Implications of LHC Higgs results

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ROMA TRE UNIVERSITÀ DEGLI STUDI

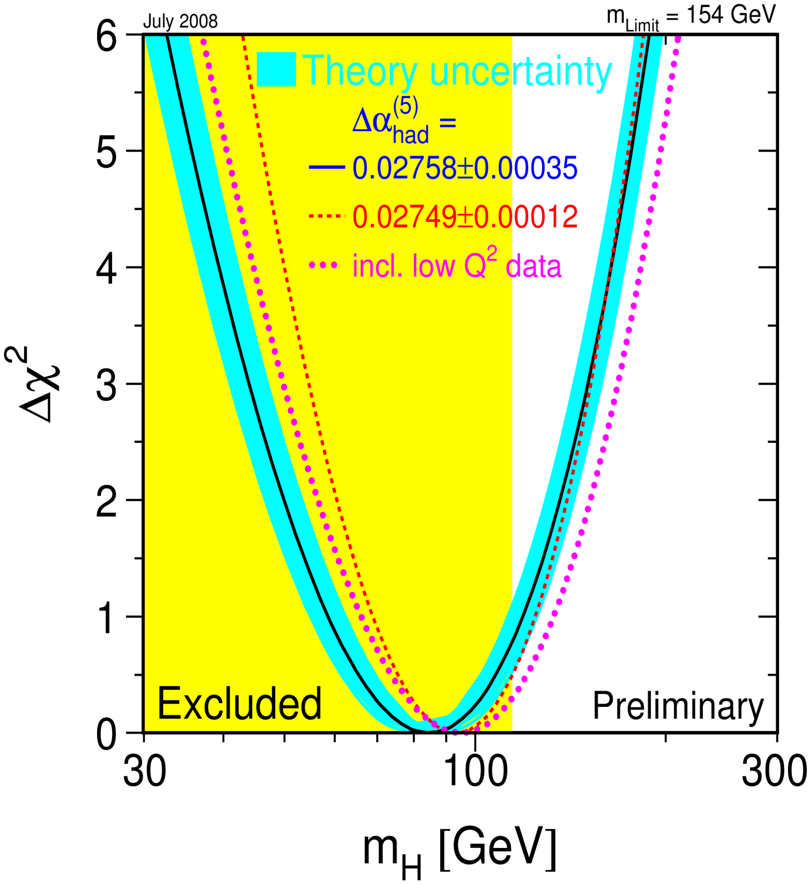
INFN Sezione di Roma III

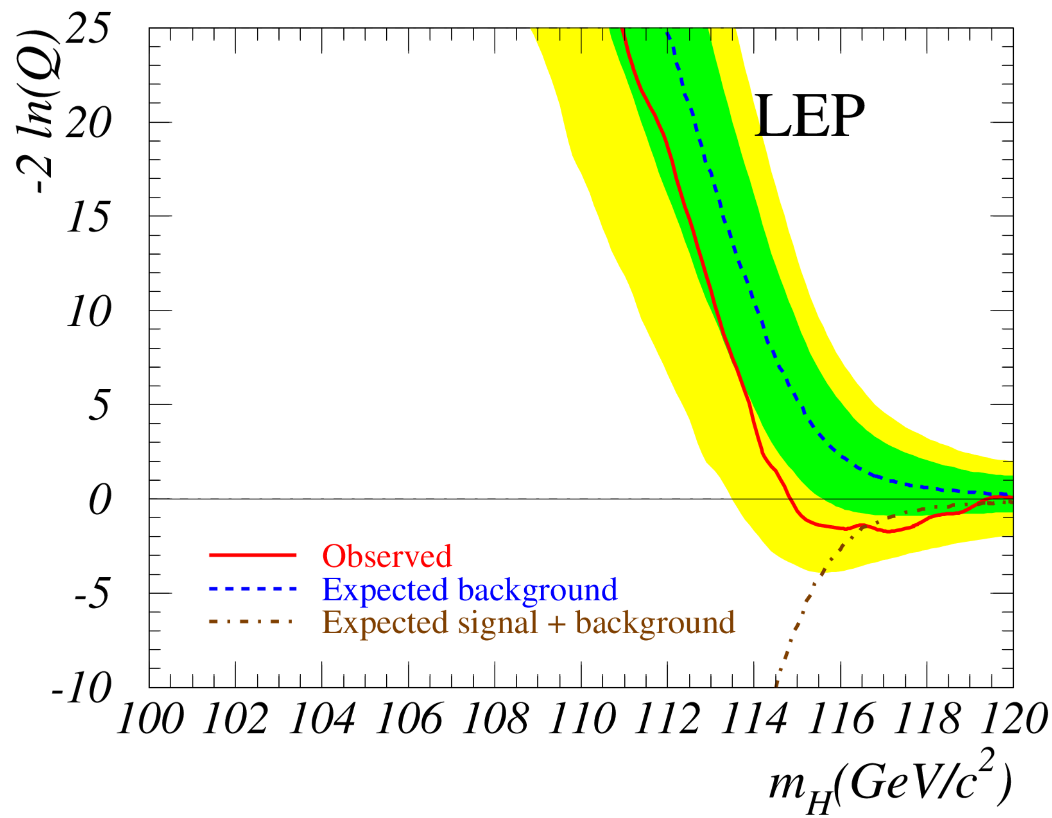
DIPARTIMENTO DI FISICA EDOARDO AMALDI

Outline

- Past and present information on the Higgs boson
- Discussing the hypothesis: $M_h \sim 125$ GeV, for the SM and the MSSM
- Higgs production cross-section. Implications of $\sigma \sim \sigma_{SM}$ for the MSSM
- Conclusions

The past: LEP

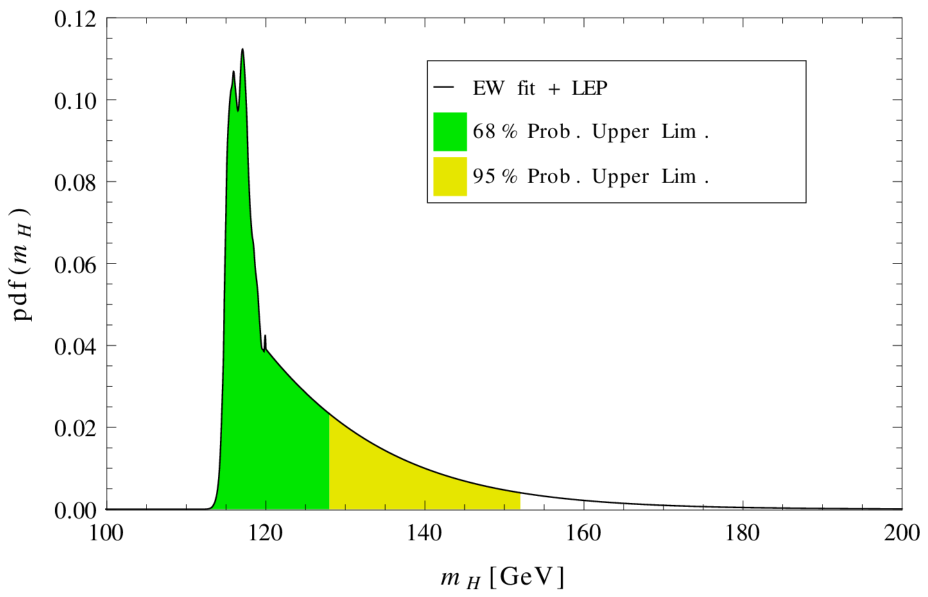


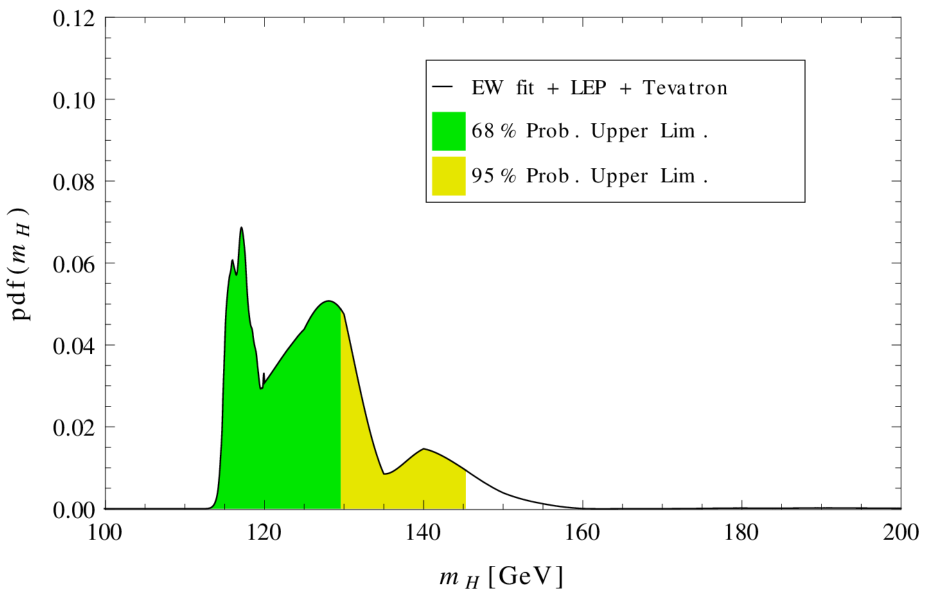


$$Q = \frac{\mathcal{L}(s+b)}{\mathcal{L}(b)}$$

The past: LEP +Tevatron

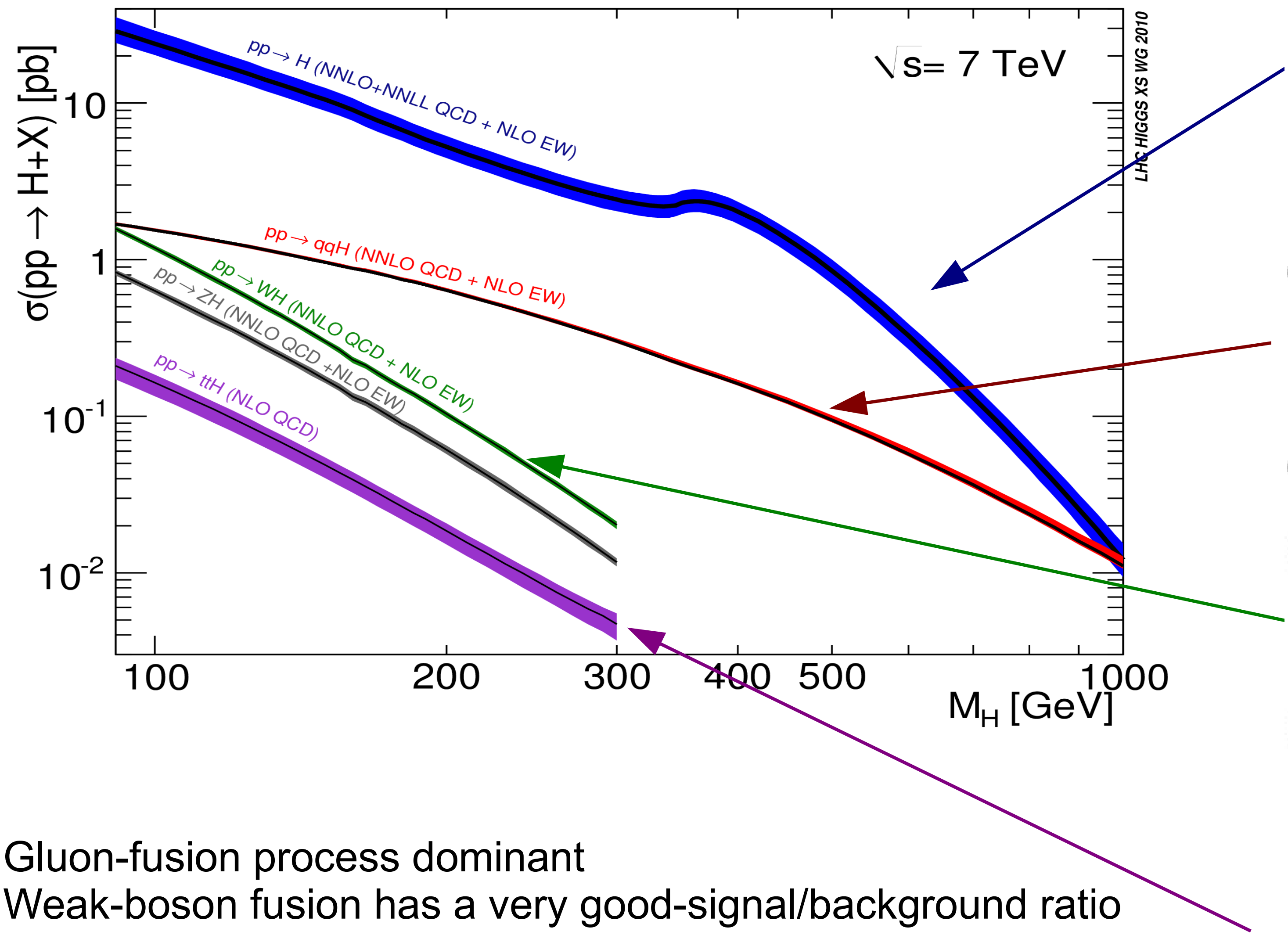
Combining direct and indirect information:

