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Higgs Properties and BSM Higgs Boson Searches at the LHC

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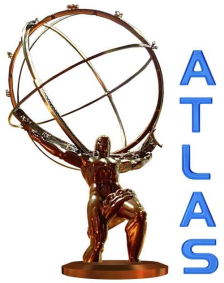
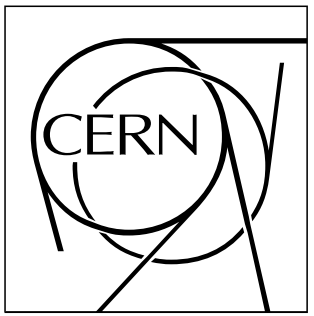
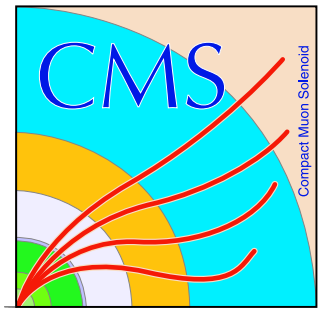
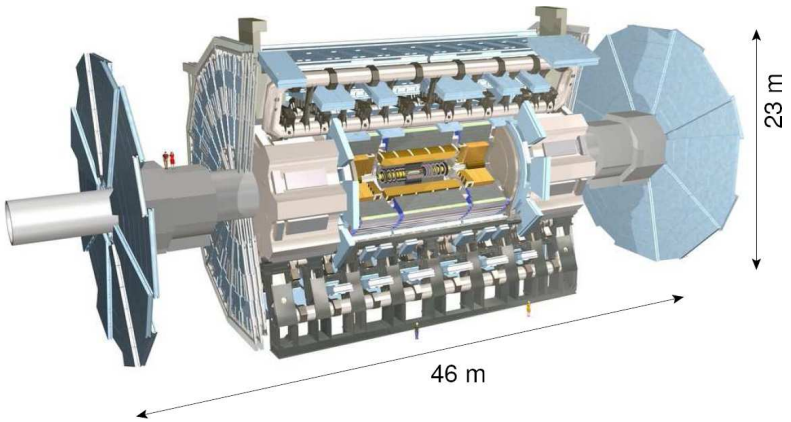
On Behalf of the ATLAS/CMS Collaboration

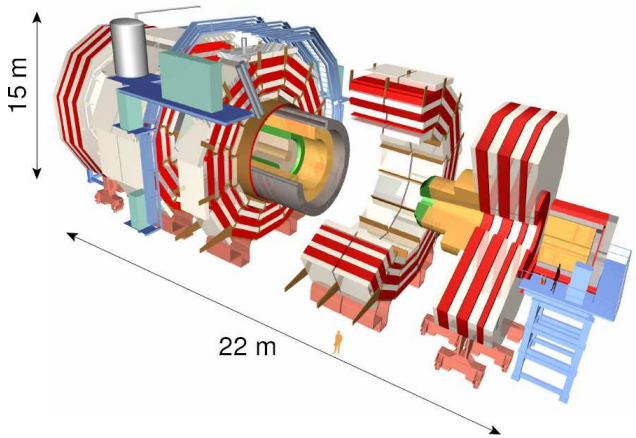






ATLAS/CMS Optimal for Higgs Searches





- Good, Hermetic Calorimetry: Missing E_T Measurement, Jet Reconstruction up to $|\eta| < 4.9$.
- Powerful Particle Identification
  - $\sim$ 97% Muon Efficiency, Cleanest Identification
  - $\sim$ 80% Electron Efficiency with Jet Rejection of 10^5
  - $\sim$ 80% Photon Efficiency with Jet Rejection of 10^3
  - $\sim$ 60% b Tagging Efficiency with Light Jet Rejection of 10^2 (Good Vertexing)
  - $\sim$ 50% Hadronic τ Efficiency with Jet Rejection of 10^2
- Excellent Electron, Photon and Muon Energy- and p_T Resolution

Covered in this Talk

- BSM Higgs Boson Searches in the MSSM
- Measurement of Higgs Boson Properties

Results Based 'Computing System Commissioning' Studies (ATLAS) and PTDR Vol.II (CMS)
(Unless Indicated Otherwise)

Part I

MSSM Higgs Boson Searches

Outline

1. $h/H/A \to \mu\mu$ Searches
2. $h/H/A \to \tau\tau$ Searches
3. Charged Higgs Boson Searches

Supersymmetry Needs Two Higgs Doublets
$\longrightarrow$ Five Physical Higgs Bosons.

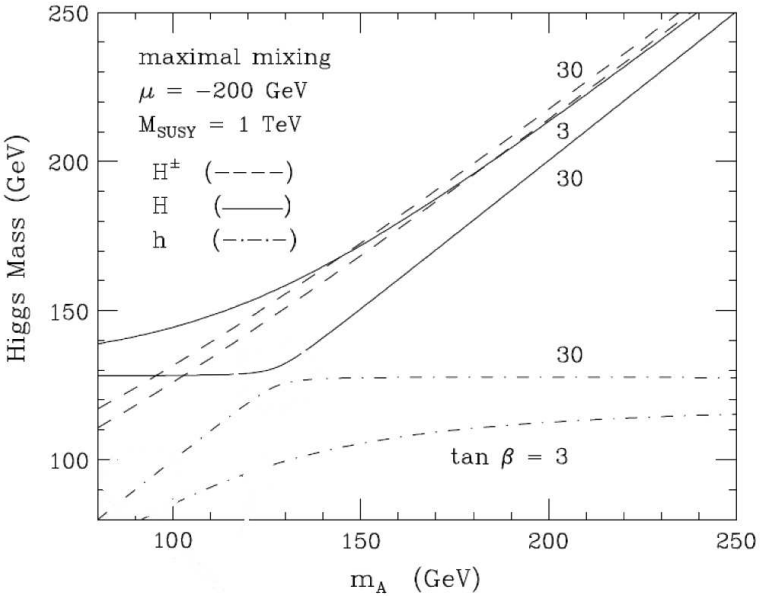
- Two CP-even: h and H
- One CP-odd: A
- Two Charged: $H^{\pm}$

At Born Level Higgs Sector Determined by Two Parameters

- Mass of CP-odd Higgs Boson m_A
- Ratio VEV of the Two Higgs Fields $\tan\beta$
- Prediction $m_h < m_Z$

Large Loop Corrections Increase this to $m_h \simeq 130\,\mathrm{GeV}$

Mass Degeneracy of At Least Two Neutral Higgs Bosons in Larger Parts of Parameter Space



Light Neutral Higgs Bosons

- Predominantly Produced in
  - Gluon-Gluon Fusion for Low $\tan\beta$
  - bb Associated Production for High $\tan\beta$
- Mainly Decay to
  - bb with BR$\sim$ 90%
  - $\tau\tau$ with BR$\sim$ 10%

MSSM $bbh/H/A$, $h/H/A \to \mu\mu$ – ATLAS

Scenario:

- Branching Fraction $h/H/A \to \mu\mu$ Highly Suppressed in Standard Model
- Enhanced with $\tan\beta$ in MSSM
- High Momentum Resolution and Identification Efficiency compensate for BR Suppression

Production Mechanism:

- **Direct Production:** $gg \to h/H/A$ Dominant at Low $\tan\beta$
- **Associated Production:** $bbh/H/A$ Dominant at High $\tan\beta$

Background Contribution:

- **Dominant:** Drell-Yan Z Production
- **With b-Tag Required:**
  - Z+b-Jets and Z+Light Jets
  - $t\bar{t} \to bb\mu\mu\nu\nu$ (High Jet Activity/E_T^{miss})
  - WW/ZZ Negligible (Low Cross Section)

Preselection:

- Single-μ Trigger (Efficiency $\varepsilon \approx 95\%$)
- Two Muons of Opposite Charge w/ $p_T > 20\,\text{GeV}$
- Muon Isolation: $E_T(\Delta R = 0.4)/p_T^{\mu} < 0.2$ (Suppression of $t\bar{t}$)
- $E_T^{\text{miss}} < 40\,\text{GeV}$ (Rejects $t\bar{t}$ and WW)

MSSM $bb\,h/H/A$, $h/H/A \to \mu\mu$ – ATLAS

Require 0/1 b-Tag:

- 1 b-Tagged Jet w/ $p_T > 20\,\mathrm{GeV}$
  - Reduces Z+Light Jet Background
  - But: Significant Reduction of Signal
- **1 b-Jet Analysis**
  - $t\bar{t}$ Background Important
  - Further Rejection:

