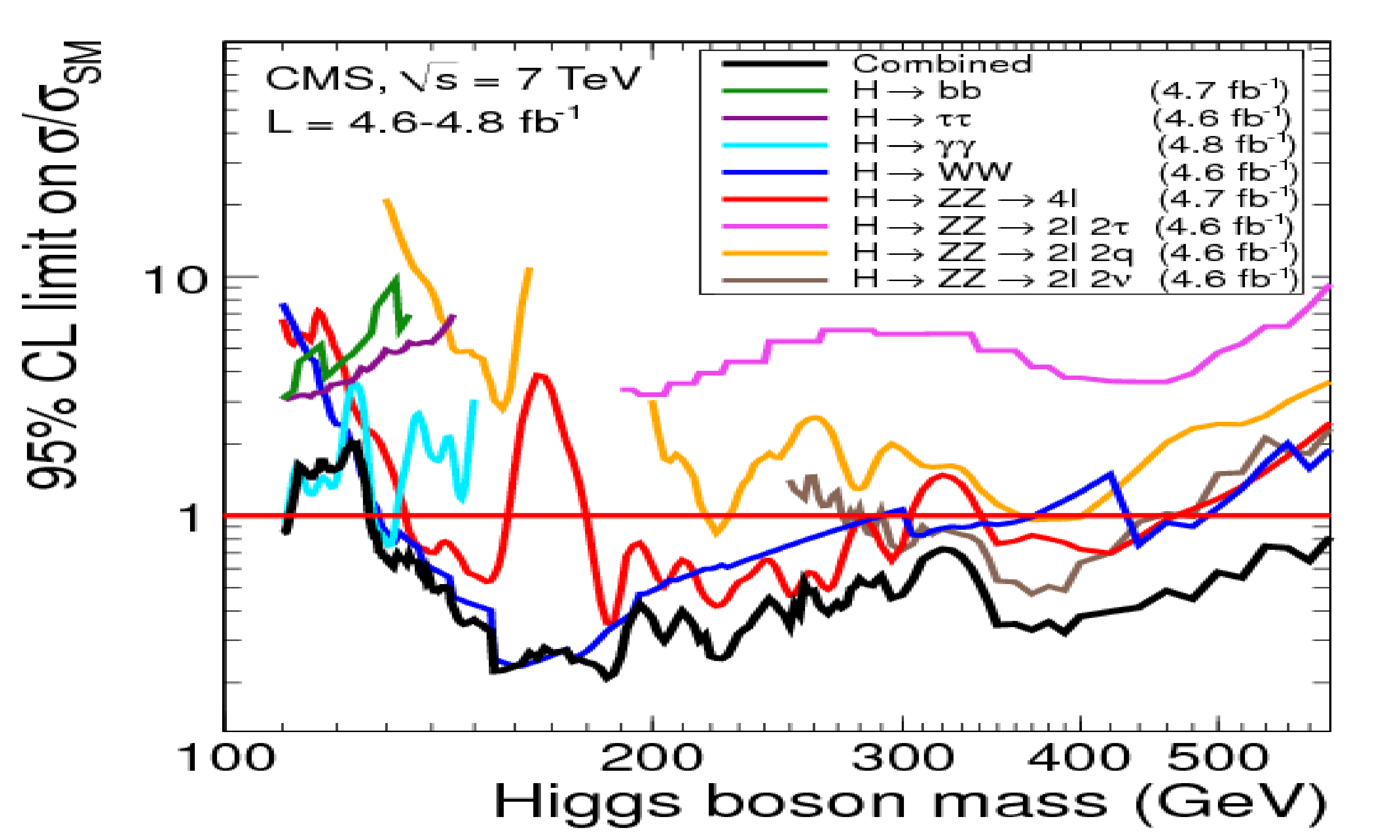
- Production cross section and decays well known
- Uncertainty in the theoretical prediction ~10-20%
  - From higher orders, PDFs, HQEF, …
  - The size depends on the channel
  - Limit to precision in SM tests
- We are behind in BSM models but
  - Quite accurate results (NLO and some NNLO) in the MSSM
  - Symmetry cancellations in Composite Higgs make inclusion of higher order terms simple

What do we know? (experiment)

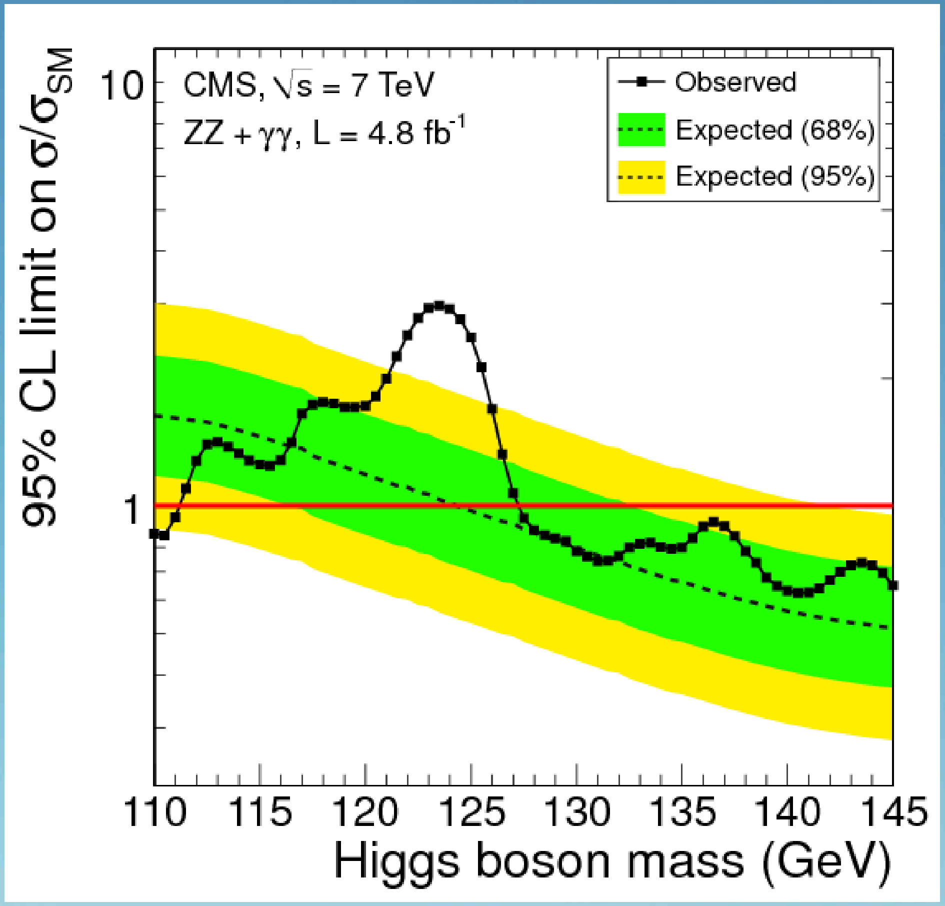
- We are finally getting our first peak at the “Higgs sector” from the Tevatron and LHC experiments
- Tevatron results will be discussed at length by Aurelio
- LHC results will be summarized by Javier
- The punch lines:
  - A SM Higgs with $128\ \mathrm{GeV} \lesssim m_h \lesssim 600\ \mathrm{GeV}$ is excluded at 95% CL (+ other lighter masses, depending on experiment)
  - TEVATRON combination and ATLAS and CMS all see an INCONCLUSIVE excess in approximately THE SAME RANGE OF HIGGS MASSES

