Higgs searches at LHC

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- Talk based on CMS & ATLAS studies
- Standard Model Higgs
- Higgs in Minimal Supersymmetry (MSSM)

Higgs in ATLAS, CMS

- **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}**
- **Simulations are constantly reevaluated**

  - most of CMS results in this talk from CMS PTDR – 2006

  - ATLAS PTDR just came out (Dec 2008), some updates included
- **Simulations performed for 14 Tev, ~ factor of 2 more luminosity needed at 10 Tev**

SM Higgs: what we know from theory

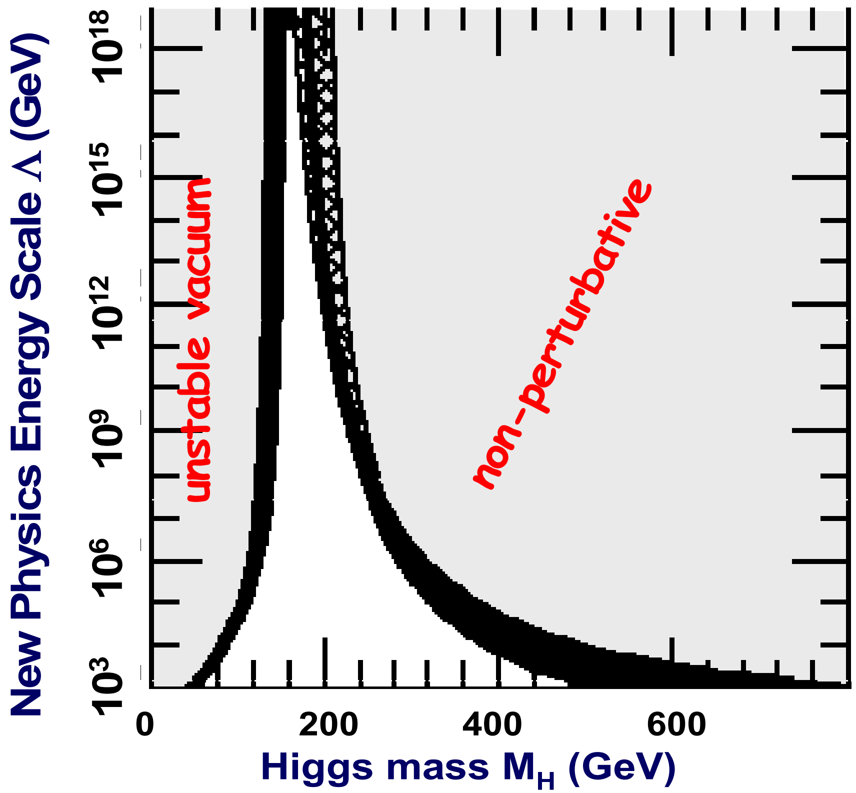
One pseudo-scalar doublet Φ (4 degrees of freedom)

Potential V = $\lambda|\Phi|^4 - \mu^2|\Phi|^2$

After spontaneous symmetry breaking:
- **$W^\pm$ and Z acquire masses (3 degrees of freedom)**
- **the last remaining degree of freedom (4-3=1): scalar CP-even Higgs of unknown mass**

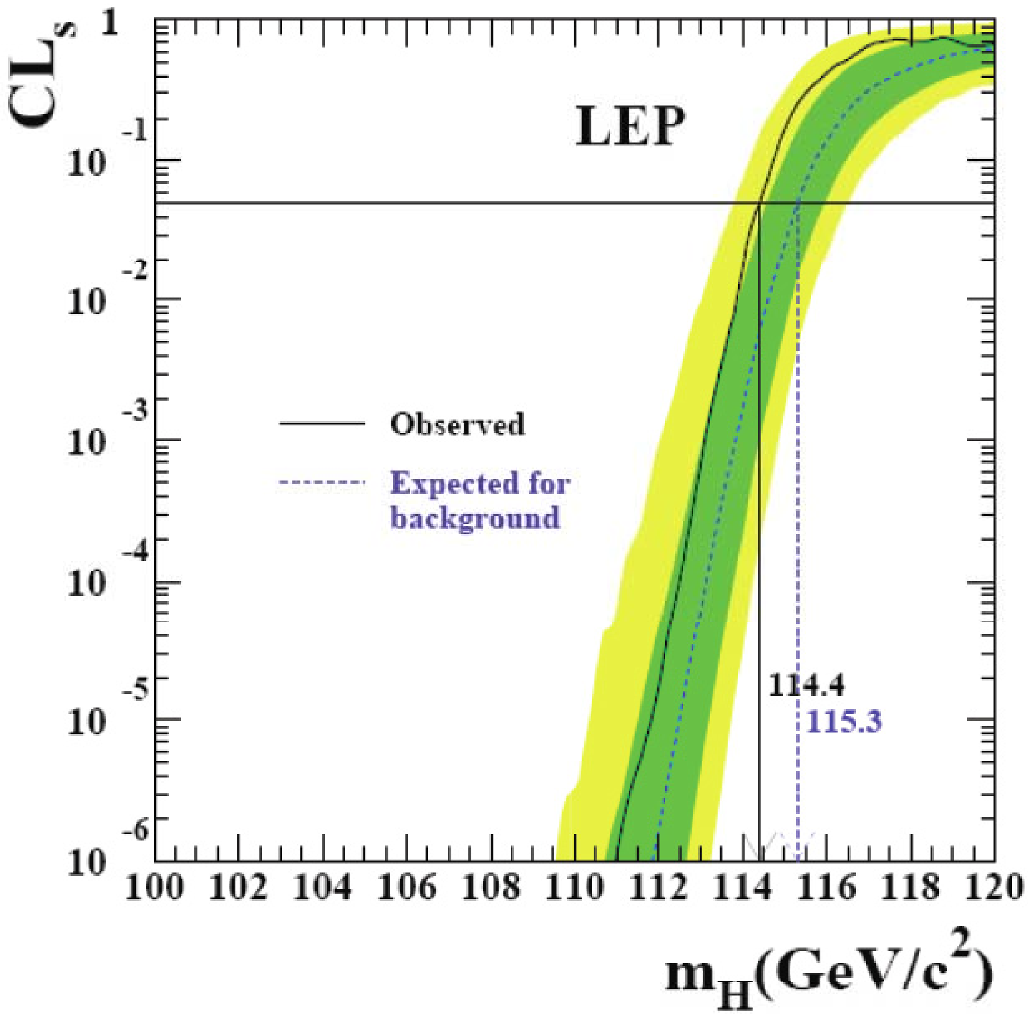
λ runs with Q:
- **small m_H at 1-TeV scale**
  at some Q, λ(Q) < 0
  V has no minimum (vacuum breaks loose)
- **large m_H at 1-TeV scale**
  at some Q, λ(Q) = ∞
  theory is non-perturbative (theorists do not like it)
- **chimney**
  λ(Q) ~ const due to cancellation of +/- terms (fine tuning)

mass must be within 50-600 TeV range



What we know experimentally: LEP

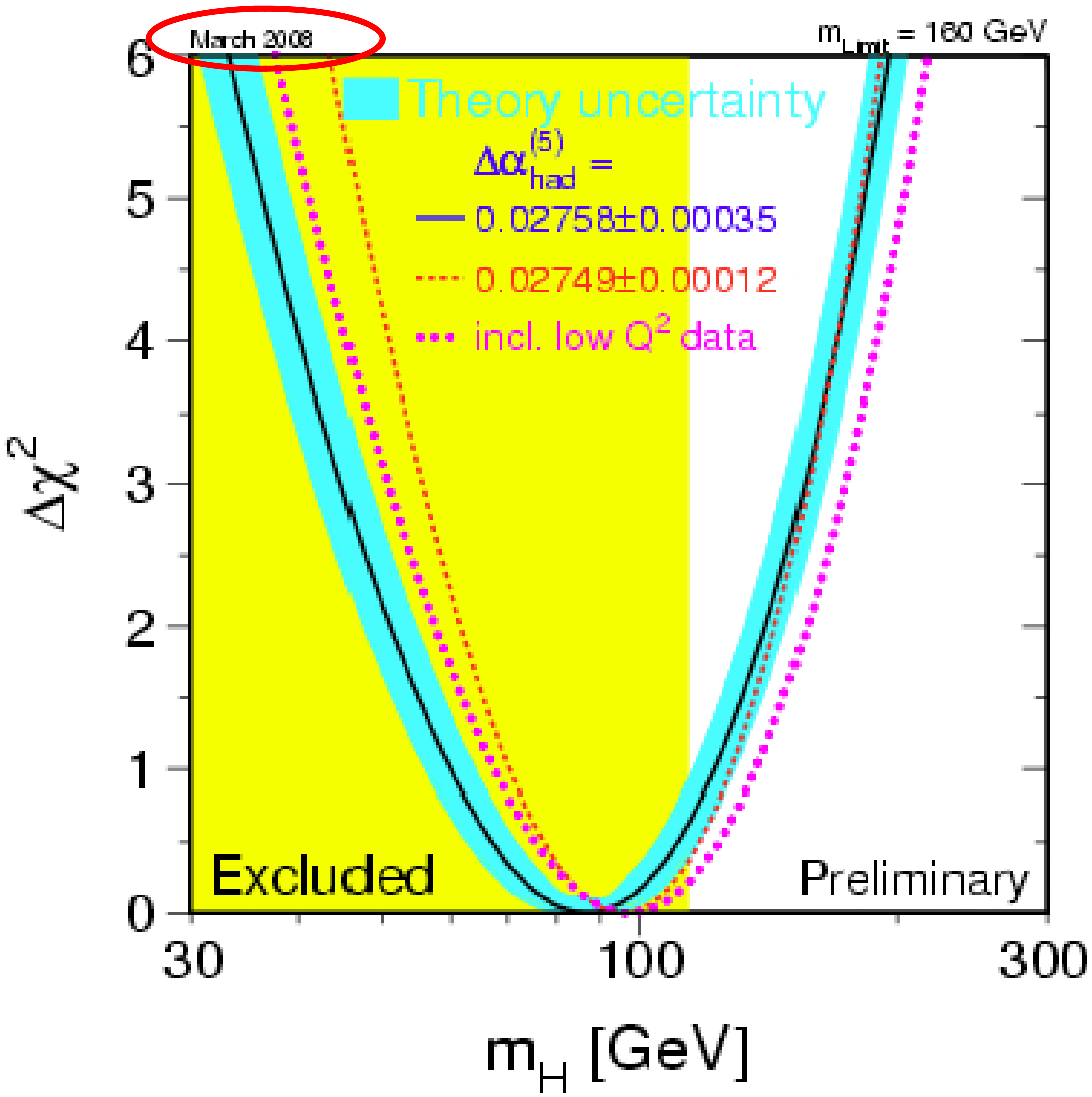
Direct search at LEP:
m_H>114.4 GeV @ 95%CL



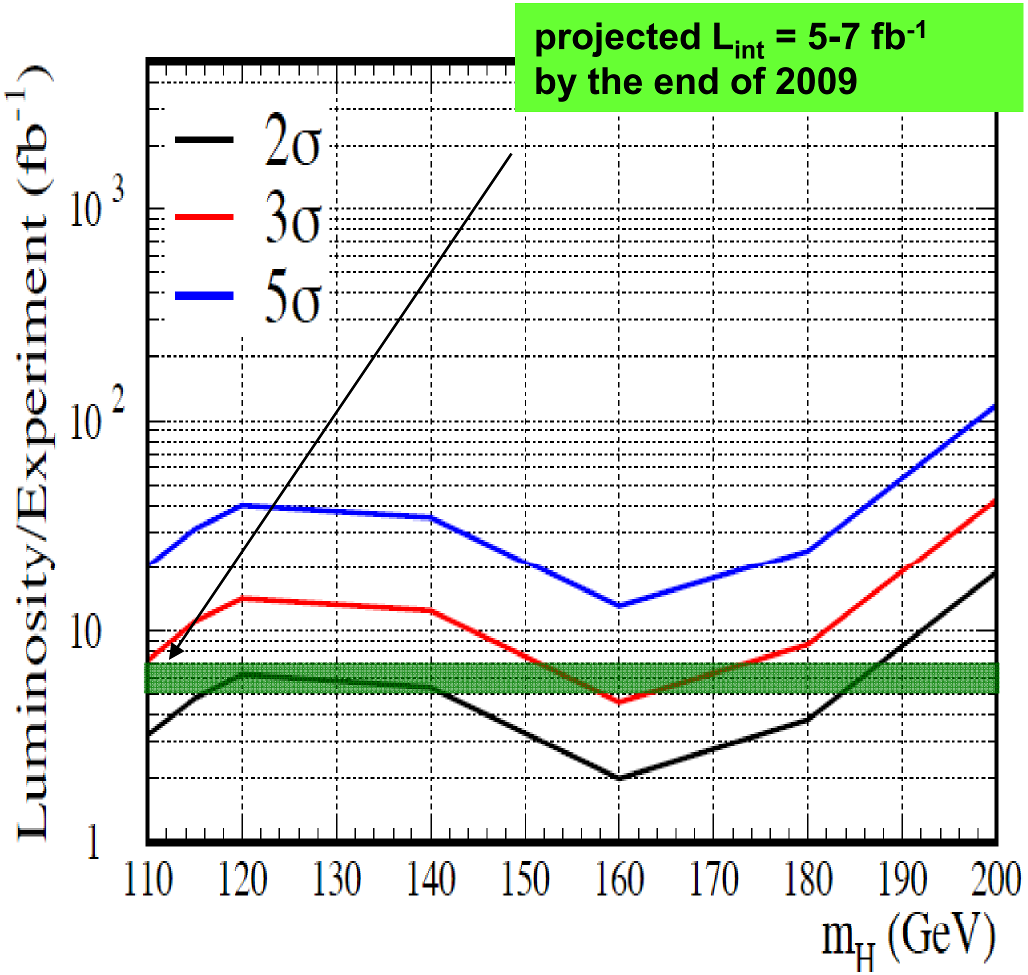
What we know experimentally: EWK fits

EWK precision data:
m_H<160 GeV @ 95%CL

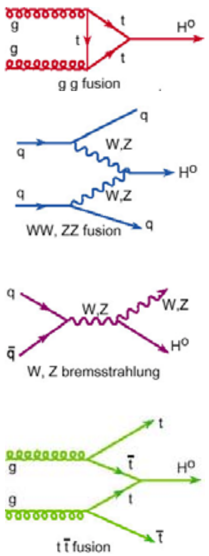
Combined with the direct search exclusion <114 GeV
m_H<190 GeV @ 95%CL