    - $\mu\mu$ Acoplanarity

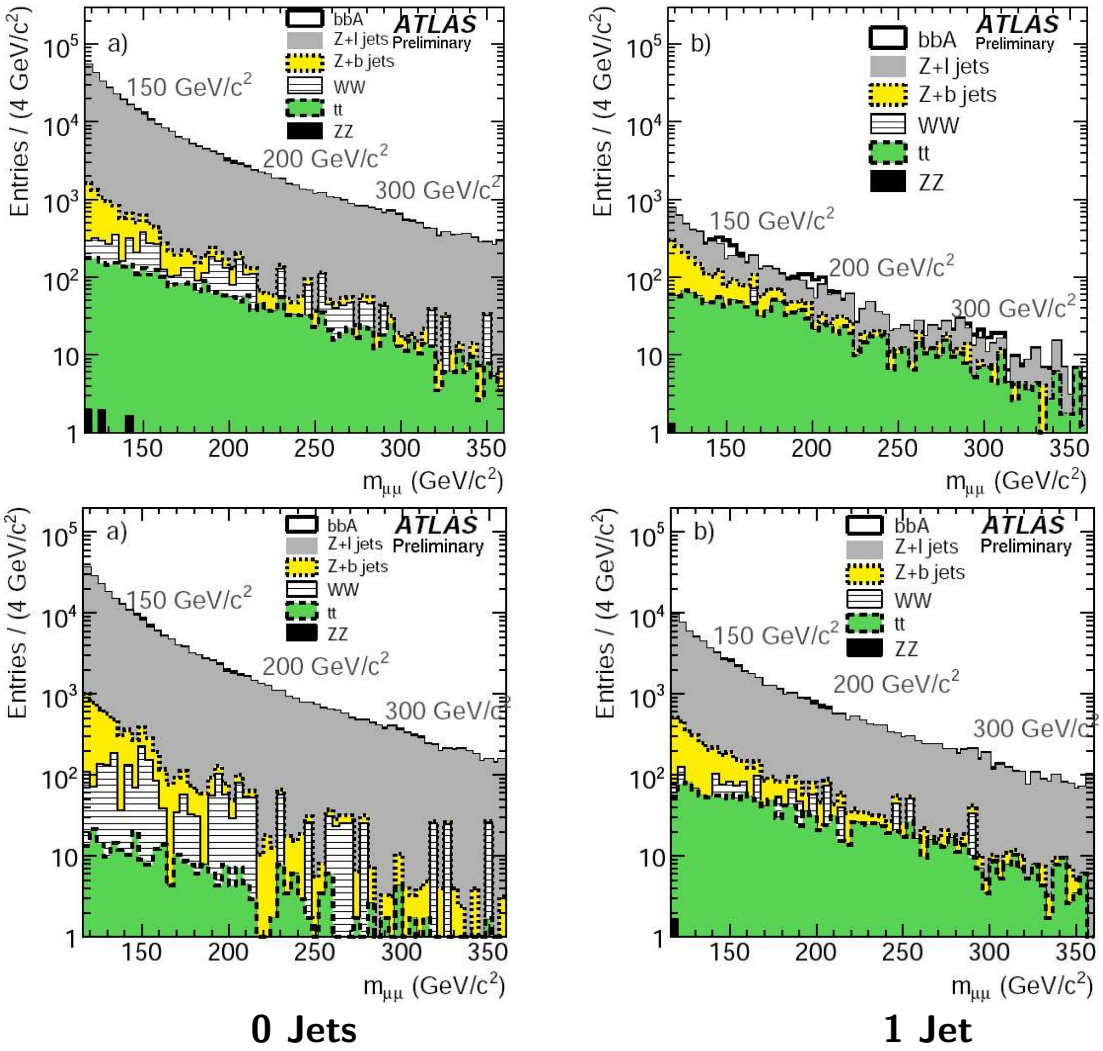
    - $\sum p_T^{\mathrm{Jet}} < 90\,\mathrm{GeV}$
- **0 b-Jet Analysis**
  - Z-Background Dominant
  - No Further Selection Cuts
- Mass Window $\Delta m = m_A \pm 2 \cdot \sigma_{\mu\mu}$

No b-Tag Requirement:

- < 2 Jets w/ $p_T > 20\,\mathrm{GeV}$ in the Event (Suppresses $t\bar{t}$)
- Remaining Topologies
  - **0 Jets:** Z Bckg. Dominant
  - **1 Jet:** $t\bar{t}$ Important

    $\rightarrow$ Cut on $\mu\mu$ Acoplanarity

0 b-Tags | **1 b-Tag**



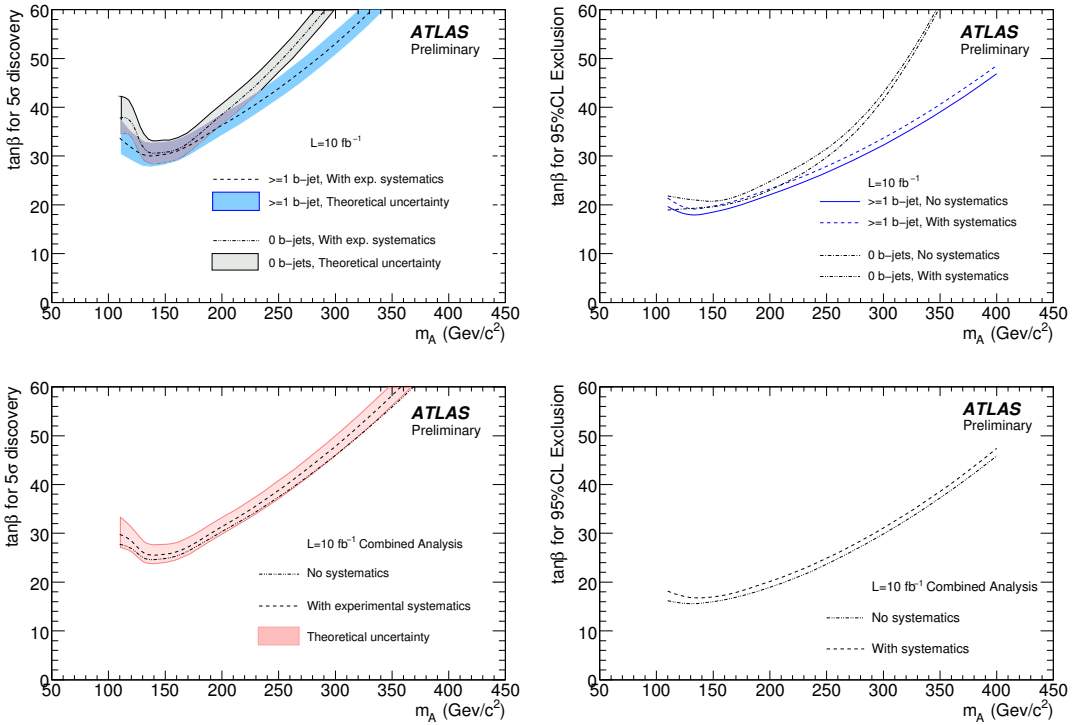
0 Jets | **1 Jet**

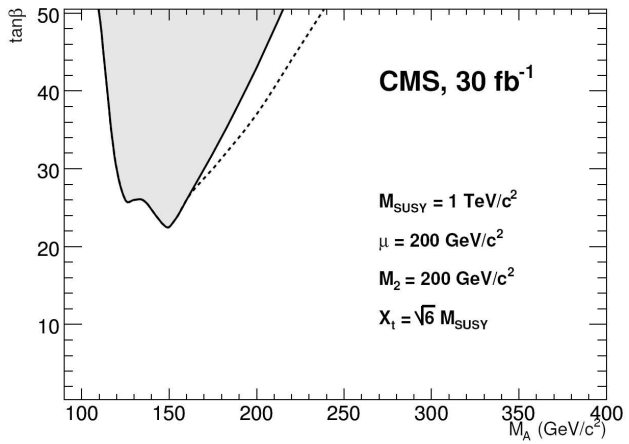
Estimation Z and $t\bar{t}$ Background from Data

Systematic Uncertainties

- Theoretical Uncertainties (Total: 17%)
  - Renormalization/Factorization Scale
    - $gg \to bbh/H/A$: $(20 - 30)\%$
    - $bbh/H/A$: $< 10\%$
  - PDF Uncertainties (MRST2002 $\to$ MRST2004): 14%
- Experimental Uncertainties
  - Muon: Reconstruction Efficiency/Momentum Resolution and Scale
  - Jet: Energy Scale / Resolution Uncertainty
  - b-Tagging: Efficiency / Light Jet Rejection

Discovery Potential and Exclusion Limit





Trigger:

- Single OR Double τ Trigger
- Double τ Tagging

Event Selection:

- $E_T^{\tau} > (50/100/150)\ \text{and}\ 50\ \text{GeV}$ for $m_A = (200/500/800)\ \text{GeV}$
- τ Identification
  - Tracker Isolation
  - $p_T^{\text{ltr}} > 50\ \text{GeV}$
  - 1 or 3 Tracks (Only 1 for high m_A) - Opposite Charge
- Exactly 1 b-Tagged Jet w/ $E_T > 20\ \text{GeV}$

Background:

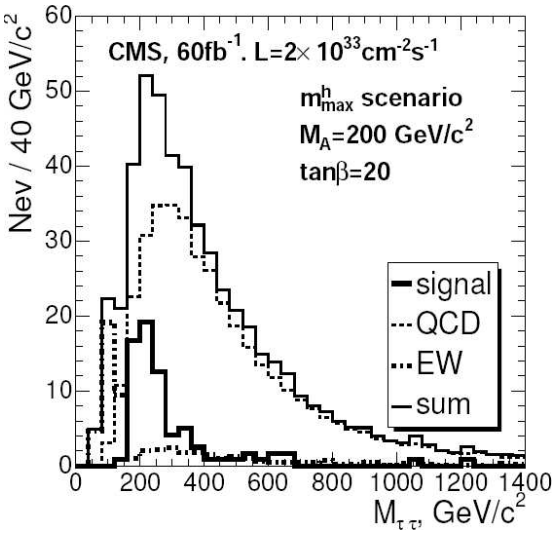
- QCD Multi-Jet Background Dominant

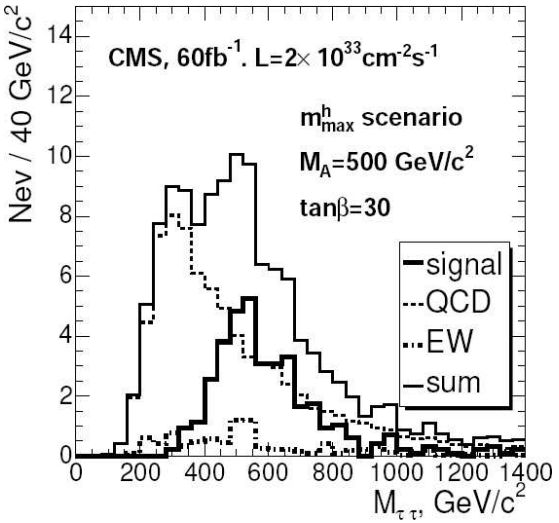
Systematic Uncertainties:

- E_T^{miss} and Jet Energy Scale
- Tracker Misalignment $\longrightarrow$ τ Fakes from QCD
- Measurement of QCD Bckgr. from Data (SS vs. OS) – $\sim (5 - 20)\%$ Systematic Uncertainty

Discovery Reach:

low $\tan\beta$ limit for 5σ discovery	Higgs boson mass		
	$m_A = 200\ \text{GeV}/c^2$	$m_A = 500\ \text{GeV}/c^2$	$m_A = 800\ \text{GeV}/c^2$
no systematics	20	32	46
with systematics	21	34	49



