Discovery Potential for MSSM Higgs Bosons with the ATLAS Experiment at the LHC

Trevor Vickey

University of Wisconsin, Madison
On behalf of the ATLAS Collaboration

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Introduction

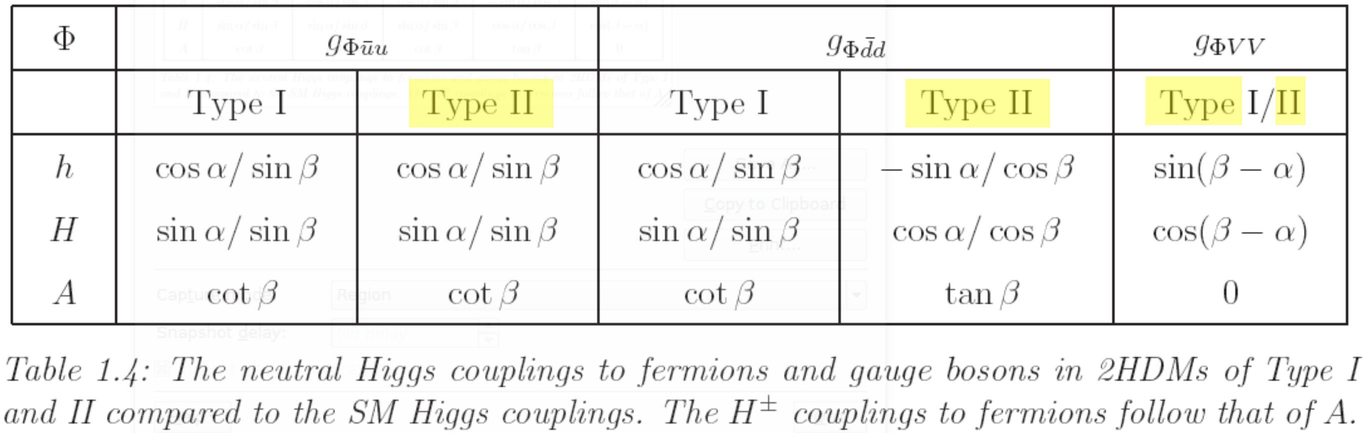
Higgs Sector in the Minimal Supersymmetric Standard Model (MSSM)

- **Two Higgs Doublets → Five physical bosons: A (CP-odd), h, H (CP-even) and $H^\pm$**
- **At tree-level, the masses of the 5 Higgs bosons are related:**

$$m_{H,h}^2 = \frac{1}{2}\left[m_A^2 + m_Z^2 \pm \sqrt{(m_A^2 + m_Z^2)^2 - 4m_A^2 m_Z^2 \cos^2 2\beta}\right],$$

$$m_{H^\pm}^2 = m_W^2 + m_A^2,$$

- **Branching ratios to down-type quarks and charged leptons are enhanced:**



Φ	$g_{\Phi\bar{u}u}$		$g_{\Phi\bar{d}d}$		$g_{\Phi VV}$
	Type I	Type II	Type I	Type II	Type I/II
h	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\beta-\alpha)$
H	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\beta-\alpha)$
A	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\tan\beta$	0

Table 1.4: The neutral Higgs couplings to fermions and gauge bosons in 2HDMs of Type I and II compared to the SM Higgs couplings. The $H^\pm$ couplings to fermions follow that of A.

A. Djouadi, hep-ph/0503173v2

$$\alpha = \frac{1}{2}\arctan\left(\tan 2\beta\,\frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2}\right), \quad -\frac{\pi}{2} \le \alpha \le 0$$

$$\tan\beta = \frac{v_2}{v_1} = \frac{(v\sin\beta)}{(v\cos\beta)}$$

Large loop corrections to masses and couplings depend on SUSY parameters:

- **Largely dependent on the top / stop sector**

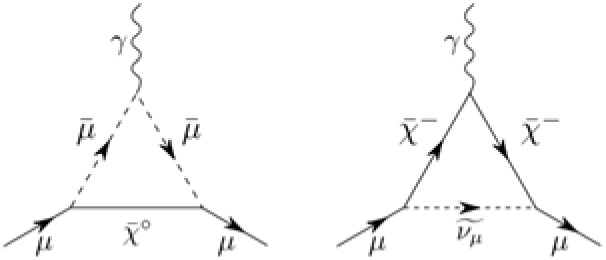
“m_h-max” scenario

- **X_t = 2 TeV, M_{SUSY} = 1 TeV, M_2 = 200 GeV, μ = 200 GeV and M_{gluino} = 800 GeV**

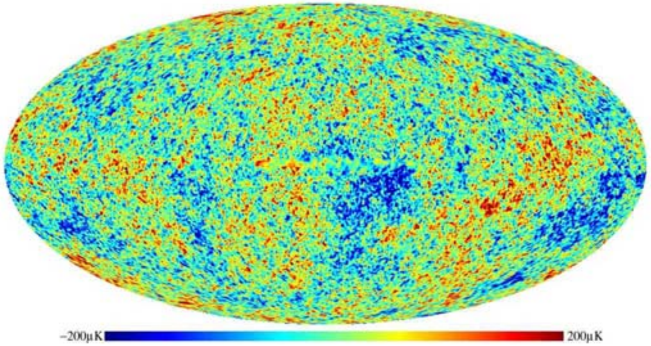
Discovery Potential and Exclusion Bounds

- **Scan the m_A – tanβ plane [CERN-OPEN-2008-020; arXiv:0901.0512]**

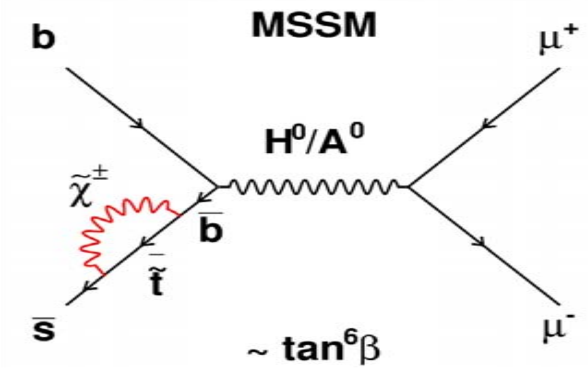
Indirect Constraints from Experiment



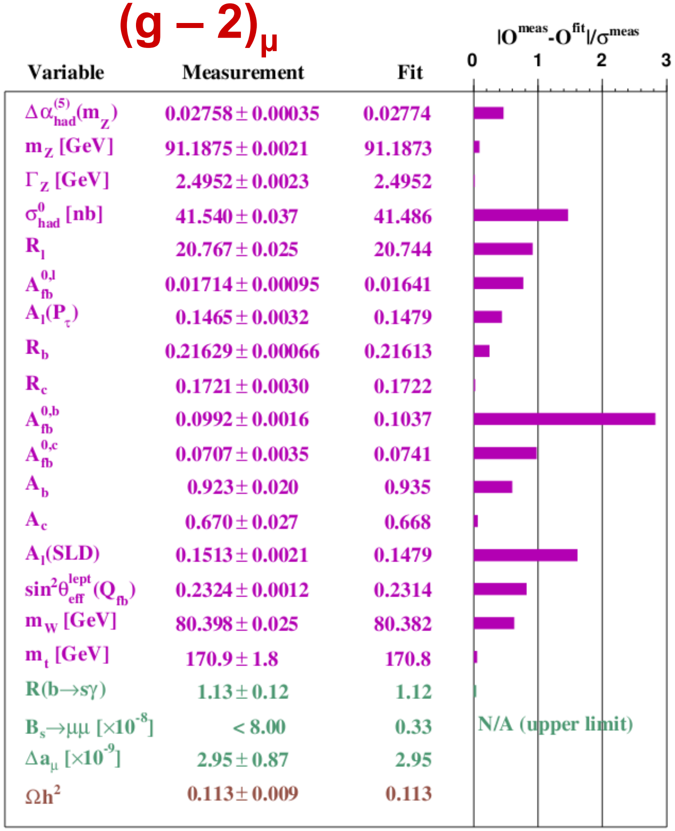
$(g-2)_\mu$



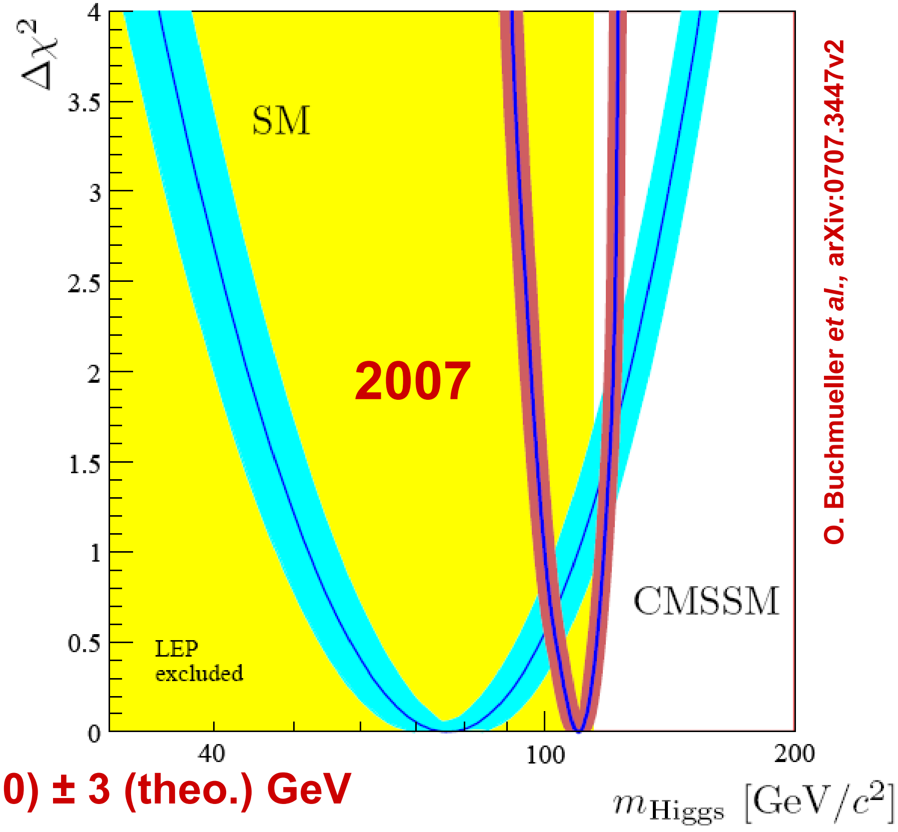
WMAP



$BR(B_s \to \mu^+\mu^-)$



Variable	Measurement	Fit	$\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02774	
m_Z [GeV]	91.1875 ± 0.0021	91.1873	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4952	
σ^0_{had} [nb]	41.540 ± 0.037	41.486	
R_l	20.767 ± 0.025	20.744	
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01641	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479	
R_b	0.21629 ± 0.00066	0.21613	
R_c	0.1721 ± 0.0030	0.1722	
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037	
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0741	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1479	
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.398 ± 0.025	80.382	
m_t [GeV]	170.9 ± 1.8	170.8	
$R(b\to s\gamma)$	1.13 ± 0.12	1.12	
$B_s\to\mu\mu$ [$\times10^{-8}$]	< 8.00	0.33	N/A (upper limit)
Δa_μ [$\times10^{-9}$]	2.95 ± 0.87	2.95	
Ωh^2	0.113 ± 0.009	0.113	



