On the possible absence of Higgs Signatures at the LHC

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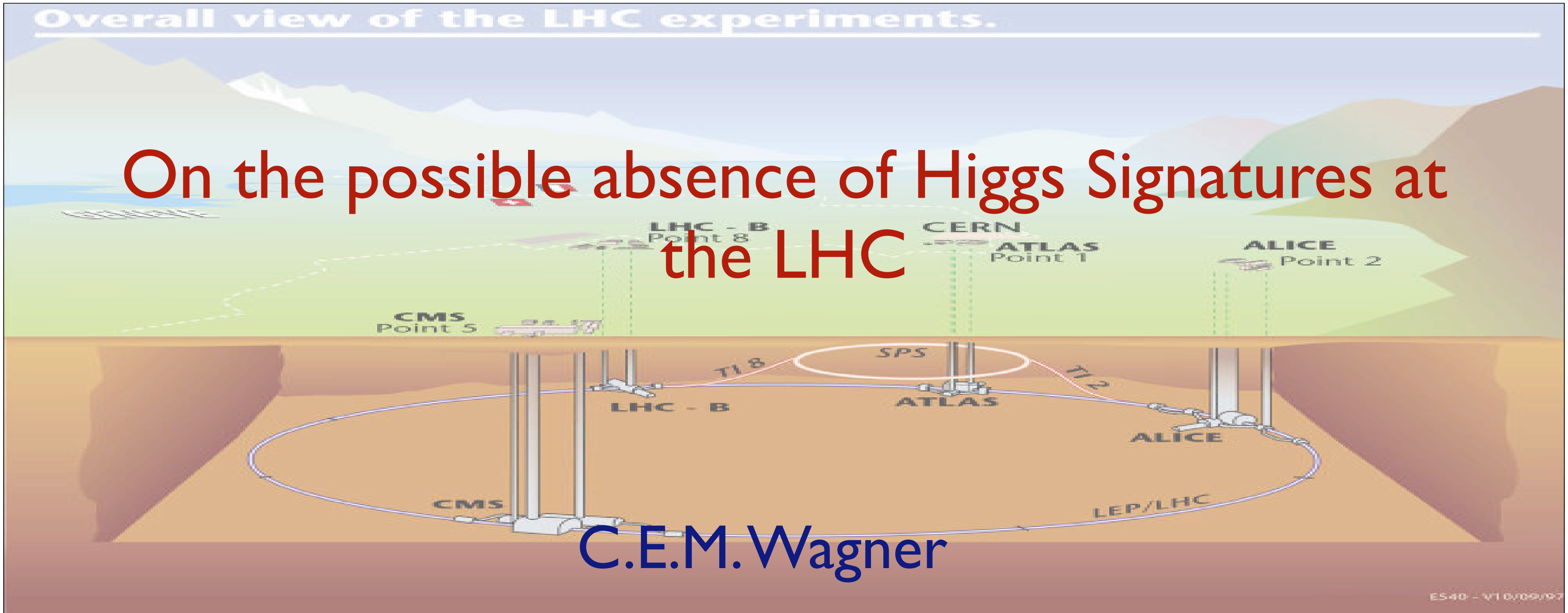


The LHC Early Phase for the ILC, Thursday, April 12, 2007

SM accurately describes all experimental observables measured at low and high energy physics experiments

Electroweak Precision Physics:

- Observables predicted in terms of:

  $M_Z = 91.1875 \pm .0021$ GeV

  $G_F = 1.16639(1) \times 10^{-5}$ GeV^{-2}

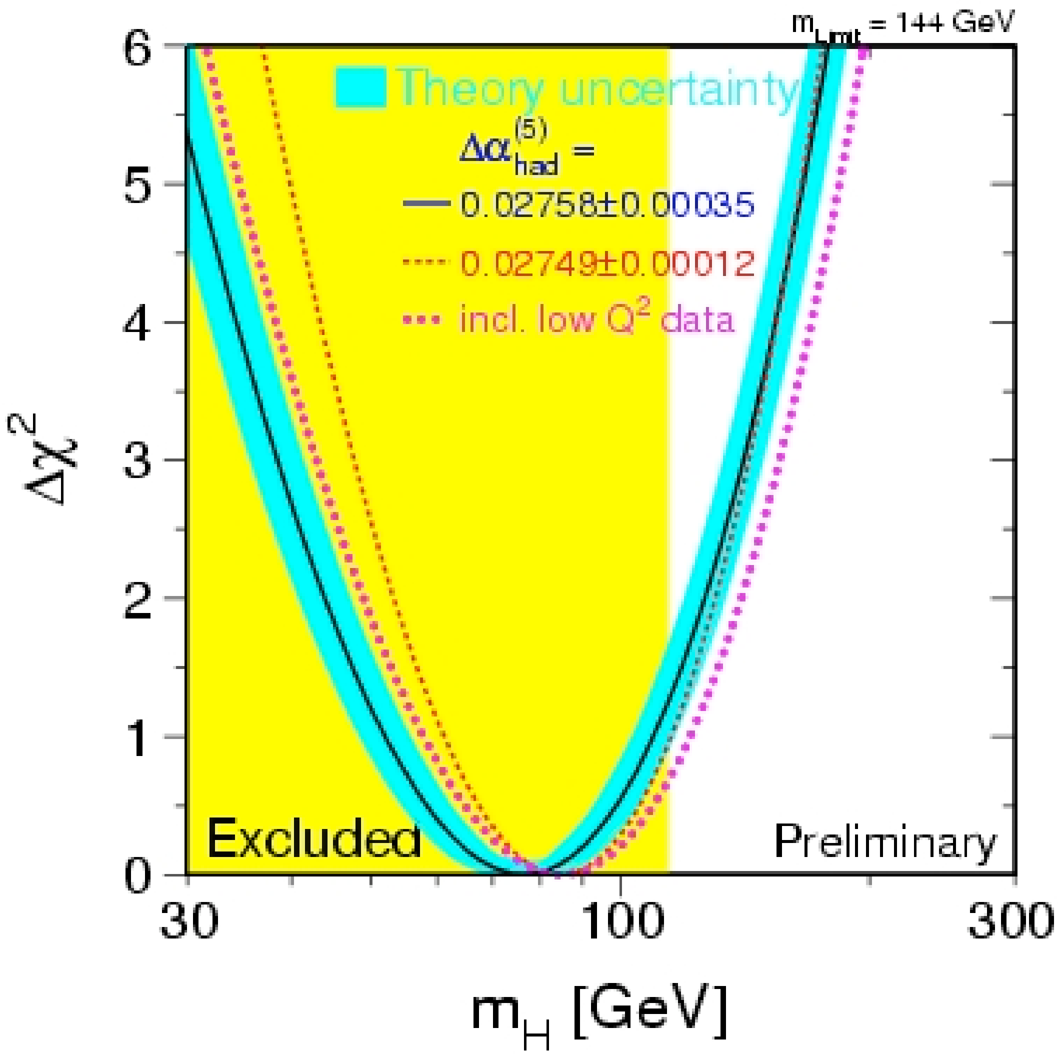
  $\alpha = 1/137.0359895(61)$

  M_h

There is a quadratic dependence of these observables on the top quark mass, and logarithmic on the Higgs mass.

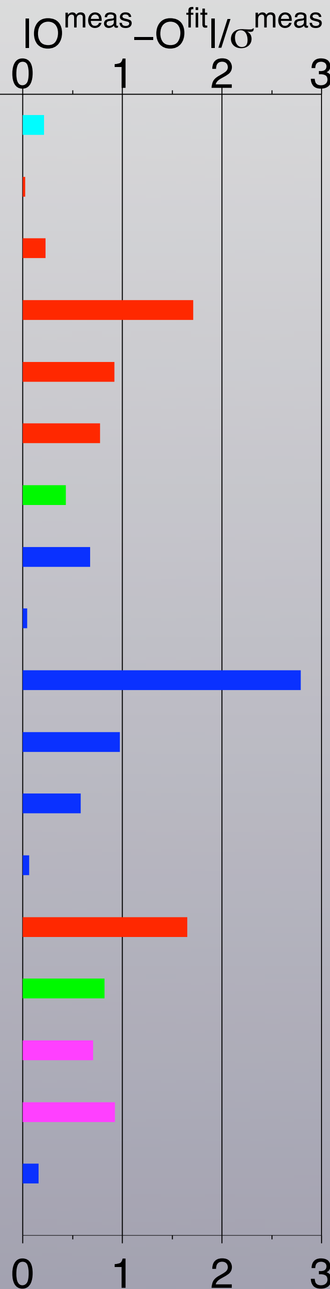
Therefore, within the SM, the knowledge of the top quark mass, and the precise measurement of the electroweak observables, allow us to predict the allowed range of Higgs mass values.

