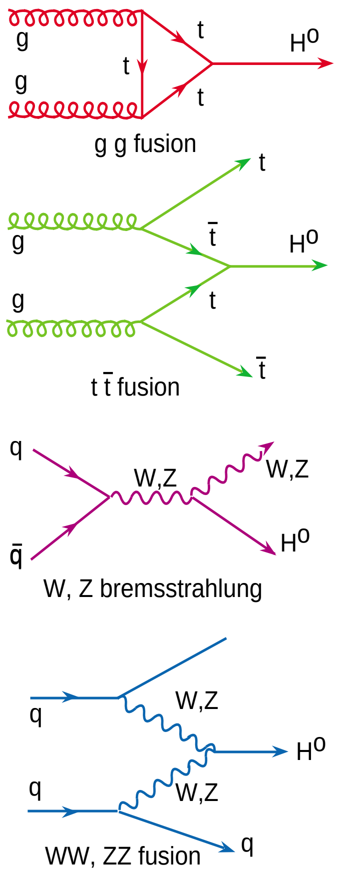
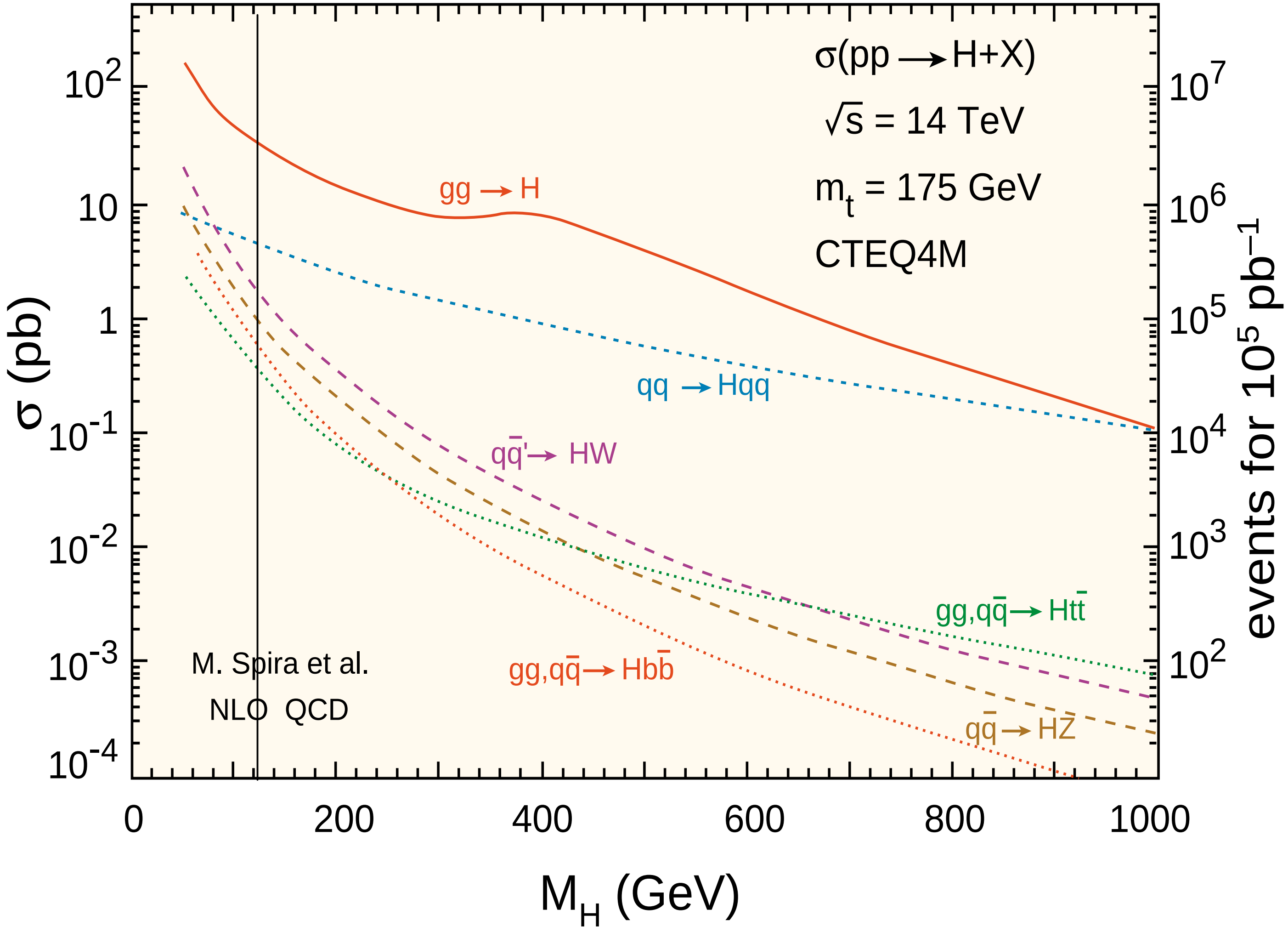
4. Search for the SM Higgs Boson

i. Production and Decay
ii. $H \rightarrow \gamma\gamma$
iii. Associated production channels
iv. $H \rightarrow ZZ^* \rightarrow 4\ \ell$, $H \rightarrow ZZ$ -> $4\ \ell$
v. M(H) ~ 1 TeV : $H \rightarrow \ell\ell\ \nu\nu$, $\ell\ell$ jet-jet
vi. Measurement of Higgs properties
vii. Other possibilities

Production of SM Higgs Boson





- gg → H : K=1.6– 1.9
- residual uncertainties on NLO cross-sections (PDF, NNLO, etc.) ≤ 20% (except ttH)

Decay Modes of the SM Higgs

■ Decays & discovery channels

■ Higgs couples to m_f^2

Heaviest fermion (b quark) always dominates

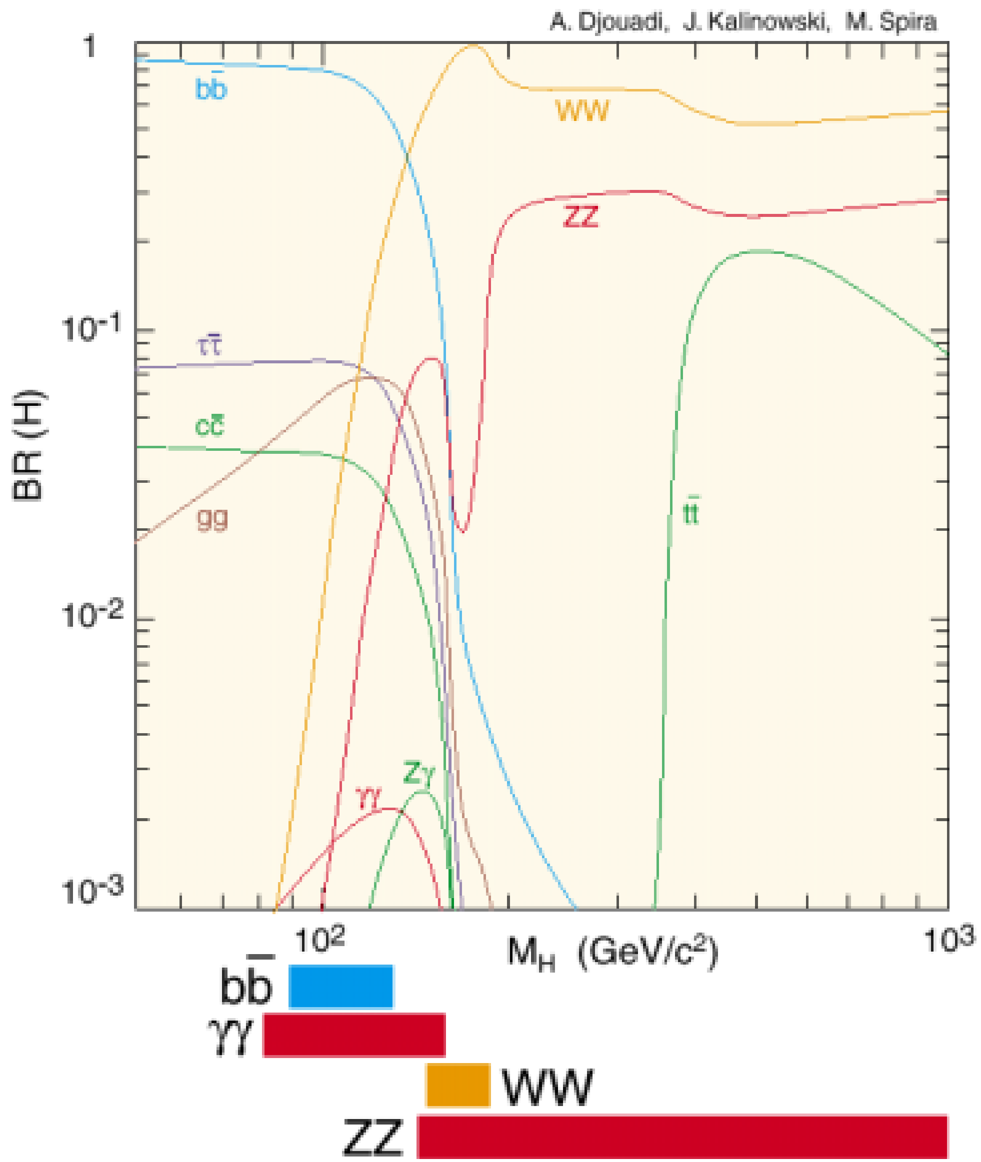
Until WW, ZZ thresholds open

■ Low mass: b quarks$\rightarrow$ jets; poor resolution ~ 15%

Only chance is to use ECAL (use $\gamma\gamma$ decay mode)

■ Once $M_H > 2M_Z$, use ZZ mode

W decays to jets or lepton+neutrino (missing E_T)



Search for SM Higgs Boson

Fully hadronic final states dominate but cannot be used due to large QCD bkg.
⇨**look for final states with isolated leptons and photons despite smaller BR**

Region 1: Intermediate mass region (LEP limit < m_H < 2 m_Z)

m_H < 120 GeV: pp → WH → $\ell\nu$ bb or tt H → $\ell\nu$X bb

m_H < 150 GeV: H → $\gamma\gamma$, Zγ

130? < m_H < 2 m_Z : H → WW* → $\ell\nu$ $\ell\nu$

130? < m_H < 2 m_Z : H → ZZ* → $\ell\ell$ $\ell\ell$

Region 2: High mass region (2 m_Z < m_H < 700)
H → ZZ → $\ell\ell$ $\ell\ell$

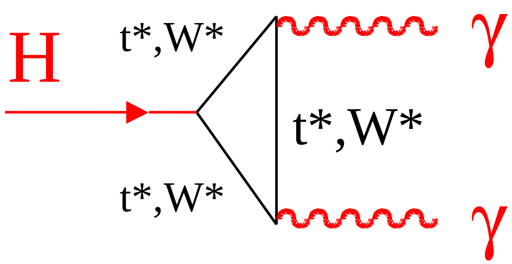
Region 3: Very high mass region (700 < m_H < 1 TeV)
H → ZZ → $\ell\ell$ $\nu\nu$, H → ZZ* → $\ell\ell$ jet-jet
H → WW → $\ell\nu$ jet-jet

forward jet tagging

Recently: qq → qqH with H → $\tau\tau$ (mH~130 GeV), H → WW etc.

$H \rightarrow \gamma\gamma$

Most promising channel in the range $m_H < 150$ GeV



($\sigma.B \sim 50.10^{-3}$ pb @ $m_H \sim 150$ GeV)
σ.B can be modified by heavy undiscovered fundamental fermions or bosons

Backgrounds are large (2pb/GeV), H natural width is small (~MeV)
⇨ **excellent mass resolution** required

$$\sigma_m/m = 0.5\ [\sigma_{E1}/E_1 \ \mathrm{O}\ \sigma_{E2}/E_2 \ \mathrm{O}\ \cot(\theta/2)\Delta\theta]$$

⇨ energy resolution and precise vertex localisation

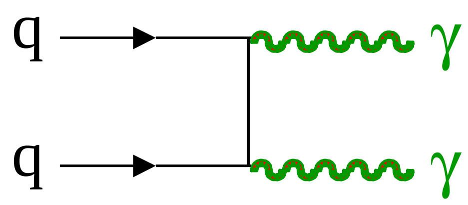
Typical Cuts
2 isolated photons – $p_T > 25, 40$ GeV with $|\eta| < 2.5$
No track or em cluster with $p_T > 2.5$ GeV in a cone size $\Delta R = 0.3$ around γs

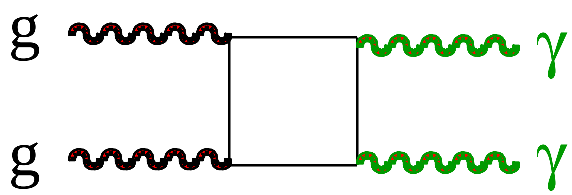
Signal: ~ 1000's of events

$H \to \gamma\gamma$: Backgrounds

Main Backgrounds

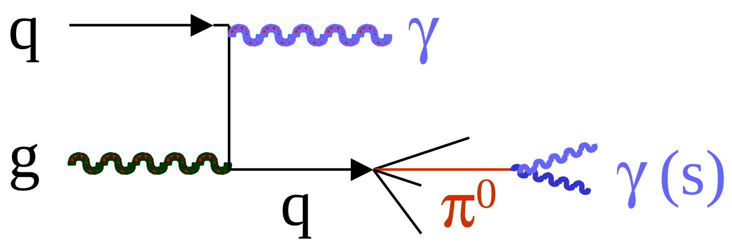
Irreducible: qq annihilation and gg 'box'





$$\frac{\sigma(\gamma\gamma)}{\sigma(H \to \gamma\gamma)} \sim 60$$

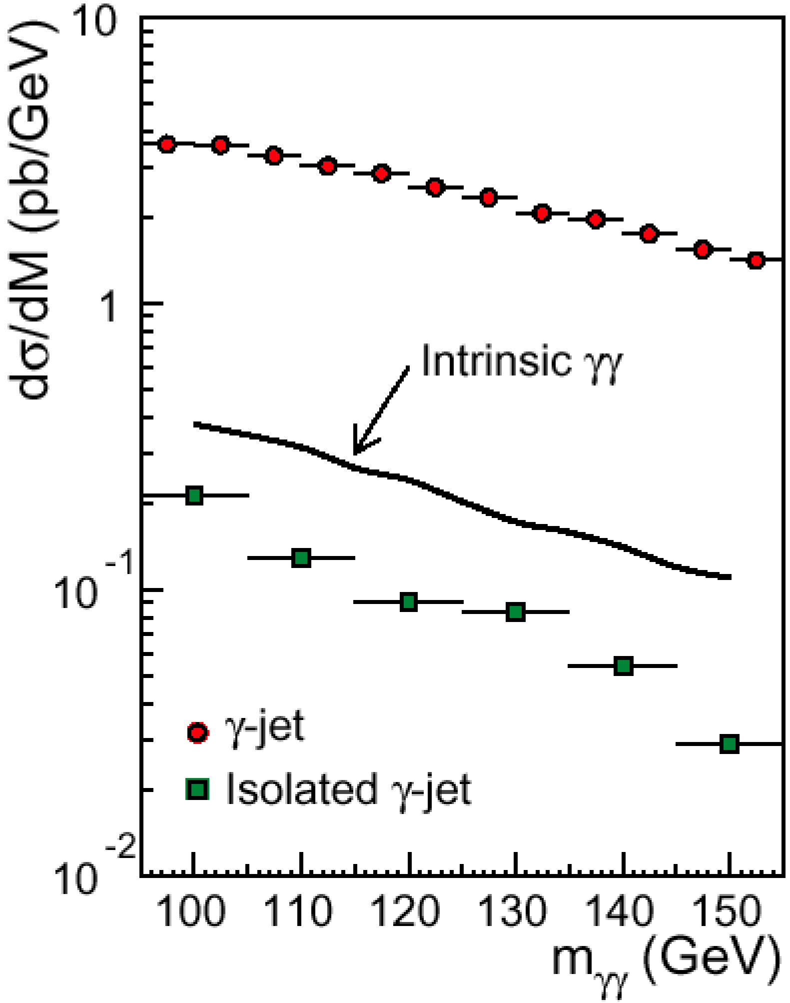
Reducible: γ-jet and jet-jet



$$\frac{\sigma_{jj}}{\sigma(H \to \gamma\gamma)} \sim 10^8$$

A need large γ-jet separation (essentially γ-π^0 separation) to reject jets faking photons