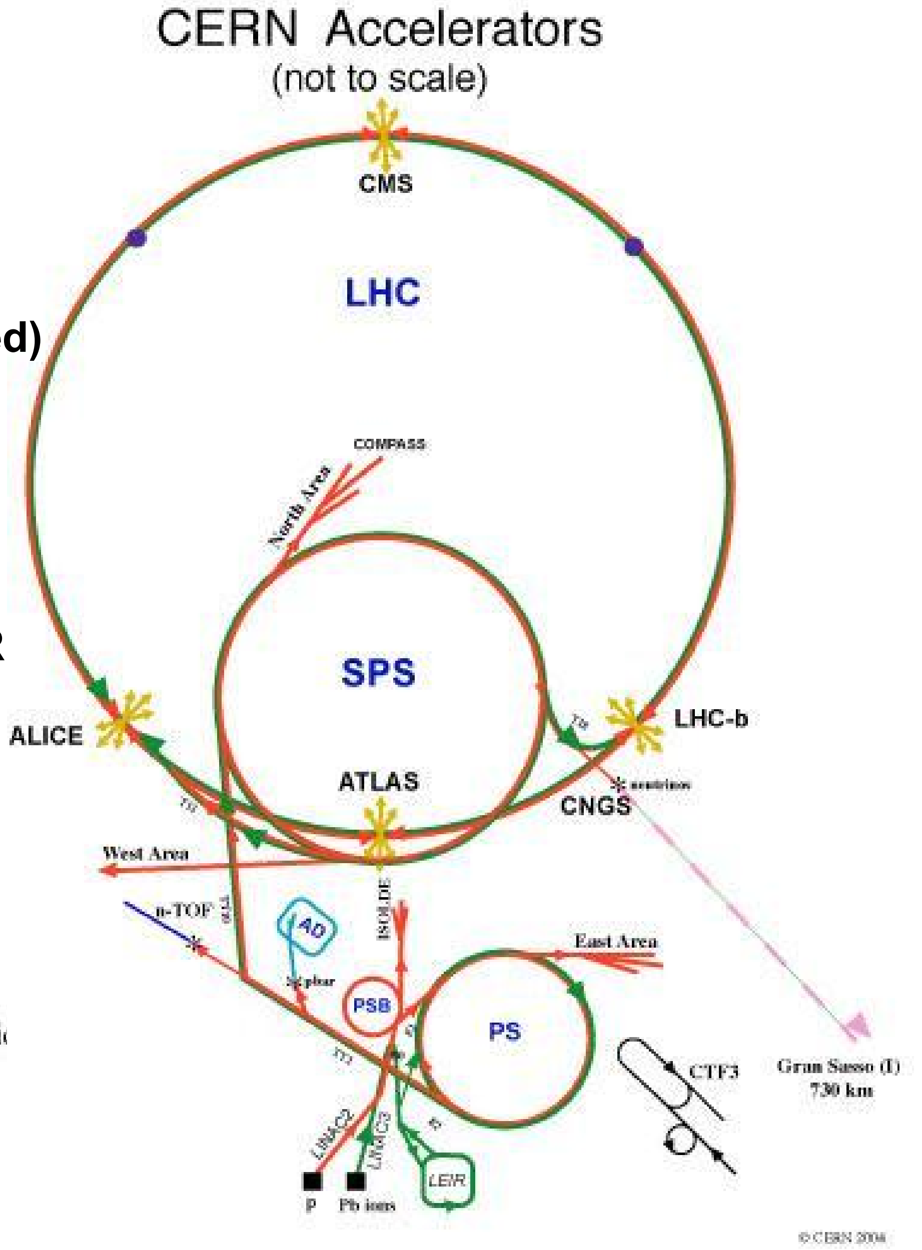
O. Buchmueller *et al.*, arXiv:0707.3447v2

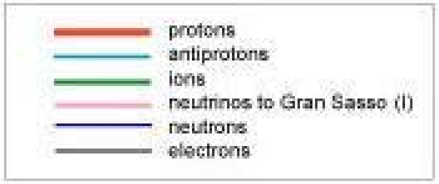
m_h = 110 (+8)(-10) ± 3 (theo.) GeV

The Large Hadron Collider

Particle accelerator located at CERN (Geneva, Switzerland)

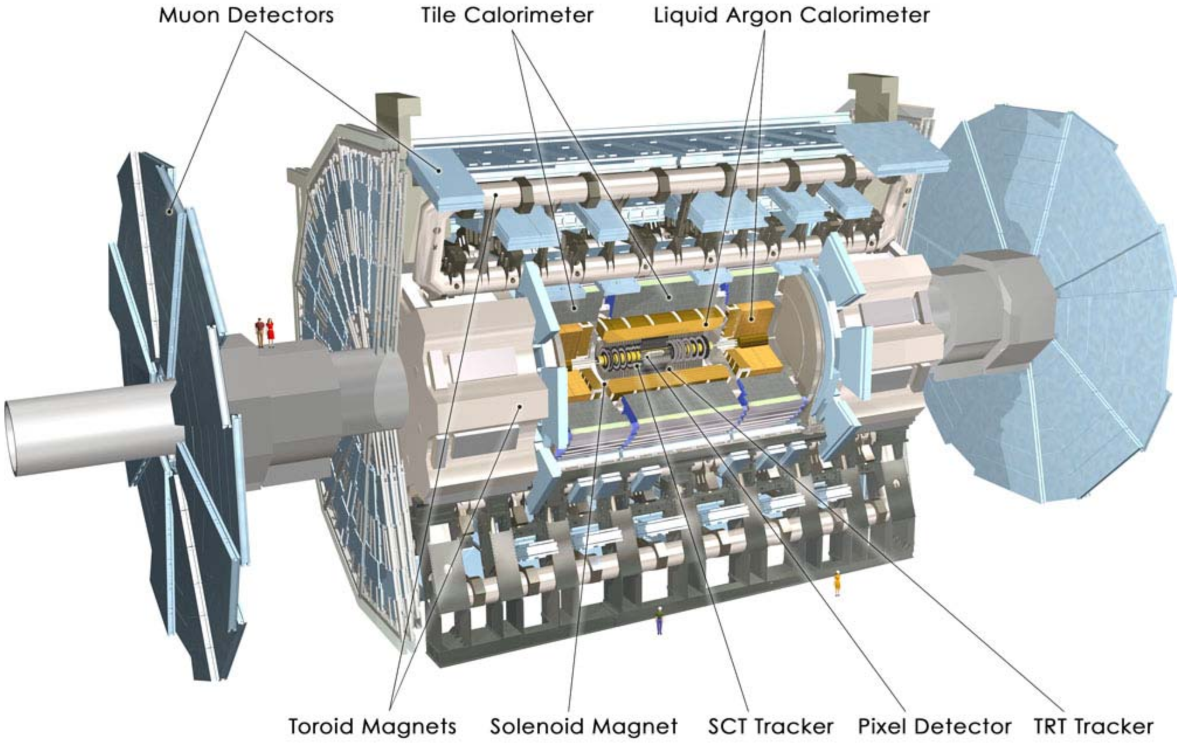
- **Collide protons at a 14 TeV CME**
- **Housed in the former LEP tunnel**
- **Dipole field at 7 TeV is 8.33 T**
- **~350 MJ per beam!**
- **Ultimately ~2800 bunches**
- **Vacuum 10^{-13} atm (~6500 m^3 pumped)**
- **1232 Dipoles (operate at 1.9 K)**
- **858 Quadrupoles**
- **Typical store lasts ~10 hours**
- **Can be used for ion collisions (Pb)**
- **Final price tag estimated at 4G EUR**





LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvi
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso

The ATLAS Experiment



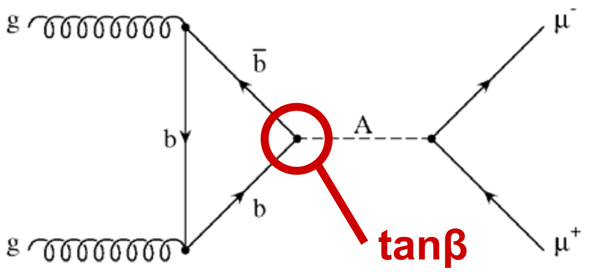
	ATLAS
Weight	7000 tons
Diameter	22m
Length	46m
Peak B Field	2T solenoid 3.9T (peak) BA toroid 4.1T (peak) EC toroids

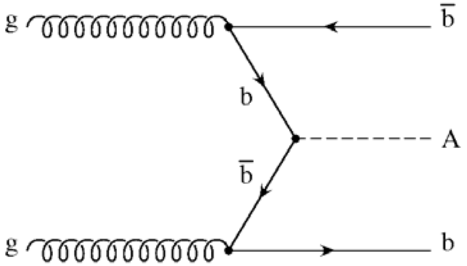
PERFORMANCE		
Tracker	Si pixels, strips + TRT (pid)	$\sigma/p_T \approx 5x10^{-4}p_T \oplus 0.01$
EM calorimeter	Pb + LAr	$\sigma/E \approx 10\%/\sqrt{E} \oplus 0.007$
Hadronic calorimeter	Fe+scintillator / Cu + LAr	$\sigma/E \approx 50\%/\sqrt{E} \oplus 0.03$
Combined Muons (ID+MS)	2%@50GeV to	10%@1TeV

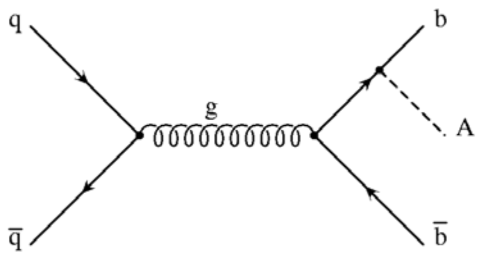
Neutral MSSM Higgs Discovery Potential

Neutral MSSM Higgs

Direct and Associated Production of the h, H and A







Enhanced for large tanβ

Investigated the decay channels (14 TeV)

- h/A/H → tau tau → 2l 4nu
- h/A/H → mu mu
- Other final states (di-tau lepton-hadron and fully hadronic) are still under study
- Early running and low-luminosity scenarios for the above channels are also being considered (should have some preliminary results soon)

Neutral Higgs mass degeneracy

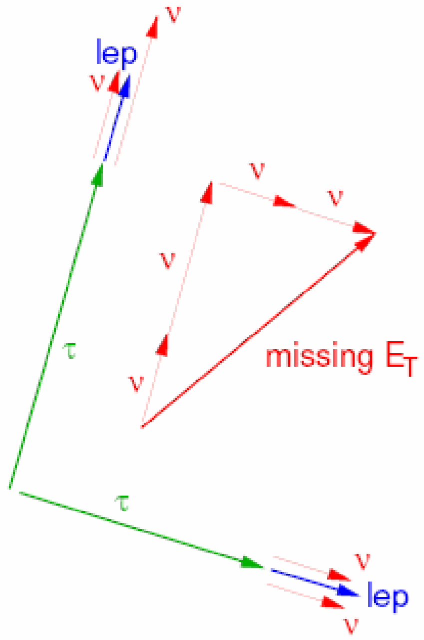
- For much of the parameter space the neutral Higgs masses are degenerate
- Cross-sections are summed

