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SM and SUSY Higgs bosons: Phenomenological aspects for the LHC

Abdelhak DJOUADI (Montpellier/Paris)

I. A brief introduction

II. The Higgs boson in the SM

- **The production processes in the SM**
- **Test of the EWSB mechanism at the LHC**

III. The Higgs bosons in the MSSM

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- **The intermediate regime**
- **The intense coupling regime**
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- **The extended regime**

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I. Brief Introduction

The Higgs sector in the SM:

One doublet of complex scalar fields $\Phi = \binom{\phi^+}{\phi^0}$ **with** $Y_\phi = +1$

3 degrees of freedom for $W_L^\pm, Z_L$ **and one is left corresponding to** H**.**

M_H **is the only free SM parameter, the information that we have is**

$$\mathbf{114.4}\ \text{GeV} \lesssim \mathbf{M_H} \lesssim \mathcal{O}(\mathbf{1}\ \text{TeV}) \quad \text{and} \quad \mathbf{M_H} \lesssim \mathbf{250}\ \text{GeV}$$

But, hierarchy (and also unification) problem in the SM ⇒ SUSY.

In the minimal SUSY version, the MSSM:

Two doublets of complex scalar fields with opposite Y**,** Φ_1 **and** Φ_2

⇒ 5 Higgs particles in the spectrum: h, H, A **and** $H^\pm$**.**

Besides the four masses, 2 parameters are needed: $\tan\beta = \frac{v_2}{v_1}$ **and** α**.**

However, there are strong constraints from SUSY:

- **Only two free parameters, taken to be** M_A **and** $\tan\beta$ **in general.**
- **Hierarchy in spectrum:** $M_h < M_A < M_H, M_{H^\pm} > M_W$, $M_h < M_Z$**.**
- **In the decoupling limit,** $M_A \gg M_Z$ **(in practice** $M_A \gtrsim 300$ **GeV):**
  - $H, A, H^\pm$ **are degenerate** $M_H \sim M_{H^\pm} \sim M_A$ **and decouple.**
  - h **has maximal mass,** $M_h = M_Z|\cos(2\beta)|$ **and SM couplings.**
  - **SM and MSSM Higgs sectors similar but there is a light Higgs.**

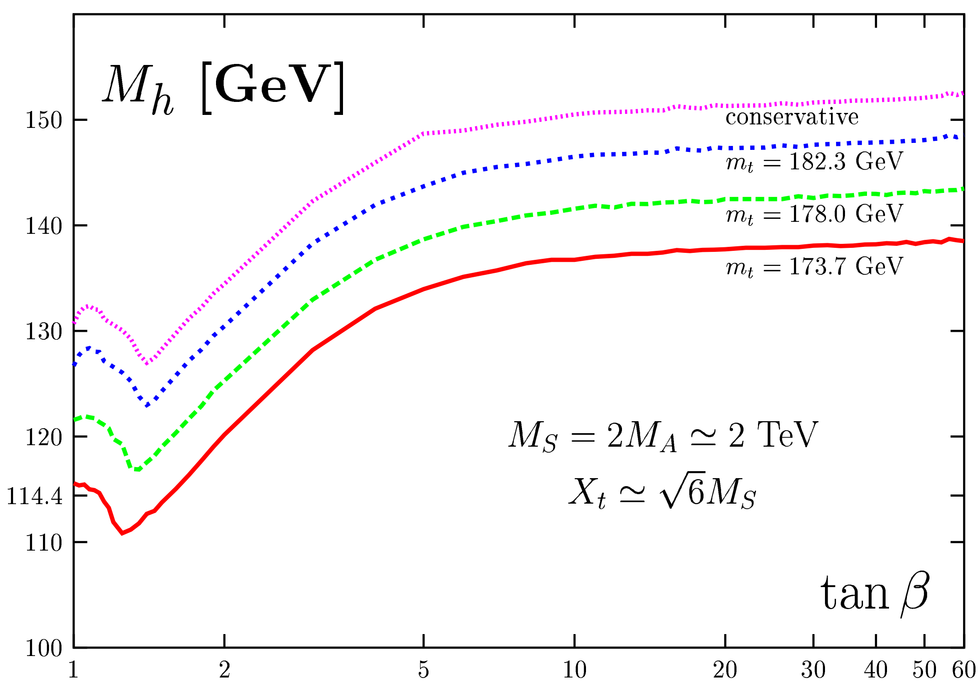
Relations broken by radiative corrections for large m_t, leading RC:

$$M_h^{\rm max} \sim M_Z|\cos 2\beta| \left[1 - \mathcal{O}\left(\frac{M_Z^2}{M_A^2}\right)\right] + \frac{3\,m_t^4}{2\,\pi^2\,v^2}\left(\ln\frac{M_S^2}{m_t^2} + \frac{X_t^2}{2\,M_S^2} - \frac{X_t^4}{12\,M_S^4}\right)$$

A large activity for the calculation of the RC in the last 15 years.

Most recent result (June 2004):

- **Full one–loop correction with all SUSY loops and q^2 dependance.**
- **All two–loop RC involving large couplings: α_S and $\alpha_t, \alpha_b, \alpha_\tau$.**
- **Estimation of all theoretical and experimental uncertainties.**
- **New Tevatron value of the top quark mass $M_t = 178.0 \pm 4.3$ GeV.**

