Prospects for Higgs Bosons Discovery at the LHC

Kétévi A. Assamagan

BNL, Department of Physics, Upton NY 11973 USA

LHC sensitivity to SM & MSSM Higgs Bosons

Montreal, December 12, 2002

- **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.**

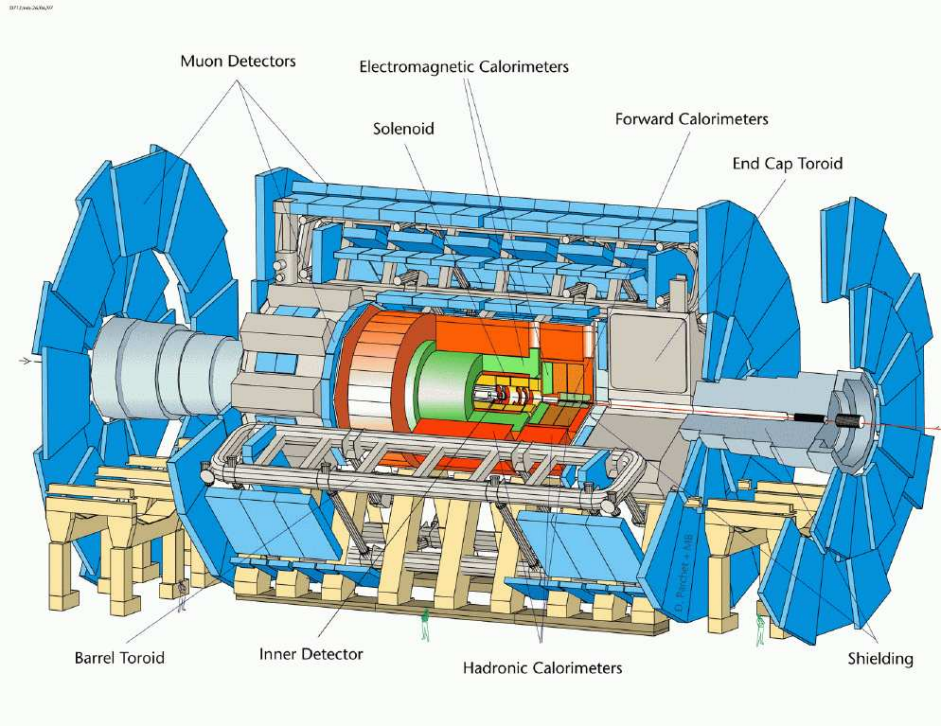
$\Longrightarrow$ high $\sqrt{s}$, $\mathcal{L}$, general-purpose detectors with excellent performance: ATLAS and CMS

Running Scenarios and Luminosities

- **Starting date: $\sim$ 2007**
- **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

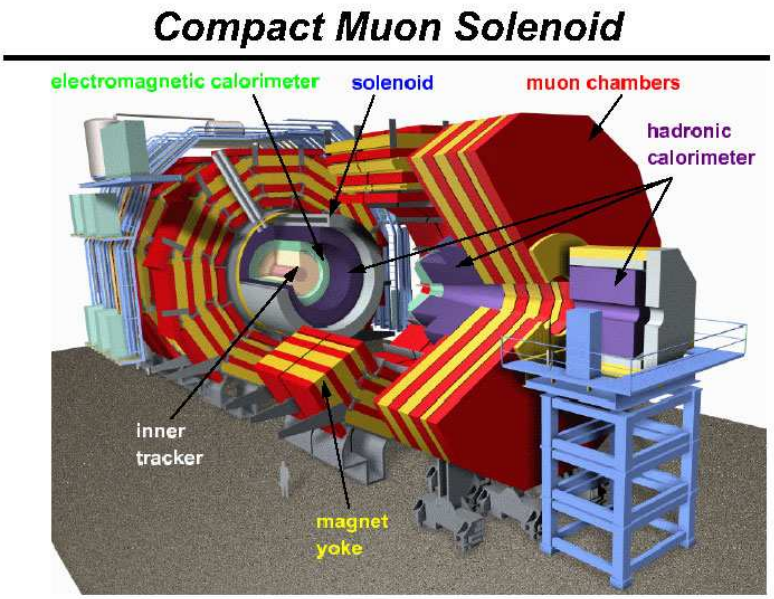
- **The Inner Detector: pixel detector, SCT Tracker, TRT $\Longrightarrow$ pattern recognition, momentum & vertex measurements, electron ID.**
- **The Calorimeter: LAr EM, Tile Hadronic, LAr Hadronic & Forward.**



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

The CMS Detector

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



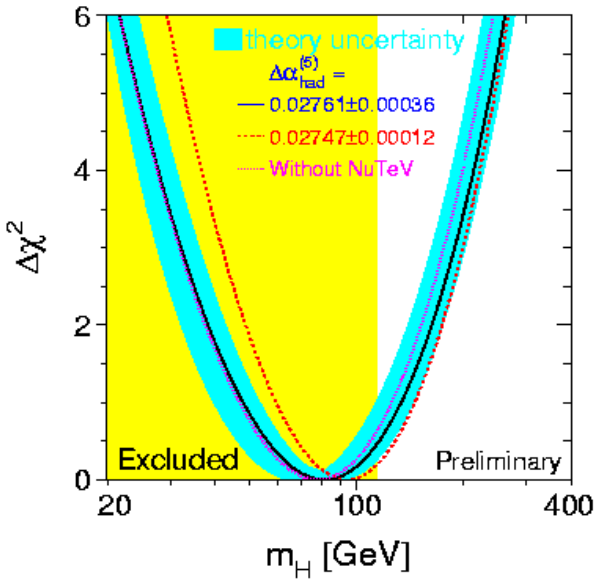
- The Muon Spectrometer: RPC, DT, CSC
- The Magnet: Super-conducting Solenoid 4T

The Standard Model Higgs

- **Higgs sector: one complex scalar doublet.**
- **Electroweak symmetry breaking $\Longrightarrow$ one physical scalar particle, the Higgs boson.**
- **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

