Higgs at LHC

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- **Talk based on CMS & ATLAS studies, emphasis on recent results**
- **Introduction: Status of LHC, ATLAS nd CMS**
- **Standard Model Higgs**
- **Higgs in Minimal Supersymmetry (MSSM)**

LHC status

- **LHC accelerator**
  - **Final design for dipoles**
  - **Pre-series tested**
- **Schedule (optimistic)**
  - **04/2006 (pilot run)**
  - **08/2006-03/2007 10fb $^{-1}$**
  - **-> 2008 30fb $^{-1}$ /year/experiment**
  - **afterwards 100fb $^{-1}$ /yr/experiment**
- **Few months potential delay**
  - **Rate of superconductor production (world production capacity limited)**
  - **Funding issues**

Status of general purpose experiments

- **Both ATLAS and CMS optimized for Higgs detection**
  - **Higgs – major reference process in design of both detectors**
  - **All signatures "detectable" : e/μ/τ, γ, jets, E_t^{miss}**
- **ATLAS and CMS detector subsystems are in production (except parts of Trigger and DAQ)**

ATLAS and CMS started delivery of detectors to CERN

CMS magnet yoke

CMS HCAL

ATLAS EM
AR

ATLAS barrel

On a personal note: CMS Muon system

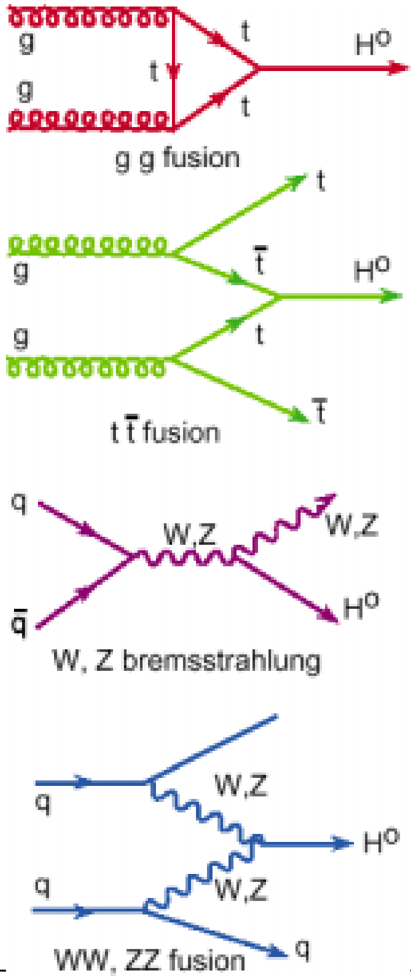
Test installation of a Cathode Strip Chamber
(CSCs in full production, >100 out of 400 produced worldwide)

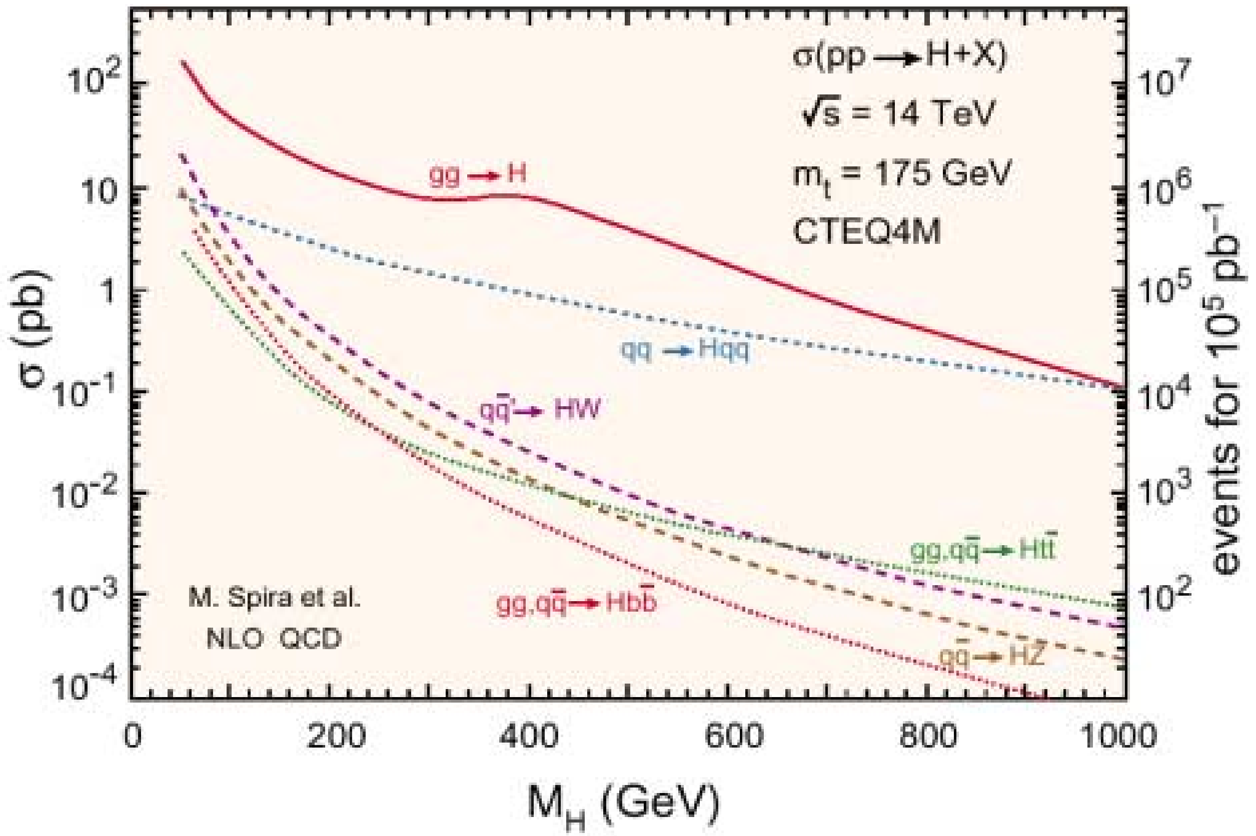
Simulation of Higgs in ATLAS & CMS

- In most cases full (GEANT) for the benchmark channels, including trigger simulations for the signal and background
  - Typically no K-factor used (σ_{LO}/σ_{NLO} ~ 1.1 -1.9) – but if included generally makes S/√B better
- Emphasis on the channels, suitable for the high luminosity
- Discovery definition: 5 σ(S/√B) per experiment / channel
- Systematical errors estimated in some cases
- Simple cuts, no Neural Nets – makes results more transparent, particularly when the background is not known well

SM Higgs: production

- **Production mechanisms & cross section**
- **10 000- 100 000 Higgses produced /year**





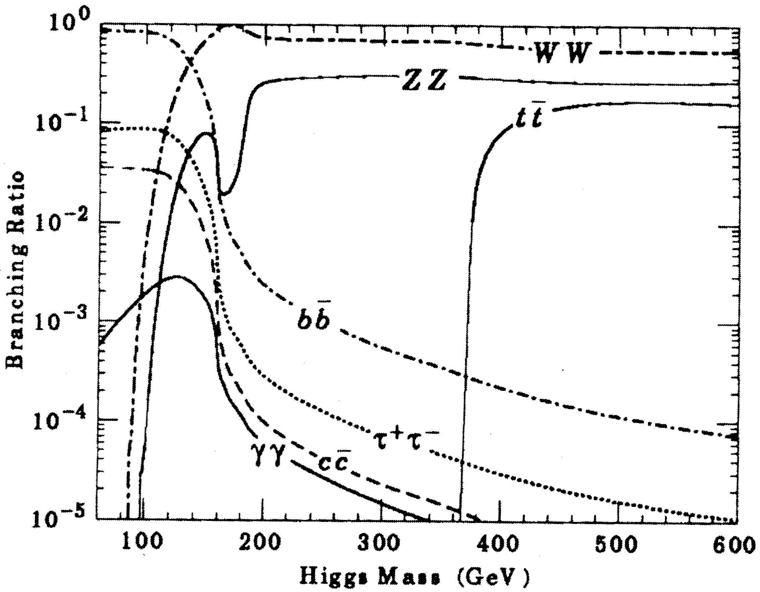
SM Higgs: final states and Branching ratios

For $m_H < 2m_Z$

- ttH → lνbbjj+bb
- H → γγ (direct & associated)
- H → ZZ* → 4l
- H → WW* → lνlν

New studies:

- qqH → WW* → lνlν (VBF)
- qqH → ττ → l+τ-jet (VBF)
- qqH → ττ → l+l (VBF)

