Higgs Searches Beyond the Standard Model

Rainer Mankel

Deutsches Elektronen-Synchrotron (DESY) 汉堡

on behalf of the ATLAS, CDF, CMS and D0 Collaborations

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HELMHOLTZ ASSOCIATION

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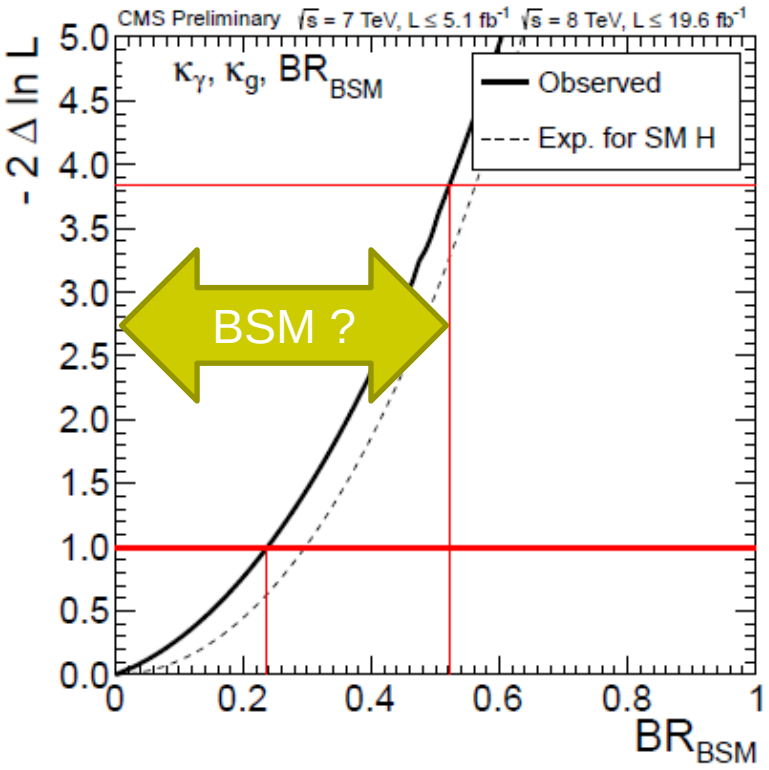
Introduction

- Most relevant questions after discovery of a Higgs boson at ~125 GeV:
  - properties of this Higgs boson, couplings etc → see talks by James, Romain & Elisabetta
  - structure of the Higgs sector
- At the level of current measurements, the observed state is compatible with the Standard Model Higgs
  - but SM features quadratically divergent self-energy corrections at high energies (Hierarchy problem)
  - many other open questions: dark matter, naturalness ("μ problem"), CP violation in early universe
- Even with SM-like tree-level production mechanisms, there is still plenty of room for non-SM decays of the H(125)
  - BR_{BSM}<52% at 95% CL

CMS PAS HIG-13-005



Searching additional Higgs states is potentially the fastest way of answering these questions

Extended Higgs Sectors

MSSM
- two complex scalar doublet fields
- five physical Higgs bosons

Standard Model
- single complex scalar doublet field
- one physical Higgs state (H)

Additional SM-like Higgs
- high mass searches

Fermiophobic
- not coupling to fermions

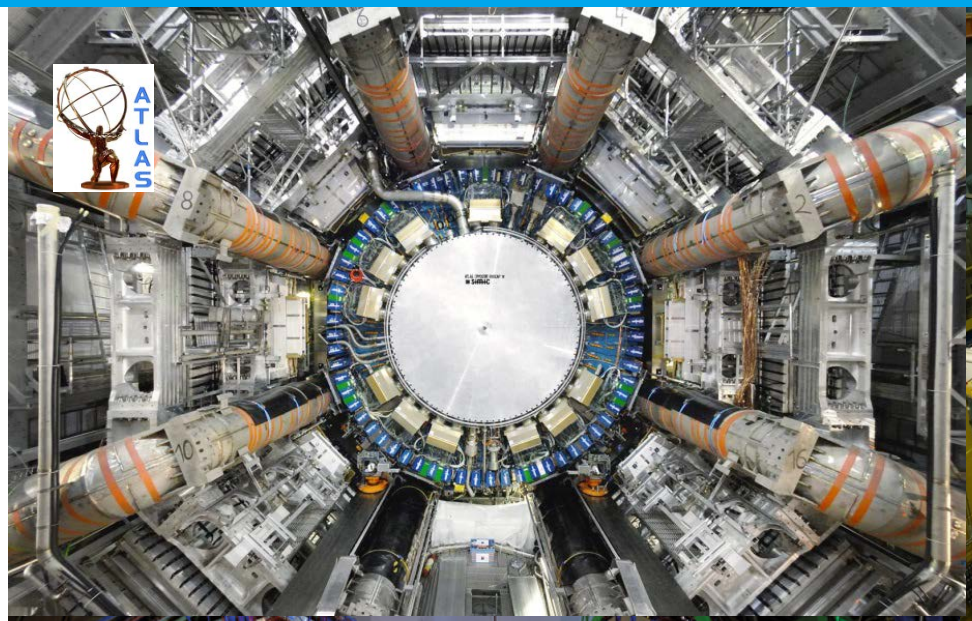
2HDM Models
- more general formulation of model with two scalar fields
  - MSSM is a type-II 2HDM
- CP violation and FCNC possible

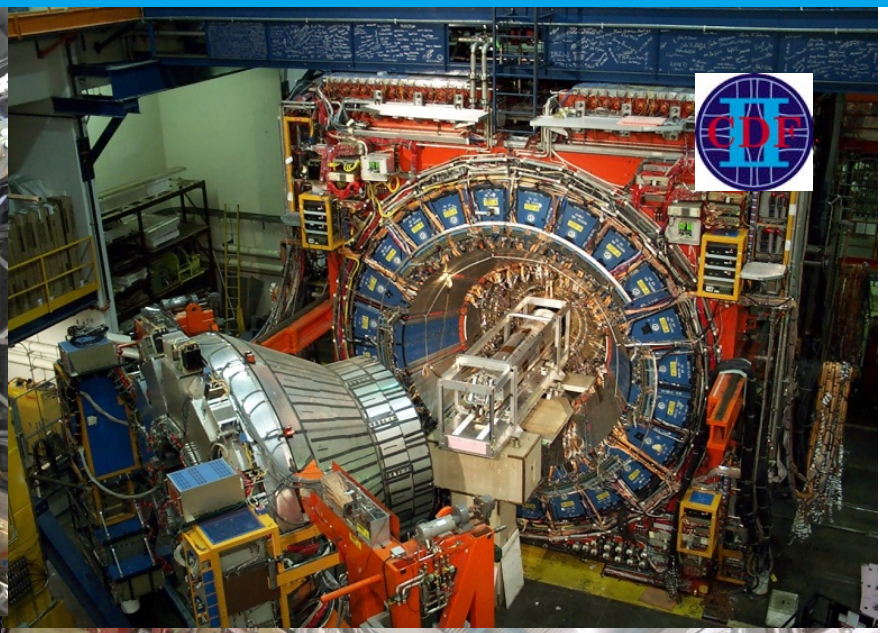
NMSSM
- two complex scalar doublet fields + additional singlet
- seven physical Higgs states

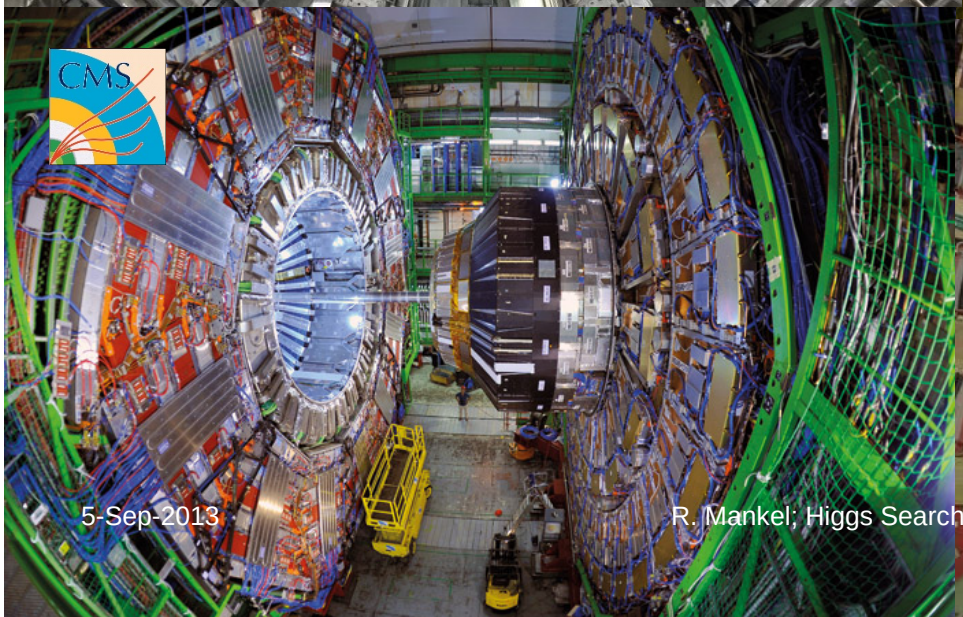
Hidden Sector
- invisible Higgs
- dark SUSY

Many others
...

The Experiments



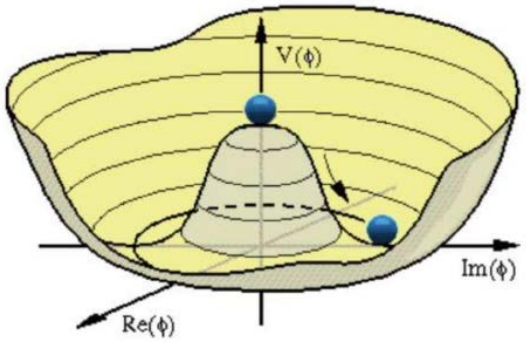




MSSM Higgs Bosons

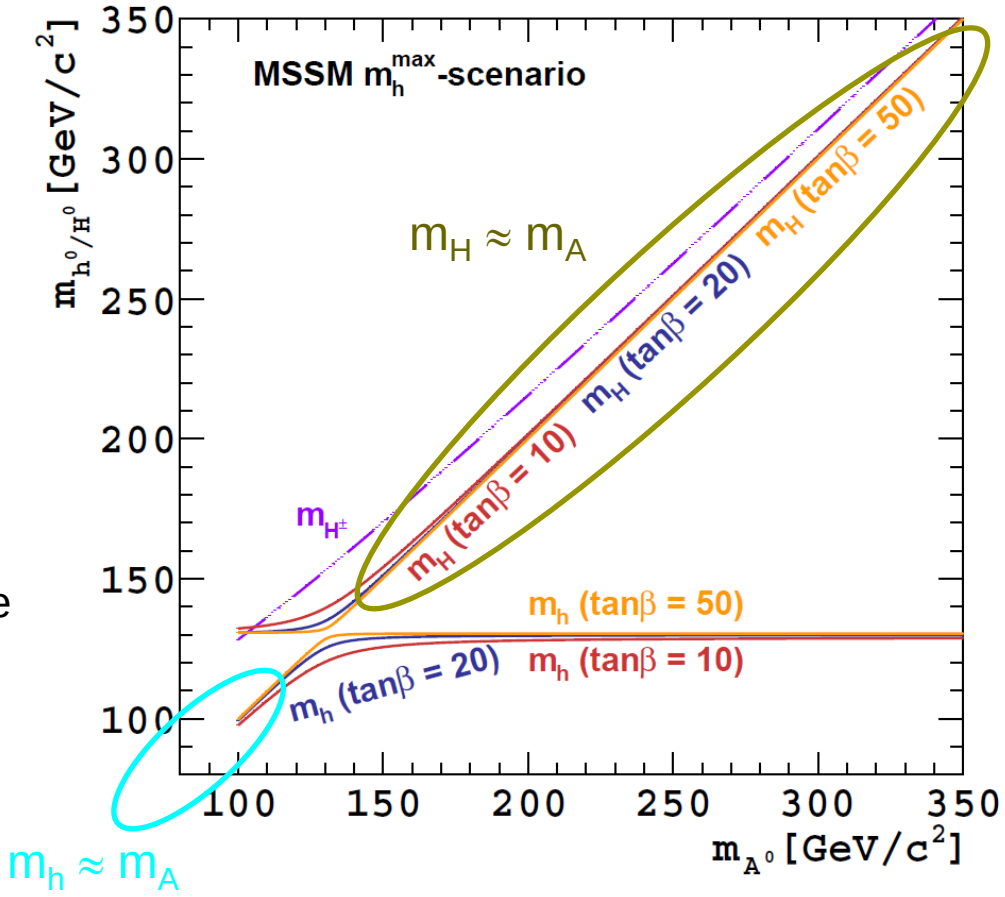
MSSM Higgs Bosons

- MSSM features two complex Higgs doublets
- ➔ Five physical Higgs bosons
  - three neutral: h, H , A
    - h, H: CP-even
    - A: CP-odd
    - denoted Φ
  - two charged: $H^{\pm}$
- At tree level, MSSM Higgs sector is governed by two parameters:
  - m_A
  - tan β (ratio of vacuum expectation values of the two Higgs doublets)
- Beyond tree level, additional parameters enter via radiative corrections
  - ➔ benchmark scenarios to compare different measurements (by default "m_h^{max} ")



