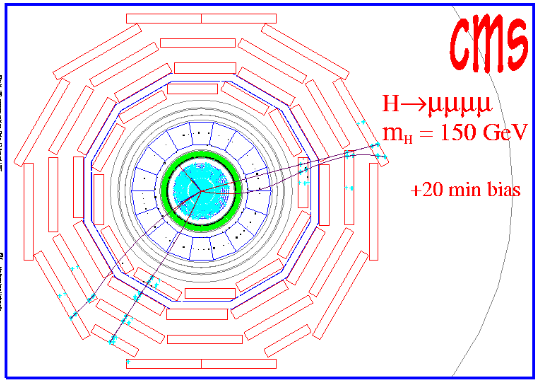

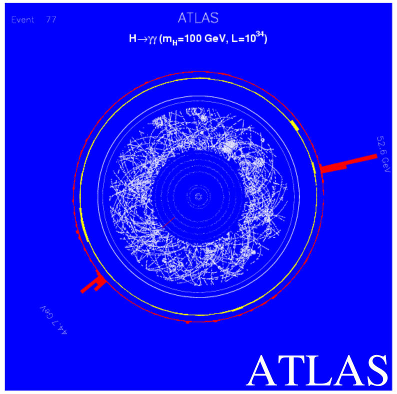

HIGGS Bosons at the LHC

- Standard Model Higgs Boson
  - Search for a light Higgs at the LHC
  - Vector boson fusion
  - Comparison to the Tevatron potential
- Measurement of Higgs boson parameters
- The MSSM Higgs sector

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Revised LHC Schedule

Dec. 2005	Ring closed and cold
Jan. - March 2006	Machine commissioning (1 beam)
April 2006	First collisions , pilot run
	$L=5\times10^{32}$ to 2×10^{33} , $\leq 1\ fb^{-1}$
	Start detector commissioning
	~ 10^5 $Z \to \ell\ell$, $W \to \ell\nu$, tt events
May - July 2006	Shutdown: continue det. installation
Aug. 2006	Physics run : $L=2\times10^{33}$, 10 fb^{-1}
- Feb. 2007	Complete detector commissioning,
	start of physics
→ 2008	$L=2\times10^{34}$, 100 fb^{-1} per year
	(high luminosity LHC)

CMS Detector construction

HCAL assembly

ATLAS detector construction

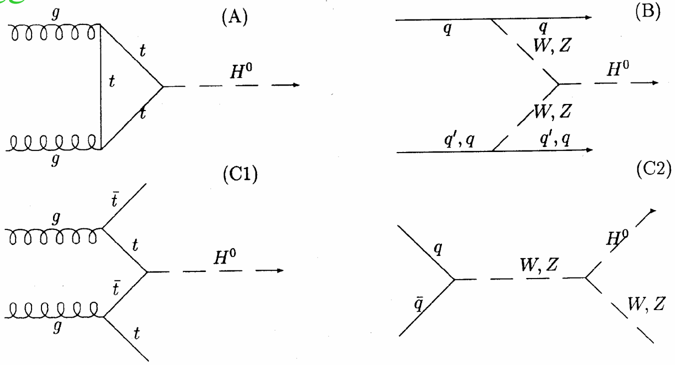
Liquid Argon Calorimeter

Superconducting solenoid ready

SM Higgs production at the LHC

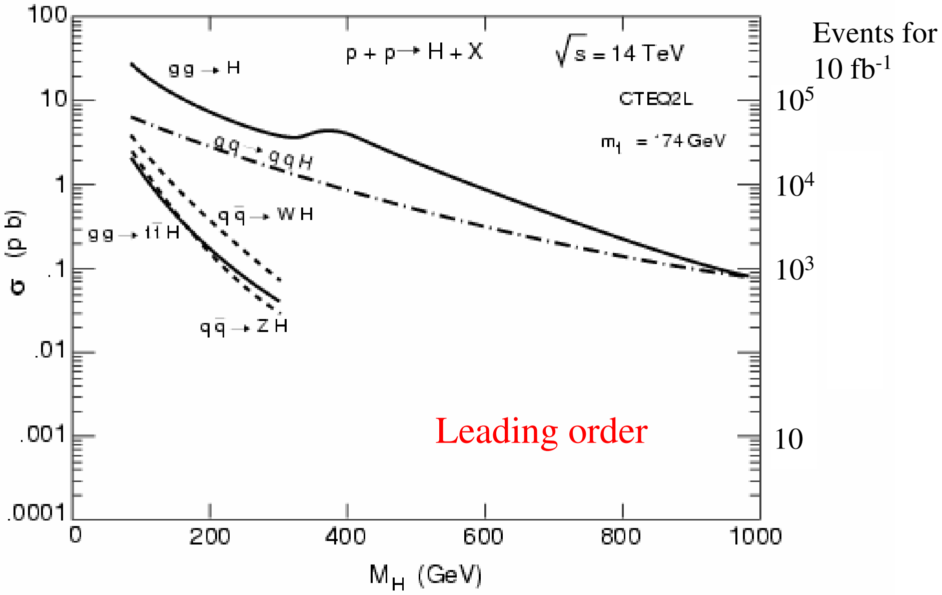
gg fusion

WW/ZZ fusion



associated $t\bar{t}H$

associated WH, ZH



- K-factors (≡ higher-order corrections) = 1.6 – 1.9 gg → H
- Residual uncertainties on NLO cross-sections (PDF, NNLO, etc.) ≤ 20% (except ttH)

Main search channels at the LHC

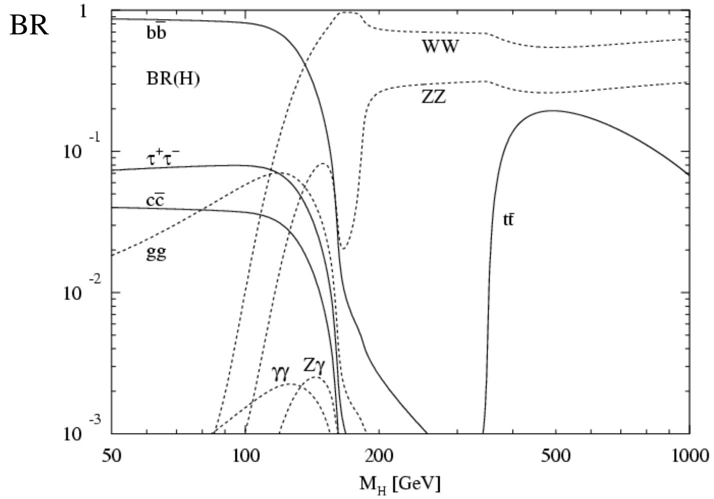
Large QCD backgrounds:

σ ($H \to b\bar{b}$) ≈ 20 pb direct production, m_H =120 GeV

σ ($b\bar{b}$) ≈ 500 μb

→ no hope to trigger / extract fully hadronic final states

→ look for final states with ℓ, γ (ℓ = e,μ)



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

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

$m_H > 2\,m_Z$: $H \to ZZ \to 4\ell$

$qqH \to ZZ \to \ell\ell\,\nu\nu$

$qqH \to ZZ \to \ell\ell\,jj$

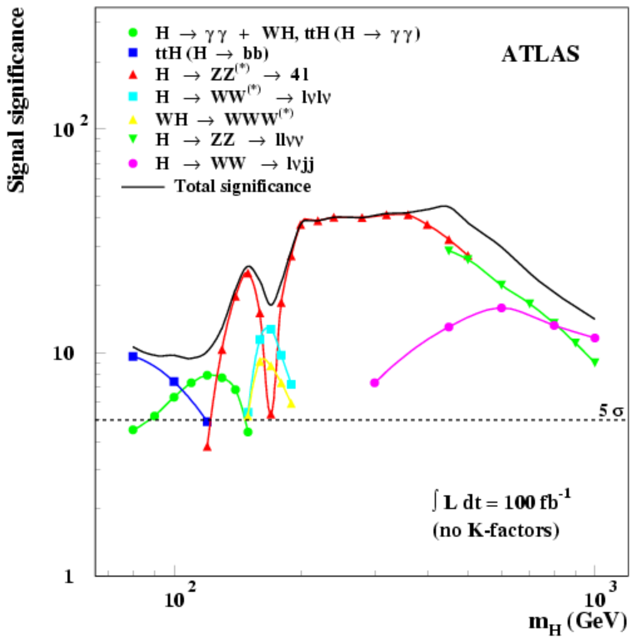
$qqH \to WW \to \ell\nu jj$

$m_H > 300$ GeV forward jet tag

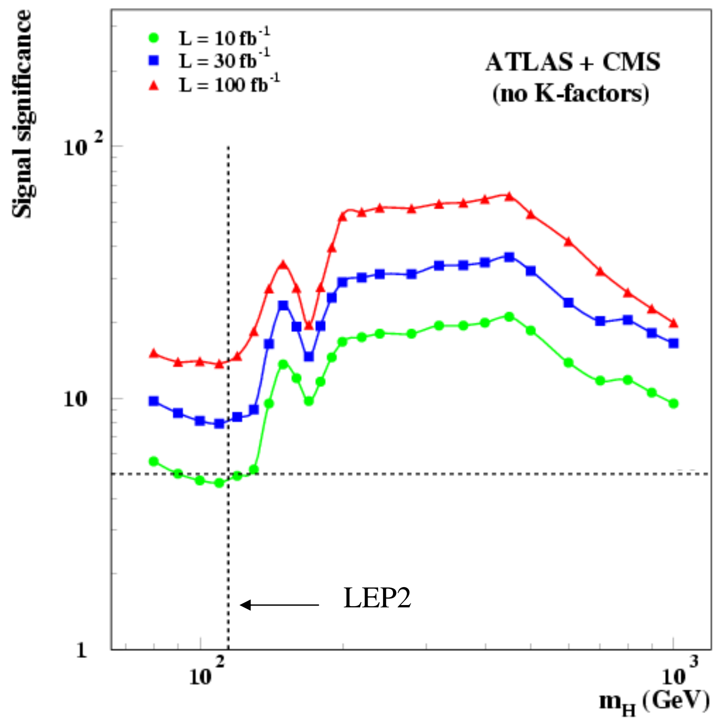
Detector performance is crucial: b-tag, ℓ/γ E-resolution, γ/j separation, E_T^{miss} resolution, forward jet tagging, ...

Discovery potential for a SM Higgs boson

$$\frac{S}{\sqrt{B}}$$



- Good sensitivity over the full mass range from ~100 GeV to ~ 1 TeV
- For most of the mass range at least two channels available



5σ

L per experiment

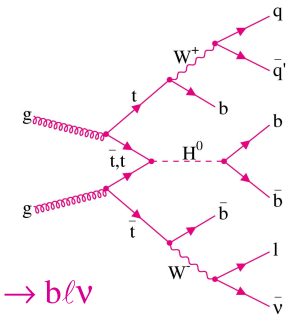
M_H = 115 GeV
10 fb^{-1}
S/ $\sqrt{B}$ = 4.7

- The Higgs boson discovery is possible over the full mass range already with ~10 fb^{-1}

However:

- It requires the combination of both experiments and two channels ($H \to \gamma\gamma$ and ttH, $H \to bb$) in the low mass region
- It will take time to operate, understand and calibrate the detectors
  $\to$ Higgs physics will not be done before 2007

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



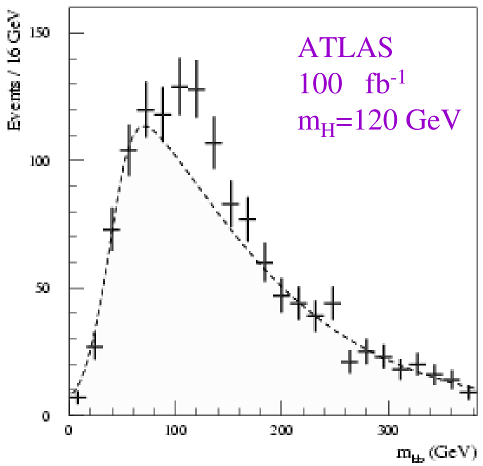
ATLAS study

σ x BR ≈ 300 fb

- Complex final state: $H \rightarrow bb$, $t \rightarrow bjj$, $t \rightarrow b\ell\nu$

•Main backgrounds:

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



S = 62 events
B = 257 events
S/B ~ 0.24

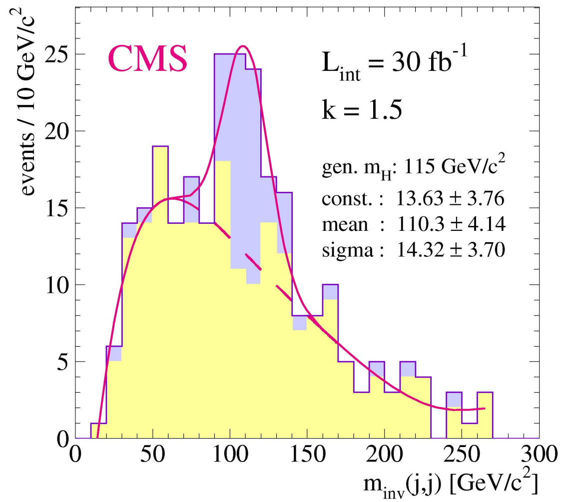
S/ $\sqrt{B}$ = 3.9

- b-tagging performance is crucial
  ATLAS results for 2D-b-tag from full simulation
  (ε_b =60% R_j (uds)~ 100 at low L)