Bounds on the SM Higgs Mass from Precision EW Data



LEP Electroweak
Working Group
Summer '06

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02766
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^0 [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01640
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479
R_b	0.21629 ± 0.00066	0.21585
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0741
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1479
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.392 ± 0.029	80.371
Γ_W [GeV]	2.147 ± 0.060	2.091
m_t [GeV]	171.4 ± 2.1	171.7



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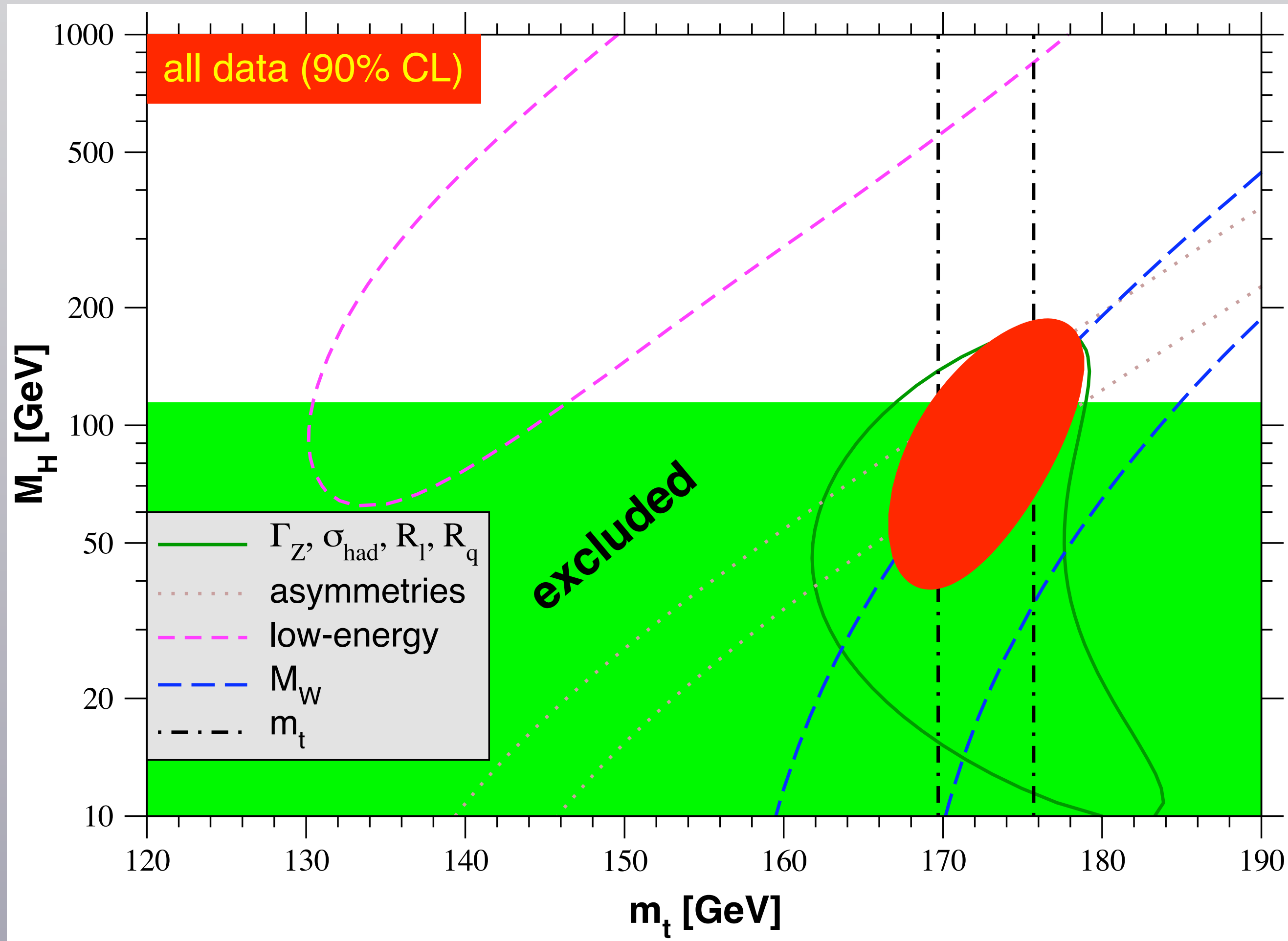
1) Light SM Higgs from the lepton asymmetries, the W mass and the Z widths
2) The heavy quark asymmetries would tend to prefer a heavier Higgs boson

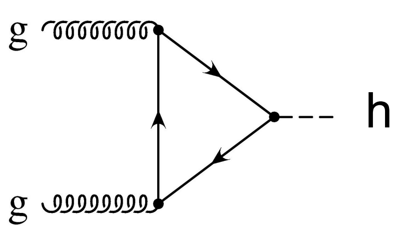


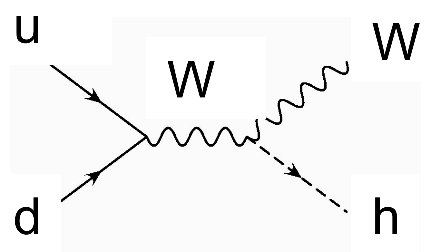
Erler, Langacker
PDG '06

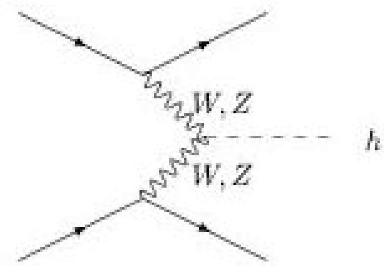
No new Physics at the TeV Scale

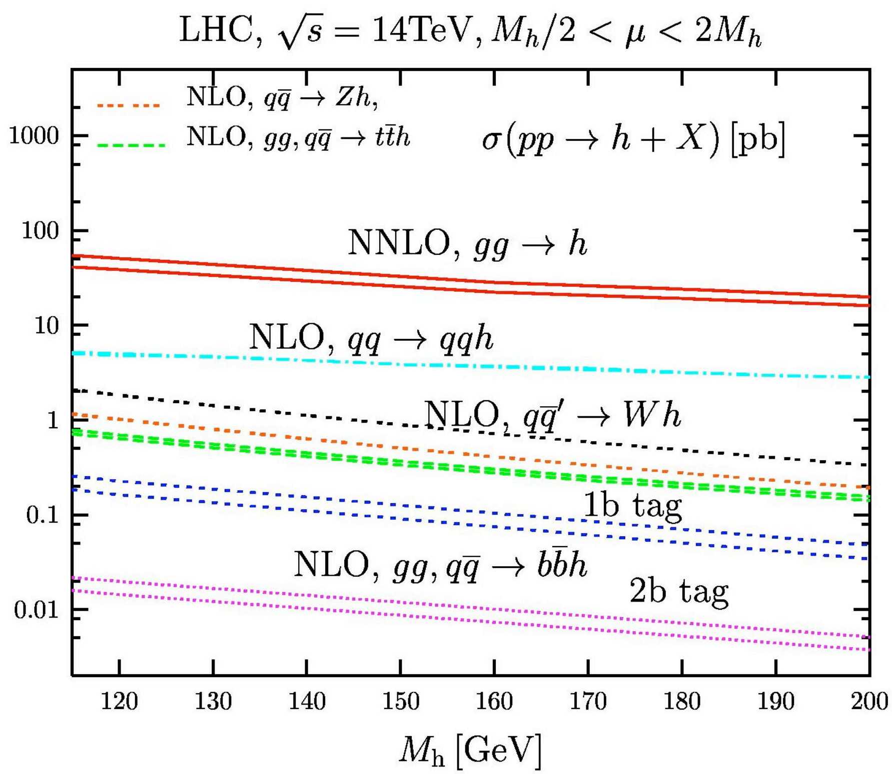
- In this case, the SM provides a good effective theory at the TeV scale, and the Higgs production cross sections and decay widths can be predicted with good accuracy
- The LHC experiments should discover the SM Higgs boson with at most a $\text{few tens of fb}^{-1}$ of data.
- This conclusion relies on the latest NLO computations of Higgs production cross sections, as well as in the latest simulations of the Atlas and CMS experiments
- Needless to say, similar accuracy in the background computations, as well as in the estimate of systematic errors, detector performance and efficiency of experimental techniques would be necessary to solidify these claims