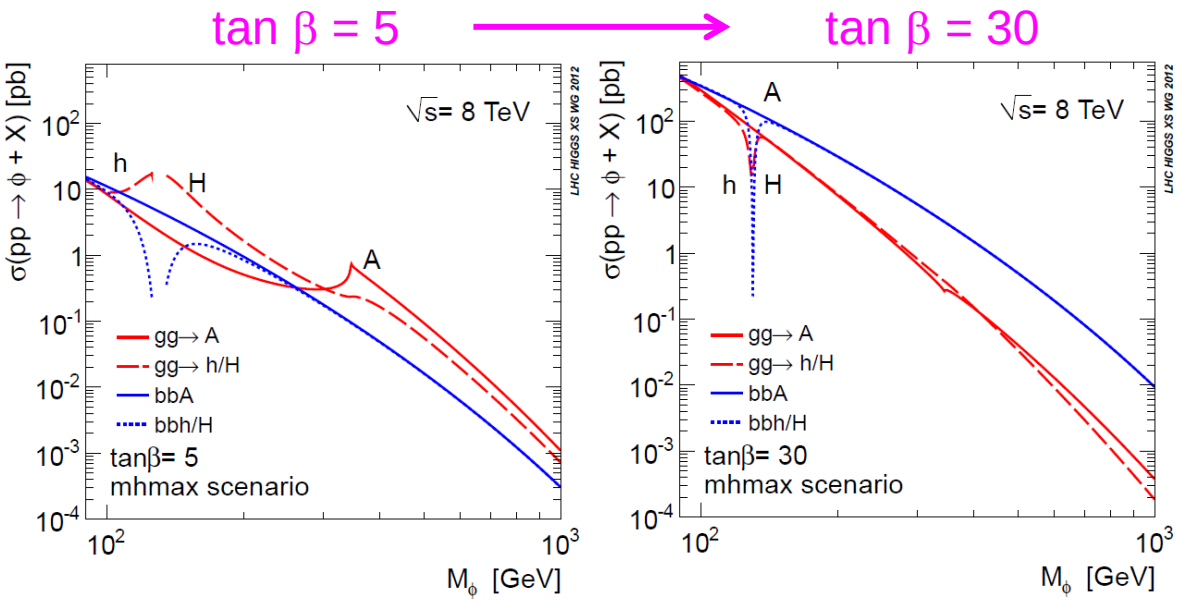
Higgs Masses in the MSSM

- The mass of the CP-odd Higgs boson A is usually ~degenerate with one of the CP-even bosons
  - $m_A \approx m_H$ for $m_A >> m_h^{max}$
  - $m_A \approx m_h$ for $m_A << m_h^{max}$
- With the exception of the $\mu\mu$ channel, this degeneracy cannot be resolved within the mass resolution
  - ➔ visible cross section effectively doubles
- ➔ Together with the effect of the Higgs coupling to b quarks, visible cross sections in b-associated production are typically enhanced by a factor of $\approx 2 \tan^2 \beta$



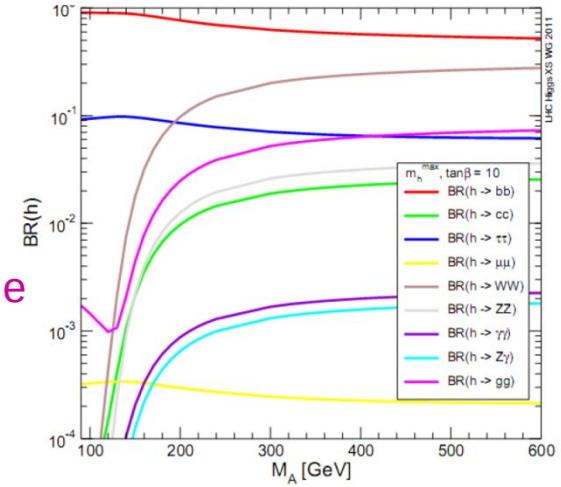
MSSM Higgs Production & Decay

- Strong enhancement of cross section with increasing tan β
  - in particular due to associated production



- Dominant decays of the neutral MSSM Higgs boson (at large tan β):
  - bb (~ 90%)
  - ττ (~ 10%)

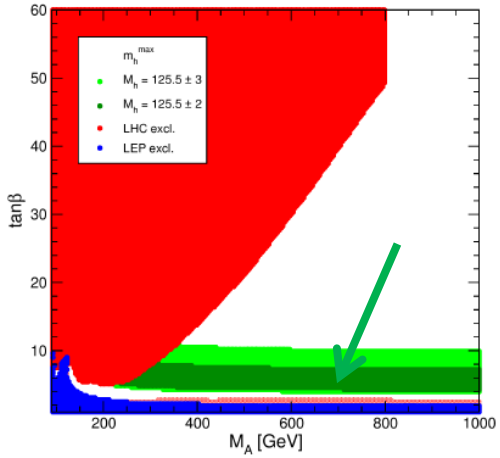
➔ Unlike the SM, these decay modes may play important rôle even at high masses



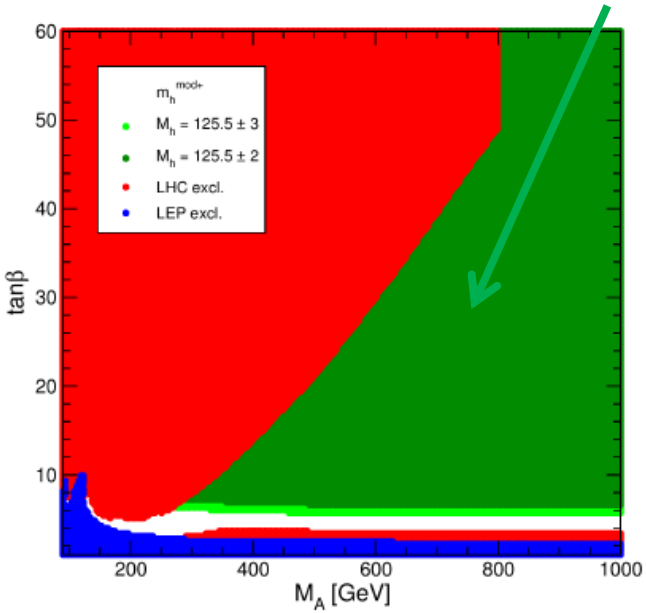
MSSM & the 125 GeV Higgs Observation

M. Carena et al.; arXiv:1302.7033

- Evaluate impact of H(125) in $m_h^{mod\pm}$ scenarios
  - re-tuned version of m_h^{max} scenario, suits better the observed Higgs mass
  - theoretical uncertainties taken into account



m_h^{max} scenario

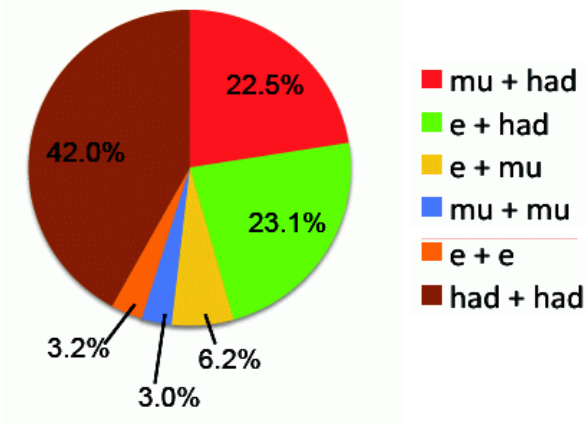


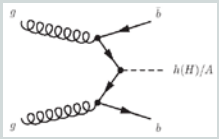
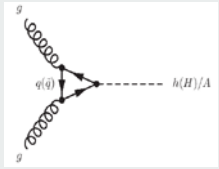
m_h^{mod+} scenario

- The H(125) observation does not exclude a heavy MSSM Higgs in wide range of tan β
- At large M_A (>>m_Z) the "light" MSSM Higgs boson (h) becomes standard model-like (decoupling limit) → direct searches are essential
- Both SM and MSSM fit the current set of H(125) measurements ~equally well

P. Bechtle et al., arXiv:1211.1955

$\Phi \rightarrow \tau\tau$ Search

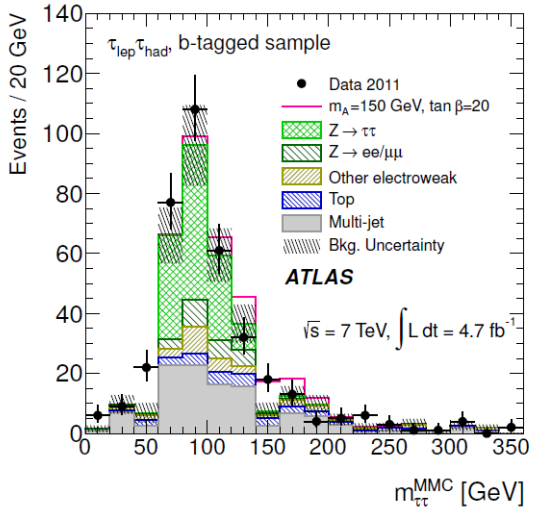


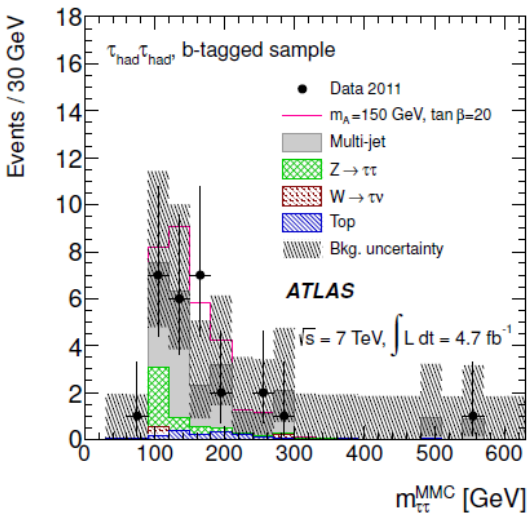
Production mechanisms & event categories	
 associated production	B-Tag at least 1 b-tagged jet
 gluon-gluon fusion	No B-Tag no b-tagged jet

- Good compromise between relatively large BR and manageable backgrounds
- To-date, analyses cover five of six possible $\tau\tau$ decay patterns
  - e+μ, e+had, μ+had, had+had (ATLAS), μ+μ (CMS)
- Mass of τ pair is reconstructed from visible τ decay products and missing E_T
  - CMS: likelihood technique
  - ATLAS: "Missing Mass Calculator" *
- Main backgrounds (in broad strokes – may differ from channel to channel):
  - **Z→$\tau\tau$:**
    - embedding technique: take Z→$\mu\mu$ from data, replace μ's by simulated τ decays
  - Z→ee / $\mu\mu$
  - $t\bar{t}$ and di-boson
  - QCD multijet, W+jets:

* A. Elagin et al., Nucl.Instrum.Meth. A654 (2011) 481-489

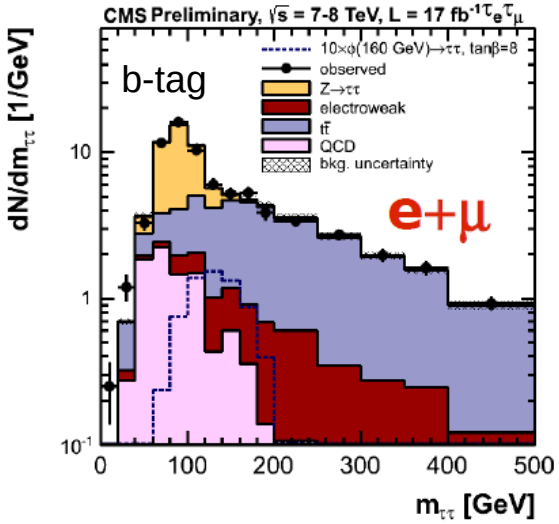
Φ → ττ: Mass Distributions (B-tag Category)