- Shape of background must be known;
  60% (from ttbb) can be measured from ttjj using anti-b tag

CMS Study (new)

- Use similar technique as ATLAS
- ttjj background generation done with CompHep + PYTHIA ISR/FSR
- Based on fast detector simulation only
- Likelihood method for reconstruction of top decays and event kinematics
- K-factors for signal included (1.5)



S = 38 events
B = 52 events
S/B ~ 0.73

S/ $\sqrt{B}$ = 3.5
for K = 1.0

- Comparable significance for K=1
  (gain in significance by using likelihood method is compensated by larger background found with Comphep ttjj calculation)

- LHC experiments need a better understanding of the signal and the backgrounds (K-factors for signal and backgrounds)

Comparison of the LHC and Tevatron potentials

Higgs signal

cross-section are ~10 times larger at LHC
for $qq \to W/Z + H$ and ~70-80 times larger
for $gg \to H$ (large g contribution to PDF's at LHC)

PYTHIA

Process	$\sigma \cdot$ BR $p\bar{p}$ 2 TeV	$\sigma \cdot$ BR pp 14 TeV	$\frac{\text{LHC}}{\text{Tevatron}}$	
$WH \to \ell \nu b\bar{b}$ m_H=120 GeV	20 fb	210 fb	10	$qq \to WH$
$H \to WW \to \ell\nu\ell\nu$ m_H = 150 GeV	15 fb	1150 fb	77	$gg \to H$
$H \to \gamma\gamma$ m_H = 150 GeV	0.3 fb	22 fb	73	$gg \to H$
$H \to ZZ \to 4\ell$ m_H = 150 GeV	0.07 fb	5.5 fb	78	$gg \to H$

$\sqrt{s}$ = 2 TeV:
- -- accessible channels: WH, ZH, $WW^{(*)}$
- -- hopeless : $H \to \gamma\gamma$, 4 ℓ (best channels at LHC) (rate limited)

Backgrounds

EW cross-section are ~10 times larger at LHC,
QCD cross-sections ~ 100 times larger
(gg and gq contributions strongly enhanced)

PYTHIA

Process	σ (pb) $p\bar{p}$ 2 TeV	σ (pb) pp 14 TeV	$\frac{\text{LHC}}{\text{Tevatron}}$
WZ	2.5	26	10
WW	8.5	71	8.5
$q\bar{q}' \to W^* \to t\bar{b}$	0.5	5	10
$t\bar{t}$	6.4	600	95
QCD jets p_T^{hard} > 30 GeV	10^6	10^8	100

Acceptance

Acceptance of cuts for <u>same detector and analysis</u> is ~ 2 times larger at Tevatron:
- -- physics is more central
  - $\to$ higher efficiency of η cuts
- -- less initial state g radiation (smaller $\sqrt{s}$)
  - $\to$ jet veto less harmful

Karl Jakobs Fermilab Higgs workshop, May 2001

<u>For the same integrated luminosity, same detector, same analysis</u>
(e.g. ATLAS detector performance and analysis for $p\bar{p}$ $\sqrt{s}$ = 2 TeV and pp $\sqrt{s}$ = 14 TeV), after kinematic cuts :

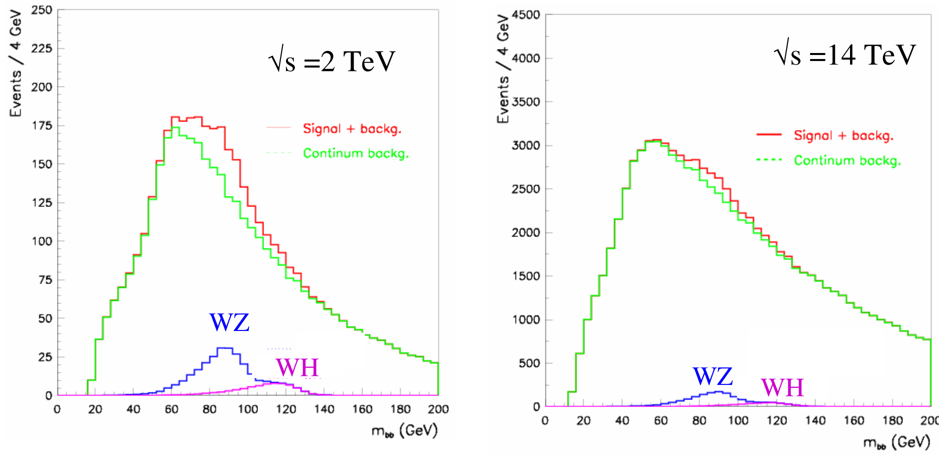
	$WH \to \ell\nu\ b\bar{b}$ $ZH \to \ell\ell\ b\bar{b}$	$H \to WW^{(*)} \to \ell\nu\ell\nu$ (m_H = 160 GeV)
S (14 TeV) / S (2 TeV)	≈ 5	≈ 30
B (14 TeV) / B (2 TeV)	≈ 25	≈ 6
S/B (14 TeV) / S/B (2 TeV)	≈ 0.2	≈ 5
S/√B (14 TeV) / S/√B (2 TeV)	≈ 1	≈ 10

➡ -- similar potential for WH and ZH, with larger S at $\sqrt{s}$ = 14 TeV and better S/B at $\sqrt{s}$ = 2 TeV

-- larger potential at $\sqrt{s}$ = 14 TeV for $H \to WW^{(*)}$
(production dominated by $gg \to H$)

Why are the WH and ZH channels (discovery channels for the Tevatron) not included in the LHC results ?

m_H = 120 GeV, 30 fb^{-1}



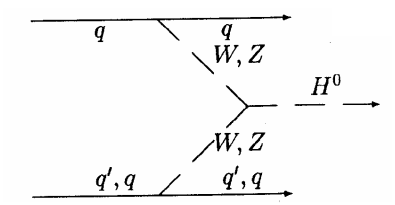
Backgrounds (tt, Wjj, Wbb, WZ):
-- large and with different shapes
-- not all well known today (missing K-factors)
-- not all can be measured precisely with data
→ large background systematics in this channel and S/B ~ few %

⬇

→ considered as marginal discovery channel at the LHC

$ZH \to \ell\ell$ bb, $ZH \to \nu\nu bb$ have smaller sensitivity and/or even higher backgrounds → hopeless

Higgs production via Weak Boson Fusion



Motivation:

- •Additional potential for Higgs boson discovery
- •Important for the measurement of Higgs boson parameters (couplings to bosons, fermions (taus), total width)
- •Detection of an invisible Higgs

proposed by D.Zeppenfeld et al. (several papers...)

