Higgs: theory review

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Perimeter Institute for Theoretical Physics

2014 CAP Congress / Congrès de l'ACP 2014

Sudbury,
June 17th 2014

The plan

1. Introduction: the discovery of a new boson

2. The Higgs in the Standard Model

- Mass
- Properties (production and decays)

3. Beyond the Standard Model Higgs bosons

- Higgs couplings (loop and tree level)
- Interplay with direct searches of New Physics particles
- Exotic decays

Focus on Supersymmetry

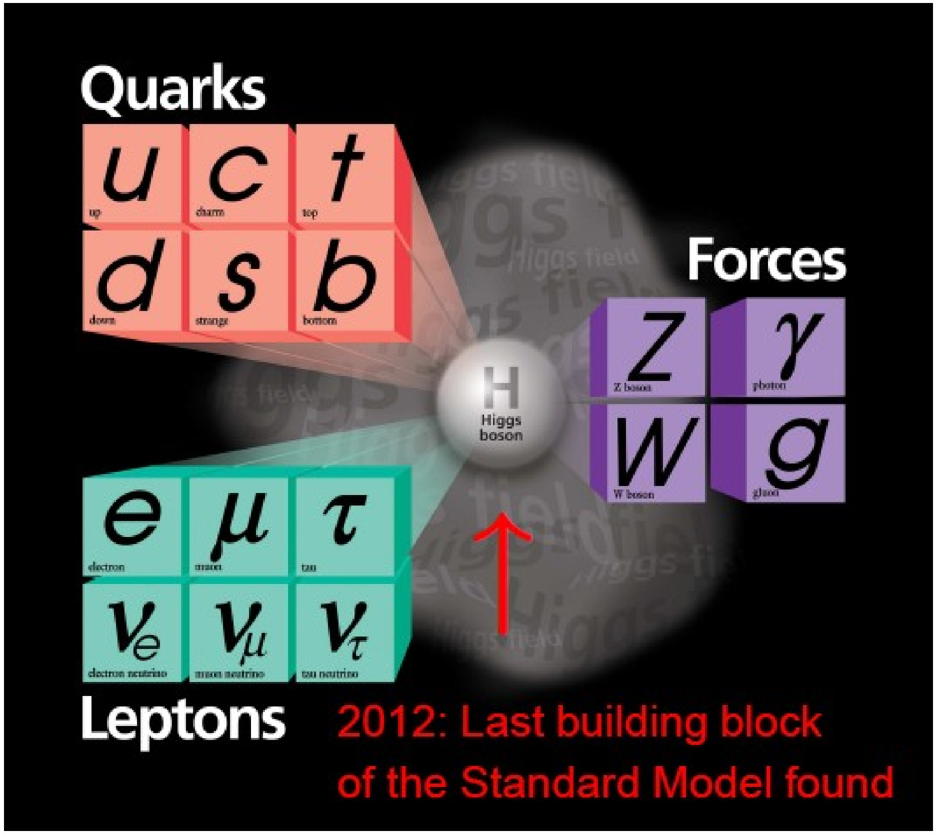
We have a new boson!

After 50 years from the theoretical proposal
&
~40 years of experimental searches:

July 4th, 2012: ATLAS and CMS: „**We have observed a new boson**“

Francois Englert   Peter Higgs

2013



2012: Last building block of the Standard Model found

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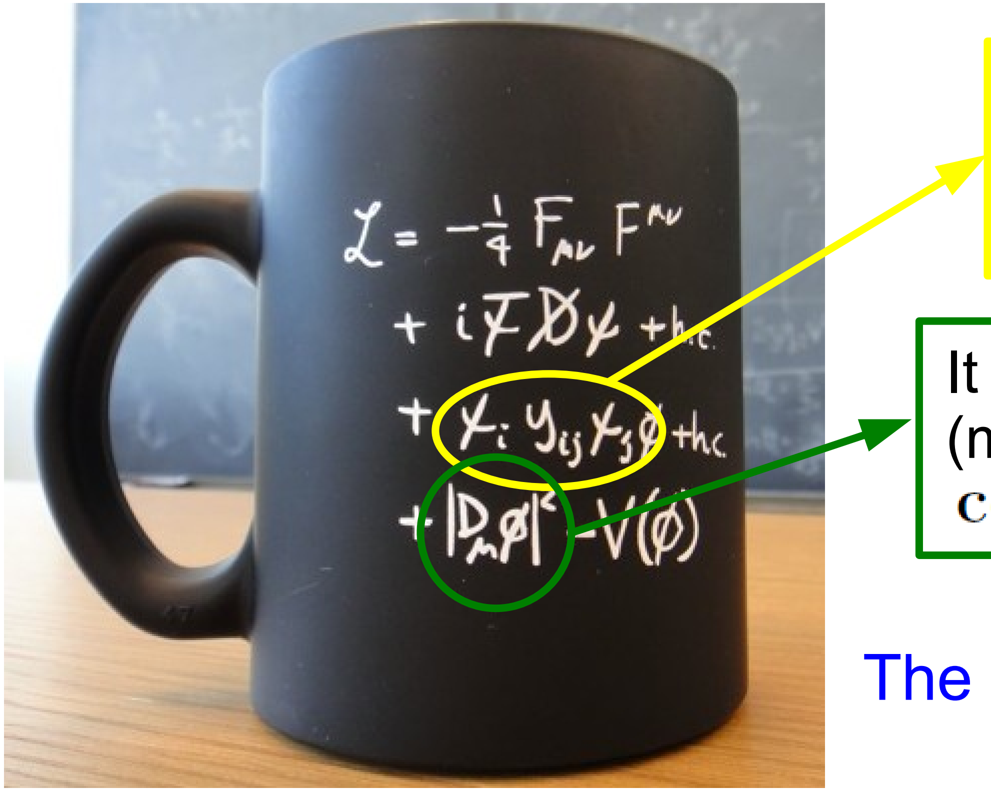


It gives mass to the fermions
$y_{ij} \propto m_f$

It gives mass to the (massive) gauge bosons
$\text{coupl} \propto m_V$

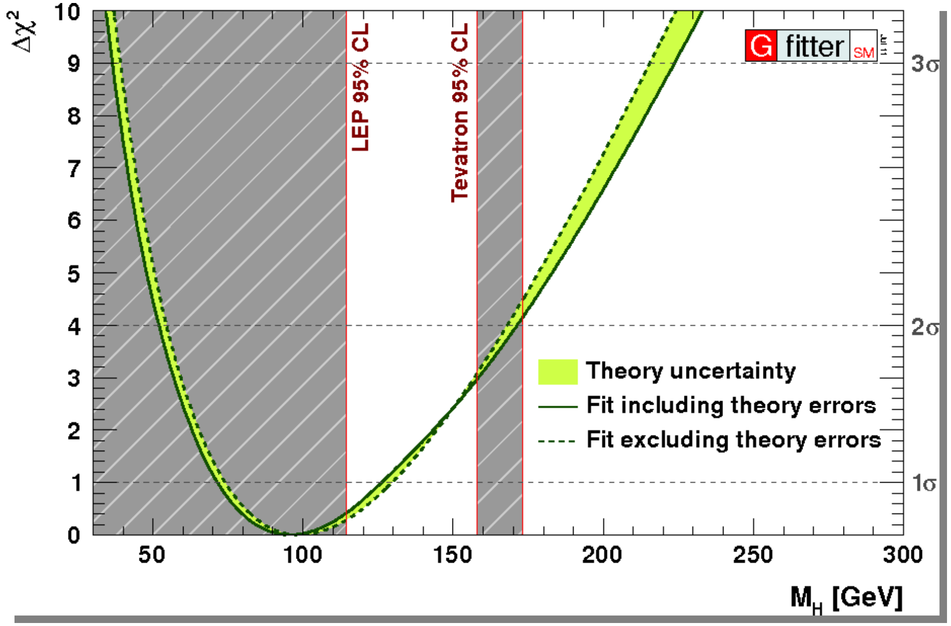
The Higgs couples to (almost) everything

What determines the Higgs characteristics?

The Higgs mass is not predicted by the Standard Model (SM)

However, once it is fixed, the full phenomenology of the Higgs is univocally determined

The SM can only „predict indirectly“ the Higgs mass:

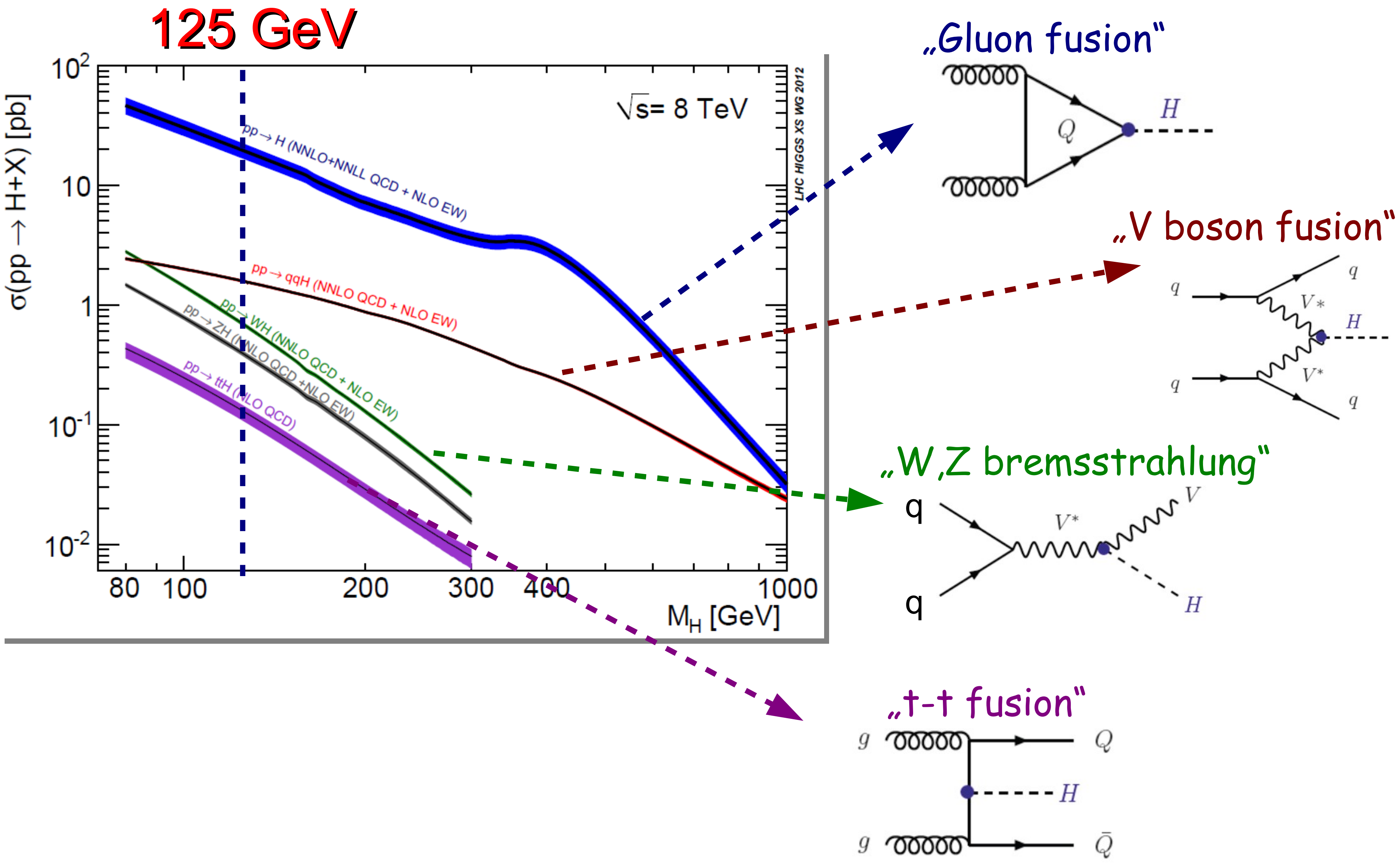


as in 2011

Putting together all the info from the measurement at LEP and at Tevatron of the electroweak precision observables

$$\boxed{m_h = 91^{+30}_{-23}\ \mathrm{GeV}}$$

The production of the Higgs...



125 GeV

„Gluon fusion“

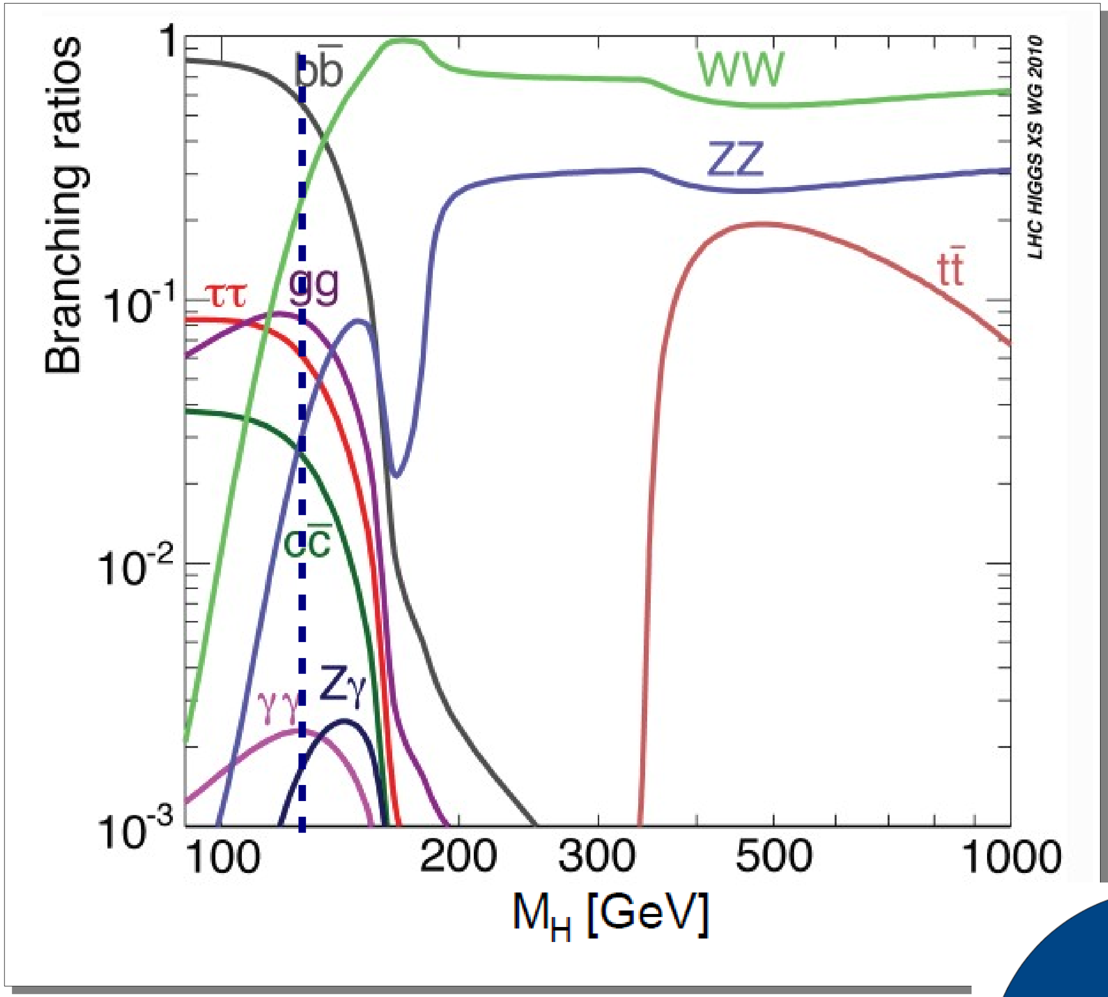
„V boson fusion“

„W,Z bremsstrahlung“

„t-t fusion“

...and its decays

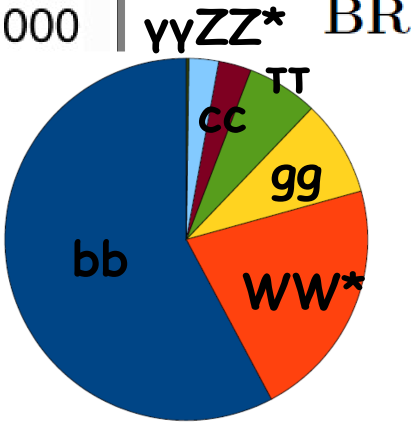
125 GeV



The Higgs decays very quickly:
$\Gamma_h \sim 4$ MeV $\Longrightarrow \tau_h \sim 2\times10^{-22}$s

A „dreamland“ for experimentalists!

$$
\begin{aligned}
\mathrm{BR}(h \to b\bar{b}) &= 58\%,\\
\mathrm{BR}(h \to ZZ^*) &= 2.7\%,\\
\mathrm{BR}(h \to WW^*) &= 21.6\%,\\
\mathrm{BR}(h \to \tau\bar{\tau}) &= 6.4\%,\\
\mathrm{BR}(h \to \gamma\gamma) &= 0.22\%,\\
\mathrm{BR}(h \to \gamma Z) &= 0.16\%,\\
\mathrm{BR}(h \to \mu\mu) &= 0.022\%
\end{aligned}
$$



How well do we know?

State of the art for the SM computation

- h ⟶ ff

QCD up to NNNNLO

Baikov, Chetyrkin, Kühn, Steinhauser ('97–'05)

- h ⟶ γγ / gg

full 2-loop result + h.o. improvements

Spira, Djouadi, Graudenz, Zerwas '95; ...
Actis, Passarino, Sturm, Uccirati '07,'08

- h ⟶ WW / ZZ

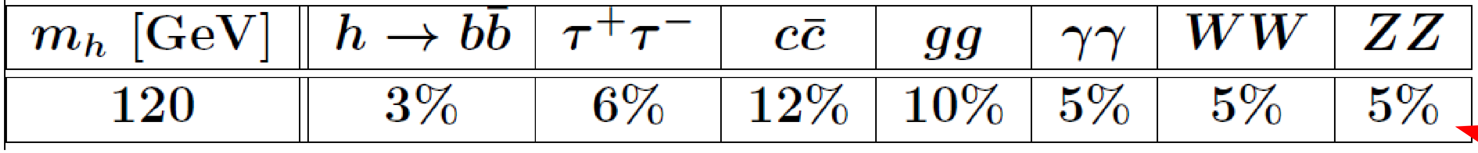
NLO for stable W/Z bosons

Fleischer, Jegerlehner '81; Kniehl '91;
Bardin, Vilenskii, Khristova '91

NLO for off-shell/decaying W/Z bosons

Bredenstein, Denner, Dittmaier., Weber '06

Parametric + theoretical uncertainty of BRs



m_h [GeV]	$h \to b\bar{b}$	$\tau^+\tau^-$	$c\bar{c}$	gg	$\gamma\gamma$	WW	ZZ
120	3%	6%	12%	10%	5%	5%	5%

LHC Higgs XS WG '10–'13

Dominated by $\delta\Gamma_{h\longrightarrow bb}$

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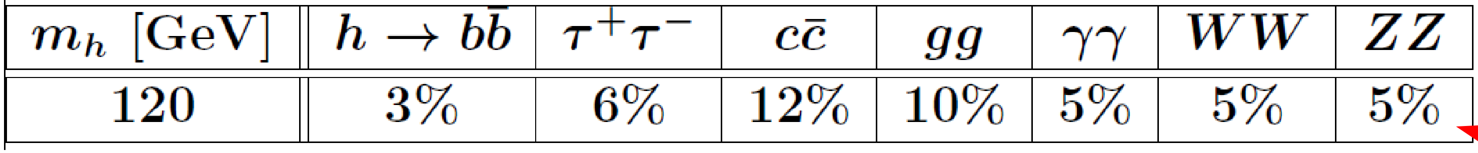