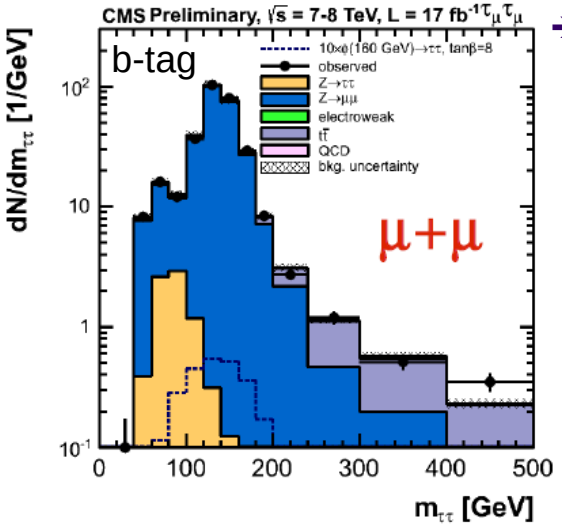




ATLAS JHEP 1302 (2013) 095

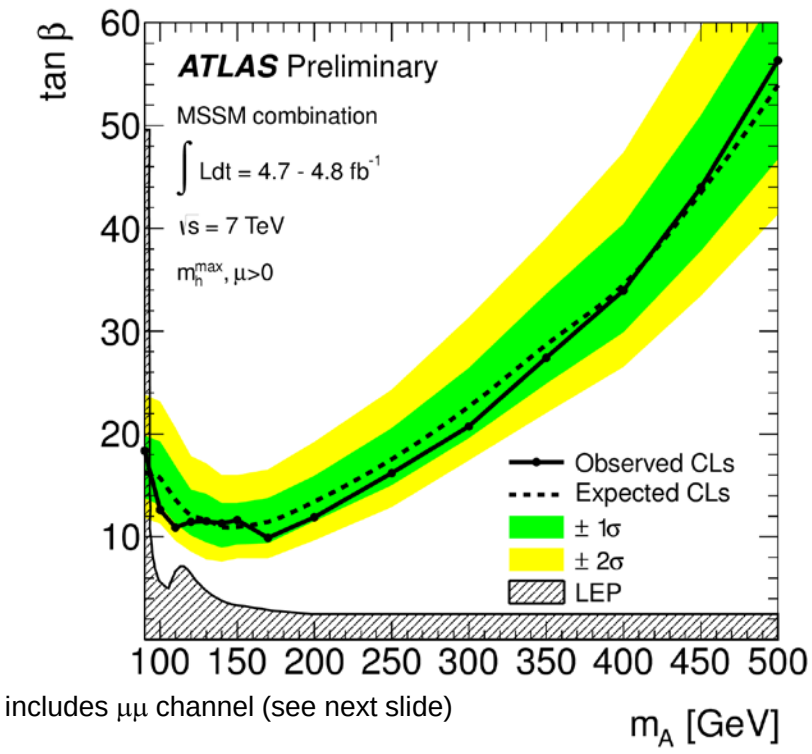
CMS PAS HIG-12-050



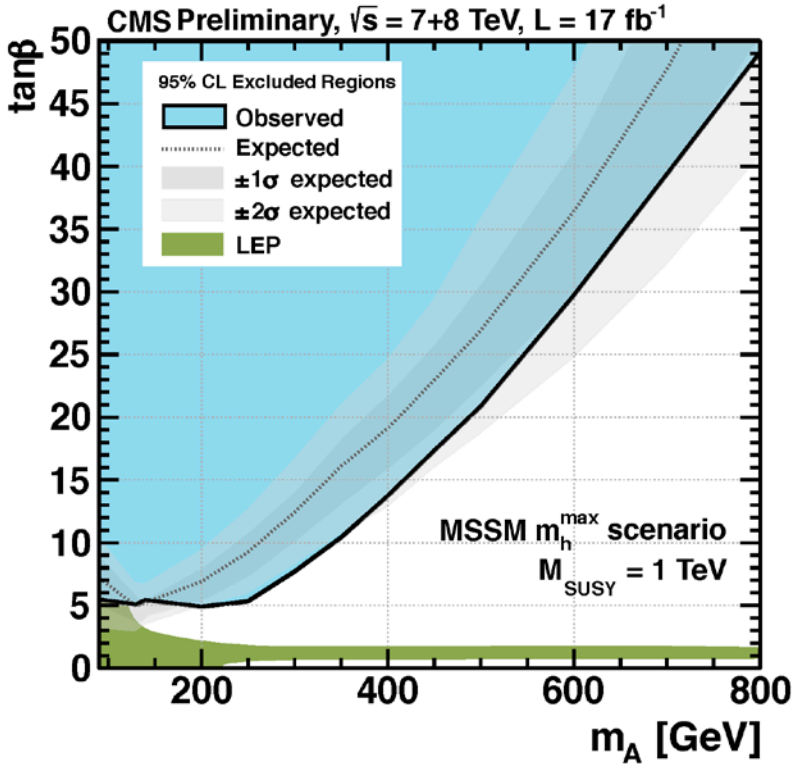


- Background compositions differ significantly across the various decay channels
- All distributions well described by background hypothesis

Φ → ττ: Results



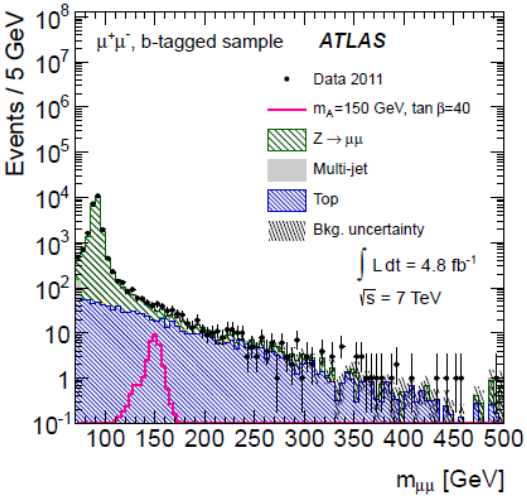
includes μμ channel (see next slide)



- Very low tan β upper limits (tan β < 5 for m_A<250 GeV !)
  - touching the LEP constraint at low m_A
- Addition of 8 TeV data → extension of mass scale up to 800 GeV (CMS)

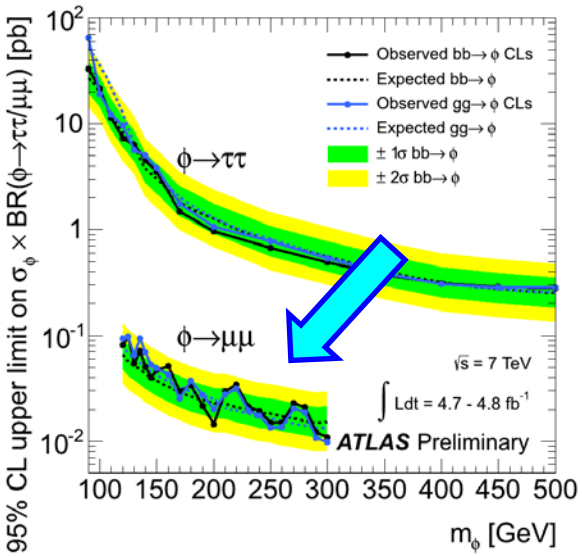
Φ → μμ Search

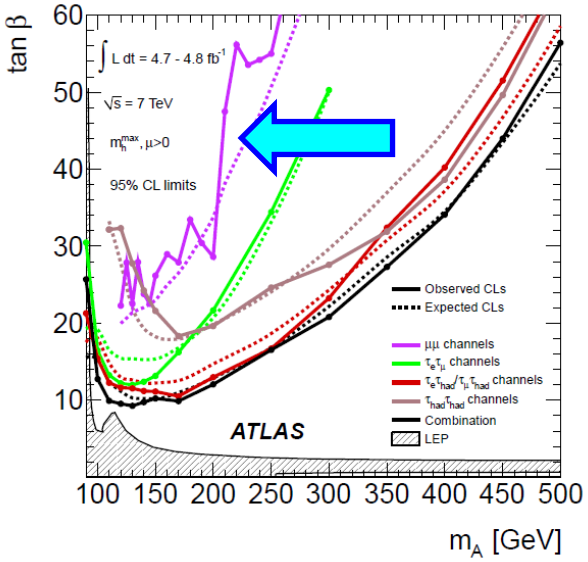
- Low BR, but also excellent mass resolution (close to Γ_Φ) and manageable BG
- Dominant backgrounds: Drell-Yan, bbZ^0, top
- ➔ Limits reach to σ * BR in the 20-100 fb range
  - ➔ significant constraints in (m_A, tan β) plane

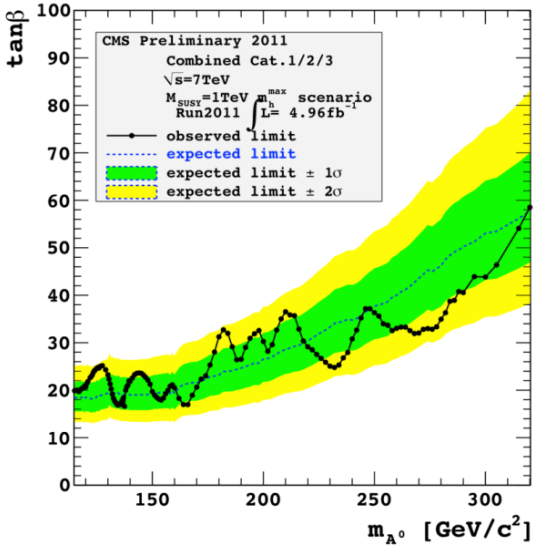


ATLAS JHEP 02 (2013) 095

ATLAS JHEP 02 (2013) 095



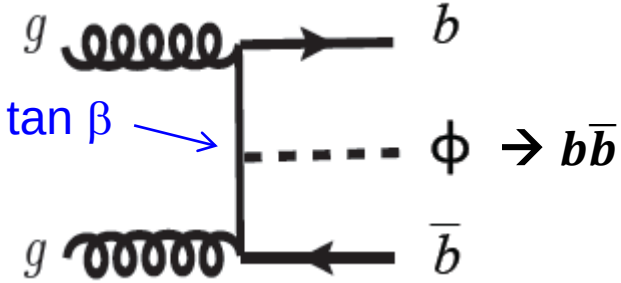




CMS PAS HIG-12-011

$\Phi \rightarrow b\bar{b}$ Search

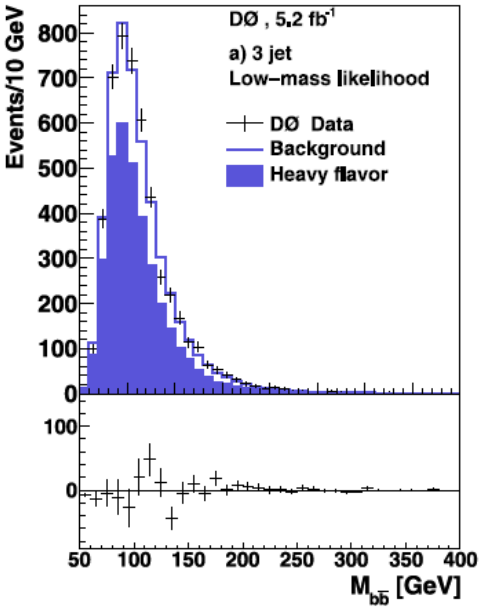
- Largest expected BR, but very difficult channel
  - huge background from multi-jet QCD
- Search for associated production with at least one additional b quark
  - ➔ enhancement if tan $\beta > 1$
- Signature: $\geq$ three b-jets + X in the final state
  - ➔ one of the most challenging triggers

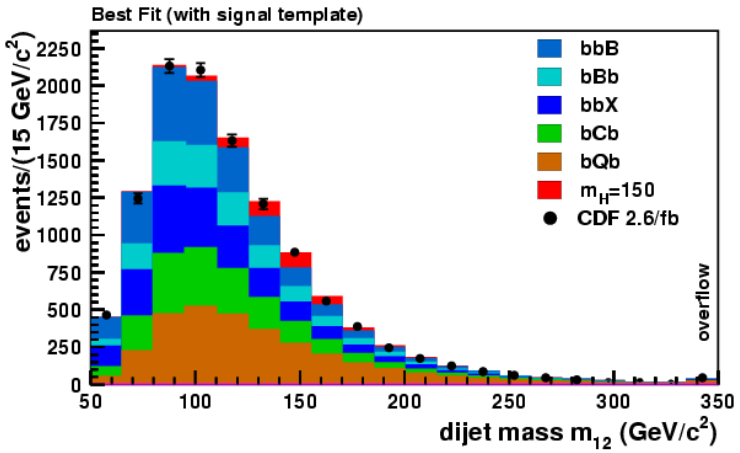


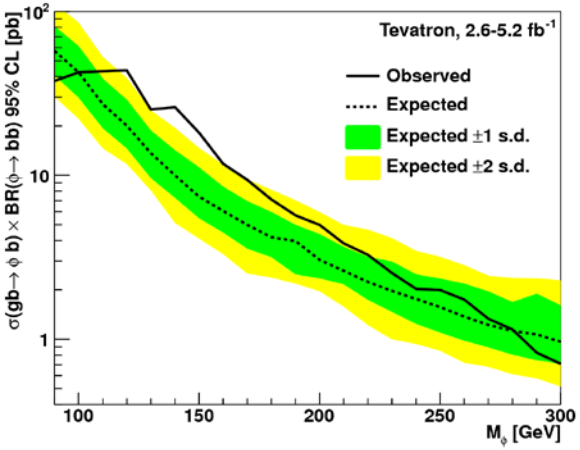
$\Phi \rightarrow b\bar{b}$: Tevatron Measurements