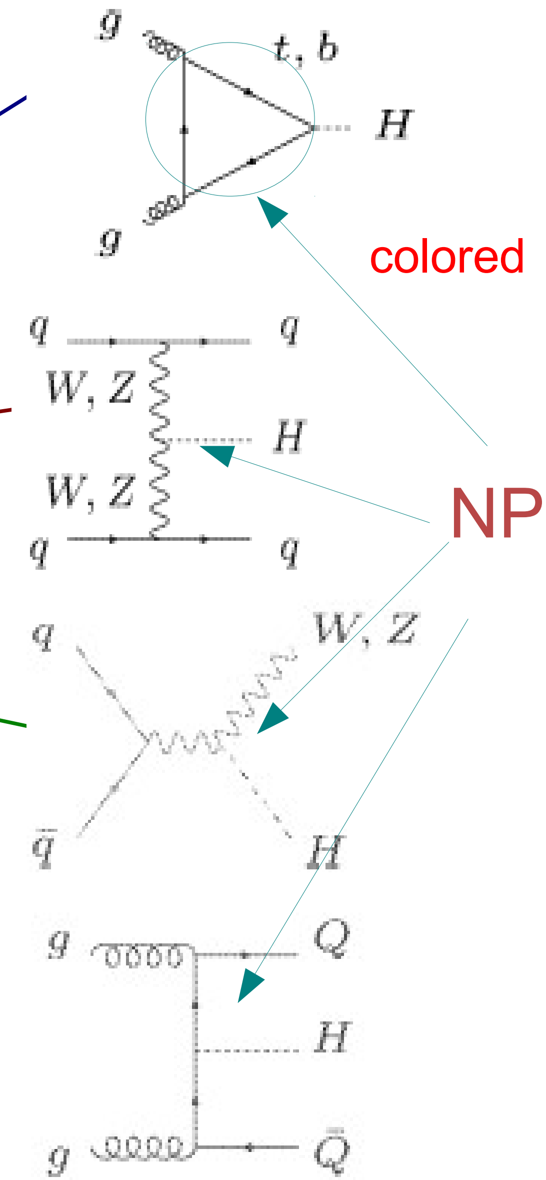




courtesy of S. Di Vita

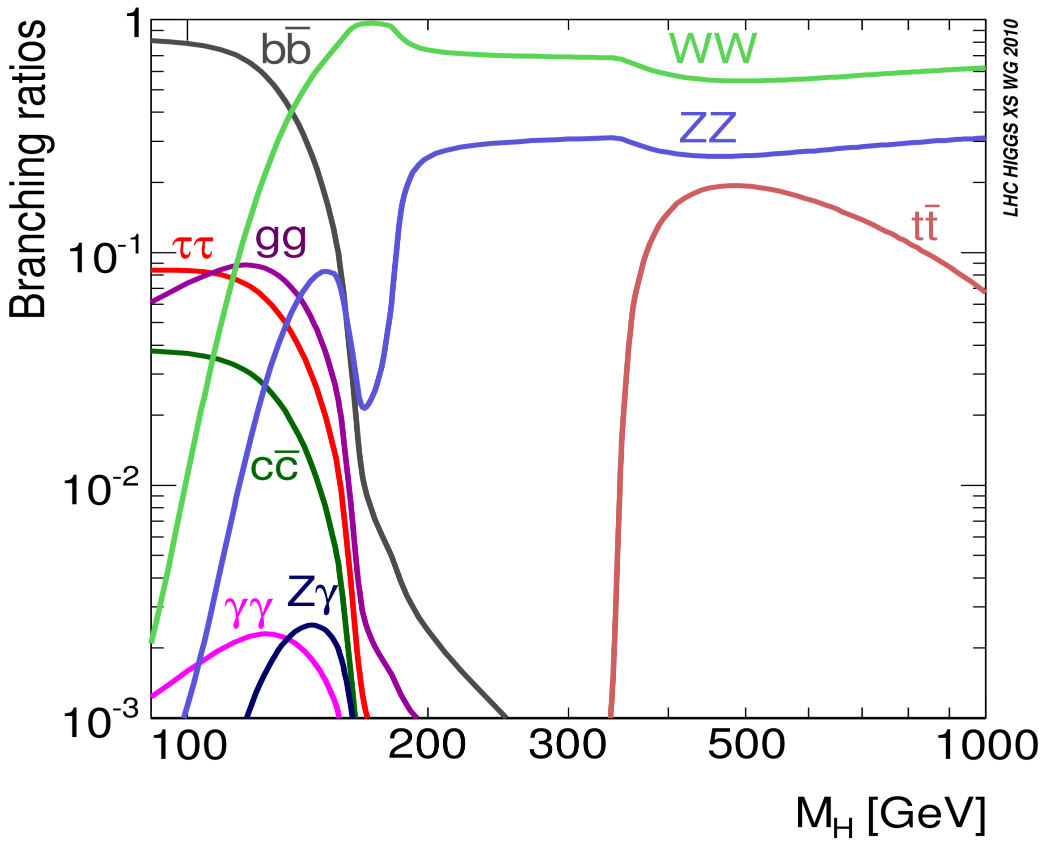
The present: LHC, Higgs Production



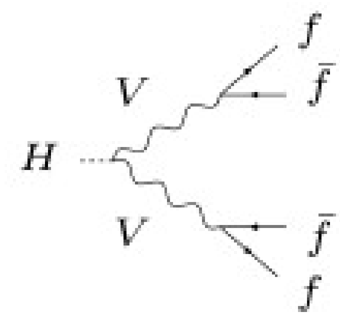


Gluon-fusion process dominant
Weak-boson fusion has a very good-signal/background ratio
Bands include: PDF + α_s + scale uncertainties
Heavy replicas of SM particles contribute to gluon-fusion:
ex. 4th generation

The present: LHC, Higgs Decays



Golden Channel V=Z

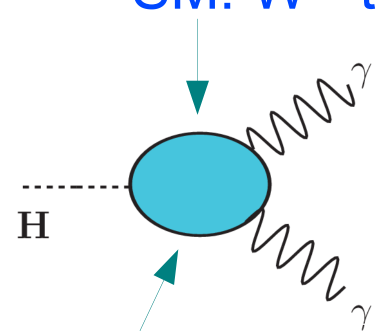


A NP increase in gluon-fusion X-sect. often corresponds to a decrease of BR$(H \to \gamma\gamma)$

The BR $(H \to \gamma\gamma)$ can increase if NP reduces the other BR's

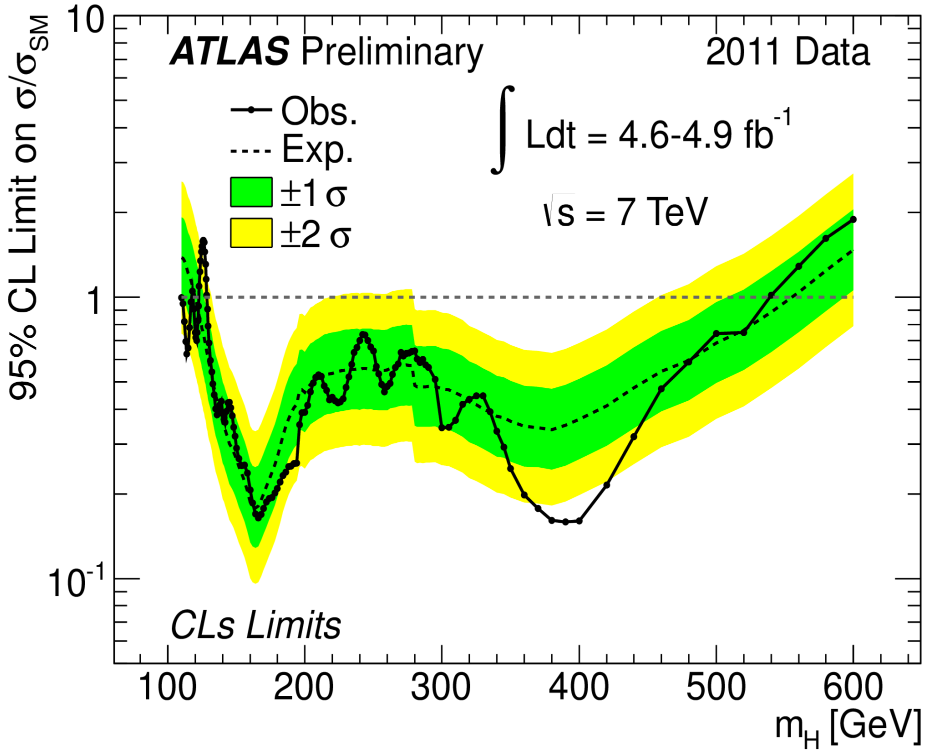
Low Higgs mass

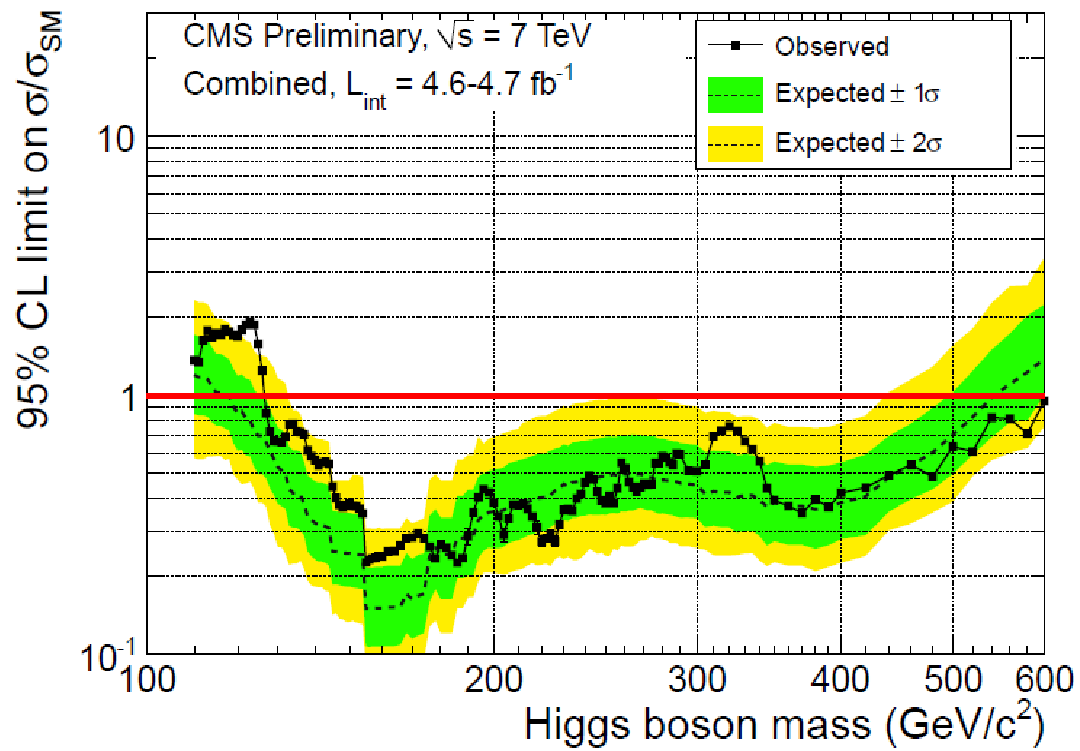
SM: W - t



NP: white + colored

The present: LHC, results





Excess of events in $H \to \gamma\gamma, H \to ZZ$

ATLAS near $M_H \sim$ 126 GeV

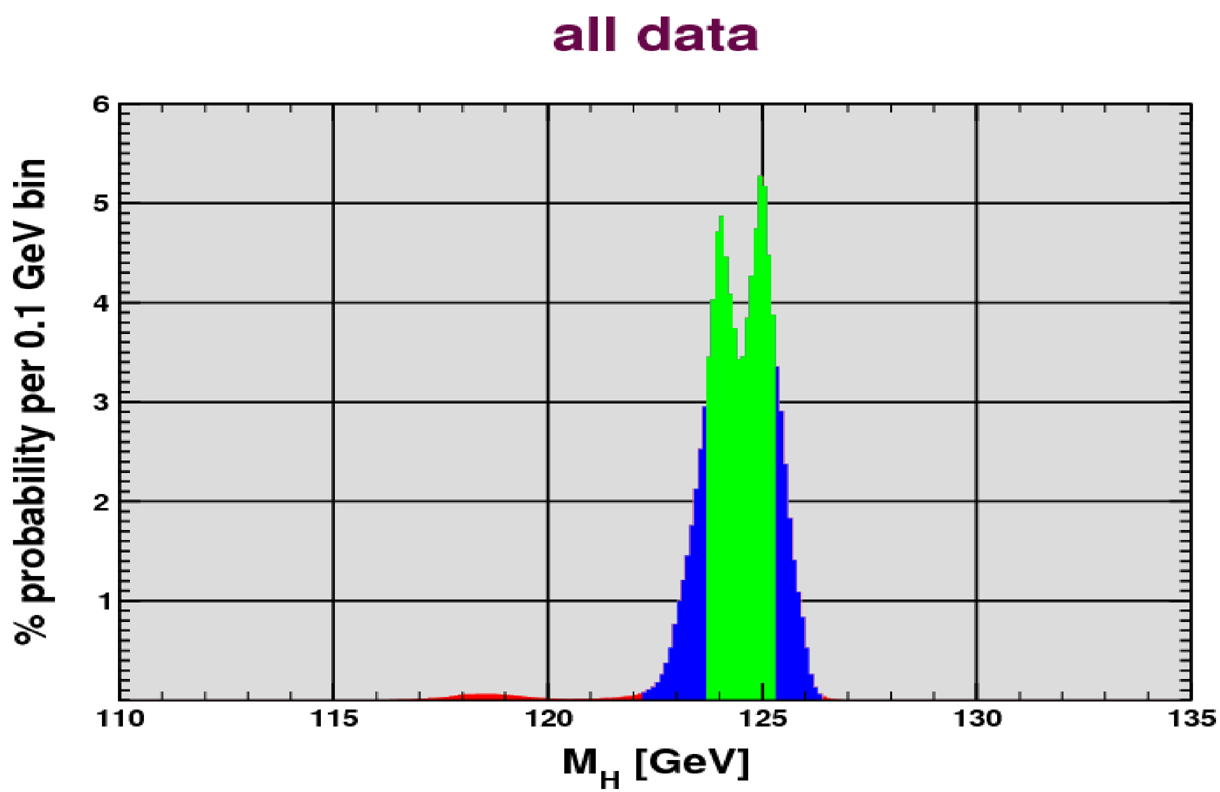
CMS near $M_H \sim$ 124 GeV
and near $M_H \sim$ 119.5 GeV

Supported by a broad excess in $H \to WW$

The present: LHC

This plot should be taken as qualitative.

