Other Scalar Searches at LHC

Chris Potter (ATLAS)

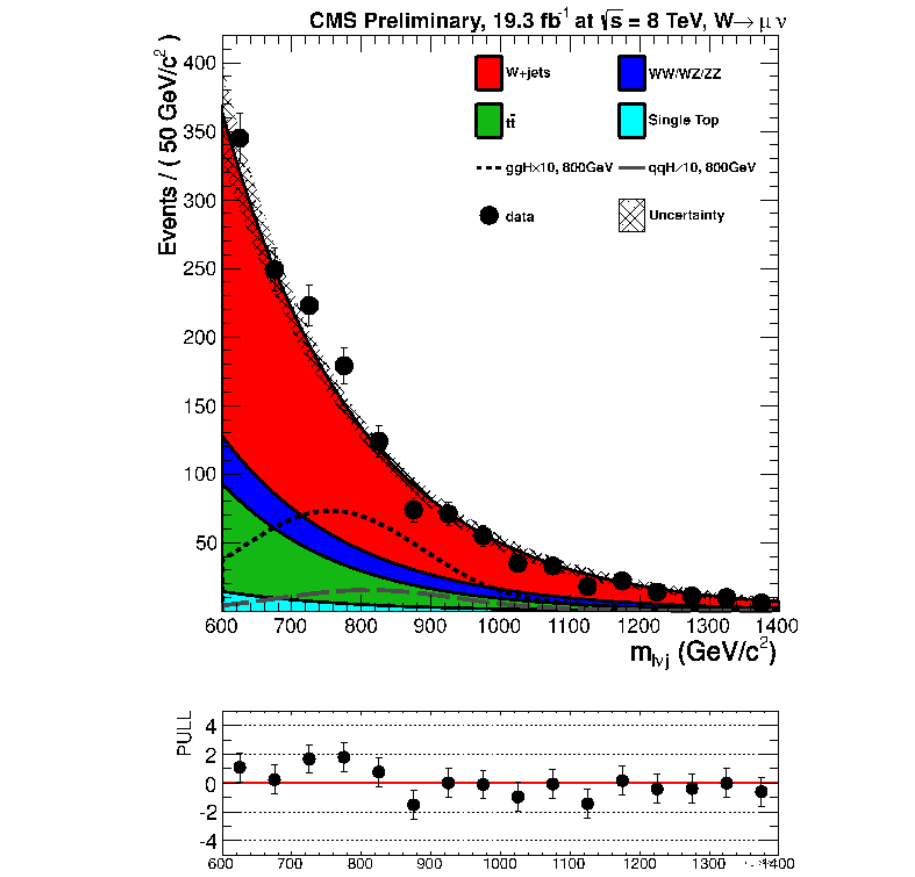
for the CMS and ATLAS Collaborations

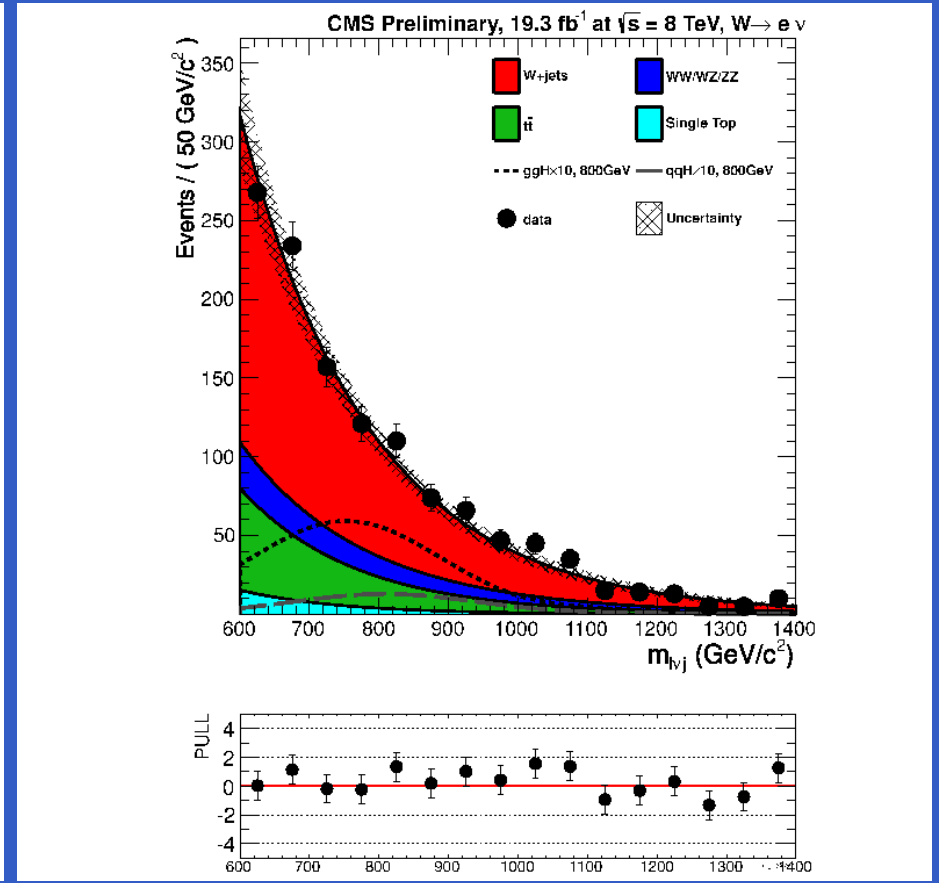
University of Oregon

SM Extensions: Beyond One Doublet

- **Doublet and Singlet**
  The simplest extension gives two physical states which mix. (CMS $H \to WW^\star$)
- **Two Doublets (2HDM)**
  Free parameters are m_H, $\cos\alpha$ (diagonalizes the CP-even mass matrix), $\tan\beta$ (ratio of doublet VEVs). Types are distinguished based on how they couple to fermions.
  - In a Type I 2HDM, only one of these doublets couples to fermions.
    The other doublet does not couple to fermions. (ATLAS $H \to WW^\star$)
  - In a Type II 2HDM, a symmetry is imposed so that one doublet couples to up-type fermions and the other couples to down-type fermions.
    The most typical SUSY scalar benchmark, the MSSM, employs a Type II 2HDM.
    (ATLAS+CMS $\phi \to \mu^+\mu^-\tau^+\tau^-$, $H^+ \to \tau^+\nu, c\bar{s}$)
  - In Types III and IV couplings to leptons differ.
- **Doublet and Triplet**
  May help explain the generation of neutrino masses in the context of the Type II seesaw model. (CMS $\phi^{++} \to \ell^+\ell^+$)
- **Two Doublets and a Singlet**
  Another typical SUSY scalar benchmark, the NMSSM, employs a 2HDM Type II and an additional singlet. (ATLAS+CMS $a_1 \to \mu^+\mu^-$)