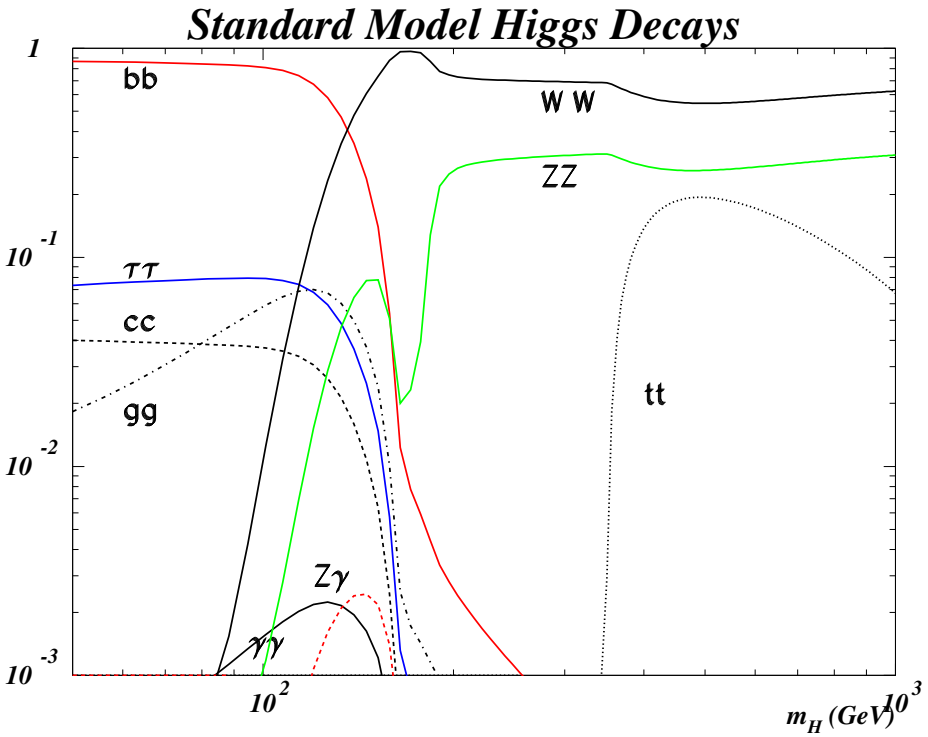
- **LEP:** $e^+e^- \rightarrow ZH$
  $m_H > 114.4$ **GeV.**
  Excess around $M_H \approx 115 - 118$ **GeV Higgs: 37% CL for S+B, 8% for B.**
- **Tevatron RUN I:** $q\bar{q} \rightarrow W(Z)H$, $H \rightarrow b\bar{b}$. **No signal found. Observed events consistent with expected background**
- **Global fit of precision electroweak data:**



$114.4 < m_H < 193$ **GeV @ 95% CL**

SM Higgs Searches at the LHC

The SM Higgs will be searched for in various decay channels



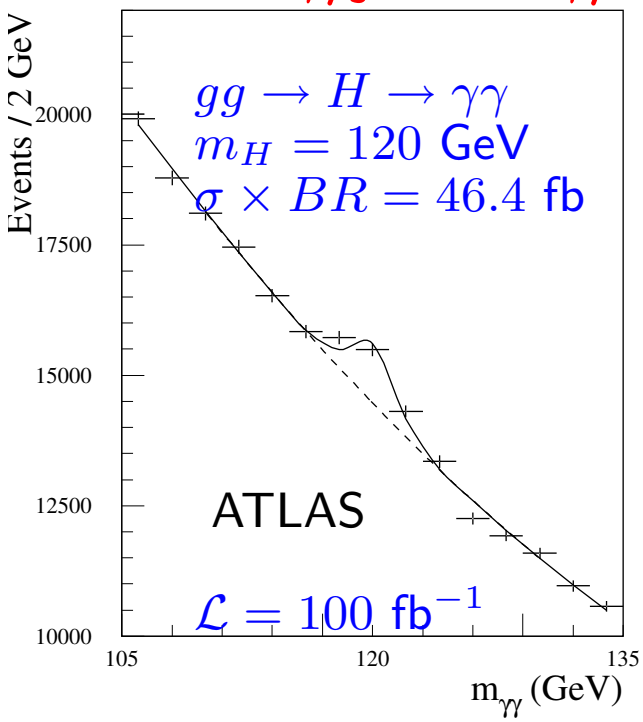
The most promising ones are:

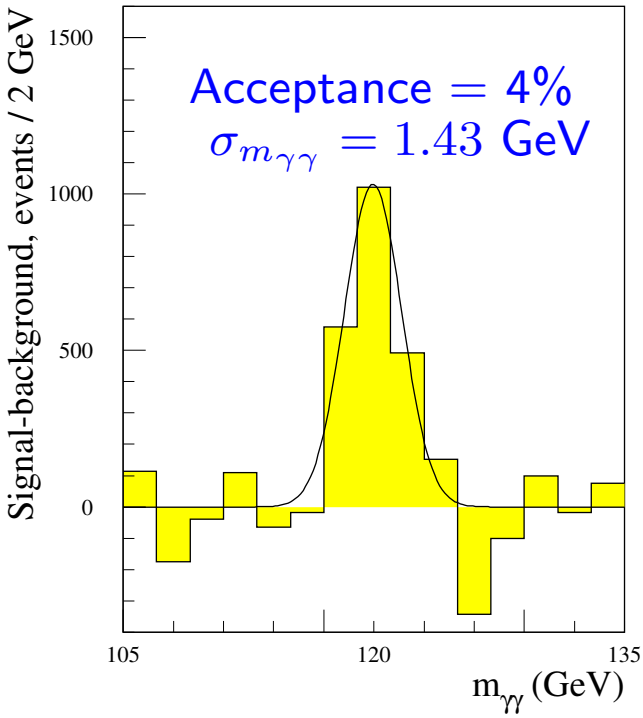
- $H \to \gamma\gamma$ and WH, $t\bar{t}H$ $(H \to \gamma\gamma)$
- $t\bar{t}H$ $(H \to b\bar{b})$
- $H \to ZZ^* \to 4l$
- $H \to WW^* \to l\nu l\nu$
- $H \to ZZ \to ll\nu\nu$
- $H \to WW \to l\nu jj$

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

- m_H(GeV) < 150, $\sigma \times BR = 50$ fb
- **Irreducible backgrounds:** $q\bar{q}\,(gg) \to \gamma\gamma$ **and** $qg \to q\gamma \to q\gamma\gamma$. $\sigma_{\gamma\gamma} \sim 2$ **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**

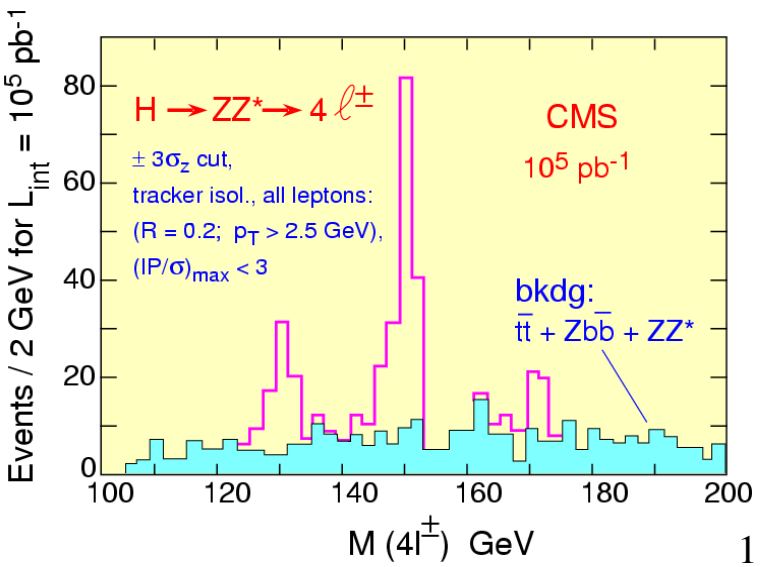




$\Longrightarrow$ **For** $\mathcal{L} = 30$ **fb**$^{-1}$, $110 < m_H < 140$ **GeV** $> 5\sigma$, **(ATLAS+CMS)!**

