Prospects for Beyond Standard Model Higgs Boson Searches at the LHC

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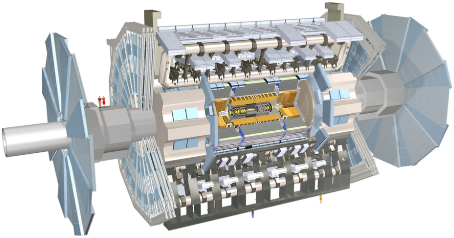
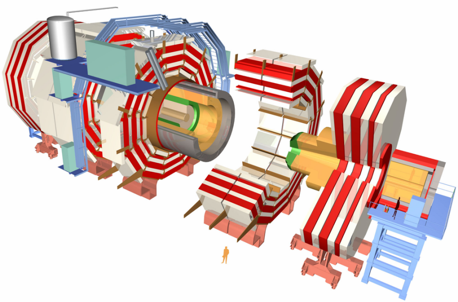
Weak Interactions and Neutrinos WIN´09

Outline

Experiments



ATLAS

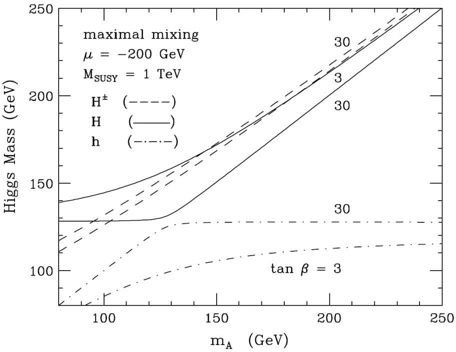


CMS

- Excellent Particle Reconstruction and Identification Performance
- Precise Calorimeters with Large Coverage (up to $|\eta| \approx 4.9$ for jets)
  - good E_T^{miss} resolution
- Toroidal Magnetic Field for Muon p_T (ATLAS)
- High Field (4T instead of ATLAS 2T) Central Solenoid (CMS)

MSSM Higgs Sector

- Five Physical Higgs Bosons
  - two CP-even: h and H
  - one CP-odd: A
  - two charged: $H^{\pm}$
- Two Free Model Parameters
  describe the Higgs sector at tree level
  - mass of CP-odd neutral boson A
  - ratio of higgs field vacuum expectation values tan β
- Large Loop Corrections Enter
  - $m_h < m_Z \rightarrow m_h \lesssim 130\text{GeV}$
  - fixed in benchmark scenarios
  - m_h max (maximal mixing)
  - no mixing in stop sector

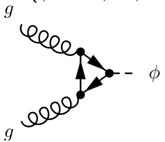


Unless otherwise noted, all plots from

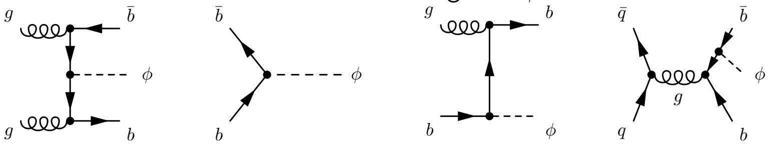
- CMS: Physics Technical Design Report Vol.II (CERN/LHCC 2006-021)
- ATLAS: Expected Performance of the ATLAS Experiment, Detector, Trigger and Physics (CERN-OPEN-2008-020)

Production and Decay of Neutral Higgs Bosons $h/H/A$

- Markedly Different from Standard Model (for two of the three bosons)
  - WW and ZZ decays suppressed or absent
  - coupling to 3rd generation fermions enhanced in large parts of parameter space
- Direct Production via Gluon Gluon Fusion
  dominates at low $\tan\beta$ and low m_A ($\phi \in h, H, A$):



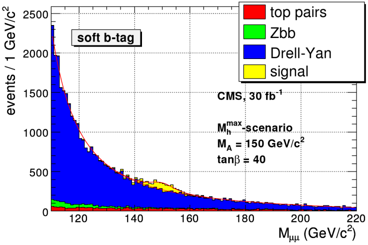
- b-quark Associated Production dominates at high $\tan\beta$:



