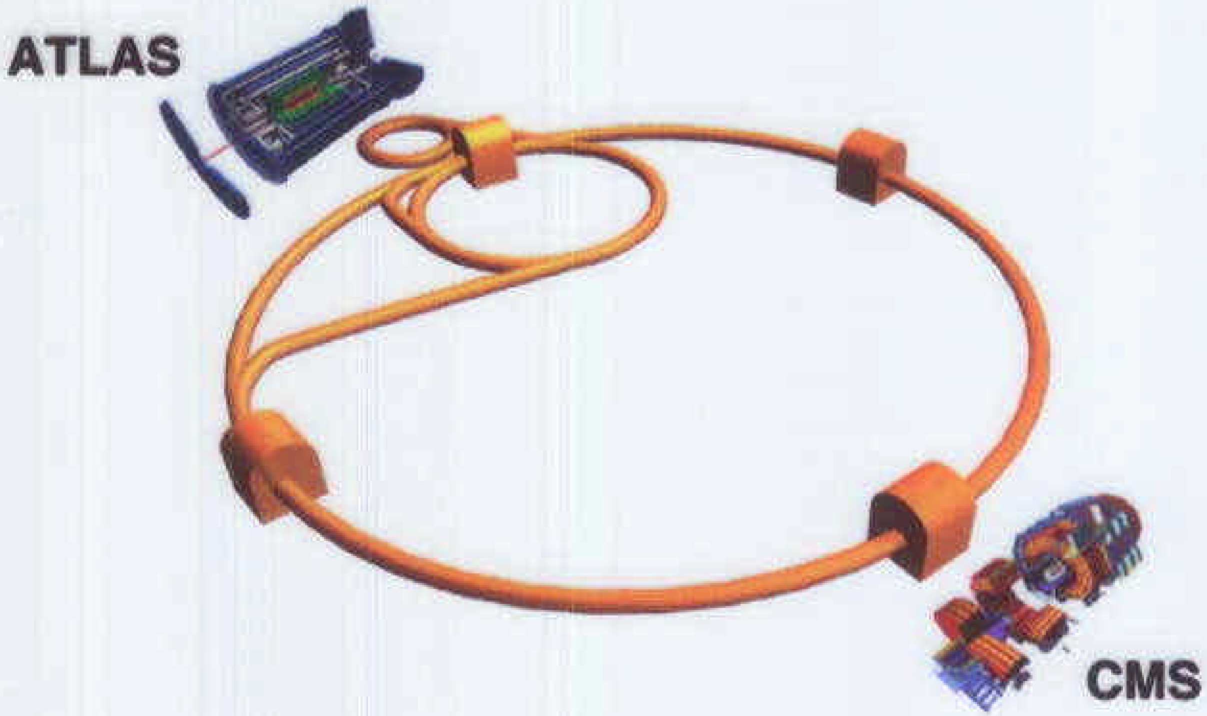
**Alessandra Caner - CERN/CMS**

# Higgs Prospects at the LHC



- SM Higgs searches
- MSSM Higgs searches
- Measurement of Higgs parameters

- Among primary LHC goals:

-- look for SM Higgs boson over

previous machines ⟶ $\sim 100\ \mathrm{GeV} < m_H \leq 1\ \mathrm{TeV}$ ⟵ theoretical upper bound

-- look for MSSM Higgs bosons over all parameter space
-- be sensitive to alternative scenarios

→ high √s and L, general-purpose detectors

¥ Main asset : large signal rates
However in many cases:
-- Backgrounds much larger → $S/B \ll 1$
-- $\Gamma_H \ll \Gamma_{\mathrm{detector}}$

⬇

-- excellent detector performance needed
-- Higgs searches used as benchmark for ATLAS and CMS detector design

⬇

**Higgs detection possible in large variety of final states: $\gamma$, e / $\mu$ / $\tau$, b-jets, $E_T^{miss}$, forward jets, top-quarks, SUSY particles, etc.**

# Framework

- $L_{peak} \approx 10^{33}\ cm^{-2}\ s^{-1}$ 2005-2008 ( low L )
  $L_{peak} \approx 10^{34}\ cm^{-2}\ s^{-1}$ 2008 → ( high L )

→ $\int L dt \approx 30\ fb^{-1}$ /expt after 3 years at low L
$\int L dt \approx 100\ fb^{-1}$ / expt after 1 year at high L

High L : ~ 20 soft interactions per crossing (pile-up)

- PYTHIA 5.7

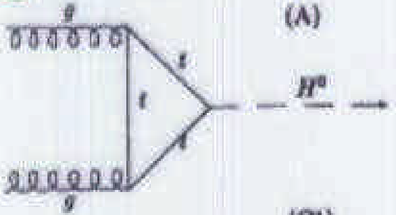
- Full detector simulation (GEANT)
  to determine efficiencies, background rejections, resolutions, tails, etc.

- Only uncontroversial channels considered:

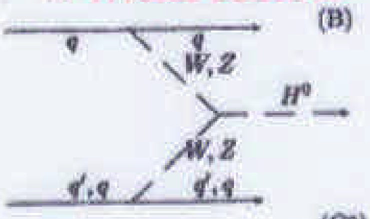
-- background under control (physics, trigger, detector)
-- $\geq$ 4–5 $\sigma$ significance per experiment per channel
-- no hopeless channels (e.g. multijet final states):
S/B ~ %
B uncertainty >> 10%

