LHC sensitivity to SM & MSSM Higgs Bosons

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- The ATLAS and CMS detectors
- Sensitivity to SM Higgs
- Sensitivity to MSSM Higgs bosons
- Conclusions

LHC Goals and Running Scenarios

LHC Primary goals include:

- Search for SM Higgs up to 1 TeV and MSSM Higgs over entire parameter space
- Sensitivity to alternative scenarios
- Precise test of SM, b-physics, etc.

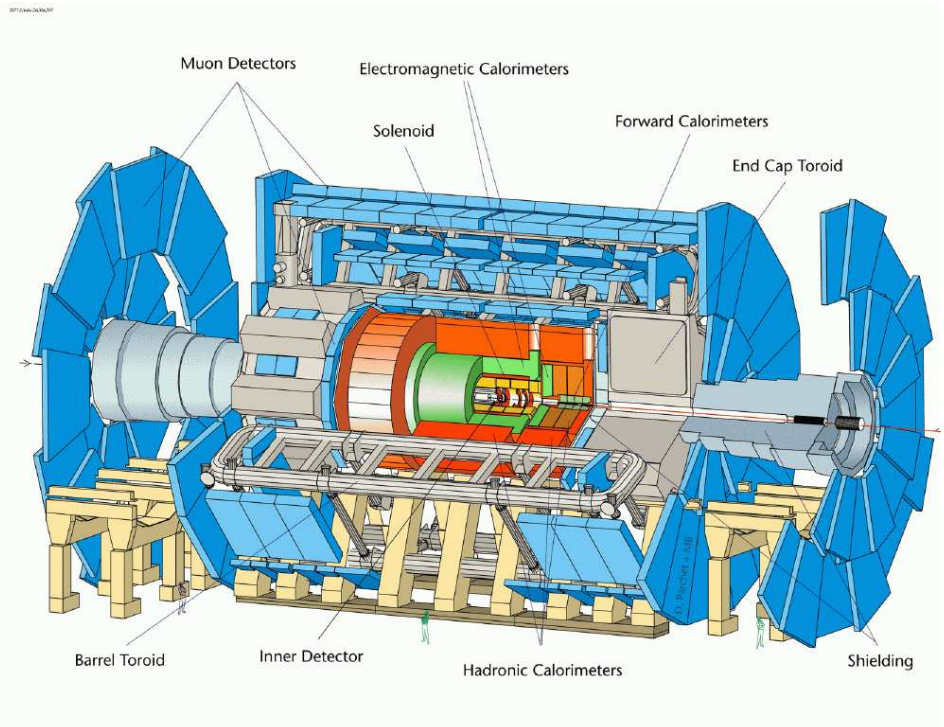
$\Longrightarrow$ high $\sqrt{s}$, $\mathcal{L}$, general-purpose detectors with excellent performance: ATLAS and CMS

Running Scenarios and Luminosities

- Starting date: $\sim$ 2006
- pp collisions at $\sqrt{s} = 14$ TeV
- Initial Luminosity: $\int \mathcal{L}dt = 10$ fb^{-1} per year
- High Luminosity: $\int \mathcal{L}dt = 100$ fb^{-1} per year

The ATLAS Detector

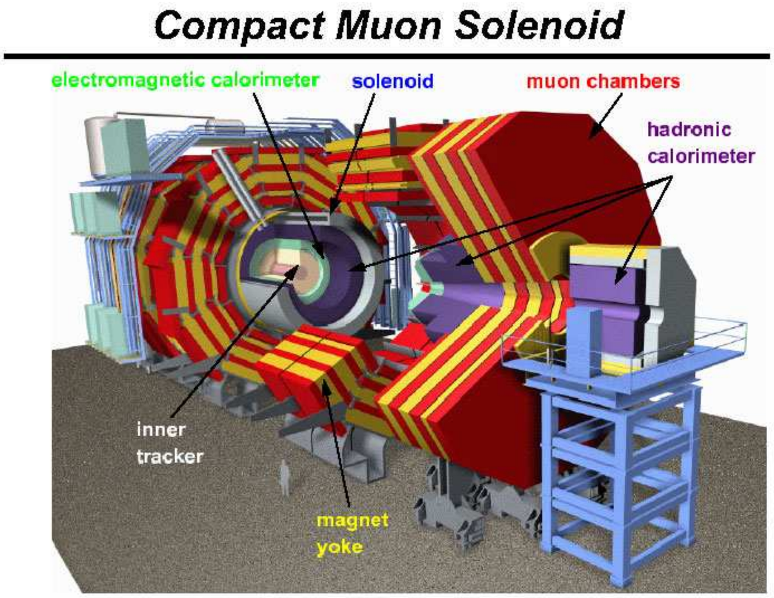
- The Inner Detector: pixel detector, SCT Tracker, TRT $\Longrightarrow$ pattern recognition, momentum & vertex measurements, electron ID.
- The Calorimeter: LAr EM, Tile Hadronic, LAr Hadronic & Forward.



- The Muon Spectrometer: Precision chambers, MDT & CSC. Trigger chambers: RPC & TGC.
- Superconducting Magnets: Central Solenoid, 2T for Inner Detector. Air-core Barrel & Endcap Toroids, for the muon spectrometer

The CMS Detector

- The Tracker: pixel & semiconductor tracker
- The Calorimeter: Scintilling crystal ECAL, Scintillating tile (with copper absorber) HCAL & Foward cal.



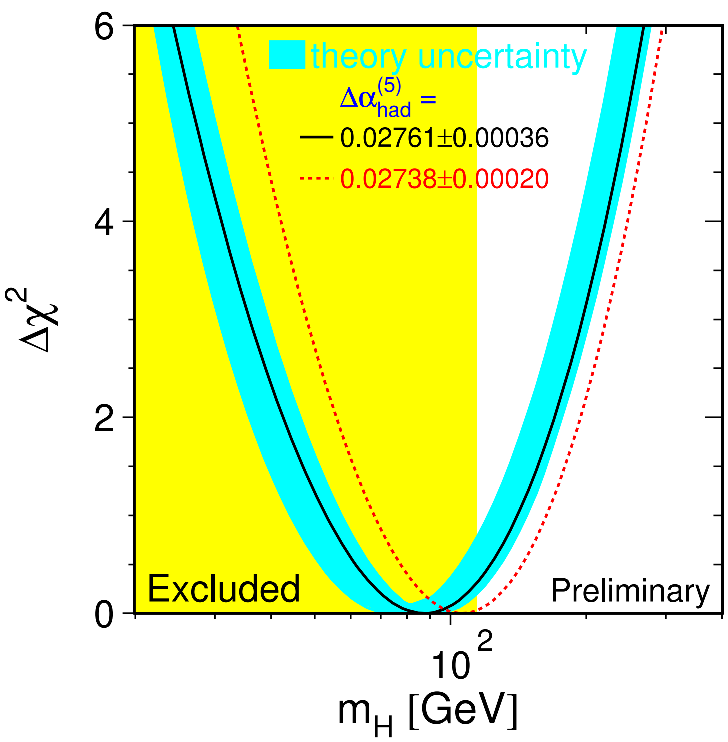
- The Muon Spectrometer: RPC, DT, CSC
- The Magnet: Superconducting Solenoid 4T

The Standard Model Higgs

- Higgs sector: one complex scalar doublet.
- Electroweak symmetry breaking $\Longrightarrow$ one physical scalar particle, the Higgs.
- m_H is free parameter. m_H fixes all couplings: to fermions, to vector bosons.
- Theoretical constraints
  - Unitarity arguments: $m_H < 1$ TeV
  - Electroweak vacuum stability & perturbative validity up to a scale Λ:
    * if $\Lambda = M_{pl} \Rightarrow 130 < M_H < 190$ GeV
    * if $\Lambda = 1$ TeV, $\Rightarrow 50 < M_H < 800$ GeV