Q is guessed.
Experiments do not provide likelihoods



Erler, 2012

Working hypothesis: M_H~ 125 GeV, $\sigma \sim \sigma_{SM}$

but data still allow M_H > 600 GeV although this region is cut by EWPT

Reversing the heavy Higgs argument

Specific type of NP could allow a heavy Higgs in the EW fit (“conspiracy”).
Take

$$\sin^2\theta^{lept}_{eff} \sim \frac{1}{2}\left\{1-\left[1-\frac{4A^2}{M_Z^2\,\hat\rho\,(1-\Delta\hat r_W)}\right]^{1/2}\right\}$$

$$\begin{aligned}\hat\rho &= \rho_0+\delta\rho\,(\rho_0^{\mathrm{SM}}=1,\delta\rho\leftrightarrow(\epsilon_1,\,T))\\ \Delta\hat r_W &\leftrightarrow (\epsilon_3,\,S)\end{aligned}$$

$$c_i > 0 \qquad \sim (\sin^2\theta^{lept}_{eff})^\circ + c_1\,\ln\left(\frac{M_H}{M_H^\circ}\right) + c_2\left[\frac{(\Delta\alpha)_h}{(\Delta\alpha)_h^\circ}-1\right] - c_3\left[\left(\frac{M_t}{M_t^\circ}\right)^2-1\right]+\ldots$$

To increase the fitted M_H: $\left\{\begin{array}{l}\hat\rho>1\rightarrow \left\{\begin{array}{l}\rho_0>1 \leftarrow \text{Extra Z}\\ \delta\rho>0 \leftarrow \text{Isosplited (s)fermions, Multi Higgs models,}\end{array}\right.\\ \Delta\hat r_W<0 \leftarrow \text{Light sleptons}\end{array}\right.$

NP (if there) seems to be of the decoupling type

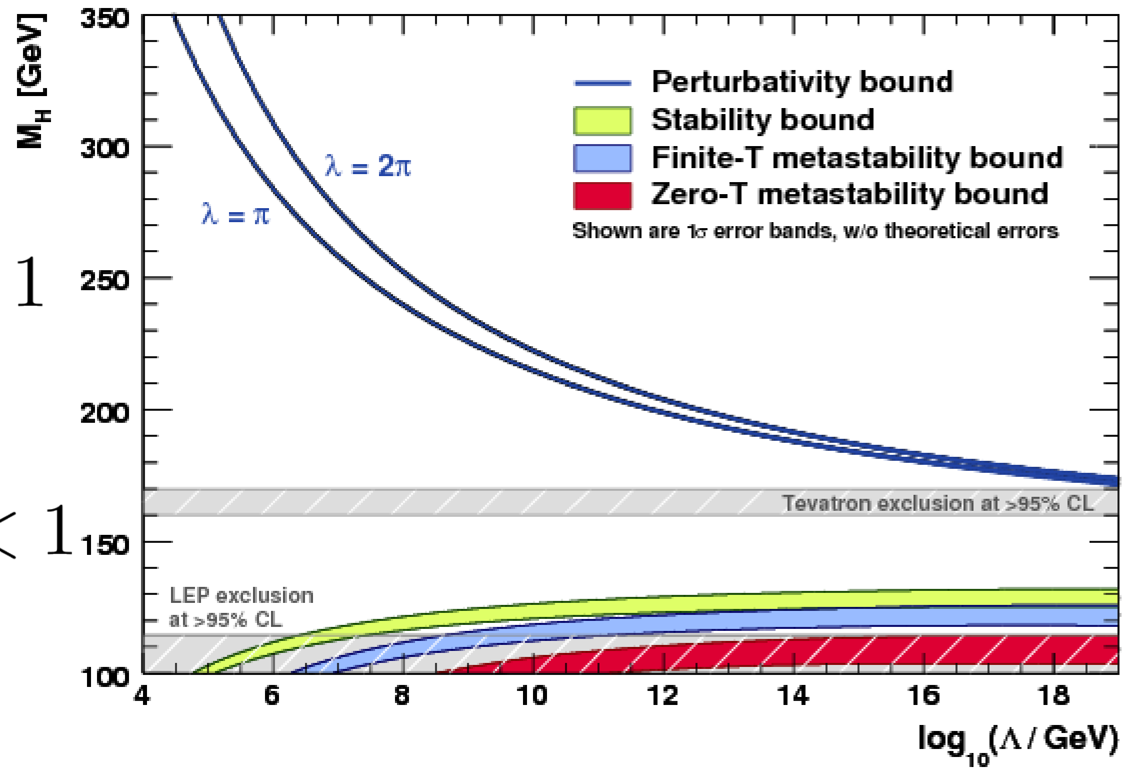
n.b. M_H > 600 GeV would point to the conspiracy

Theoretical bounds on the Higgs mass in the SM

$$V_{\rm Higgs} \approx \frac{\lambda}{4} h^4$$

M_H large $\lambda(m_t) \to \lambda(\Lambda) \gg 1$
non-perturbative regime

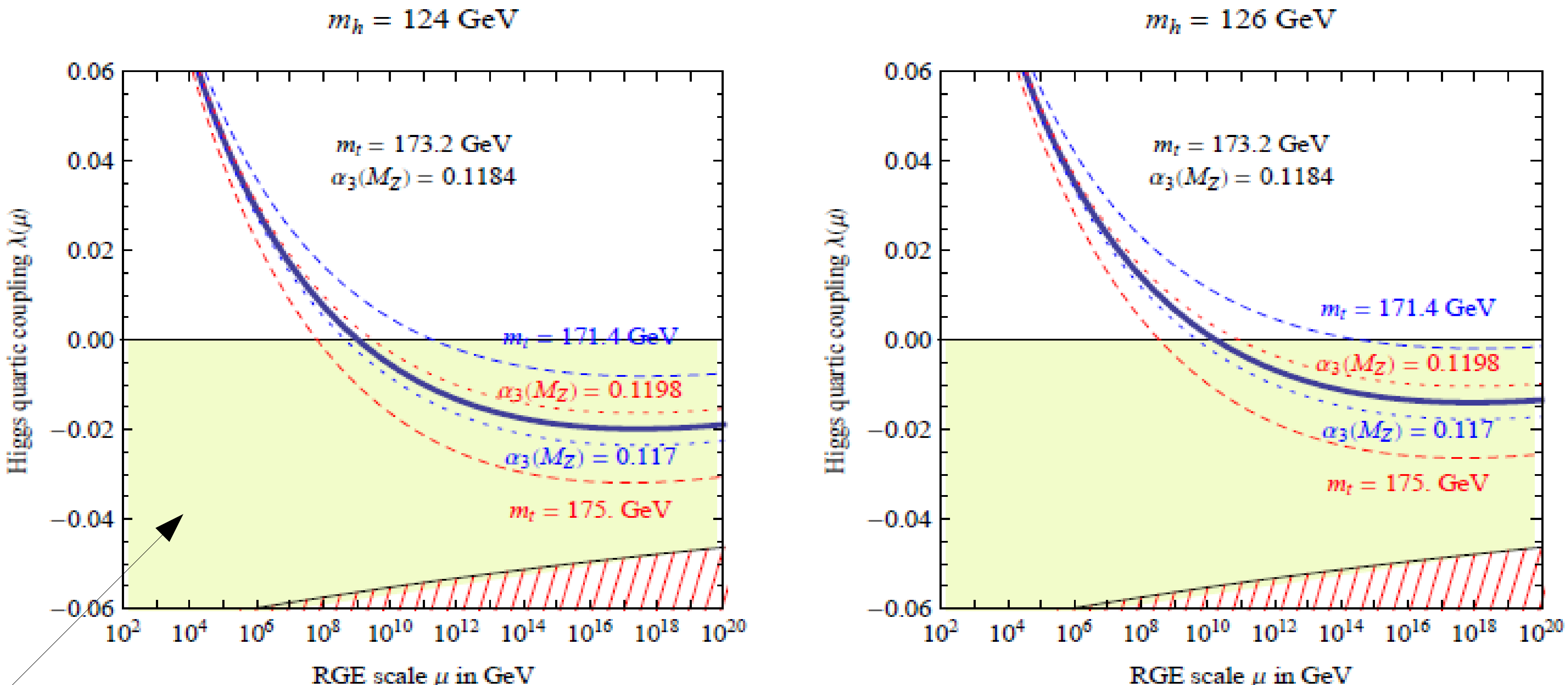
M_H small $\lambda(m_t) \to \lambda(\Lambda) \ll 1$
vacuum (meta)stability



Ellis et al. 2009

Running depends on $m_t,\ \alpha_s, \ldots$

$M_H \sim 125$ GeV, no problem with the Landau pole, perturbativity up to the Planck scale



Elias-Miro' et al. 2011

Metastability region

Full stability is at the border. Universe becomes metastable at $\Lambda \sim 10^{10}$ GeV.
λ never becomes too negative, small probability of quantum tunneling.
Lifetime of the EW vacuum longer than the age of the Universe.
SM ok up to Planck mass.

M_H ~ 125 GeV and the MSSM

$$\beta,\ \alpha$$

Higgs sector: $H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}, \quad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \Longrightarrow h, H, A, H^\pm$

Higgs masses: predicted at the tree level in terms of M_A, tan β, $M_h < M_Z$

Including radiative corrections: dependence on all SUSY(-breaking) parameters

$$(A_t, A_b, \mu \ldots)$$

$$M_h \lesssim 135\,\mathrm{GeV}$$

$$M_{A,H,H^\pm} \sim 100 \ldots \mathrm{TeV}$$

$\xrightarrow{\text{decoupling}}$ h SM-like

$$M_A \sim M_H \sim M_H^\pm > \mathcal{O}(200\mathrm{GeV})$$

ϕ	$g^\phi_{u\bar{u}}$	$g^\phi_{d\bar{d}}$	g^ϕ_{VV}
h	$\cos\alpha\,/\sin\beta \to 1$	$-\sin\alpha\,/\cos\beta \to 1$	$\sin(\beta-\alpha) \to 1$
H	$\sin\alpha\,/\sin\beta \to 1/\tan\beta$	$\cos\alpha\,/\cos\beta \to \tan\beta$	$\cos(\beta-\alpha) \to 0$
A	$1/\tan\beta$	$\tan\beta$	0

Large tanβ

$g^\phi_{d\bar{d}}$ ↑

decoupling

$$g^\phi_{d\bar{d}} \to \frac{0}{0}$$

delayed decoupling

How easy is to get M_H ~ 125 GeV in the MSSM ?

$$M_h^2 \simeq M_Z c_{2\beta}^2 + \frac{3\, m_t^4}{4\,\pi^2 v^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12\, M_S^2}\right)\right] + \ldots$$