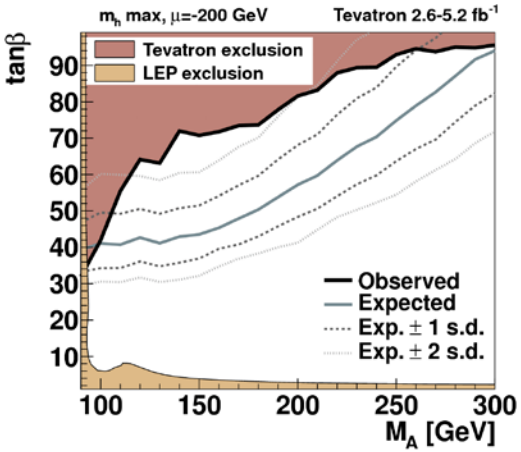
CDF+D0 Phys.Rev. D86 (2012) 091101

- Search for MSSM Higgs boson decaying to b quarks, and produced with at least one additional b jet
- Background treatment:
  - CDF: mass + global b-tag templates, derived from double btag sample with btag efficiency weights. Combination fitted to data.
  - D0: fractional contributions of multi-jet processes determined by fitting p_T distributions from simulation to the data.
- ➔ No signal seen over background expectation
  - modest excesses of ~2.8σ (CDF) and ~2.5σ (D0)









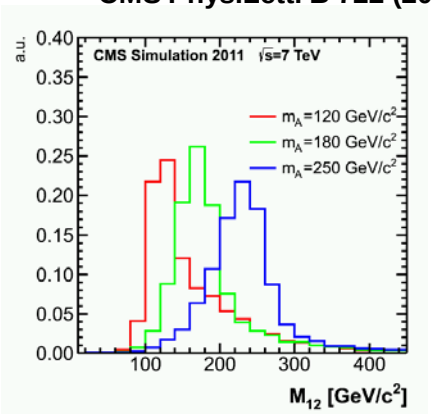
CMS $\Phi \rightarrow b\bar{b}$ Search

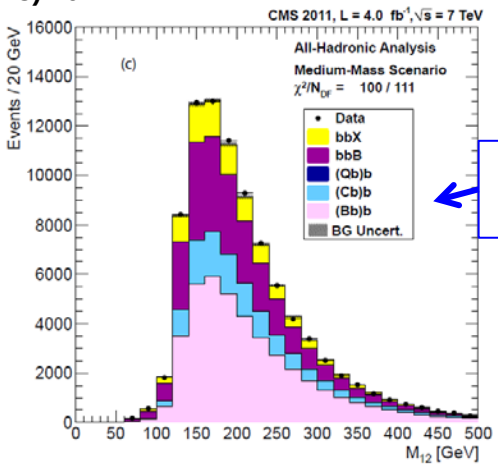
- CMS analysis searches in all-hadronic (shown) and semi-leptonic signatures (see backup)
- All-hadronic analyses inspired by CDF method

➔ Background-only fit with shapes determined from double-btag sample gives excellent agreement with triple-btag data

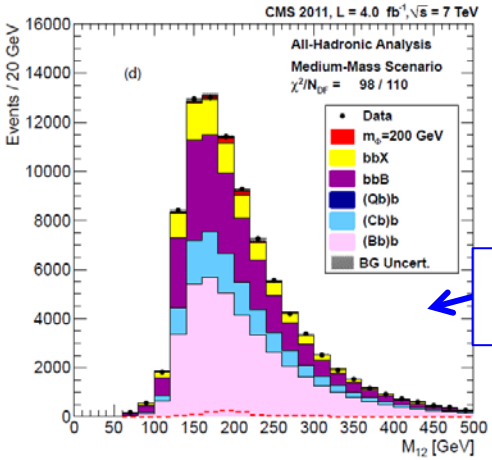
- No signal observed
- First measurement of this kind at the LHC

CMS Phys.Lett. B 722 (2013) 207





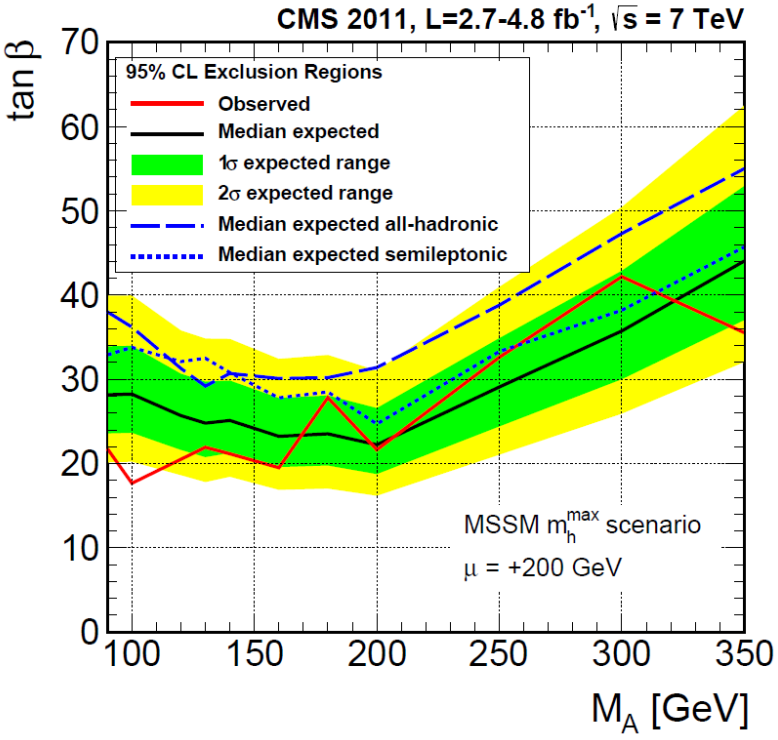
BG-only fit

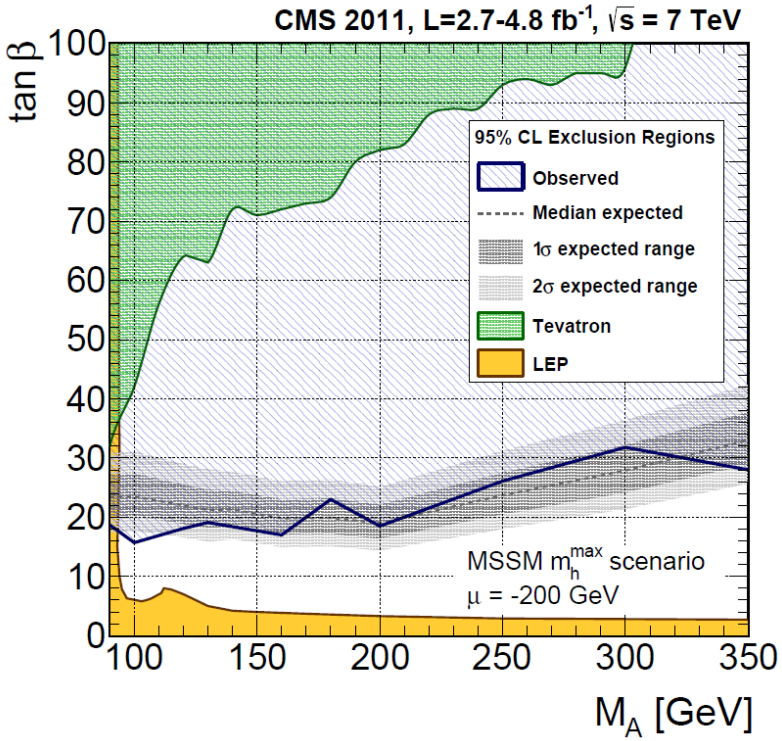


m_Φ=200 GeV (1.4 σ)

Φ → bb Search: Combination of CMS Analyses & Comparison with Tevatron

CMS Phys.Lett. B 722 (2013) 207





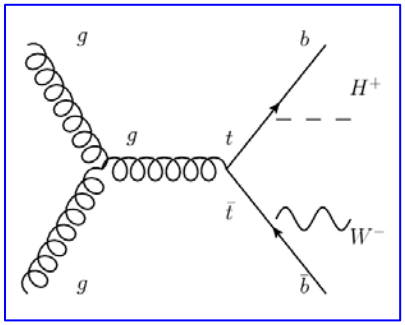
- For comparison with Tevatron, CMS results also given for μ= -200 GeV (right)
- ➔ Already with 2011 data, CMS has significantly higher sensitivity
- ➔ CMS does not confirm ~2σ-level excesses seen by CDF + D0

$H^{\pm}$ Search ($H^+ \rightarrow \tau\nu_\tau$ Mode)

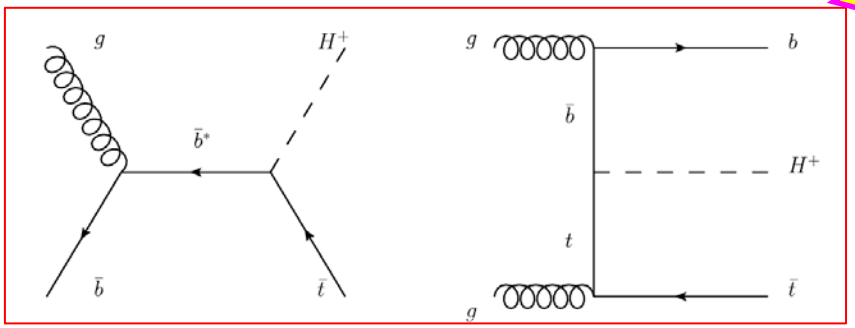
- $H^+ \rightarrow \tau\nu_\tau$ dominant decay mode for tan β>5 and m(H^+)<m_t

ATLAS CONF-2013-090

- Main production modes:
  - top decays (m(H^+)<m_t)

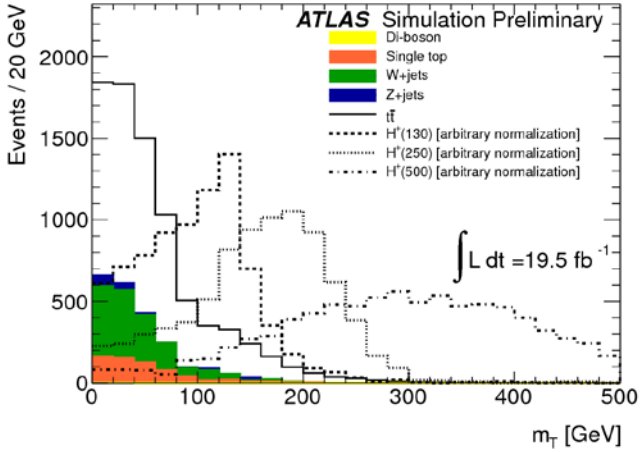


  - top-associated production (m(H^+)>m_t)



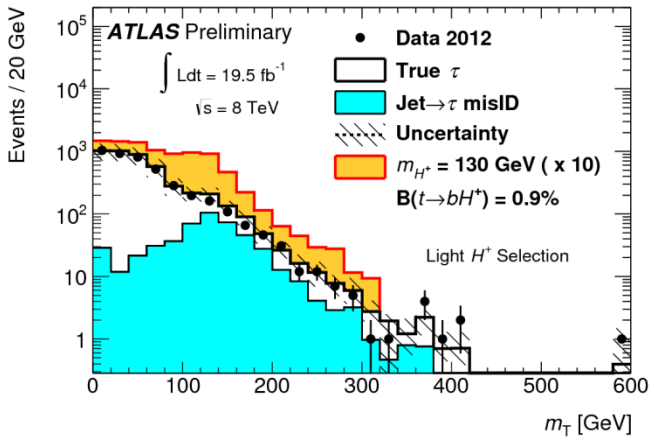
Brand New

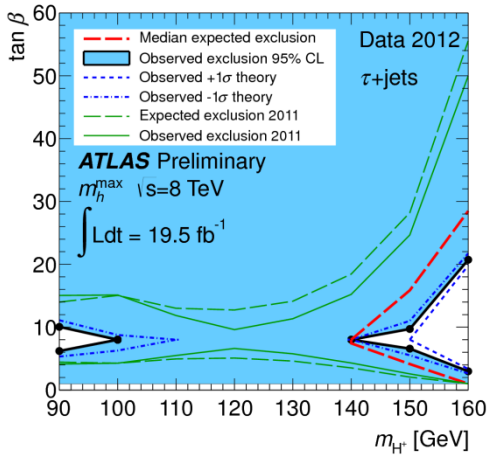
- Fully hadronic final states (ATLAS):
  - veto on other leptons
  - 3-4 jets (≥1 b-tagged)
  - large MET
- Discriminating variable m_T
  (= transverse invariant mass of τ + MET)
- Backgrounds: $t\bar{t}$, single-top, W/Z+jets, di-bosons, QCD