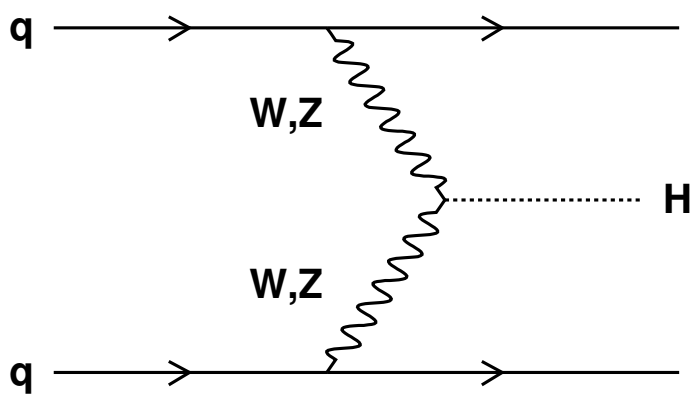
$H \to ZZ^* \to eeee,\ ee\mu\mu,\ \mu\mu\mu\mu$

- $\sim 120 < m_H(\text{GeV}) < 2m_Z$, $\sigma \times Br = 3$ 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 $b \to l + X \Longrightarrow t\bar{t} + Zb\bar{b} < 10\%$ of ZZ^*



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

Vector Boson Fusion

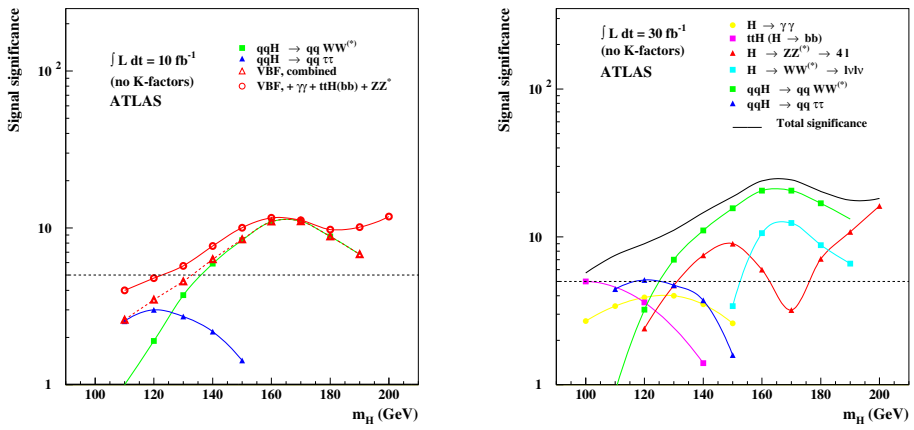


- Addition potential for Higgs discovery
- Measurements of Higgs couplings to bosons, fermions, and of the total widths
- Detection of Higgs decays to invisible
- Cross section $\sim$ 20% of the total: but distinctive features
  - Two high p_T jets in the forward region
  - Little jet activity in the central region

Vector Boson Fusion

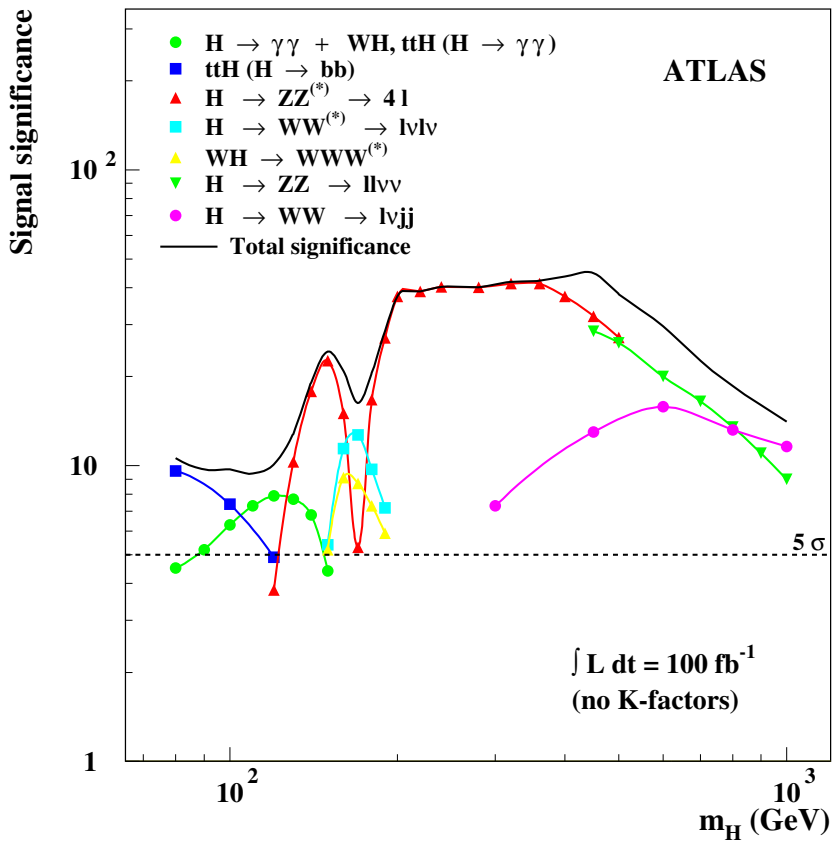
Channels studied so far:

- $qq' \longrightarrow qq'H\,(\longrightarrow WW^* \longrightarrow l\nu l\nu)$
- $qq' \longrightarrow qq'H\,(\longrightarrow \tau\tau)$



- **For 10^{-1} fb, $5\,\sigma$ for $120 < m_H < 190$ GeV**
- **In the low mass region, vector boson fusion channels improve sensitivity**