Main Higgs Production Cross Sections

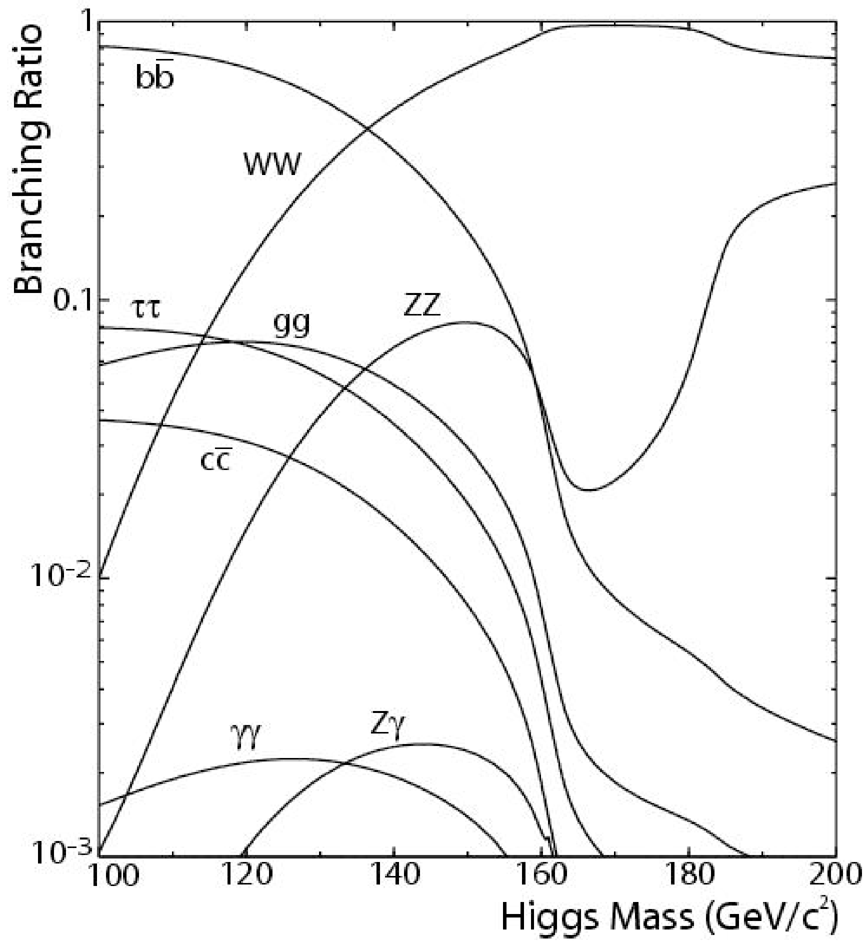






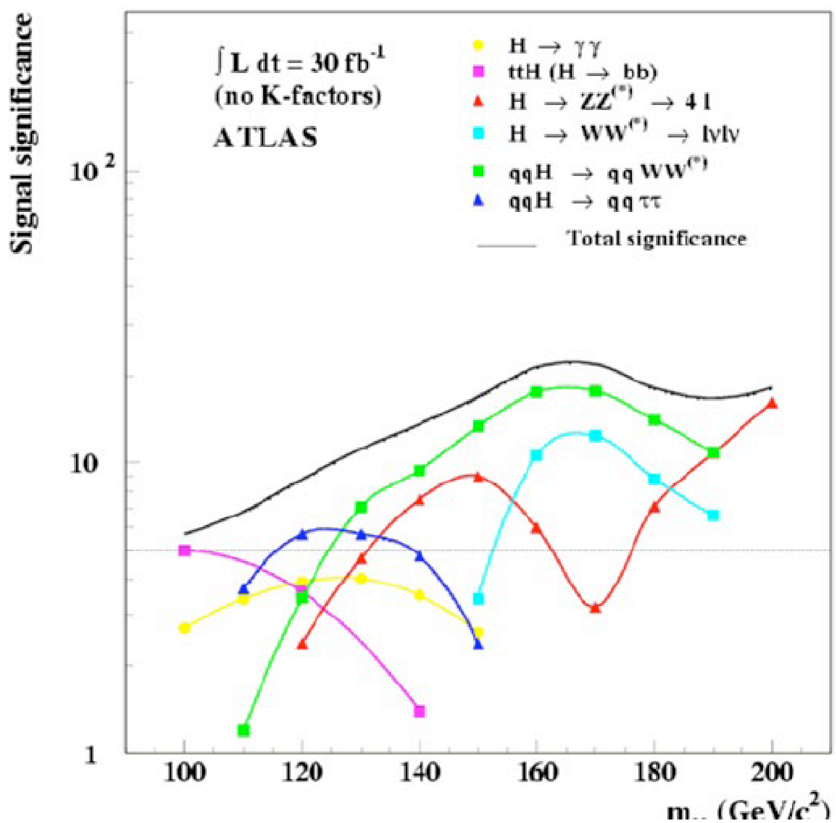


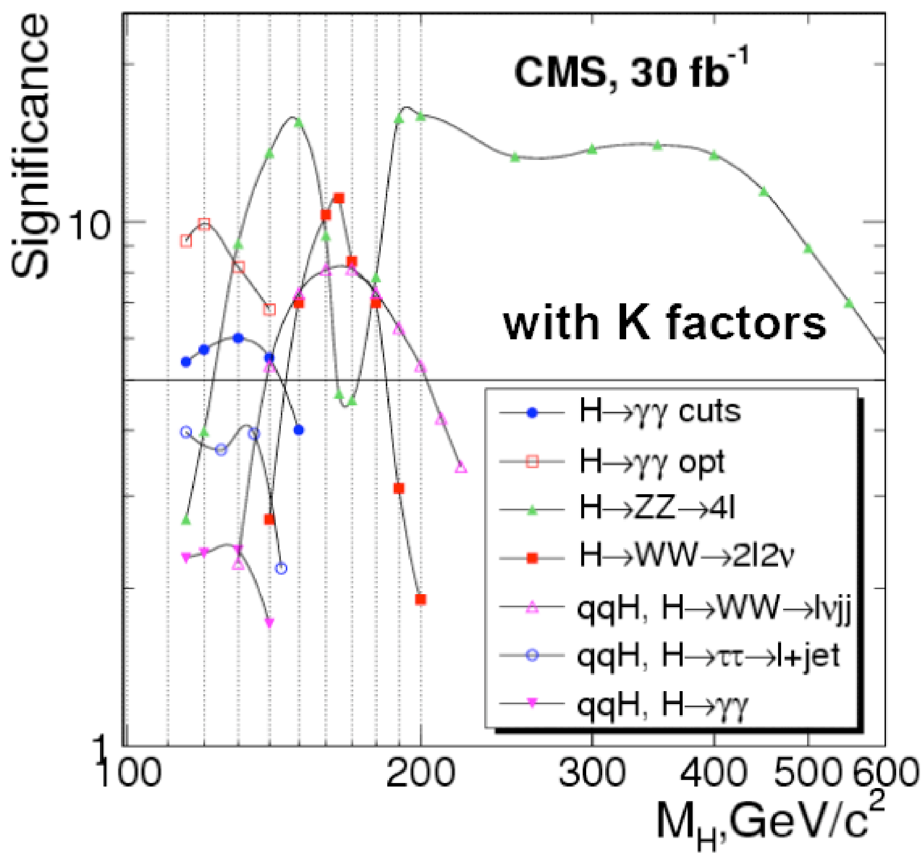
Main SM-Higgs Decay Branching Ratios



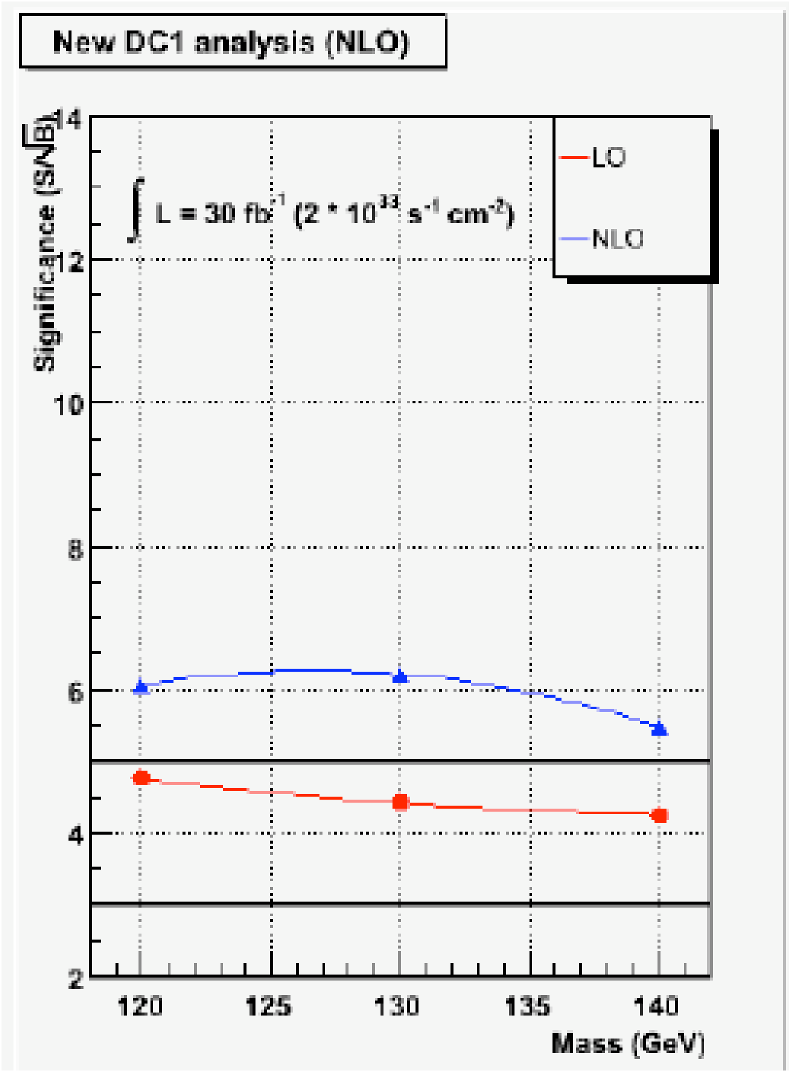
SM-Higgs Discovery Reach of the LHC experiments