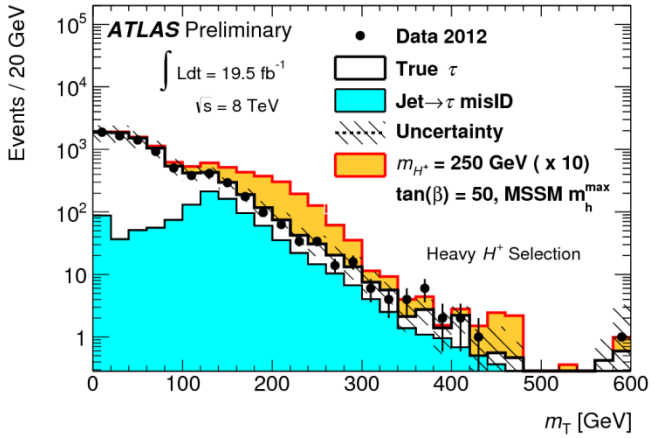
$H^+ \rightarrow \tau\nu_\tau$ Search (cont'd)

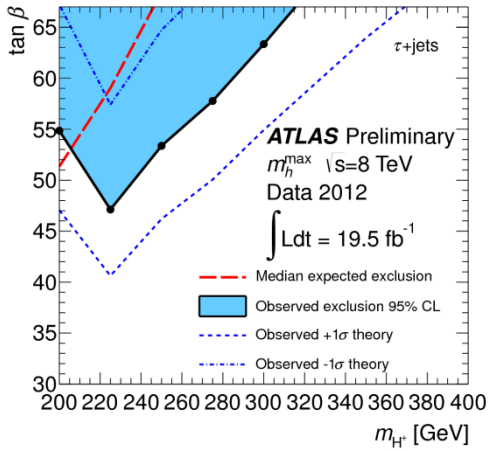
Light H^+ analysis





Heavy H^+ analysis





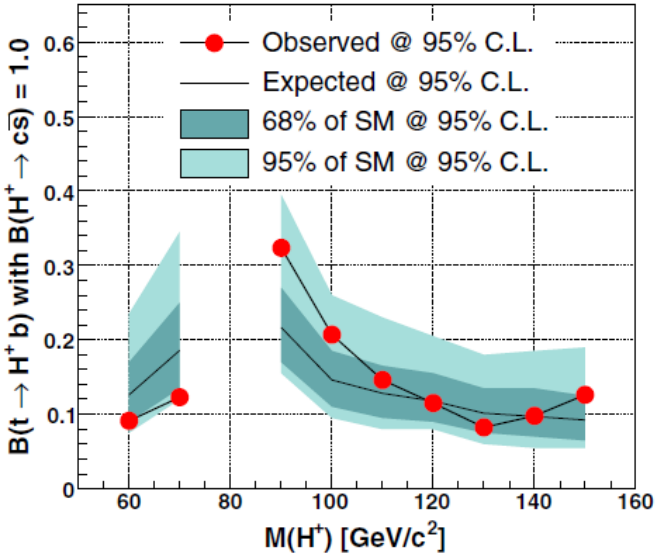
ATLAS CONF-2013-090

- Full 2012 dataset used
- Mass ranges 90-160, 180-600 GeV covered
- No evidence for H^+ found
- At low m(H^+), large parts of MSSM parameter space excluded

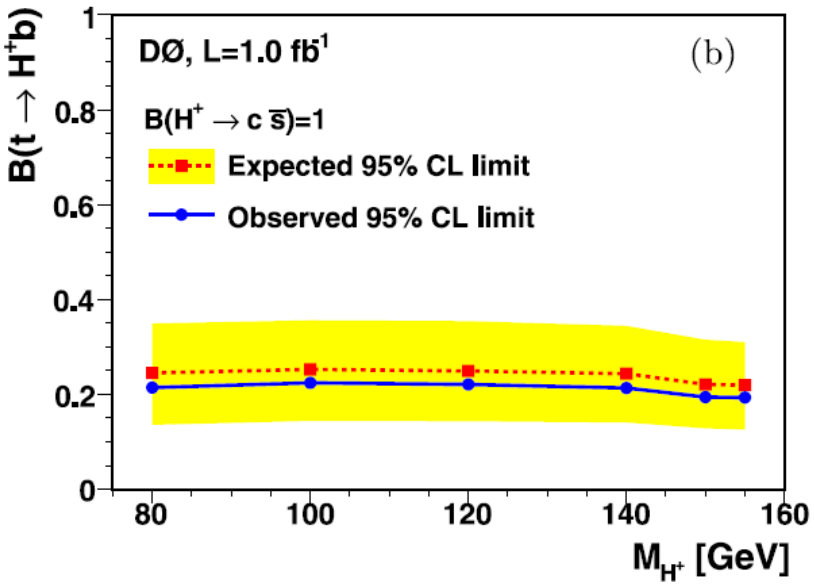
Light $H^{\pm}$ Search in $c\bar{s}$

- For tan β<1, $H^{\pm} \rightarrow c\bar{s}$ becomes the dominant decay mode (~70% for $m_{H^{\pm}}$~110 GeV)
- First investigation of this process by CDF and D0 at the Tevatron collider
  - ➔ no indication for H^+ signal
  - ➔ upper limits on B(t→H^+ b) around 10-30%, assuming B(H^+→ $c\bar{s}$)=100%
- In the mean time, has been measured by ATLAS at the LHC

CDF, Phys. Rev. Lett. 103 (2009) 101803.



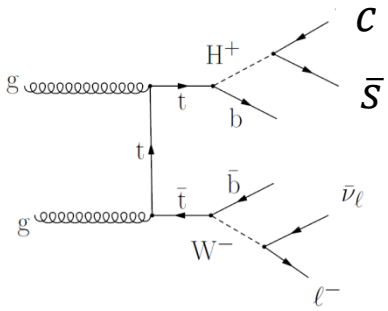
D0, Phys. Lett. B 682 (2009) 278.



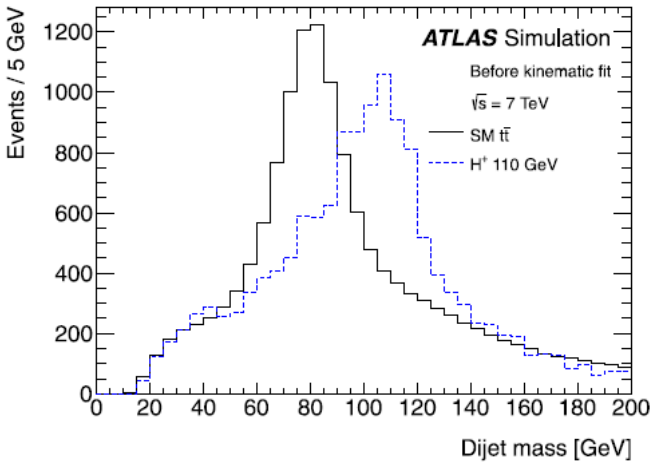
Light $H^{\pm}$ Search in $c\bar{s}$ (cont'd)

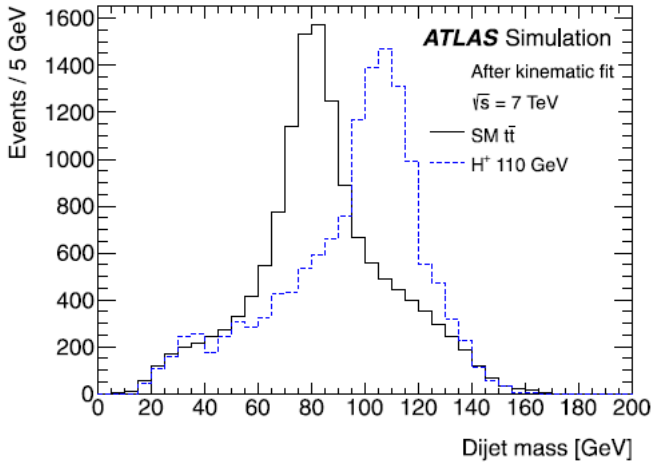
- Same topology as $t\bar{t}$ decays in lepton + jets channel
- Search for second peak in the di-jet mass distribution
- Event selection:
  - isolated lepton, 4 jets (two with b-tag)
  - MET
- Kinematic fit for mass reconstruction is essential

➔ Significant improvement of separation between standard ttbar background and signal (σ_m~12 GeV)



ATLAS Collab., Eur. Phys. J. C 73 (2013) 2465.

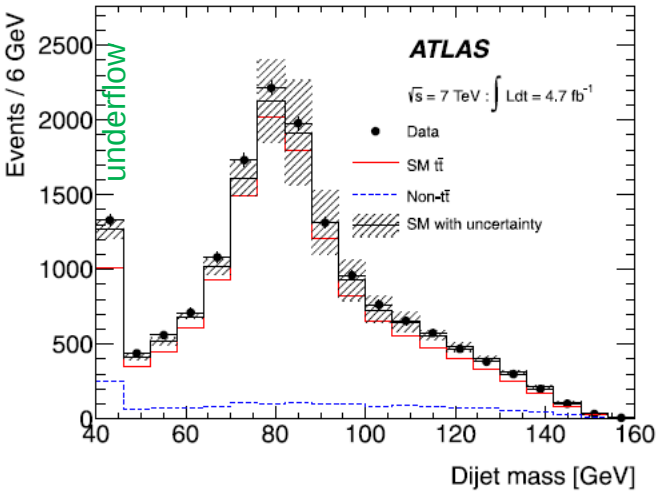


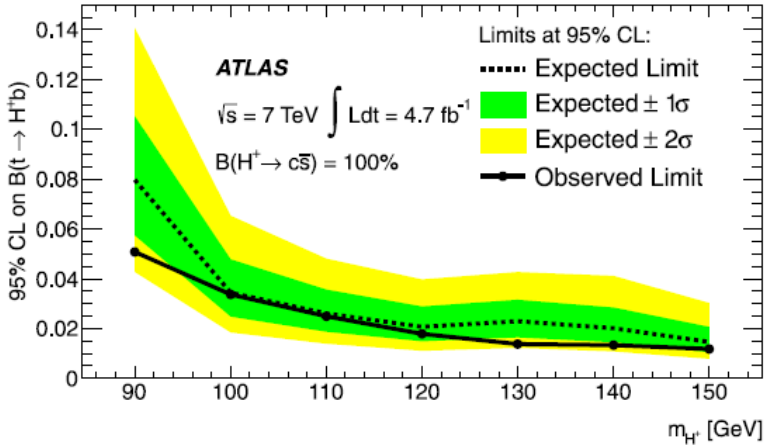


Light $H^{\pm}$ Search in $c\bar{s}$ (cont'd)

ATLAS Collab., Eur. Phys. J. C 73 (2013) 2465.

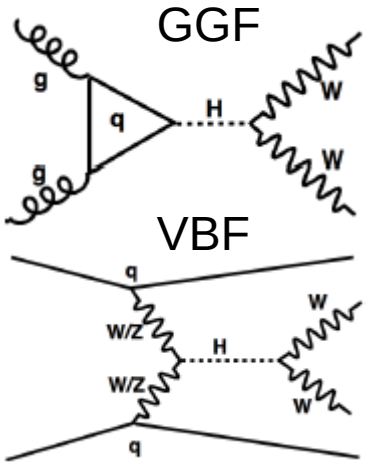
- Main backgrounds:
  - SM $t\bar{t}$
  - QCD multi-jet (data-driven, shape from semi-isolated lepton control region)
  - W/Z+jets, single top
- ➔ Observed mass spectrum well described by background estimation
  - no indication for H^+ signal
- ➔ Observed limits between 1-5 %
- ➔ Most stringent results to date in $c\bar{s}$ channel





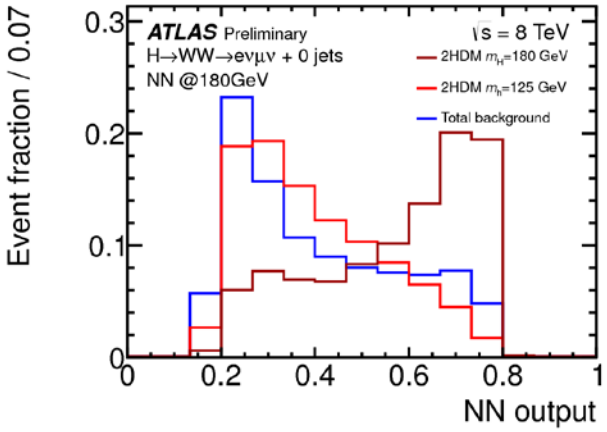
Two Higgs Doublet Model (2HDM)

Generic 2HDM Higgs Search



- Phenomenological approach: simple extension of SM Higgs sector by second complex Higgs doublet
  - five Higgs bosons: h, H, A, $H^{\pm}$
  - can accommodate CP violation (as opposed to MSSM at tree level) → possible explanation of baryon asymmetry in universe?
- Examples of 2HDM models with natural flavor conservation:
  - Type I: all quarks couple only to one Higgs doublet
  - Type-II: up-type quarks (Q=+2/3) couple to one, down-type quarks (Q=-1/3) couple to the other Higgs doublet
  - tan β: ratio of VEVs. α: scalar mixing angle
- ATLAS analysis: h / H → $WW^{(*)}$→eνμν, assume m_h=125 GeV
  - pseudoscalar A does not decay to W pairs
  - exactly 2 leptons of opposite charge, $E_{T,rel}^{miss}$
  - gluon-gluon fusion (GGF) selection: zero jets
  - vector-boson fusion (VBF) selection: two jets
  - neural network combines kinematic variables to enhance S/B
    - trained for each mass point