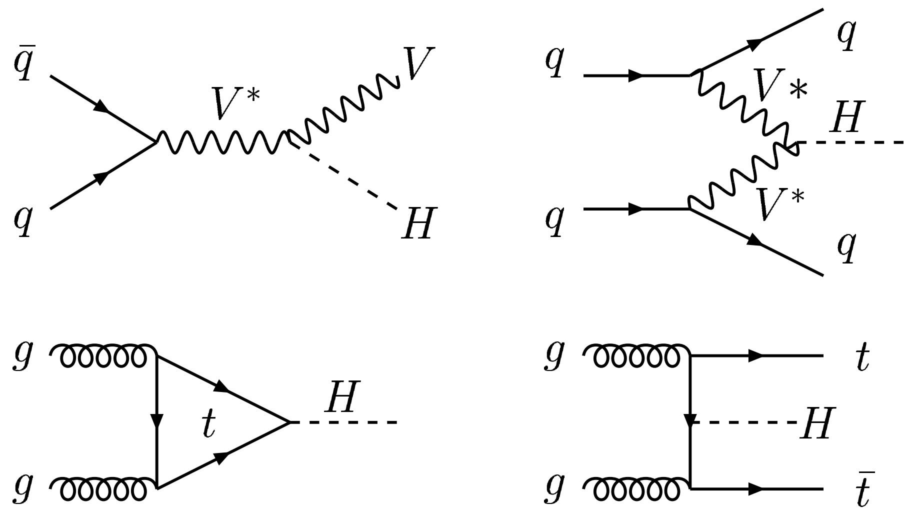


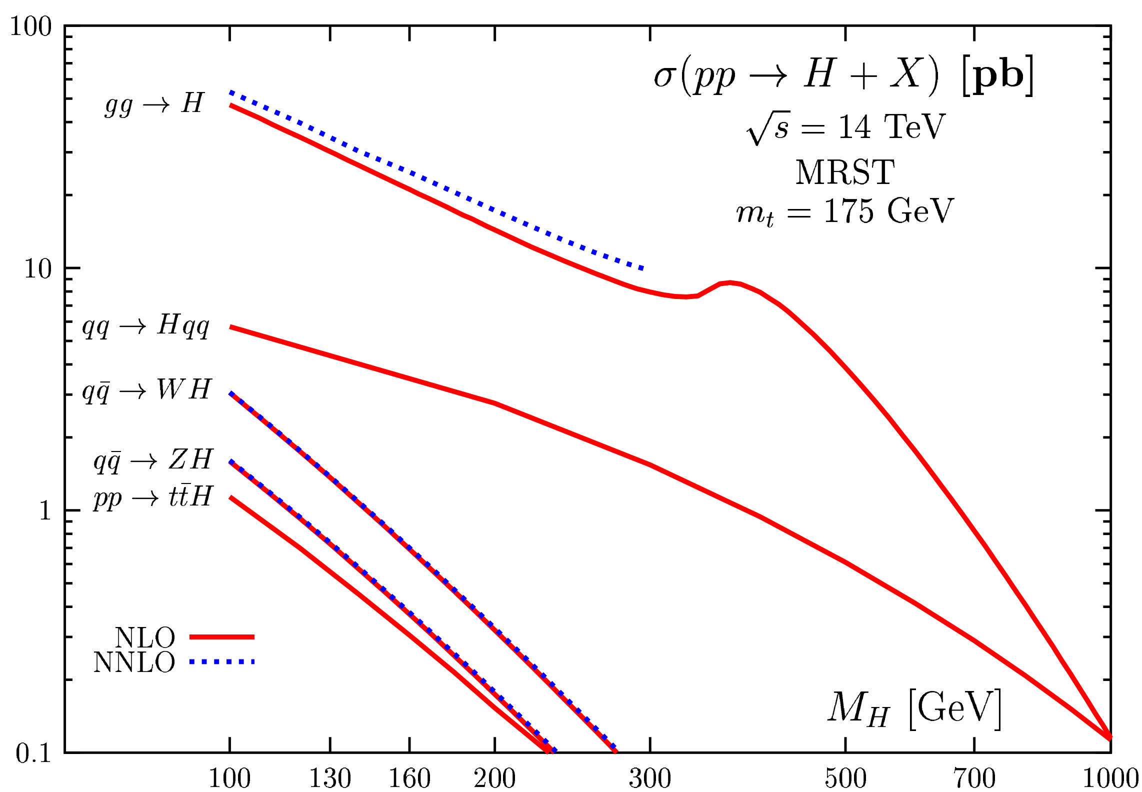
Allanach, AD, Kneur, Porod and Slavich

Consequences : $\mathbf{M_h^{max} \sim 150}$ GeV , $\tan\beta|^{\rm min} \sim 1$

II. The Higgs boson in the SM

Production processes and cross sections at the LHC in the SM:





(a) gg $\rightarrow$ H: dominant production mechanism $\Rightarrow$ discovery channel:

– $M_H \lesssim 130$ **GeV:** $H \rightarrow \gamma\gamma$

– $M_H \gtrsim 130$ **GeV:** $H \rightarrow WW^{(*)}/ZZ^{(*)} \Rightarrow \ell^+\ell^-\nu\nu, \ell\nu jj/4\ell^\pm, \ell^+\ell^-\nu\nu$

Theoretical status:

– $K_{\rm NLO} \sim 1.7$ **known for arbitray** m_t **and including** b**–loop (MSSM).**

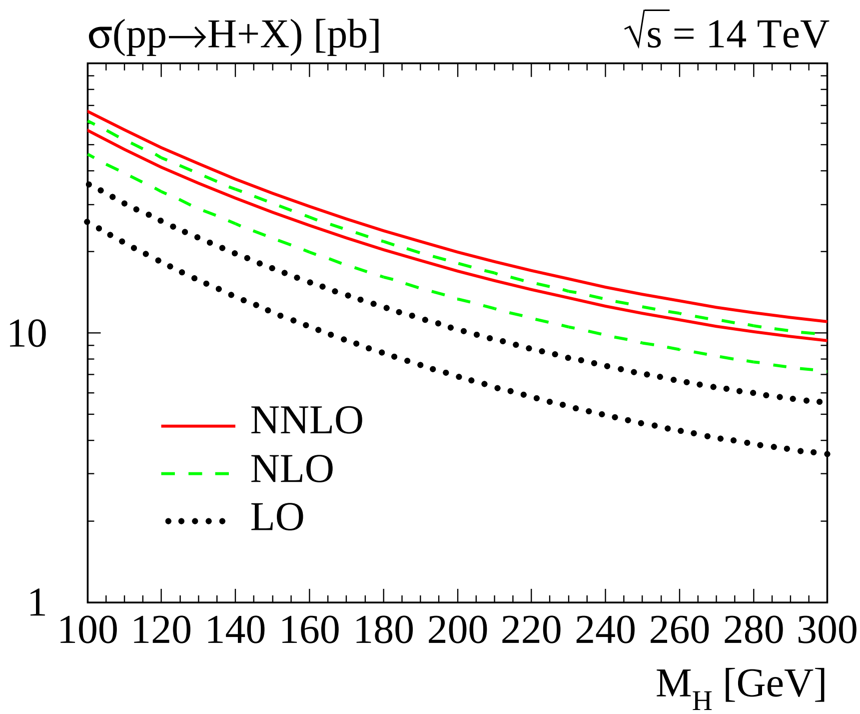
Spira, AD, Graudenz, Zerwas (1995).

– $K_{\rm NNLO} \sim 2$ **recently derived in the infinite** m_t **limit (also NNLL).**

NLO: AD+Spira+Zerwas; Dawson
NNLO: Harlander+Kilgore; Anastasiou+Melnikov; Ravindran+Smith+van Neerven
NNLL: Catani, de Florian, Grazinni, Nason

– **Large correction but nice convergence of the perturbative series.**

– **Scale dependence (measure of higher orders) strongly reduced.**



Harlander, Kilgore

(b) qq → qqH: most promising channel for couplings measurements

- **Large enough rates, $\sigma(qq \to qqH) \sim \mathcal{O}$(pb) for $M_H \lesssim 300$ GeV.**
- **Forward jets (tags) and central Higgs decays (mini-jet veto).**
- **Rather small backgrounds, $S/B \sim \mathcal{O}(1)$, allowing measurements.**

Zeppenfeld, Plehn, Rainwater, $\cdots$

– $H \to \tau^+\tau^-$, $WW^{(*)}$, $\gamma\gamma$ **feasible.**

– $H \to ZZ$, $b\bar{b}$, $\mu^+\mu^-$ **at high $\mathcal{L}$ and more studies?**

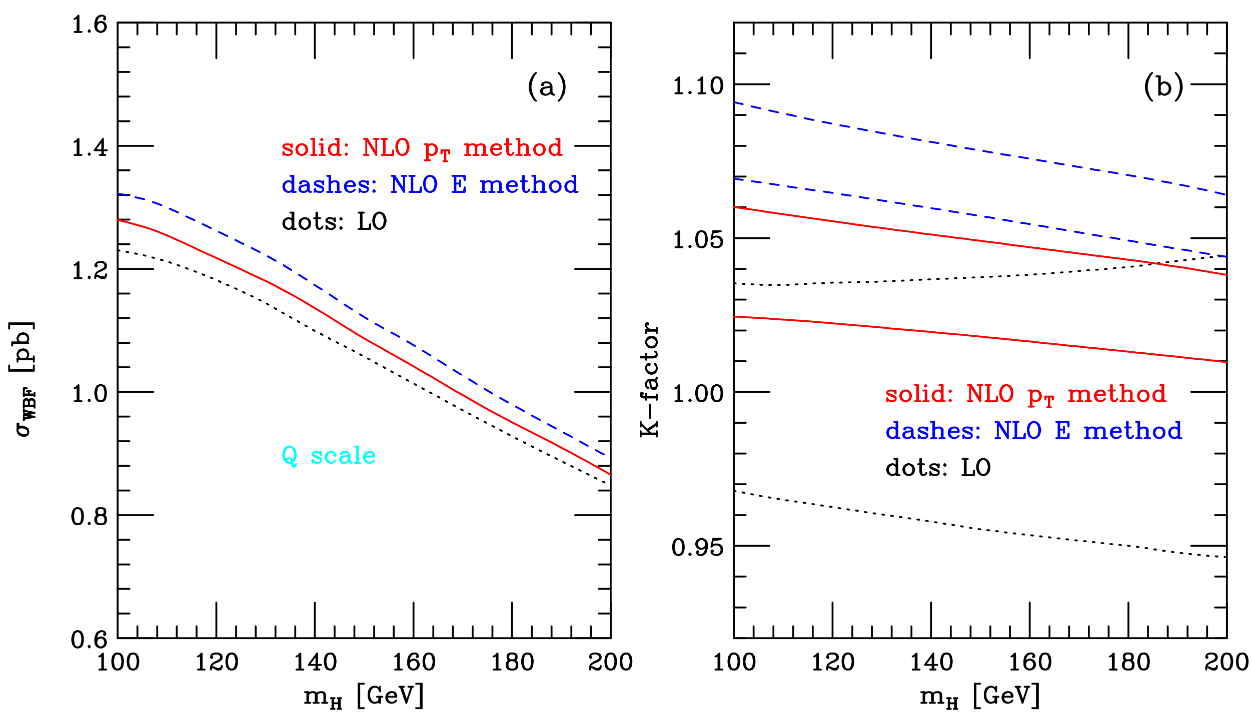
Theoretical status:

– $K_{\text{NLO}} \sim 1.1$ **and very small scale dependance.**

Han+Valencia+Willenbrock; Figy+Oleari+Zeppenfeld

– K_{NLO} **now available for p_T and η distributions.**

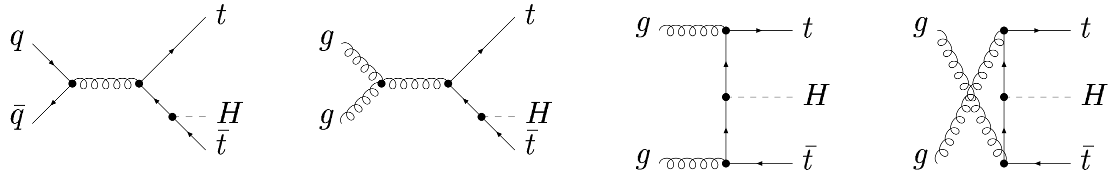
– **Still questions about backgrounds and central jet veto.**



Figy, Oleari and Zeppenfeld

(c) qq/gg $\to$ ttH:

Most complicated Higgs production channel at hadron colliders:



Usefull for measuring the ttH coupling in $pp \to \ell\nu\gamma\gamma$ of $\ell\nu b\bar{b}$.

– **The LO cross section available since 1984 (Kunszt).**

– **Full NLO calculation available only since two years:**

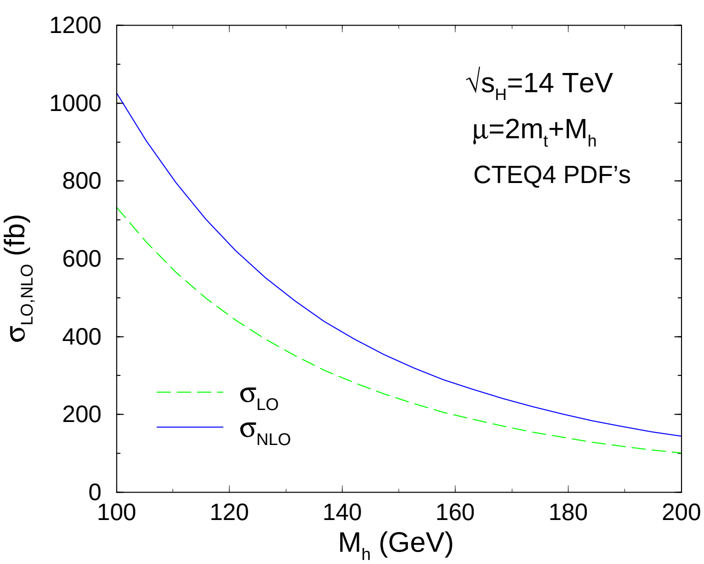
Dawson, Orr, Reina, Wackeroth .
Beenakker, Dittmaier, Kramer, Plumper, Spira, Zerwas .

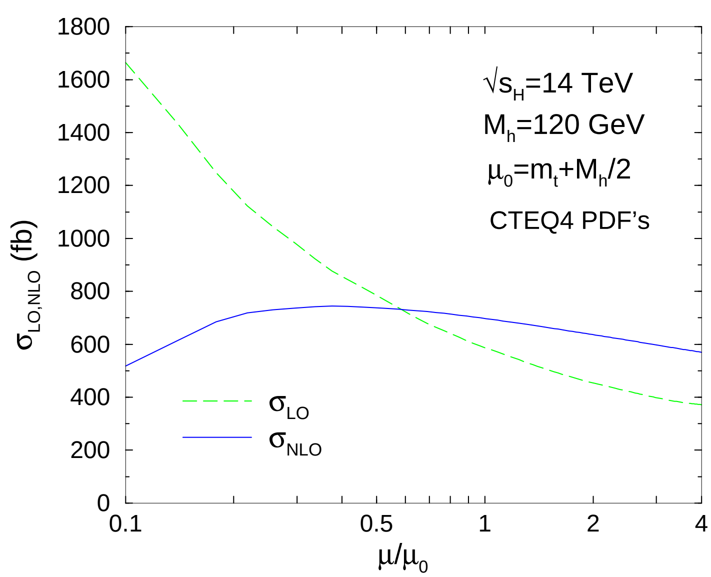
Main results:

– **K–factors ~ 1.2 at the LHC [and 0.8 at the Tevatron!]**

– **Scale dependence drastically reduced $\sim 10-20\%$.**

– **K–factors also available in the $b\bar{b}$+Higgs case (MSSM).**





(d) $q\bar{q} \to$ HW,HZ: the Tevatron channels

This production channel is the most important one at the Tevatron:

- $M_H \lesssim 130$ **GeV:** $H \to b\bar{b}$ $\Rightarrow \ell\nu b\bar{b}, \nu\bar{\nu}b\bar{b}, \ell^+\ell^-b\bar{b}$.
- $M_H \gtrsim 130$ **GeV:** $H \to WW^*$ $\Rightarrow \ell^\pm\ell^\pm jj$.

Up-to-now, plays only a marginal role at LHC (small rates etc...).

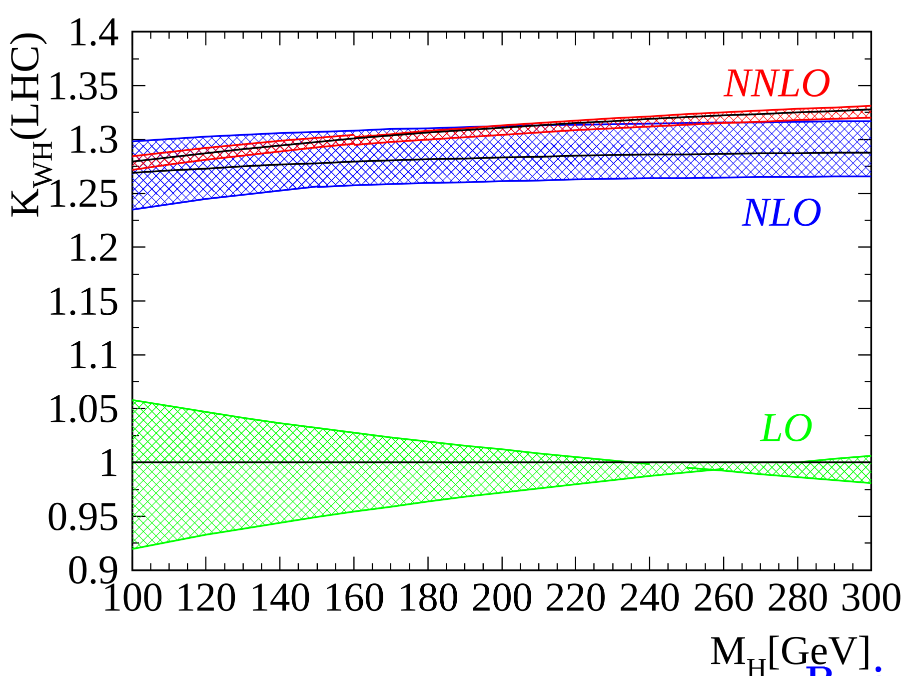
However, theoretically very clean channel:

- **K–factor** ~ 1.35 **made recently available at NNLO**

  Han+Willenbrock (NLO), Brein+AD+Harlander (NNLO)
- **Electroweak corrections are also available** (-5%).