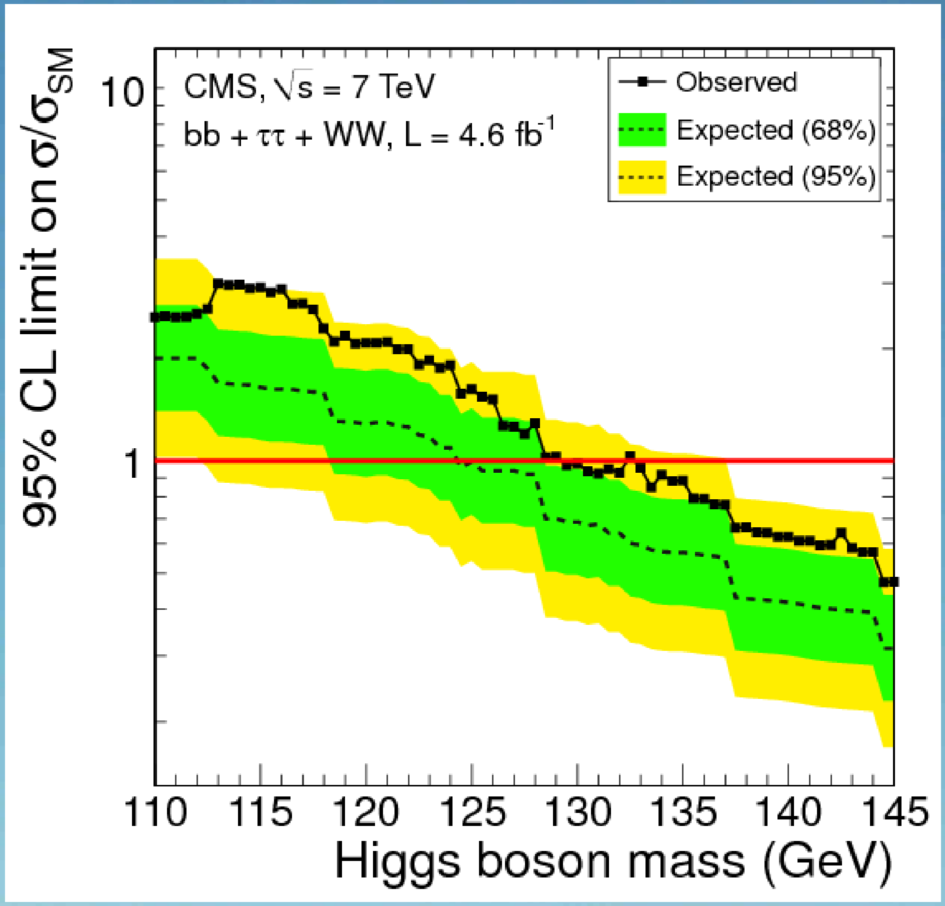
Compatible with the SM Higgs
… and with many other things

What do we know? (experiment)



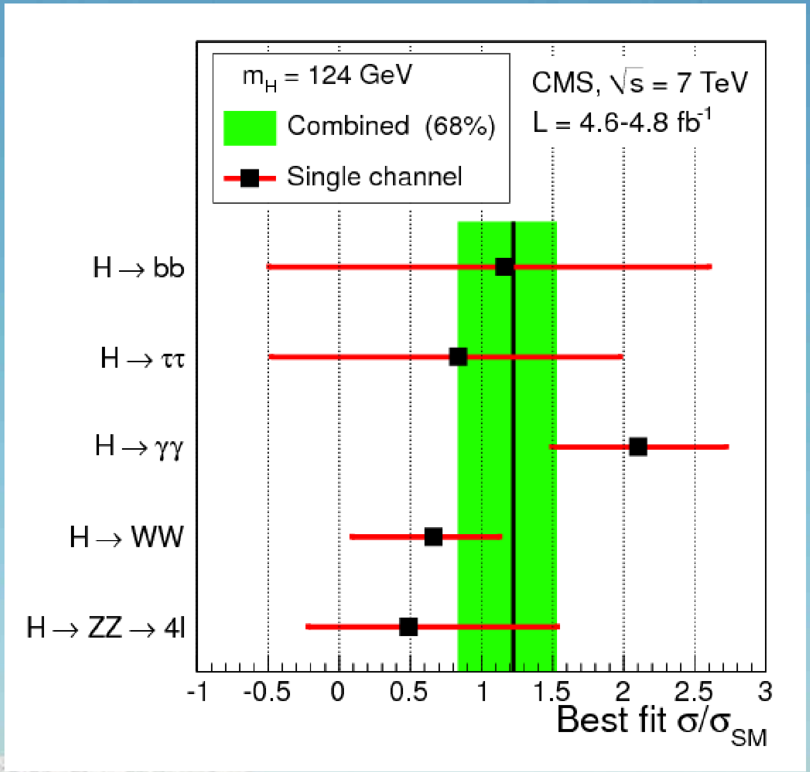
What do we know? (experiment)





What do we know? (experiment)

- Evaluation of the excess (CMS, “similar” for ATLAS):
  - Excess found at mh=124 GeV with a local significance of 3.1σ, down to 1.5 (2.1) after LEE

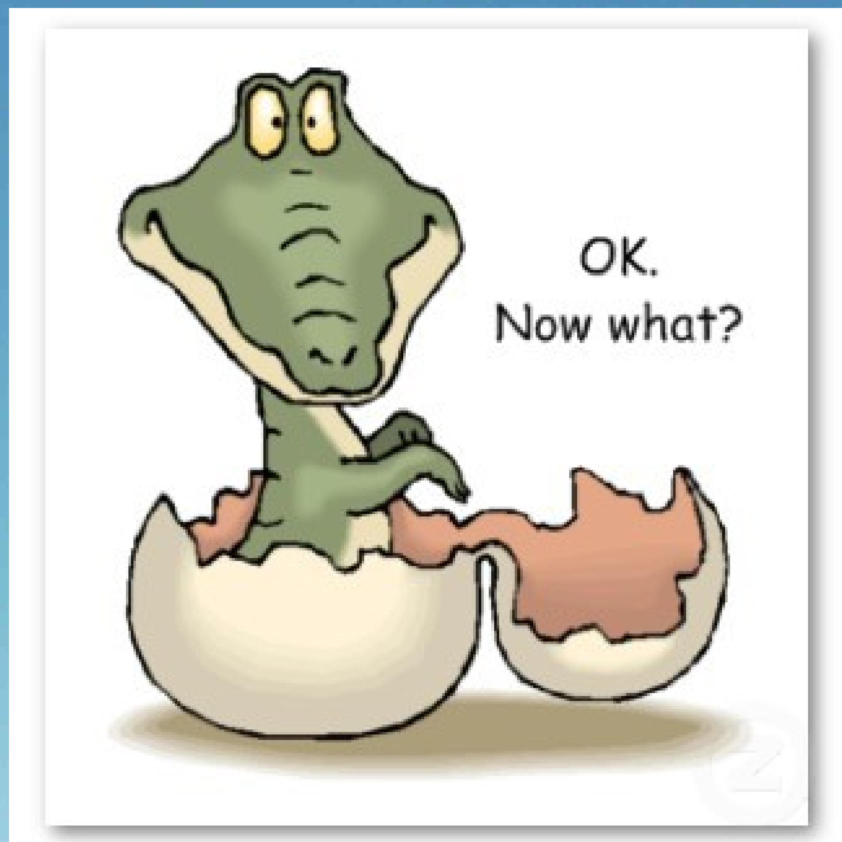


What do we know? (experiment)

- BSM Higgs searches also on-going

Examples from BSM Higgs boson searches

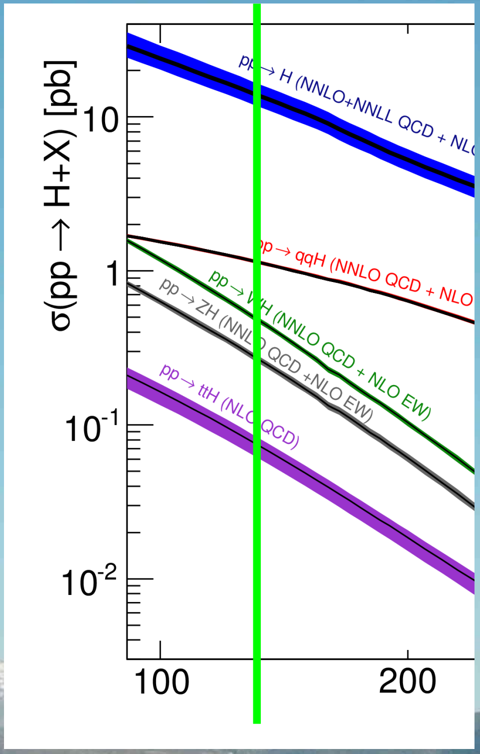
$H \rightarrow \tau\tau$	(2 HDM, MSSM)
$H+ \rightarrow \tau\nu$ (cs)	(2HDM, MSSM)
Fermiophobic Model	
4th Generation „SM“	
$a \rightarrow \mu\mu$	(extra singlet, NMSSM)
$H++ \rightarrow l^+l^+$	(Higgs Triplett, Little Higgs)
Long lived H	(Hidden Valley, R-Par-Vio. SUSY, NMSSM)

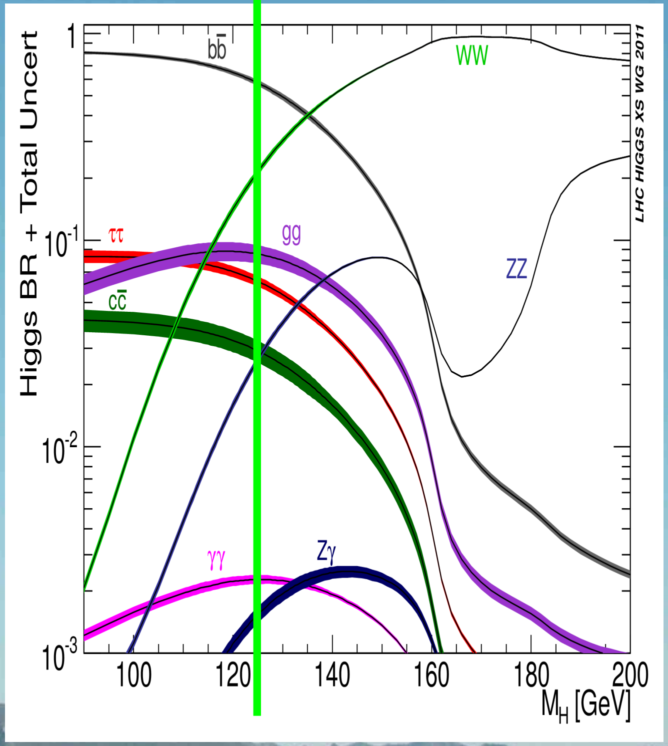

OK.
Now what?