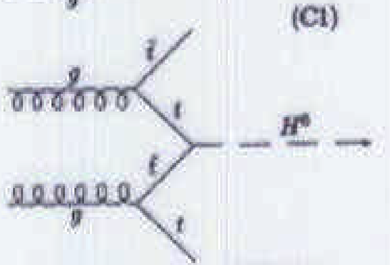
# SM Higgs production at LHC

gg fusion

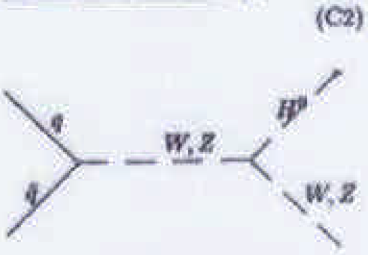


WW/ZZ fusion

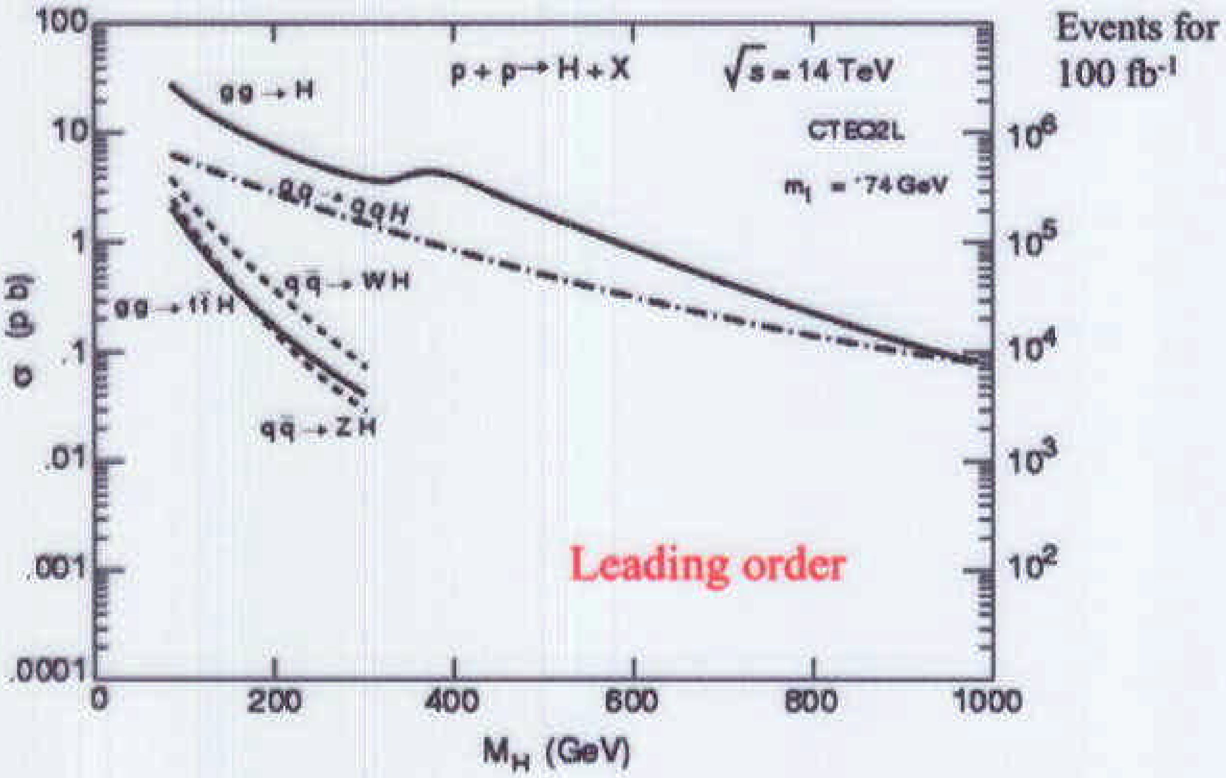




associated $t\bar{t}H$



associated WH, ZH



- gg → H : K=1.6– 1.9 (not included)
- residual uncertainties on NLO cross-sections (PDF, NNLO, etc.) ≤ 20% (except ttH)

# Main search channels at LHC

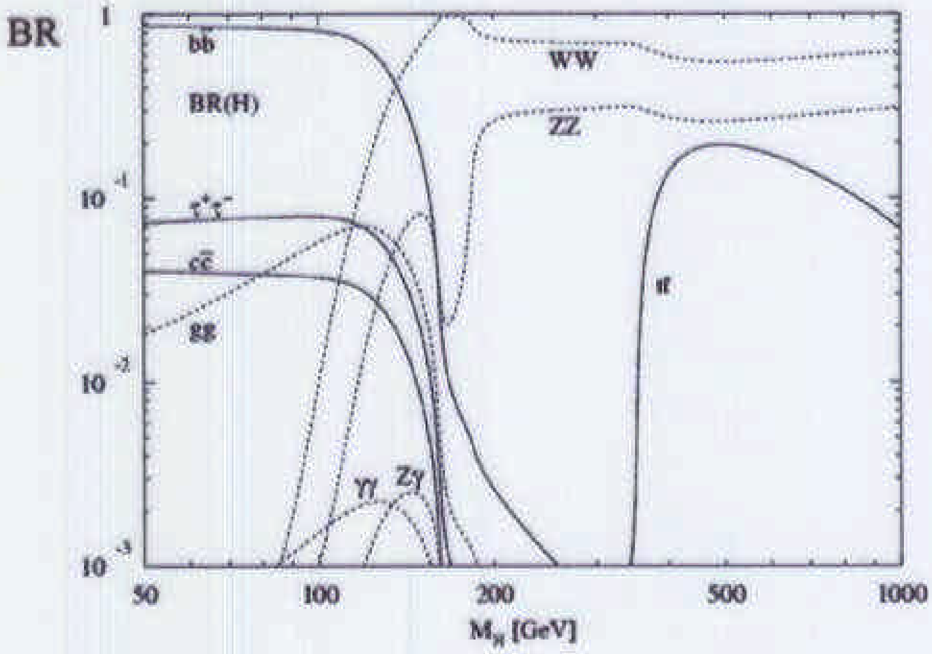
Large QCD backgrounds:

e.g. $\sigma\,(H \to b\bar{b}) \approx 20$ pb direct production, $m_H = 120$ GeV

$\sigma\,(b\bar{b}) \approx 500\ \mu$b

→ no hope to trigger / extract fully hadronic final states

→ look for final states with $\ell, \gamma$ ($\ell = e, \mu$)



$m_H < 2\,m_Z$ : $t\bar{t}H \to \ell b\bar{b} + X$, $H \to \gamma\gamma$

$H \to ZZ^* \to 4\ell$, $H \to WW^{(*)} \to \ell\nu\ell\nu$

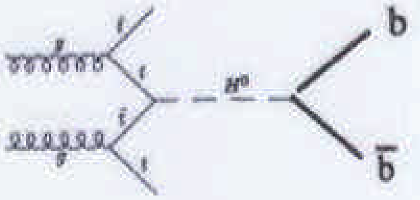
$m_H > 2\,m_Z$ : $H \to ZZ \to 4\ell$ (gold-plated)

$$\left.\begin{array}{l} H \to ZZ \to \ell\ell\nu\nu \\ H \to ZZ \to \ell\ell jj \\ H \to WW \to \ell\nu jj \end{array}\right\} \begin{array}{l} m_H > 300 \text{ GeV} \\ \text{forward jet tag} \end{array}$$

Detector performance is crucial: b-tag, $\ell/\gamma$ E-resolution, $\gamma$/j separation, $E_T^{miss}$ resolution, forward jet tag, etc.

# $t\bar{t}H \rightarrow t\bar{t}b\bar{b}$

$m_H \leq 130$ GeV



- $\sigma \times BR \approx 300$ fb
- Complex final state: $H \rightarrow b\bar{b}$, $t \rightarrow bjj$, $t \rightarrow b\ell\nu$

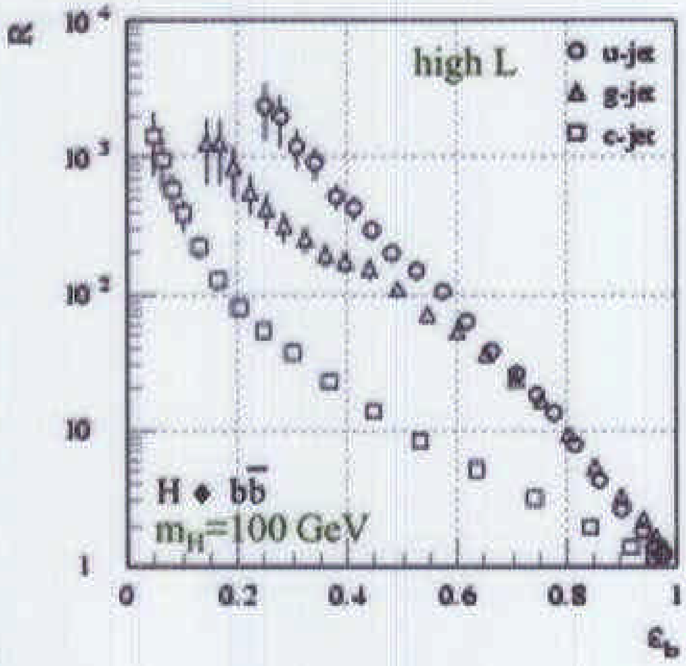
$\ell = e, \mu$ for trigger
and background rejection

- Main backgrounds:

-- combinatorial from signal (4b in final state)
-- Wjjjjjj, WWbbjj, etc.
-- ttjj (dominant, non-resonant)

reduced by reconstructing both top quarks

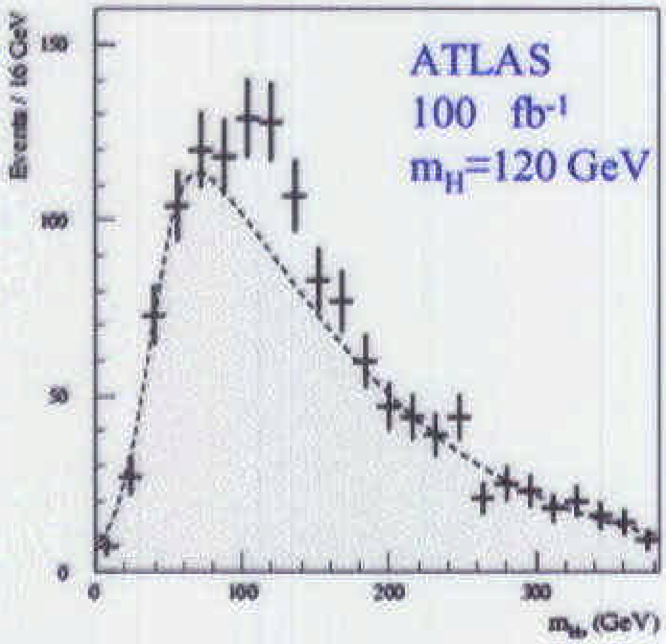
→ b-tagging is crucial



ATLAS, full simulation

2D b-tag (used here):
$\varepsilon_b$ =50% (60 %) $R_j$ (uds)=100
at high (low) L

3D b-tag: $R_j$ is ~ 2 larger
for same $\varepsilon_b$



Background (~ 60% from $t\bar{t}b\bar{b}$) can be measured with $t\bar{t}jj$ with j anti b-tagged

$t\bar{t}b\bar{b}$ : good agreement PYTHIA- CompHEP (ME)

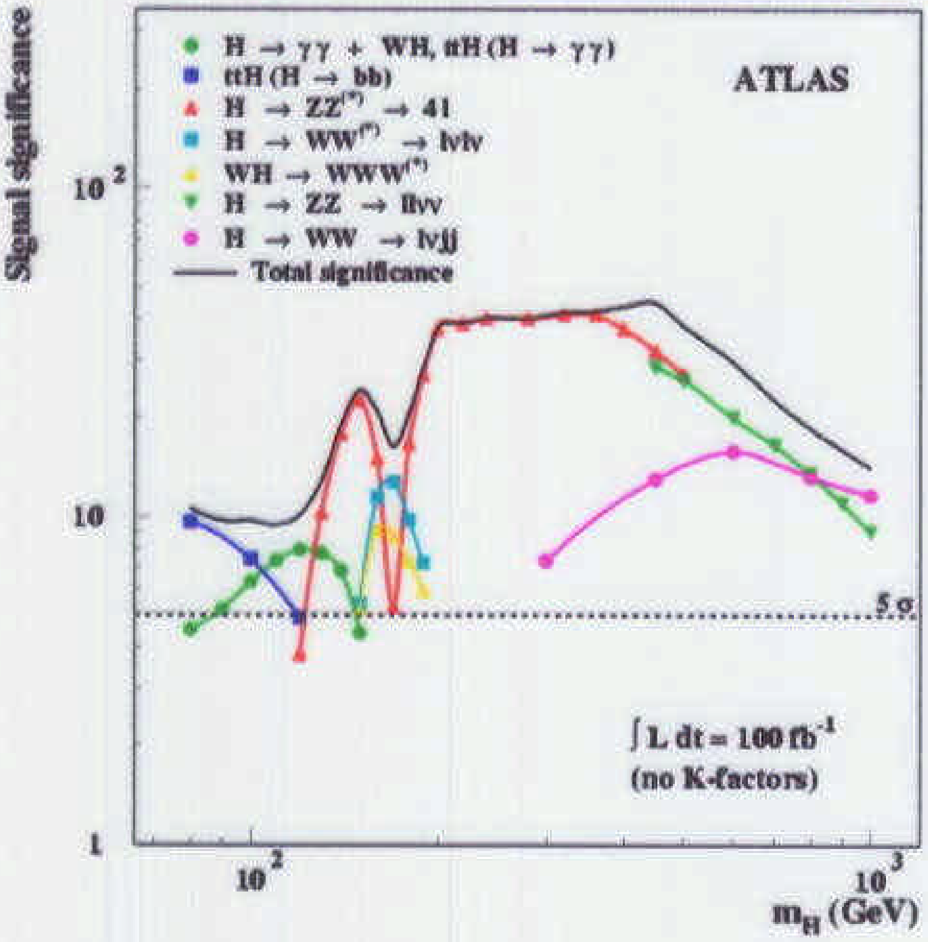
| $m_H$ (GeV) | 100 | 120 |
|---|---|---|
| S | 140 | 80 |
| S/B | 0.4 | 0.25 |
| S/√B | 7.5 | 4.5 |
| S/√B 30 fb$^{-1}$ ATLAS + CMS | 7.0 | 5.0 |

1 experiment
100 fb$^{-1}$

Conclusions:

-- 5σ discovery at low L for $100 \leq m_H \leq 120$ GeV ATLAS + CMS
-- complementary to $H \rightarrow \gamma\gamma$
-- large coverage in MSSM
-- allows measurement of top Yukawa coupling
-- crucial detector performance : b-tagging

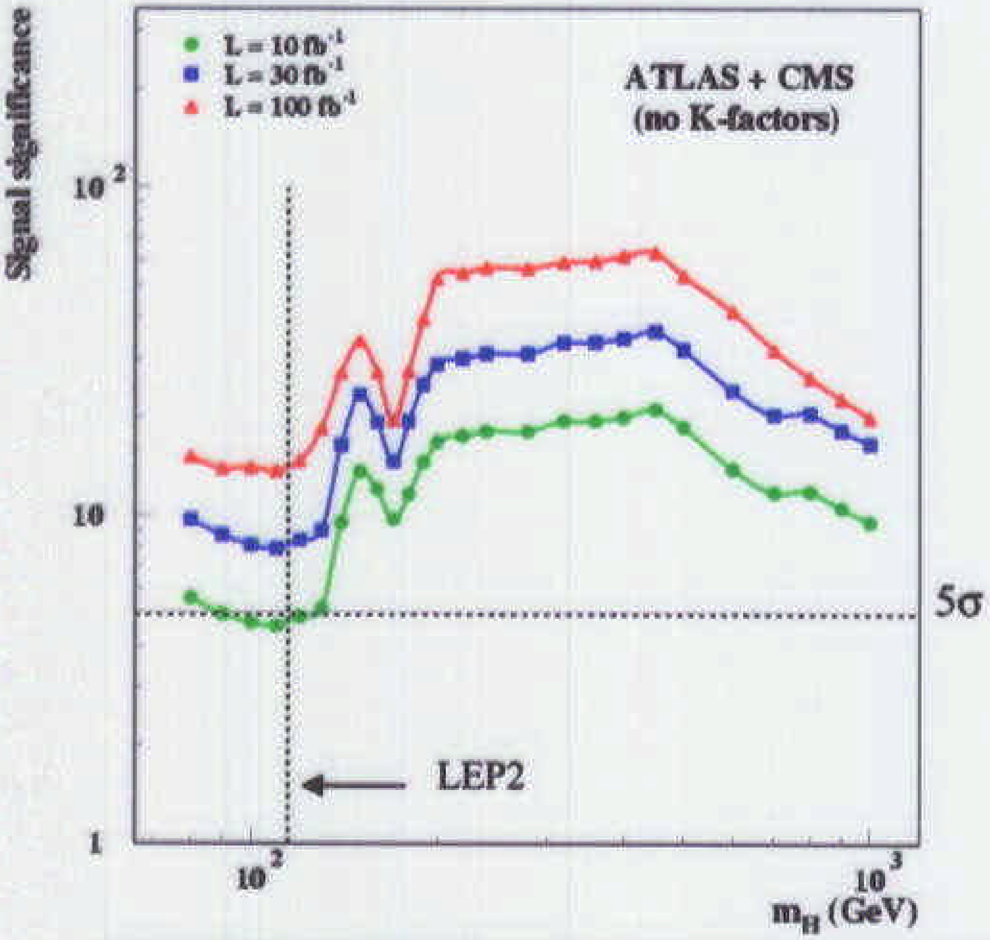
# Overall discovery potential for SM Higgs



$m_H < 180$ GeV : many complementary channels ($\gamma\gamma$, bb, $2\ell$, $3\ell$, $4\ell$, etc.)

