Implications of the first Supersymmetric Higgs searches at the lHC

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1. **The Higgs sector: SM versus MSSM**
2. **Higgs production at the LHC**
3. **ATLAS/CMS searches and implications**
4. **Outlook**

Based on J. Baglio and AD, arXiv:1012.0530 and arXiv:1103.6247

1. The Higgs sector SM versus MSSM

To generate particle masses in an SU(2)$\times$U(1) gauge invariant way:

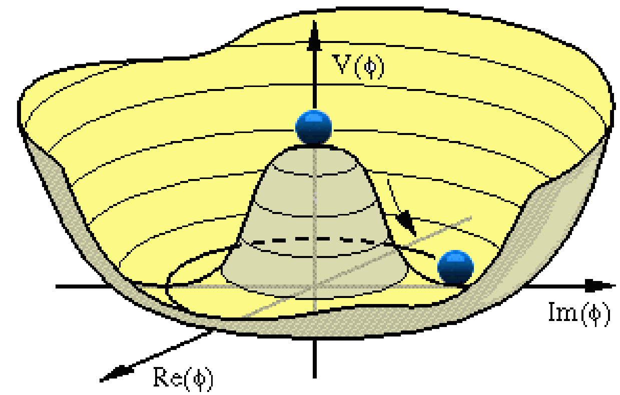
In SM: $\Phi = \binom{\Phi^+}{\Phi^0}$ **with** $\langle 0|\Phi^0|0\rangle = v$

$\mathcal{L}_S = D_\mu \Phi^\dagger D^\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda(\Phi^\dagger \Phi)^2$

Fermions: $\mathcal{L}_{\rm Yuk} = -f_e(\bar{e}, \bar{\nu})_L \Phi e_R + \ldots$

$\Rightarrow$ **three d.o.f. for** $M_{W^\pm}$ **and** M_Z

One residual dof: the Higgs boson H



Since couplings $\propto$ masses, only free parameter in SM is M_H.

In the MSSM: two Higgs doublets: $H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}$ **and** $H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$,

three dof to make $W_L^\pm, Z_L \Rightarrow$ **5 physical states left out:** $h, H, A, H^\pm$

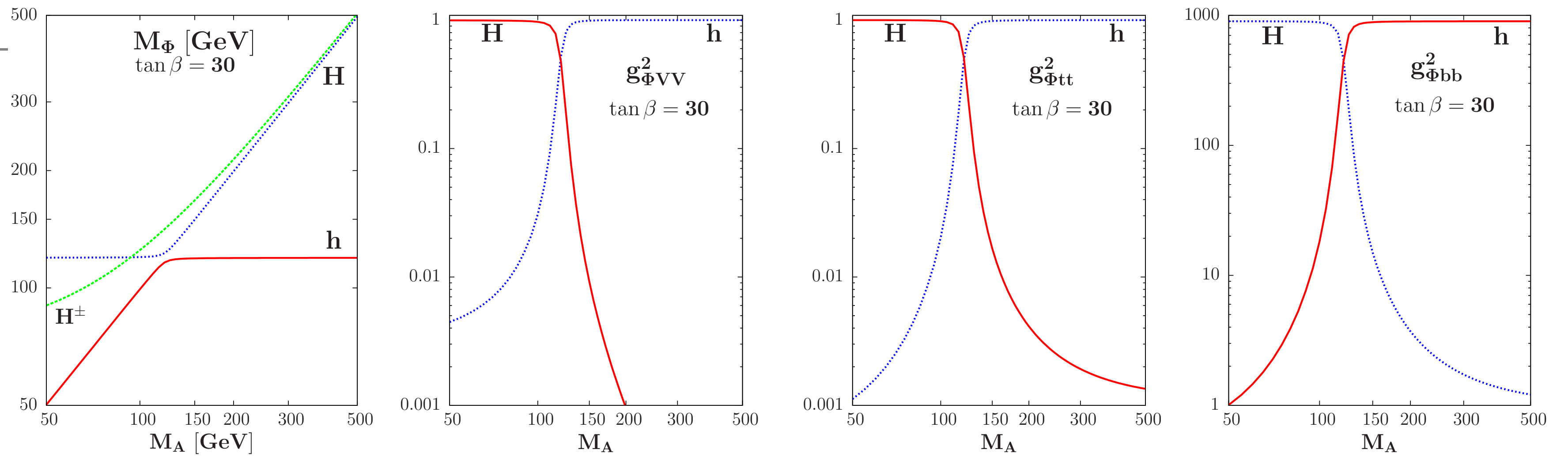
Only two free parameters at tree–level: for instance $\tan\beta, M_A$

Radiative corrections in Higgs sector very important: for large M_S**:**

$$M_h \lesssim M_Z |\cos 2\beta| + RC \rightarrow \begin{array}{l} \lesssim 140~{\rm GeV~for}~M_h^{\rm max}~{\rm scenario}~~(A_t/M_S \approx \sqrt{6}) \\ \lesssim 120~{\rm GeV~for}~M_h^{\rm min}~{\rm scenario}~~(A_t/M_S \approx 0) \end{array}$$

For the heavy Higgs states: $M_H \approx M_A \approx M_{H^\pm} \lesssim M_{EWSB}$

1. The Higgs sector SM versus MSSM: spectrum



– **Couplings of h, H to VV are suppressed; no AVV couplings (CP).**

– **For $\tan\beta \gg 1$: couplings to b (t) quarks enhanced (suppressed).**

Φ	$g_{\Phi\bar{u}u}$	$g_{\Phi\bar{d}d}$	$g_{\Phi VV}$
h	$\frac{\cos\alpha}{\sin\beta} \rightarrow 1$	$\frac{\sin\alpha}{\cos\beta} \rightarrow 1$	$\sin(\beta-\alpha) \rightarrow 1$
H	$\frac{\sin\alpha}{\sin\beta} \rightarrow 1/\tan\beta$	$\frac{\cos\alpha}{\cos\beta} \rightarrow \tan\beta$	$\cos(\beta-\alpha) \rightarrow 0$
A	$1/\tan\beta$	$\tan\beta$	0

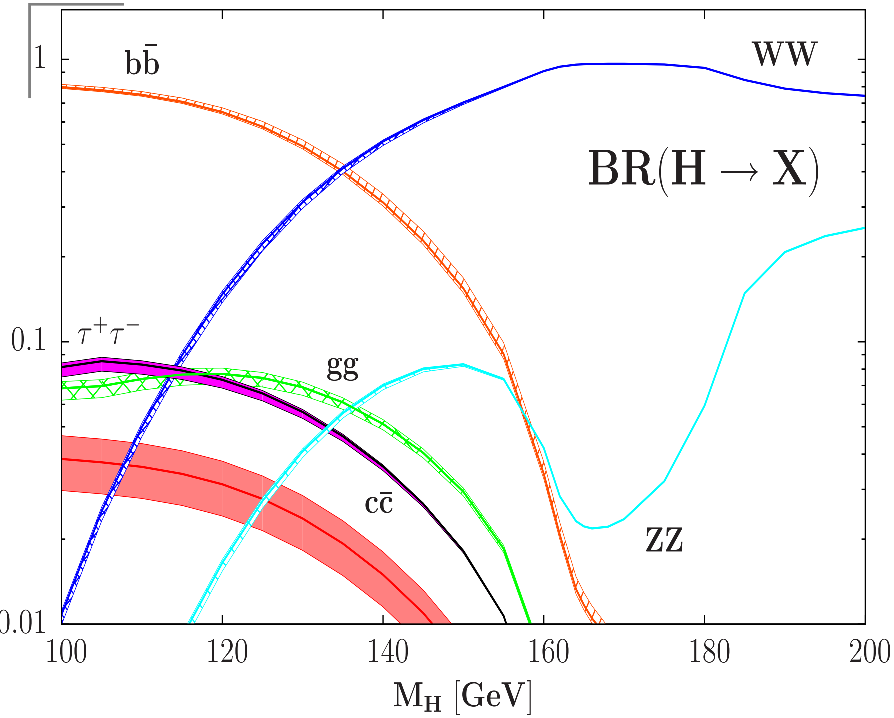
In the decoupling limit: MSSM reduces to SM but with a light Higgs...

