Higgs Sector Beyond the Standard Model

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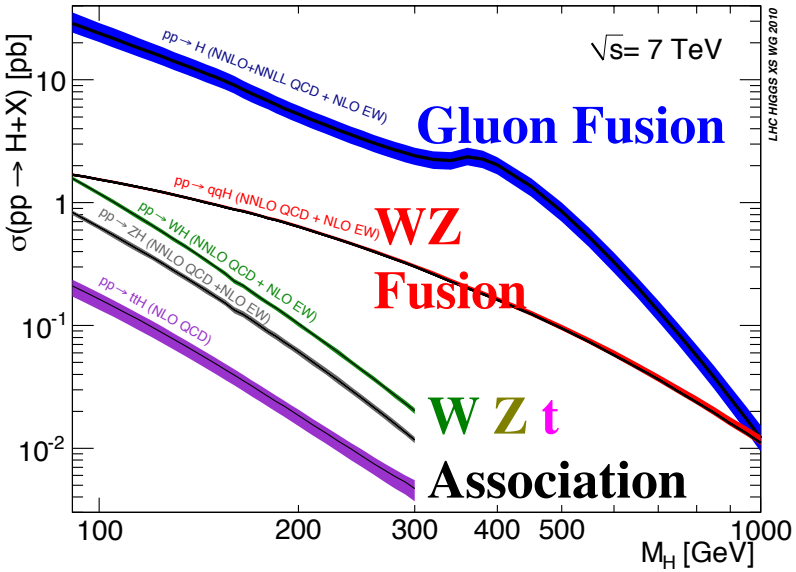
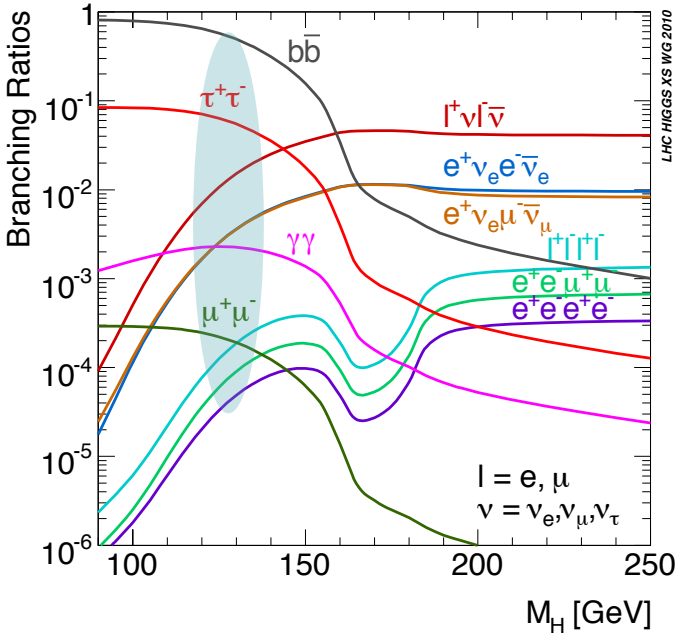
With results from
ATLAS & CMS Collaborations

Standard Model Scalar Sector

Generating masses for weak bosons and fermions

- Minimal model including one doublet of complex scalar fields
- Spontaneous symmetry breaking of electro-weak symmetry
- Provides masses for W and Z gauge bosons of weak sector
  - Predicts single neutral scalar boson
- Yukawa coupling to fermions provides them masses
  - Precise predictions of production and decays as a function of mass





Beyond the Standard Model

There are many possibilities that change the precise predictions of the minimal higgs sector of the Standard Model

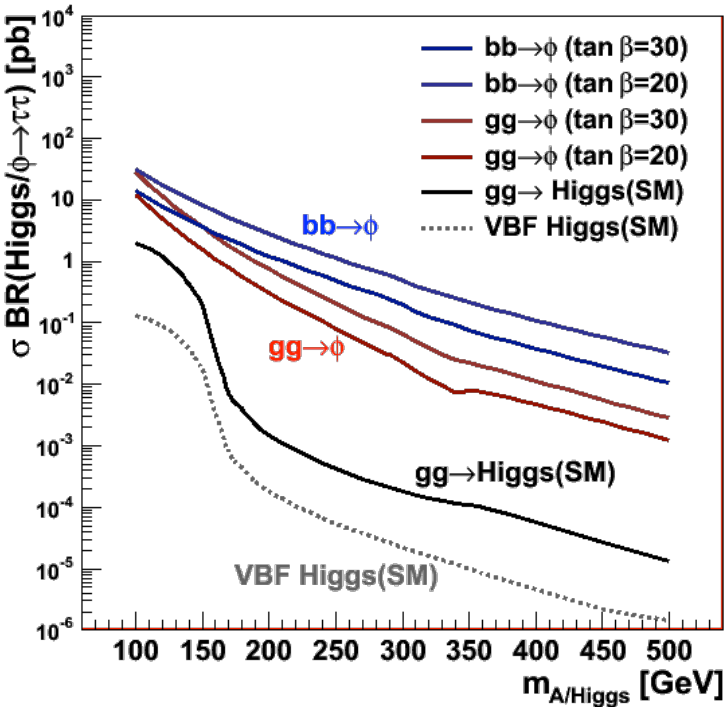
- Fourth (heavy) generation of fermions modify H couplings
  - Enhances SM4 higgs cross section over SM
  - Already ruled out in entire parameter space with 2011 data
- Fermiophobic – fermion mass of different origin than higgs
  - Changes low mass higgs production & decays dramatically
  - Also ruled out for 126 GeV object
- Beyond minimal higgs doublet field
  - Two higgs doublet model (2HDM)
    - Multiple higgs bosons: 3 neutral and 2 charged
    - Minimal Supersymmetric Model (MSSM) requires 2HDM
  - NMSSM, triplets … have even more higgses
    - Very light pseudoscalar higgs, Doubly charged …
- This talk focuses on these non-standard higgs bosons

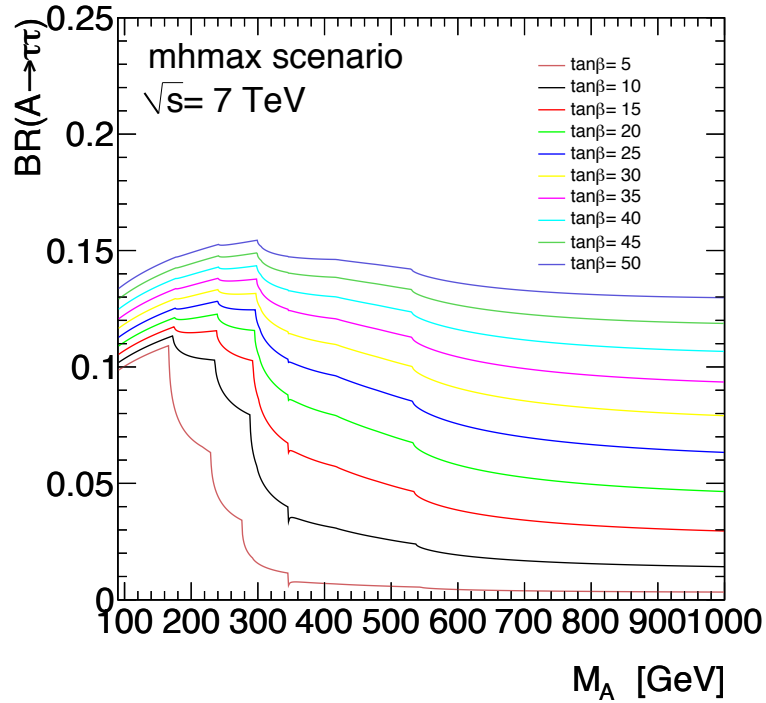
MSSM Higgs

- Higgs sector in SUSY theory is more complicated
  - Need 2 higgs doublets each with 4 degrees of freedom
    - Results in the Standard Model like Higgs (h^0)
    - Plus, two neutral higgs (A^0, H^0) and charged ($H^\pm$)
    - However, only 2 parameters (M_A, $\tan\beta$ – ratio of the two doublets)
    - Masses of higgs and Z related
    - Search in (M_A, $\tan\beta$) plane
- Neutral Higgs
  - Look for ϕ=(h^0, A^0, H^0) in decays to tau-leptons
- Charged Higgs
  - Look for $H^\pm$ in top decays

MSSM ϕ(h, H, A)

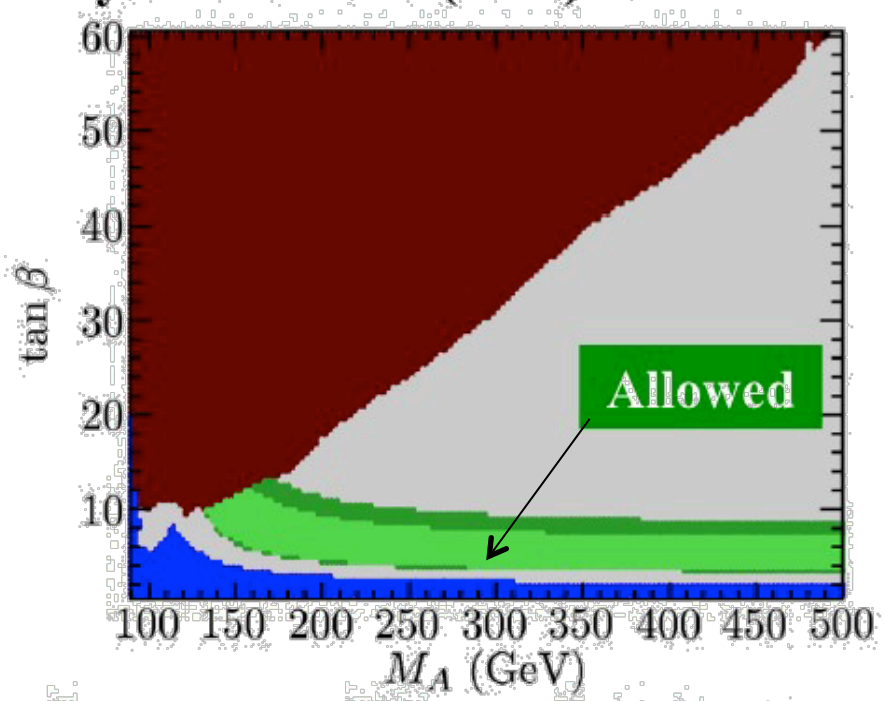
- Use MHMAX Scenario
- Enhanced coupling to b-quarks and τ-leptons
  - Production rate enhanced × $\tan^2\beta$
    - Gluon fusion with b,t loops + associated b quark production
  - Decays to b-quark and τ-lepton pairs enhanced at all masses