$m_H > 180$ GeV : discovery is straightforward with gold-plated $H \to ZZ \to 4\ell$ (S/B > 5). Complemented by $H \to WW \to \ell\nu\, jj$, $H \to ZZ \to \ell\ell\nu\nu$, $\ell\ell\, jj$ (forward jet tag)

> 1 channel observable over most of range → robustness, measurement of couplings



L is per experiment

SM Higgs boson can be discovered at ≈ 5 σ after ≈ 1 year of operation (10 fb$^{-1}$/ experiment) for $m_H \leq 150$ GeV

Discovery faster for larger masses

Whole mass range can be excluded at 95% CL after ~1 month of running at $10^{33}$ cm$^{-2}$ s$^{-1}$.

Results are conservative:

-- no K-factors

-- simple cut-based analyses

-- conservative assumptions on detector performance

-- channels where background control is difficult not included e.g. WH → $\ell \nu b\bar{b}$ (large systematics)

# MSSM HIGGS searches : h, H, A, H±

Large variety of channels:

e.g. – $h \to \gamma\gamma$, $t\bar{t}h \to t\bar{t}b\bar{b}$, $ZZ^{(*)} \to 4\ell$ also in SM

– $A/H \to \mu\mu, \tau\tau, t\bar{t}$, $H^{+} \to \tau\nu, cs, tb$

– $H \to hh$, $A \to Zh$

} typical of MSSM

– $A/H$ ◆ $\chi^0_2\chi^0_2$

– $\chi^0_2$ ◆ $h\,\chi^0_1$

} if SUSY particles accessible

Note :

-- suppression/absence of WWH, ZZH, WWA, ZZA couplings

-- strong enhancement of bbA, bbH couplings for large tanβ

} compared to SM

→ $A/H \to \mu\mu, \tau\tau$ accessible

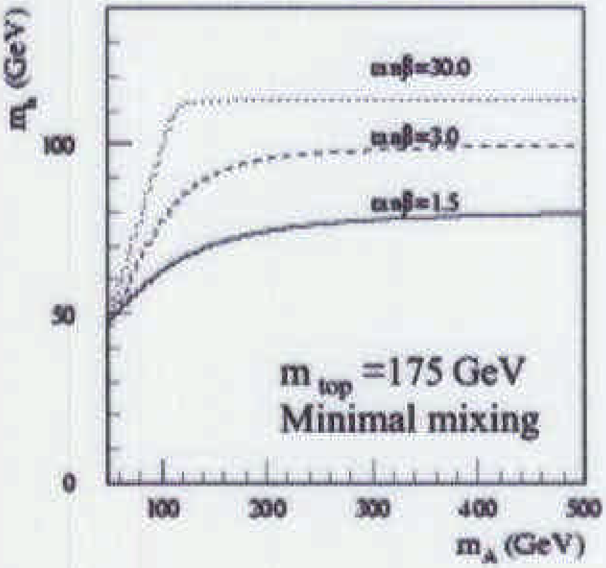
2 steps:

✡ SUSY particles are heavy → do not contribute to Higgs production / decay

+ SUSY particles contribute

## Masses

- h mass increases with $m_A$, tanβ, top mass, stop mass, stop mixing



e.g. :

$m_{top}$ =174.3 GeV
$M_{SUSY} = f\,(m_{\tilde{t}_1}, m_{\tilde{t}_2}) = 1$ TeV
Minimal mixing ($A_t$, $\mu \ll M_{SUSY}$)

} $m_h < 115.5$ GeV → MSSM ~fully covered by LEP

However:

-- theoretical uncertainties : $\Delta m_h \approx 3$ GeV
-- $m_{top}$ =180 GeV (+ 1σ ) : $m_h < 118.4$
-- maximal mixing : $m_h \leq 130$ GeV
-- more general SUSY models : $m_h < 205$ GeV
(Quiros and Espinosa, CERN-TH/98-292)

} beyond LEP sensitivity

- A, H, H± heavier and ~ degenerate for $m_A > 200$ GeV

- 2-loop calculations for masses and couplings
(Carena et al., Phys. Lett. B355, 1995)

- Results are 5σ discovery contours on $m_A$, tanβ plane for $m_{top}$ =175 GeV, $M_{SUSY}$ = 1 TeV, max mixing (LEP curves: P. Janot)

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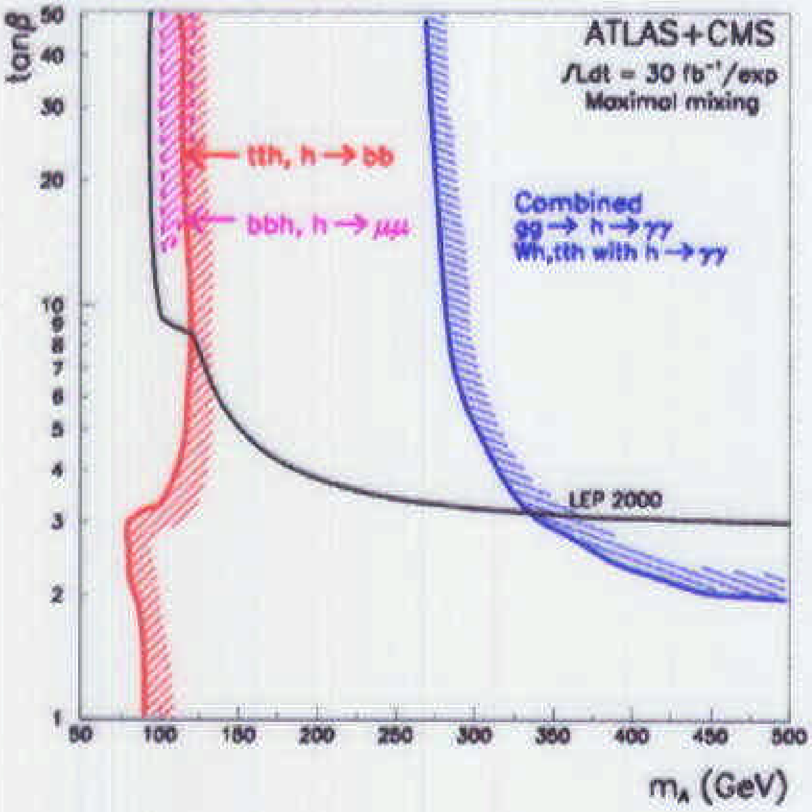
# h boson