- Decay Mostly to bb and $\tau\tau$
  - bb BR $\approx$ 90% (very difficult)
  - $\tau\tau$ BR $\approx$ 10%
  - $\mu\mu$ BR $\approx$ 0.03%

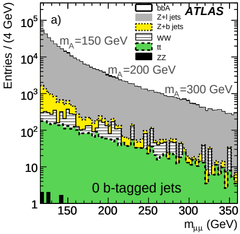
$bbh/H/A, h/H/A \rightarrow \mu\mu$

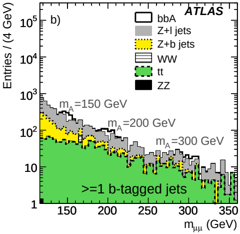
- Motivation
  - BR small in SM but enhanced by $\tan\beta$
  - excellent mass resolution
  - potential to distinguish between h, H and A in the intensive coupling region
- Backgrounds and Event Selection
  - trigger and cut on μ
  - $Z+$ jets: b-tagging
  - $t\bar{t}$: E_T^{miss}, central jet veto, μ angular correlations
  - $t\bar{t}$: estimated by data driven methods



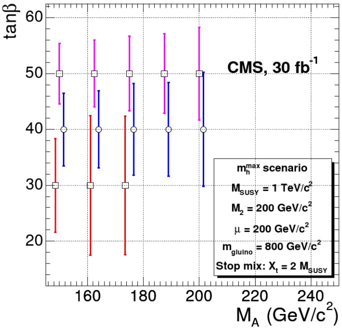
- CMS Analysis
  - soft b-tag to improve low p_T efficiency

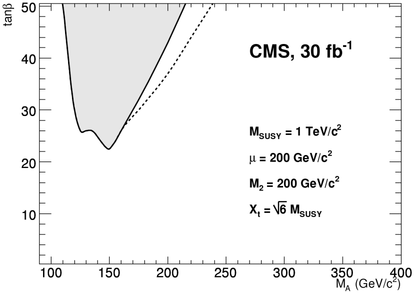
- ATLAS Analysis
  - 0 b-tagged jets dominated by $Z+$ jets
  - ≥ 1 b-tagged jets dom. by $t\bar{t}$ and $Z+$ jets

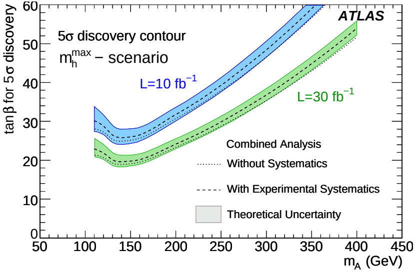




$bbh/H/A, h/H/A \to \mu\mu$ Discovery Potential



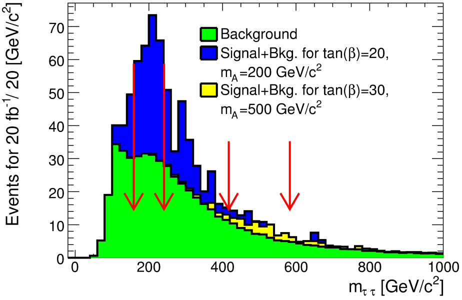


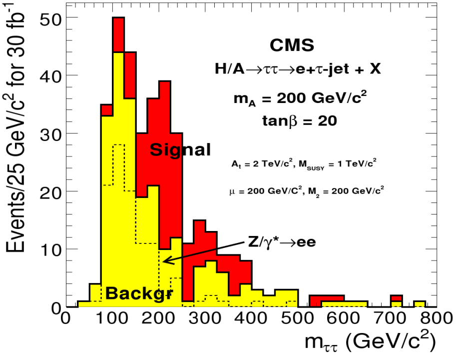


- Results
  - low to medium mass coverage for $\tan\beta > 20$
  - sensitivity to $\tan\beta$ from Higgs boson width (CMS)