σ = 4 pb (20% of total cross section for m_H = 120 GeV)
however: distinctive signature of

- two high P_T forward jets
- little jet activity in the central region

ATLAS and CMS studies have been performed,
first, preliminary results available

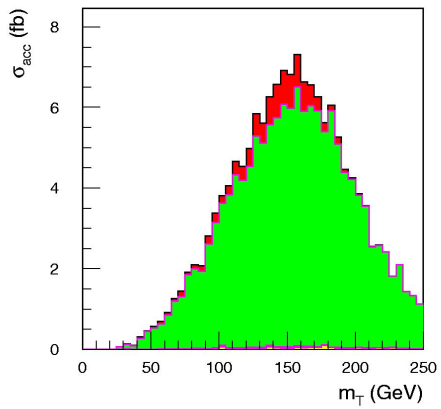
qqH →qq WW → qq l ν l ν

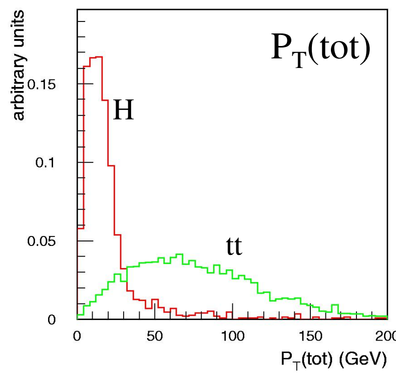
ATLAS:

- Signal and background simulations with PYTHIA
- El.weak backgrounds (t-channel vector boson exchange from matrix element calculation, D.Zeppenfeld et al.)
- Initial and final state radiation included (PYTHIA)

• Basic cuts on isolated leptons: $P_T > 20$ GeV
$|\eta| < 2.5$
• Basic cuts on tagging jets: $P_T > 20$ GeV
$\Delta\eta > 4.4$

Dominant background at that level: tt production





Additional rejection:

- M_{jj} (inv. Mass of tag jets)
- P_T (tot) = $P_T(l_1) + P_T(l_2) + P_t^{miss} + P_T(j_1) + P_T(j_2)$
  (less sensitive to pile-up than jet-veto over large rap.)
- Jet Veto (no jets with $P_T > 20$ GeV in $|\eta| < 3.2$)

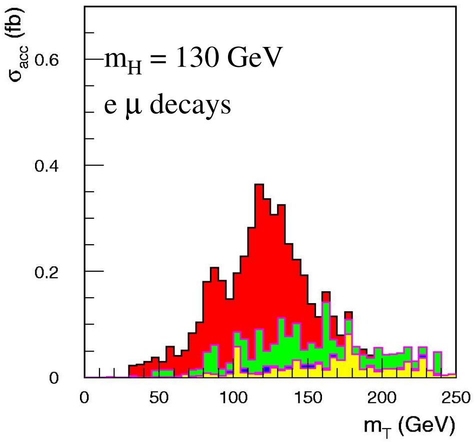
Karl Jakobs Fermilab Higgs workshop, May 2001

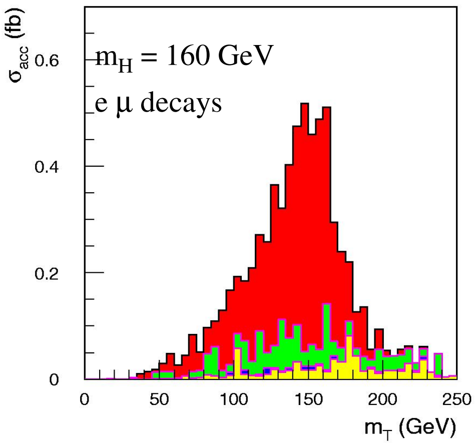
Expected event rates for 10 fb^{-1}: m_H =160 GeV

preliminary

m_H (GeV)	130	140	150	160	170	180	190	200
Signal	11	20	31	50	53	47	37	28
S/B	0.5	0.9	1.4	2.3	2.4	2.1	1.7	1.3

Main background: remaining tt background (13.1 events)
WW el. weak background (7.1 events)





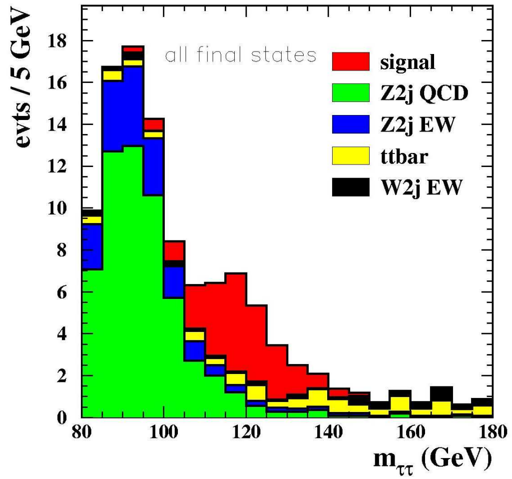
- For the same cuts: significance is worse than in orig. publ. by Zeppenfeld et al. (ISR/FSR effects, jet calibration, efficiencies)

However: confirmed that WBF channel has a large discovery potential

- Still to be done:
proper estimate of forward jet tag efficiencies in a full simulation,
combination with ee and μμ signature, optimization of cuts

qqH → qq τ τ → qq l ν ν l ν ν

ATLAS:
- Similar basic cuts as in WW analysis
- Tau mass reconstruction using collinear approximation
- Optimized cuts for eμ, ee and μμ channels



m_H = 115 GeV
30 fb^{-1}

all channels
(eμ best channel)

S = 17.3 events
B = 11.4 events
S/B > 1

Combined significance (ee, μμ, eμ):

m_H (GeV)	110	115	120	125	130	140	150
10 fb^{-1}	2.2	2.6	2.6	2.4	2.3	1.3	0.6 σ
30 fb^{-1}	3.8	4.3	4.3	4.1	3.8	2.7	1.4 σ