Combining different channels ensures the discovery of a SM Higgs in all the allowed range. For a Higgs boson at the edge of LEP bound, weak boson fusion and gamma-gamma channels are most relevant

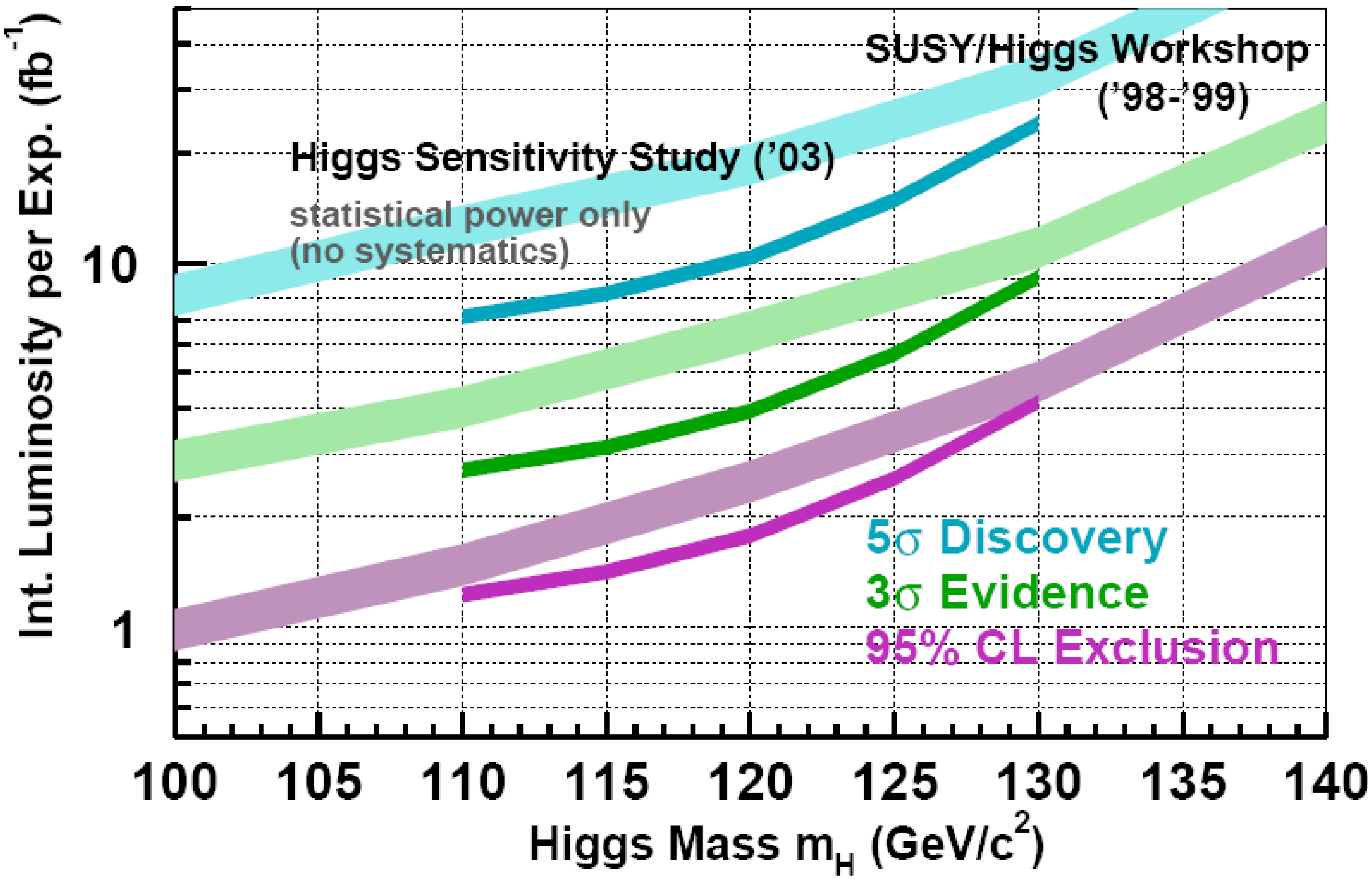




New Atlas Reach in the gamma-gamma channel



Tevatron SM Higgs boson sensitivity



No Higgs signatures at the LHC

- Three possibilities:
- There is no Higgs, or it is a very broad resonance (see S. Chivukula's talk). It would demand new physics at the TeV scale.
- There is a Higgs with SM properties. It is light, but our estimates of the LHC discovery reach are wrong. For instance, gamma background may have been underestimated, or it may prove impossible to tag forward jets may in the way expected. I doubt this is a realistic possibility. It may take longer than expected, but a light Higgs with SM properties will be seen at the LHC.
- There are Higgs bosons responsible for electroweak symmetry breaking, but their production and/or decay properties are highly non-standard. I will mainly concentrate on this case.

Modified Higgs signature at the LHC

- New physics at the weak scale can affect both the production cross section as well as the decay modes
- Of the production channels, those relying on loop effects are the most susceptible of large modifications
- Weak Boson Fusion Production, as well as the Associated Production with Gauge Bosons depend on coupling intimately related to the e.w. symmetry breaking mechanism

$$(\mathcal{D}_\mu H)^\dagger \mathcal{D}_\mu H \to \frac{g^2}{2} W^{+\mu} W^-_\mu \left(v^2 + \sqrt{2} v\, h\right)$$

- Therefore, these production cross sections can only be modified if there are more than one sources of e.w. symmetry breaking, or if the physical Higgs boson mixes with other neutral scalar states, for instance singlets

Higgs Mixing Effects

- Higgs Mixing occurs even in minimal extensions of the Higgs sector, like in the MSSM

- The SM couplings to the gauge bosons may be "shared" by different Higgs particles, which fulfill a sum rule,

$$\sum_i g^2_{VVH_i} = (g^2_{VVH})^{SM}$$

- If no new light particles exist, and all Higgs bosons remain heavy, the effects depend on the quantum numbers and the relative couplings of these Higgs bosons to bottom and tau particles and to the top (which affect the loop-induced decays)

- In the MSSM case, even with CP-violation, large mixings tend to occur naturally only when the masses are close, and there is a complementarity of different channels that makes detection possible in most cases.

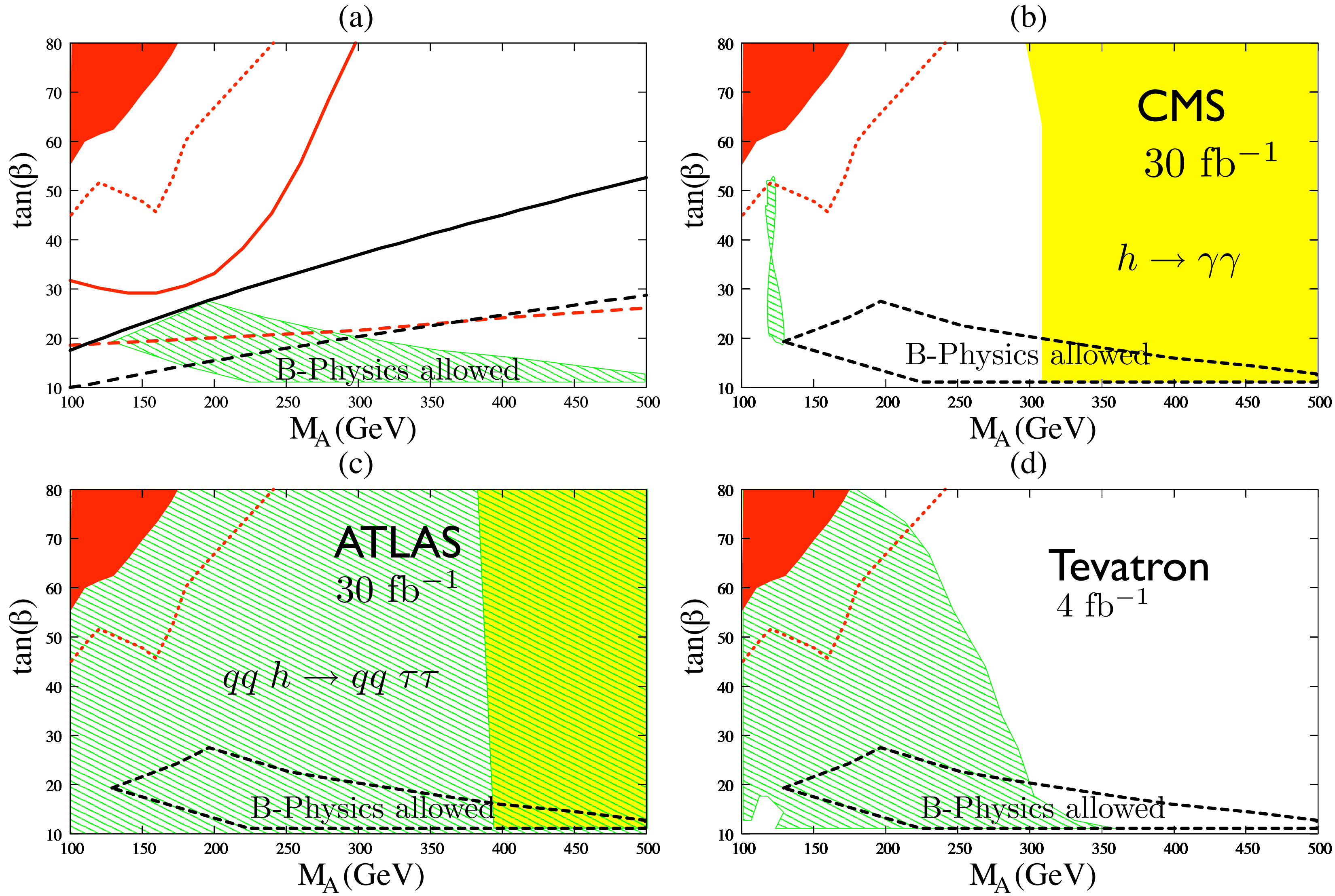
Red: $p\bar{p}, pp \rightarrow H/A \rightarrow \tau^+\tau^-$
with 1 and 4 fb^{-1} at the Tevatron
with 30 fb^{-1} at the LHC

black lines: $BR(B_s \rightarrow \mu^-\mu^+)$ reach:

Tevatron: 2×10^{-8} ($8 fb^{-1}$)

LHC: 5.5×10^{-9} ($10 fb^{-1}$)

Large Maximal Mixing Scenario
$A_t = 2.4\ M_{SUSY},\ \mu = -0.2 M_{SUSY}$



M.C., A. Menon, C.Wagner' 07

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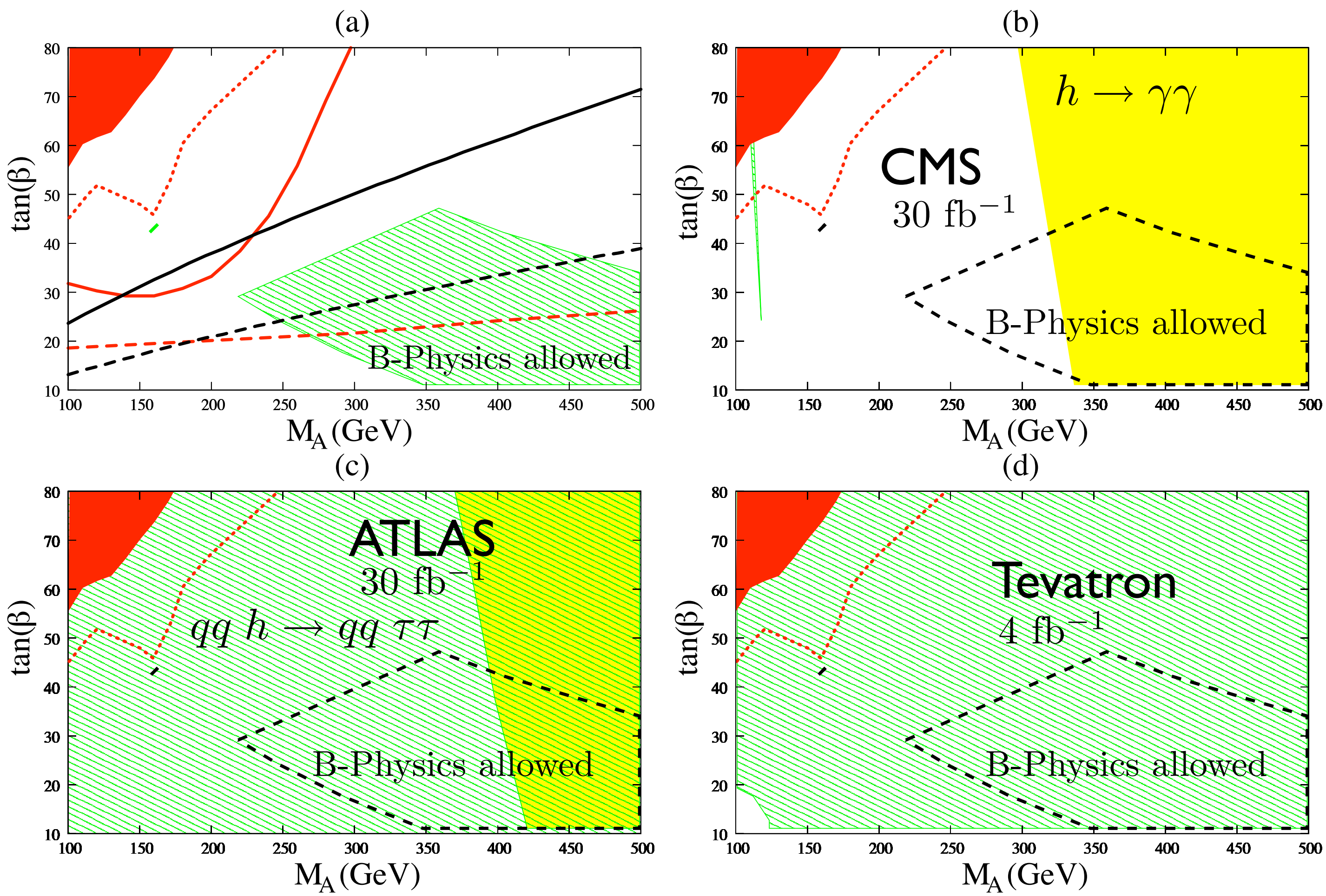
Moderate Mixing Scenario
$A_t = M_{SUSY}$, $\mu = -0.2 M_{SUSY}$



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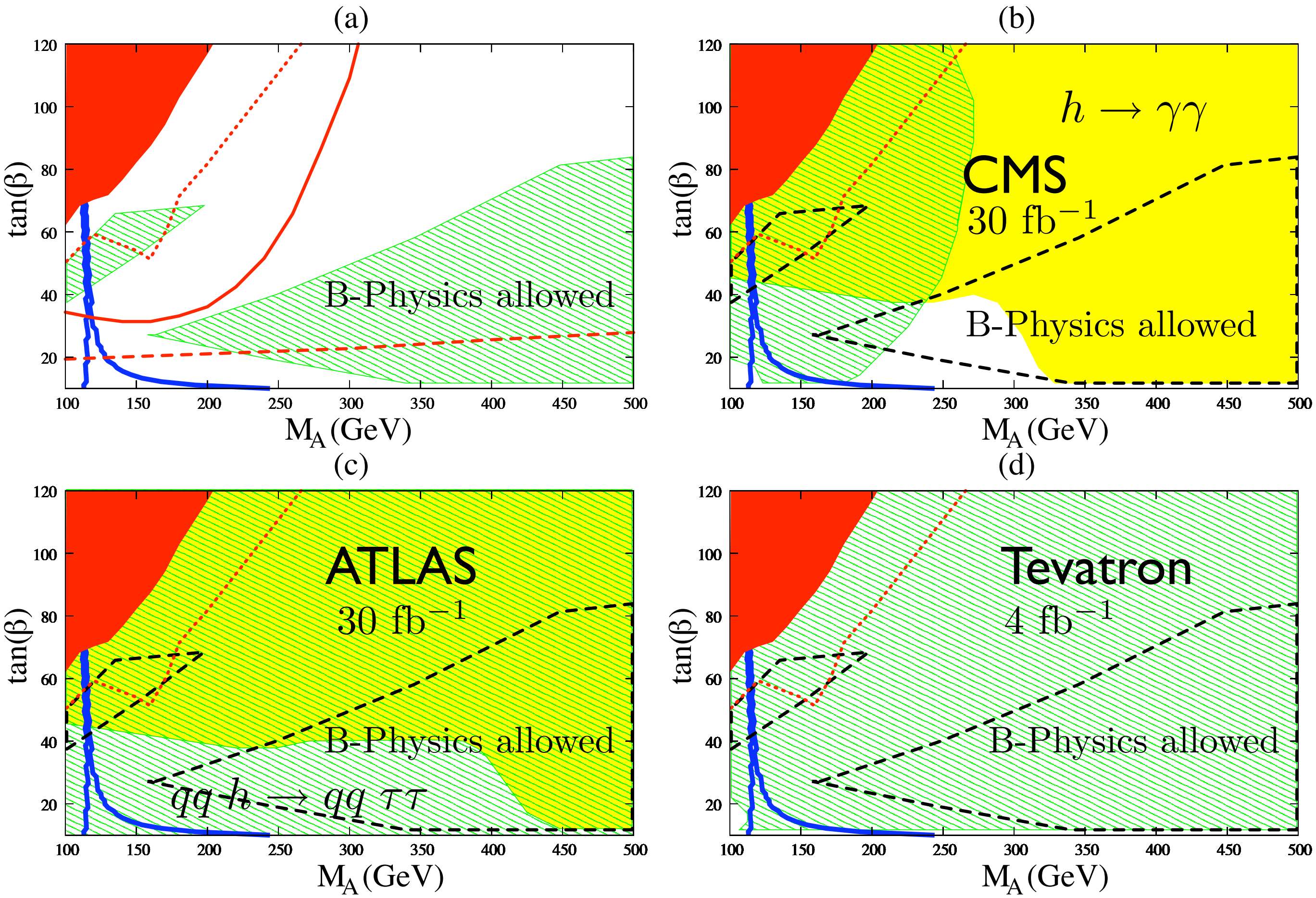
LHC: 5.5×10^{-9} (10 fb^{-1})