Now What?

- Confirm (or rule out) the discovery of “a Higgs”
- Study its properties:
  - Mass and couplings (to SM, to self, invisible)
  - Spin, CP properties

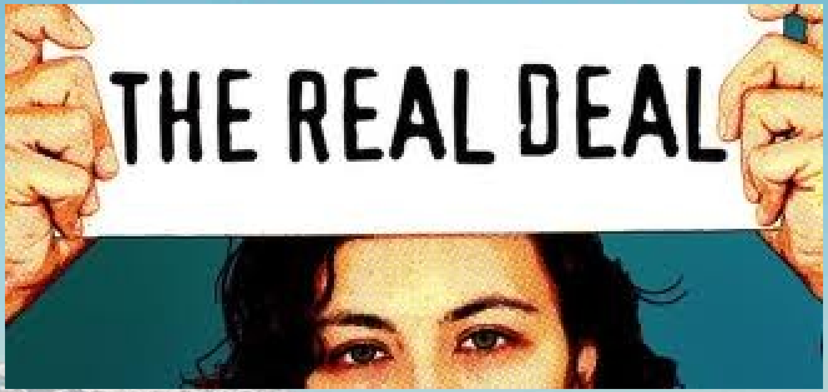
$$m_h = 125\ \mathrm{GeV}$$





Now What?

- Confirm (or rule out) the discovery of “a Higgs”
- Study its properties:
  - Mass and couplings (to SM, to self, invisible)
  - Spin, CP properties
- Most BSM theories motivated by (lack of) naturalness in the SM Higgs sector: profound implications of Higgs searches in BSM

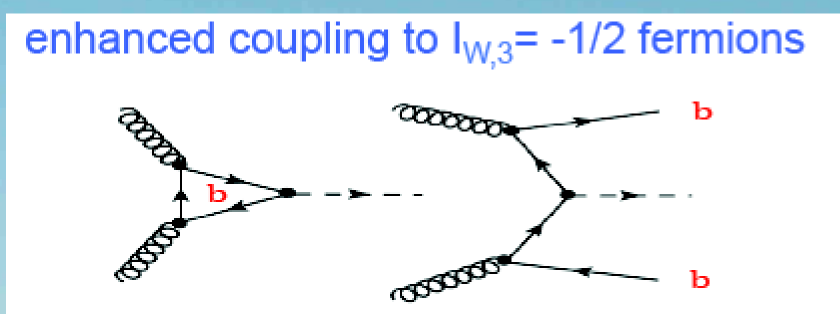


2HDM and SUSY

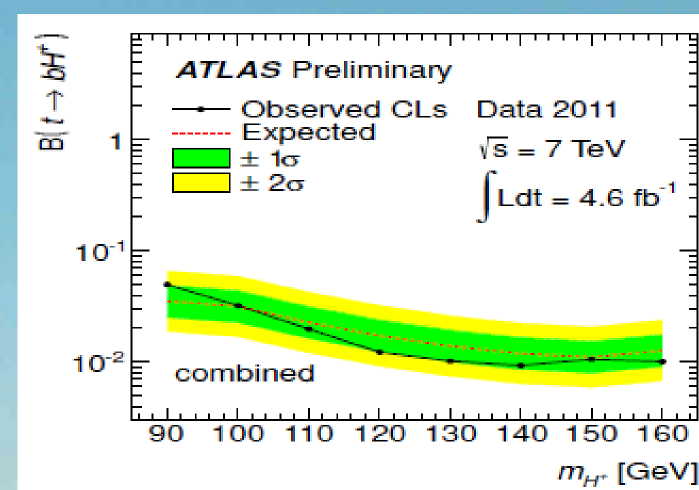
2HDM and SUSY

- SUSY implies 2HDM: 5 real scalars $h, \ H, \ A, \ H^{\pm}$
- Two main features beyond general 2HDM:
  - Couplings governed by SUSY: e.g. light h in MSSM
  - Complementary constraints from other searches (beyond the Higgs)

$\tan\beta$ enhancement

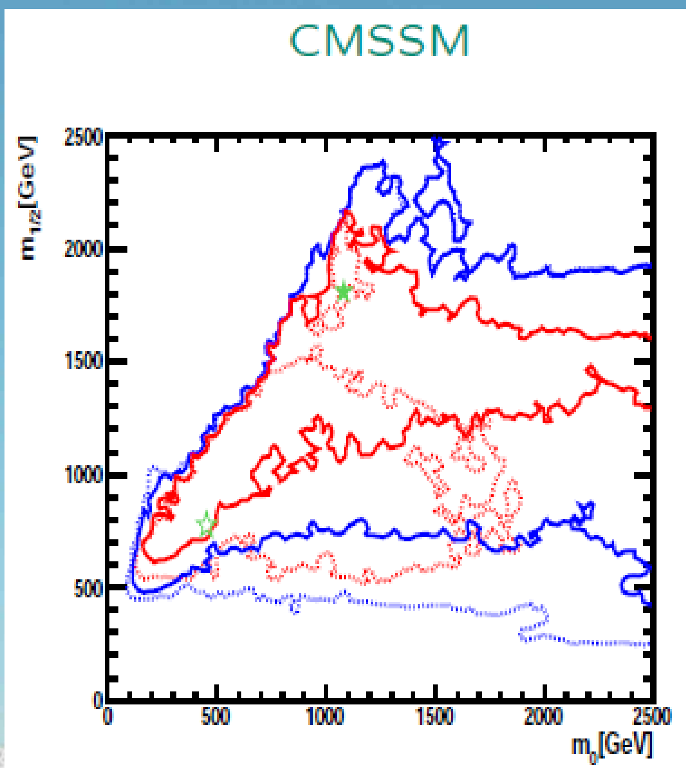


$H^{\pm}$ searches



2HDM and SUSY

- Current Higgs and sparticle searches impose important restrictions on minimal supersymmetric models (to be added to EWPO, g-2, DM, ...)



Model	Min. χ^2	Prob.	$m_{1/2}$ (GeV)	m_0 (GeV)	A_0 (GeV)	$\tan\beta$
CMSSM	21.5/20	37%	360	90	-50	15
LHC 1 fb^{-1}	28.8/22	15%	780	450	-1100	41
$M_h = 125$	30.6/23	13%	1800	1080	860	48

- General picture:
  - Heavy colored particles (LHC)
  - Light uncolored particles (EWPO)

Other models
...or rather

NO MODELS®
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Reinterpretation of SM searches

- Most searches interpreted in terms of a SM Higgs
- Reinterpretation in other models often non-trivial:
  - Possible if same kinematics (coupling changes) and channel by channel efficiencies/likelihoods known
  - Interpretation strategy required:
    - Arbitrary couplings
    - Effective Lagrangians (classes of theories)
    - Simplified models (interpretation of previous analyses)