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LHC Higgs XS WG '10–'13

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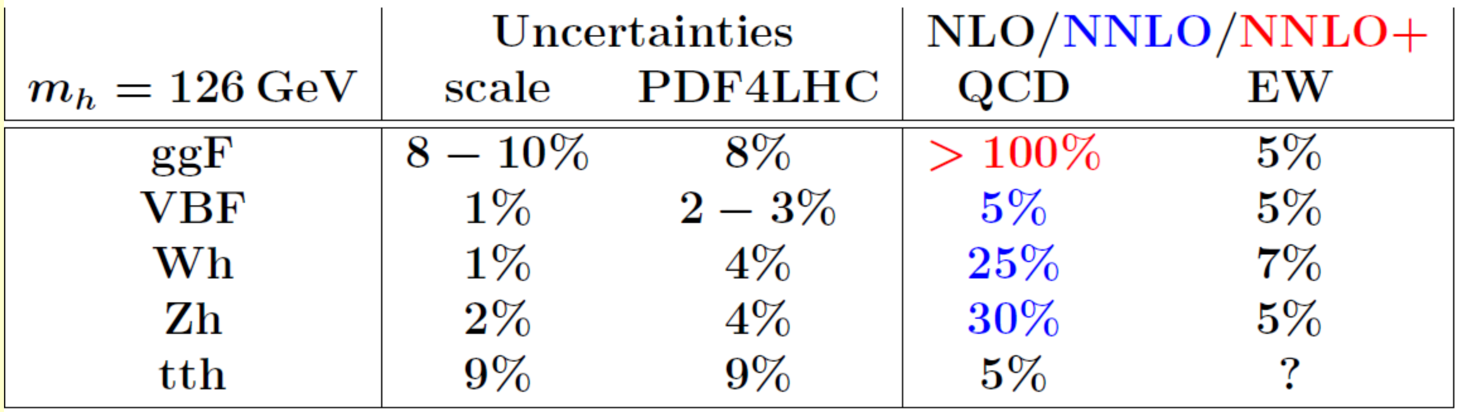
Numbers for the 7 TeV LHC:



$m_h = 126$ GeV	Uncertainties scale	 PDF4LHC	NLO/NNLO/NNLO+ QCD	 EW
ggF	8 – 10%	8%	> 100%	5%
VBF	1%	2 – 3%	5%	5%
Wh	1%	4%	25%	7%
Zh	2%	4%	30%	5%
tth	9%	9%	5%	?

The Higgs as a portal to New Physics

The discovery of the Higgs is the manifestation of the hierarchy problem

$$m_h^2 \sim \mu^2 + c\,\Lambda^2, \quad c = \mathcal{O}(0.01)$$

$$V(H) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

Fundamental scale beyond the SM:

$\Lambda \approx M_{Pl} = 10^{19}$ GeV (Planck scale)

Needed a cancellation to the precision of 10^{-32}
to have m_h(physical) ≈ 125 GeV

14884157194850192375385501928538182559-
14884157194850192375385501928538166934 = 125^2

Whatever cancels the quadratic sensitivity of the Higgs mass to the high energy scale must:

- couple to the Higgs
- be relatively light (TeV-scale?)

Testing the Higgs
to discover New Physics (NP)

Beyond the Standard Model Higgs

UnHiggs

Littlest Higgs

Private Higgs

Gaugephobic Higgs

Composite Higgs

Intermediate Higgs

Twin Higgs

Fat Higgs

Slim Higgs

Portal Higgs

Simplest Higgs

Gauge Higgs

Lone Higgs

Phantom Higgs

Supersymmetric Higgs

Beyond the Standard Model Higgs

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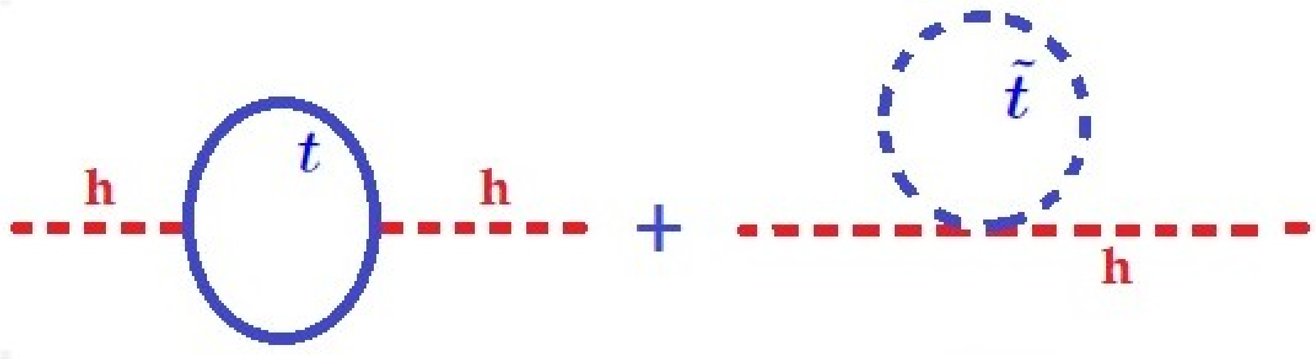
Supersymmetry and the hierarchy problem

An elegant way to keep quantum corrections to the Higgs mass under control



$$m_h^2 = m_{h0}^2 + c\Lambda^2,$$

Quadratic corrections cancelled

$$\delta m_h^2 = m_{\rm SUSY}^2 \left(\frac{y_t^2}{8\pi^2} \log\left(\frac{\Lambda}{m_{\rm SUSY}}\right) + \cdots \right)$$

The mass scale of the NP (susy) particles should be relatively low

What are the implications?

The mass of the Higgs is predicted in concrete SUSY models

<u>Example</u>: in the Minimal Supersymmetric Standard Model (MSSM)

MSSM: a two Higgs doublet model.
In total: 2 scalar Higgs bosons, 1 pseudoscalar and 1 charged Higgs

$$m_h^2 \simeq \underbrace{M_Z^2 \cos^2 2\beta}_{} + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\frac{X_t^2}{M_{\rm Susy}^2}\left(1-\frac{X_t^2}{12 M_{\rm Susy}^2}\right)+\log\frac{M_{\rm Susy}^2}{m_t^2}\right]$$

At the tree level, the MSSM predicts
a quite low Higgs mass

Stop loop contributions

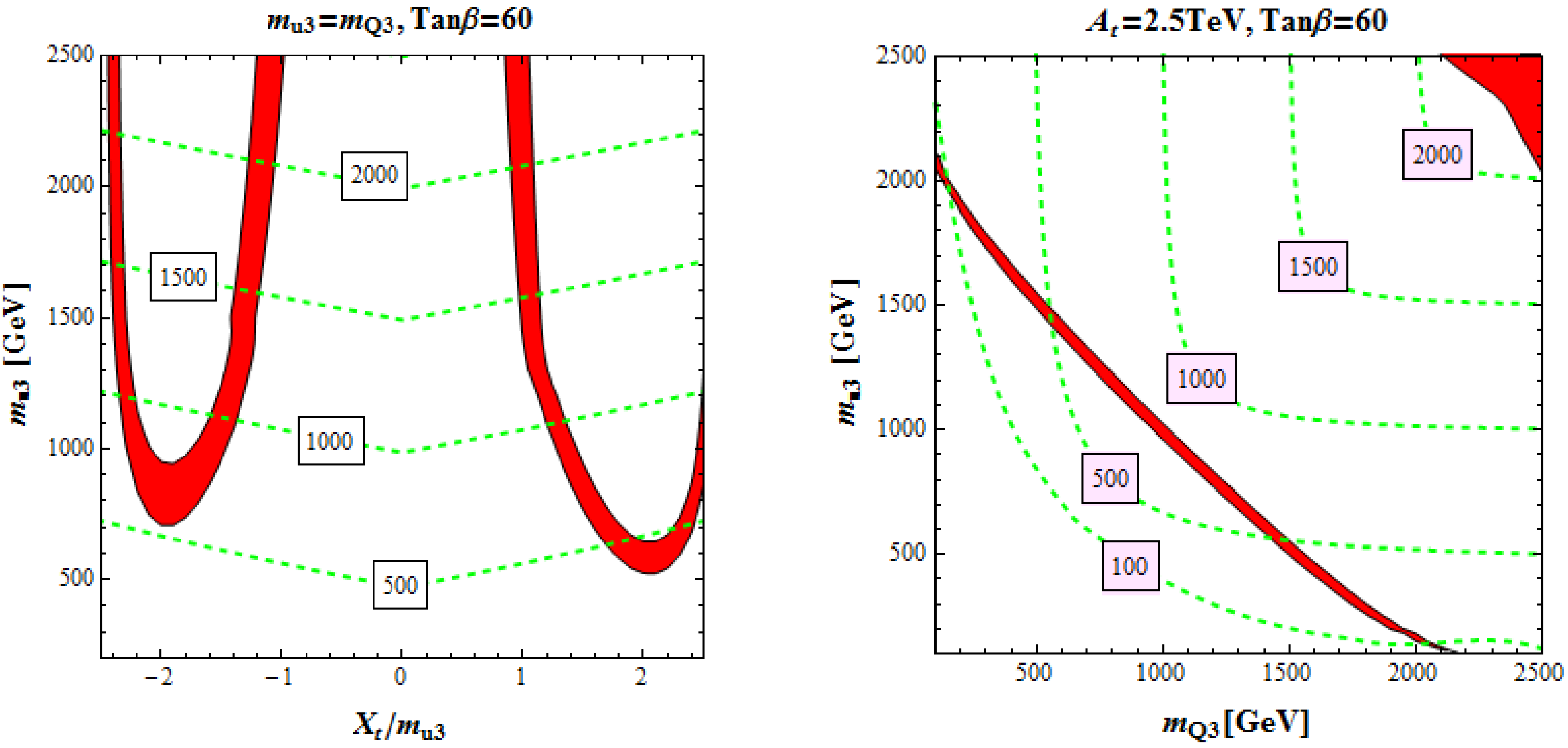
$$\mathcal{M}_{stop}^2 = \begin{pmatrix} m_{Q_3}^2 + m_t^2 + D_L & m_t X_t \\ m_t X_t & m_{u_3}^2 + m_t^2 + D_R \end{pmatrix}$$

Higgs mass directly connected to the stop spectrum

What are the implications?

