Higgs Searches Beyond the Standard Model

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HELMHOLTZ ASSOCIATION

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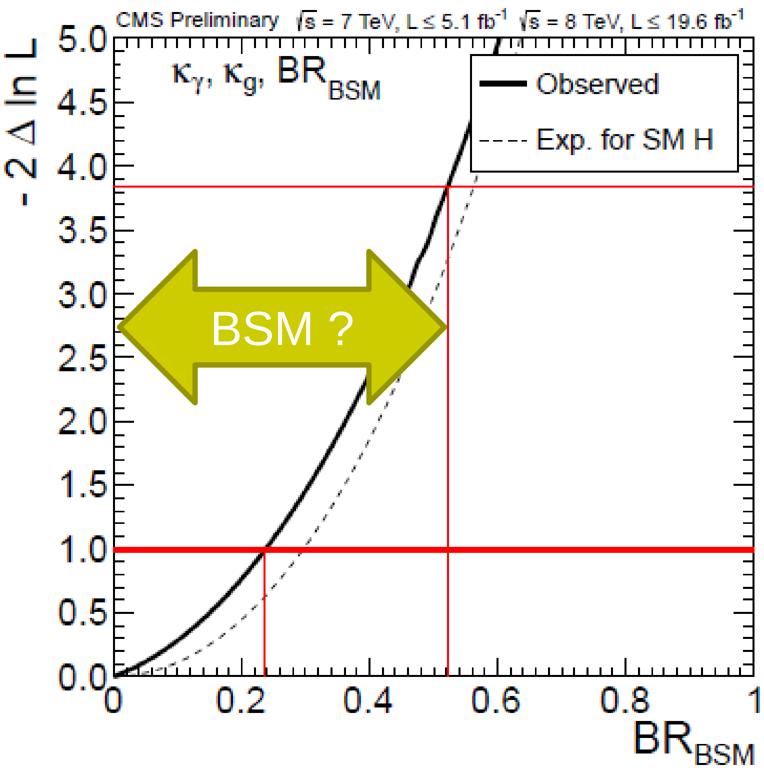
Introduction

CMS PAS HIG-13-005

- 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



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

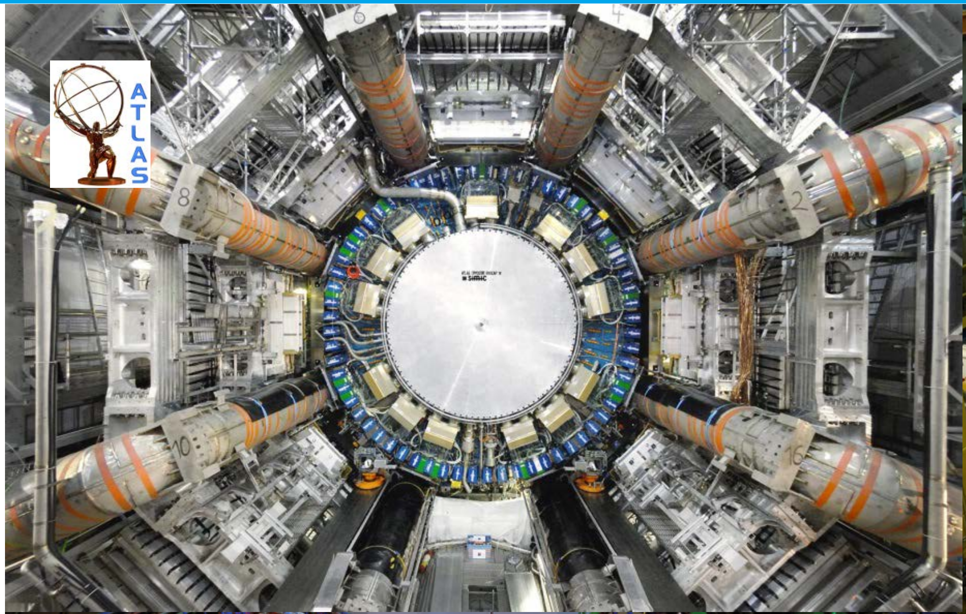
NMSSM
- two complex scalar doublet fields + additional singlet
- seven physical Higgs states

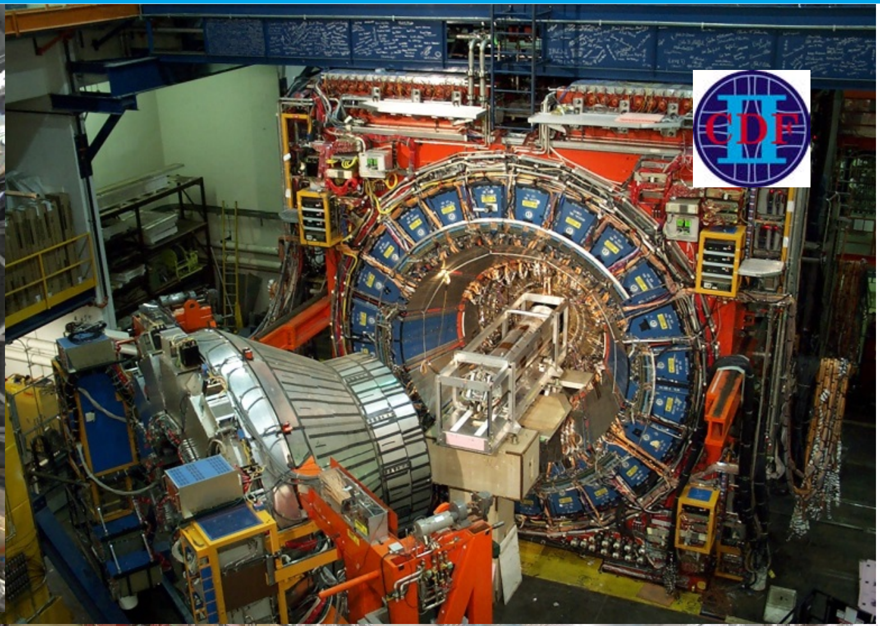
Hidden Sector
- invisible Higgs
- dark SUSY

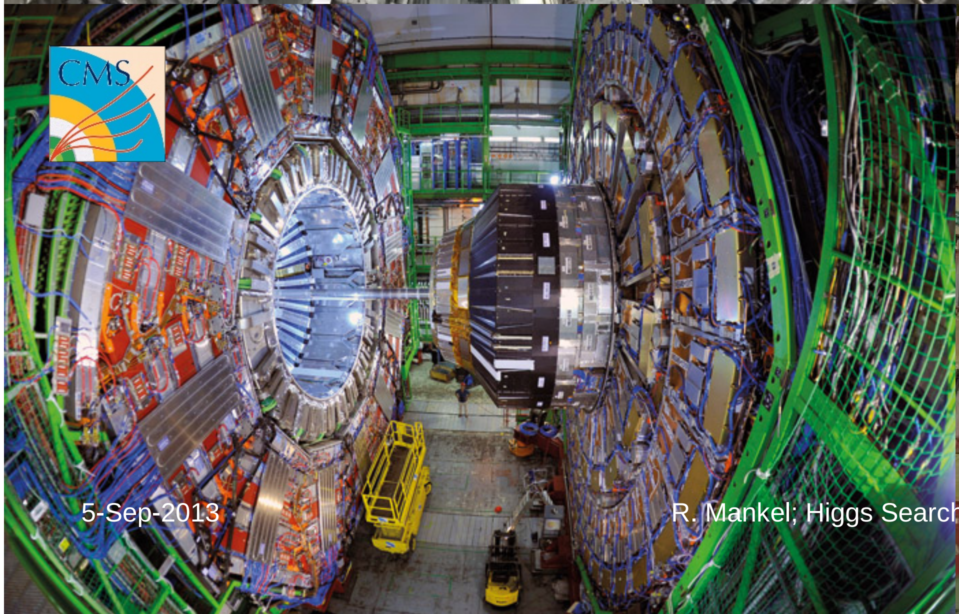
Many others

…

The Experiments



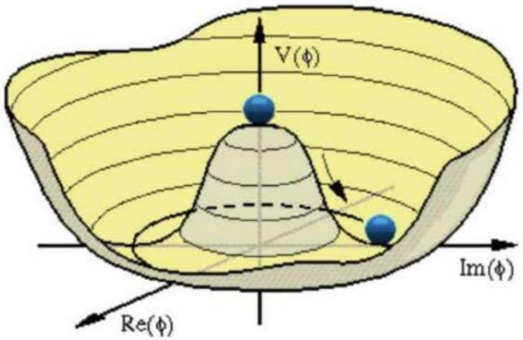




MSSM Higgs Bosons

MSSM Higgs Bosons

- MSSM features two complex Higgs doublets
- ➔ Five physical Higgs bosons
  - three neutral: $\underbrace{\underbrace{h, H}_{\text{CP-even}}, \underbrace{A}_{\text{CP-odd}}}_{\text{denoted } \Phi}$
  - two charged: $H^{\pm}$

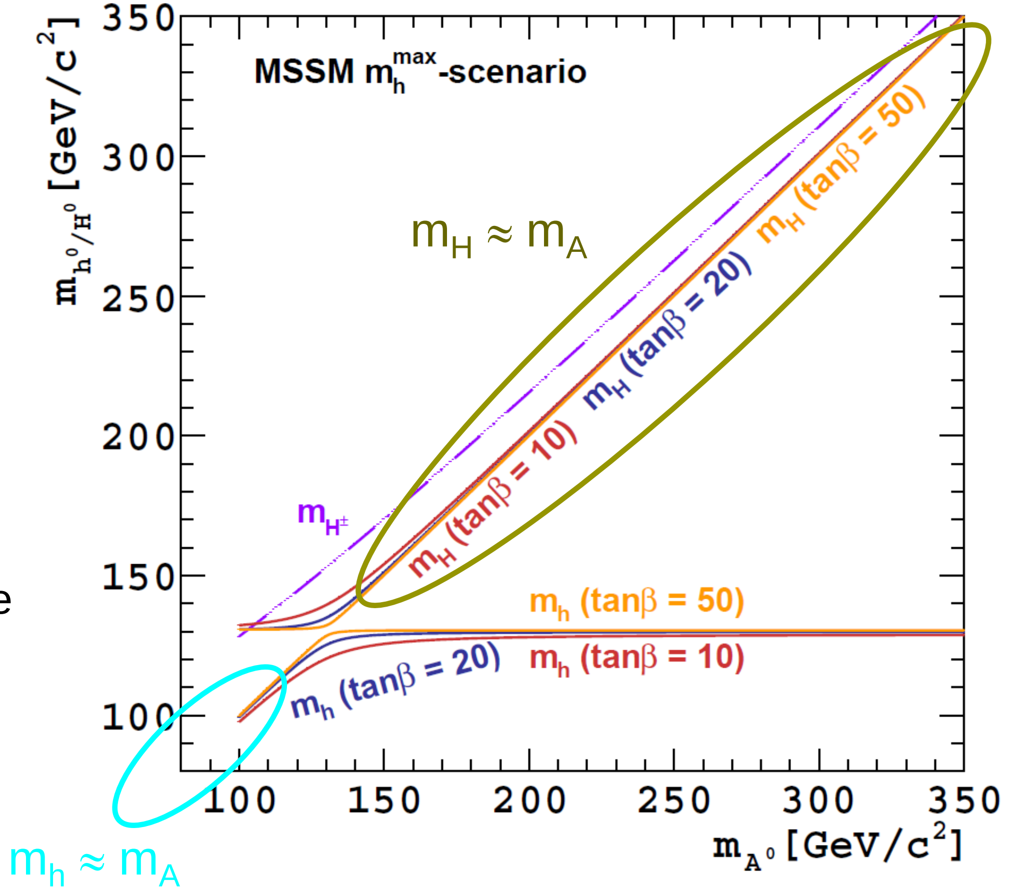


- At tree level, MSSM Higgs sector is governed by two parameters:
  - m_A
  - tan β (ratio of vacuum expectation values of the two Higgs doublets)
- Beyond tree level, additional parameters enter via radiative corrections
  - ➔ benchmark scenarios to compare different measurements (by default "m_h^{max}")

Higgs Masses in the MSSM

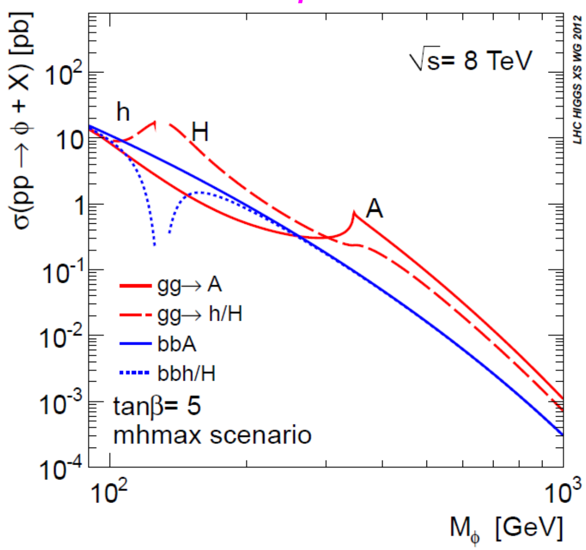
- The mass of the CP-odd Higgs boson A is usually ~degenerate with one of the CP-even bosons
  - $m_A \approx m_H$ for $m_A >> m_h^{max}$
  - $m_A \approx m_h$ for $m_A << m_h^{max}$
- With the exception of the $\mu\mu$ channel, this degeneracy cannot be resolved within the mass resolution
  - ➔ visible cross section effectively doubles

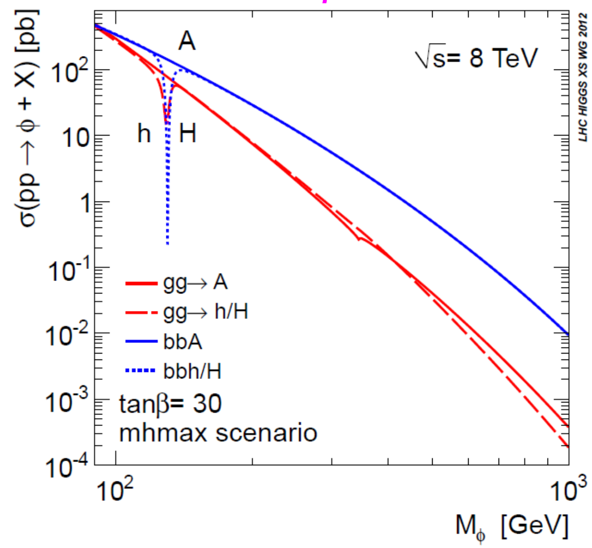
➔ Together with the effect of the Higgs coupling to b quarks, visible cross sections in b-associated production are typically enhanced by a factor of $\approx 2 \tan^2 \beta$



MSSM Higgs Production & Decay

tan β = 5 → tan β = 30

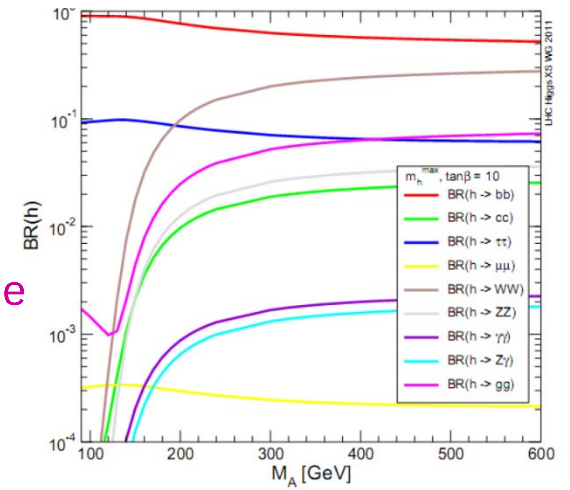




- Strong enhancement of cross section with increasing tan β
  - in particular due to associated production

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

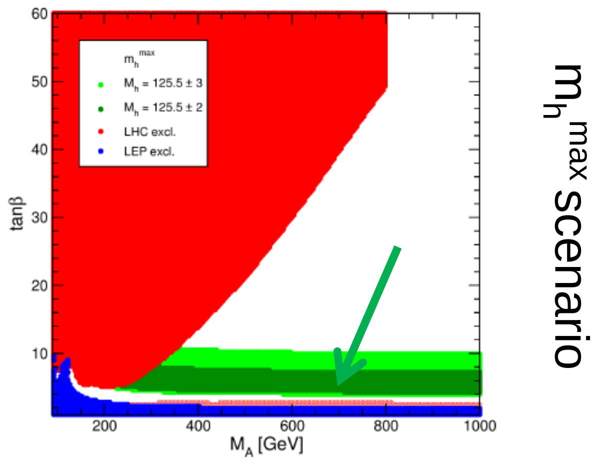
➔ Unlike the SM, these decay modes may play important rôle even at high masses