$bbh/H/A, h/H/A \to \tau(\mathrm{lep})\tau(\mathrm{had})$ (CMS)

- **Motivation**
  - good BR because of hadronic decay
  - e/μ to trigger on
- **Trigger**
  - single e/μ or $e/\mu + \tau$
- **Backgrounds and Event Selection**
  - τ selection, exactly one b-tag
  - $t\bar{t}$: jet veto, E_T^{miss} to lepton correlation
  - $t\bar{t}$ dominant for μ+jet
  - Z+jets, $Z \to$ leptons $\propto t\bar{t}$ for e+jet



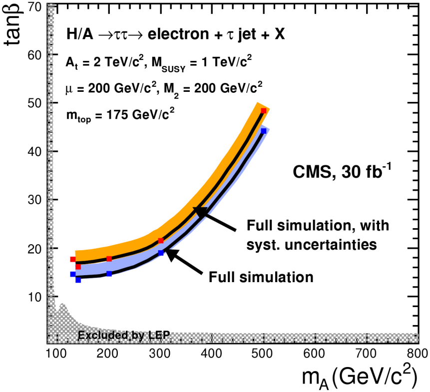


left: μ+jets CMS Note 2006/105
right: e+jets CMS Note 2006/75

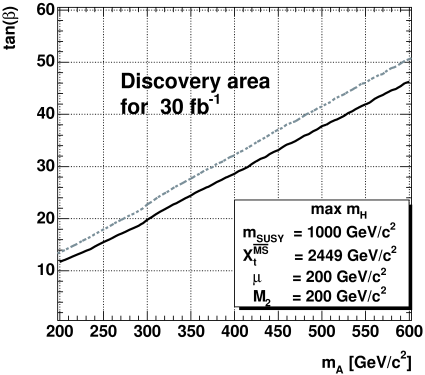
$bbh/H/A, h/H/A \rightarrow \tau(\mathrm{lep})\tau(\mathrm{had})$ (CMS)

Discovery Potential

e + jets



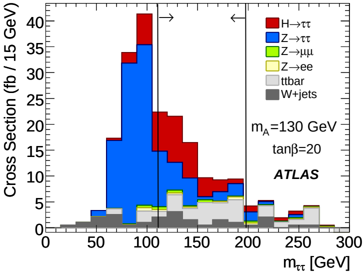
μ + jets

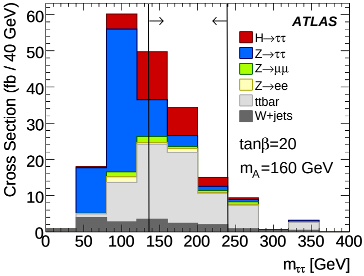


- good for intermediate to low mass range
- (ATLAS analysis in preparation)
- at high masses higher sensitivity in the fully hadronic channel

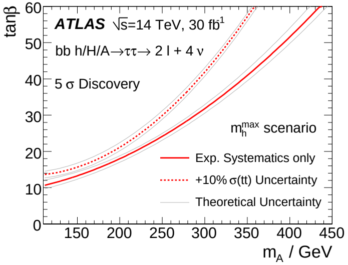
$bbh/H/A, h/H/A \rightarrow \tau\tau \rightarrow 2\ell 4\nu$ (ATLAS) / $e\mu 4\nu$ (CMS)

- Motivation
  - two leptons to trigger on
  - collinear approximation for $m_{\tau\tau}$
  - good at low mass
- Backgrounds and Event Selection
  - $Z \rightarrow ee/\mu\mu$: cut on dilepton mass, E_T^{miss}
  - $Z \rightarrow \tau\tau$ (dominates at low mass): b-tag
  - $Z \rightarrow \tau\tau$: shape and normalization estimated by data driven methods
  - $t\bar{t}$ (dominates at high mass): veto additional jets
  - cut on displaced vertices of τs (CMS)
- Systematic Uncertainties
  - jet energy scale / resolution
  - b-tagging efficiency