ATLAS CONF-2013-027

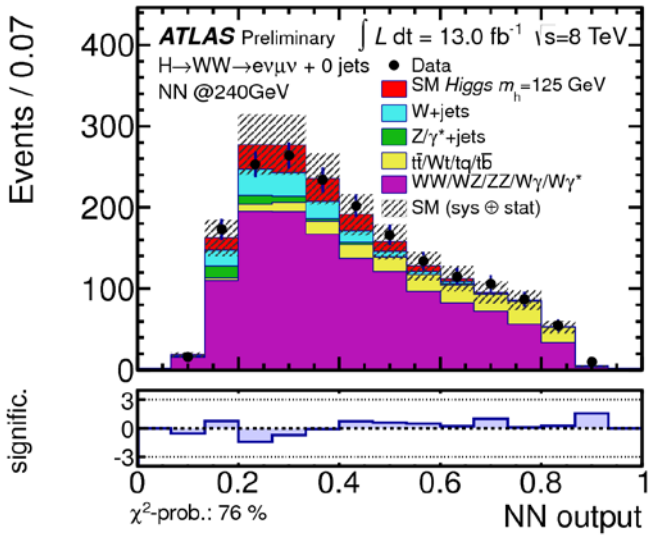


2HDM Higgs Search: Results

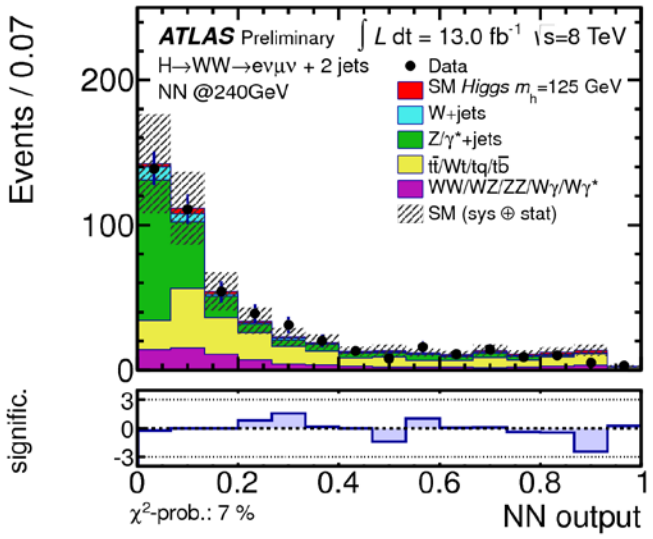
- H(125) treated as "background"
- ➔ No indication of a signal (would appear at large NN output)

ATLAS CONF-2013-027

GGF Selection

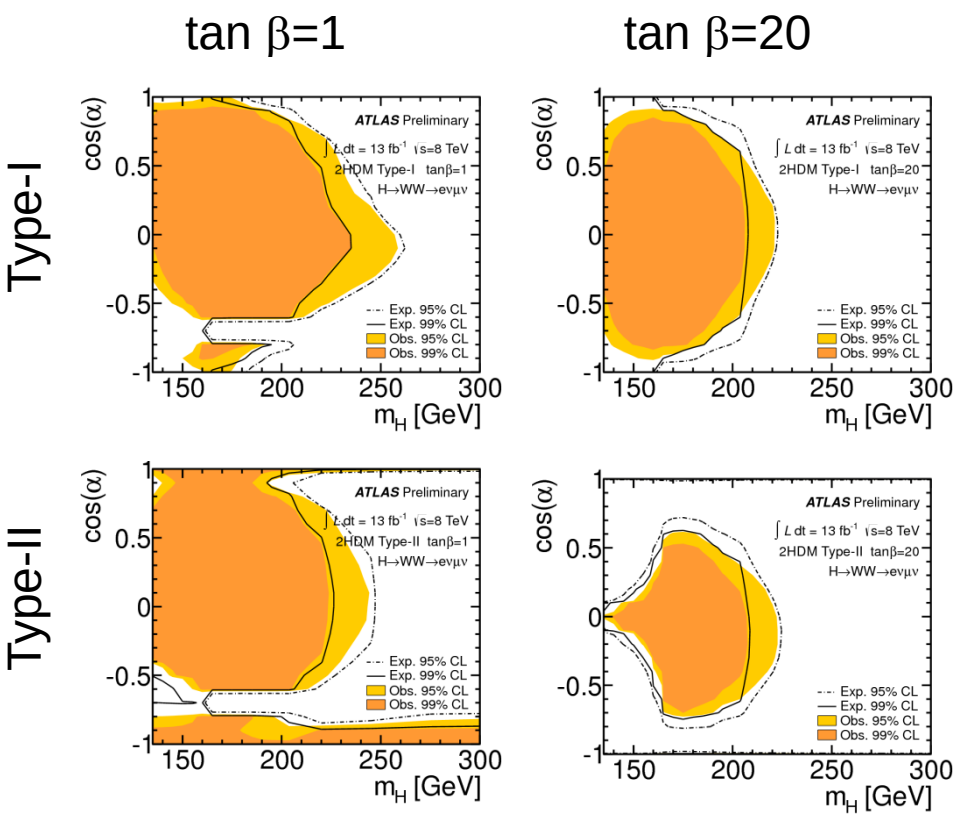


VBF Selection



2HDM Higgs Search: Results

ATLAS CONF-2013-027

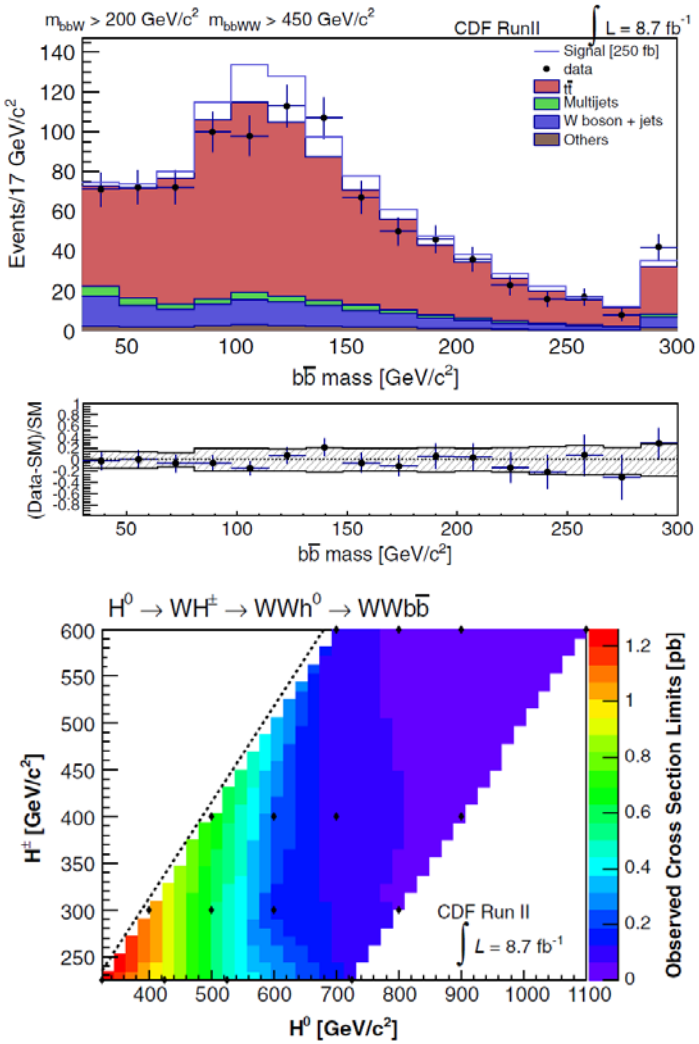


- Interpretation: exclusion contours in the cos α - m_H plane for different values of tan β
  - different results for Type-I and Type-II 2HDM models
- ➔ For low masses (< 200 GeV), significant parts of the cos α range are excluded

2HDM Search in Cascade Decays

Phys.Rev.Lett. 110 (2013) 121801

- Search for a heavy scalar H^0 with a cascade decay:
  - $H^0 \rightarrow H^+W^- \rightarrow (h^0W^+)\, W^- \rightarrow (b\bar{b})\, W^+\, W^-$
    - one W decaying leptonically
  - final state similar to ttbar events
  - 1 lepton, ≥4 jets, ≥1 b-tags, MET>20 GeV
- Dominant backgrounds:
  - $t\bar{t}$ production modeled by MC (PYTHIA)
  - W+jets background modeled with ALPGEN/PYTHIA
- Reconstruct 1 W from lepton+MET and the other from jet pair with matching mass
  - search signal in m_{bb}
- Cross section upper limits obtained scanning the space of $H^\pm$ and H^0 masses
  - assume $B(H^0 \rightarrow H^+W^-) = B(H^+ \rightarrow h^0W^+) = 100\%$
  - ➔ limits range between 1.3-0.015 pb
  - ➔ first measurement of this kind



NMSSM Higgs Bosons

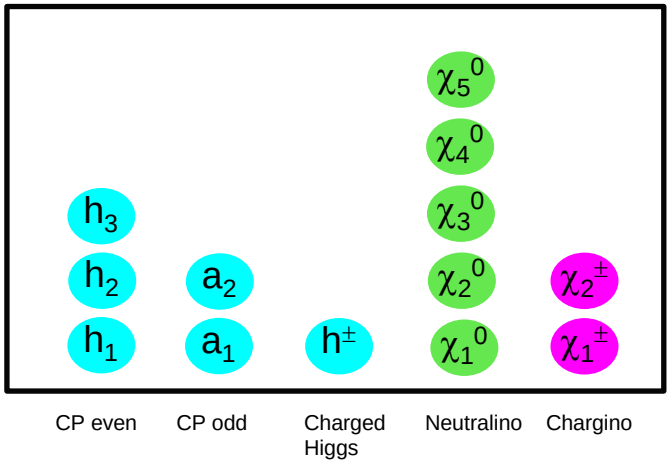
The NMSSM Higgs Sector

- Two complex Higgs doublets + additional scalar field
- Physical states are mixtures: h_1, h_2, h_3, a_1, a_2, $h^{\pm}$

CP-even CP-odd

➔ Requires less fine tuning for Higgs mass, solves "μ problem" of MSSM

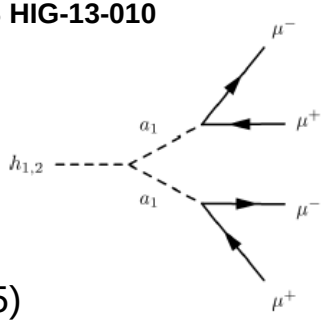
➔ Rich phenomenology

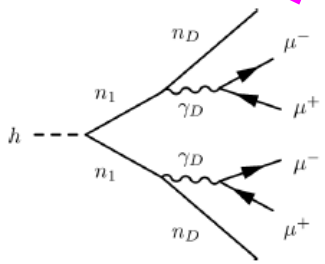


$h_{1,2} \rightarrow aa \rightarrow (\mu\mu)\,(\mu\mu)$ Search

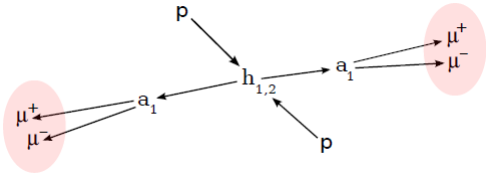
New!