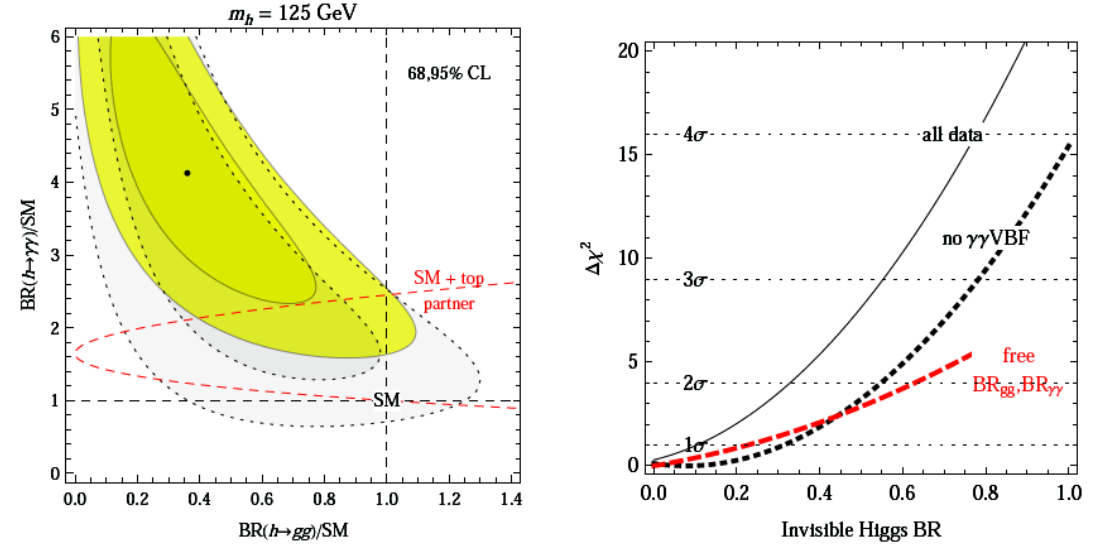
Reinterpretation of SM searches

- Fit to data with arbitrary couplings:
  - Sfitter: $g_{xxH} \equiv g_x = (1+\Delta_x) g_x^{\rm SM}$
  - In an effective theory below mt

Carmi, Falkowski, Kuflik, Volansky, 1202.3144

$$\mathcal{L}_{eff} = c_V \frac{2m_W^2}{v} h\, W_\mu^+ W_\mu^- + c_V \frac{m_Z^2}{v} h\, Z_\mu Z_\mu - c_b \frac{m_b}{v} h\, \bar{b} b - c_\tau \frac{m_\tau}{v} h\, \bar{\tau}\tau$$
$$+ c_g \frac{\alpha_s}{12\pi v} h\, G^a_{\mu\nu} G^a_{\mu\nu} + c_\gamma \frac{\alpha}{\pi v} h\, A_{\mu\nu} A_{\mu\nu}\,.$$

  - Can also include invisible decays

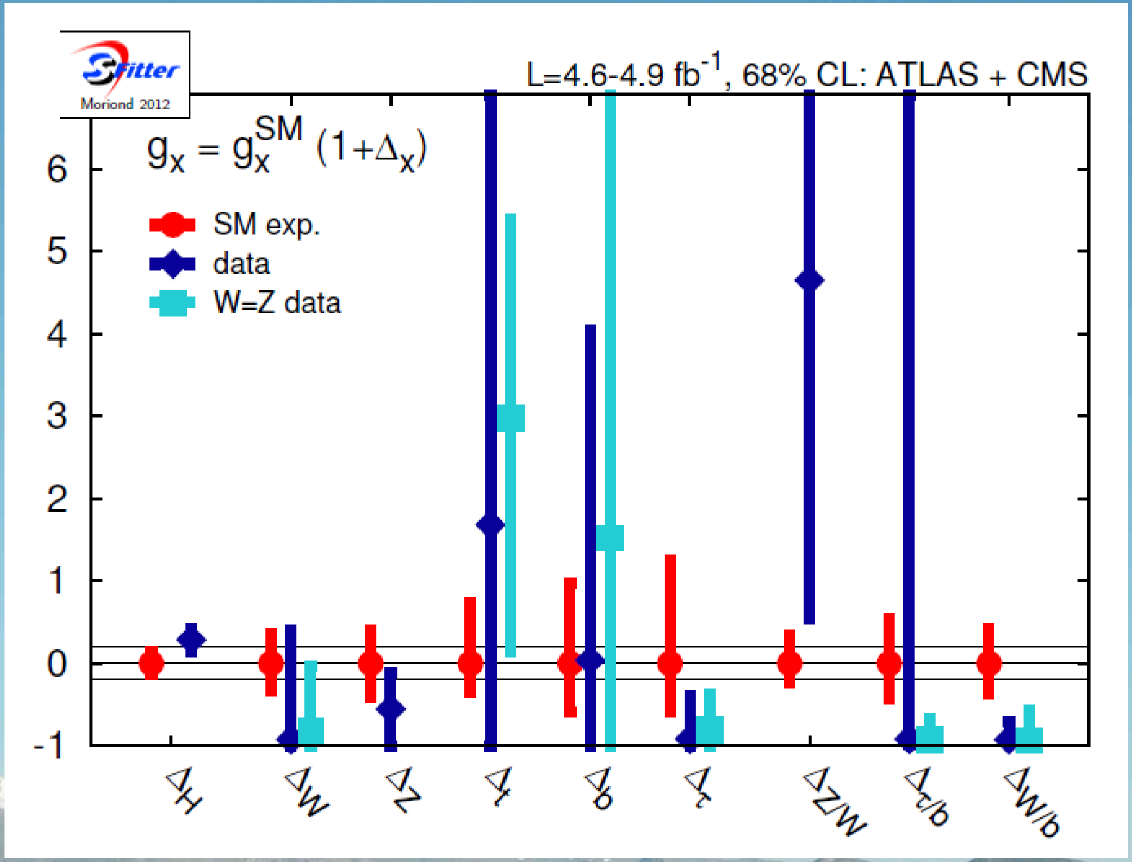


Giardino, Kannike, Raidal, Strumia, 1203.4254

Reinterpretation of SM searches

- Fit to data with arbitrary couplings:
  - Sfitter:

Klute, Lafaye, Plehn, Rauch, Zerwas, 1205.2699



} $\pm 20\%$

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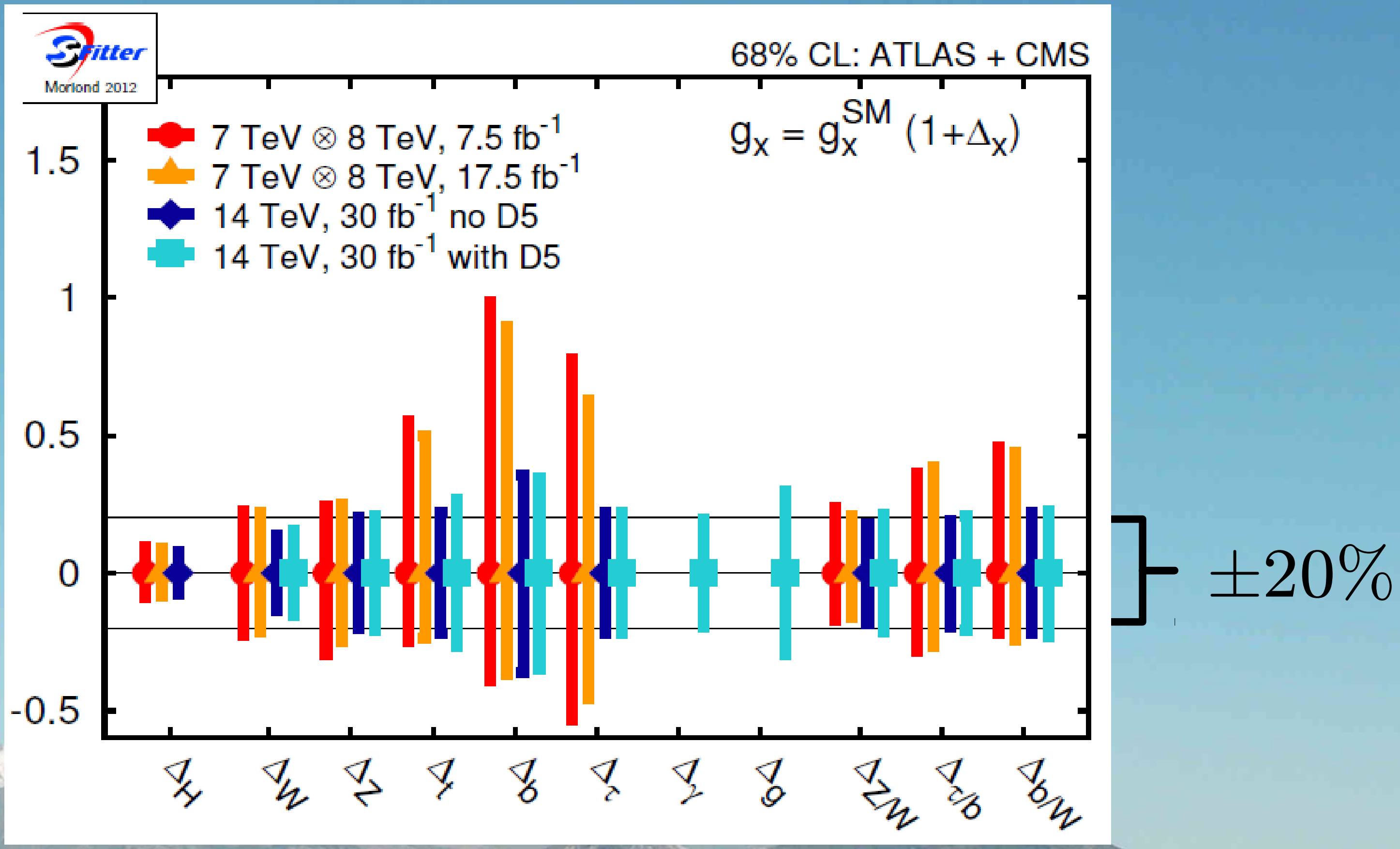