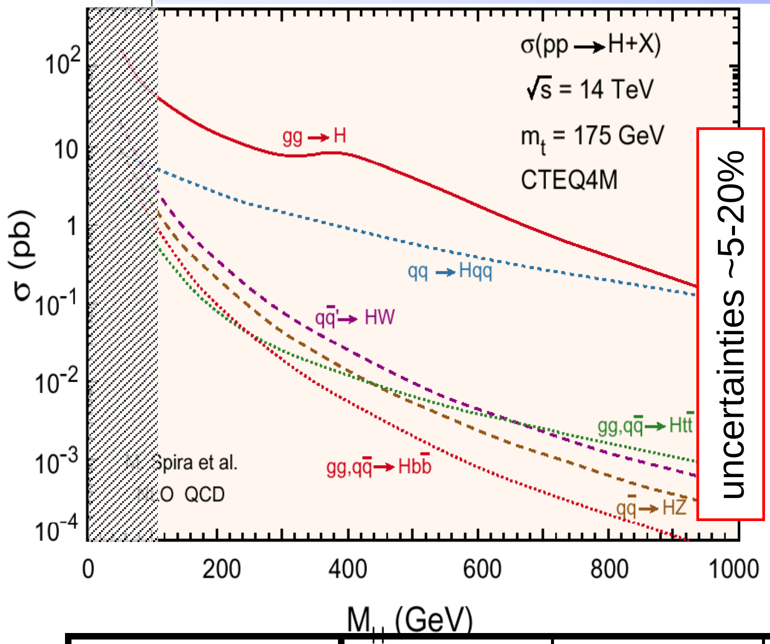


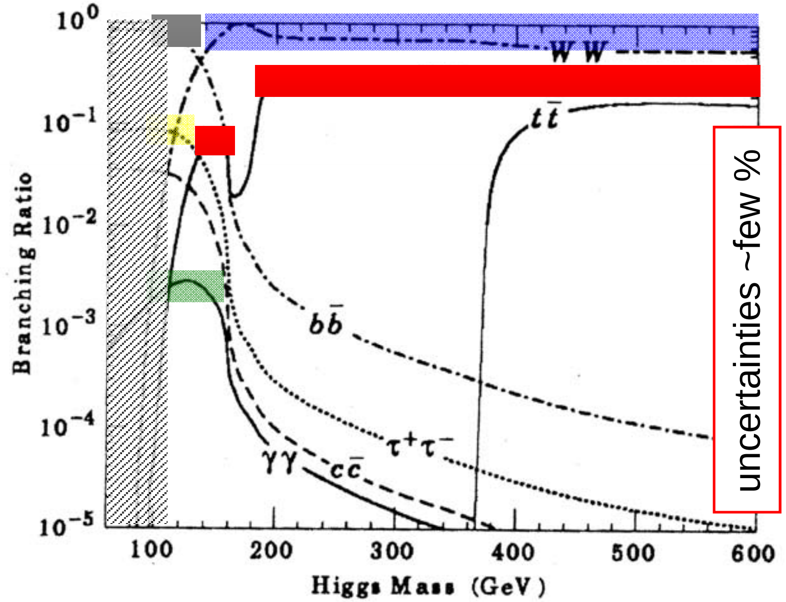
What Tevatron can do
(also see Higgs at Tevatron talk)



SM Higgs at LHC





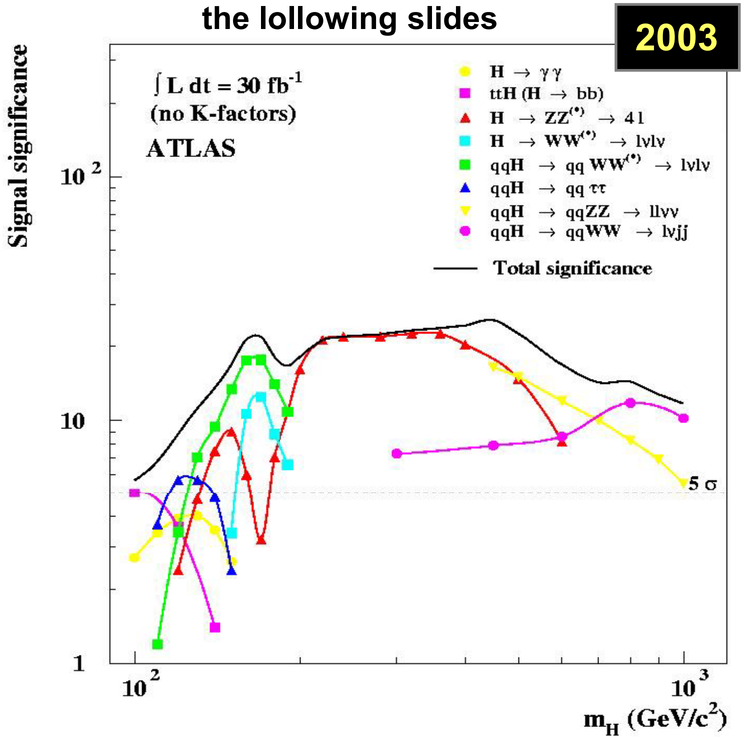


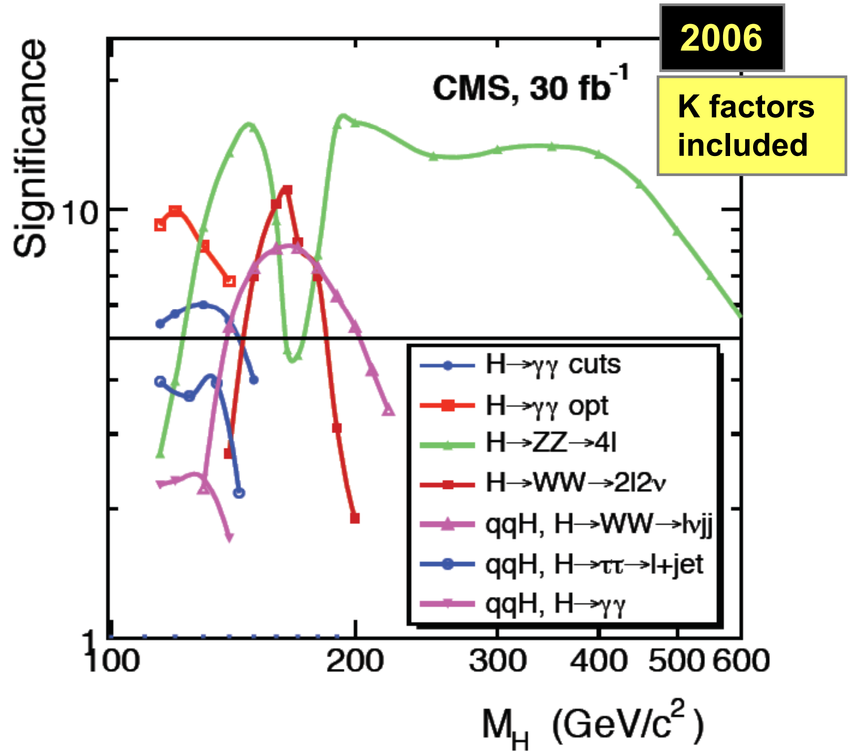
	H→bb	H→ττ	H→γγ	H→WW	H→ZZ
inclusive			YES	YES	YES
VBF (qqH)		maybe		YES	YES
W/Z+H					
ttH					

- **Colored cells = { detailed studies available }**
- **YES = { discovery in the appropriate range of masses at L<30 fb^{-1} }**

Summary: CMS (2006) and ATLAS (2003)

- ATLAS updates on the lollowing slides



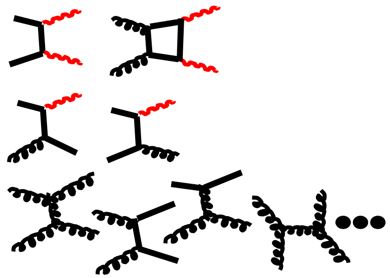


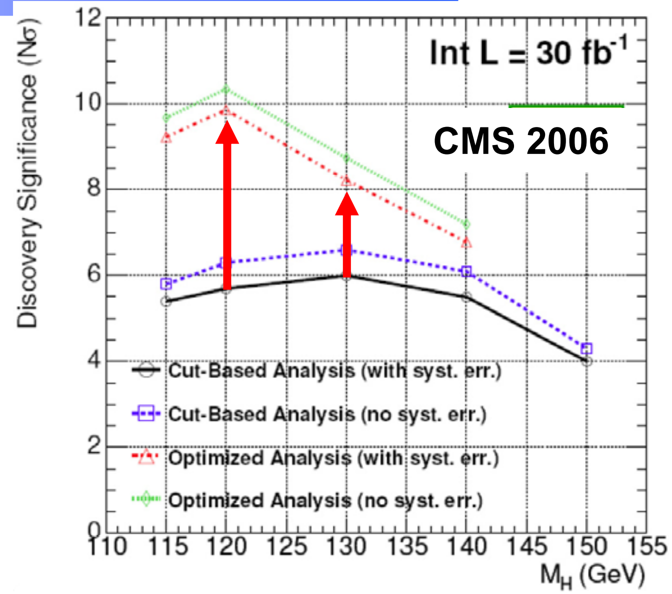
Lead channels (forerunners)

mass	~120	~140	~160	190-600
ATLAS 2003	VBF, H→ττ incl., H→γγ	VBF, H→WW*	VBF, H→WW	incl., H→ZZ
CMS	incl., H→γγ	incl., H→ZZ*	incl., H→WW	

SM Higgs: H→γγ

- **Backgrounds:**
  - prompt γγ
  - prompt γ + jet(brem γ, $\pi^0 \rightarrow \gamma$)
  - dijets

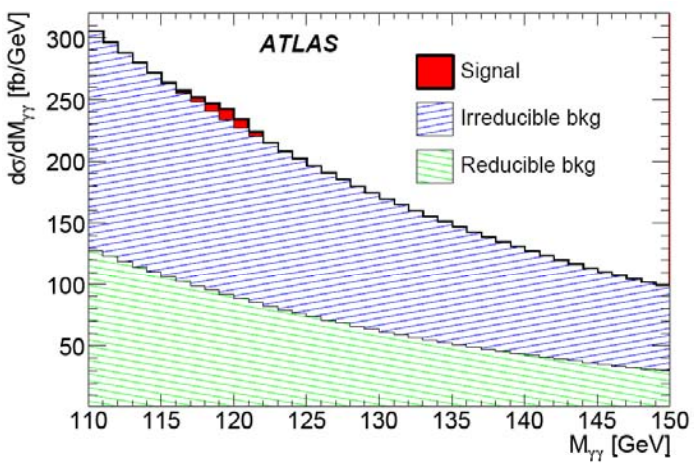




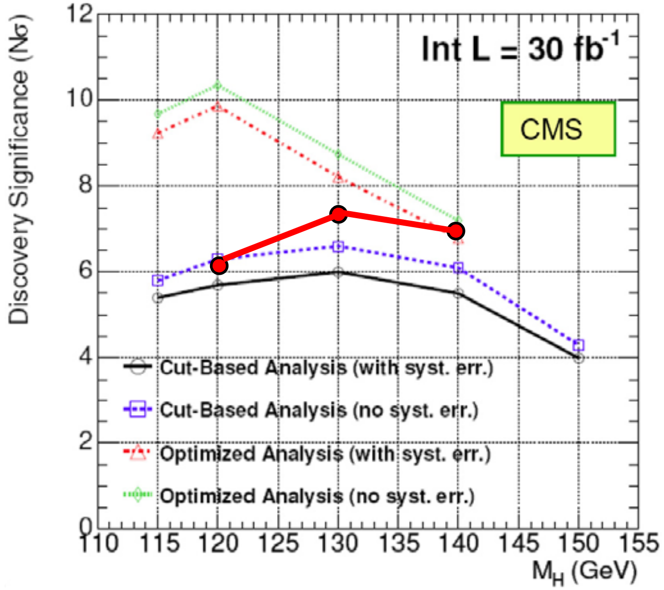
- **CMS-2006 analysis:**
  - cut-based
    - events sorted by "em shower quality"
    - kinematics, isolation, $M_{\gamma\gamma}$-peak
  - optimized
    - loose sorting and kinematical cuts
    - event-by-event kinematical Likelihood Ratio
      with bkgd pdf taken from sidebands, signal pdf from MC
  - systematic errors folded in

ATLAS update 2008 $H \to 2\gamma$

- **ATLAS new "PTDR":**
  - **now combines: inclusive, H+1jet, H+2jets (VBF)**
  - **includes systematic errors**
  - **performance now:**
    - **better compared to plots from 2003**
    - **worse than in preliminary studies from 2006**
    - **not as good as CMS at lower masses**

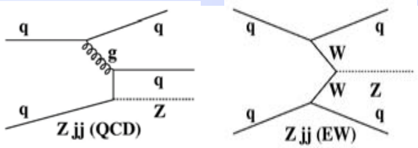


Overlaid solid red:
ATLAS 2008 (extrapolated to L=30 fb^{-1})