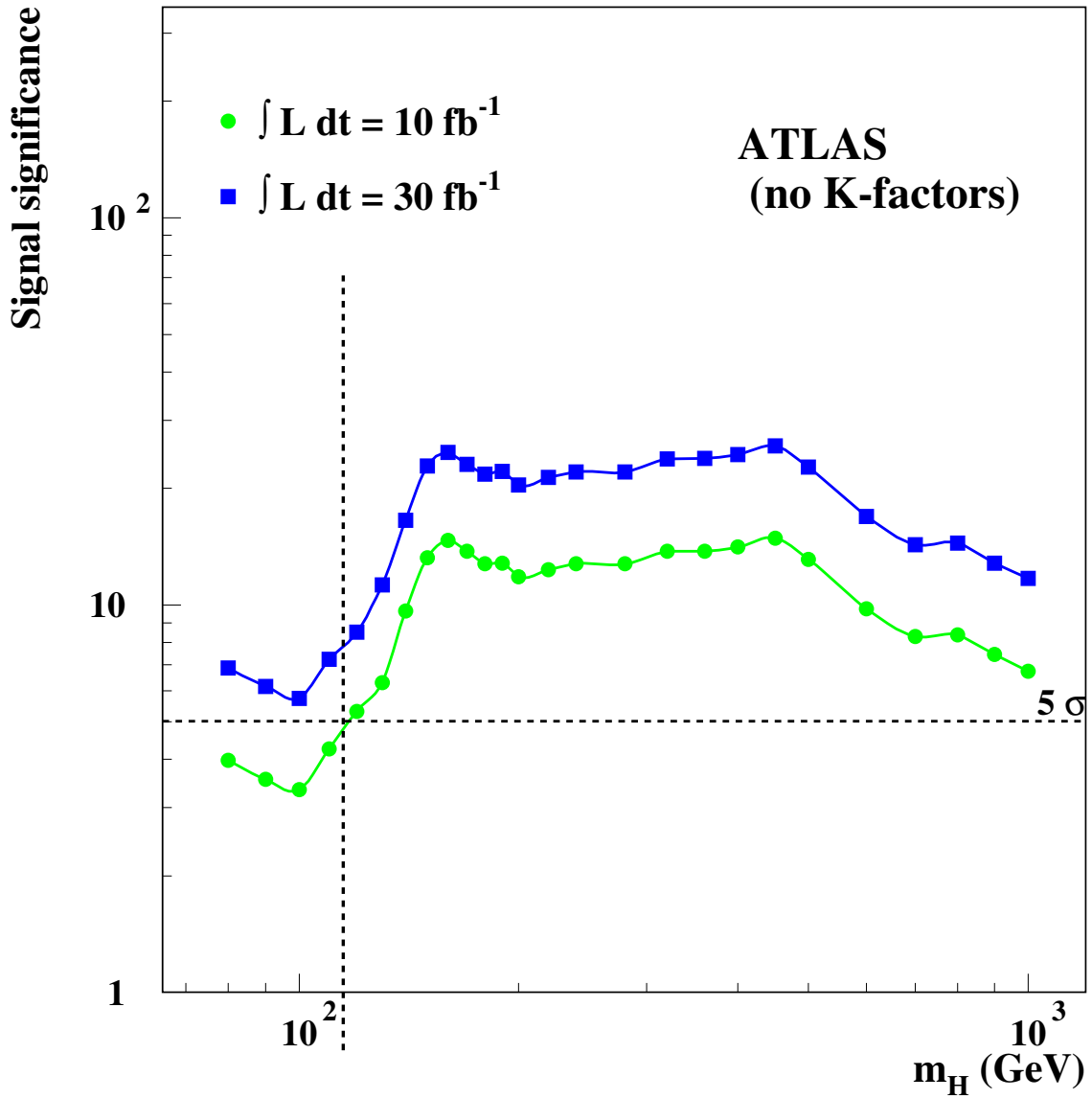
Sensitivity to SM Higgs Searches



- **Good sensitivity over the full mass range**
- **At least 2 discovery channels available over most of the mass range**

Sensitivity to SM Higgs Searches

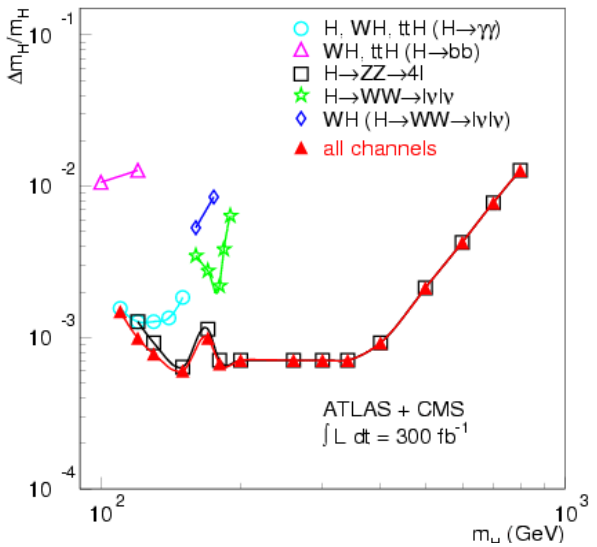
Combined Channels & Experiments

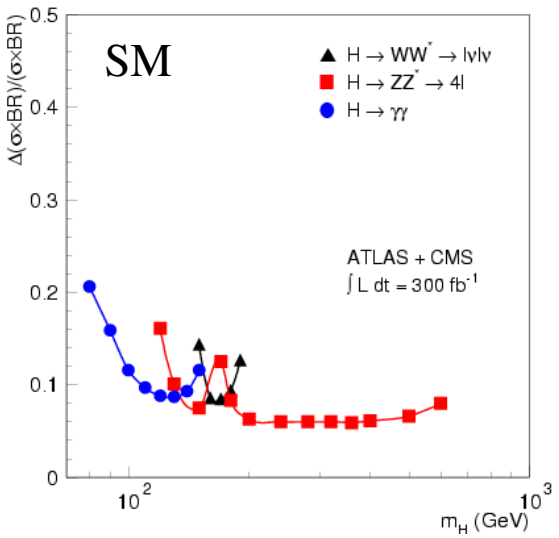


- **Faster discovery for higher masses**
- **Combined channels & experiments:**
  $S/\sqrt{B} > 5$ already for 10 fb^{-1}!

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 rate depends on $\Delta\mathcal{L}$ (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**

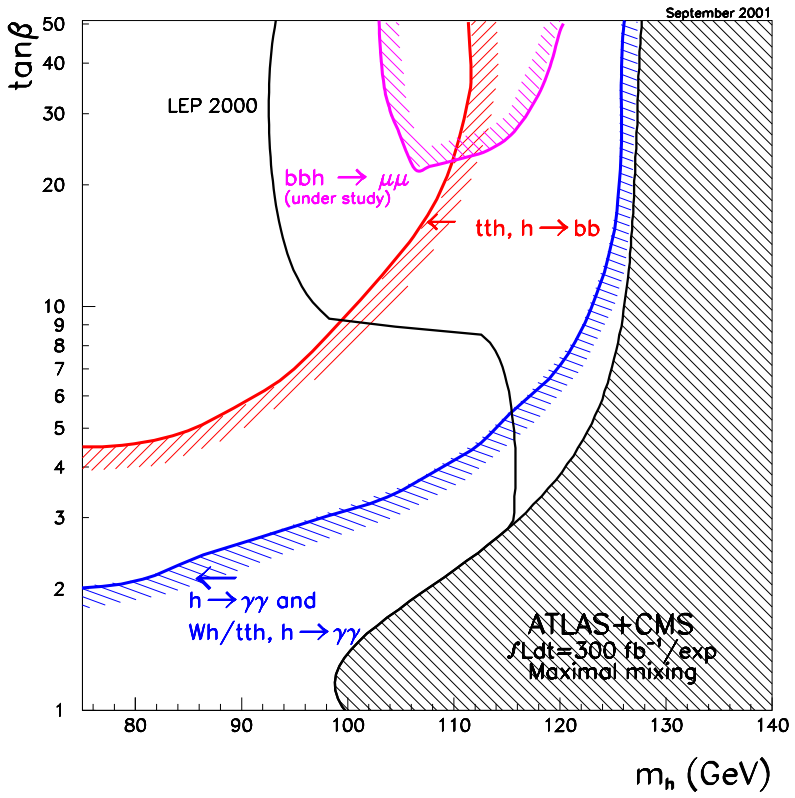
- **LEP: search for $e^+e^- \to H^+H^-$**