Minimal Mixing Scenario
$A_t = 0, \quad \mu = 1.5 M_{SUSY}$
$M_{SUSY} = 2$ TeV



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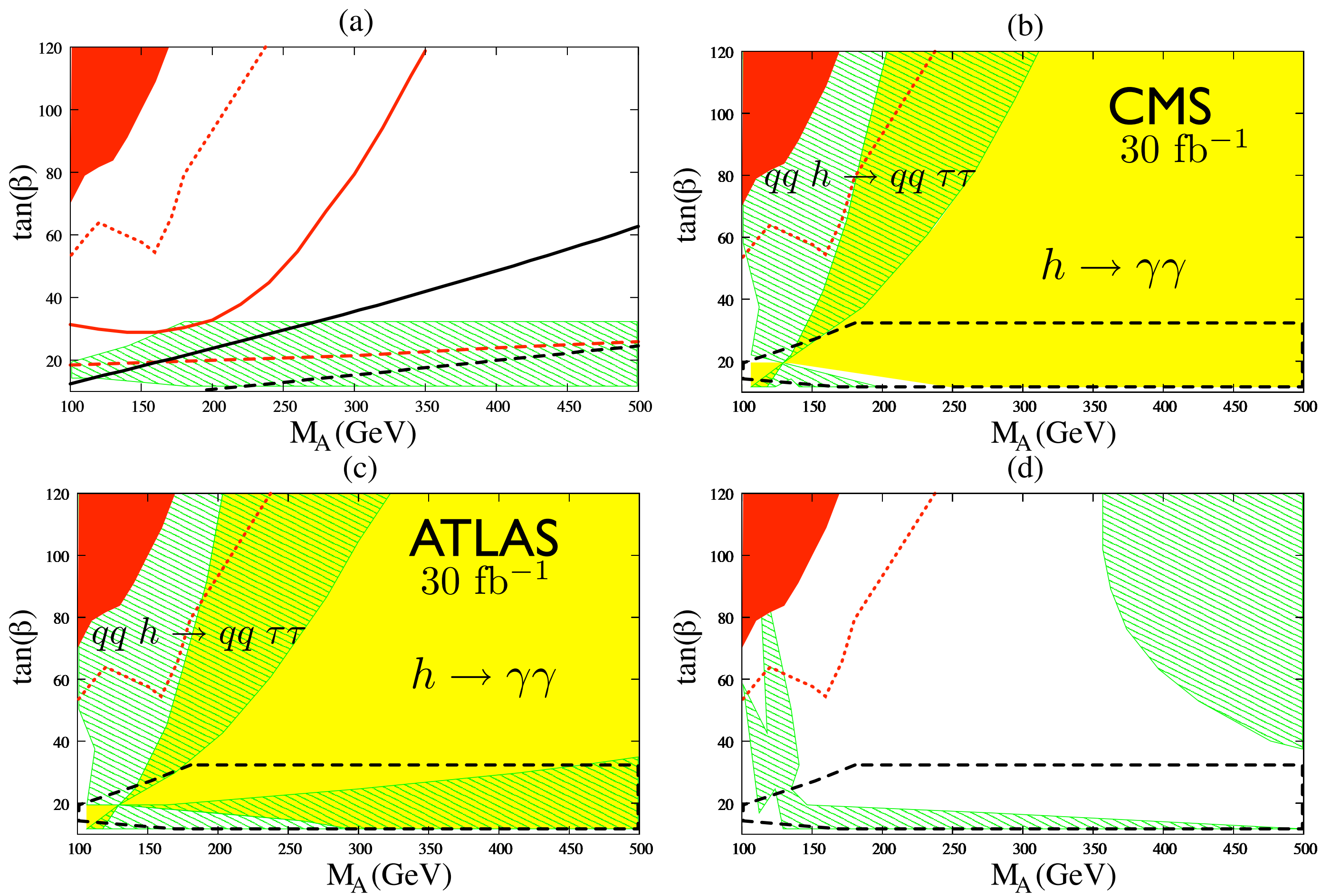
B

Suppression of bottom and tau couplings by mixing effects



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Additional Decay Channels

- A different, perhaps more logical possibility is the fact that there is mainly one Higgs particle responsible for electroweak symmetry breaking, but it decays in unexpected ways
- Again, the unexpected decays could be due to mixing with other Higgs particles, but here I want to explore the possibility that it is due to the presence of new physics, that has avoided detection so far
- This possibility has been explored with frequency lately, in order to avoid the LEP bounds ($m_h > 114$ GeV) and bring the Higgs mass closer to the preferred electroweak precision value and/or avoid the SUSY small hierarchy problem and/or explain small excesses seen at LEP.
- In general, the new decays are associated with a light particle χ

$$h \to \chi\chi$$

and if χ decays in such a way that the LEP bounds are avoided, detectability at the LHC is quite hard.

How likely is this possibility ?

- In the SM, all fundamental particle masses arise from the v.e.v. of the Higgs field

- If the Higgs is lighter than 130 GeV, the dominant SM-Higgs decay width is into bottom quarks, the heaviest of the SM fermions the Higgs can decay into,

$$\Gamma_b \simeq m_H \frac{3h_b^2}{8\pi}$$

- But the bottom Yukawa coupling is quite small, $h_b(m_H) \simeq 1/60$

- Therefore, if there are additional particles, with mass smaller than half of the Higgs mass and non-trivial couplings to the Higgs, they are likely to dominate the Higgs decay width

- If Higgs is heavy, instead, decay width into gauge bosons grows fast and a large modification is less likely,

$$\Gamma(H \to VV) \simeq \frac{G_F(|Q_V|+1)}{\sqrt{2}\,16\pi} m_H^3 \left(1 - \frac{4M_V^2}{m_H^2} + 3\frac{4M_V^4}{m_H^4}\right)\left(1 - \frac{4M_V^2}{m_H^2}\right)^{1/2}$$

Why we did not see these light particles?

- Let us assume that the Higgs is light, with mass smaller than about 130 GeV.
- The new light particles must have weak couplings to the Z-boson to avoid the LEP1 constraints
- They must also have small e.m. charges to avoid LEP2 and lower energy electron-positron collider bounds
- Easiest possibility: A light, neutral, scalar or fermion particle, with a dominant component in a singlet of the electroweak interactions
- If this particle was stable, it would lead to invisible decays of the Higgs (and therefore this Higgs mass must be larger than 114 GeV to satisfy the LEP bounds and it will be detected at the LHC in the weak boson fusion channel)

NMSSM Case

- Higgs spectrum includes three CP-even scalars and two CP-odd scalars
- A light, mainly singlet CP-odd scalar may fulfill all required properties, namely $\chi \equiv a_1$
- If its mass is larger than $2\, m_\tau$ but smaller than $2\, m_b$ dominant decay mode

$$h \to a_1 a_1 \to 4\, \tau' s$$

Dermisek, Gunion
Chang, Fox, Weiner
Graham, Pierce, Wacker

- Such a Higgs may have escaped detection at LEP. Branching ratio of decay into bottom quarks reduced. If of order 0.1 may explain LEP small excess at 100 GeV
- Detectability at the LHC difficult (see Ellwanger et al, **hep-ph/0503203; T.Han et al., in preparation)**
- Possible signal at the Tevatron with 6 fb-1 ? (see Graham et al, **hep-ph/0605162)**