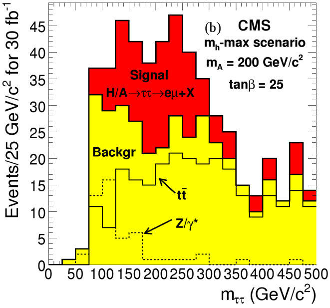


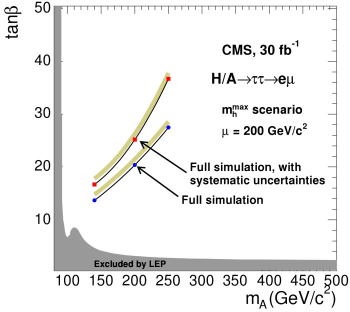


$bbh/H/A, h/H/A \to \tau\tau \to 2\ell 4\nu$ (ATLAS) / $e\mu 4\nu$ (CMS)



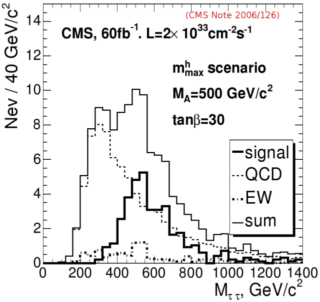
- Discovery Potential
  - best at low mass
  - needed tan β rises quickly with mass

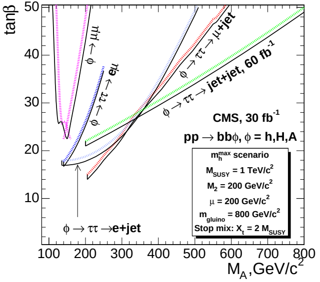




$bbh/H/A, h/H/A \rightarrow \tau(\mathrm{had})\tau(\mathrm{had})$ (CMS)

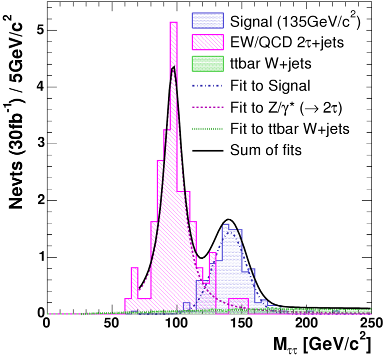
- **Motivation**
  - high hadronic branching ratio
  - dominant $h/H/A \rightarrow bb$ overwhelmed by QCD
  - τ tagging makes channel feasible
  - sensitivity for high masses
- **Event Selection**
  - hadronic final state, need good τ-trigger
  - τ identification
    - isolation in tracker
    - 1 or 3 tracks, hard leading track ($pt > 50\mathrm{GeV}$)
    - $\approx 50\%$ efficiency at a rejection of 100
  - exactly one b-tagged jet
- **Backgrounds and Systematics**
  - QCD jets: shape from data-driven method using signal free same-sign τs
  - uncertainty of τ fake rate due to tracker misalignment
  - E_T^{miss} scale uncertainty



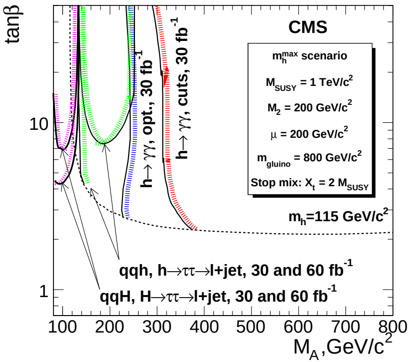


$h \to \gamma\gamma$ and VBF $h/H \to \tau\tau$ reinterpreted in MSSM

- VBF $qqh/H \to \tau\tau$
  - tag forward jets, large $|\Delta\eta|$
  - central jet veto
  - EW/QCD $\to 2\tau$ dominates