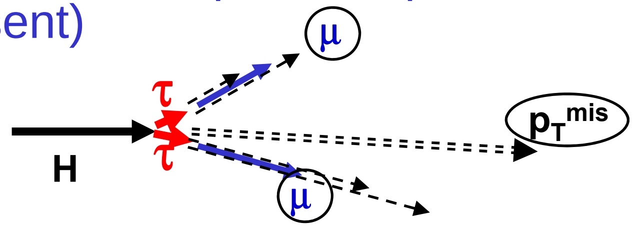


SM Higgs: VBF, H→ττ

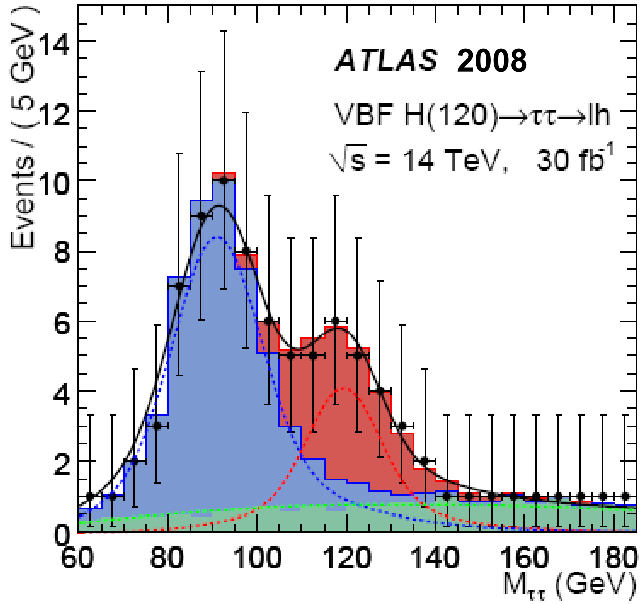
- **Background**
  - **Zjj, tt**

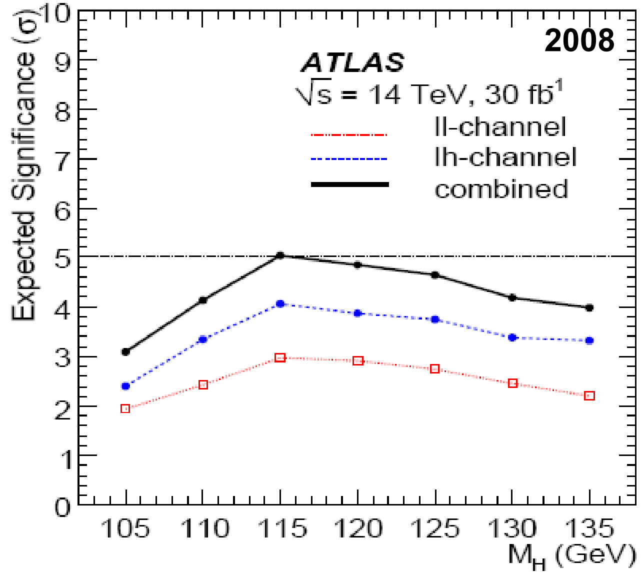


- **ATLAS-2008 analysis:**
  - **two forward jets, central jet veto**
  - **two leptons (e, μ, or τ-jet) and MET**
  - **inv. mass $m_{\tau\tau}$ built from *l*, (*l* or *τ-jet*), and p_T^{mis} in collinear approximation** (works quite well, despite multiple neutrinos present)



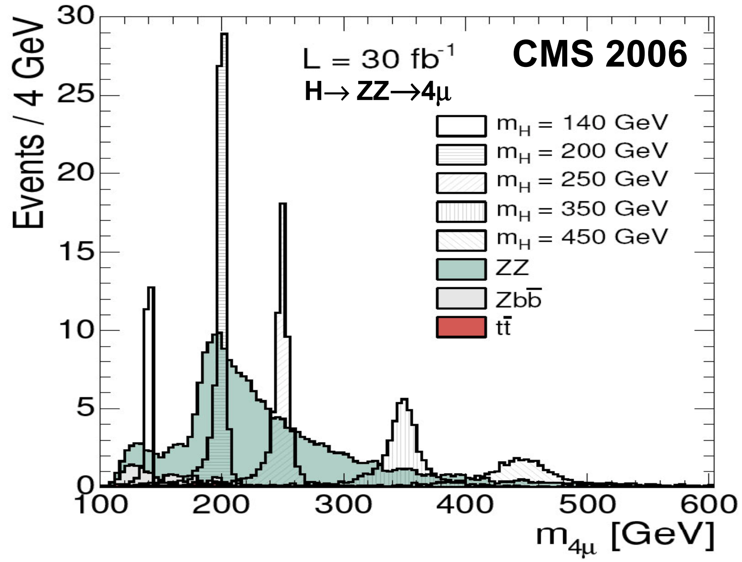
  - **now qqH, H→ττ**
    - gives significance below 5σ (despite including K_{NLO})
    - ATLAS and CMS agree

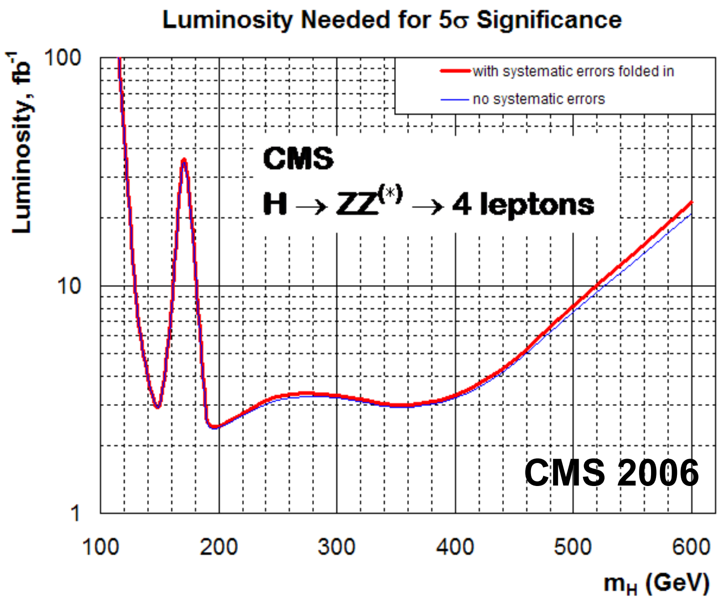




SM Higgs: H→ZZ→4l

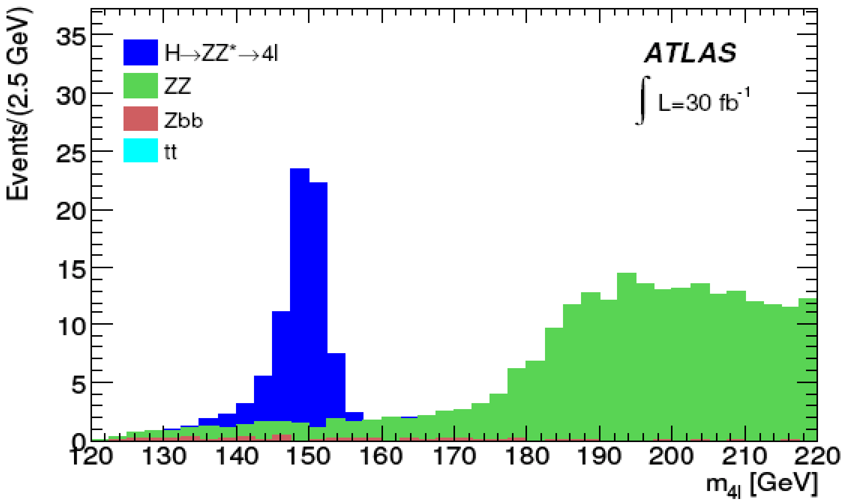
-
- **Backgrounds:**
  – ZZ, Zbb, tt
- **CMS-2006 analysis:**
  – NLO cross sections
  – ZZ:
    - 4-lepton mass dependent $K_{NLO}(m_{4l})$, <K>~1.35
    - NNLO gg→ZZ box diagram, ~0.2 wrt LO
  – cuts:
    - isolation, vertex, e/μ kinematics, m_{4l} peak
  – control samples for ZZ background:
    - Z-peak (Z and ZZ production are very similar) - preferred
    - sidebands (low statistics, shape is not trivial)
  – Data-driven methods to measure
    - lepton reconstruction efficiency
    - isolation cut efficiency per event
    - vertex cut efficiency per event
  – full treatment of systematic errors (*small effect*)

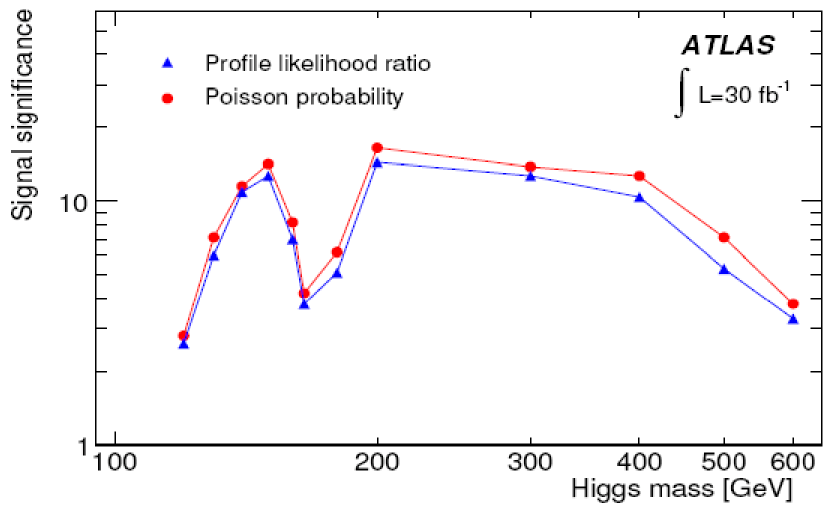




$H \rightarrow ZZ$, ATLAS update 2008

- **ATLAS new "PTDR" vs 2003 results**
  - **performance at mH~150 is better now**
  - **performance at mH>200 is worse now**
  - **very comparable to CMS in the full range of masses**

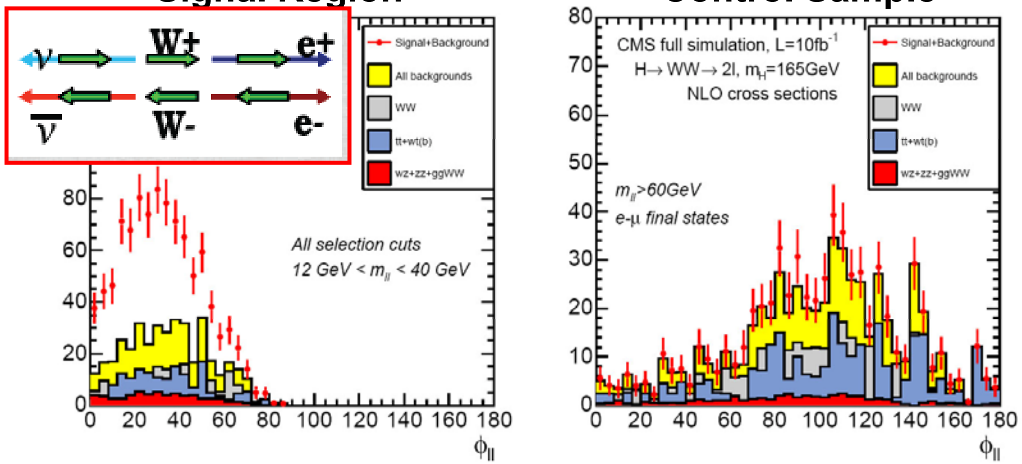


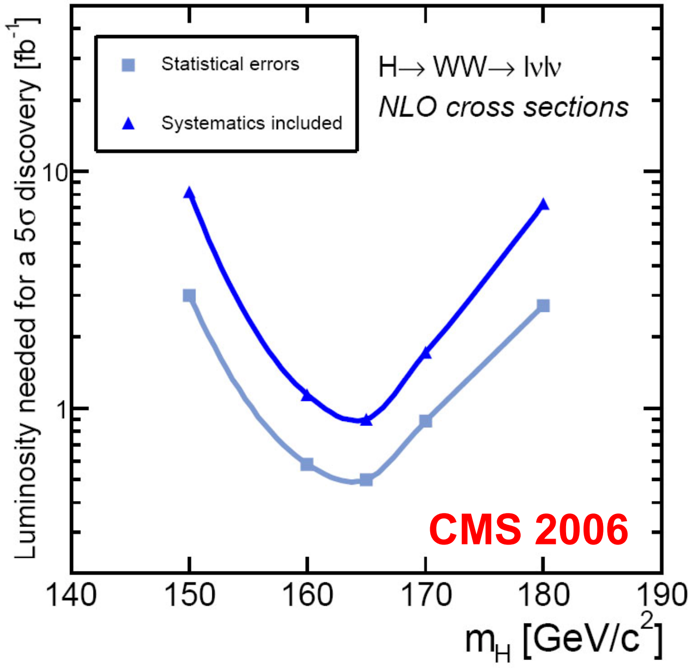


SM Higgs: H→WW→2l2ν

- **Backgrounds:**
  - WW, tt, Wt(b), WZ, ZZ
  - gg→WW (box)

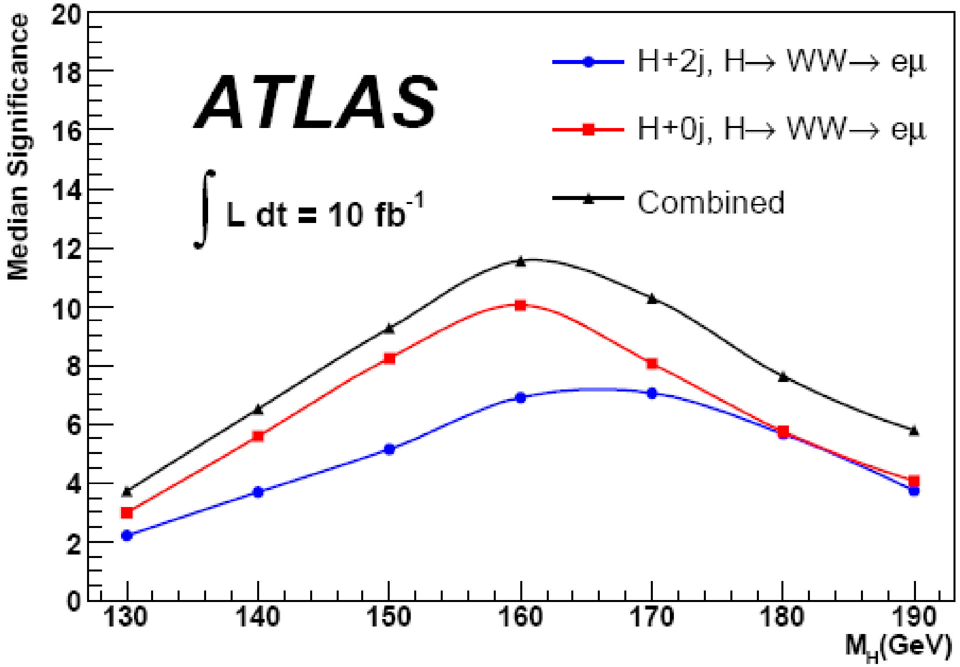
- **CMS-2006 analysis:**
  - $K_{NLO}(p_T^{WW})$
  - cuts:
    - e/μ kinematics, isolation, jet veto, MET
  - counting experiment, <u>no peak</u>
  - background from a control sample:
    - signal: $12<m_{ll}<40$ GeV
    - control sample: $m_{e\mu}>60$ GeV
    - reduce syst. errors, but pay stat. penalty
  - systematic errors are folded in