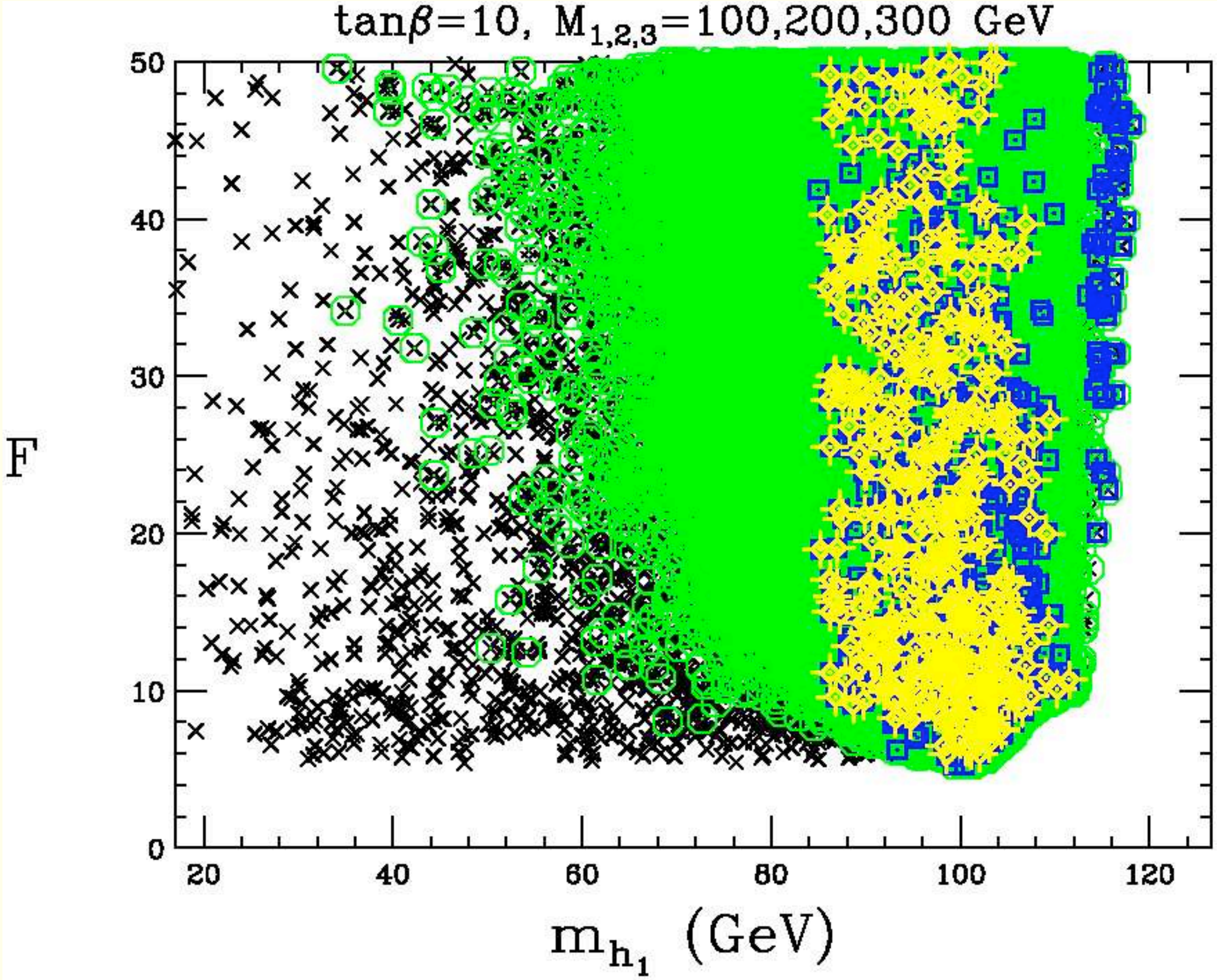


Figure 9: *F vs. m_{h^0} in the NMSSM for $\tan\beta = 10$, $M_{1,2,3}(m_Z) = 100, 200, 300$ GeV. Large yellow crosses are fully consistent with LEP constraints. See earlier Dermisek + JFG refs.*

– **A large majority of the yellow crosses have $B(h_1 \to b\bar{b}) \sim 0.1$ or so**

MSSM with R-Parity Violation

- If χ is a neutralino, which decays mainly into jets, the dominant Higgs decay would be

$$h \to \chi\chi, \quad \chi \to 3 \text{ jets}$$

- Such a Higgs could escape the LEP bounds, and may have a mass of about 100 GeV
- Detectability at the LHC would become virtually impossible due to large backgrounds

L. Carpenter, D.E. Kaplan and E.J. Rhee '06

Can the χ particle be colored ?

- Hadronic cross section constraints are quite strong, and essentially rule out the possibility of an additional light colored fermion, that could couple to the Higgs with renormalizable couplings, since in such a case it should carry electroweak charges (Higgs field is a doublet).
- A singlet, colored fermion, coupled in a relevant way to the Higgs via non-renormalizable interactions remains as a possibility, and it would be interesting to see what are the HERA, Tevatron and LEP constraints on such a light particle.
- Surprisingly enough, a scalar quark, with a charge equal to the down quark and small couplings to the Z is still an available option
- If such a particle exists, it can have relevant coupling to the Higgs boson and dominate its decay modes. If this “down squark” decays into jets, detectability of the Higgs at the LHC will be very difficult

Motivation for a light sbottom

- Light sbottoms were first explored since they were suggested to explain some anomalous CDF heavy flavor signatures (see, for instance, Apollinari et al., **hep-ex/0511053)**

- It was found that for a large range of values of the sbottom mixing, they could evade experimental constraints and be consistent with precision measurements (M. Carena, S. Heinemeyer, C.W. and G. Weiglein '00)

- They were further proposed to explain the discrepancy between the Run I bottom quark cross section and the theoretical predictions. This demanded R-parity violating decays of light sbottoms, with mass of about 5 GeV, plus a gluino with mass of about 10--15 GeV (E. Berger, B. Harris, D.E. Kaplan, Z. Sullivan, T. Tait and C.W. '00)

- Independently of these original motivations, the presence of light sbottoms is still possible. At present, for instance, light sbottoms which decay mainly into jets, may only be excluded if their mass is below 7.5 GeV (P. Janot '04)

Example: A Light sbottom

M. Carena, S. Heinemeyer, C.W. and G. Weiglein '00

- Coupling to the Z

$$g_{Z\tilde{b}\tilde{b}} \simeq (-\frac{sin^2\theta_b}{2} + \frac{\sin^2\theta_W}{3})$$

$$|\tilde{b}_1\rangle = \sin\theta_b|\tilde{b}_L\rangle + \cos\theta_b|\tilde{b}_R\rangle$$

$$\begin{pmatrix} m_{\tilde{Q}}^2 + m_b^2 + D_L & m_b\,[A_b - \mu\tan\beta] \\ m_b\,[A_b - \mu\tan\beta] & m_{\tilde{b}}^2 + m_b^2 + D_R \end{pmatrix}$$

- Hence, the coupling to the Z vanishes at $\sin\theta_b \simeq 1/6$, with

$$\sin 2\theta_b = \frac{2m_b(A_b - \mu\tan\beta)}{m_{\tilde{b}_1}^2 - m_{\tilde{b}_2}^2}$$

- Couplings to the Higgs dictated by these parameters,

$$g_{h\tilde{b}\tilde{b}^*} \simeq \frac{g\;\mu\;m_b(m_h)\tan\beta}{2m_W(1+\Delta_b)}\sin 2\theta_b$$

Higgs Decay Widths

$$\frac{\Gamma_{\tilde{b}}}{\Gamma_b} = \frac{(\mu \tan\beta)^2}{2m_h^2} \sin^2 2\theta_b \left(1 - 4\frac{m_{\tilde{b}}^2}{m_h^2}\right)^{\frac{1}{2}}.$$