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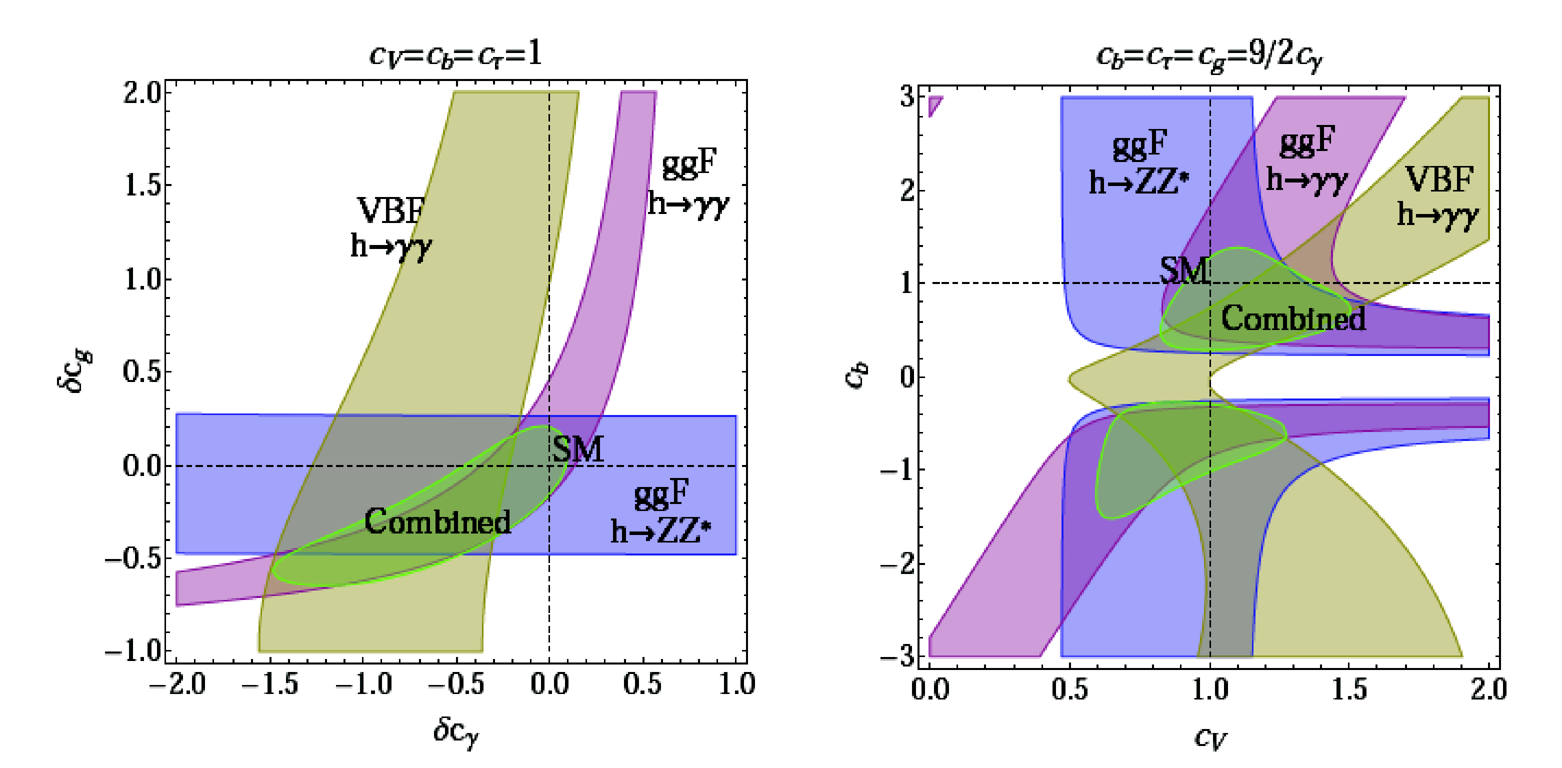
Carmi, Falkowski, Kuflik, Volansky, 1202.3144



Easy to map to simplified models

We could use a guiding principle

Reinterpretation of SM searches

- Effective Lagrangian description:
  - Choose your assumptions such that
    - A large class of models can be studied with a (relatively) small number of free parameters
    - Further features of the models can be explored
  - Example: Models of strong EWSB
    - No light new particles
    - New physics is custodially symmetric
    - No (large) flavor violation in the Higgs sector

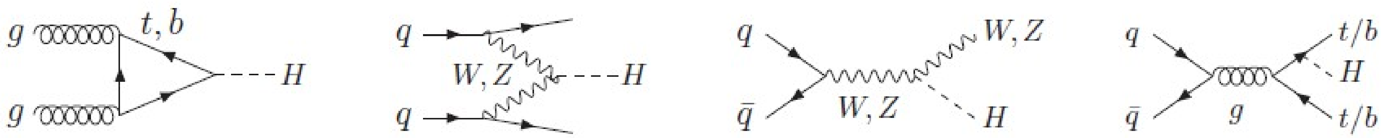
Reinterpretation of SM searches

- Example: Models of strong EWSB

Contino, Grojean, Moretti, Piccinini, Rattazzi, 1002.1011

$$\mathcal{L}^{(2)} = \frac{1}{2}(\partial_\mu h)^2 + \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right)\left(1 + 2a\,\frac{h}{v} + b\,\frac{h^2}{v^2} + \cdots\right)$$
$$- \frac{v}{\sqrt{2}}\lambda^u_{ij}\left(\bar{u}^{(i)}_L, \bar{d}^{(i)}_L\right)\Sigma\left(u^{(i)}_R, 0\right)^T\left(1 + c_u\,\frac{h}{v} + c_{2u}\,\frac{h^2}{v^2} + \cdots\right) + h.c.$$

$$V(h) = \frac{1}{2}m_h^2 h^2 + d_3\,\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + d_4\,\frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \ldots$$



$$\frac{\sigma_{NLO}}{\sigma^{SM}_{NLO}} = \quad c^2 \quad a^2 \quad a^2 \quad c^2$$

Reinterpretation of SM searches

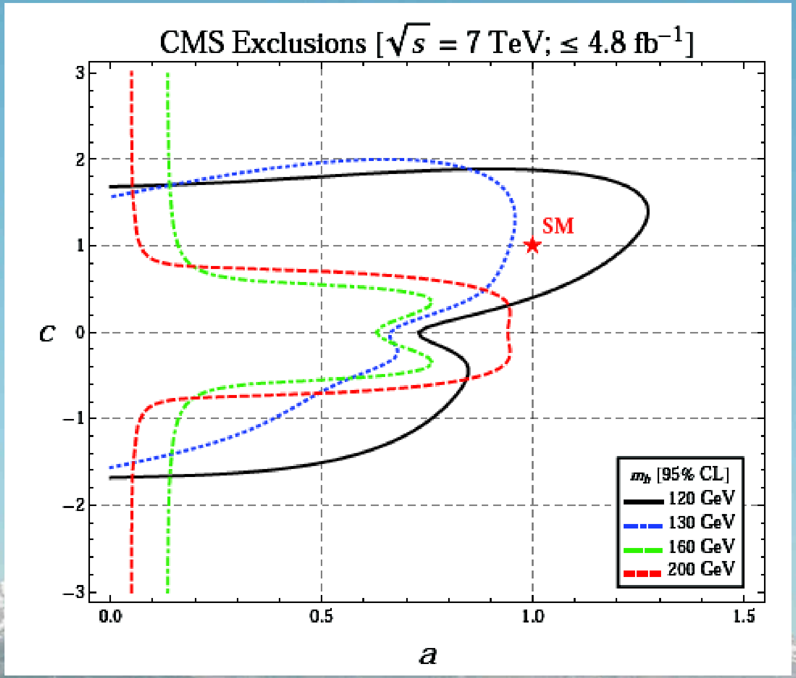
- Models of strong EWSB: implications of H searches