MSSM Higgs Di-Tau Analysis

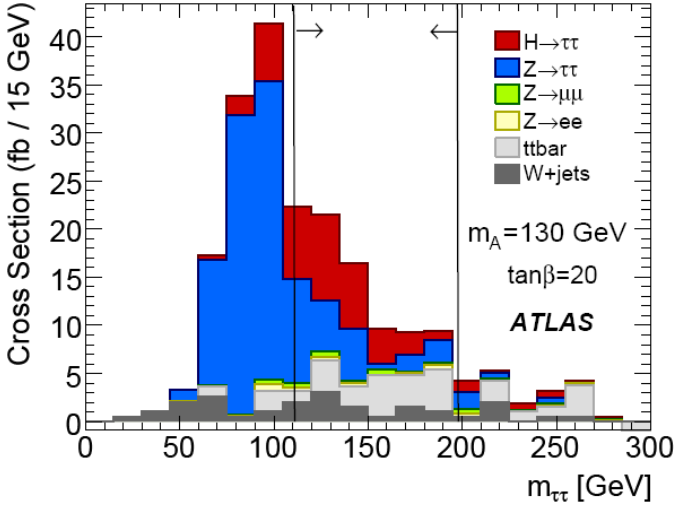
Branching-Ratio to taus is enhanced in the MSSM

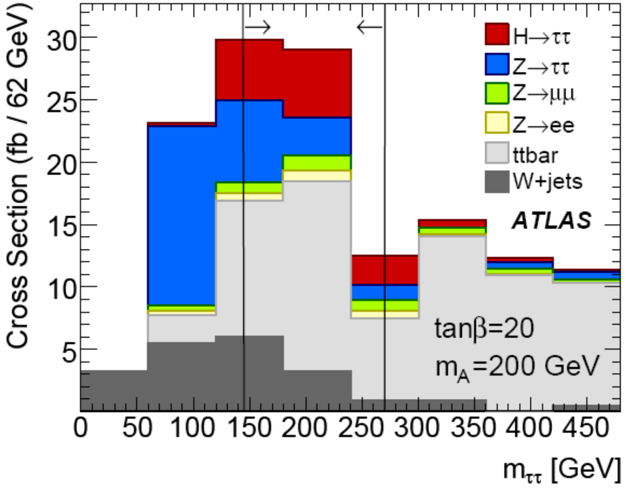
- **Investigated h/A/H → tau tau → 2l 4nu with associated b-jets**
- **High-pT electron or muon triggers**
- **Imposed lepton kinematic requirements**
- **Required at least one b-jet to be present in the event**
- **Expect a large amount of missing transverse energy**

Mass reconstruction is done via the collinear approximation



$$m_{\tau\tau} = \frac{m_{ll}}{\sqrt{x_1 x_2}} \qquad x_i = \frac{p_{T,li}}{p_{T,\tau i}}$$

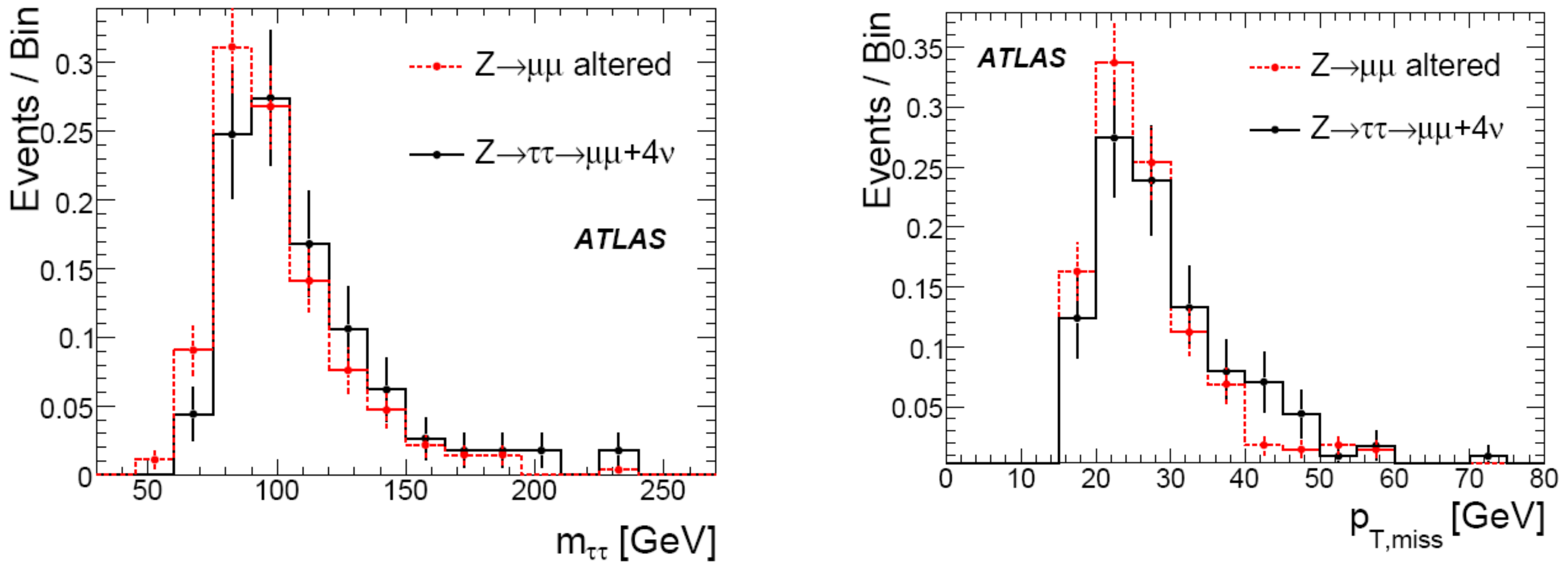




Backgrounds to the Di-Tau Analysis

For mA < 200 GeV, dominant background is Z + jets with Z → tau tau

- **This is an irreducible background**
- **The shape and normalization can be taken from data-driven control samples**
- **Scale the energy of the Z → mu mu events collected in collision data to match that expected from Z → tau tau**



For mA ≥ 200 GeV, ttbar events become a significant background

- **Can get a handle on this by cutting on the jet multiplicity ($N_{jets} \leq 2$)**

Di-Tau Analysis Potential

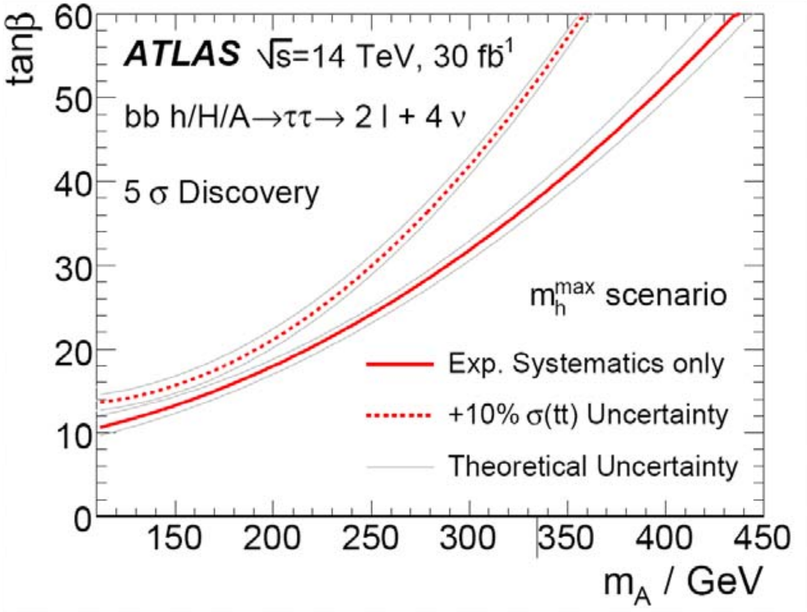
The high tanβ, low m_A region is well covered with 30 fb^{-1}

- **Counting experiment with multiple mass windows**

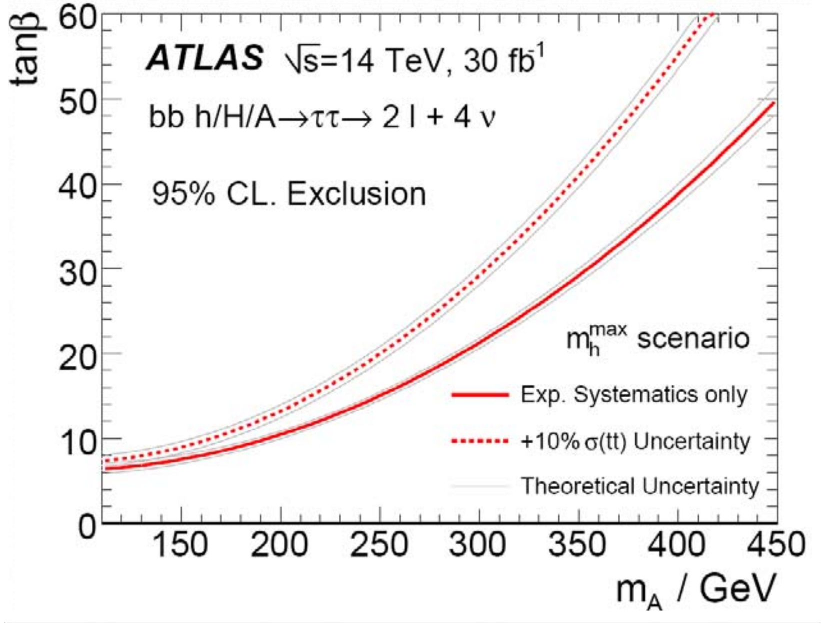
Dominant systematic uncertainties

- **Jet resolution and energy scale**
- **b-jet identification**

5σ Discovery



95% C.L. Exclusion



MSSM Higgs Di-Muon Analysis

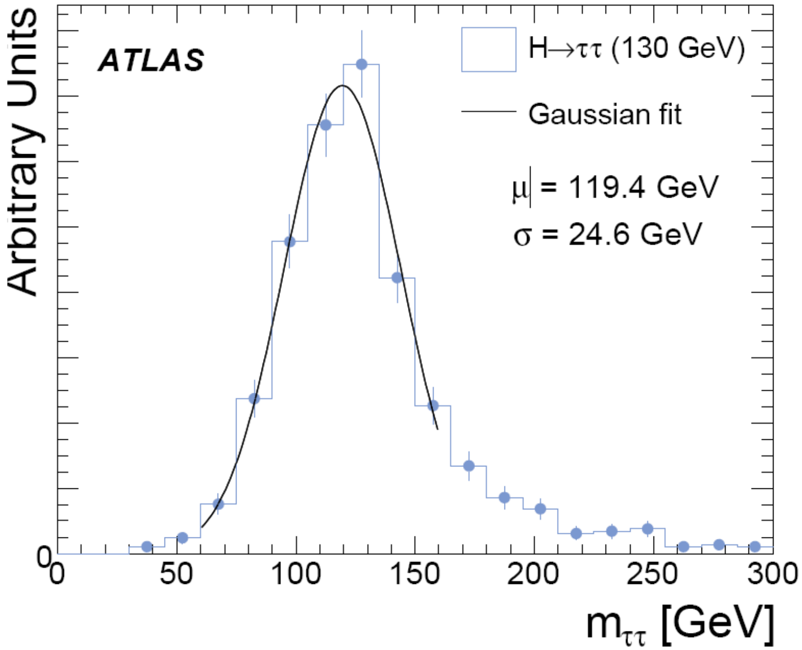
Some advantages

- **Cleaner signal than the di-tau analysis**
- **Excellent mass resolution (~3% versus ~20% for the di-tau)**