CMS Singlet Ext.: $H \rightarrow WW^{\star}$ ($\int \mathcal{L}dt$ =19.3 fb^{-1})



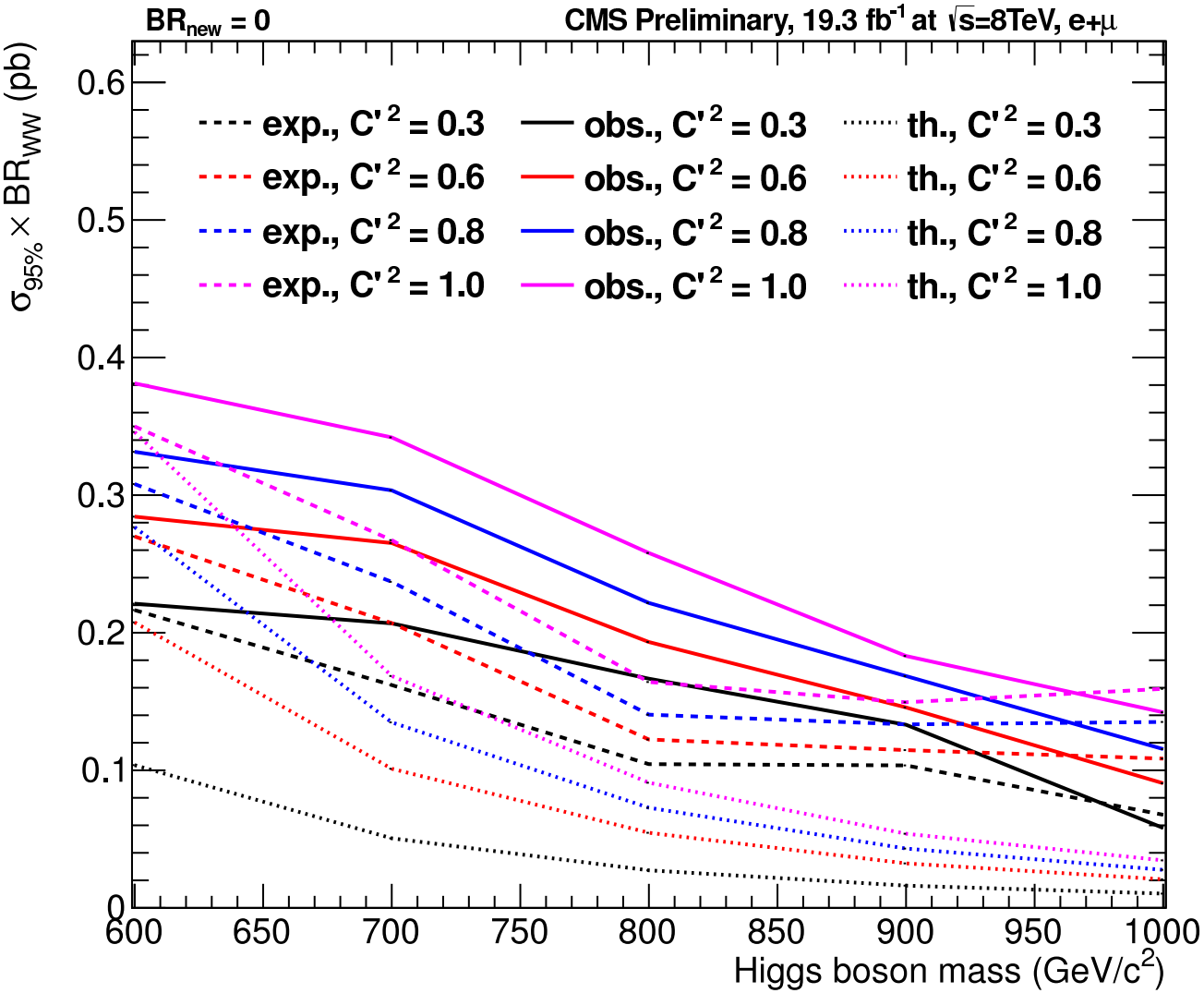


CMS-PAS-HIG-13-008

The search is performed in the semi-leptonic channel where the hadronically decaying W boson is highly boosted and its decay products are contained in one jet. Jet substructure techniques are used in identifying the hadronically decaying W. Final distribution in $m_{\ell\nu J}$ are shown for the signal region for the 800 GeV signal mass point in the muon channel (left) and the electron channel (right).

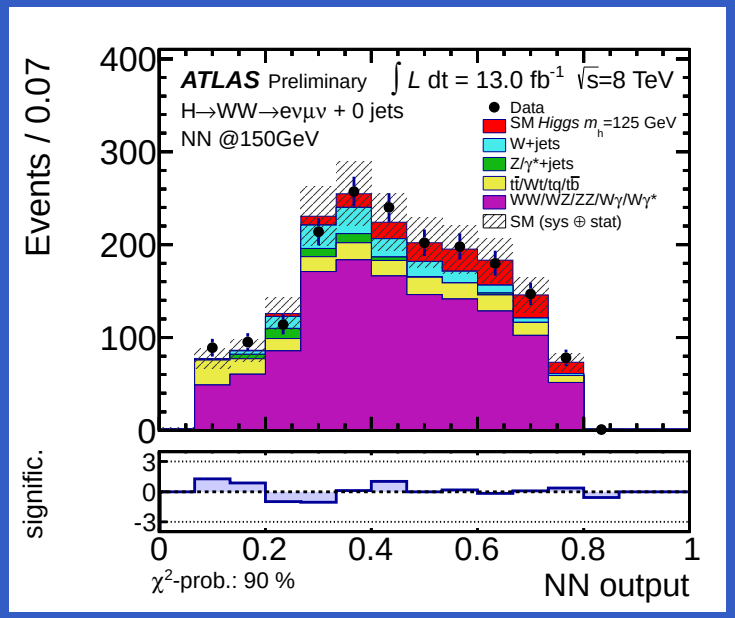
CMS Singlet Extension Limits ($\int \mathcal{L}dt$ =19.3 fb^{-1})