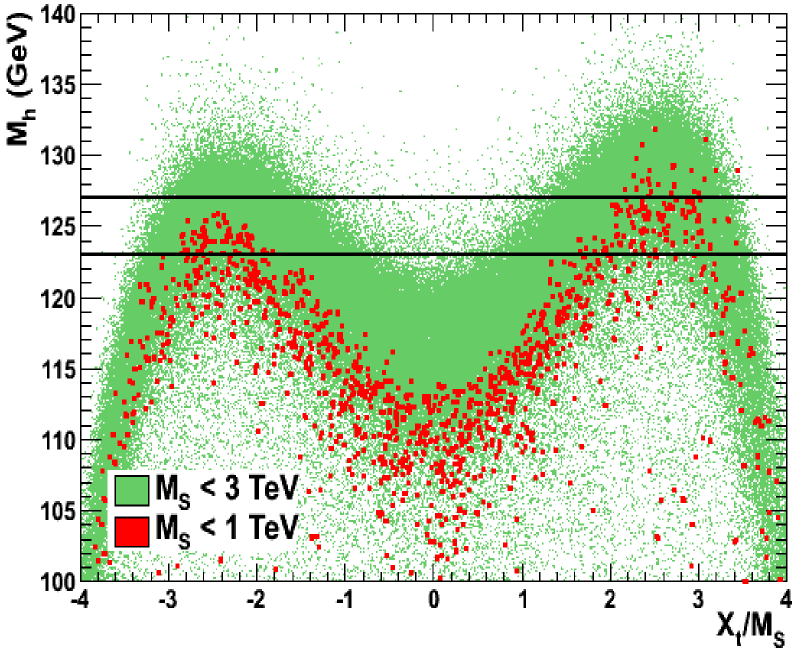
SUSY breaking parameters

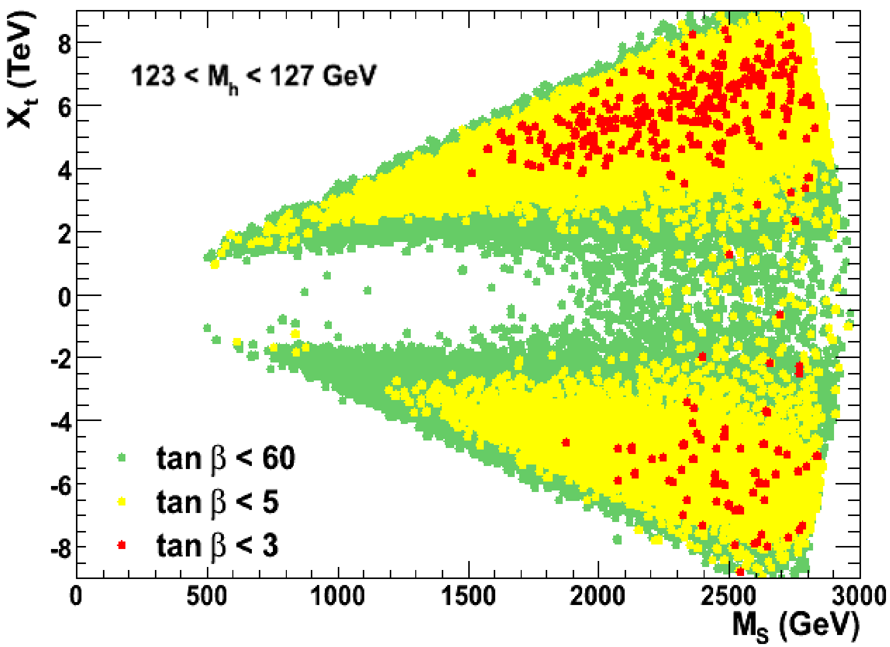
$$X_t = A_t - \mu \cot\beta, \;\; M_S = \sqrt{M_{\tilde{t}_1} M_{\tilde{t}_2}})$$

To get M_H ~ 125 GeV:

- Large tan β, tan β > 10 (increase the tree-level)
- Heavy stops, i.e. large M_S (increase the ln)
- Large stop mixing, i.e. large X_t

The more assumptions we take on the mechanism of SUSY-breaking, the more difficult becomes to get M_h ~ 125 GeV pMSSM: minimal assumptions on SUSY-breaking parameters





Arbey et al., 2011

22 input parameters varying in the domains:

$$1 \leq \tan\beta \leq 60\,,\;\; 50\ \mathrm{GeV} \leq M_A \leq 3\ \mathrm{TeV}\,,\;\; -9\ \mathrm{TeV} \leq A_f \leq 9\ \mathrm{TeV}\,,$$
$$50\ \mathrm{GeV} \leq m_{\tilde{f}_L}, m_{\tilde{f}_R}, M_3 \leq 3\ \mathrm{TeV}\,,\;\; 50\ \mathrm{GeV} \leq M_1, M_2, |\mu| \leq 1.5\ \mathrm{TeV}.$$

Costrained scenarios:

(no) GMSB:

$\tan\beta,\ sign(\mu),\ M_{mess},\ N_{mess}, \Lambda$

(no) AMSB:

$\tan\beta,\ sign(\mu),\ m_0,\ m_{3/2}$

(yes) MSUGRA:

$\tan\beta,\ sign(\mu),\ m_0,\ m_{1/2},\ A_0$

(no) no-scale:

$$m_0 \approx A_0 \approx 0$$

(yes) VCMSSM :

$$m_0 \approx -A_0$$

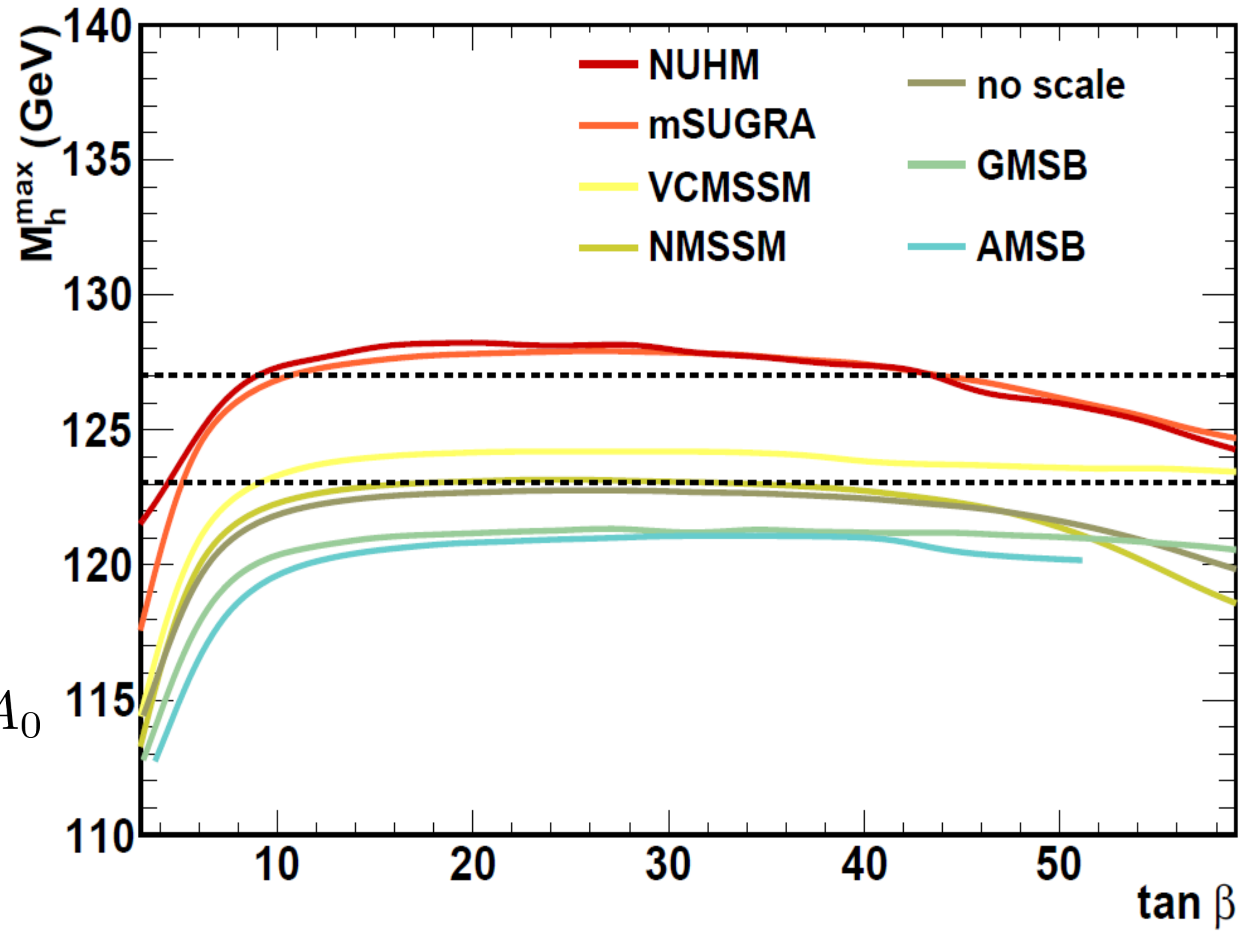
(no) NMSSM :

$$m_0 \approx 0,$$

$$A_0 \approx -1/4 m_{1/2}$$

(yes) NUHM:

non universal m_0



Arbey et al., 2011

mSUGRA:	$50\ \text{GeV} \le m_0 \le 3\ \text{TeV}$,	$50\ \text{GeV} \le m_{1/2} \le 3\ \text{TeV}$,	$\lvert A_0\rvert \le 9\ \text{TeV}$;
GMSB:	$10\ \text{TeV} \le \Lambda \le 1000\ \text{TeV}$,	$1 \le M_{\text{mess}}/\Lambda \le 10^{11}$,	$N_{\text{mess}} = 1$;
AMSB:	$1\ \text{TeV} \le m_{3/2} \le 100\ \text{TeV}$,	$50\ \text{GeV} \le m_0 \le 3\ \text{TeV}$.	

$\sigma(gg \to \phi)$

$$\sigma(h_1 + h_2 \to \phi + X) = \sum_{a,b} \int_0^1 dx_1 dx_2 \; f_{a,h_1}(x_1, \mu_F^2)\, f_{b,h_2}(x_2, \mu_F^2) \int_0^1 dz\, \delta\left(z - \frac{\tau_H}{x_1 x_2}\right) \hat{\sigma}_{ab}(z)$$

LO
virtual

NLO
virtual + real

$$\hat{\sigma}_{ab}(z) = \sigma^{(0)}\, z \left(G_{ab}^{(0)}(z) + \frac{\alpha_s}{\pi} G_{ab}^{(1)}(z) + \mathcal{O}(\alpha_s^2) \right)$$

$$\sigma^{(0)} = \frac{G_\mu\, \alpha_s^2(\mu_R^2)}{128\sqrt{2}\,\pi} \left| \mathcal{H}_\phi^{1\ell} \right|^2$$

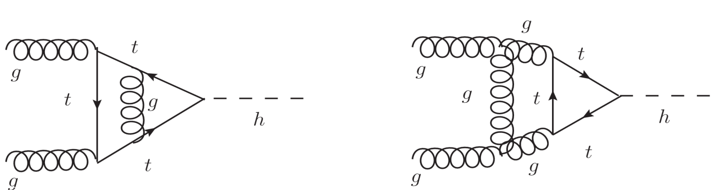
exact

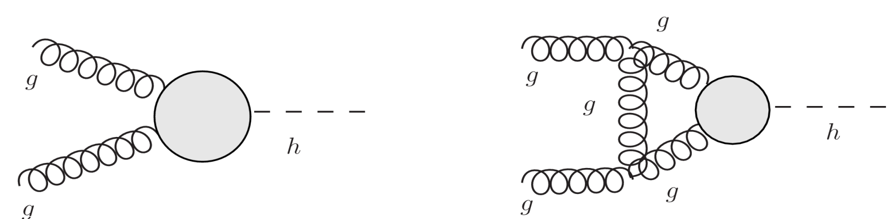
evaluated via E.T.

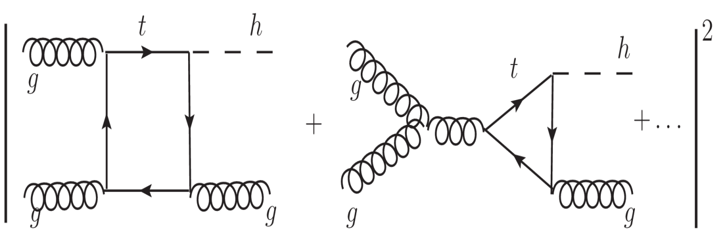
form factor $gg\phi$ coupling

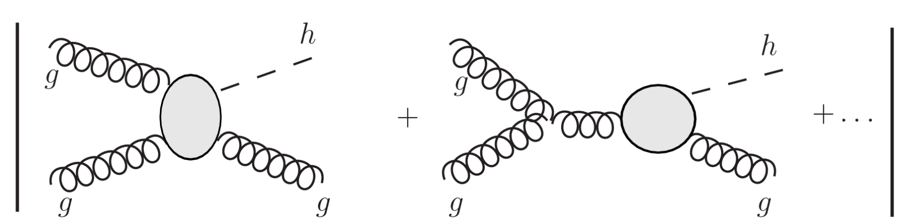
Effective approximation (expected to work up to the first threshold)

Kraemer, Laenen, Spira (98)