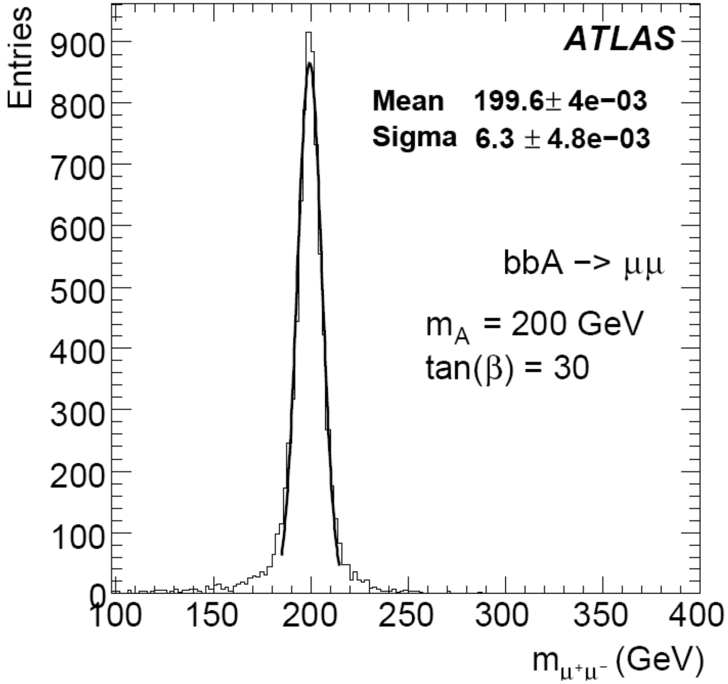
Disadvantage

- **h/A/H di-muon ranching ratio is ~300% smaller than that of the di-tau**

MSSM h/A/H→tau tau mass (collinear)



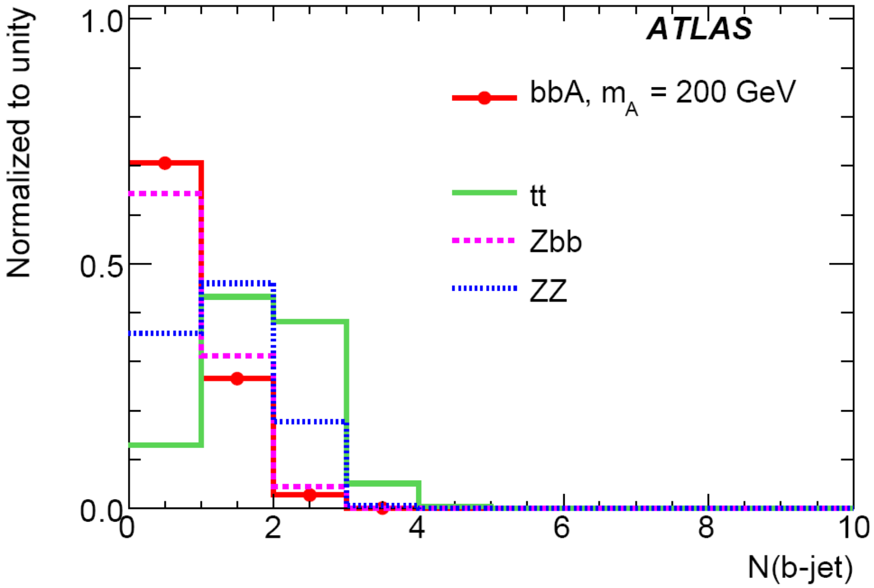
MSSM h/A/H→μμ mass



MSSM Higgs Di-Muon Analysis

Divide the analysis into two uncorrelated channels

- **0 b-jets channel (to suppress the ttbar background)**
- **≥1 b-jets channel (suppress the Z background; impose additional cuts to reduce ttbar)''**



Data-driven background estimation

- **For higher masses the tail of the Z resonance provides a large irreducible background, sensitive to detector systematic effects**
- **BR(h/A/H→ee) ~0**
- **BR(Z→μμ) = BR(Z→ee), so use Z→ee events from data as a control sample**

Di-Muon Analysis Potential

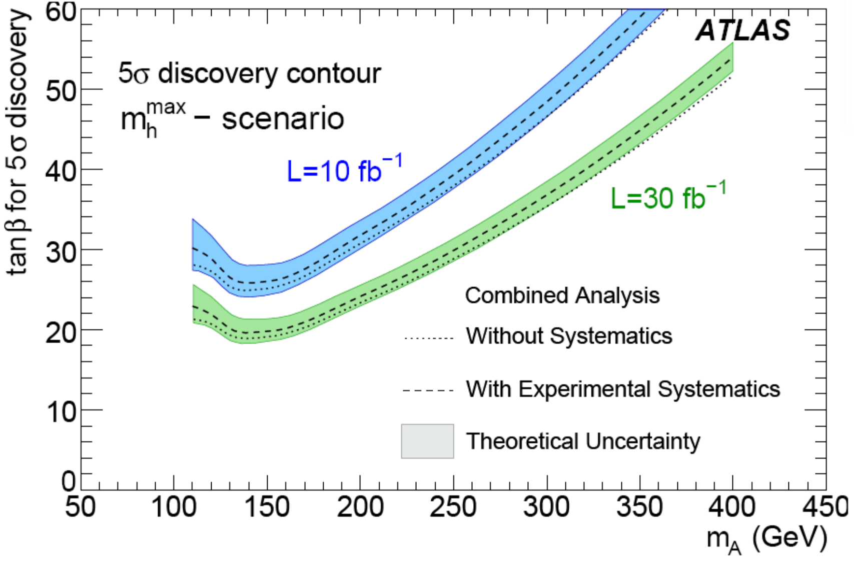
Less coverage than the di-tau analysis

- **But the two analyses could be combined to increase the sensitivity**

Systematic uncertainties

- **Around 5 – 10% for the signal processes**
- **Predominantly from the jet energy scale and b-jet identification**
- **Systematic uncertainties degrade the signal significance by up to 20% at large values of tanβ**

5σ Discovery



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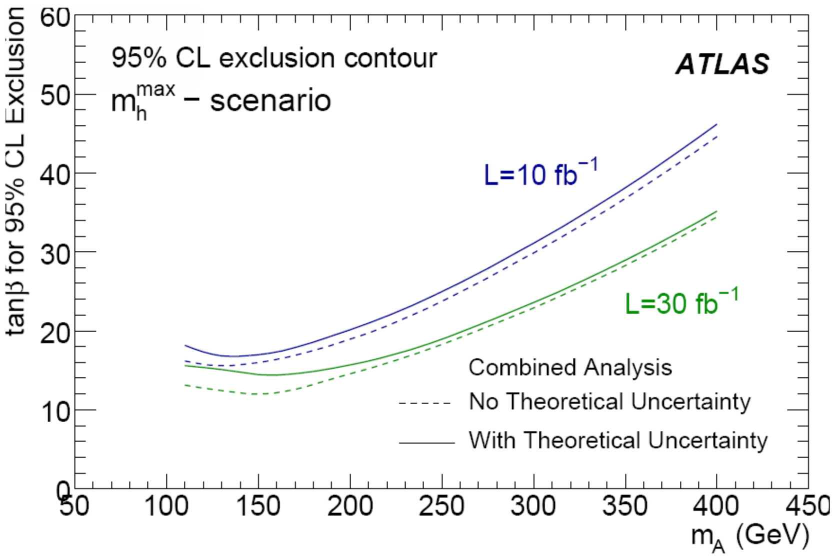


Charged MSSM Higgs Discovery Potential

Charged MSSM Higgs

Production mode greatly depends on $m_{H\pm}$

Three different analyses for a low mass ($m_{H\pm} < m_{top}$)

- $t\bar{t} \rightarrow bH^{\pm}bW \rightarrow b\tau_H \nu bqq$
- $t\bar{t} \rightarrow bH^{\pm}bW \rightarrow b\tau_L \nu bqq$
- $t\bar{t} \rightarrow bH^{\pm}bW \rightarrow b\tau_H \nu bl\nu$

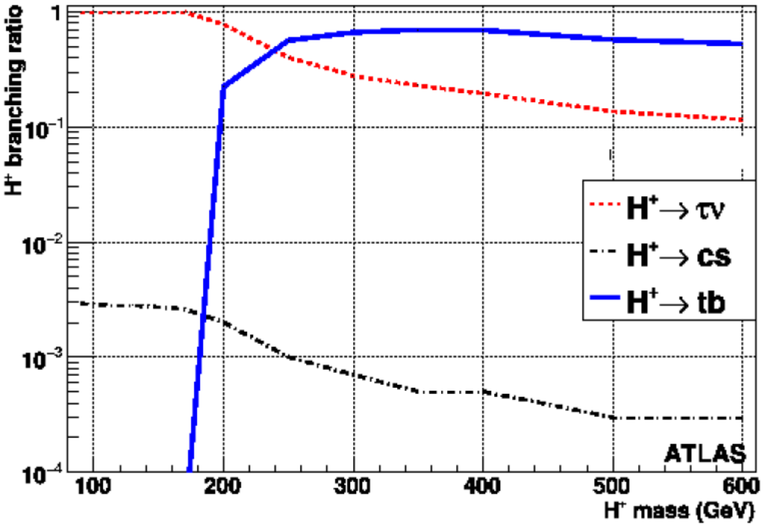
Two analyses considered for a high mass ($m_{H\pm} > m_{top}$)

- **Production via:** $gg \rightarrow H^{\pm}tb$ **and** $gb \rightarrow H^{\pm}t$
- **Decay modes:**