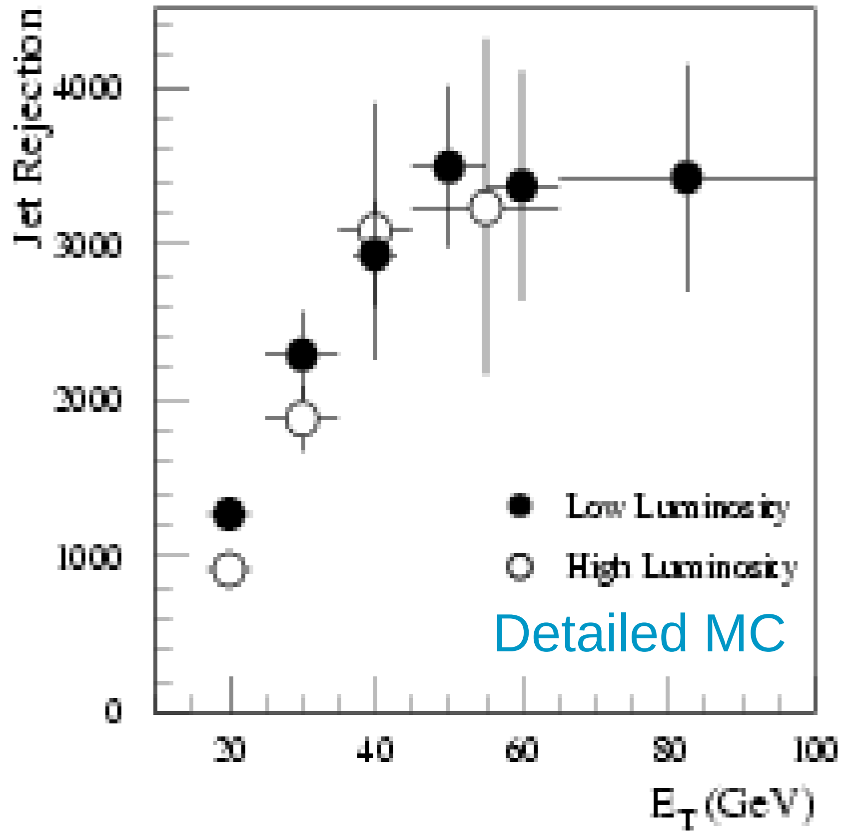
H → γγ : Background Rejection



ATLAS EM calorimeter

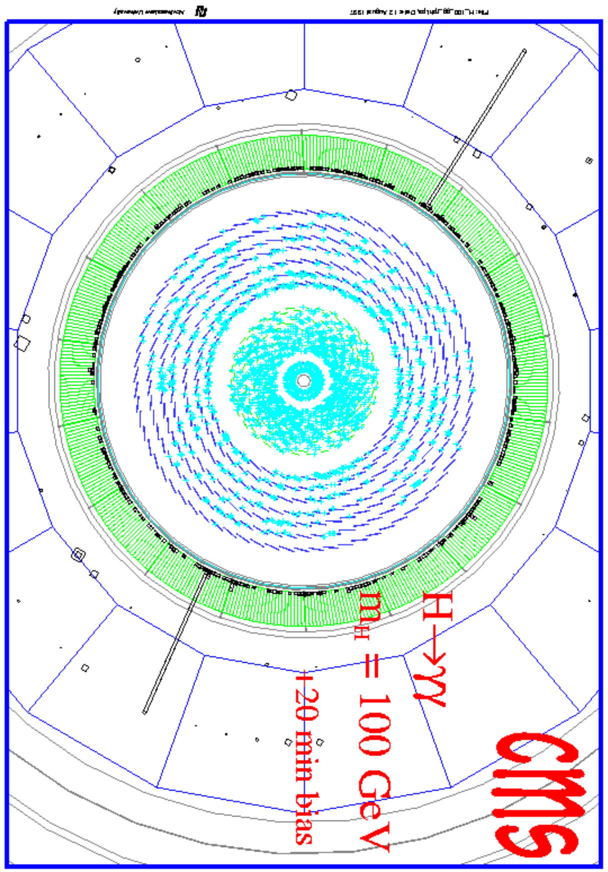
4 mm η-strips in first compartment

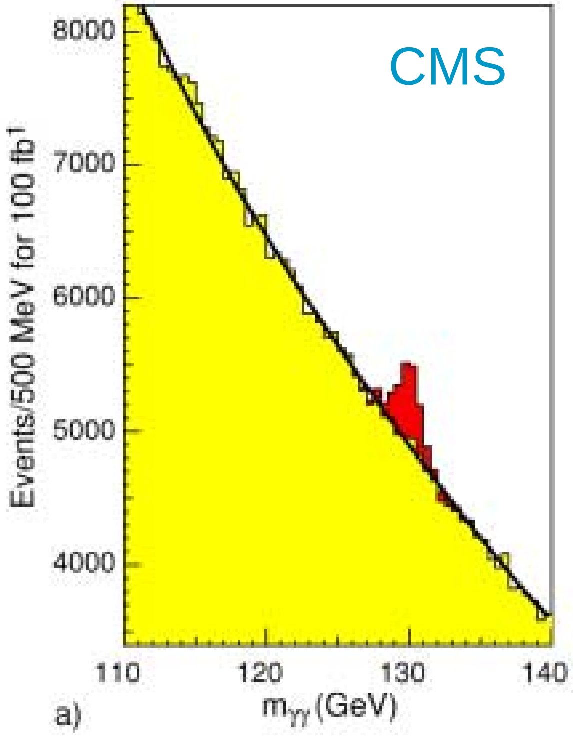
3 longitudinal segments

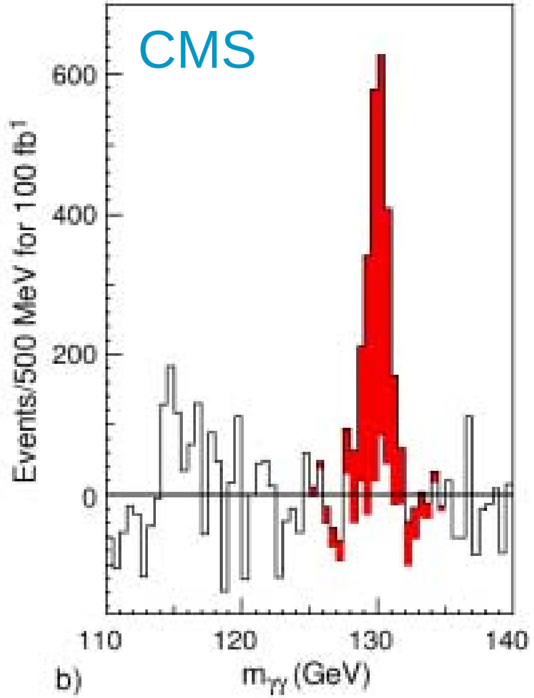


⇨ (γ–jet + jet-jet) < 40% γγ

H → γγ : Signal in CMS







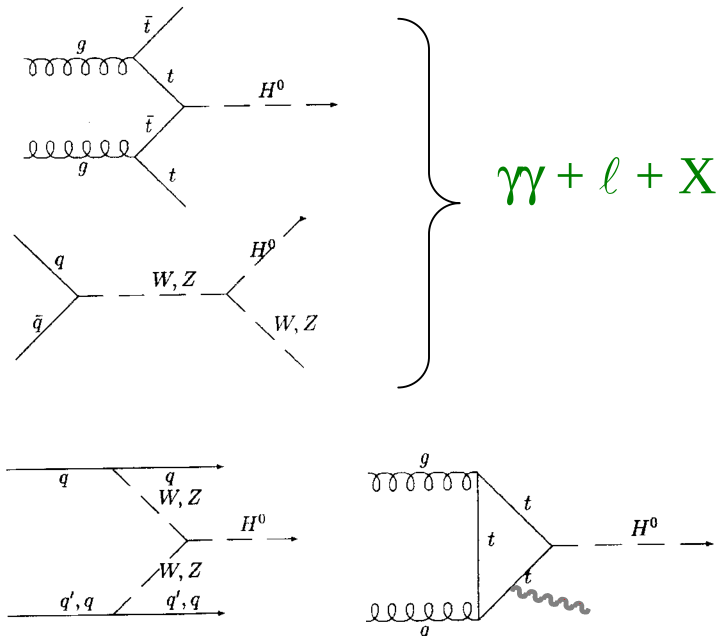
ATLAS, 100 fb^{-1}

m_H (GeV)	120	130	150
S (evts)	1280	1200	650
S/B	0.03	0.035	0.03
S/√B	6.5	6.5	4.3

ATLAS + CMS

S/√B 30 fb^{-1}	5.8	5.9	3.9

$H \rightarrow \gamma\gamma$: Associated Production



$\gamma\gamma + \ell + X$

$\gamma\gamma + \geq 2$ jets
$p_T > 40$ GeV

m_H=120 GeV, 1 experiment, 100 fb^{-1}

	$H_{direct} \rightarrow \gamma\gamma$	$\gamma\gamma + \ell$	$\gamma\gamma +$ jet
S	1280	13	~100
S/B	0.03	2.3	0.3
S/ √B	6.5	4.3	~5

complementary to $H \rightarrow \gamma\gamma$
smaller S but better S/B
needs ≈ 100 fb^{-1} → confirm discovery,
measure ttH, WWH couplings
$\gamma\gamma$ + jets : large theoretical uncertainties

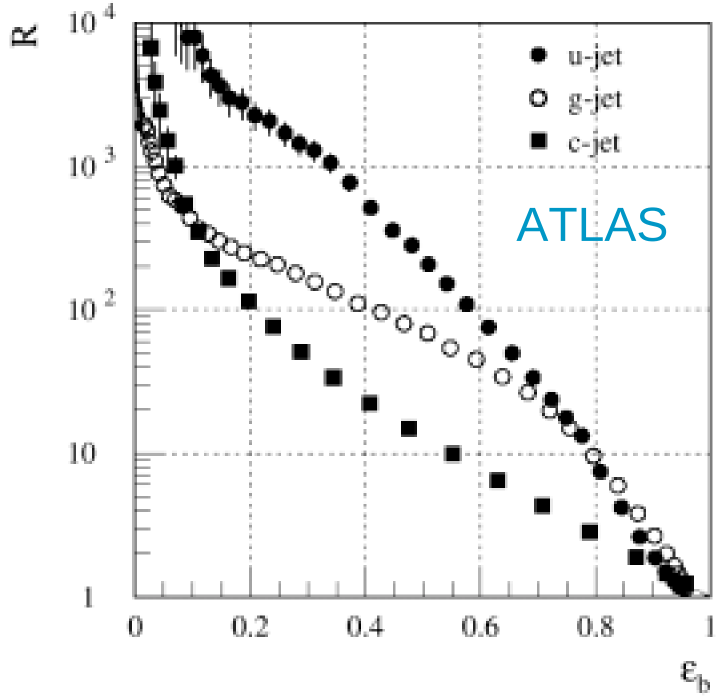
$H \rightarrow bb$ in Associated Production I

Dominant decay for $m_H < 2\ m_H$ is **$H \rightarrow bb$** ($\sigma \sim 20$ pb)
Signal for Higgs produced *in isolation* impossible to extract
no Level-1 trigger and QCD production of bb pairs is v large $N_S/N_B < 10^{-5}$

Associated production: **$pp \rightarrow WH \rightarrow \ell\nu$ bb or tt $H \rightarrow \ell\nu X$ bb** ($\sigma \sim 1$ pb)
a high p_T lepton from W or tt can provide the trigger

ATLAS Study
L-1 Trigger: muon (electron)
with $p_T > 6$ (20) GeV with $|\eta| < 2.5$

$\varepsilon_b \sim 60\%$ for rejection of 100 against light quarks (~ obtained in CDF)



$H \rightarrow bb$ in Associated Production II

ttH channel more powerful

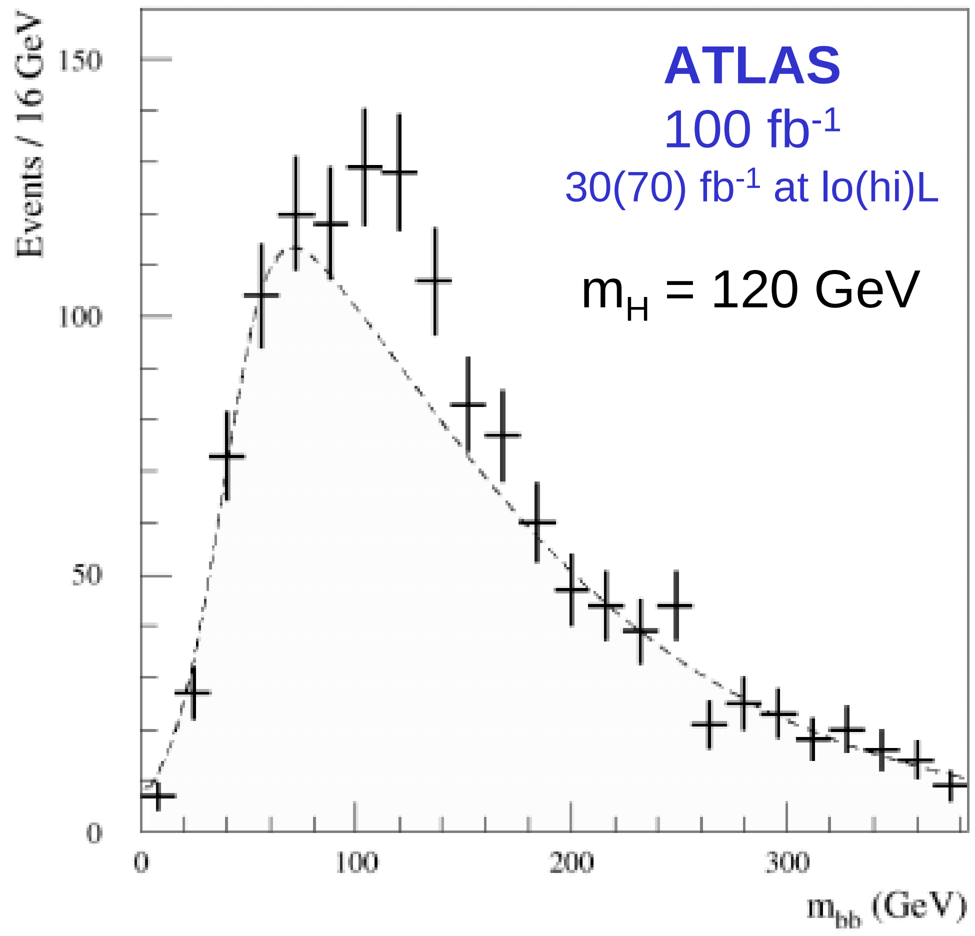
Typical Cuts
Jets retained if p_T > 15 (30)GeV lo(hi)L
No isolated lepton with p_T > 6 GeV
4 tagged b-jets
Reconstruct both top quarks

Signal (100 fb^{-1})
62 evts for m_H= 120 GeV

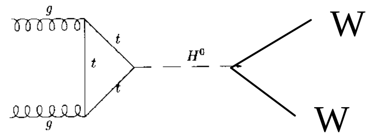
Background
tt *jj* is the most important
~ 250 evts in a bin of width 30 GeV

S/N ~ 0.2 – depends critically on ε_b
and background rejection

2^{nd} observation of H in this mass range

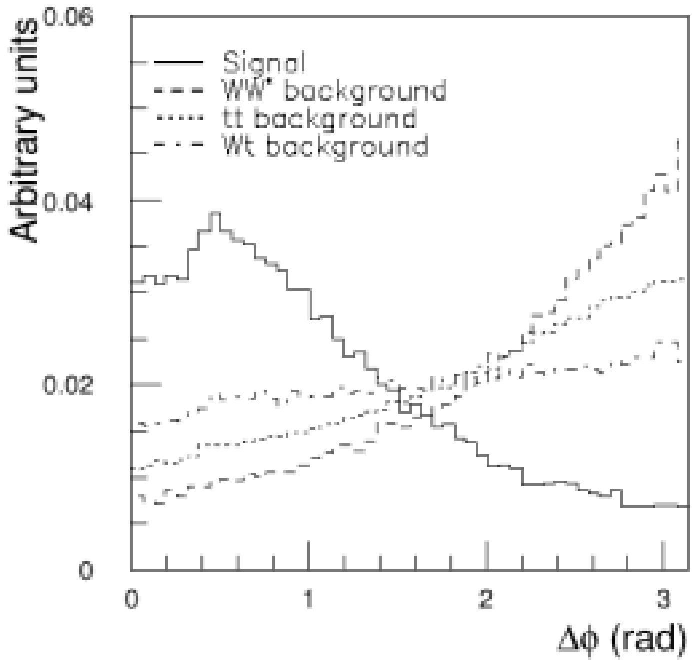


$H \rightarrow WW^* \rightarrow \ell^+\nu\ell^-\nu$



Important around m_H~170 GeV
Where BR(H→ZZ) reduced

Large rate : $\sigma \times BR \approx$ 700 fb
BR ($H \rightarrow WW^{(*)}$) > 70%
Counting channel (no mass peak)
⇨ precise knowledge of bkg needed



Main Backgrounds

- $WW^{(*)}$ (irreducible) $\sigma \approx$ 5 pb
- $WZ \rightarrow \ell\nu\ell\ell$, $ZZ \rightarrow \ell\ell\nu\nu$ $\sigma \approx$ 1 pb
- Wt, Wbb → 2ℓ+X $\sigma \approx$ 120 pb

Typical Cuts

2 isolated opp sign leptons (e, μ) p_T > 20, 10 GeV,
$10 < m_{\ell\ell} < 80$ GeV with $\Delta\phi_{\ell\ell} < 1$ and $\Delta\eta_{\ell\ell} < 1.5$ (rejects WZ, ZZ)
no jets p_T > 15 GeV in $|\eta| < 3$ (rejects tt,Wt,Wbb)
E_T^{miss} > 40 GeV, m_T ($\ell\ell$ E_T^{miss}) between m_H-30 GeV and m_H

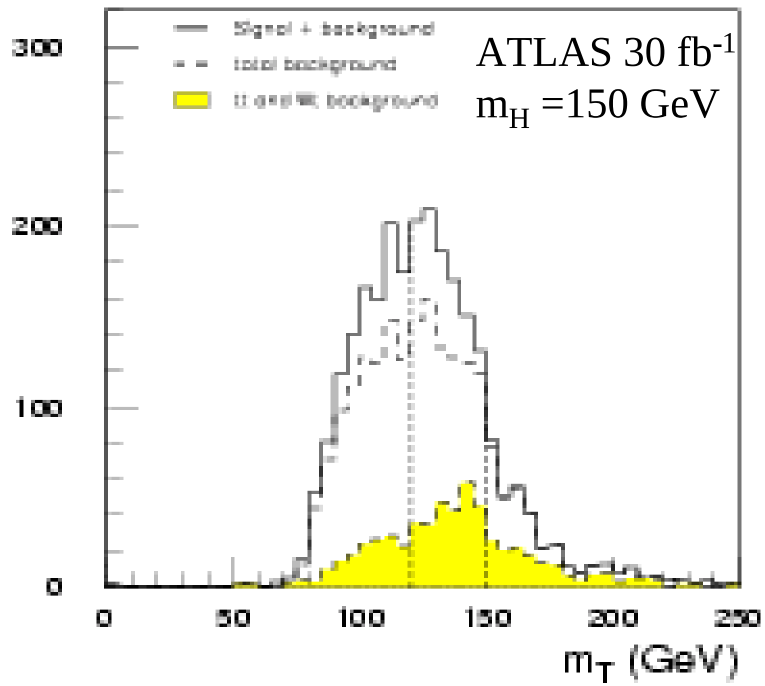
$H \rightarrow WW^* \rightarrow \ell^+\nu\ell^-\nu$

1 experiment, 30 fb^{-1}

m_H(GeV)	150	160	170	180	190
S	340	580	460	400	180
S/B	0.35	0.77	0.95	0.74	0.55
$S/\sqrt{B}$(*)	5.8	12.3	14.1	11.2	7.4
$S/\sqrt{B}$(*) 100 fb^{-1}	6.6	14.5	17.6	13.8	9.9

(*) 5% background systematics included

Count excess of events in signal region
Signal and background have similar shapes
$\rightarrow$ very tight mass window to optimise $S/\sqrt{B}$

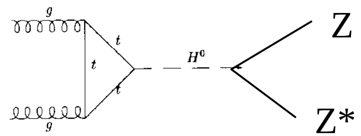


Conclusions:

- 5σ discovery at low L for $150 \leq m_H \leq 200$ GeV
- complementary to $H \rightarrow 4\ell$
  larger rate, better sensitivity for
  $160 \leq m_H < 180$ GeV, but no mass peak
- crucial : background knowledge

$H \to ZZ^* \to 4\ell$: Introduction

σ x BR ≈ 3 fb



$120 \le m_H \le 2\, m_Z$

Main backgrounds:

ZZ^*, $Z\gamma^*$ continuum (irreducible)
$Zb\bar{b} \to 4\ell + X$, $t\bar{t} \to 4\ell + X$ (2 ℓ from b-decays)

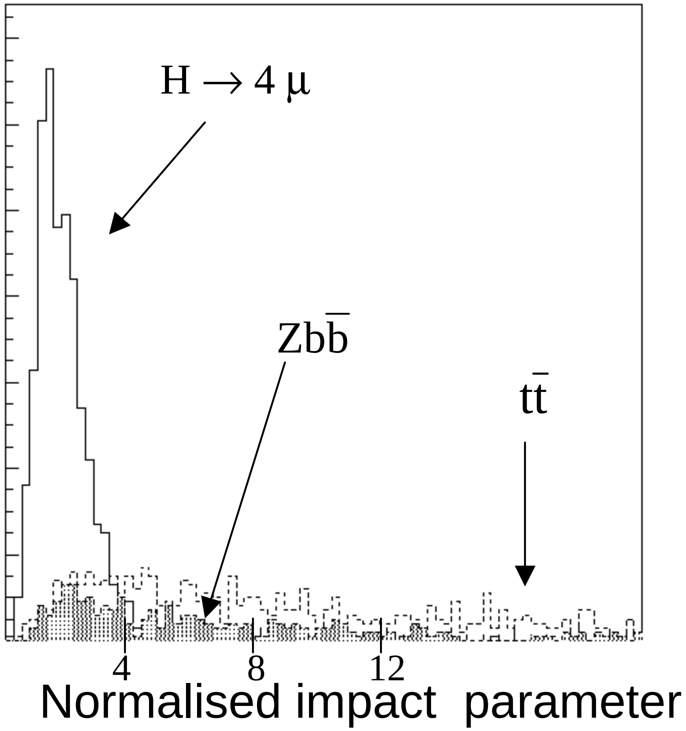
Typical Cuts

Four isol leptons p_T > 20, 20, 7, 7 GeV
m ($\ell_1\ell_2$) compatible with m_Z (rejects $t\bar{t}$)
m ($\ell_3\ell_4$) > 15-60 GeV
lepton isolation and impact parameter } rejects $b \to \ell X$ decays $\to t\bar{t} + Zb\bar{b} < 10\%\ ZZ^*$

ATLAS full simulation

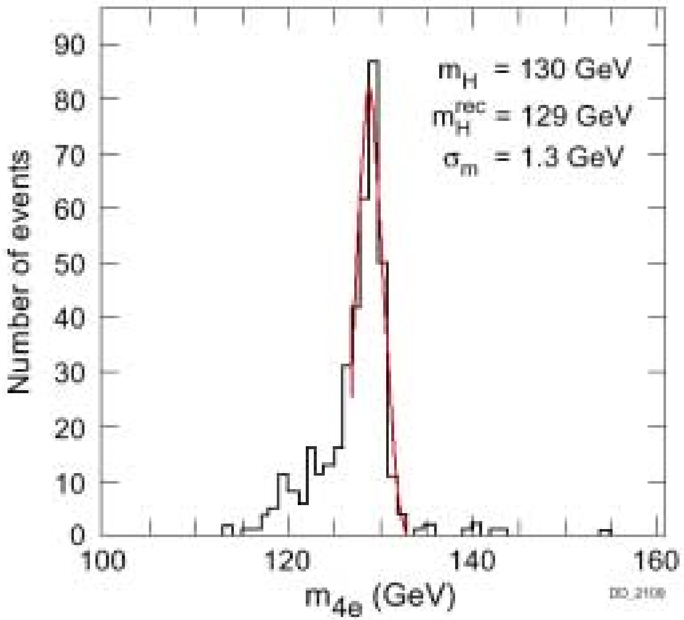
Largest normalised impact parameter of the four muons in the transverse plane