SM Higgs: Experimental Constraints

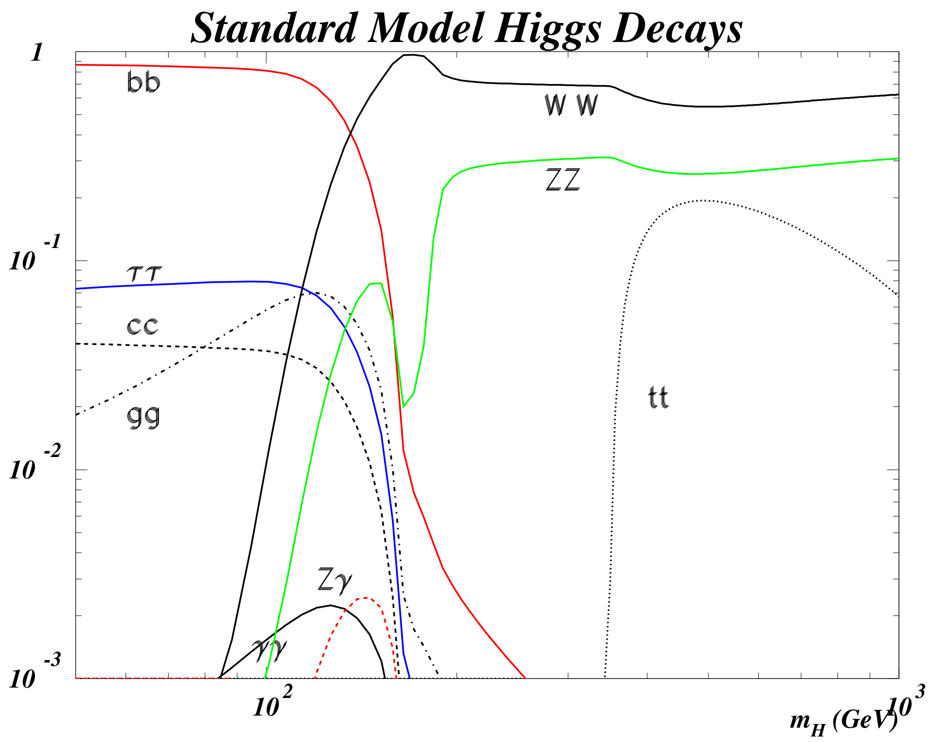
- LEP: $e^+e^- \to ZH$
  $m_H > 114.1$ GeV.
  2.1σ evidence for $M_H \approx 115.6$ GeV Higgs
- Tevatron RUN I: $q\bar{q} \to W(Z)H$, $H \to b\bar{b}$. No signal found. Observed events consistent with expected background
- Global fit of precision electroweak data:



$114.1 < m_H < 212$ GeV @ 95% CL

SM Higgs Searches at the LHC

The SM Higgs will be searched for in various decay channels



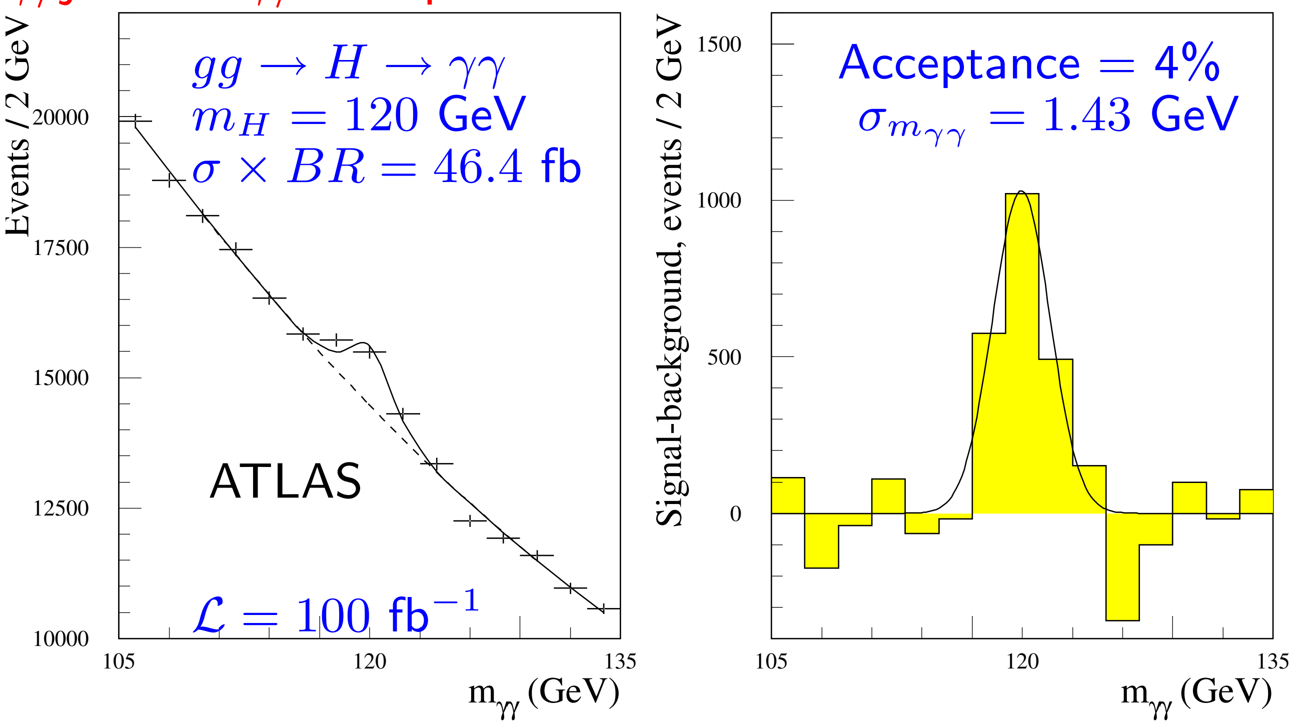
The most promising ones are:

- $H \rightarrow \gamma\gamma$ and WH, $t\bar{t}H$ $(H \rightarrow \gamma\gamma)$
- $t\bar{t}H$ $(H \rightarrow b\bar{b})$
- $H \rightarrow ZZ^* \rightarrow 4l$
- $H \rightarrow WW^* \rightarrow l\nu l\nu$
- $H \rightarrow ZZ \rightarrow ll\nu\nu$
- $H \rightarrow WW \rightarrow l\nu jj$

$gg \to H \to \gamma\gamma$ (Direct Production)

- m_H(GeV) < 150, $\sigma \times BR = 50$ fb
- Irreducible backgrounds: $q\bar{q}\,(gg) \to \gamma\gamma$ and $gg \to q\gamma \to q\gamma\gamma$. $\sigma_{\gamma\gamma} \sim 2$ pb/GeV
- Reducible backgrounds: jet-jet, γ-jet and $Z \to ee$ events. $\sigma_{\gamma j+jj} \sim 10^6\,\sigma_{\gamma\gamma}$, $\longrightarrow$ need $R_j > 10^3$ at $\epsilon_\gamma = 80\%$ for $\sigma_{\gamma j+jj} \ll \sigma_{\gamma\gamma}$!

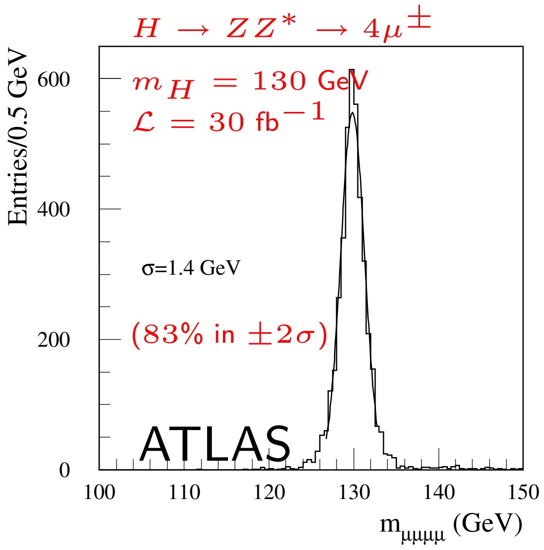
$\Longrightarrow$ Requires excellent energy and angular resolution, γ/jet and γ/π^0 separation

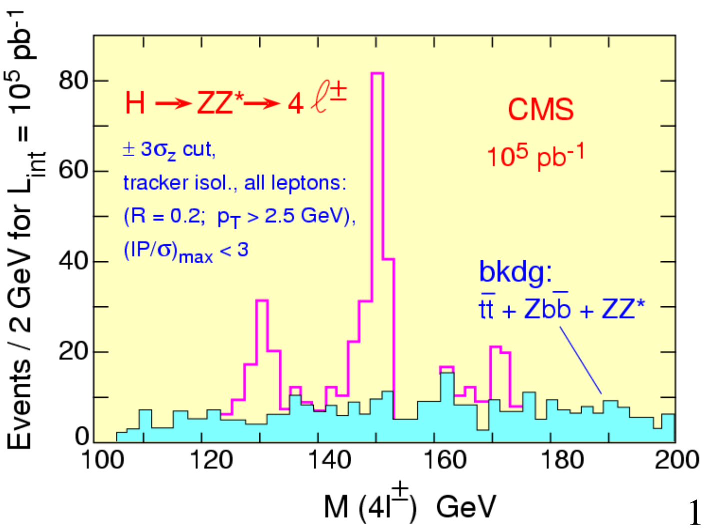


$\Longrightarrow$ For $\mathcal{L} = 30$ fb^{-1}, $110 < m_H < 140$ GeV $> 5\sigma$, (ATLAS+CMS)!