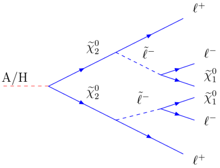


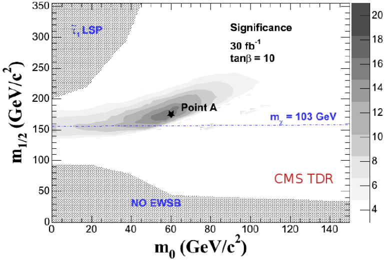
- $h \to \gamma\gamma$
  - tag γ pairs
  - need good EM calorimetry
  - small peak on huge QCD background

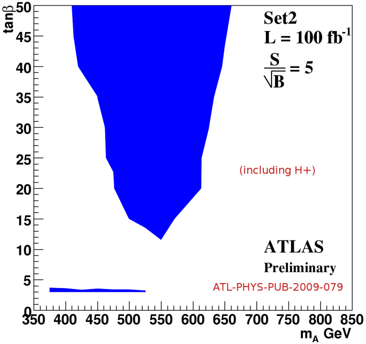


$A/H \to \tilde{\chi}_2^0 \tilde{\chi}_2^0 \to 4\ell + E_T^{\text{miss}}$

- Analysis
  - MSSM / mSUGRA points optimized for lepton BR



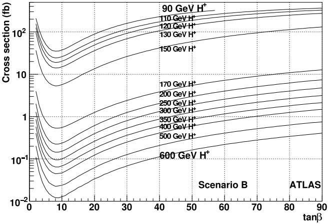




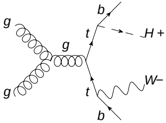
- Backgrounds and Event Selection
  - 4 leptons, opposite signs and flavours
  - $t\bar{t}$: jet multiplicity
  - ZZ, Zbb: E_T^{miss} lower bound, dilepton masses
  - SUSY, E_T^{miss} upper bound, jet multiplicity
- Systematic Uncertainties
  - little experimental uncertainty
  - strongly model dependent

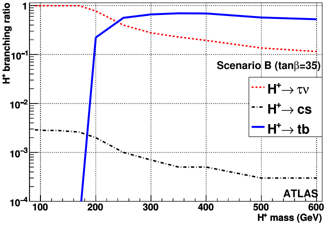
Charged Higgs Boson $H^\pm$ Searches

- Motivation
  - predicted by two Higgs doublet models (e.g. MSSM)
  - models with Higgs triplets (e.g. little Higgs)
  - smoking gun evidence for physics beyond the SM

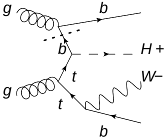


- Low Mass Case $m_{H^+} < m_t$
  - production via $t \rightarrow H^+ b$
  - decay via $H^+ \rightarrow \tau\nu$
  - small tan β: $H^+ \rightarrow cs$ (ATLAS analysis in preparation)





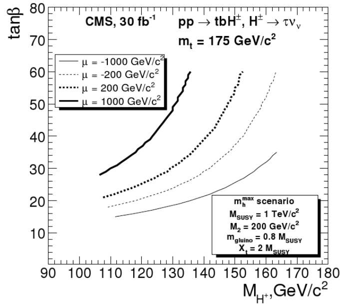
- High Mass Case $m_{H^+} > m_t$
  - production via $gg \rightarrow tbH^+$ and $gb \rightarrow tH^+$
  - decay via $H^+ \rightarrow tb$

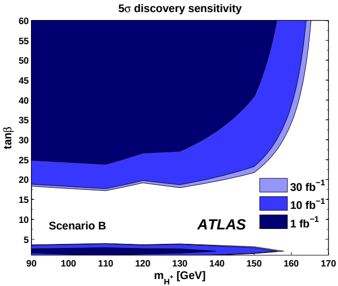


Light Charged Higgs Boson $m_{H^+} < m_t$

- Process $t\bar{t} \rightarrow bH^+bW \rightarrow b\tau\nu bW$
  - $b\tau(\mathrm{had})\nu bW(\mathrm{had})$ (ATLAS)
  - $b\tau(\mathrm{lep})\nu bW(\mathrm{had})$ (ATLAS)
  - $b\tau(\mathrm{had})\nu bW(\mathrm{lep})$ (ATLAS/CMS)
  - (ATLAS dilepton analysis in preparation)
- Selection and Reconstruction
  - b-tagged jets
  - τ-jets and/or leptons
  - hadronic W
    - t reconstruction
  - leptonic W
    - additional E_T^{miss}
    - lepton charge correlation with τ
  - hadronic τ
    - higher branching ratio
    - τ trigger crucial if W decays hadronically
  - leptonic τ
    - additional E_T^{miss} (relative to hadronic τ)
    - lepton to t angular correlation $\neq$ leptonic Ws from background