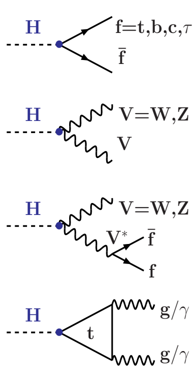
At $\tan\beta \gg 1$: one SM–like and two CP–odd like Higgses with cplg to b,τ

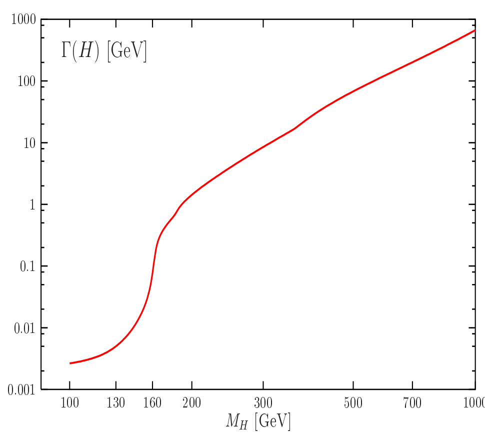
$$\mathrm{M_A} \gtrsim \mathrm{M_h^{max}} \Rightarrow \mathrm{h} \equiv \mathrm{H_{SM}}, \mathrm{H} \approx \mathrm{A}$$

$$\mathrm{M_A} \lesssim \mathrm{M_h^{max}} \Rightarrow \mathrm{H} \equiv \mathrm{H_{SM}}, \mathrm{h} \approx \mathrm{A}$$

1. The Higgs sector SM versus MSSM: decays







Higgs decays in the SM:

- **H decays into the heaviest particle available by phase space: $g \propto m$**
- $M_H \lesssim 130$ GeV, $H \to b\bar{b}$
  - $H \to cc, \tau^+\tau^-, gg = \mathcal{O}(\text{few}\,\%)$
  - $H \to \gamma\gamma = \mathcal{O}(0.1\%)$
- $M_H \gtrsim 130$ GeV, $H \to WW, ZZ$
  - **below threshold decays possible**
  - **above threshold: B(WW)=$\frac{2}{3}$, B(ZZ)=$\frac{1}{3}$**
  - **decays into $t\bar{t}$ for heavy Higgs**
- **Total Higgs decay width:**
  - **very small for a light Higgs**
  - **comparable to mass for heavy Higgs**
- **Uncertainties from m_b, m_c, α_s:**

For $M_H \approx$120–150 GeV: 5–10% for $H \to b\bar{b}$ and $H \to WW, ZZ, \gamma\gamma, \tau\tau$

1. The Higgs sector SM versus MSSM: decays

Higgs decays in the MSSM:

- h: **same as** $\mathrm{H_{SM}}$ **in general**

(in particular in decoupling limit)

$\mathrm{h}\to\mathrm{b\bar{b}}$, $\tau\tau$ **same or enhanced**

- A: **only** $\mathrm{b\bar{b}}, \tau^+\tau^-$, $\mathrm{t\bar{t}}$ **decays**

(no VV decays, hZ **suppressed).**

- H: **same as** A **in general**

$(\mathrm{WW}, \mathrm{ZZ}, \mathrm{hh}$ **suppressed).**

- $\mathrm{H^\pm}: \tau\nu$ **and** tb **decays**

(depending if $\mathrm{M_{H^\pm}} <$ **or** $> \mathrm{m_t}$**).**

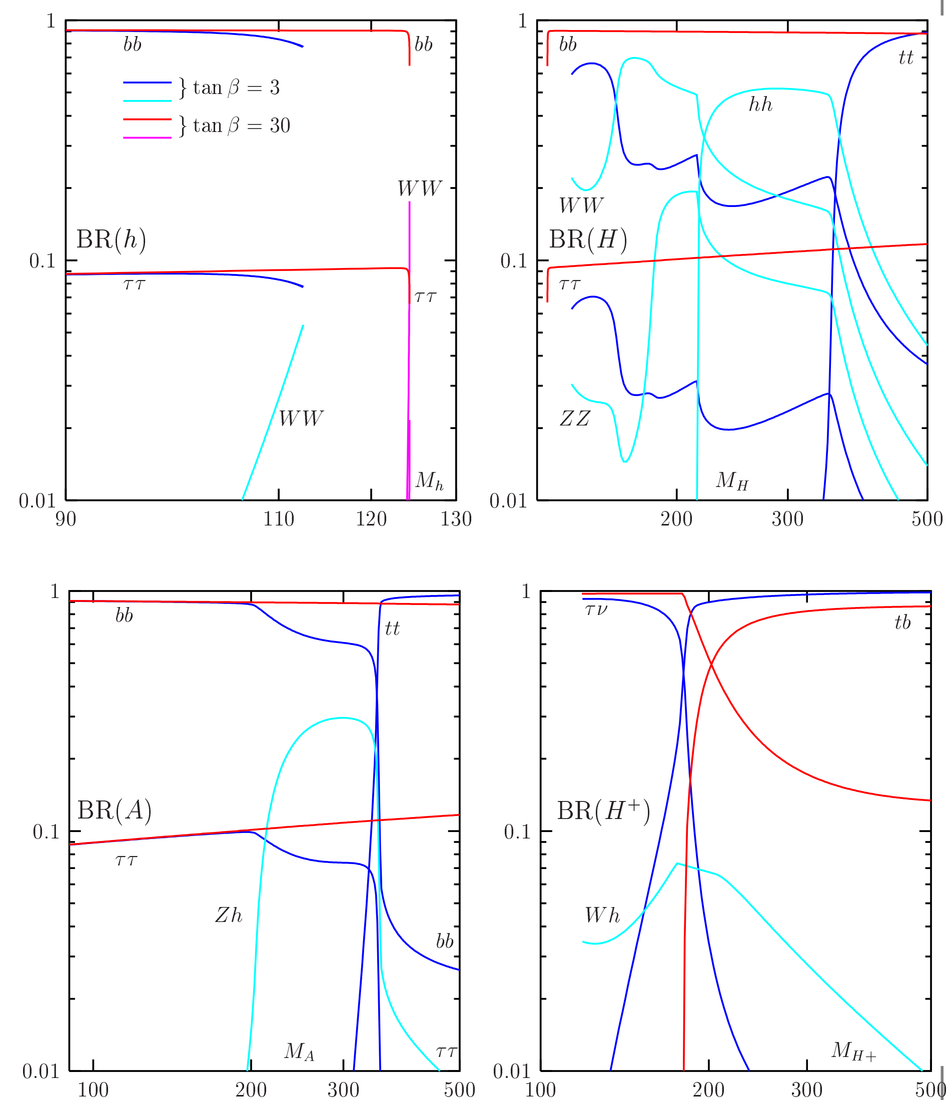
- **Possible new effects from SUSY**

Note: total decay widths small....

