Higgs search at LHC

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Outline

- **Standard Model Higgs Boson:**
  - discovery channels at LHC over the Higgs mass range.

    Discussion on the main channels in each Higgs mass region. Overall view of the statistical significance for the discovery as a function of M_H
  - SM Higgs parameters measurement: determining the Higgs sector after the discovery

- **MSSM Higgs:**
  - discovery perspectives for the LHC experiments

All the results assume full operative detector (full detector installed, final performances in terms of alignment, calibration, etc.)

SM Higgs boson - Introduction

- The Higgs boson mass is not predicted by the theory. Both theoretical and experimental limits exist

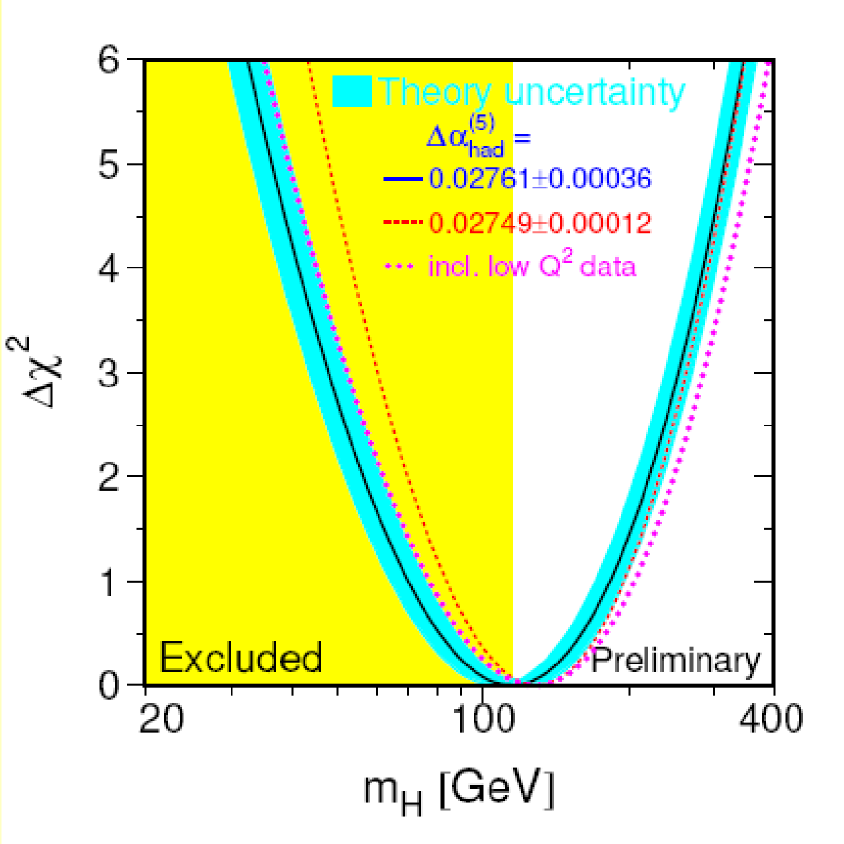
From direct LEP search:

$M_H > 114.4$ GeV

From the Electroweak fit of the standard model

$M_H < 260$ GeV

$M_H > 1$ TeV is theoretically forbidden

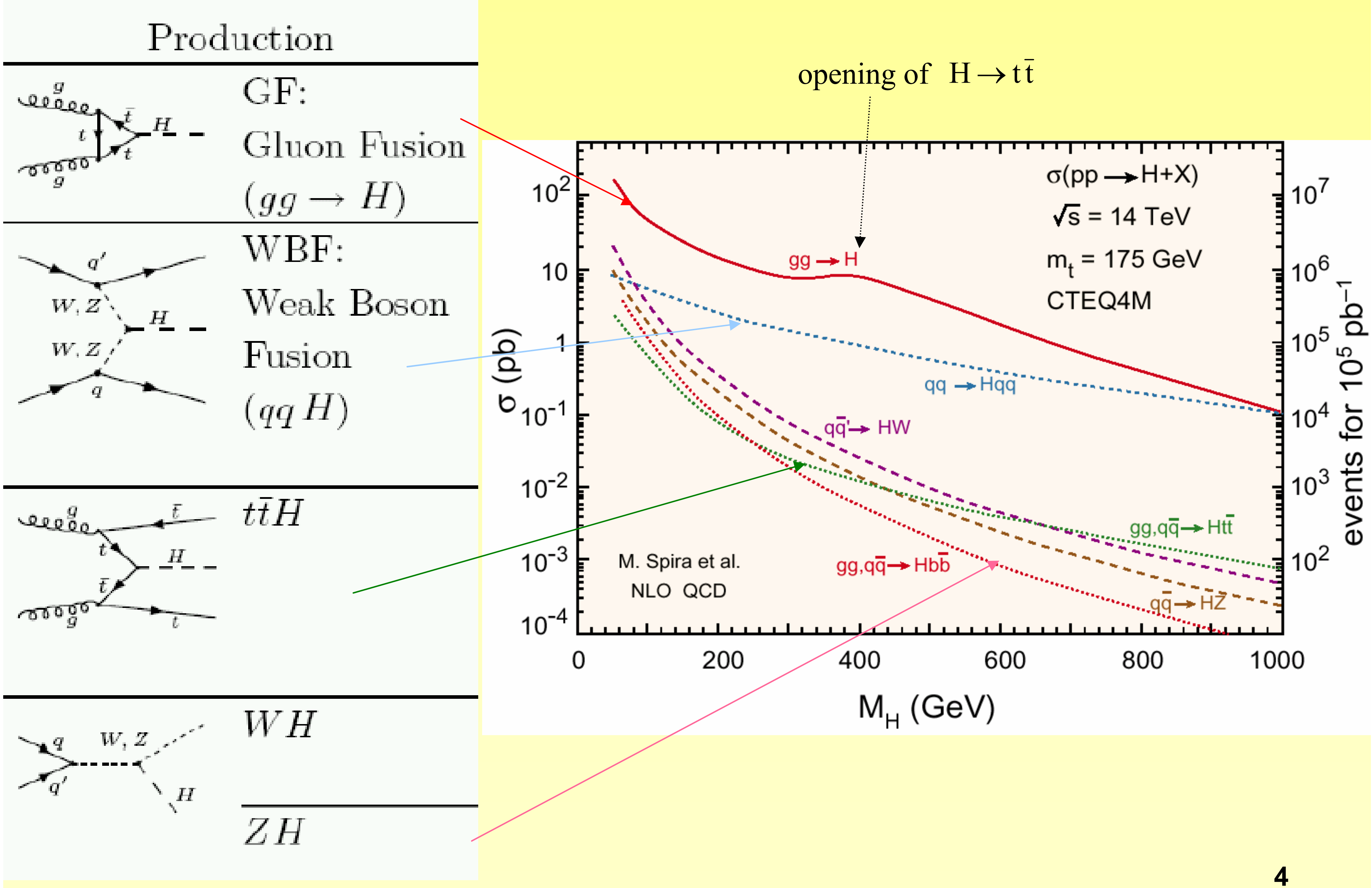


The LHC experiments have to cover

from the LEP limit up to

few 100 GeV ... the TeV scale

Production mechanisms & cross-sections

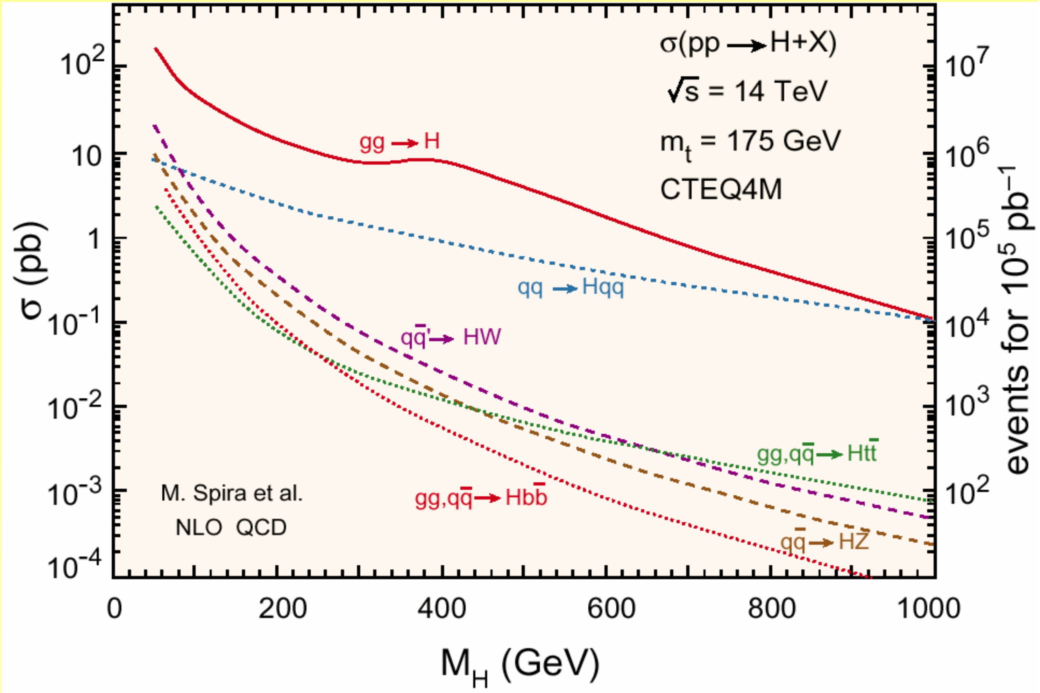


Cross sections…

Higgs production cross sections available at NLO.

Gluon fusion is the dominant production channel

Vector Boson Fusion (VBF) in the following is the second production channel over the whole mass range



VBF is characterized by energetic jets in the forward region and by lack of hadronic activity in the central region

Though less important in terms of absolute cross section values, associated productions (ttH,WH), provide distinctive signatures. Relevant for largely background dominated decay channels, e.g. bb

… and Branching Ratios

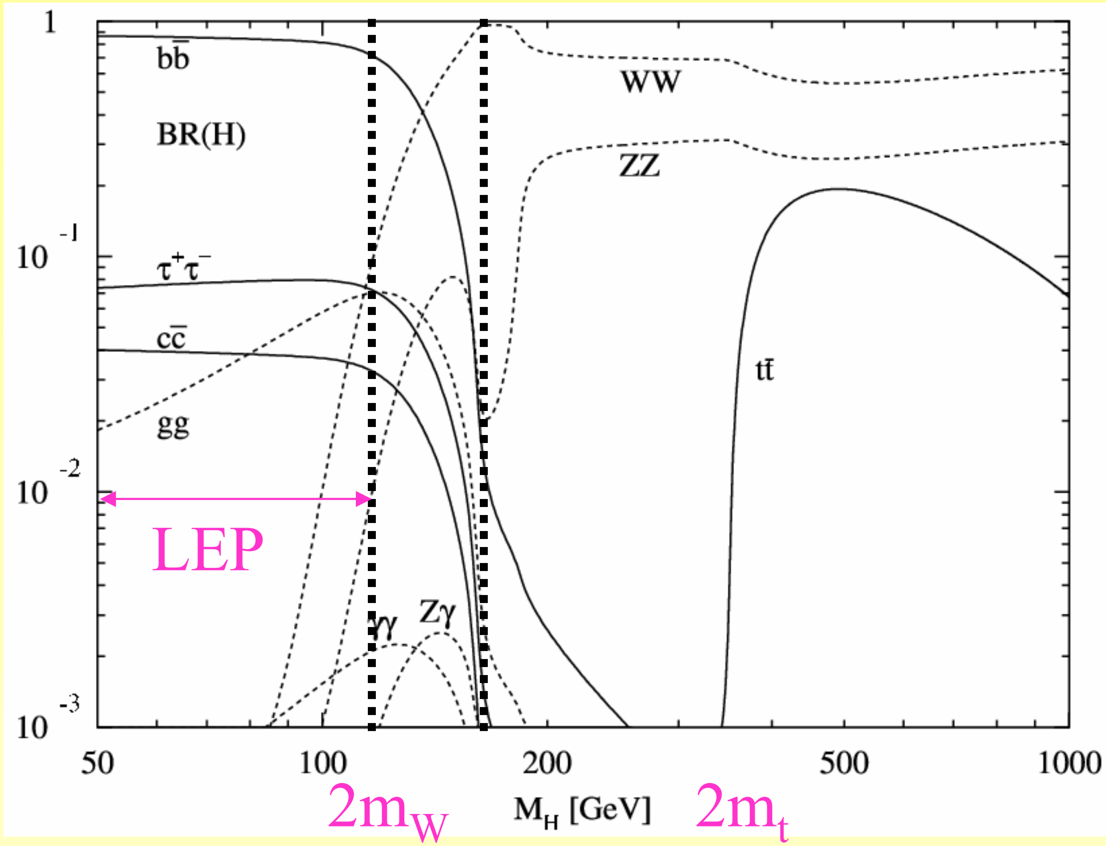
Decays into third generation down-type fermions largely dominating at low mass (M_H < 130 GeV)

H→bb decay detection feasible only if the associated production ttH is considered.