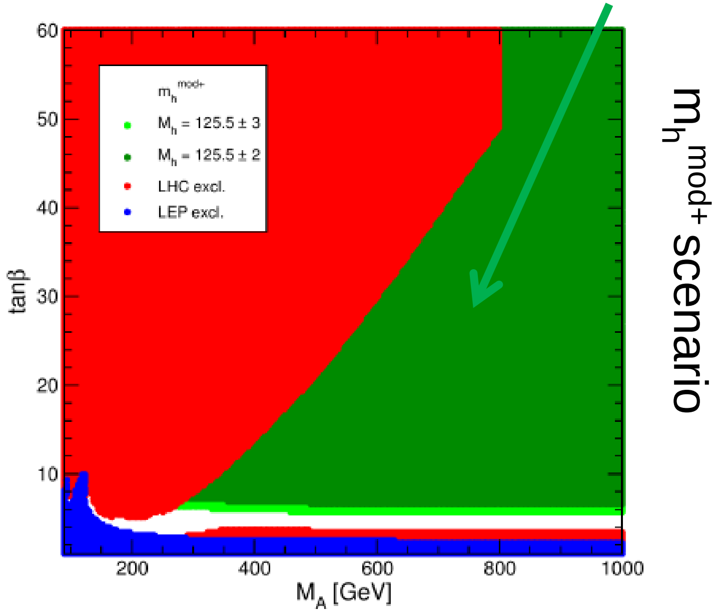


MSSM & the 125 GeV Higgs Observation

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

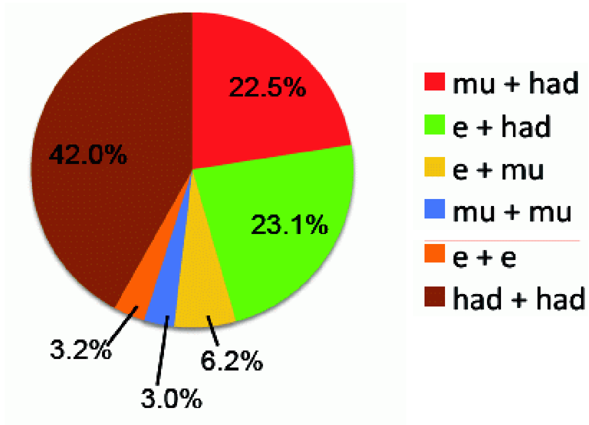




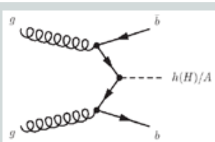
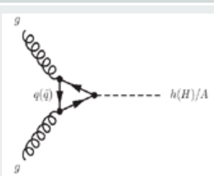
- The H(125) observation does not exclude a heavy MSSM Higgs in wide range of tan β
- At large M_A (>>m_Z) the "light" MSSM Higgs boson (h) becomes standard model-like (decoupling limit) → direct searches are essential
- Both SM and MSSM fit the current set of H(125) measurements ~equally well

P. Bechtle et al., arXiv:1211.1955

$\Phi \rightarrow \tau\tau$ Search



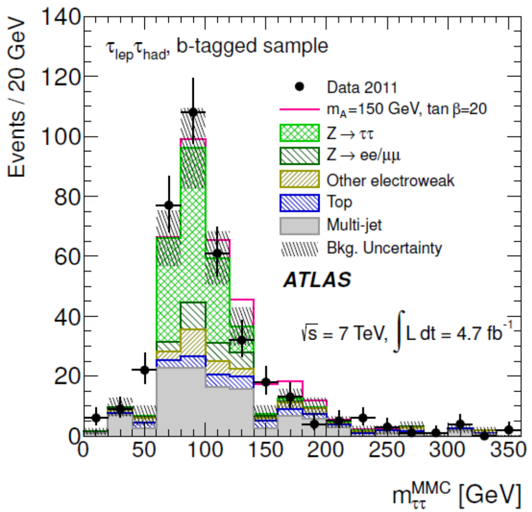
Production mechanisms & event categories

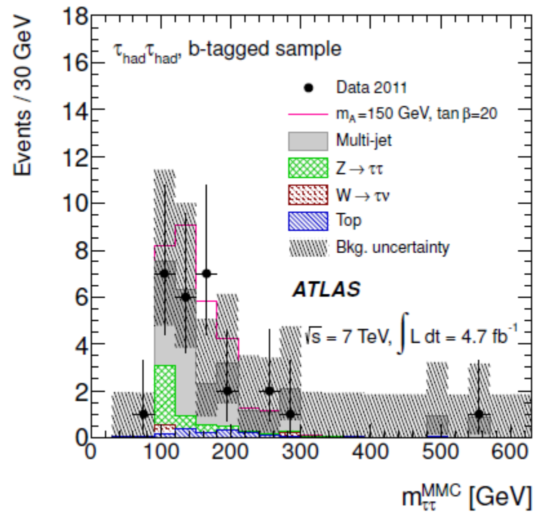
 associated production	B-Tag at least 1 b-tagged jet
 gluon-gluon fusion	No B-Tag no b-tagged jet

- 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):
  - **$Z \rightarrow \tau\tau$:**
    - embedding technique: take $Z \rightarrow \mu\mu$ from data, replace μ's by simulated τ decays
  - $Z \rightarrow ee$ / $\mu\mu$
  - $t\bar{t}$ and di-boson
  - QCD multijet, W+jets:

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

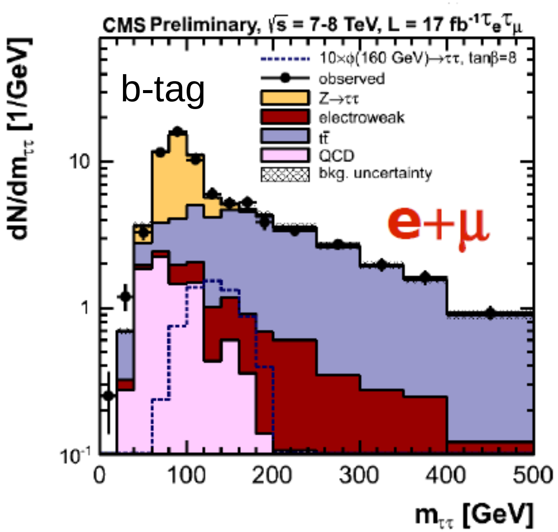
$\Phi \rightarrow \tau\tau$: Mass Distributions (B-tag Category)

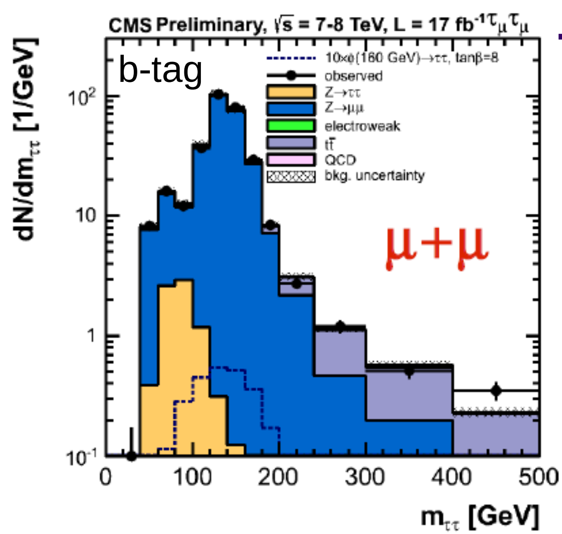




ATLAS JHEP 1302 (2013) 095

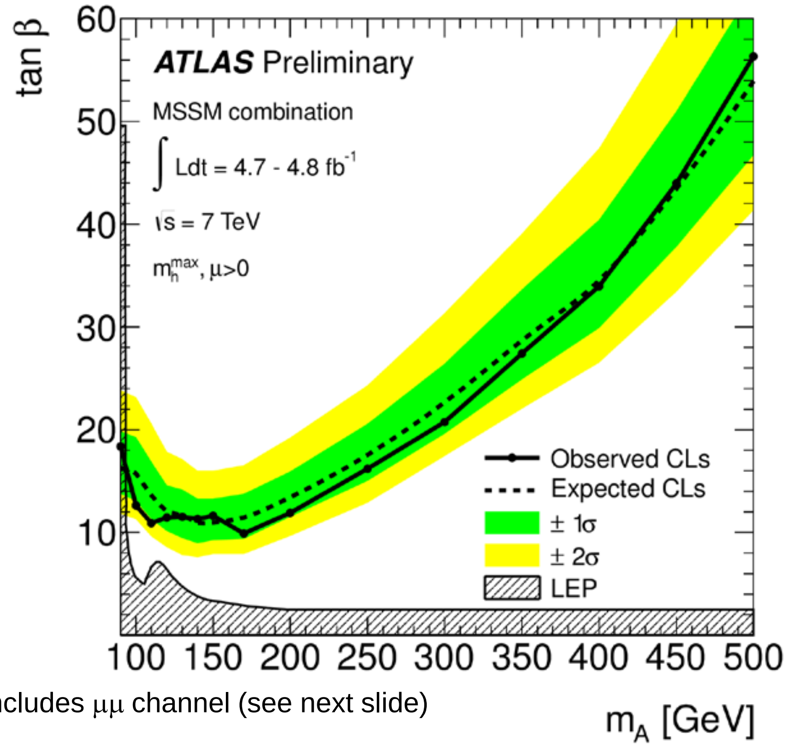
CMS PAS HIG-12-050



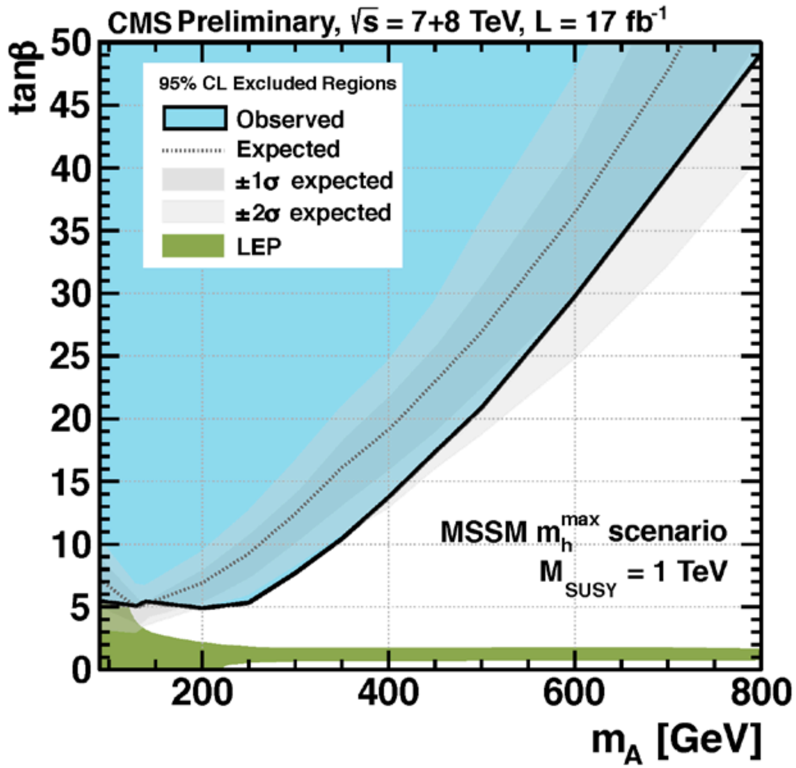


- ➔ Background compositions differ significantly across the various decay channels
- ➔ All distributions well described by background hypothesis

Φ → ττ: Results



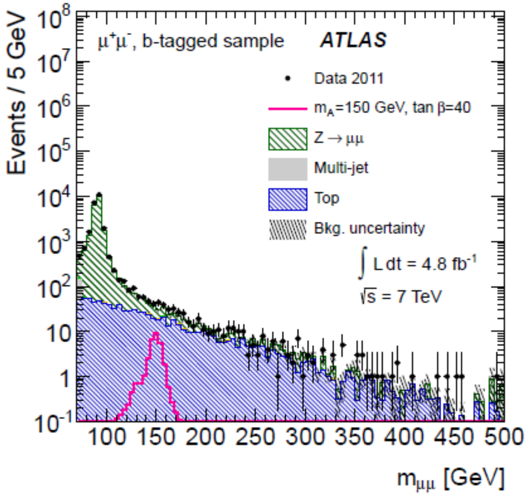
includes μμ channel (see next slide)



- ➔ 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)

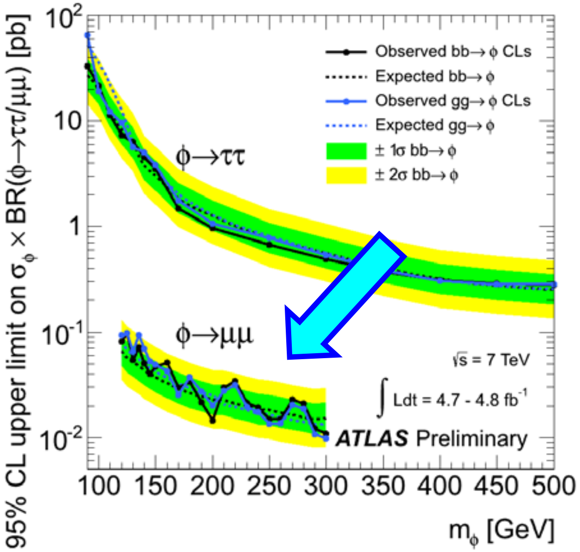
$\Phi \rightarrow \mu\mu$ Search

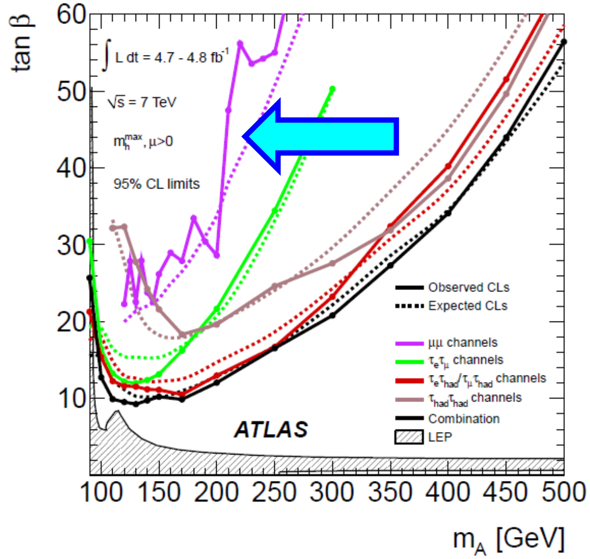
- Low BR, but also excellent mass resolution (close to Γ_Φ) and manageable BG
- Dominant backgrounds: Drell-Yan, bbZ^0, top
- ➔ Limits reach to σ * BR in the 20-100 fb range
  - ➔ significant constraints in (m_A, tan β) plane

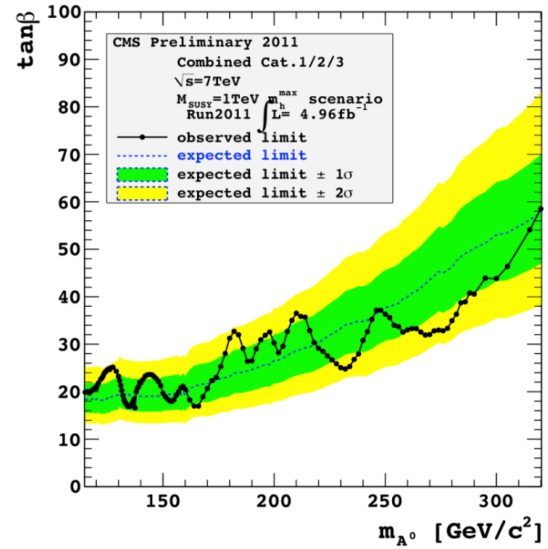


ATLAS JHEP 02 (2013) 095

ATLAS JHEP 02 (2013) 095

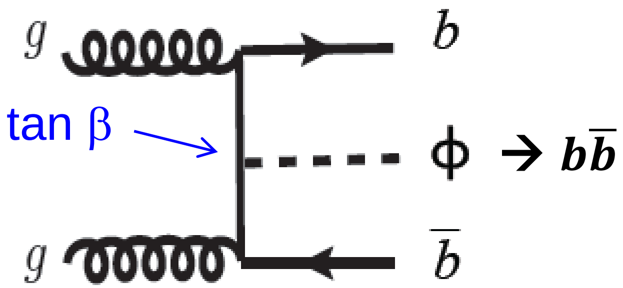






CMS PAS HIG-12-011

- 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 β > 1
- Signature: ≥ three b-jets + X in the final state
  - ➔ one of the most challenging triggers