Implications of SM Like H126 on MHMAX scenario

Phys. Lett. B 710 (2012) 201



Interpret as CP-even light h with

$123 < M_h < 127$ GeV

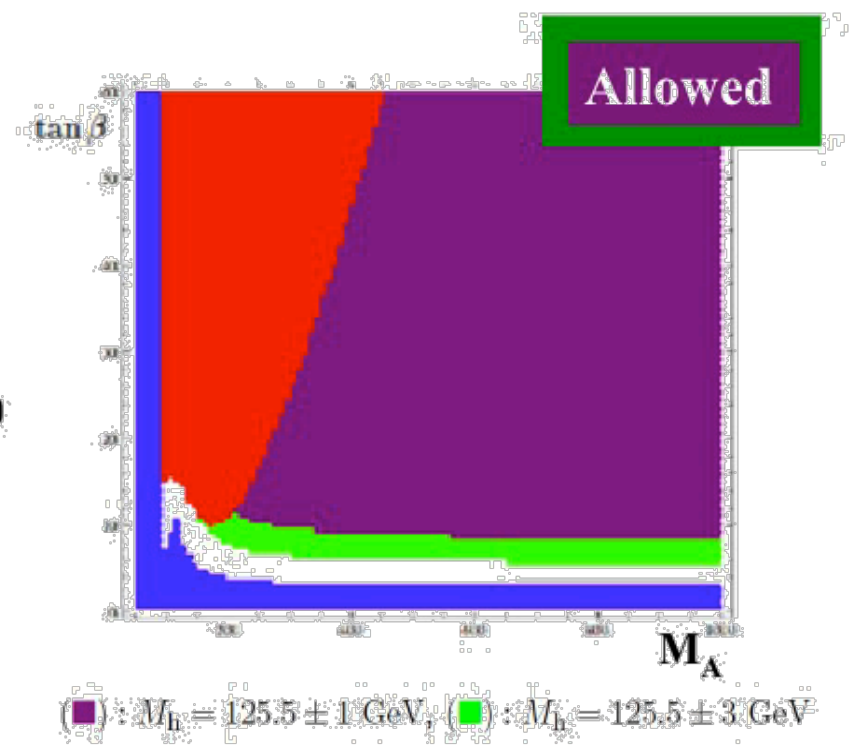
(theoretical uncertainty on $M_h + m_{top}$)

Allowed region strip in M_A-tanβ

mhmax scenario

Modified $m_{h,max}$ scenario

X_t ~1300 GeV

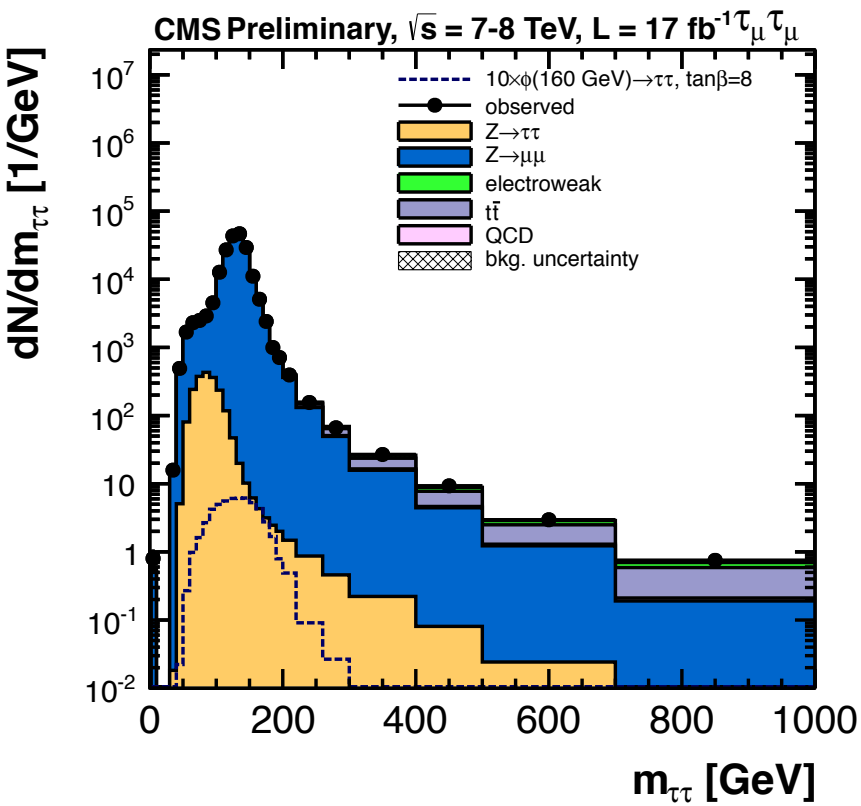


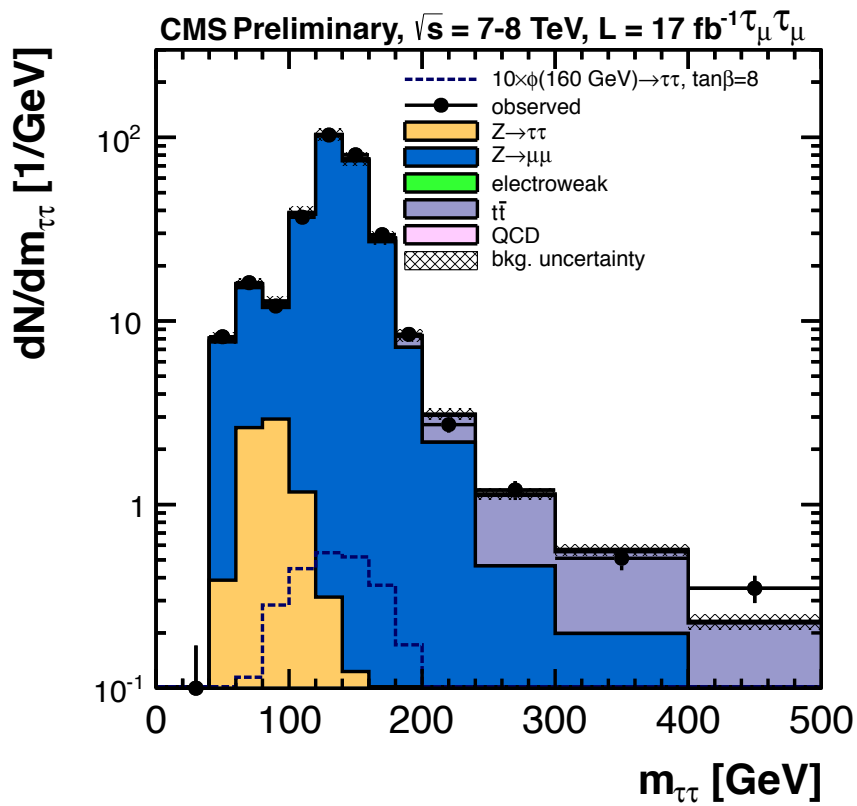
X_t: stop mixing paramater

Mass of ττ : 17 fb^{-1} Data

CMS HIG-12-051

Tau pairs reconstructed in decays to leptons (e or μ) + hadrons (1 or 3 prong) or two leptons (eμ)
Kinematic fit to obtain tau pair mass – used to search for H to ττ contribution
Two categories: non-b-tagged and b-tagged to enhance bbϕ





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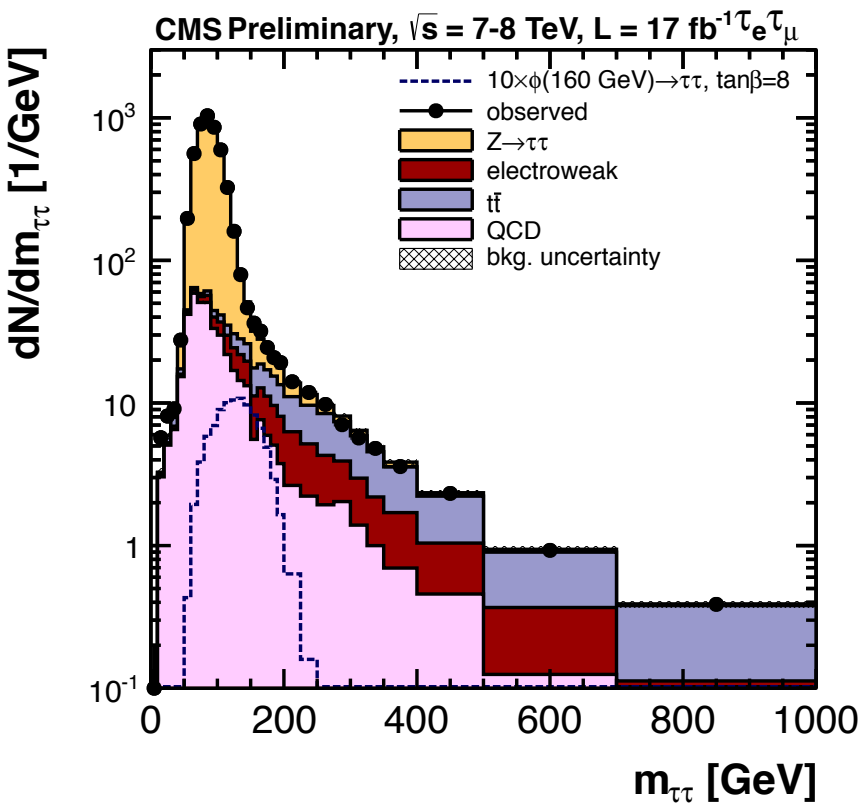