$$H^{\pm}t \rightarrow \nu\tau_H bqq$$

$$H^{\pm}t \rightarrow tbt \rightarrow bWbbW \rightarrow bqqbbl\nu$$

"m_h-max" scenario with tanβ = 35

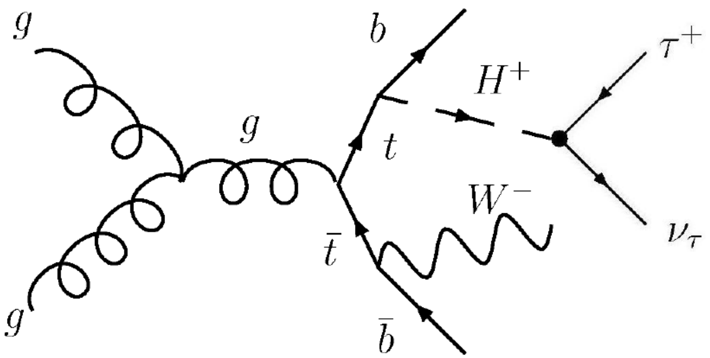


Dominant Backgrounds

- **ttbar (primary)**
- **QCD di-jets**
- **W+jets**
- **Single top**

Data-driven Background Estimation

Signal Final State

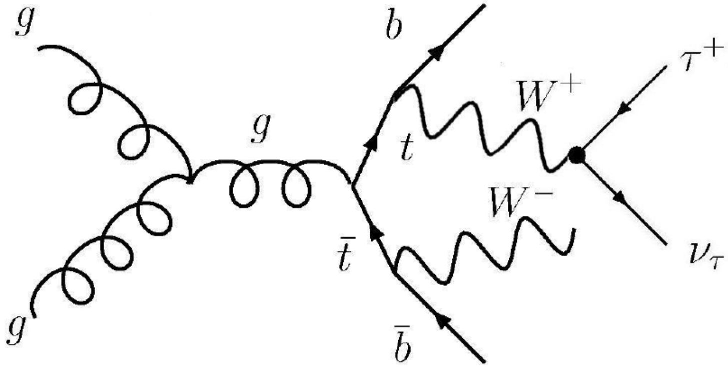


$$H^+ \to \tau_H \nu;\ W \to qq$$

$$H^+ \to \tau_L \nu;\ W \to qq$$

$$H^+ \to \tau_H \nu;\ W \to l\nu$$

Dominant Background



$$W \to \tau_H \nu;\ W \to qq$$

$$W \to \tau_L \nu;\ W \to qq$$

$$W \to \tau_H \nu;\ W \to l\nu$$

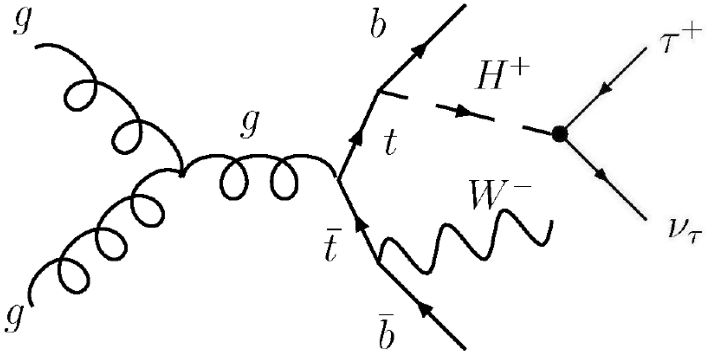
Do not trust Tevatron extrapolations

Difficult to obtain clean samples from data

Unknowns related to analysis-specific variables exist

Data-driven Background Estimation

Signal Final State



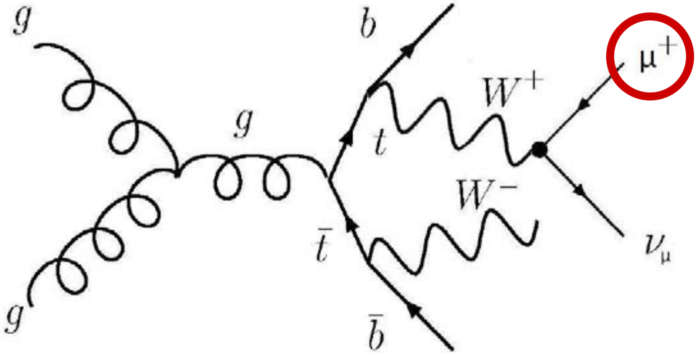
$$H^+ \rightarrow \tau_H \nu;\, W \rightarrow qq$$

$$H^+ \rightarrow \tau_L \nu;\, W \rightarrow qq$$

$$H^+ \rightarrow \tau_H \nu;\, W \rightarrow l\nu$$

Background Control Sample

Change muons into taus using the TAUOLA package



Leptonically- and hadronically-decaying taus can be emulated

Does not rely on the Tevatron

Clean samples can be obtained from data

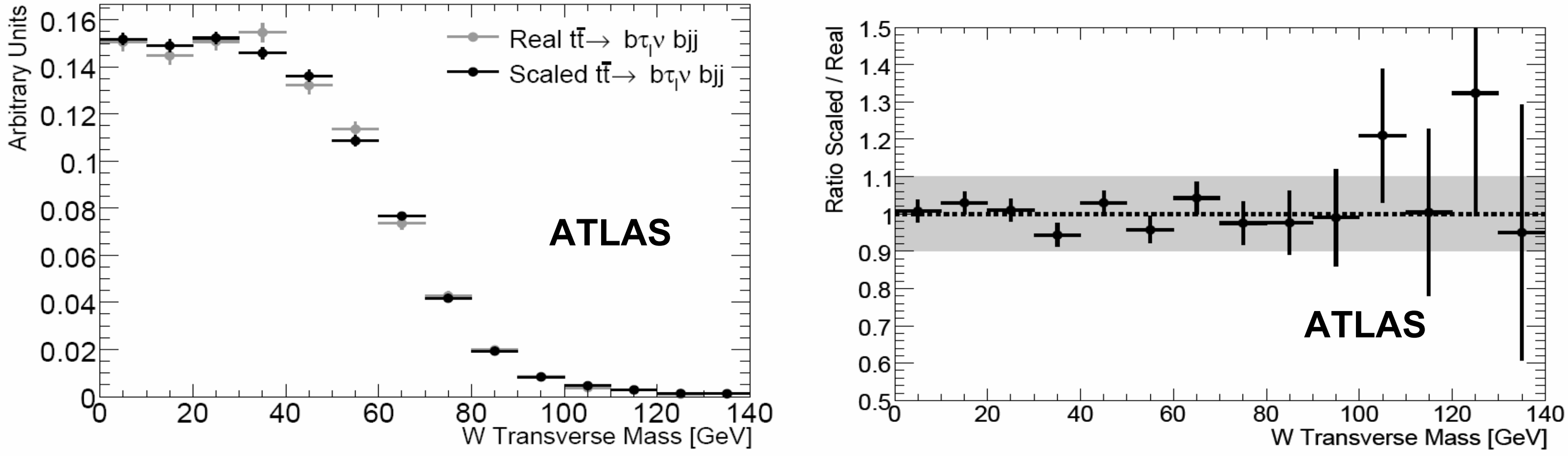
Unknowns related to analysis-specific variables included

Data-Driven Background Estimation

W Transverse Mass (complex quantity; relevant correlations preserved)

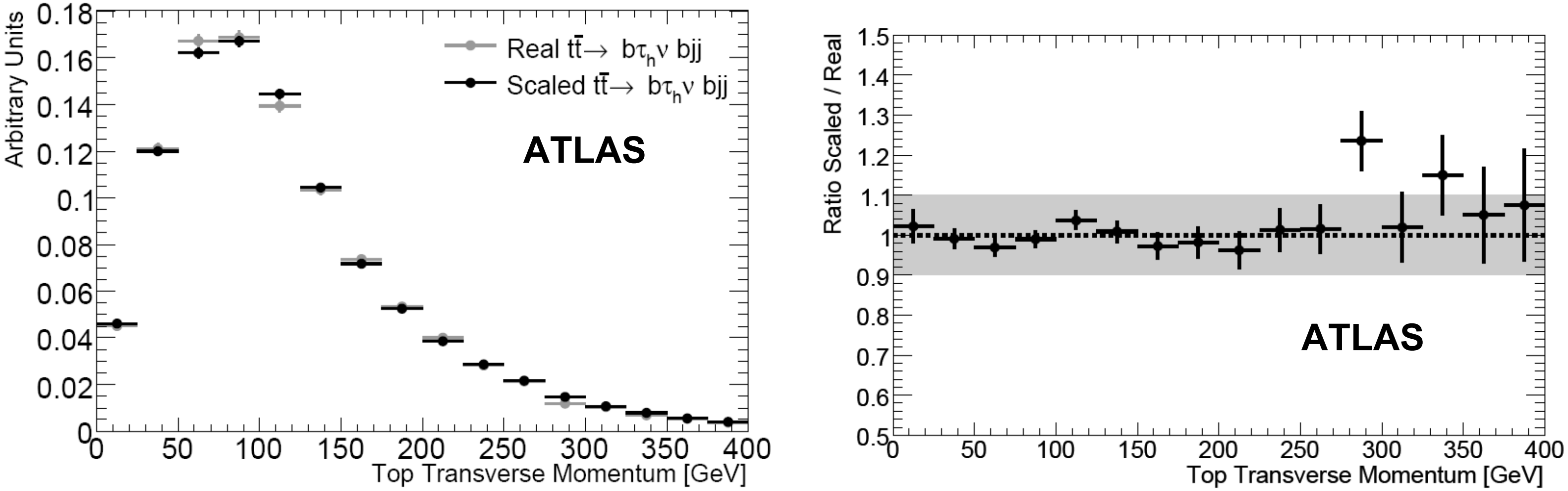
- **Leptonically decaying tau (** $t\bar{t} \rightarrow b\tau_L\nu bqq$ **)**

$$m_T = \sqrt{2p_T^l p_T^{miss}(1 - \cos(\Delta\phi))}$$



Top Quark Transverse Momentum (complex quantity)

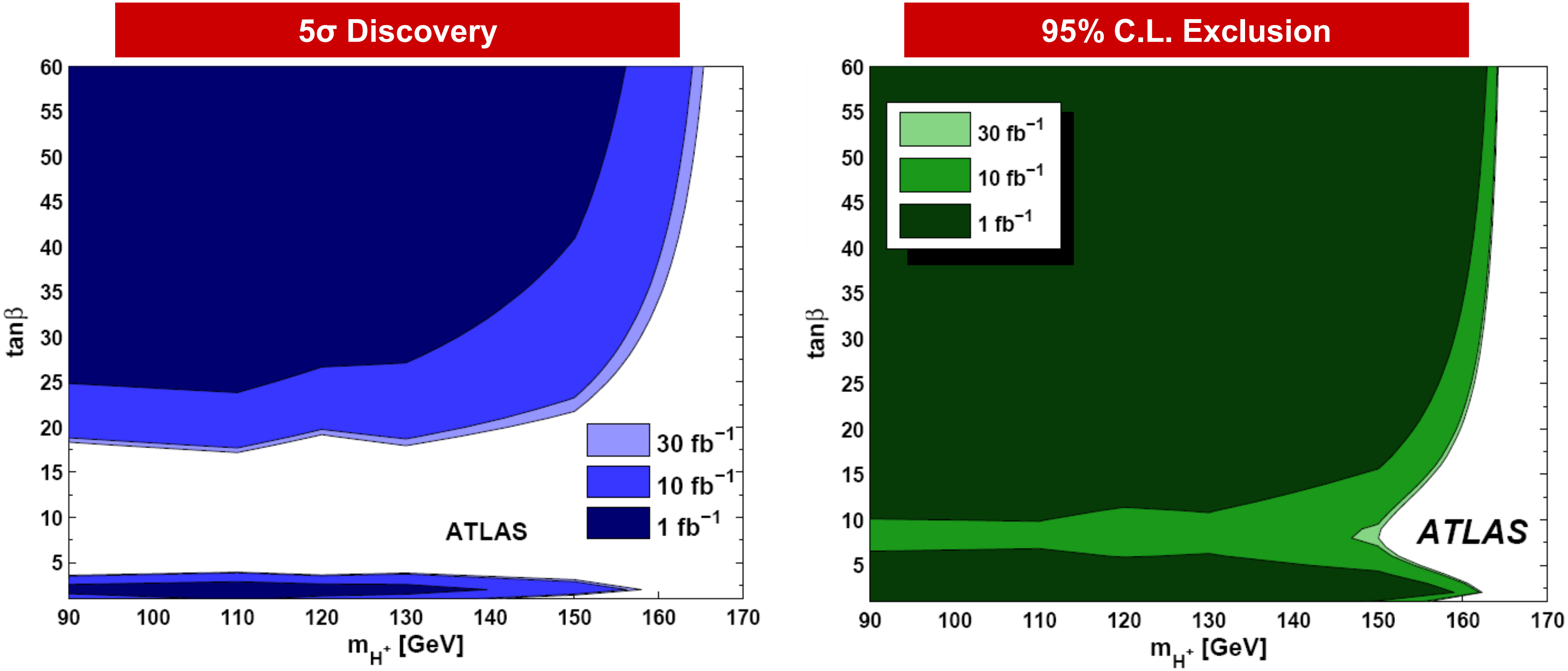
- **Hadronically decaying tau (** $t\bar{t} \rightarrow b\tau_H\nu bqq$ **)**



Light H± Discovery Potential

Individual analysis cuts vary depending on the final state

- **Most promising is $t\bar{t} \rightarrow bH^{\pm}bW \rightarrow b\tau_H \nu bqq$ due to the large branching fractions into this final state; also challenging due to the high hadronic activity and lack of leptons**