  Ciccolini, Dittmaer, Krämer (EW)
- **Scale dependence extremely small** $\sim 3-5\%$.
- **Small PDF uncertainties (normalisation to DY?).**

  Dittmar, Pauss, Zürcher

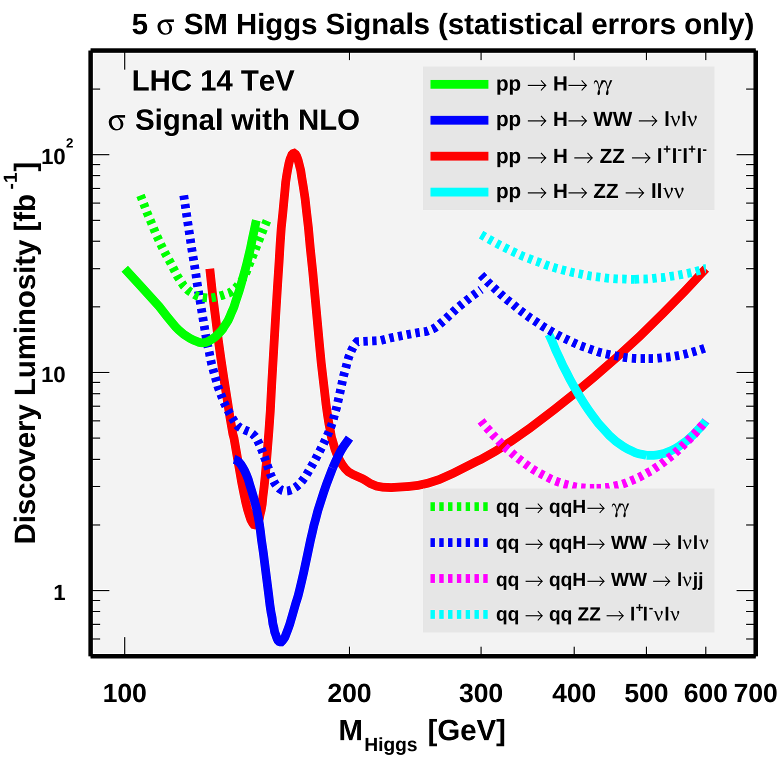


Brein, AD, Harlander

In the SM: Higgs detection is in principle guaranteed.

– Many redundant production and detection channels

– $> 5\sigma$ discovery once all channels are combined for low $\mathcal{L}$.



The next step is to perform detailed tests of the EWSB mechanism:

– Measure the Higgs mass and total width

Easy if $H \to \gamma\gamma, ZZ \to 4 \ll$

– Measure the coupling to fermions and gauge bosons (WBF+...).

Starded already; see M. Dührssen for instance

– Measure the Higgs self–coupling and reconstruct $V_{\rm scal}$ (!).

Seems to be hopeless; see Baur, Plehn and Rainwater

– Determine the Higgs spin and parity quantum numbers (!).

A very challenging issue.

III. The Higgs bosons of the MSSM

Production processes and cross sections in the MSSM:

For the neutral Higgs bosons:

Same channels as in SM apply but rates enhanced/suppressed by different Higgs couplings to fermions and gauge bosons.

In particular, for $\tan\beta \gg 1$ and $M_A \gtrsim 150$ GeV:

– b–**loops dominant in the** $gg \to H/A$ **processes** ($g_{\Phi bb} \propto \tan\beta$).

– $b\bar{b}$ **final states dominant in** $pp \to Q\bar{Q} + H/A$ ($\sigma \propto \tan^2\beta$).

– **No VV fusion or** VH **production for** A **(CP) and** H **(suppressed).**

– **BR**($H/A \to \gamma\gamma, ZZ$) **very small and BR**($H/A \to b\bar{b}, \tau^+\tau^-$) $\sim 90\%, 10\%$.

– **For** h**: same (or slightly smaller) cross sections as in SM.**

– **Since** $M_h \lesssim$ **130–150 GeV, rely on** $h \to \gamma\gamma$ **and** $h \to WW^*$.

For the charged Higgs boson:

the production processes, depending on the $H^\pm$ **mass, are:**

– $M_{H^\pm} \lesssim m_t$: $gg/q\bar{q} \to t\bar{t} \to H^\pm + X \to \tau^\pm\nu + X$.

– $M_{H^\pm} \gtrsim m_t$: $gb \to H^-t$ **and** $gg/q\bar{q} \to H^-t\bar{b} \to \tau\nu$ **or** tb.

See D.P. Roy

(a) The decoupling regime: $M_A \gg M_Z$ and $\tan\beta \gg 1$

In constrained MSSMs, most of the time in the decoupling regime.

- **The h boson is SM–like with 115 GeV $\lesssim M_h \lesssim 150$ GeV**
  - $gg \to h$ **with** $h \to \gamma\gamma, WW^* \to \ell\ell\nu\nu, ZZ^* \to 4\ell$
  - $qq \to qqh$ **with** $h \to \tau^+\tau^-, \gamma\gamma, WW^* \to \ell\ell\nu\nu$
  - $q\bar{q} \to Wh$ **and** $q\bar{q}/gg \to t\bar{t}h$ **with** $h \to \gamma\gamma, b\bar{b}$**.**
- $H, A, H^\pm$ **are heavy and their search is separated. For** $\tan\beta \gg 1$**:**
  - $gb \to b + H/A$ **or** $q\bar{q}/gg \to b\bar{b} + H/A$ **with** $H/A \to \tau^+\tau^-$ **(**$\mu^+\mu^-$**).**
  - $gb \to H^- t$ **and** $gg/q\bar{q} \to H^- t\bar{b}$ **with** $H^- \to \tau\nu$ **or** $b\bar{t}$**.**

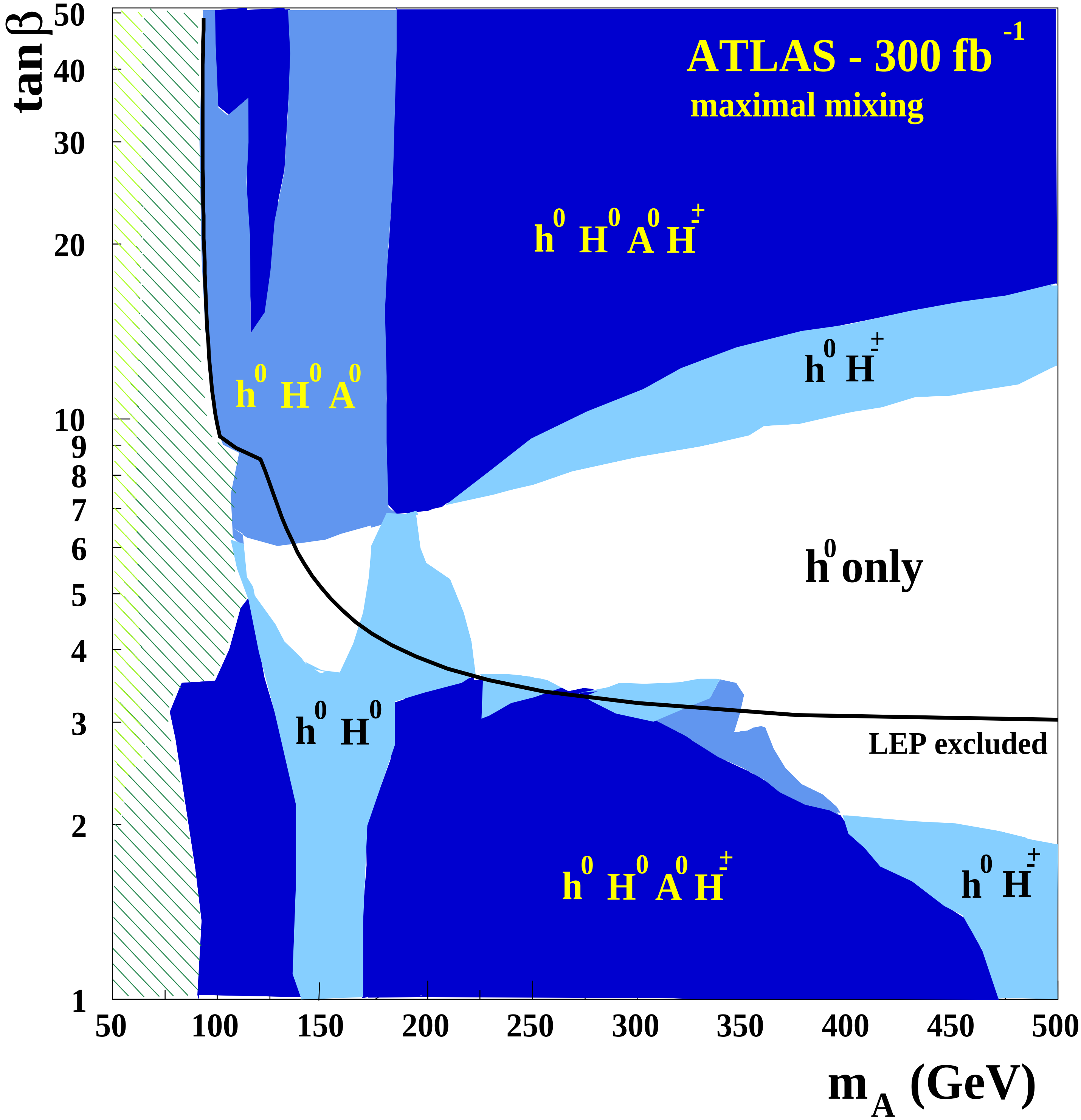
(b) The intermediate regime: $M_A \lesssim 500$ GeV and $\tan\beta \lesssim 5$–10