The mass of the Higgs is predicted in concrete SUSY models

Example: in the Minimal Supersymmetric Standard Model (MSSM)



Carena, SG, Shah, Wagner, 1112.3336

What are the implications?

The mass of the Higgs is predicted in concrete SUSY models

Ex

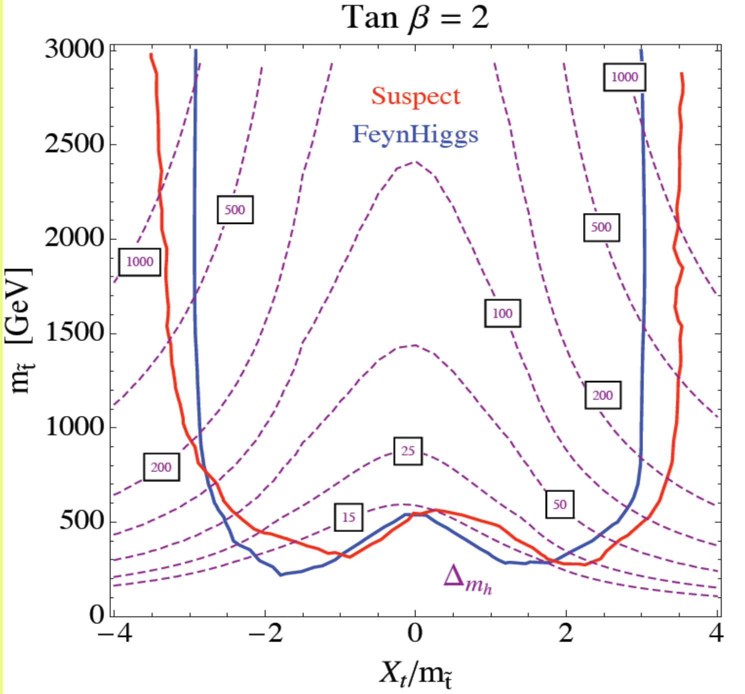
Different implications if we consider Susy models beyond the MSSM

Example:

The NMSSM: a two Higgs doublet + 1 singlet model. $\mathcal{W} \supset \lambda S H_1 H_2$

In total: 3 scalar Higgs bosons, 2 pseudoscalar and 1 charged Higgs

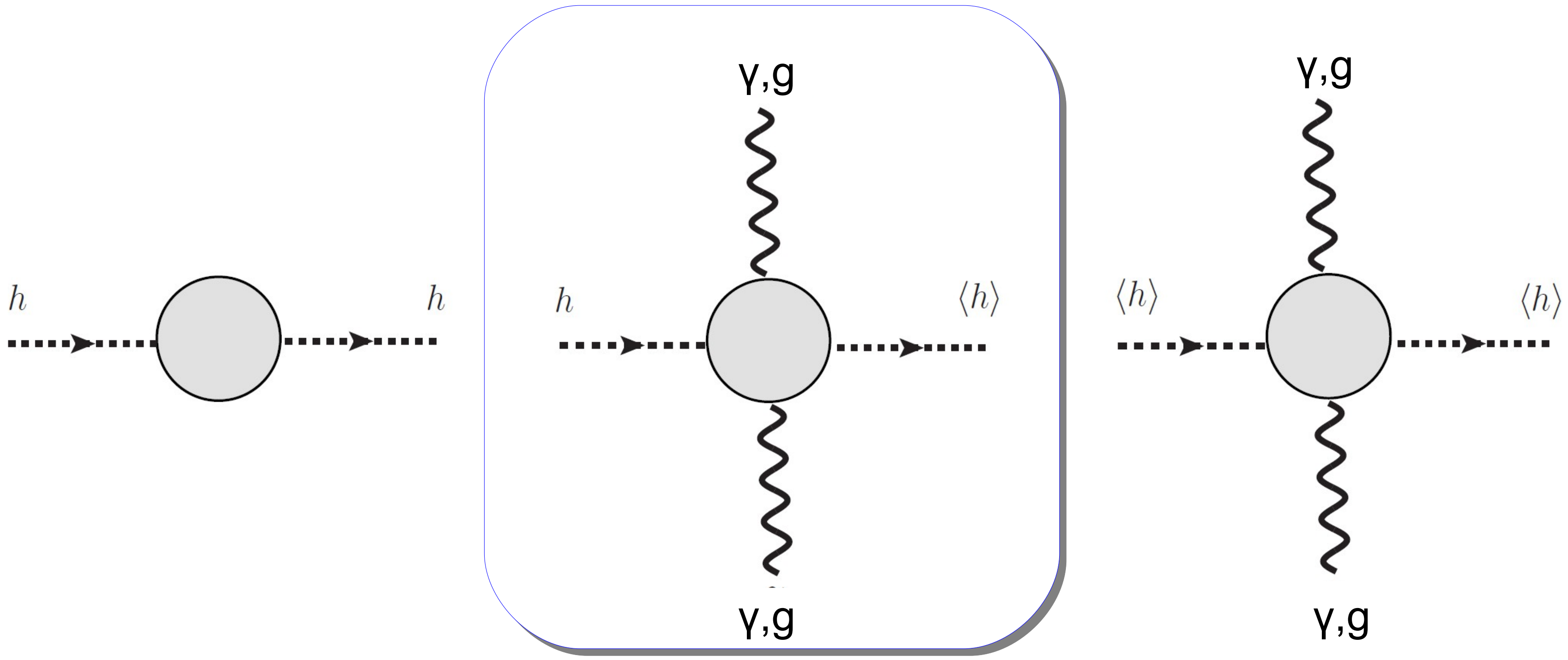
$$(m_h^2)_{\text{tree}} \lesssim m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta$$



Hall, Pinner, Ruderman, 1112.2703

Caren

Higgs couplings (loop)



Hierarchy problem → Higgs pheno ↔ QED (QCD) beta functions

Indirect probe of Naturalness

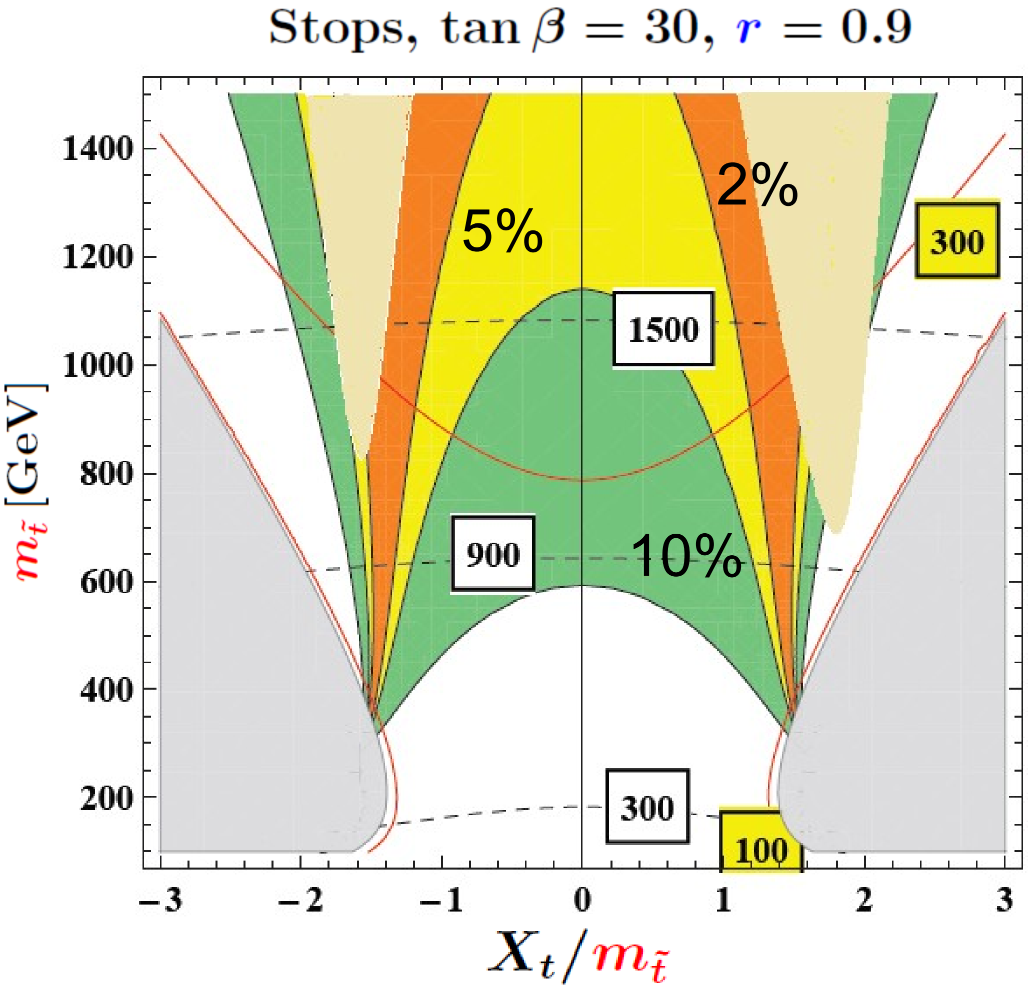
recent studies:
Farina, Perelstein, Rey-Le Lorier, 1305.6068
Craig, Englert, McCullough, 1305.5251