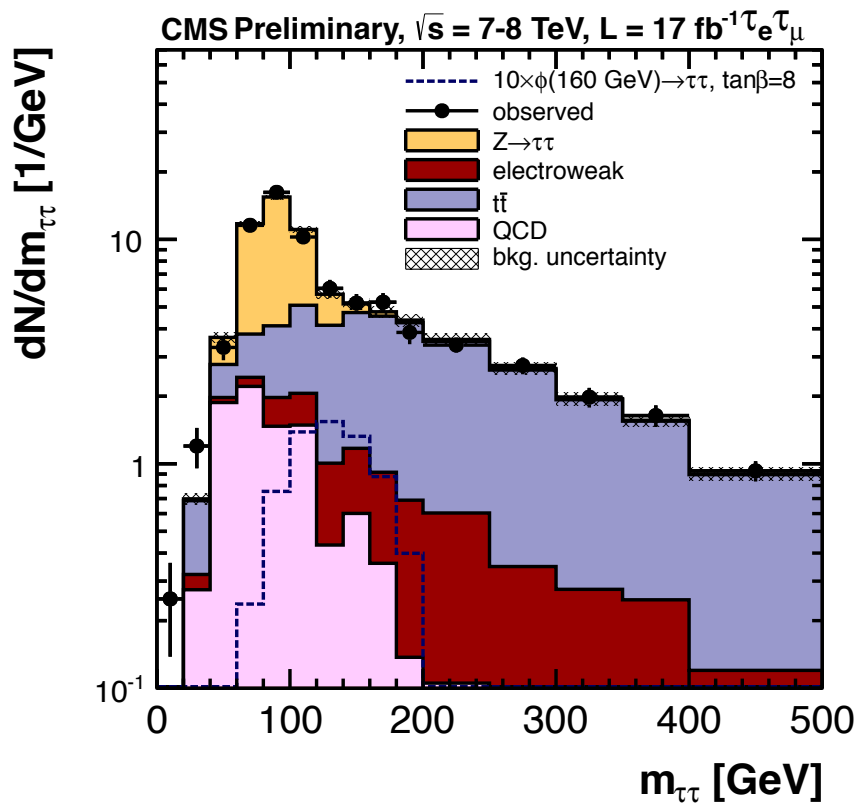

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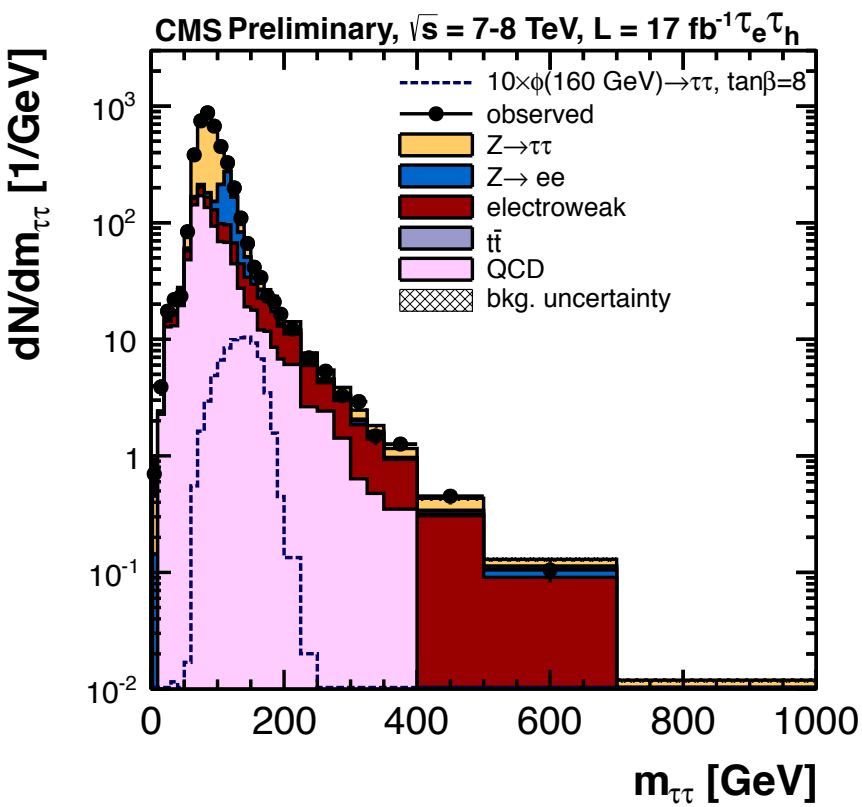

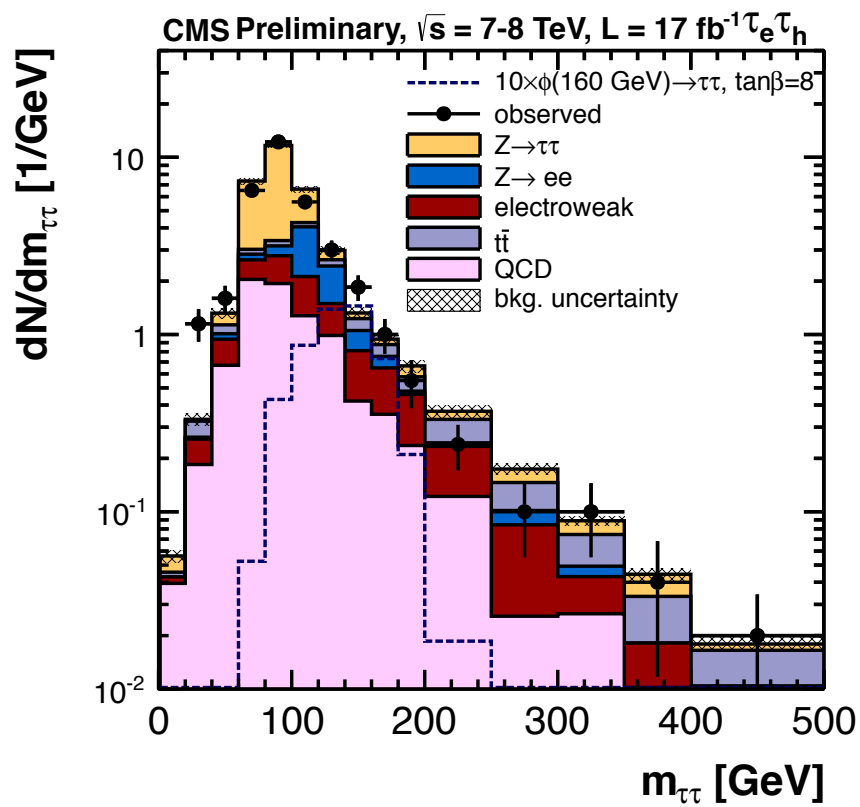

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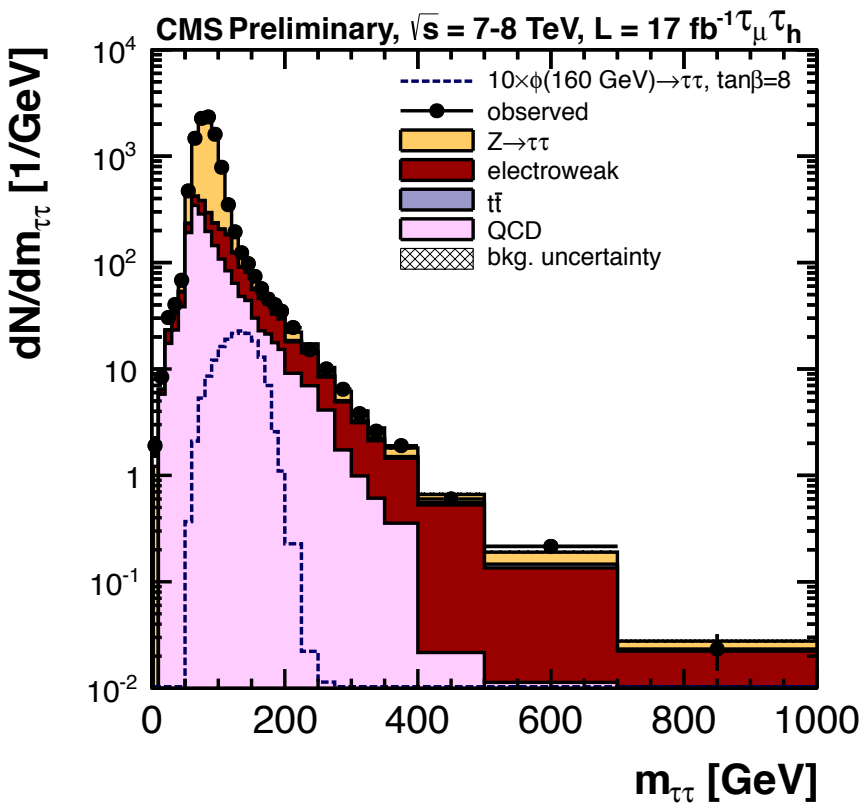
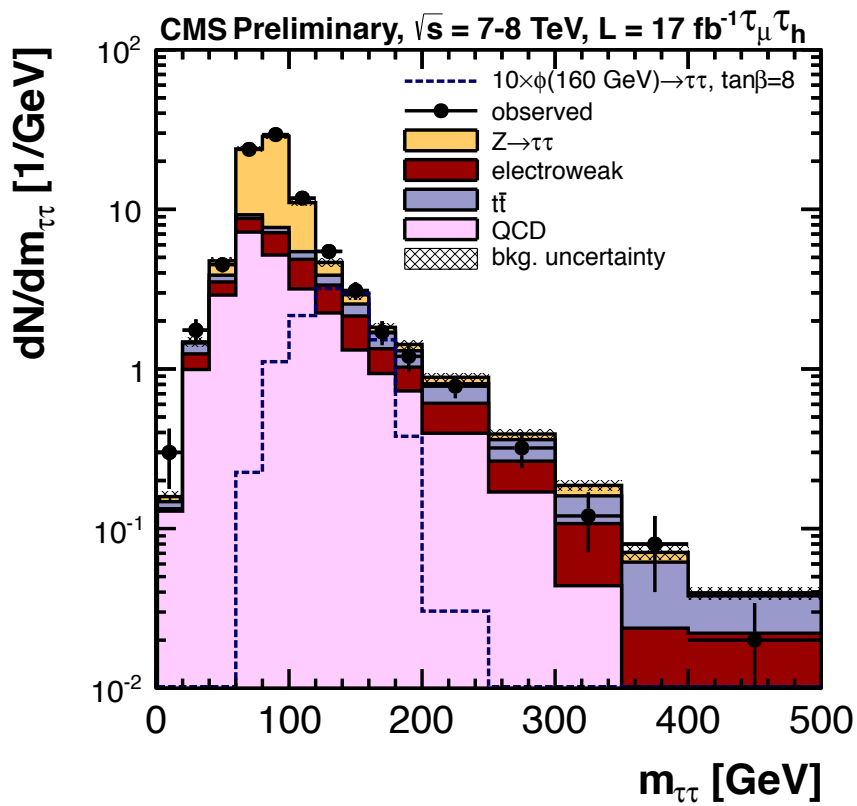
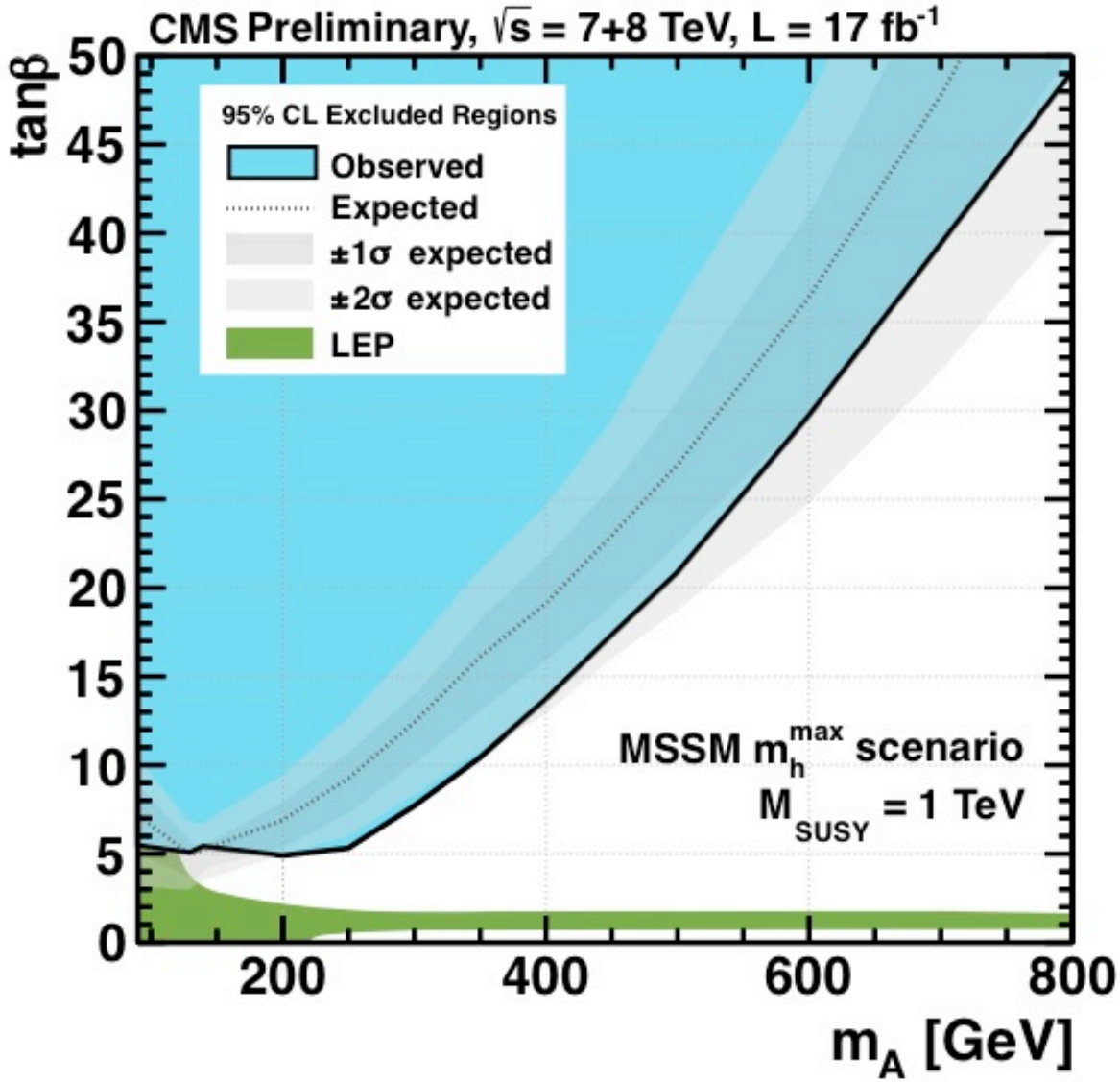