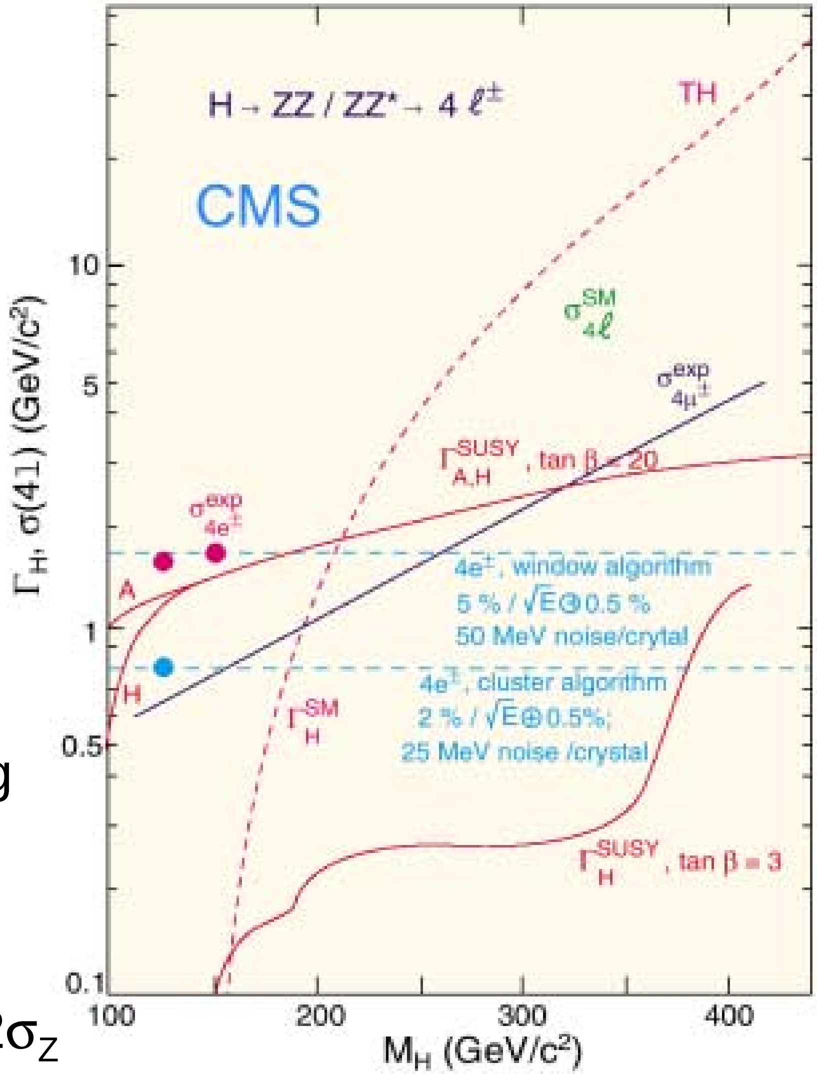
σ (d_0) ~ 20 μm



$H \to ZZ^* \to 4\ell$: Resolution

Intermediate m_H : $\Gamma_H << \sigma_m$
High m_H : $\Gamma_H \sim \sigma_m$ or $\Gamma_H > \sigma_m$





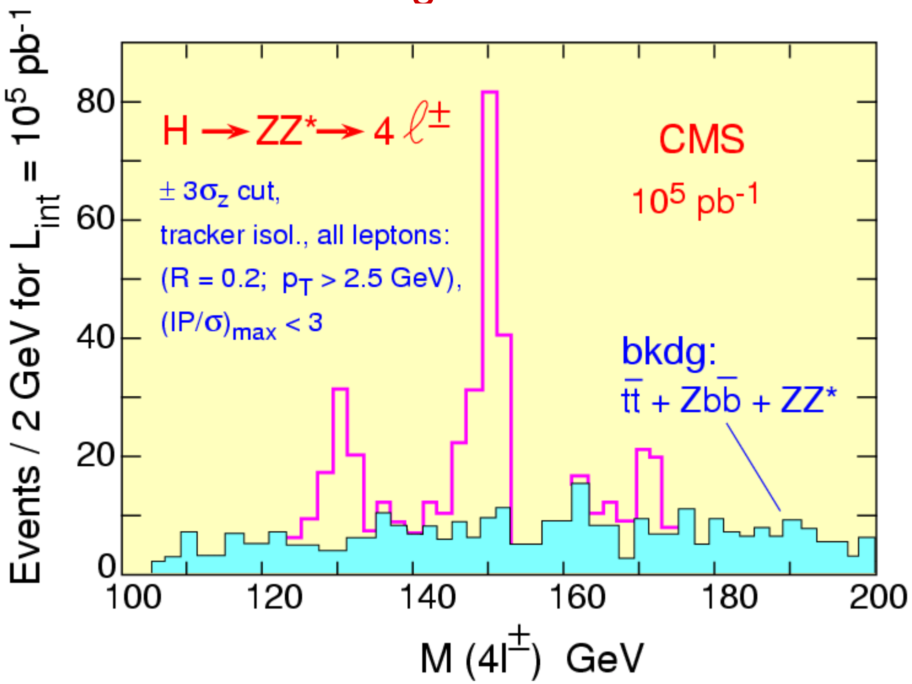
Additional complication: internal bremstrahlung
8% of reconstructed $Z \to \mu\mu$ fall outside window
$m_Z \mp 2\sigma_Z$ at m_H=150 GeV
Efficiencies: 70% per electron in CMS
Incl internal, external bream, 5x7 array, $m_Z \mp 2\sigma_Z$

$H \rightarrow ZZ^* \rightarrow 4\ell$: Signal - Intermediate m_H

1 experiment, 30 fb^{-1}

m_H (GeV)	120	130	150	170	180
S	4	11	27	8	20
S/B	2.7	4.4	9	2.7	6.7
$S/\sqrt{B}$ 30 fb^{-1} (Poisson)	2.4	4.8	15.5	3.2	11.2
$S/\sqrt{B}$ 100 fb^{-1} (Poisson)	3.8	10.3	22.6	5.3	16.7

~90% of bkg comes from ZZ*



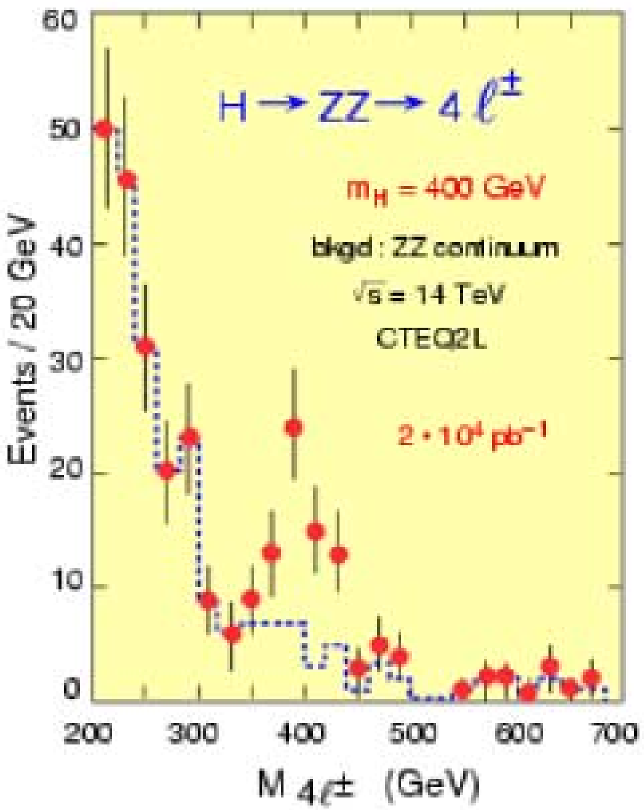
Conclusions

- 5σ discovery at low L for 130 < $m_H \leq$ 180 GeV 1 expt (except 160–170 GeV)
- require excellent ℓ reconstruction and identification efficiency and resolution down to $p_T \sim 5$ GeV (low-rate signal)

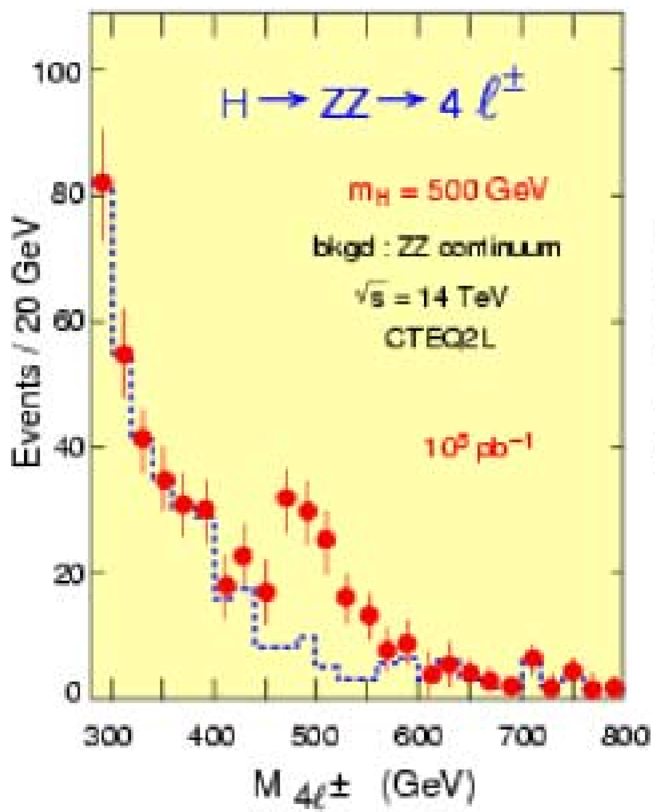
Note : -- $m_H > 2\ m_Z$: gold-plated $H \rightarrow ZZ \rightarrow 4\ell$ (background free)
-- $m_H \approx 160$ GeV : dip due to $H \rightarrow WW$ opening

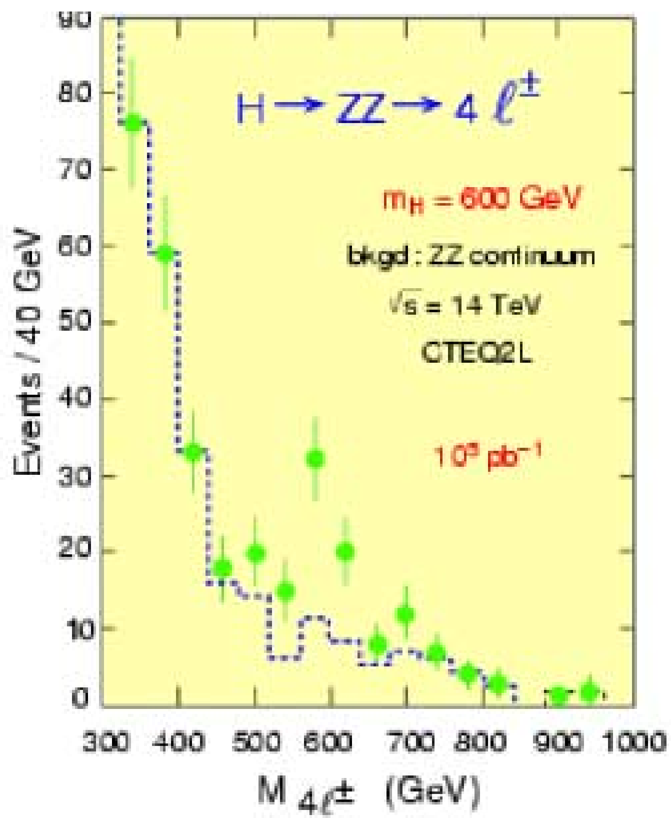
$H \rightarrow ZZ \rightarrow 4\ell$: Signal - High m_H

20 fb^{-1}



100 fb^{-1}

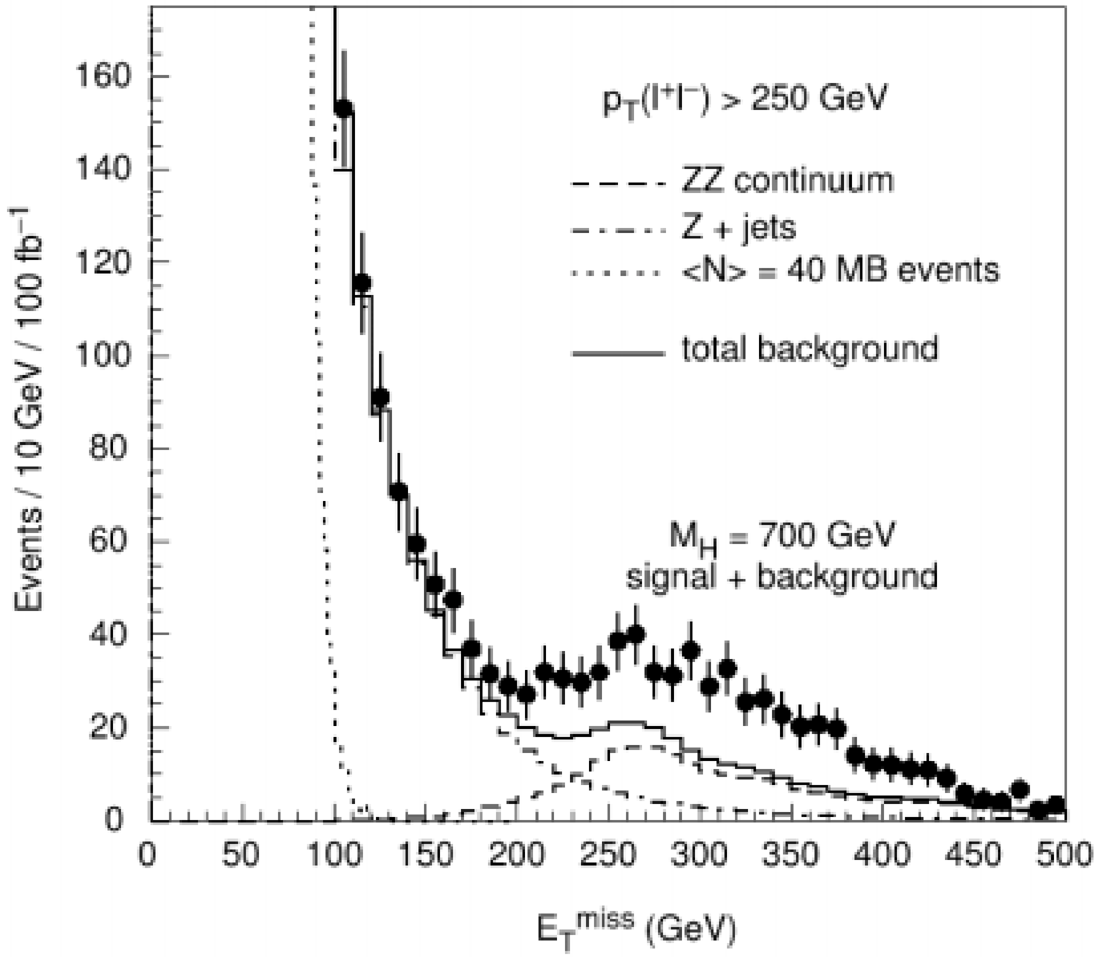




$m_H \sim 1$ TeV : $H \rightarrow ZZ \rightarrow \ell\ell\,\nu\nu$

As m_H increases further, Γ_H increases and σ falls ⇨ turn to higher BR modes

ATLAS : 100 fb^{-1}



Signal: Jacobian peak in E_T^{miss} in events with Z + large E_T^{miss}

Typical Cuts

2 isol ℓ : p_T^{ℓ} >20 GeV, $p_T(Z)$>60 Ge

E_T^{miss} > 100 GeV

1 tagging jet E^j > 1 TeV, in $|\eta|$>2.5

Backgrounds: irreducible – ZZ, reducible – Z + jets

Z+jets: parton level simulation

Forward jets can be used

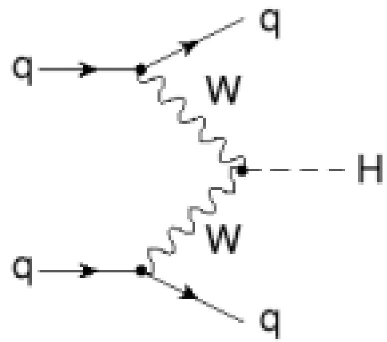
$m_H \sim 1$ TeV : $H \to \ell\ell$ jj, $\ell\nu$ jj

Larger statistics if use decay modes $H \to WW \to \ell\nu$+jets and $H \to ZZ \to \ell\ell$+jets
BUT need to reduce enormous W+jets and Z+jets background

Consider WW final state (ZZ similar)
Find jets in $\Delta R=0.2$ with $E_T>50$ GeV, reconstruct $W \to jj$
$E_T(jj) > 150$ GeV, $m_W - 2\sigma < m_{jj} < m_W + 2\sigma$
$p_T(\ell) > 50$ GeV, $E_T^{miss} > 50$ GeV
$p_T(W) > 200$ GeV
Backgrounds from W+jets and $tt \to WbWb$ roughly equal but still large

$\varepsilon(W \to jets) \sim 60\%$,
$\sigma(m_W) \sim 7$ GeV

Use **forward tagging jets from $qq \to Hqq$**
$E_T^{tag} > 15$ GeV, $E > 600$ GeV with $2 < |\eta| < 5$
$E_T^{cell} > 3$ GeV
Low L : no additional jets with $E_T>20$ GeV in $|\eta|<2$



Fake tag prob. from MinBias
Single jet - 4.6%, double jet - 0.07%

$m_H \sim 1$ TeV : $H \rightarrow ZZ \rightarrow \ell\ell$ jj,

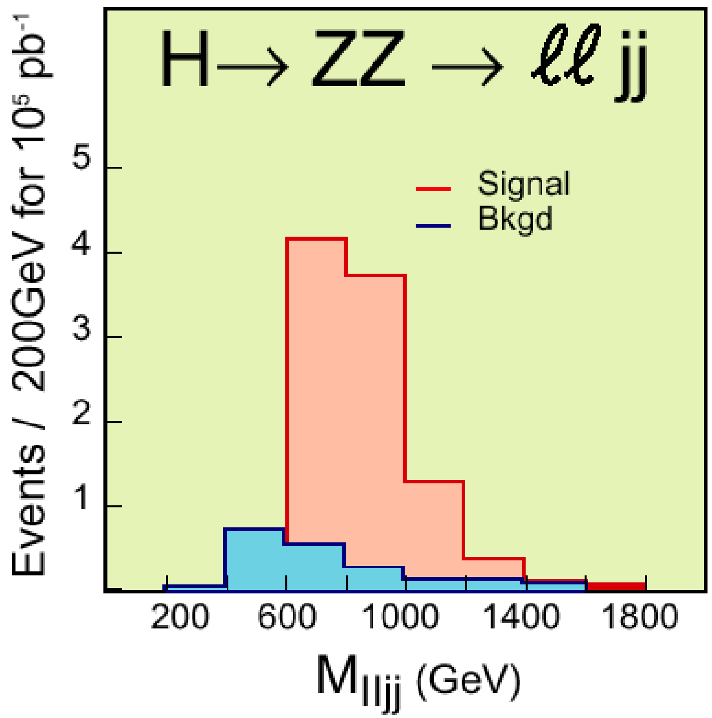
Typical Cuts

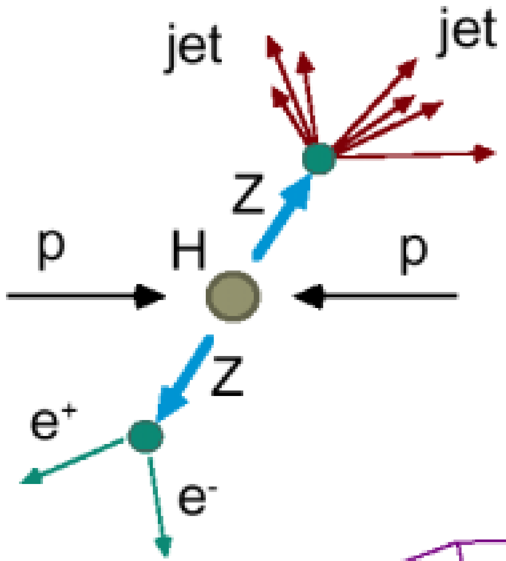
2 isol ℓ : p_T^{ℓ} >50 GeV, $p_T(Z)$>150 GeV

$M_{\ell\ell} = m_Z$ -10 GeV

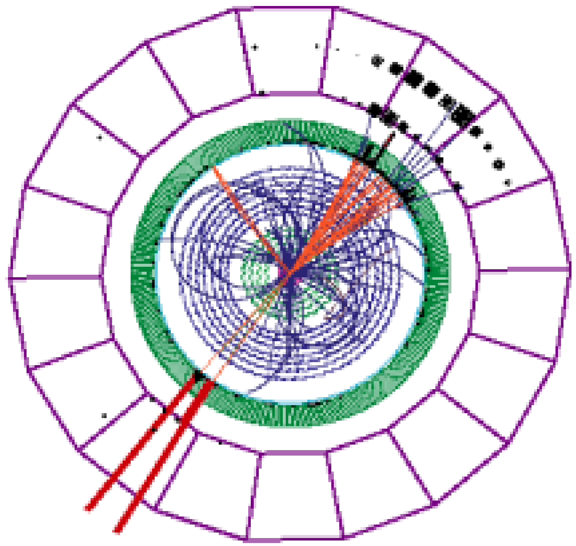
I.e. 2 central jets E_T^j > 40 GeV in $|\eta|$<3