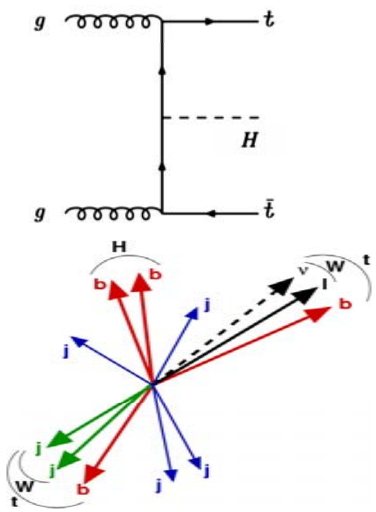
$H \to WW$, ATLAS update 2008

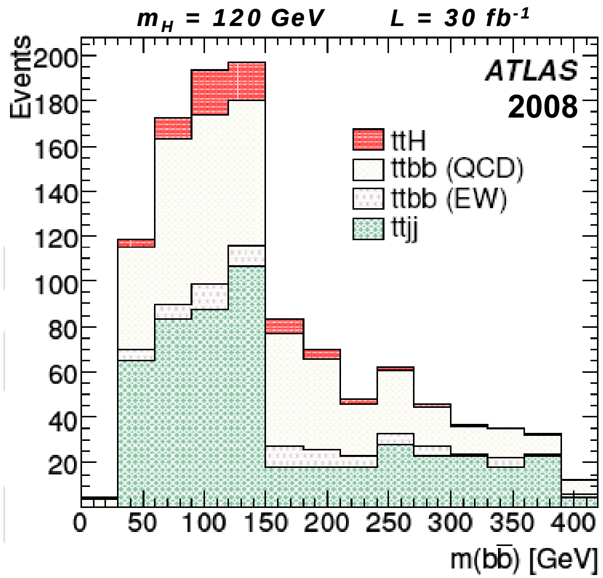
- **ATLAS updated only eμ-channel**
  - **inclusive WW is now better than VBF**
    - **this order now agrees with CMS**
    - **is reverse to ATLAS simulations in 2003**
  - **the curve of significance is now broader vs mH**

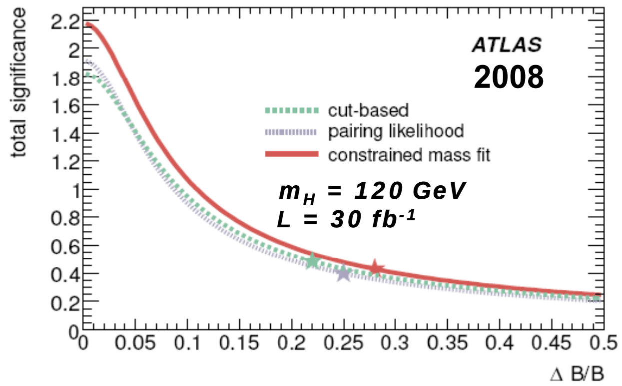


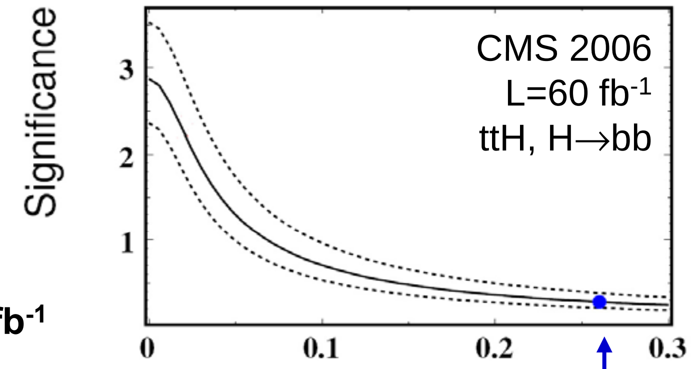
SM Higgs: ttH, H→bb

ttH is (was?) the best bet to see H→bb









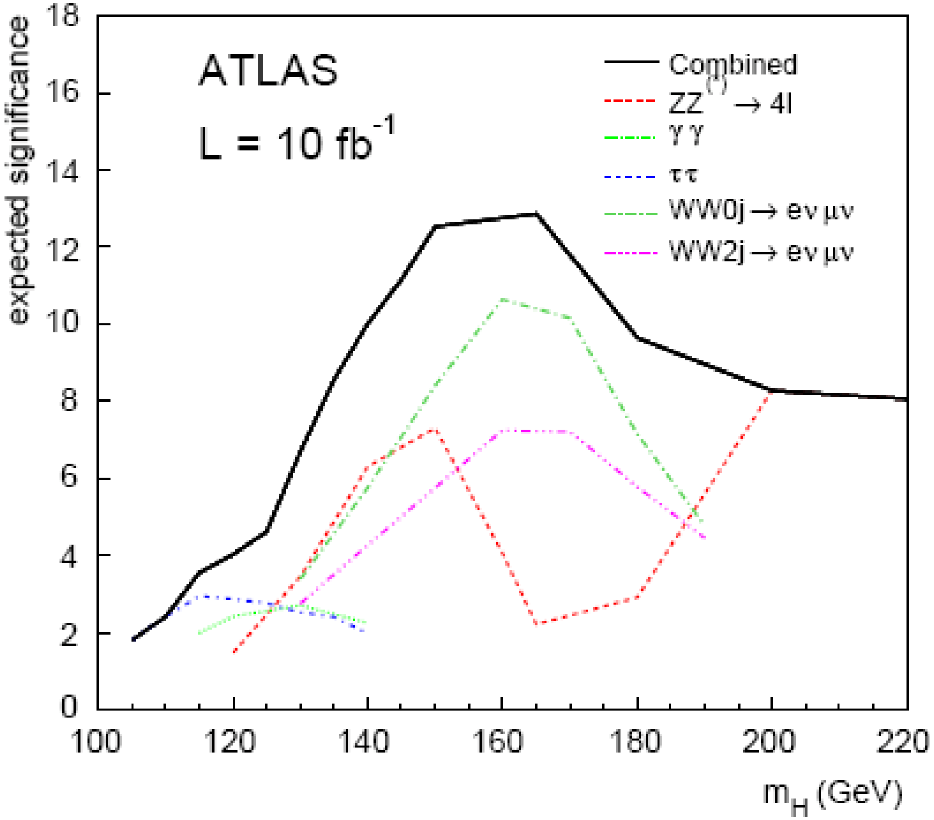
dB

current estimate of background uncertainties

jet energy scale (3-10%)
jet energy resolution (10%)
b/c-tag efficiency (4%)
uds/g-tag efficiency (10%)
luminosity (3%)

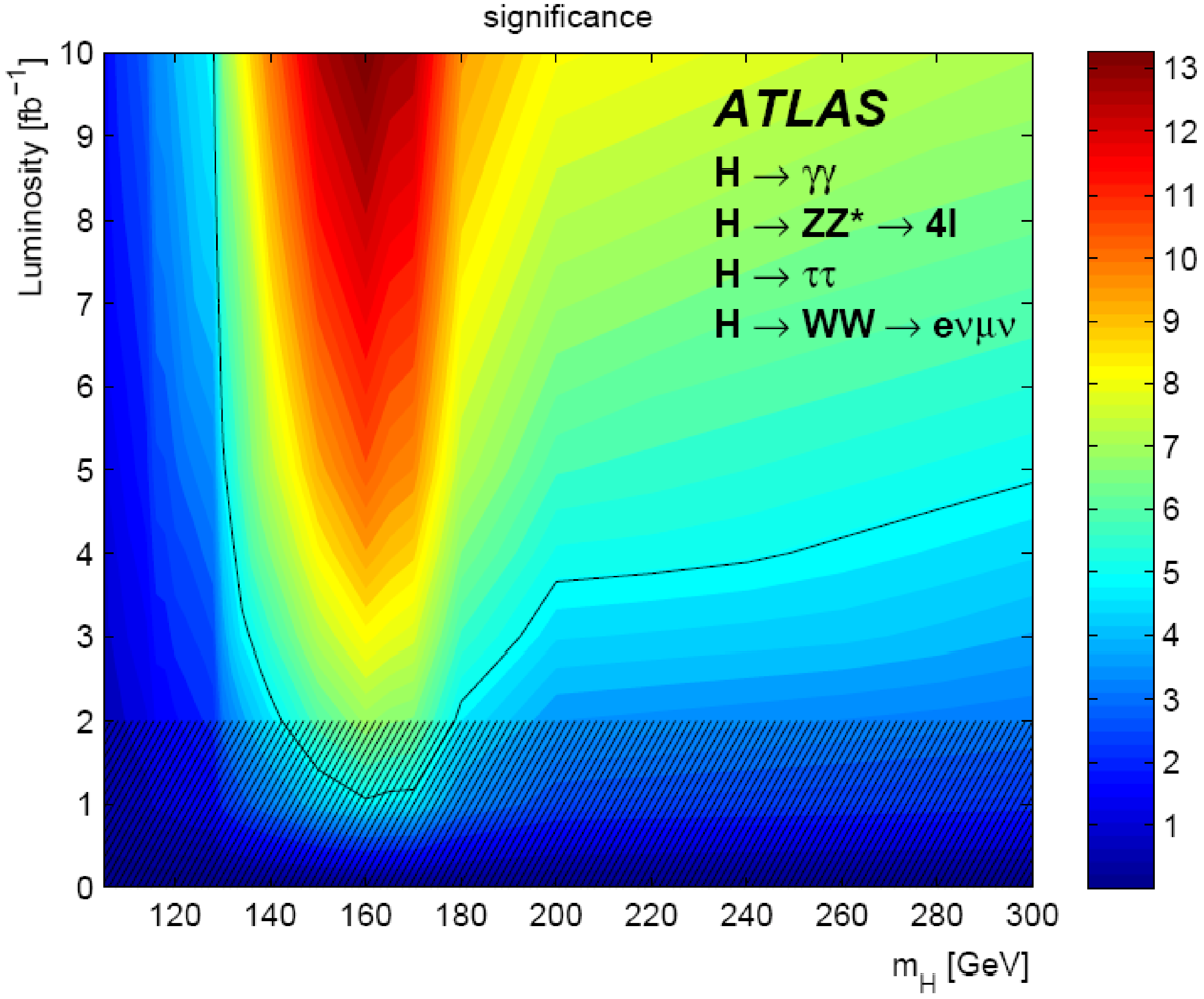
- **Early projections:** **might be observable already at L=30 fb^{-1}**
- **CMS-2006 analysis:**
  - **systematic error control at a percent level is needed—not feasible...**
-
- **ATLAS-2008 analysis:**
  - **same conclusions**

ATLAS SM Higgs 2008 update, low mass region summary

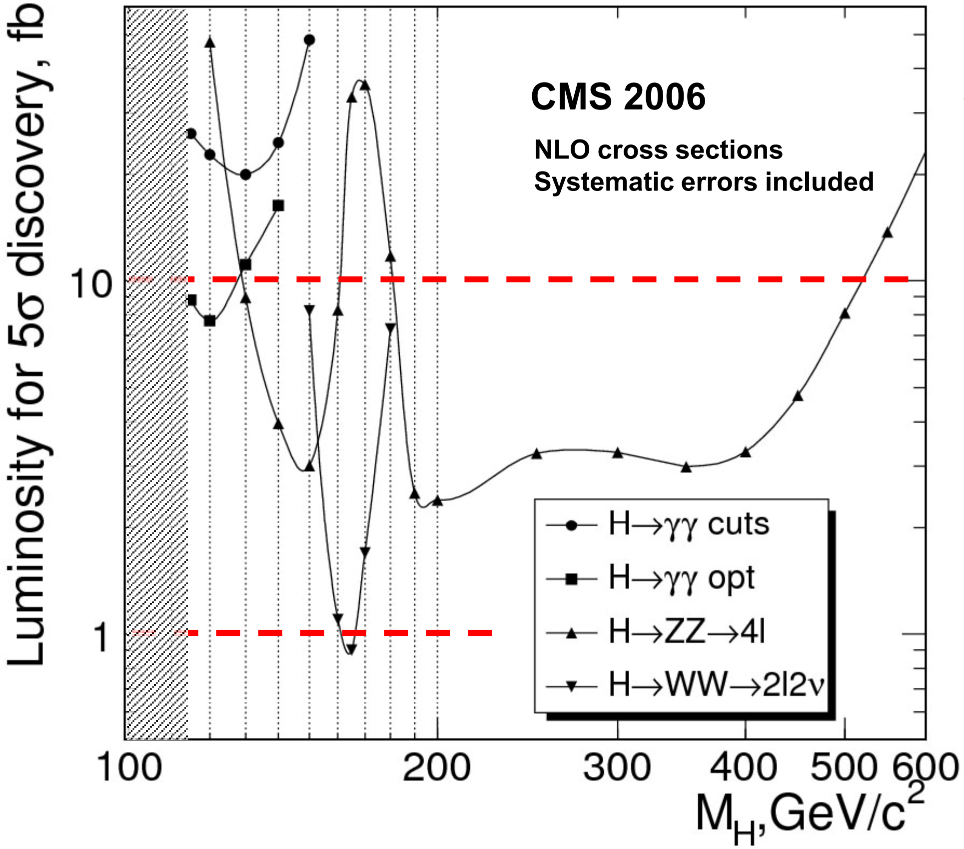


10 inv.fb is not enough for discovery in ATLAS below 127 Gev (different from CMS) difference in **H→gamma gamma** channel (optimized in CMS, using neral networks), needs to be understood better