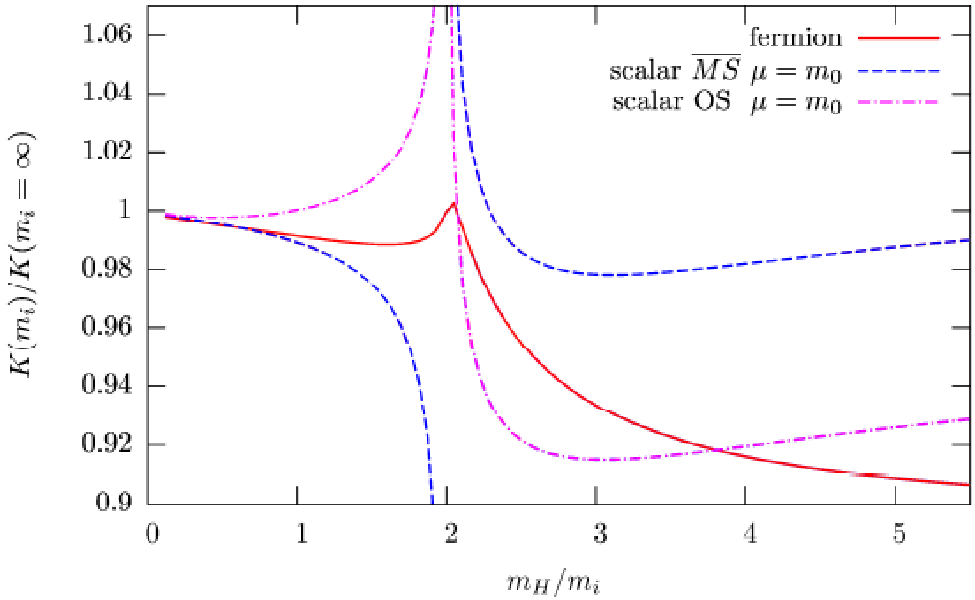




numerical integration

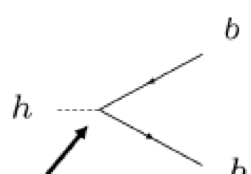
analytic integration

Testing the E. A. : cross-section

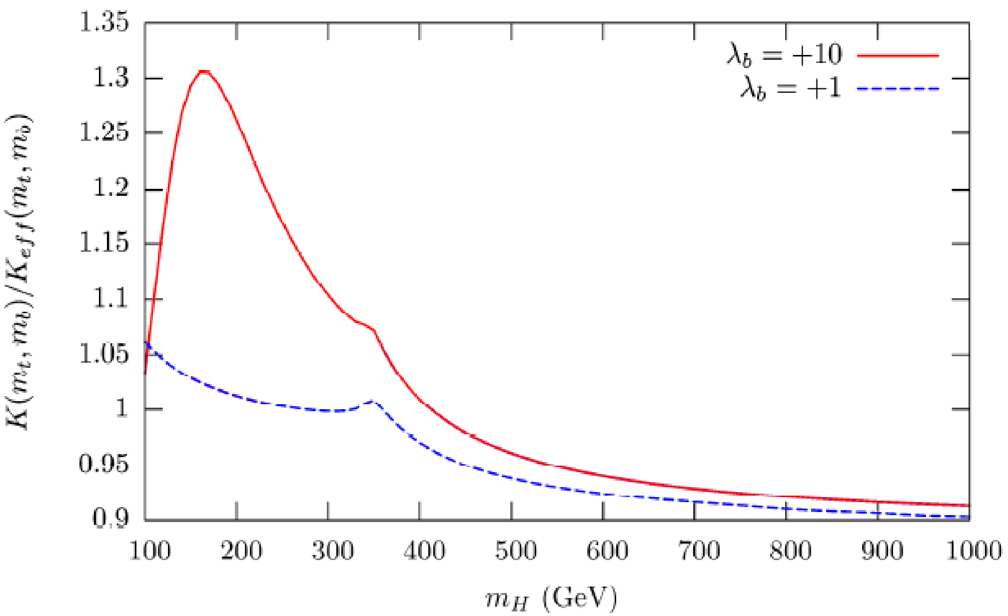


$$K \equiv \frac{\sigma_{NLO}}{\sigma_{LO}}$$

Amplifying the bottom coupling



$$h_b \longrightarrow \lambda_b g \frac{m_b}{M_w}$$



Testing the E. A. : distributions, using POWHEG

PO(sitive)W(eight)H(ardest)E(mission)G(enerator)

Nason et al. (04--)

- Matching NLO-QCD matrix elements with Parton Showers. Generate the hardest emission first, with NLO accuracy, independently of the PS. Can be interfaces to several SMC programs (HERWIG/PHYTIA). NLO accuracy of the total cross-section preserved.

- Original release with SM Higgs gluon-fusion production implemented in the E.A.
  Alioli, Nason, Oleari, Re (09)
- New release SM Higgs gluon-fusion production with exact quark mass effects
  Bagnaschi, Slavich, Vicini, G.D (11).

Basic POWHEG formulas:

m.e. for real emission

$$d\sigma = \bar{B}(\bar{\Phi}_1)\, d\bar{\Phi}_1 \left\{ \Delta\left(\bar{\Phi}_1, p_T^{min}\right) + \Delta\left(\bar{\Phi}_1, p_T\right) \frac{R\left(\bar{\Phi}_1, \Phi_{\rm rad}\right)}{B\left(\bar{\Phi}_1\right)}\, d\Phi_{\rm rad} \right\} + \sum_q R_{q\bar{q}}\left(\bar{\Phi}_1, \Phi_{\rm rad}\right) d\bar{\Phi}_1 d\Phi_{\rm rad} \, .$$

Born

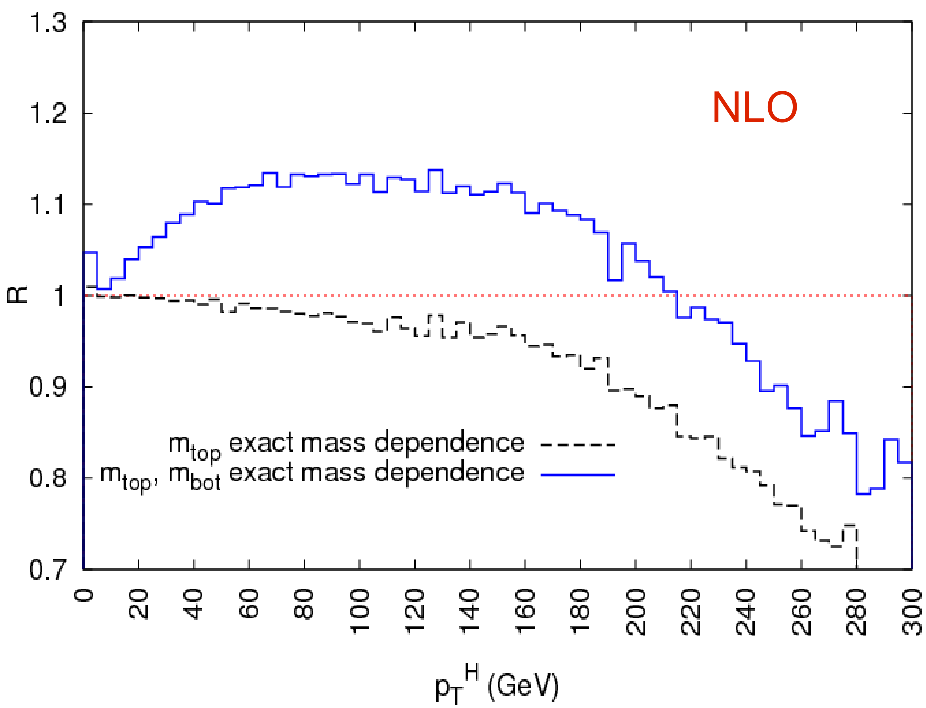
$$\Delta(\bar{\Phi}_1, p_T) = \exp\left\{ - \int d\Phi_{\rm rad} \frac{R(\bar{\Phi}_1, \Phi_{\rm rad})}{B(\bar{\Phi}_1)} \theta(k_T - p_T) \right\}$$

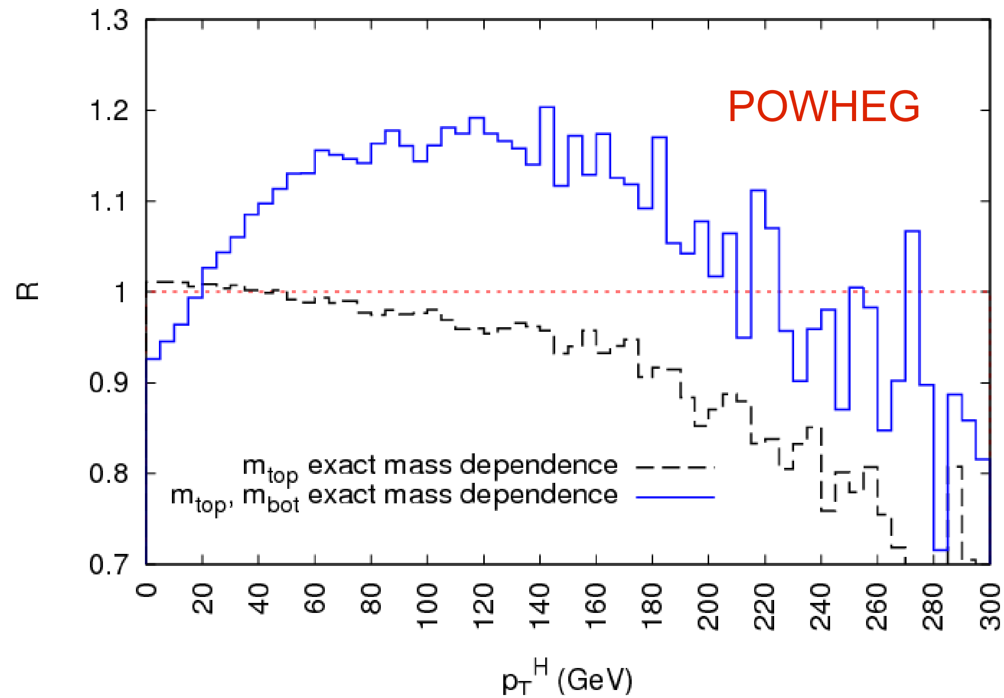
Sudakov

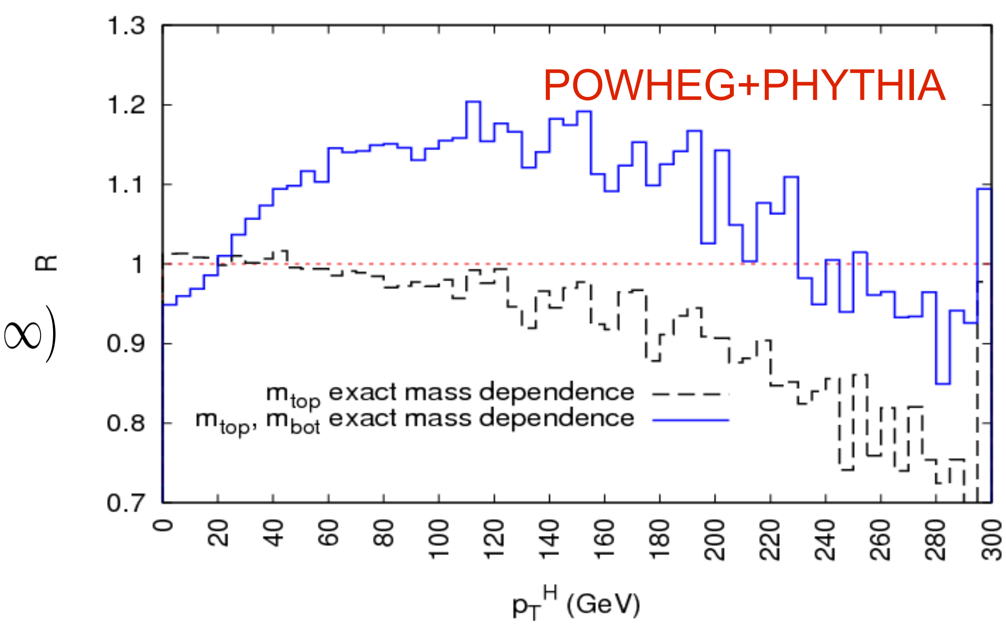
Testing the E. A. : distributions, using POWHEG