2 tagging jets E^j > 400 GeV, E_T^j>20 GeV





CMS



$m_H \sim 1$ TeV : $H \to WW \to \ell\nu\, jj$

Typical Cuts

1 isol ℓ : p_T^{ℓ} >30 GeV in $|\eta|<2.5$

E_T^{miss} > 100 GeV

I.e. 2 central jets E_T^{j} > 40 GeV in $|\eta|<3$

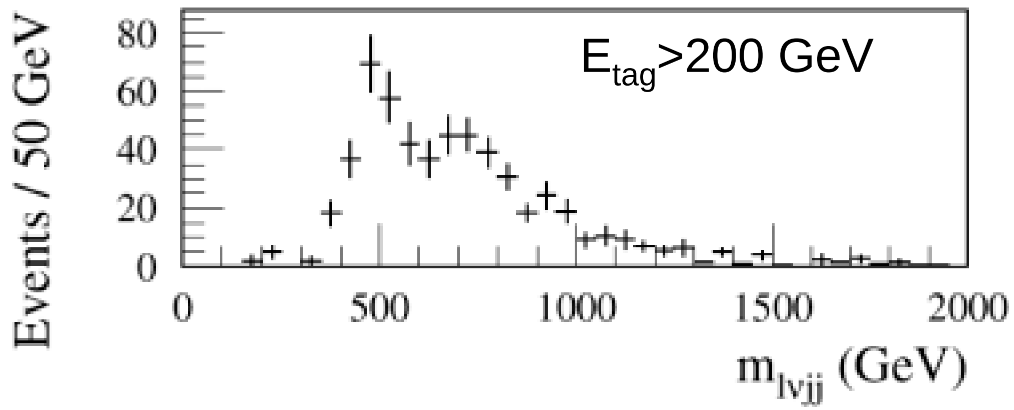
2 tagging jets E^{j} > 400 GeV, E_T^{j}>20 GeV

p_T^{W}>100 GeV in $\ell\nu$ and jj modes

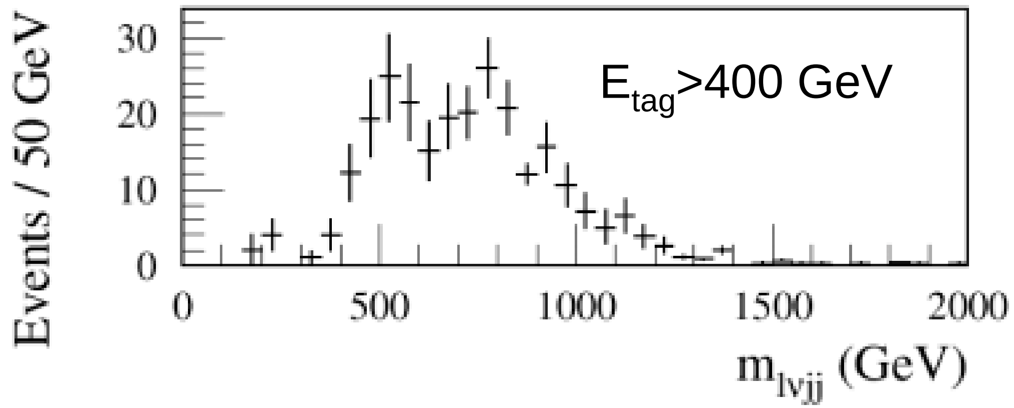
ATLAS

m_H = 1TeV, 30fb^{-1}

Process	Central cuts	Jet veto	Double tag
$H \to WW$	222	143	73
$t\bar{t}$	38300	2800	85
$W + jets$	15700	6900	62



m_H = 800 GeV, 30 fb^{-1}

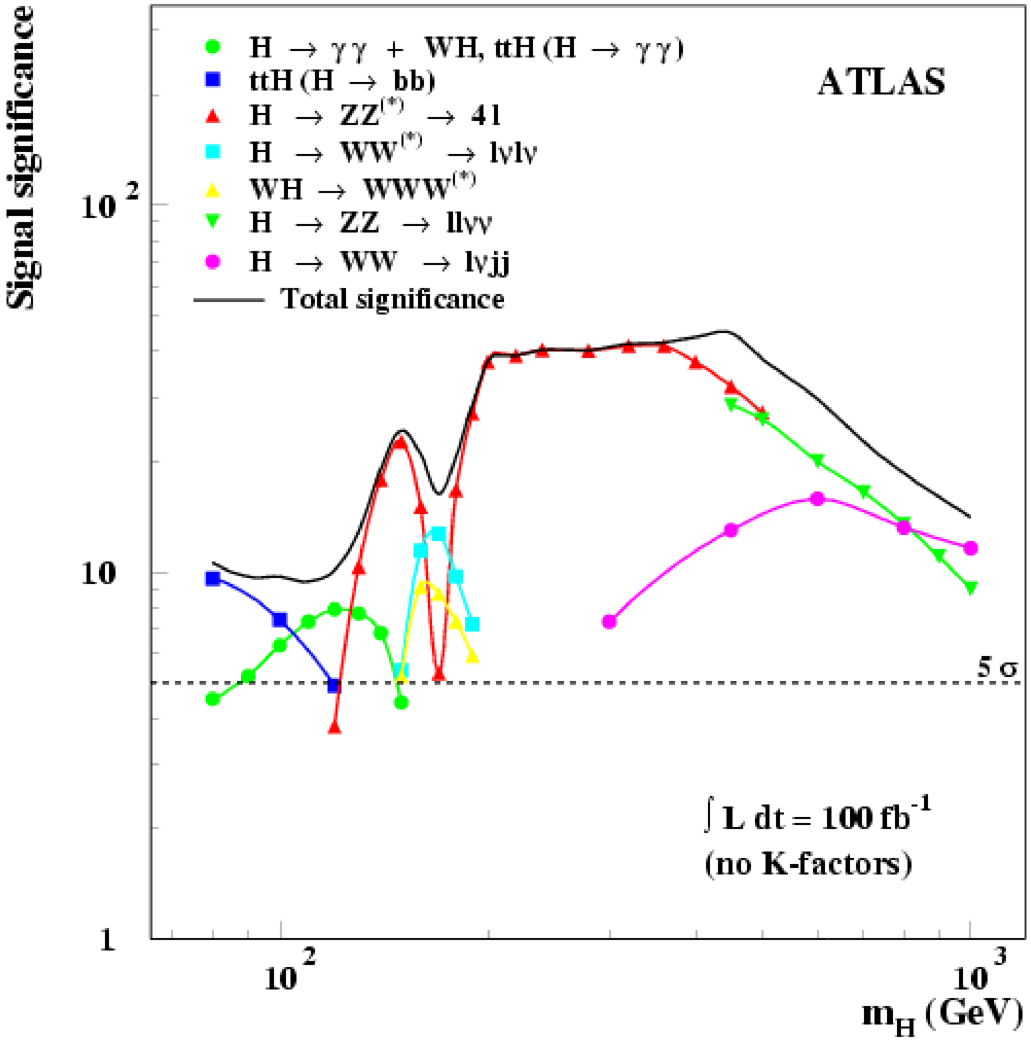


Summary: Search for SM Higgs

m_H < 180 GeV
many complementary channels
(gg, bb, 2ℓ, 3ℓ, 4ℓ, 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

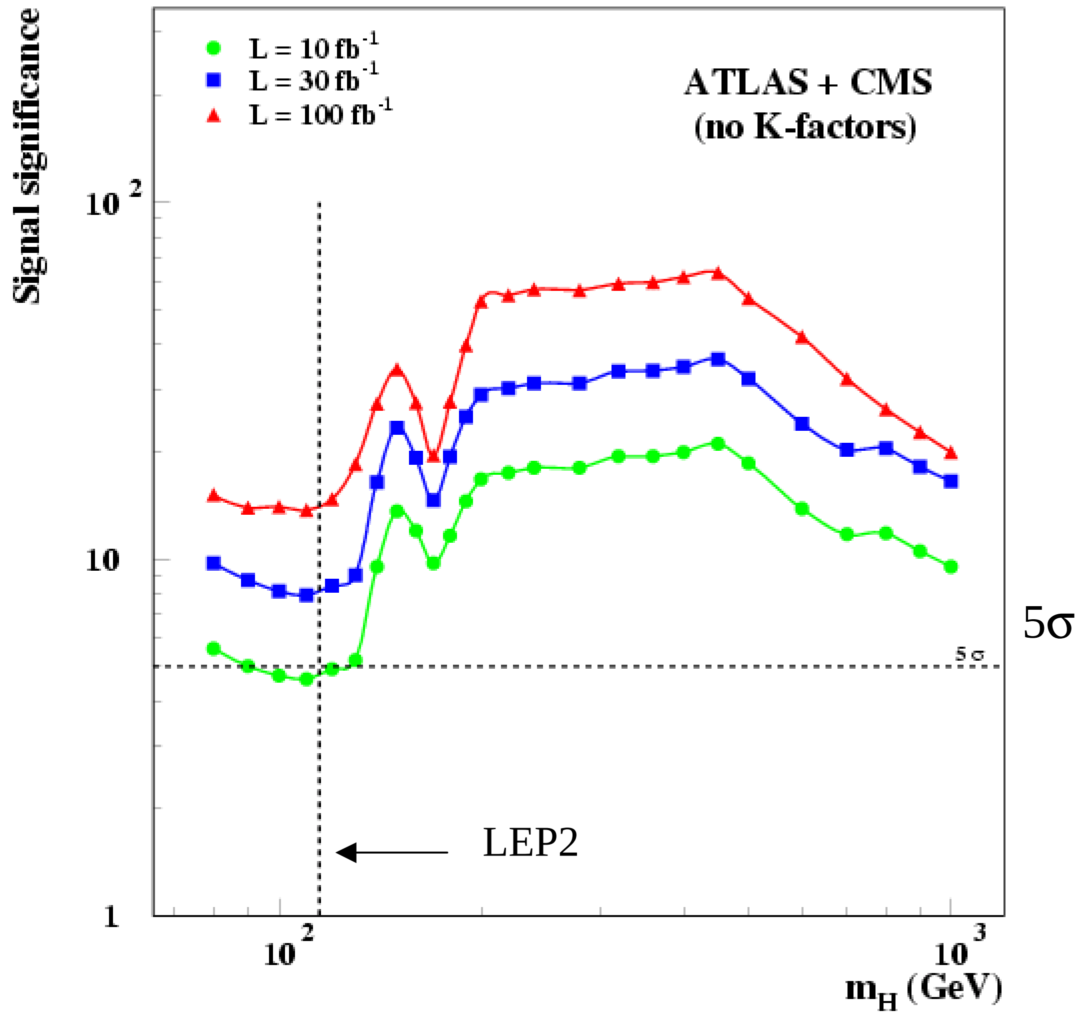


Summary: Search for SM Higgs

SM Higgs boson can be **discovered** at $\approx$ 5 σ after 1 year of operation (10 fb^{-1}/ experiment)
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 are not included
 e.g. $WH \rightarrow \ell \nu b\bar{b}$ (large systematics)

L is per experiment



Measurement of Higgs Properties: Mass

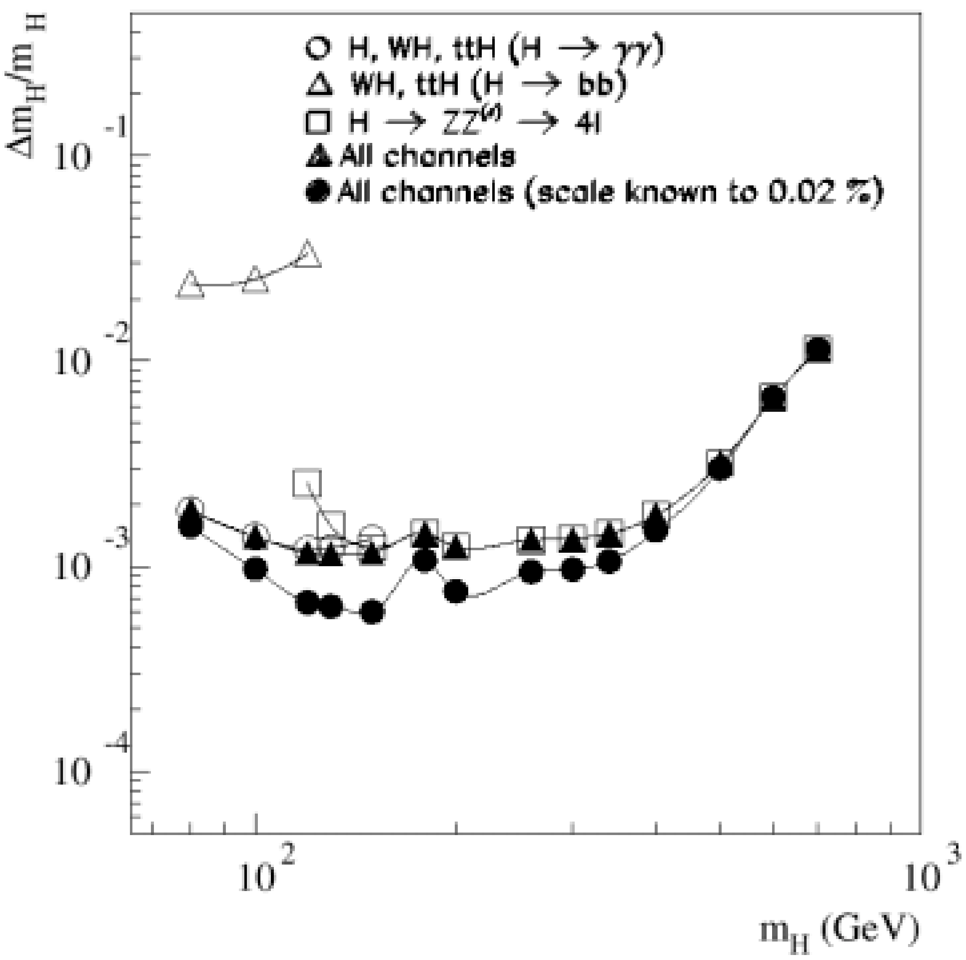
Mass

Favoured mass of SM Higgs

113.5 < mH < 212 GeV

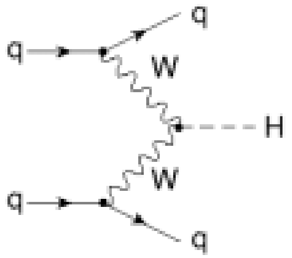
In this range m_H can be measured to 0.1% using $\gamma\gamma$ and 4ℓ channels

Energy scale can be calibrated to 0.1% using $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$



Measurement of Higgs Properties: Cross-sections

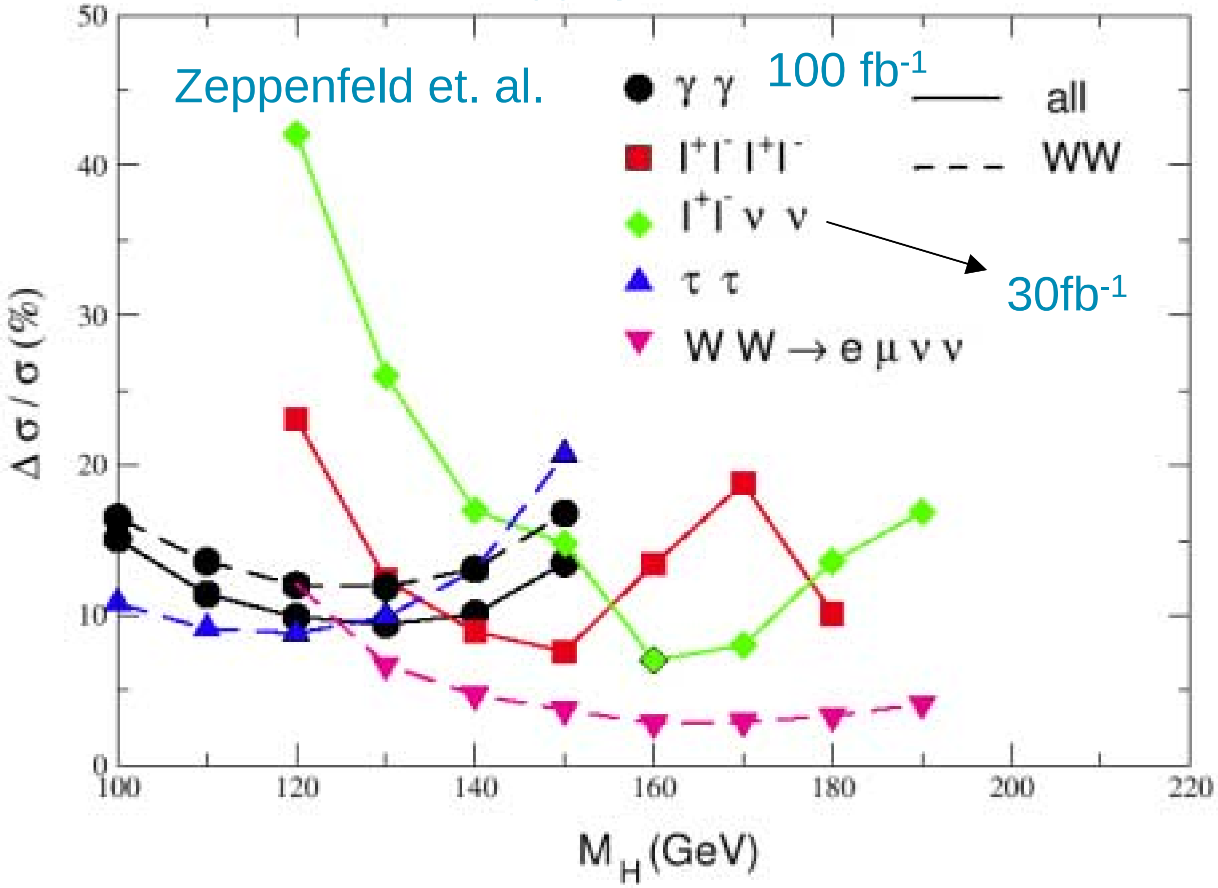
10% of σ in intermediate mass region comes from WW fusion
Identified by requiring forward tagging jets and no additional central jets



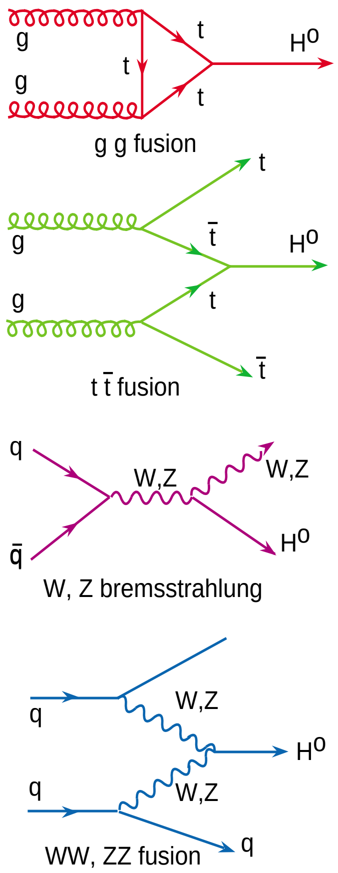
Errors
Statistical: 5 – 20%
γγ and 4ℓ well understood
Modes involving fwd jets more difficult to estimate

Corrected σ compared with perturbative QCD calculations
Known to NLO for all and NNLO for gg→H processes

Higgs production via WW fusion



Measurement of Couplings and BR



Use various Higgs production and decay modes
In ratios luminosity uncertainty largely cancels
Assuming 300 fb-1

$$\frac{\sigma.B(t\bar{t}H+WH\to\gamma\gamma)}{\sigma.B(t\bar{t}H+WH\to b\bar{b})}\Rightarrow\frac{BR(H\to\gamma\gamma)}{BR(H\to b\bar{b})}$$

$$\frac{\sigma.B(H\to\gamma\gamma)}{\sigma.B(H\to ZZ*)}\Rightarrow\frac{BR(H\to\gamma\gamma)}{BR(H\to ZZ*)}$$

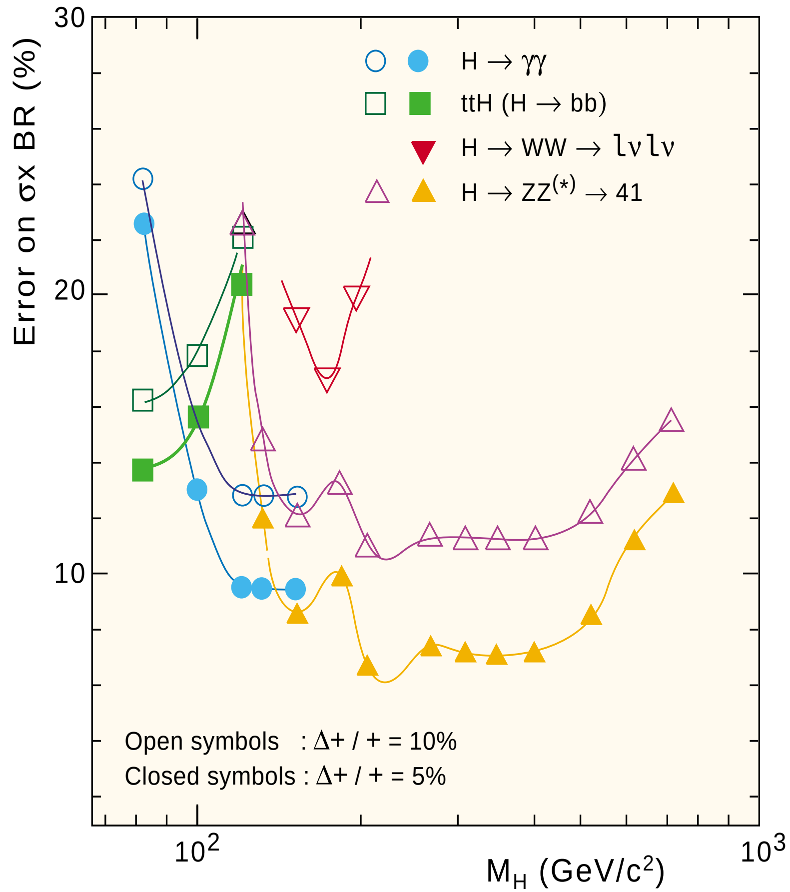
$$\frac{\sigma.B(t\bar{t}H\to\gamma\gamma/b\bar{b})}{\sigma.B(WH\to\gamma\gamma/b\bar{b})}\Rightarrow\frac{g^2_{Ht\bar{t}}}{g^2_{HWW}}$$

$$\frac{\sigma.B(H\to WW*/W)}{\sigma.B(H\to ZZ*/Z)}\Rightarrow\frac{g^2_{HWW}}{g^2_{HZZ}}$$

Measurement of Higgs Properties: BR

BR cannot be measured directly at the LHC
But possible to infer ratios of couplings from measured rates

Measure	Error	M_H range
$\frac{B(H \to \gamma\gamma)}{B(H \to b\bar{b})}$	30%	80–120
$\frac{B(H \to \gamma\gamma)}{B(H \to ZZ^*)}$	15%	125–155
$\frac{\sigma(t\bar{t}H)}{\sigma(WH)}$	25%	80–130
$\frac{B(H \to WW^{(*)})}{B(H \to ZZ^{(*)})}$	30%	160–180



5. Search for the Supersymmetric Higgs Boson

i. Production and Decay
ii. SM-like decays
iii. H/A → $\tau\ \tau$
iv. H/A → $\mu\mu$
v. A → $\gamma\gamma$
vi. Charged Higgs
vii. Other signatures

SUSY Higgs: Particle Content

Complex analysis; 5 Higgs' ($H^{\pm}$;H^0,h^0,A^0)

- At tree level, all masses & couplings depend on only two parameters; tradition says take M_A & tanβ
- Modifications to tree-level mainly from top loops

  Important ones; e.g. at tree-level, $M_h < M_Z \cos\beta$; radiative corrections push this to 150 GeV.