$H \to ZZ^* \to eeee,\ ee\mu\mu,\ \mu\mu\mu\mu$

- $\sim 120 < m_H$(GeV) $< 2m_Z$, $\sigma \times Br = 3$ fb.
  Irreducible backgrounds: ZZ^* and $Z\gamma^*$
  Reducible: $t\bar{t}$, $Zb\bar{b}$ ($\to 4l + X$)
- 4 leptons: $p_T > 20, 20, 7, 7$ GeV, m_{12} consistent with $m_Z \longrightarrow$ reject $t\bar{t}$ and $m_{34} > 15 - 60$ GeV.
- Impact parameter & Isolation cuts $\longrightarrow$ reject $b \to l + X \implies t\bar{t} + Zb\bar{b} < 10\%$ of ZZ^*





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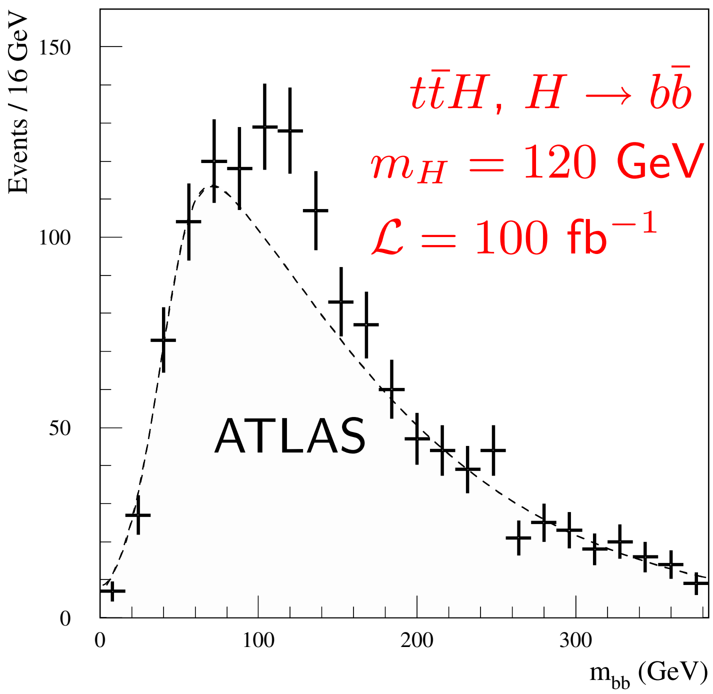
$\implies > 5\sigma$ possible at $\mathcal{L} = 30$ fb^{-1} in the range $\sim 130 < m_H$(GeV) ≤ 180 (except 160-170 GeV)

$H \to b\bar{b}$ (Associated Production)

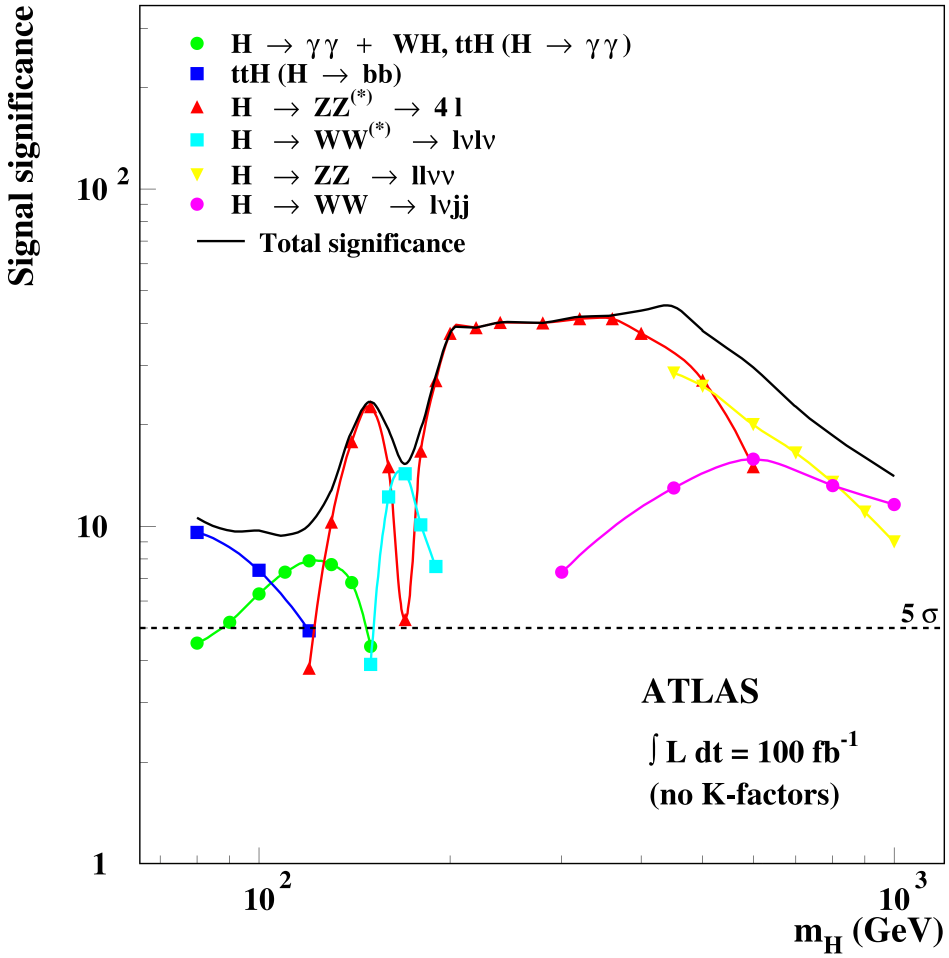
- $H \to b\bar{b}$ $(m_H < 2m_W)$
  - Direct production $gg \to H \to b\bar{b}$: large QCD jj backgrounds
  - Associated productions WH, ZH or $t\bar{t}H$: only way observe $H \to b\bar{b}$
- $gg \to t\bar{t}H$ with $t \to l\nu b$ $\bar{t} \to jjb$ and $H \to b\bar{b}$
  - Must recontruct both top-quarks
  - 4 b-jet final state: Excellent b-tagging required



  - Knowledge of $t\bar{t}jj$ background shape

$\Longrightarrow$ $> 5\sigma$ possible for $100 < m_H < 120$ GeV and $\mathcal{L} = 30$ fb^{-1}, ATLAS+CMS!