ATLAS SM Higgs update 2008



Standard Model Higgs: Summary



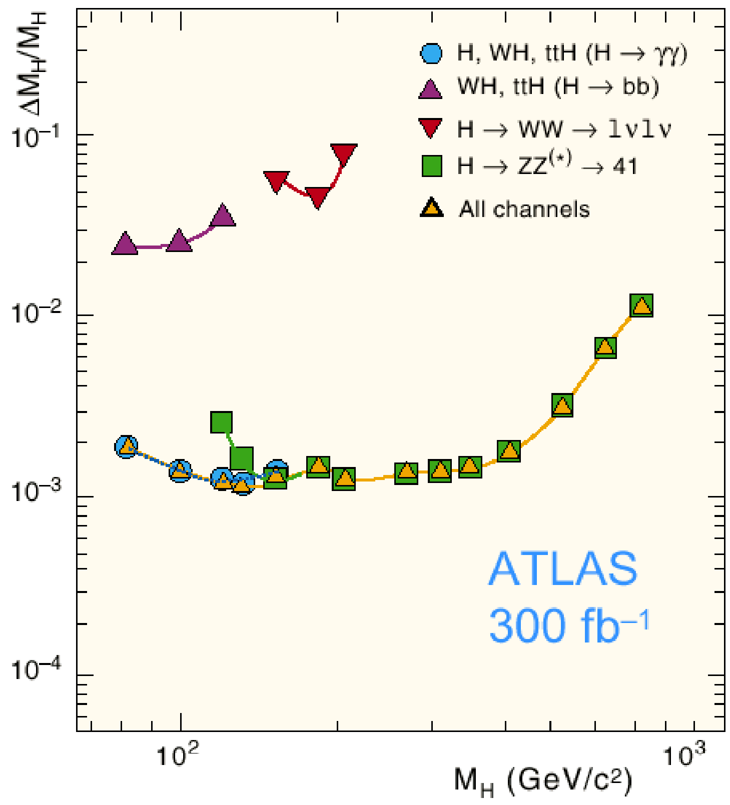
ATLAS 2008 updates just became available

CMS and ATLAS different at low mass region, ~agree elsewhere

- **Benchmark luminosities:**
  - **0.1 fb^{-1}:** **exclusion limits will start carving into SM Higgs cross section**
  - **1 fb^{-1}:** **discoveries become possible if M_H~160-170 GeV**
  - **10 fb^{-1}:** **SM Higgs is discovered (or excluded) including low mass range (CMS)**

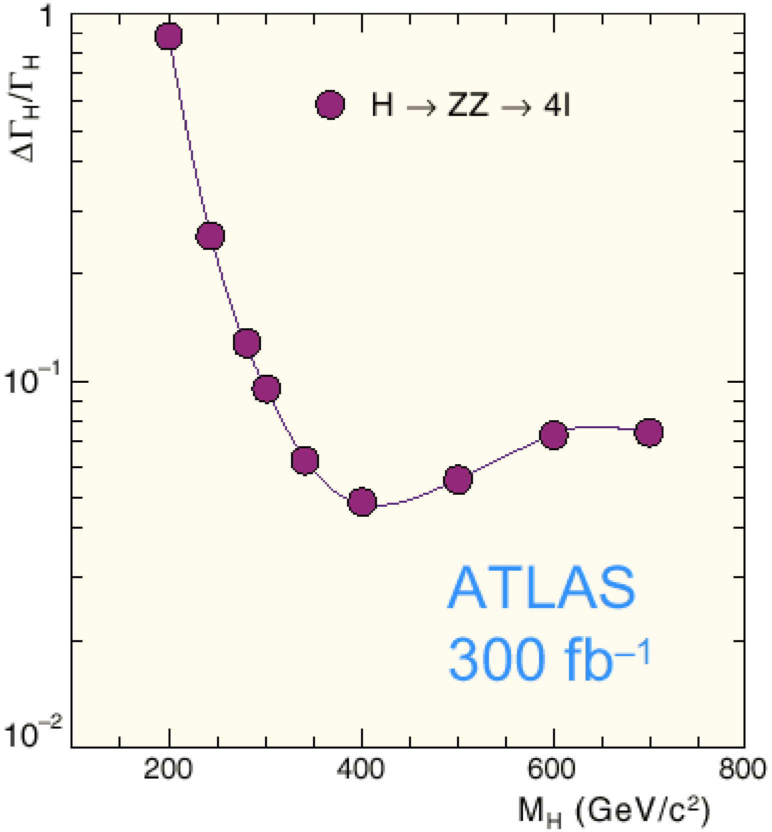
SM Higgs properties: mass

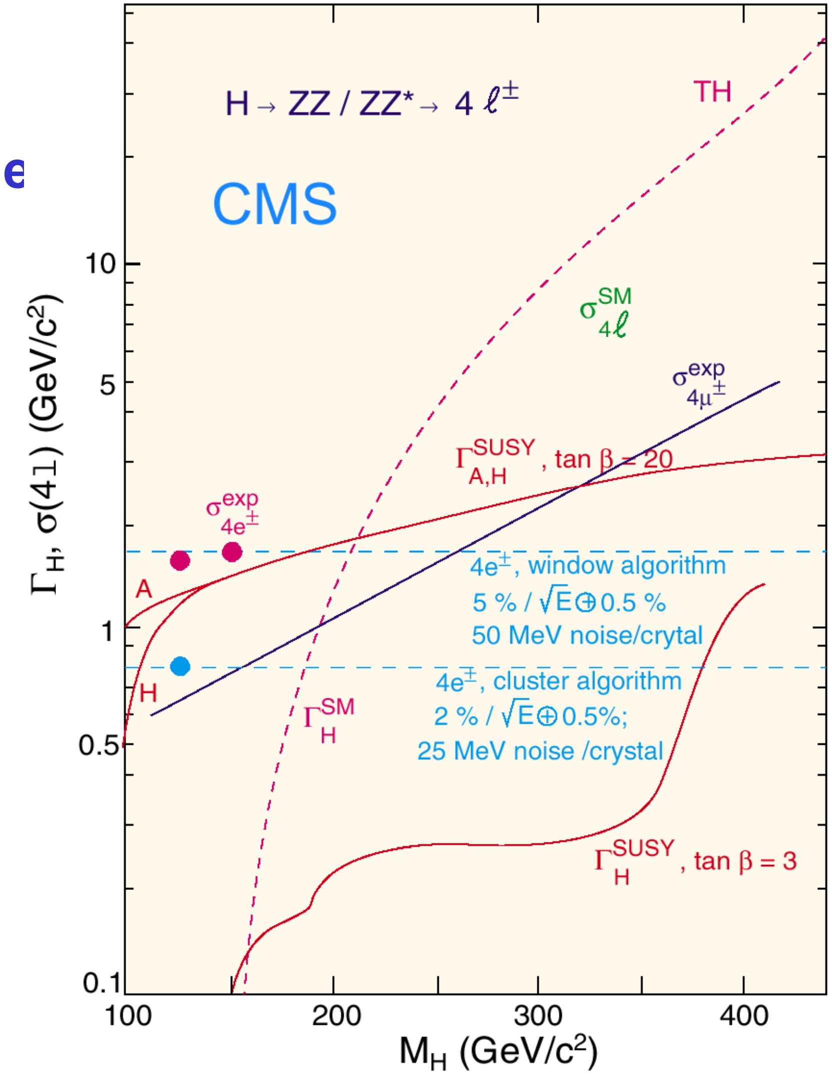
- **Mass measurement**
  - Limited by absolute energy scale
    - leptons & photons: 0.1% (with Z calibration)
    - Jets: 1%
  - Resolutions:
    - For $\gamma\gamma$ & $4\ell \approx 1$ GeV/c^2
    - For bb ≈ 15 GeV/c^2
  - At large masses: decreasing precision due to large Γ_H
  - CMS ≈ ATLAS



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)

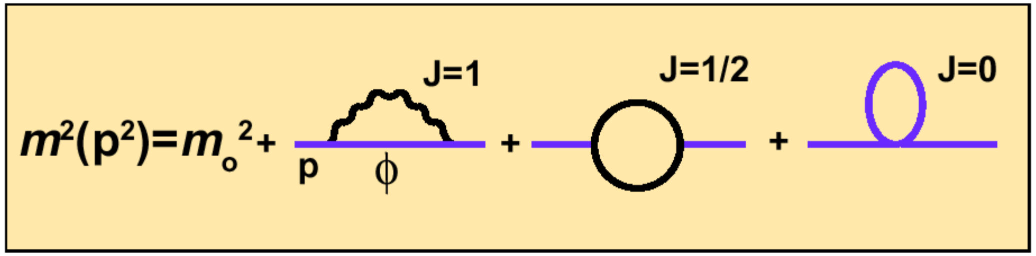
- **Combine measurements of several Higgs channels in VBF and gg production: $qq \to qqH$, $gg \to H$**
  - **Can measure the following: $X_i = \Gamma_W \Gamma_i / \Gamma$ from $qq \to qqH \to qqii$**
    - **Here: $i = \gamma, \tau, W(W^*)$; precision~10-30%**
  - **Measure also $Y_i = \Gamma_g \Gamma_i / \Gamma$ 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**

Problems with the SM Higgs

- **Quadratic divergence of its mass**



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

  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

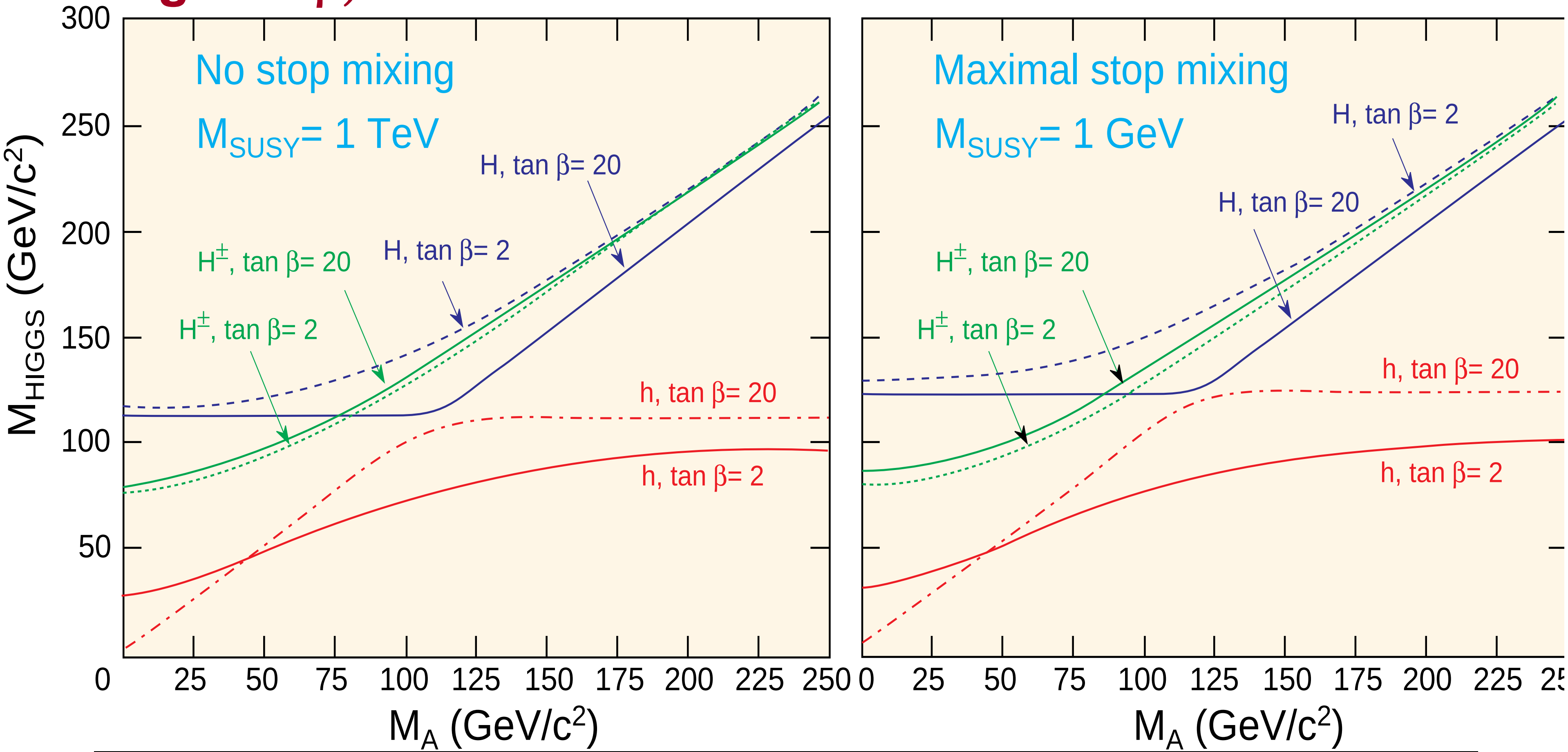
    (b) M<1 TeV (i.e. allows decays of the Higgses to sparticles); "new"

    2: stop mixing:

    Maximal–No mixing

MSSM Higgs masses (as a function of M_A)