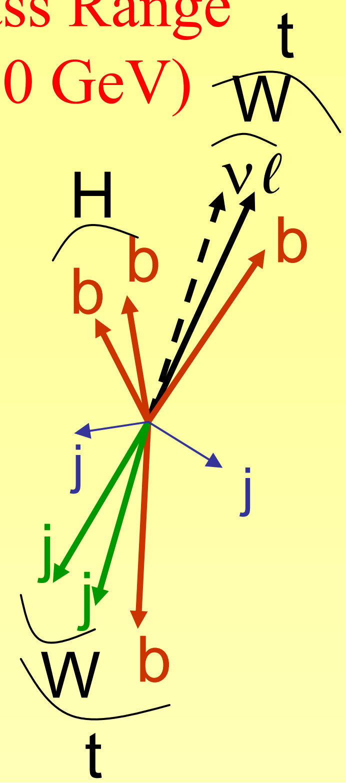
H→γγ suppressed, but it provides a very clear signature.

Higgs decay into tau pairs important if VBF production is considered

Vector Boson decays important at large M_H and in the intermediate mass region



Low Mass Range (until 120 GeV)



$t\bar{t}H(\rightarrow b\bar{b})$

- $\sigma(pp \rightarrow \bar{t}tH_{120})xBr(H \rightarrow \bar{b}b) \sim 0.36$ pb
- $t\bar{t}b\bar{b}$: 9.5 pb, $\bar{t}t$+jj (≥ 6 jets) ~60 pb

Tag the top quark to reject background

1) t→W(→μν)b (lepton for the trigger)

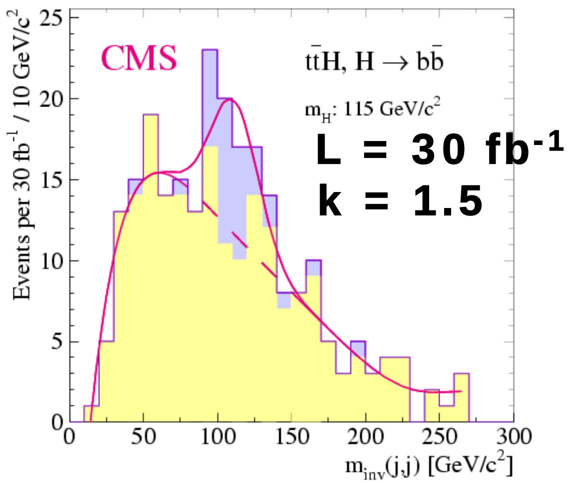
2) t→W(→jj)b

-6 jets

-need good b-tagging to reduce combinatorics

-pairing likelihood w/ 6 variables→best combination

$$\Delta = (m_{\ell vb} - m_{top})^2 + (m_{jjb} - m_{top})^2$$



Reducible background: tt+jets,W+jets production

Irreducible background: ttbb production

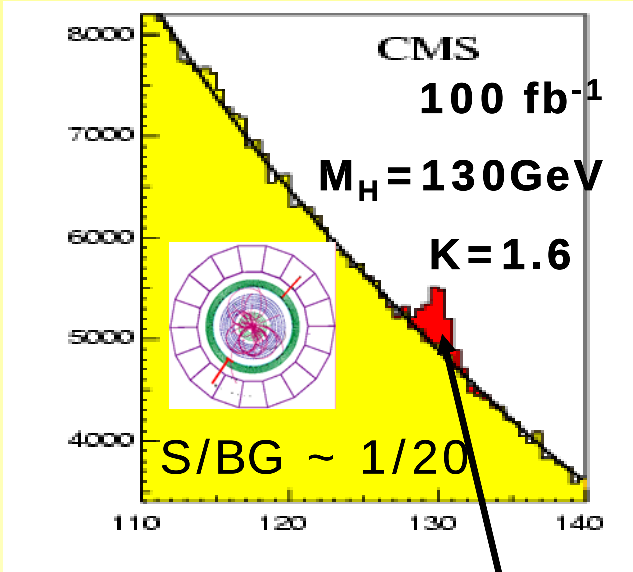
CMS applies KttH=1.5 → S/√B = 5.3

ATLAS (no K,ttbb at ME,CTEQ5L)→ S/√B = 2.8

Higgs decay into γγ

The Higgs decay into γγ is a challenge for the EM calorimeters.

Key points: calorimeter resolution (and linearity), id of photons vs rejection against π_0



Calorimeter segmentation is critical to reject jets. For ~80% efficiency, the jet rejection factor is 1000 to 4000, depending on the E_T

Dedicated algorithm for the recovery of photon conversion (~1/3) in the material in front of the EM calorimeter

Main backgrounds: irreducible γγ dominant. γj and jj together are half the irreducible background

Higgs decay into ZZ

Final states investigated: 2e2μ, 4μ, 4e

Irreducible background coming from direct ZZ production

Reducible background coming mainly from tt,Zbb

The reducible background are strongly reduced by isolation criteria on the leptons and by b-veto

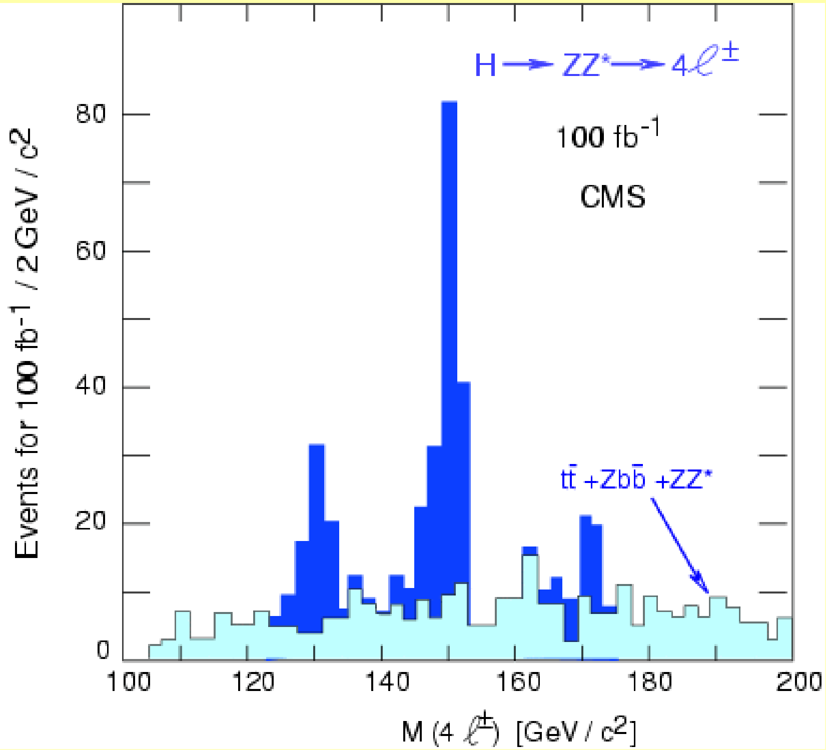
The channel is useful for the Higgs discovery in the ranges

130 GeV < M_H < 150 GeV

and

180 GeV < M_H < 600 GeV

(H→WW is opened at ~160 GeV)

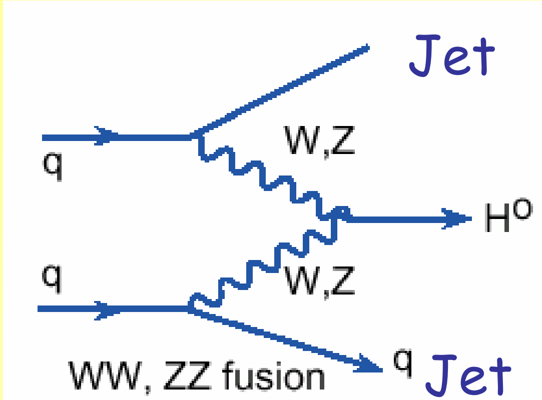


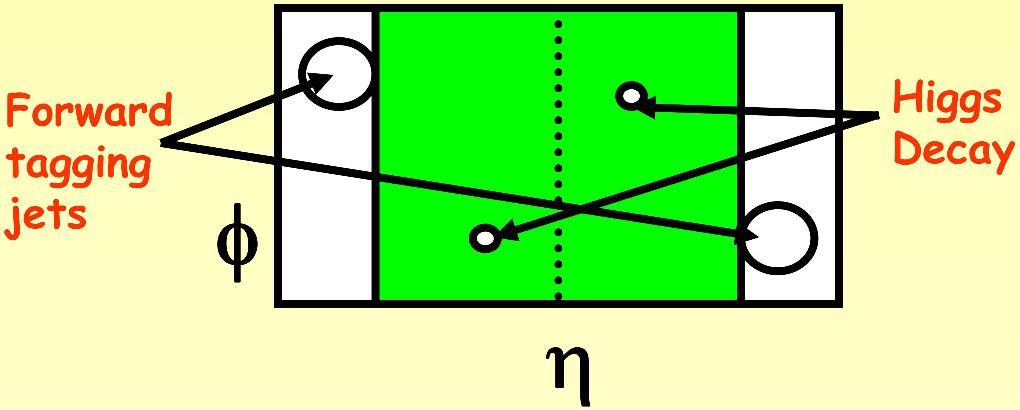
Vector Boson Fusion

During the last years a lot of work has been put on the VBF production channels.