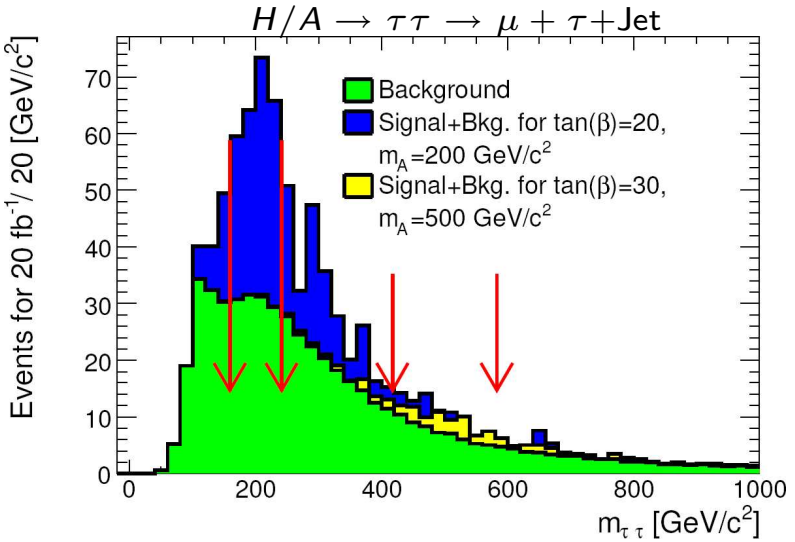


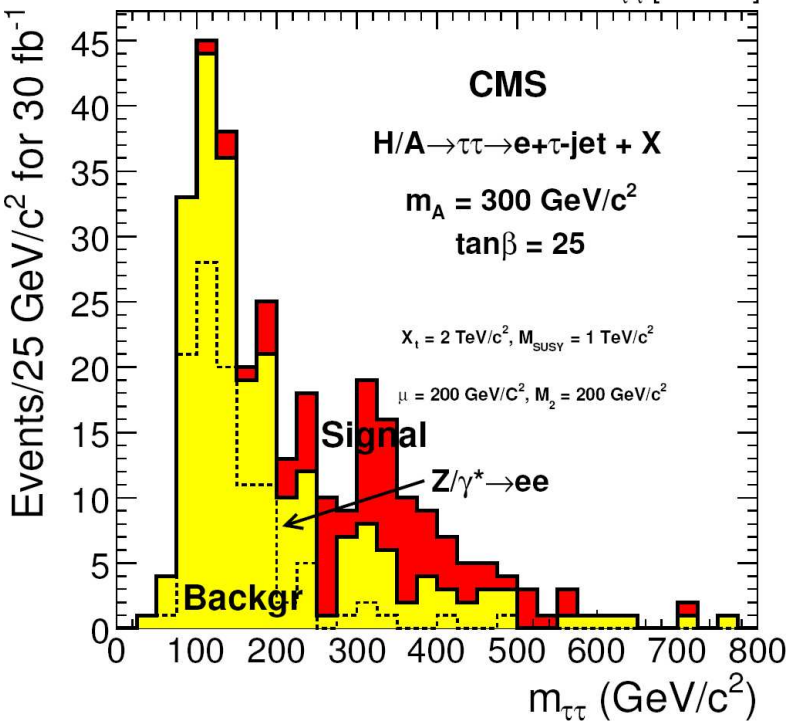
TRIGGER:

- **e+Jet Final State:**
  Single e OR Single e+τ Jet
- **μ+Jet Final State:**
  Single μ @L1
  Single μ OR Single μ+τ Jet @HLT

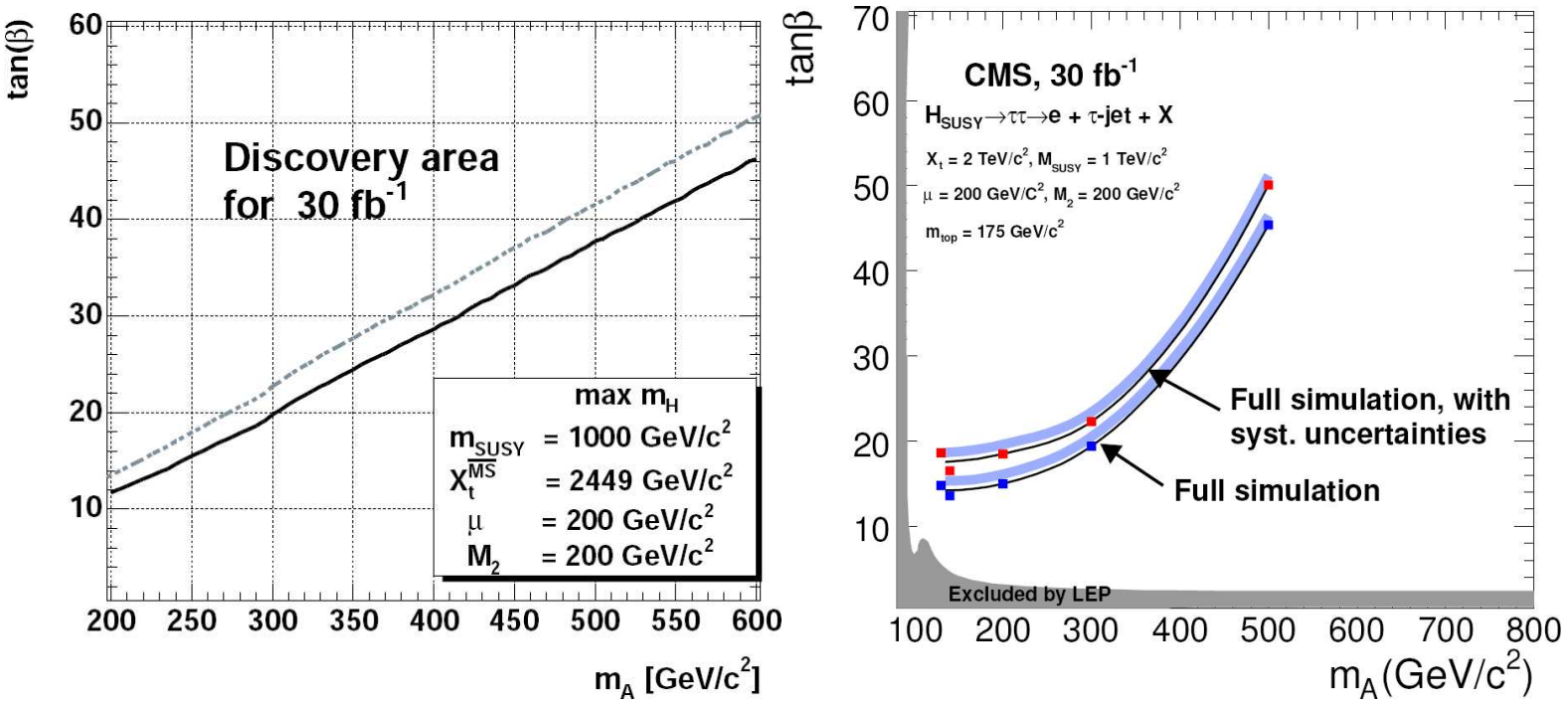
SELECTION:

- **μ+Jet Final State:**
  - $p_T^{\mathrm{ltrk}} > 10(20)\,\mathrm{GeV}$ for 1 (3) Track τ-Jets
  - 1 b Tagged Jet ($E_T > 20\,\mathrm{GeV}$)
  - $m_T(\mu,\ E_T^{\mathrm{miss}}) > 60\,\mathrm{GeV}$
    (Reduces $t\bar{t}$, Wt, and W+Jets Bckgr.)
  - Cut on $E^{\mathrm{HCAL}}/p^{\mathrm{ltrk}}$
  - Angle $\phi(p_T,\ E_T^{\mathrm{Jet}})$
  - Central Jet Veto ($E_T > 20\,\mathrm{GeV}$)
- **e+Jet Final State:**
  - Electron Isolation
  - $E^{\mathrm{hadronic}}/E^{\mathrm{elm}} < 0.2$
  - $E^{\mathrm{SuperCluster}}/p^{\mathrm{track}} < 0.2$
  - Dedicated Cuts to Suppress Z/γ^*, $t\bar{t}$, W+jets and QCD



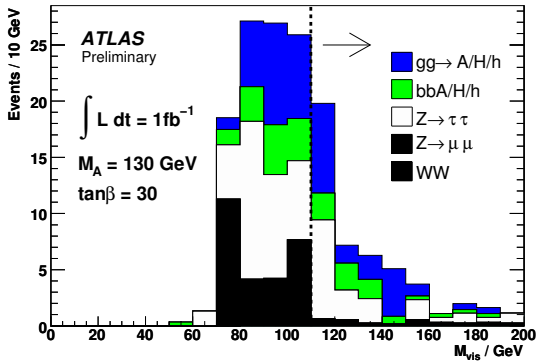


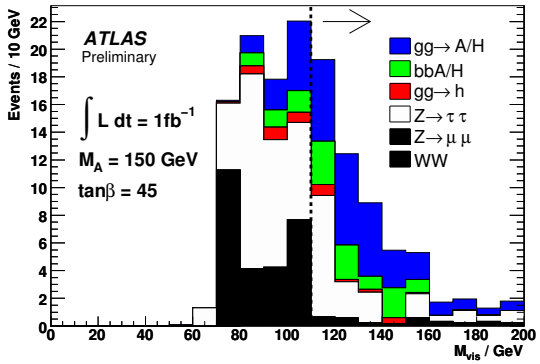
DISCOVERY POTENTIAL for μ had (left) and e had (right)

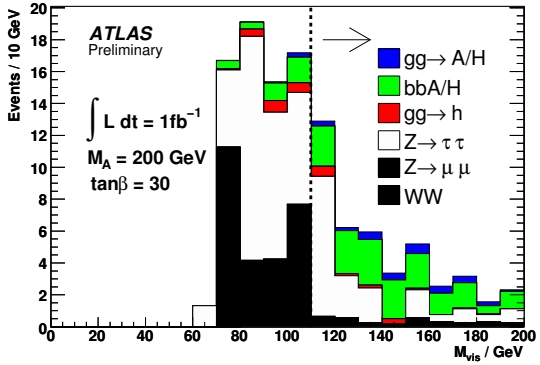


- Low m_A Range: Discovery Possible Already at Low tan β
- High m_A Range: Challenging Even for High tan β

ATLAS Study for lep-had and had-had Ongoing







Analysis:

- Aiming at Early Data Taking Period (No b-Tagging)
- Contribution to Production Cross Section from Direct- and Associate Production.
- Reconstruction of Visible Mass

Preselection:

- Trigger: Electron/Muon Trigger
- Zero Jets with $p_T > 20\mathrm{GeV}$

Selection Results:

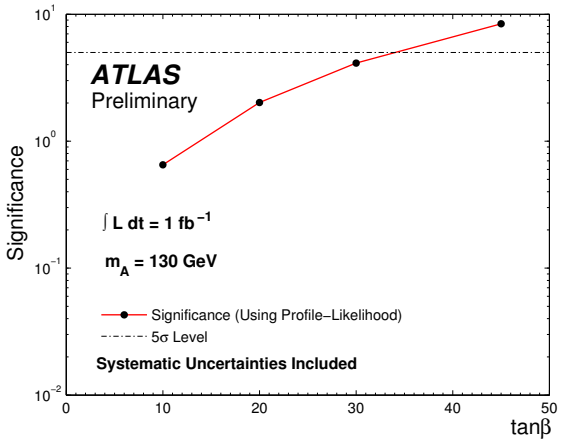
Cut	bbΦ	ggΦ	ttbar	WW	Z → ee	Z → μμ	Z → ττ
Precuts	1 390	606	1 340	1 097	254 k	420 k	5 870
$p_{T,Higgs} < 35$ GeV	1 329	584	70	1055	249 k	410 k	5 752
$0 < x_1, x_2 < 1$	709	333	7	51	77 k	121 k	3 008
$p_{T,leptons} > 40$ GeV	196	90	5	33	50 k	79 k	182
eμ final state	91	46	1	18	0	83	87
$\cos\Phi_{lep\text{-}pT,miss} > 0.95$	50	29	0	7	0	29	56
$m_{vis} > 110$ GeV	20	13	0	6	0	0	19

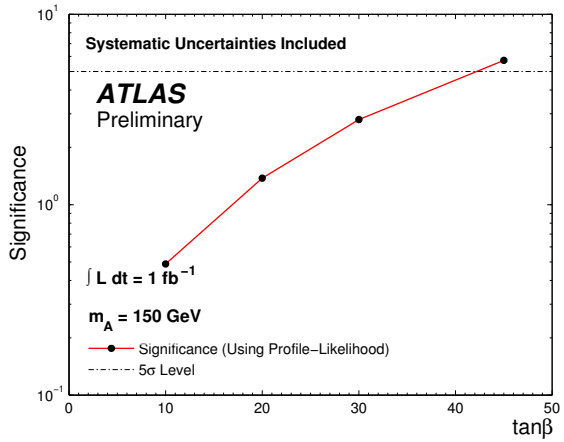
(Cross Section (in pb) for $m_A = 130\mathrm{GeV}$ and $\tan\beta = 45$)

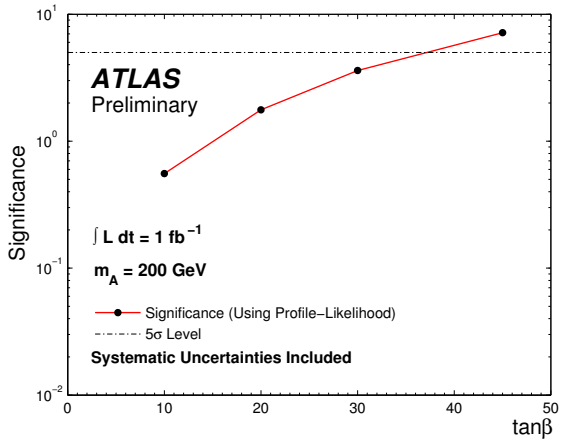
Systematic Uncertainties:

- $Z \to \tau\tau$ Assumed to be 10%
- Other Backgrounds (WW, $t\bar{t}$): 30%

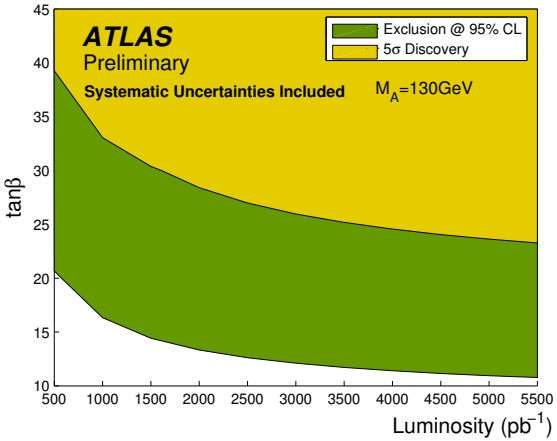
Significance as a Function of tan β

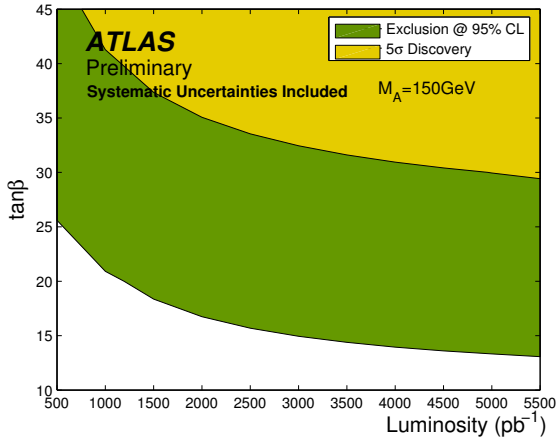


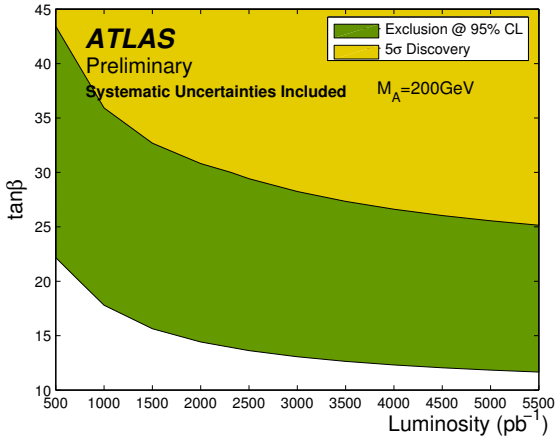




Discovery and Exclusion Limits as a Function of Integrated Luminosity







$bb\,h/H/A,\ h/H/A \to \tau\tau \to 2\ell 4\nu$ – Exclusive Analysis – ATLAS

Analysis: (All Leptonic Final States Considered)

- Triggered on Leptons (e/μ)
- At Least on b-Tagged Jet
  ($\longrightarrow$ No Contribution from Direct Production)
- $m_{\tau\tau}$ Using Collinear Approximation

Selection:

Variable	$H \to \tau\tau$	ttbar	$Z \to \mu\mu$	$Z \to \tau\tau$
Precuts	224± 7	10271± 106	7715± 178	1243 ± 27
Number jets	151± 6	1228± 37	3461± 119	641 ± 20
Dilepmass, GeV	123± 5	436± 22	106 ± 21	604± 19
$x_1 \cdot x_2$	110± 5	325± 19	33± 12	498± 17
$p_{T,\mathrm{miss}}$, GeV	95± 5	316± 18	8.1± 6	378± 15
$p_{T,\tau\tau}$, GeV	83± 4	165± 13	8.1± 6	325 ± 14
$p_{T,\ell\ell}$, GeV	77± 4	114± 11	4.1± 4	297± 13
$p_{T,\mathrm{leading\ bjet}}$, GeV	66± 4	54± 8	4.1± 4	257± 12
$\Delta\Phi_{\ell\ell}$	61± 4	44± 7	4.1± 4	188± 11
$p_{T,\mathrm{leading\ lep}}$, GeV	60± 4	37± 6	4.1± 4	186± 11

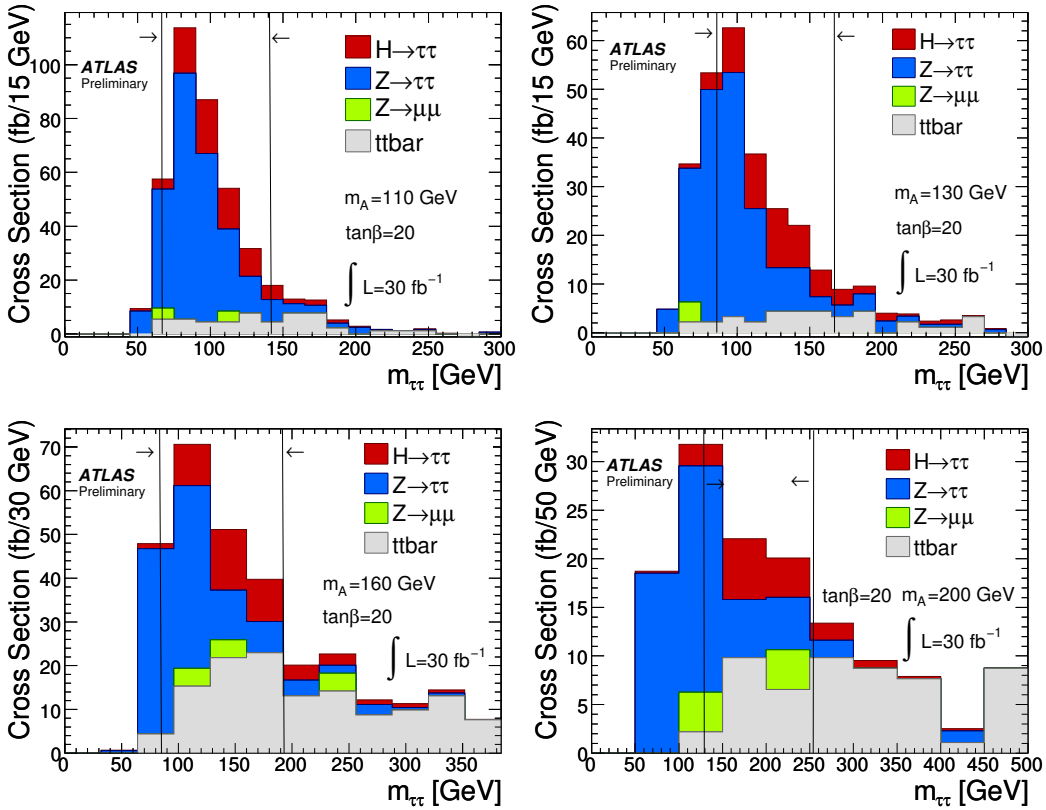
(Cross Section (in pb) for $m_A = 130\mathrm{GeV}$ and $\tan\beta = 20$)

Results:

- Low m_A Range: $Z \to \tau\tau$ Dominant Bckg.
- High m_A Range: $t\bar{t}$ Background Dominant