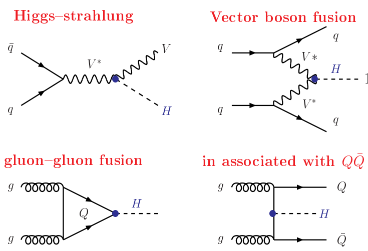
For tan$\beta \gg 1$**, only decays into b/**τ**:**

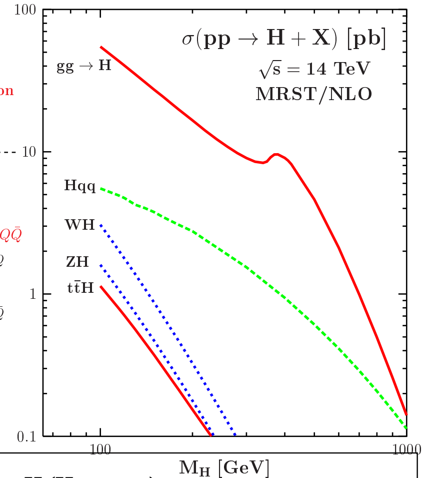
– $\mathrm{BR}(\Phi \to \mathrm{b\bar{b}}) \approx 90\%^{+1\%}_{-0.5\%}$

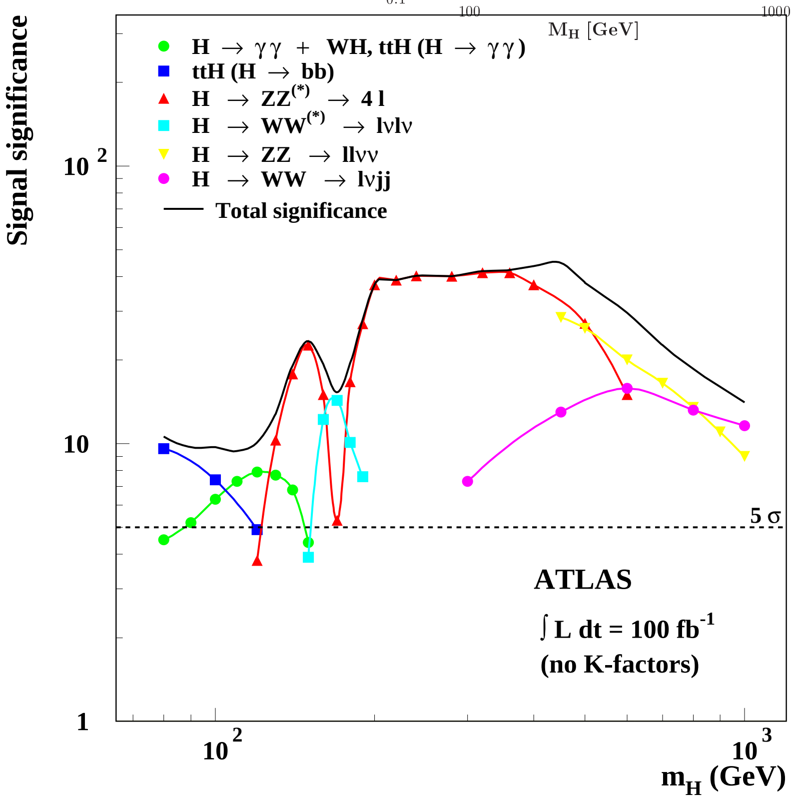
– $\mathrm{BR}(\Phi \to \tau\tau) \approx 10\%^{+0.3\%}_{-0.8\%}$



2. Higgs production at the LHC







Planned schedule (before 2008...):

LHC: $\sqrt{s}=7+7=14$ TeV $\Rightarrow \sqrt{s}_{\rm eff} \sim \sqrt{s}/3 \sim 5$ TeV
$\mathcal{L} \sim 10\,{\rm fb}^{-1}$ first years and $100\,{\rm fb}^{-1}$ later

gluon–gluon fusion:

$gg \to \tau\tau, b\bar{b}, t\bar{t}$ **hopeless**

$gg \to H \to \gamma\gamma$ **(below $M_H \approx$ 150 GeV)**

$gg \to H \to ZZ^* \to 4\ell$ **(130–500 GeV)**

$gg \to H \to WW \to \ell\nu\ell\nu$ **(130–200 GeV)**

$H \to ZZ, WW \to jj + \ell$ **(above 500 GeV)**

Vector boson fusion:

S/B $\sim$ 1 after standard VBF cuts

$pp \to H \to \tau\tau, \gamma\gamma, ZZ^*, WW^*$

Association with top pairs:

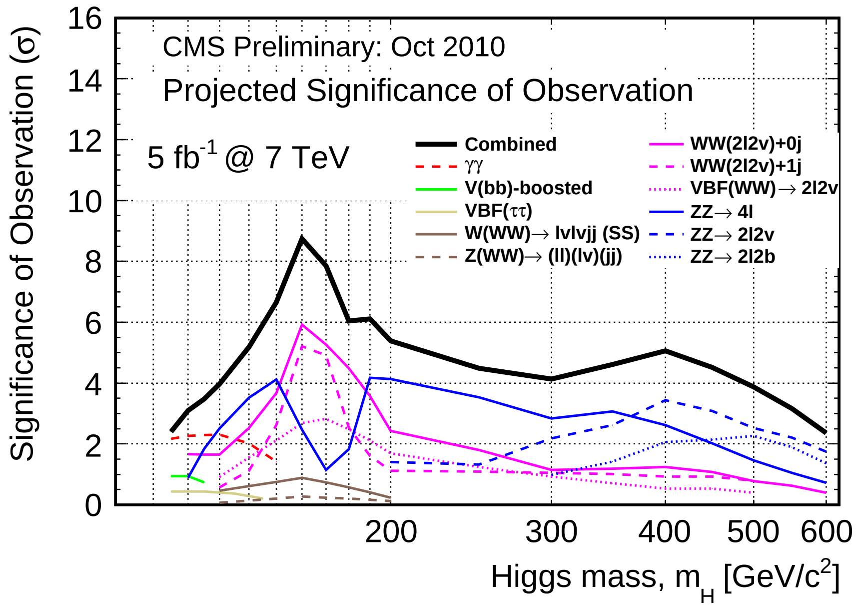
$H \to \gamma\gamma$ **bonus,** $H \to b\bar{b}$ **hopeless?**