CMS PAS HIG-13-010





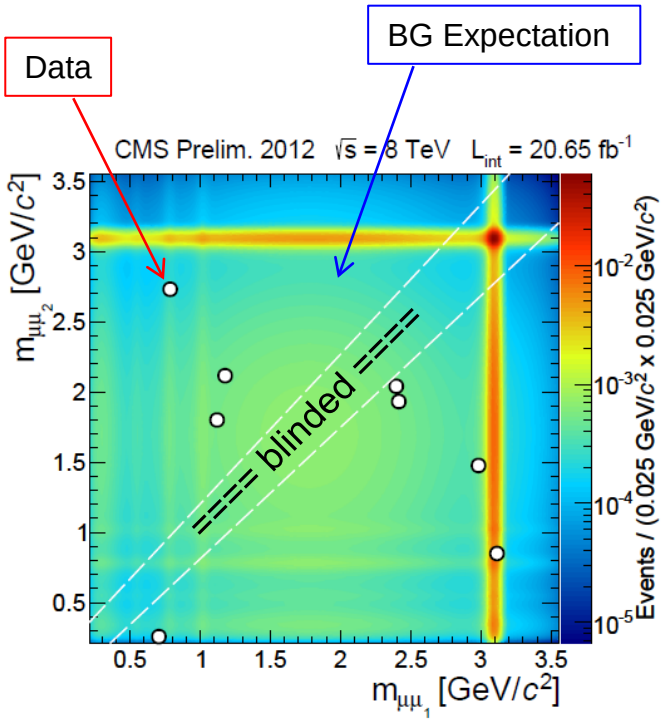
- Search for a non-standard Higgs decay into two very light bosons, resulting in two boosted pairs of muons
- NMSSM interpretation: $h_{1,2} \rightarrow a_1 a_1 \rightarrow (\mu\mu)\,(\mu\mu)$
  - either h_1 or h_2 could correspond to observed H(125)
  - a_1 is a new light CP-odd Higgs boson ($m < 2m_\tau$)
- Dark SUSY interpretation: $h \rightarrow 2\, n_1 \rightarrow 2\, n_D + 2\, \gamma_D \rightarrow 2\, n_D + (\mu\mu)\,(\mu\mu)$
  - models motivated by excesses in positron spectra observed by satellite experiments
    - cold dark matter with a mass scale of ~1 TeV
  - n_1 is lightest visible neutralino, n_D is light dark fermion, and γ_D light (massive) dark photon that weakly couples to SM particles
- Search for events with two isolated, boosted muon pairs
  - consider $0.25 < m_a < 3.55$ GeV and $m_h > 86$ GeV
- Signal region: $m_{\mu\mu 1} \approx m_{\mu\mu 2}$
- Main backgrounds:
  - direct double-J/ψ production
  - $b\bar{b}$ production with subsequent di-muon decays (double-semileptonic or resonances)



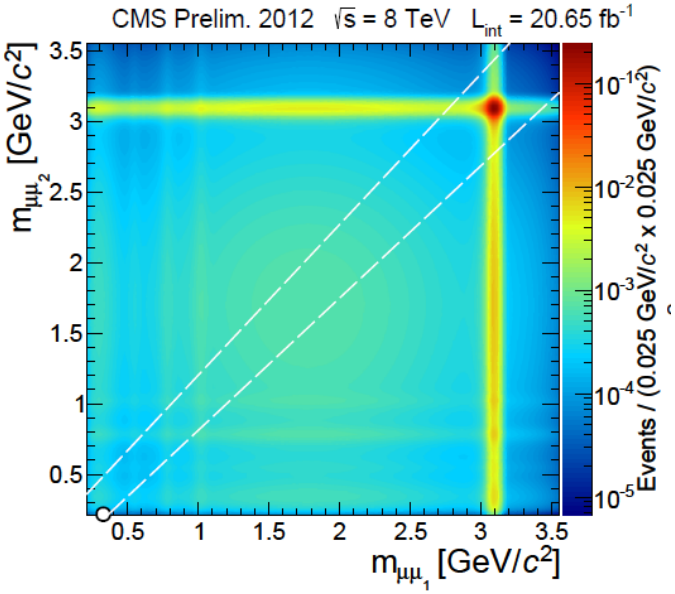
$h_{1,2} \rightarrow aa \rightarrow (\mu\mu)\,(\mu\mu)$: Results

- $b\bar{b}$ background from bb-enriched control sample, double-J/ψ production from PYTHIA
- ➔ 8 events observed in off-diagonal sideband
- ➔ After unblinding, only 1 event is observed in the diagonal signal region
  - ➔ expected background: 3.8 ± 2.1 events

CMS PAS HIG-13-010

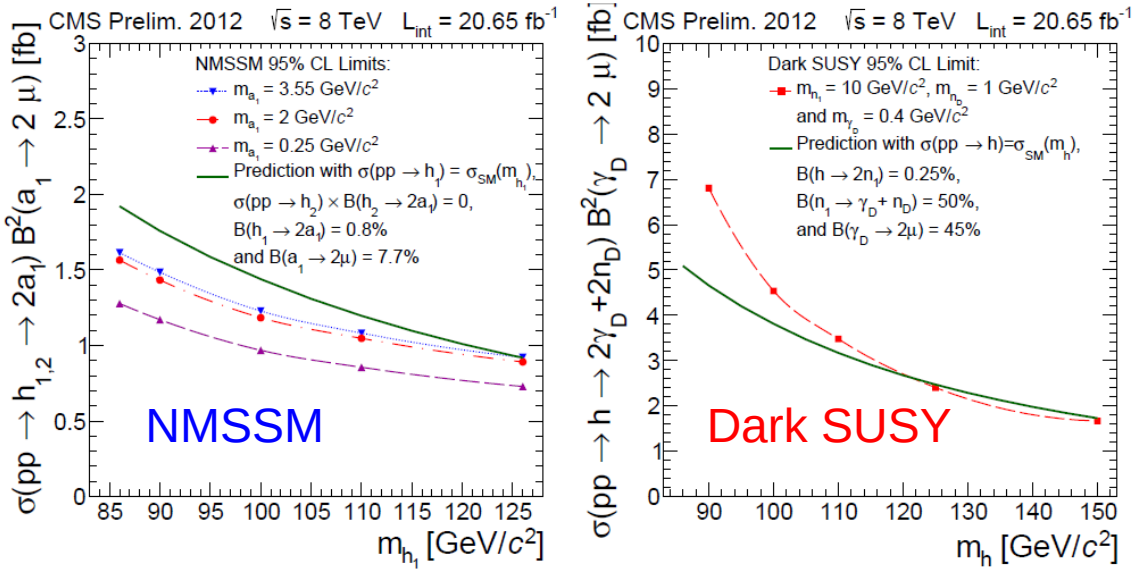


after unblinding (signal region):



$h_{1,2} \rightarrow aa \rightarrow (\mu\mu)\,(\mu\mu)$: Results

CMS PAS HIG-13-010

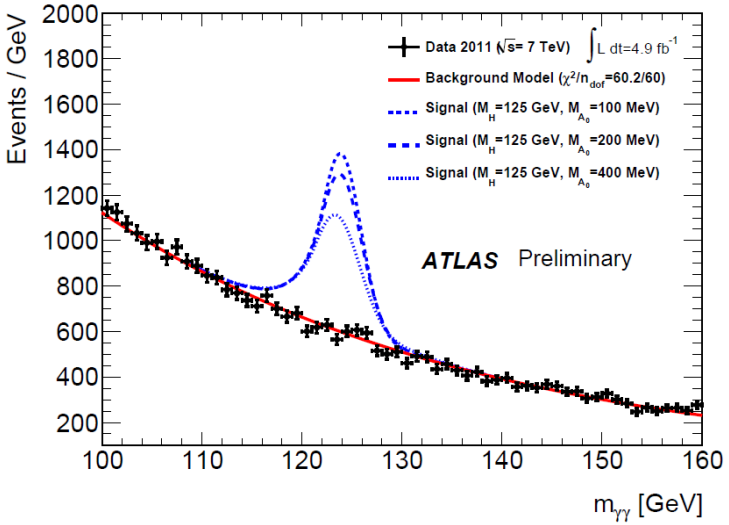


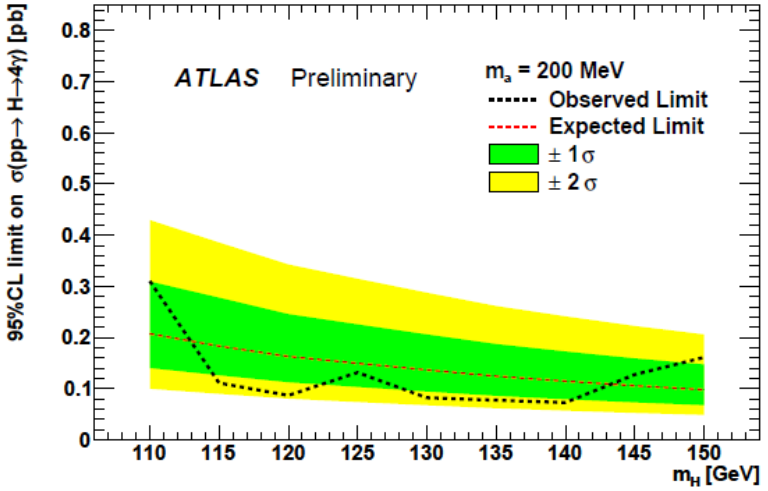
- Results are interpreted in context of NMSSM and dark-SUSY benchmark models
  - signal efficiencies depend on assumptions for either m_a or m_h
- ➔ NMSSM: upper limits vs m_{h1} and m_{a1}
  - m_{h2} unrestricted → conservative assumption on efficiency
  - for NMSSM prediction, assume that only h_1 decays into $2a_1$
- ➔ Dark SUSY: upper limits vs m_h
- ➔ Best experimental limits in this signature

H(125) Decays to Light NMSSM Pseudo-Scalars

- If very light NMSSM CP-odd Higgs bosons exist, they might be observed in the decay
  H(125) → a a → (γγ)(γγ)
- Here: assume m_a=100-400 MeV
  - di-photon system would be highly boosted. Potential background for SM H→ γγ analysis
- Analysis similar to SM H→ γγ
  - additional selection based on shower shape variables & calorimetric isolation
- → No signal observed
  - upper limits of σ*BR(H→aa→ (γγ)(γγ)) in 0.1-0.2 pb range

ATLAS CONF-2012-079

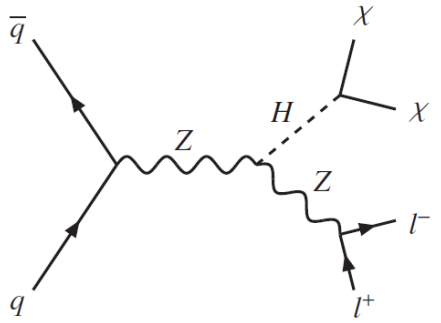




Exotic Higgs Bosons

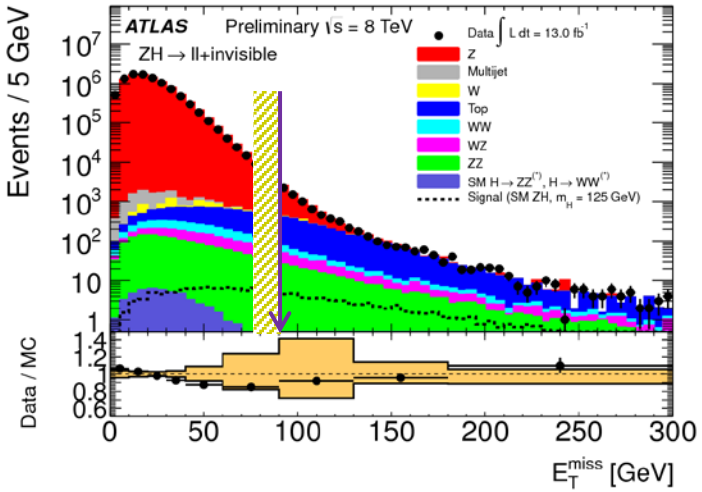
Invisible Higgs

- If the Higgs would decay with a significant fraction to invisible particles, this might be detectable in associated production with a Z boson
  - ➔ look for events with $Z \rightarrow l^+l^-$ plus missing E_T, and little else
- Main backgrounds:
  - $ZZ \rightarrow ll\nu\nu$, $ZW \rightarrow ll\, l\nu$, $WW \rightarrow l\nu\, l\nu$
  - Z+jets

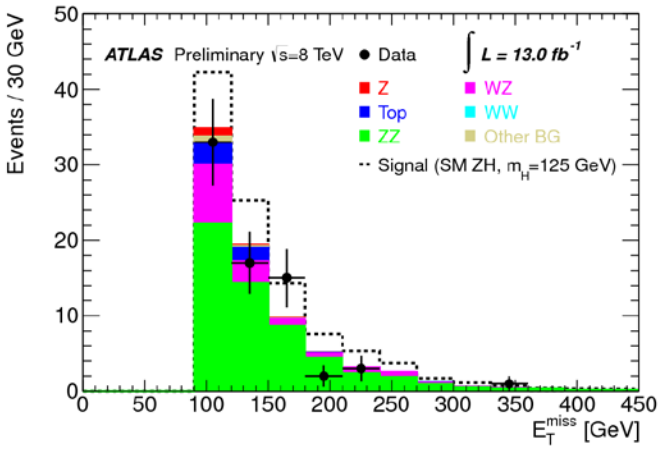


ATLAS-CONF-2013-011

After just Z selection:



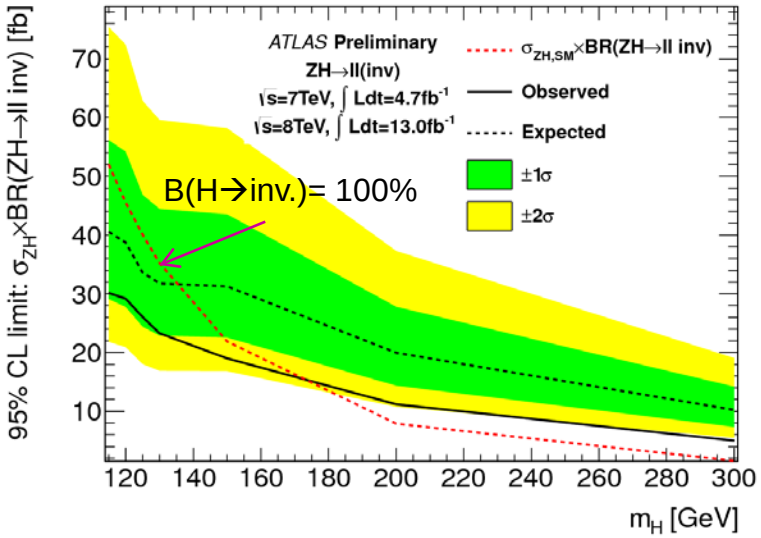
After final selection (8 TeV shown):