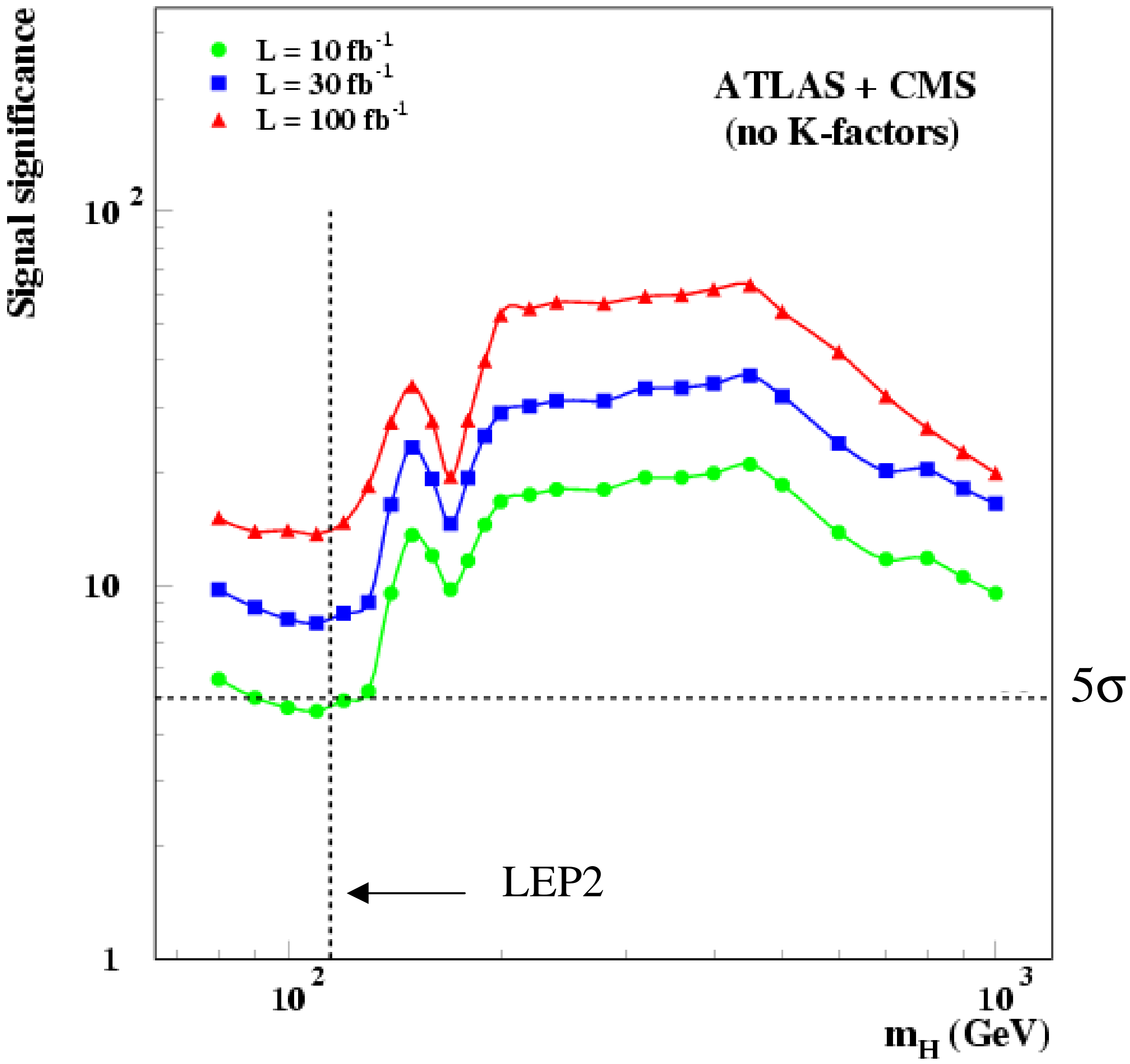
Sensitivity to SM Higgs Searches



- $80 < m_H < 130$ GeV: $H \rightarrow \gamma\gamma$, $H \rightarrow b\bar{b}$, and $H \rightarrow ZZ^* \rightarrow 4l$
- Around $m_H \sim 170$ GeV: $H \rightarrow WW^* \rightarrow l\nu l\nu$
- At least 2 discovery channels available over most of the mass range with $S/\sqrt{B} > 5$ for 100 fb^{-1} (1 EXP.)

Sensitivity to SM Higgs Searches

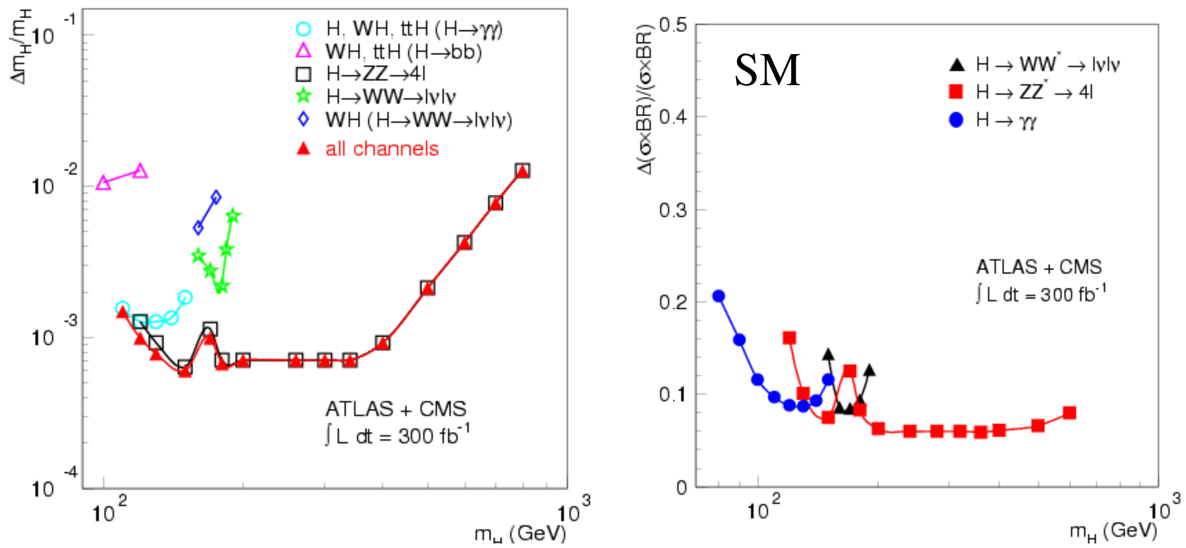
Combined Channels & Experiments



- Faster discovery for higher masses
- Combined channels & experiments: $S/\sqrt{B} > 5$ already for 10 fb^{-1}!

Determination of SM Higgs Parameters

- The ultimate precision on m_H depends on:
  - Statistical errors on peak positions
  - systematic errors on energy scale:
- The uncertainty on the rate depends on the knowledge of luminosity (statistical errors $< 10\%$)



- $\Delta\, m_H/m_H \sim 0.1\%$ up to 400 GeV
- $\Delta\, R/R \sim$ 7%-20% for $\Delta\mathcal{L}/\mathcal{L} = 5\%$.
- $\Delta\,\Gamma/\Gamma$ can be measured directly using $H \to ZZ \to 4l$ for $m_H > 200$ GeV
- For $m_H < 200$ GeV, indirect determination of $\Delta\,\Gamma/\Gamma$ through cross-sections in $q\bar{q}H\,(H \to WW,\, \gamma\gamma,\, \tau\tau)$

Two Higgs Doublet Model (2HDM)

- 2 complex scalar doublets
- 5 physics Higgs bosons
  - 2 neutral CP even bosons: h^0 and H^0 $(m_h < m_H)$
  - one neutral CP odd scalar: A^0
  - 2 charged Higgs: $H^{\pm}$
  - 6 parameters: m_h, m_H, m_A, $m_{H^{\pm}}$ and 2 angles: α, mixing angle in CP-even sector, $\tan\beta = v_2/v_1$
- Type of 2HDM determined by couplings of Higgs doublets to fermions:
  - 2HDM-I: quarks and leptons couple only to the second doublet
  - 2HDM-II: first doublet couples to down-type quarks and leptons. Second doublet couples to up-type quarks and neutrinos.
- In absence of supersymmetry, spectrum would contains the 5 Higgs bosons & SM particles

Minimal Supersymmetric Standard Model

- MSSM is a 2HDM-II
- Introduction of supersymmetry adds new particles & some constraints on the Higgs sector.
- Tree level: Higgs sector fixed by m_A and $\tan\beta$.
  - $m_h < m_Z$
  - $m_h < m_A$
  - $m_H > m_Z$
  - $m_{H^\pm} > m_W$
  - $m_{H^\pm}$ and m_H depend linearly on m_A
  - Large m_A; H^0, $H^\pm$ and A^0 degenerate in mass!
- Radiative corrections can modify tree level relation significantly: $m_h < 135$ GeV

MSSM Higgs: Experimental Constraints

- LEP: search for $e^+e^- \to Zh^0$ and $e^+e^- \to A^0h^0$

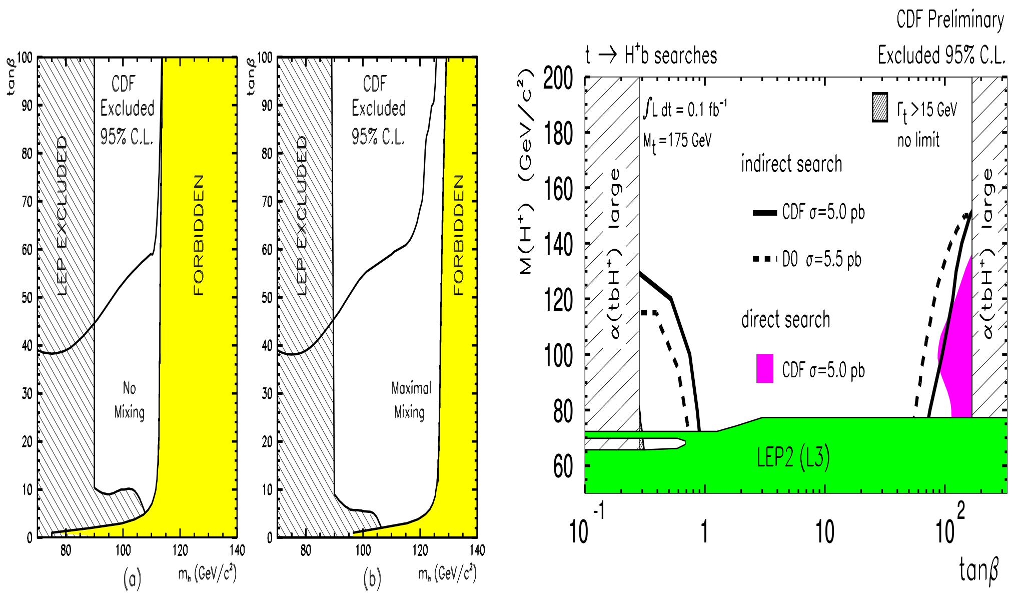
  $m_h > 91.0$ GeV $m_A > 91.9$ GeV @ $95\%\,CL$