  $m_{H^\pm} > 78.6$ **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

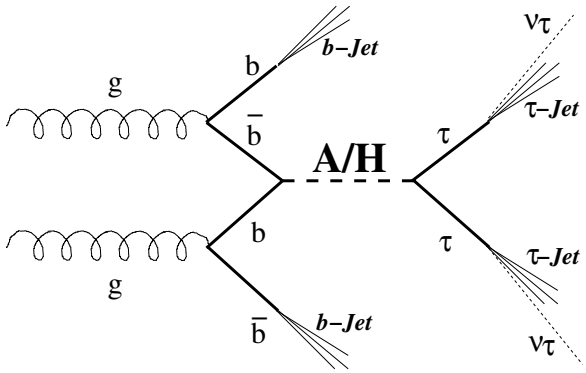
- In MSSM, $\sigma \times Br$ for $h \longrightarrow b\bar{b}$ and $h \longrightarrow \gamma\gamma$ suppressed compared to SM cases
- As $m_h \longrightarrow m_h^{max}$, enhancement by 10-20%
- Sensitivity to $t\bar{t}h$, Wh $(h \longrightarrow b\bar{b})$ and $h \longrightarrow \gamma\gamma$ computed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

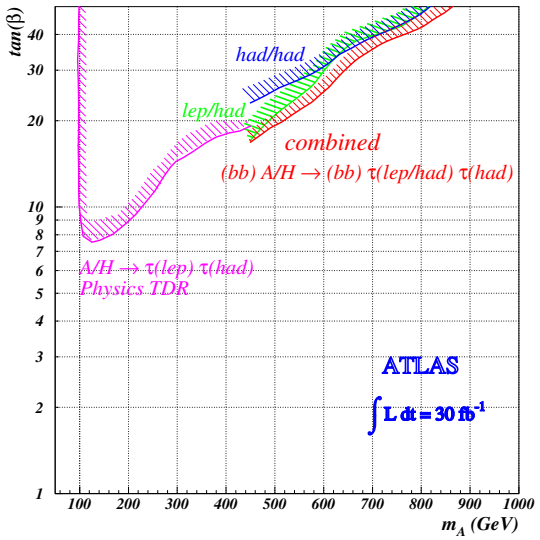


- $m_A < 100$ GeV: $h \longrightarrow \gamma\gamma$, $h \longrightarrow b\bar{b}$ suppressed. At high $\tan\beta b\bar{b}h$ $(h \longrightarrow \mu\mu)$ observable
- $m_A > 100$ GeV: $m_h \longrightarrow m_h^{max}$ of $\sim$ 130 GeV and h similar to SM Higgs $\Longrightarrow$ other channels to disentangle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



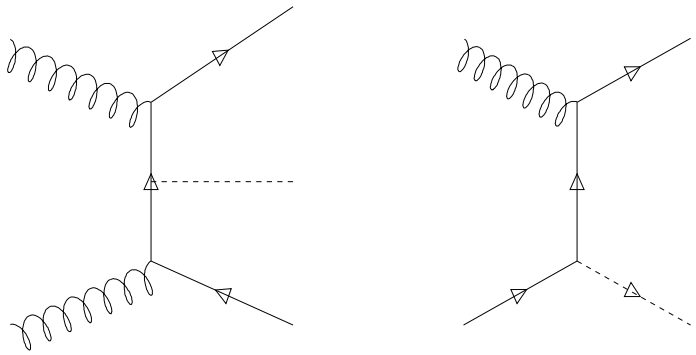


$\tan\beta > 7 \Longrightarrow A/H \to \tau\tau,\ \mu\mu$ observable and cover a large part of parameter space

$H^{\pm}$ 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

- $m_{H^{\pm}} < m_T$: $t \rightarrow bH^{\pm}$
- **In SUSY cascade decays:**

$$\begin{aligned} pp &\rightarrow \tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{q}\tilde{g} \\ &\rightarrow \chi_2^{\pm}, \chi_3^0, \chi_4^0 + X \\ &\rightarrow \chi_1^{\pm}, \chi_2^0, \chi_1^0 + H^{\pm} + X \end{aligned}$$