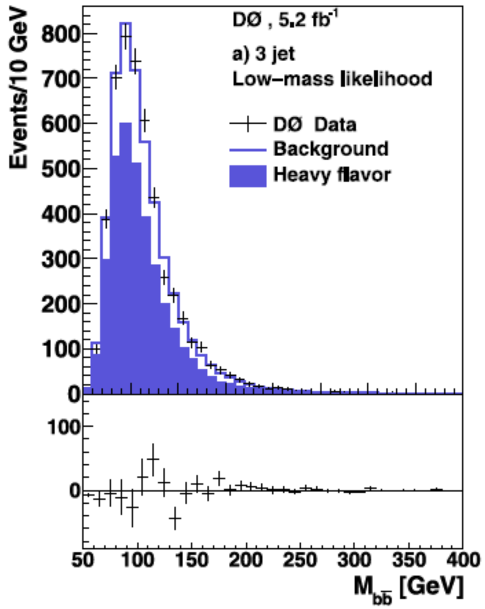


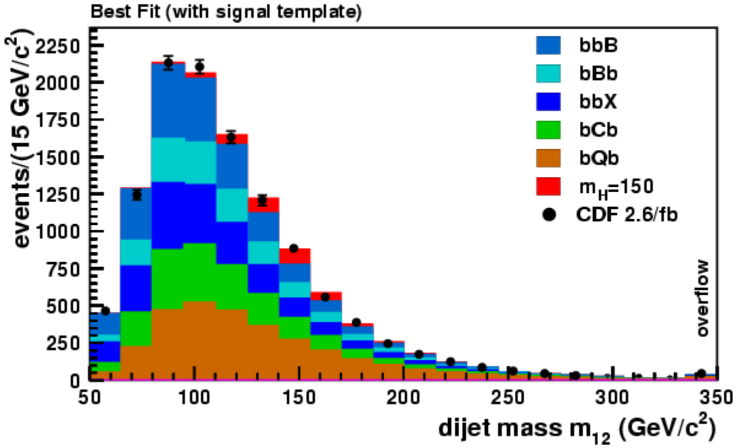
$\Phi \rightarrow b\bar{b}$: Tevatron Measurements

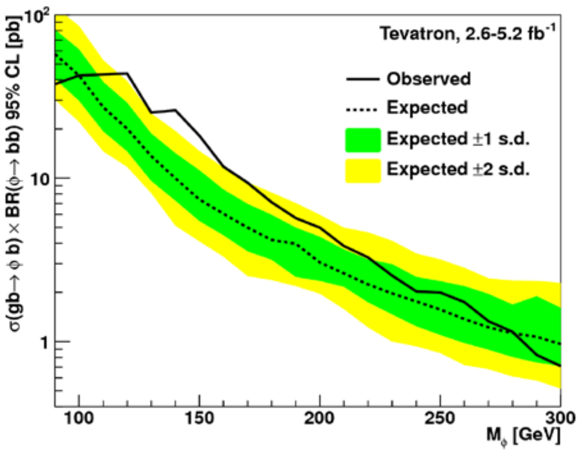
CDF+D0 Phys.Rev. D86 (2012) 091101

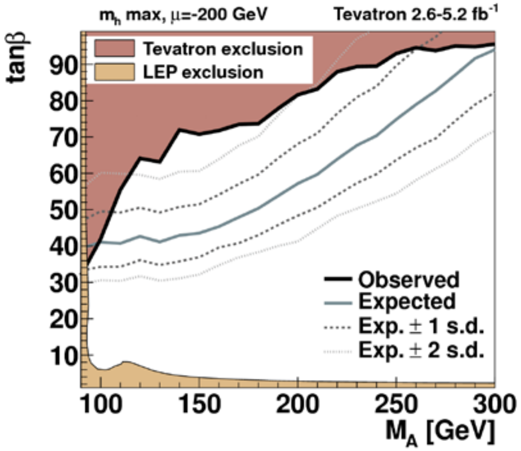
- Search for MSSM Higgs boson decaying to b quarks, and produced with at least one additional b jet
- Background treatment:
  - CDF: mass + global b-tag templates, derived from double btag sample with btag efficiency weights. Combination fitted to data.
  - D0: fractional contributions of multi-jet processes 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)









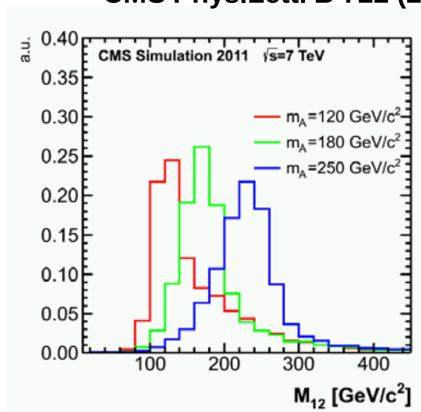
CMS $\Phi \rightarrow b\bar{b}$ Search

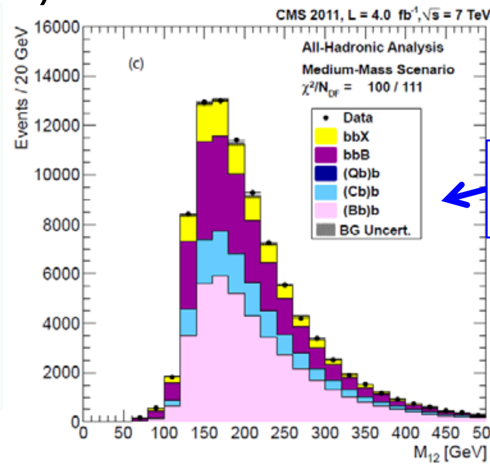
- CMS analysis searches in all-hadronic (shown) and semi-leptonic signatures (see backup)
- All-hadronic analyses inspired by CDF method

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

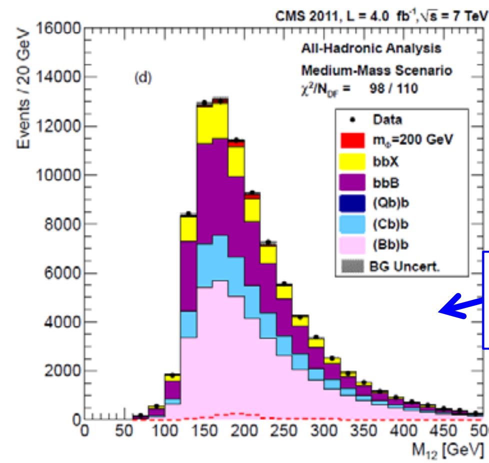
- No signal observed
- First measurement of this kind at the LHC

CMS Phys.Lett. B 722 (2013) 207





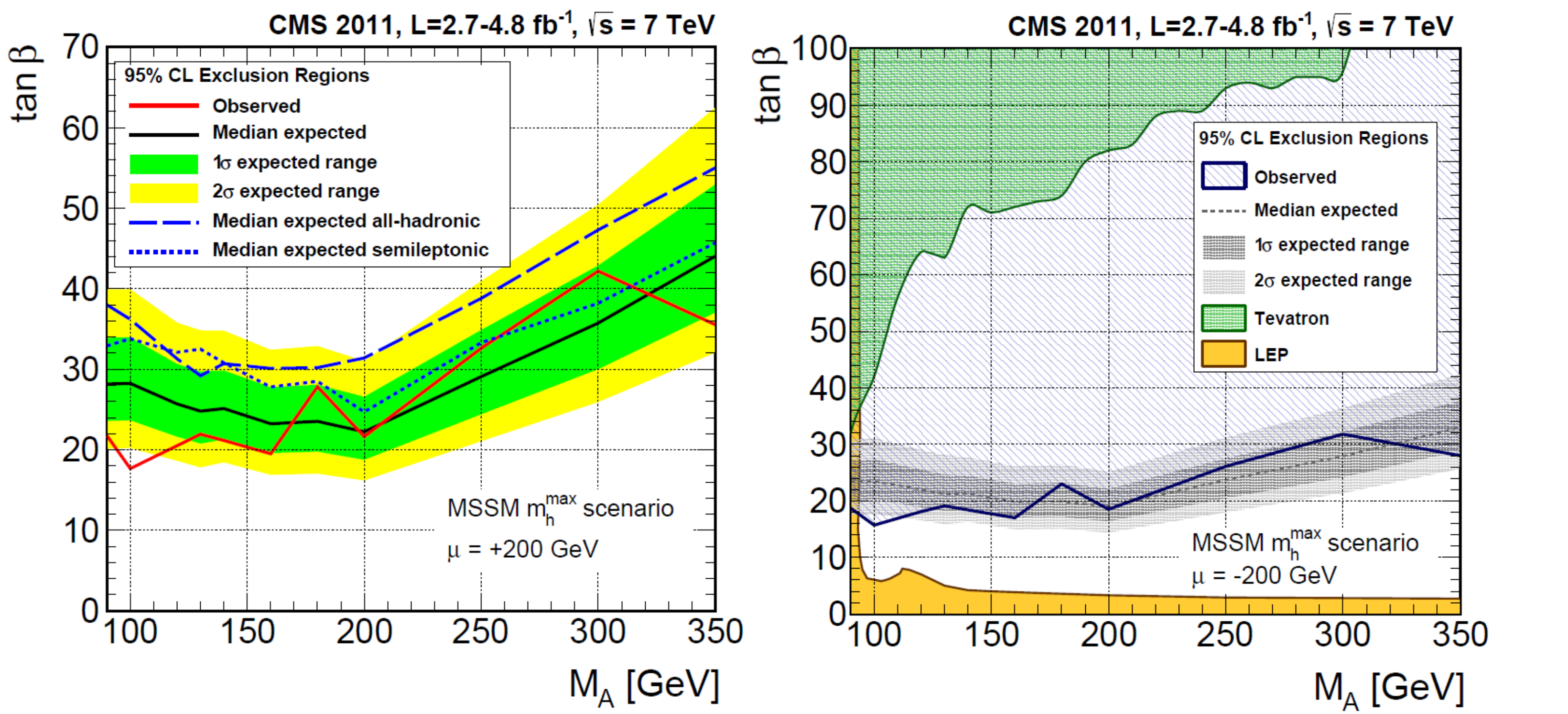
BG-only fit



m_{Φ}=200 GeV (1.4 σ)

$\Phi \rightarrow bb$ Search: Combination of CMS Analyses & Comparison with Tevatron

CMS Phys.Lett. B 722 (2013) 207



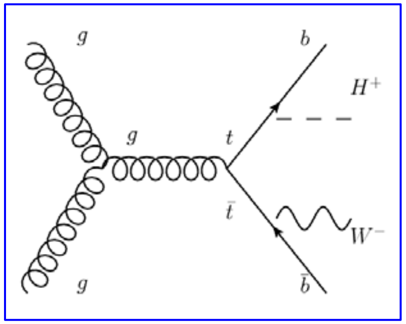
- For comparison with Tevatron, CMS results also given for μ= -200 GeV (right)
- ➔ Already with 2011 data, CMS has significantly higher sensitivity
- ➔ CMS does not confirm ~2σ-level excesses seen by CDF + D0

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

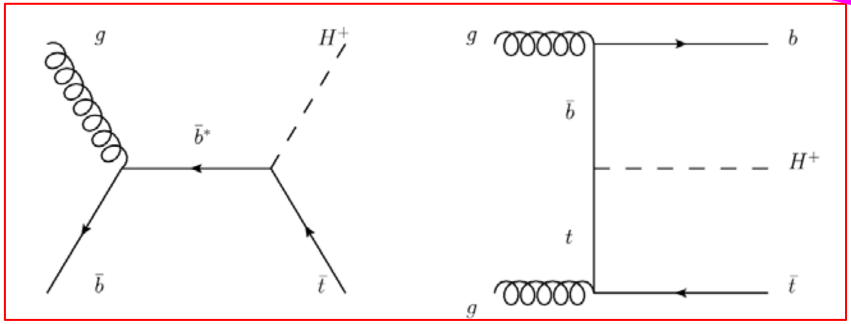
ATLAS CONF-2013-090

Brand New

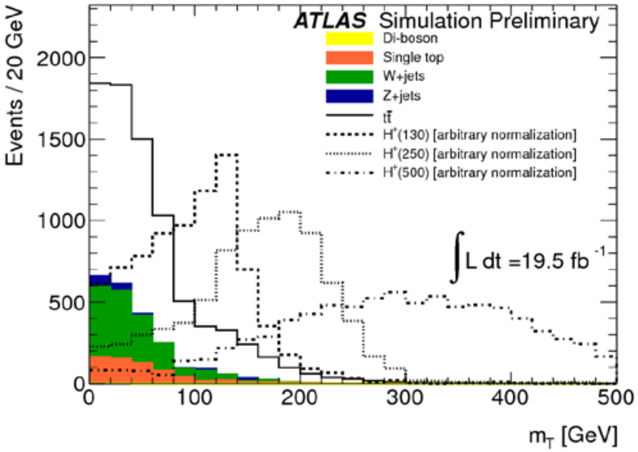
- $H^+ \rightarrow \tau\nu_\tau$ dominant decay mode for tan β>5 and $m(H^+)<m_t$
- Main production modes:
  - top decays ($m(H^+)<m_t$)



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



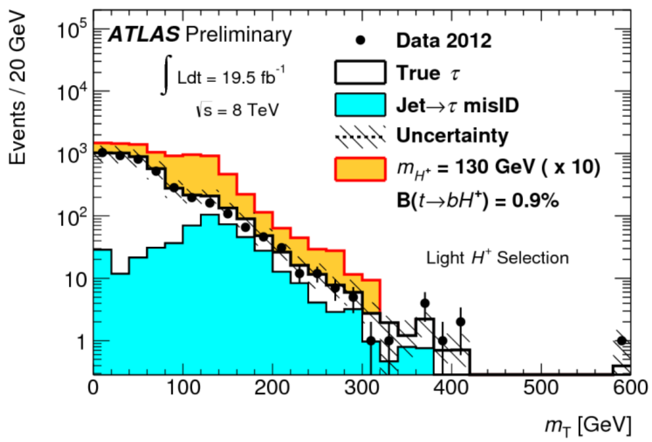
- Fully hadronic final states (ATLAS):
  - veto on other leptons
  - 3-4 jets (≥1 b-tagged)
  - large MET
- Discriminating variable m_T (= transverse invariant mass of τ + MET)
- Backgrounds: $t\bar{t}$, single-top, W/Z+jets, di-bosons, QCD

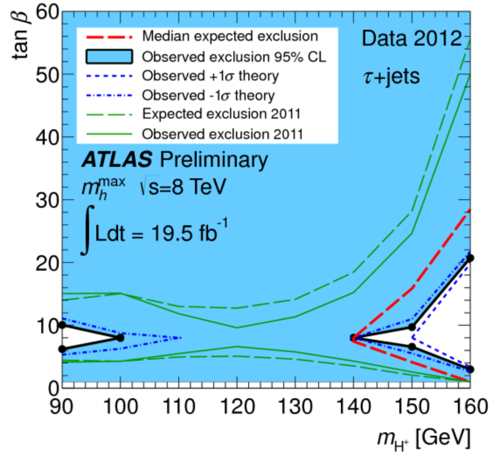


$H^+ \rightarrow \tau\nu_\tau$ Search (cont'd)

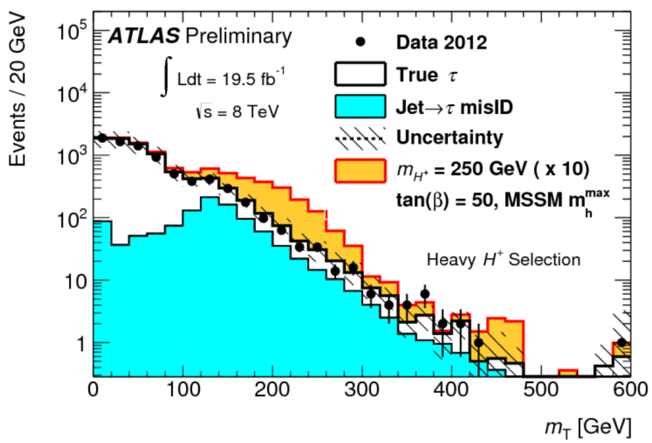
ATLAS CONF-2013-090

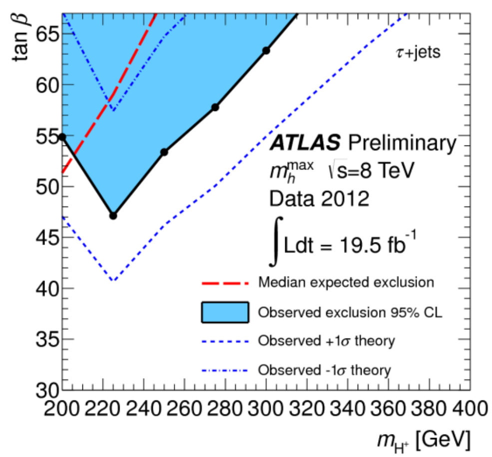
Light H^+ analysis





Heavy H^+ analysis



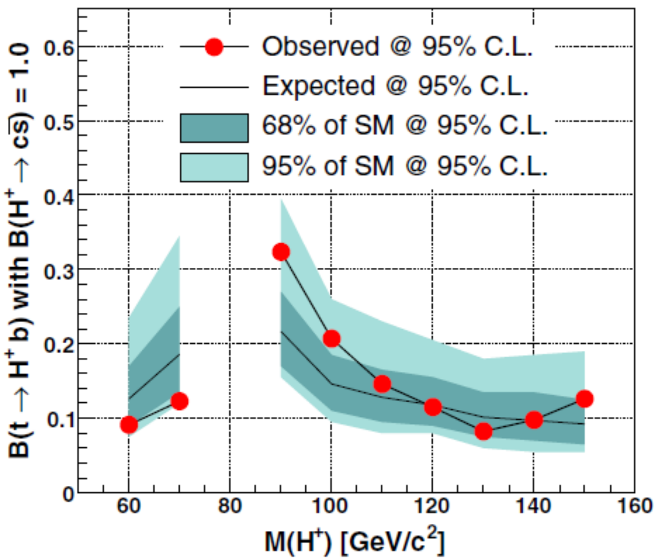


- Full 2012 dataset used
- Mass ranges 90-160, 180-600 GeV covered
- No evidence for H^+ found
- At low $m(H^+)$, large parts of MSSM parameter space excluded