Low energy Higgs theorem

Ellis, Gaillard, Nanopoulos, 1976
Shifman, Vainshtein, Voloshin, Zakharov, 1979

Higgs di-gluon/di-photon coupling

Stops & Higgs coupling to gluons



$$m_{\tilde{S}}^2 = \frac{m_L^2 + m_R^2}{2}, \; r = \frac{m_L^2 - m_R^2}{m_L^2 + m_R^2}$$

SG, Low, 1307.0496

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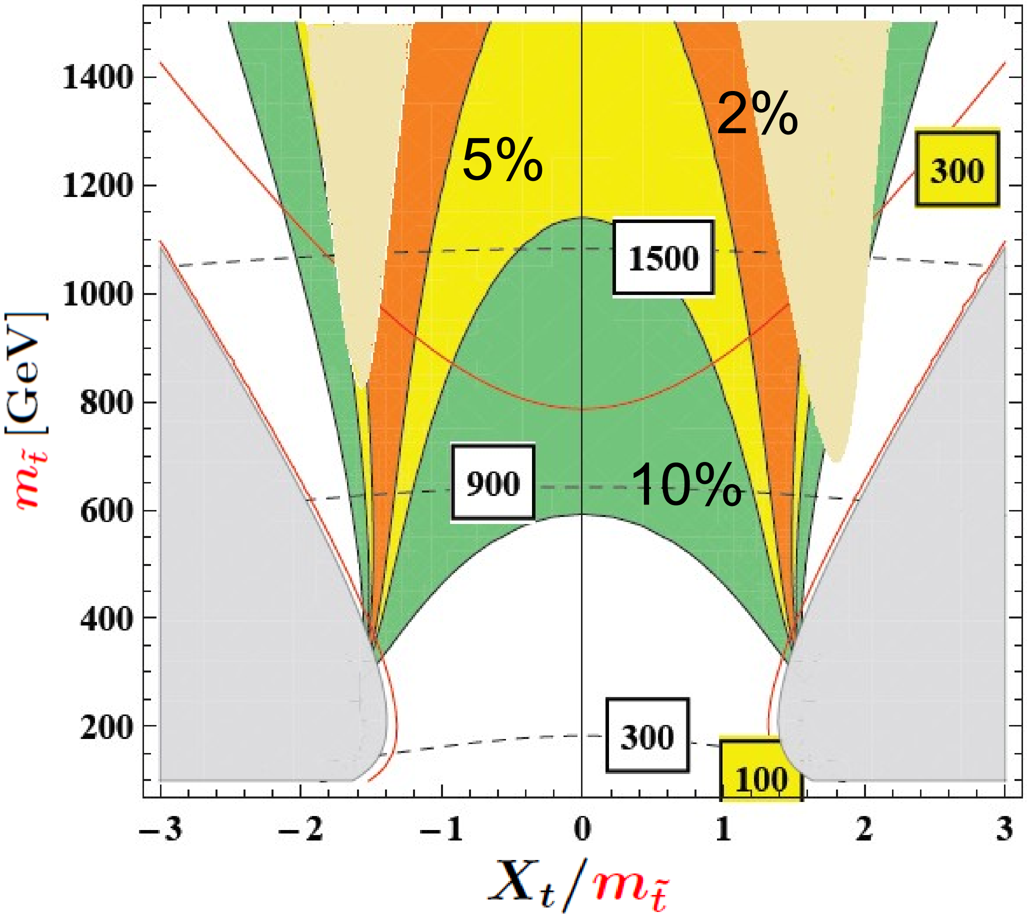
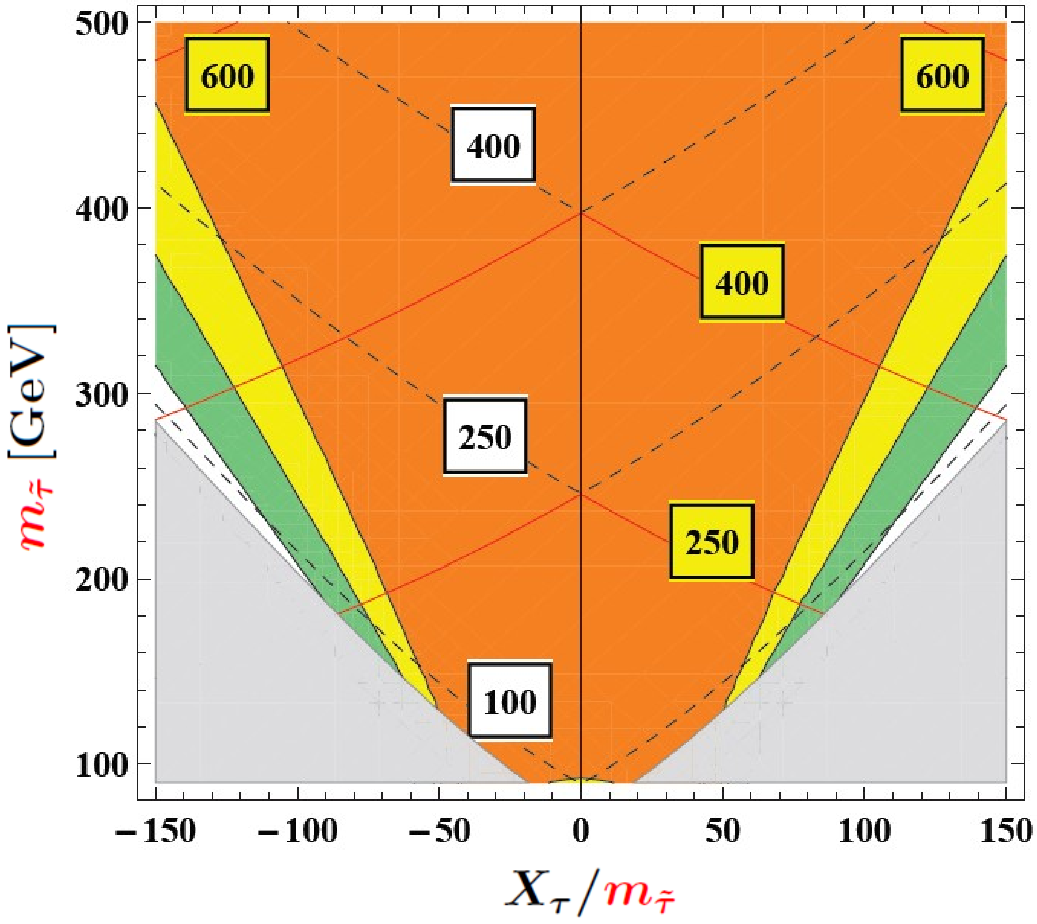


Stops, $\tan\beta = 30$, $r = 0.9$

Staus & Higgs coupling to photons



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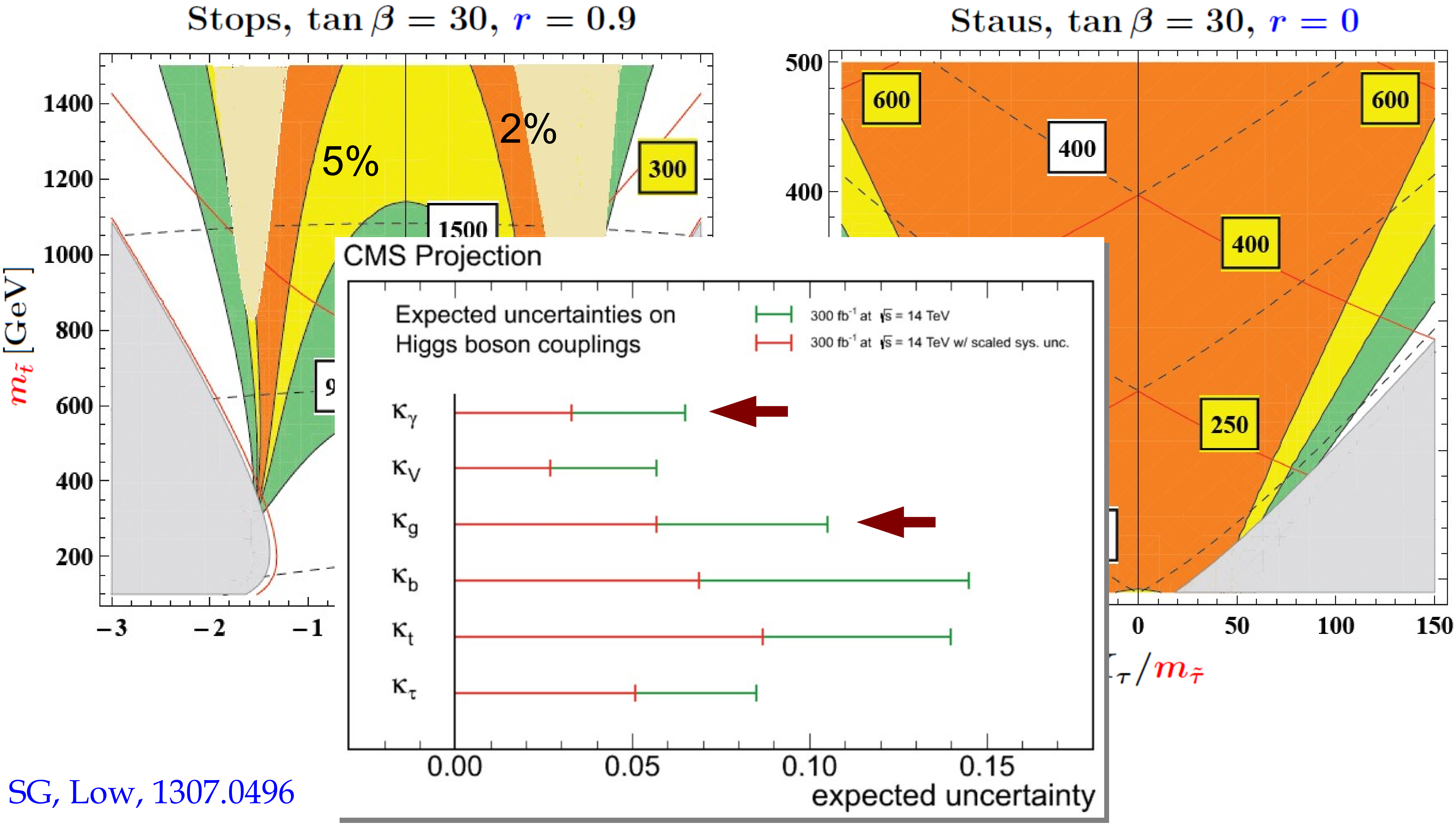