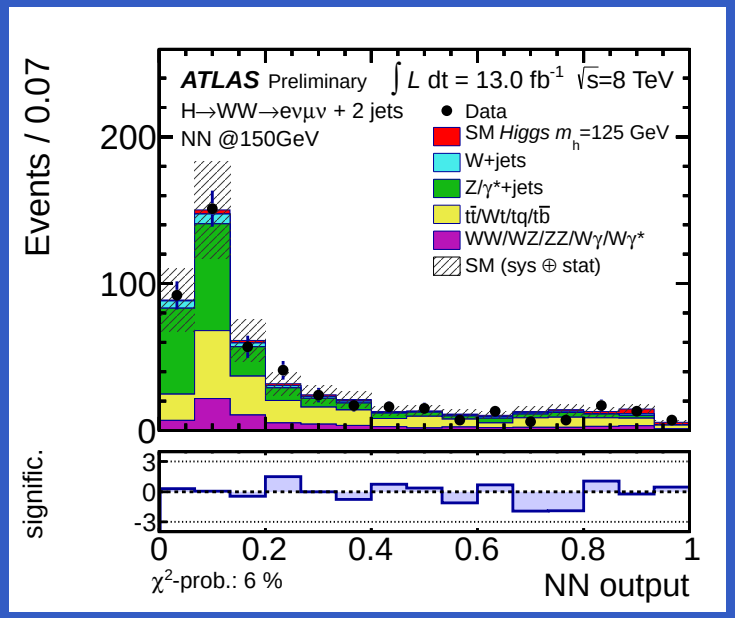
C' is the scale factor of the coupling of the high mass scalar with respect to the Standard Model.

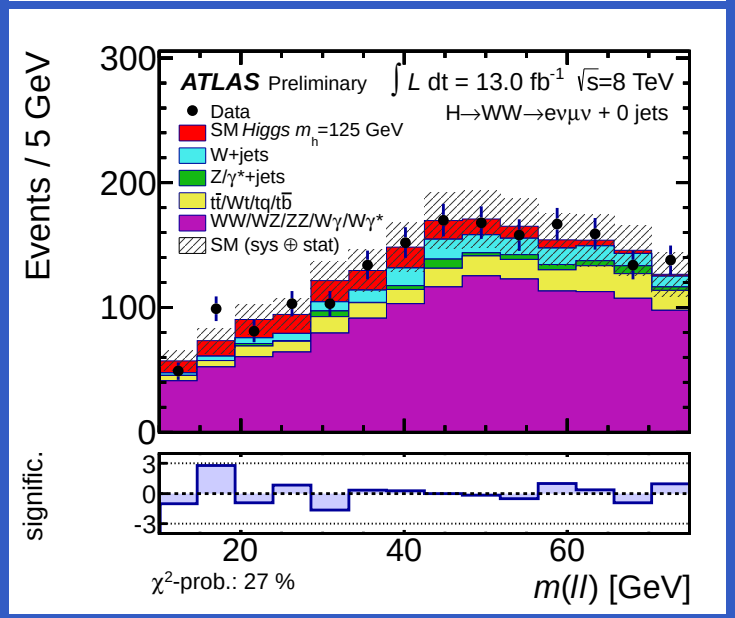


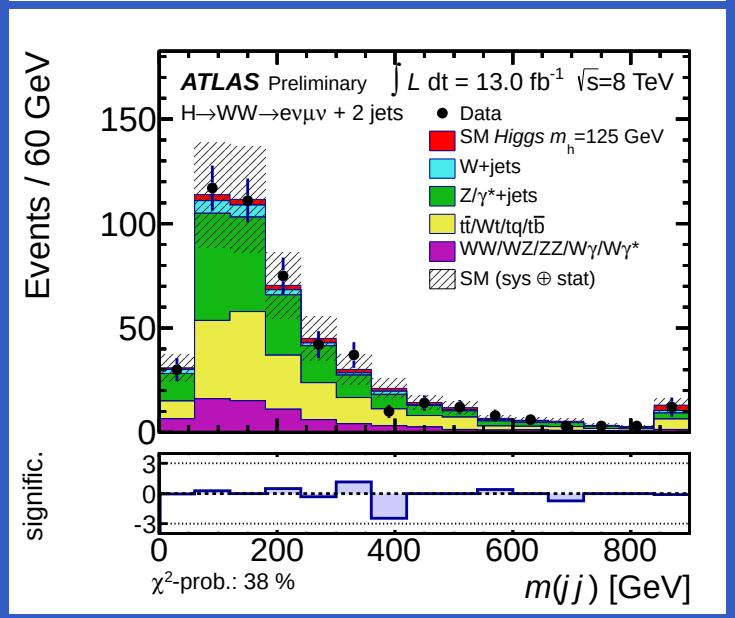
CMS-PAS-HIG-13-008

ATLAS 2HDM $H \rightarrow WW^{\star}$ ($\int \mathcal{L}dt$ =13.0 fb^{-1})