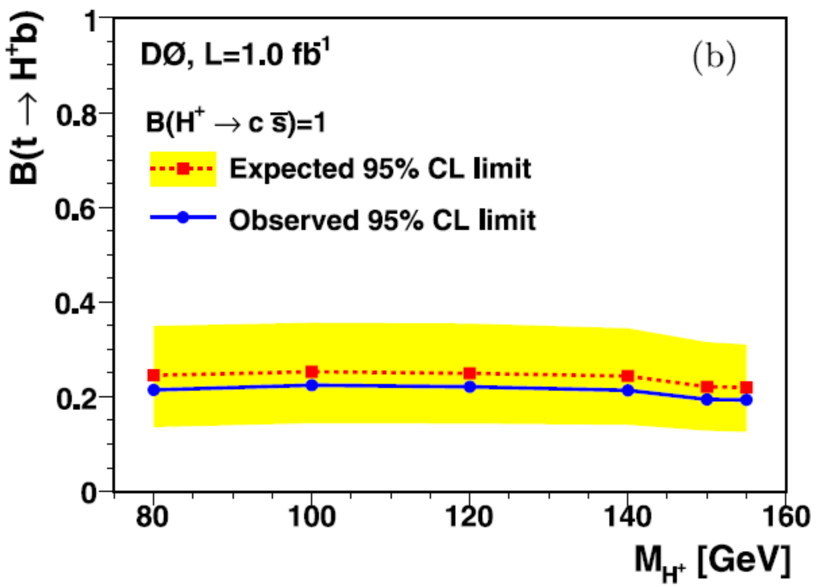
Light H± Search in $c\bar{s}$

- 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.



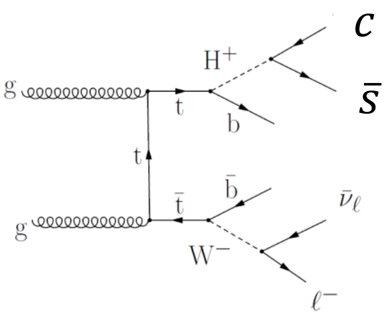
D0, Phys. Lett. B 682 (2009) 278.



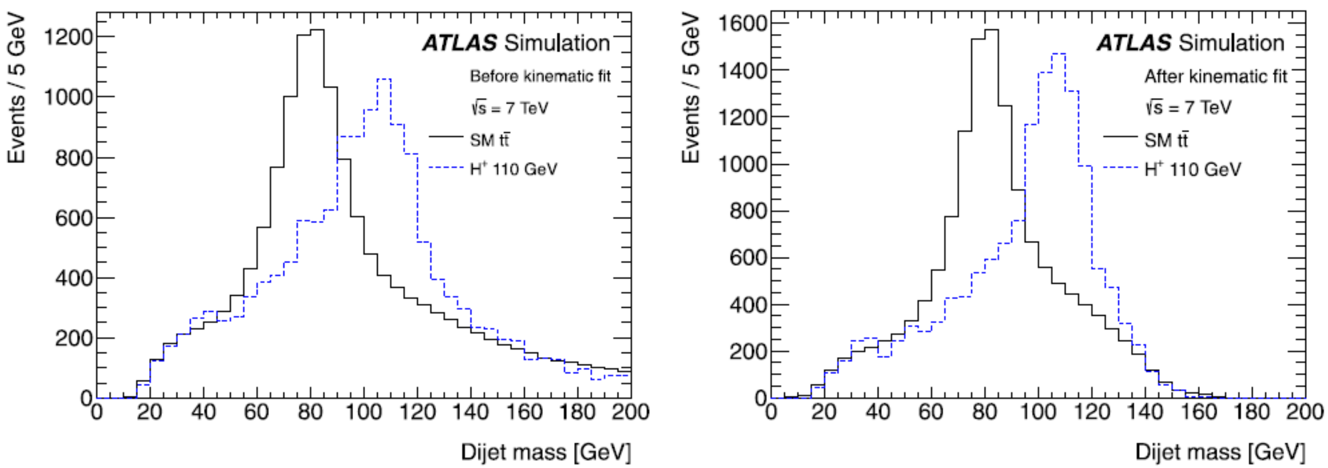
Light H± Search in $c\bar{s}$ (cont'd)

- 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)



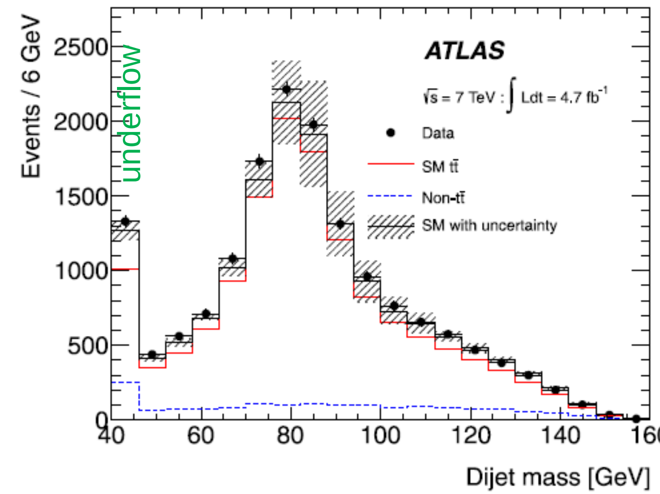
ATLAS Collab., Eur. Phys. J. C 73 (2013) 2465.

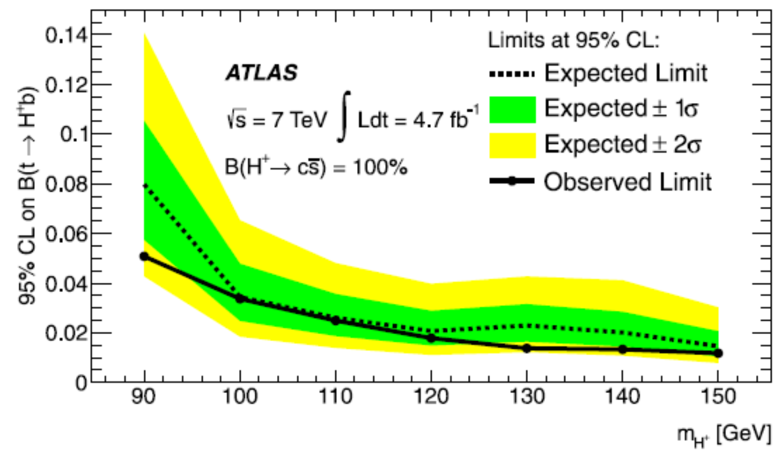


Light H$^{\pm}$ Search in $c\bar{s}$ (cont'd)

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

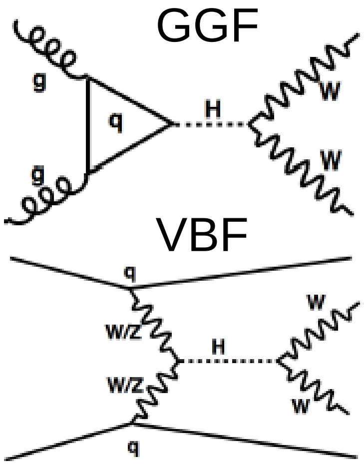




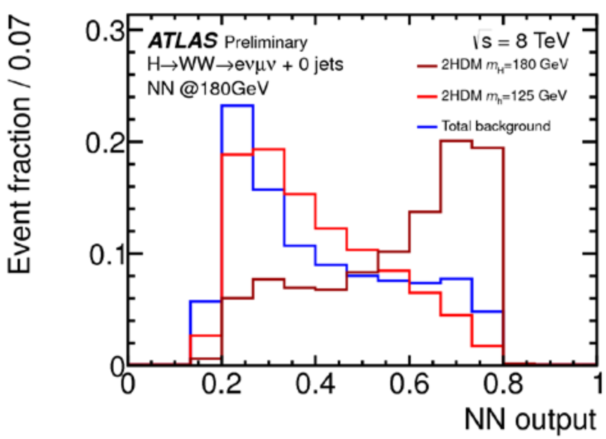
Two Higgs Doublet Model (2HDM)

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 → $WW^{(*)} \rightarrow e\nu\mu\nu$, 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



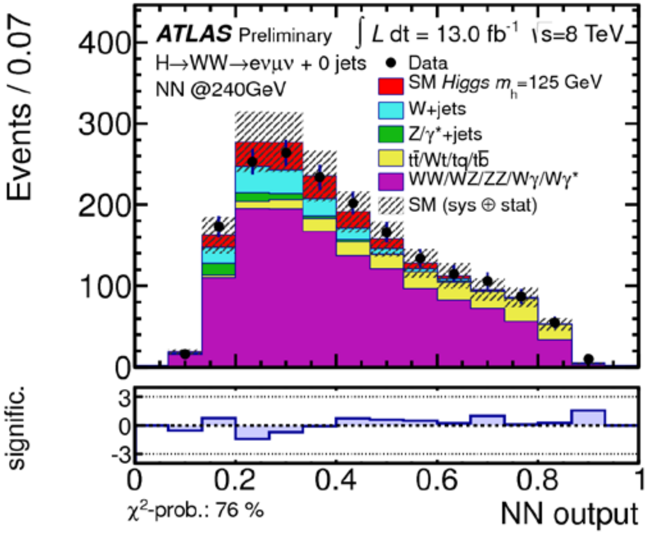
2HDM Higgs Search: Results

- H(125) treated as "background"

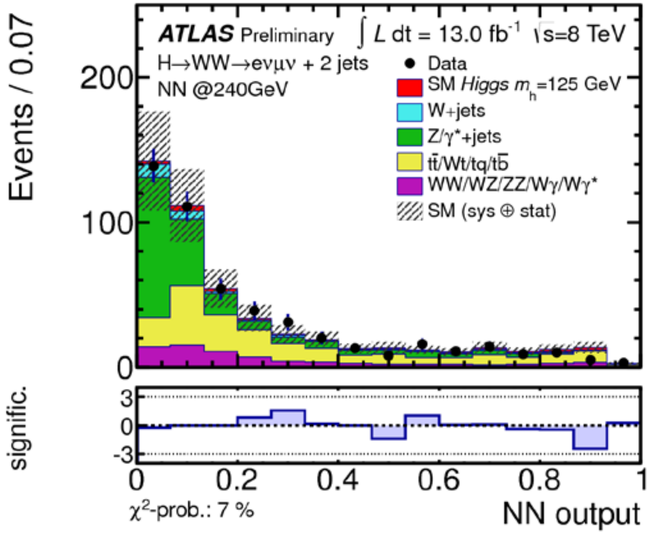
➔ No indication of a signal (would appear at large NN output)

ATLAS CONF-2013-027

GGF Selection

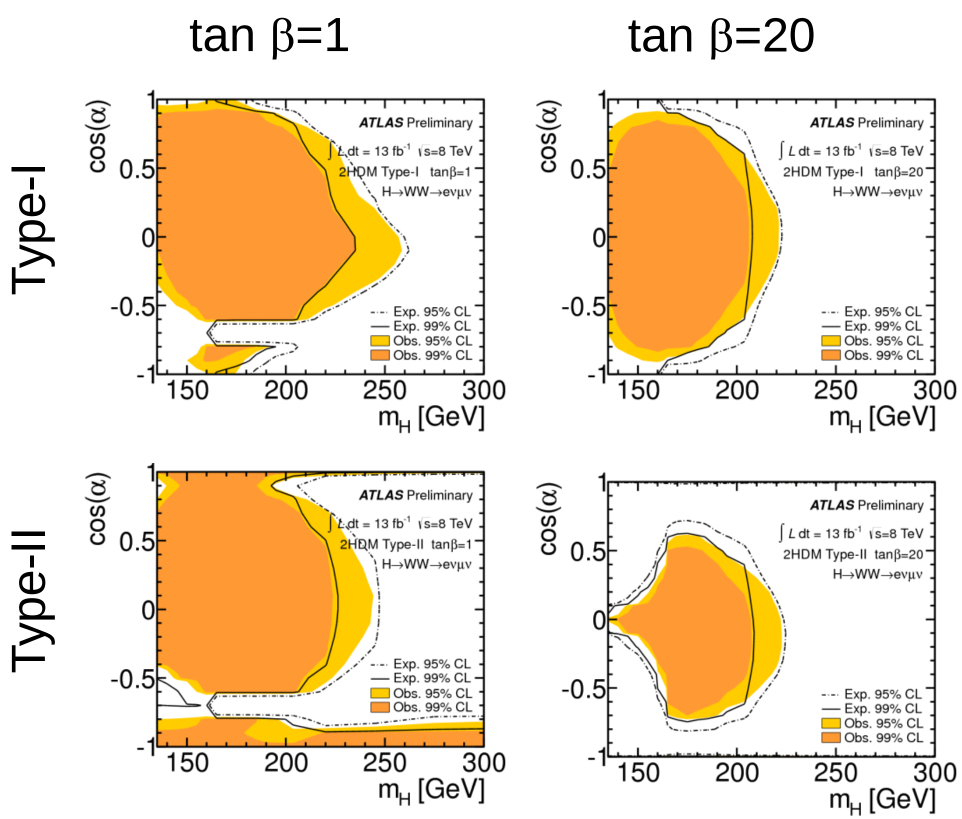


VBF Selection



2HDM Higgs Search: Results

ATLAS CONF-2013-027



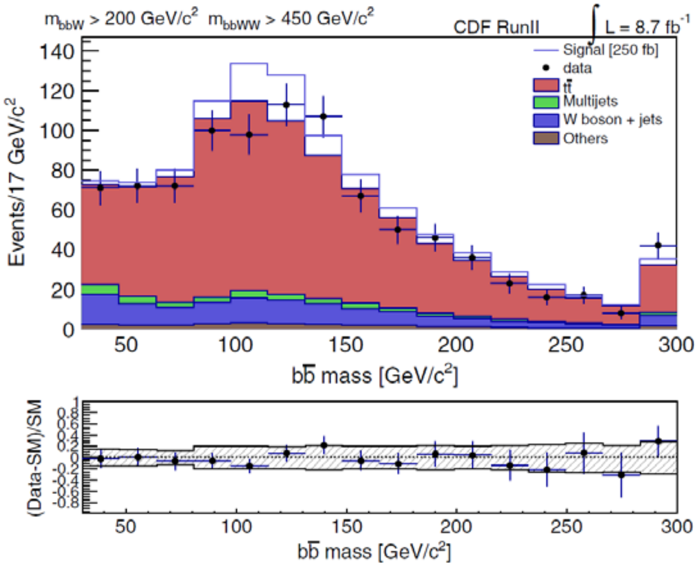
- Interpretation: exclusion contours in the cos α - m_H plane for different values of tan β
  - different results for Type-I and Type-II 2HDM models

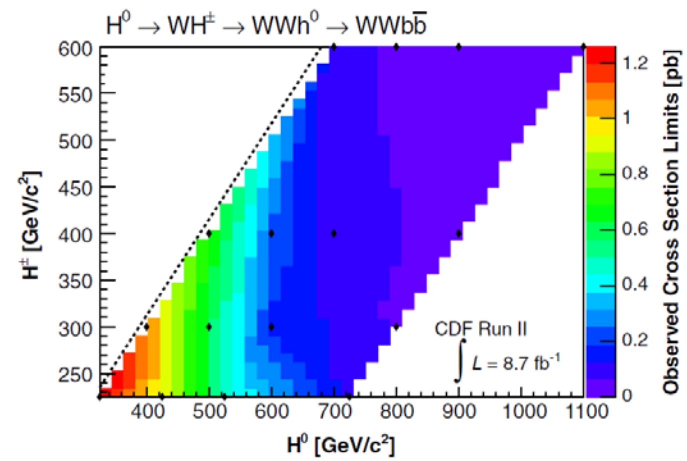
➔ For low masses (< 200 GeV), significant parts of the cos α range are excluded