- **The h boson is not yet SM–like: more difficult than in SM**
  - **Couplings to** WW, ZZ, tt **suppressed and to** $bb, \tau\tau$ **enhanced.**
  - **All production channels have cross sections smaller than in SM.**
  - **Decay modes into** $WW, ZZ, \gamma\gamma$ **suppressed.**
- **Situation more tricky for** $H, A, H^\pm$ **bosons:**
  - **Production cross sections not large (**t **down but** b **not yet up).**

    $\sigma(gg \to H/A)$ **larger than** $\sigma(gg \to b\bar{b} + H/A)$ **or** $\sigma(gg \to t\bar{t} + H/A)$**.**
  - **But some special (clean) decays are now revived (**$\tan\beta \sim 1$–**3):**

    $H \to hh,\ A \to Zh,\ H^\pm \to Wh$ **and maybe** $H/A \to t\bar{t}$**.**

Some work to be redone?


ATLAS - 300 fb^{-1}
maximal mixing
h^0 H^0 A^0 $H^{\pm}$
h^0 $H^{\pm}$
h^0 H^0 A^0
h^0 only
h^0 H^0
LEP excluded
h^0 H^0 A^0 $H^{\pm}$
h^0 $H^{\pm}$
$\tan\beta$
50
40
30
20
10
9
8
7
6
5
4
3
2
1
50
100
150
200
250
300
350
400
450
500
m_A (GeV)

(c) The intense coupling regime: $M_A \lesssim$ 120–150 GeV and $\tan\beta \gg 1$

New and/or interesting features:

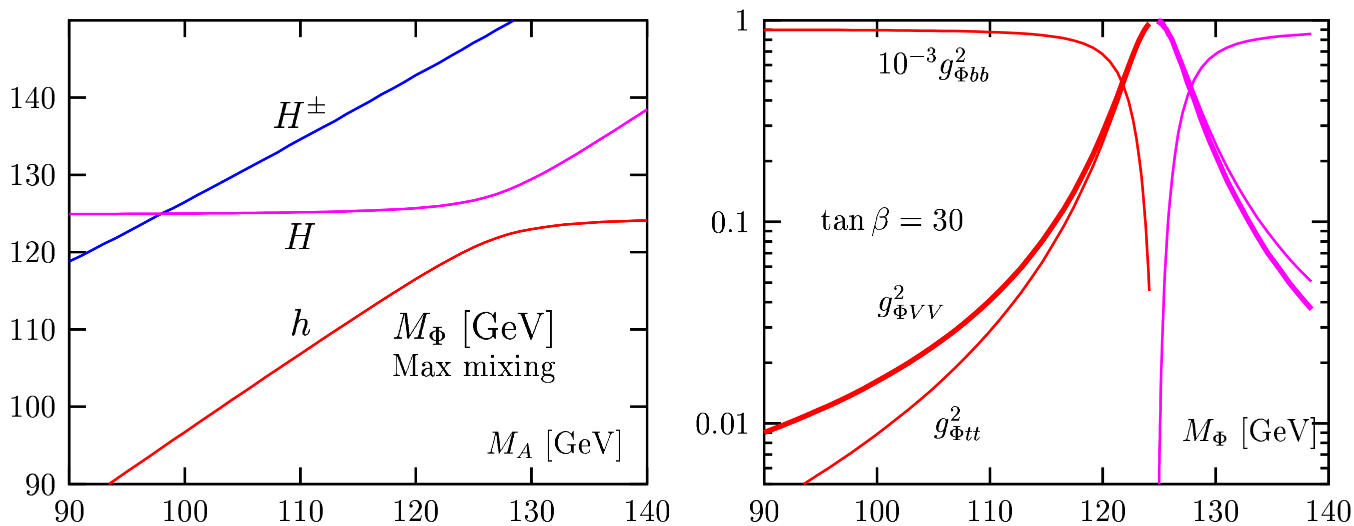
– h, H, A **light,** $M_h \sim M_A \sim M_H$**, all processes are in principle accessible.**

– **production cross sections rather large for many channels.**

– **complete coverage of the MSSM is theoretically possible.**

But many problems and challenges too:

- **The** h, A, H **masses are too close to each other.**
- **The widths are large and must be taken into account.**
- **The interesting BRs suppressed v.s. SM for both** h **and** H**.**
- **The signal for one process is a background for the other.**
- **The** bb **decays are hopeless and the** $\tau^+\tau^-$ **resolution too bad.**