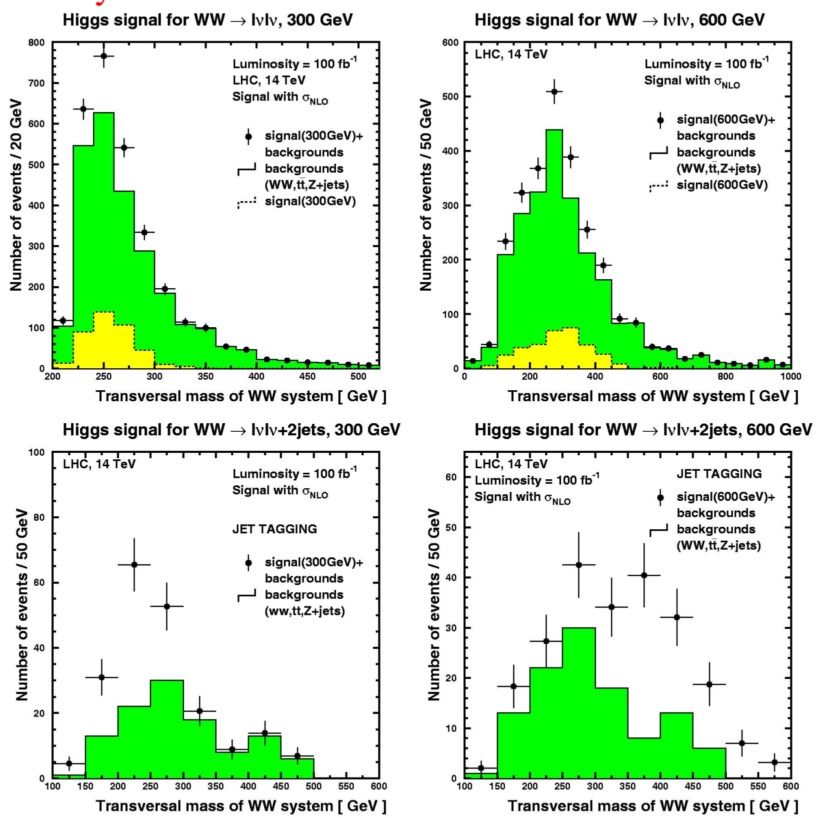
Preliminary, no systematics yet, l-had channel to be added

*) More details in talk by G. Azuelos

Can VBF improve the significance at high mass ?

Signals with $H \to WW \to \ell\nu\ell\nu$

CMS Study



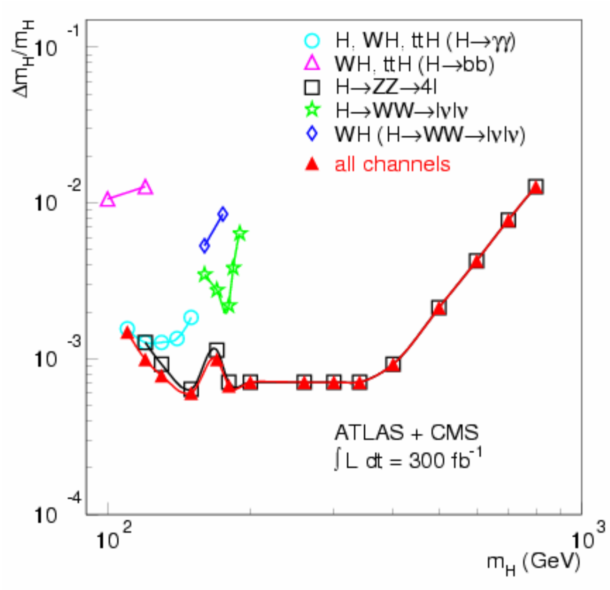
marginal signals for $gg \to H \to \ell\nu\ell\nu$
perhaps possible once M_H known!

good signals with jet tagging $qq \to qqH$:
M_H=300–600 GeV: $\approx 100 - 150$ events

*) more details in talk by M.Dittmar

Measurement of the Higgs boson parameters

Mass of Standard Model Higgs boson



No theoretical error
e.g. mass shift for large Γ_H (interference resonant/non-resonant production)

Dominant systematic uncertainty: γ/ℓ E scale.
Assumed 1‰
Goal 0.2‰
Scale from $Z \to \ell\ell$ (close to light Higgs)

Mass of MSSM Higgs bosons

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

300 fb^{-1}

Measurements of Higgs couplings

- Without theoretical input only measurment of coupling ratios possible

i) Ratio between couplings to bosons

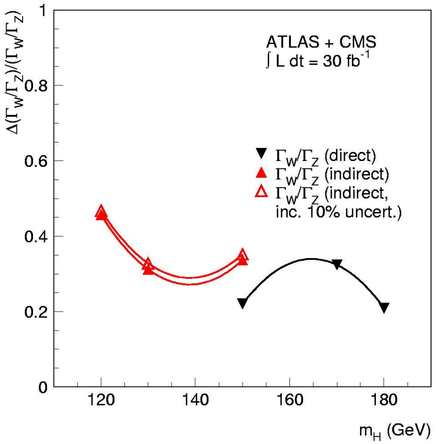
- Direct measurement – $\frac{\sigma \times BR(H \to WW^*)}{\sigma \times BR(H \to ZZ^*)} = \frac{\Gamma_g \Gamma_W}{\Gamma_g \Gamma_Z} = \frac{\Gamma_W}{\Gamma_Z}$

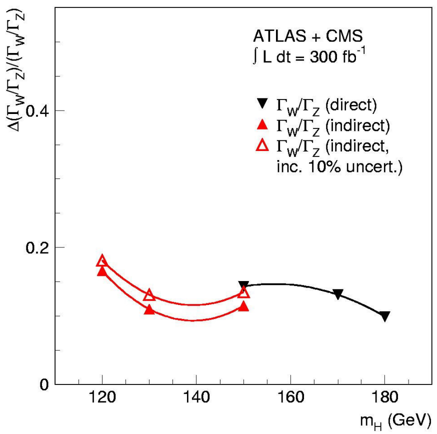
(QCD corrections cancel)

- Indirect measurement – $\frac{\sigma \times BR(H \to \gamma\gamma)}{\sigma \times BR(H \to ZZ^*)} = \frac{\Gamma_g \Gamma_\gamma}{\Gamma_g \Gamma_Z} \sim \frac{\Gamma_W}{\Gamma_Z}$

(Use proportionality between Γ_W and Γ_γ,
needs theoretical input, 10% uncertainty assumed)