2HDM Search in Cascade Decays

- Search for a heavy scalar H^0 with a cascade decay:
  - $H^0 \to H^+W^- \to (h^0W^+)\,W^- \to (b\bar{b})\,W^+\,W^-$
    - 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 $B(H^0 \to H^+W^-) = B(H^+ \to h^0W^+) = 100\%$
  - → limits range between 1.3-0.015 pb
  - → first measurement of this kind

Phys.Rev.Lett. 110 (2013) 121801





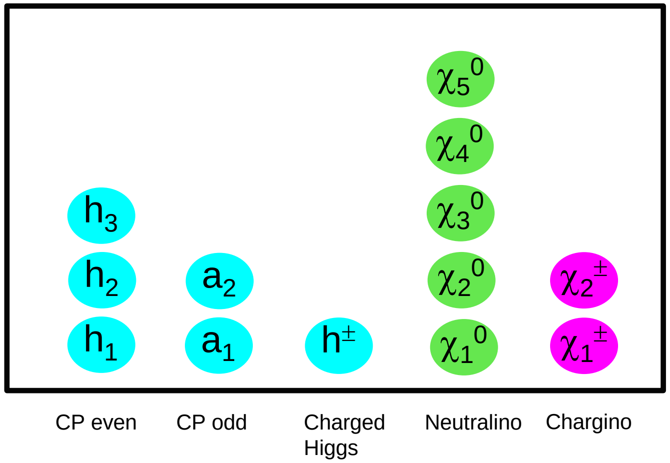
NMSSM Higgs Bosons

The NMSSM Higgs Sector

- Two complex Higgs doublets + additional scalar field
- Physical states are mixtures: $\underbrace{h_1, h_2, h_3}_{\text{CP-even}}, \quad \underbrace{a_1, a_2}_{\text{CP-odd}}, \quad h^{\pm}$

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

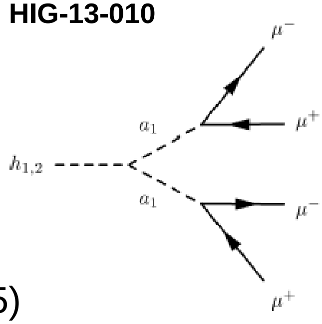
➔ Rich phenomenology

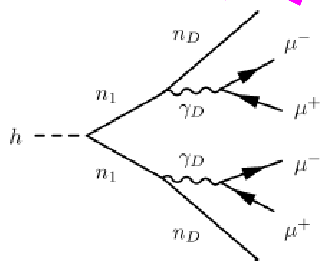


$h_{1,2} \rightarrow aa \rightarrow (\mu\mu)\,(\mu\mu)$ Search

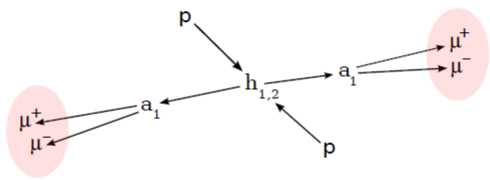
New!

CMS PAS HIG-13-010





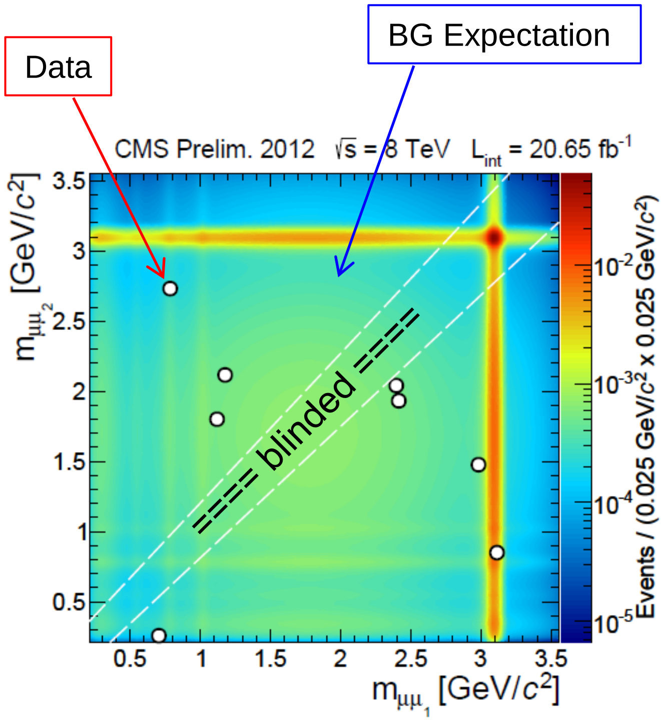
- Search for a non-standard Higgs decay into two very light bosons, resulting in two boosted pairs of muons
- NMSSM interpretation: $h_{1,2} \rightarrow a_1 a_1 \rightarrow (\mu\mu)\,(\mu\mu)$
  - either h_1 or h_2 could correspond to observed H(125)
  - a_1 is a new light CP-odd Higgs boson ($m<2m_\tau$)
- 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)



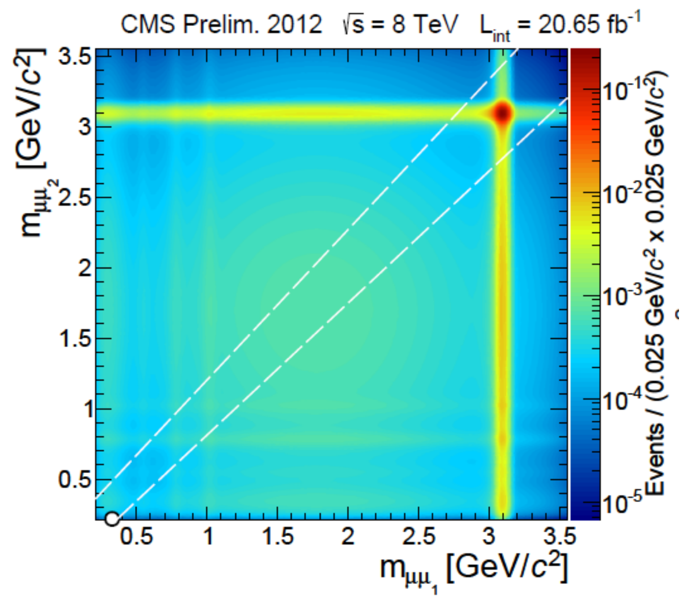
$h_{1,2} \rightarrow aa \rightarrow (\mu\mu)(\mu\mu)$: Results

- $b\bar{b}$ 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

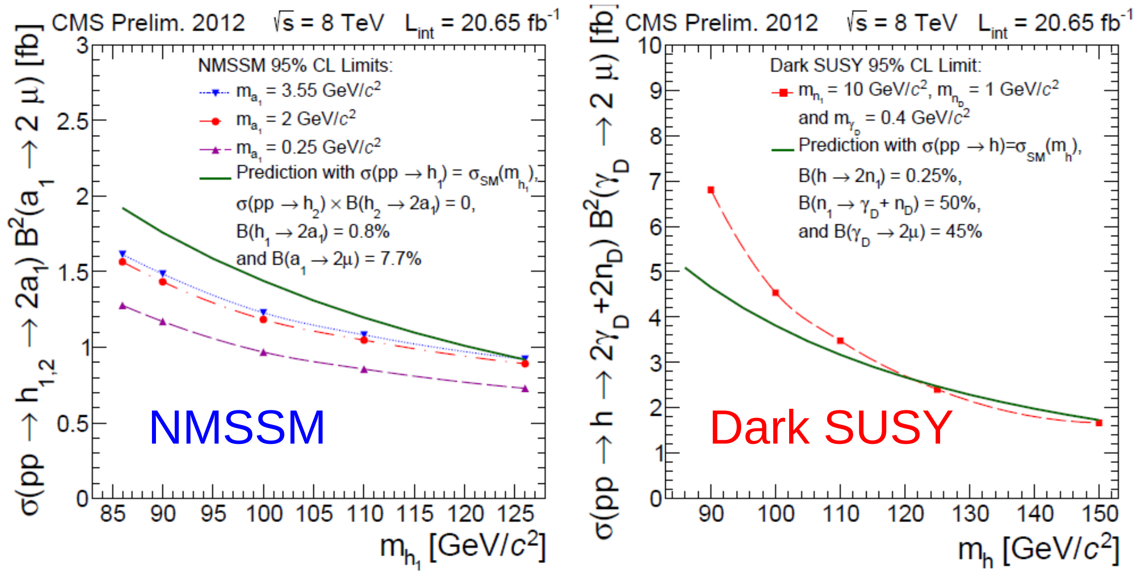


after unblinding (signal region):



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

CMS PAS HIG-13-010



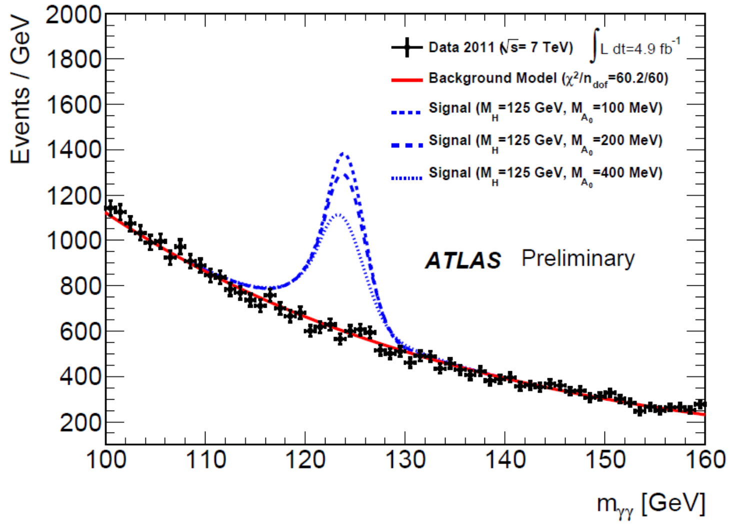
- Results are interpreted in context of NMSSM and dark-SUSY benchmark models
  - signal efficiencies depend on assumptions for either m_a or m_h
- ➔ NMSSM: upper limits vs m_{h1} and m_{a1}
  - m_{h2} unrestricted → conservative assumption on efficiency
  - for NMSSM prediction, assume that only h_1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

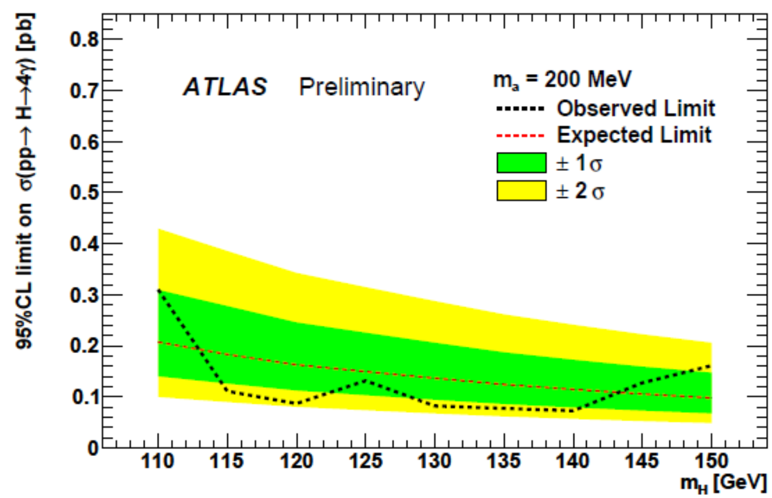
H(125) Decays to Light NMSSM Pseudo-Scalars

- If very light NMSSM CP-odd Higgs bosons exist, they might be observed in the decay
  $H(125) \rightarrow a\, a \rightarrow (\gamma\gamma)(\gamma\gamma)$
- Here: assume m_a=100-400 MeV
  - di-photon system would be highly boosted. Potential background for SM $H\rightarrow \gamma\gamma$ analysis
- Analysis similar to SM $H\rightarrow \gamma\gamma$
  - additional selection based on shower shape variables & calorimetric isolation

➔ No signal observed
  - upper limits of σ*BR($H\rightarrow aa\rightarrow (\gamma\gamma)(\gamma\gamma)$) in 0.1-0.2 pb range

ATLAS CONF-2012-079

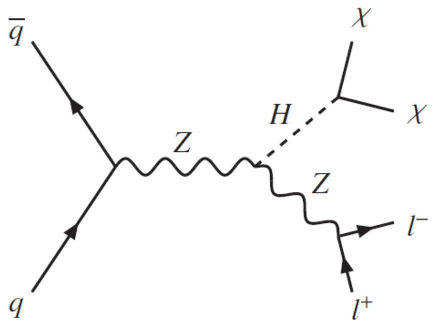




Exotic Higgs Bosons

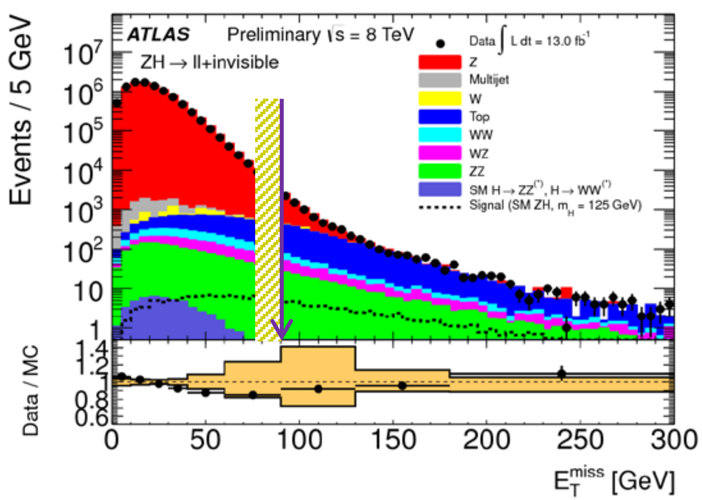
Invisible Higgs

- 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→l^+l^- plus missing E_T, and little else
- Main backgrounds:
  - ZZ→llνν, ZW→ll lν, WW→ lν lν
  - Z+jets

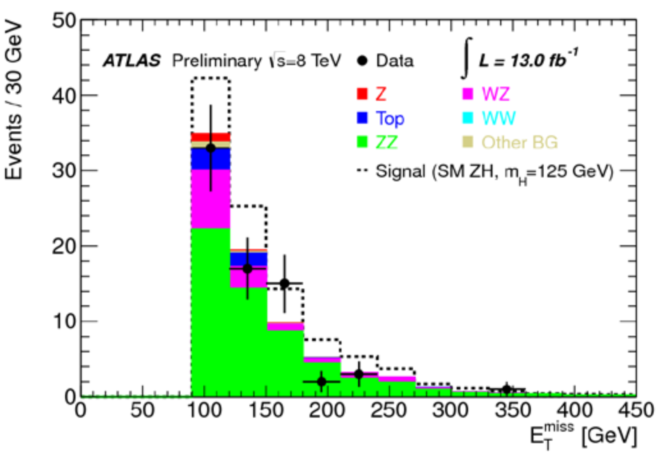


ATLAS-CONF-2013-011

After just Z selection:



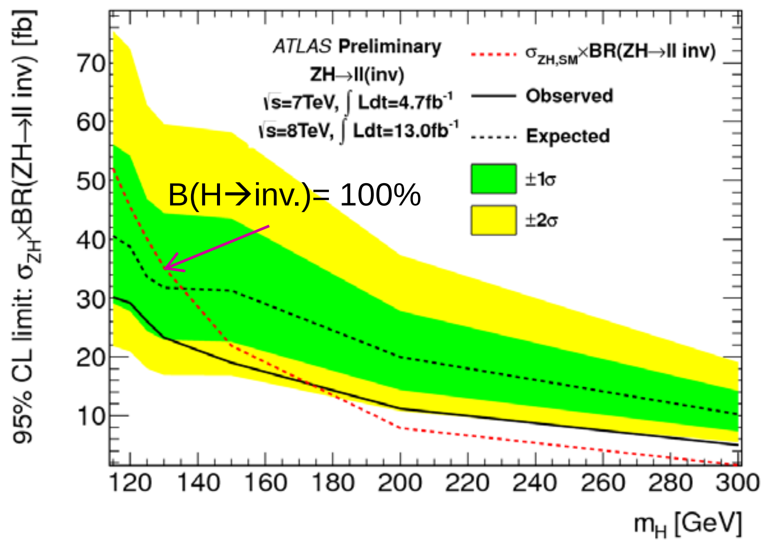
After final selection (8 TeV shown):