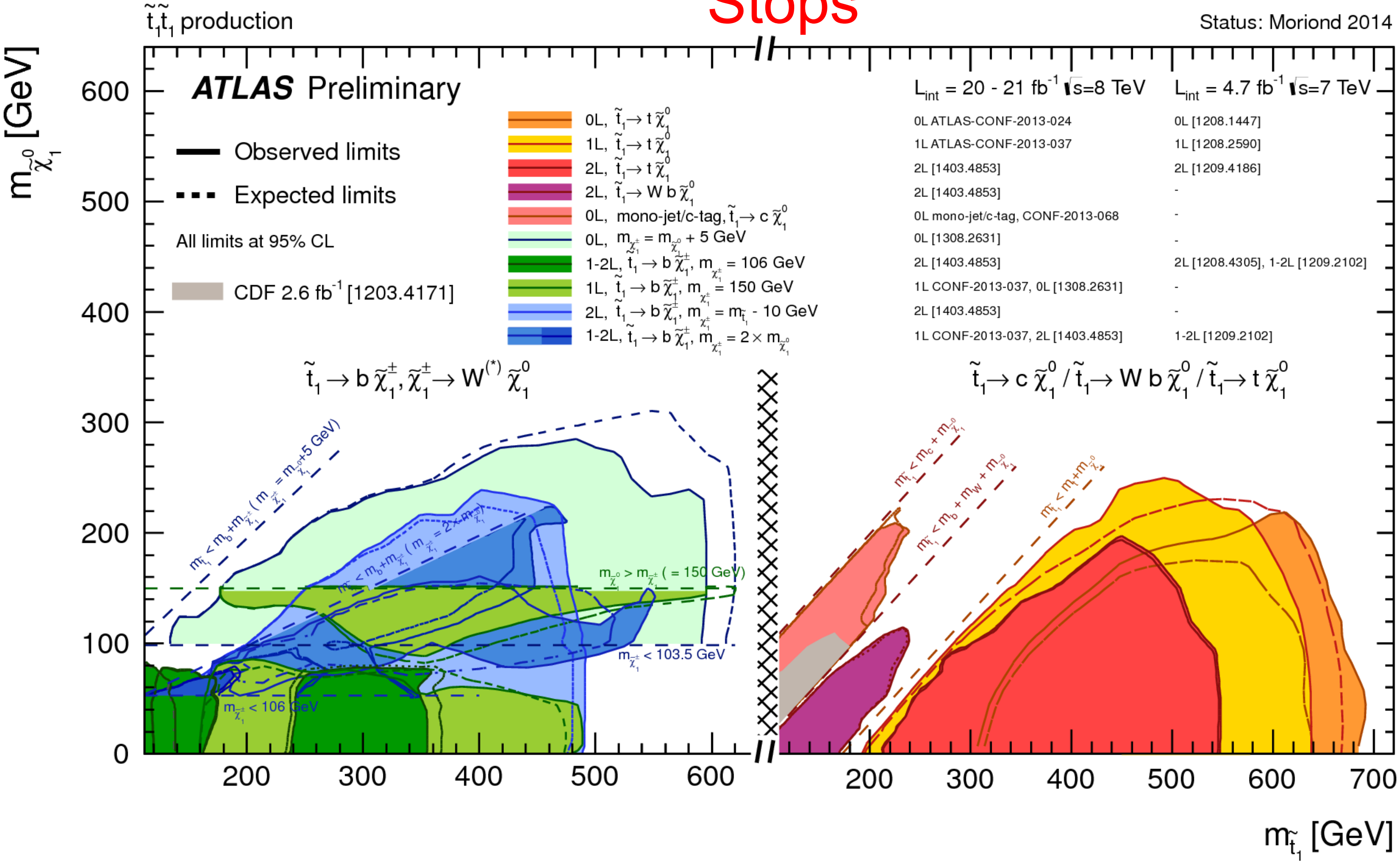
SG, Low, 1307.0496

Complementarity with direct searches

Measuring more and more precisely the coupling of the Higgs to gluons and photons gives us info on the Susy (stop/stau) spectrum

Complementarity with direct searches:

Stops



Staus

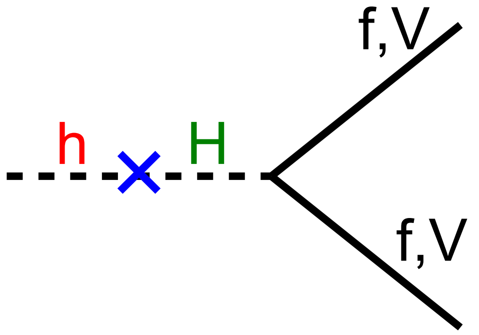
No bounds from direct searches of Drell-Yan produced staus

(if promptly decaying)

Higgs couplings (tree)

$$\begin{pmatrix} H_u \\ H_d \end{pmatrix} = \begin{pmatrix} v\sin\beta \\ v\cos\beta \end{pmatrix} + \frac{1}{\sqrt{2}} R_\alpha \begin{pmatrix} h \\ H \end{pmatrix} + \frac{i}{\sqrt{2}} R_\beta \begin{pmatrix} G \\ A \end{pmatrix}$$

$$R_\alpha = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix}, \quad R_\beta = \begin{pmatrix} \sin\beta & \cos\beta \\ -\cos\beta & \sin\beta \end{pmatrix}$$



$$\xi_u^h \sim \frac{\cos\alpha}{\sin\beta} \Rightarrow 1 + \frac{2m_Z^2}{m_H^2\tan^2\beta}$$

$$\xi_d^h \sim \xi_\ell^h \sim \frac{-\sin\alpha}{\cos\beta} \Rightarrow 1 - \frac{2m_Z^2}{m_H^2}$$

$$\xi_V^h \sim \sin(\beta-\alpha) \Rightarrow 1 - \frac{2m_Z^4}{m_H^4\tan^2\beta}$$

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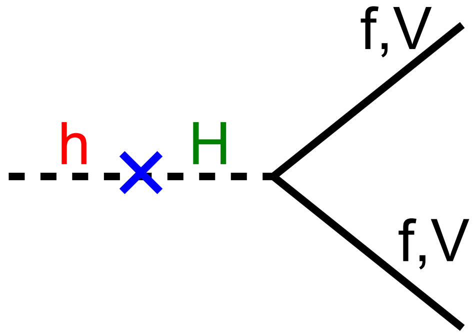

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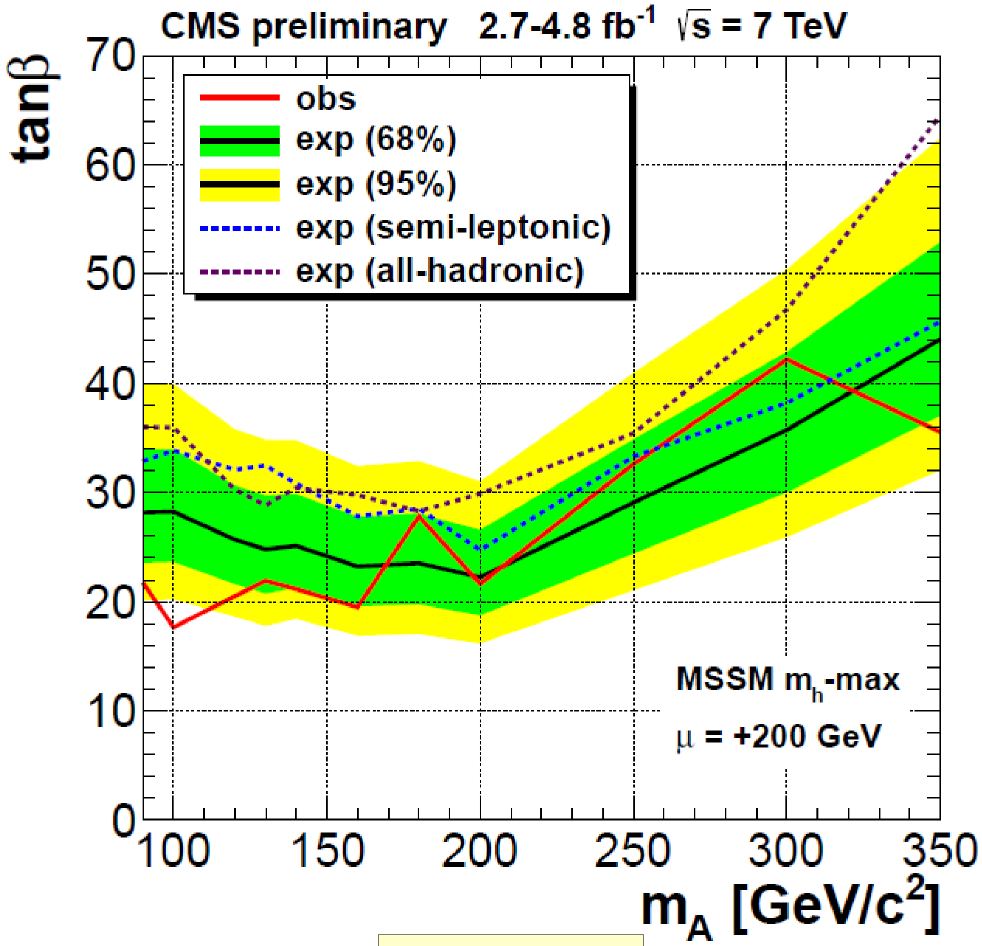
$$\xi_V^h \sim \sin(\beta - \alpha) \Rightarrow 1 - \frac{2m_Z^4}{m_H^4 \tan^2\beta}$$