One expects two hard jets in the forward and backward regions of the detector → forward jet tagging

Lack of color exchange between partons in the initial state → reduced hadronic activity in the central region → central jet veto (pile-up effect critical)





Extremely useful for Higgs discovery in the low and intermediate mass region

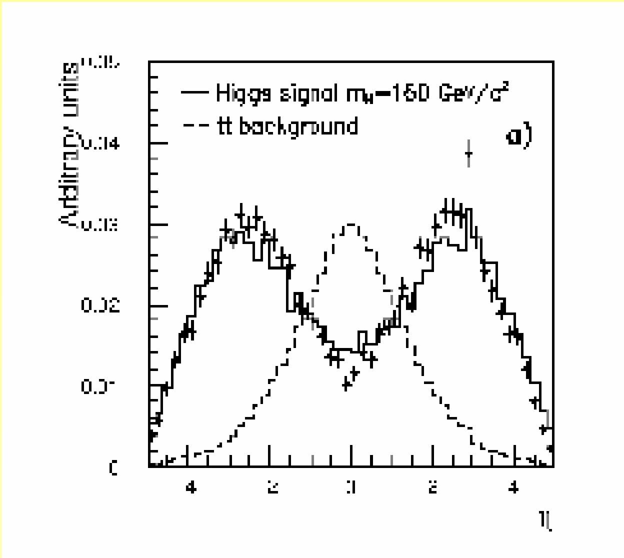
It can be used for several Higgs decay channel →useful to measure Higgs coupling

Vector Boson Fusion (2)

Implementation of fwd jet tagging and jet veto algorithms:

•Associated jets are "forward". They are well separated in pseudorapidity

•Veto any jet in the central region (except decay products of the Higgs)



Forward jets are the "signature" of VBF

Central jet veto effective for QCD background rejections, in particular against the inclusive tt production, which is a common background for all the VBF channels

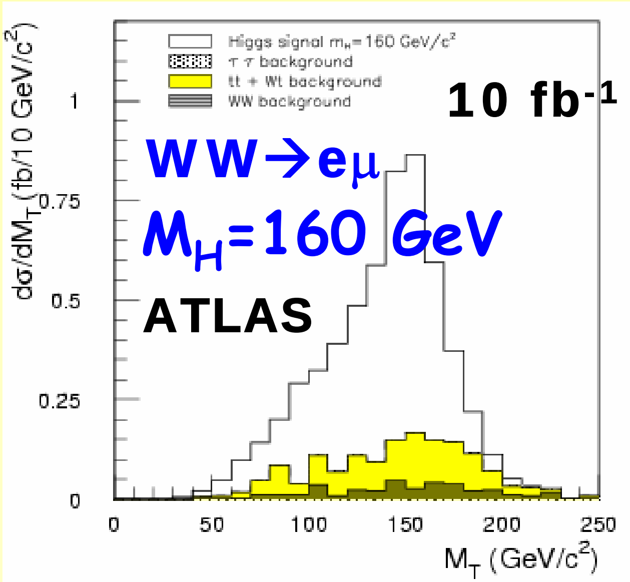
VBF H→WW

The best results are obtained if the leptonic decay is considered for both the Ws.

Dominant backgrounds come from tt production (reduced by the central jet veto and b-jet veto), WW production

Selection includes fwd tagging, central and b jet veto, spin correlations between leptons

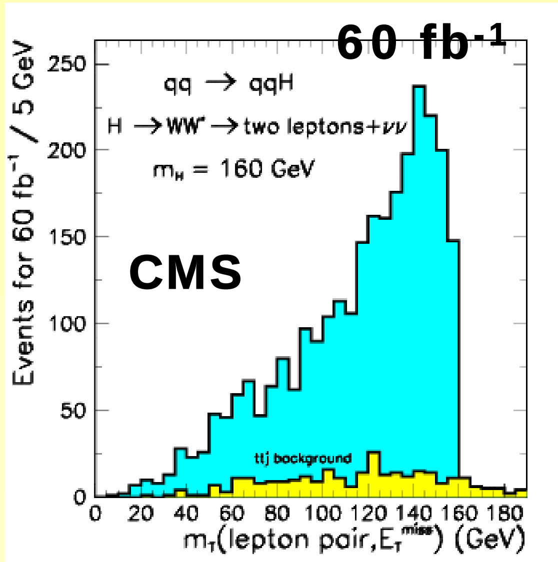
Careful study on the bakground systematics due to generator uncertainties → most of the multijet final states generated with ME generators. There are preliminary results for NLO tt calculation.



The normalization of the background value can be estimated at 10% level from data. Background shape taken from MC

The channel is one of the most promising for

135 GeV < M_H <190 GeV



VBF H→ττ

Investigated both in the $\ell\ell E_T^{miss}$ and in the $\ell j E_T^{miss}$ channel

ATLAS: it provides the cleanest signal for the discovery in the low mass range (M_H< 140-150 GeV)

CMS: useful complementary tool to the H→γγ channel

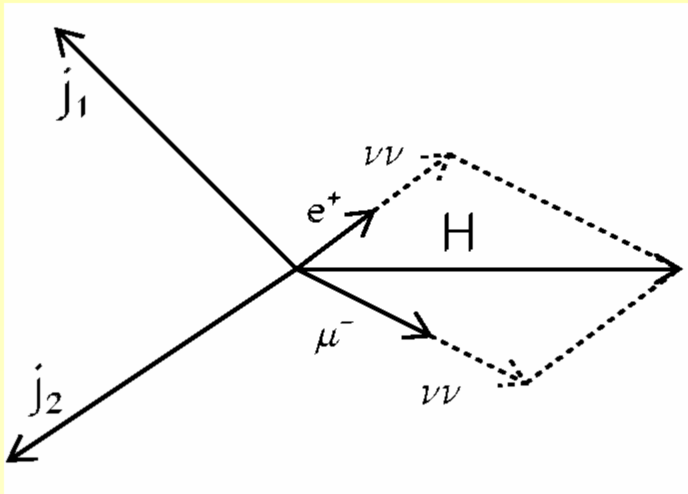
The difference relies on the difference in calorimeter and muon spectrometer design

Main backgrounds: Z+nj, tt, W+nj (hadronic decay of one of the two τ)

The Higgs mass can be completely reconstructed using the collinear approximation for the τ decay.

Defining: $$x_i = \frac{P_{l_i}}{P_{l_i} + P_i^{miss}}$$

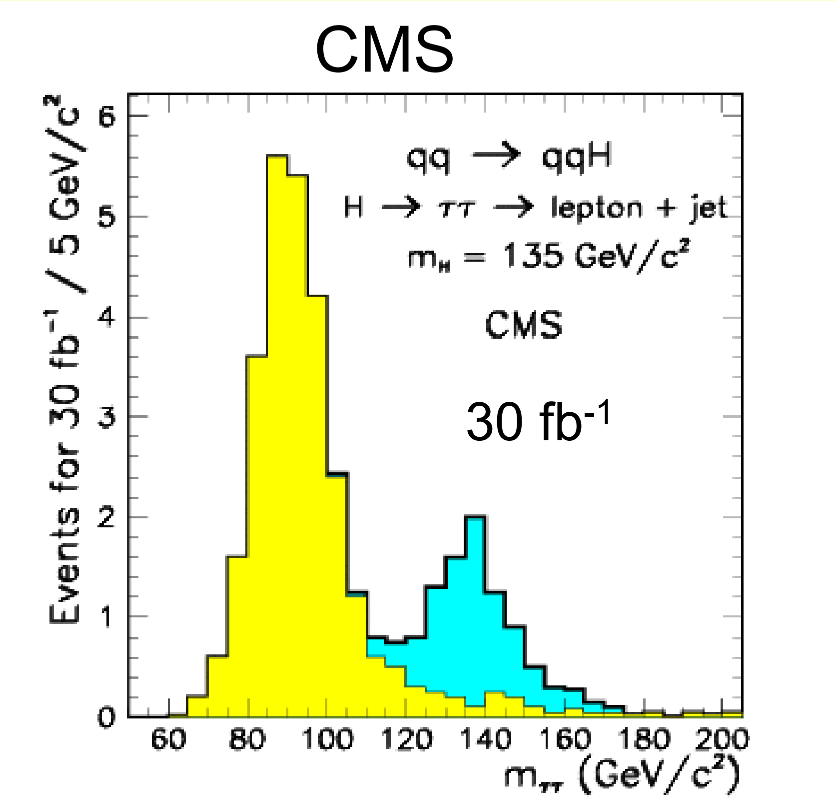
It can be shown that $$m_{\tau\tau} = \frac{m_{ll}}{\sqrt{x_1 x_2}}$$

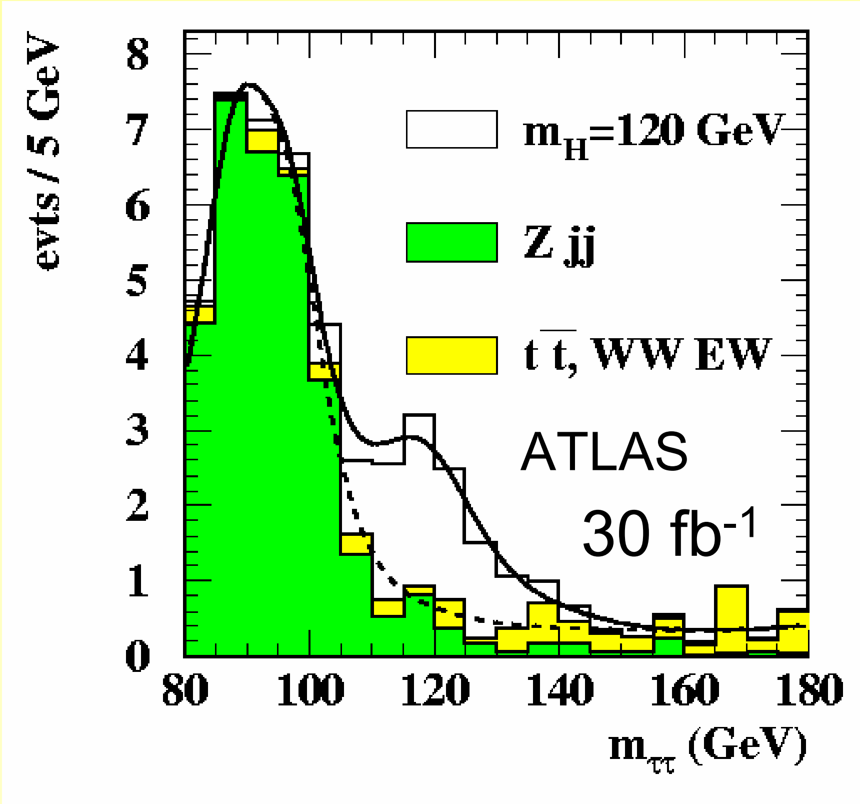


VBF H→ττ(2)