- Important branch 1: SUSY particle masses

  (a) M>1 TeV (i.e. no decays of the Higgs' to them); well-studied

  (b) M<1 TeV (i.e. allows decays of the Higgs' to them); "new"

- Important branch 2: stop mixing; value of tanβ

  (a) Maximal–No mixing

  (b) Low (1.5) and high (≈30) values of tanβ

SUSY Higgs Channels Studied

$H, h \to \gamma\gamma$, $b\bar{b}$ ($H \to b\bar{b}$ in WH, $t\bar{t}H$)

$h \to \gamma\gamma$ in WH, $t\bar{t}h \to \ell\,\gamma\,\gamma$

$h, H \to ZZ^*, ZZ \to 4\,\ell$

$h, H, A \to \tau^+\tau^- \to (e/\mu)^+ + h^- + E_T^{miss}$

$\to e^+ + \mu^- + E_T^{miss}$ — inclusively and in $b\bar{b}H_{SUSY}$

$\to h^+ + h^- + E_T^{miss}$

$H^+ \to \tau^+ \nu$ from $t\bar{t}$

$H^+ \to \tau^+ \nu$ and $H^+ \to t\,\bar{b}$ for $M_H > M_{top}$

$A \to Zh$ with $h \to b\bar{b}$; $A \to \gamma\gamma$

$H, A \to \tilde{\chi}^0_2\tilde{\chi}^0_2, \tilde{\chi}^0_i\tilde{\chi}^0_j, \tilde{\chi}^+_i\tilde{\chi}^-_j$

$H^+ \to \tilde{\chi}^+_2\tilde{\chi}^0_2$

$qq \to qqH$ with $H \to \tau^+\tau^-$ — using OO code (tough…)

$H \to \tau\tau$, in WH, $t\bar{t}H$ — work started; tough…

Searches for SUSY Higgs

Large variety of channels:

e.g.
$- h \to \gamma\gamma, t\bar{t}h \to t\bar{t}b\bar{b}, H \to ZZ^{(*)} \to 4\ell$ 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

Note :

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

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

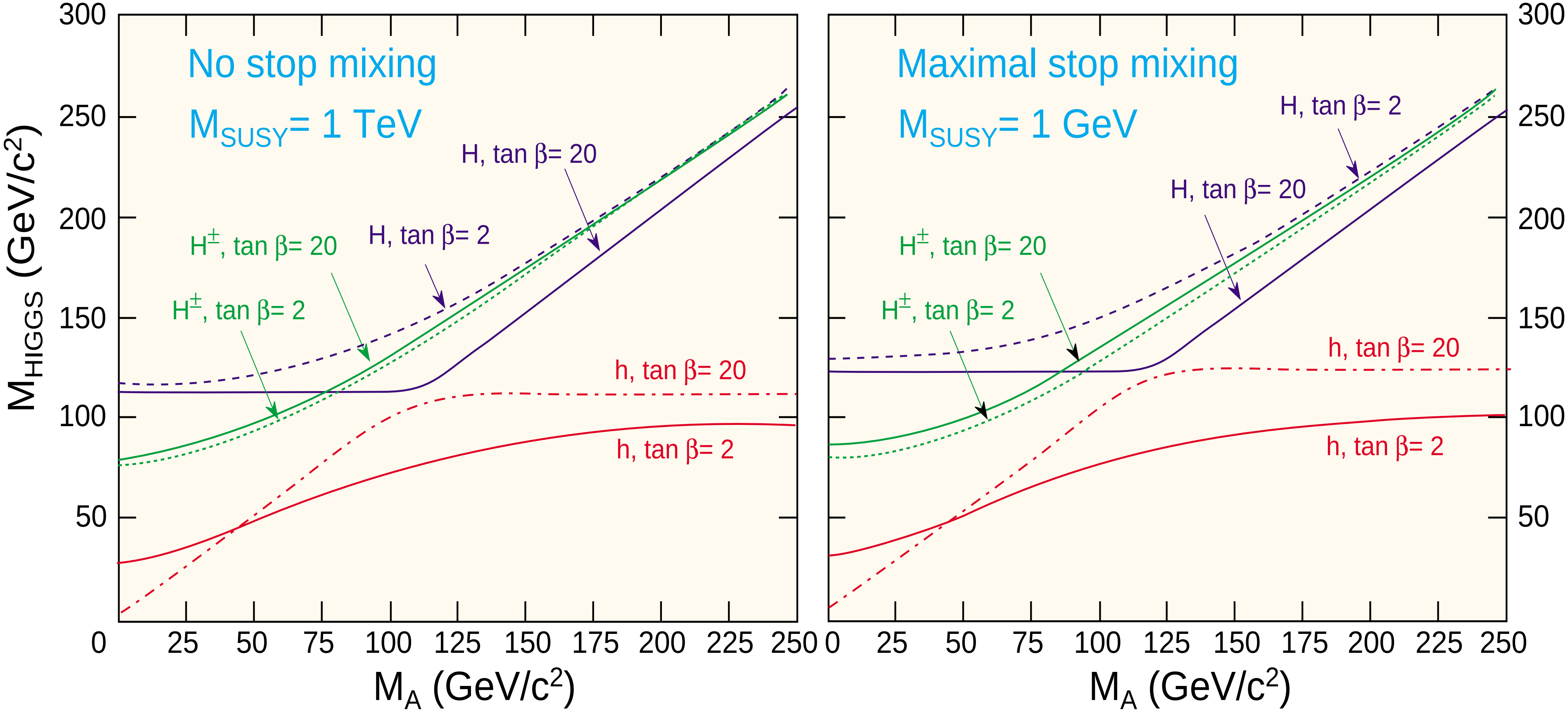
$\to A/H \to \mu\mu, \tau\tau$ accessible

} compared to SM

SUSY Higgs: Mass Spectra

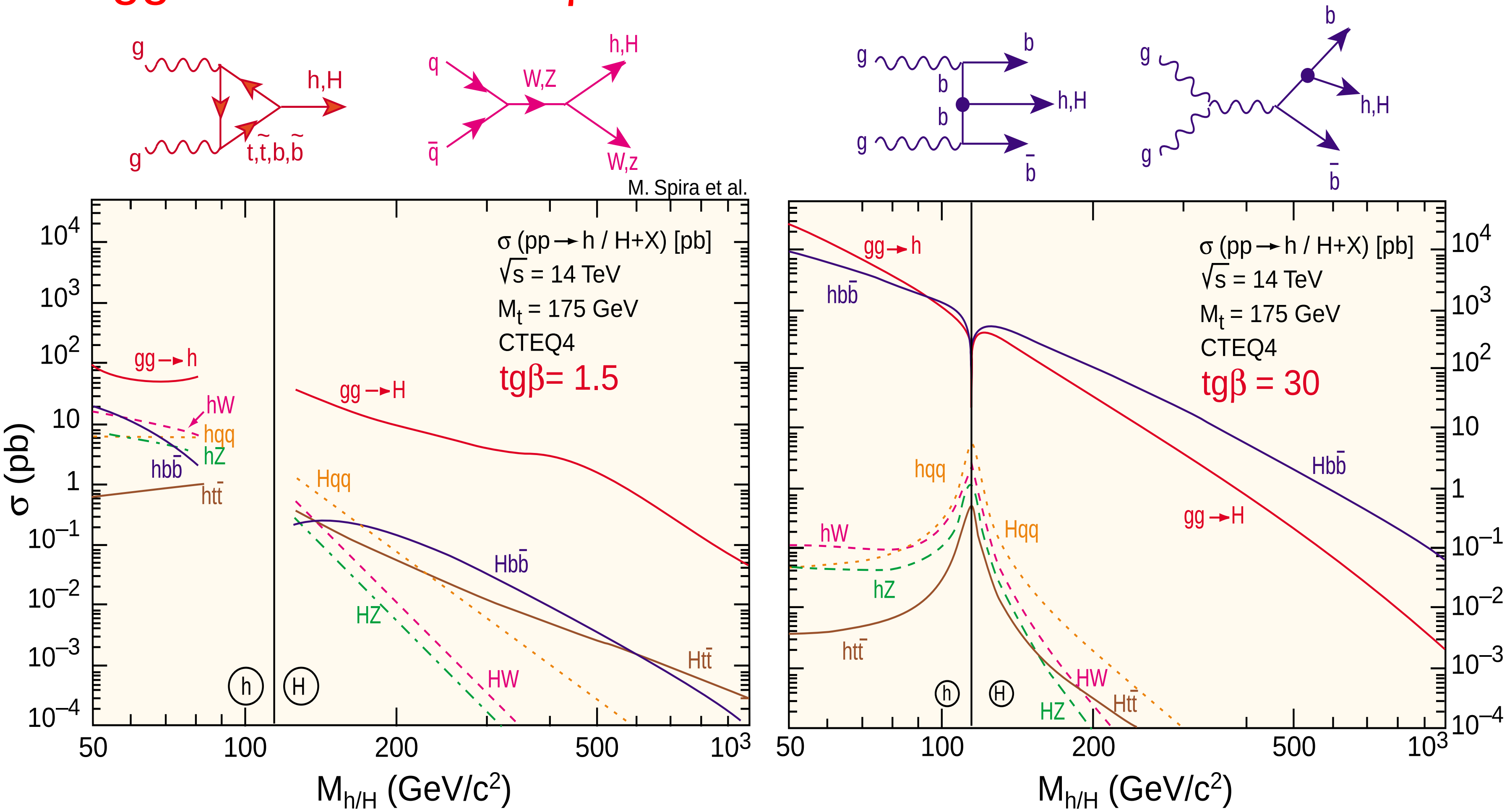
Mass spectra for M_{SUSY}>1TeV

Two-loop / RGE-improved radiative corrections included



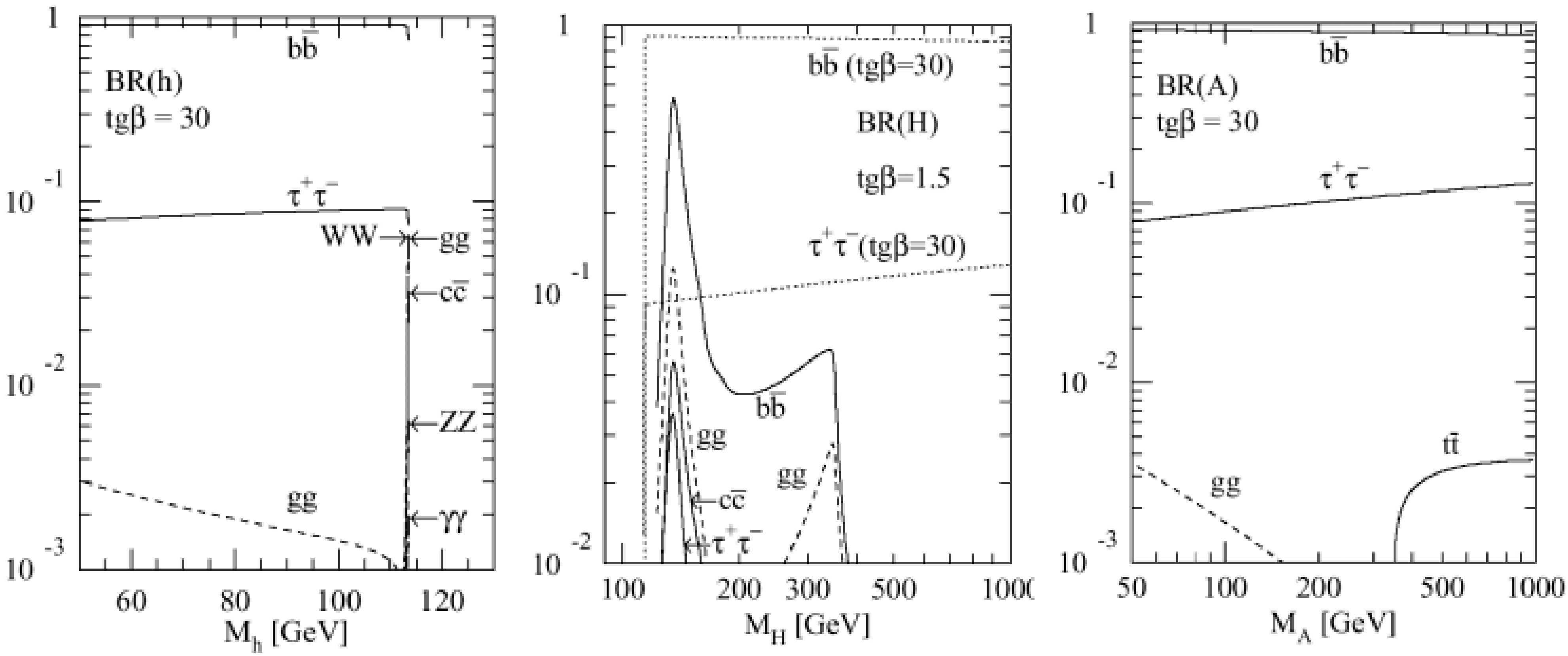
SUSY Higgs: Production

Biggest branch is tanβ



SUSY Higgs: Decay Modes

No mixing, M_S=1TeV

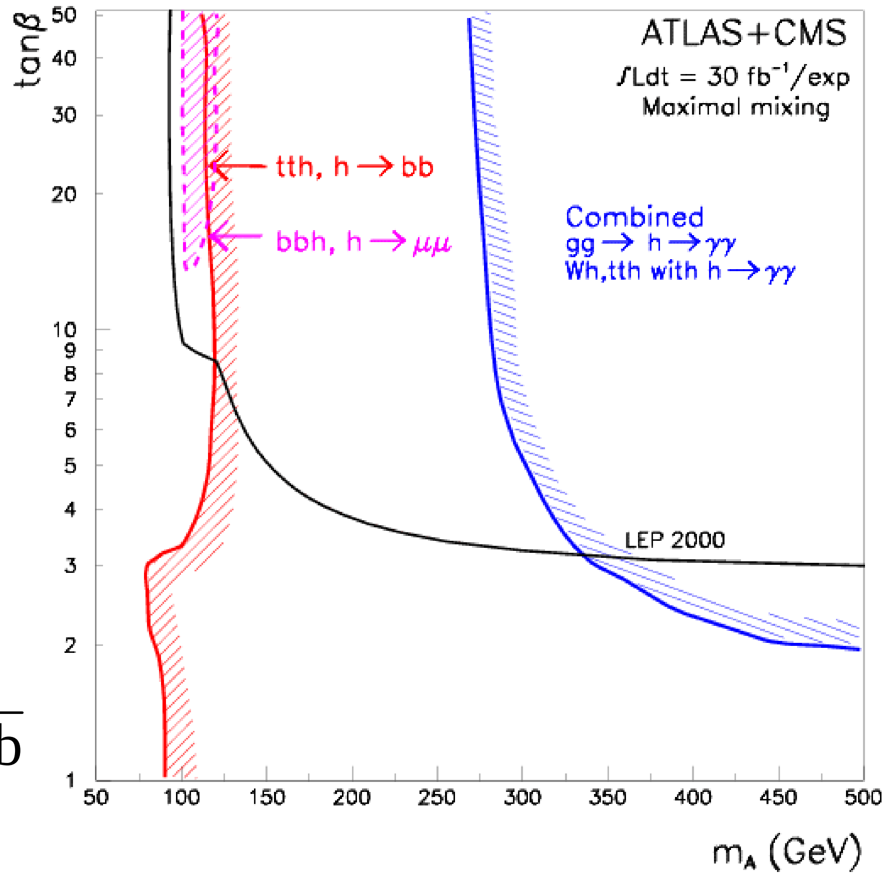


Search for the h

m_A > 100 GeV:
- h mass close to max value (~ 130 GeV)
- h behaves as SM Higgs

m_A < 100 GeV:
- h mass decreases
- BR ($h \to \gamma\gamma$) and $t\bar{t}h$ prodn suppressed
- large $\tan\beta$: bbh production enhanced

$bbh \to bb\,\mu\mu$ channel observable



- 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/H $\rightarrow \tau\tau \rightarrow \ell\nu\nu\ h^{\mp}\nu$

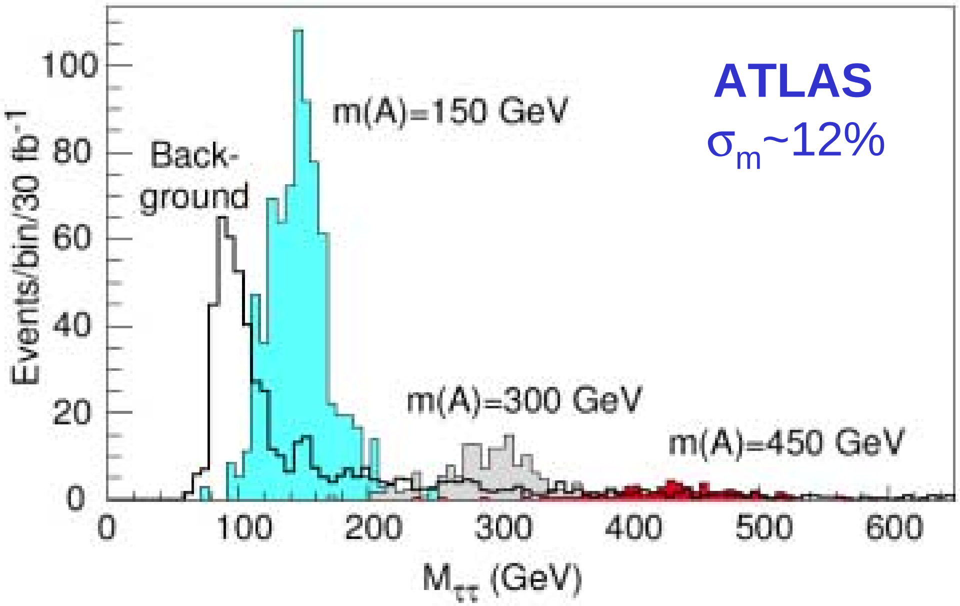
In MSSM, at large tanβ, H/A → ττ rates strongly enhanced over SM

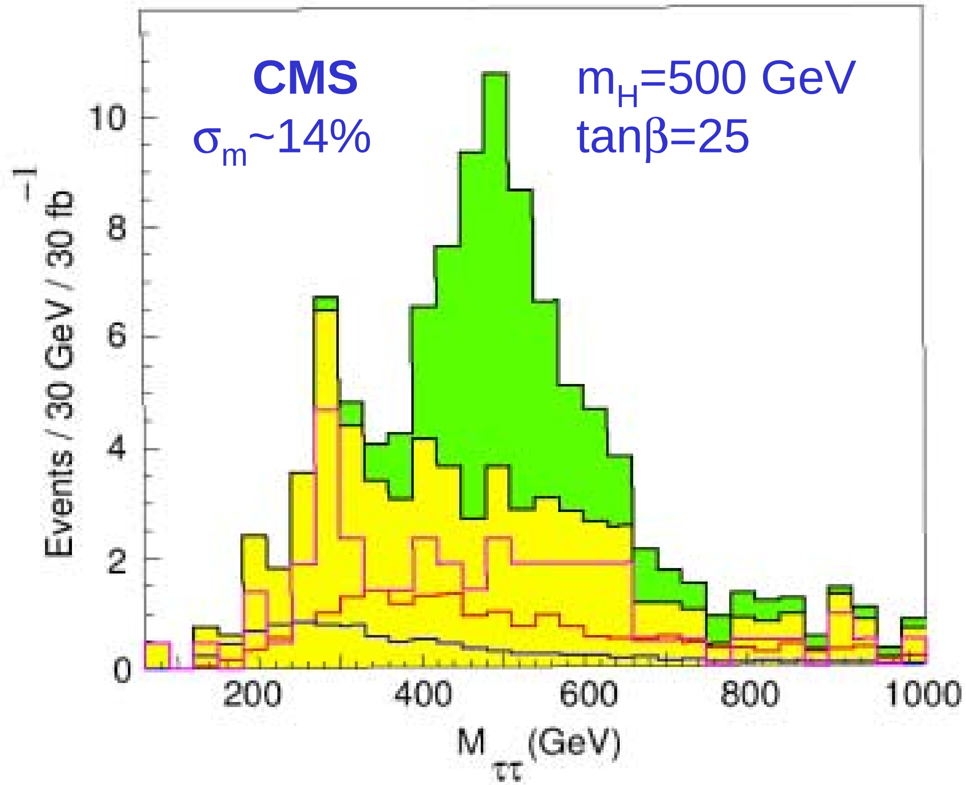
All final states accessible
$\ell\ell$, ℓ-had, had-had

A/H $\rightarrow \tau\tau \rightarrow \ell\nu\nu\ h^{\mp}\nu$

Cuts (e.g. CMS)
1 isolated lepton with p_T> 15-40 GeV
1 tau jet candidate, E_T>40 GeV
No jet with E_T>25 GeV in |η|<2.4

Backgrounds
$Z \rightarrow \tau\tau$, W+ jets (dominant), $t\bar{t}, b\bar{b}$

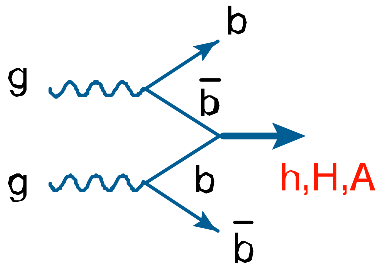




A/H → ττ → $h^{+}\nu$ $h^{-}\nu$

Provides best reach for large m_A.