Results for 30 fb-1 and 300 fb-1 per experiment



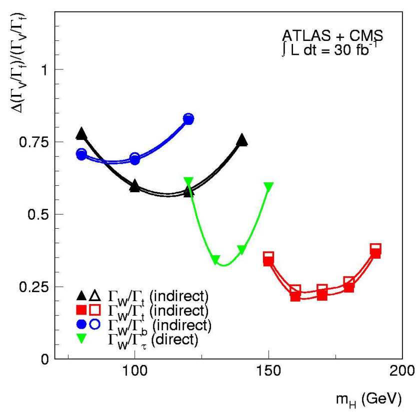


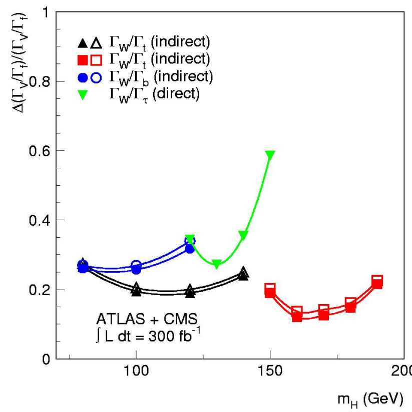
Ratios of boson/fermion couplings

- Direct measurement
  – $\frac{\sigma \times BR(qq \to qqH(H \to WW))}{\sigma \times BR(qq \to qqH(H \to \tau\tau))} = \frac{\Gamma_W \Gamma_W}{\Gamma_W \Gamma_\tau} = \frac{\Gamma_W}{\Gamma_\tau}$
- Indirect measurement
  – $\frac{\sigma \times BR(WH(H \to \gamma\gamma))}{\sigma \times BR(H \to \gamma\gamma)} = \frac{\Gamma_W \Gamma_\gamma}{\Gamma_g \Gamma_\gamma} \sim \frac{\Gamma_W}{\Gamma_t} * C_{QCD}$
  – $\frac{\sigma \times BR(WH(H \to WW))}{\sigma \times BR(H \to WW^*)} = \frac{\Gamma_W \Gamma_W}{\Gamma_g \Gamma_W} \sim \frac{\Gamma_W}{\Gamma_t} * C_{QCD}$
  – $\frac{\sigma \times BR(ttH(H \to bb))}{\sigma \times BR(ttH(H \to \gamma\gamma))} = \frac{\Gamma_t \Gamma_b}{\Gamma_t \Gamma_\gamma} \sim \frac{\Gamma_b}{\Gamma_W}$

  * Uncertainties on the ratio arising through different production processes are not included

Results for 30 fb^{-1} and 300 fb^{-1} per experiment

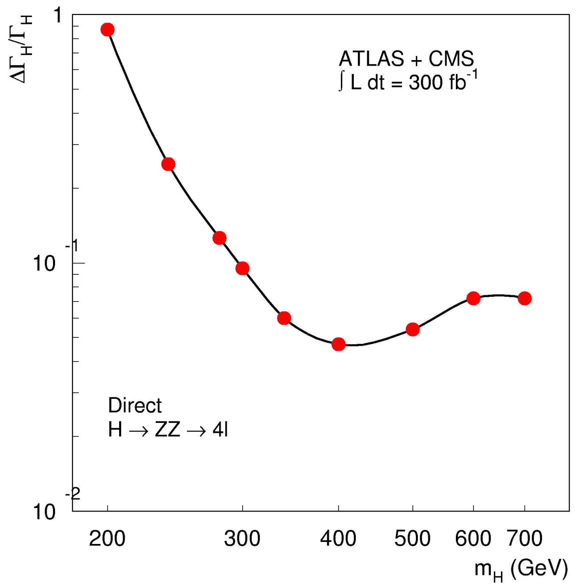




*) More details in Marc Hohlfeld's talk

Measurement of the Higgs width

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



For lower masses, only indirect methods possible:

from rates of $qq \to qq\,H$ with $H \to \gamma\gamma, \tau\tau, WW$
(Zeppenfeld et al., Phys. Rev. D62 (2000))

⇒ talk by D.Zeppenfeld

MSSM HIGGS searches : h, H, A, $H^\pm$

Large variety of channels:

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

– $A/H \to \mu\mu, \tau\tau, t\bar{t}$, $H^\pm \to \tau\nu$, cs, tb
– $H \to hh$, $A \to Zh$
typical of MSSM

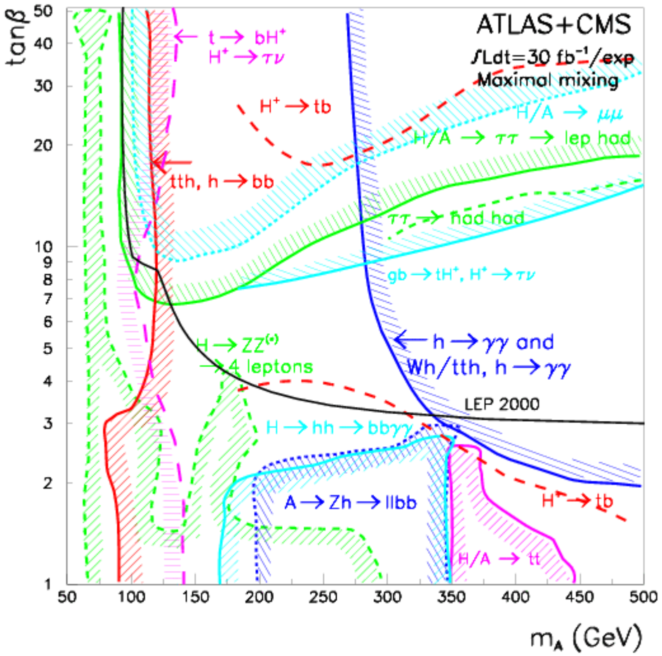
– $A/H \to \chi^0{}_2\chi^0{}_2$
– $\chi^0{}_2 \to h\,\chi^0{}_1$
if SUSY particles accessible

2 steps:
☆ SUSY particles are heavy → do not contribute to Higgs production / decay
🕐 SUSY particles contribute

Results are 5σ discovery contours on m_A, $\tan\beta$ plane for m_{top} =175 GeV, M_{SUSY} = 1 TeV, max mixing (for minimal mixing $m_h < 115.5$ GeV → MSSM ~ fully explored by LEP).