Limit in m_A-tanβ Plane

CMS HIG-12-051



Charged Higgs Selection

Look for $H^{\pm}$ in top decays: τ+jets, eτ, μτ and eμ modes considered

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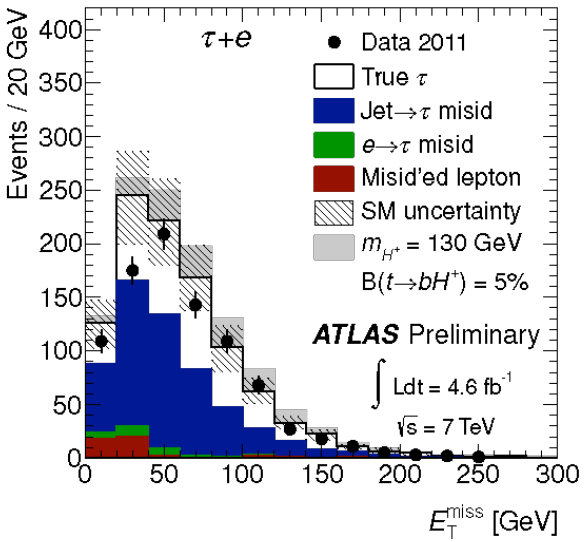
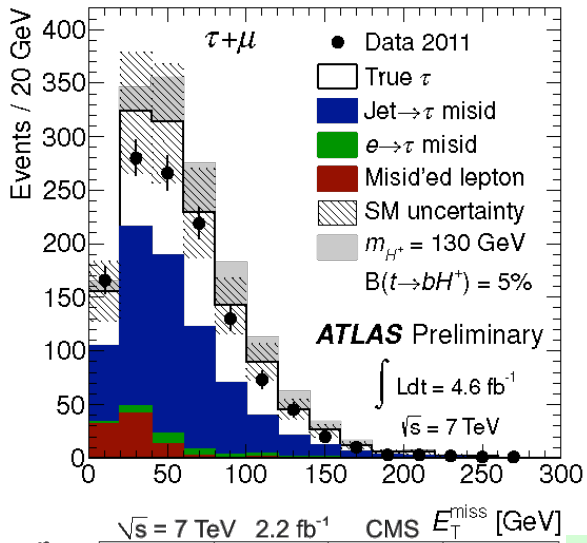
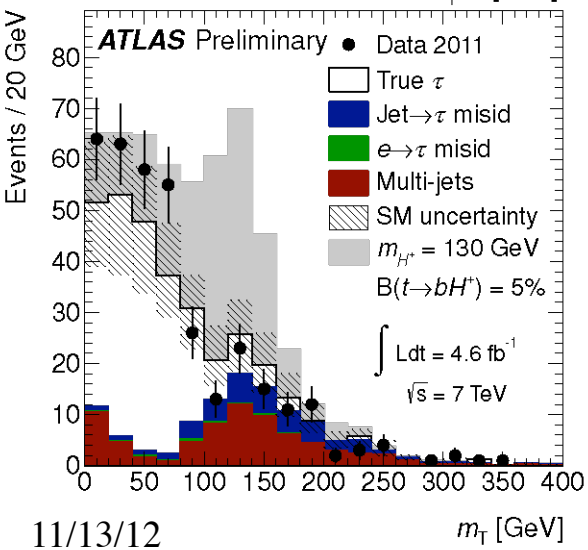
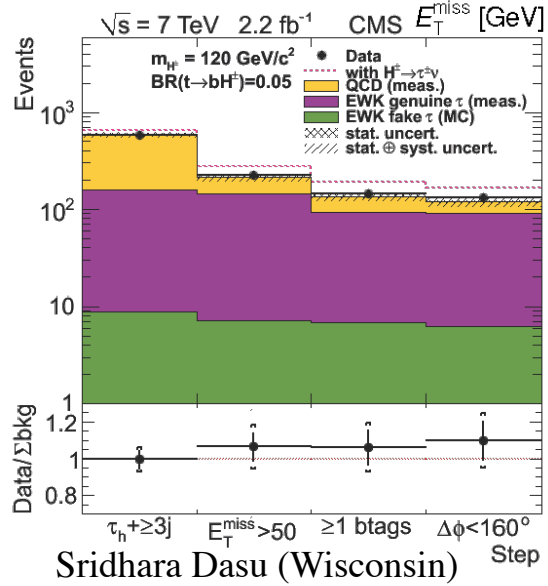
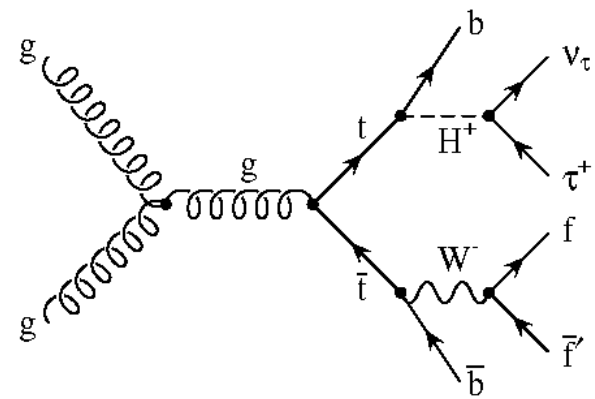








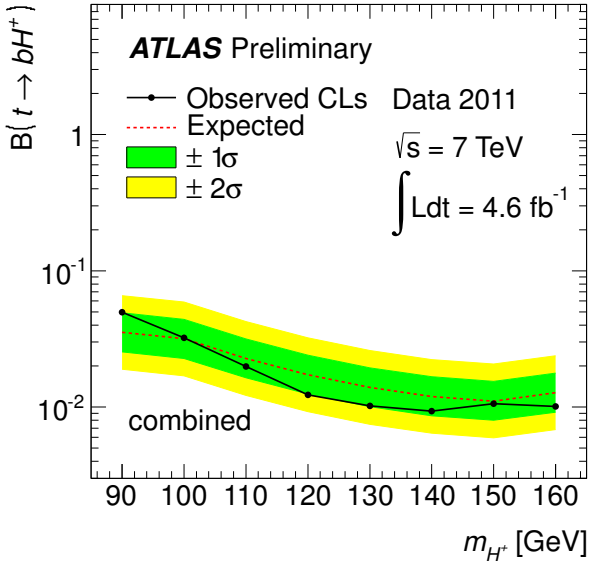
CMS PAS HIG-11-019



Event with
τ + MET from $H^{\pm}$
2 b-jets,
2 jets from W or
e/μ + MET from W

Cut progression includes
MET, bTags

Charged Higgs Limits



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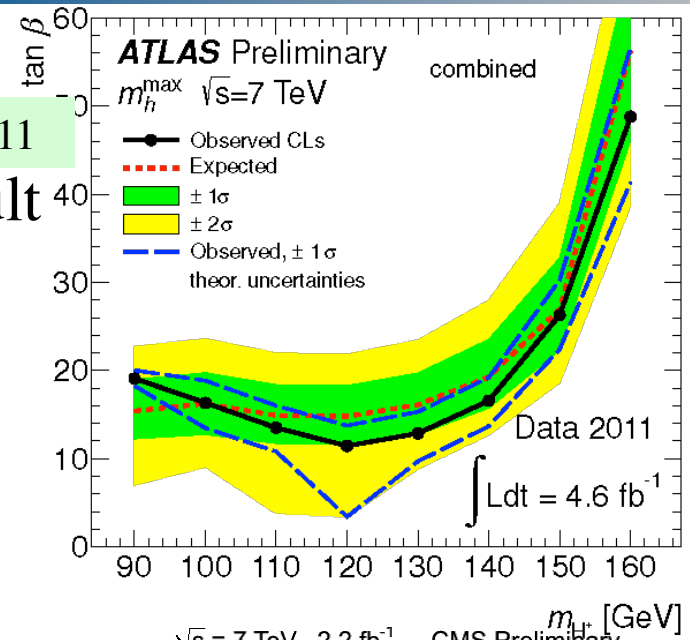
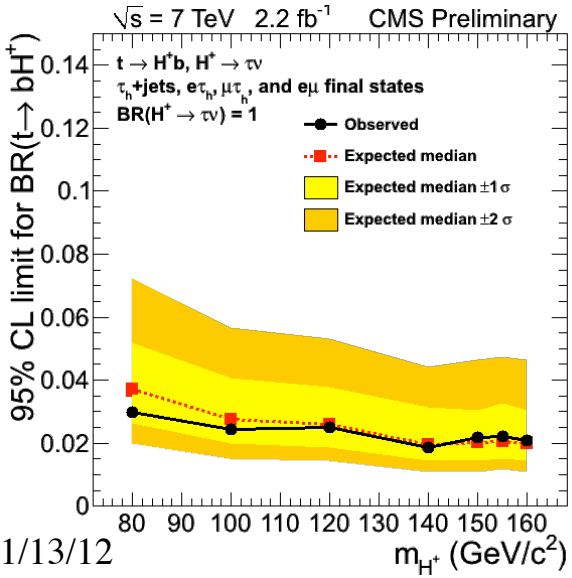
ATLAS Result