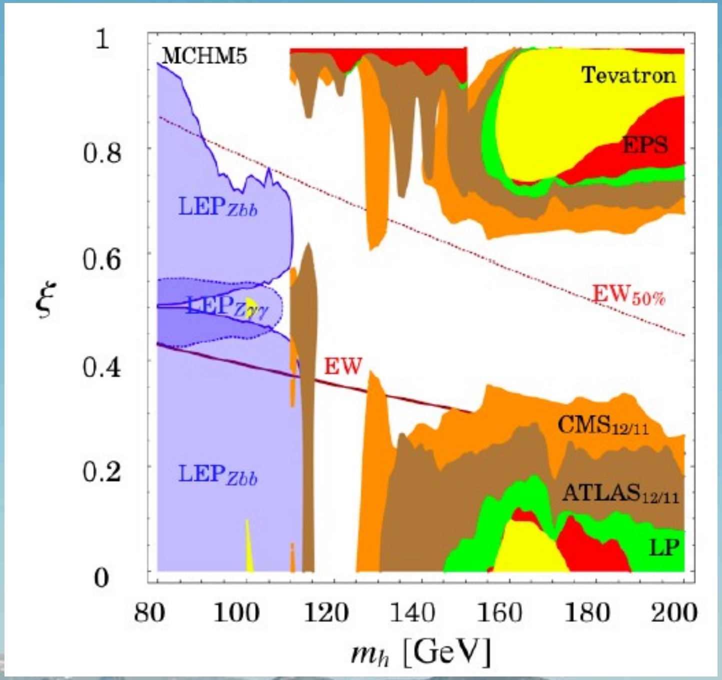
Azatov, Contino, Galloway, 1202.3415
Espinosa, Grojean, Müllheitner, Trott, 1202.3697

Bounds as a function of Higgs mass

Heavy Higgs allowed!!

Espinosa, Grojean, Müllheitner, 1202.1286





MCHM$_5$

$$a = \sqrt{1-\xi}$$

$$c = \frac{1-2\xi}{\sqrt{1-\xi}}$$

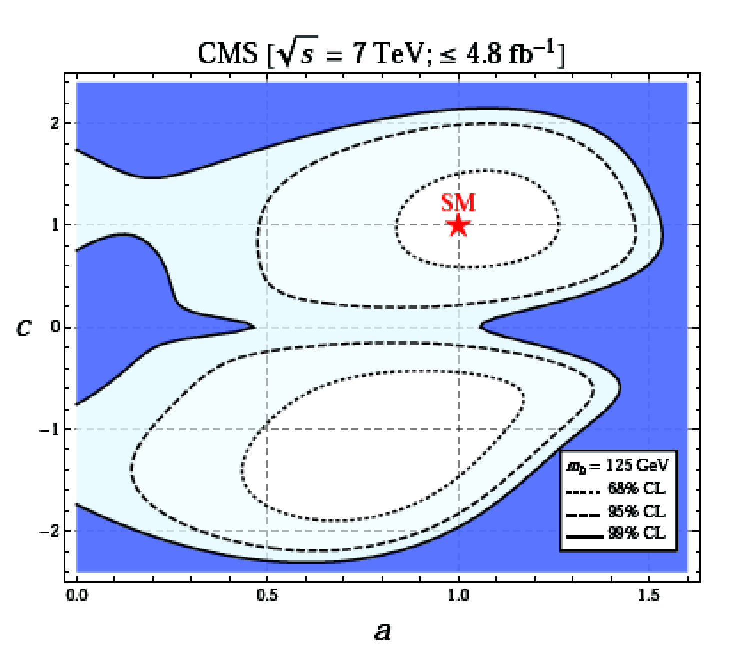
Reinterpretation of SM searches

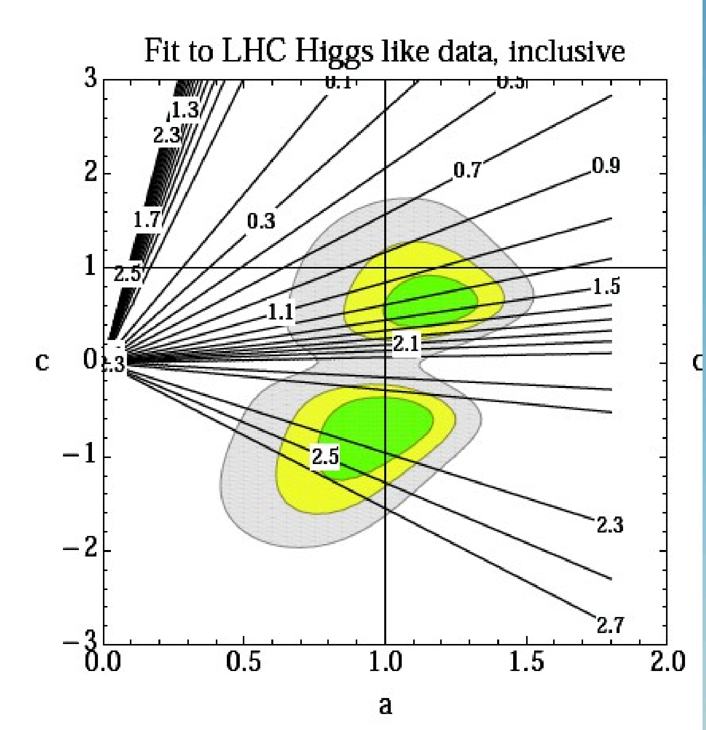
- Example: Models of strong EWSB

Azatov, Contino, Galloway, 1202.3415;
Espinosa, Grojean, Müllheitner, Trott, 1202.3697

125 GeV excess in the a,c plane

$$\frac{h \to ZZ}{h \to \gamma\gamma}$$

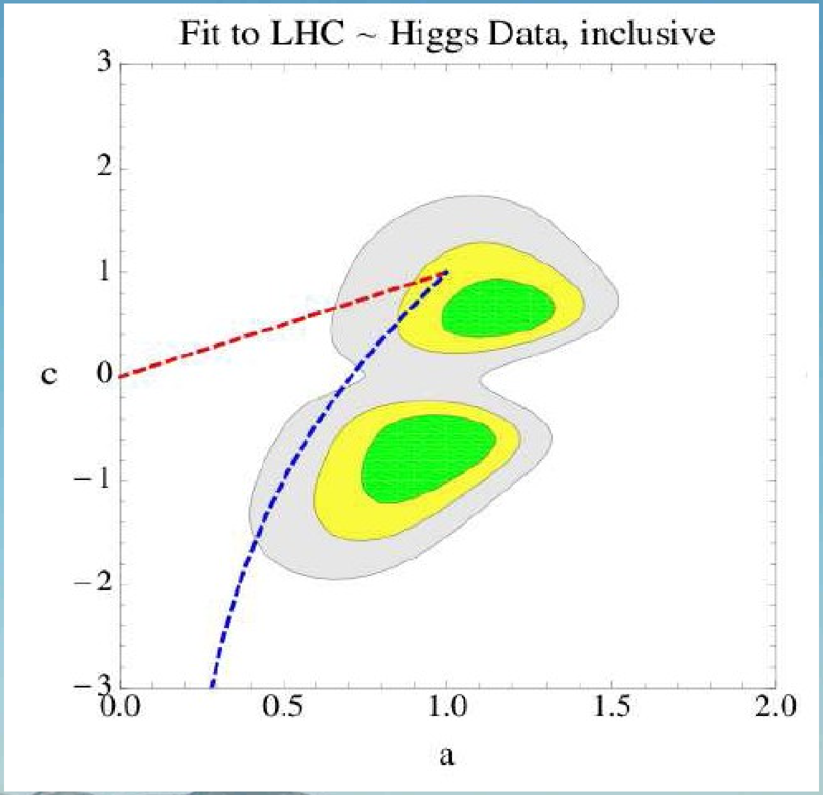




Don't forget non-minimal models

- Higgs searches are starting to constraint minimal models (much more to come with new data)
- Much more freedom in simple extensions
- Example:
  - Minimal Composite Higgs models: SO(5)/SO(4)