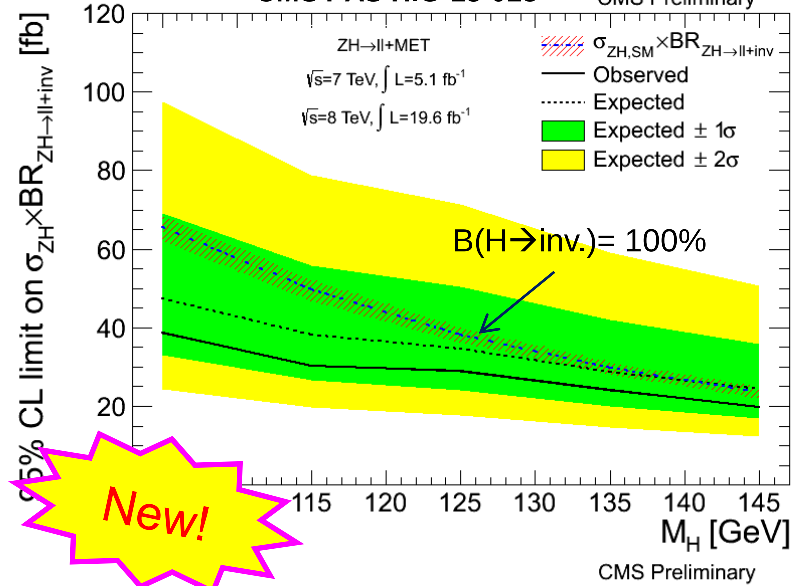
- azimuthal separation
- MET balancing
- veto on additional jets

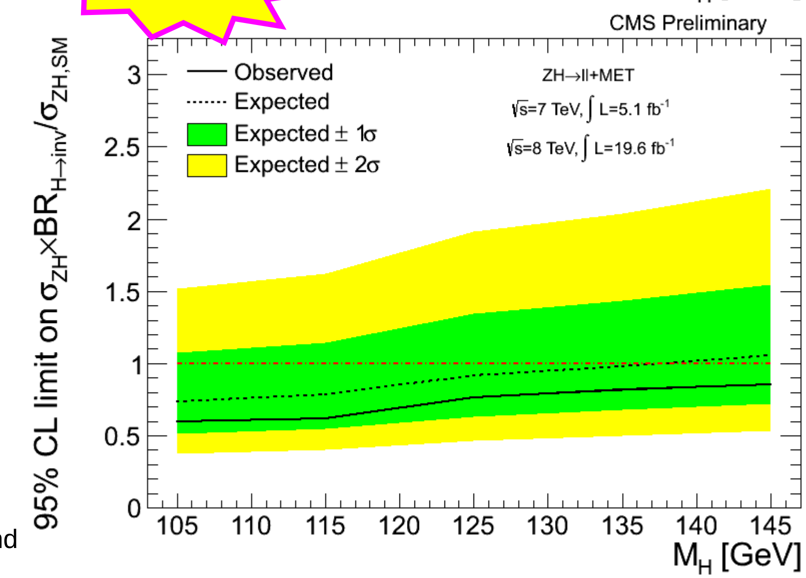
Invisible Higgs: Results

ATLAS-CONF-2013-011



CMS PAS HIG-13-018



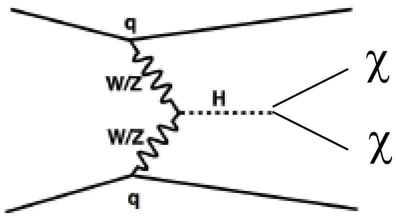


- Invisible BR <65% (ATLAS) and <75% (CMS) for SM Higgs @ 125 GeV (95% C.L.)

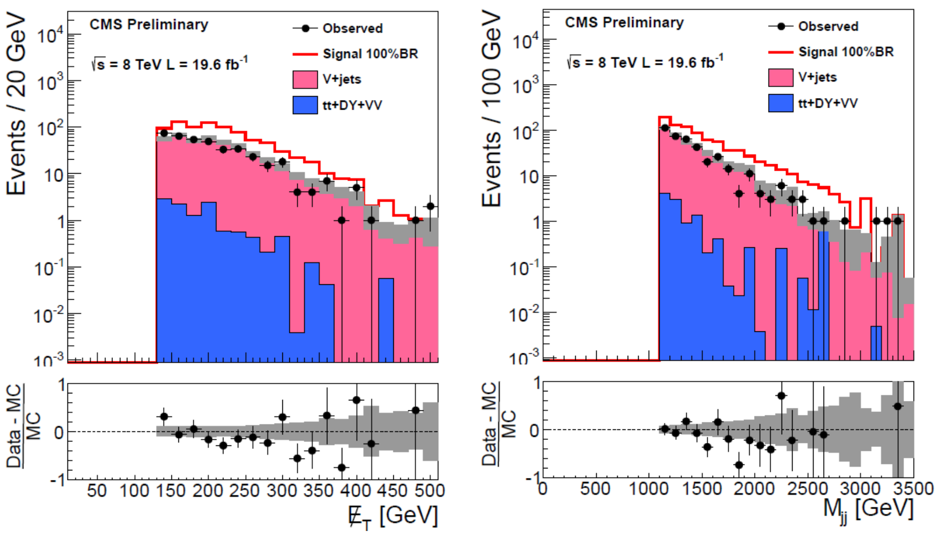
➔ Leaves plenty of room for invisible decay modes

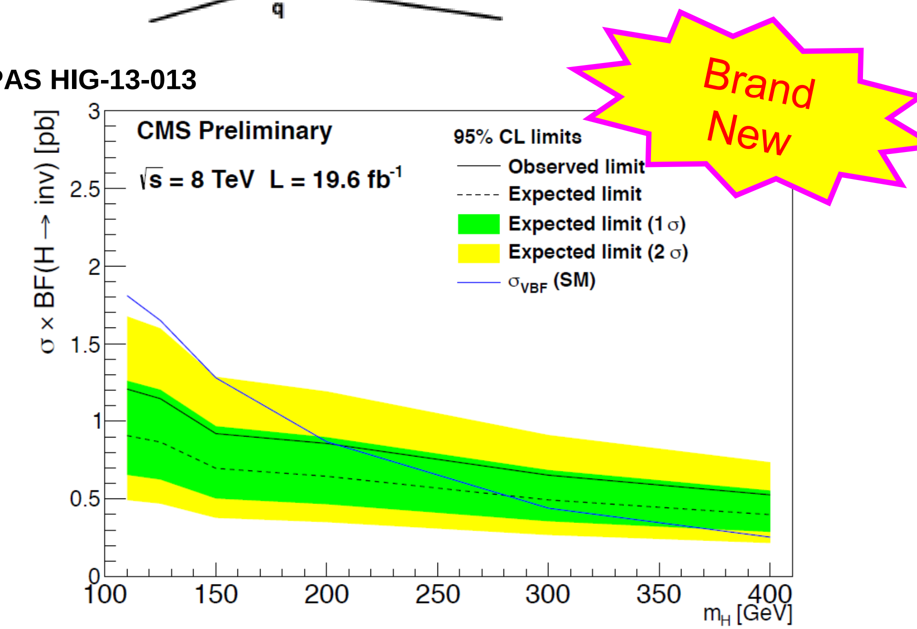
Invisible Higgs (cont'd)

- 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)

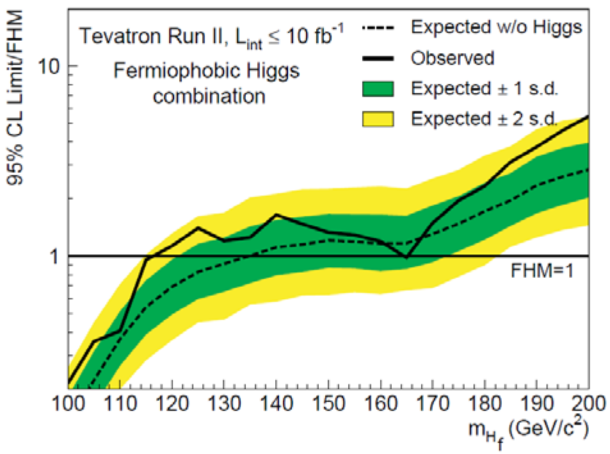
➔ Invisible BR<69% for SM Higgs @ 125 GeV (95% C.L.)

Fermio-Phobic Higgs

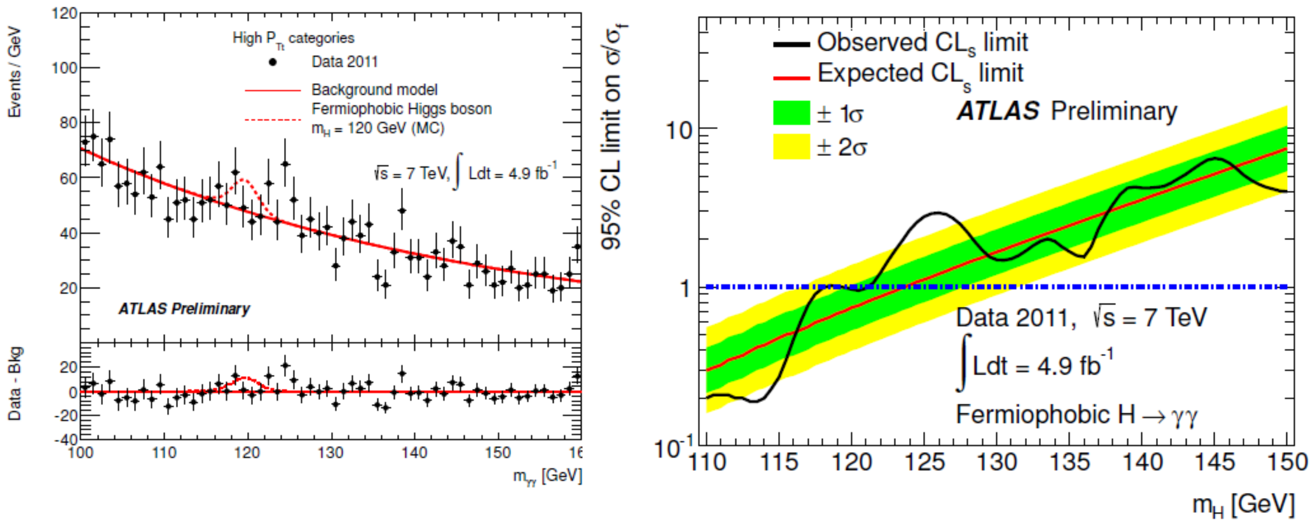
- If a Higgs boson does not couple to fermions
  - ➔ production via gluon-gluon fusion impossible
  - ➔ standard production channel is vector boson fusion (VBF) or vector-boson associated production (VH)
  - ➔ BRs for di-boson modes enhanced
- Analysis largely similar to SM analysis

➔ Fermio-phobic Higgs excluded within m_H= 100-147 GeV

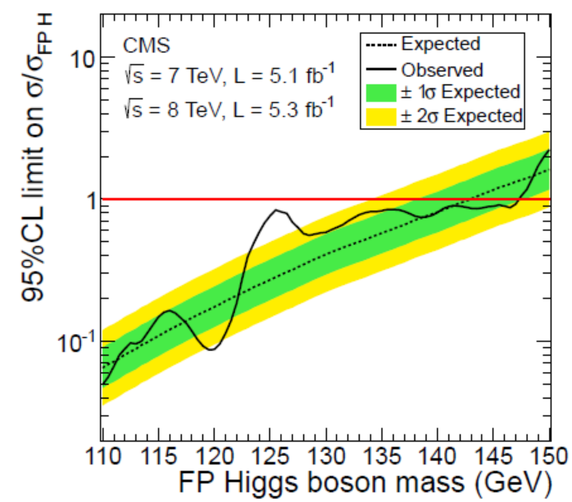
CDF+DZero arXiv:1303.6346



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

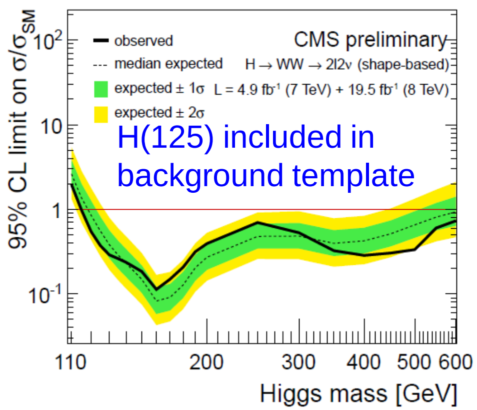
A sublime field for Hadron Colliders as discovery machines at the energy frontier!

Backup

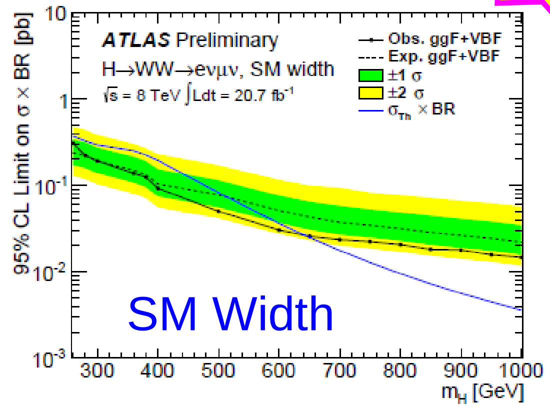
Heavy SM-like H→WW

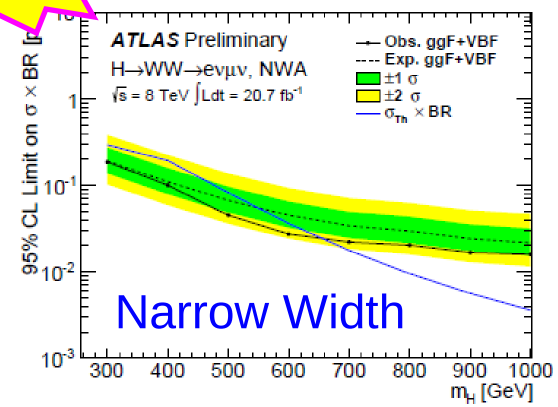
New!

CMS PAS HIG-13-003

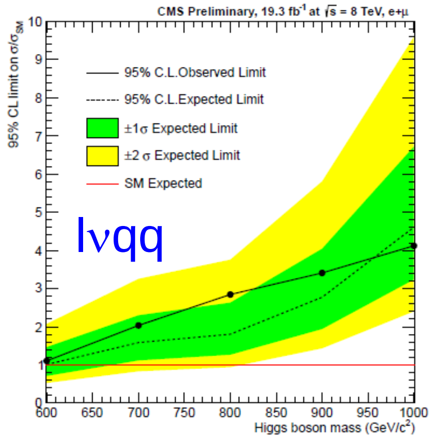


ATLAS CONF-2013-067

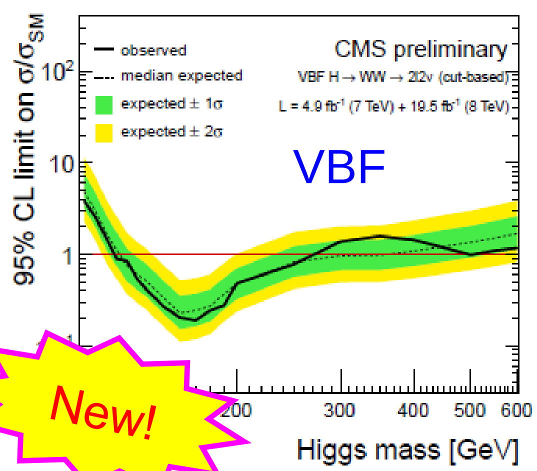




CMS PAS HIG-13-008



CMS PAS HIG-13-022



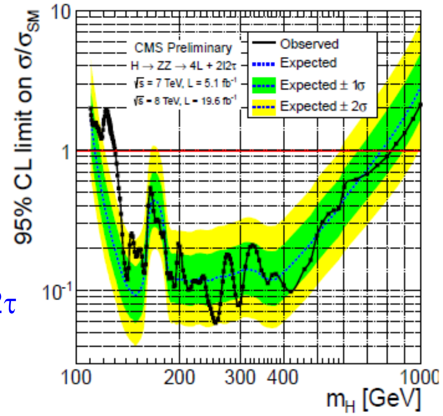
New!