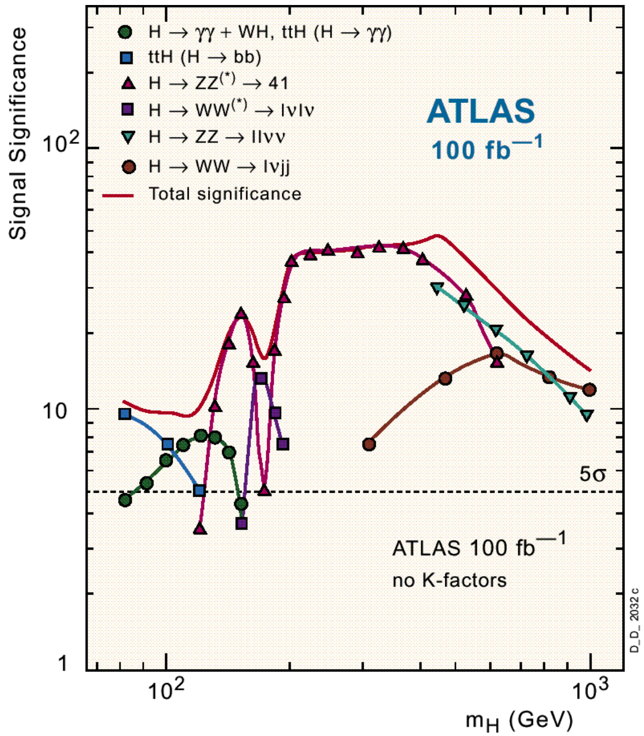


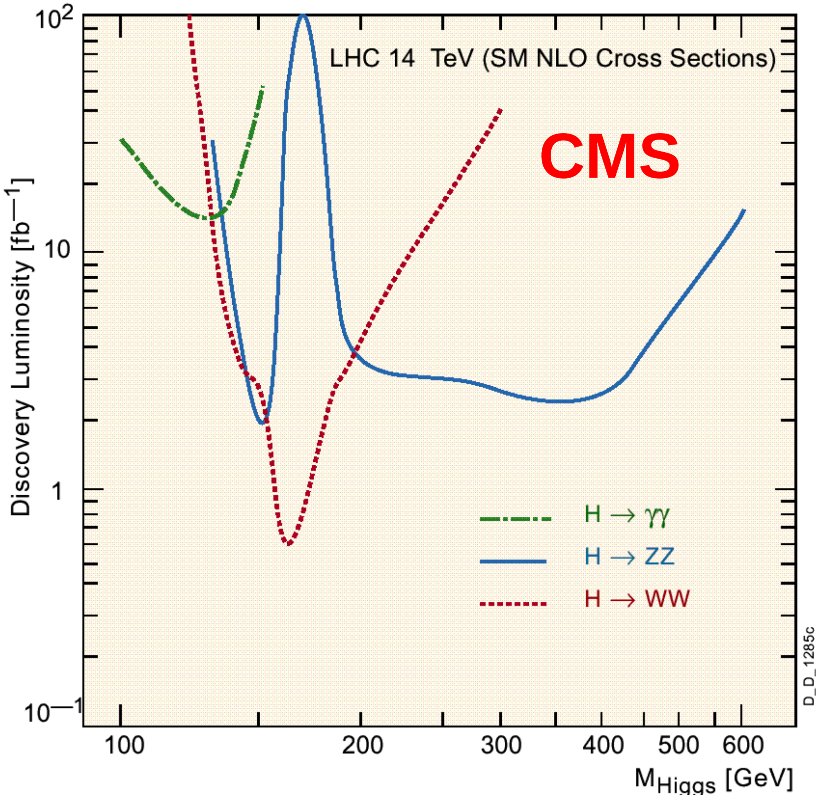
For $m_H > 2m_Z$

- H → ZZ → 4l
- qqH → ZZ → llνν (VBF)
- qqH → WW → lνjj (VBF)
- qqH → WW → lνlν (VBF)

SM Higgs discovery prospects - summary

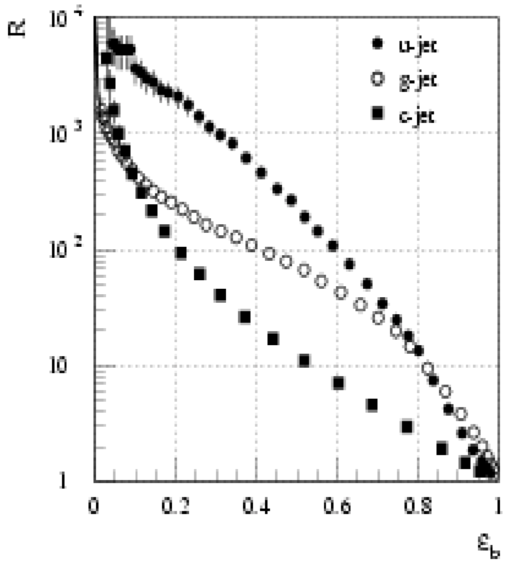
- **All masses (100 Gev – 1 Tev) covered**
  - in most cases a few months at low luminosity are adequate for a 5σ observation
  - qq $\rightarrow$ qqH $\rightarrow$ qq $\tau\tau$, qqWW,qq $\gamma\gamma$ under study in low mass region



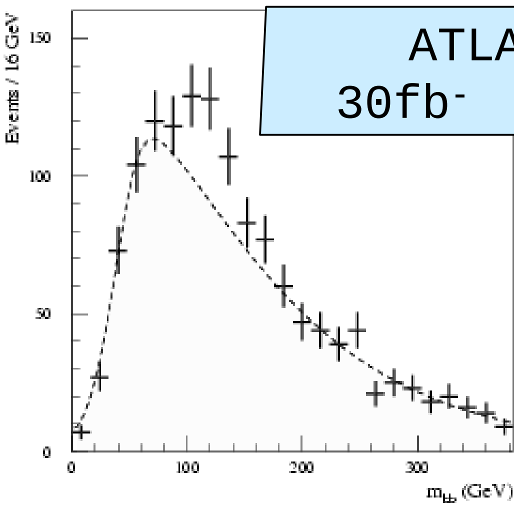


SM Higgs – low mass

- **$ttH \rightarrow ttbb \rightarrow l\nu b+bjj+bb$**



- **Complex final state :**
- **Bckd reduced by 2 tops reconstruction and B-tagging**
- **$\Delta(m_{bb})$ ~ 15%, may be with tracker (?)**
- **complementary to $\gamma\gamma$**

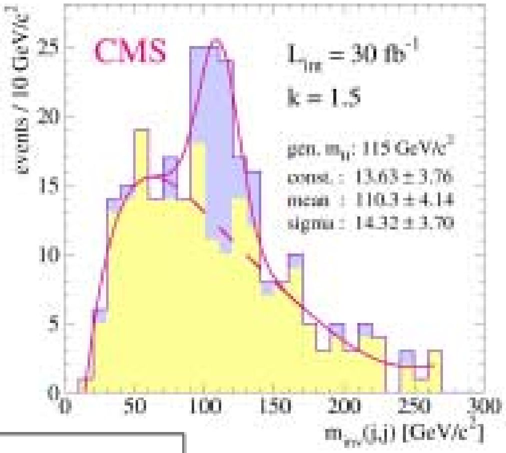


- **knowledge of background**
  5σ for 120 GeV if 5%

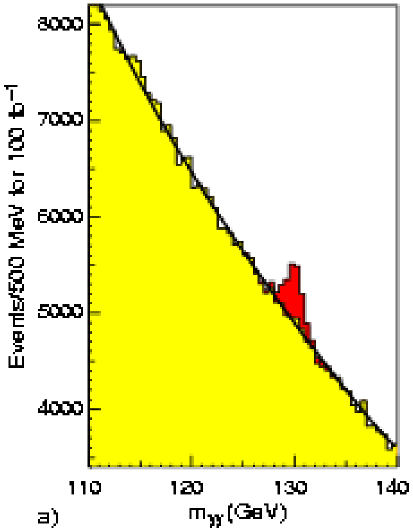
SM Higgs – low mass (cont)

- **$H \rightarrow bb$ via ttH (cont'd)**
  - **CMS study**
  - **Use likelihood for t decays & event kinematics**

CMS 30fb-
S=38



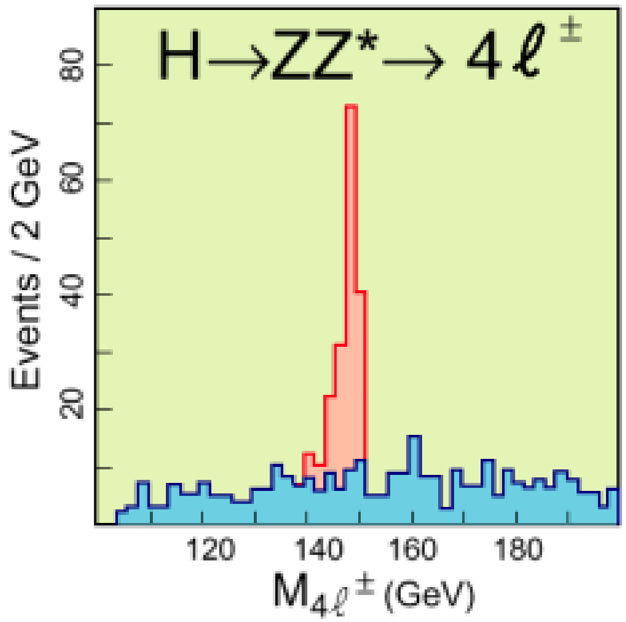
- **$H \rightarrow \gamma\gamma$: decay is rare ($B \sim 10^{-3}$)**
  - **good resolution essential**
  - **reason for LAr/$PbWO_4$**
  - **CMS: at 100 GeV, $\sigma \approx 1$GeV**
    - **S/B ≈ 1:20**

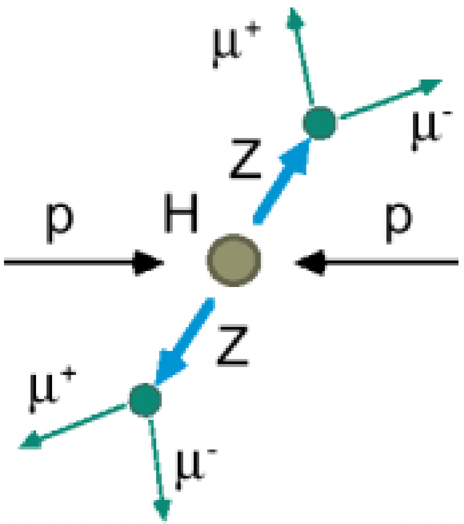


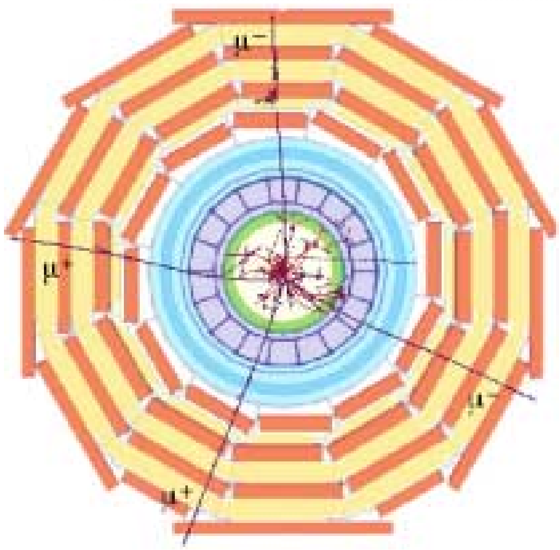
CMS
$100fb^{-1}$
K=1.6, S/B

SM: Intermediate mass Higgs

- **$H \to ZZ \to \ell^+\ell^- \ \ell^+\ell^-$ (ℓ =e,μ)**
  - **Very clean**
    - **Resolution: ~ 1 GeV**
  - **Works for the mass range $130 < M_H < 500$ GeV/c^2**