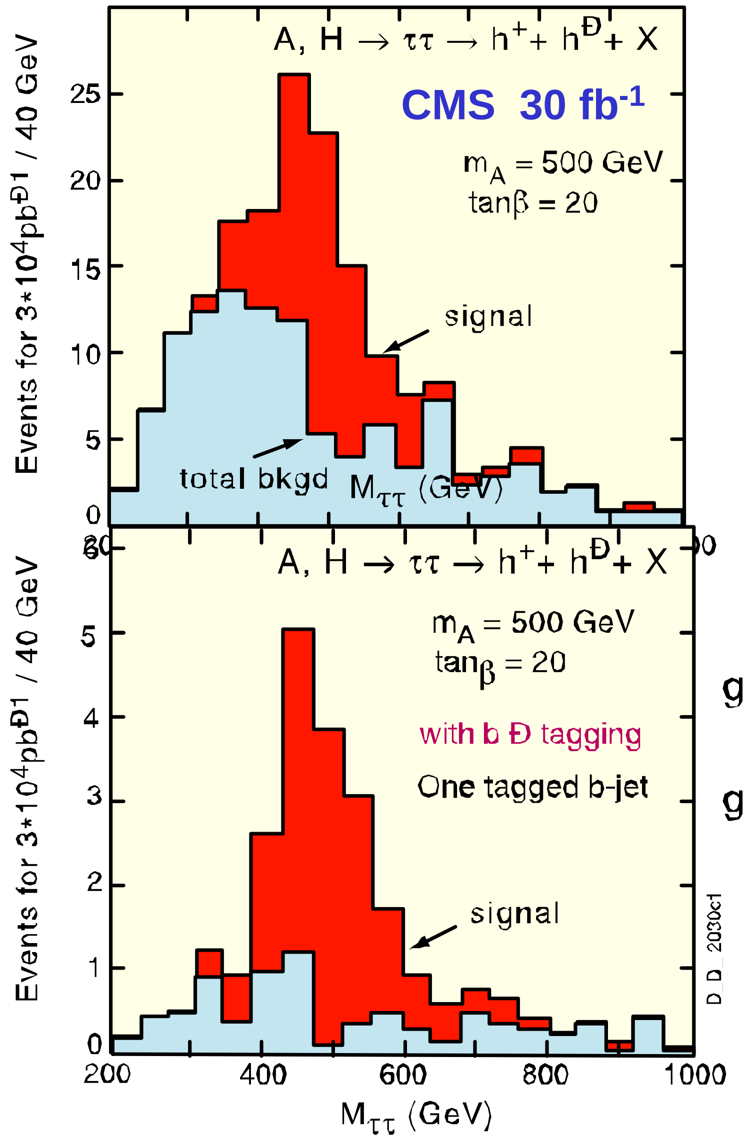
Signature: two stiff opposite-sign isolated tracks and missing transverse energy.



Typical Cuts

E_T^j>60 GeV, p_T^h>40 GeV

$\Delta\phi_{jj}$<175°, E_T^{miss}>40 GeV



Background: Main challenge: reject QCD jet background (already at L1 trigger !).

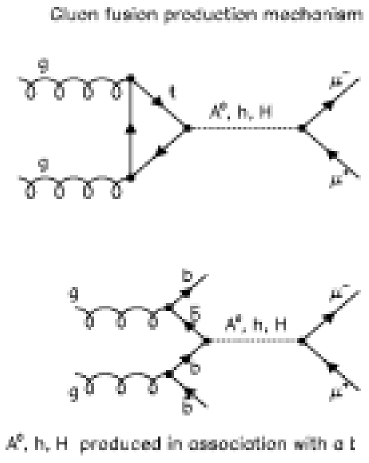
Feasible for m_A > 300 GeV: hadrons have high p_T, E_T^{miss} is large, etc..

$R_{QCD} \sim 10^{10}$ → QCD background << 10% (tt + Z/γ* → ττ)

B-tagging improves S/B, $\sigma_M \sim 10\%$

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

H/A → μμ



Dominant Backgrounds

Z/γ*, tt

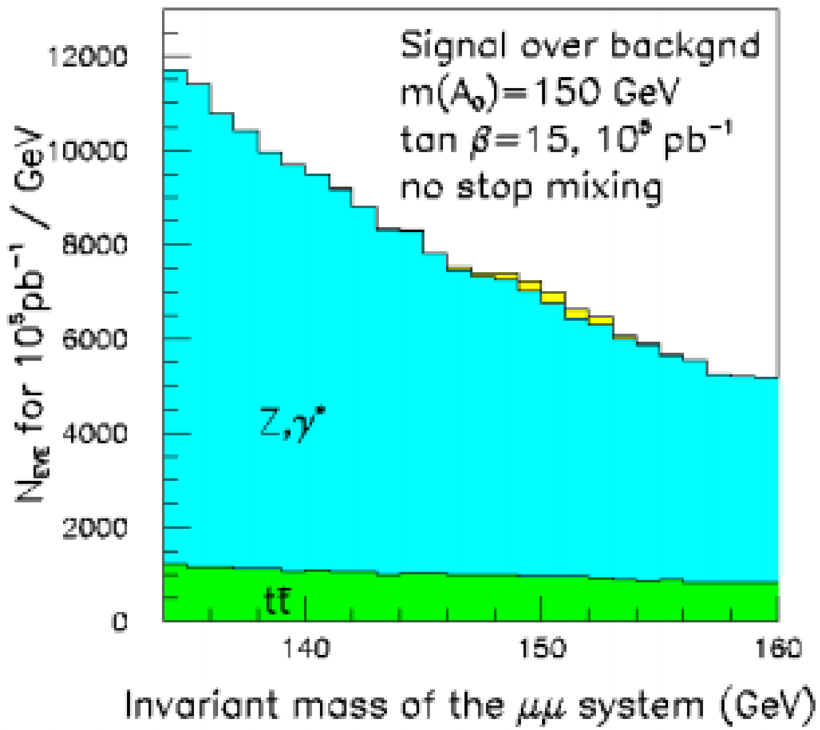
Typical Cuts

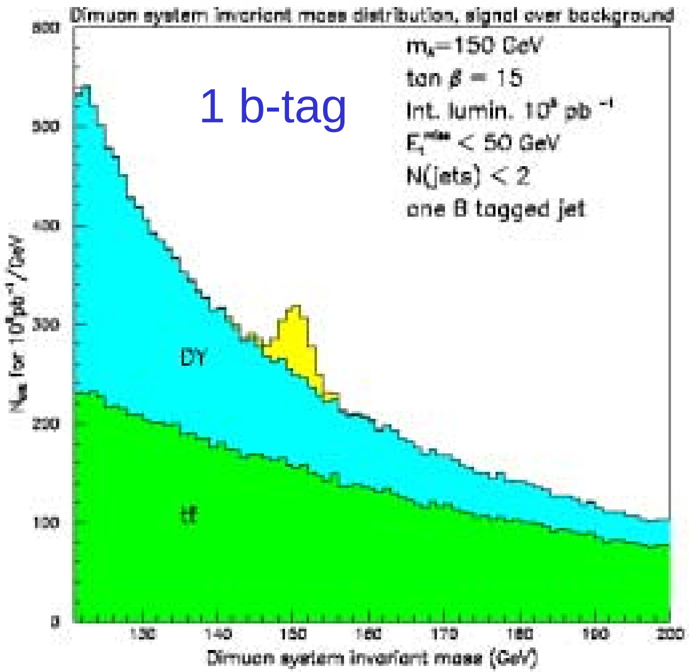
2 isol μ p_T^{μ} > 10 GeV

Df(mm) > 120°

E_T^{miss} >40 GeV

b-tag in assoc. channel





Search for the A and H

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

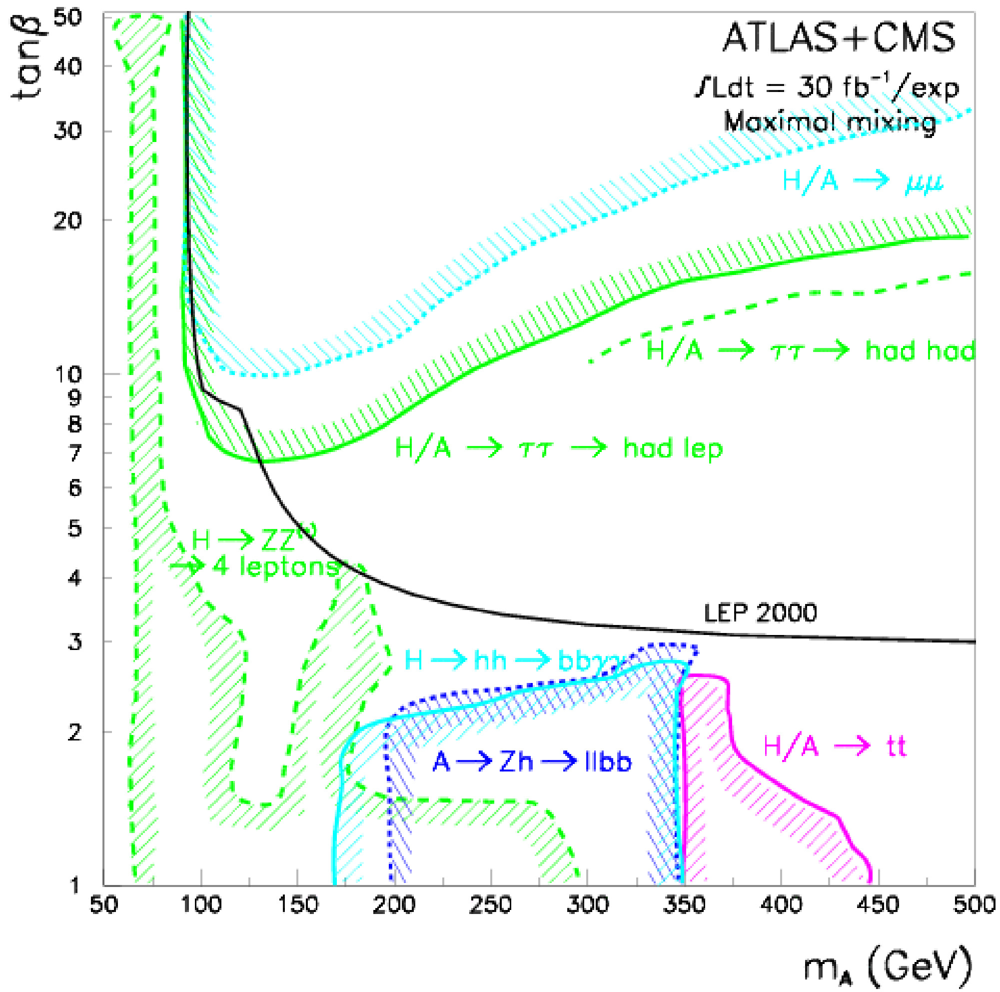
Small tanβ

large number of channel

→ measurement of many couplings

including Hhh, AZh

m_A > 200 GeV: A and H are ~ degenerate



Search for $H^{\mp}$

$m_{H\pm} < m_t - m_b$

LEP: $M_{H+} < 78.6$ GeV

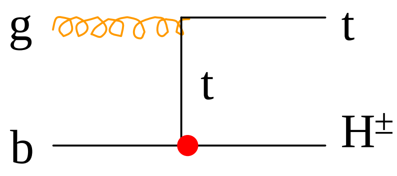
Production via gg → tt
then (t → b H^{+}) and ($H^+ \to \tau\nu$)
Signature – violation of lepton universality in semi-leptonic top decays

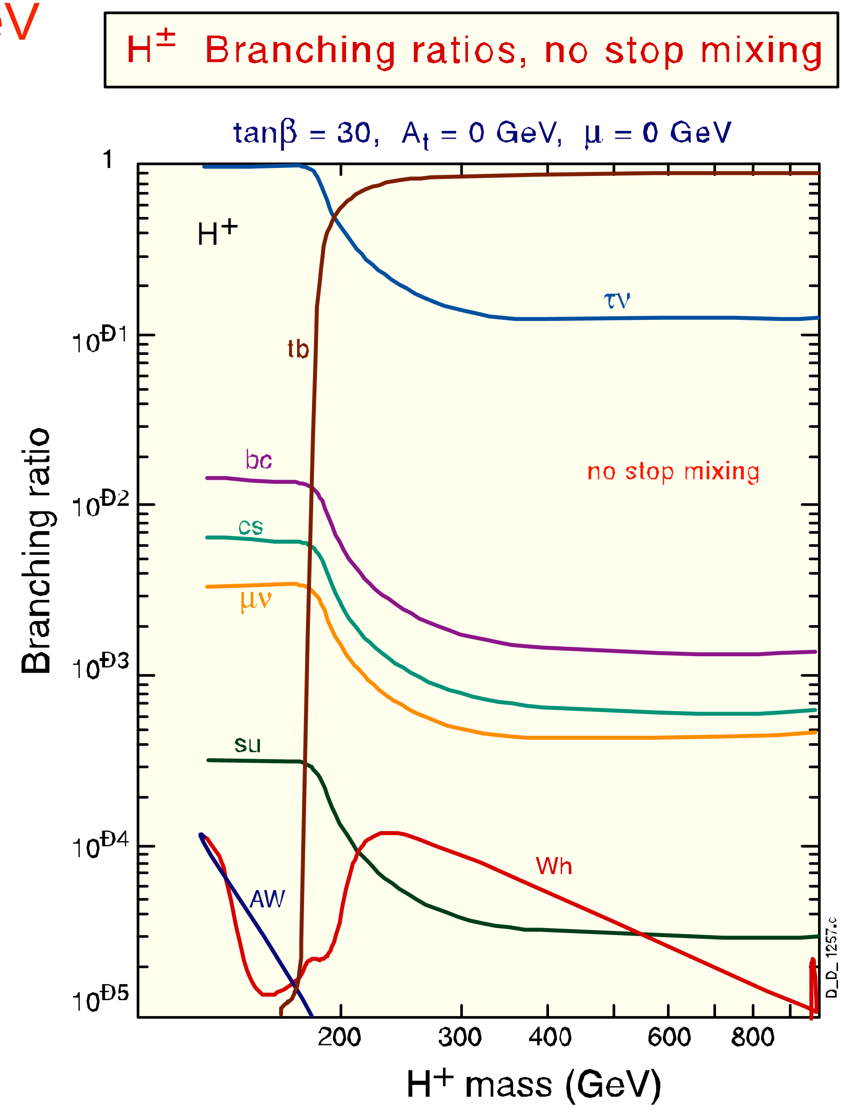
$$R = \frac{BR(t \to \tau^+ \nu_\tau b)}{BR(t \to \mu^+ \nu_\mu b)} = 1 + \Delta R$$

$$where\ \Delta R = \frac{BR(t \to H^+ b) \bullet BR(t \to \tau^+ \nu_\tau)}{BR(t \to W^+ b) \bullet BR(W \to \mu^+ \nu_\mu)}$$

$m_{H\pm} > m_t$

gb → $H^\pm$ t → tb t
gb → $H^\pm$ t → τν t





Due to τ polarisation π from τ→πν is harder from τ produced in H^+ decay than in W decay

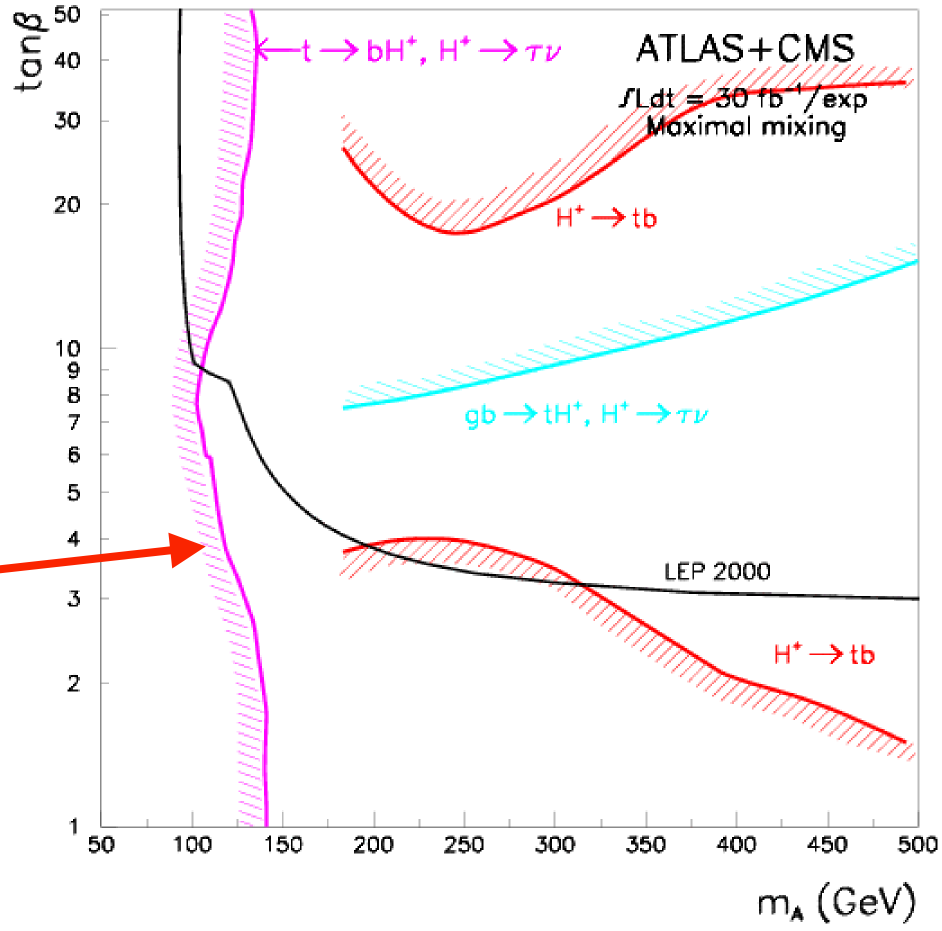
Search for $H^{\mp}$ ($m_H<m_t$)

Typical Cuts

1 isol ℓ p_T> 20 GeV in $|\eta|<2.5$ (trigger)
1 τ-jet E_T^j>40 GeV $|\eta|<2.5$
1 isol hard track p_T^h> 30 GeV pointing to τ-jet ($\Delta R<0.1$)
ge. 3 jets with p_T>20 in $|\eta|<2.5$ with ge. 2 b-jets

ATLAS: 30 fb^{-1}, tanβ=5

m_{H+} (GeV)	**110**	**130**	**150**
σ.BR(pb)	23	13	5
Signal	3050	1550	380
Bkg.	7020	7170	9120
Signif.	13.1	6.6	1.3