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

LHC discovery potential for MSSM Higgs bosons



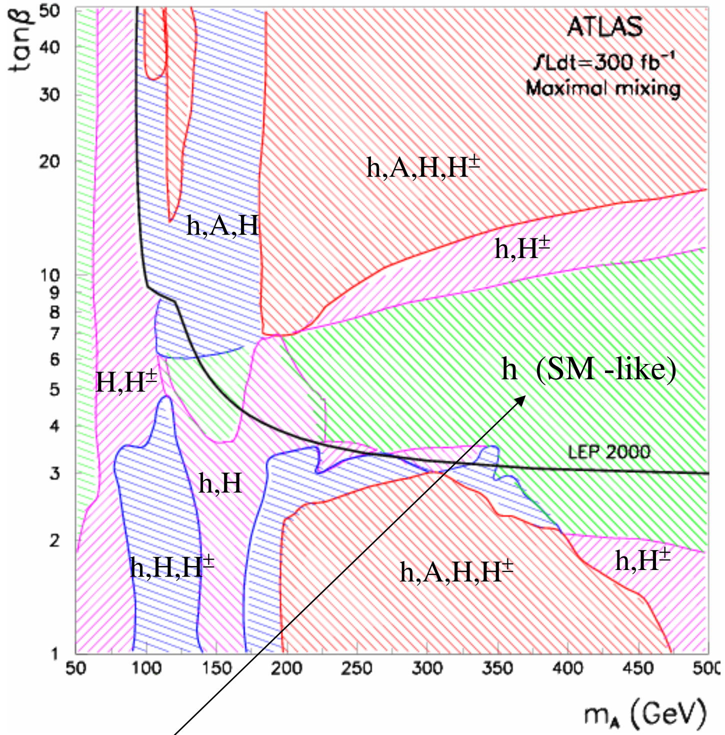
Assuming SUSY particles are heavy

Not all channels shown

- Plane fully covered (no holes) at low L (30 fb^{-1})
- Main channels : $h \to \gamma\gamma$, $b\bar{b}$, A/H $\to \mu\mu$, $\tau\tau$, $H^{\pm} \to \tau\nu$
- Two or more Higgs can be observed over most of the parameter space → disentangle SM / MSSM

- If LEP excess due to hZ production (tanβ > 2, m_A>115GeV), LHC will observe:

h for any tan β and m_A
A,H,H$^{\pm}$ for large tan β and moderate m_A



4 Higgs observable
3 Higgs observable
2 Higgs observable
1 Higgs observable

5σ contours

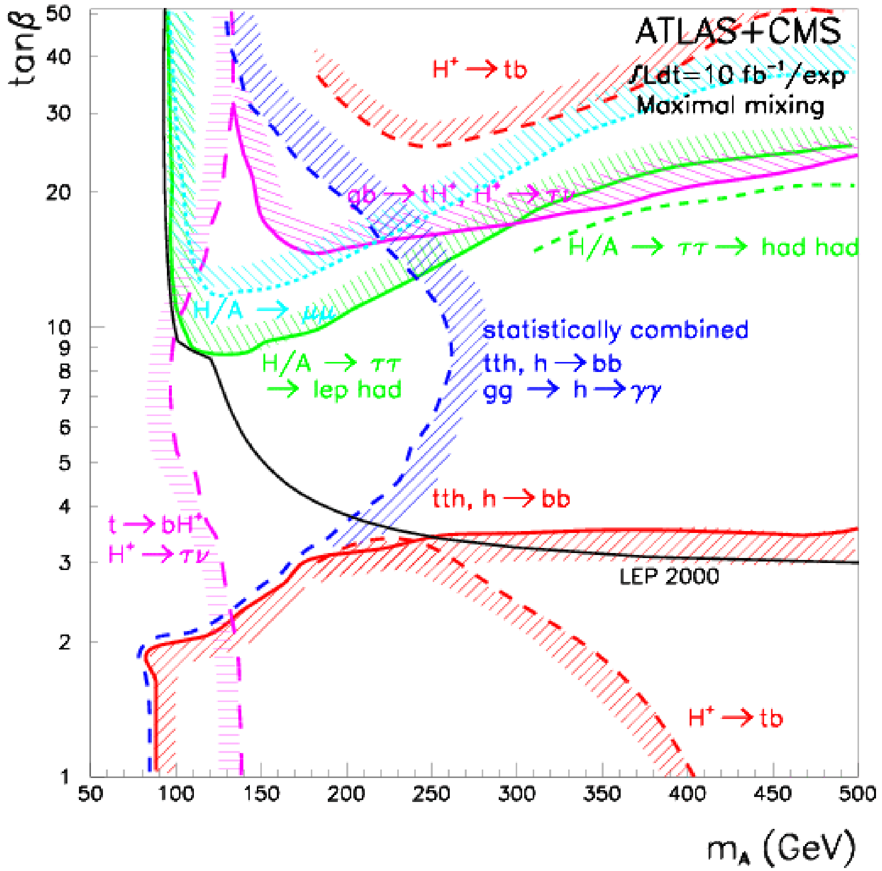
Assuming decays to SM particles only

Here only SM-like h observable if SUSY particles neglected.

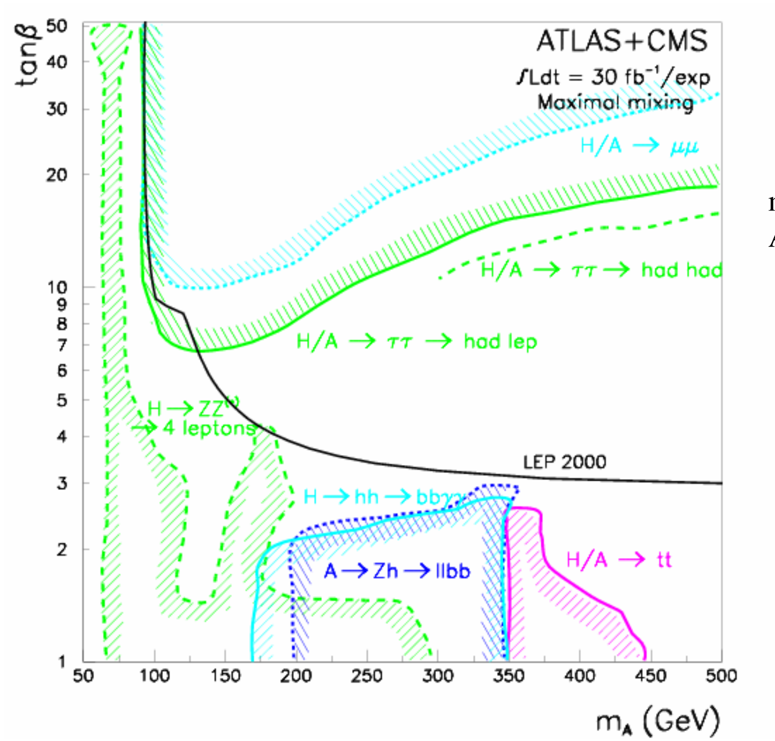
Discovery potential for 10 fb^{-1}

Large part of plane can be explored in 2007

5σ contours



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
  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)