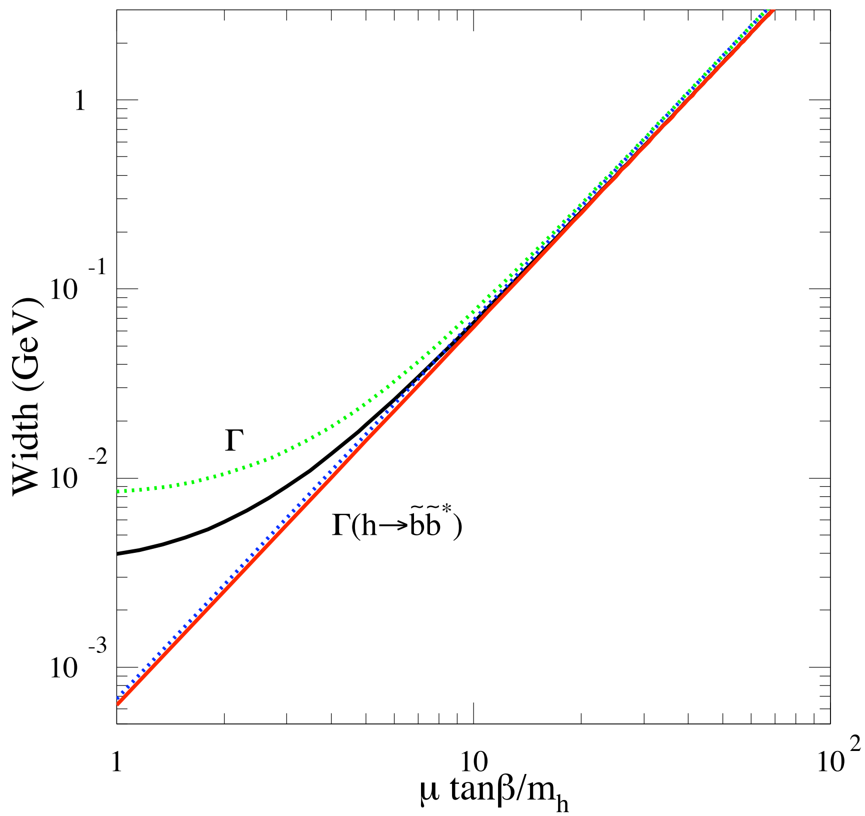


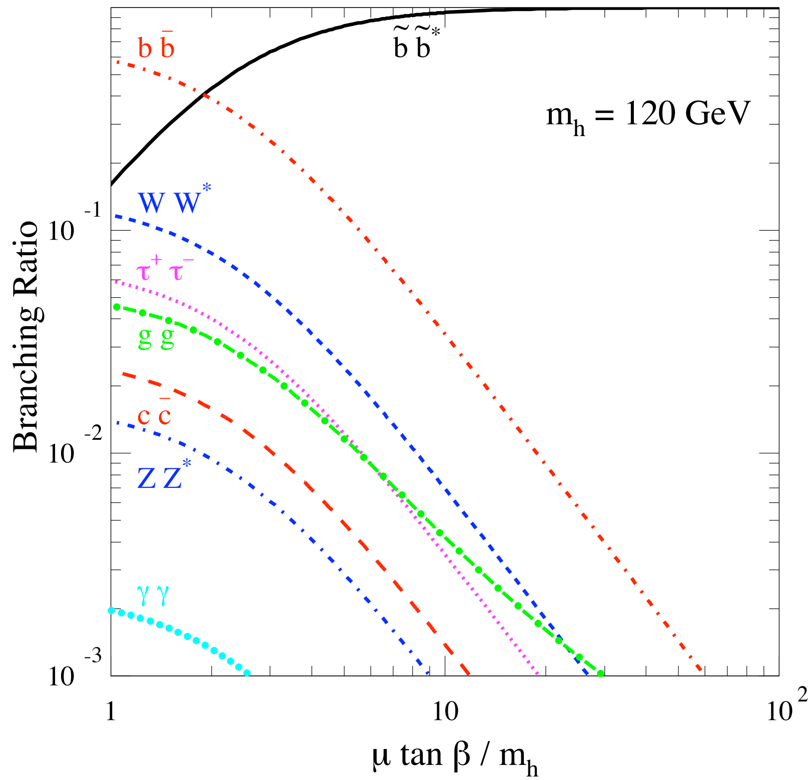
FIG. 4: *Total width of the Higgs boson and the partial width into a pair of bottom squarks as a function of the ratio* $\mu \tan\beta/m_h$, *with* $m_h = 120$ *GeV and* $m_h = 140$ *GeV. We take* $m_h \gg m_{\tilde{b}}$ *For each pair of curves, the solid represents* $m_h = 120$ *GeV and the dotted* $m_h = 140$ *GeV.*

Higgs Decay Branching Ratios

	BR $\times 10^2$							
m_h	120 GeV				140 GeV			
$\mu \tan\beta / m_h$	SM	10	20	50	SM	10	20	50
$\tilde{b}\tilde{b}^*$	0	94.9	98.6	99.7	0	90.3	97.3	99.5
$b\bar{b}$	69	3.4	0.89	0.14	34	3.3	0.88	0.14
WW^*	14	0.69	0.18	0.029	51	4.9	1.3	0.21
ZZ^*	1.66	0.082	0.021	0.003	6.3	0.60	0.16	0.027
$\tau^+\tau^-$	7.1	0.35	0.091	0.015	3.6	0.34	0.093	0.015
gg	5.2	0.42	0.16	0.061	3.5	0.51	0.19	0.069
$c\bar{c}$	2.8	0.14	0.036	0.006	1.4	0.13	0.036	0.006
$\gamma\gamma$	0.24	0.011	0.003	0.0004	0.20	0.019	0.005	0.0007
Γ_{total} (MeV)	3.3	67	257	1585	7.8	82	303	1850

TABLE I: Branching ratios and total widths of the Higgs boson for masses of 120 and 140 GeV and $\mu \tan\beta / m_h = 10, 20, 50$. We fix $m_{\tilde{b}} = 5$ GeV in obtaining these values.

Higgs Decay Branching Ratios



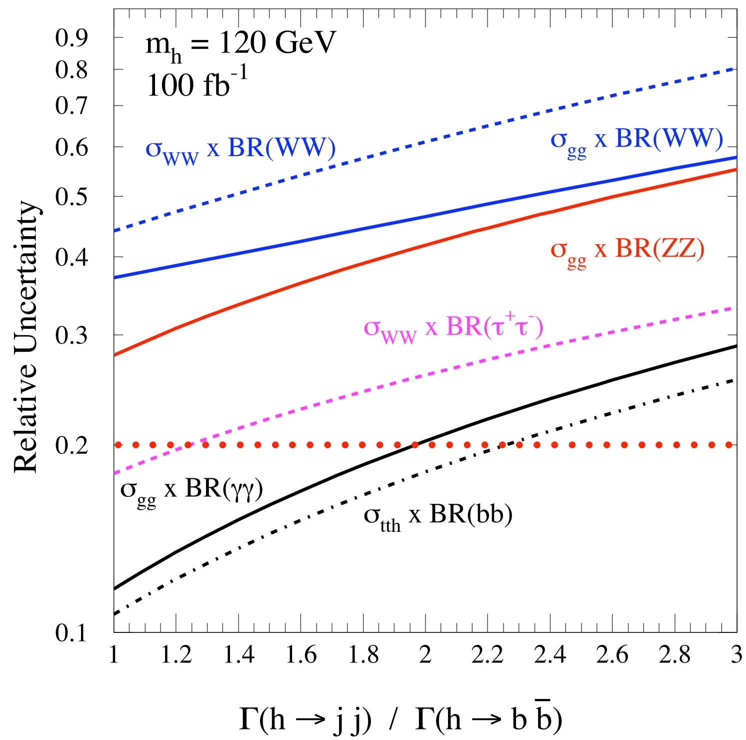
For $\mu \tan\beta / m_h > 10$, Branching ratio of Higgs decay into SM particles becomes negligible

LHC Higgs Discovery reach

- General Conclusion of our study was that once the Higgs sbottom decay channel width was larger than a few times the bottom one, detectability at the LHC became impossible
- So, in this case Higgs could be there and it will not be detected at the LHC
- Detection of the Higgs will only be possible at a future linear collider ILC
- Detection of the Higgs may be done by studying the recoil of the Z gauge boson, its associated production with gauge bosons, as well as its weak boson fusion production.
- Using these methods, the couplings of the Higgs to gauge bosons and jets may be determined

LHC Higgs couplings determination

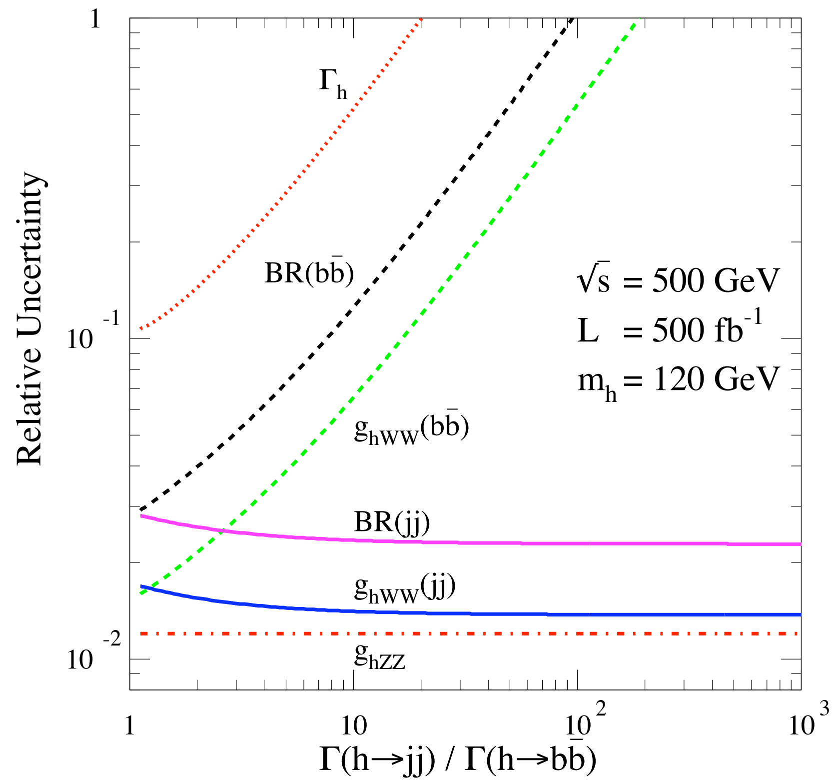
- $gg \to h$, with $h \to \gamma\gamma$, $h \to W^+W^-$, or $h \to ZZ$;
- $t\bar{t}h$, with $h \to b\bar{b}$ or $h \to \gamma\gamma$;
- $W^+W^-(ZZ) \to h$, with $h \to W^+W^-$, $h \to \gamma\gamma$, or $h \to \tau^+\tau^-$.



E. L. Berger, C. W. Chiang, J. Jiang, T. M. Tait and C. E. M. Wagner '02

ILC Higgs couplings determination

ILC will provide precise measurements of Higgs properties



E. L. Berger, C. W. Chiang, J. Jiang, T. M. Tait and C. E. M. Wagner **'02**

Conclusions

- Consistency of the SM at the quantum level requires the presence of a light Higgs particle, which will be probed by the Tevatron and certainly detected at the LHC
- New physics, however, can affect the Higgs production and decay properties, making Higgs detection at the LHC difficult
- Heavy Higgs decay will be dominated by gauge bosons and will be more susceptible to mixing effects or to high multiplicity particles with strong coupling to the Higgs
- Light Higgs decay properties are easily modified by the presence of new particles. In this talk, we have explored a few of such cases
- In these cases, the ILC will be essential to discover the Higgs boson and understand the mechanism of electroweak symmetry breaking

Additional Slides