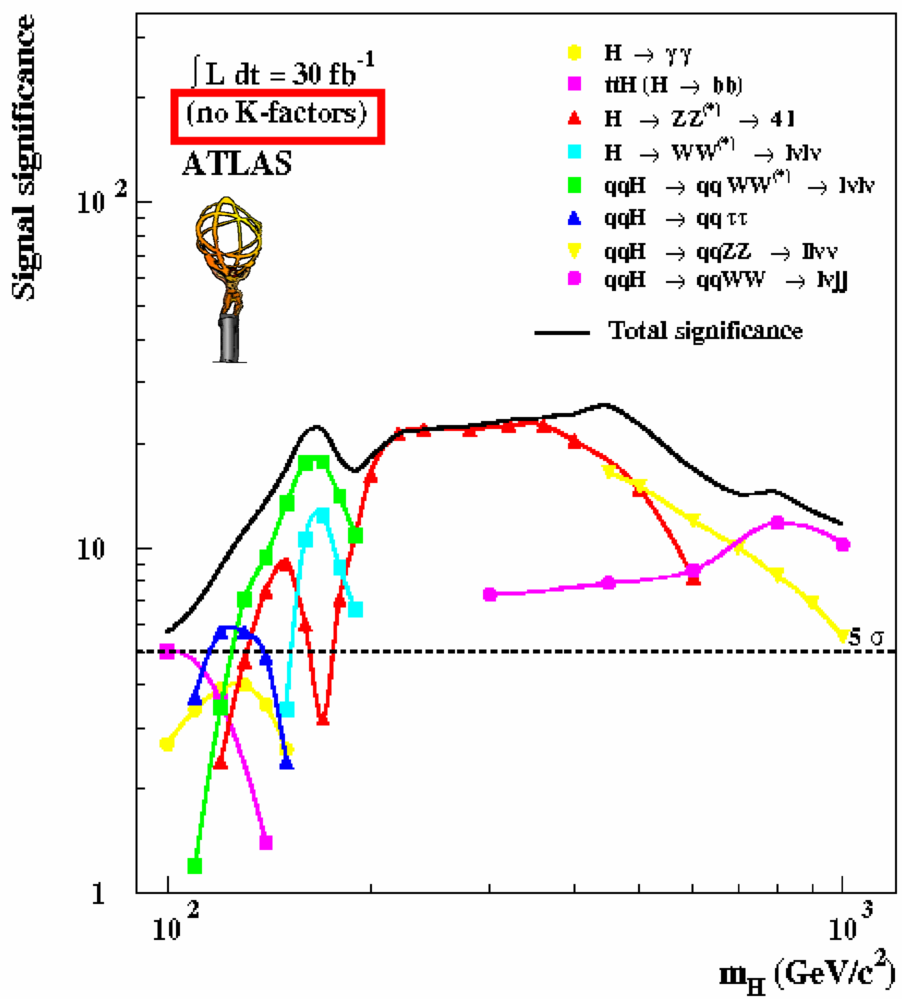
Statistical significance (Poisson statistics) above 5 for 30 fb^{-1} if 110 GeV<M_H<140 GeV

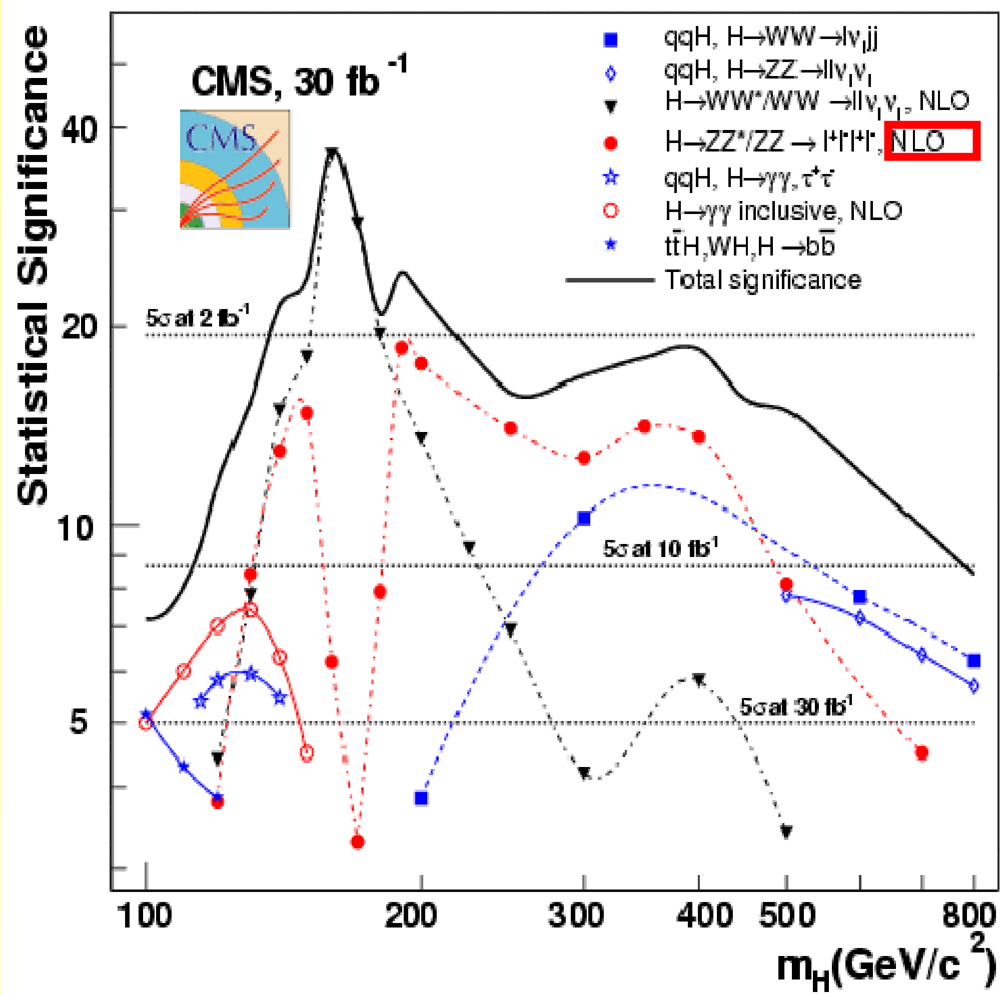
Background normalization control at 10% level from the expected Z→ττ peak and from the high sideband





SM Discovery potential





Almost all allowed mass range explored in 1st year (10 fb^{-1}) for ATLAS-CMS

With 30 fb^{-1}, more than 7 σ for the whole range (provided systematics on the background are under control)

Low mass region is the most difficult: combination of different channels, all channels put strong requirements on detector

Determination of Higgs parameters

Once the Higgs boson would be discovered, we want to measure its parameters (mass, spin, partial widths, coupling constants)

Most of the coupling measurements will be possible because in the whole Higss mass range more than one decay is accessible at one time

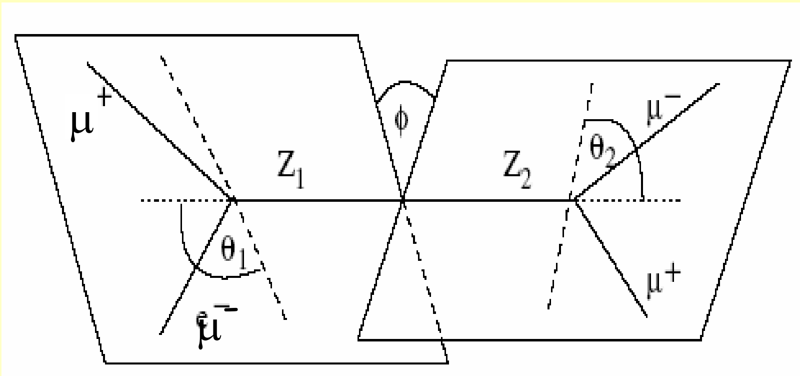
Spin determination examples:

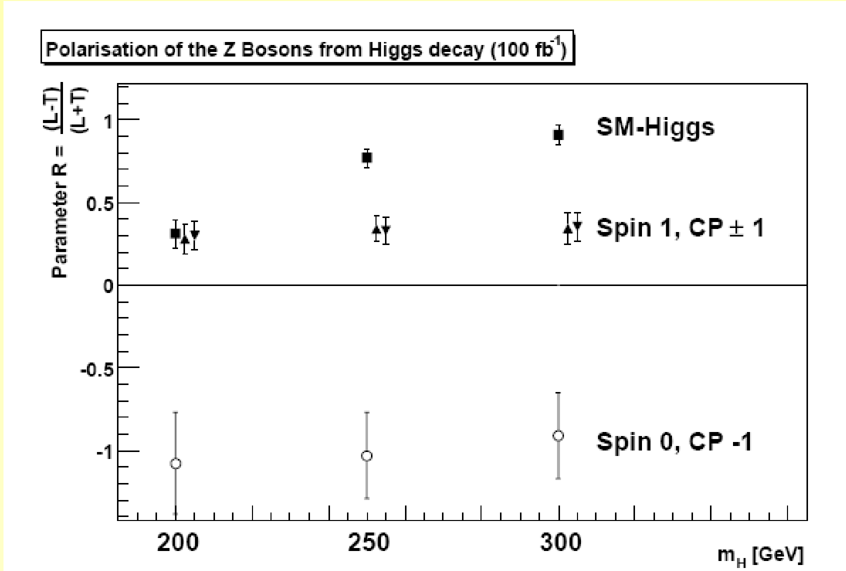
•spin 1 ruled out if H→$\gamma\gamma$ or gg→H is observed

• H→ZZ: angular distributions provide information on the spin

$$G(\theta) = T(1+\cos^2\theta) + L\sin^2\theta$$

$$R = \frac{L-T}{L+T}$$

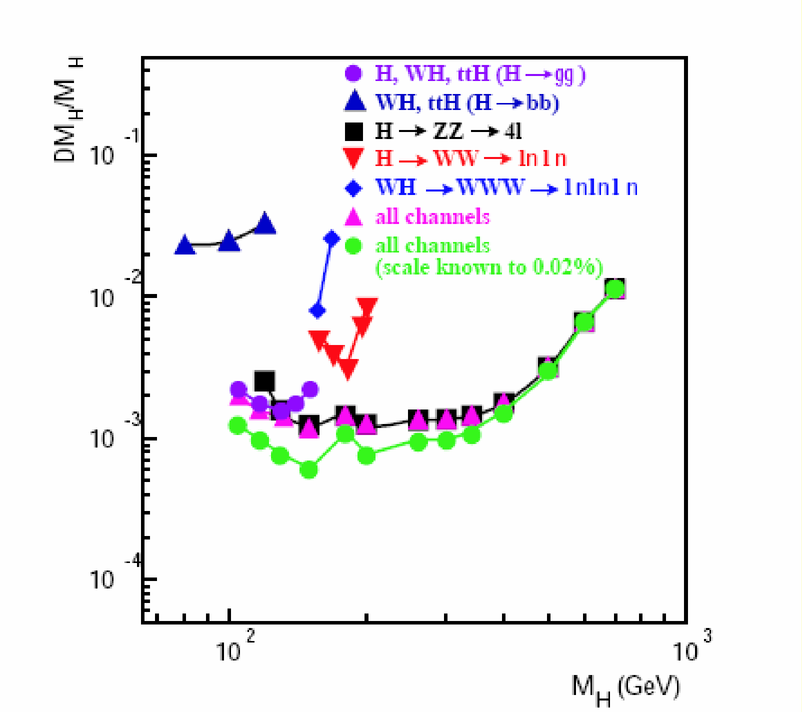


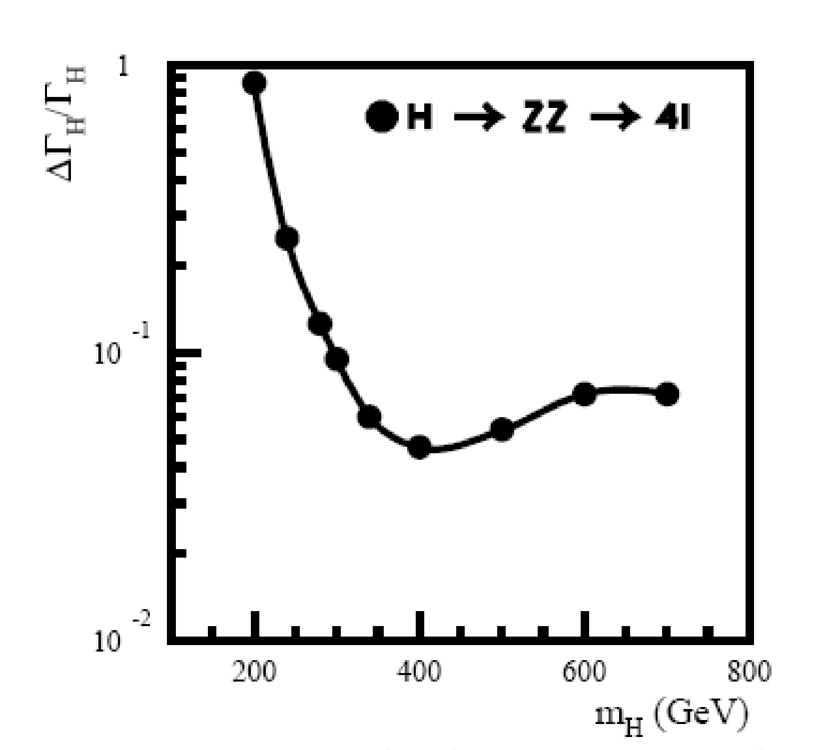


Determination of Higgs parameter(2)

Precision on the mass: it assumes 0.1% precision on lepton measurement, 1% precision on jet measurement (probably optimistic….)