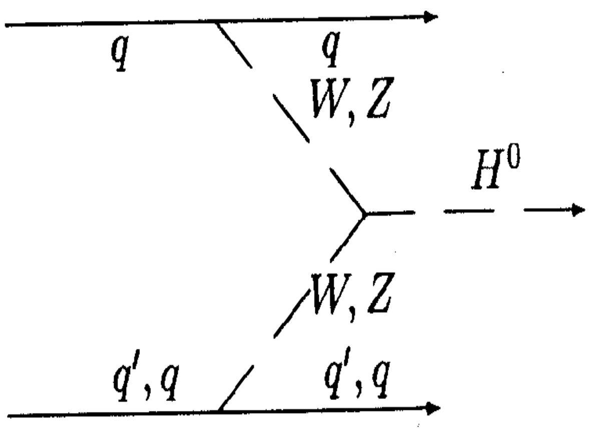




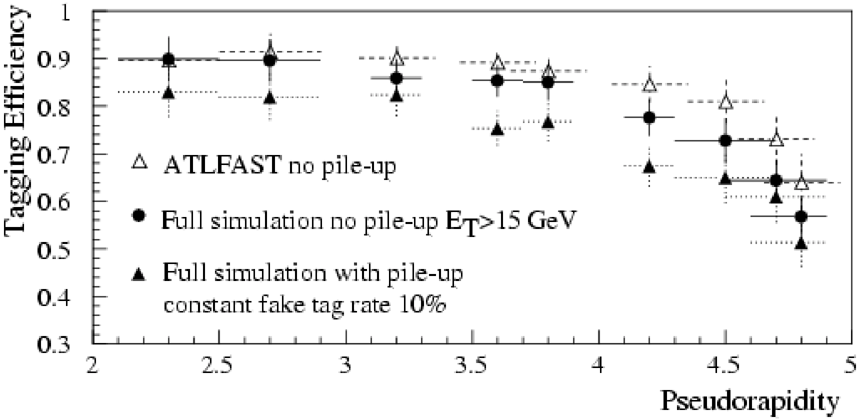


Recent studies: SM Higgs - Vector Boson Fusion (VBF)

- Proposed by D. Zeppenfeld et al.



- 20% of gg-fusion
- better trigger, better signature
  (2 forward jets, low central activity)
- measurement of couplings ($H\tau\tau$), Γ_H
- detection of invisible Higgs



- Forward jet tagging
  - Full simulation
  - High efficiency, low fake

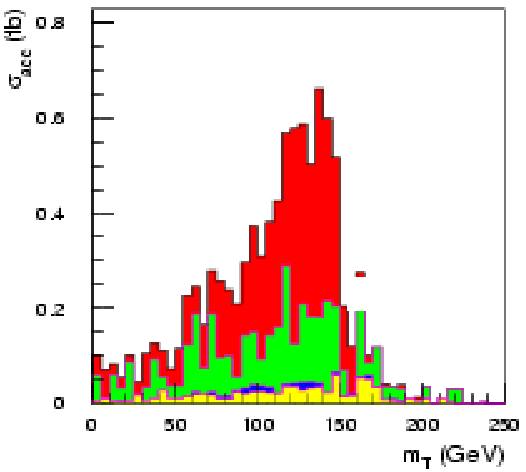
- Double tag efficiency
- Fake double tag < 1% @

recent studies: VBF, Higgs--WW

- **qqH $\rightarrow$qqWW $\rightarrow$ qq lν lν**
  - **Backgrounds: tt, WW cont.**
  - **Cuts: p_T(tot) & jet veto**

m_H (GeV)	**130**	**150**	**170**	**190**
S	10	30	55	40
S/B	0.3	0.9	1.5	1.1
S/$\sqrt{B}$	1.4	5.0	8.8	6.3

ATLAS, eμ, 10
m_H = 160



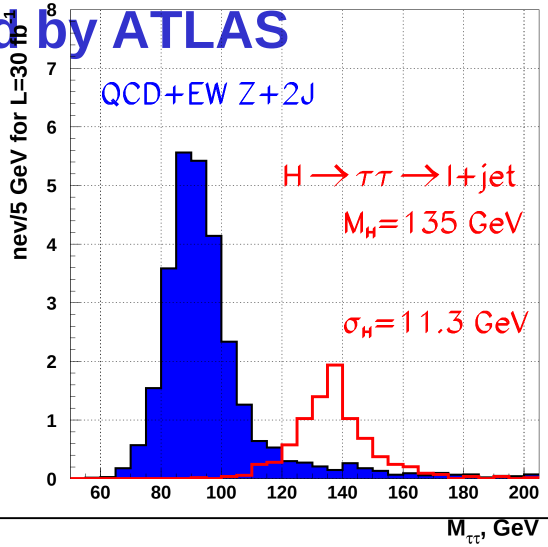
$$m_T = \sqrt{2\, p_T^{\ell\ell}\, E_T^{miss}\, (1 - \cos\Delta\varphi)}$$

  - **Counting experiment @ low mass**
    - **5% systematics included in B**
  - **Good S/$\sqrt{B}$ at the WW threshold: max signal & good background supression based on V-A spin correlation for WW, charged leptons emitted in the same direction**

recent studies: VBF, Higgs--$\tau\tau$

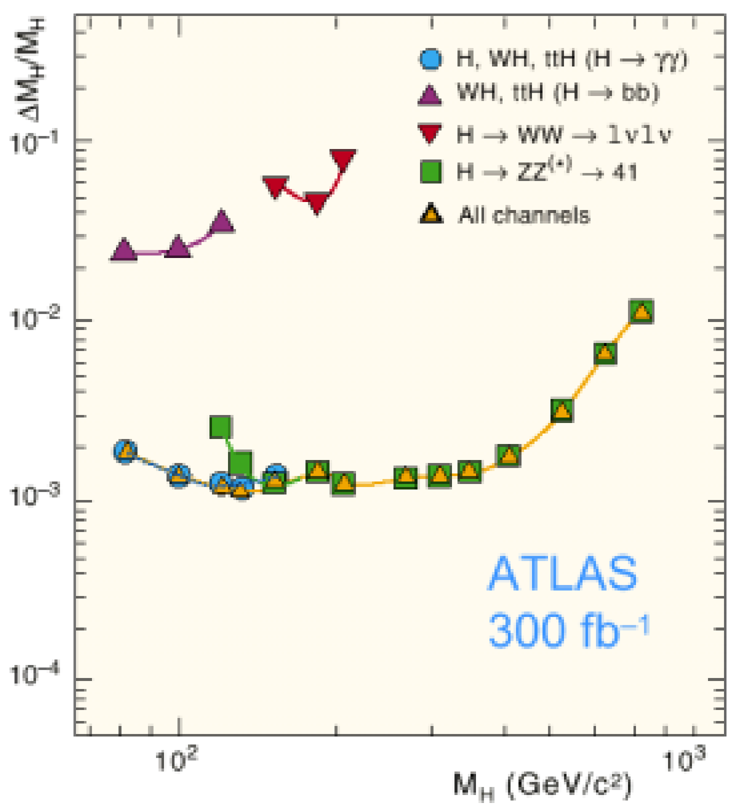
- **Important for the Higgs couplings measurement**
- **qqH $\rightarrow$ qq $\tau\tau$ $\rightarrow$ qq+l$\nu\nu$+jν**
  - Selection and cuts similar to WW
  - τ reconstruction using collinear approximation
  - Systematic errors to be included
  - l$\nu\nu$, l$\nu\nu$ channel has been studied by ATLAS
  - CMS fast simulation confirms parton level estimates by D.Zeppenfeld et al.