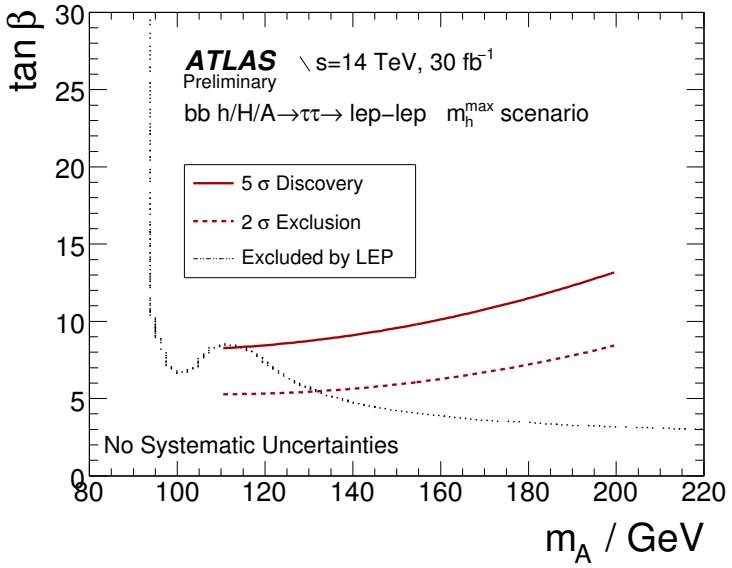
Dominant Systematic Uncertainties:

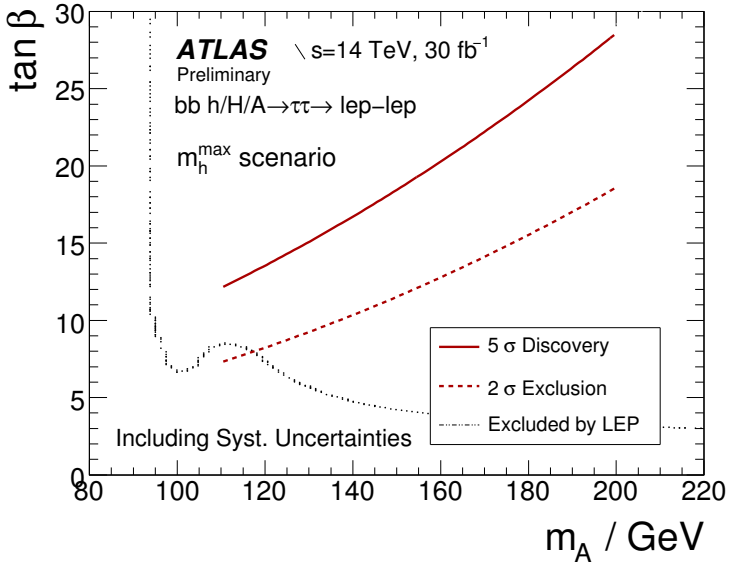
- Jet Energy Scale/Resolution
- b Tagging Efficiency

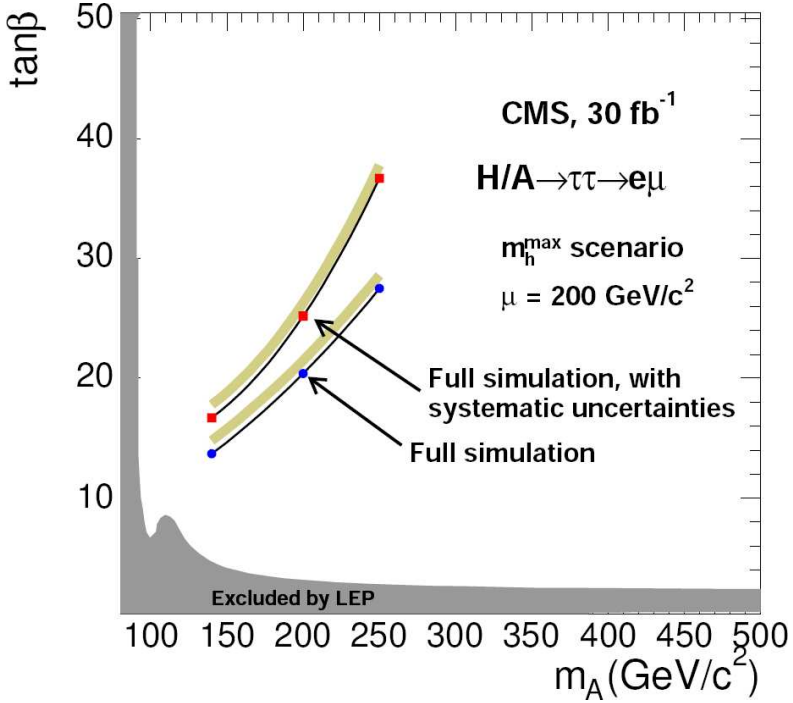


$Z \to \tau\tau$ Background Shape and Normalization Estimated from Data

Discovery Potential and Exclusion Limits:

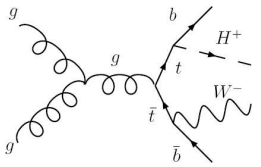




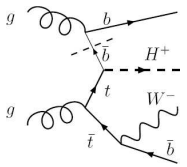


Production and Decay:

- $m_{H^+} < m_t$: $t \to H^+ b$, $H^+ \to \tau\nu$
  - $b\tau_{\mathrm{had}}\nu bqq$
  - $b\tau_{\mathrm{lep}}\nu bqq$
  - $b\tau_{\mathrm{had}}\nu b\ell\nu$

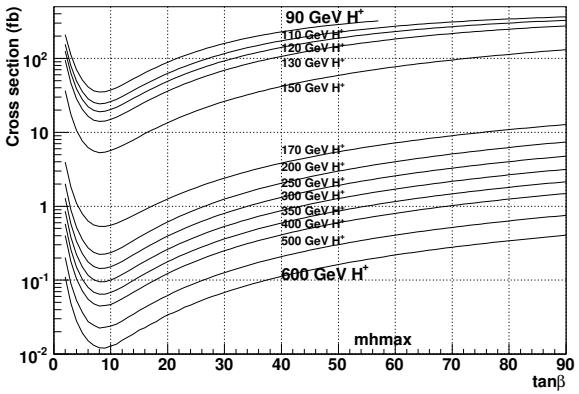


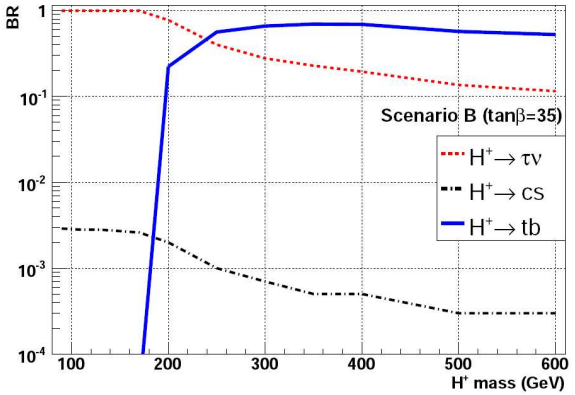
- $m_{H^+} > m_t$: $gb \to tH^+$, $H^+ \to tb$
  - $gg/gb \to t[b]H^+ \to bqq[b]\tau_{\mathrm{had}}\nu$
  - $gg/gb \to t[b]H^+ \to t[b]tb \to bW[b]bWb \to b\ell\nu[b]bqqb$



Triggers:

- High E_T Lepton
- Hadronic τ Decays
- High Missing E_T





$t \to bH^+ \to b\tau_{\mathrm{had}}\nu$ $\qquad$ $t \to bqq$:

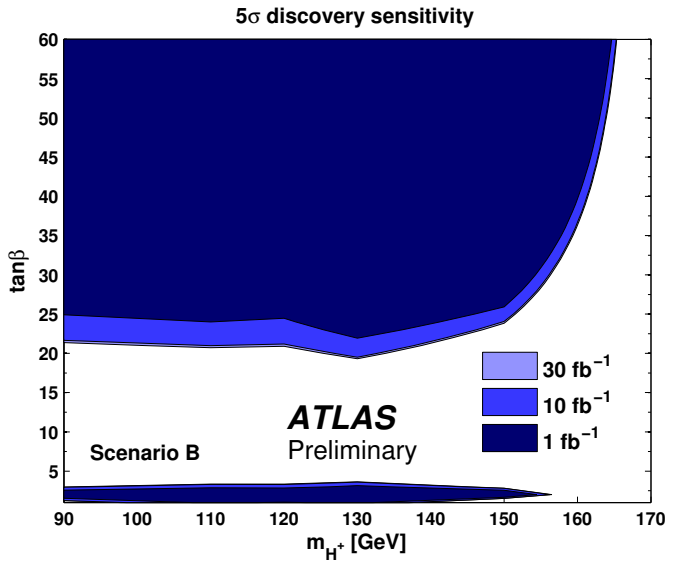
High Cross Section × Branching Fraction

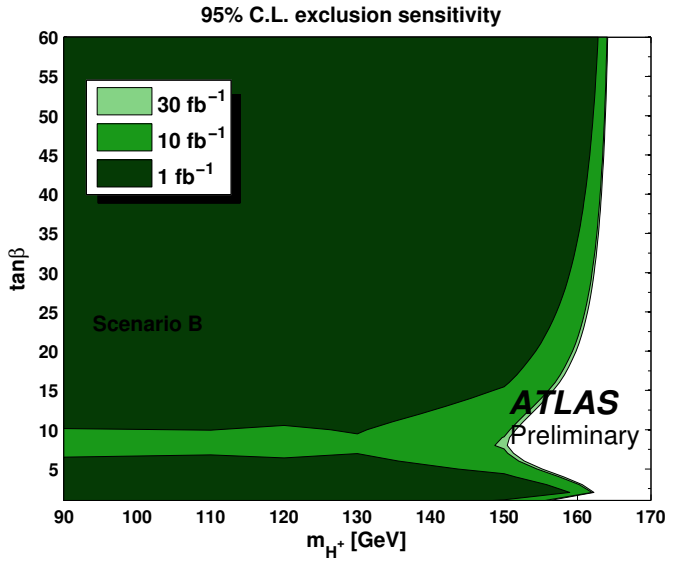
Main Backgrounds:

- $t\bar{t} \to WbWb$ with one $W \to \tau_{\mathrm{had}}\nu$
- Single Top
- W+Jets
- QCD Dijet Events

Selection:

- **Preselection:**
  - τ Jet
  - 2 b-Jets
  - $\geq$ 2 non-b-jets
  - Lepton Veto
  - $E_T^{\mathrm{miss}} > 30\,\mathrm{GeV}$
- **Anti-QCD Cuts:**
  - W/t Mass Reconstruction
  - $p_{T,\,t_1}/p_{T,\,t_2}$
  - $\Delta\phi(t_1,\,t_2)$
- **Likelihood Discriminant**
  - Seven Variables
  - Against Dominant $t\bar{t}$ Background