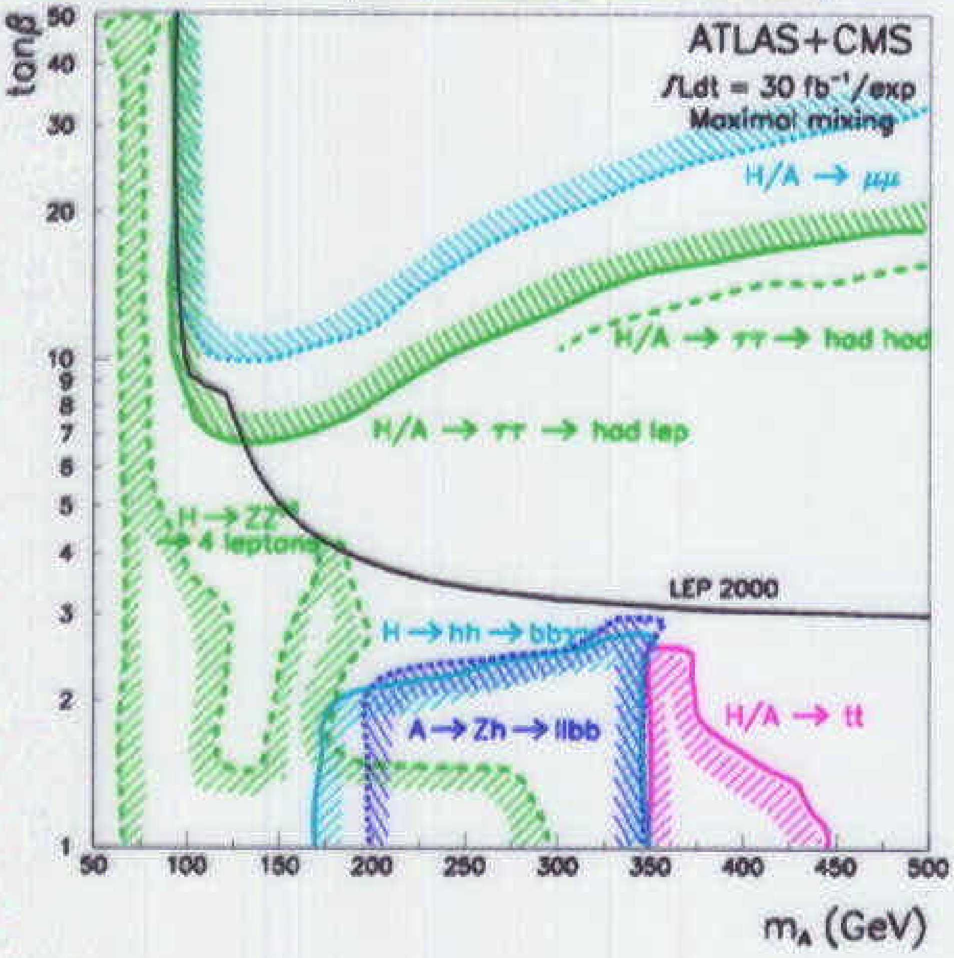


$m_A$ > 100 GeV:
- -- h mass close to max value (~ 130 GeV)
- -- h behaves as SM Higgs → SM production and decay modes

$m_A$ < 100 GeV:
- -- h mass decreases
- -- BR ($h \to \gamma\gamma$) and $t\bar{t}h$ production suppressed
- -- large tanβ : bbh production enhanced → bb μμ channel observable

Robust coverage:
- -- different production mechanisms : $gg \to h$ (loops), Wh, $t\bar{t}h$
- -- different decays : $h \to \gamma\gamma$ (loops), $h \to b\bar{b}$

# A and H bosons



$m_A$ > 200 GeV:
A and H are
~ degenerate

- Large tanβ : $b\bar{b}H, b\bar{b}A$ strongly enhanced
  e.g. σ (MSSM) / σ (SM) ≈ 5000 tanβ =30, m =300 GeV

⇨ H/A → ττ, μμ observable and cover large part of parameter space

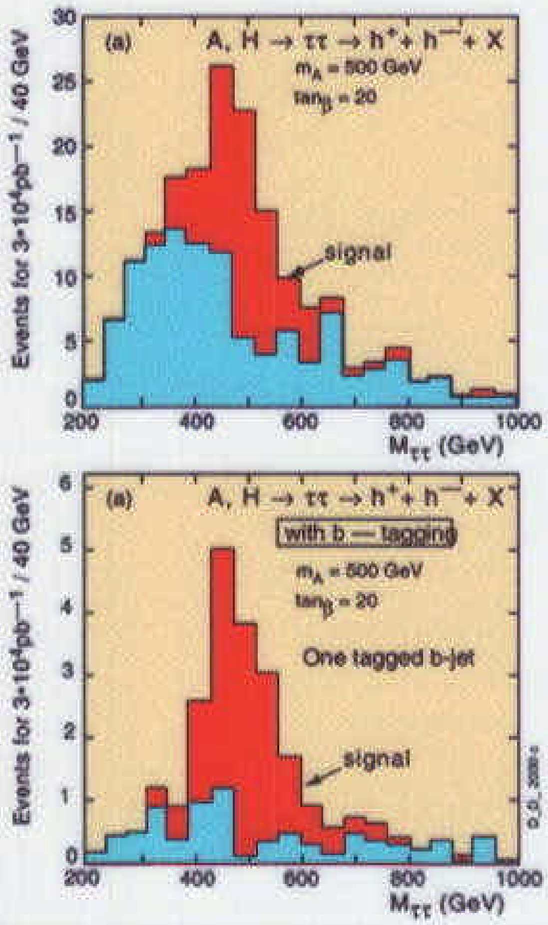
- Small tanβ : large number of channels
  → measurement of many couplings
  including Hhh, AZh

## $A/H \to \tau\tau \to h^+\nu\, h^-\nu$ :

Provides best reach for large $m_A$.
Signature: two stiff opposite-sign isolated tracks and missing transverse energy.

Main challenge: reject QCD jet background (already at trigger !).
Feasible for $m_A > 300$ GeV: hadrons have high $p_T$,
$E_T^{miss}$ is large, etc..
$\to R_{QCD} \sim 10^{10} \to$ QCD background << 10% ($tt + Z/\gamma^* \to \tau\tau$)

Events selected as: $E_t^{jet} > 60$ GeV
$p_t^h > 40$ GeV, $\Delta\phi(jj) < 175°$, $E_t^{miss} > 40$ GeV