Width determination: detector dominated is M_H < 200 GeV. If M_H> 200 GeV the H→4l is used for direct determination.





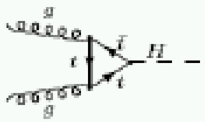
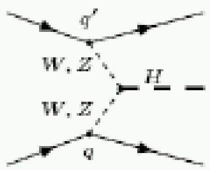
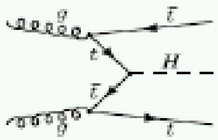
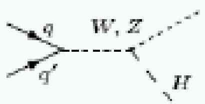
Measuring Higgs couplings

- Use all the observable signals to perform a likelihood fit.

Take into account:

- Statistical fluctuations
- Cross talk between signal channels.
- Systematic uncertainties (luminosity, efficiencies).
- Statistical and systematic uncertainties on the backgrounds.

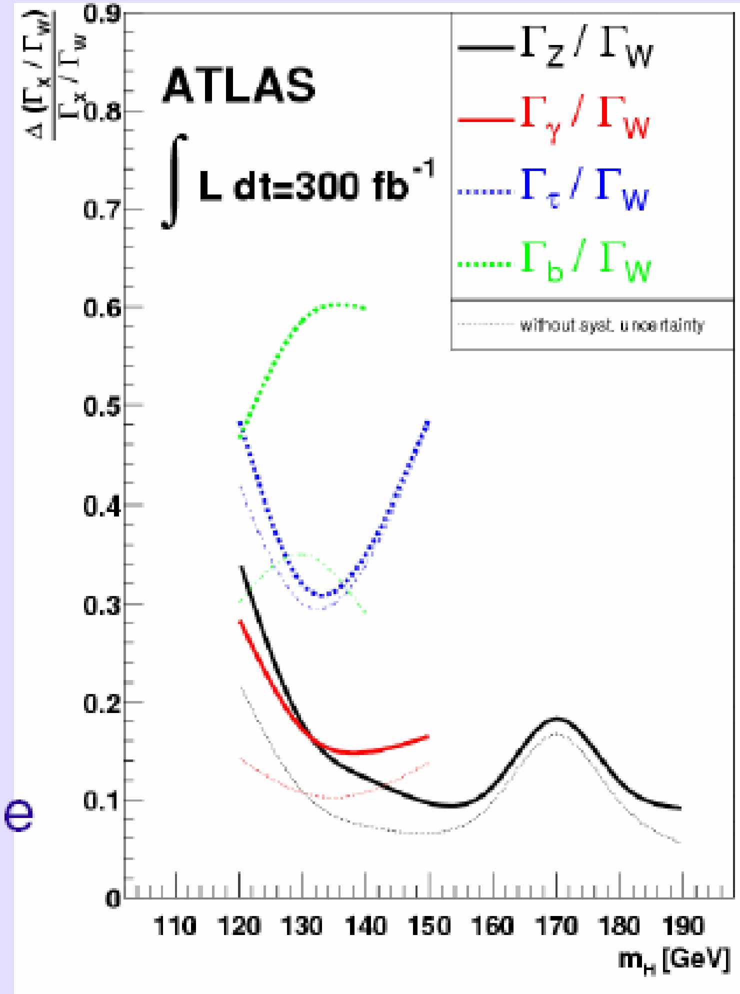
Making different assumptions we can extract different quantities.

Production		Decay
	GF: Gluon Fusion $(gg \to H)$	$H \to ZZ^{(*)} \to 4l$ $H \to WW^{(*)} \to l\nu\, l\nu$ $H \to \gamma\gamma$
	WBF: Weak Boson Fusion $(qq\,H)$	$H \to ZZ^{(*)} \to 4l$ $H \to WW^{(*)} \to l\nu\, l\nu$ $H \to \tau\tau \to l\nu\nu\, l\nu\nu$ $H \to \tau\tau \to l\nu\nu\, \mathrm{had}\nu$ $H \to \gamma\gamma$
	$t\bar{t}H$	$H \to WW^{(*)} \to l\nu\, l\nu\, (l\nu)$ $H \to b\bar{b}$ $H \to \tau\tau$ (not included) $H \to \gamma\gamma$
	WH	$H \to WW^{(*)} \to l\nu\, l\nu\, (l\nu)$ $H \to \gamma\gamma$
	ZH	$H \to \gamma\gamma$

Ratio of partial decay widths

Likelihood method assuming: Spin=0, CP-even and only one Higgs boson.

- $H \rightarrow bb$: low S/B, large systematics.
  - Uncertainty on the background dominates.
- For all other channels:
  - Ratios of partial widths can be measured with accuracy better than 50%

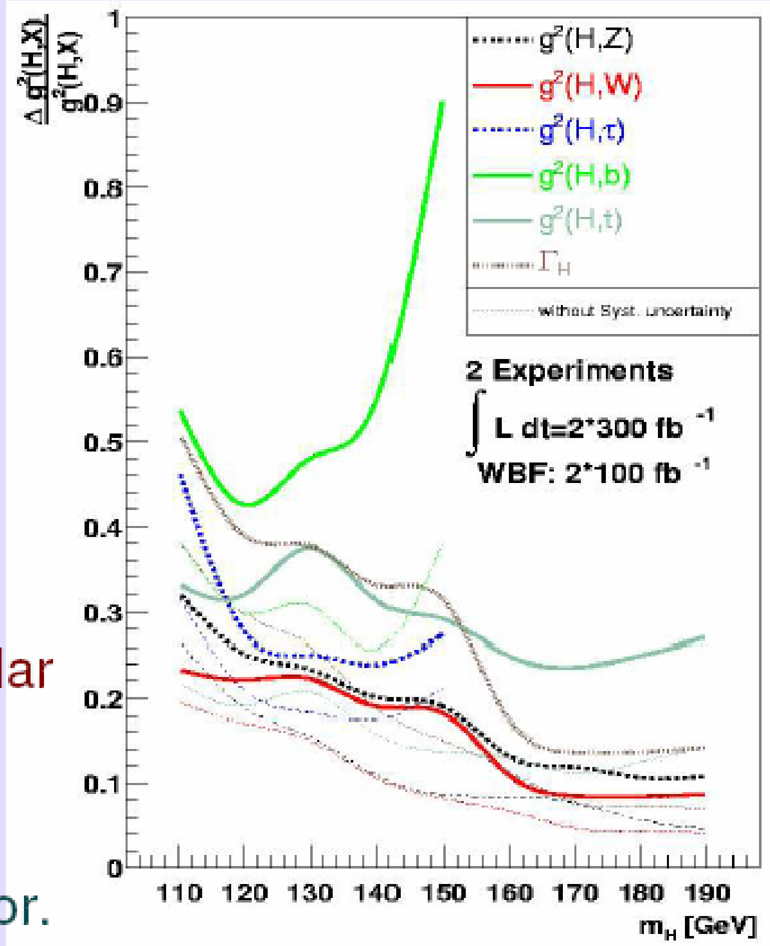


Higgs boson couplings

Same method but assuming:

- $\Gamma_V \leq \Gamma_V^{SM}$, V = W,Z.
- Allow for undetected Higgs decays and contributions to loops from non SM particles.

Assumptions valid for an arbitrary number of Higgs doublets (with or without Higgs singlet) and in particular for MSSM.



Precisions of 20-50% for m_H<150 GeV

Systematics account for half of the error.

Dominant systematic for m_H<150 GeV: background.

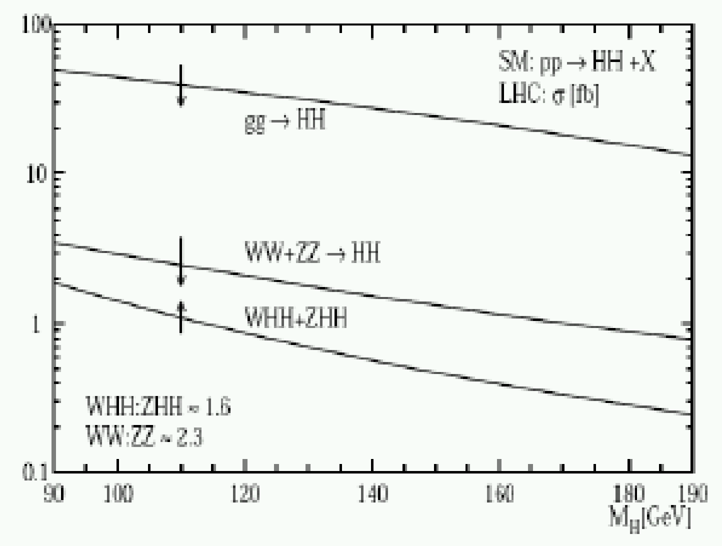
Higgs boson self coupling

Higgs potencial: $V_H = \frac{1}{2}m_H^2 H^2 + \lambda v H^3 + \frac{1}{4}\lambda' H^4$

$v = (\sqrt{2}G_F)^{-\frac{1}{2}}$: vacuum expectation value.

SM: $\lambda = \lambda' = \frac{m_H^2}{2v^2}$

HHHH not accesible at LHC



- Studied gg fusion for HH→WWWW→νlqqνlqq.
- Main backgrounds:
  - WWWjj
  - ttW
  - ttj + lepton from b decay.
- S/B ratio ~ 10%.

- Signal not observable at LHC
- Some sensitivity could be possible at Super-LHC.
- Bounds to be investigated.

SM Higgs boson - conclusion

- ATLAS will be able to detect a Higgs signal with significance > 5σ for all m_H, for 30 fb^{-1} of data.
- After the discovery, precise measurements of its properties have to be done:
  - The Higgs boson mass can be measured with good resolution for all m_H (1‰ for m_H<400 GeV).
  - Non SM spin/CP hypothesis can be ruled out with 100 fb^{-1} for m_H>230 GeV.
  - Coupling constants could be measured combining all available signals, with a precision of 10-50%, with 300 fb^{-1} of data.
  - Higgs self couplings may be accesible at SLHC.