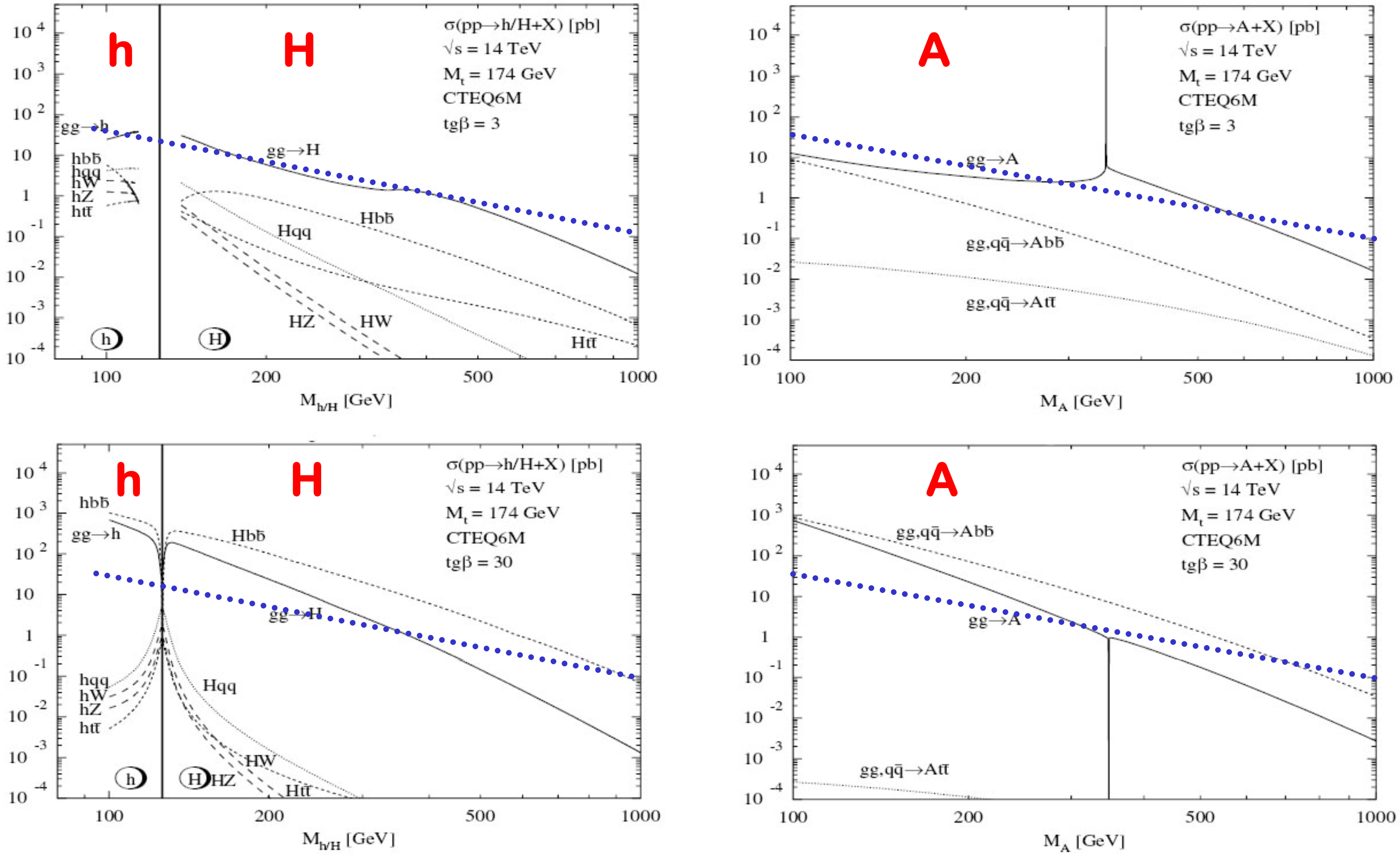
For high M_A – decoupling limit regime: M_{h+}=M_h(max), h similar to SM, M_A~M_H, coupling of A,H similar (for high tanβ)



MSSM Higgs boson: h, H, A production

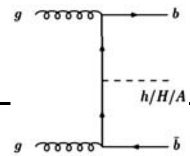
tanβ=3

tanβ=30



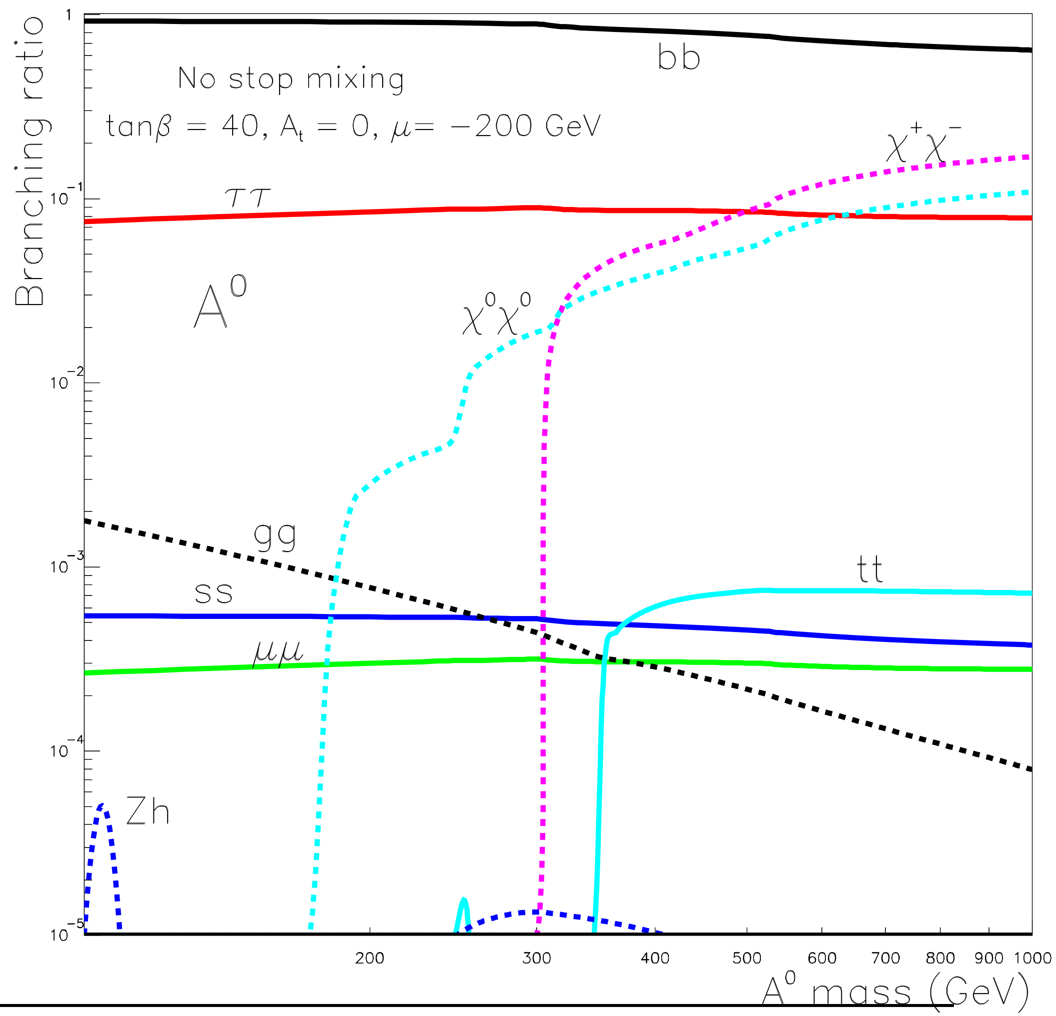
– **x-sections** **are comparable or larger than SM (dotted line)**

– **bb(h/H/A) production** **is very important**



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**



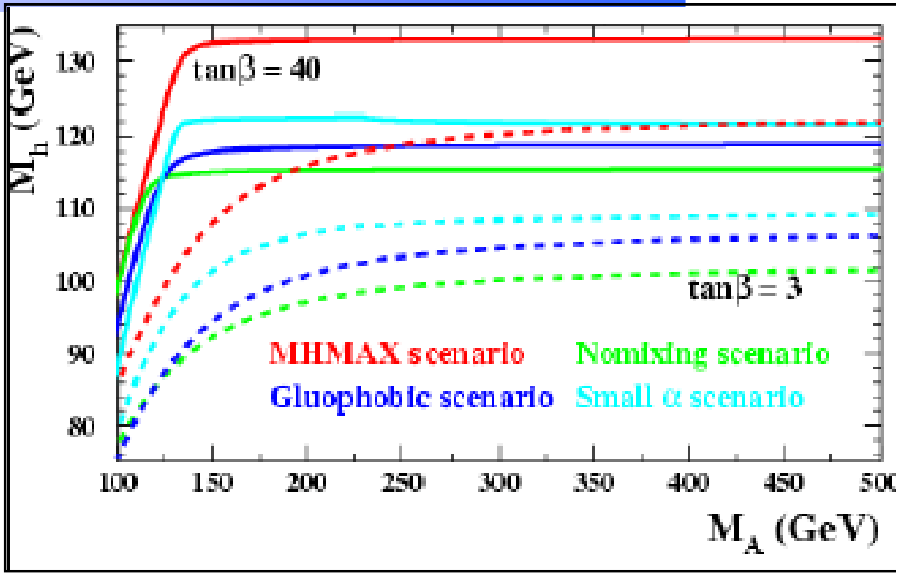
MSSM Higgses – final states

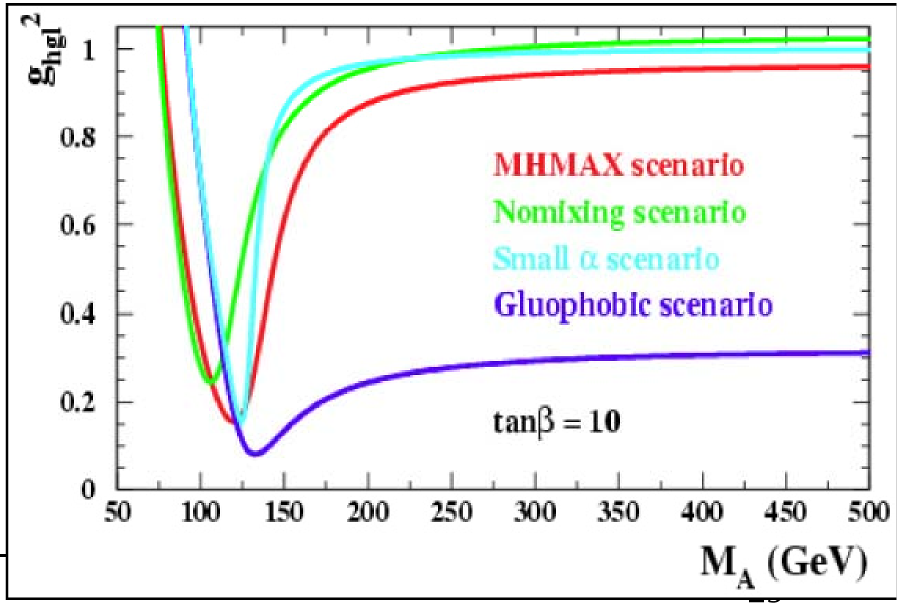
- **Most important channels being investigated:**
  - $h \to \gamma\gamma$
  - $h, H, A \to \tau^+\tau^- \to (e/\mu)^+ + hadr + E_T^{miss}$
    $\to e^+ + \mu^- + E_T^{miss}$
    $\to hadr^+ + hadr^- + E_T^{miss}$
    } gg →higgs and gg →bbH_{SUSY}
  - $H^+ \to \tau^+ \nu$, (higgs from t decays, $M_H < M_{top}$)
  - $H^+ \to \tau^+ \nu$ and $H^+ \to t\, b$ (for $M_H > M_{top}$)
  - $H, A \to \tilde{\chi}^0_2\tilde{\chi}^0_2, \tilde{\chi}^0_i\tilde{\chi}^0_j, \tilde{\chi}^+_i\tilde{\chi}^-_j$
  - $H^+ \to \tilde{\chi}^+_2\tilde{\chi}^0_2$
    } If SUSY masses low enough

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

MSSM Higgs: benchmark points

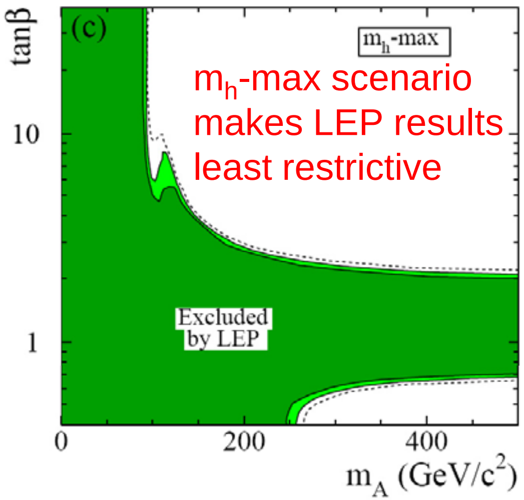
- Loop corrections give sensitivity to the rest of SUSY sector
- Special benchmark points*:
  - max stop mixing (m_h-max):
    - maximizes m_h
    - m_h < 133 GeV
    - LEP results are least restrictive
  - no mixing:
    - opposite extreme to above
    - m_h < 116 GeV
  - gluophobic h
    - gg→h production is suppressed (top+stop loop cancellation)
    - m_h < 119 GeV
  - small α_{eff} (mixing of Φ_u/Φ_d):
    - $h \rightarrow \tau\tau$ and bb BR's are suppressed even for large tanβ
    - m_h < 123 GeV



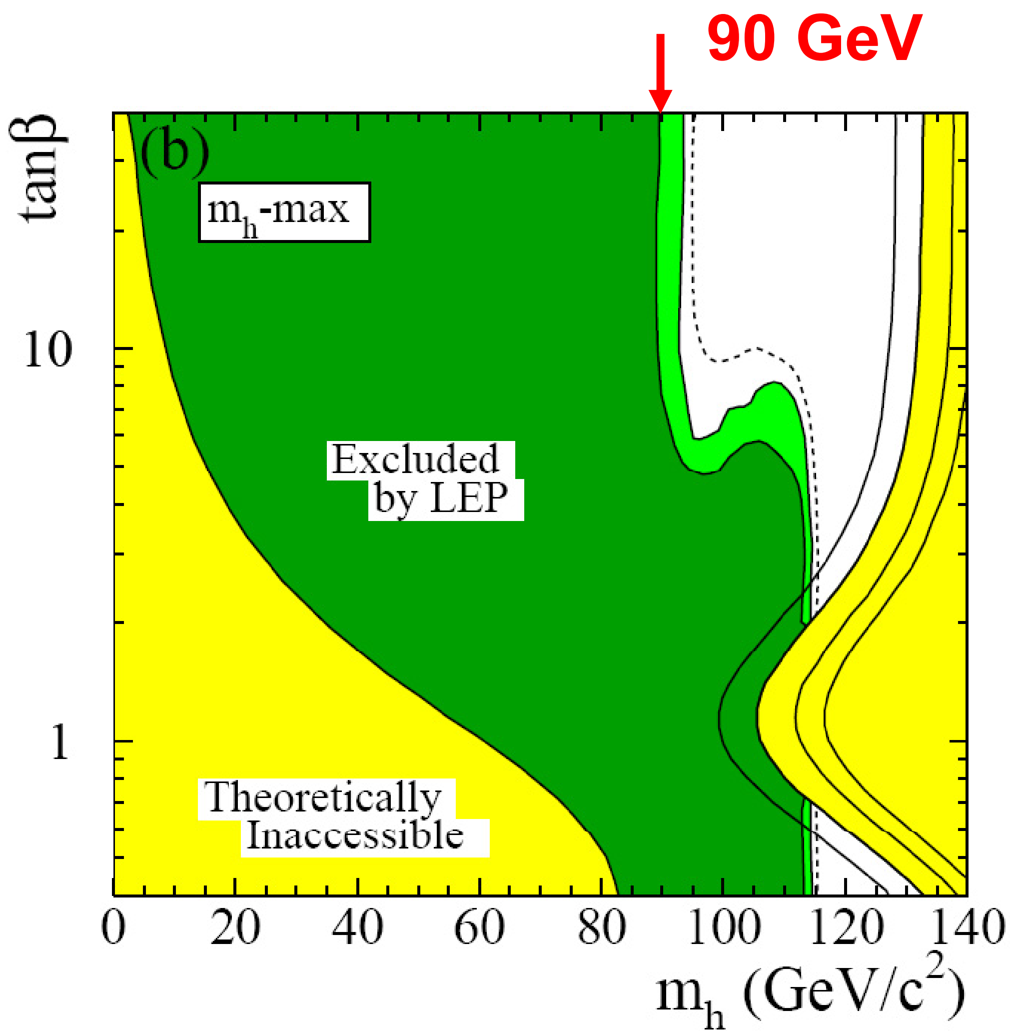


*Suggested by Carena et al., Eur.Phys.J. C26, 601(2003)