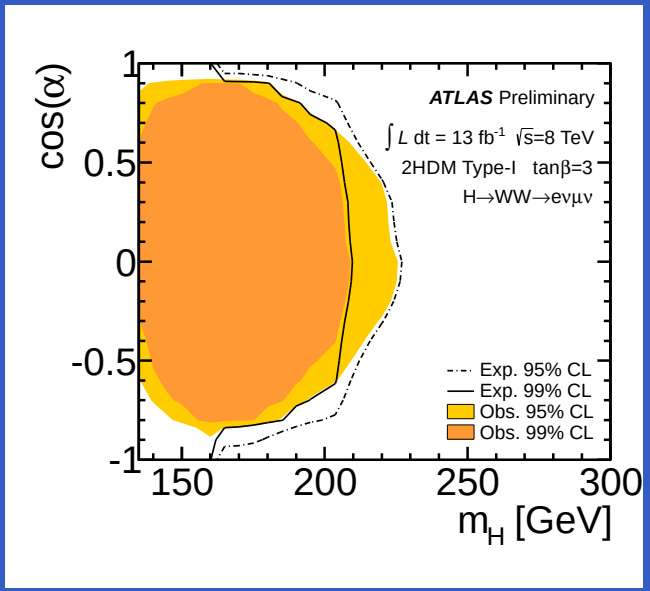


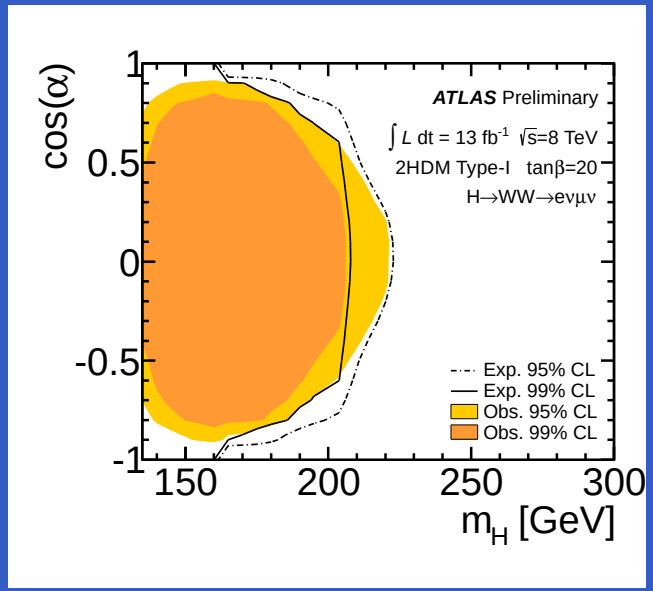


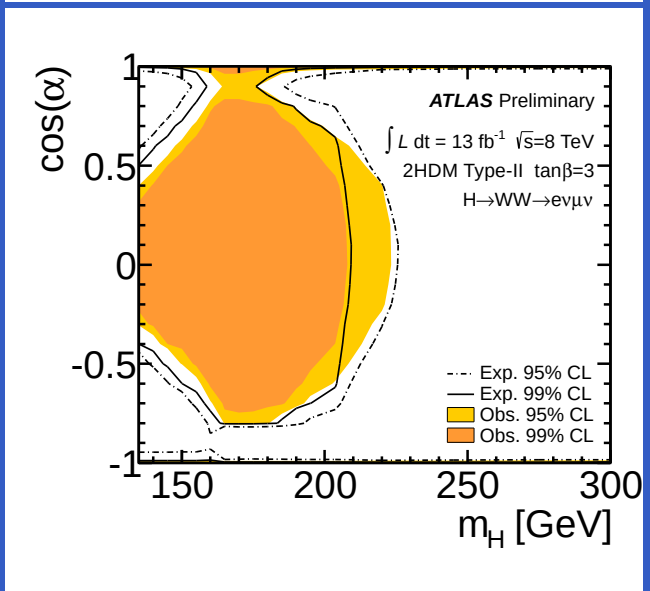
ATLAS-CONF-2013-027

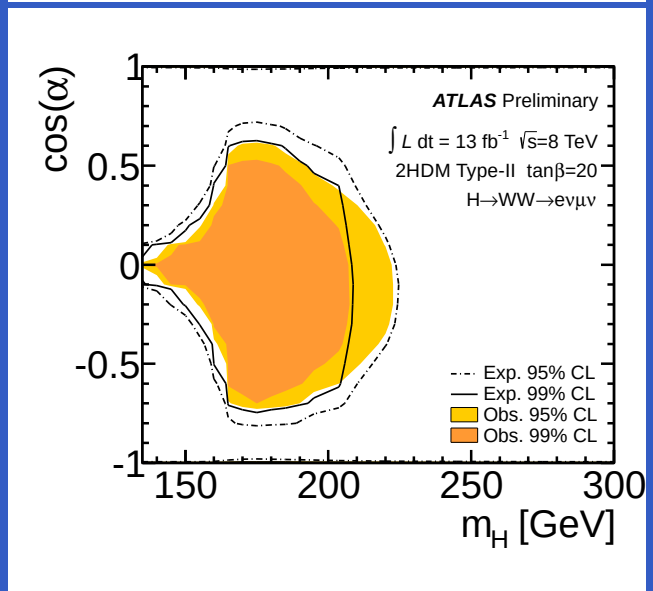
ATLAS 2HDM Types I,II Limits ($\int \mathcal{L}dt$ =13.0 fb^{-1})

The angle α diagonalizes the CP-even scalar mass matrix.