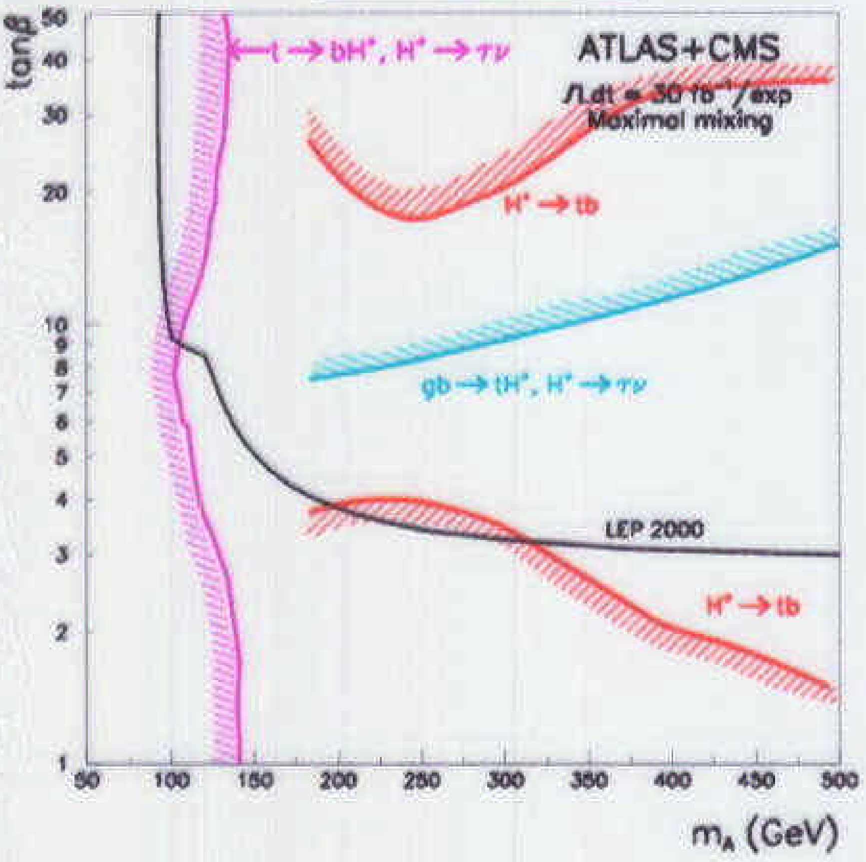
CMS
30 $fb^{-1}$

In addition b-tag
improves S/B

Mass resolution ~10%

More study (trigger, background) needed $m_A < 300$ GeV.
Additional tools: calorimeter isolation, impact parameter

# $H^\pm$ bosons



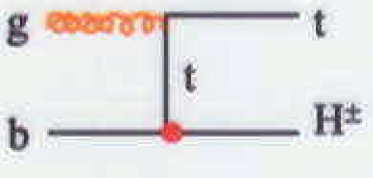
- $m_{H^\pm} < m_t$: $t \to b H^+ \ (H^+ \to \tau\nu)$ competes with $t \to bW$

$\to$ count excess of τ s in $t\bar{t}$ final states

$$\left.\begin{array}{l}3000\ W \to \tau\nu \\ 1500\ H^\pm \to \tau\nu \quad m=130\text{ GeV}\ \ \tan\beta=5 \\ 4000\text{ fake }\tau\text{ from }W \to jj\end{array}\right\}\quad t\bar{t}\text{ events, }30\text{ fb}^{-1}$$

$\tan\beta \le 1.5$ : $H^\pm \to cs$

- $m_{H^\pm} > m_t$:
  - -- $gb \to H^\pm t \to tb\,t$
  - -- $gb \to H^\pm t \to \tau\nu\ t$

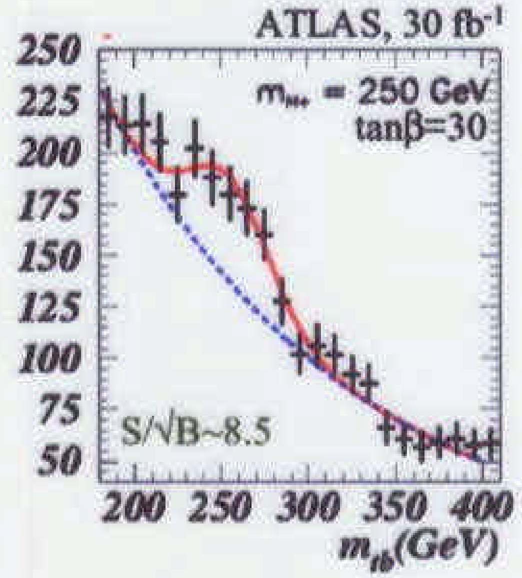


$gb \rightarrow H^{\pm} t$

$\hookrightarrow tb$

Both top quarks reconstructed
Background from $t\bar{t}b$ plus
combinatorial from signal

ATLAS, 30 fb$^{-1}$



$gb \rightarrow H^{\pm} t$

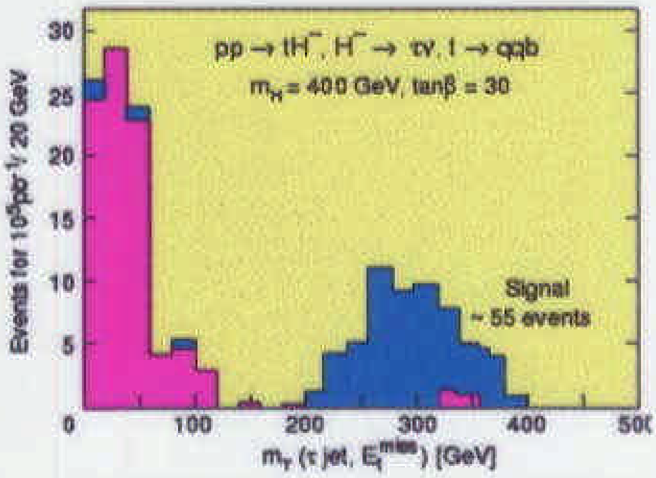
$\hookrightarrow \tau\nu$

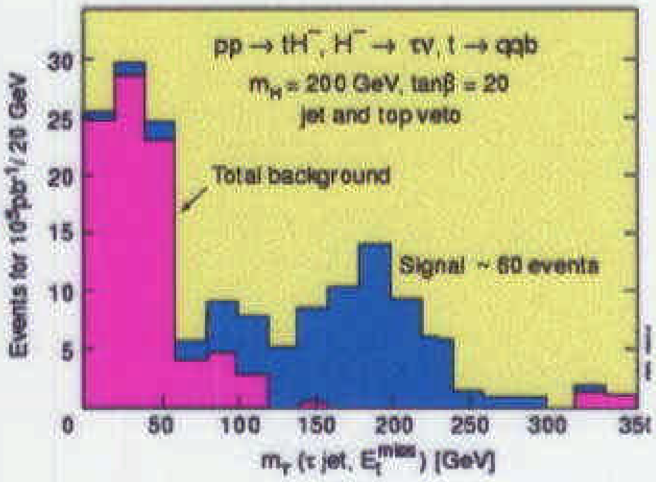
Backgrounds: W+ jets,
$t\bar{t}$, Wtb, QCD jets

- $p_T$ (τ-jet) > 100 GeV
- $E_T^{miss}$ > 100 GeV
- only one reconstructed top
- jet veto
- τ-polarisation
  ($p^{\pi} / E^{\tau} > 0.8$)

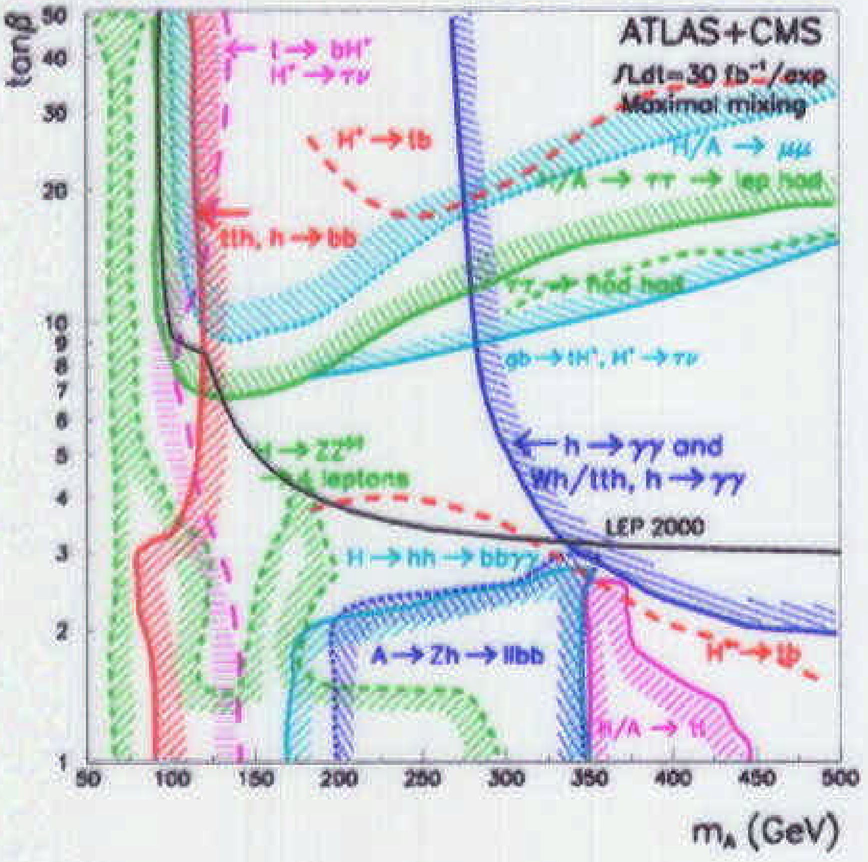
Transverse mass {τ-jet, $E_t^{miss}$}
for background (dominated
by $t\bar{t}$ ) is < $m_W$ (if perfect
resolution)