CMS, 30 fb^{-1}
m_H = 135



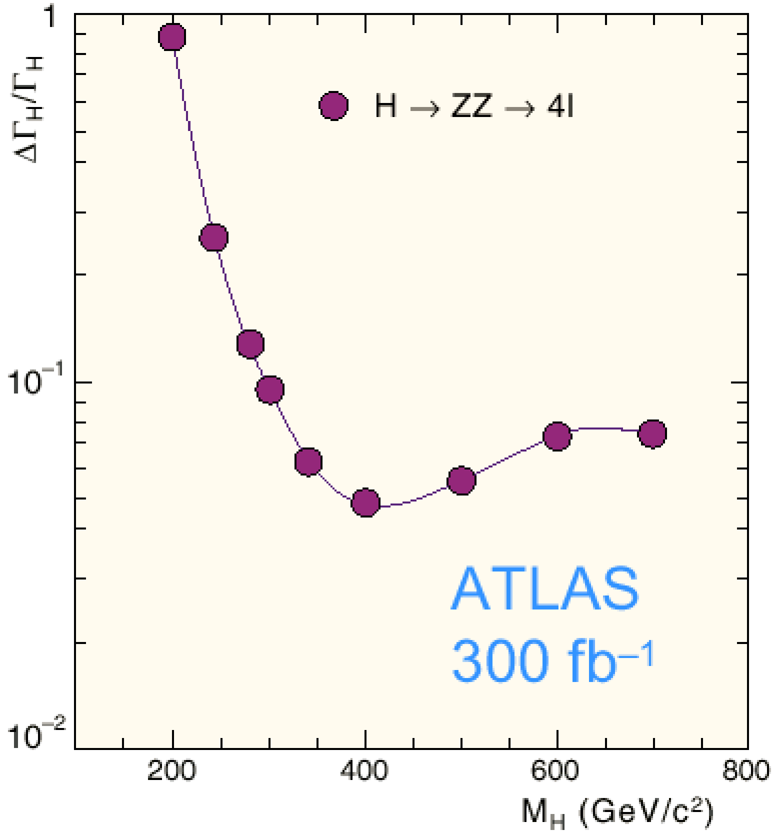
SM Higgs properties: mass

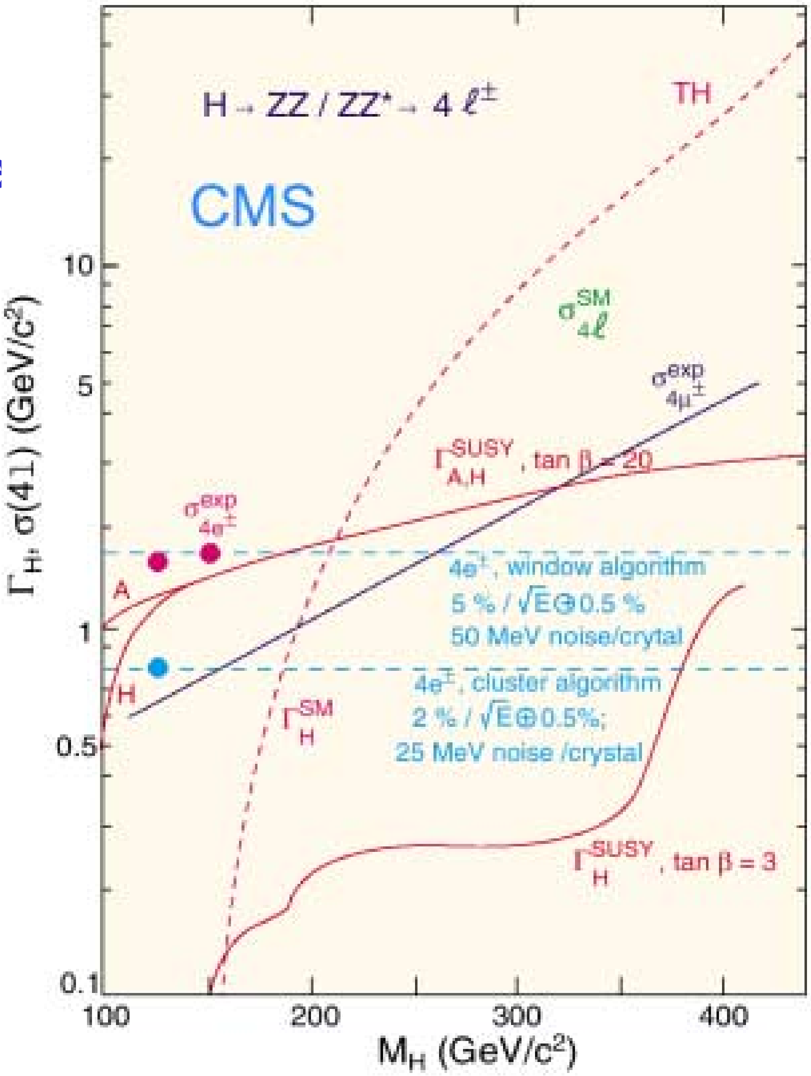
- **Mass measurement**
  - **Limited by absolute energy scale**
    - **leptons & photons: 0.1% (with Z calibration)**
    - **Jets: 1%**
  - **Resolutions:**
    - **For $\gamma\gamma$ & $4\ell \approx 1$ GeV/c^2**
    - **For bb ≈ 15 GeV/c^2**
  - **At large masses: decreasing precision due to large Γ_H**
  - **CMS ≈ ATLAS**



SM Higgs properties: width
(for M_H>200 Gev)

- **Width:**
  - Direct measurement for M_H>200 using golden mode (4ℓ)

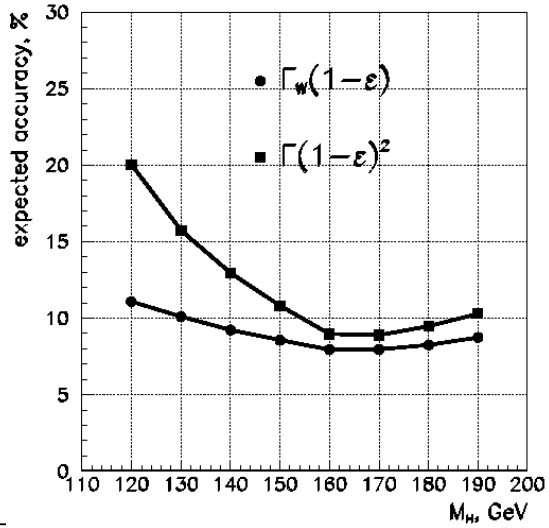




SM Higgs properties: width (for low M_H, indirect measurement)

- **Combine measurements of several Higgs channels in VBF and gg production: $qq \to qqH$, $gg \to H$**
  - Can measure the following: $X_i = \Gamma_W \Gamma_i / \Gamma$ from $qq \to qqH \to qqii$
    - Here: $i = \gamma, \tau, W(W^*)$; precision~10-30%
  - Measure also $Y_i = \Gamma_g \Gamma_i / \Gamma$ from $gg \to H \to ii$
    - Here: $i = \gamma, W(W^*), Z(Z^*)$; precision~10-30%
  - Ratios of X_i and Y_i (~10-20%) $\to$ couplings
  - Γ and Γ_W can be estimated from:
    - $(1-\varepsilon)\Gamma_W = X_\tau(1+y) + X_W(1+z) + X_\gamma + Y_W$
    - $\varepsilon = (1-(B_b+B_\tau+B_W+B_Z+B_g+B_\gamma)) = B_C \ll 1$
    - From SM: $z = \Gamma_W/\Gamma_Z$; $y = \Gamma_b/\Gamma_\tau = 3\eta_{QCD}(m_b/m_\tau)^2$
    - $X_W = (\Gamma_W)^2 / \Gamma$ - observable

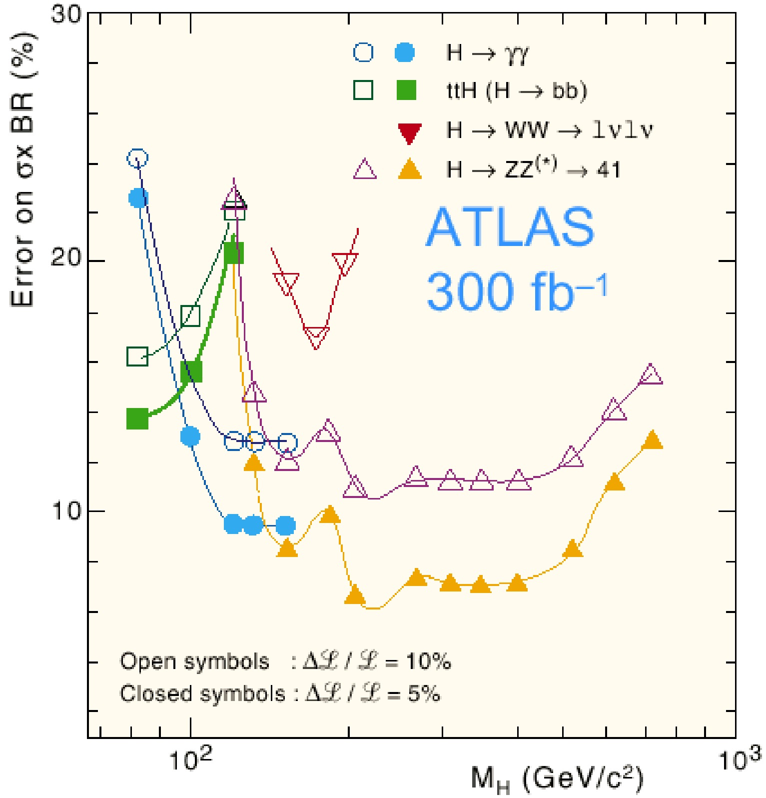
CMC + ATLAS 100



SM Higgs properties – ratio of couplings

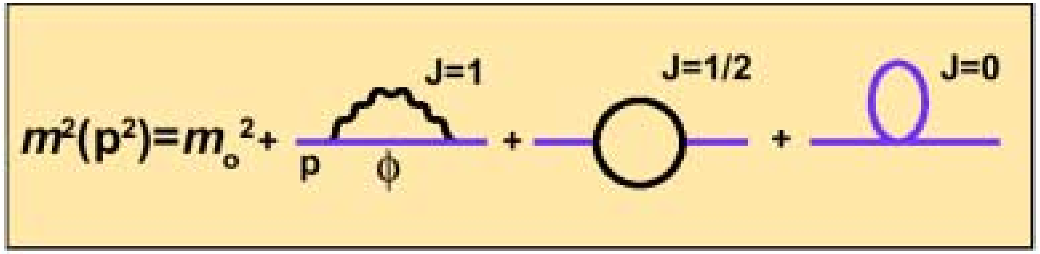
- **Systematic uncertainty: luminosity dominated?**
- **Relative couplings statistically limited**

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



Problems with the SM Higgs

- **Quadratic divergence of its mass**



$$m^2\left(p^2\right)=m^2\left(\Lambda^2\right)+Cg^2\int_{p^2}^{\Lambda^2}dk^2$$

  - Λ is a cutoff momentum
  - In other words: why is the Higgs mass low?