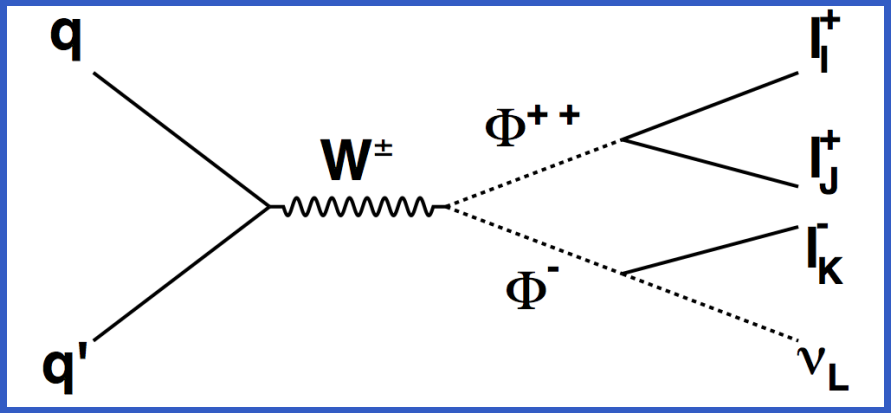


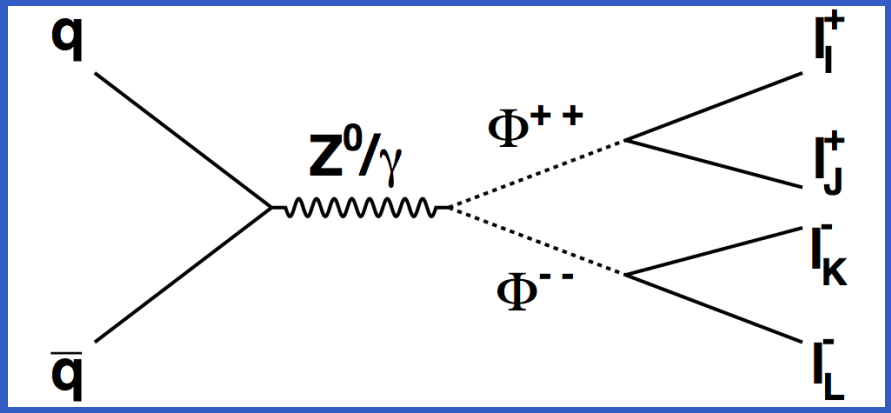


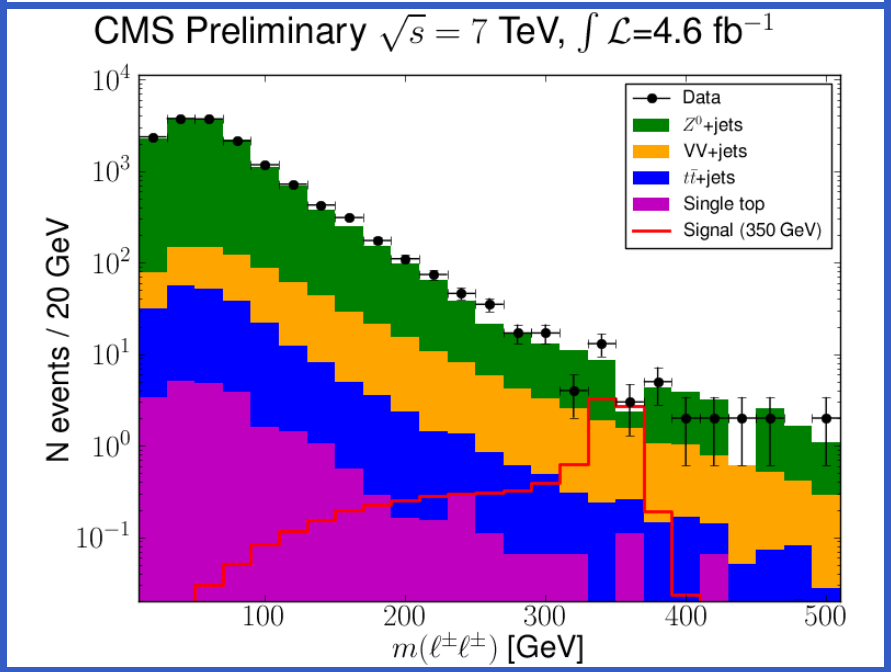


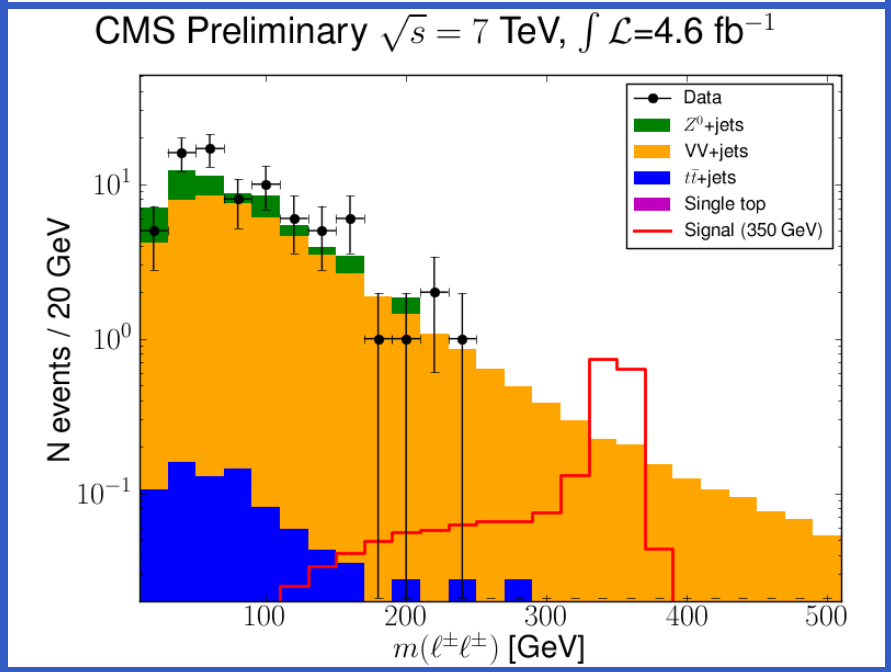
ATLAS-CONF-2013-027

CMS Triplet Ext.: $\Phi^{++} \to \ell^+\ell^+$ ($\int \mathcal{L}dt$ =4.6 fb^{-1})