  $0.5 < \tan\beta < 2.4$ excluded

- LEP: search for $e^+e^- \to H^+H^-$

  $m_{H^\pm} > 78.6$ GeV @ $95\%\,CL$ for any $\tan\beta$

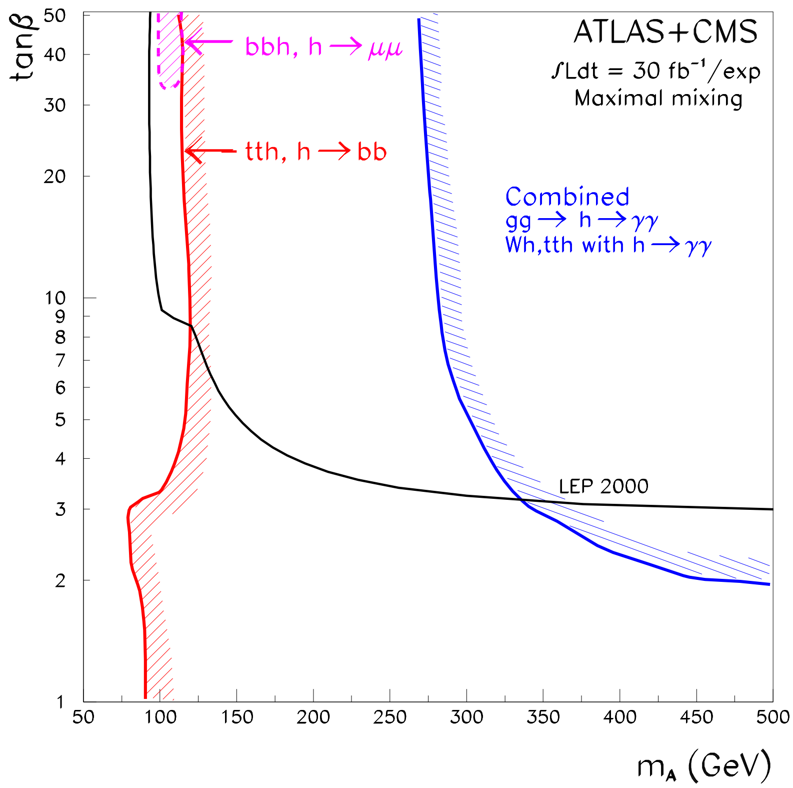
- Tevatron RUN I:



  - $p\bar{p} \to b\bar{b}h^0\ (\to b\bar{b})$: probes $\tan\beta > 35$, region not accessible at LEP. No signal observed.
  - $t \to bH^\pm$. CDF direct search $H^\pm \to \tau\nu$. CDF & DØ indirect searches. low & high $\tan\beta$ excluded.

The h^0 Boson of MSSM at the LHC

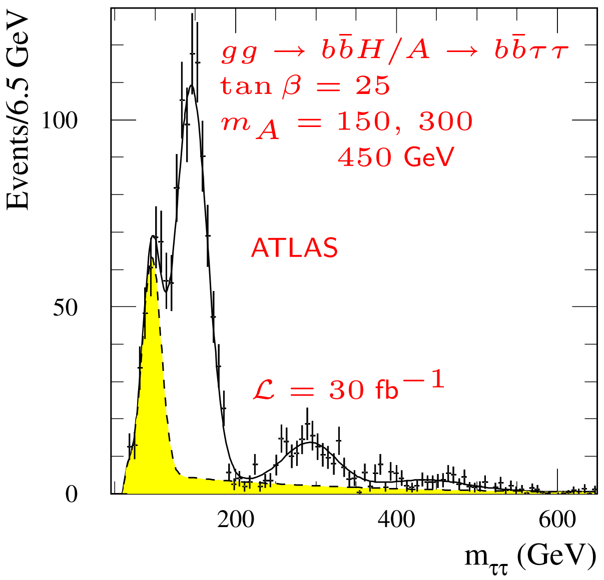
- In MSSM, $\sigma \times Br$ for $h \rightarrow b\bar{b}$ and $h \rightarrow \gamma\gamma$ suppressed compared to SM cases
- As $m_h \longrightarrow m_h^{max}$, enhancement by 10-20%
- Sensitivity to $t\bar{t}h$, Wh $(h \rightarrow b\bar{b})$ and $h \rightarrow \gamma\gamma$ computed from SM results.

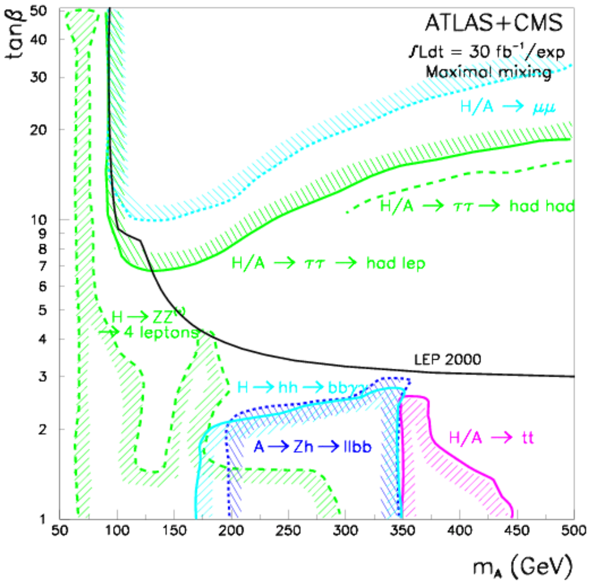


- $m_A < 100$ GeV: $h \rightarrow \gamma\gamma$,$h \rightarrow b\bar{b}$ suppressed. At high $\tan\beta$ $b\bar{b}h$ $(h \rightarrow \mu\mu)$ observable
- $m_A > 100$ GeV: $m_h \longrightarrow m_h^{max}$ of ~ 130 GeV and h similar to SM Higgs $\Longrightarrow$ other channels to disentangle SM/MSSM

$H/A \to \tau\tau$: Direct/Associated Production

- $gg \to H/A \to \tau\tau$: b-jets veto against $t\bar{t}$ and $b\bar{b}$ backgrounds
- $gg \to b\bar{b}H/A \to b\bar{b}\tau\tau$: b-jets tagging to suppress $Z \to \tau\tau$, W+jets, and $t\bar{t}$ backgrounds
- Excellent τ/jet separation and E_T^{miss} resolution: $\epsilon(A \to \tau\tau) \simeq 20$ %, $R_{\text{jet}} = 10^2 - 10^3$
- For $m_A > 150$ GeV, H and A are degenerate!



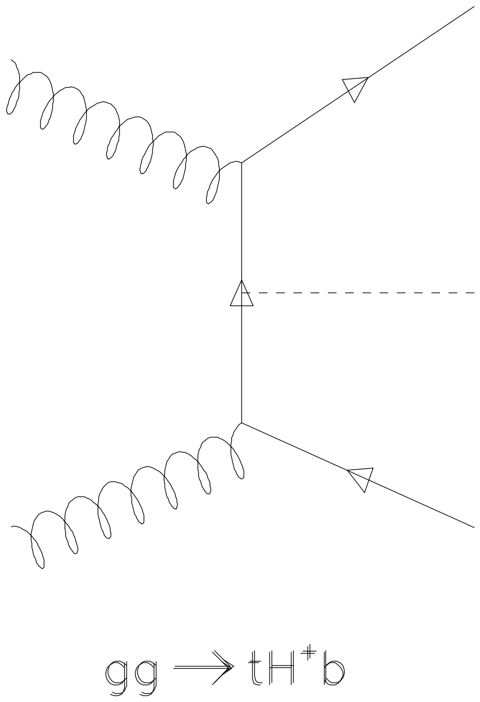


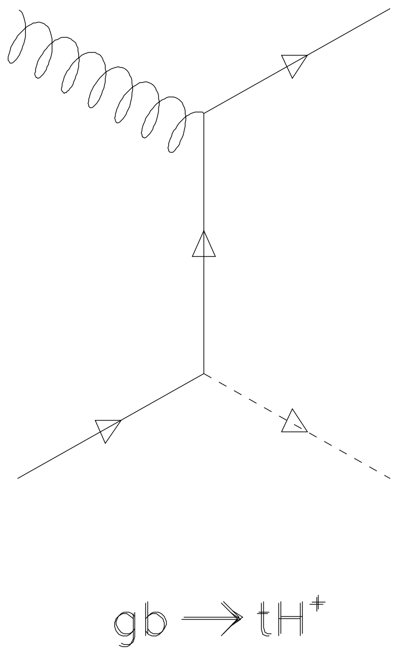
$S/B > 15\%$ over $100 < m_A < 500$ GeV, $\tan\beta > 7$
$\Longrightarrow$ $A/H \to \tau\tau,\ \mu\mu$ observable and cover a large part of parameter space