5σ Discovery

95% C.L. Exclusion

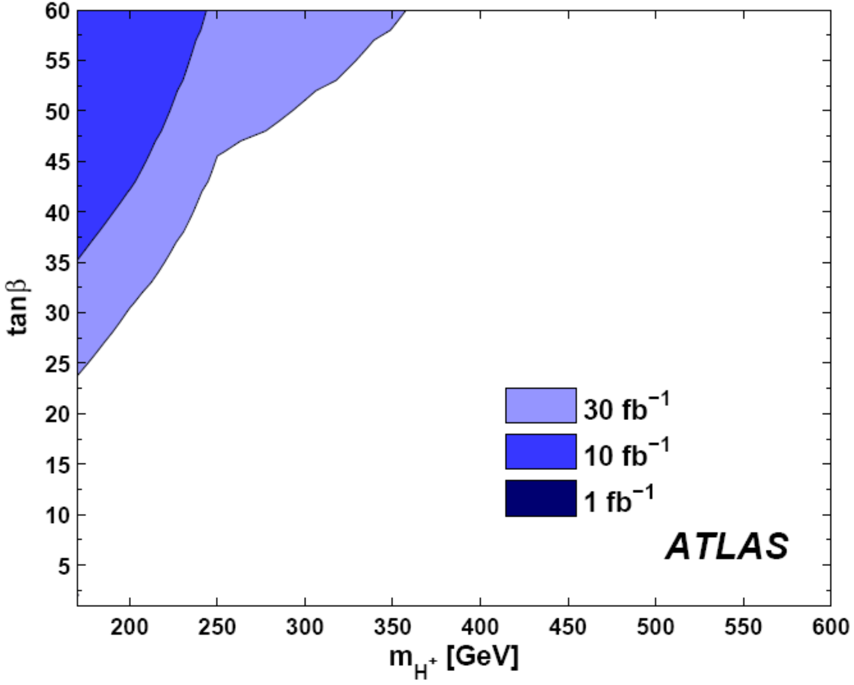
- **The other final states contain one charged lepton; exploit signal and background kinematics to get the upper hand on the backgrounds**

Heavy H± Discovery Potential

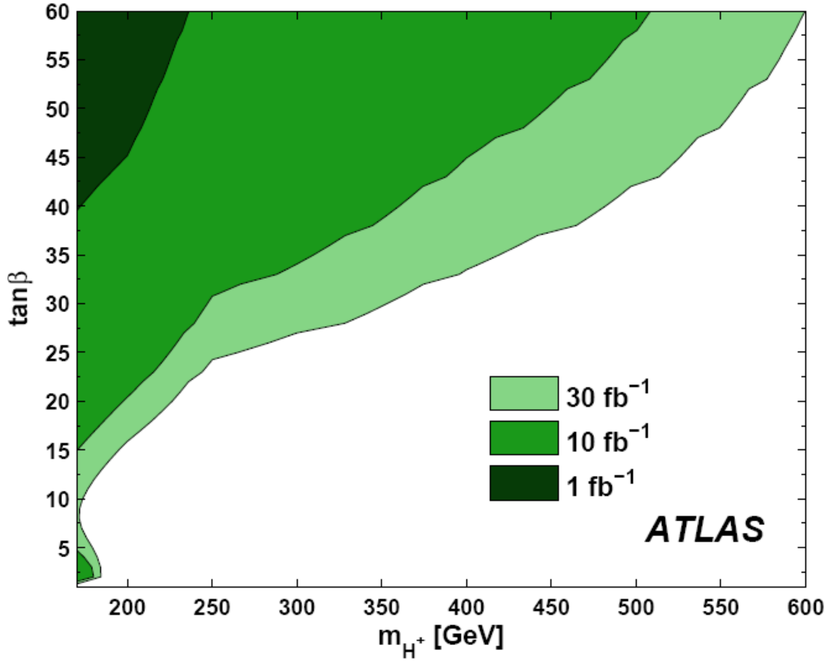
Individual analysis cuts vary depending on the decay of top and H±

- **For $H^{\pm}t \rightarrow \nu\tau_H bqq$ cut on the quality of the reconstructed top and W boson; use likelihood background discrimination based on the hadronic tau and MET**

5σ Discovery



95% C.L. Exclusion

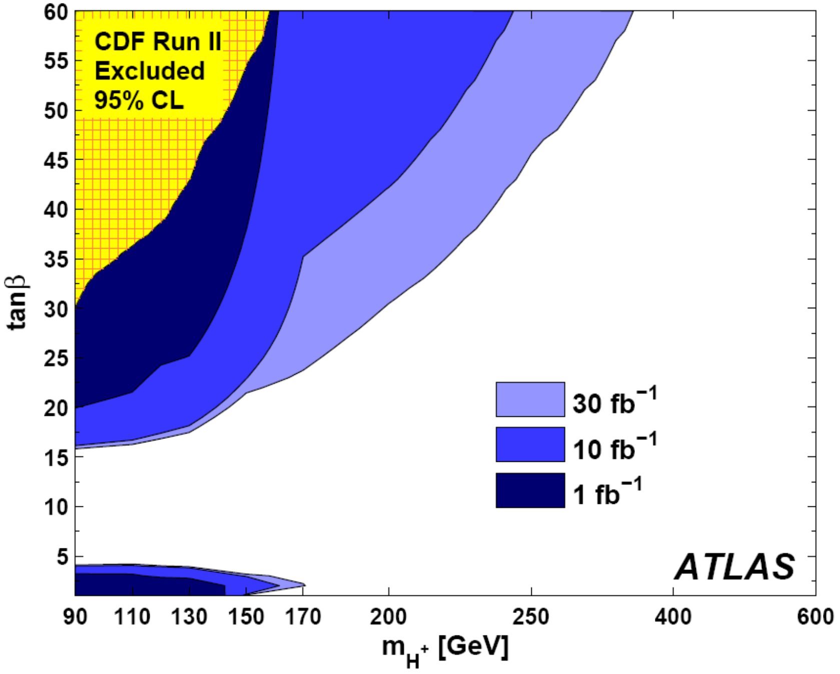


- **For $H^{\pm}t \rightarrow tbt \rightarrow bWbbW \rightarrow bqqbbl\nu$ jet assignment combinatorics make this channel difficult; reduce the background by reconstructing the W and top quark; a combinatorial likelihood analysis is used**

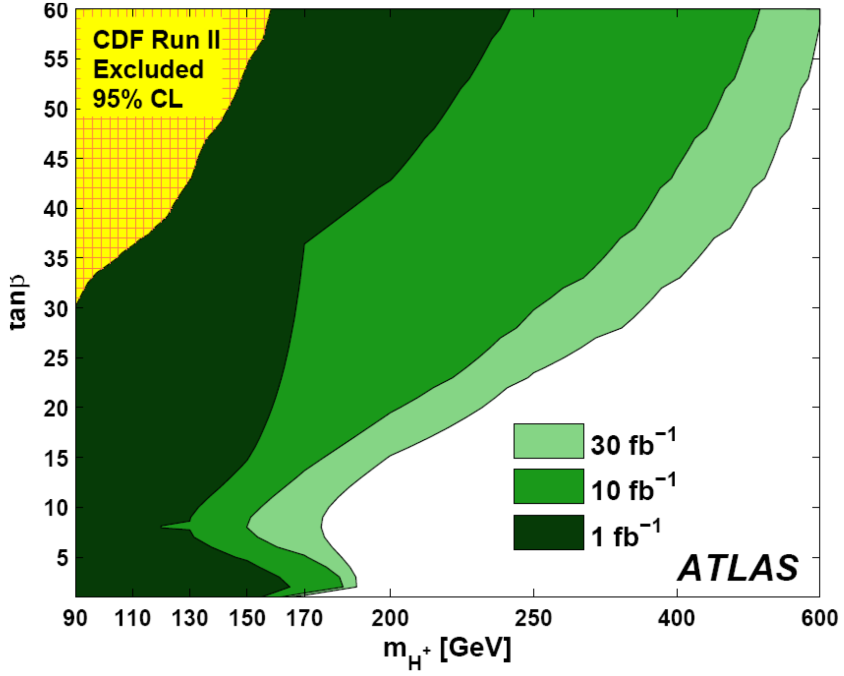
Combined $H^\pm$ Discovery Potential

Good sensitivity for high tanβ and low $m_{H\pm}$ even with 1 fb^{-1} of data

5σ Discovery



95% C.L. Exclusion



$H^\pm$ is invisible in the so-called "wedge region" of intermediate tanβ where the charged Higgs cross-section is at a minimum

Conclusions

Neutral Higgs discovery potential

- With 10 - 30 fb^{-1} we have good discovery potential for high tanβ and low m_A
- Of the results shown here, the di-tau analysis has the best sensitivity
- Discovery potential in other final states are currently being investigated

Charged Higgs discovery potential

- Decays of the $H^{\pm}$ to a tau an a neutrino offer the best sensitivity for light and heavy charged Higgs bosons in ATLAS; good discovery potential for 1 – 30 fb^{-1}
- Other final states are being investigated here as well (e.g., via decay to a chargino and neutralino)

Data-driven background estimation

- Each analysis shown here contains data-driven methods for estimating dominant and irreducible backgrounds
- Further refinements of these studies are currently underway

Results shown here are for 14 TeV with 1 – 30 fb^{-1} of data

- Studies currently underway in ATLAS to evaluate non-Standard Model Higgs boson exclusion and discovery with both a reduced center-of-mass energy and less integrated luminosity