3000 W $\to \tau\nu$
4000 fake τ from W $\to$ jj

Syst error on bkg 3%

Search for $H^{\mp}$ $(m_H > m_t)$

Backgrounds

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

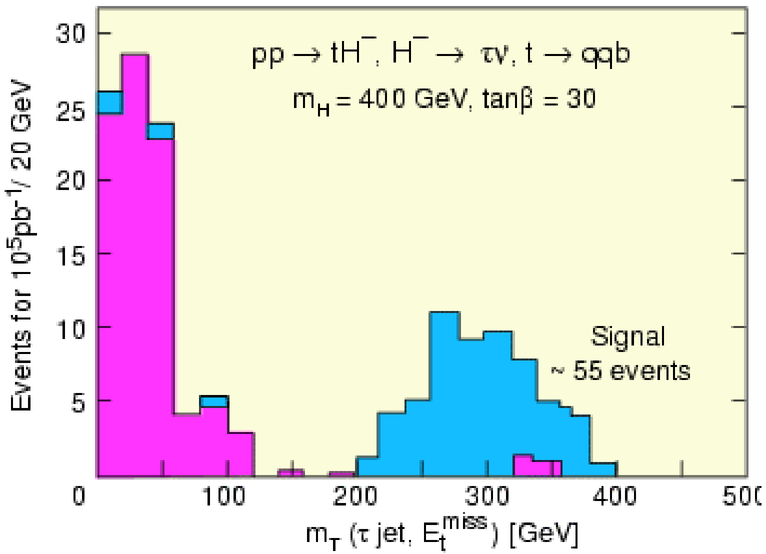
$gb \rightarrow H^{\pm} t$, with $H^{\pm} \rightarrow \tau\nu$

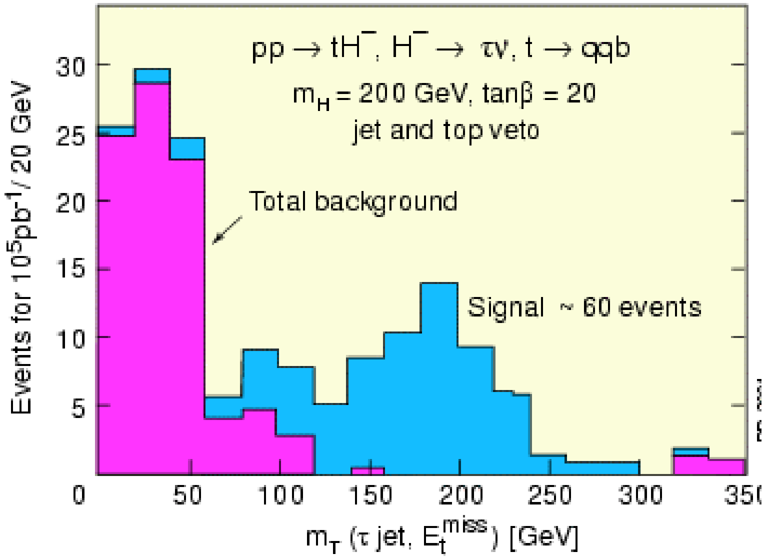
Cuts

1. E_T (τ-jet) > 100 GeV
2. τ-polarisation ($p^{\pi} / E^{\tau\text{-jet}} > 0.8$)
3. E_T^{miss} > 100 GeV
4. reconstruct W, top
5. $m_T(\tau\text{-jet}, E_T^{miss})$ >100 GeV

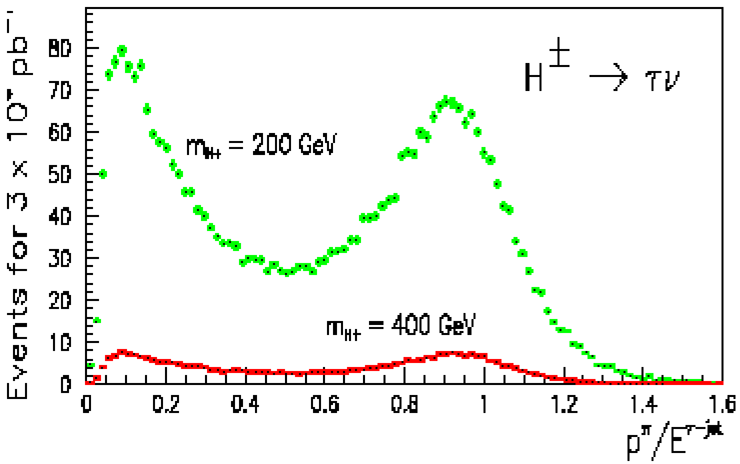
$30 fb^{-1}$

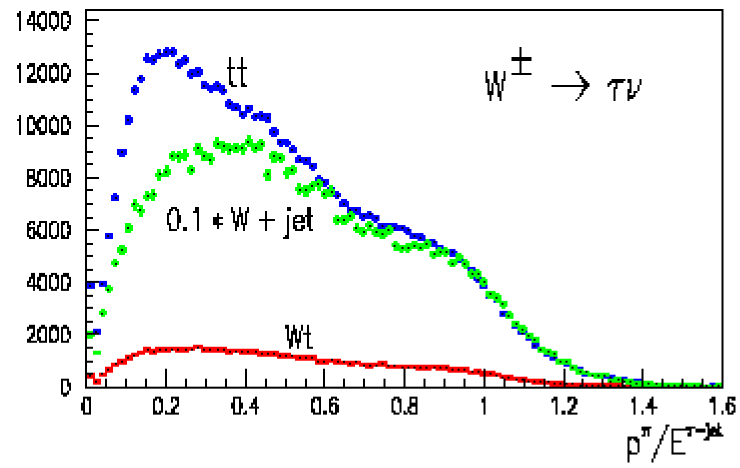
	200	tt	W+jet	Wtb
Evts	4k	10^6	5.10^7	10^5
Cut 1	900	48k	10^5	3k
Cut 2	330	4k	26k	280
Cut 3	88	1.4k	7.7k	104
Cut 4	26	460	240	24
Cut 5	9	1.6	0.4	0.1

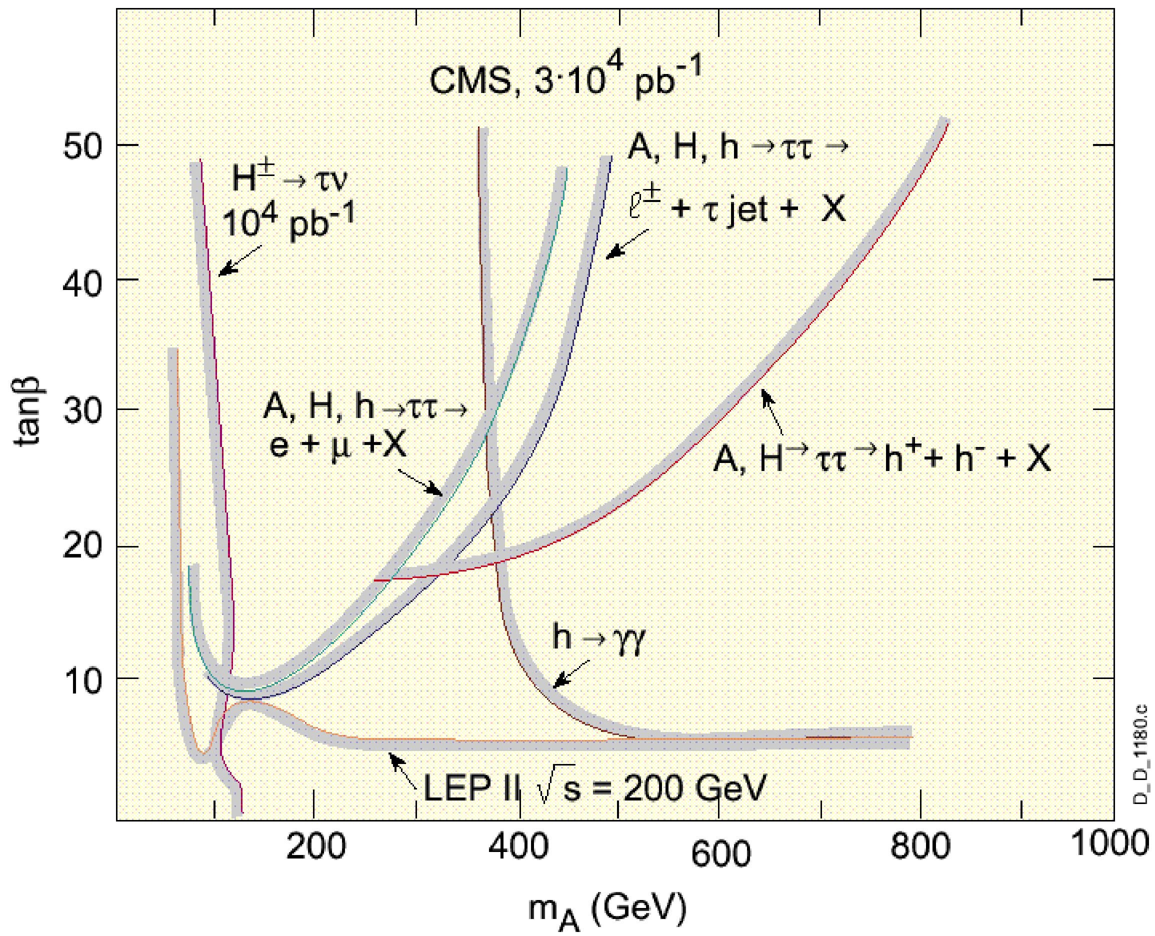




Search for $H^{\mp}$





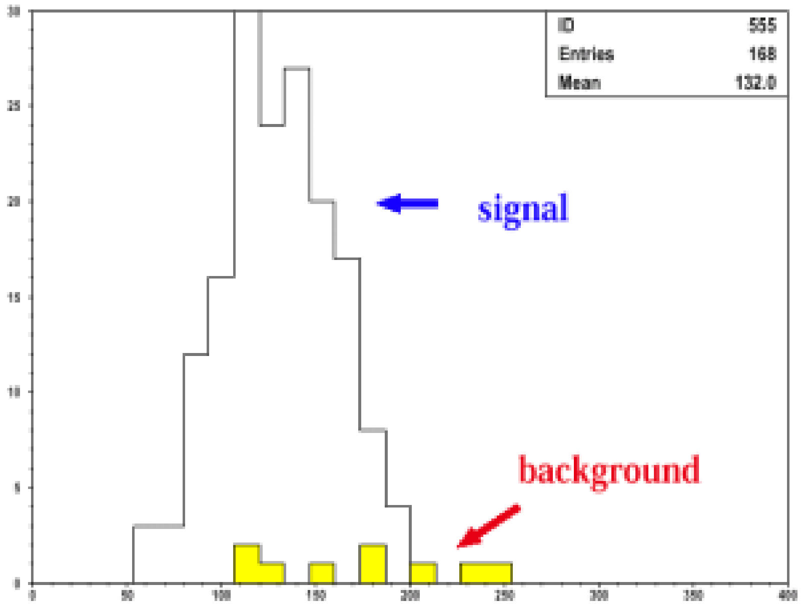


H Decays to Sparticles

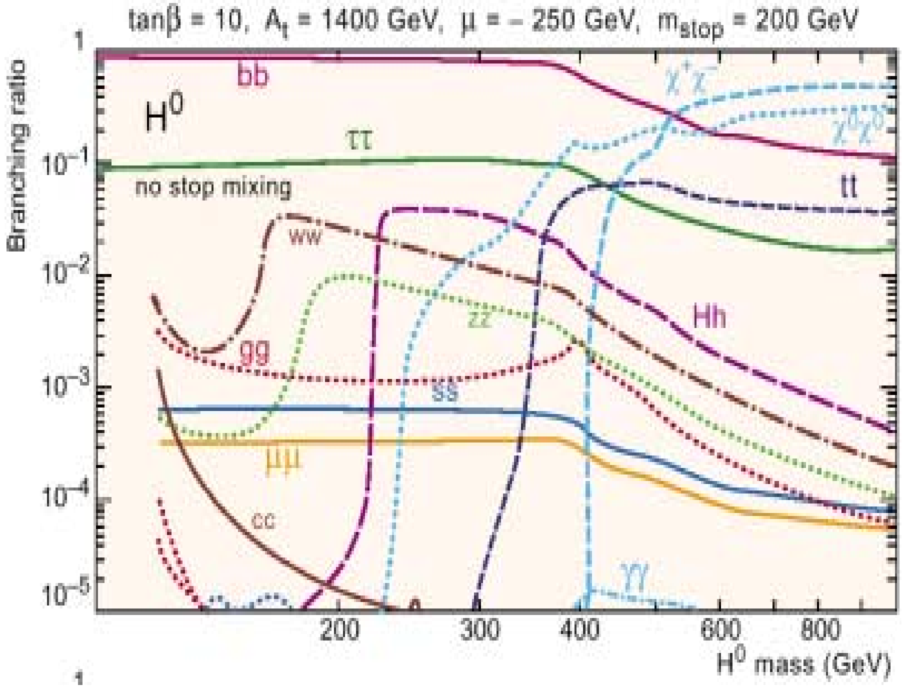
If mass of charg(neutra)linos < 1 TeV

e.g. Decays $H^0 \to \tilde{\chi}^0_2\tilde{\chi}^0_2$, $\tilde{\chi}^+_i\tilde{\chi}^-_j$ become important

- $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 \ell^+\ell^-$ has spectacular edge on the dilepton mass distribution
- Example: $\tilde{\chi}^0_2\tilde{\chi}^0_2$. Four (!) leptons (isolated); plus two edges



Four-lepton mass



Central point in MSSM parameter space :

$M_{A,H} = 350$ GeV	$\tan\beta = 5$
$M_{\tilde{l}} = 250$ GeV	$\mu = -500$ GeV
$M_{\tilde{\chi}^0_1} = 60$ GeV	$M_{\tilde{\chi}^0_2} = 110$ GeV
$M_{\tilde{q}} = M_{\tilde{g}} = 1$ TeV	

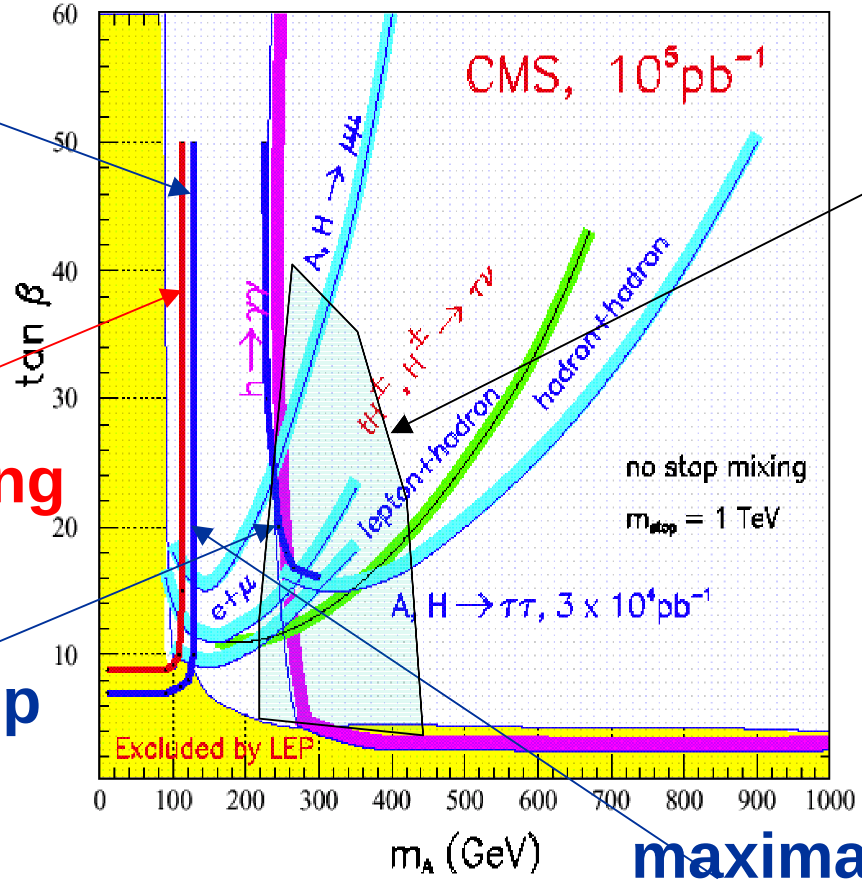
If $M_{charg(neutra)linos}$ < 1 TeV

Adding $b\bar{b}$ on the τ modes can "close" the plane

Wh

(e/μ)ν $b\bar{b}$

No stop mixing



Area covered by $H^0 \to \tilde{\chi}^0_2 \tilde{\chi}^0_2$, $\to 4\ell$eptons 100 fb^{-1}

maximal stop mixing with 30 fb^{-1}

maximal stop mixing with 300 fb^{-1}

Summary: SUSY Higgs'

Plane fully covered (no holes) at low L (30 fb^{-1}). Main channels :

$$h \rightarrow \gamma\gamma, b\bar{b}, \quad A/H \rightarrow \mu\mu, \tau\tau, H^{\pm} \rightarrow \tau\nu$$

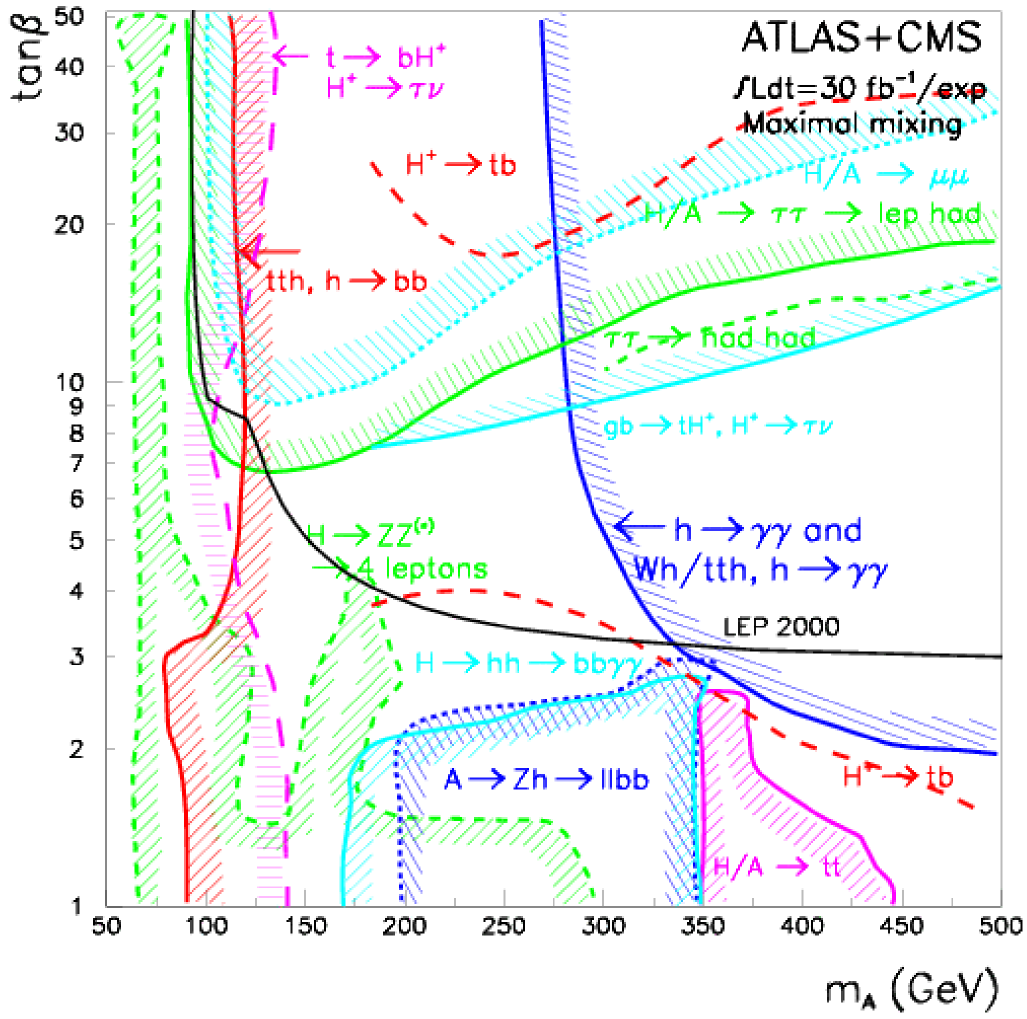
Two or more Higgs can be observed over most of parameter space ⇨ can disentangle SM / MSSM