- Additional SM-like H→WW excluded up to 600 GeV (CMS), 642 GeV (ATLAS)
  - ATLAS analysis covers also narrow-width case
  - also leptonic tau decays included

Heavy SM-like H→ZZ

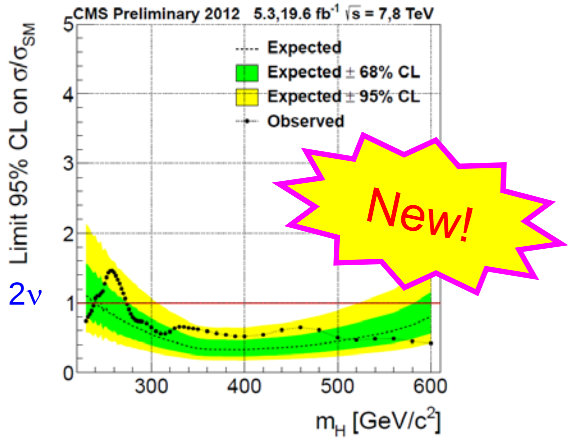
CMS PAS HIG-13-002

4l + 2l 2τ

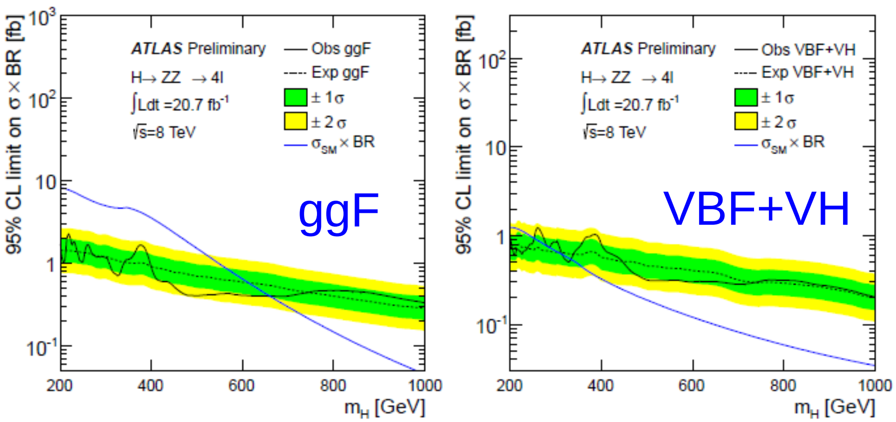


CMS PAS HIG-13-024

2l + 2ν



ATLAS CONF-2013-013



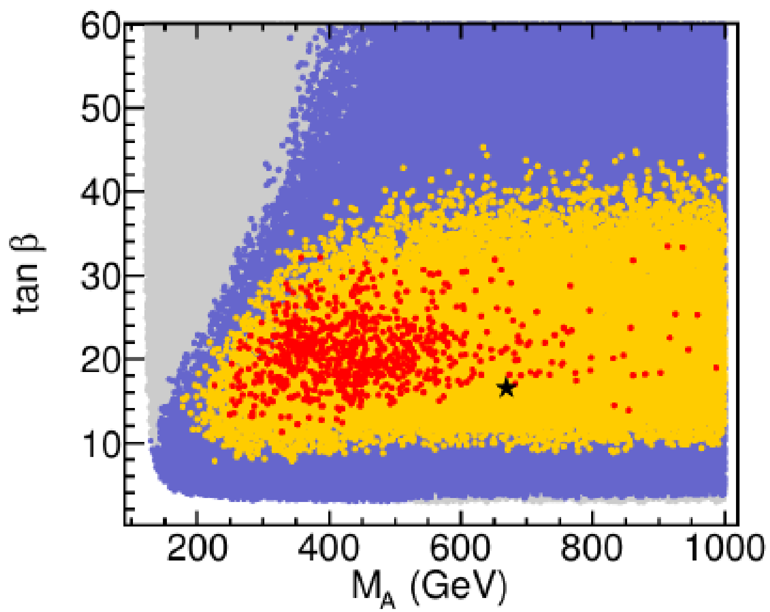
- Additional SM-like H→ZZ excluded up to 832 GeV

MSSM and the 125 GeV Boson Observation (cont'd)

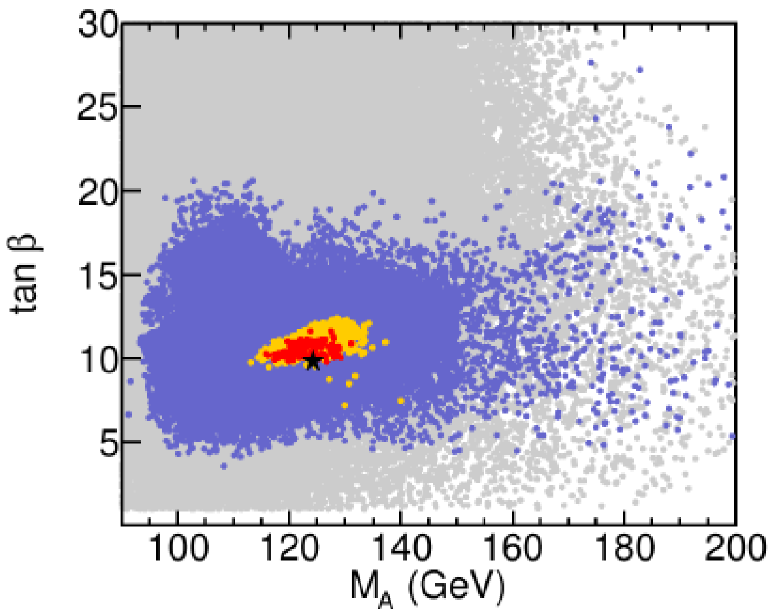
- Overall fits of the available data find
  - ➔ "light Higgs" assumption: no real upper limit for m_A, and large values of tan β are possible
    - for $m_A \gg m_Z$, MSSM Higgs sector reproduces the SM ("decoupling limit")
  - ➔ "heavy Higgs" assumption: all five MSSM Higgs bosons must be light

➔ Message for experiments: very important to search at large Higgs masses in channels sensitive to large tan β

"light Higgs"



"heavy Higgs"



P. Bechtle et al., arXiv:1211.1955

The m_h^{max} Benchmark Scenario

- Designed to yield the maximum value of the light MSSM Higgs mass, m_h
  - A_t, A_b : stop and sbottom trilinear couplings
  - X_t : stop mixing parameter
  - μ : Higgsino mass parameter
  - M_{SUSY} : common soft-SUSY-breaking squark mass of the third generation

- $M_{SUSY} = 1$ TeV
- $X_t = 2M_{SUSY}$
- $\mu = 200$ GeV
- $M_{gluino} = 800$GeV;
- $M_2 = 200$ GeV
- $A_b = A_t$
- $M_3 = 800$ GeV
- $X_t = A_t - \mu / \tan\beta^2$

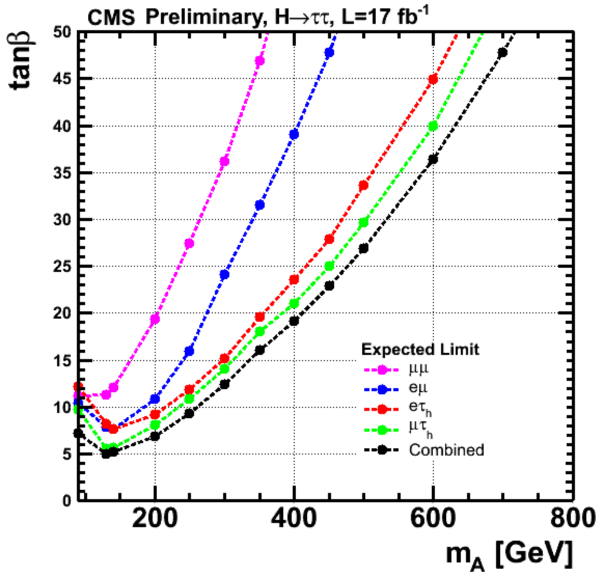
$\Phi \rightarrow \tau\tau$: Analysis & Main Backgrounds

- Mass of τ pair is reconstructed from visible τ decay products and missing E_T
  - CMS: likelihood technique
  - ATLAS: "Missing Mass Calculator"
  - → $m_{\tau\tau}$ average result consistent with true value, width ~13-20%
    - whereas visible mass distribution would be non-Gaussian, σ~24% (CMS)
- Main backgrounds (in broad strokes – may differ from channel to channel):
  - **$Z \rightarrow \tau\tau$:**
    - embedding technique: take $Z \rightarrow \mu\mu$ from data, replace μ's by simulated τ decays
    - normalization according to measured $Z \rightarrow \mu\mu$ cross section
  - $Z \rightarrow ee$ / $\mu\mu$:
    - from simulation. Correct for fake rates
  - ttbar and di-boson:
    - from simulation. Normalization in background-enriched regions.
  - QCD multijet, W+jets:
    - same-charge $\tau\tau$ events, events with large m_T , di-lepton events with one loosely selected lepton, ABCD method

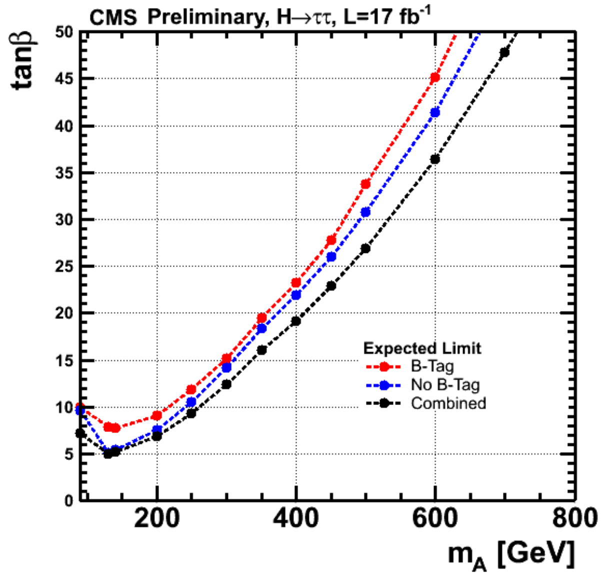
$\Phi \rightarrow \tau\tau$: Sensitivity vs Category & Decay Pattern

CMS PAS HIG-12-050

Sensitivity vs. decay pattern



Sensitivity vs category



- ➔ Strong impact of hadronic tau decays
- ➔ Combination of all decay modes and event classes gives best result
- Outlook for $\Phi \rightarrow \tau\tau$: extension to full 8 TeV dataset
  - still additional decay modes to add

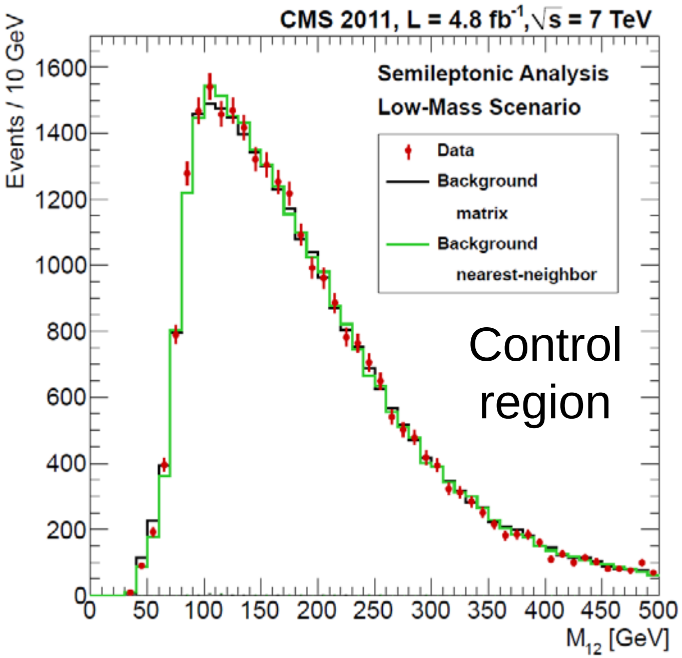
$\Phi \rightarrow \tau\tau$: Systematic Uncertainties (CMS)

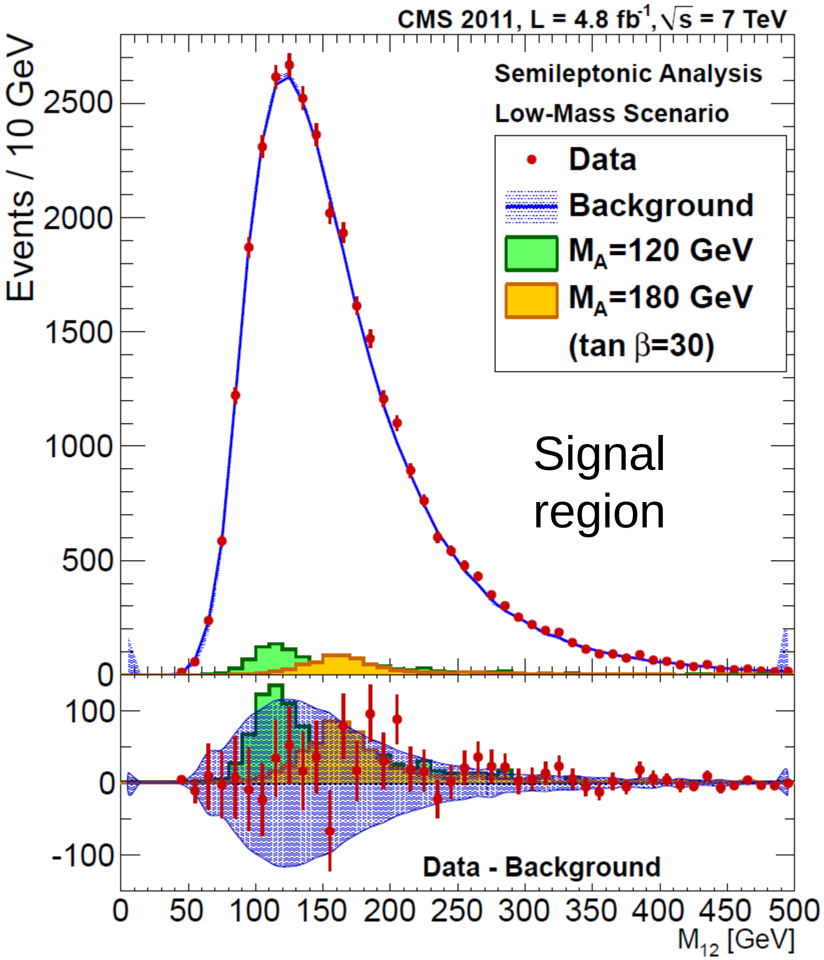
- Total integrated luminosity: 4.5%
- Jet energy scale: 2-5%, depending on eta + pt
- Background normalization: (see tables)
- Z boson production cross section: 2.5%
- Lepton id and isolation efficiency: 1.0%
- Trigger efficiency: 1.0%
- Tau-id efficiency uncertainty: 7% (tag & probe)
- b-tagging efficiency: 10%
- b-mistag rate: 30%
- Mass spectrum shape from energy scales: 3% (tau), 1% (muon), 1.5% (electron)
- MSSM theoretical cross sections: up to 25% (depending on mA + tan-beta)
- PDF (MSTW2008): 2-10%
- Renormalization + factorization scale: 5-25% (gg-fusion), 8-15% (ass. prod.)