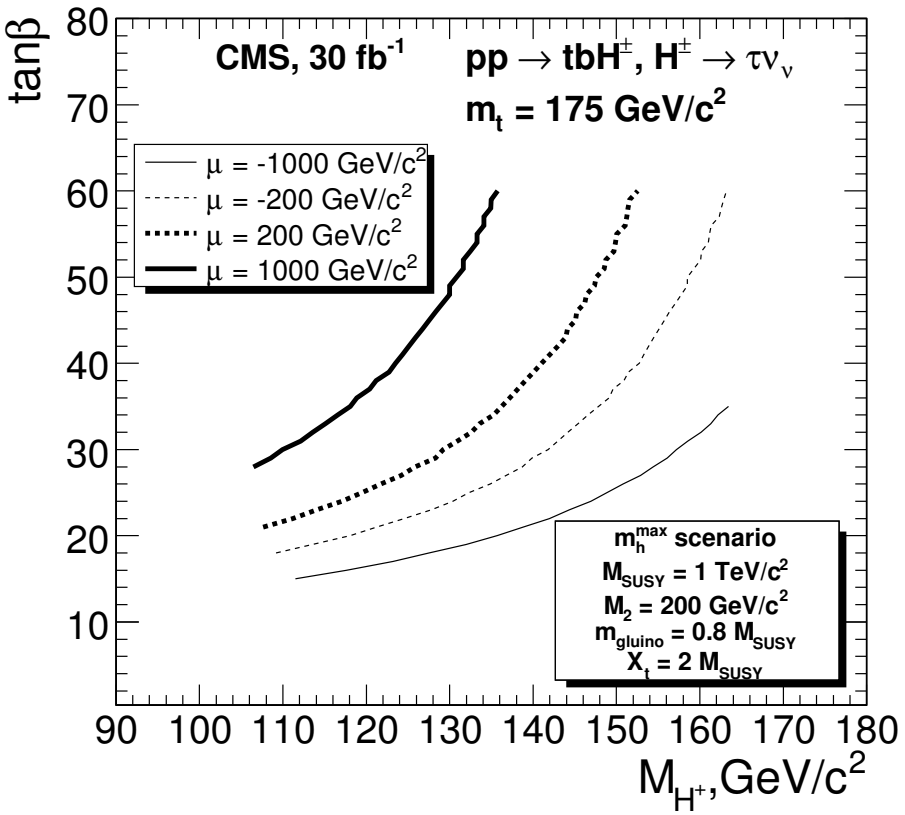
$t \to bH^+ \to b\tau_{\mathrm{had}}\nu$ $\quad$ $t \to b\ell\nu$:

MAIN BACKGROUNDS:

- $t\bar{t} \to WbWb$ with one $W \to \ell\nu$
- W + 3 Jets with one $W \to \ell\nu$

SELECTION:

- **Preselection:**
  - Triggered Lepton
  - $\geq$ 3 Jets (1 b tagged)
  - τ Jet
    ($E_T > 40\,\mathrm{GeV}$ and $p^{\mathrm{track}}/E^{\tau} > 0.8$)
  - Charge: $Q(\ell) + Q(\tau) = 0$
  - $E_T^{\mathrm{miss}} > 70\,\mathrm{GeV}$
- **Main Systematic Uncertainties:**
  - $t\bar{t}$ Cross Section
  - Luminosity Measurement
  - τ (b)-Tagging
  - Jet Energy Scale
- **Discovery Sensitivity**
  - $\tan\beta > 50$: Up to almost m_t
  - All $\tan\beta$: For $m_{H^+} < 130\,\mathrm{GeV}$



$t \to bH^+ \to b\tau_{\mathrm{lep}}\nu$ $\quad$ $t \to bqq$:

Event Characteristics:

- Isolated Lepton from τ Decay
- Large E_T^{miss}

Main Background: SM $t\bar{t}$ **Selection:**

- $p_T^{\ell} > 5\,\mathrm{GeV}$
- $E_T^{\mathrm{miss}} > 120\,\mathrm{GeV}$
- ≥ 4 Jets ($p_T > 40\,\mathrm{GeV}$ (2 b-Tags)

Reconstruction:

- W Mass Reconstruction
- Assignment of b Jet
  - Angular Correlation
  - Jet Charge
- $100\,\mathrm{GeV} < m(t_{\mathrm{had}}) < 300\,\mathrm{GeV}$

$t\bar{t}$ Suppression:

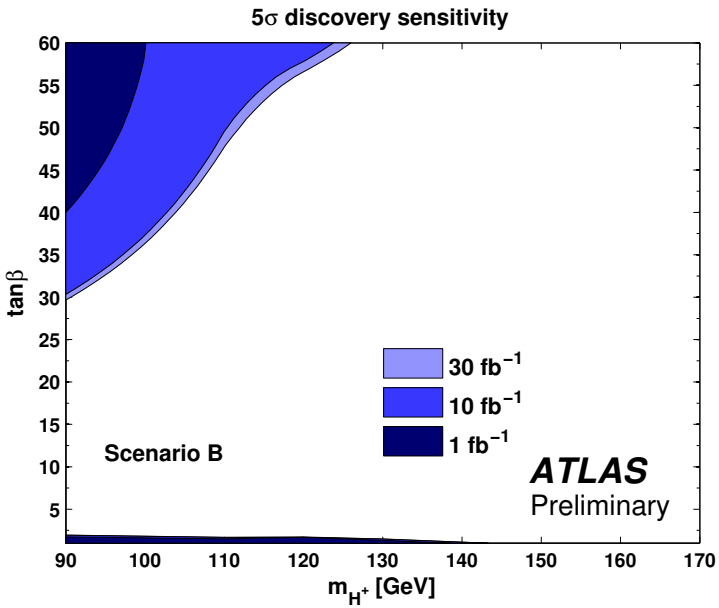
- Angle ψ in W Center-of-Mass Frame

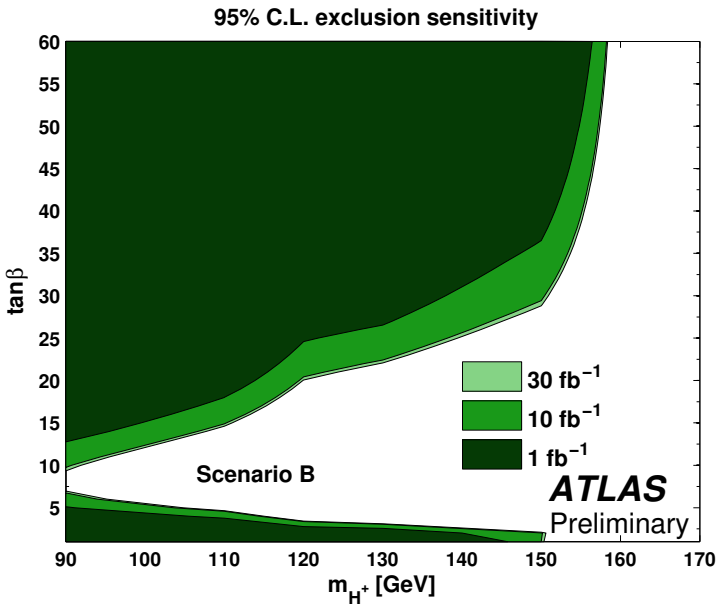
$$\cos\psi = \frac{2m_{\ell b}^2}{m_t^2 - m_W^2} - 1$$

- Transverse W Mass m_W^T

Statistical Significance:

- Calculated from m_W^T and $m_{H^+}^T$ Distributions





$b\underbrace{\ell\nu[b]b}_{H^+\to tb}qqb$:

Event Characteristics:

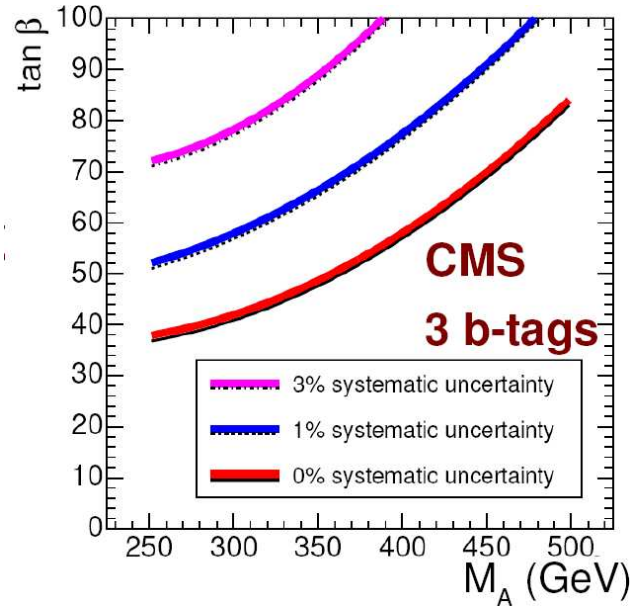
- 3-4 b Jets
- Lepton from W Decay
- 2 Reconstructed Ws (Tops)

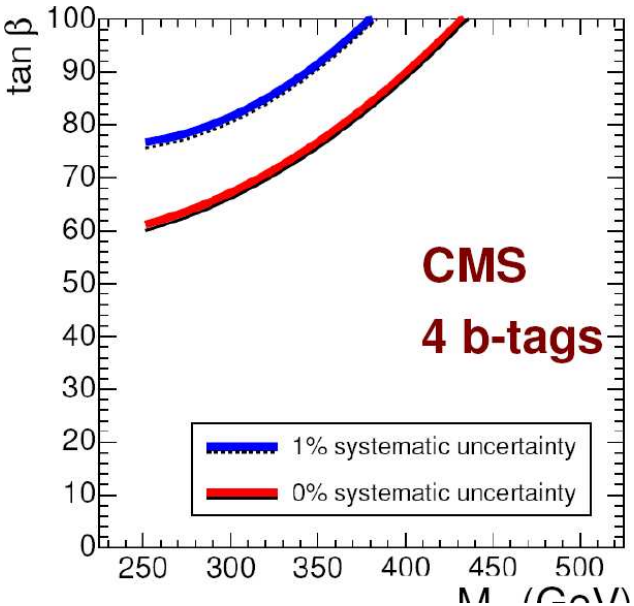
Event Selection: 3 (4) b-Tags

- One Muon w/ $p_T > 20\,\mathrm{GeV}$
- $\geq 5(6)$ Jets with $p_T > 25\,\mathrm{GeV}$
- 3(4) b-Tags
- Kinematic Fit w/ Mass Constraint for W and t
- Likelihood to Suppress Combinatorial Background
- 3 b-Tags: Likelihood to Suppress $t\bar{t}+X$
  4 b-Tags: b Discriminator