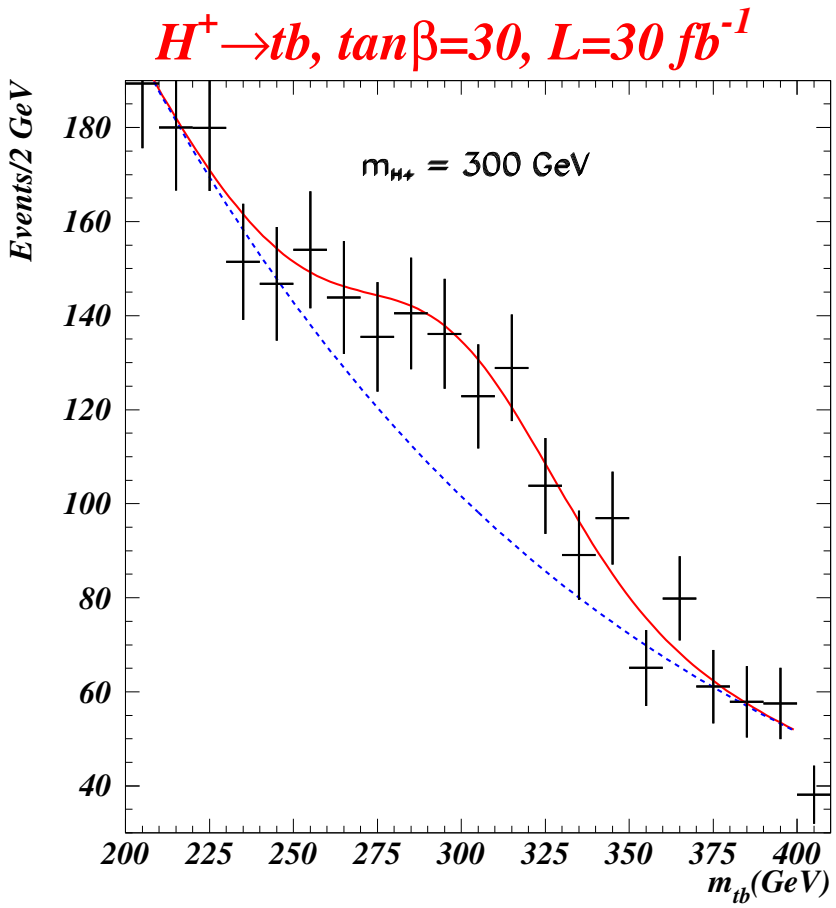
- **Other production mechanisms:**

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

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

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

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

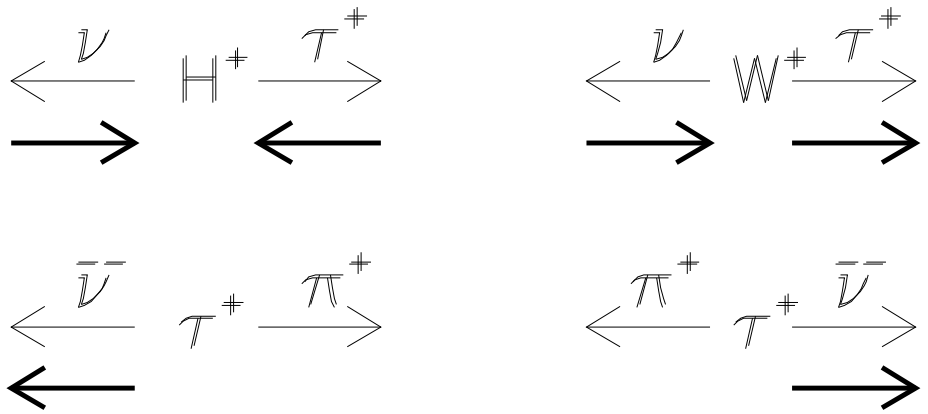


Discovery possible up to 450 GeV for $\tan\beta > 15$ & $\tan\beta < 3$

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

- **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**

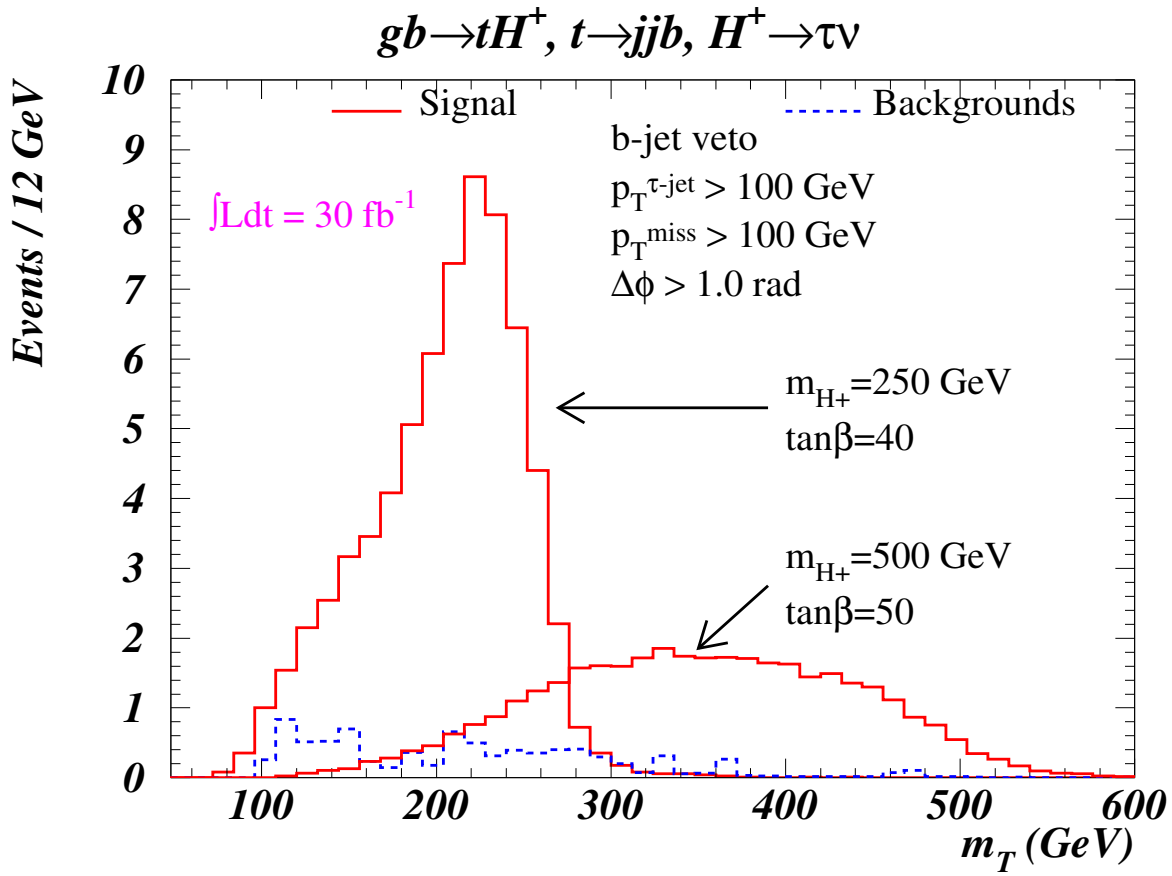
  with one $W \to \tau\nu$ and the other $W \to jj$
- **τ polarization effect: For 1-prong decays,**



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

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

- 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 $\sim$ 600 GeV, $\tan\beta > 10$!