LHC will observe h, A, H, H$^{\pm}$ for m_A < 400 GeV

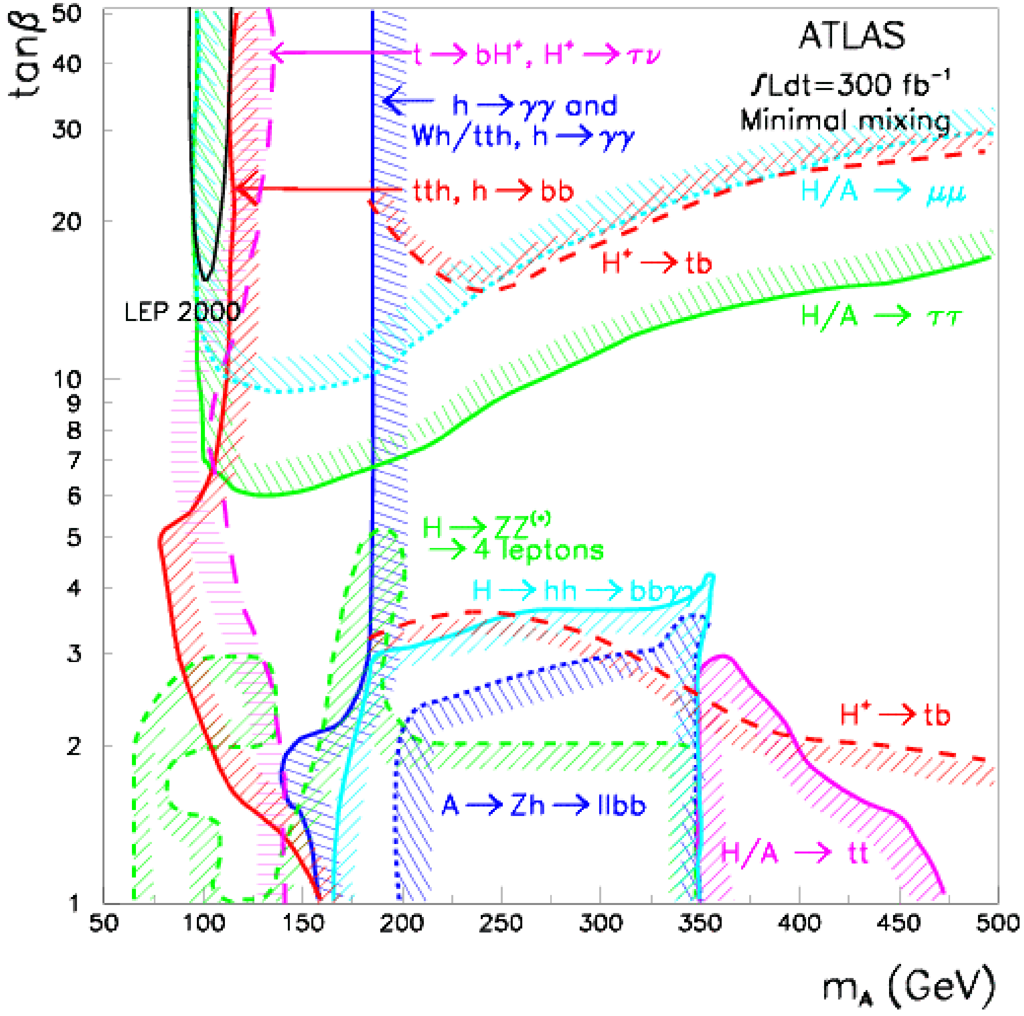
Uncertainties : $\Delta m_A \approx \pm$ 30 GeV (e.g. from Δm_h ~3 GeV), $\Delta\tan\beta \approx \pm$ 0.7

Impact of mixing on couplings studied for minimal mixing

but not for all possible mixing (evolving theory predictions)



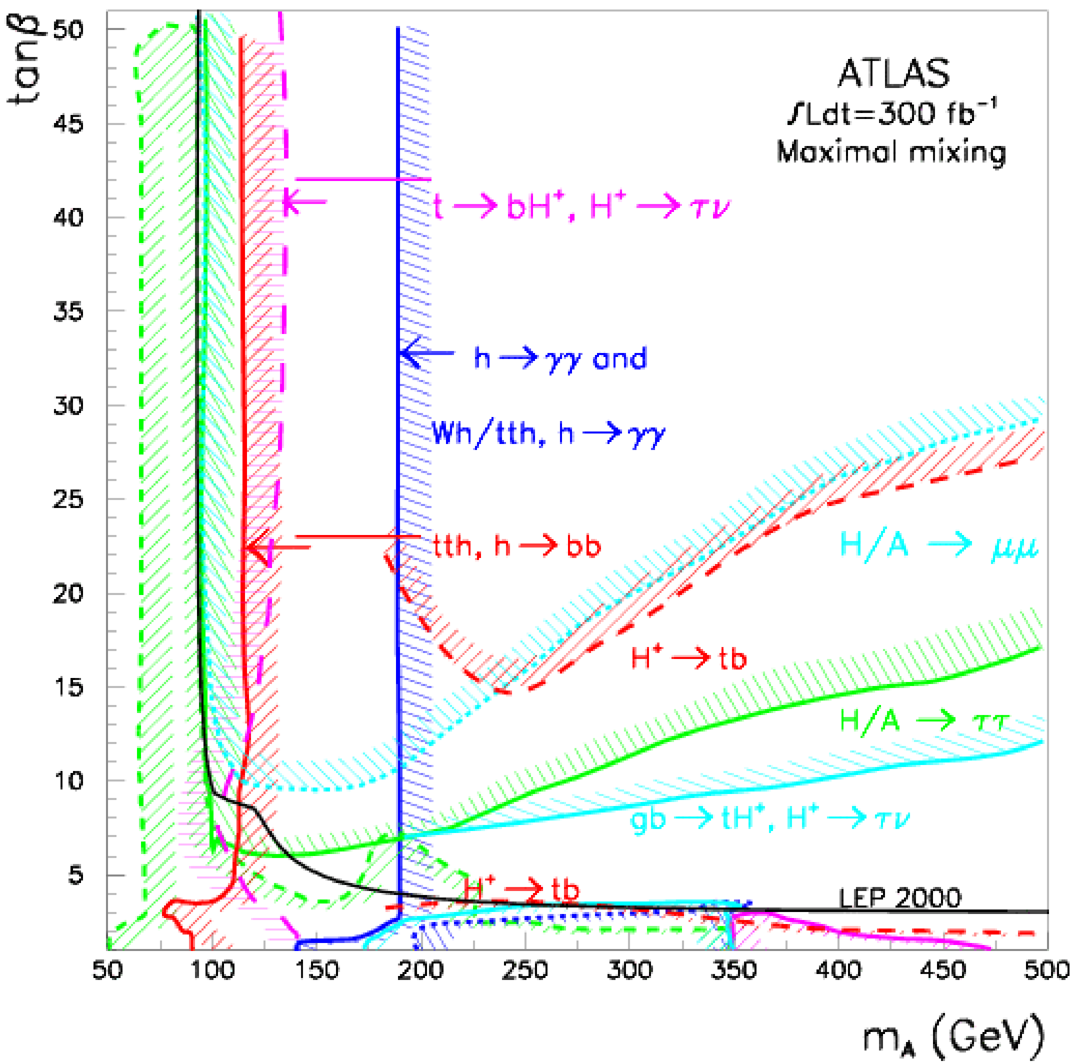
Minimal Mixing



Minimal mixing
(m_h < 115.5 GeV)
NB: log scale

Caveat: coverage depends strongly on exact upper bound on m_h

Maximal Mixing

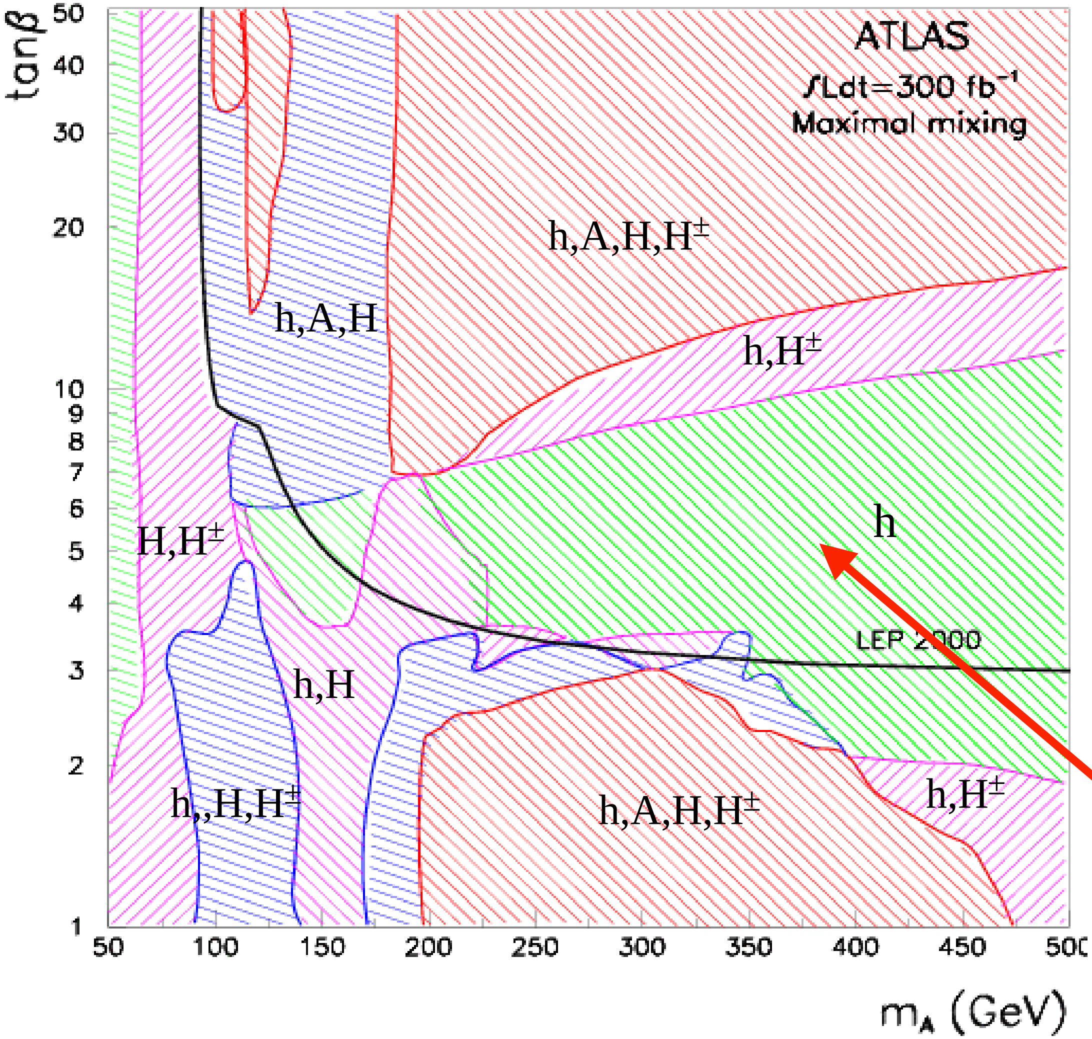


Maximal mixing
(m_h < 130 GeV)
NB: linear scale

Caveat: possible suppression of e.g. bbH coupling could affect significantly
H observation at LHC

How Many Higgs Discoverable ?

MSSM Higgs bosons



4 Higgs observable

3 Higgs observable

2 Higgs observable

1 Higgs observable

5σ contours

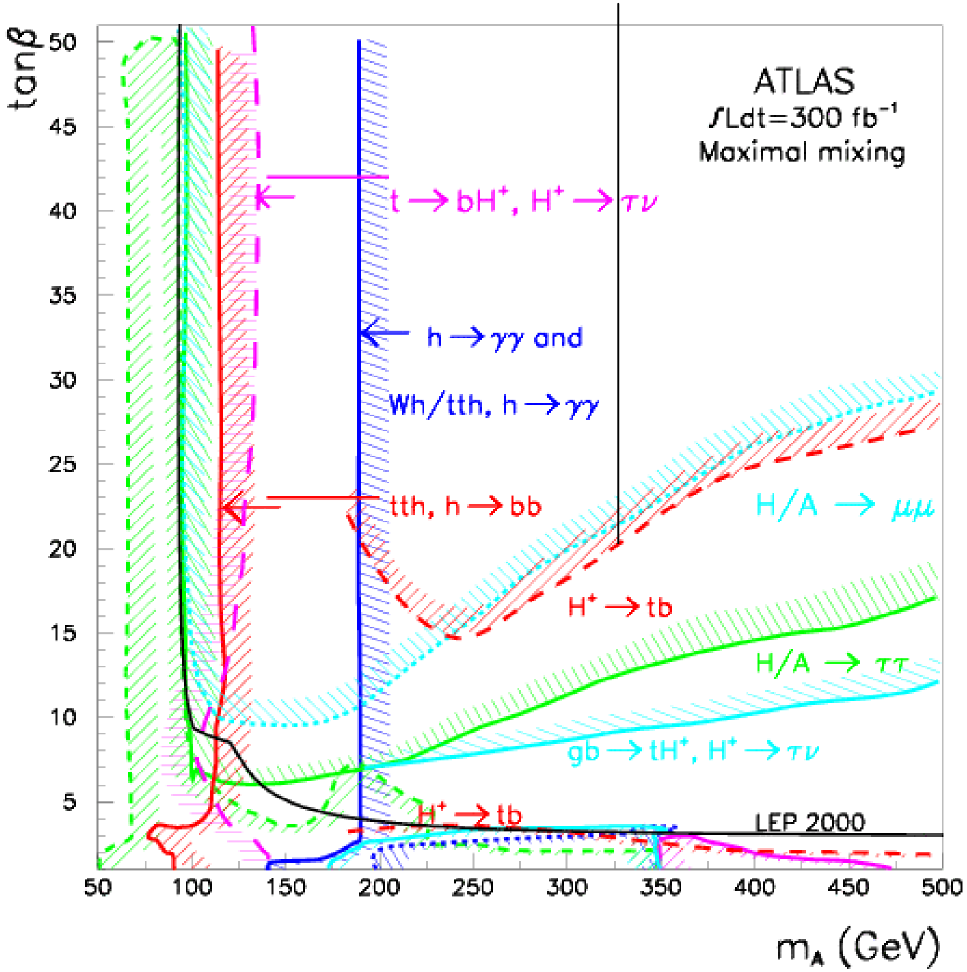
Assuming decays to SM particles only

In this region only h observable (h ≈ SM Higgs)

→ disentangle SM /MSSM ?

SUSY Higgs Boson: Mass

Maximal mixing (m_h < 130 GeV)
NB: linear scale



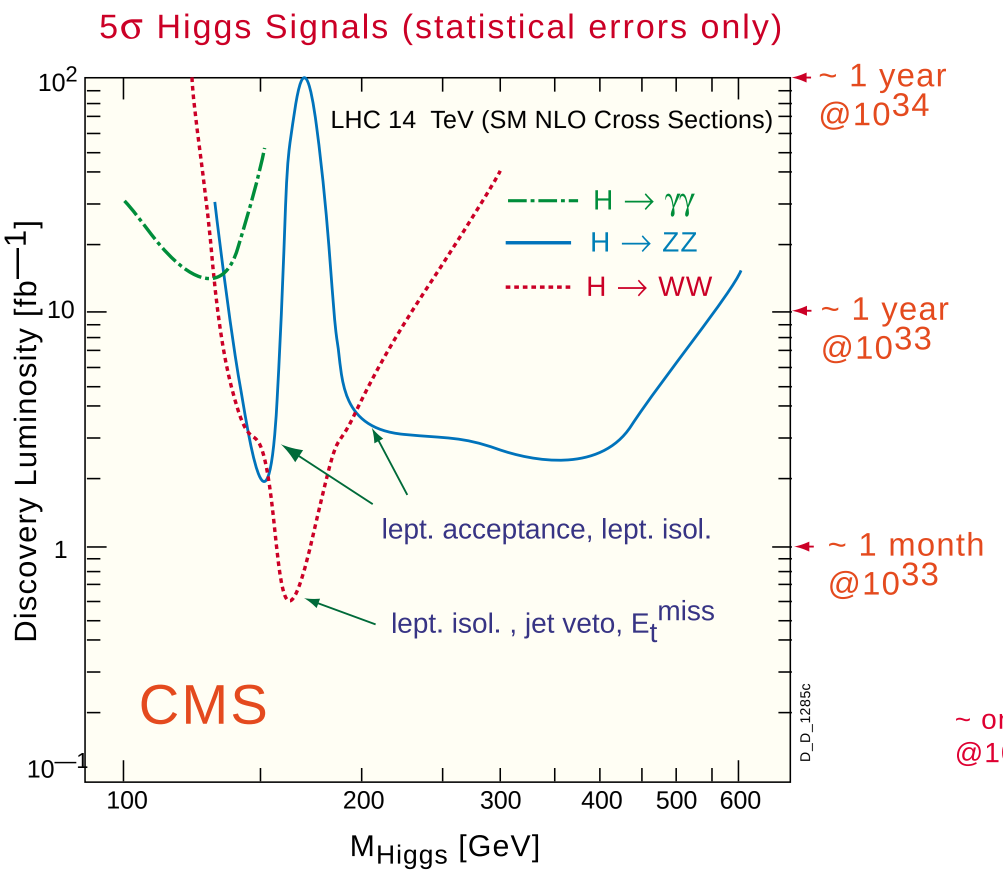
300 fb^{-1}

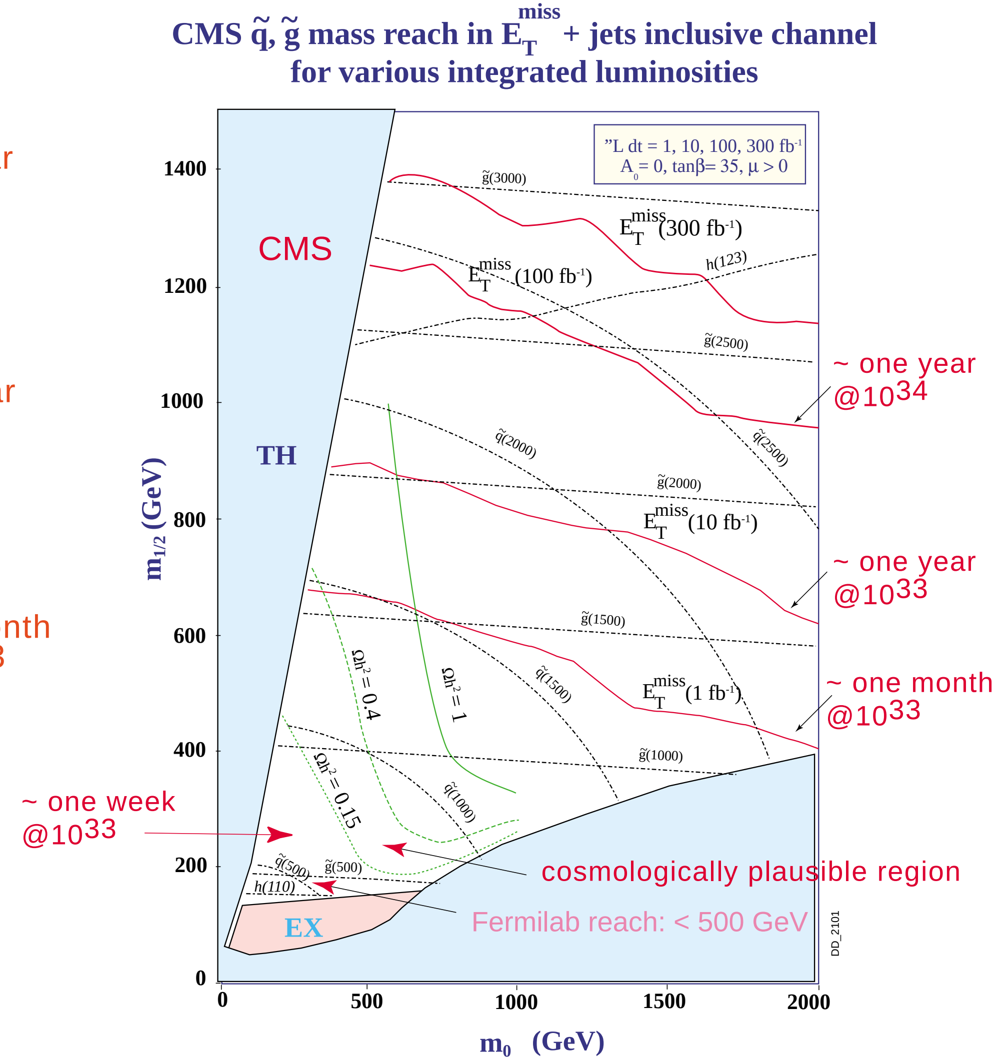
MSSM Higgs	$\Delta m/m$ (%)
h, A, H → γγ	0.1–0.4
H → 4 ℓ	0.1–0.4
H/A → μμ	0.1-1.5
h → bb	1–2
H → hh → bb γγ	1-2
A → Zh → bb ℓℓ	1–2
H/A → ττ	1-10

Present theoretical error Δm_h ~ 3 GeV

Caveat: possible suppression of e.g. bbH coupling could affect significantly H observation at LHC

Physics Reach ?





Conclusions

- Higgs is still missing
  - Symmetry Breaking in the SM (and beyond!) still not understood
  - LHC and ATLAS/CMS designed to find it
  - Numerous challenges, mostly “solved”
- Physics at the LHC will be extremely rich
  - SM Higgs (if there) in the pocket
    - Now turning to measurements of couplings, etc.
  - Supersymmetry (if there) ditto
    - Can perform numerous accurate measurements
  - Large com energy: new thresholds
    - Compositeness, new bosons, large extra dimensions within reach
  - LHC++?
- Just need to build machine/experiments.