M_h = 120 GeV, LHC = 7 TeV

$$R = \frac{\text{new}}{\text{original}}$$





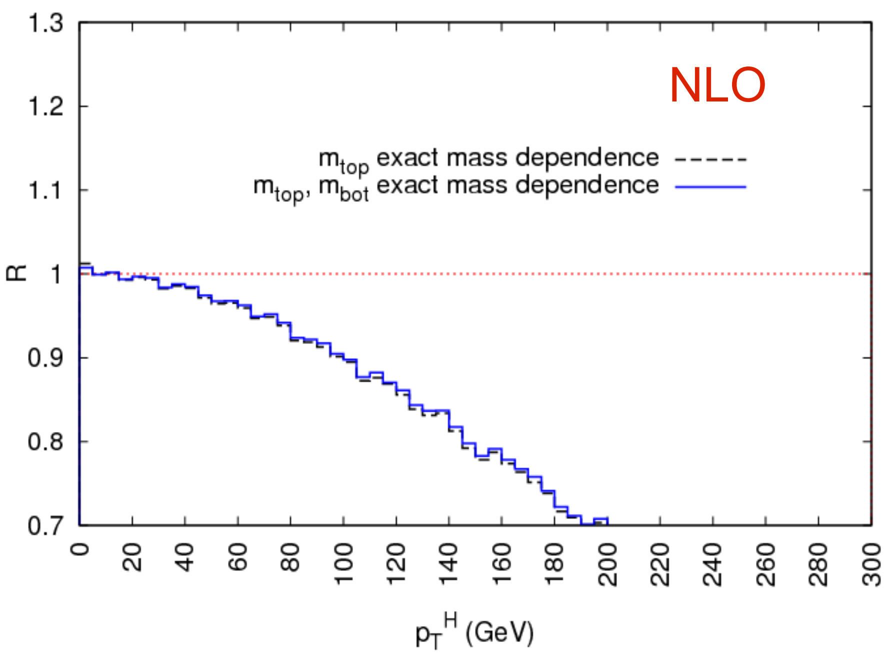


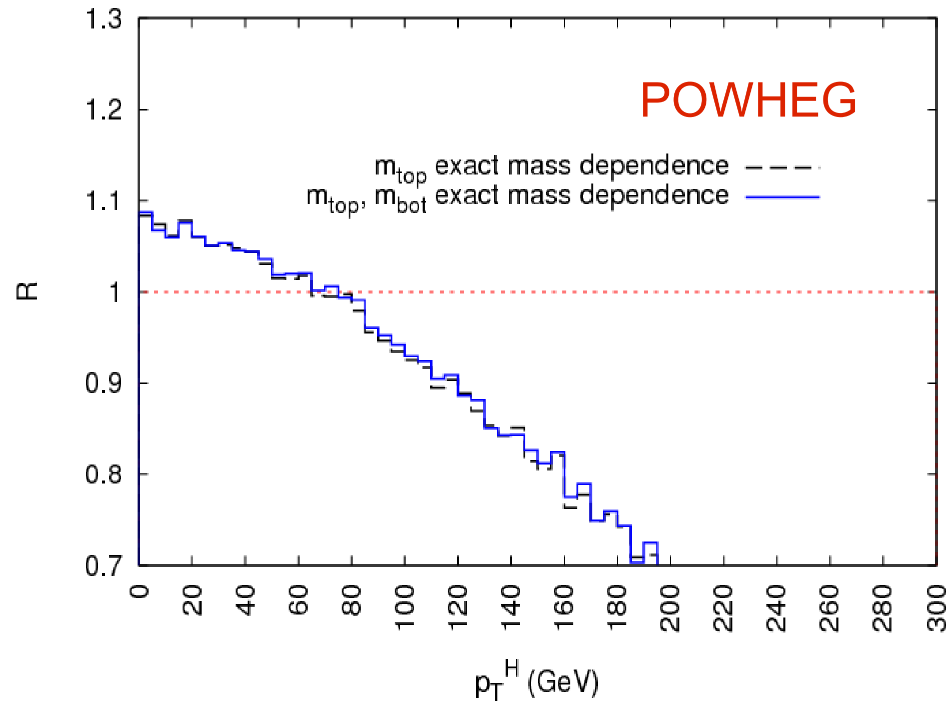
POWHEG

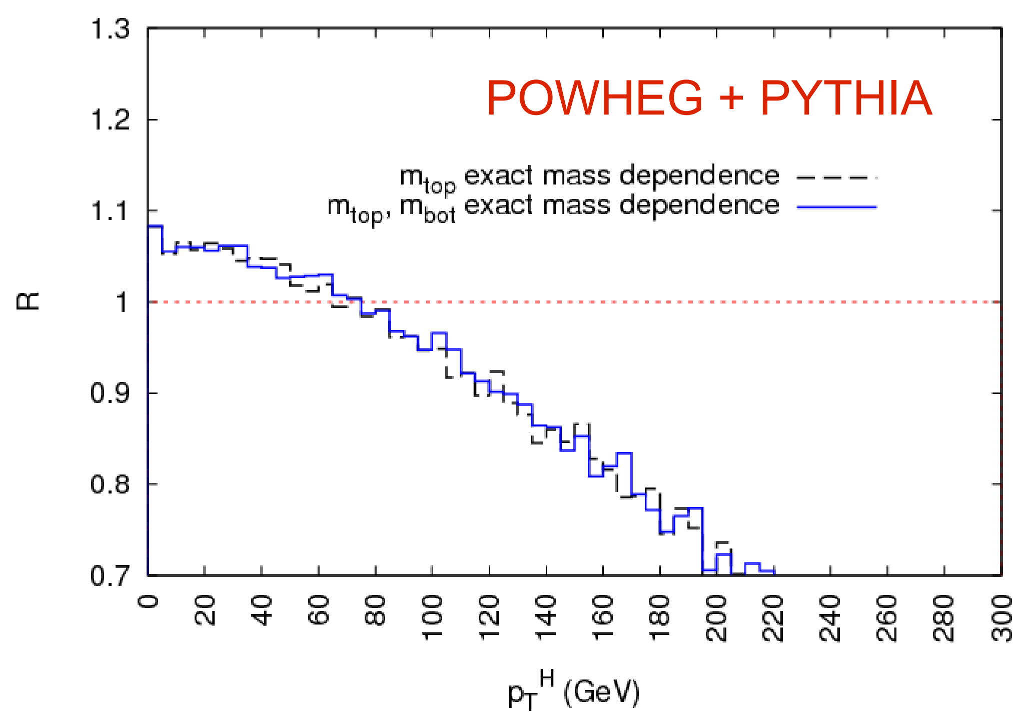
$$R(t+b, exact) > R(t, \infty),\ B(t+b, exact) < B(t, \infty)$$

Exact Sudakov < E.A. Sudakov
Suppression for $p_T^H \simeq 30$ GeV

M_h = 500 GeV, LHC = 7 TeV



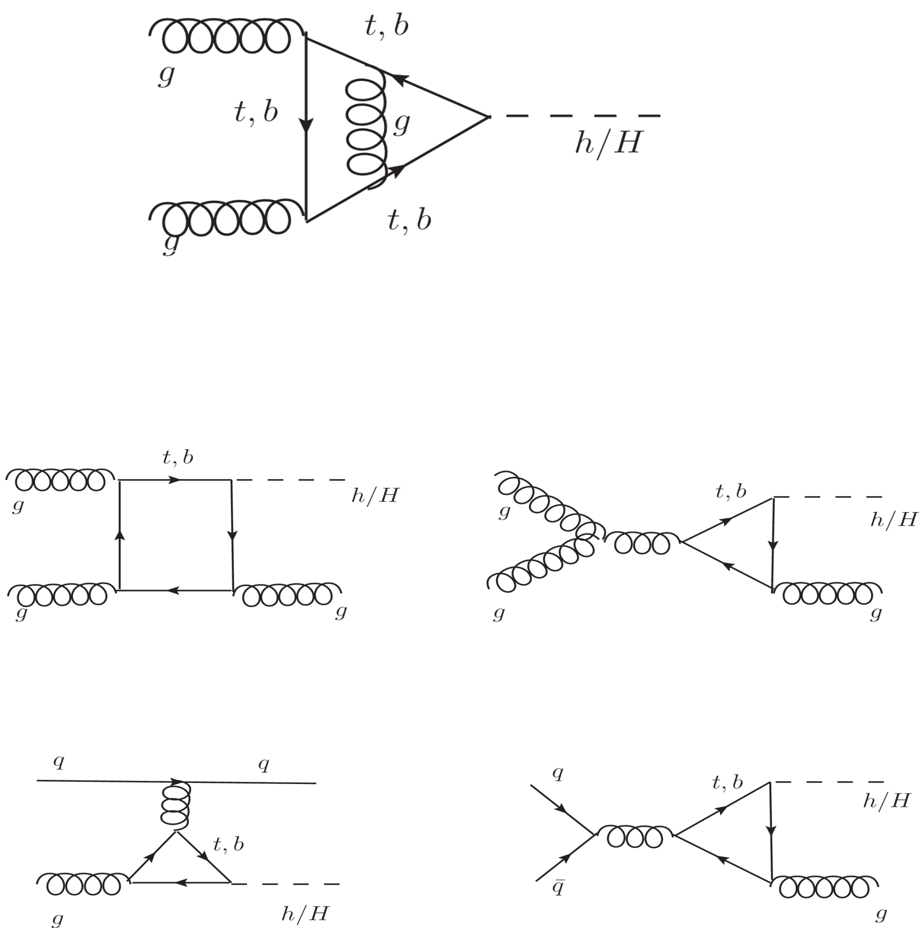




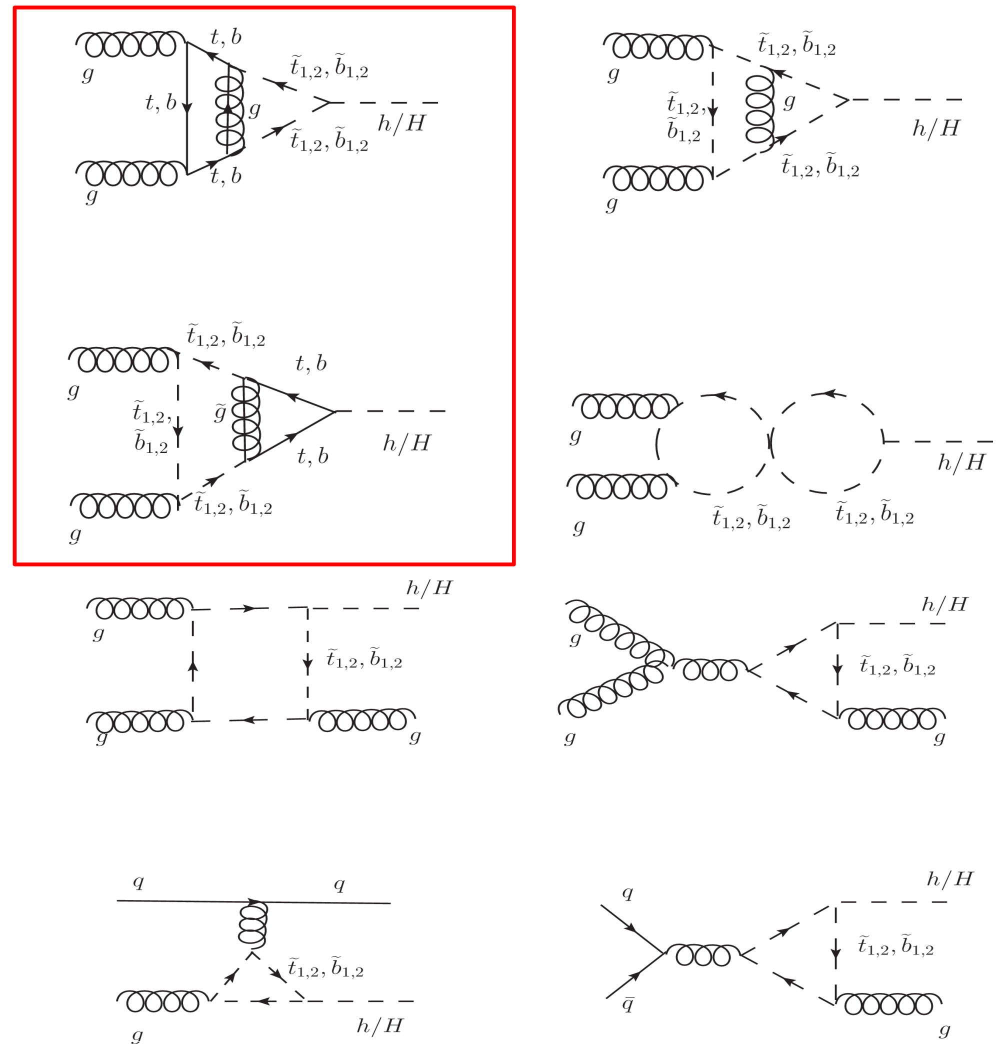
$\sigma(gg \to \phi)$ in the MSSM

Higgs coupling to gluons mediated by quarks and squarks.

SM rescaled



New



$\sigma(gg \to \phi)$ in the MSSM

NLO

Gluon-squark: virtual & real contribution in the vanishing Higgs-mass limit (VHML)
Dawson, Djouadi, Spira (96)

Gluon-squark: virtual & real contribution complete (analytic)
Anastasiou, Beerli, Bucherer, Daleo, Kunszt (07),
Aglietti, Bonciani, Vicini, G.D. (07)
Muehlleitner, Spira (07), Bonciani, Vicini, G.D. (07)

Gluino-top-stop: virtual contribution in the VHML (not applicable to the bottom case)
Harlander, Steinhauser (03-04), Harlander, Hofmann (06)
(code evalcsusy.f)
Slavich, G.D. (08) (analytic)

Gluino-quark-squark: virtual contribution complete
semianalytic, not yet available to the public as computer code
Anastasiou, Beerli,Daleo (08)
Muehlleitner, Rzehak, Spira (?)

Results in a “finite” time?

NNLO

Gluino-top-stop: virtual contribution in the VHML
Pak, Steinhauser, Zerf (10)

Alternative approach:
Gluino-quark-squark contribution can be evaluated via an asymptotic expansion (A.E.) in the large supersymmetric masses.
Analytic result: i) easily implemented in computer codes; ii) fast evaluation
Validity: up to the first squark threshold

$\sigma(gg \to h)$ OK

E.A. + bottom contribution via A.E. (large tan β)

dominated by $\mathcal{O}(\frac{m_b m_g}{M_h^2})$ terms from $hb\bar{b}$ coupling (reabsorbable)

contribution from $h\tilde{B}\tilde{B}$ can be made small

Slavich, G.D. (10)
Harlander, Hofmann, Mantler (11)

$\sigma(gg \to H, A)$ OK up to $M_{H,A} < 2M_{\tilde{Q}}$

gluino-top-stop,via E.A. or A.E., gluino-bottom-sbottom via A.E.

Di Vita, Slavich, G.D. (10 -11)

Implementing in POWHEG the gluon-fusion process in the MSSM

E. Bagnaschi, P. Slavich, A. Vicini,G.D. (11)

The evaluation of the Higgs masses and of the gluon-fusion production cross-section are linked. The (renormalized) parameters that enter the evaluation of the cross-section must be the same that are used in the evaluation of the masses.