MSSM Higgs Sector

- MSSM: 2 Higgs doublets → 5 physical bosons: h, H, A, H^+, H^-
- phenomenology at Born level described by $\tan\beta$, m_A
- mass prediction: $M_h < M_Z$
- couplings: $g_{MSSM} = \xi \cdot g_{SM}$
  - no coupling of A to W/Z
  - large $\tan\beta$: large BR($h,H,A \rightarrow \tau\tau, bb$)

ξ	t	b/τ	W/Z
h	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\alpha-\beta)$
H	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\alpha-\beta)$
A	$\cot\beta$	$\tan\beta$	-----

α: mixing angle between CP even Higgs bosons (calculable from $\tan\beta$ and M_A)

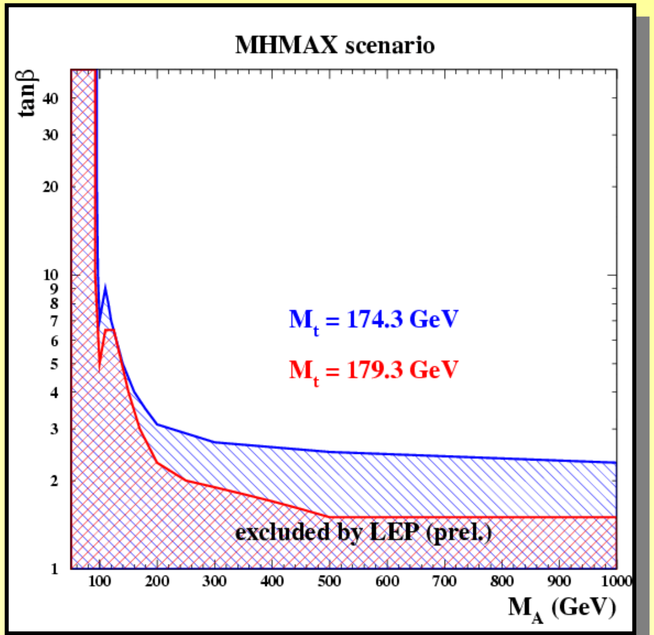
- large loop corrections to masses and couplings
- mainly dependent on $t/\tilde{t}$ sector
- parameters: M_{top} and X_t, M_{SUSY}, M_2, μ, M_{gluino}
- mass prediction $M_h < 133$ GeV (for $M_t = 175$GeV)

for exclusion bounds and discovery potential: fix the 5 parameters in benchmark scenarios and scan ($\tan\beta$, M_A)- plane

The (tanβ, M_A)-Plane

current exclusion in (tanβ,M_A)-plane:

- LEP excludes low tanβ and low M_A region
- note: no exclusion from LEP for M_t larger ~183 GeV

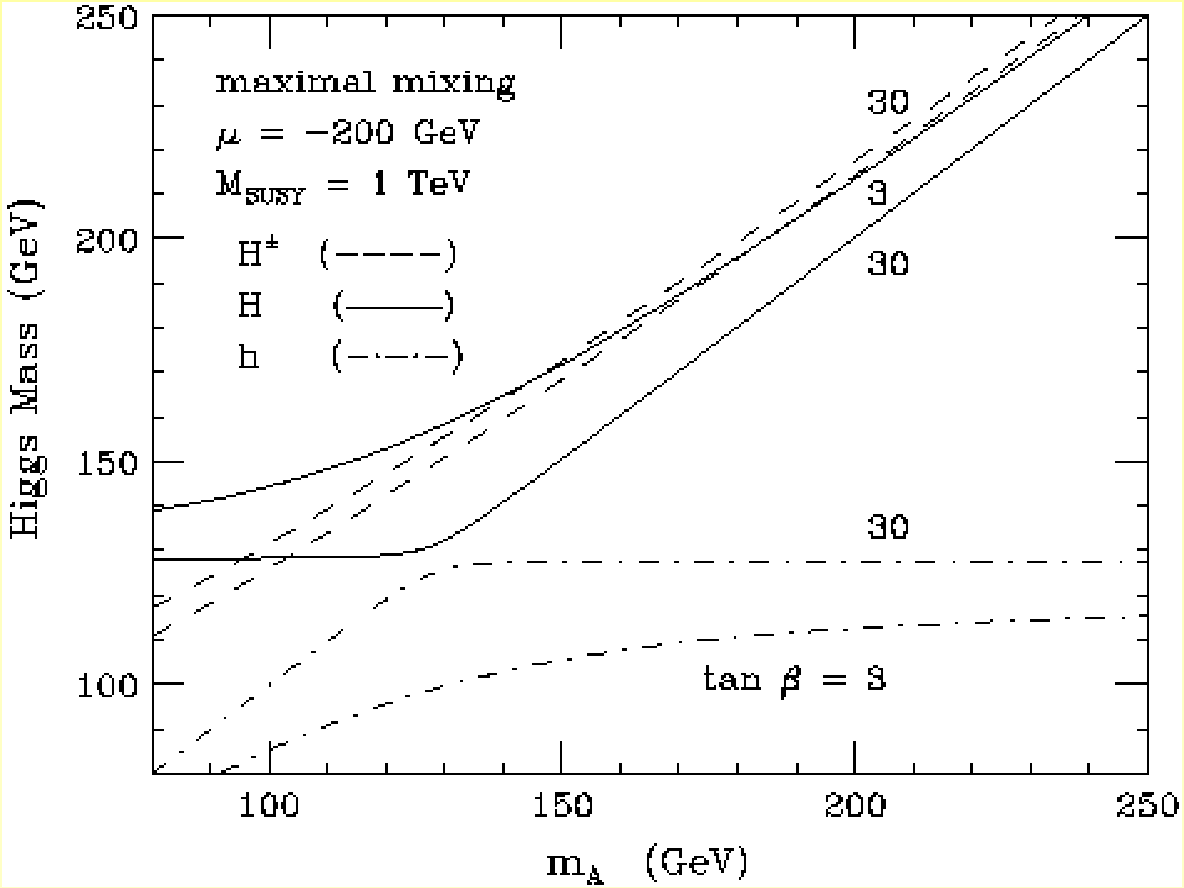


main questions for LHC/ ATLAS:

- **Can at least 1 Higgs be discovered in the allowed parameter space?**
- **How many Higgs bosons can be observed ?**
- **Can the SM be discriminated from models with extended Higgs sectors (like MSSM) ?**

MSSM

At high M_A the heavy bosons degenerate in mass while the h saturate at a limit value (around 130 GeV)



h search at LHC

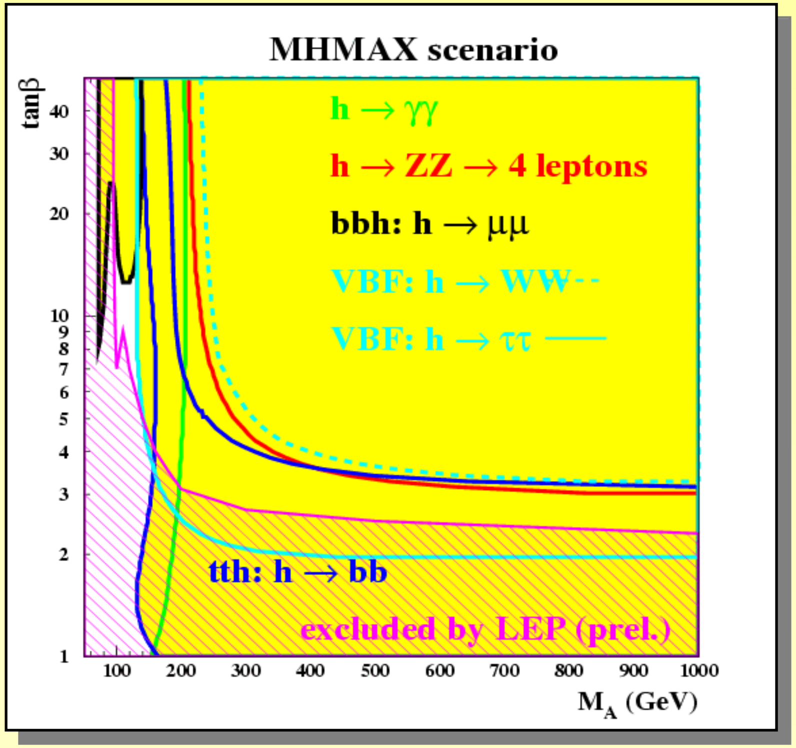
Most of the studies done in the LEP maximal mixing scenario (μ=-200 GeV, M_{SUSY} = 1 TeV, M_2 = 200 GeV, M_g = 800 GeV)

In the decoupling limit (high M_A), the h behaves like a SM Higgs boson. Decay into bb enhanced at high tgβ

- Most of the parameter plane covered by h→bb
- VBF channels also important

→ large area covered by several channels

→ stable discovery and parameter determination possible



Discovery contours

Heavy Neutral Higgs Bosons

bbH/A → bbμμ: cross section higher than in the SM at high tgβ.

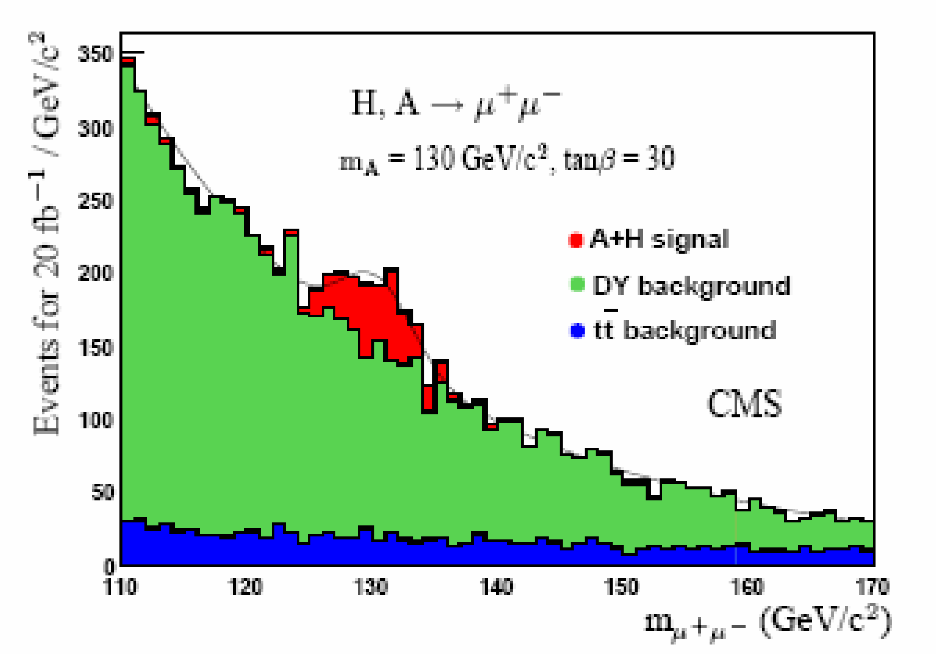
Studied performed in full simulation by CMS.

Main backgrounds coming from Drell-Yan production and tt.

At 130 GeV, the resolution (1%) is not enough to resolve the mass difference between H and A

Most of the background rejected with the requirement of b-tag.