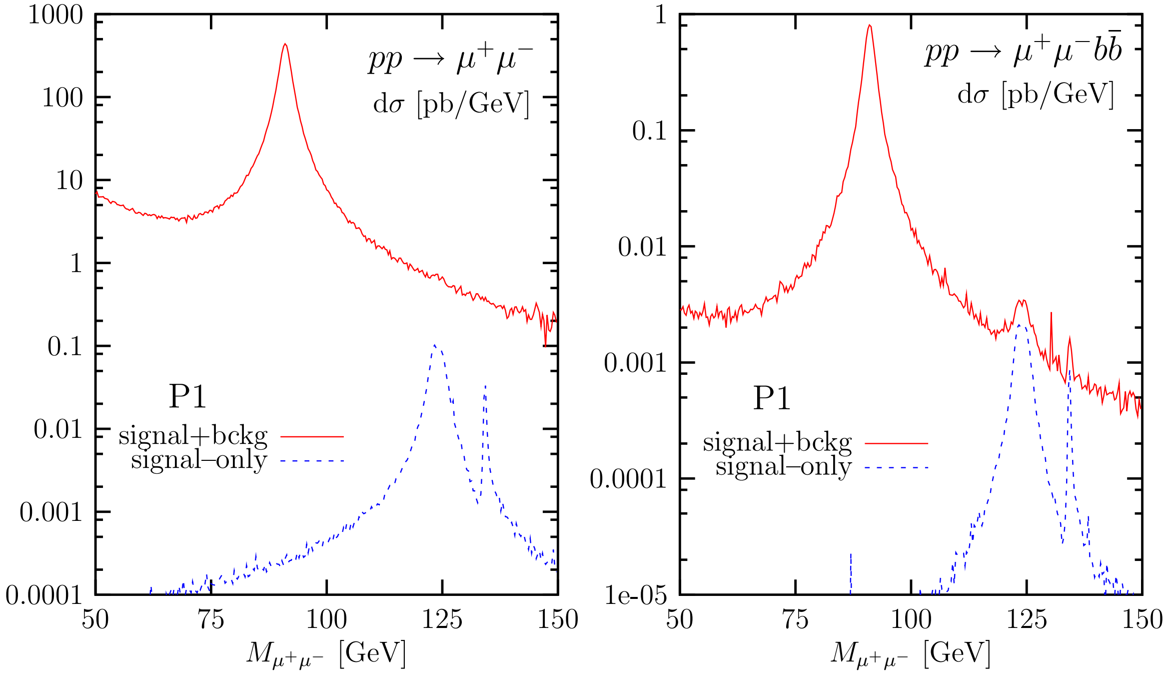


Go for the $h, H, A \to \mu^+\mu^+$ **channels:**

Boos, AD, Nikitenko

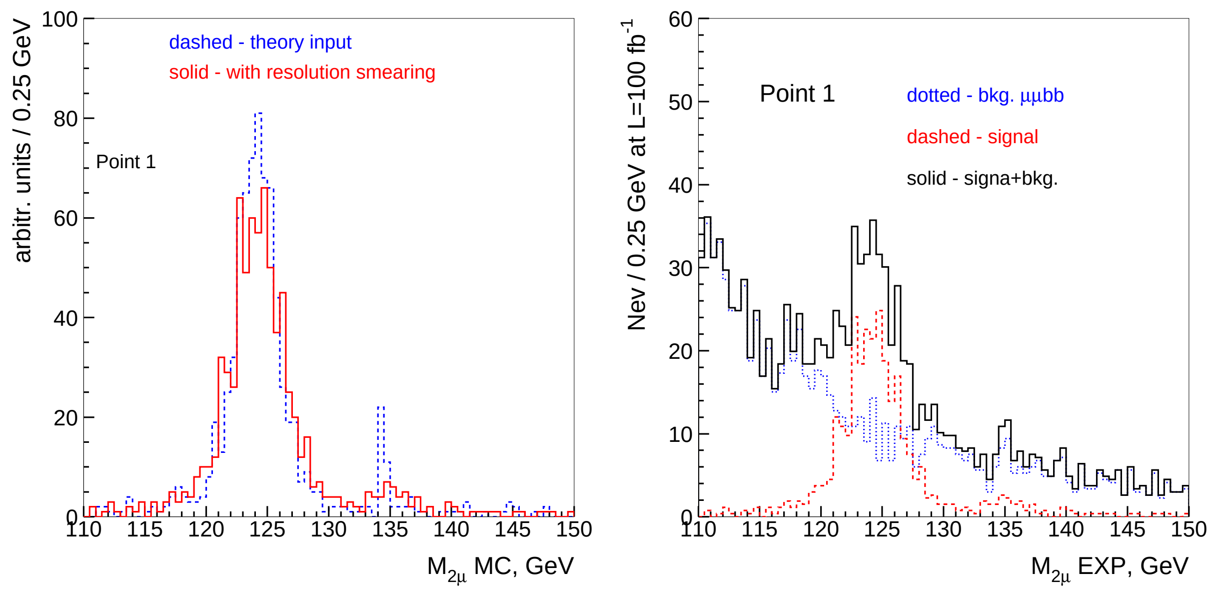
P1: $M_A = 125$ **GeV,** $\tan\beta = 30 \Rightarrow M_h = 123.3$ **GeV,** $M_H = 134.3$ **GeV.**

S and B for: $pp(\to \Phi) \to \mu^+\mu^-$ and $pp(\to \Phi b\bar{b}) \to \mu^+\mu^- b\bar{b}$:



– $gg \to \Phi \to \mu^+\mu^-$ **seems to be hopeless** $S/B \ll 1$

– $pp \to \Phi b\bar{b} \to \mu^+\mu^- b\bar{b}$ **seems OK: simulation**



– **Still difficult to disentagle h and A.**

– **For some other points: situation even more complicated.**

(d) The SUSY regime: not too heavy SUSY particles

- **SUSY loops might play an important role in production/decay.**

ex: light $\tilde{t}$ with strong couplings to h (large stop mixing)

the loops might make $\sigma(gg \to h) \times \mathrm{BR}(h \to \gamma\gamma)$ very small.

- **In this case, a complementary h SUSY production channel is:**

$pp \to gg/q\bar{q} \to h\tilde{t}_1\tilde{t}_1$ **with cross section as large as $\sigma(tth)$ possible.**

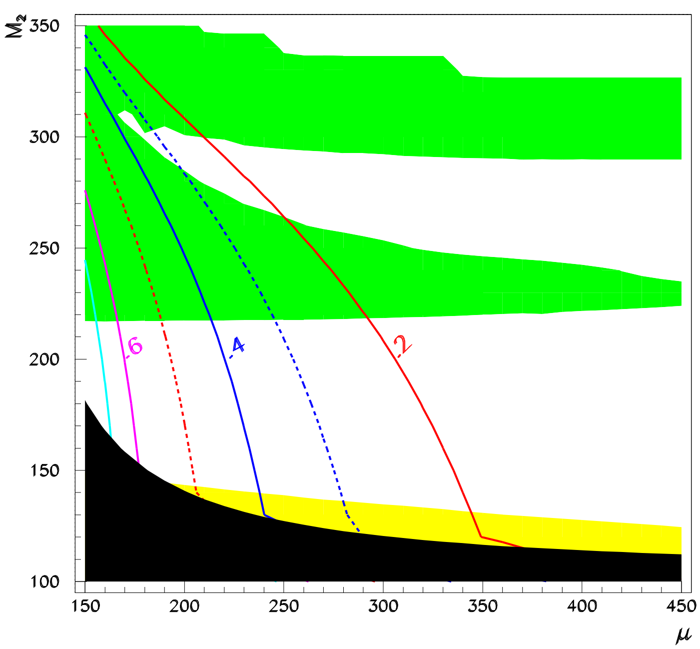
AD, Kneur, Moultaka

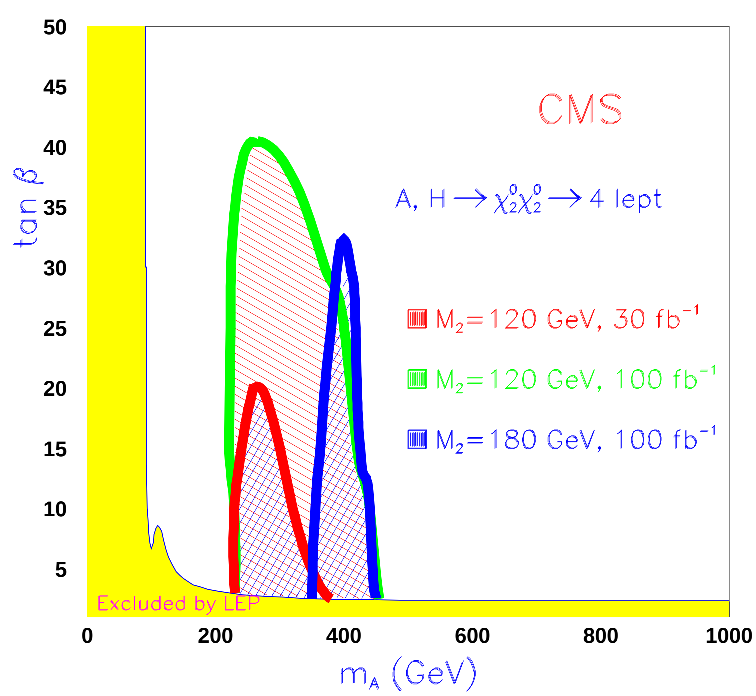
- **SUSY decays, if allowed, might alter the search strategies:**

– $h \to \chi_1^0\chi_1^0, \tilde{\nu}\tilde{\nu}$ **are still possible in non universal models...**

– **Decays of $A, H, H^{\pm}$ into $\chi_i^{\pm}, \chi_i^0$ are possible but can be useful...**

Boudjema et al. **Abdullin, Denegri, Moortgat**





- **Cascade decays of SUSY particles:**

$\tilde{q}, \tilde{g}$ **are copiously produced at the LHC (strongly interacting).**

Possible large branching ratios for cascades into MSSM Higgs bosons?

- **In the past, the "little cascade" has been analyzed for the h boson:**

$$pp \to \tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{q}\tilde{q}^*, \tilde{q}\tilde{g} \to \chi_1^\pm, \chi_2^0 + X \to \chi_1^0 + h(H^\pm, H, A) \ + X$$

- **One can also look at the "big cascade" processes for all Higgsses:**

$$pp \to \tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{q}\tilde{q}^*, \tilde{q}\tilde{g} \to \chi_2^\pm, \chi_{3,4}^0 + X \to \chi_1^\pm, \chi_{1,2}^0 + h, H, A, H^\pm \ + X$$

- **Also possible in some areas of the MSSM parameter space: direct decays of $\tilde{t}, \tilde{b}$ and for a light $H^\pm$, new decays through top quarks.**

Processes particularly suited for the intense coupling regime!