τj, eτ, μτ

4.6 fb^{-1}



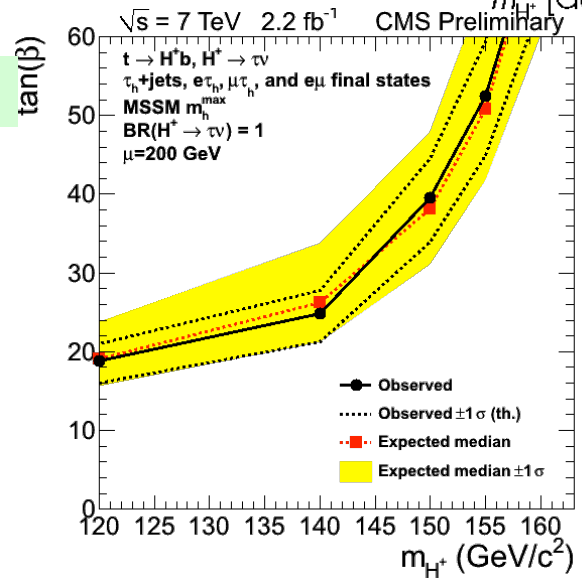


CMS PAS HIG-11-019

CMS Result

τj, eτ, μτ, eμ

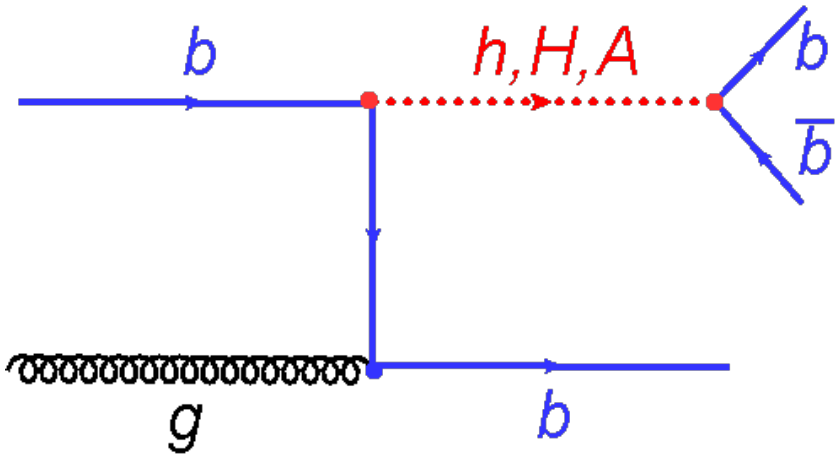
2.2 fb^{-1}

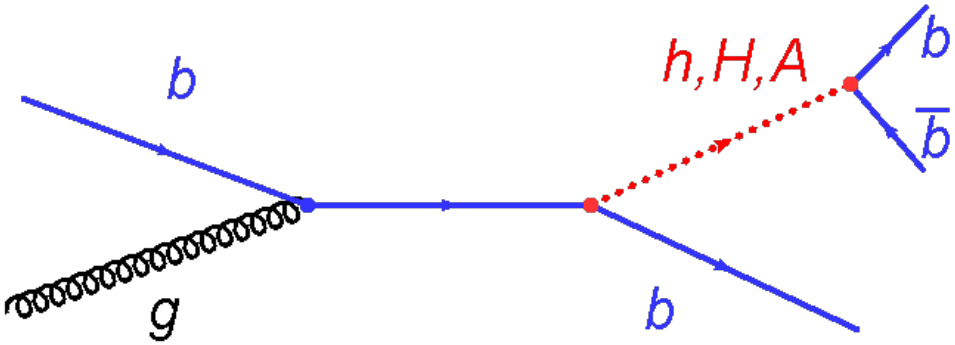


MSSM Neutral Higgs to bb

CMS PAS HIG-12-026
CMS PAS HIG-12-027

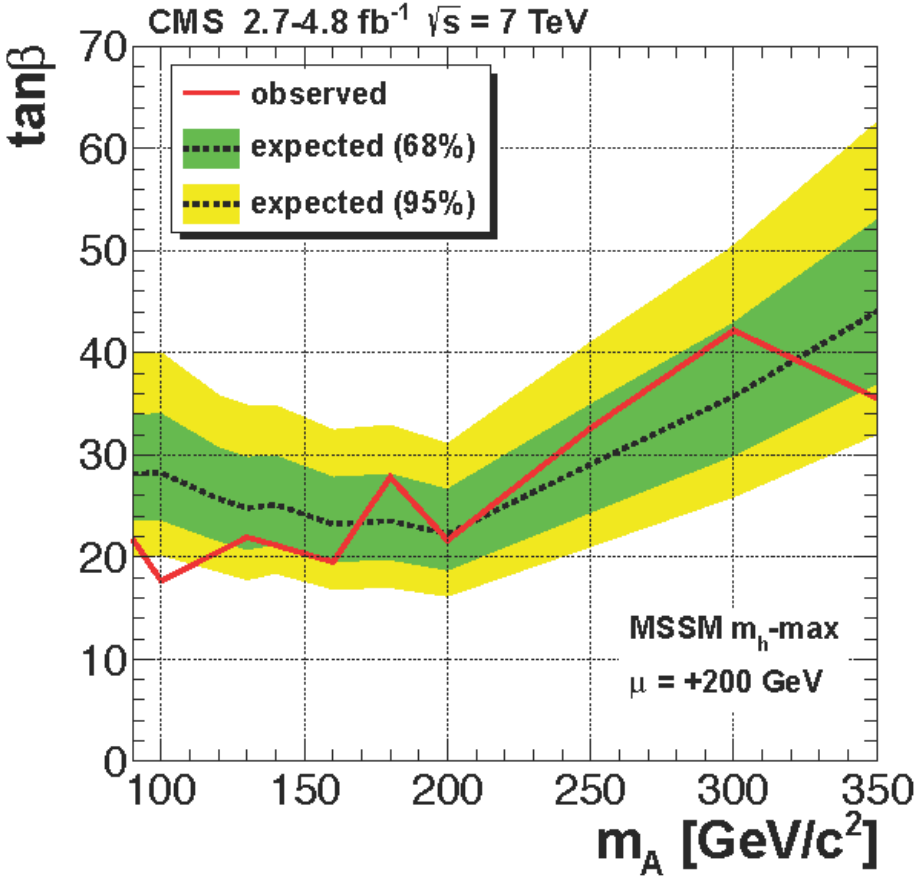
- Three b-jet events
  - More difficult to trigger
  - Larger backgrounds than tau modes
  - Mass resolution is a bit better
  - Considered semi-leptonic and hadronic b tags