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

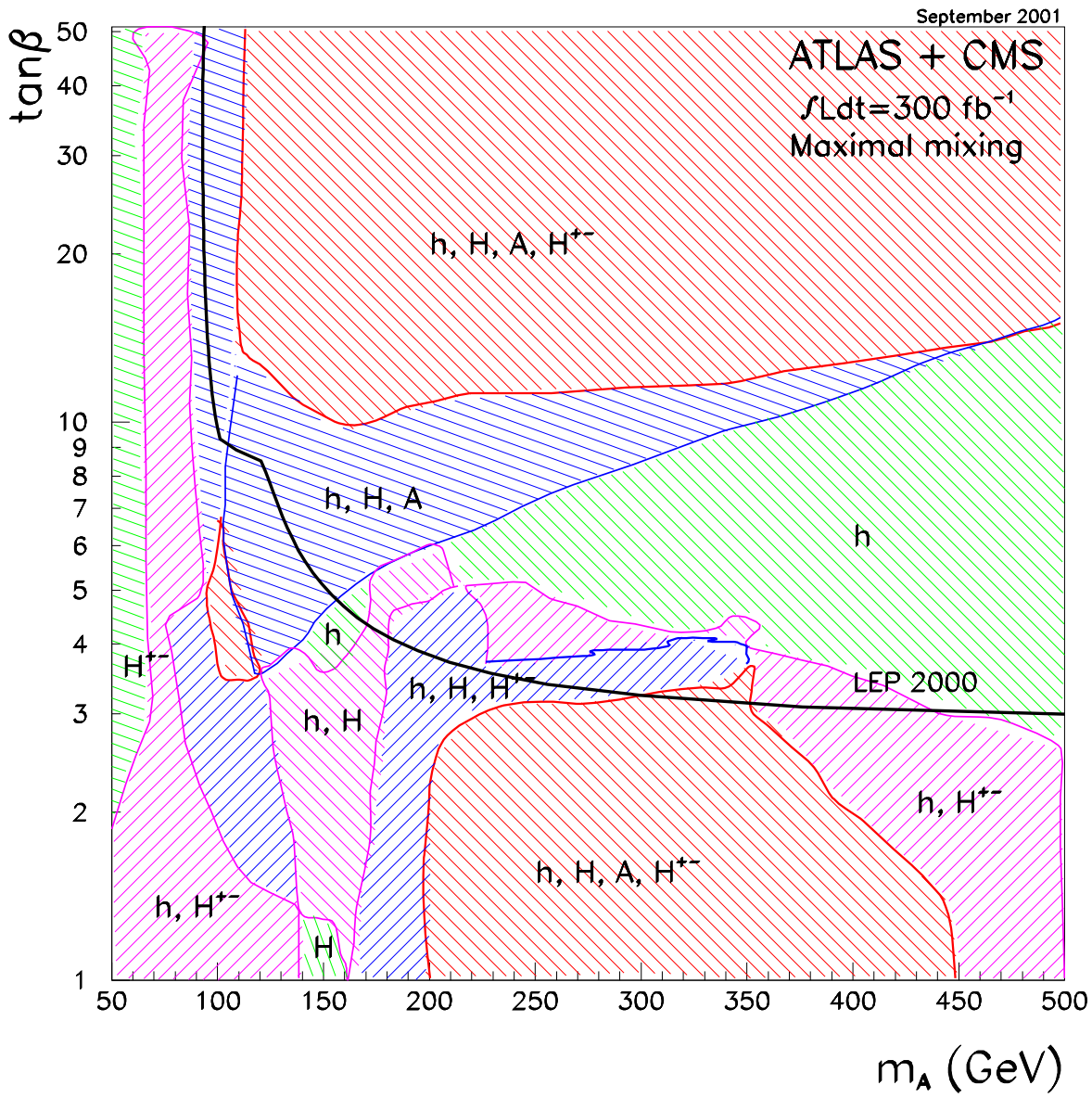
As a result

- $m_{H^{\pm}}$ 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

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

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 $H^{\pm} \to \tau\nu$.**

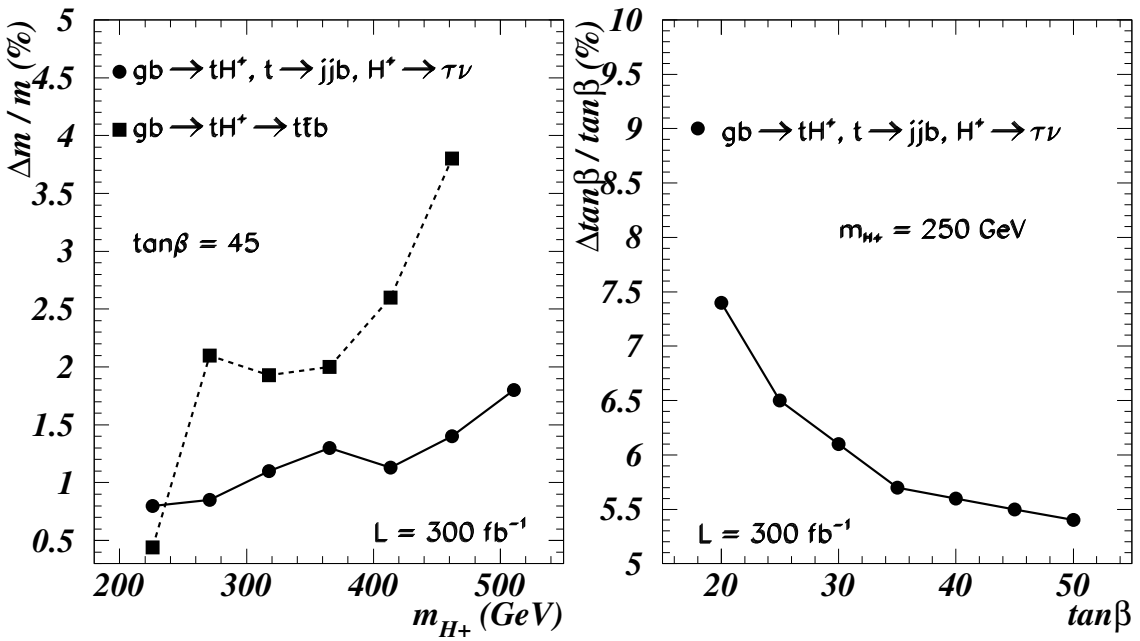
Prospects for $m_{H^\pm}$ Determination

ATL-PHYS-2001-017

- Determination of $m_{H^\pm}$ using $H^\pm \longrightarrow tb$. Two different methods used:
  - Maximum likelihood
  - Fit signal + background
- Determination of $m_{H^\pm}$ using $H^\pm \longrightarrow \tau\nu$:
  - Maximum likelihood only: shape of the background not known well enough

Prospects for $m_{H^\pm}$, $\tan\beta$ Determination

Overall expected precisions on $m_{H^\pm}$ and $\tan\beta$ determination for $\mathcal{L} = 300$ fb^{-1}



- Better precisions on $m_{H^\pm}$ in $H^\pm \to \tau\nu_\tau$ compared to $H^\pm \to tb$ except at low Higgs masses
- Precision on $\tan\beta$ improves as the rate of $H^\pm \to \tau^\pm\nu_\tau$ increases with $\tan\beta$

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: $\tilde{\chi}_2^0 \longrightarrow \tilde{\chi}_1^0 h\,(h \longrightarrow b\bar{b})$

Impact on decays to SM particle is small:

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

$H^{\pm} \to \tau\nu$ in Large Extra Dimensions

- In the 2HDM-II,

$$\mathbf{H^- \to \tau_R^- \bar{\nu}} \text{ or } \mathbf{H^+ \to \tau_L^+ \nu}$$