(arXiv:0804.1228v1)

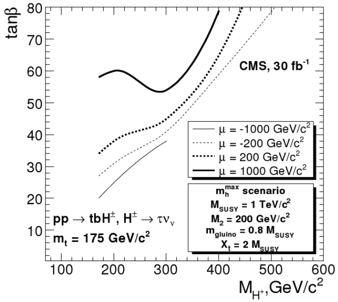


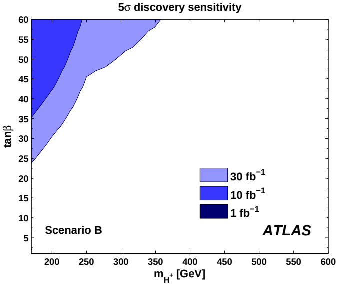


Heavy Charged Higgs Boson $m_{H^+} > m_t$

- Processes $gg \to tbH^+$ and $gb \to tH^+$
  - $t \to bW(\text{lep}),\ H^+ \to tb \to bW(\text{had})b$
    - $b\ell\nu btb \to b\ell\nu bbqqb$
    - $b\ell\nu tb \to b\ell\nu bqqb$
  - $t \to bW(\text{had}),\ H^+ \to \tau(\text{had})\nu$
    - $bqqb\tau(\text{had})\nu$
    - $bqq\tau(\text{had})\nu$
- Fully Hadronic Channel most sensitive
  - transverse mass of H^+ from MET and τ
  - t reconstructed as for light charged Higgs Boson
- Backgrounds
  - $t\bar{t}$+2b and $t\bar{t}$+jets dominate
  - W+jets, single top, QCD multi jet
- Exploit Helicity Correlation
  - $W \to \tau\nu$ different from $H^+ \to \tau\nu$
  - high momenum charged track

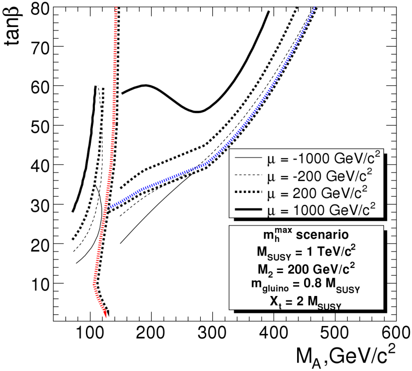
(arXiv:0804.1228v1)

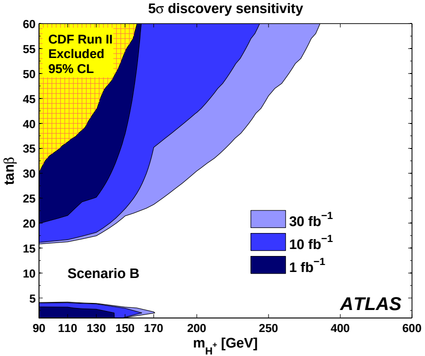




ATLAS and CMS Expected Discovery Countours (m_h max)

(arXiv:0804.1228v1)





- Light Charged Higgs Boson $m_{H^+} < m_t$
  - mostly covered at LHC
    - difficult in intermediate tan β range with standard model decays of H^+
    - H^+ to SUSY particles might offer sensitivity
  - CMS: SUSY corrections sizable, lower sensitivity estimate
  - ATLAS: limited MC statistics
- Heavy Charged Higgs Boson $m_{H^+} > m_t$
  - difficult except for the highest tan β