- **With SUSY, quadratic divergences disappear:**
    - As long as $M_p=M_{sp}$
- **SUSY requires more Higgs-like particles**

MSSM Higgses: choice of parameters

- **5 Higgses in Minimal Supersymmetry ($H^{\pm}$;H^0,h^0,A^0)**
- **2 charge, 3 neutral: 2 CP – even (light h and heavy H), and one CP – odd (heavy A)**
- **SUSY has a lot of parameters, but only 4 are important for the Higgs sector in MSSM!**
  - **At tree level, all masses & couplings depend on only two parameters (usually M_A & tanβ)**
  - **Modifications to tree-level mainly from top loops**
  - **Additional parameters:**

    1: SUSY particle masses:

    (a) M>1 TeV (i.e. no decays of the Higgses to sparticles); well-studied

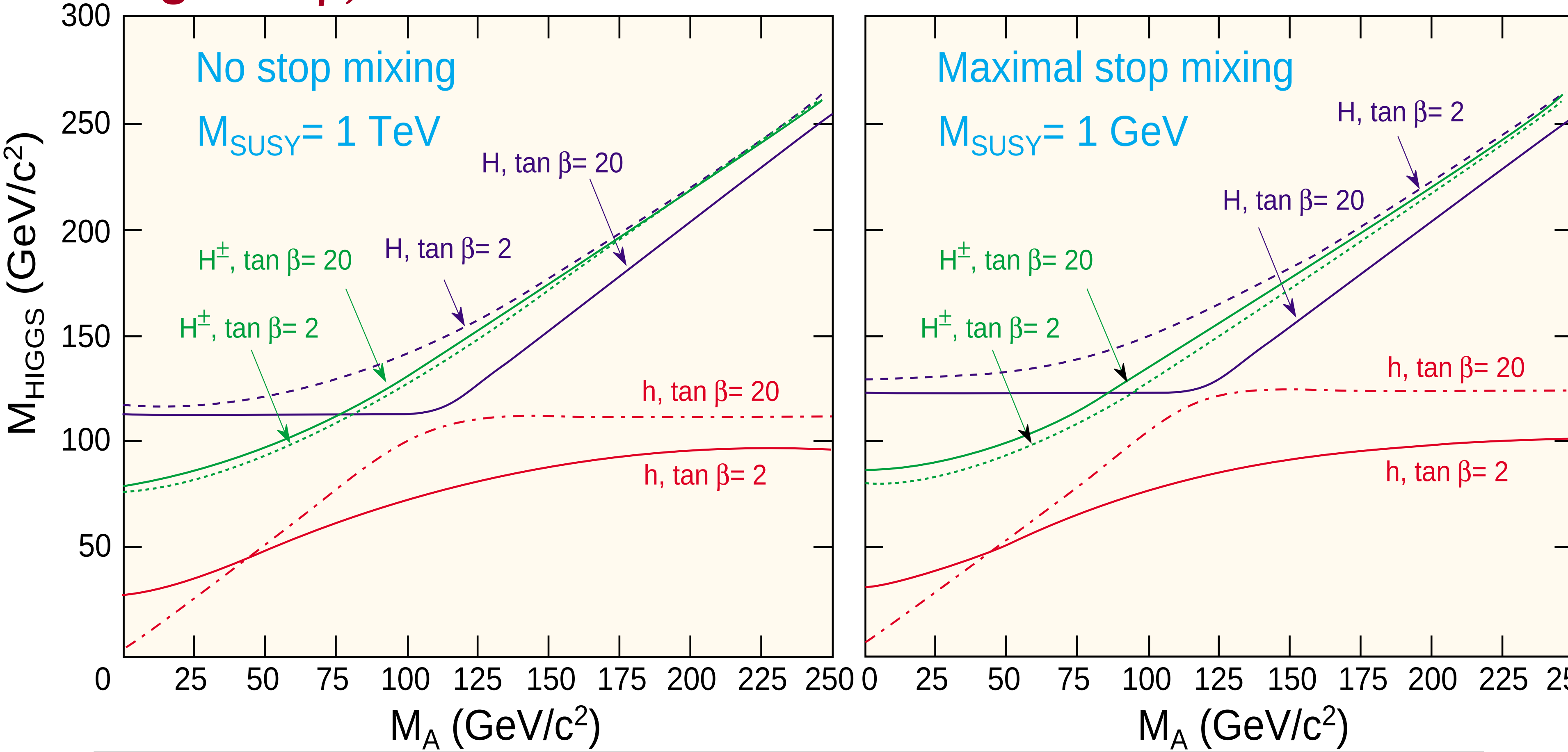
    (b) M<1 TeV (i.e. allows decays of the Higgses to sparticles); “new”

    2: stop mixing:

    Maximal–No mixing

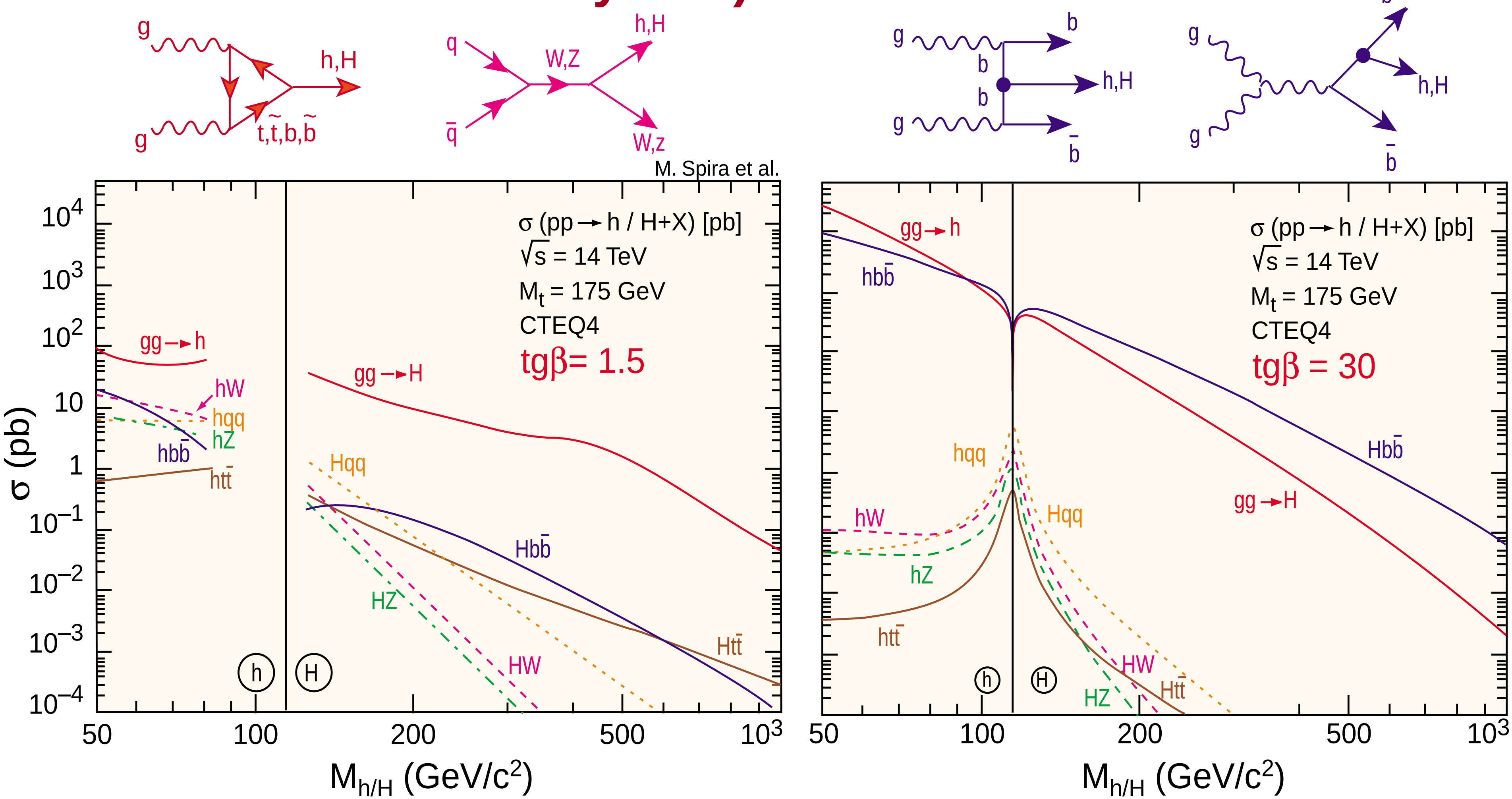
MSSM Higgs masses (as a function of M_A)

For high M_A – decoupling limit regime: M_{h+}=M_h(max), h similar to SM, M_A~M_H, coupling of A,H similar (for high tanβ)