H^- to τ_L^- (or H^+ to τ_R^+) suppressed

- In Large Extra Dimensions, $H^- \to \tau_L^- \psi$ can be enhanced by large number of KK states. Thus,

$$\mathbf{H^- \to \tau_R^- \bar{\nu} + \tau_L^- \psi}$$

with an asymmetry

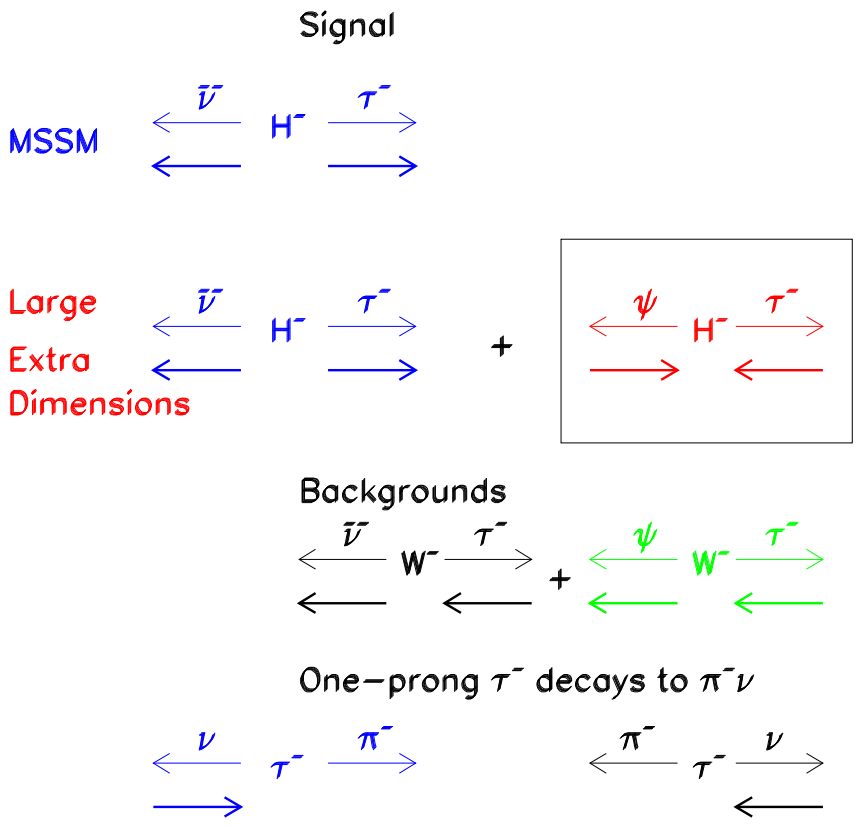
$$\mathbf{A = \frac{\Gamma(H^- \to \tau_L^- \psi) - \Gamma(H^- \to \tau_R^- \bar{\nu})}{\Gamma(H^- \to \tau_L^- \psi) + \Gamma(H^- \to \tau_R^- \bar{\nu})}}$$

- Can $H^- \to \tau_L^- \psi$ be observed at the LHC?
- If yes, can it be used to distinguish between 2HDM and Large Extra Dimensions?

$H^{\pm} \longrightarrow \tau\nu$ in Large Extra Dimensions

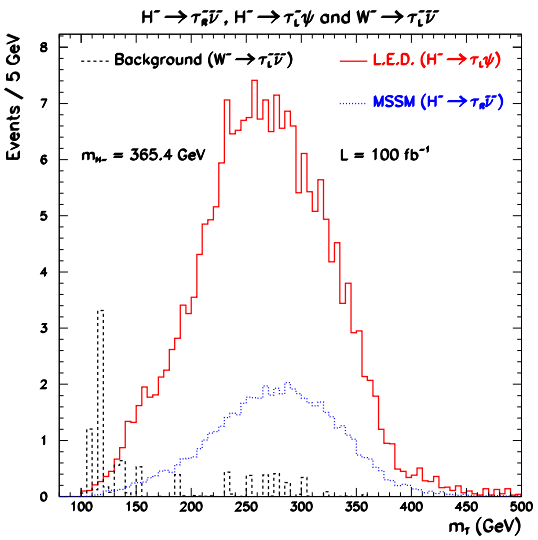
- **No additional Higgs boson:** $gb \longrightarrow tH^{\pm}$
- **Consider 1-prong hadronic τ decays:**

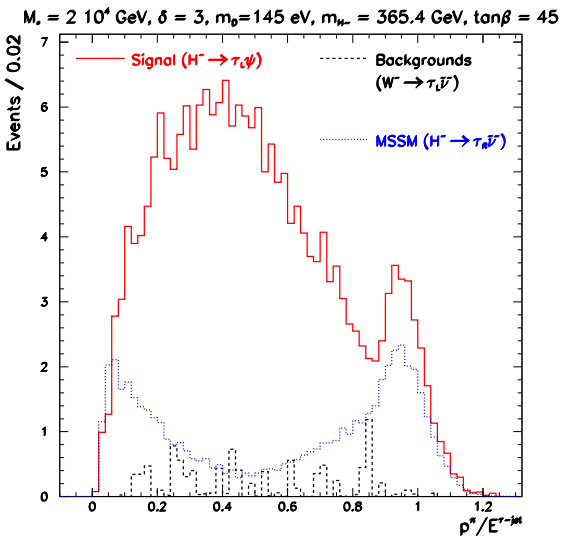
$$\tau^{\pm} \longrightarrow \quad \pi^{\pm}\nu_{\tau} \qquad (11.1\%)$$
$$\tau^{\pm} \longrightarrow \quad \rho^{\pm}(\longrightarrow \pi^{\pm}\pi^{0})\ \nu_{\tau} \qquad (25.2\%)$$
$$\tau^{\pm} \longrightarrow \quad a_1^{\pm}(\longrightarrow \pi^{\pm}\pi^{0}\pi^{0})\ \nu_{\tau} \qquad (9.0\%)$$



$\Rightarrow$ **τ polarization can help distinguish between 2HDM and Large Extra Dimensions**

$H^{\pm} \to \tau\nu$ in Large Extra Dimensions





- **The observation of a signal in m_T distribution insufficient to distinguish between 2HDM (MSSM) and Large Extra Dimensions**
- **In addition, the reconstruction of the fraction of energy carried by the charged track in 1-prong hadronic τ may provide a signature for Large Extra Dimensions**

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 $H \longrightarrow \gamma\gamma$, $t\bar{t}H\,(\longrightarrow b\bar{b})$, $H \longrightarrow ZZ^* \longrightarrow 4l$ and $H \longrightarrow WW^* \longrightarrow l\nu l\nu$.
- In MSSM, the $(m_A, \tan\beta)$ plane is fully covered at $\mathcal{L} = 30$ fb^{-1}. The main discovery channels are: $h \longrightarrow \gamma\gamma$, $t\bar{t}h\,(h \longrightarrow b\bar{b})$, $b\bar{b}h\,(h \longrightarrow \mu\mu)$, $A/H \longrightarrow \tau\tau$, $\mu\mu$ and $H^{\pm} \longrightarrow \tau\nu$.
- Evidence for large extra dimensions can be inferred from $H^{\pm} \longrightarrow \tau^{\pm}\nu$ by reconstructing:
  - the transverse mass
  - the energy of the charged track in 1-prong hadronic τ decays