ATLAS and CMS Expected Discovery Countours (m_h max)

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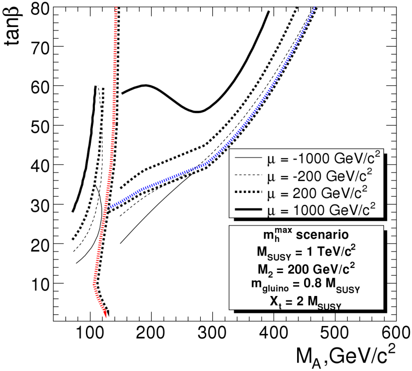

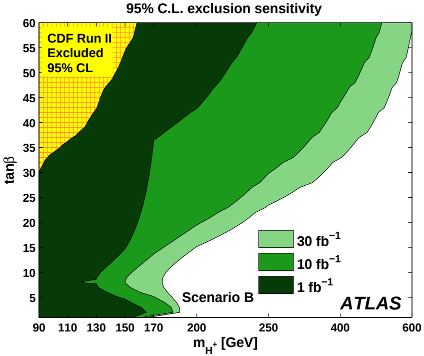

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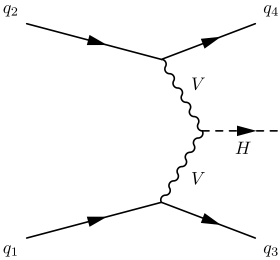
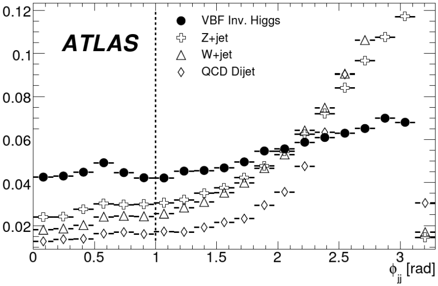
Invisible Higgs Bosons in Vector Boson Fusion (ATLAS)

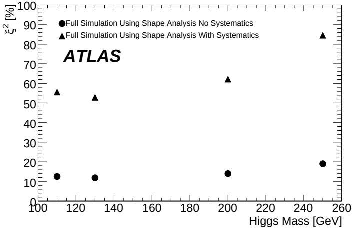


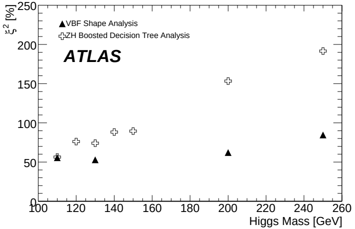
- Higgs Bosons Might Decay Invisibly
  - R-parity conserving MSSM: LSP
  - R-parity violating MSSM: majorons
  - models with extra dimension: graviscalars
- Strategy look for E_T^{miss} and jets in VBF
  - more sensitive than associated production: $ZH, Z \to \ell\ell$
  - ϕ_{jj} shape well known theoretically
- Backgrounds
  - QCD jets (fake E_T^{miss})
  - W+jets, $W \to \ell\nu$ (acceptance)
  - Z+jets, $Z \to \ell\ell$ (acceptance)
  - Z+jets, $Z \to \nu\nu$ (irreducible)
  - non standard model backgrounds not considered (model dependent)
- Trigger
  - $E_T^{\text{miss}} > 70\text{GeV}$ ($\approx 98\%$)
  - (forward) jet triggers



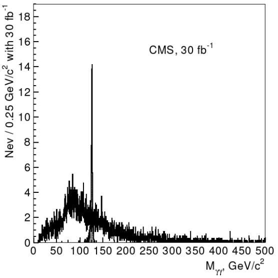
Invisible Higgs Bosons in Vector Boson Fusion (ATLAS)