Openning the Pandora box: quick analysis in some scenarios:

Sc 1: $m_{\tilde{q}} > m_{\tilde{t}_1} > m_{\tilde{g}}, \ m_{\chi_1^\pm, \chi_2^0} - m_{\chi_1^0} < M_\Phi \to$ **big cascade.**

Sc 2: $m_{\tilde{q}} > m_{\tilde{t}_1} > m_{\tilde{g}}, \ m_{\chi_1^\pm, \chi_2^0} - m_{\chi_1^0} > M_\Phi \to$ **small+big cascade.**

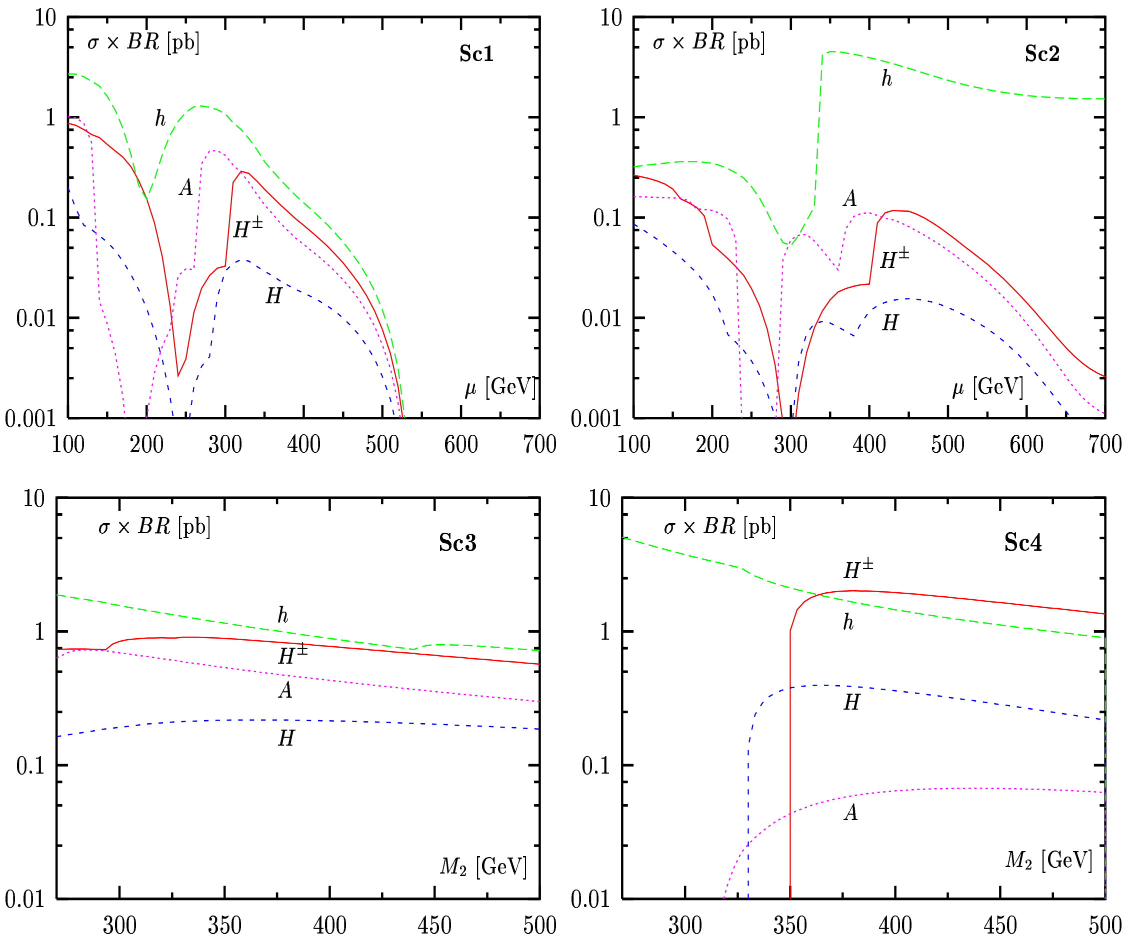
Sc 3: $m_{\tilde{q}} > m_{\tilde{t}_1} > m_{\tilde{g}},$ **small μ (higgsino):** $\tilde{q} \to$ **big cascade.**

Sc 4: $m_{\tilde{q}} > m_{\tilde{t}_1} > m_{\tilde{g}},$ **small μ (gaugino):** $\tilde{q} \to$ **small cascade.**

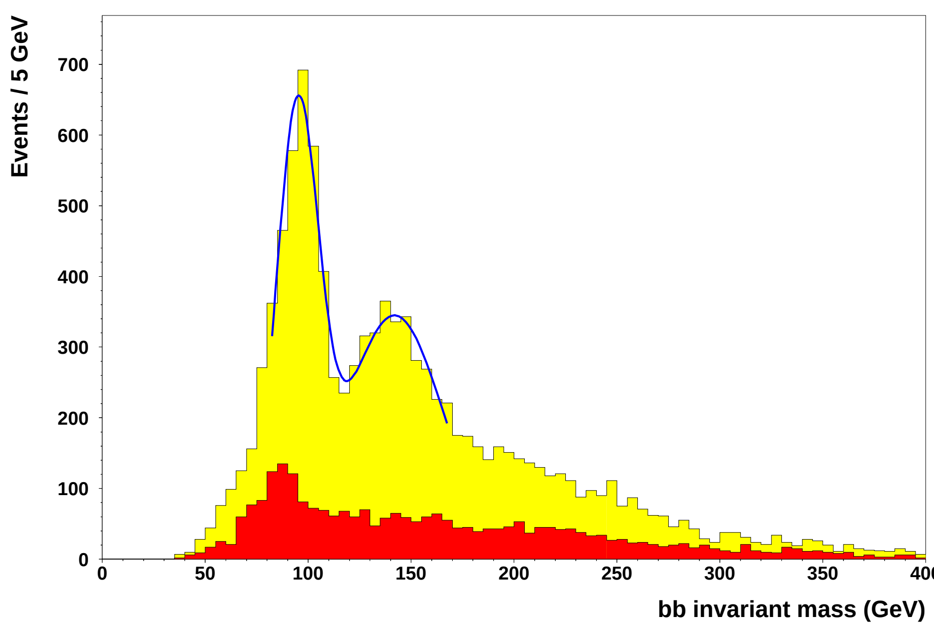
and it looks very promising....

More studies are needed in the near future.