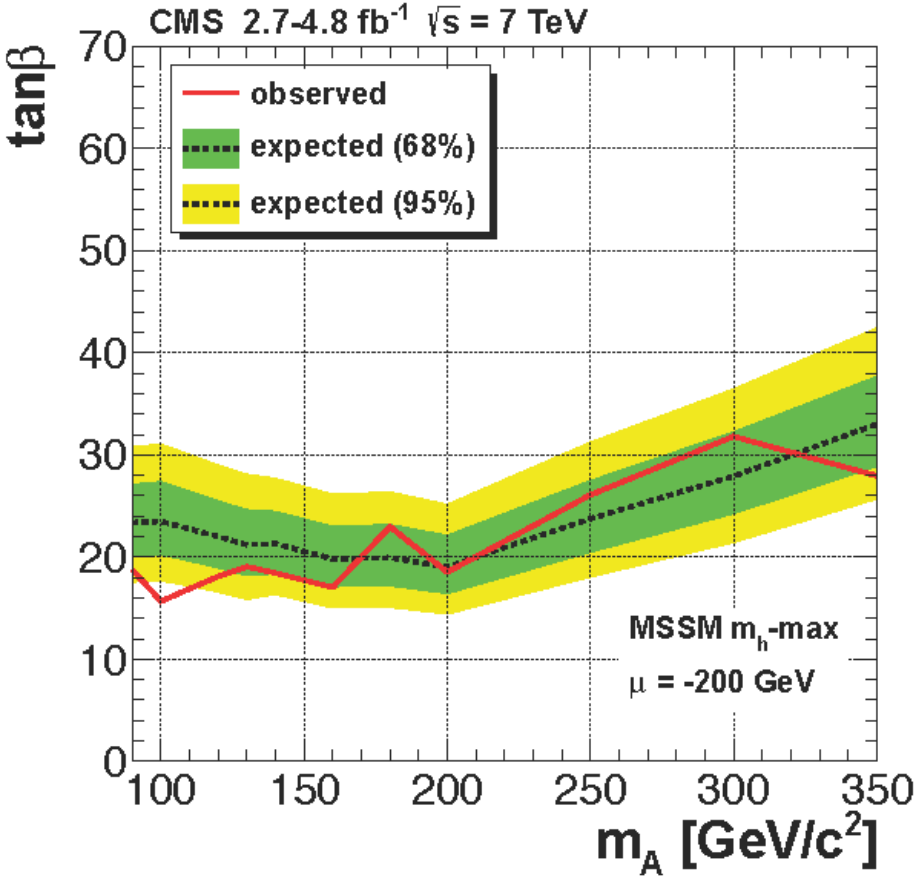




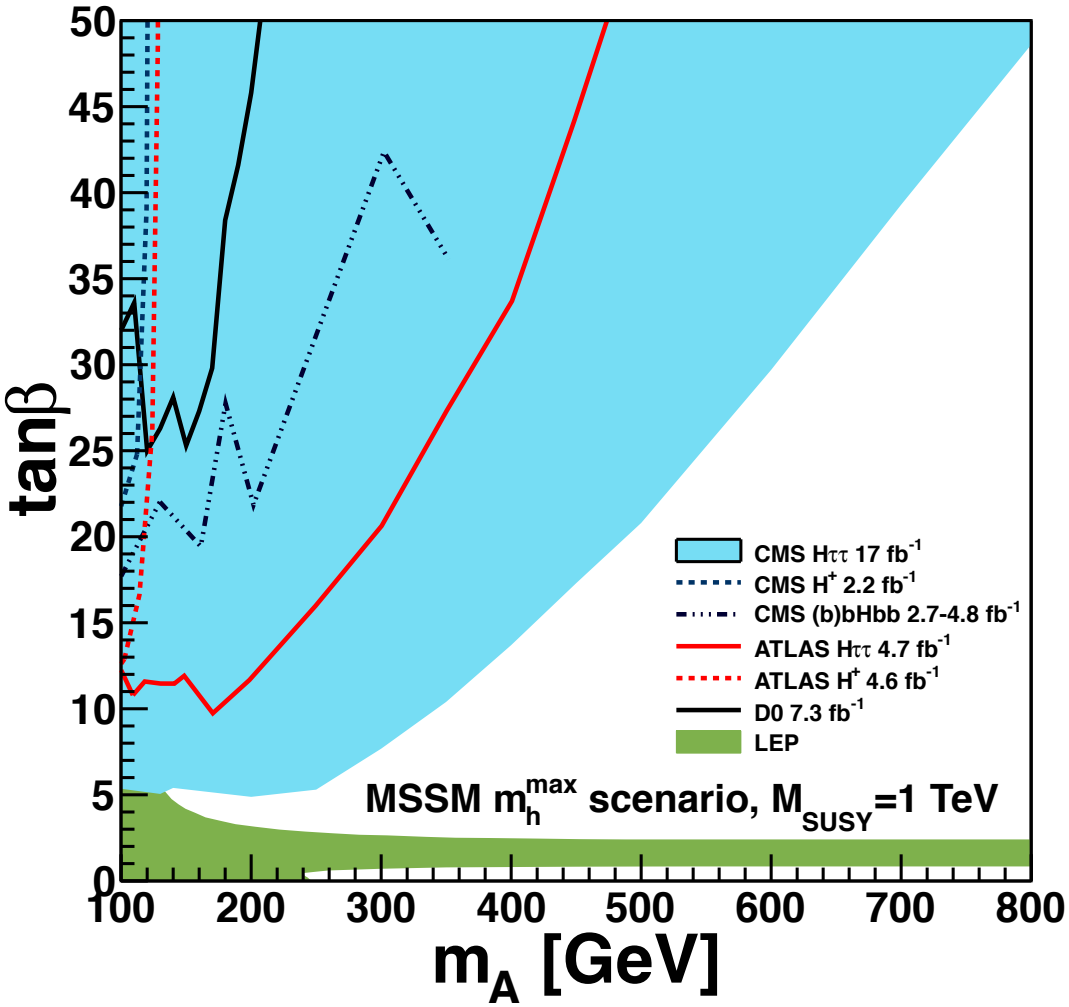
ϕ(h, H, A) in bbBar Mode
m_A-tanβ Limit

CMS PAS HIG-12-026
CMS PAS HIG-12-027





MSSM Higgs Summary



CMS PAS HIG-11-019

ATLAS CONF 2012-11

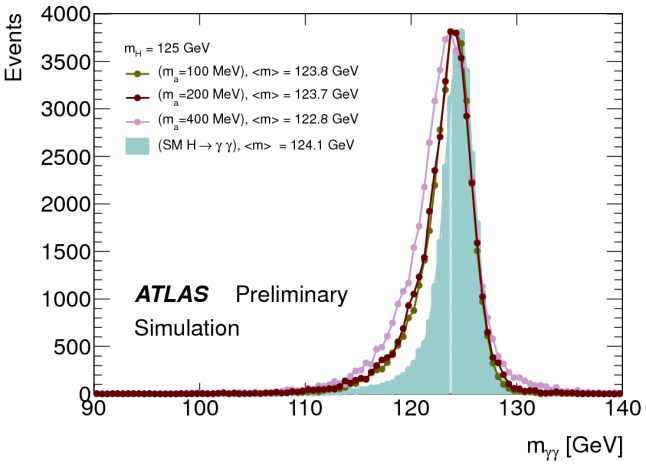
CMS PAS HIG-12-026
CMS PAS HIG-12-027

CMS PAS HIG-12-050

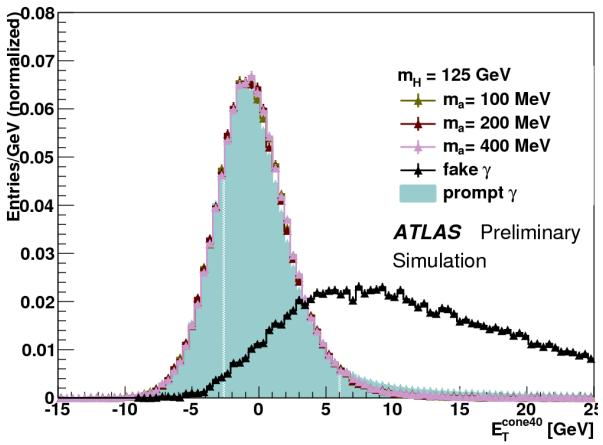
H → aa → γγ γγ

ATLAS CONF 2012-079

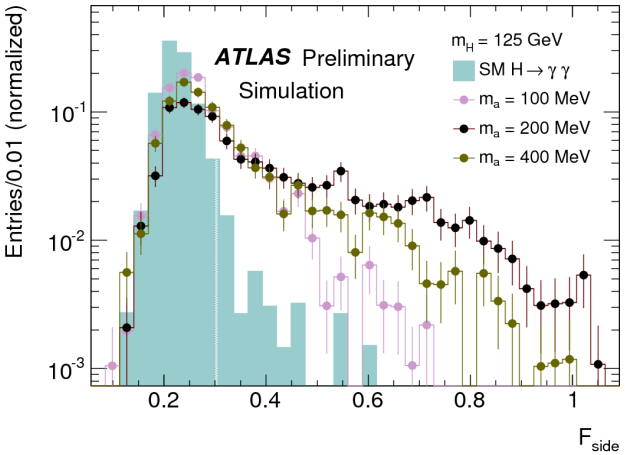
- Next-to-Minimal Supersymmetric Standard Model (NMSSM): Adds singlet scalar field, thereby expanding the Higgs sector to three CP-even (h_1, h_2 and h_3), two CP-odd (a_1, a_2) and two charged scalars (H^+, H^-)
- The lightest pseudo-scalar, if less massive than $3M_{\pi 0}$, decays to γγ
- SM like Higgs can decays to four photons via an a-pair



Photon invariant mass has broader peak than H→γγ



Isolation provides separation from prompt γ BG



Shower shape analysis provides discrimination from SM H→γγ

H → a a → γγ γγ

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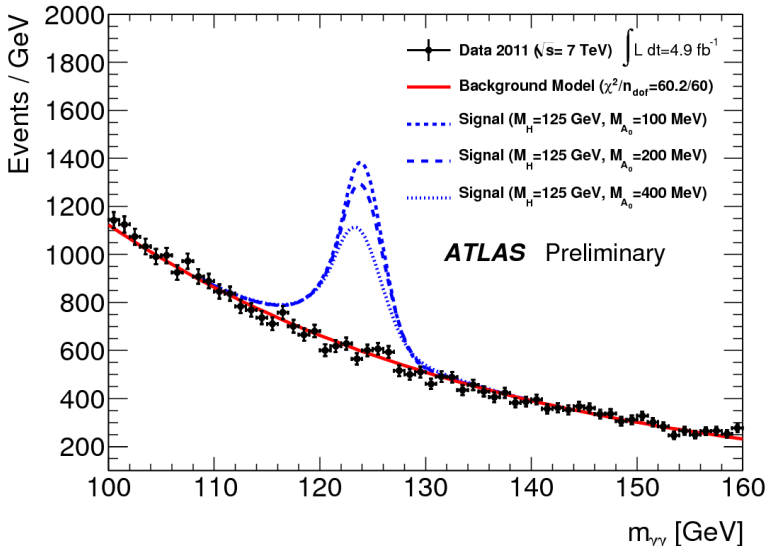
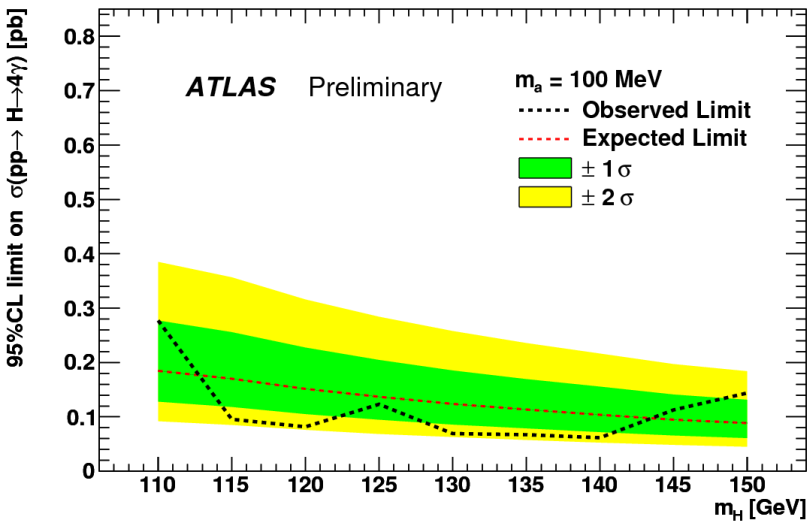
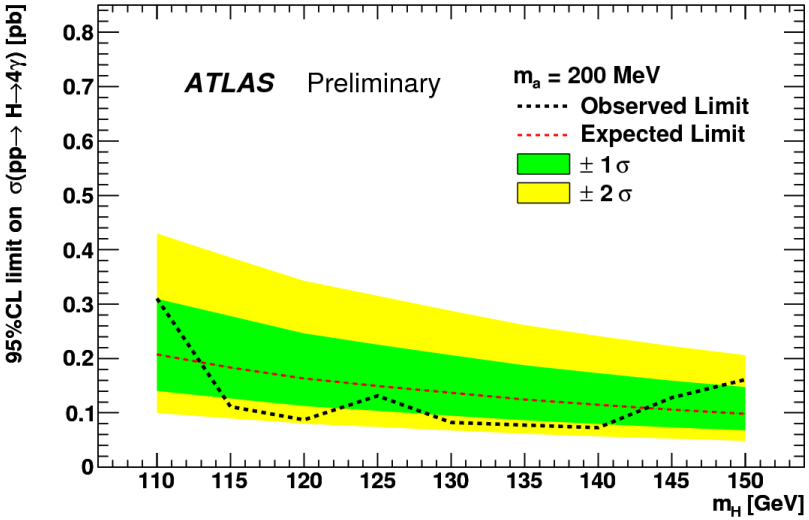
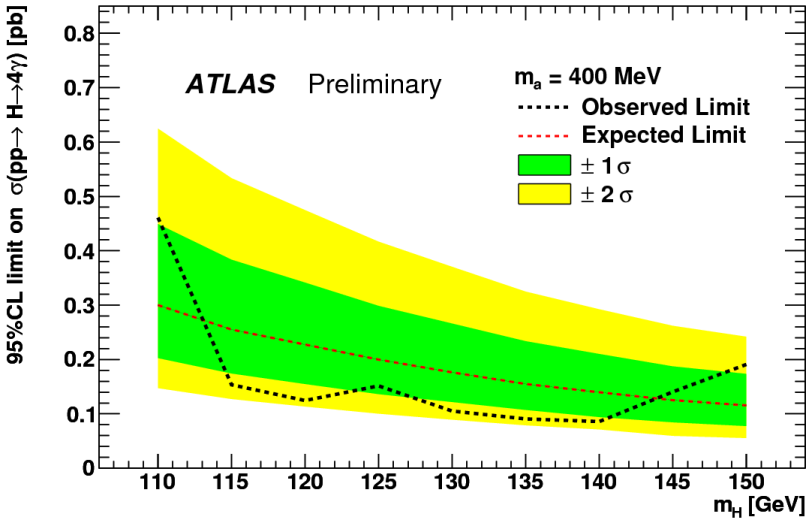