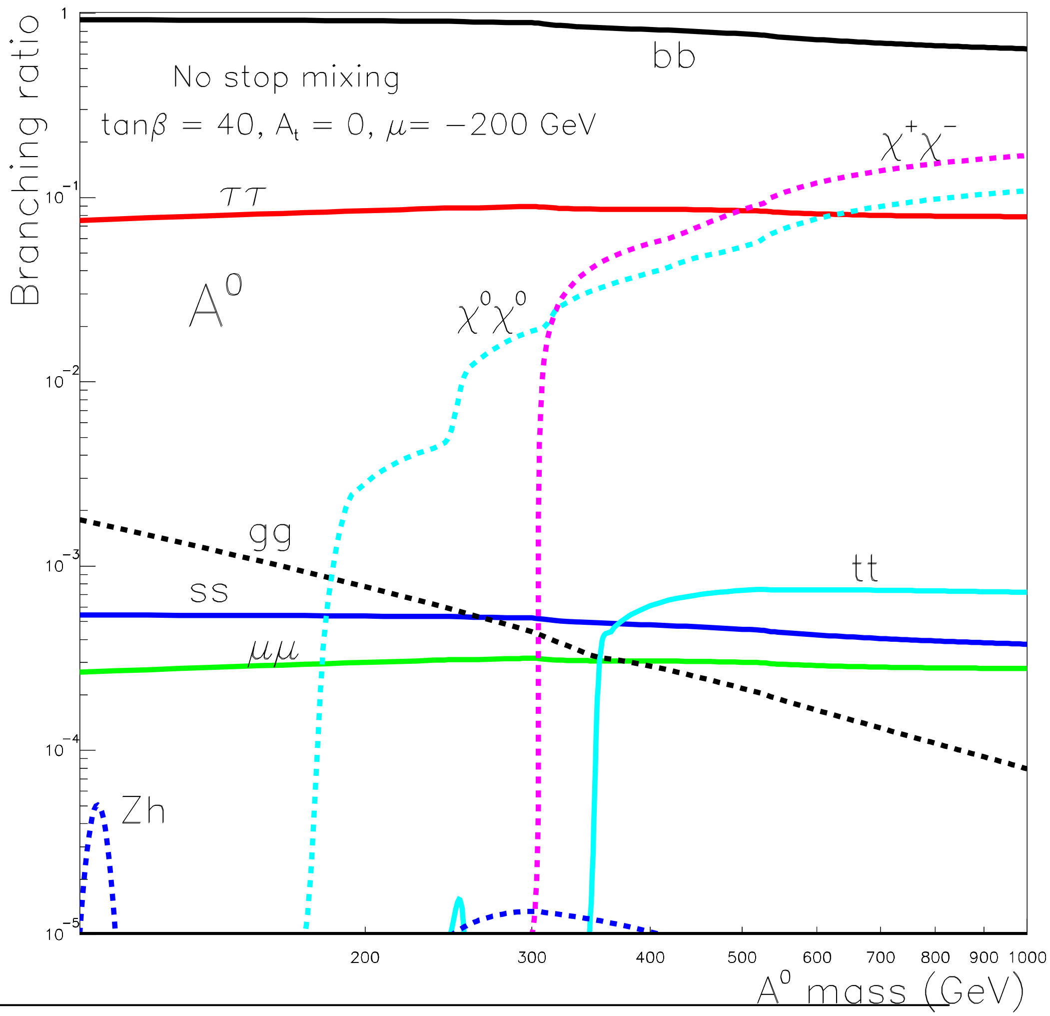
MSSM: h/H production

- **Couplings: important dependence on tanβ (low tanβ almost excluded by LEP). Associated bb enhanced**



MSSM: h/H/A decays - Branching ratios

- **Branching ratios for h as SM in decoupling limit**
- **H,A different from SM**
- **for A and tanβ = 40 shown**
  - **Decays to bb (90%) & $\overline{\tau\tau}$ (8%)**
    - **Decays to cc, gg suppressed**
  - **Decays to top open at low tanβ**
- **WW/ZZ channels suppressed for A (everywhere) and for H (at high tanβ) – lose golden modes for H, A**



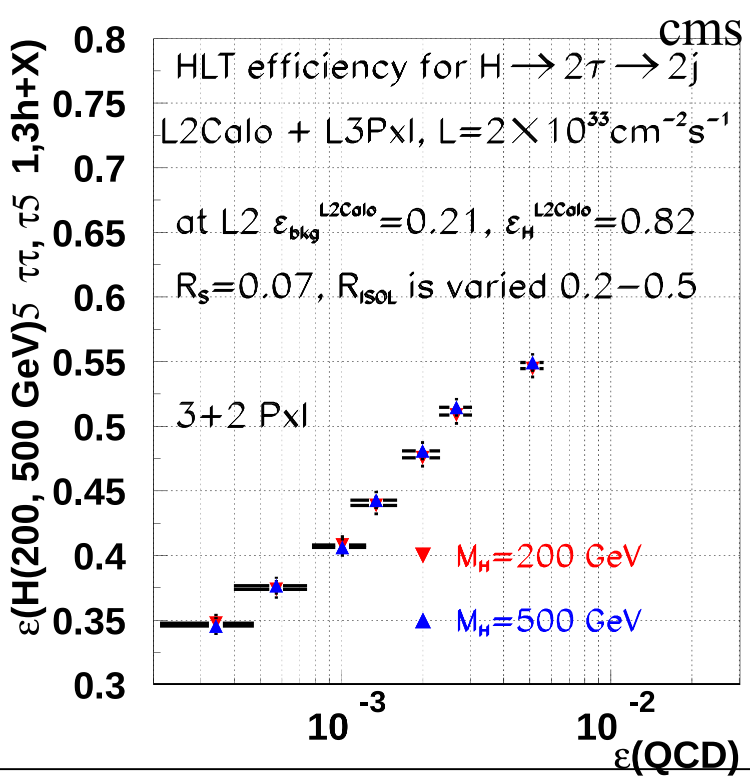
MSSM Higgses – final states

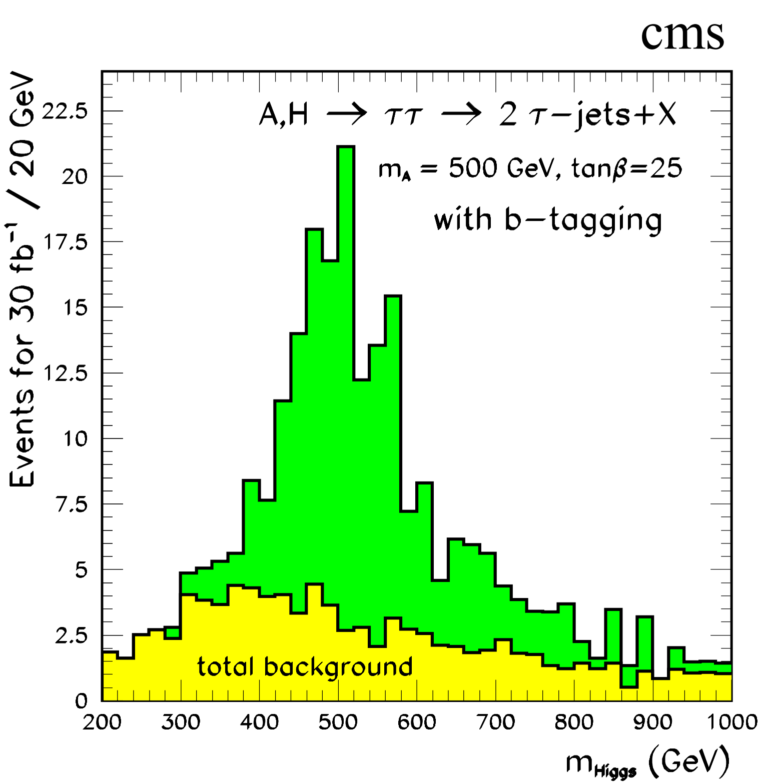
- **Most important channels being investigated:**
  - $h \to \gamma\gamma$, bb (in tth , Wh – recalculation from SM simulation)
  - h, H, A$\to \tau^+\tau^- \to (e/\mu)^+ +$ hadr$+ E_T^{miss}$
    $\to e^+ + \mu^- + E_T^{miss}$
    $\to$ hadr$^+ +$ hadr$^- + E_T^{miss}$
    } gg $\to$higgs and gg $\to$bbH_{SUSY}
  - $H^+ \to \tau^+ \nu$, (higgs from t decays, $M_H < M_{top}$)
  - $H^+ \to \tau^+ \nu$ and $H^+ \to$ t b (for $M_H > M_{top}$)
  - H, A $\to \tilde{\chi}^0_2\tilde{\chi}^0_2, \tilde{\chi}^0_i\tilde{\chi}^0_j, \tilde{\chi}^+_i\tilde{\chi}^-_j$
  - $H^+ \to \tilde{\chi}^+_2\tilde{\chi}^0_2$
    } new and promising

- **Channels contributing at low tanβ are not considered here, since this region is practically excluded by LEP**

MSSM Higgses: H,A→ττ

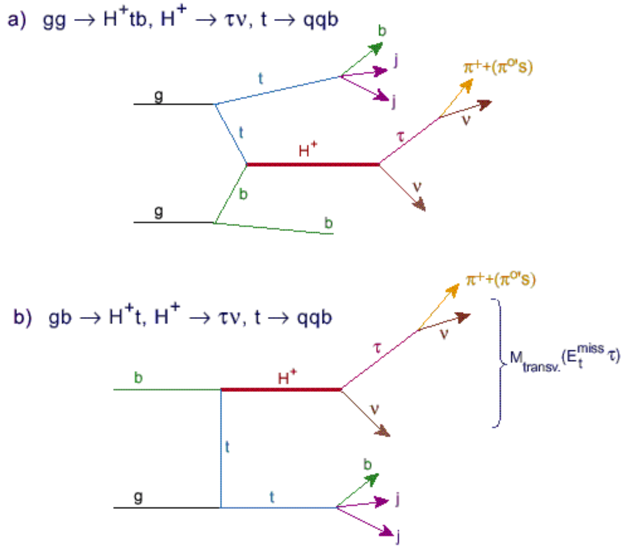
- **Very promising modes for H,A (BR 8%)**
  - τ's identified either in hadronic or leptonic decays
  - Mass reconstruction: take lepton/jet direction to be the τ direction
  - Dedicated trigger with calo and tracker developed in CMS and ATLAS