Backup Slides

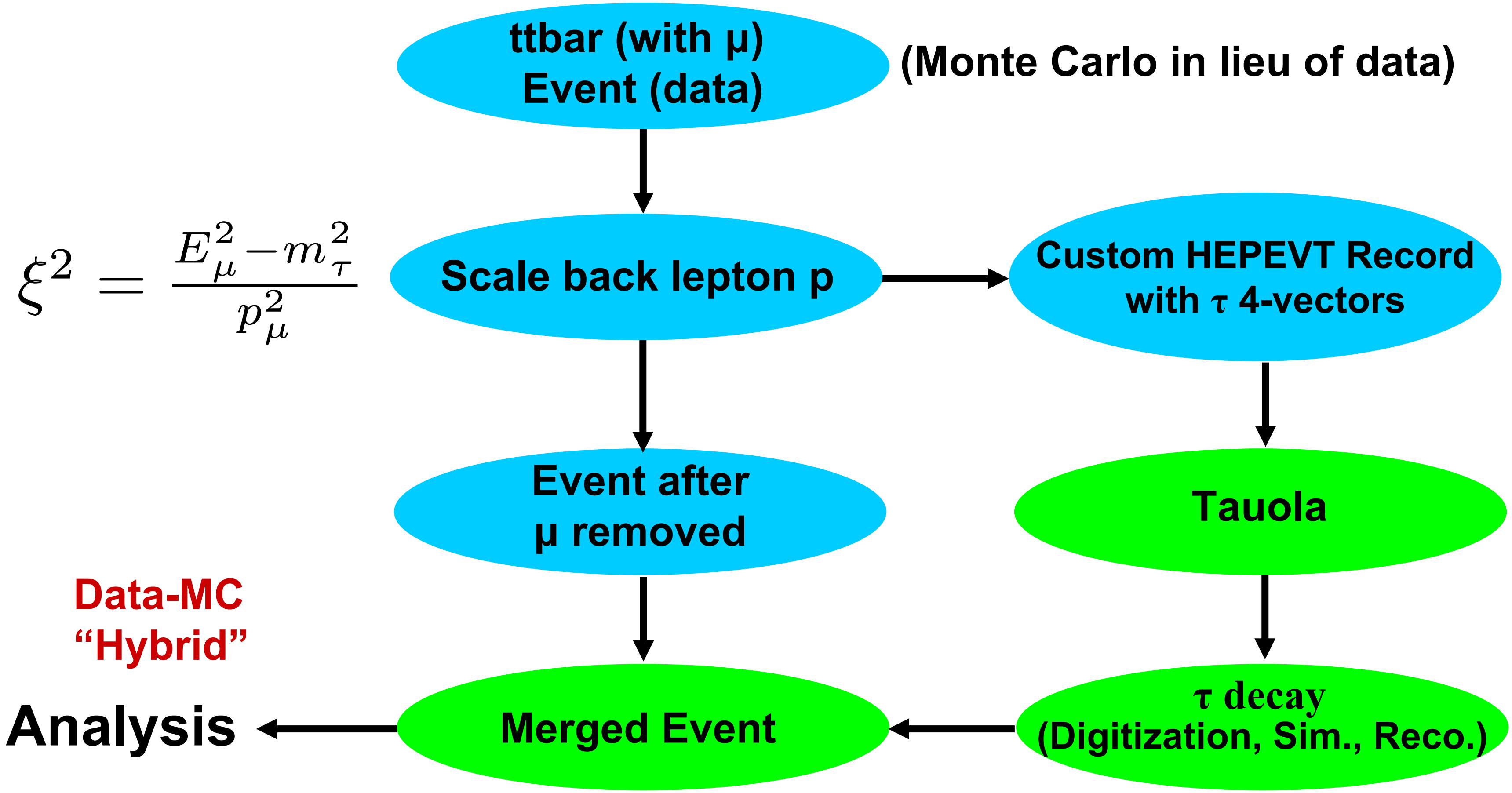
Data-driven Background Method

Based on a method used in ATLAS for SM and MSSM neutral Higgs searches

- **Generate control samples for the Z+jets backgrounds**

Original implementation (ATLAS CSC studies)

- **Done at the ntuple-level and used the full ATLAS detector simulation**
- **Applicable to many different final states**



ttbar (with μ) Event (data)

(Monte Carlo in lieu of data)

$$\xi^2 = \frac{E_\mu^2 - m_\tau^2}{p_\mu^2}$$

Scale back lepton p

Custom HEPEVT Record with τ 4-vectors

Event after μ removed

Tauola

Data-MC “Hybrid”

Analysis

Merged Event

τ decay (Digitization, Sim., Reco.)

ATLAS Offline Software Framework (ATHENA)

“Best-fit” Supersymmetric Spectra

The Constrained MSSM (CMSSM) predicts A/H masses ~425 GeV

In the single-parameter Non-Universal Higgs Model (NUHM1) A/H ~300 GeV

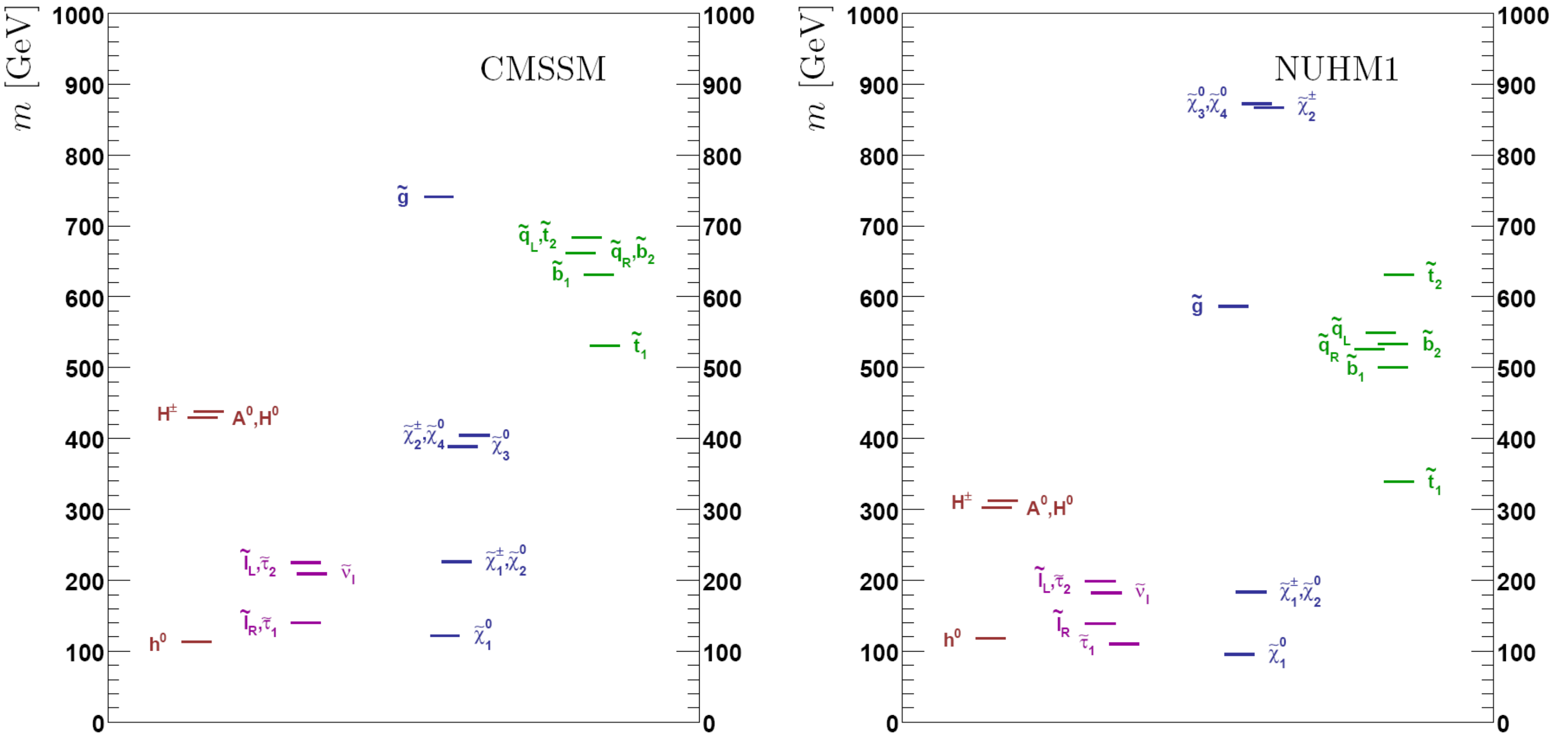


Figure 2. The spectra at the best-fit points: left — in the CMSSM with $m_0 = 60$ GeV, $m_{1/2} = 310$ GeV, $A_0 = 240$ GeV, $\tan\beta = 11$, and right — in the NUHM1 with $m_0 = 100$ GeV, $m_{1/2} = 240$ GeV, $A_0 = -930$ GeV, $\tan\beta = 7$, $m_H^2 = -6.9 \times 10^5$ GeV^2 and $\mu = 870$ GeV.

Figure taken from O. Buchmueller et al., arXiv:0707.3447v2 [hep-ph]

mh-max Scenario

Evolved out of the LEP2 era

- **Extremely common in the literature (e.g., PDG review)**
- **Using this scenario will allow for easy / direct comparison with previously published results**

$$m_t = 174.3\ \text{GeV}, \quad M_{SUSY} = 1\ \text{TeV}, \quad \mu = 200\ \text{GeV}, \quad M_2 = 200\ \text{GeV},$$
$$X_t^{\text{OS}} = 2\, M_{SUSY}\ (\text{FD calculation}), \quad X_t^{\overline{\text{MS}}} = \sqrt{6}\, M_{SUSY}\ (\text{RG calculation})$$
$$A_b = A_t, \quad m_{\tilde{g}} = 0.8\, M_{SUSY}\ .$$

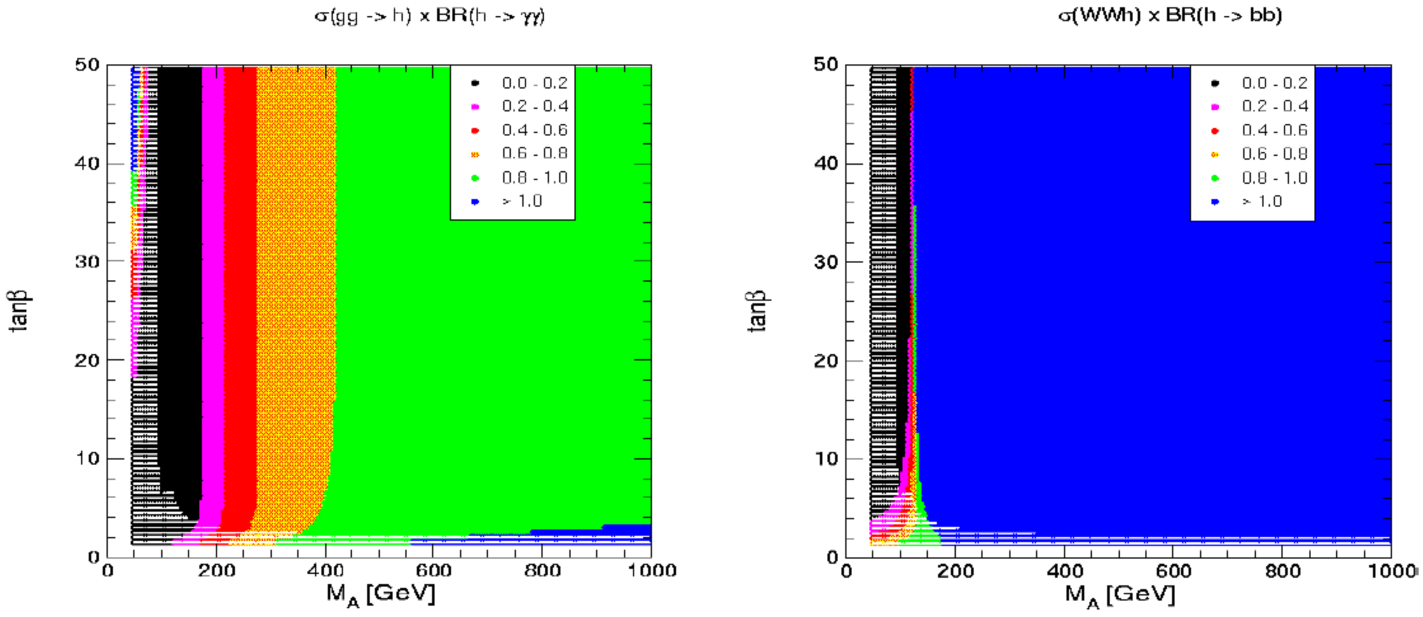


Figure 1: $[\sigma \times \text{BR}]_{\text{MSSM}}/[\sigma \times \text{BR}]_{\text{SM}}$ is shown for the channels $gg \to h \to \gamma\gamma$ (left plot) and $W^* \to Wh \to Wb\bar{b}$ (right plot) in the $M_A - \tan\beta$-plane for the m_h^{max} scenario. The white-dotted area is excluded by LEP Higgs searches.