Since the associated b are soft (E_T < 50 GeV), a special tagging algorithm (use of secondary vertex and impact parameter without the jet requirement in the calorimeter) has been used to increase the b-jet ID



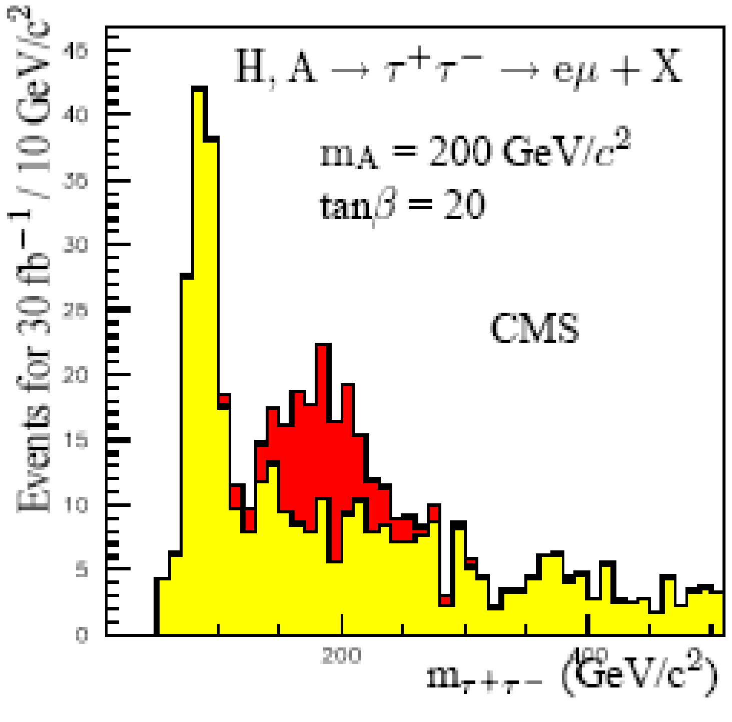
H/A decay into τ's

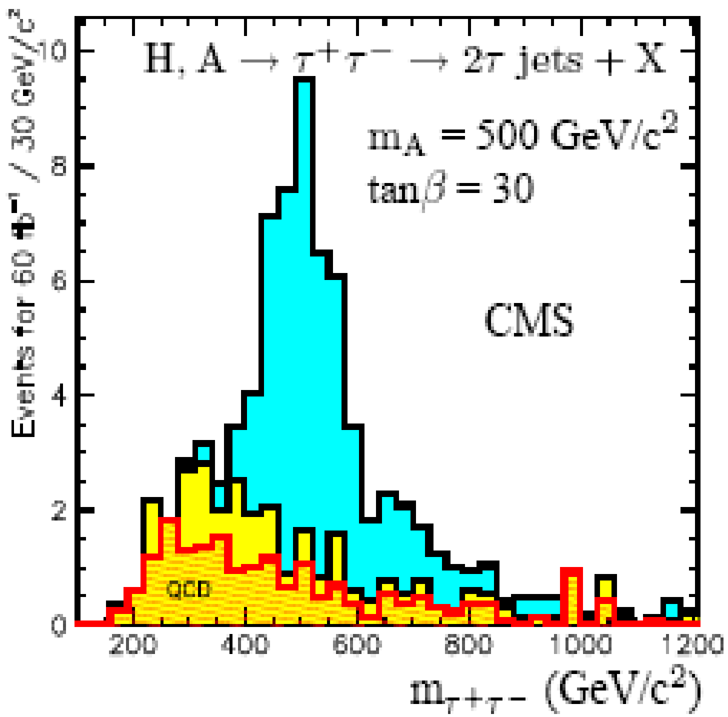
The tau decays provides the cleanest signature for the heavy Higgs discovery at high mass (and relatively high tgβ)

Investigated all the final states (ll, lj, jj). All of them contribute (at different M_A).

The associated production (bbA/H) provides additional rejection against the main backgrouds (Z+jet, WW, QCD (double hadronic tau decay only)

Trigger issues solved w.r.t. the full hadronic final state





Overall coverage of the M_A-tgβ plane for A/H

The A/H Higgs boson can be detected thanks to the A/H→μμ decay in the low mass- high tgβ region

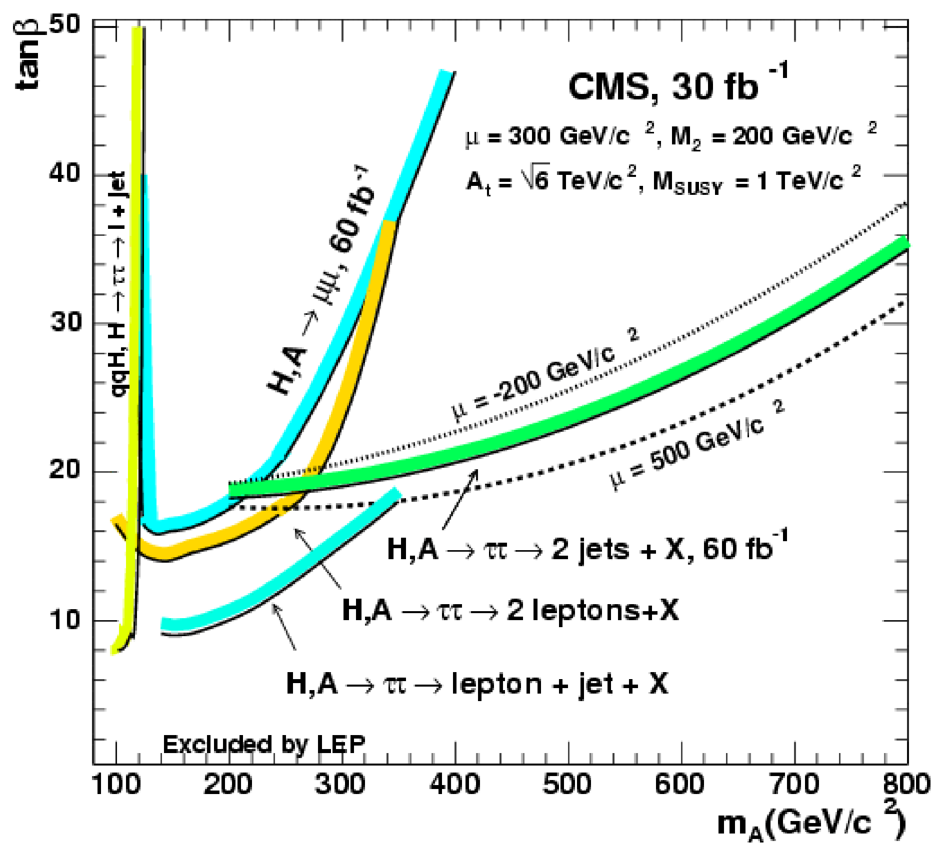
The decay into ττ allows (with different final states) to cover a large part of the plane

There is no coverage

(with 30 fb^{-1}) for the large mass-intermediate tgβ region

The very high mass region can be reached only by the full hadronic final state of the ττ

Similar plot for ATLAS



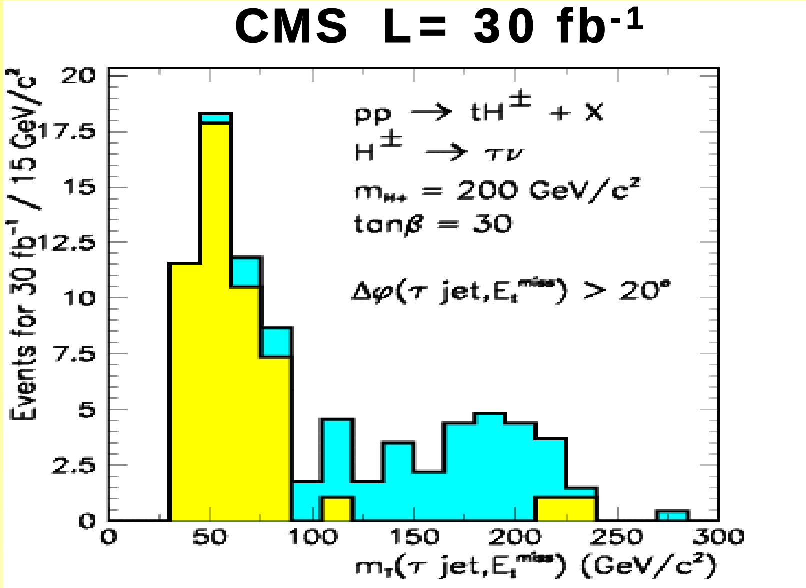
Charged Higgs decay

Two channel are of particular interest if $M_H > M_t$.

- $H^+ \rightarrow \tau\nu$; $\tau \rightarrow$ hadr

Reconstruction of the top decay and of the hadronic tau.

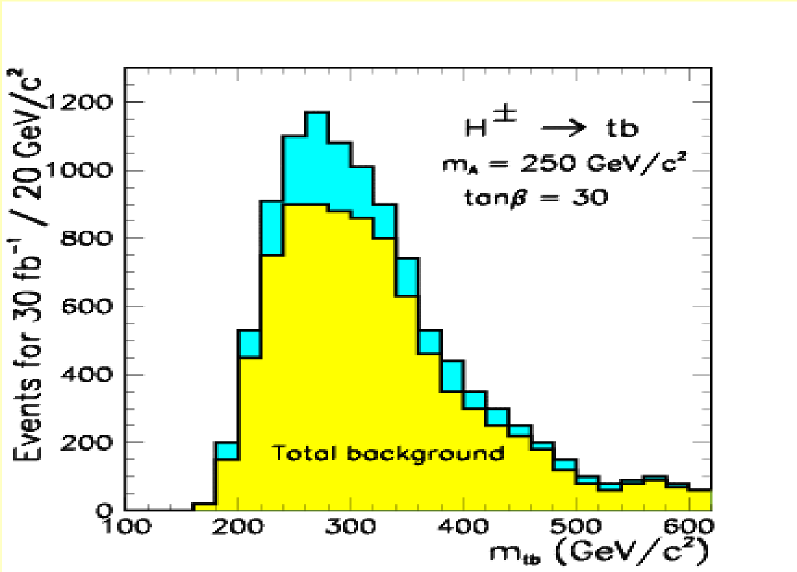
tt and Wt backgrounds suppressed exploiting spin correlations → One single π has to carry the largest part of the tau energy.