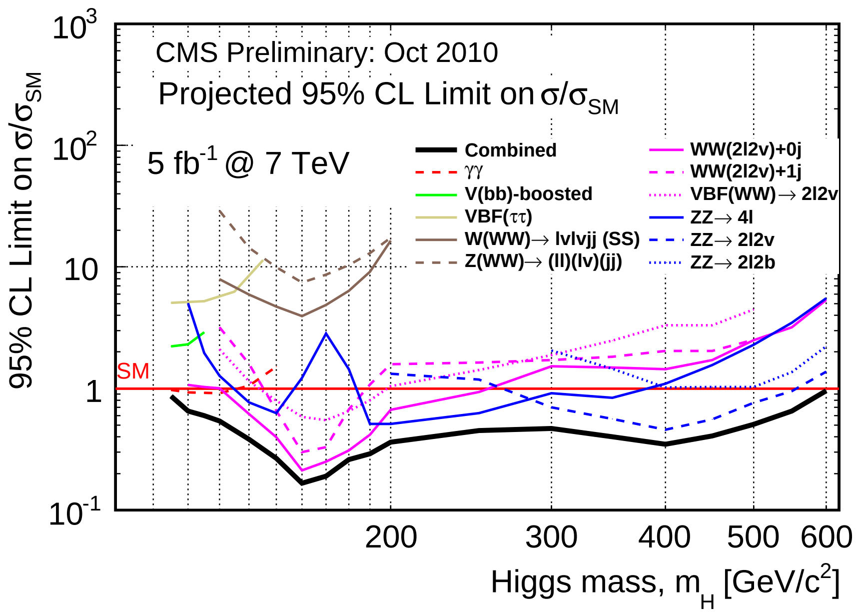
Association with W,Z:

jet substructure; measurements?

Higgs to be found; only question: when?

2. Higgs production at the lHC





Present schedule (after 2009...):

LHC $\Rightarrow$ lHC or $\frac{1}{2}$ LHC

– $\sqrt{s} = 3.5 + 3.5 = 7$ TeV
possibility to increase to $\sqrt{s} \sim 8$ TeV
– $\mathcal{L} \approx 1\ \text{fb}^{-1}$ (maybe more?)
possibility to collect a few fb^{-1} later

$\Rightarrow$ 5σ Higgs discovery possible only in limited mass range $M_H \approx$ 130–200 GeV

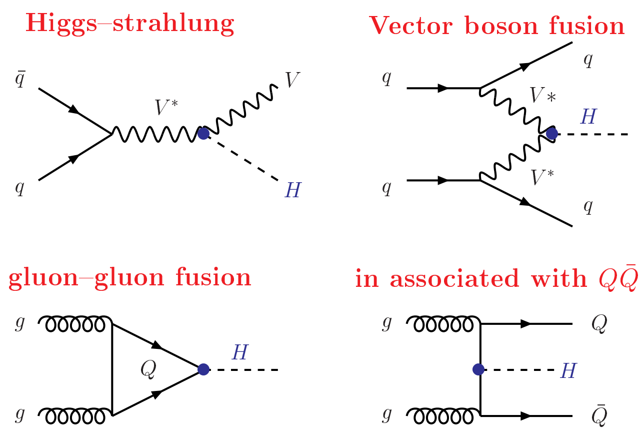
But sensitivity or exclusion at 95% CL OK for $M_H \lesssim 600$ GeV with 5 fb^{-1}@7 TeV...

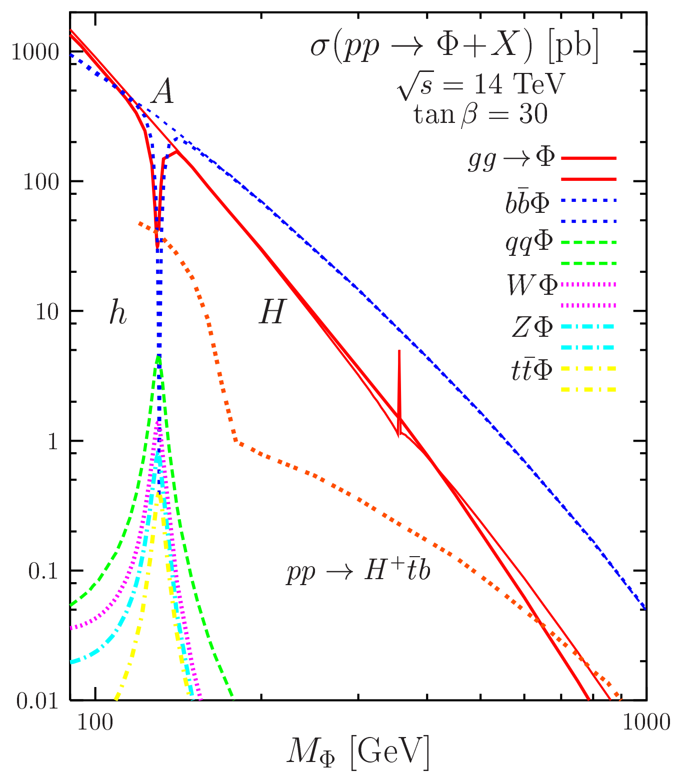
Main sensitive channels

$gg \to H \to \gamma\gamma$ (below $M_H \approx$ 130 GeV)
$gg \to H \to WW \to \ell\nu\ell\nu$ (130–250GeV)
$gg \to H \to ZZ^* \to 4\ell, 2\ell 2\nu, 2\ell 2b$
with a little help from $pp \to qqWW^*$
all other channels very difficult....
some help also from VBF with $H \to \tau\tau$

2. Higgs production at the LHC

SM production mechanisms





What is different in MSSM

- **All work for CP–even h,H bosons.**
- **in ΦV, $qq\Phi$: h/H complementary**
- $\sigma(h) + \sigma(H) = \sigma(H_{SM})$
- **additional mechanism: $q\bar{q} \to A + h/H$**
- **For $gg \to \Phi$ and $pp \to Q\bar{Q}\Phi$**
- **include contribution of b–quarks**
- **dominant contribution at high tanβ!**
- **For pseudoscalar A boson:**
- **CP: no ΦA and qqA processes**
- **$gg \to A$ and $pp \to bbA$ dominant.**
- **For charged Higgs boson:**
- $M_H \lesssim m_t$: $pp \to t\bar{t}$ **with** $t \to H^+ b$
- $M_H \gtrsim m_t$: **continuum** $pp \to t\bar{b}H^-$

At high tanβ values:

- **h/H as in SM with $M_{h/H}$=115-140 GeV**
- **dominant: $gg, b\bar{b} \to \Phi \to \tau^+\tau^-$**

2. Higgs production at the lHC

At the lHC: good chances at high tanβ

For CP–odd like Higgs $\Phi = A, h/H$

$$gg \to \Phi \to \tau^+\tau^-$$

(with only b–loop taken into account)

$$b\bar{b} \to \Phi \to \tau^+\tau^-$$

(equivalent to pp$\to$bbΦ with lost b's)

Large production rates at tan$\beta \gg 1$:

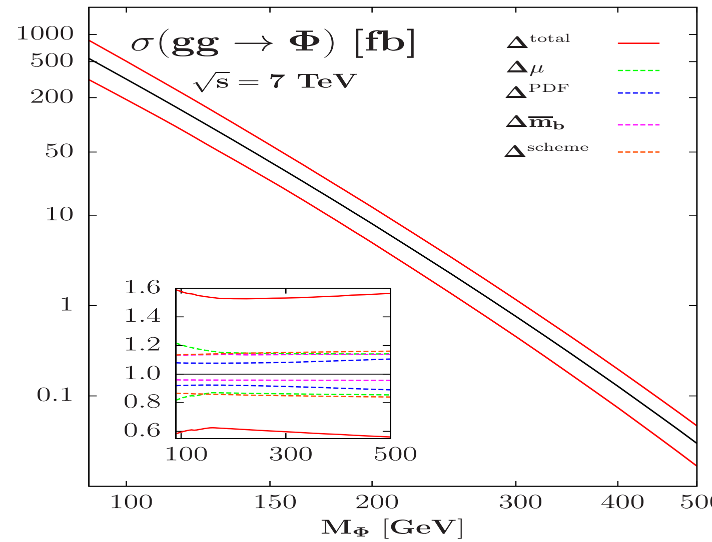
$$\sigma(\Phi) = 2\tan^2\beta \times \sigma(A_{SM})$$

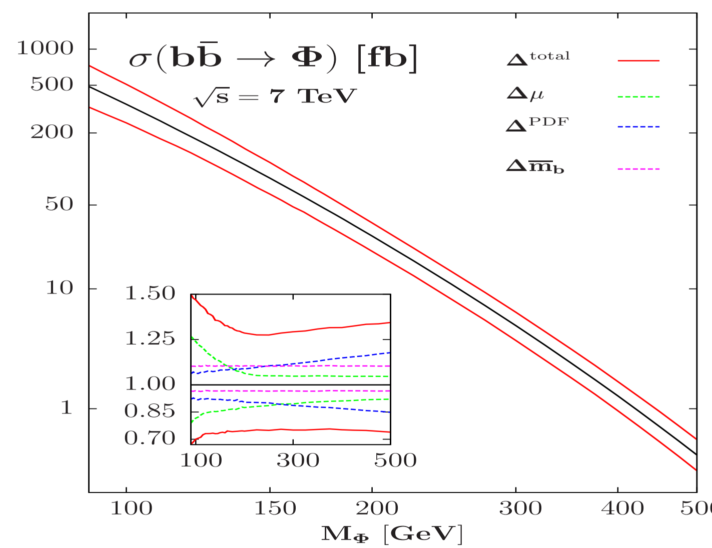
(chiral symmetry holds for $M_\Phi \gg m_b$)

It reduce then to a QCD problem:

- known higher order corrections
- but rather large QCD uncertainties:

– renorm/fact. scale dependence
– renor. scheme dependence for m_b
– PDF uncertainties (at high–x)
– parametric errors from m_b, α_s

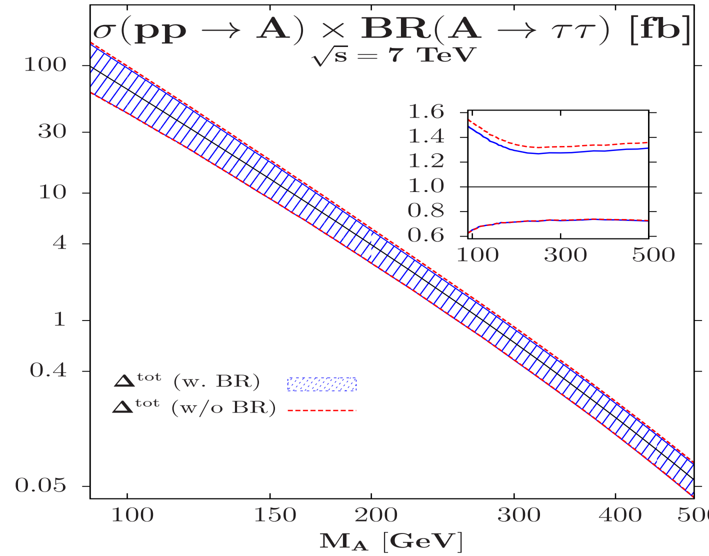




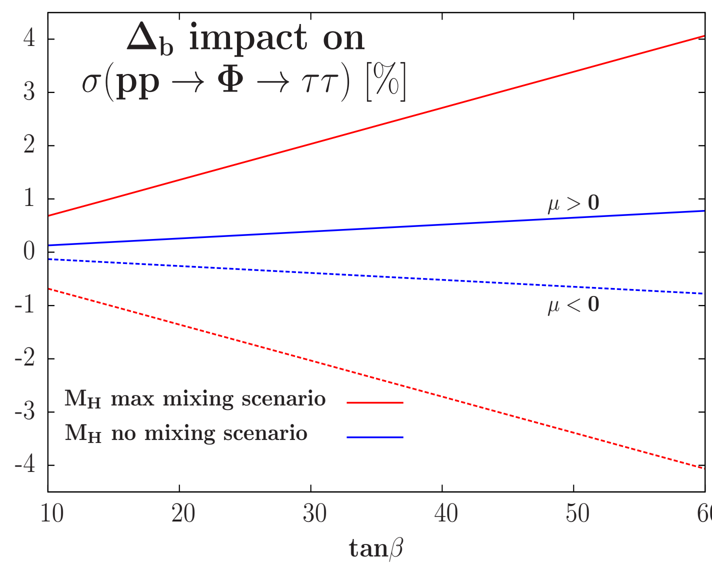
$\Rightarrow \pm 30\%$ theoretical uncertainty in combined $b\bar{b} + gg \to \Phi \to \tau^+\tau^-$

2. Higgs production at the lHC

Combine the gg and bb fusion channels:
easy for inclusive search (e.g. no b–tag)
$\Rightarrow$ **just sum of xsections/uncertainties**
Multiply by the branching $\Phi \to \tau\tau$ ratio
BR$(\tau\tau) \approx \Gamma(\Phi \to \tau\tau)/\Gamma(\Phi \to \mathrm{bb})$
$\Rightarrow$ **parametric errors cancel out**
$\Rightarrow$ **error on $\sigma \times$BR $<$ error on σ**



There are also large SUSY corrections!
– dominant one from $\lambda_b \to \lambda_b(1+\Delta_b)$
– $\Delta_b \approx \frac{\alpha_s}{\pi}\mu\tan\beta/\max(\tilde{m}_g, \tilde{m}_b)$
– large at high tanβ and/or high μ
– large EW corrections also present
$\Rightarrow$ **only effect of $\neq$ SUSY scenarii!**
Affect both $\sigma(\Phi)$ and BR($\Phi \to \tau\tau$)
Most of it cancels in product $\sigma\times$ BR
$\Rightarrow$ **effect negligible comp. QCD...**