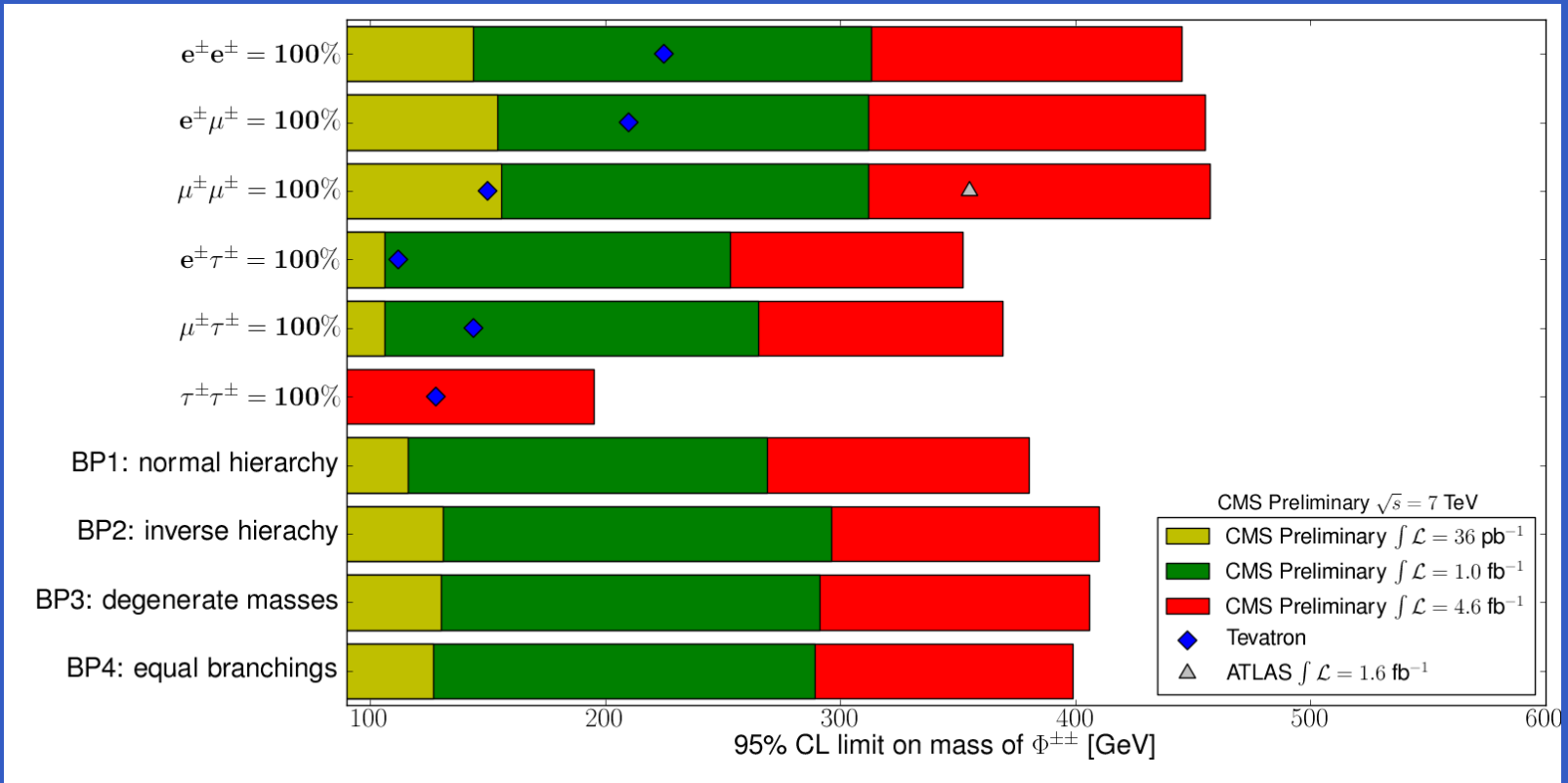




CMS-PAS-HIG-12-005

The search is inclusive and is performed in events with three or more isolated charged leptons of all flavors originating from the decays of pair produced triplet components.

CMS Triplet Extension Limits ($\int \mathcal{L}dt$ =4.6 fb^{-1})



CMS-PAS-HIG-12-005

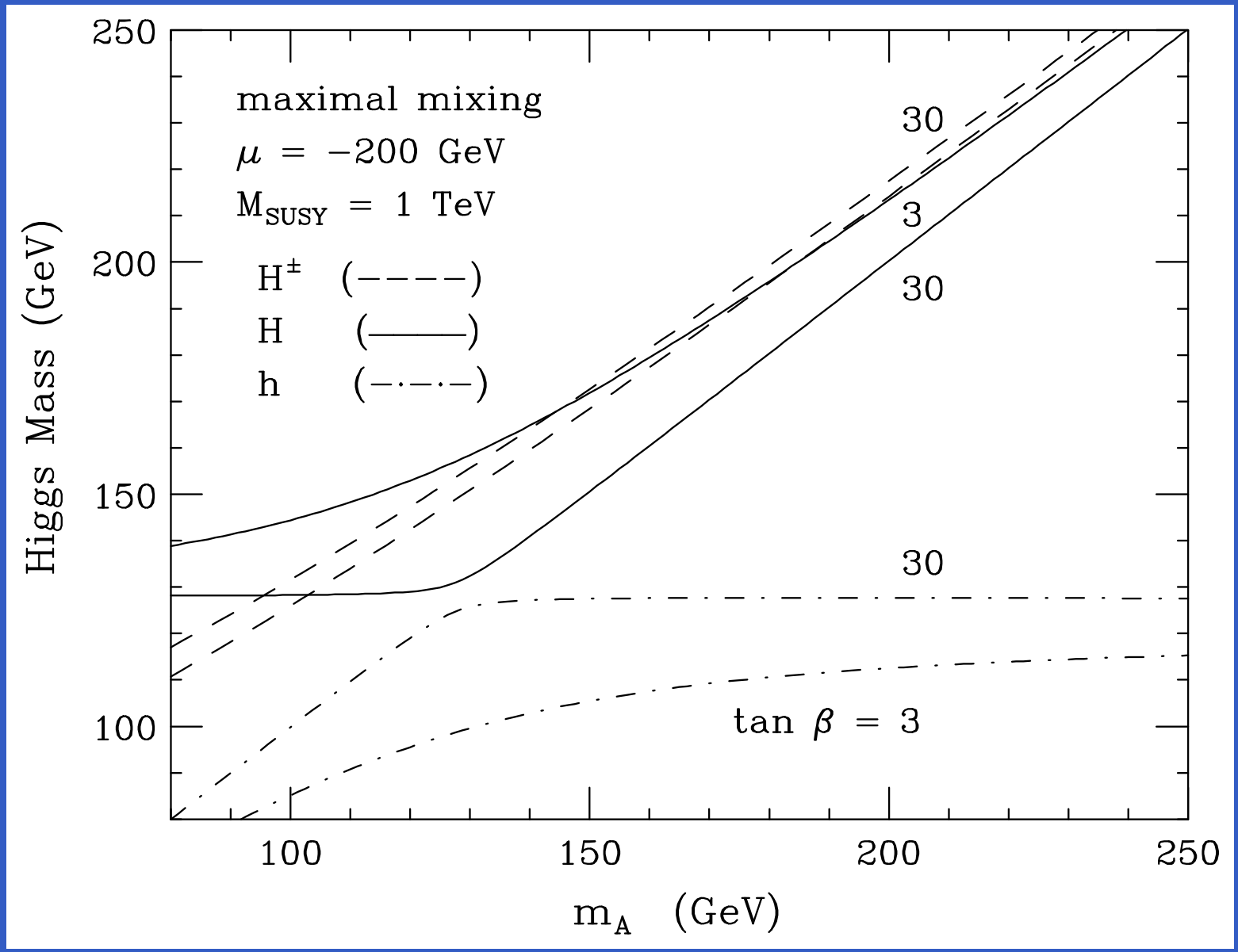
- BP1: massless neutrinos with a normal mass hierarchy BR=(0,0.01,0.3,0.01,0.38,0.3)
- BP2: massless neutrinos with an inverted mass hierarchy BR=(1/2,0,1/8,0,1/4,1/8)
- BP3: degenerate neutrino mass spectrum with mean mass 0.2 eV BR=(1/3,0,1/3,0,0,1/3)
- BP4: equal branching ratio to each lepton generation BR=(1/6,1/6,1/6,1/6,1/6,1/6)

Supersymmetry: SUSY, MSSM, NMSSM

- Supersymmetry (SUSY)
  - SUSY provides an elegant solution to the Hierarchy Problem of the SM.
  - Gauge couplings unify at the GUT scale and there exists a good candidate for Dark Matter - the neutralino χ^0.
- Minimal-SUSY (MSSM)
  - Introduces soft term to the SUSY potential for the broken symmetry.
  - Requires 2HDM Type II with doublet VEVs v_u and v_d.
  - Scalar sector reduces to a two free parameters at tree level ($m_A, \tan\beta \equiv v_u/v_d$).
  - Two neutral CP-even (h, H), one neutral CP-odd (A) and charged CP-even (H^+, H^-).
  - m_h-max Benchmark: remaining free SUSY parameters are selected to maximize m_h.
- Next-to-MSSM (NMSSM)
  - Solves the MSSM μ-term problem without fine tuning by adding one singlet to the MSSM.
  - Three CP-even (h_1, h_2, h_3), two CP-odd (a_1, a_2) and charged CP-even (h^+, h^-).
  - Ideal Scenario ($m_a < 2m_b$) can explain the anomalous muon magnetic moment and the combined LEP 2.3σ $m_{b\bar{b}}$ excess. (Phys.Rev.D79:055014,2009).