MSSM Higgses: H^{+} detection

- **Associated top-H^{+} production:**
  - **Use all-hadronic decays of the top (leave one "neutrino")**
  - **H decay looks like W decay → Jacobian peak for τ-missing E_T**
  - **Trigger on τ-jet & missing E_T**

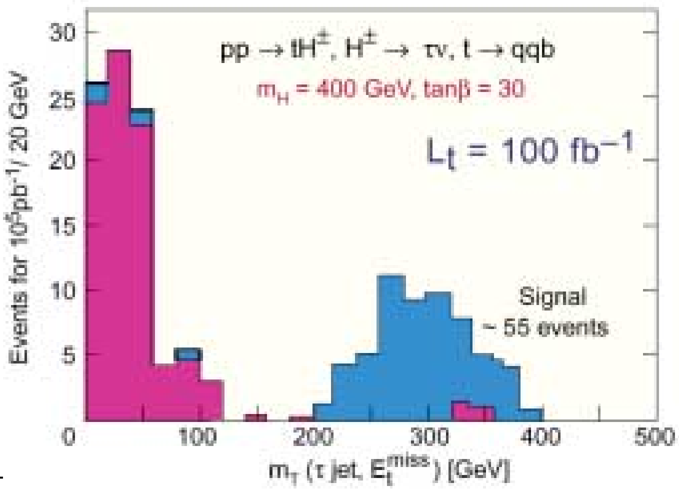


Cuts:
E_T(jet)>100

$|\eta|$<2.4

Veto on extra jet, and on second top

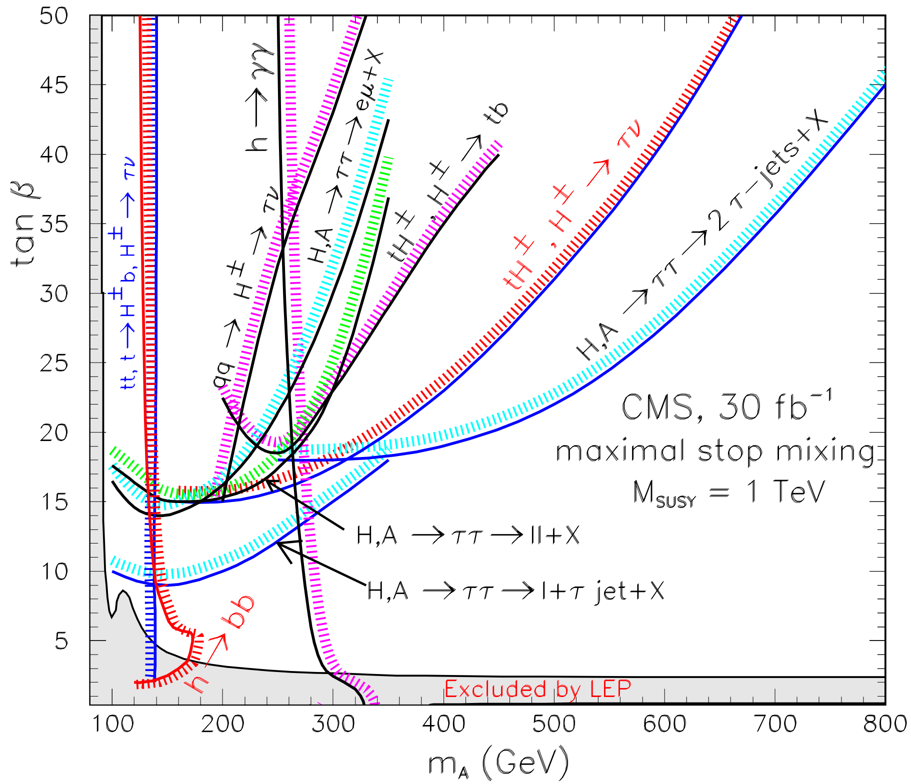
Bkg: $t\bar{t}H$



cms

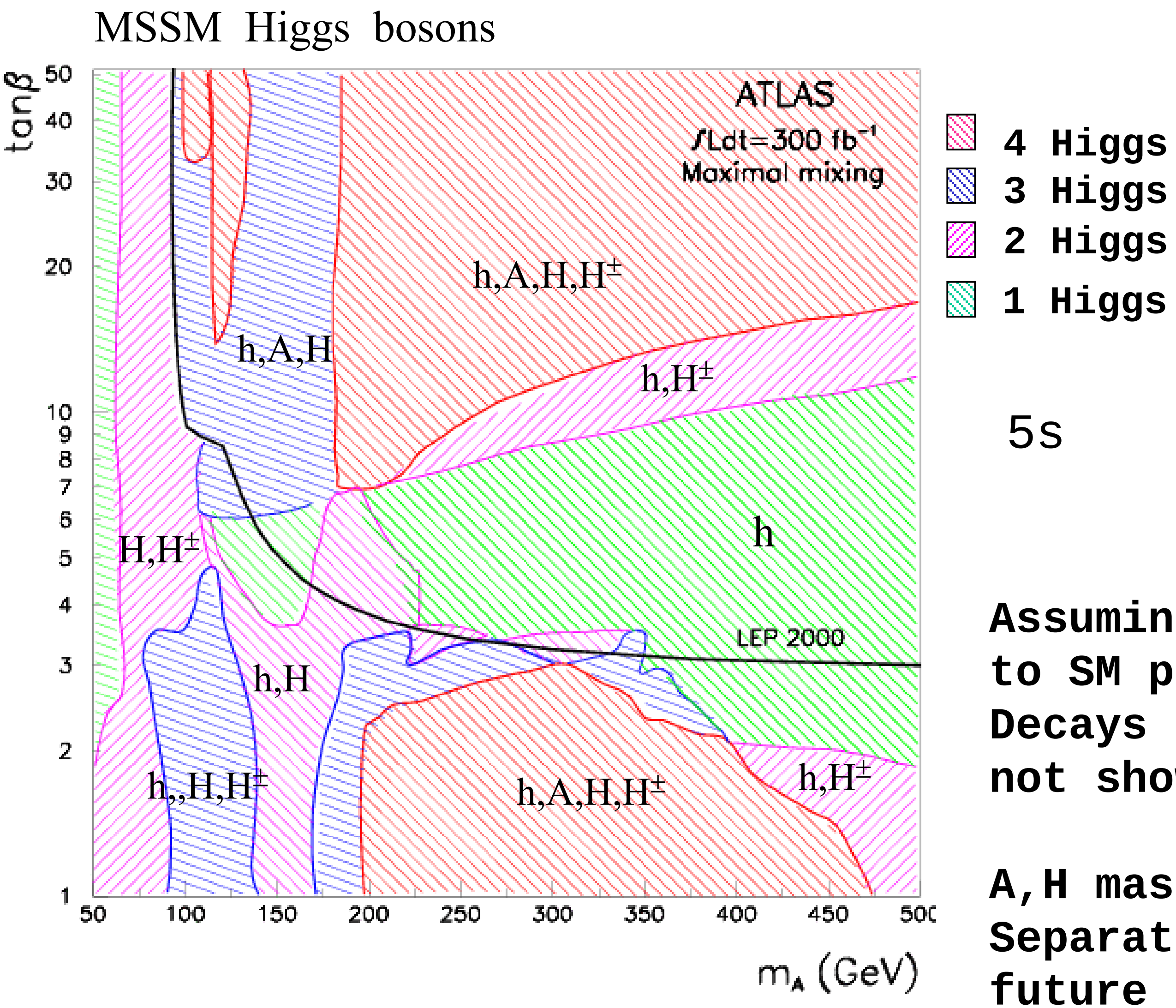
Reach in M_A - tanβ plane

- **H+ decays and H,A→ττ cover substantial area**
- **Still large area is covered by h decays only (recalculated from SM) – difficult to separate SM and MSSM in this area**
- **Higgs decays to sparticles may help**



CMS, 30 fb

Observability of MSSM Higgses



5s

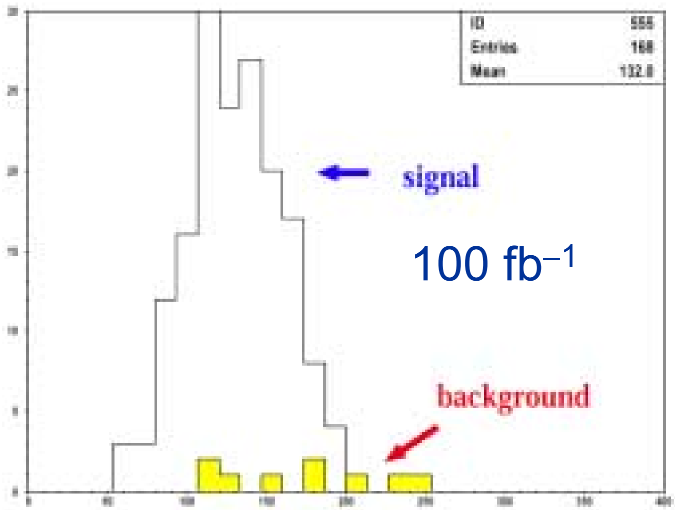
Assuming decays to SM particles
Decays to sparticles not shown