3. Implications of ATLAS/CMS searches

CMS/ATLAS searches with 36 pb^{-1}

– $\mathrm{pp} \to \mathrm{h}, \mathrm{H}, \mathrm{A} \to \tau\tau + \mathrm{X}$

– completely inclusive/no b–tagging

– one $\tau \to \mathrm{had}$ and one $\tau \to \ell$

– also subleading channel $\tau\tau \to e\mu$

– main background $\mathrm{pp} \to \mathrm{Z} \to \tau\tau$

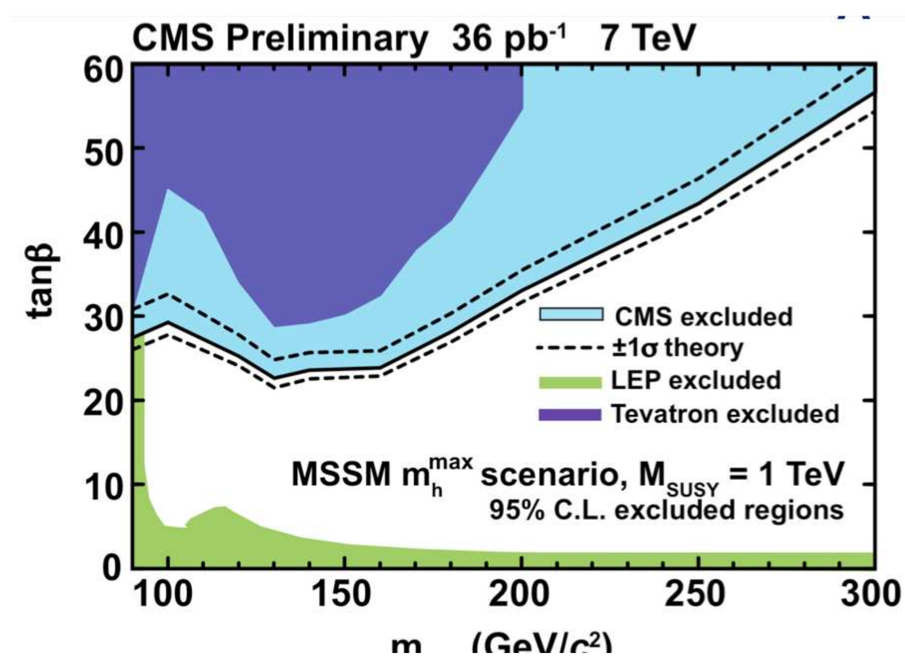
– important to reconstruct $\mathrm{M}_{\tau\tau}$ peak

No excess in $\sigma(\mathrm{pp} \to \tau\tau)$ vs SM

To be interpreted in the MSSM case

$\Rightarrow$ **strong limits in $[\mathrm{M_A}, \tan\beta]$ plane**

already more stringent than Tevatron...



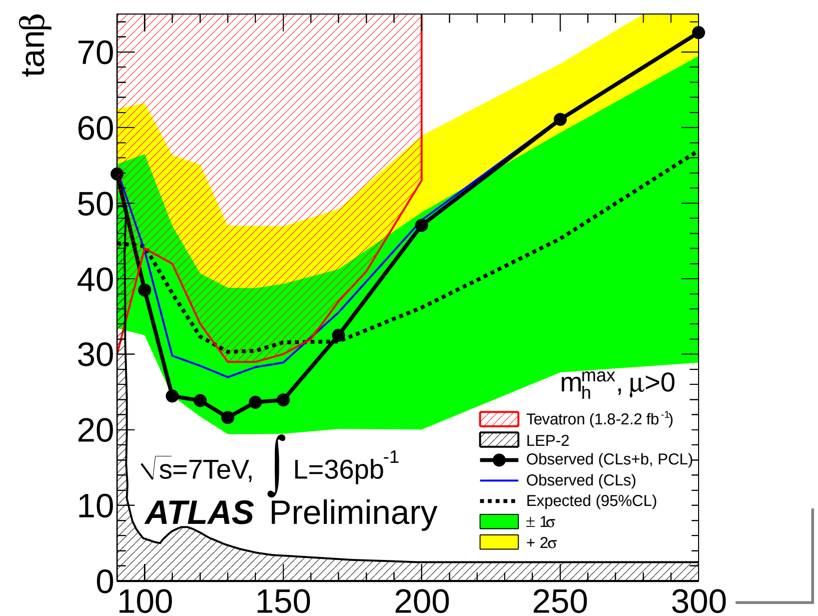
Note:

– results shown for max mixing scenario

– smaller TH uncertainties than above...

– but error statistics dominated...

– excludes tan$\beta \lesssim$23 for $\mathrm{M_A} \approx 130$ GeV



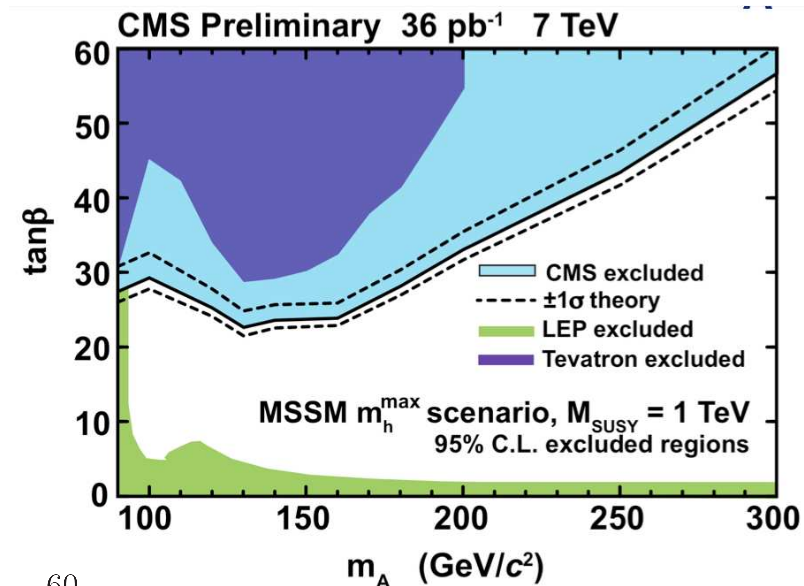
3. Implications of ATLAS/CMS searches

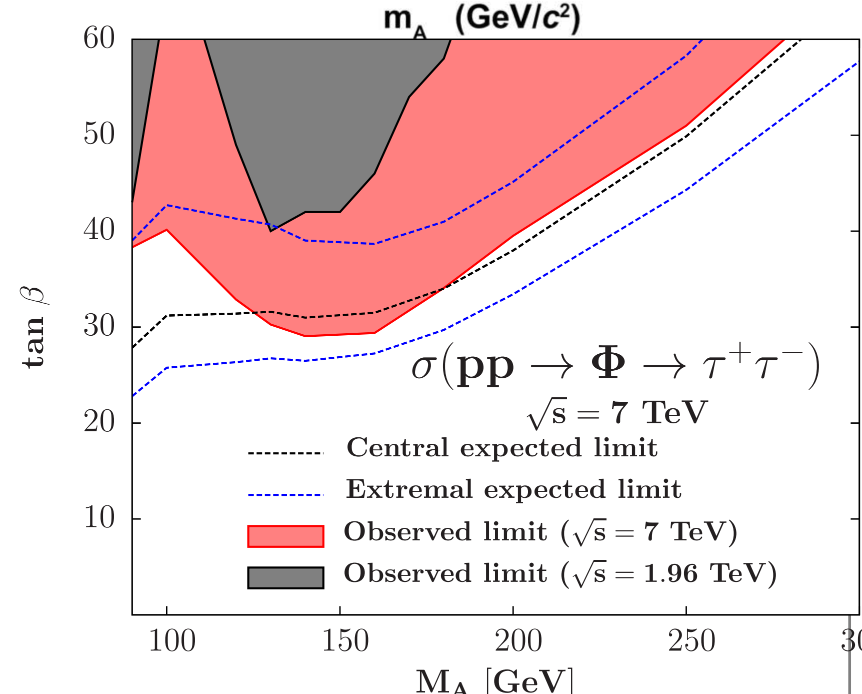
However, CMS/ATLAS constraints:

● valid in many SUSY scenarios
(which differ only in canceling Δ_b..)
$\Rightarrow$ the bound is more general!