The measurement of these couplings give information about the spectrum of the additional Higgs bosons

Looking for additional Higgs bosons

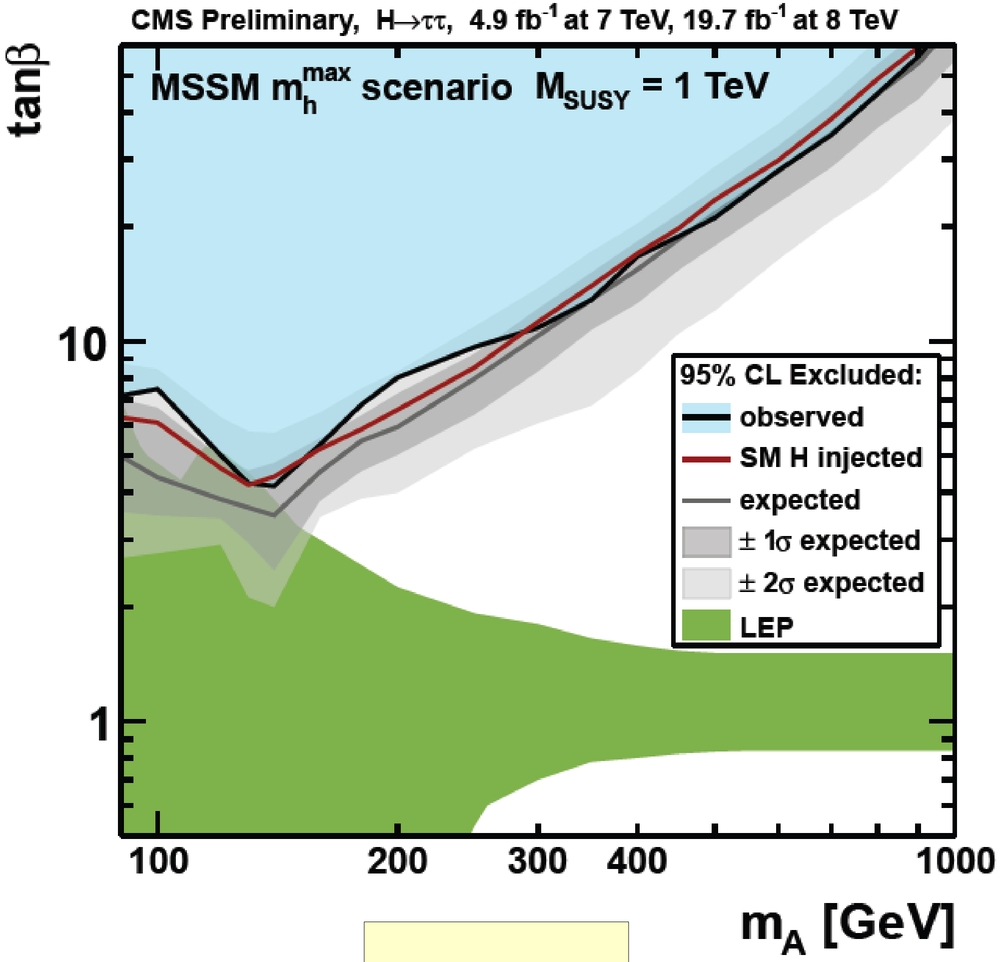
Complementarity with direct searches of additional Higgs bosons:

CMS-PAS-HIG-12-033



H⟶bb

CMS-PAS-HIG-13-021



H⟶ττ

Non-SM Higgs couplings: invisible Higgs

Beyond the SM theories can have particles lighter than the Higgs boson

A typical example:

models with a Dark Matter (DM) candidate with $M_{DM} \leq M_h/2 \sim 60$ GeV

These models can predict a non-zero BR(h⟶DM DM)

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Searches for an „invisible Higgs boson“ are already performed at ATLAS and CMS

- Higgs produced in VBF: $\mathrm{BR}(h \to \mathrm{inv}) \leq 69\% \, (53\%)$

  CMS PAS HIG-13-013

- Higgs produced in association with a leptonic Z:

  $\mathrm{BR}(h \to \mathrm{inv}) \leq 75\% \, (91\%)$ CMS PAS HIG-13-018

  $\mathrm{BR}(h \to \mathrm{inv}) \leq 75\% \, (62\%)$ ATLAS 1402.3244

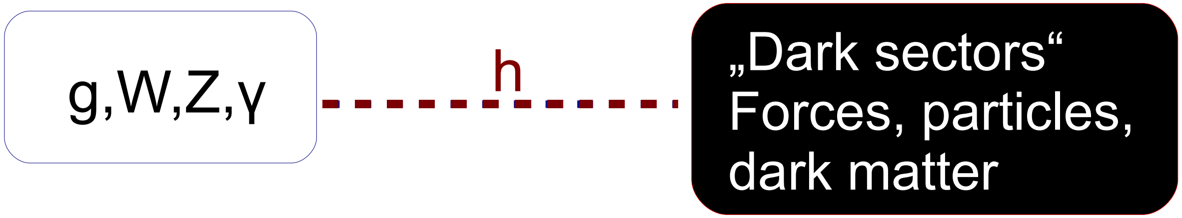
- Higgs produced in association with a Z decaying to bottom quarks:

  $\mathrm{BR}(h \to \mathrm{inv}) \leq 1.82 \, (1.99)$ CMS PAS HIG-13-028

Higgs exotic decays

h⟶NP particles
is an extremely rich theoretical and experimental physics program

1. Well motivated:
very many models predict NP particles only very weakly coupled
to the SM particles. The Higgs can give us access to the „dark sector“: ex. $|H|^2 \, |S|^2$



2. Theoretically it is easy to get sizable Higgs exotic branching ratios:
it is sufficient a small coupling of the Higgs to
NP particles, to get a sizable (≥10%) branching ratio (the Higgs is very narrow)

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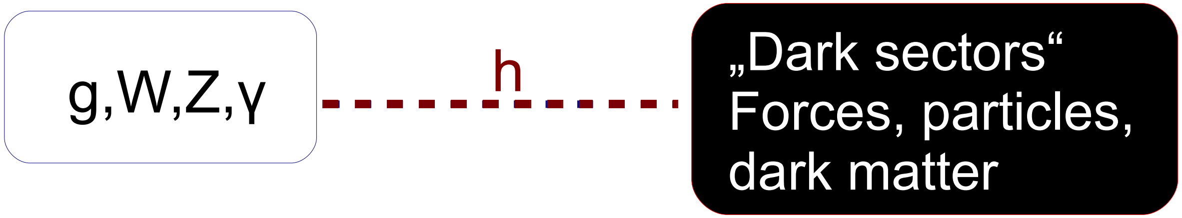

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3. Experimentally hidden if we do not look for them with dedicated searches
Projections for the 13 TeV LHC show that, with 300 fb^{-1} data, we will not determine the width of the Higgs with an accuracy better than ~10%

Exotic Decays of the 125 GeV Higgs Boson, 1312.4992

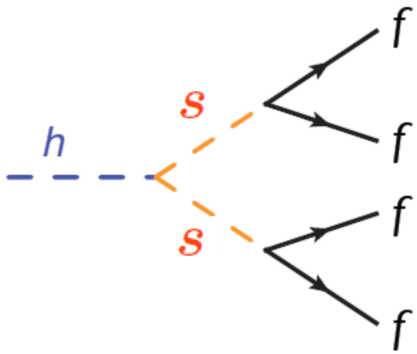
D. Curtin, R. Essig, SG, P. Jaiswal, A. Katz, T. Liu, Z. Liu, D. McKeen,
J.Shelton, M. Strassler, Z. Surujon, B. Tweedie, Y-M. Zhong

A simple theory for a multitude of signatures

Example. Very simple extension of the SM:

SM + singlet real scalar

$$\Delta\mathcal{L} = \frac{\zeta}{2} s^2 |H|^2$$



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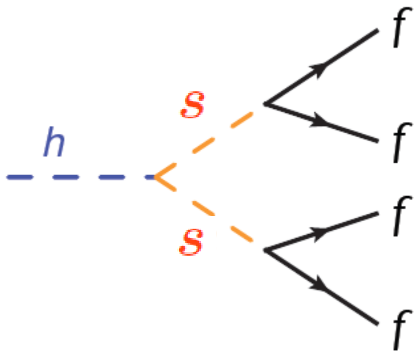


(experiment)
h ⟶ 4b

(theory)
aa ⟶ 4b

Decay Mode $\mathcal{F}_i$	Projected/Current 2σ Limit on $\mathrm{BR}(\mathcal{F}_\mathrm{i})$ 7/8 [14] TeV	Production Mode	quarks allowed		quarks suppressed	
			$\frac{\mathrm{BR}(\mathcal{F}_\mathrm{i})}{\mathrm{BR}(\mathrm{non-SM})}$	Limit on $\frac{\sigma}{\sigma_{\mathrm{SM}}} \cdot \mathrm{BR}(\mathrm{non\text{-}SM})$ 7/8 [14] TeV	$\frac{\mathrm{BR}(\mathcal{F}_\mathrm{i})}{\mathrm{BR}(\mathrm{non-SM})}$	Limit on $\frac{\sigma}{\sigma_{\mathrm{SM}}} \cdot \mathrm{BR}(\mathrm{non\text{-}SM}$ 7/8 [14] TeV
$b\bar{b}b\bar{b}$	0.7^R $[0.2^L]$	W	0.8	0.9 [0.2]	0	–
$bb\tau\tau$	> 1 $[0.15^L]$	V	0.1	> 1 [1]	0	–
$b\bar{b}\mu\mu$	$(2-7) \cdot 10^{-4\ T}$ $[(0.6-2) \cdot 10^{-4\ T}]$	G	3×10^{-4}	$0.6-1$ $[0.2-0.7]$	0	–
$\tau\tau\tau\tau$	$0.2-0.4^R$ [U]	G	0.005	$40-80$ [U]	1	$0.2-0.4$ [U]
$\tau\tau\mu\mu$	$(3-7) \cdot 10^{-4\ T}$ [U]	G	3×10^{-5}	$10-20$ [U]	0.007	$0.04-0.1$ [U]
$\mu\mu\mu\mu$	$1 \cdot 10^{-4\ R}$ [U]	G	$1 \cdot 10^{-7}$	1000 [U]	$1 \cdot 10^{-5}$	10 [U]