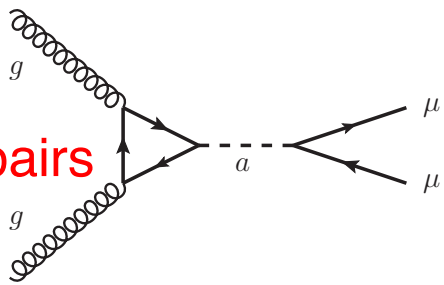


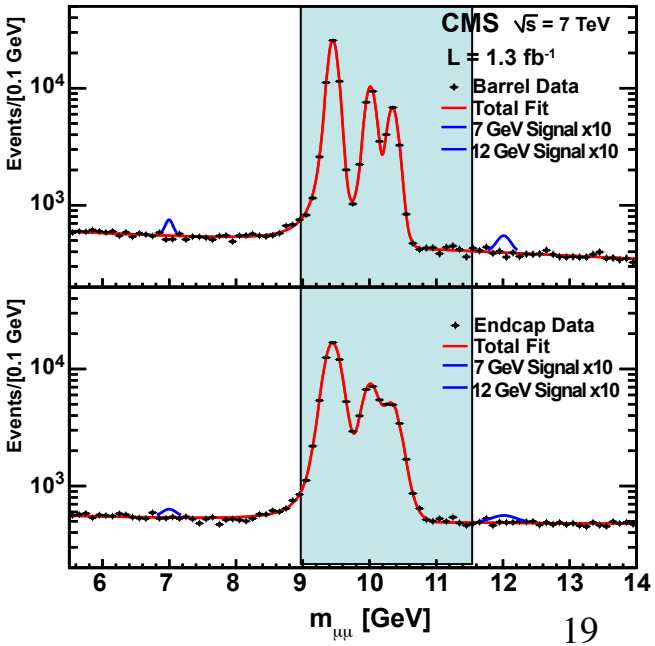


NMSSM: $a_1 \rightarrow \mu^+\mu^-$

CMS PAS HIG-12-004

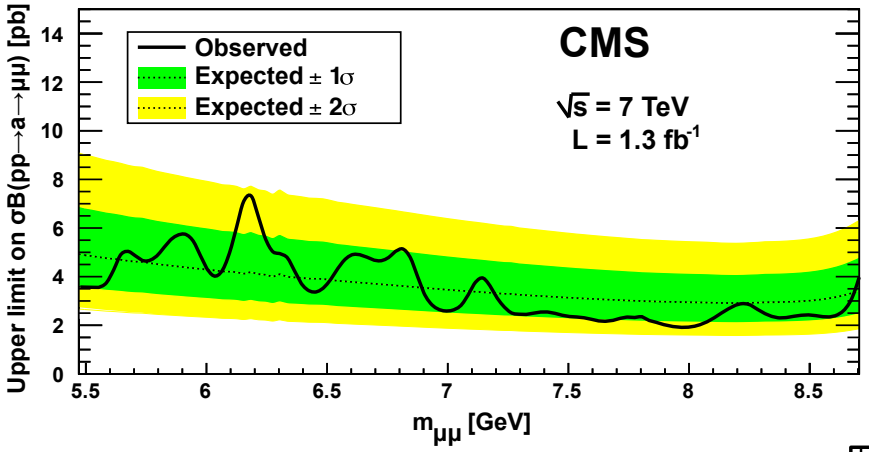
- Next-to-Minimal Supersymmetric Standard Model (NMSSM): Adds singlet scalar field, thereby expanding the Higgs sector to three CP-even (h_1, h_2 and h_3), two CP-odd (a_1, a_2) and two charged scalars (H^+, H^-)
- A light (~10 GeV) boson produced
- Search for a_1 in its decays to opposite sign di-muon pairs
  - Di-tau BR is higher but is deemed impossible
- Analysis strategy
  - Chose isolated opposite sign dimuons with $p_{T\mu} > 4$ GeV & $p_{T\mu\mu} > 6$ GeV
  - Search above/below the upsilon peaks in dimuon invariant mass
    - $5.5 < M_{\mu\mu} < 9$ GeV
    - $11.5 < M_{\mu\mu} < 14$ GeV