● slightly looser exclusion limits:
– TH uncertainties slightly larger
(ren. scheme error not included...)
– exclusion for lower TH prediction!
– only tan$\beta \lesssim$28 excluded @130 GeV

● In fact here: intense coupling...
– $M_H \approx M_h \approx M_A$
– $\Delta M_{Higgs} \lesssim \Gamma_{Higgs}$
(smaller than the 10 GeV bins)
– $\sigma(H) + \sigma(h) \simeq \sigma(A)$
$\Rightarrow$ previous approximation valid
and the search/results are OK too....



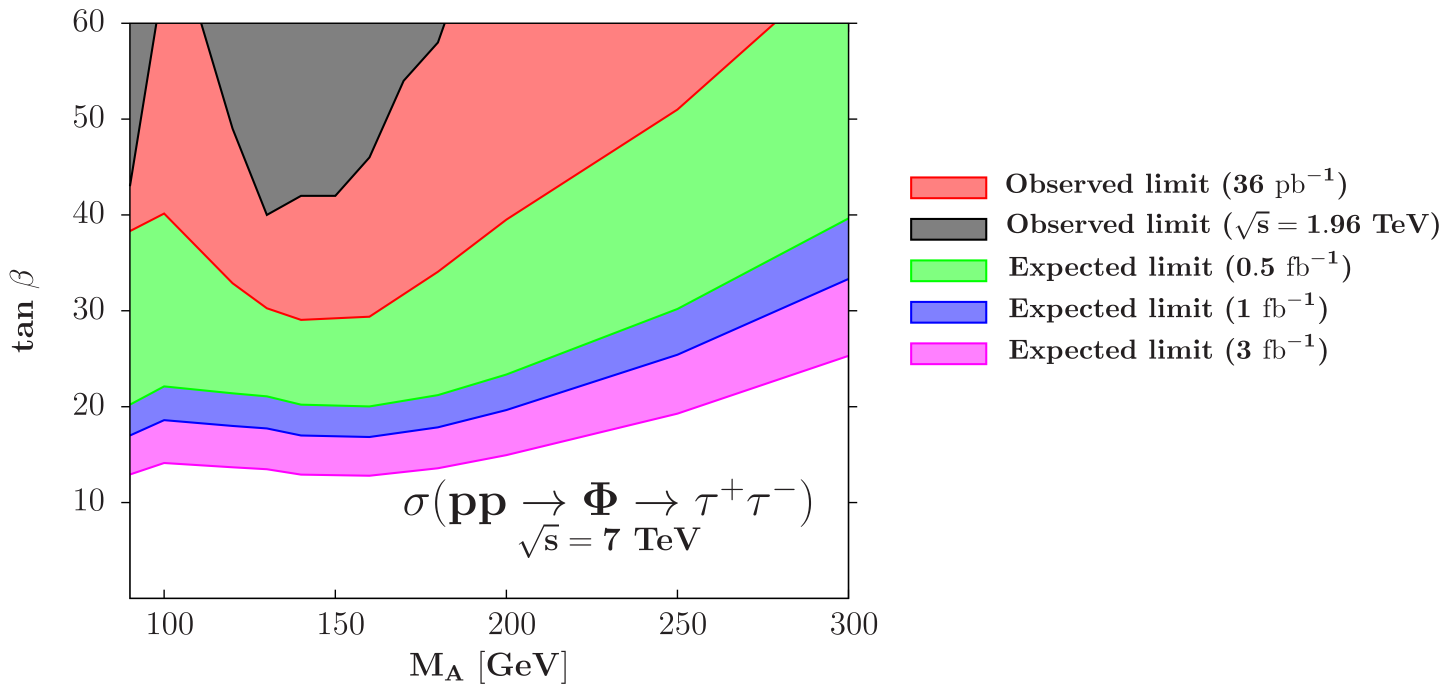


3. Implications of ATLAS/CMS searches

The reach in [$M_A, \tan\beta$] much better than previously expected...

The channel is very performant!

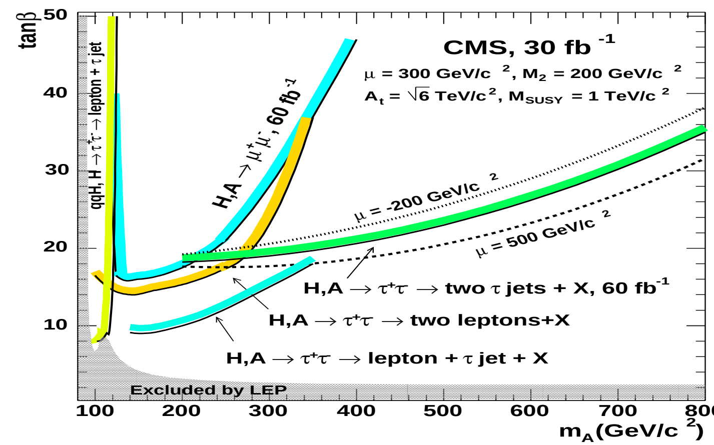
What would happen if more luminosity is collected at $\sqrt{s} = 7$ TeV?



values $\tan\beta \approx 10$ can be reached with 5fb@7TeV with CMS+ATLAS!

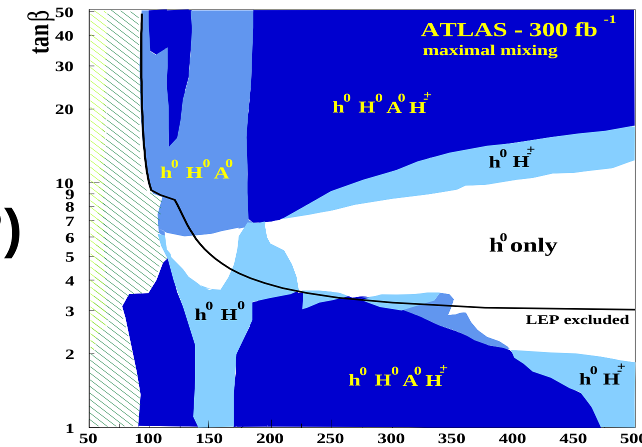
(the reach will further increase if the lHC c.m. energy raised to 8 TeV..)

3. Implications of ATLAS/CMS searches



Implications in the MSSM:

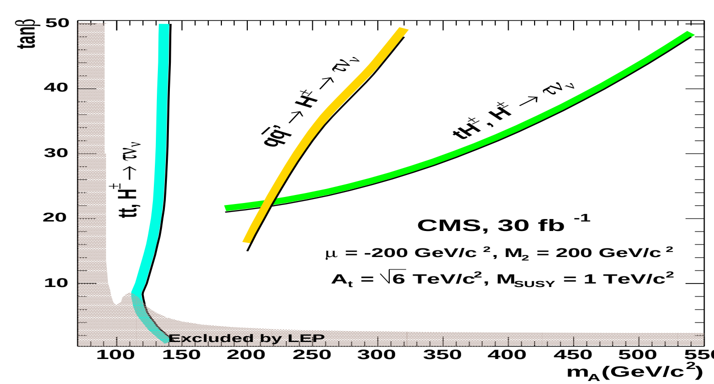
- **Reaching $\tan\beta \approx 10$ was expected only at LHC with $\sqrt{s}=$ 14 TeV and 30 fb^{-1} data!**
$\Rightarrow$ much smaller tanβ values can be probed at the end of the lHC run (1.5 years?)....