M. Carena et al., hep-ph/0202167

No-Mixing Scenario

Evolved out of the LEP2 era

$$m_t = 174.3\ \text{GeV}, \quad M_{SUSY} = 2\ \text{TeV}, \quad \mu = 200\ \text{GeV}, \quad M_2 = 200\ \text{GeV},$$
$$X_t = 0\ (\text{FD/RG calculation}), \quad A_b = A_t, \quad m_{\tilde{g}} = 0.8\, M_{SUSY}\ .$$

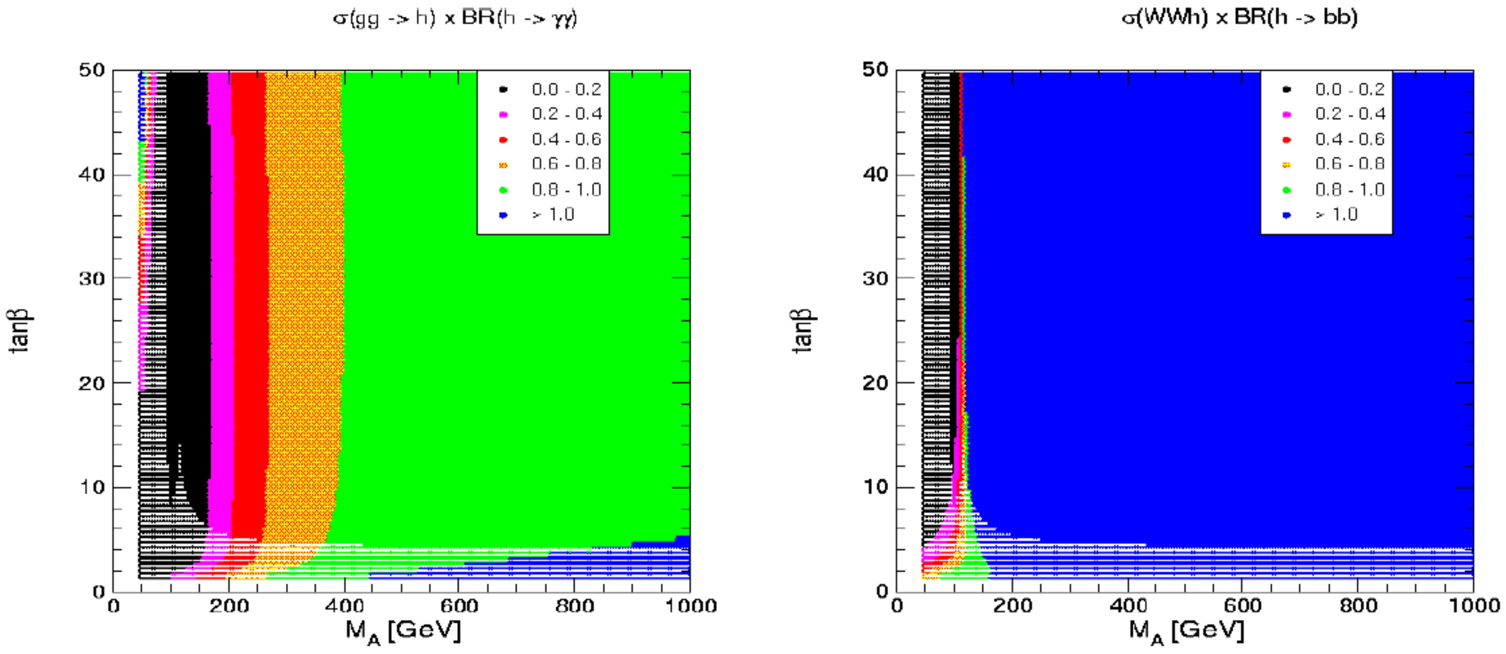


Figure 2: $[\sigma \times \text{BR}]_{\text{MSSM}}/[\sigma \times \text{BR}]_{\text{SM}}$ is shown for the channels $gg \to h \to \gamma\gamma$ (left plot) and $W^* \to Wh \to Wb\bar{b}$ (right plot) in the $M_A - \tan\beta$-plane for the no-mixing scenario. The white-dotted area is excluded by LEP Higgs searches.

M. Carena et al., hep-ph/0202167

Gluophobic Higgs

Hadron collider

$$m_t = 174.3 \text{ GeV}, \quad M_{SUSY} = 350 \text{ GeV}, \quad \mu = 300 \text{ GeV}, \quad M_2 = 300 \text{ GeV},$$
$$X_t^{\mathrm{OS}} = -750 \text{ GeV (FD calculation)}, \quad X_t^{\overline{\mathrm{MS}}} = -770 \text{ GeV (RG calculation)}$$
$$A_b = A_t, \quad m_{\tilde{g}} = 500 \text{ GeV} .$$

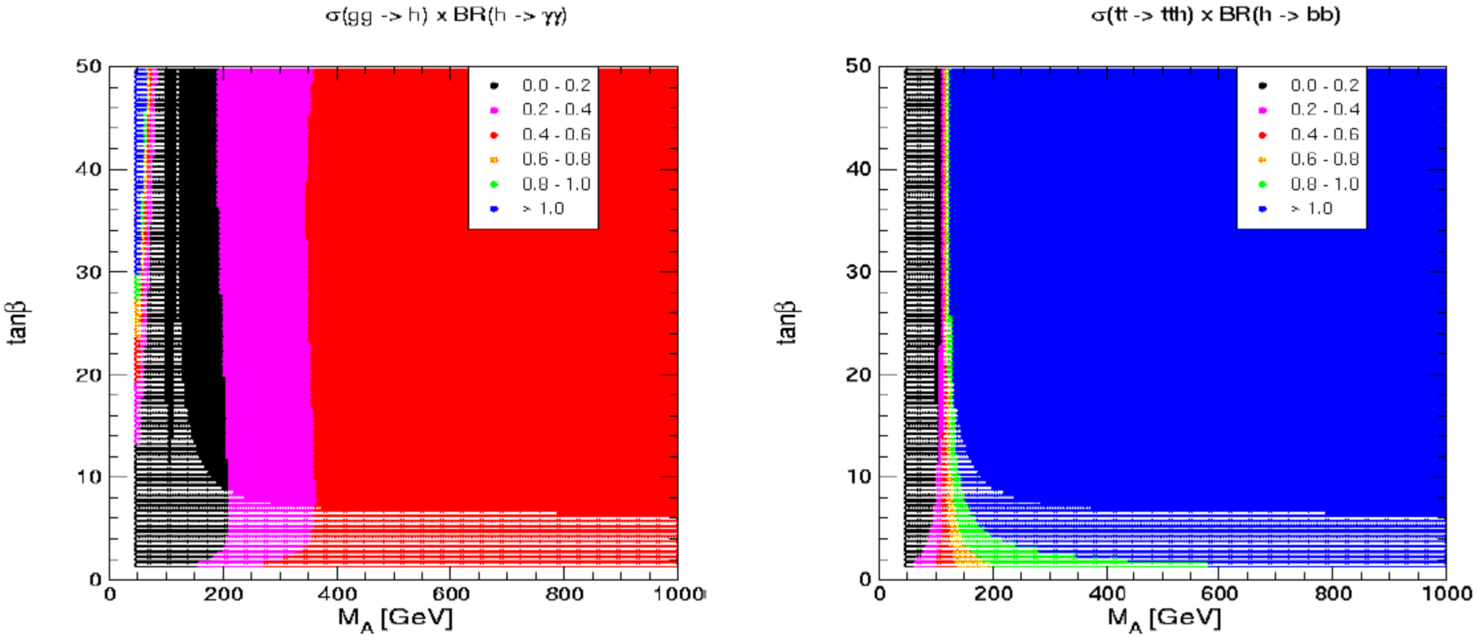


Figure 3: $[\sigma \times \mathrm{BR}]_{\mathrm{MSSM}}/[\sigma \times \mathrm{BR}]_{\mathrm{SM}}$ is shown for the channels $gg \to h \to \gamma\gamma$ (left plot) and $t\bar{t} \to t\bar{t}h \to t\bar{t}b\bar{b}$ (right plot) in the $M_A - \tan\beta$-plane for the gluophobic Higgs scenario. The white-dotted area is excluded by LEP Higgs searches.

M. Carena et al., hep-ph/0202167

Small α_{eff}

Hadron collider

$$m_t = 174.3 \text{ GeV}, \quad M_{SUSY} = 800 \text{ GeV}, \quad \mu = 2.5\, M_{SUSY}, \quad M_2 = 500 \text{ GeV},$$
$$X_t^{\text{OS}} = -1100 \text{ GeV (FD calculation)}, \quad X_t^{\overline{\text{MS}}} = -1200 \text{ GeV (RG calculation)}$$
$$A_b = A_t, \quad m_{\tilde{g}} = 500 \text{ GeV} \ .$$

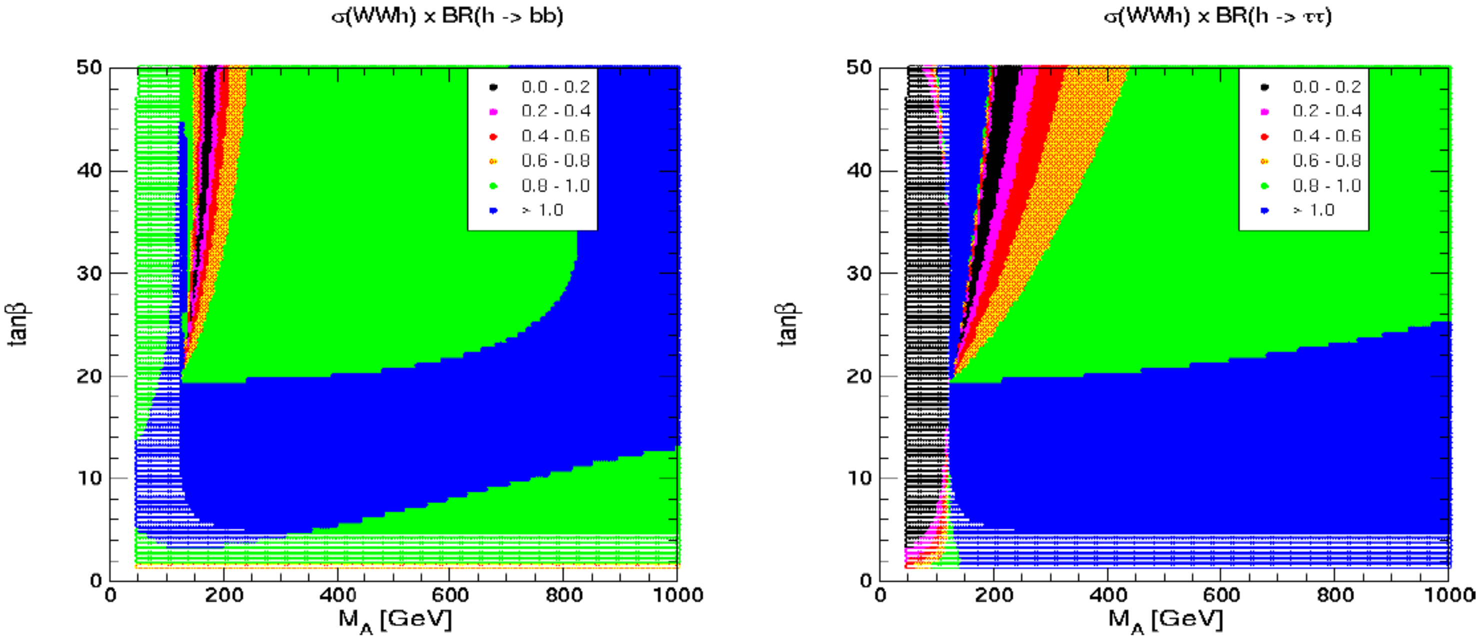


Figure 4: $[\sigma \times \text{BR}]_{\text{MSSM}}/[\sigma \times \text{BR}]_{\text{SM}}$ is shown for the channels $W^* \to Wh \to Wb\bar{b}$ (left plot) and $W^* \to Wh \to W\tau^+\tau^-$ (right plot) in the $M_A - \tan\beta$-plane for the small α_{eff} scenario. The white-dotted area is excluded by LEP Higgs searches.

M. Carena et al., hep-ph/0202167