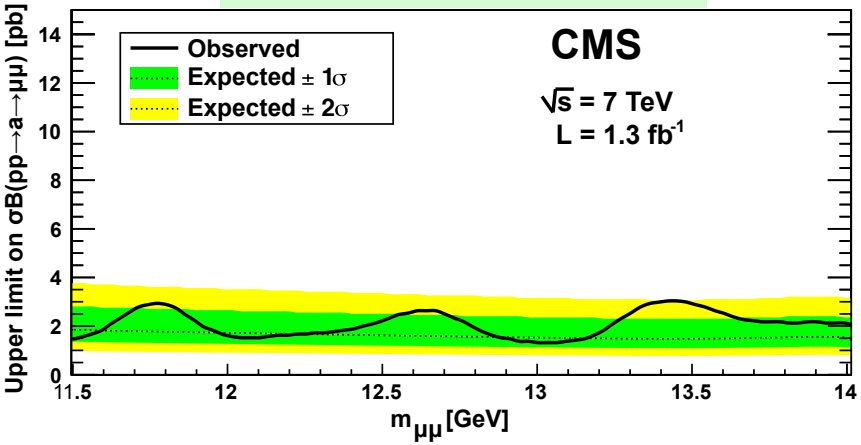




NMSSM: $a_1 \rightarrow \mu^+\mu^-$ Limits

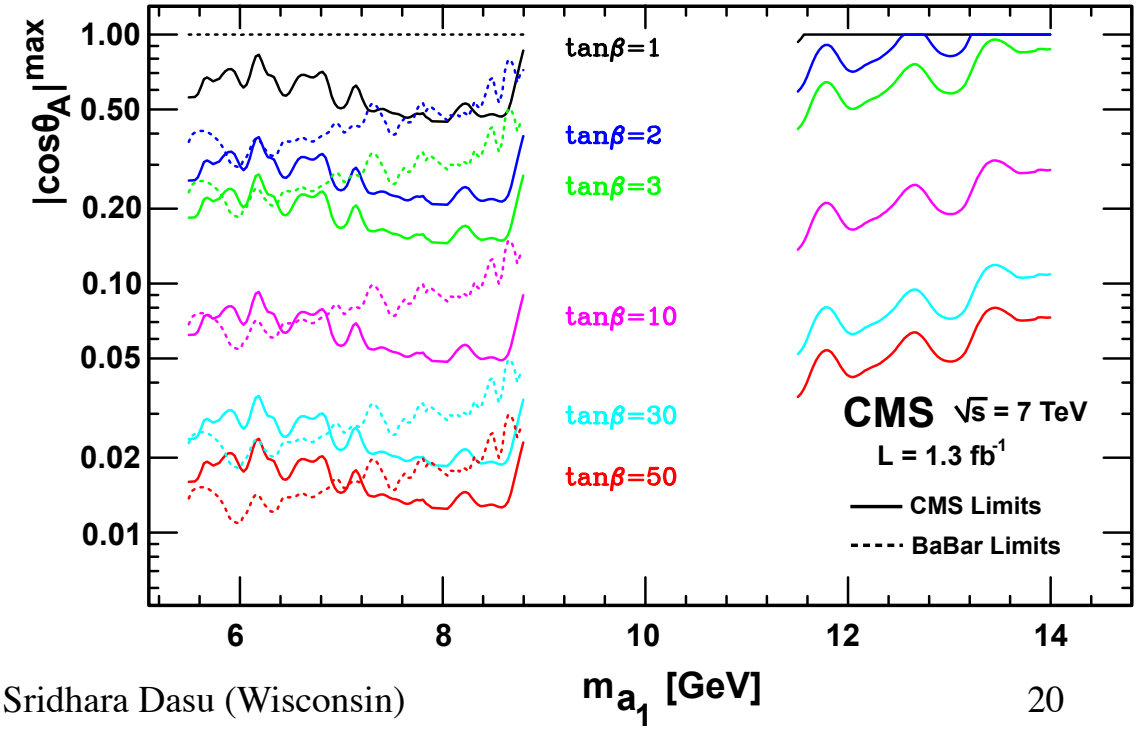
CMS PAS HIG-12-004





Three parameters

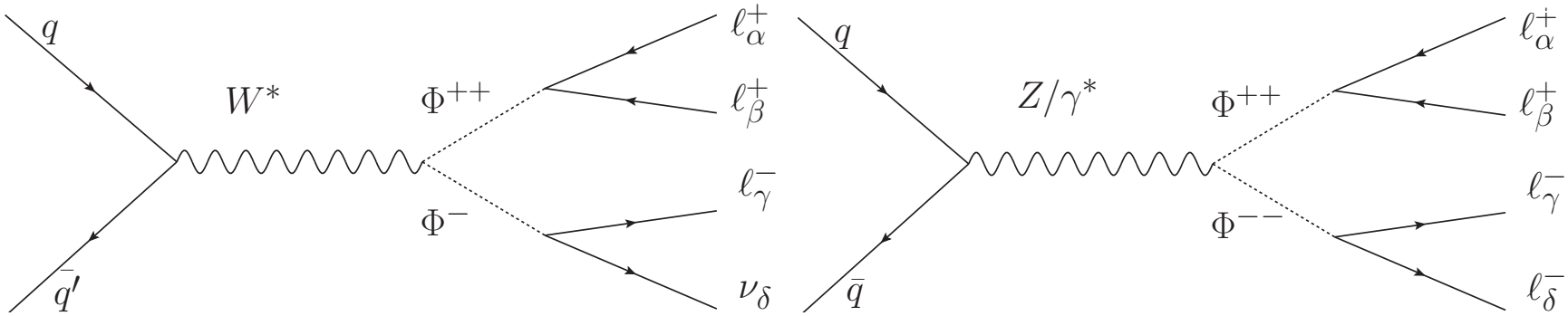
$m_a, \tan\beta, \cos\theta_A$

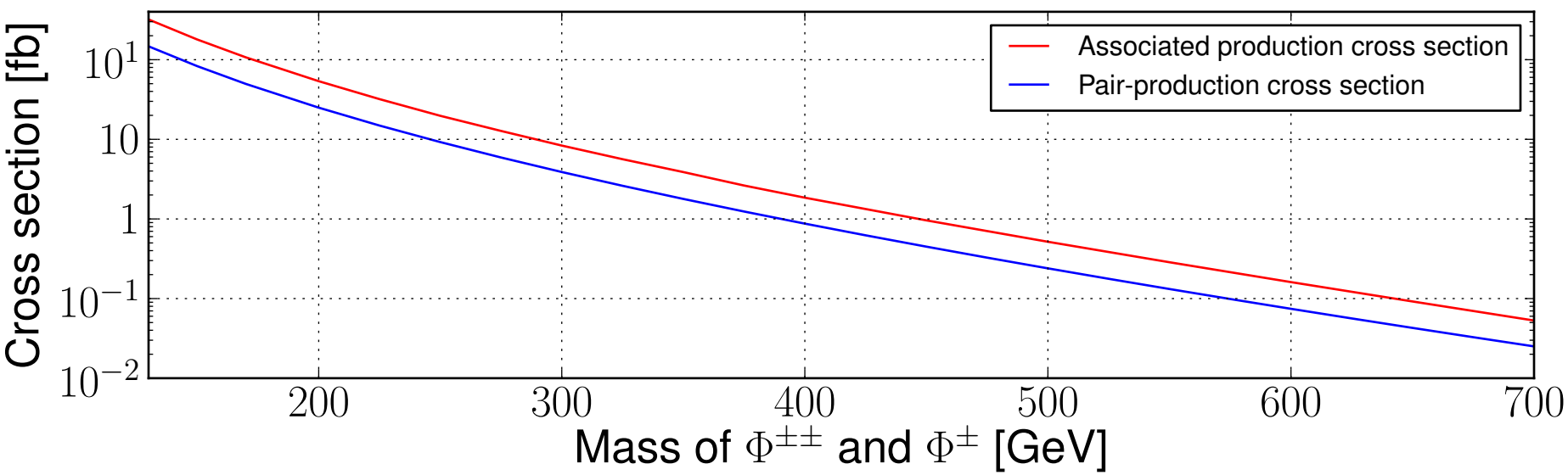


Doubly Charged $\Phi^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$

CMS PAS HIG-12-005

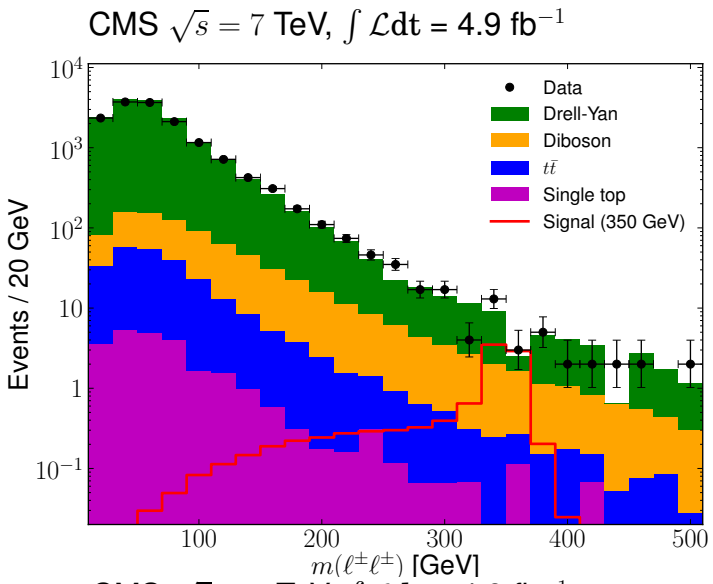
- Models with triplet of higgs fields, predict doubly charged bosons
  - Interestingly triplet models can include fermiophobic neutral higgs
- Search for like-sign dilepton production

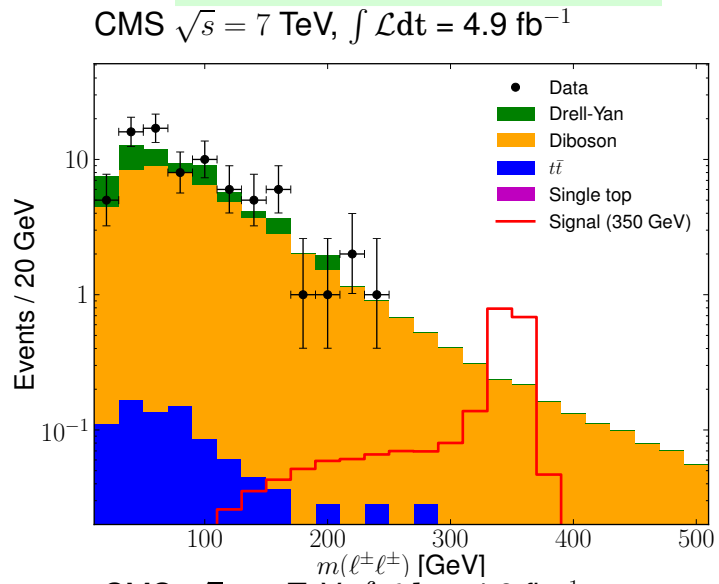


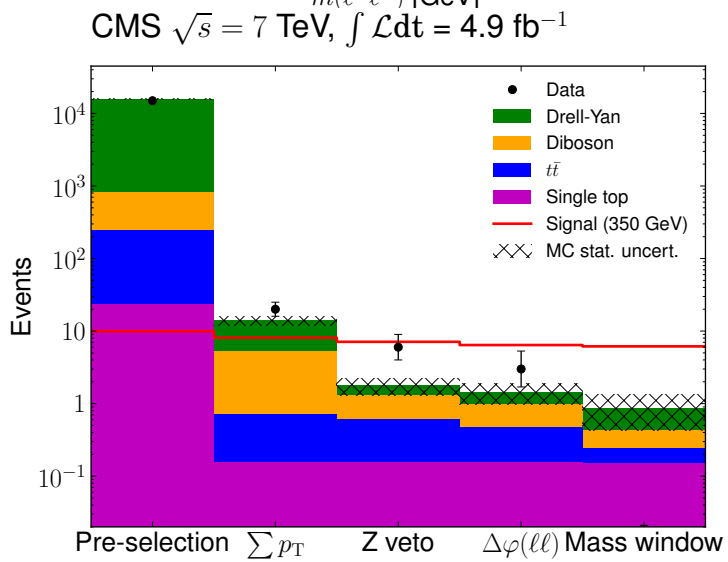


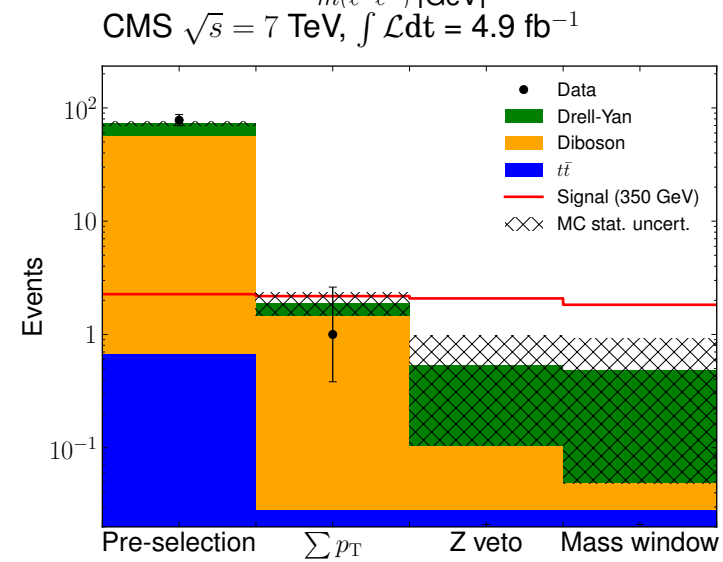
Trilepton & Quadlepton Modes

CMS PAS HIG-12-005



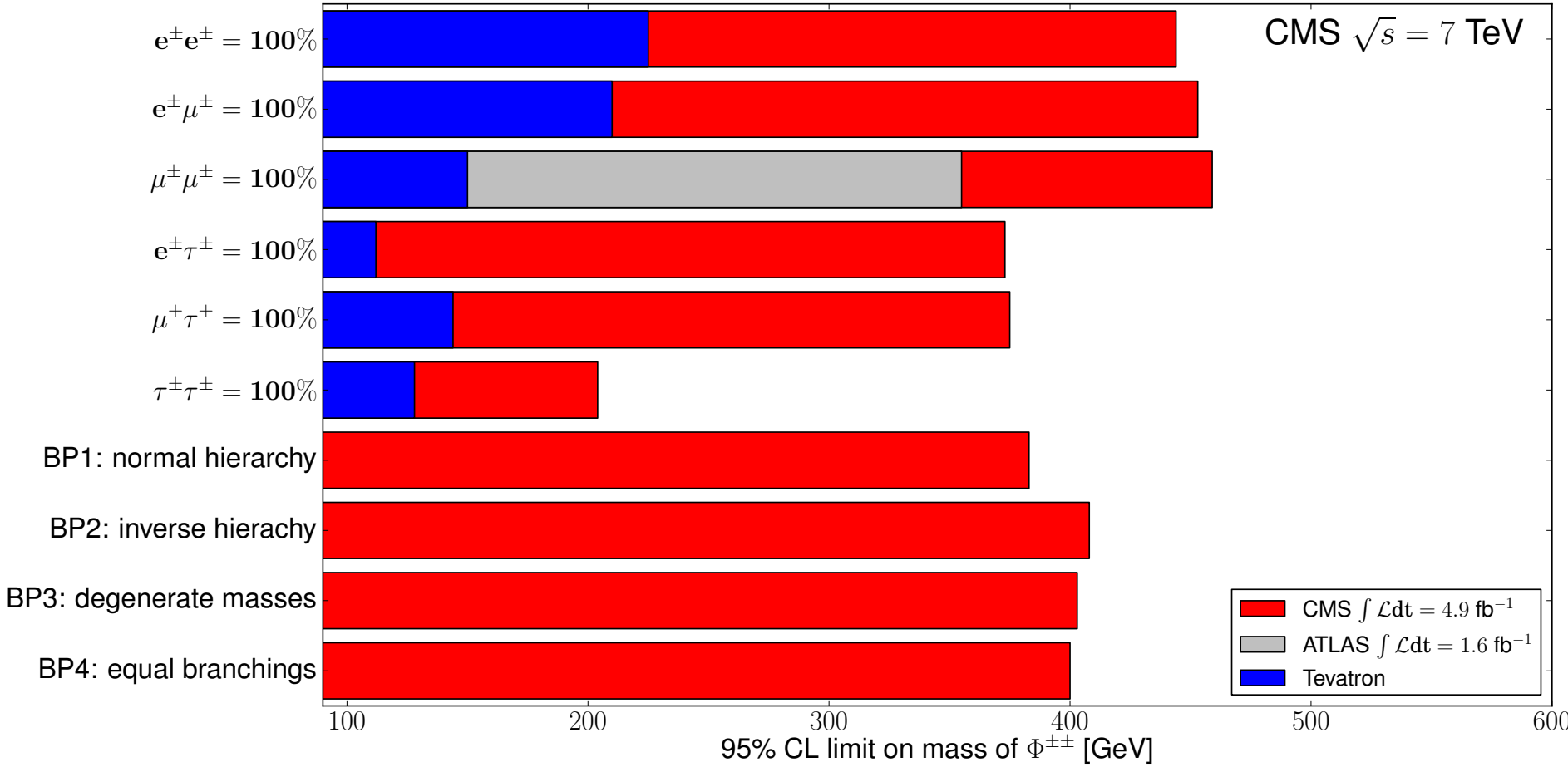






Doubly Charged $\Phi^{\pm\pm} \to l^{\pm} l^{\pm}$ Limits

CMS PAS HIG-12-005



Summary

- MSSM higgs parameter space is being constrained using modes with τ-leptons and b-jets
- No evidence for non-standard higgs production or decay is found in several models
- It remains to be seen if the 125 GeV object has partners lurking around the corner