- **The hole in the MSSM parameter space for $M_A \approx 150$ GeV could be closed?**
(also H/A could also be seen for tan$\beta \lesssim 3-5$?)
- **Would $\Phi \to \mu\mu$ also improve?**

– yes: this will add some sensitivity...

– no: forget this channel already now....



- **Charged Higgs searches possible in**
$\rm t \to bH^+ \to b\tau\nu \ for \ M_H \lesssim m_t$
$\rm gb \to tH^- \to t\tau\nu \ for \ M_H \gtrsim m_t$
reach at high mass indirectly probed by $\tau\tau$...

3. Implications of ATLAS/CMS searches

In fact, can also be used for SM H:

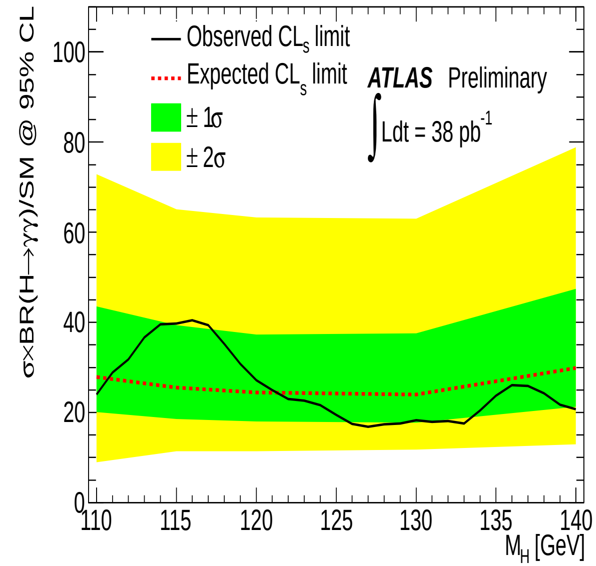
SM case not for tanβ=1 but tan$\beta \approx$5

– no bb$\longrightarrow$H but top–loop in gg$\longrightarrow$H

– BR($\mathrm{H} \to \tau\tau) \gtrsim 5\%$ below 130GeV

– add data from VBF with $\mathrm{H} \to \tau\tau$

– can also add ttH and WH/ZH channels



Interpret ATLAS/CMS for SM Higgs:

$\Rightarrow$ still factor 40 away in sensitivity

However, for SM $\mathrm{gg} \to \mathrm{H} \to \gamma\gamma$

(best channel for $\mathrm{M_H} \lesssim 130$ GeV)

only a factor 20 of sensitivity so far.

$\Rightarrow$ comparable sensitivities!

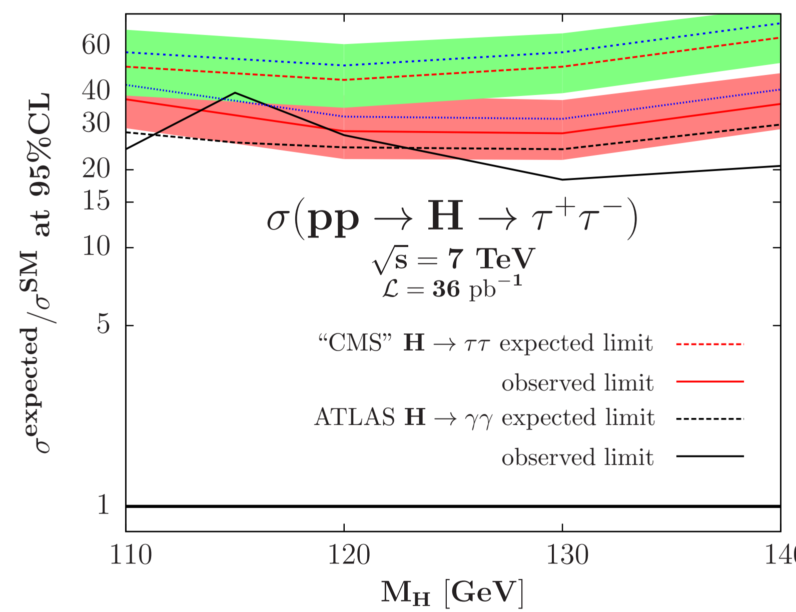
$\mathrm{H} \to \tau\tau$ might be improved:

– better τ–ID, $\tau\tau$ recons., $\ell\ell$ mode

– split into jet multiplicities

– τ polarisation against $\mathrm{Z} \to \tau\tau$

$\Rightarrow$ $\mathrm{H} \to \tau\tau$ adds to total sensitivity..



4. Conclusion

- First ATLAS/CMS Higgs searches with 36 pb^{-1} very impressive!
- $\mathrm{pp} \to \Phi \to \tau\tau$ extremely performant process for the MSSM:

– The reach in [$\mathrm{M_A}, \tan\beta$] much better than previously expected...

– Values tan$\beta \lesssim 10$ (at least?) can be probed at the end of lHC run

– Might probe the entire MSSM parameter space at the end of LHC....

- Can be also used for SM:

– $\mathrm{gg} \to \mathrm{H} \to \tau\tau$ via top–loop

(inclusive and not only in VBF)

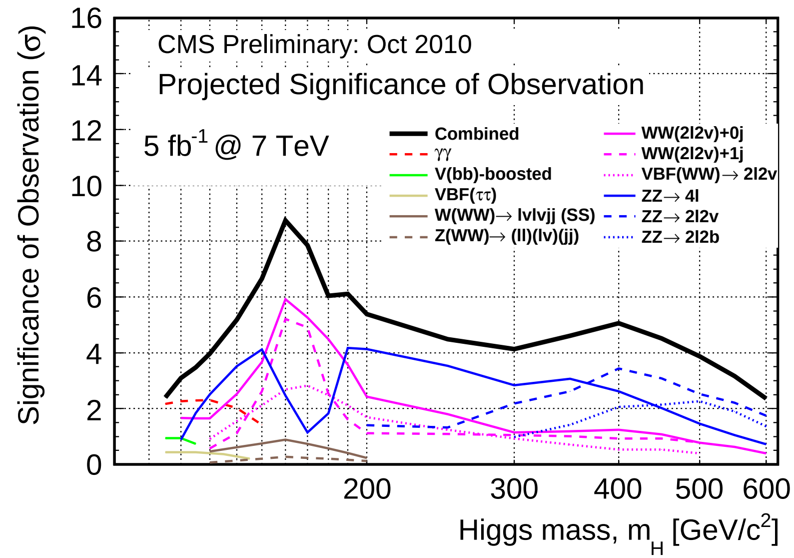
– equivalent to tan$\beta \approx$ 5

– comparable to $\mathrm{H} \to \gamma\gamma$

– more room for improvement (?)

– could add to total sensitivity

in difficult $\mathrm{M_H} \lesssim$ 130 GeV range



$\Rightarrow$ very promising channel indeed!