A,H masses Separation difficult, future studies

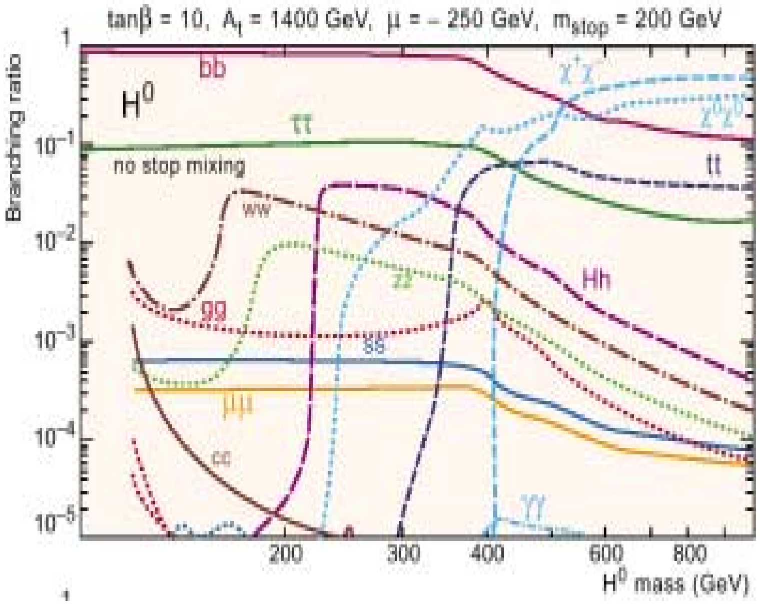
MSSM Higgses: decays into SUSY particles

- **If SUSY < 1 Tev, $H^0 \to \tilde{\chi}^0_2\tilde{\chi}^0_2,\ \tilde{\chi}^+_i\tilde{\chi}^-_j$**
  - $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 \ell^+\ell^-$

    Four isolated leptons



Four-lepton mass



Central point in MSSM parameter space :

$M_{A,H}$ = 350 GeV tan β = 5

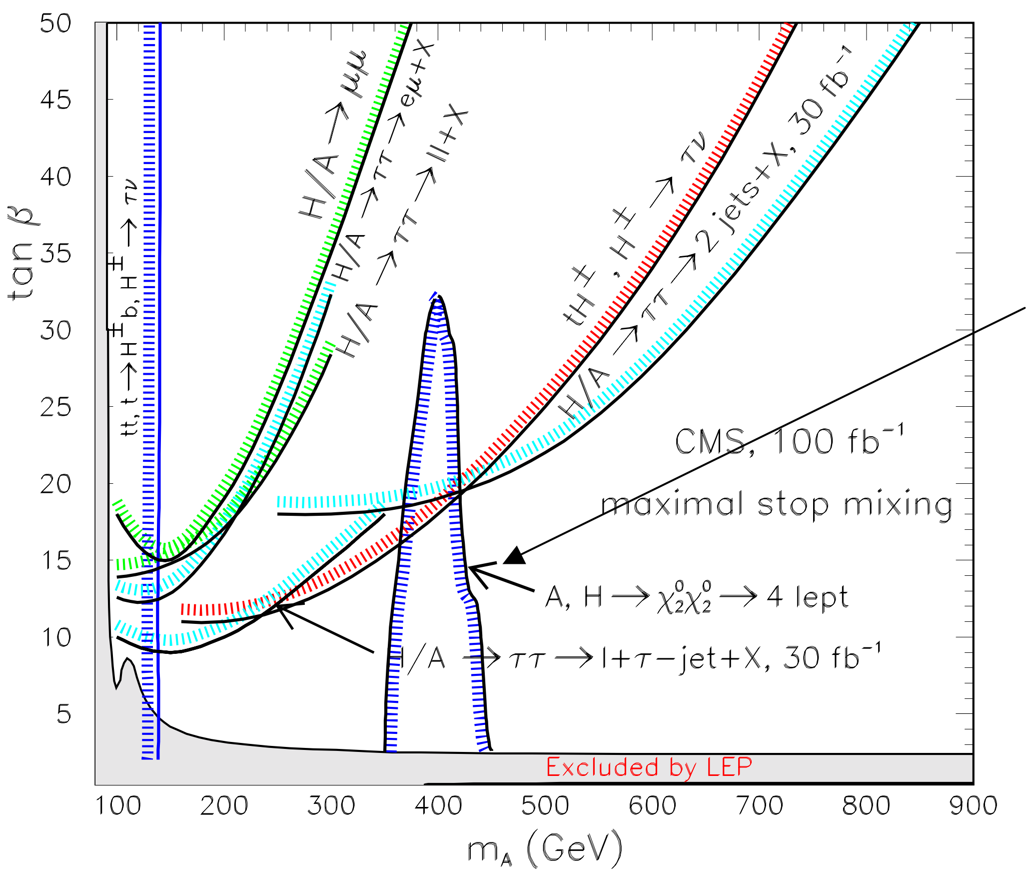
$M_{\tilde{l}}$ = 250 GeV μ = - 500 GeV

$M_{\tilde{\chi}^0_1}$ = 60 GeV $M_{\tilde{\chi}^0_2}$ = 110 GeV

$M_{\tilde{q}}$ = $M_{\tilde{g}}$ = 1 TeV

M_A – tanβ reach (including Higgs decays into sparticles)

- .

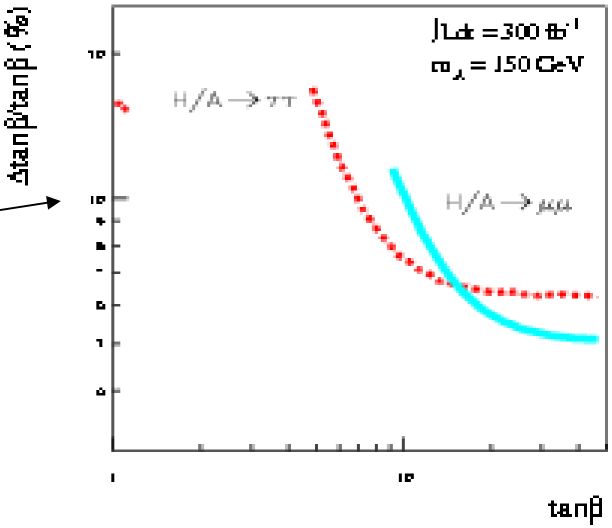


Area covered by $H^0 \to \tilde{\chi}^0_2 \tilde{\chi}^0_2$, $\to 4\ell$eptons $100\ fb^{-1}$, CMS

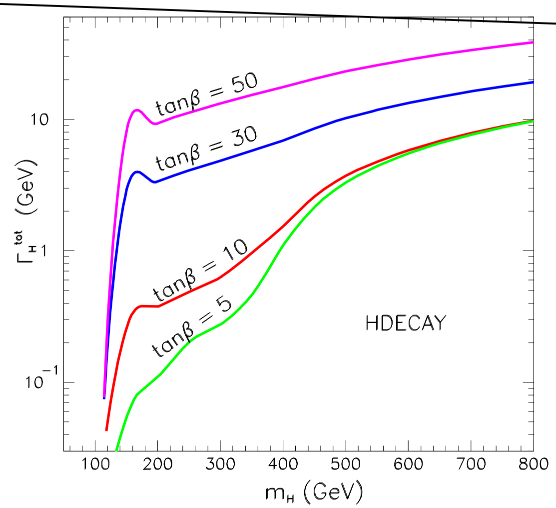
MSSM Higgs properties

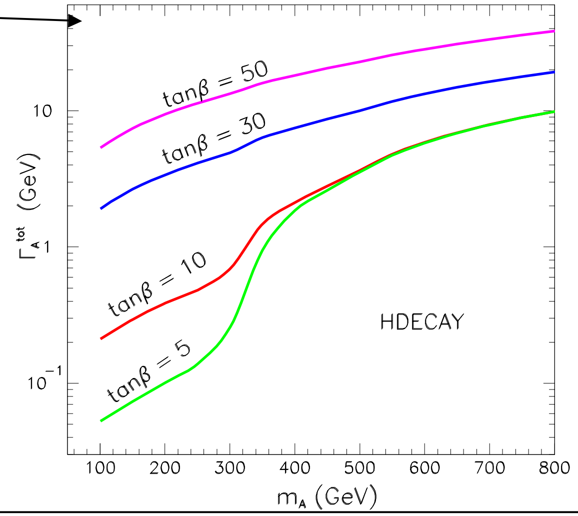
-

- **Higgs Mass**
  h - use SM channels, in particula
  $M_{H/A}$~ .1% in μμ - the best channel
- ***tanβ*** - measured by mass and cross section measurement for H,A
- **Width**: can be measured for $M_{H/A}$ >150-200 Gev and large *tanβ* with H/A-- μμ



H width





A width

On-going and future studies

- More simulations of the decays into sparticles
- H spin (e.g. using angular correlations in 4l decays)
- A,H separation (mass difference –only al low masses, to use CP?)
- CP-violation, CP-mixing (different Higgs couplings to W/Z bosons
- CP accessible at “medium” tanβ with high statistics (?)
  - SUSY: complex breaking parameters in the Stop/Sbottom/Gluino sector ? Then:
  - Mixing between 3 neutral states is possible
  - “h, H, A” $\rightarrow H_1, H_2, H_3$ mixed CP states
  - Higgs couplings to W/Z and fermions differ
  - CP violation study of Higgs sector may be relevant to the mechanism for EW Baryogenesis
- Higgs self couplings (experiments may have to wait LC):
  - SM: tens of events with 10 years of LHC in WWWW (ATLAS, preliminary) …hard
  - MSSM – H→hh→bbbb….

Summary

- **SM Higgs**
  - Discovery over full mass range with > $10fb^{-1}$
  - LHC/Tevatron competition in ~ 2007 ?
- **MSSM**
  - At least one Higgs can be discovered experimentally anywhere in the MSSM parameter space
    - In large area difficult to distinguish between SM and MSSM, Higgs decays to sparticles may help – studies continue
- **Higgs properties measurements**
  - Masses, width, couplings, tanβ can be measured in broad area of parameters
  - Interesting studies remain to be done…
- **Thanks to many CMS and ATLAS colleagues, who performed the studies, and in particular to A. Nikitenko, K.Lassila-Perini, D. Denegri, F.Gianotti, L.Poggioli, P.Sphicas and K.Jakobs for providing material and discussions**