CMS 100 fb$^{-1}$





# All (almost ) channels together .



Assuming
SUSY particles
are heavy

Not all channels
shown

- Plane covered at low L (30 fb$^{-1}$)
- Main channels : $h \blacklozenge \gamma\gamma, b\bar{b}$, A/H $\blacklozenge\ \mu\mu, \tau\tau$, H$^{\pm} \blacklozenge\ \tau\nu$
- Two or more Higgs can be observed over most of parameter space → disentangle SM / MSSM

Uncertainties : $\Delta m_A \approx \pm 30$ GeV (e.g. from $\Delta m_h \sim 3$ GeV), $\Delta\tan\beta \approx \pm 0.7$
Impact of mixing on couplings studied for minimal mixing
but not for all possible mixing (evolving theory predictions)

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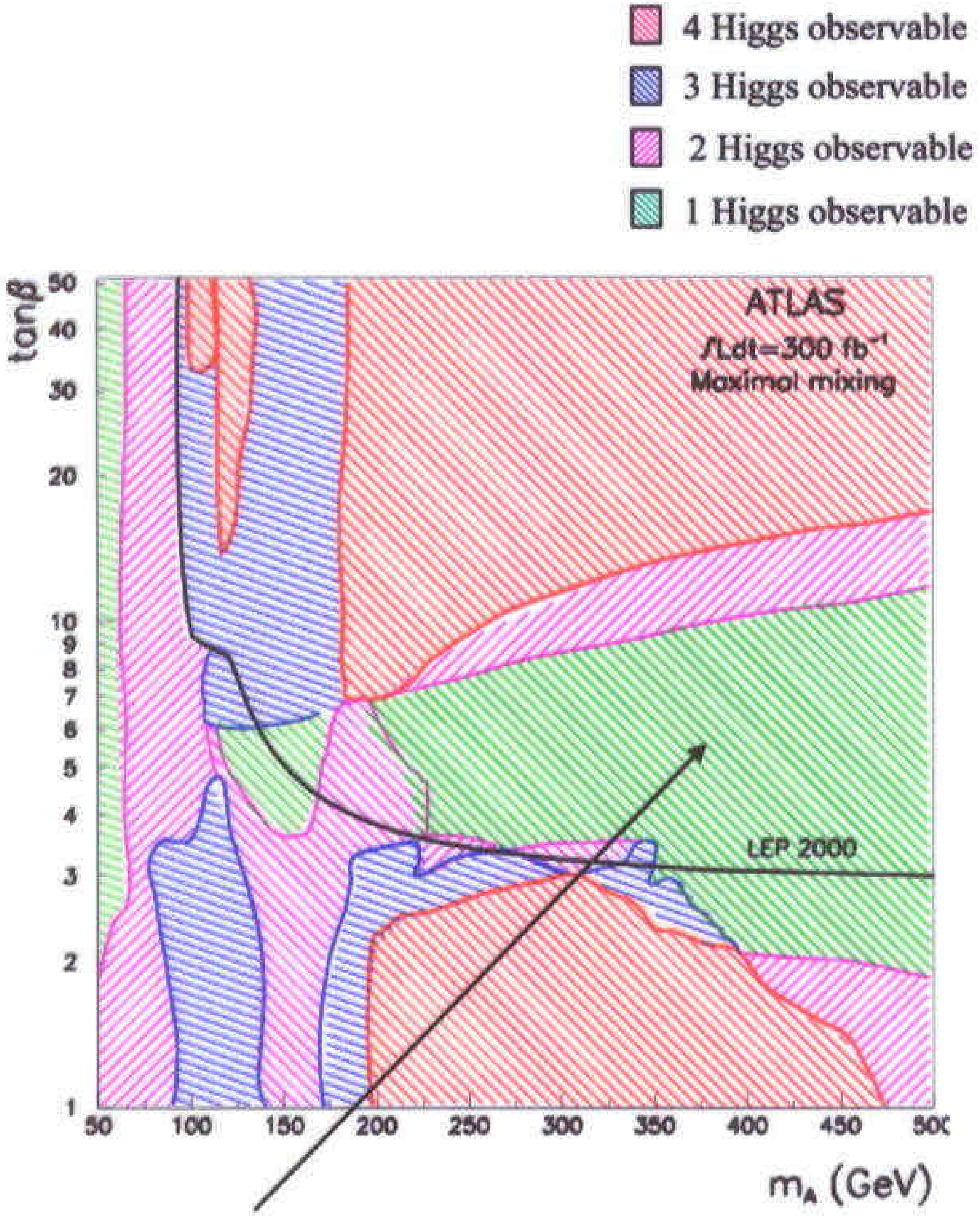


Here:

-- only h observable
-- h ≈ SM Higgs

} → disentangle SM /MSSM ?

## Measurement of the Higgs mass

| MSSM Higgs | $\Delta m/m$ (%) |
|---|---|
| h, A, H $\rightarrow \gamma\gamma$ | 0.1–0.4 |
| H $\rightarrow 4\ell$ | 0.1–0.4 |
| H/A $\rightarrow \mu\mu$ | 0.1-1.5 |
| h $\rightarrow$ bb | 1–2 |
| H $\rightarrow$ hh $\rightarrow$ bb $\gamma\gamma$ | 1-2 |
| A $\rightarrow$ Zh $\rightarrow$ bb $\ell\ell$ | 1–2 |
| H/A $\rightarrow \tau\tau$ | 1-10 |

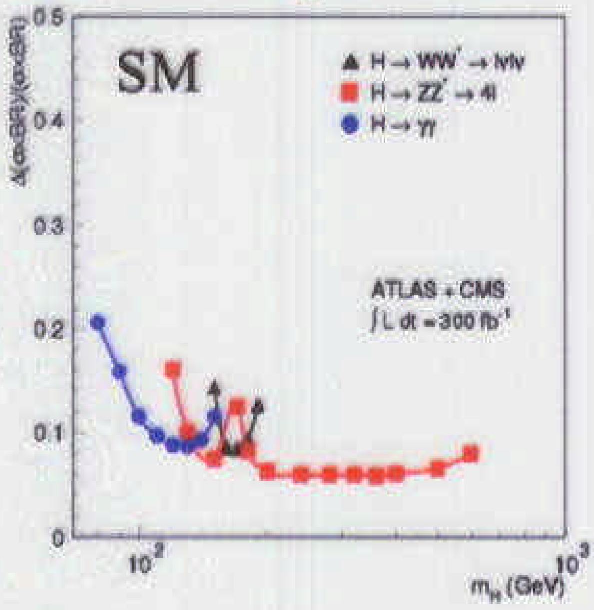
300 $fb^{-1}$

Assumed E-scale uncertainty 1% (g/leptons). Target 0.2% (Z decays)