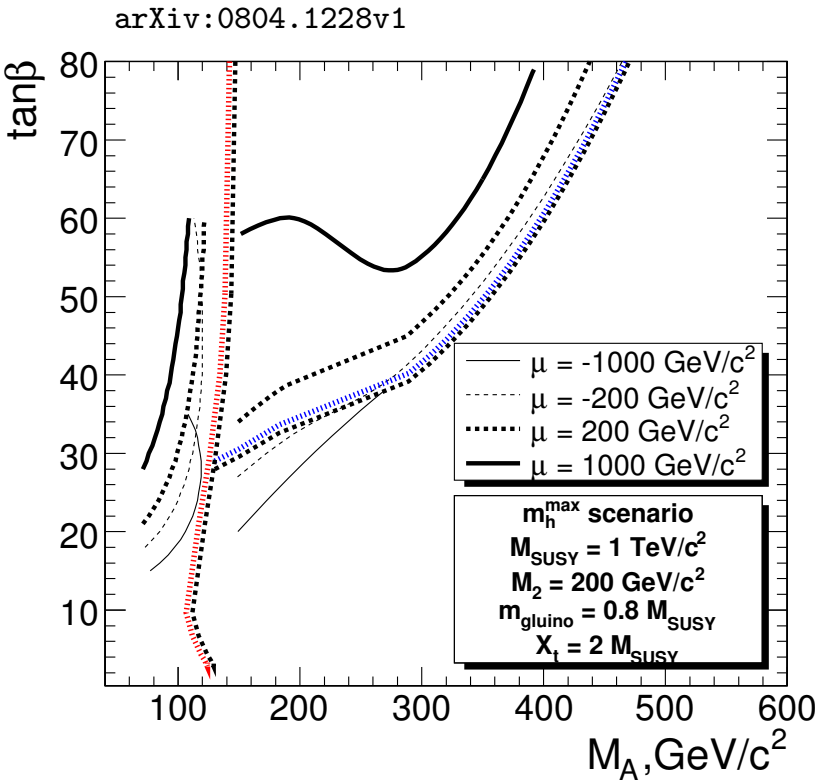
Discovery Reach:

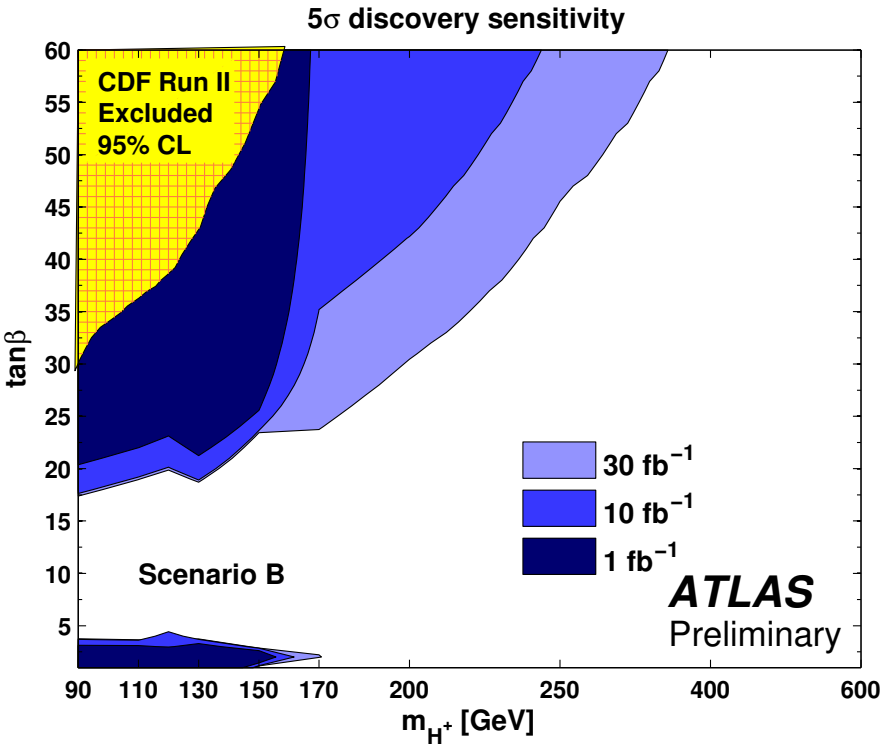
- Even Assuming Low Systematic Uncertainties:
  Almost no Sensitivity in MSSM Space





CMS AND ATLAS Discovery Contours in the MSSM ($m_h^{\max}$ Scenario)





Conclusion

- $M_{H^+} \leq m_t$: Will be Covered at LHC
  (Even Though High Luminosities Integrated Might be Needed)
- $M_{H^+} > m_t$: Sensitivity Only for High tan β
- (ATLAS: Low-m_A/Low-tan β Region Has Limited MC Statistics)

Part II

Measurement of Higgs Boson Properties

$h/H/A \to \mu\mu$:

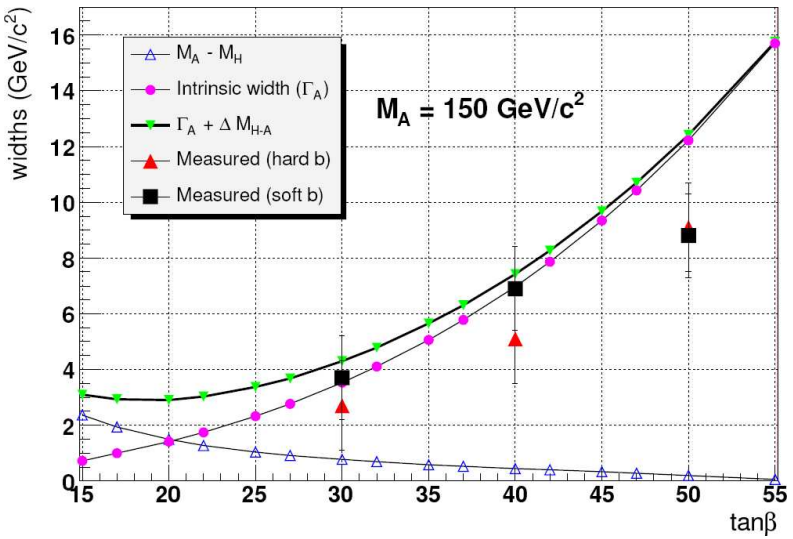
- Natural Higgs Boson Width Comparable to $m_{\mu\mu}$ Resolution $\mathcal{O}(\text{few MeV})$

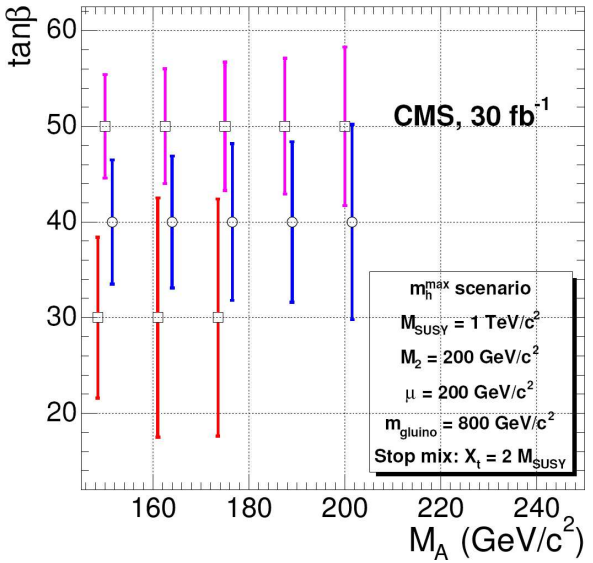
  $\to$ Possibility of Direct Measurement of Higgs Boson Width
- Higgs Boson Width is Function of $\tan\beta$

  $\to$ Sensitivity to $\tan\beta$ for $m_A \geq 150\,\text{GeV}$

MEASUREMENT:

- Fit $m_{\mu\mu}$ Distribution (Voigtian)
- Correct for Mass Resolution
- Correct for Not-Perfect Mass Degeneracy of m_A and m_H

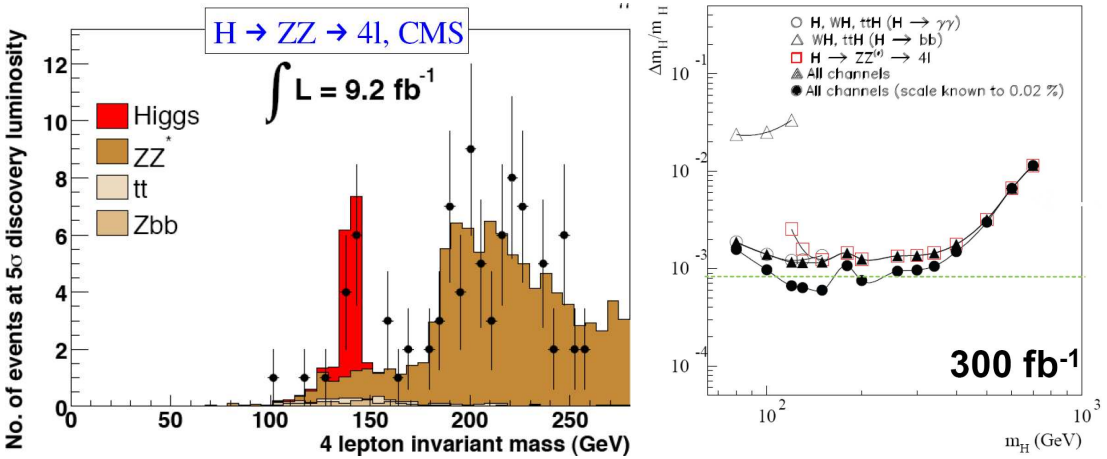




Measurement of the Higgs Boson Mass

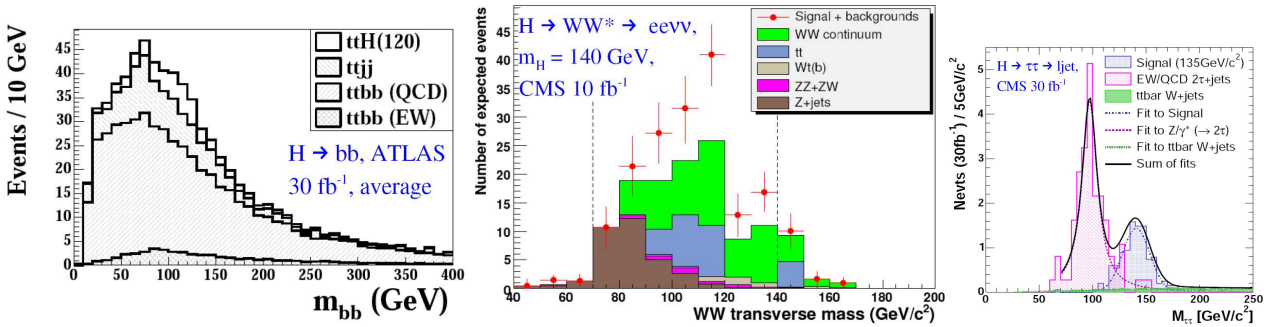
Standard Model Higgs Boson

- Use $H \longrightarrow \gamma\gamma$ or $H \longrightarrow ZZ \longrightarrow 4\ell$
- Measure Invariant Mass Peak
- Precision: 0.1% for $m_H < 400\,\mathrm{GeV}$
- Systematics Dominated by Knowledge of Energy Scale