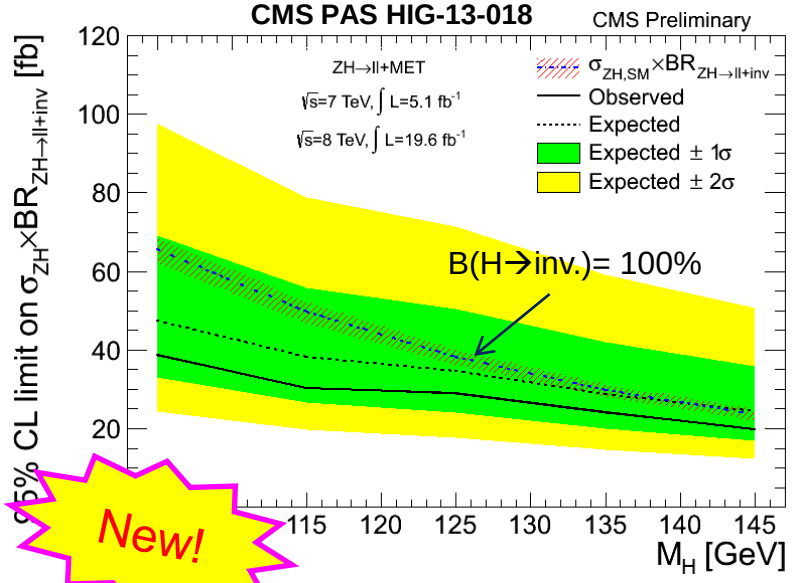
- azimuthal separation
- MET balancing
- veto on additional jets

Invisible Higgs: Results

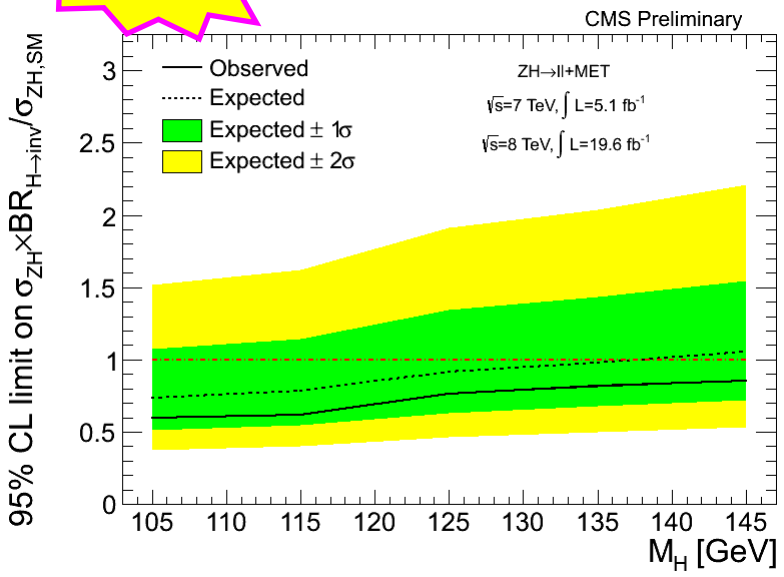
ATLAS-CONF-2013-011



CMS PAS HIG-13-018



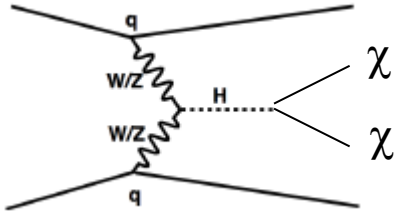
New!



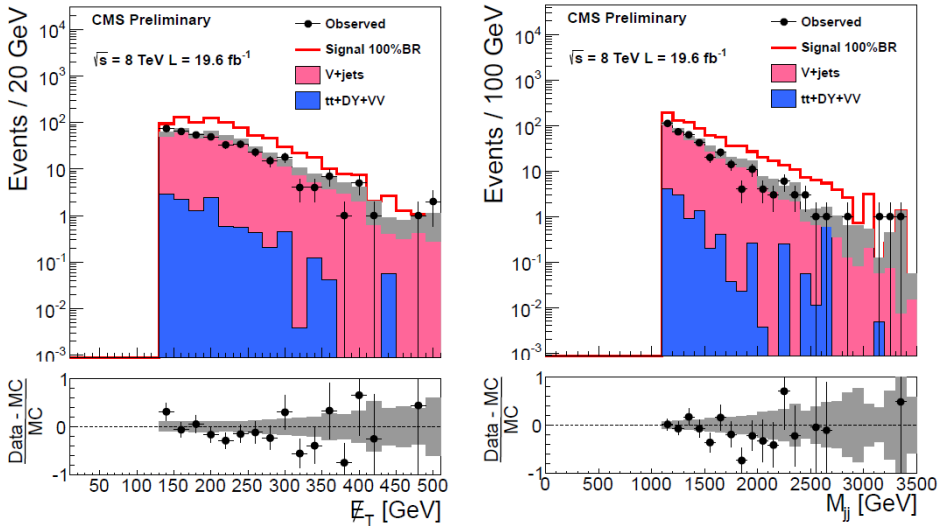
- Invisible BR <65% (ATLAS) and <75% (CMS) for SM Higgs @ 125 GeV (95% C.L.)
- ➔ Leaves plenty of room for invisible decay modes

Invisible Higgs (cont'd)

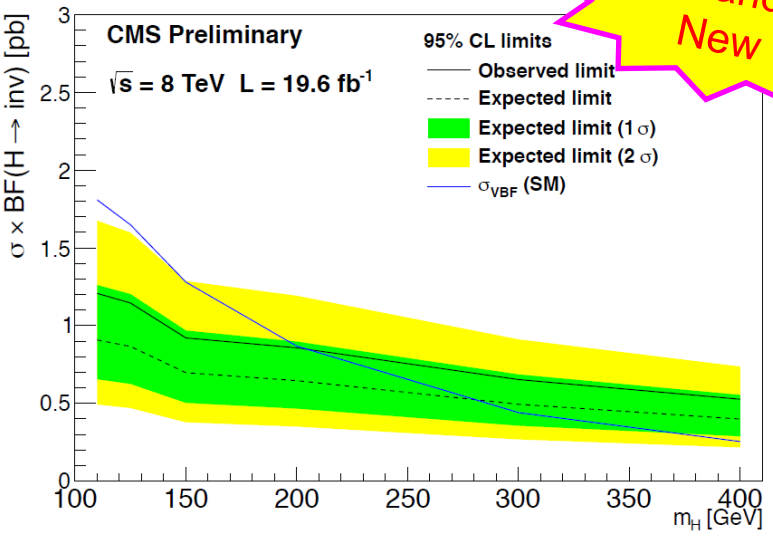
- Invisible Higgs can also be searched in VBF
  - cross section higher than in ZH production
  - special VBF+MET triggers
  - large efforts to reduce QCD background



CMS PAS HIG-13-013



➔ Data in good agreement with SM backgrounds (mainly V+jets)



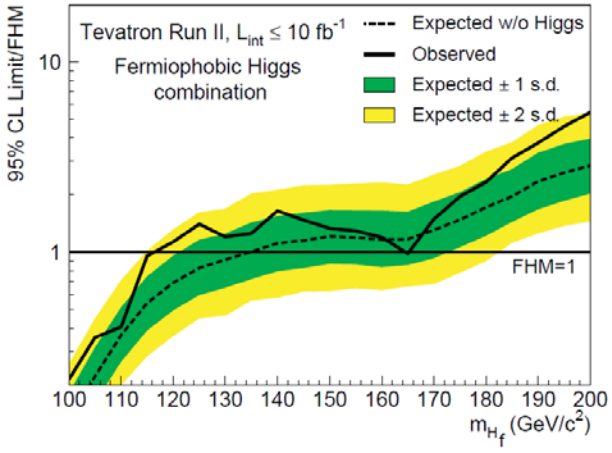
Brand New

➔ Invisible BR<69% for SM Higgs @ 125 GeV (95% C.L.)

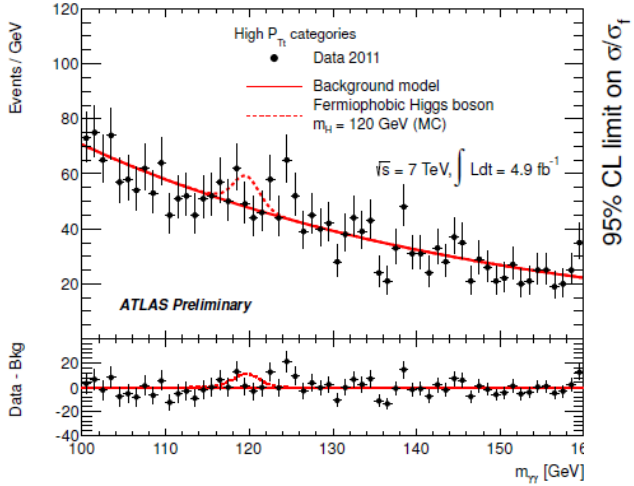
Fermio-Phobic Higgs

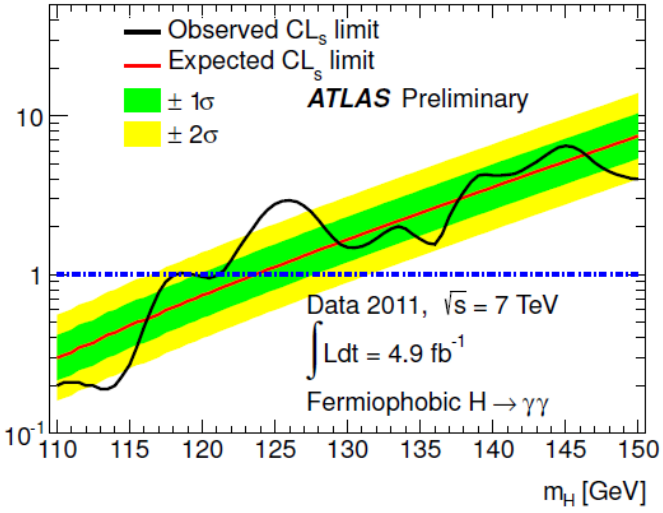
- If a Higgs boson does not couple to fermions
  - ➔ production via gluon-gluon fusion impossible
  - ➔ standard production channel is vector boson fusion (VBF) or vector-boson associated production (VH)
  - ➔ BRs for di-boson modes enhanced
- Analysis largely similar to SM analysis
- ➔ Fermio-phobic Higgs excluded within m_H= 100-147 GeV

CDF+DZero arXiv:1303.6346

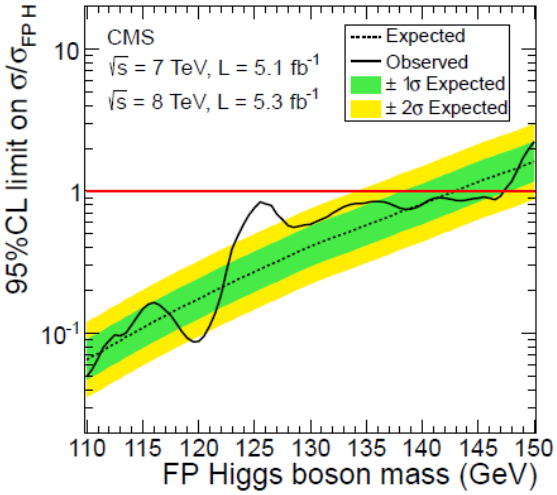


ATLAS CONF-2012-013





CMS PAS HIG-12-013



Summary

- Observation of SM-like features of the H(125) state does not imply that the Higgs sector must have SM structure
  - best way of clarification: direct search for additional Higgs signatures
- A broad attack is launched to clarify whether the Higgs sector reaches beyond the Standard Model.
  - MSSM: at low m_A (<140 GeV) LHC & LEP limits close. Large m_A and tan β still possible. Improved constraints for $H^{\pm}$
  - 2HDM: constraints in (cos α, tan β) space. First searches in cascade decays
  - NMSSM: wide open range of possibilities.
    - only few channels/signatures addressed so far.
    - already relatively stringent limits for light CP-odd Higgs bosons
    - additional analyses are underway.
    - also Dark SUSY interpretation possible
  - Invisible Higgs: first limits obtained in associated production and VBF. Still large BR(H→inv) possible.
  - Fermio-phobic Higgs excluded within 100-147 GeV

Outlook

- Non-SM Higgs searches have just scratched the surface
  - many LHC BSM analyses still need to be updated with full 8 TeV statistics
  - many additional new analyses underway
  - 13 TeV running will further extend the reach towards higher masses
- A rich research program for the future