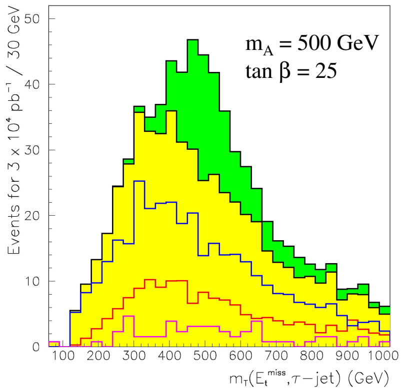
$A/H \to \tau\tau \to h^+\nu\ h^-\nu$:

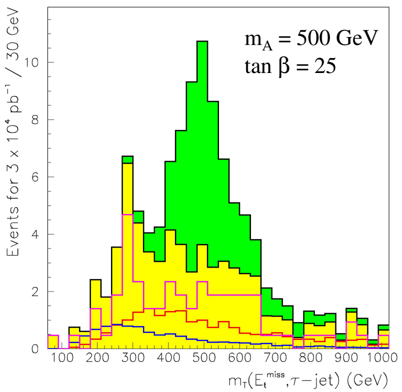
Provides best reach for large m_A. (CMS and ATLAS analyses)

Signature: two stiff opposite-sign isolated tracks ($P_T > 40$ GeV)
P_T^{miss} or 1 b-tagged jet (bbA/H)

Main challenge: reject QCD jet backgr. (already at trigger-level)
Feasible for $m_A > 300$ GeV: (high P_T hadrons, larger P_T^{miss},
larger rejection from isolation)

$\to R_{QCD} \sim 10^{10}$ $\to$ QCD background << 10% ($t\bar{t} + Z/\gamma^* \to \tau\tau$)





CMS P_T^{miss} analysis
30 fb^{-1}

b-tag requirement
improves S/B

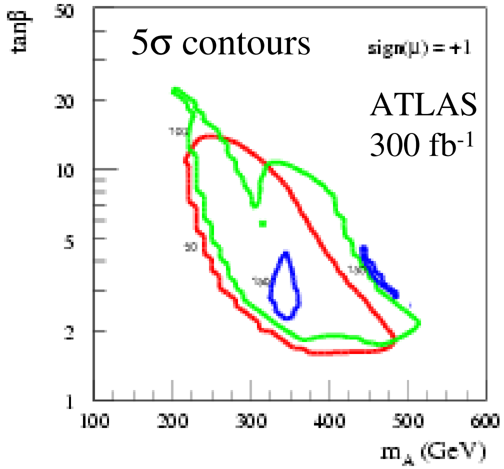
Mass resolution ~10%

CMS: Additional studies on trigger acceptance performed

*) see talk by A.Nikitenko for details

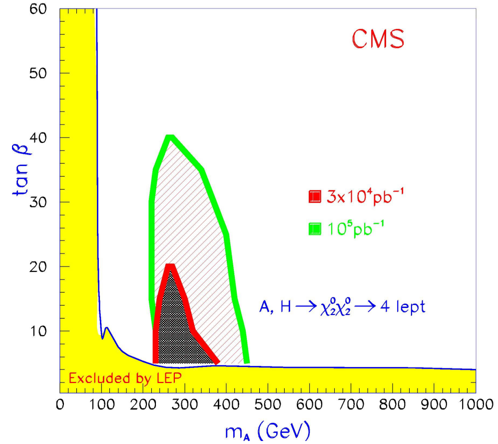
Higgs decays via SUSY particles

If SUSY exists : search for
$H/A \to \chi^0_2\chi^0_2 \to \ell\ell\chi^0_1\ \ell\ell\chi^0_1$



ATLAS:
SUGRA scan

m_0 = 50 - 250 GeV
$m_{1/2}$ = 100 - 300 GeV
tan β = 1.5 - 50
A_0 = 0



CMS:
special choice in MSSM
(no scan)
M_1 = 60 GeV
M_2 = 110 GeV
μ = -500 GeV

Exclusions depend on MSSM parameters (slepton masses, μ)

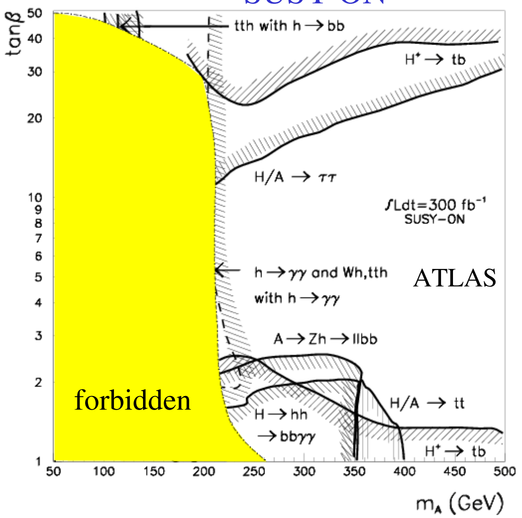
How robust is this potential ?

- SUSY loops can enhance/suppress Higgs production (e.g. gg → h) and decay (e.g. h → γγ)
- A/H/H± → sparticles can compete with SM decays

Preliminary study : mSUGRA impact of SUSY on Higgs decays to SM particles is small :

-- gg → h → γγ 10% smaller
-- tth/Wh → γγ 30% smaller
-- ttH → tt bb not affected
-- BR (A/H/H± → SM particles) reduced by at most 40%

SUSY ON



However : impact of mixing on couplings not studied for all possible mixing scenarios → more work needed

Conclusions

1. LHC has a large discovery potential for a Standard Model and for MSSM Higgs Bosons

-- SM Higgs can be discovered over full allowed mass range after ~ 1 year at 10^{33} cm^{-2} s^{-1} (provided detectors are well understood)

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

-- In addition, precise measurements of Higgs boson parameters (mass and couplings) can be performed

2. Vector Boson fusion channel seems to significantly enhance the discovery potential

-- Tau tau channel in the low mass region
-- Enhanced WW channels
-- Can it be used to see invisible Higgs decays ?

3. New promising channels also in the MSSM section (Charged Higgs, had. Tau decays)

4. Next steps:

- use improved calculations (K-factors for S and B)
- MC work important (Tevatron data → MC → LHC)
- new topics (CP violation, ...)
- .... prepare for the discovery / measurement ....