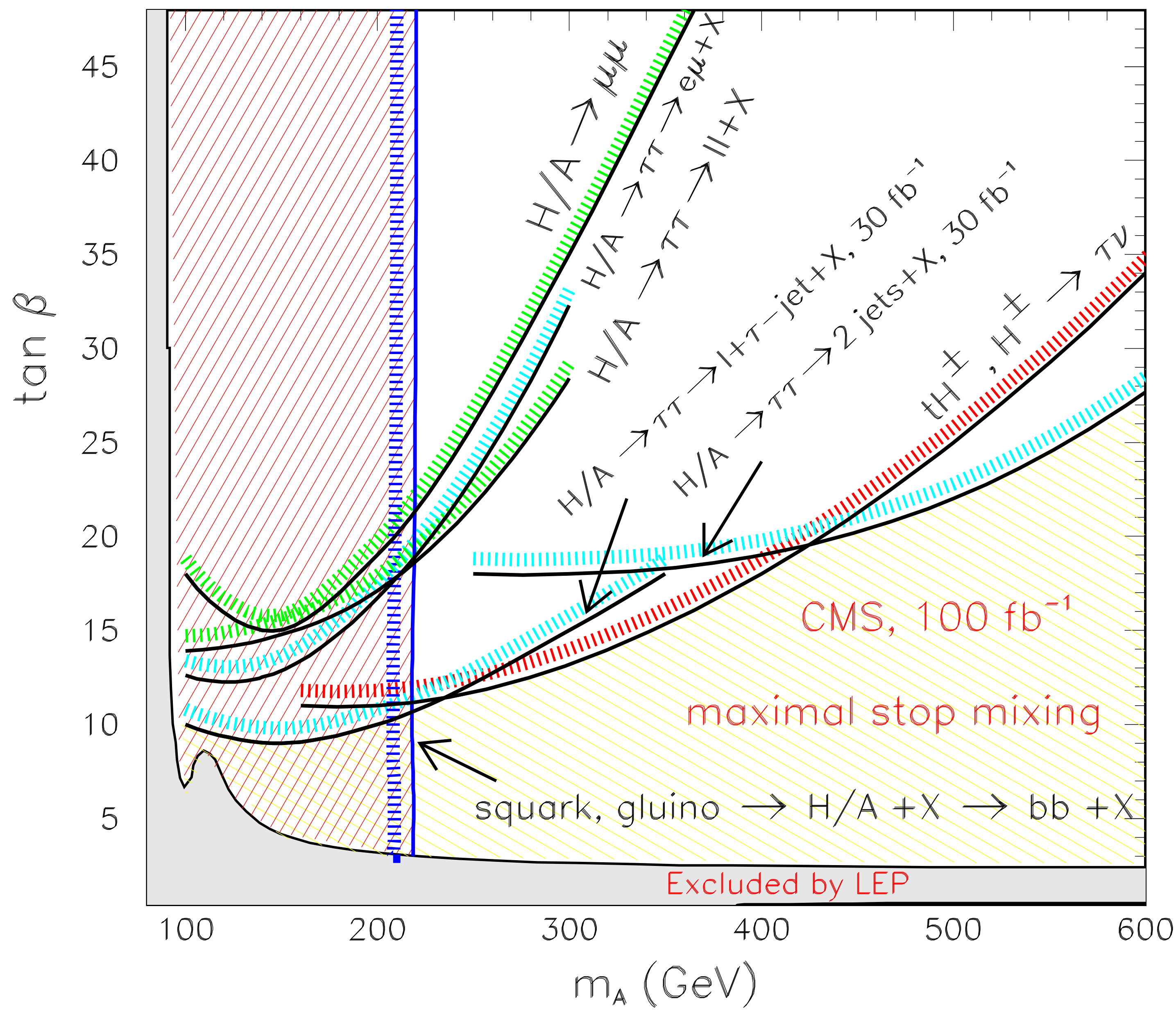
See talk by N. Marinelli



$\sigma \times BR$ [pb]
Sc1
Sc2
Sc3
Sc4
h
A
$H^{\pm}$
H
μ [GeV]
M_2 [GeV]



Events / 5 GeV
bb invariant mass (GeV)


tan β
m_A (GeV)
H/A → μμ
H/A → ττ → eμ+X
H/A → ττ → ll+X
H/A → ττ → l+τ-jet+X, 30 fb^-1
H/A → ττ → 2 jets+X, 30 fb^-1
tH^±, H^± → τν
CMS, 100 fb^-1
maximal stop mixing
squark, gluino → H/A +X → bb +X
Excluded by LEP

(e) The extended regime:

The orthodox MSSM (2HDM+CP) might not be the entire truth.

Some SUSY extensions are possible and must be studied:

- **CP violation in the Higgs and/or SUSY sectors.**
- **More complicated Higgs representations (doublet/triplets, etc..).**

Example of possible change: the NMSSM with an additional singlet:

$$W = \lambda S H_1 H_2 + \kappa/3 \cdot S^3 + \cdots$$

- **Gives a natural reason for $\mu \equiv \lambda \langle S \rangle$ to be at the low scale.**
- **Has less fine tunning than the MSSM....**

Higgs sector extended to include: h_1, h_2, h_3, a_1, a_2 and $h^\pm$.

- **Couplings of h_1, h_2, h_3 to W/Z suppressed compared to h.**
- **Constraints from LEP2 do not hold. Ex: $M_{a_1} \lesssim 50$ GeV possible.**
- **Not yet a "no–loose theorem" for Higgs discovery at the LHC.**

Ellwanger, Hugonie, Gunion, Moretti

A special scenario: h_1, h_2 have SM–like couplings and a_1 is light

$pp \to h_i + X$ **with** $h_i \to a_1 a_1$ **with** $a_1 \to b\bar{b}, \tau^+\tau^-$

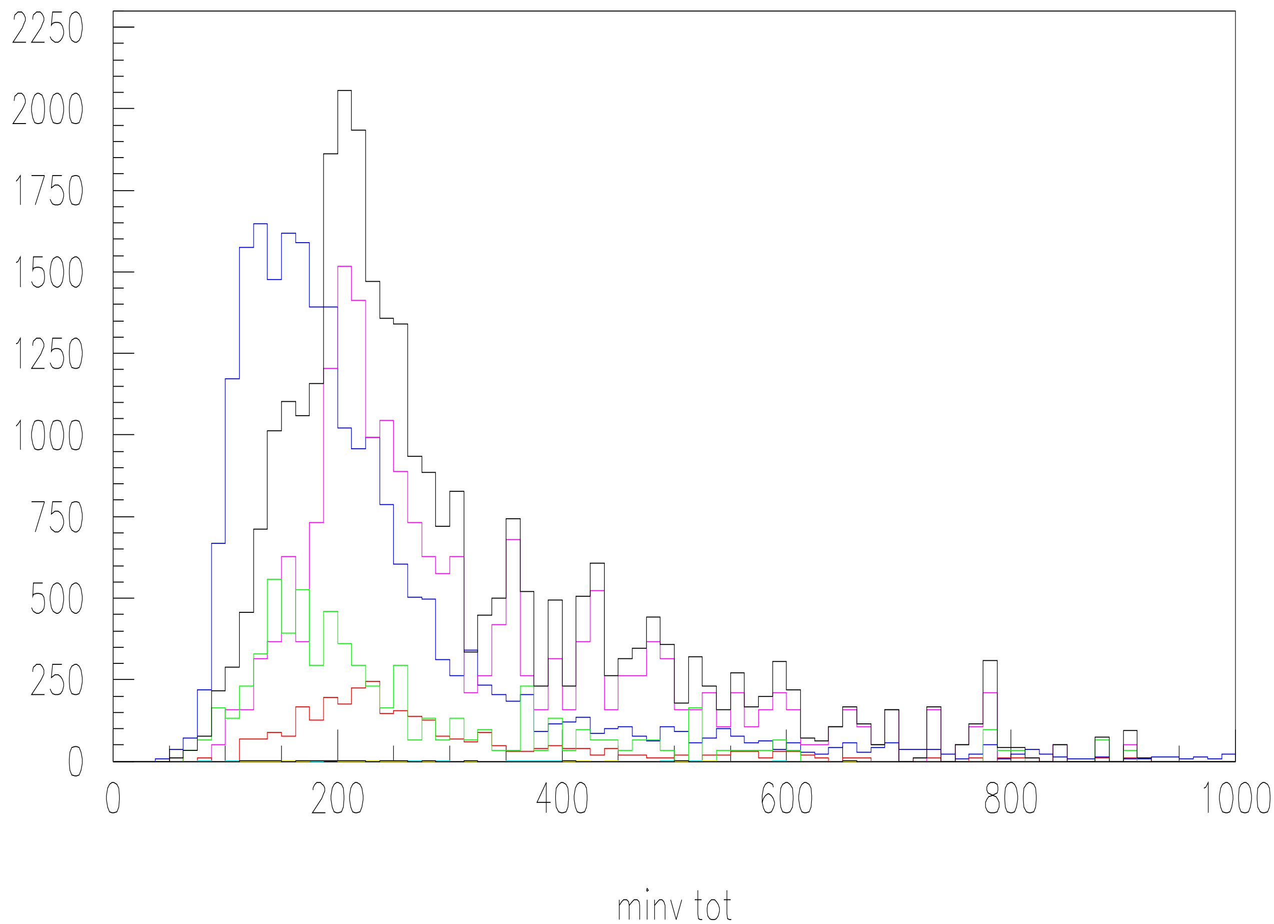
It has been tried in WBF for $qq \to W^*W^*/Z^*Z^* \to qqh_i \to b\bar{b} + \tau^+\tau^-$ in a fast (ATLAS) simulation. Very difficult (if not hopeless)...

$qq \to W^*W^*/Z^*Z^*qq \to qqh_i \to b\bar{b} + \tau^+\tau^-$

– $M_{h_1} \sim 150$ **GeV,** $M_{a_1} \sim 50$ **GeV, usual WBF cuts.**

– **Assumes 300 fb^{-1} luminosity**

S. Baffioni



The signal and backgrounds as a function of the invariant mass $M_{bb\tau\tau}$ **in GeV.**

——— $h_1 \to a_1 a_1 \to b\bar{b}\tau^+\tau^- \times 500.$

——— $t\bar{t}$**,** ——— $\gamma^* \to e^+e^-, \mu\mu$**,** ——— $Z \to \tau^+\tau^-$**,**

——— **total background.**

IV. Conclusions

In the SM:

A large (th.+exp.) activity for the search of Higgs bosons at LHC.

Output: Higgs detection is in principle guaranteed for any mass.

The next step is to perform detailed test of the EWSB mechanism:
Measure the mass, total width, couplings to fermions/gauge bosons and self–coupling and determine spin and parity quantum numbers.

In SUSY extensions:

Also in the MSSM, the light Higgs cannot escape detection and in large areas of parameter space, more than one Higgs can be found.

But still watch out:

– there are still tricky areas of parameter space.

– complications if SUSY decays+production allowed.

– what about other SUSY non-minimal extensions?

.... Still a lot of work to be done ....