$\Phi \rightarrow bb$ Search: Semileptonic Analysis

CMS Phys.Lett. B 722 (2013) 207

- Background shape determined from two independent methods applied to single and double btag samples
- ➔ No indication of a signal

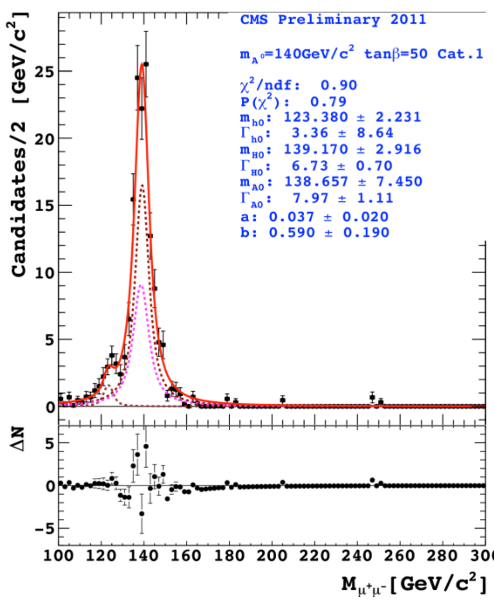


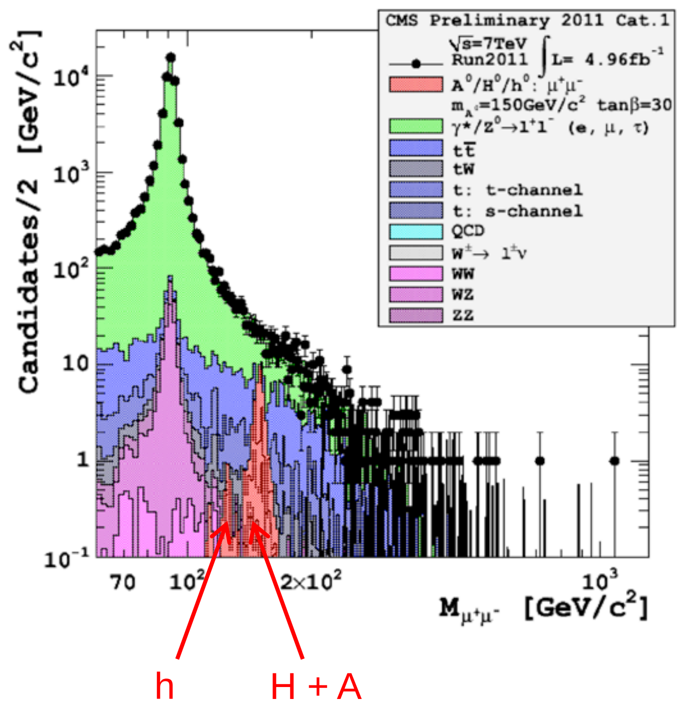


Φ → μμ Search (CMS)

CMS PAS HIG-12-011

- Low BR, but also excellent mass resolution (close to Γ_Φ) and manageable BG
- Signature: two oppositely charged muons
  - + b-tagged jet (Cat. 1), non-isolated 3rd muon (Cat. 2), otherwise (Cat. 3)





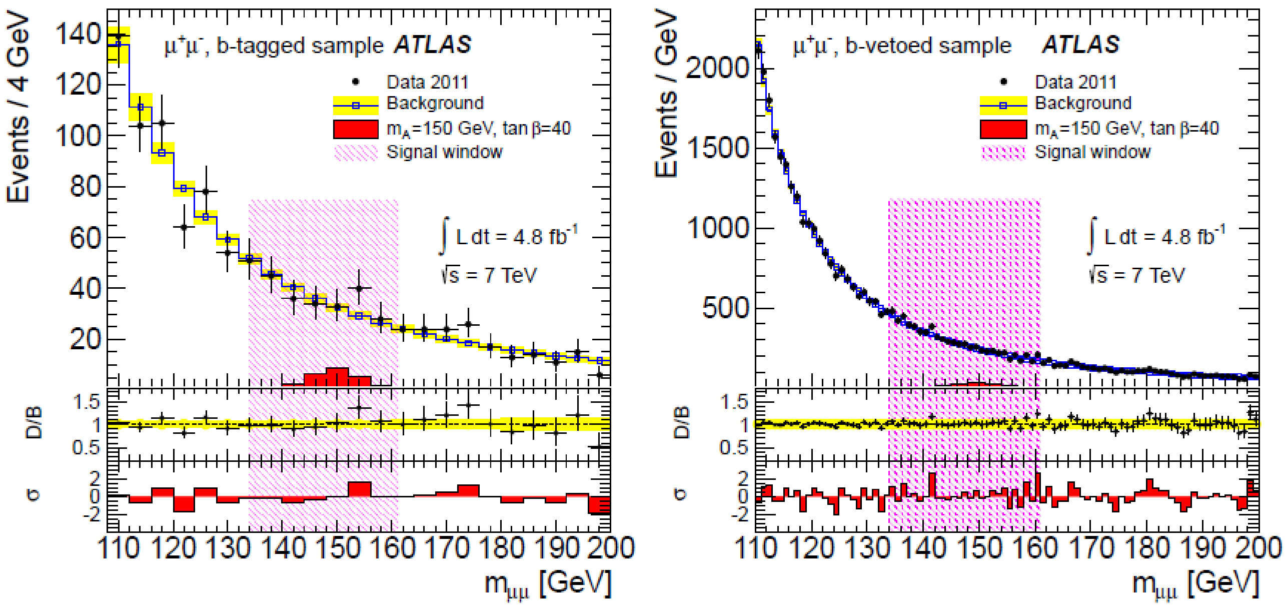
- Dominant background: Drell-Yan, bbZ^0
- Fit detailed mass spectrum of the three Φ states

Φ → μμ Search (cont'd)

- Data-driven estimation of backgrounds from sideband fits
- Signal model from simulation

➔ Background model fits the data well

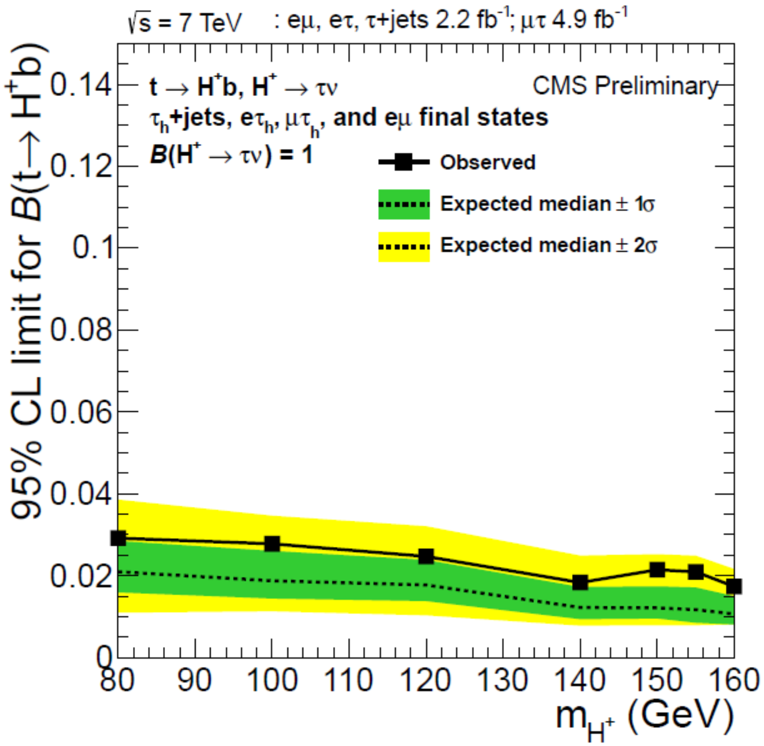
ATLAS JHEP 1302 (2013) 095

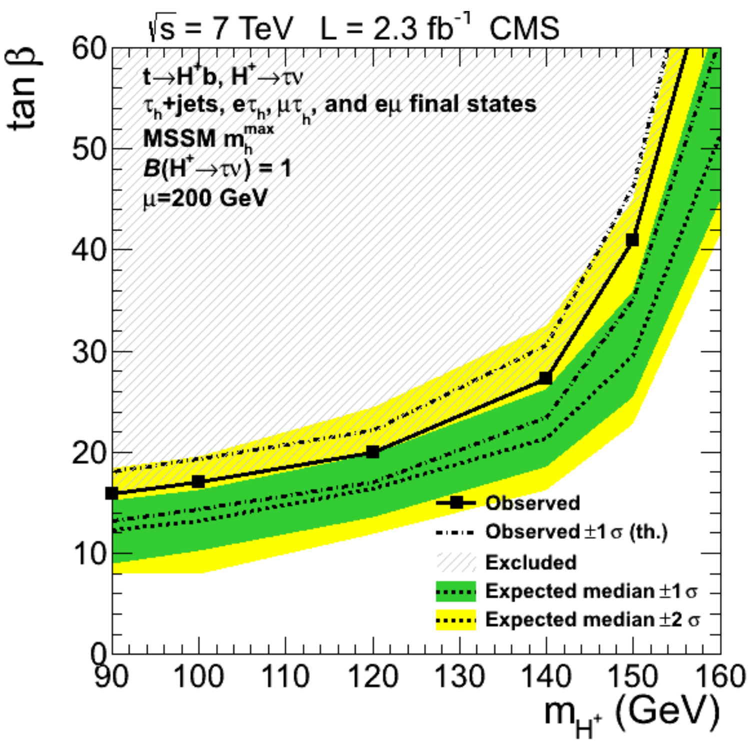


Light H± Search (CMS)

CMS PAS HIG-12-052

- Expected limits on BR(t → b H^+) in the range ~ 1-2%.
- Observed limits slightly higher (coming from τ_h +jets channel)
- MSSM interpretation still based on 2.3 fb^{-1}





Φ → μμ Search

- Low BR, but also excellent mass resolution (close to Γ_Φ) and manageable BG
- Signature: two oppositely charged muons
  - division into "b-tagged" and "b-vetoed" samples

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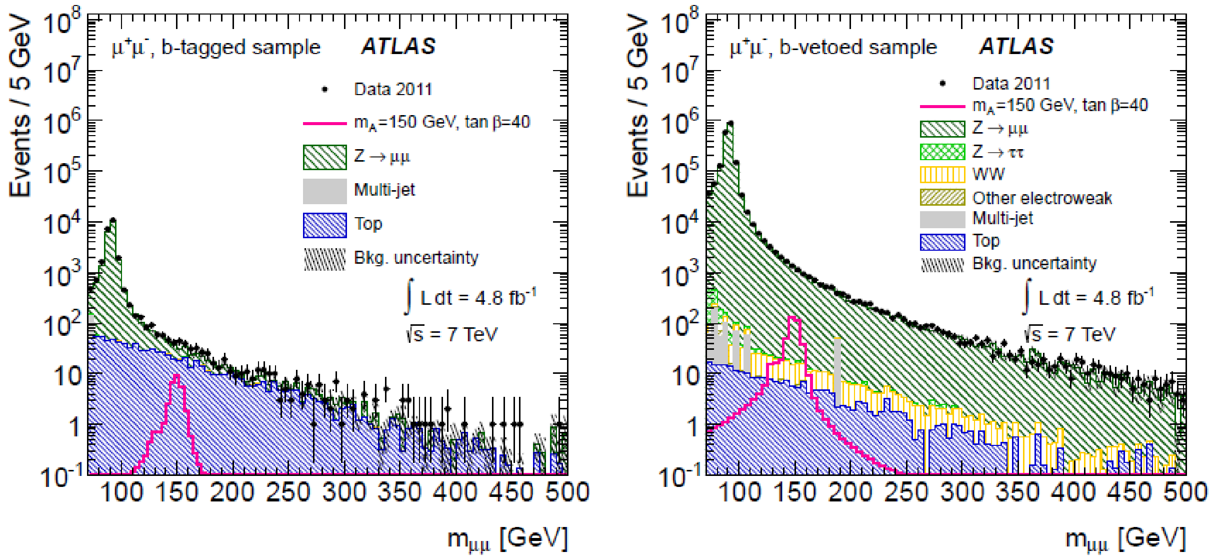

- Dominant background: Drell-Yan, bbZ^0
  - Drell-Yan background greatly reduced in b-tagged sample
- Data-driven estimation of backgrounds from sidebands, signal model from simulation

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

- $b\bar{b}$ background modeled as 2D templates, determined from bb-enriched control sample
  - with one di-muon and one muon (no isolation requirement)
- Direct double-J/ψ production modeled with PYTHIA
- ➔ 8 events observed in off-diagonal sideband

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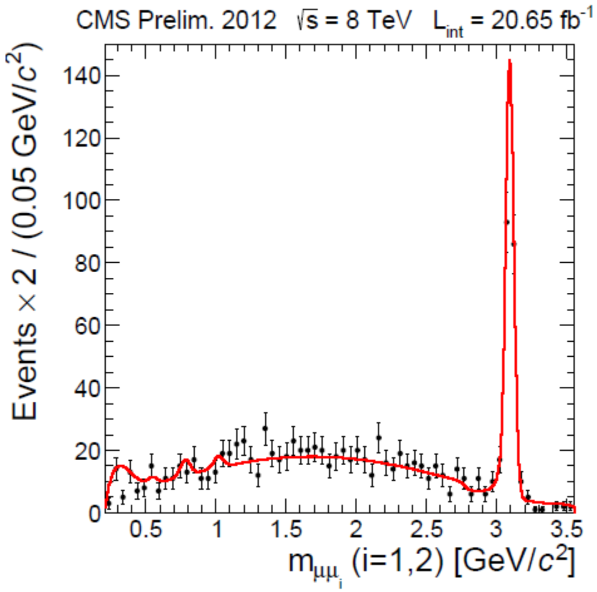
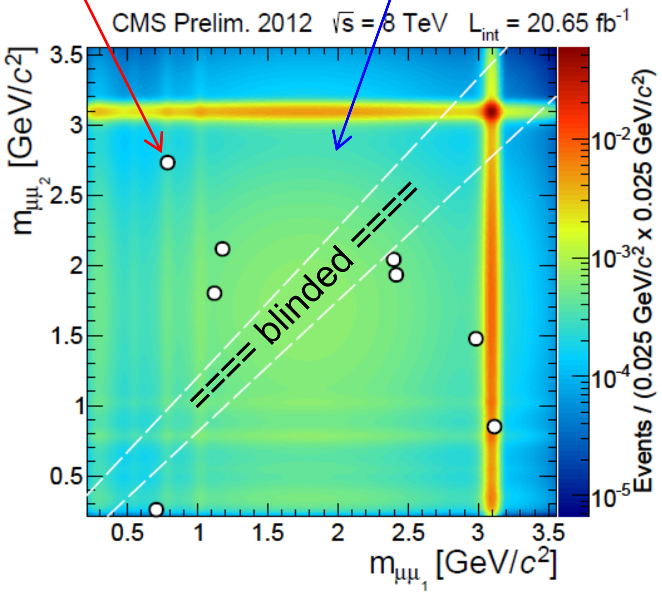
BG test with isolation requirement dropped:



Data

BG Expectation



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

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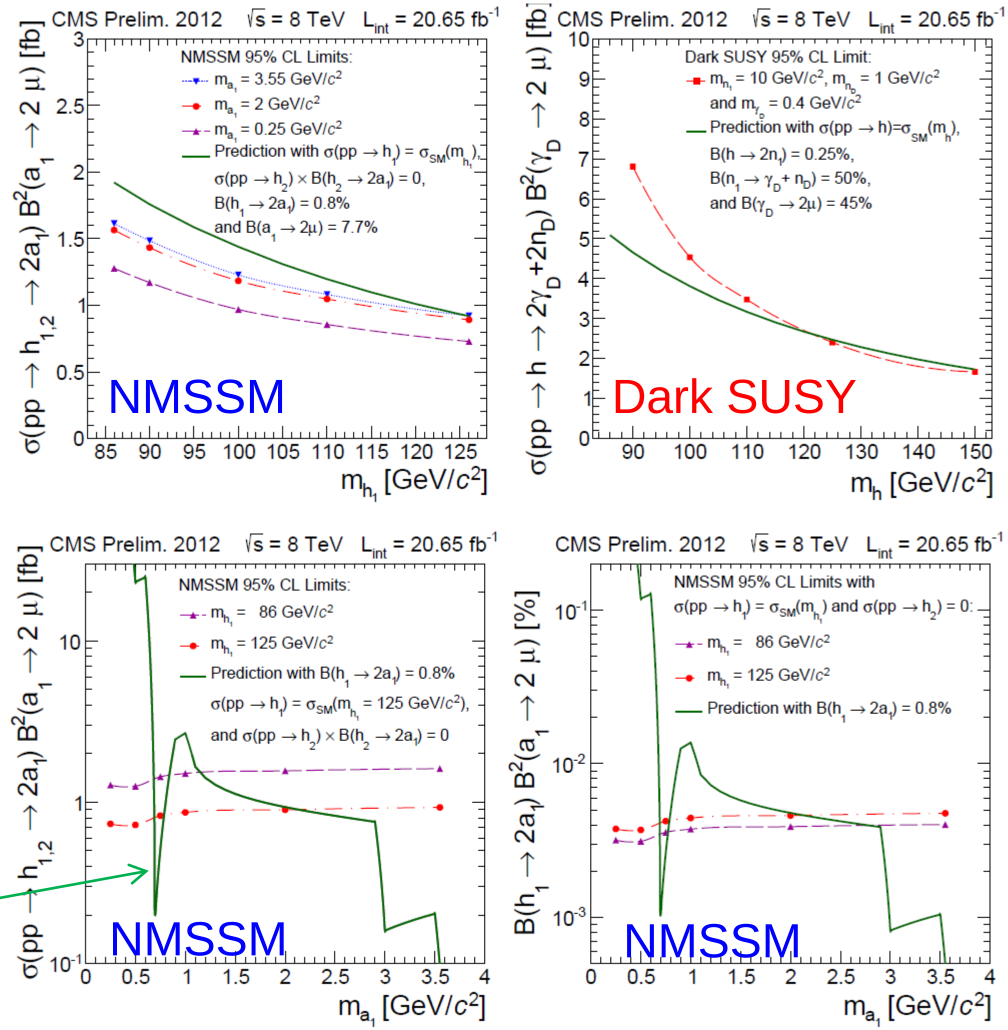
- Results are interpreted in context of NMSSM and dark-SUSY benchmark models
  - signal efficiencies depend on assumptions for either m_a or m_h

→ 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



internal quark loop thresholds