Agashe, Contino, Pomarol, ph/0412089



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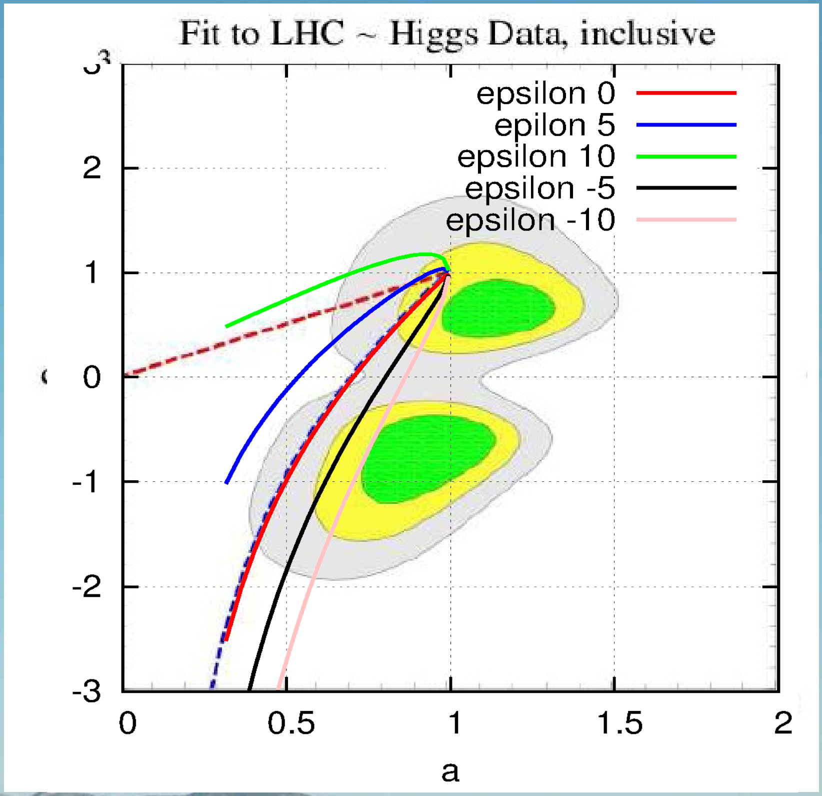
Agashe, Contino, Pomarol, ph/0412089

  - Next to minimal CHM: SO(6)/SO(5)

Gripaios, Pomarol, Riva, Serra, 0902.1483
Redi, Tesi, 1205.0232
Chala, Grojean, Santiago, in progress



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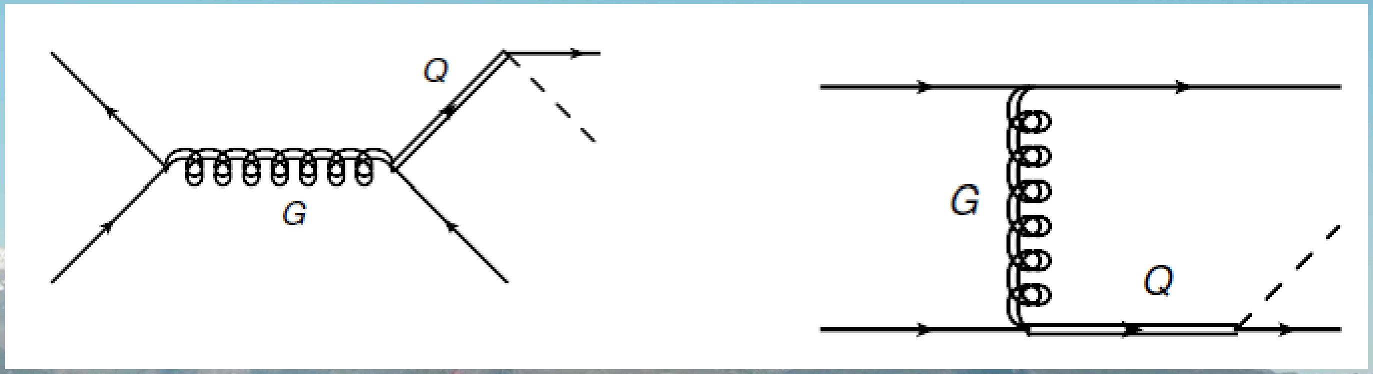
Redi, Tesi, 1205.0232
Chala, Grojean, Santiago, in progress

Richer phenomenology (heavy Higgs, doublet-singlet interplay, ...)

New old channels

- SM-like channels can have very different origin and properties in BSM scenarios
  - Keep an open mind (in exp. analyses)
  - Higgs searches can give valuable information on models of new physics (Higgs window to NP)
- New old channels in Composite Higgs models:
  - $Ht\bar{t}$ and Hqq mediated by new vector and fermion resonances

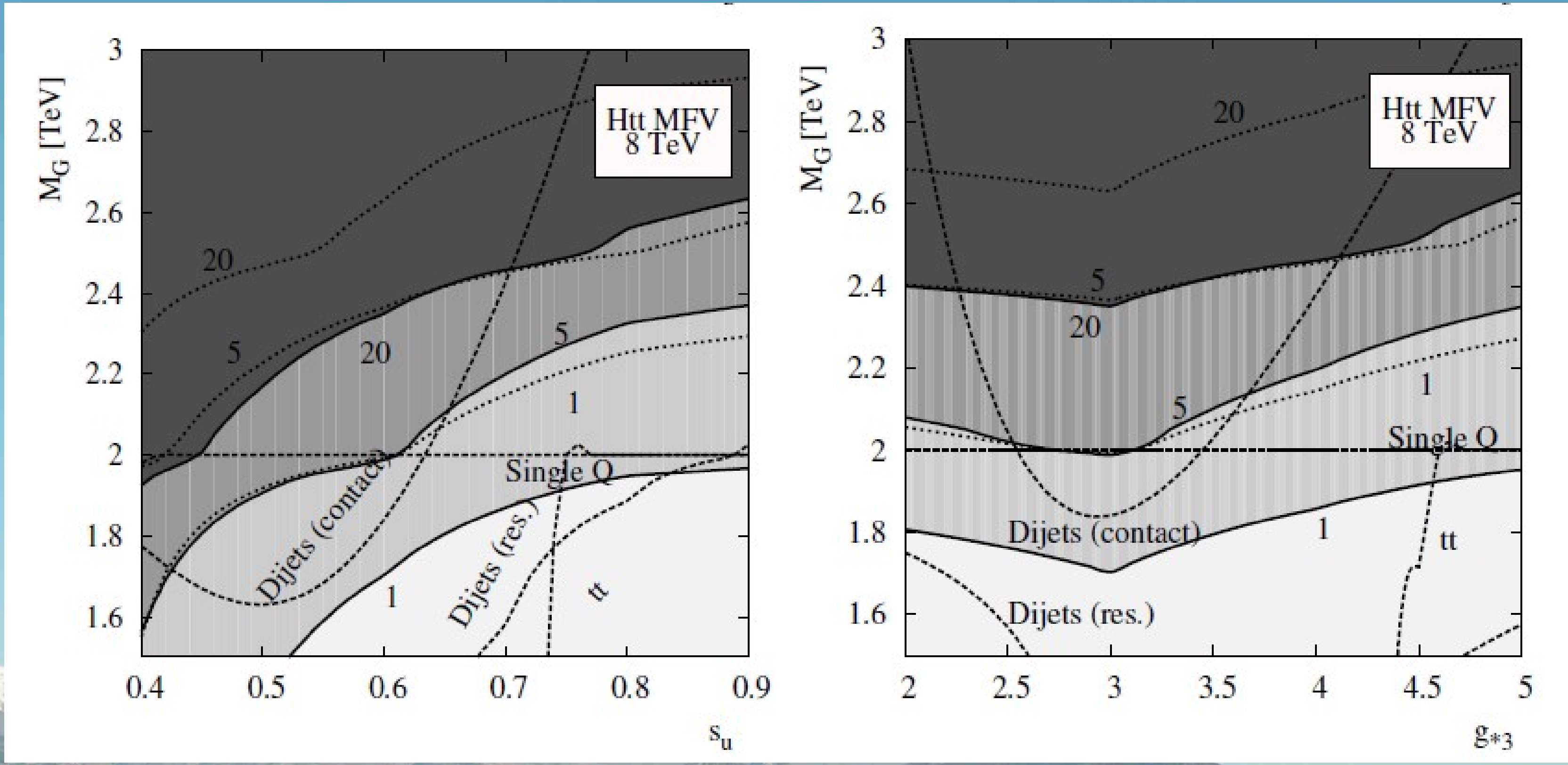
Carmona, Chala, Santiago, 1205.2378



New old channels

Carmona, Chala, Santiago, 1205.2378

- New old channels in Composite Higgs models:
  - $Ht\bar{t}$ NOT related to λ_t (accessible at 7/8 TeV)
  - Hqq two central, hard jets (as opposed to VBF)