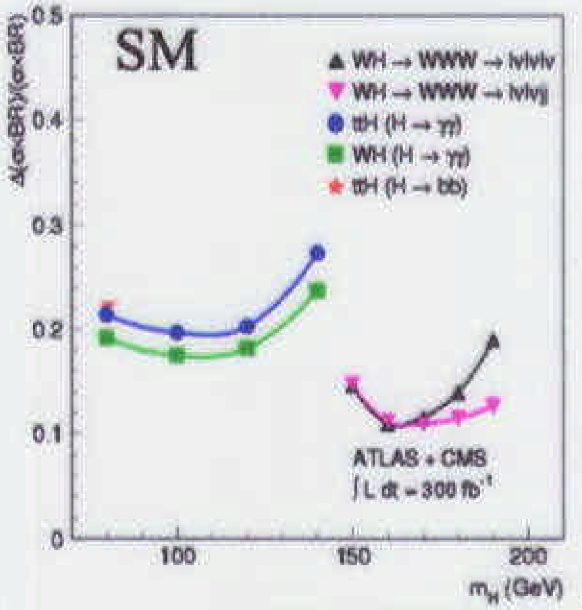
## Measurement of the Higgs production rates ($\sigma \cdot$BR)

Typical precisions: 7% -20% (vs m and MSSM parameters)
Dominant errors: statistics, luminosity (5-10%), background systematics

Associated production



gg fusion



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# Measurement of couplings and branching ratios

- Can be obtained from rate measurements if $\sigma(pp \to H+X)$ known from theory
- Otherwise: measure ratios of rates for different channels → ratios of couplings → many constraints of theory
- Here only few examples (preliminary )

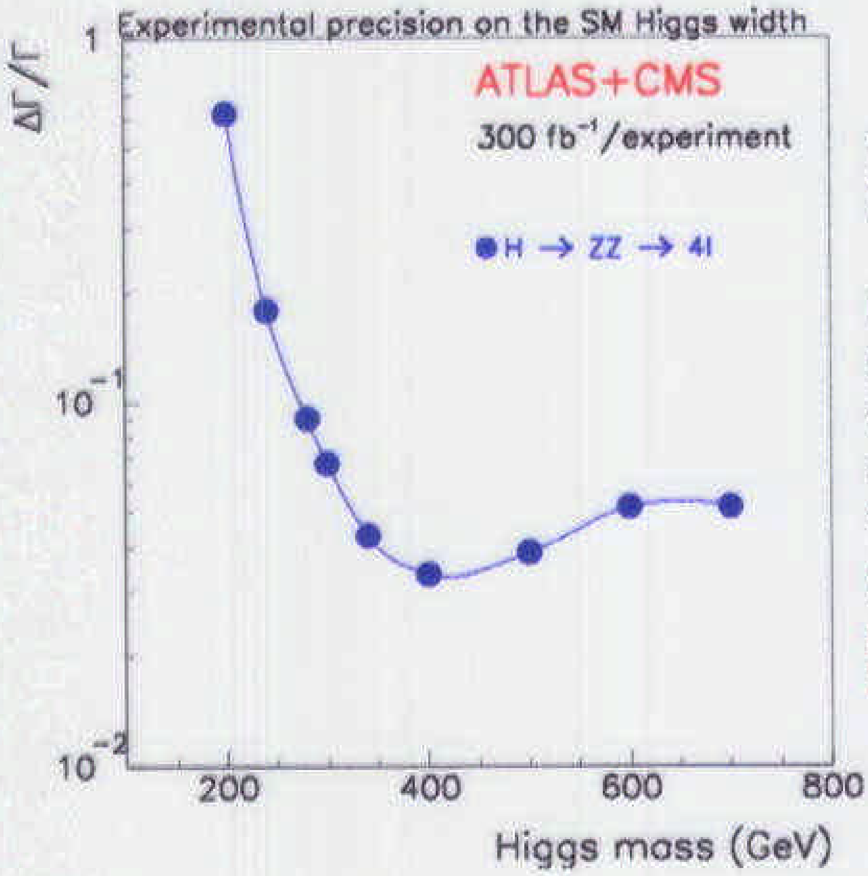
| From | One measures | Error (300 $fb^{-1}$) |
|---|---|---|
| $\frac{(t\bar{t}H + WH) \to \gamma\gamma + X}{(t\bar{t}H + WH) \to b\bar{b} + X}$ | $\frac{BR(H \to \gamma\gamma)}{BR(H \to b\bar{b})}$ | ≈ 15 % (*)<br>80-120 GeV |
| $\frac{H \to \gamma\gamma}{H \to 4l}$ | $\frac{BR(H \to \gamma\gamma)}{BR(H \to ZZ^*)}$ | ≈ 7 %<br>120-150 GeV |
| $\frac{t\bar{t}H \to \gamma\gamma, b\bar{b}}{WH \to \gamma\gamma, b\bar{b}}$ | $\left(\frac{t\bar{t}H}{WWH}\right)^2$ | ≈ 15 % (*)<br>80-120 GeV |
| $\frac{H \to ZZ^{(*)} \to 4\ell}{H \to WW^{(*)} \to \ell\nu\ell\nu}$ | $\left(\frac{ZZH}{WWH}\right)^2$ | ≈ 10 %<br>130-190 GeV |

(*) also in MSSM for $m_A > 200$ GeV

-- Error dominated by statistics in many cases.
-- No theoretical error included (e.g. different K-factors for ttH/WH)
-- Many other possibilities under study.
E.g. WW/ZZ fusion $qqH \to qq\,\tau\tau$ gives access to
H-fermion couplings (D. Zeppenfeld et al., hep-ph/0002036)

# Measurement of Higgs width

Direct measurement : from width of reconstructed mass peak for $m_H > 200$ GeV ($\Gamma_H > \Gamma_{detector}$ in SM)



No theoretical error included

Experimental systematics dominated by uncertainty on $\ell$ energy resolution ($\leq 1.5\%$ from radiative $Z \rightarrow \ell\ell\gamma$ decays)

Indirect measurement at lower masses by measuring cross-sections (hence couplings) for $qq \rightarrow qqH$ with $H \rightarrow \gamma\gamma, \tau\tau, WW$ (Zeppenfeld et al. ) ?

MSSM Higgs bosons: too narrow for direct measurements, except $A,H \rightarrow \mu\mu$ for large $\tan\beta$

# Conclusions

LHC prospects for Higgs Physics

- SM Higgs can be detected in full mass range after 2 years of low luminosity run time (and after understanding of detectors!)

- MSSM sector should be fully explored. Two or more Higgs particles observable in many cases.

- Precice measurements of Higgs mass (0.1%-1%), width (<<10% $m_H$> 250 GeV), couplings (15-20%) achievable.

-Large number of accessible channels demonstrate sensitivity of ATLAS and CMS to large variety of signatures --> potential also for other scenarios

- Higgs discovery at the LHC will provide interesting clues on the question "what's next"

- A light Higgs (m<130) will be a strong clue for existence of SUSY

- A heavier Higgs (M>200) will be a strong clue for the existence of new interactions . Most SUSY model would be ruled out

- "Higgs " not observed.... we have to think again