What we know experimentally: LEP



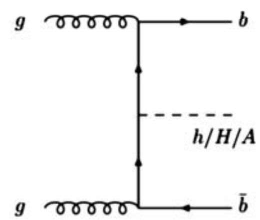
m_h-max scenario makes LEP results least restrictive



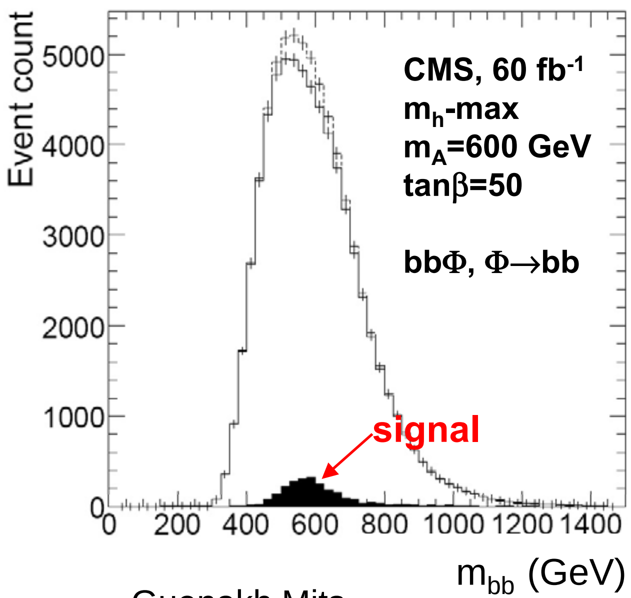
dotted line – expected limit
light green – 99% CL, dark green – 95% CL
yellow – theoretically not accessible

MSSM Higgs: heavy neutral H, A (Φ)

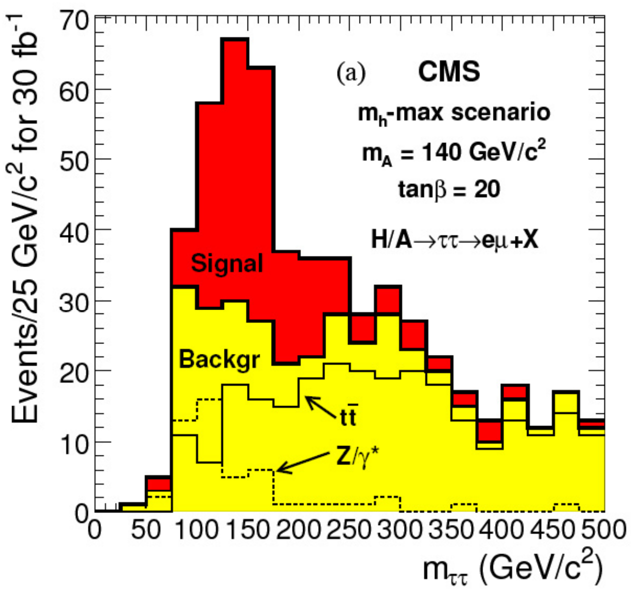
- given the H/A mass degeneracy, they are often referred to as Φ
- production in association with bb (especially good at large tanβ)
- Decays (large tanβ):
  - bb-decay mode (~90%) is overwhelmed with QCD background
  - ττ-decay mode (~10%) is the best bet
  - μμ-decays (~0.03%) allow for direct measurement of Γ



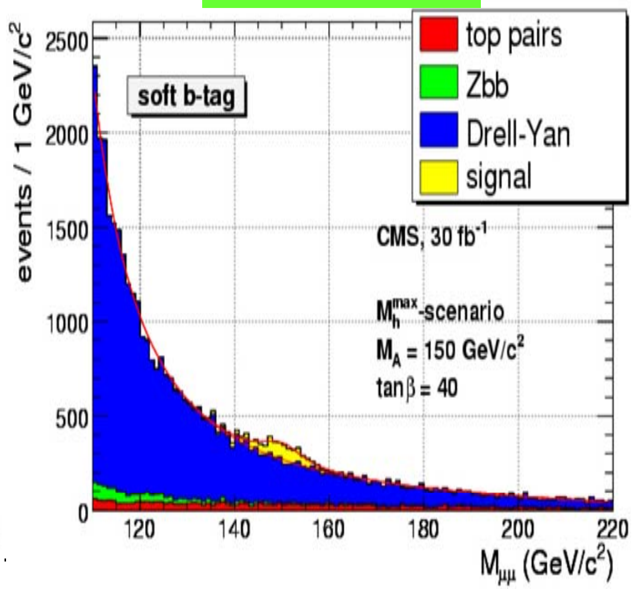
bbΦ, Φ→bb



bbΦ, Φ→ττ

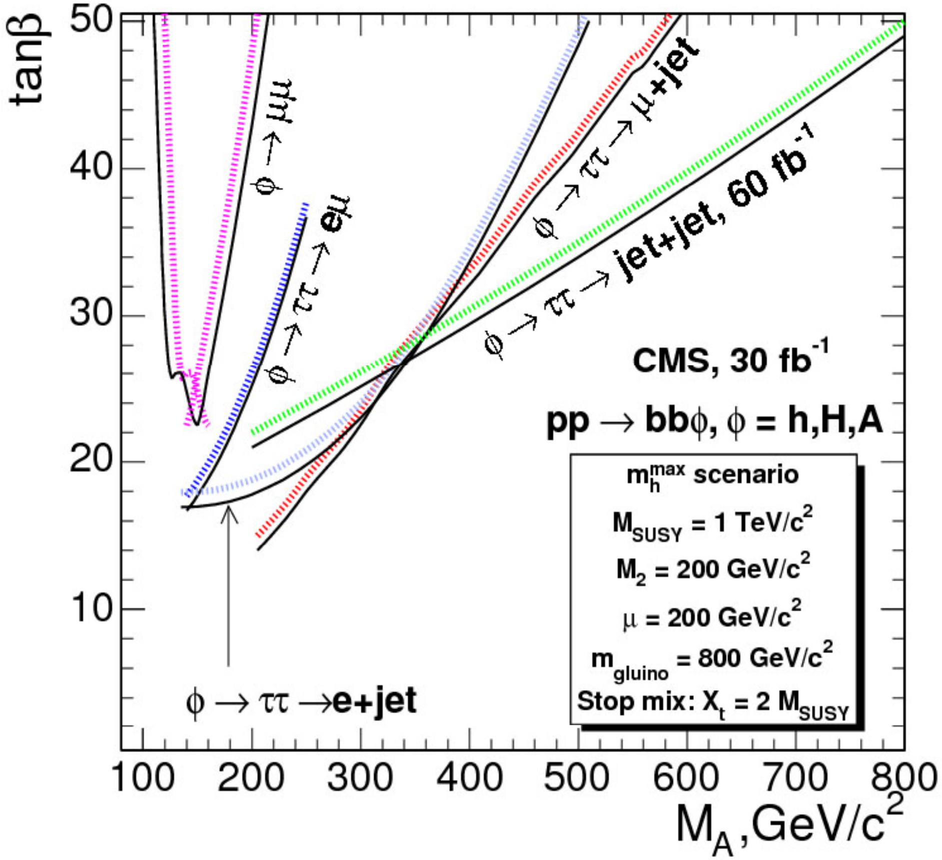


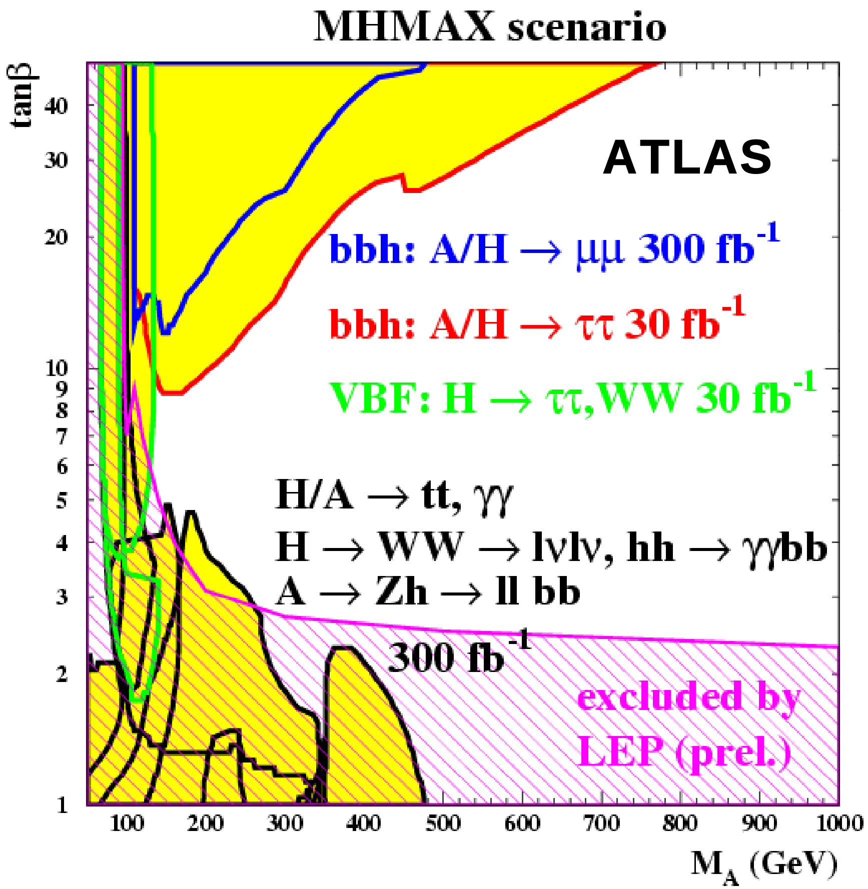
bbΦ, Φ→μμ



MSSM Higgs: heavy neutral H, A (Φ)

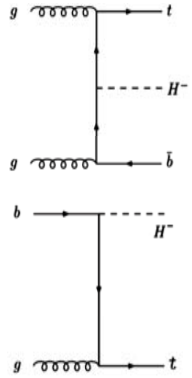
CMS 2006

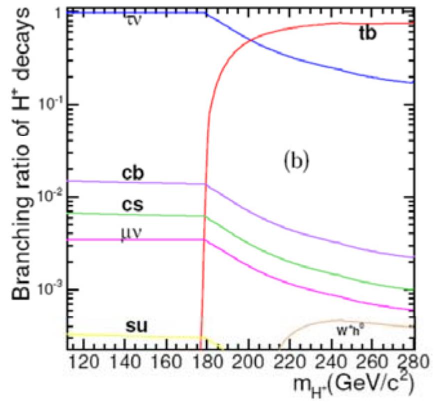


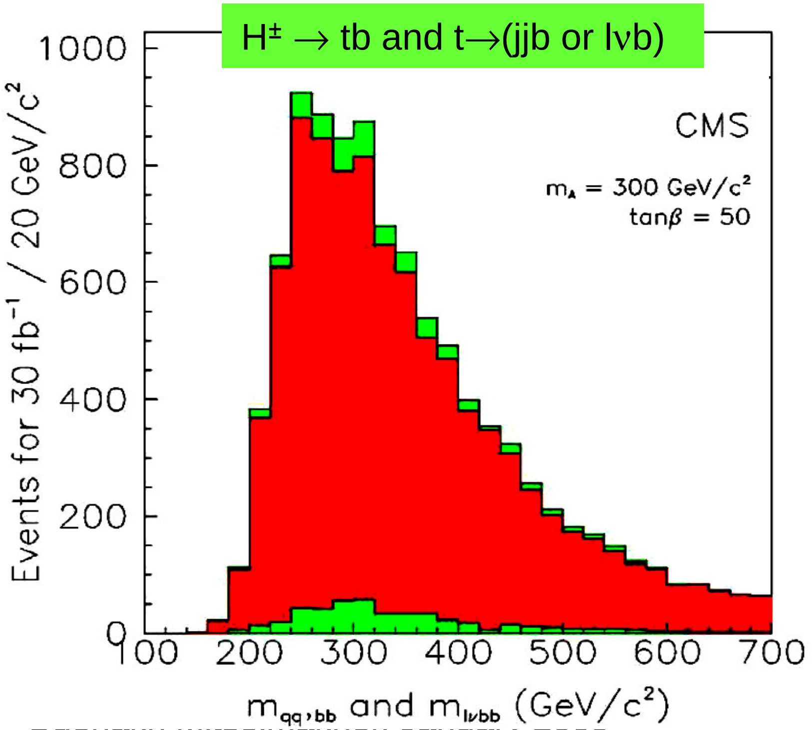


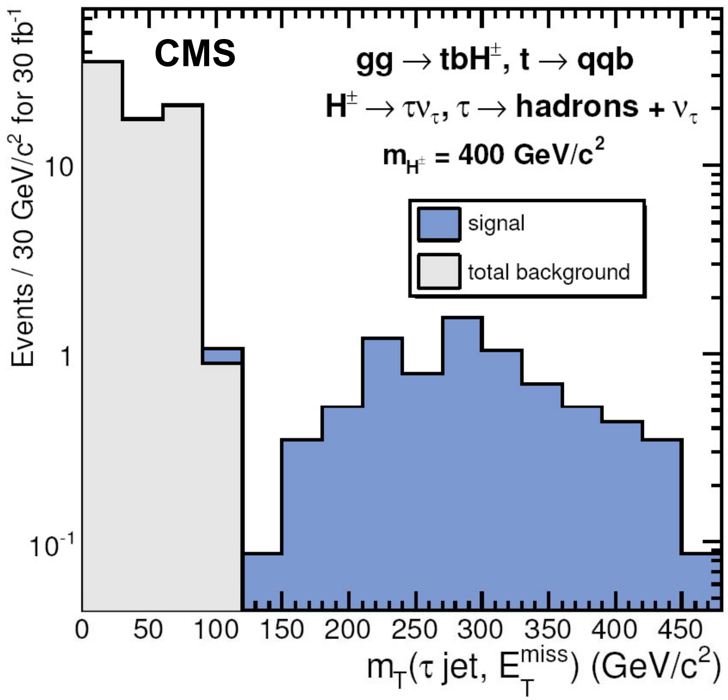
MSSM Higgs: Heavy H±

- **Heavy H± (M>m_{top}):**
  - production via **gg→tbH±** and **gb→tH±**
    - **t→jjb**
    - **H± →tb (BR~80%) overwhelmed by bkgd**
    - **H± →τν (BR~20%)**
  - backgrounds: **tt+jets, tW+jets, W+jets**