Conclusions & Outlook

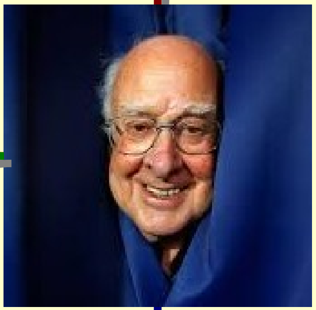
The Higgs is a unique laboratory to test New Physics

Not discussed in this talk,
but of crucial importance:

BSM $\longrightarrow$ Higgs

Exotic production modes

Higgs & flavor



Higgs $\longrightarrow$ BSM

Exotic decay modes

Higgs mass measurement

Higgs SM coupling measurement

(including those couplings that are very suppressed in the SM e.g. Zγ)

Staus direct searches

At the LHC, direct searches for promptly decaying staus are difficult

Strong production

- Searches for staus NLSP produced from gluino & squark cascade decays. (GMSB models) At least one tau, jets and missing energy. ATLAS-CONF-2013-026, CMS-SUS-12-004

EW production

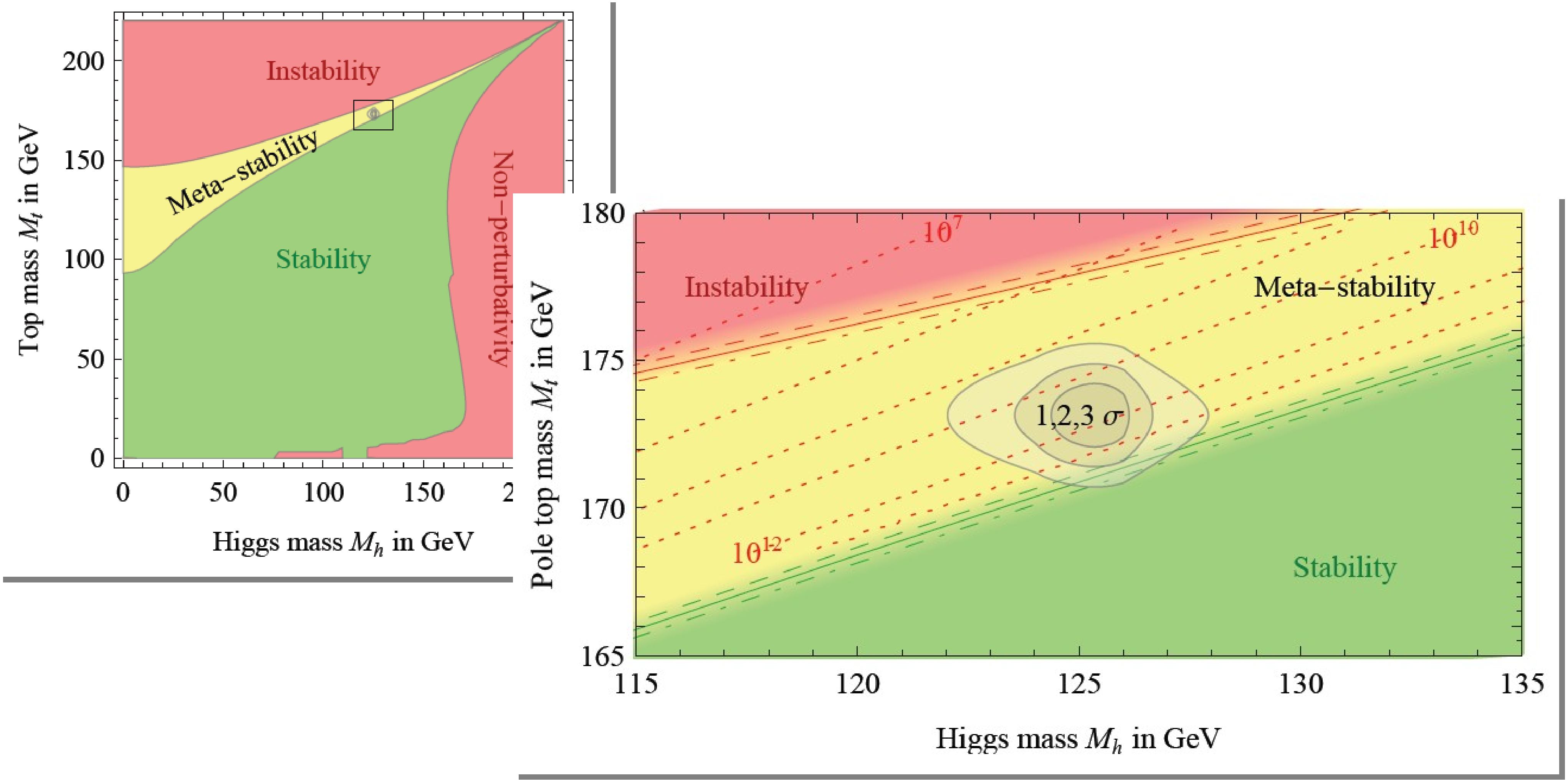
- ATLAS: searches for staus NLSP produced from neutralino/chargino cascade decays. At least 2 taus and missing energy. ATLAS-CONF-2013-028
- Multilepton searches. 2 or more leptons and missing energy. ATLAS-CONF-2013-049, ATLAS-CONF-2013-035, ATLAS-CONF-2013-036, CMS-PAS-SUS-13-002, CMS-PAS-SUS-13-006.

Improved strategies to look for our light staus?

Vacuum stability in the SM

@ NNLO:

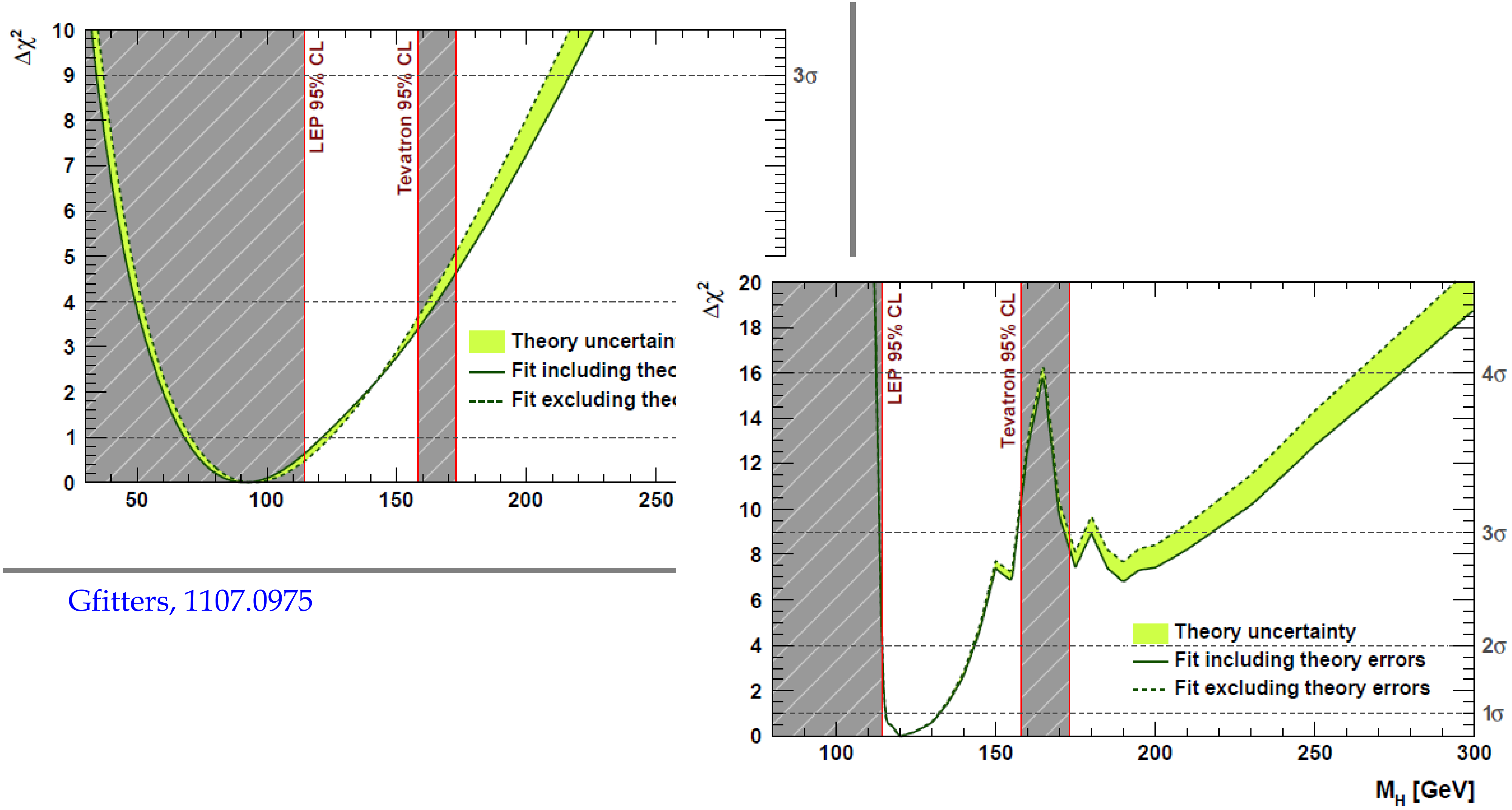
Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice,Isidori, Strumia,1205.6497



We live in a metastable minimum

The mass of the Higgs

A mass that one could have expected?



Gfitters, 1107.0975