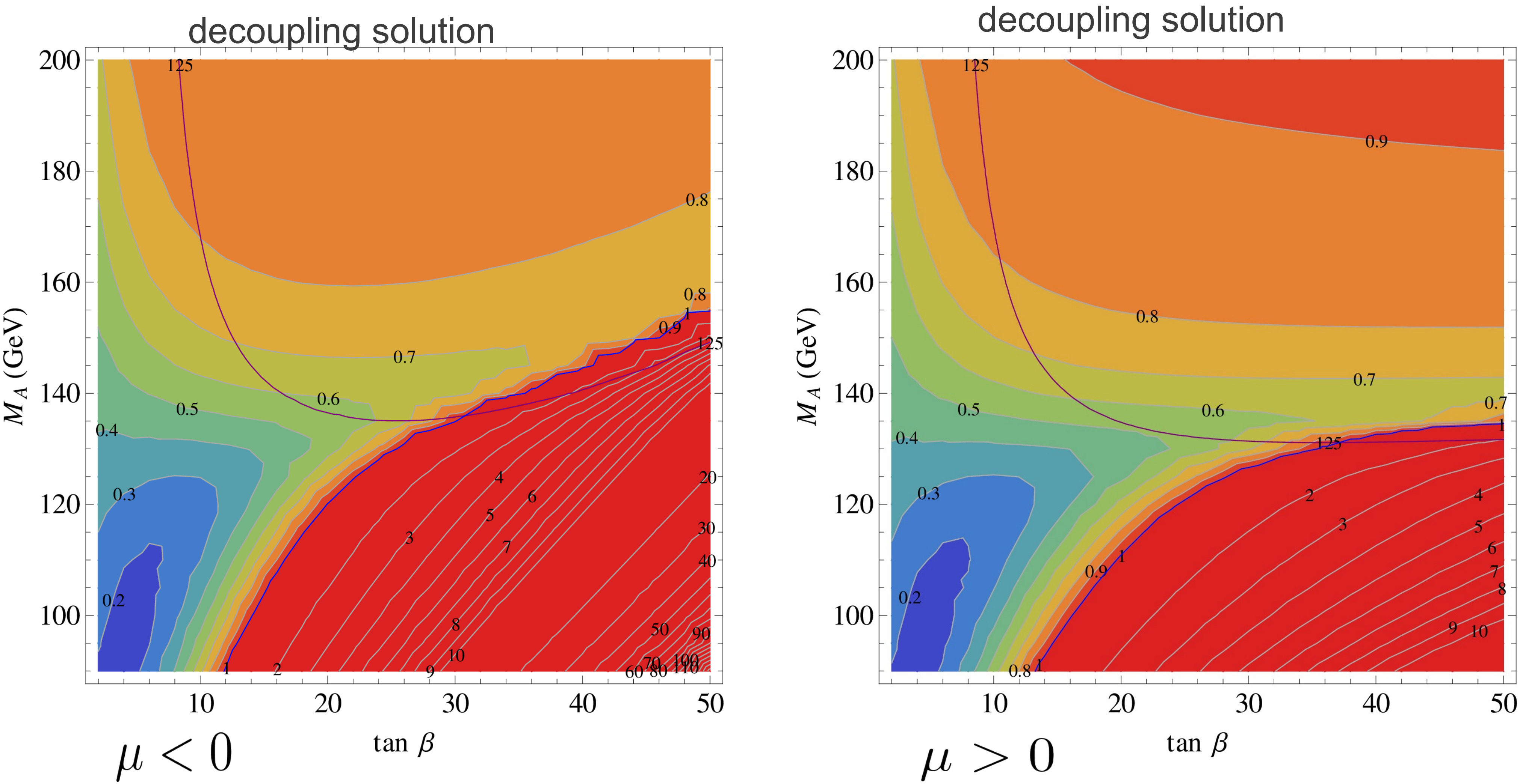
→ Interface POWHEG with a mass spectrum generator that provides Higgs masses and couplings.
Choice of the renormalization scheme: $\overline{DR}$ (Soft-Susy + …), OS (FeynHiggs)

MSSM POWHEG implementation:

a) rescale the SM contribution.
b) insert the SUSY correction: gluon-squark-squark exact (IR cancellation)
gluino-quark-squark via E.A. or A.E.

$\sigma \sim \sigma_{SM}$, M_h = 125 GeV

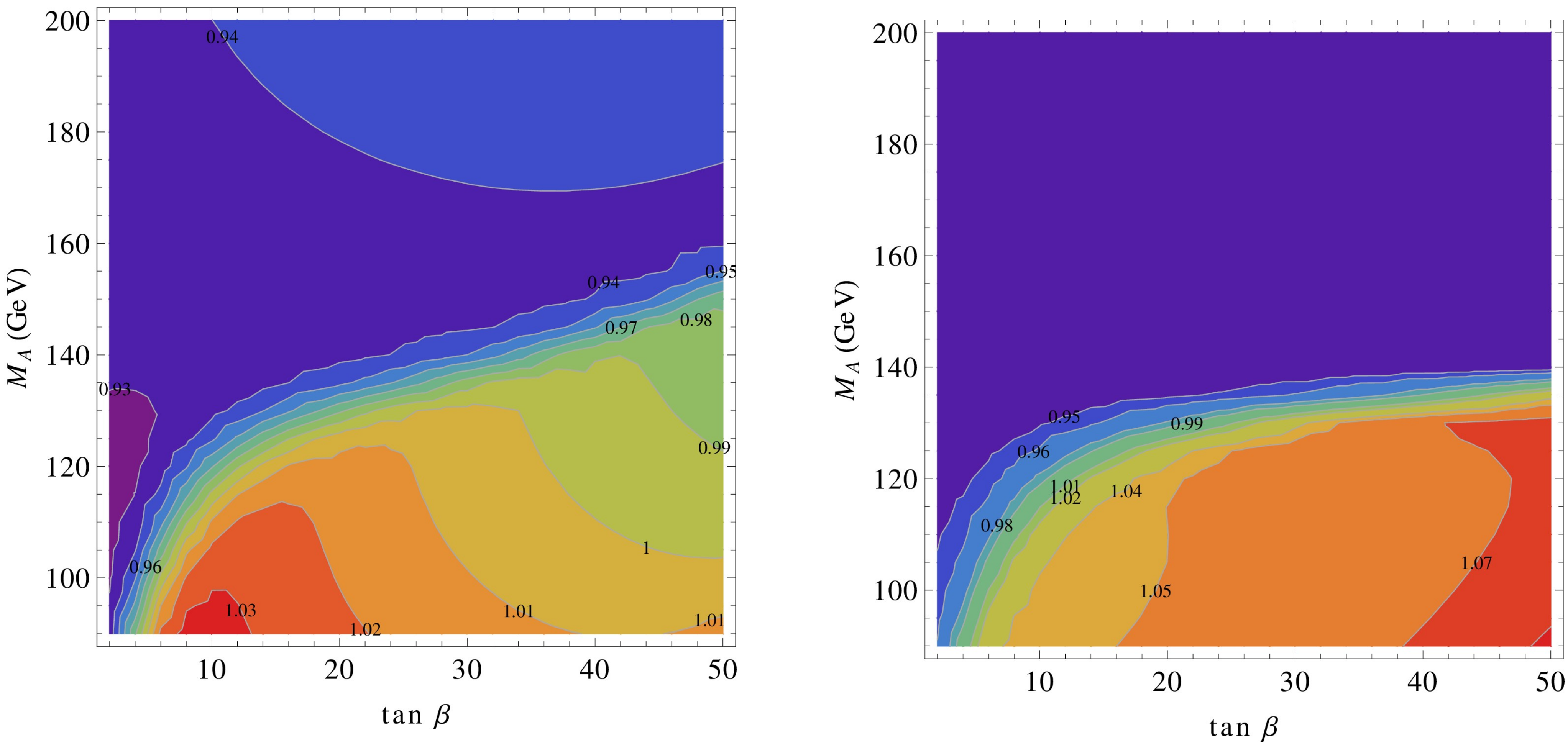
$$\frac{\sigma(g\,g \to h)}{\sigma(g\,g \to h_{SM})}$$



$m_Q=m_U=m_D$= 1000 GeV, $X_t= A_t-\mu \cot\beta$=2500 GeV, M_3= 800 GeV, $M_2 = 2\,M_1$ =200 GeV, $|\mu|$ = 200 GeV

$$\frac{\sigma(g\,g \to h)}{\sigma(g\,g \to h_{SM})_{\text{rescaled}}}$$

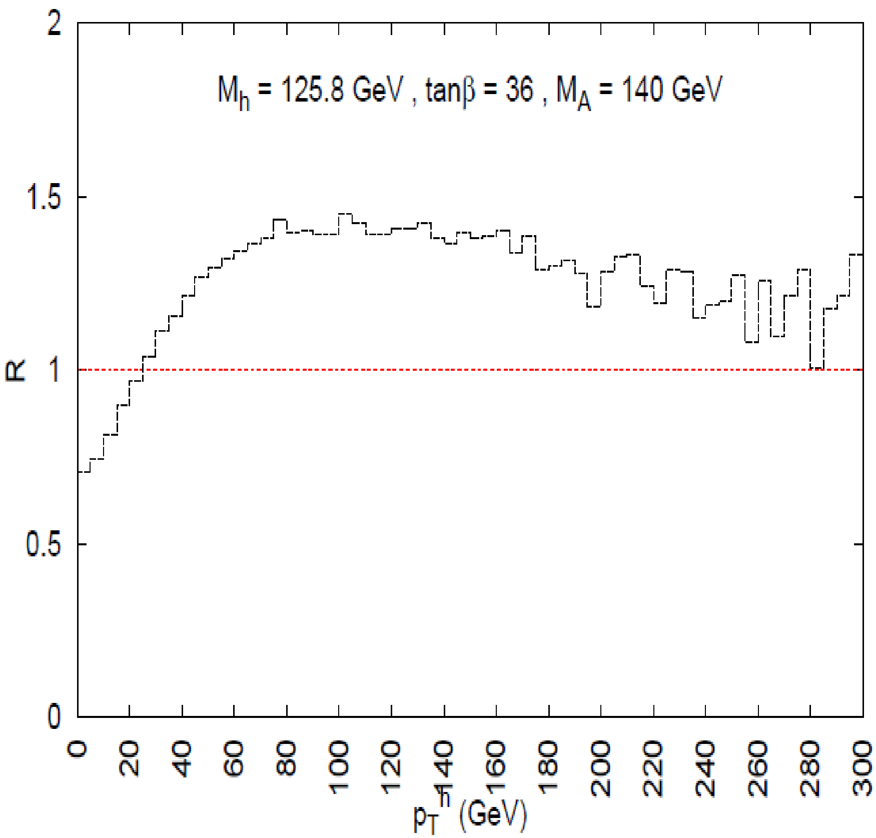
$\mu < 0$ $\qquad\qquad$ $\mu > 0$



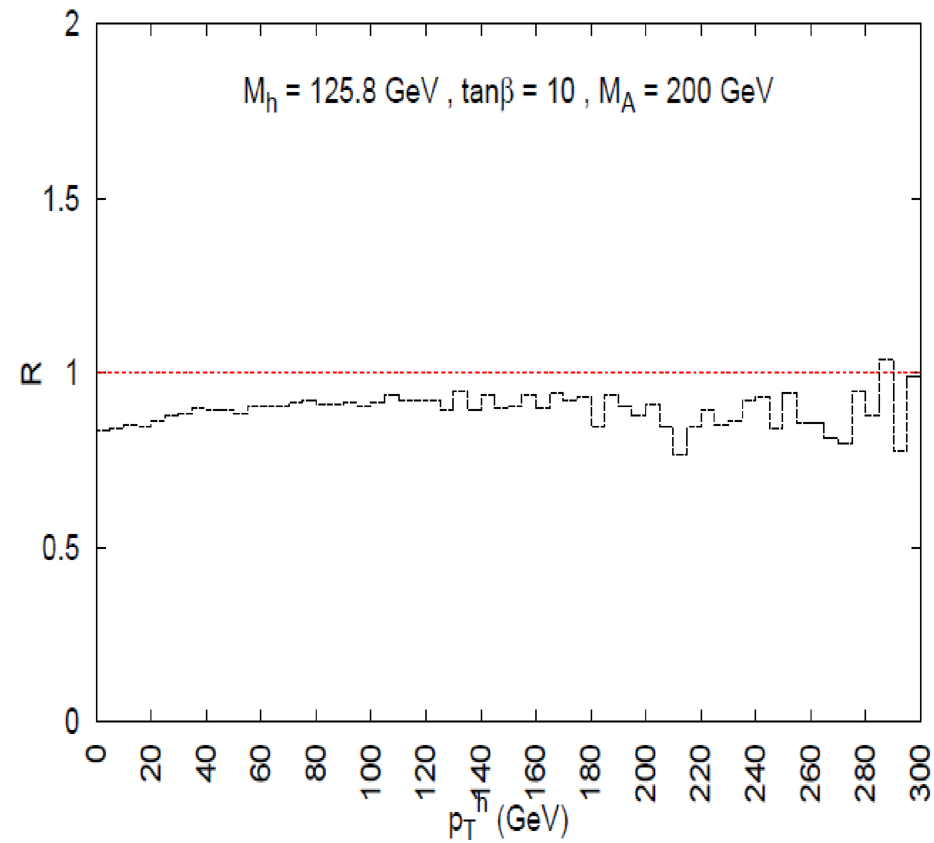
Squarks are heavy: corrections up to 10%