MSSM Scalar Mass Spectrum

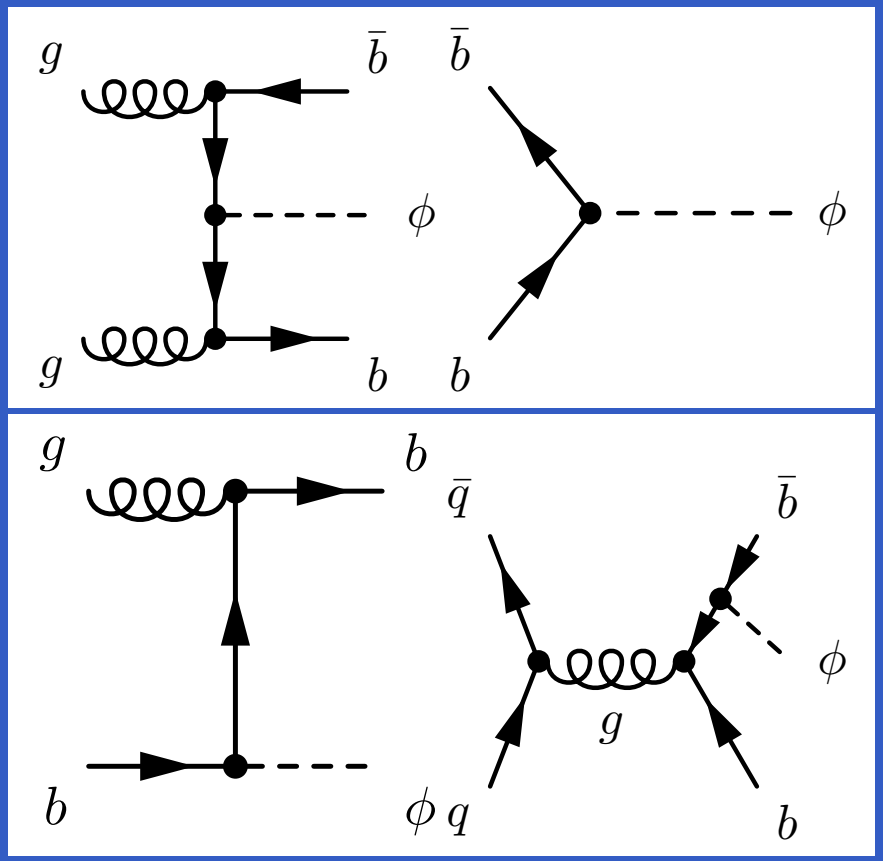
The MSSM h mass is bounded above by $m_h < 135$ GeV



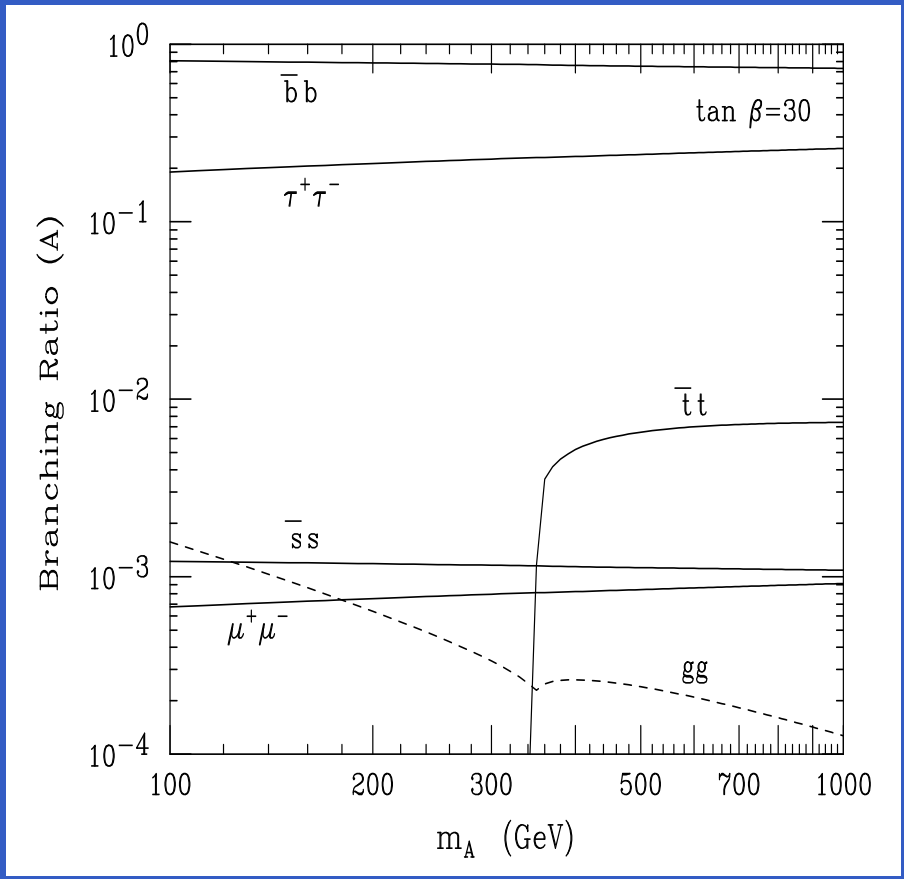
Prog.Part.Nucl.Phys.50:63-152,2003

MSSM Neutral $\phi^0 = A/H/h$ Phenomenology

CERN-OPEN-2008-020 (arXiv:0901.0512)