Higgs Portal

- Another example of Higgs window to new physics

$$\Delta\mathcal{L} = \phi^\dagger \phi \, \mathcal{O}_{\text{Hidden}}$$

- Can modify $h\gamma\gamma,\ hgg$ couplings (if new particles colored or charged): constrained by Higgs searches
  - Example: new scalars

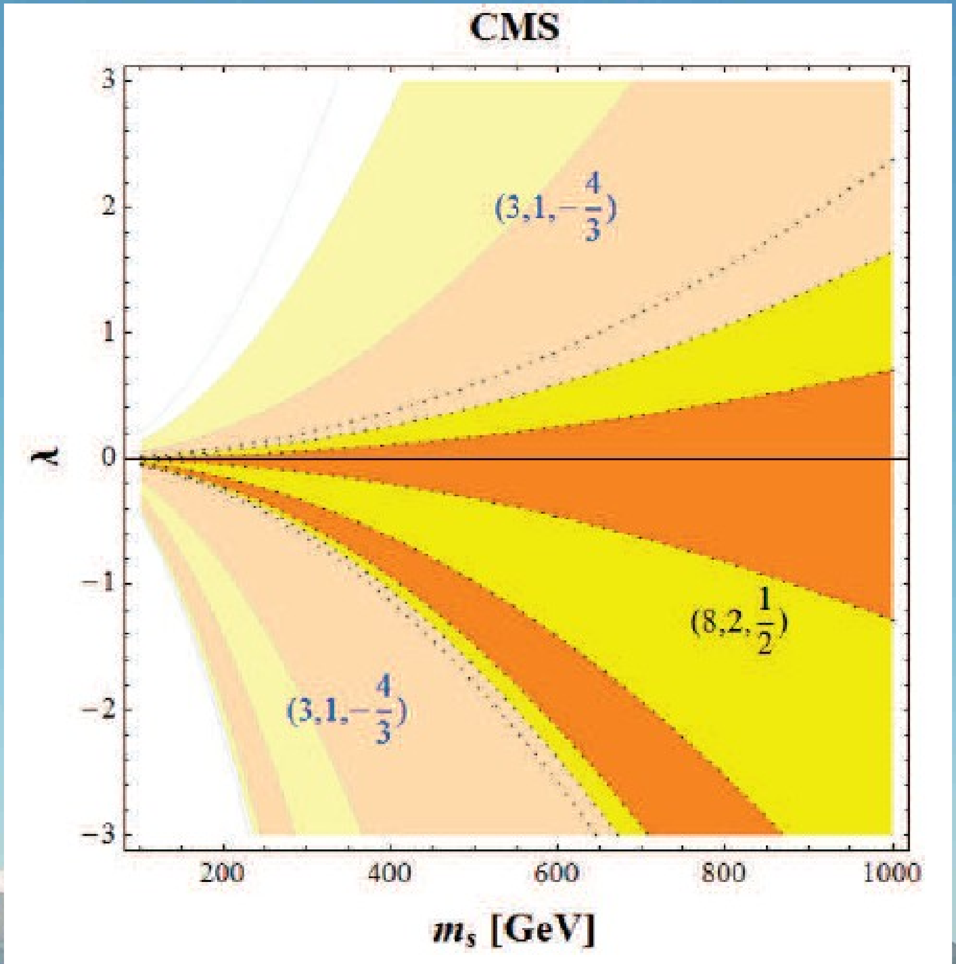
$$\Delta\mathcal{L} = -\lambda |S|^2 \phi^\dagger \phi$$

  - New fermions or vectors expected to be more suppressed (Higher dimensional operators)

Higgs Portal

- Example: new scalars $$\Delta\mathcal{L} = -\lambda|S|^2\phi^\dagger\phi$$

Batell, Gori, Wang, 1112.5180



Higgs Portal

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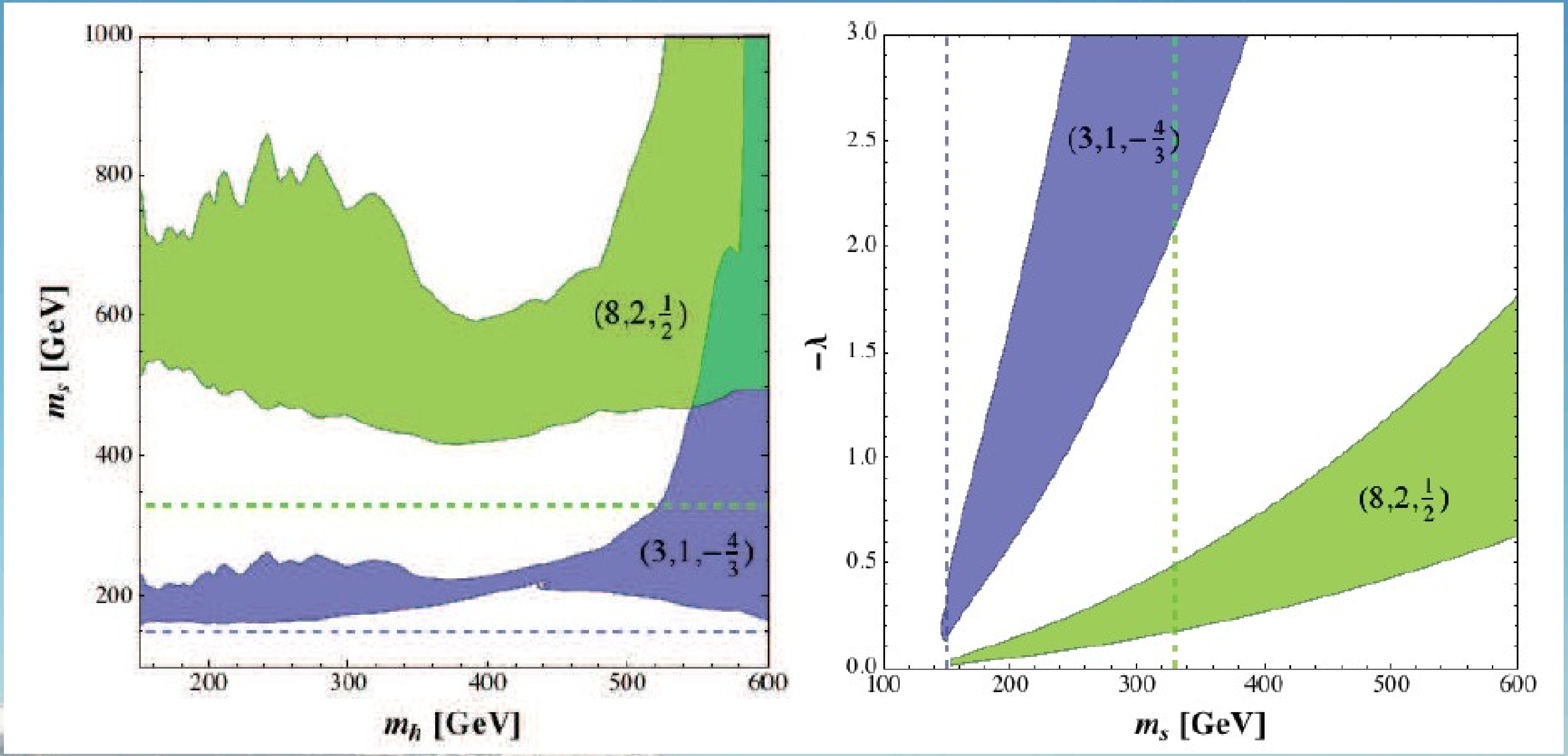
Batell, Gori, Wang, 1112.5180



Higgs Portal

- Example: Higgs portal to DM

  Djouadi, Falkowski, Mambrini, Quevillon, 1205.3169

  - Constraints on Higgs coupling to DM particles from invisible H decays
  - Direct constraint from mono-jet searches
    - $gg \to Hj(j) \to \not{E}_T j(j)$ at $(N)NLO$
    - $qq \to Hqq \to \not{E}_T jj$ (VBF)
  - Not competitive with indirect bounds for SM but it is in BSM when production is enhanced
  - Complementary to direct DM detection

Outlook

- We are finally entering the Higgs era
- Data still inconclusive (things should improve soon)
- Ideally experimental analyses should be as general and easy to reinterpret as possible
- BSM intertwined with Higgs physics
- Higgs searches can give valuable information on aspects of BSM models beyond the Higgs sector

Outlook

- The horizon is still wide open:
  - H could be at 125 GeV (or not)
  - it could be SM-like (or not)
  - it could be much heavier (with reduced couplings)
  - there could be more (or even less) than one

The fun is just starting!!