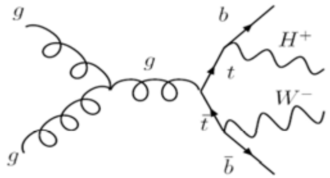


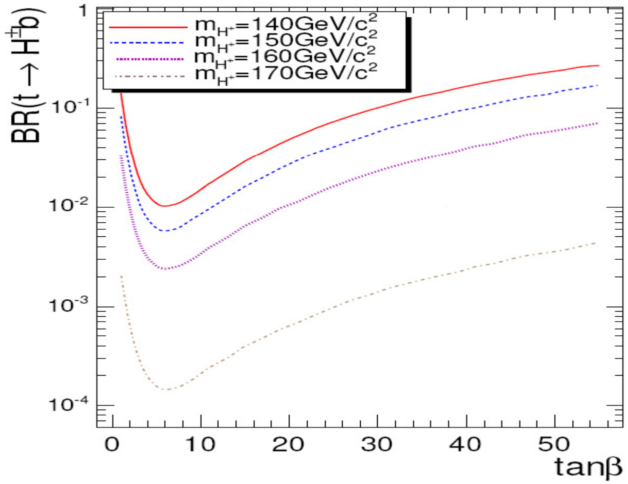
MSSM Higgs: Light H±

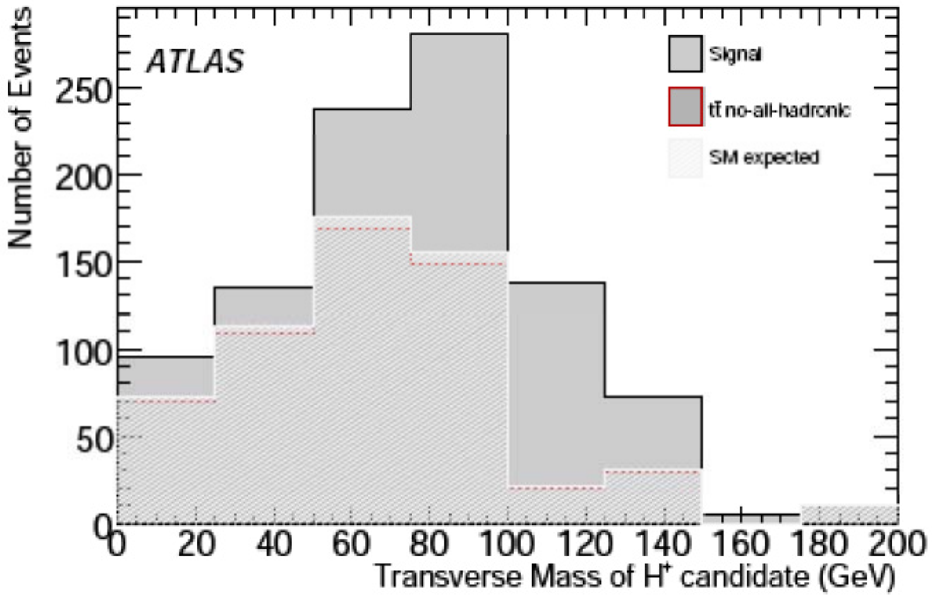
- **Light H± (M<m_{top}):**
  - production via **qq/gg→tt**
    - **t→jjb**
    - **t→bH± (depends on mass and tanβ)**

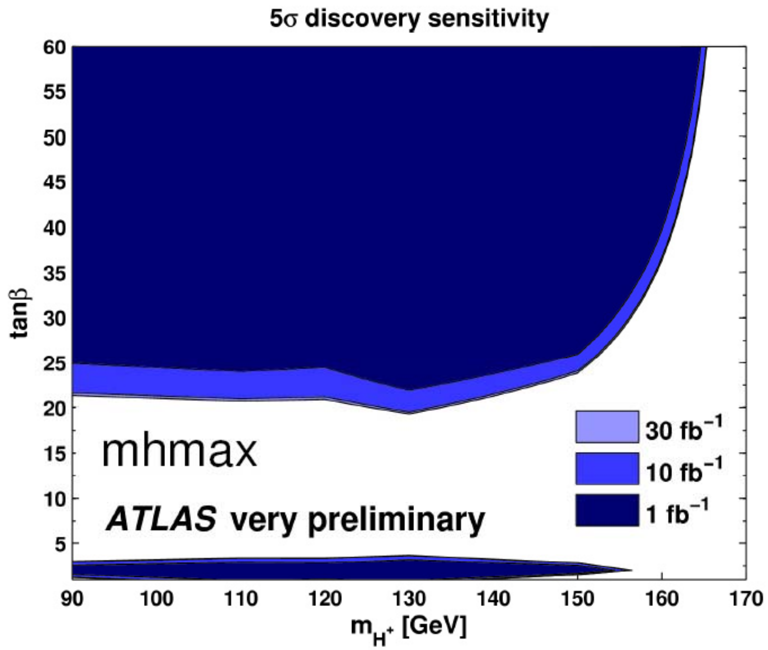
      H± →τν (BR~100%)

      τ→τ-jet (best channel)
  - main backgrounds: **tt**

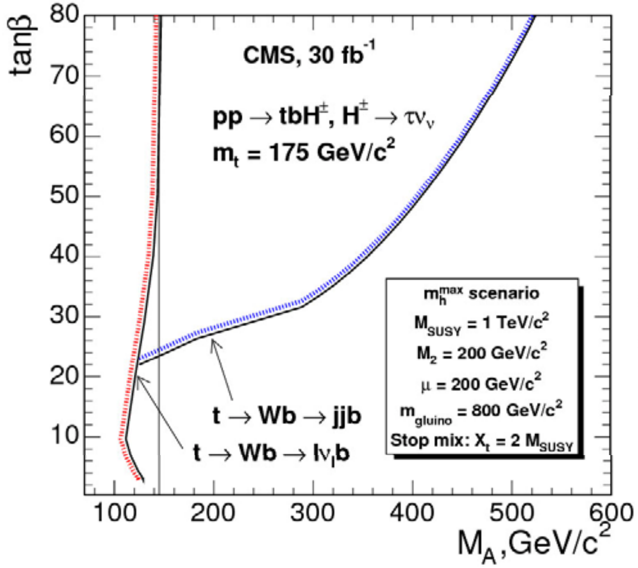


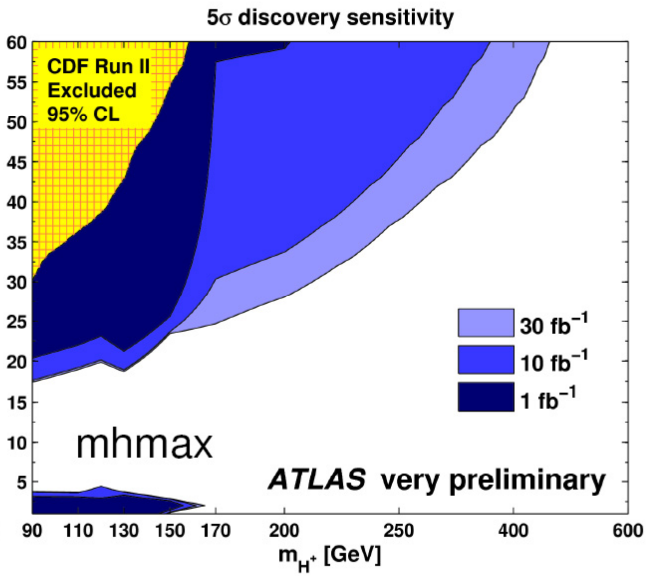


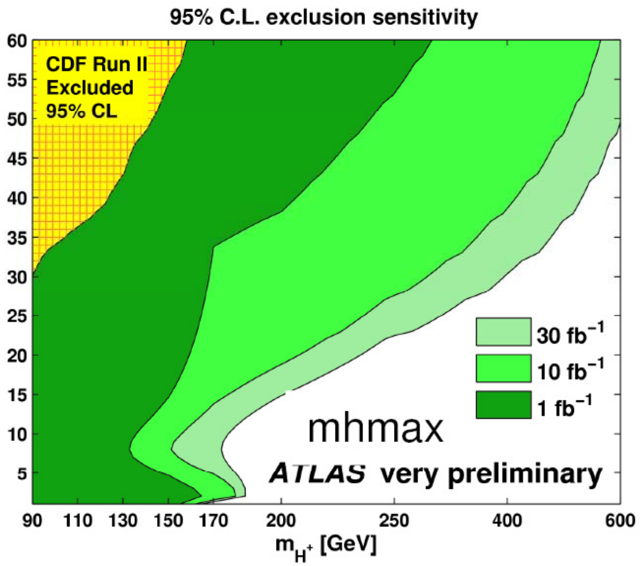




MSSM Higgs: H± summary

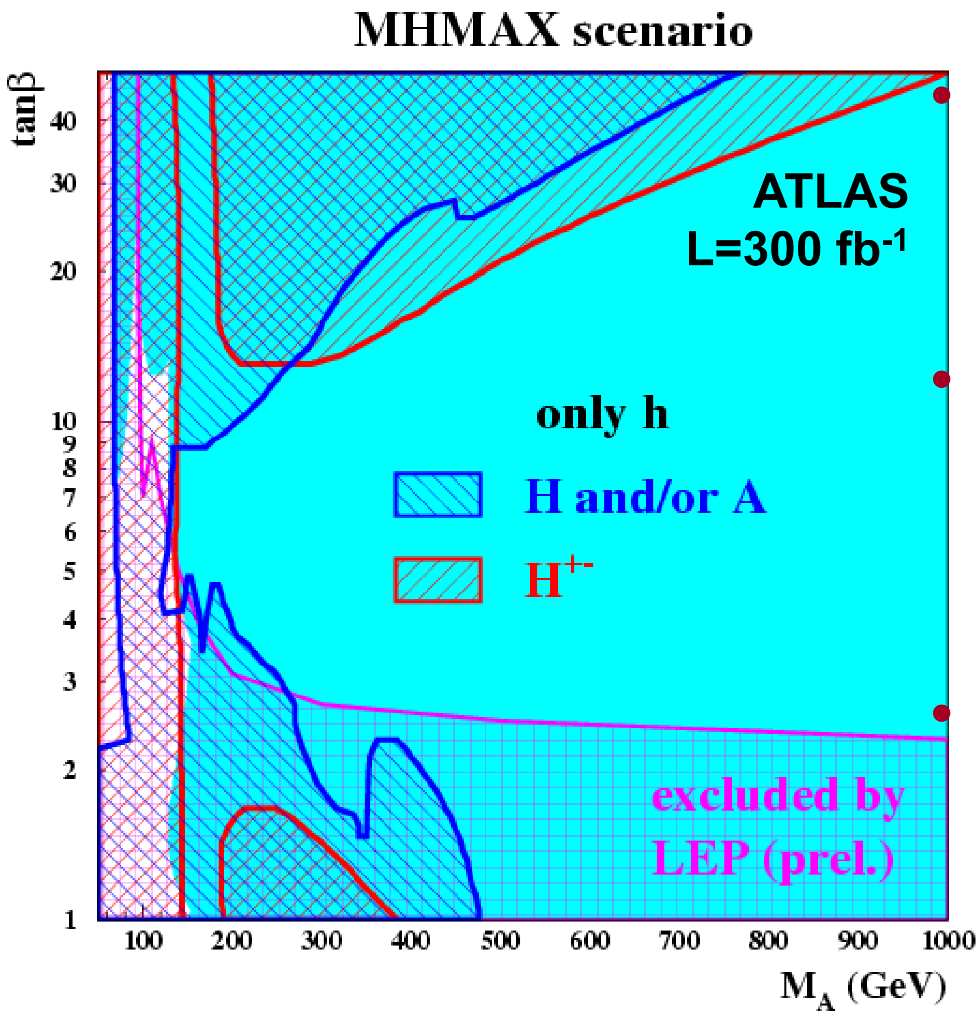






$$M_{H^{\pm}} \sim \sqrt{M_A^2 + M_W^2}$$

Combining all together…



- **MSSM Higgs or SM Higgs?**
- **SM-like h only:**
  - considerable area…
  - even at L=300 fb^{-1}
- **Any handles?**
  - measure branching ratios?
  - decays to SUSY particles?
  - SUSY particle decays?

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 (impossible?, 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 wait for SLHC or LC):
  - SM: tens of events with 10 years of LHC in WWWW channel …hard
  - MSSM – H—hh—bbbb….

Summary

- **SM Higgs**
  - Discovery over full mass range with > 10fb^{-1}
  - LHC/Tevatron competition in ~ 2008-2009
  - forerunner search channels at LHC: **WW, ZZ**, $\gamma\gamma$
- **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
  - forerunner search channels for h, H/A, $H^{\pm}$: $\gamma\gamma$, $\tau\tau$, $\tau\nu$
- **Higgs properties measurements**
  - Masses, width, couplings, can be measured in broad area of parameters
  - Interesting new studies in progress…e.g. CP-violation in Higgs sector?
- **Thanks to many CMS and ATLAS colleagues, who performed the studies**

SM Higgs: production

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