Using the p_t^h to disentangle between SM and MSSM

$\mu < 0$



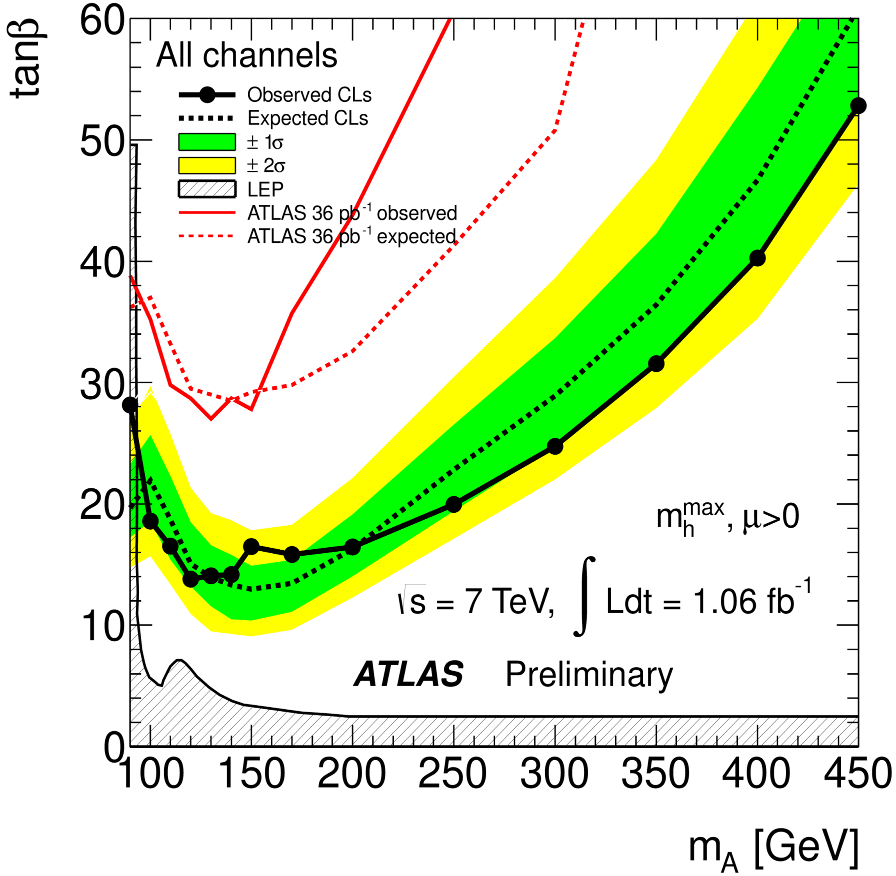
$\mu > 0$

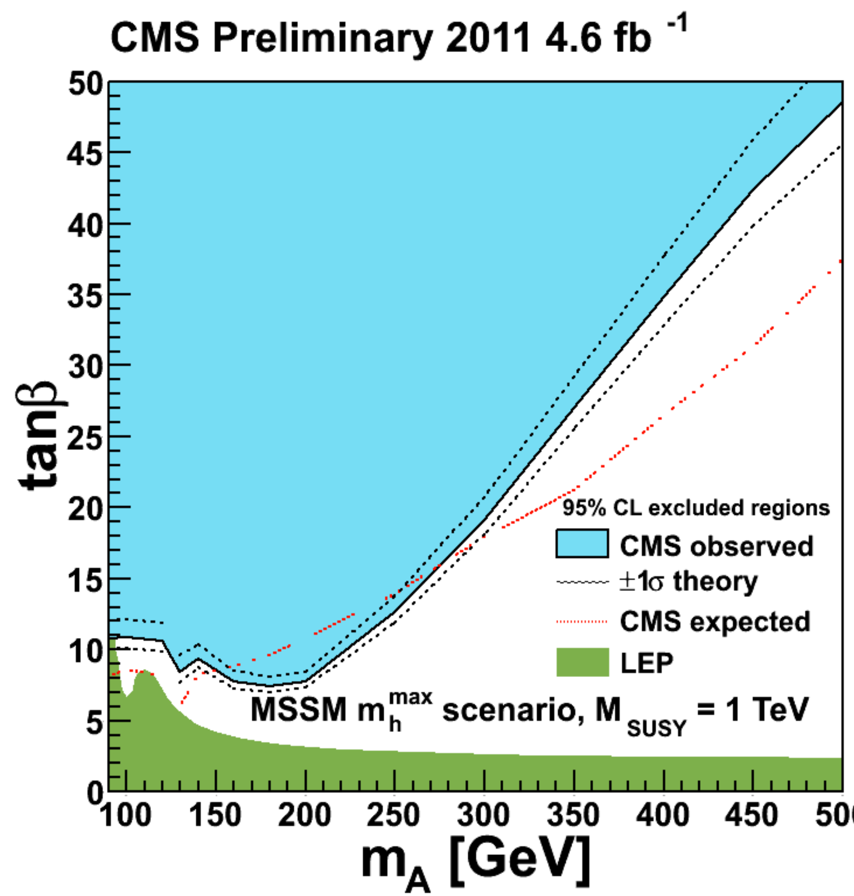


R= ratio $\dfrac{d\,\sigma}{d\,p_t^h}$ MSSM over SM

obtained using POWHEG + HERWIG

$\phi \to \tau\tau\ (\phi = h, H, A)$ kills the non-decoupling solution



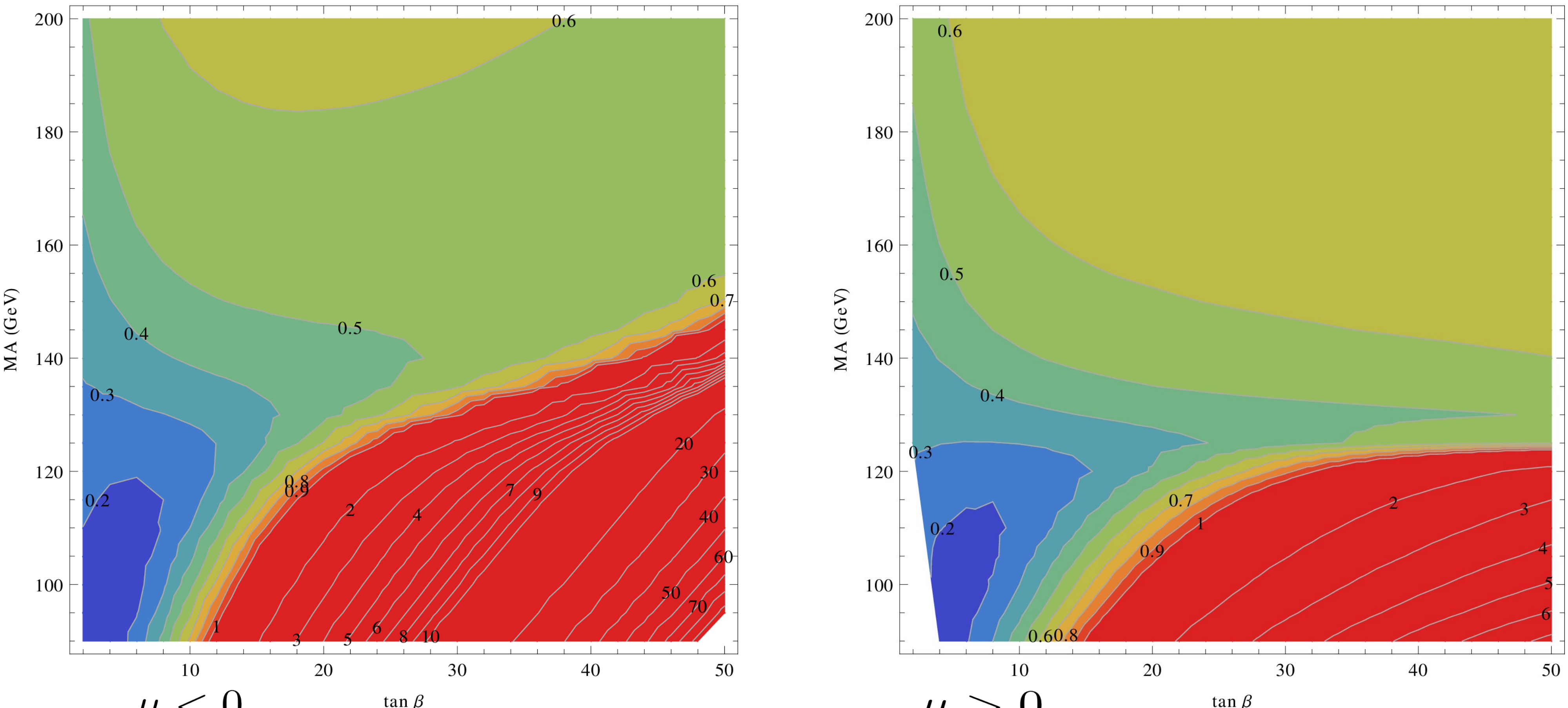


The ATLAS, CMS plots represent points in the MSSM parameter space different from ours, the SUSY corrections are not included in these plots, but with these limits ……

M_H ~ 125 GeV: Large M_A , to be in the decoupling regime

Light Stops

$$\frac{\sigma(g\,g \to h)}{\sigma(g\,g \to h_{SM})}$$



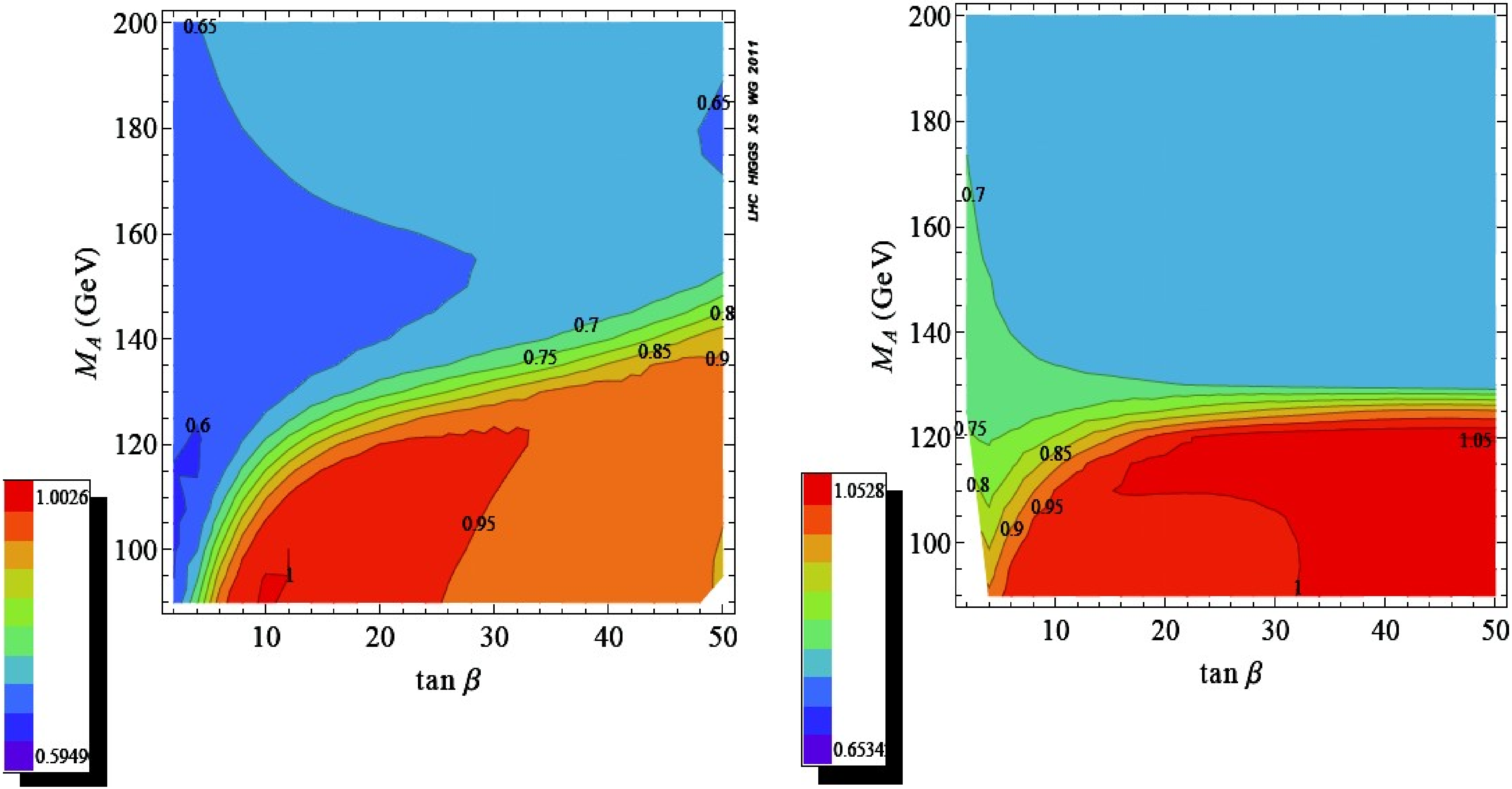
$\mu < 0$ $\mu > 0$

m_Q=m_U=m_D= 500 GeV, X_t= A_t-μ cot β=1250 GeV, M_3= 2 M_2 = 4 M_1 =400 GeV, |μ| = 200 GeV

$$M_{\tilde{t}_1} \sim 280\,\mathrm{GeV},\; M_{\tilde{t}_2} \sim 660\,\mathrm{GeV},\; M_h^{max} < 123\,\mathrm{GeV}$$

$$\frac{\sigma(g\,g \to h)}{\sigma(g\,g \to h_{SM})_{\text{rescaled}}}$$

$\mu < 0$ $\mu > 0$



For M_A ~ 200 GeV squarks corrections are large (30–40%) and genuine SUSY

Conclusions

- It is too early to make any firm statement.

- Personally, I believe that a Higgs boson is in the mass range 116-126(+2): M_h = 121 ± 5 GeV

- The exact value of the Higgs mass is very important.
  A single GeV makes the difference.

- M_h = 125 GeV is a very intriguing value.
  For the SM it is at the “border” of the stability region.
  For the MSSM it is at the ”border” of the mass-predicted region.

- Light stops require a lighter Higgs with a production cross section reduced with respect to the SM.