- $H^+ \rightarrow tb$ t → bW → blnqq

large background (tt+jets)

reconstruct tops and Higgs → M_H

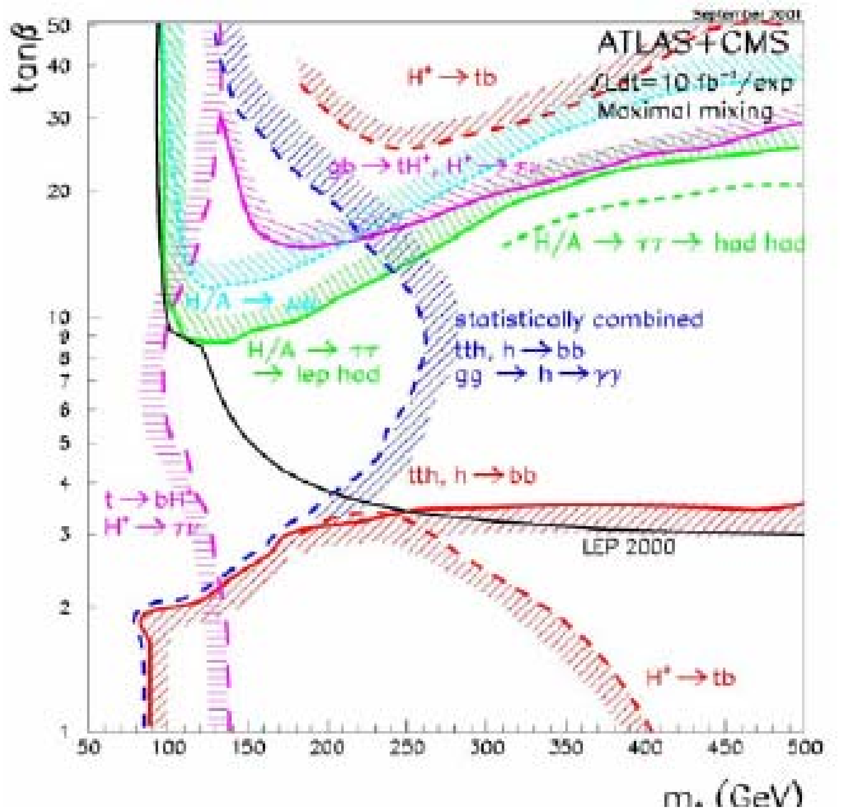


Overall view (10 fb^{-1})

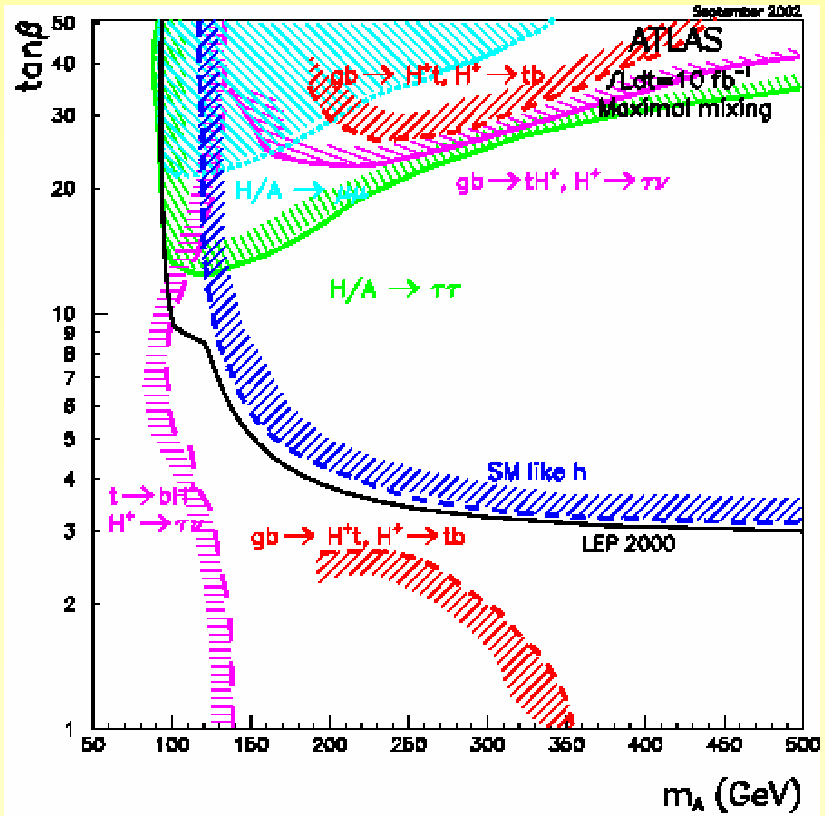
Rather small statistics (of good data) is enough to cover most of the M_A-tgβ plane

But a lot of questions to address before: machine operations, detector understanding, background measurement….

No VBF



with VBF



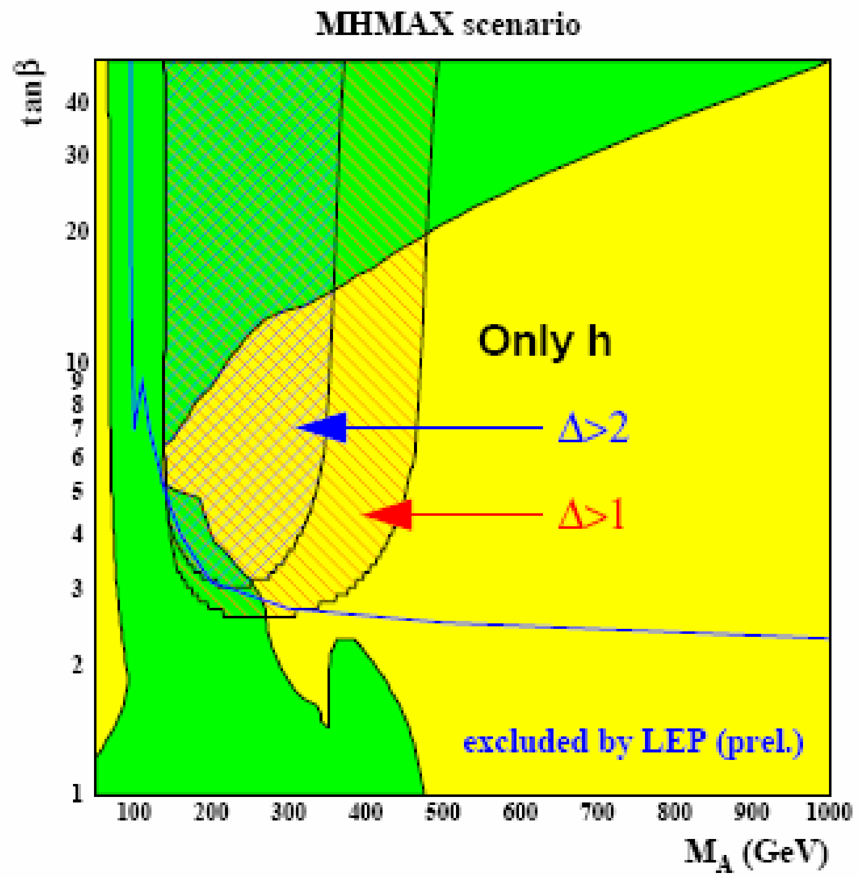
Overall view (300 fb^{-1})

Can we disentangle between SM and MSSM just from the Higgs sector?

In most of the parameters space more than 1 Higgs boson is detectable.

In the yellow region just the h is detectable

Still in a region we can disentangle looking at the ratio between the BR into $\tau\tau$ and WW. Anyway, it is difficult….



$$R = \frac{BR(h \to \tau\tau)}{BR(h \to WW)} \qquad \Delta = \frac{R_{MSSM} - R_{SM}}{\sigma_{erw}}$$

Conclusions

-Standard Model Higgs detectable with few tens of fb^{-1} over all the mass range. In the most likely region, VBF production plays a relevant role

-Spin measurement feasible in its ZZ decay.

-Coupling measurement will require full luminosity in most of the mass range. Achievable precisions: 15-50% depending on the channel

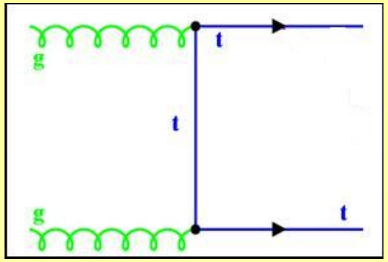
-MSSM plane coverage requires few tens of fb^{-1} in a maximal mixing scenario. Higgs decays into third generation fermions play an extremely relevant role. VBF important for the h in the decoupling limit

Back-up slides

Higgs search – problem

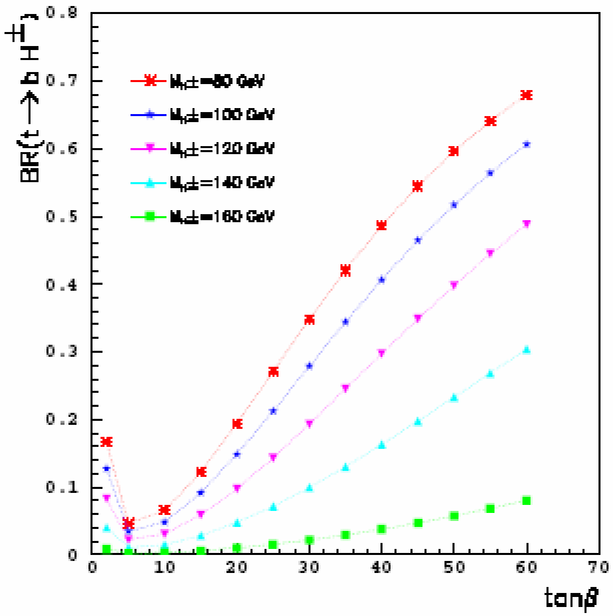
"Light" charged Higgs search : $m_H+ < m_{top}$

σ_{tt} ~ 1nb

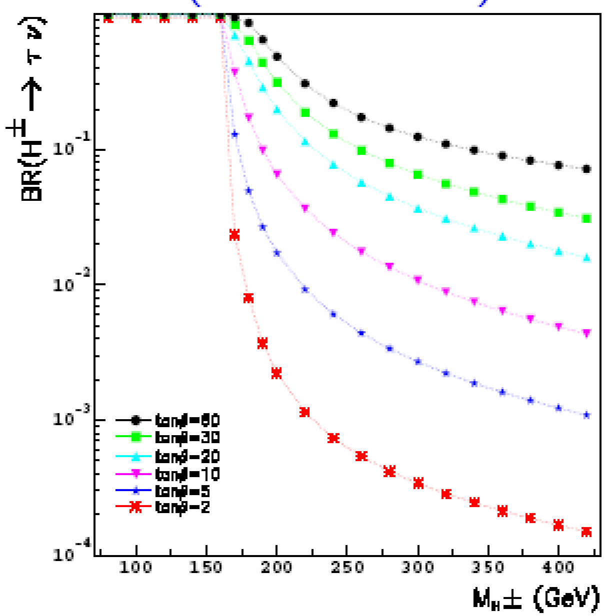


large ttbar sample is available

BR($top \rightarrow H^{\pm}b$)



BR($H^{\pm} \rightarrow \tau^{\pm}\nu$)



non excluded region: Br t→H+b 20% ↓ 0%

Br H+ → τ ν ~93%

Higss search – problem

How to observe the signal ?

- Draw ttbar decay topology in most important decay modes
- Br($t \to Wb$) complement of Br($t \to Wb$)
- Br ($W \to l \nu$)~ 10%   Br ($W \to qq$)~ 70%
- Check how well the final state is constraint for various decay possibilities
- Think about information that can be obtained from p_T^{miss}
- Do not forget the trigger

LHC Phenomenology – problem

Final states with e or μ
done in '94 in ATLAS

$$t \to W^+ b$$
$$W^+ \to e\ (or\ \mu)\ + X$$
$$\bar{t} \to H^- \bar{b}$$
$$H^- \to \tau^- \nu_\tau$$
$$\tau^- \to had.\ \bar{\nu}_\tau$$

- Trigger on the isolated lepton
- BR($W^+ \to e(\mu) + X$): 24.8%
- $M_{H^\pm}$ reconstruction difficult (3 or more ν in 2 hemispheres)

Can only look for an excess of taus over the SM prediction

Hadronic final state
new approach

$$t \to W^+ b$$
$$W^+ \to q\bar{q}'$$
$$\bar{t} \to H^- \bar{b}$$
$$H^- \to \tau^- \nu_\tau$$
$$\tau^- \to had.\ \bar{\nu}_\tau$$

- Trigger based on jet+$\not{E}_T$
- BR($W^+ \to q\bar{q}'$): 68.5%
- Simplified $M_{H^\pm}$ reconstruction (2 ν in the same hemisphere)

Some mass reconstruction is possible:

- show that it is a particle
- measure its mass

LHC Phenomenology – problem

$$M_T = \sqrt{2.E_T^{miss}.p_T(\tau - jet).cos(\Delta\phi)}$$