$H^{\pm}$ Productions at the LHC

Main processes with sizeable cross sections:

$$m_{H^{\pm}} > m_T$$





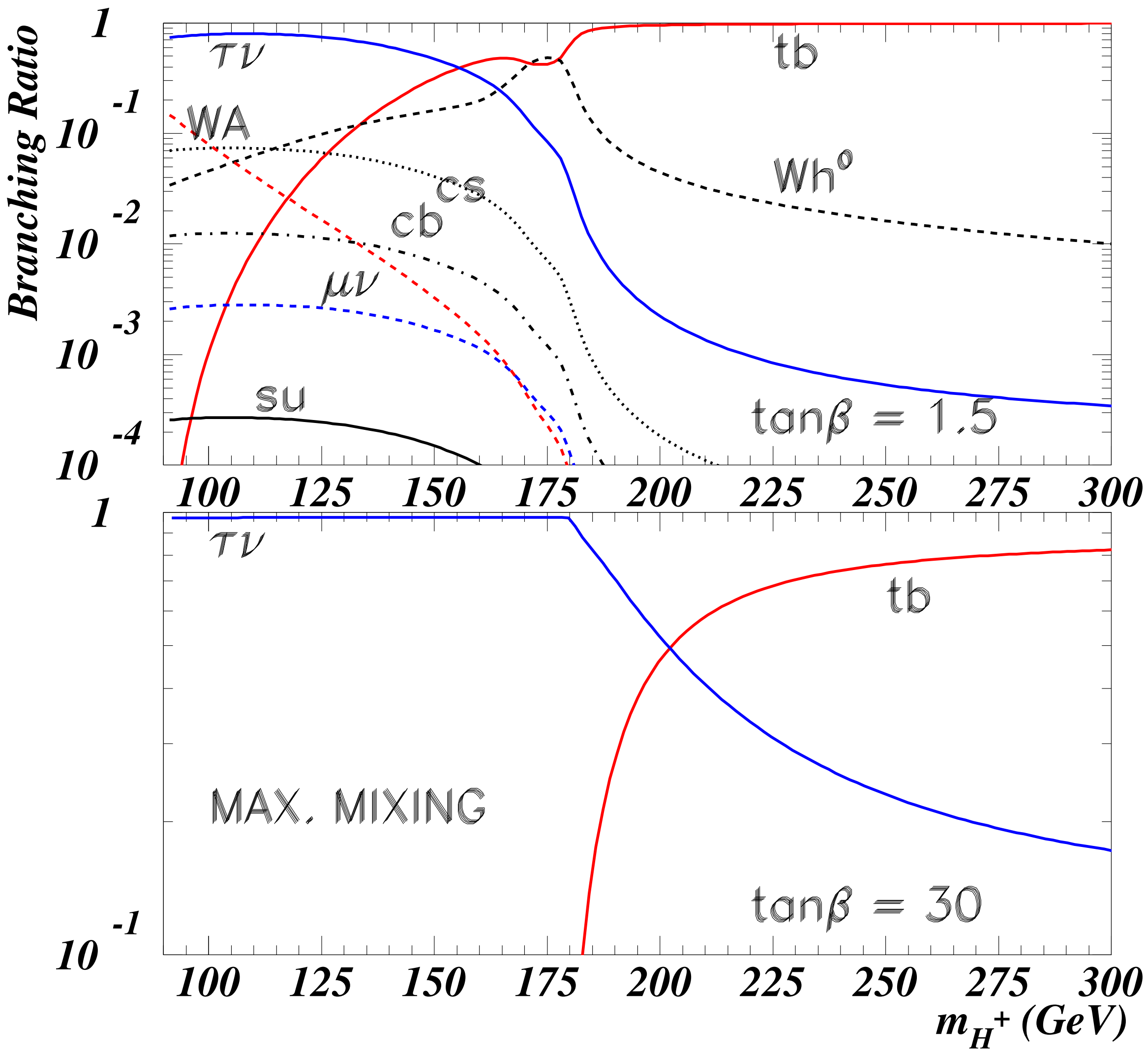
σ(inclusive) is the sum after subtraction of common terms

$$m_{H^{\pm}} < m_T\text{: } t \rightarrow bH^{\pm}$$

Other production mechanisms (low rate at LHC):

$$\begin{aligned} qq &\longrightarrow H^+H^- \\ &\longrightarrow H^{\pm}W^{\pm} \\ gg &\longrightarrow H^+H^- \end{aligned}$$

$H^{\pm}$ Decays at the LHC



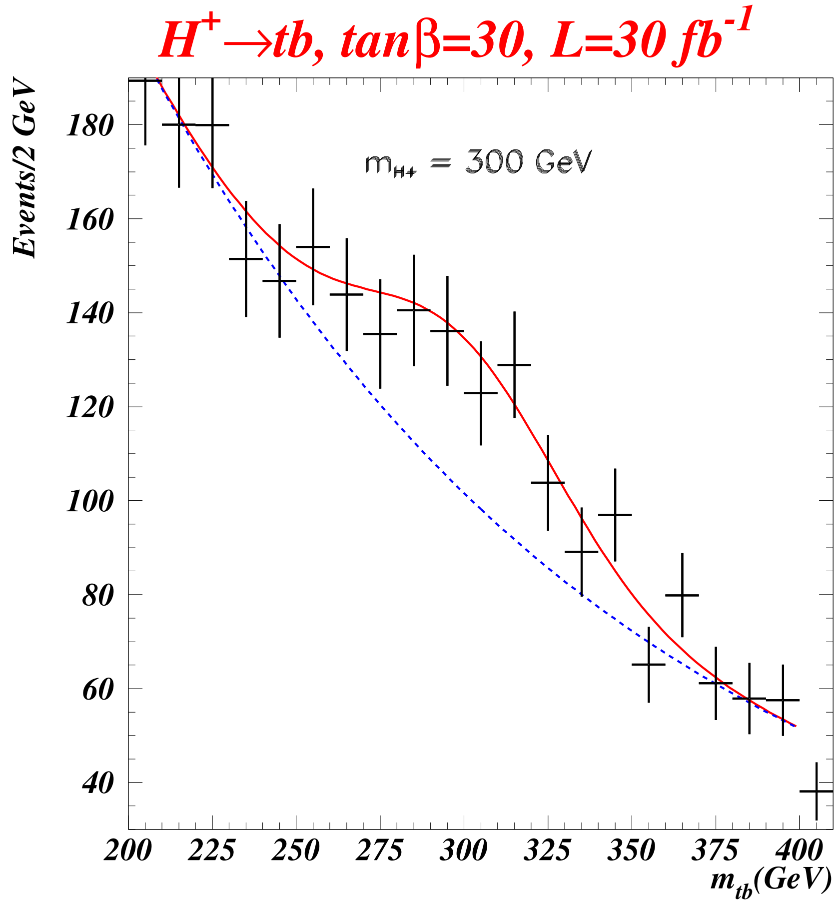
Relevant channels at the LHC:

$$
\begin{aligned}
H^{\pm} &\rightarrow \tau\nu \\
&\rightarrow tb,\ t^{*}b \\
&\rightarrow Wh,\ W^{*}h
\end{aligned}
$$

$pp \to tH^{\pm}$ $(m_{H^{\pm}} > m_t)$

$H^{\pm} \to \bar{t}b$, $t \to Wb \to l\nu_l b$ and $\bar{t} \to Wb \to jjb$

- Signal: $\tan\beta = 30$, $m_{H^{\pm}} = 250$ GeV, $\sigma \times \text{BR} = 1.2$ pb.
- Background: $pp \to t\bar{t}b$, $\sigma \times \text{BR} = 228$ pb

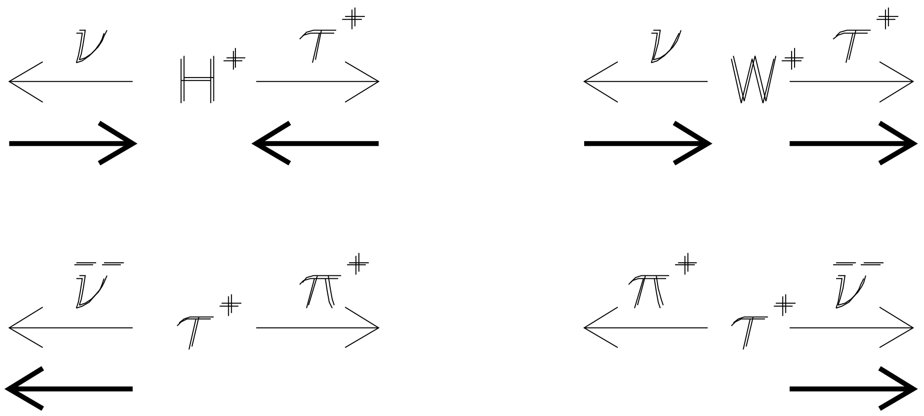


Discovery possible up to 450 GeV for $\tan\beta > 15$ & $\tan\beta < 3$

$pp \to tH^\pm,\ t \to jjb,\ H^\pm \to \tau\nu_\tau\ (m_{H^\pm} > m_t)$

- Signal, $H^\pm \to \tau\nu$: $\tan\beta = 40$, $m_{H^\pm} = 250$ GeV, $\sigma \times$ BR $= 0.91$ pb.
- Backgrounds:
  - $pp \to t\bar{t} \to WbWb$, $\sigma \times$ BR $= 84$ pb
  - $pp \to Wt$ ($p_T > 30$ GeV), $\sigma \times$ BR $= 56$ pb
  - $pp \to W +$ jets, $\sigma \times$ BR $= 1.64\,10^4$ pb