- Event Selection
  - E_T^{miss} cut crucial against QCD
  - lepton veto vs. W and Z + jets
  - VBF tagging jets, $\eta_1 \eta_2 < 0$, $\Delta\eta > 4.4$
  - central jet veto
  - $I = \min\left[\varphi(E_T^{\text{miss}}) - \varphi(\text{tagjets})\right] > 1\text{rad}$ vs. mismeasured QCD
- Systematic Uncertainties
  - underlying event (CJV): 49%
  - jet energy scale / resolution: 10%
    - also affects E_T^{miss}
  - ϕ_{jj} shape 10% th., 11.3% th. + exp
- Results and Conclusion
  - $\xi^2 = \text{BR}(h \to inv.)\frac{\sigma_{BSM}}{\sigma_{SM}}$
  - 30fb^{-1}: 95% exclusion up to 250GeV for SM-cross section

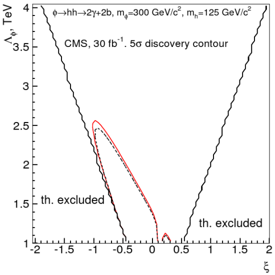


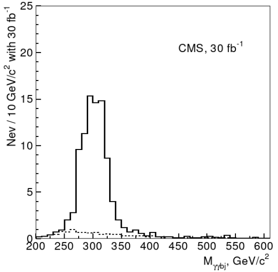


Radions in 5D Randall-Sundrum Model (CMS)



- Motivation
  - provides solution for hierarchy problem
- Channels
  - $\Phi \to hh \to \tau\tau bb$ (< 960fb)
  - $\Phi \to hh \to \gamma\gamma bb$ (< 71fb) more sensitive
- Analysis Strategy
  - diphoton trigger
  - $\gamma\gamma + \text{jets}$: b-tagging
  - excellent mass resolution: background from data
  - $m_{\gamma\gamma}$ cut





More Beyond Standard Model Higgs Boson Searches

- Fermiophobic Higgs Boson: can reinterpret SM searches
  - associated WH to 3 leptons and $h \to \gamma\gamma$
- $A \to ZH \to \ell\ell bb$
  - promising for low $\tan\beta$ and $m_Z + m_h < m_a < 2m_t$
- Higgs Boson Production in SUSY Cascades
  - strongly dependent on SUSY point and parameters
- CP violating MSSM
  - promising in VBF, $bbh, h \to \mu\mu$
  - in maximally CP-violating scenario CPX only a small region is uncovered
- Doubly Charged Higgs Bosons
  - littlest Higgs model, left-right symmetric models
  - VBF $qqH^{++} \to WW$ double leptonic
- Generic Resonances in VBS
  - generic phenomenological approach to EWSB
  - can also model Higgs boson-like scalars

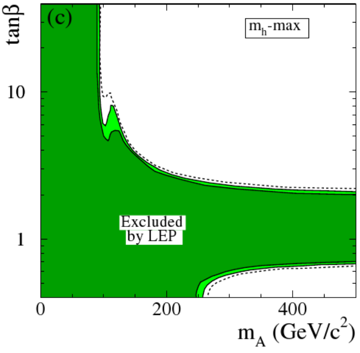
Conclusion and Outlook

- ATLAS and CMS are Prepared to Find MSSM Higgs Bosons
  - if MSSM is realized at least one Higgs boson will be found
  - discovery for some parameter points may need a lot of data
  - large regions in parameter space can be excluded quickly
- More Exotic Models are Also Tested
  - other supersymmetric models
  - Littlest Higgs model
  - Randal-Sundrum models
  - Invisible Higgs Bosons
  - generic resonances in VBS and more . . .
- The Experiments are Already Taking Data
  - cosmic muons help understand the running detectors
  - well prepared for collisions at the end of the year

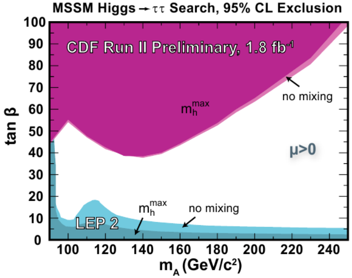
Appendix

Neutral MSSM Higgs Boson Exclusion Limits

(CERN-PH-EP/2006-001)



(CDF note 9071)



(D0 note 5935-CONF)