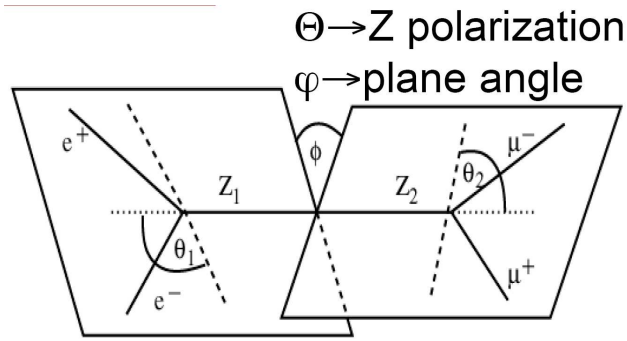
Non-Standard Model Higgs Boson

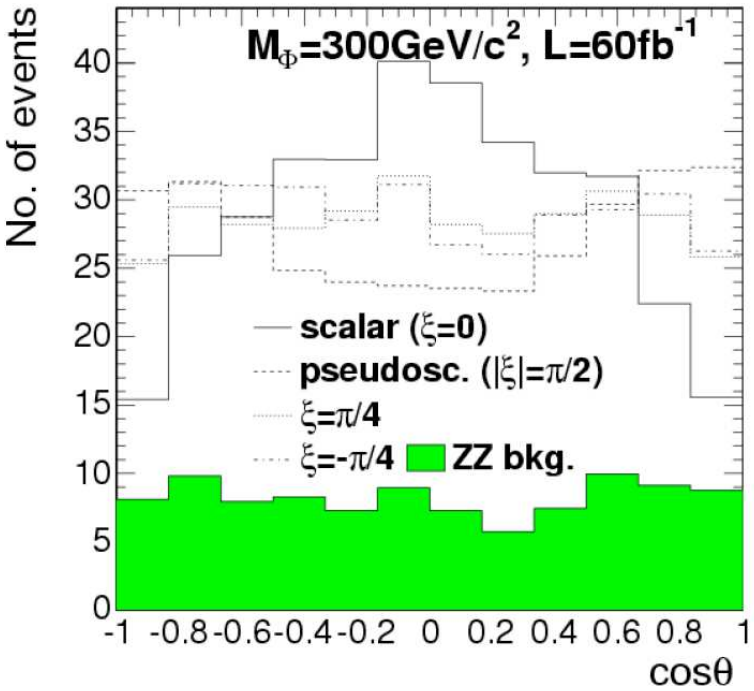
- Coupling to Z and W Suppressed
- Reconstruction in $H \longrightarrow bb$, $H \longrightarrow \tau\tau$ (Collinear Approximation), $H \longrightarrow WW$ (Transverse Mass)

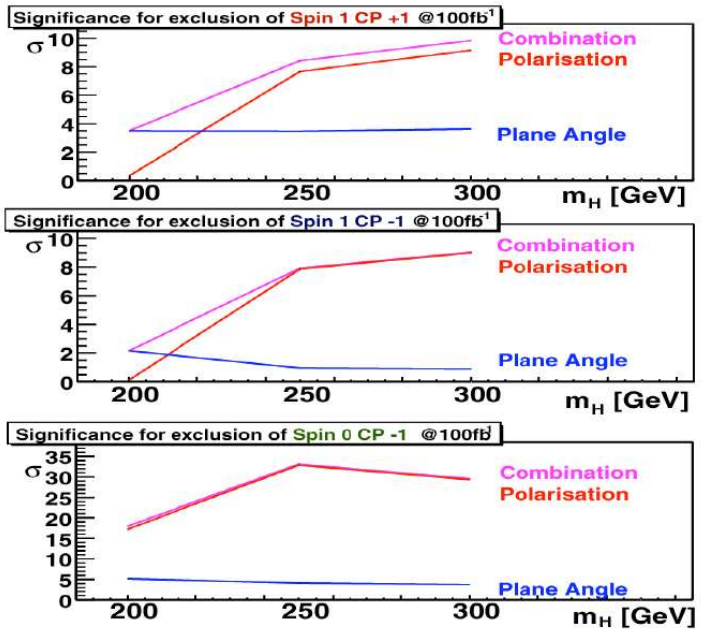


Measurement of Spin/CP of the Higgs Boson

- Observation of $gg \longrightarrow H$ or $H \longrightarrow \gamma\gamma$ Excludes Spin-1
- For $m_H > 200\,\mathrm{GeV}$ Study Spin/CP from $H \longrightarrow ZZ \longrightarrow 4\ell$
- Exclusion can be deduced from θ and ϕ Distributions







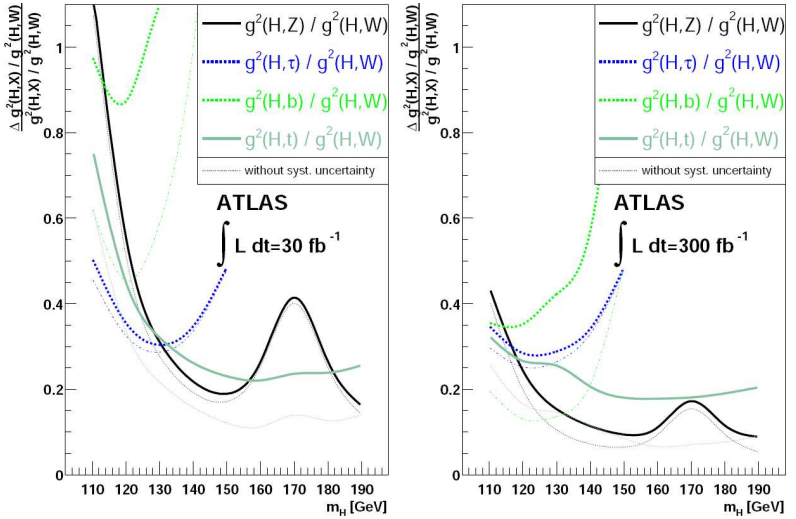
The rate for $H \longrightarrow xx$ is given by (Intermediate Mass Range – Narrow Width Approximation)

$$\sigma(H) \times \mathcal{B}(H \longrightarrow xx) = \frac{\sigma(H)^{\mathrm{SM}}}{\Gamma^{\mathrm{SM}}} \cdot \frac{\Gamma_p \Gamma_s}{\Gamma}$$

Model-Independent Approach (ATL-PHYS-2003-030)

- At Hadron Colliders Not All Decay Modes Observable
- Only Ratios of Couplings Measurable
- Global Likelihood Fit at Each Possible Higgs Mass

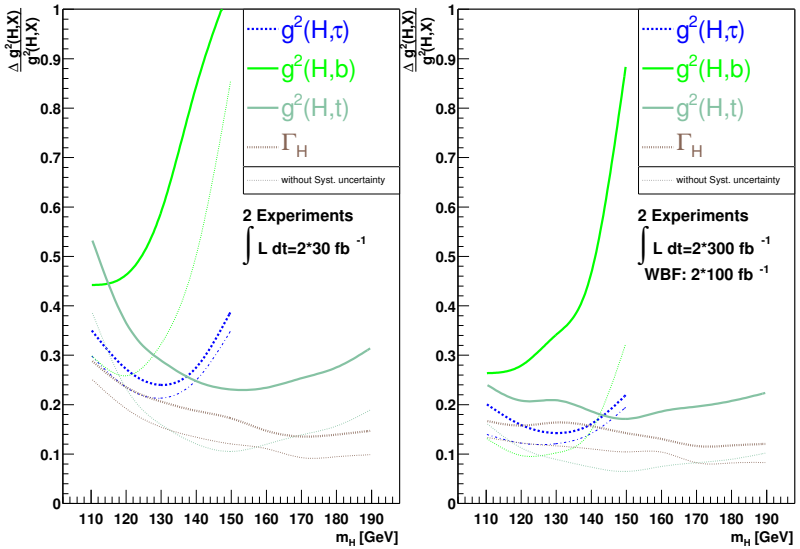
  Input: Measured Rates for Each Production Mode
  Output: Couplings Normalized to WW Coupling



(Almost) Model-Independent Approach

(Phys Rev D70,113009,2004)

- Allows for Extraction of Absolute Couplings
- Perform General Fit Assuming $\Gamma_V \leq \Gamma_V^{\mathrm{SM}}$
  Measured $\Gamma(H \longrightarrow VV)$ Puts Upper Bound Total Higgs Width
- Fitting Procedure Similar to Model Independent Approach
- Additional Assumption:
  - No Non-SM Particles in $H \longrightarrow \gamma\gamma$ and $gg \longrightarrow H$.
  - SM Couplings for W/Z



MSSM Higgs Boson Discovery Potential and Measurement of Higgs Boson Properties have been Reviewed

MSSM Discovery Potential:

- $h/H/A \to \mu\mu$:
  - Discovery Possible for $m_A \sim 150\,\mathrm{GeV}$ and Medium $\tan\beta$ (~ 30)
  - For Higher m_A Large $\tan\beta$ Required
- $h/H/A \to \tau\tau$:
  - Mass Range up to $m_A = 800\,\mathrm{GeV}$ Covered
  - High Higgs Boson Masses Need High $\tan\beta$
- **Charged Higgs:**
  - $H^+ \to \tau\nu$ Prime H^+ Discovery Channel in MSSM
  - $H^+ \to tb$ Does Not Have Discovery Sensitivity
  - Light H^+ Mass: Sensitive up to Masses Close to m_t
  - High H^+ Mass: High Luminosity Needed and Medium $\tan\beta$ Range not Covered

Measurement of Higgs Boson Properties:

- Important Measurements Possible Like
  - Mass
  - Width
  - Spin/CP
  - Couplings