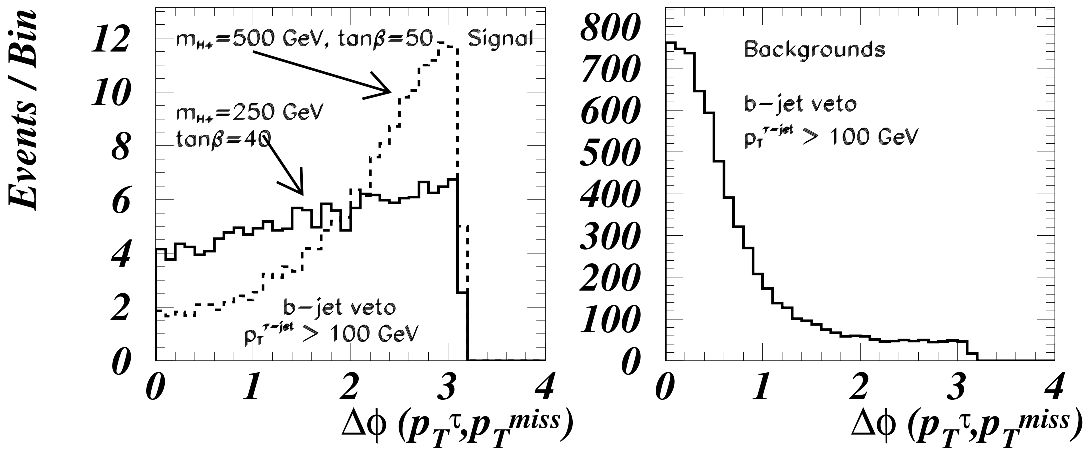
  with one $W \to \tau\nu$ and the other $W \to jj$
- Take advantage of differences in τ polarization: For 1-prong decays,



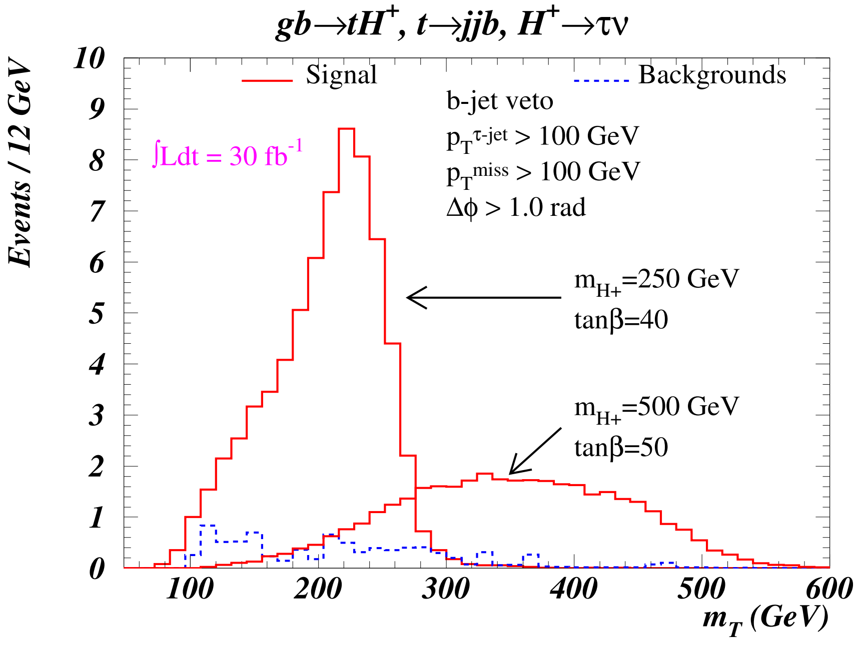
Harder π from $\tau \to \pi\nu$ and longitudinal ρ and a_1 in H^+ than W^+

$pp \rightarrow tH^{\pm},\ t \rightarrow jjb,\ H^{\pm} \rightarrow \tau\nu_{\tau}\ (m_{H^{\pm}} > m_t)$

- Take advantage of differences in kinematics



- Transverse mass $m_T = \sqrt{2p_T^{\tau}p_T^{miss}[1 - \cos(\Delta\phi)]}$



- Channel almost background free. Discovery limited by signal size itself. Reach extended to $\sim$ 700 GeV, $\tan\beta > 10$!

$t \to bH^\pm \to b\tau^\pm\nu \; (m_{H^\pm} < m_t)$

- Signal:

$$\begin{aligned} pp &\to t\bar{t} \\ t &\to bH^\pm \to b\tau^\pm\nu_\tau \to b\text{hadrons}\,\nu_\tau \\ \bar{t} &\to bW^\pm\,(H^\pm) \to bl^\pm\nu_l\,(l^\pm\nu_l\nu_\tau) \end{aligned}$$

- Backgrounds: $pp \to t\bar{t}$, $W+$jets, $b\bar{b}$
- Search for 1 hadronic τ, 1 isolated lepton, $\geq$ 3 jets (with 2 b-tagged)
- $m_{H^\pm}$ cannot be reconstructed. Signal appears as an excess of τ leptons
- $\tan\beta = 5$ and $m_{H^\pm} = 130$ GeV, $\sigma \times \mathrm{BR} = 13.1$ pb

$\sim$1200 τ from $H^\pm$

$\sim$2500 τ from $W^\pm$

$\sim$3400 fake τ's

Significance $= 6.6$ (3% systematics on fake τ efficiency)

- Discovery possible for $m_{H^\pm} < m_t - 20$ GeV over most of the $\tan\beta$ range.

$H^\pm \to Wh$ (W^*h) in MSSM

Current LEP limits on h and A searches:

$$m_h\,(m_A) \quad > \quad 91 \text{ GeV.}$$

The MSSM relation $m^2_{H^\pm} = m^2_A + m^2_W$

$$\Longrightarrow m_{H^\pm} > 122 \text{ GeV}$$

In fact, for $\tan\beta = 3$, $m_{H^\pm} > 200$ GeV

Thus, $H^\pm \to Wh$ has a high threshold in the LEP allowed region where $BR < 5\%$.

For $\mathcal{L} = 300$ fb^{-1}, $\tan\beta = 3$ and $m_{H^\pm} = 200$ GeV:

Signal Events	236
Background Events	5000
$S/\sqrt{B}$	3.3

$\Longrightarrow$ channel not viable in MSSM

$H^{\pm} \to Wh(W^{*}h)$ **in NMSSM**

The Higgs Sector of NMSSM:

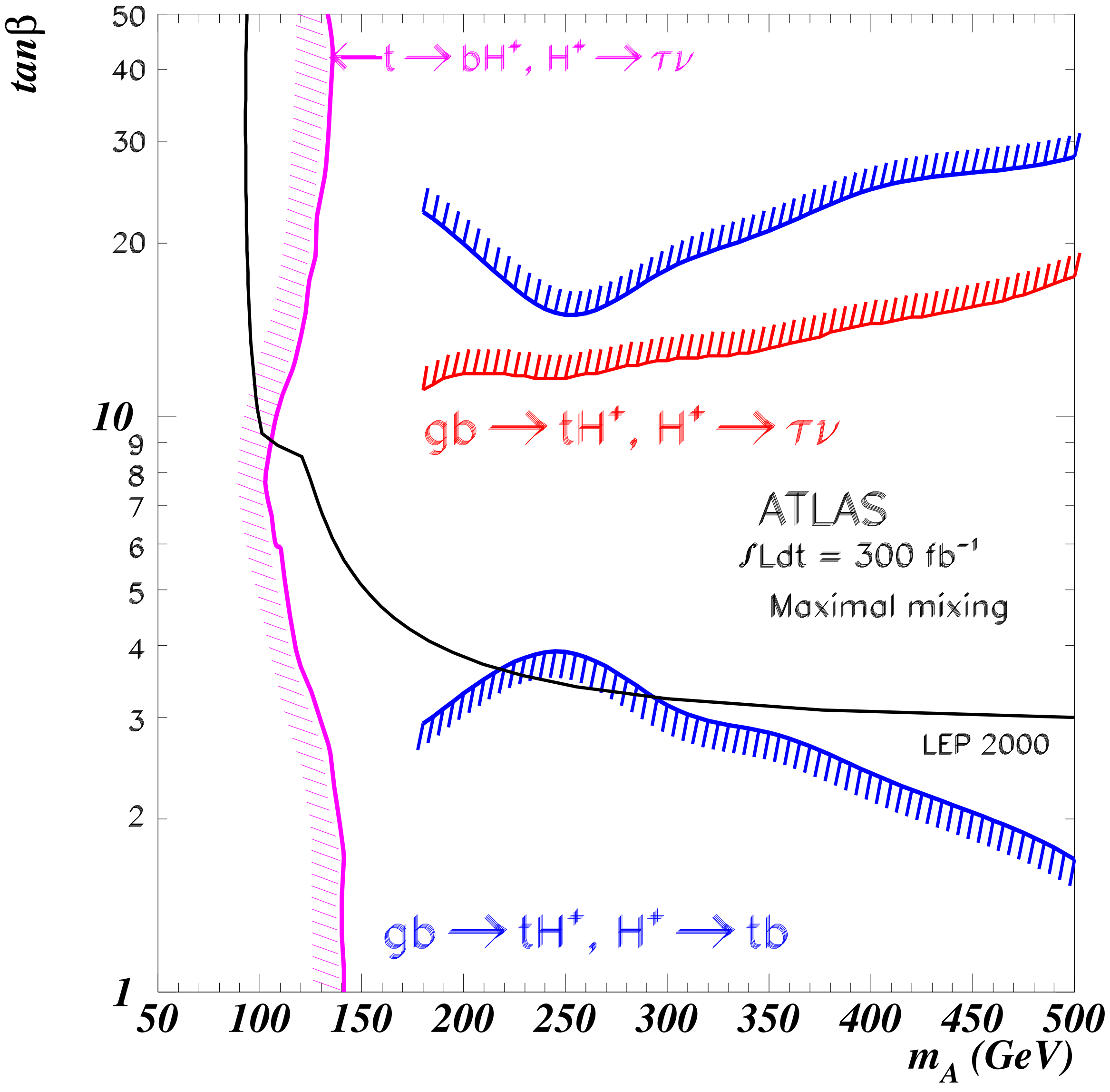
- 2 Higgs doublets + 1 Singlet $\Longrightarrow$
- 7 Physical States: h^0, H_1^0, H_2^0, A_1^0, A_2^0 and $H^{\pm}$
- Parameter space less constrained than in MSSM
- Indirect lower bounds from LEP go away
- Mixing between doublet and singlet states would dilute the direct lower bounds from LEP

As a result

- $m_{H^{\pm}}$ can be less than m_t down to $\tan\beta = 1.5$
- $H^{\pm} \to W^{\pm}(h_1^0, A_1^0)$ dominant decay mode for low $\tan\beta$ and $m_{H^{\pm}} \sim 160$ GeV.
- BR(MSSM) $<$ 5% $\longrightarrow$ $>$ 50% in NMSSM

$H^{\pm} \to Wh$ marginally viable in MSSM but spectacular signal in NMSSM!

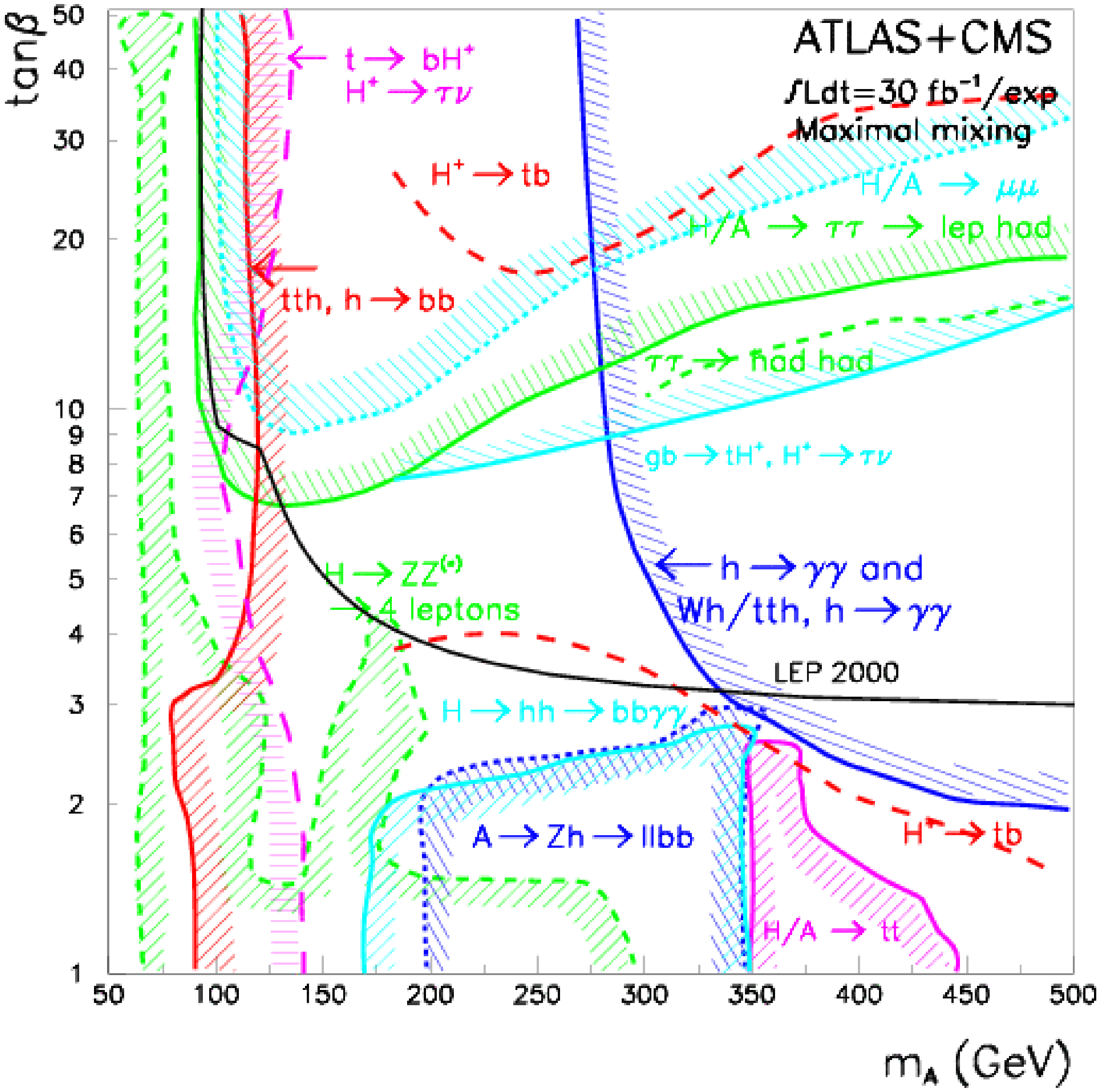
ATLAS discovery Potential for $H^{\pm}$



Discovery relies on: $H^{\pm} \to \tau\nu$ and on $H^{\pm} \to tb$

Sensitivity to MSSM Higgs Searches

Assuming a heavy SUSY spectrum...



$\Longrightarrow$ Discovery potential in $(m_A, \tan\beta)$ plane relies on $H/A \to \tau\tau$, $t\bar{t}h\,(h \to b\bar{b})$, $h \to \gamma\gamma$, and on $H^\pm \to \tau\nu$.

Impact of SUSY particles

Preliminary studies in Minimal SUGRA

- SUSY loop can enhance/suppress Higgs productions
- $A/H/H^{\pm} \longrightarrow$ SUSY particles compete with $A/H/H^{\pm} \longrightarrow$ SM particles
- h can appear in cascade decays of SUSY particles: $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h\,(h \rightarrow b\bar{b})$

Impact on decays to SM particle is small:

- $gg \rightarrow h \rightarrow \gamma\gamma$ down by 10%, $t\bar{t}h$, $Wh\,(h \rightarrow \gamma\gamma)$ by 30%
- $t\bar{t}h$, $(h \rightarrow b\bar{b})$ not affected.
- Br $(A/H/H^{\pm} \rightarrow$ SM particles) down by 40% at most

Conclusions

- ATLAS and CMS will make substantial contributions to the search for the Higgs
- The SM Higgs can be discovered with 5σ after just 1 year at the LHC for $m_H < 150$ GeV. A Higgs with a higher mass can be discovered in less than 1 year. Discovery relies on $H \to \gamma\gamma$, $t\bar{t}H\,(\to b\bar{b})$, $H \to ZZ^* \to 4l$ and $H \to WW^* \to l\nu l\nu$.
- In MSSM, the $(m_A, \tan\beta)$ plane is fully covered at $\mathcal{L} = 30$ fb^{-1}. The main discovery channels are: $h \to \gamma\gamma$, $t\bar{t}h\,(h \to b\bar{b})$, $b\bar{b}h\,(h \to \mu\mu)$, $A/H \to \tau\tau$, $\mu\mu$ and $H^{\pm} \to \tau\nu$.