Prog.Part.Nucl.Phys.50:63-152,2003

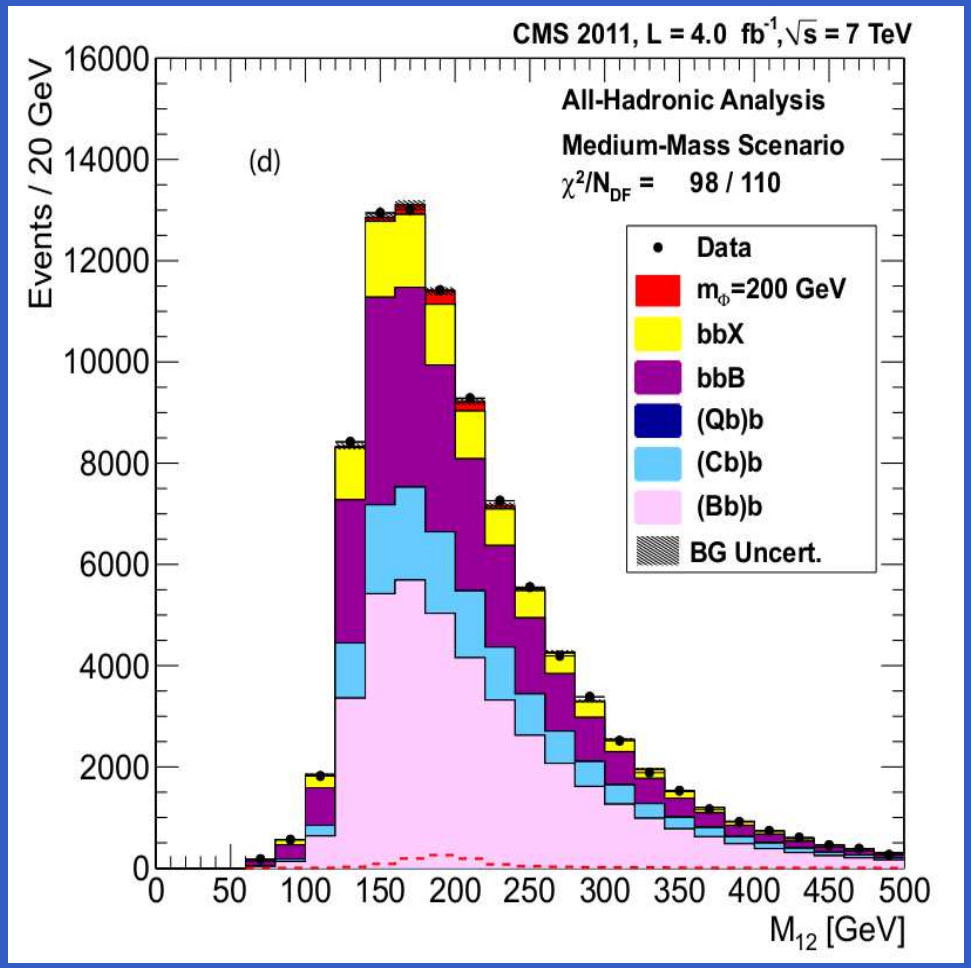


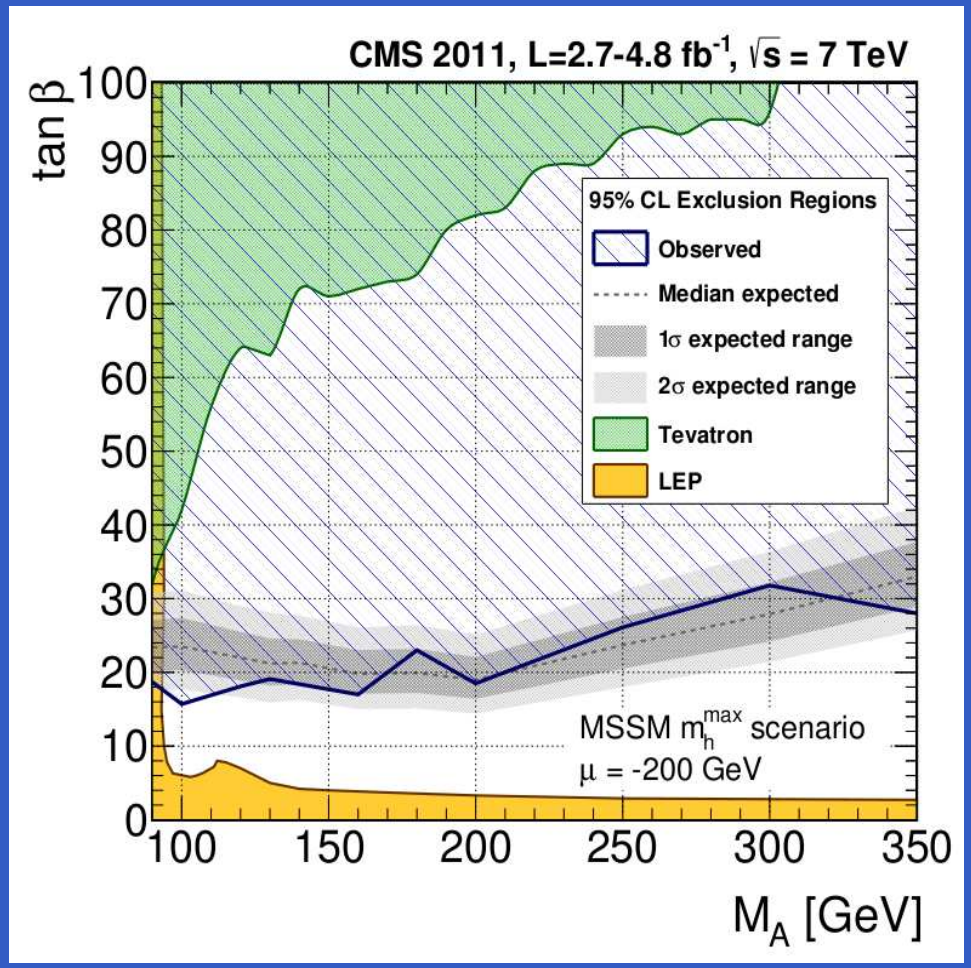
If $\tan\beta$ is large ($> \mathcal{O}(10)$), the coupling of down-type fermions is enhanced and to up-type fermions is suppressed. In the MSSM the coupling is $g_{\phi bb}^{MSSM} = \tan\beta \times m_b/v$. So

- for large $\tan\beta$, ϕ production with b quarks is enhanced by $\tan^2\beta$
- for large $\tan\beta$, $\mathcal{BR}(\phi \to b\bar{b}) \approx 0.9$ and $\mathcal{BR}(\phi \to \tau^+\tau^-) \approx 0.1$

MSSM results which follow assume m_h-max benchmark, in which parameters maximize m_h.

CMS $h/H/A \to b\bar{b}$ ($\int \mathcal{L}dt$ =2.7-4.8 fb^{-1})

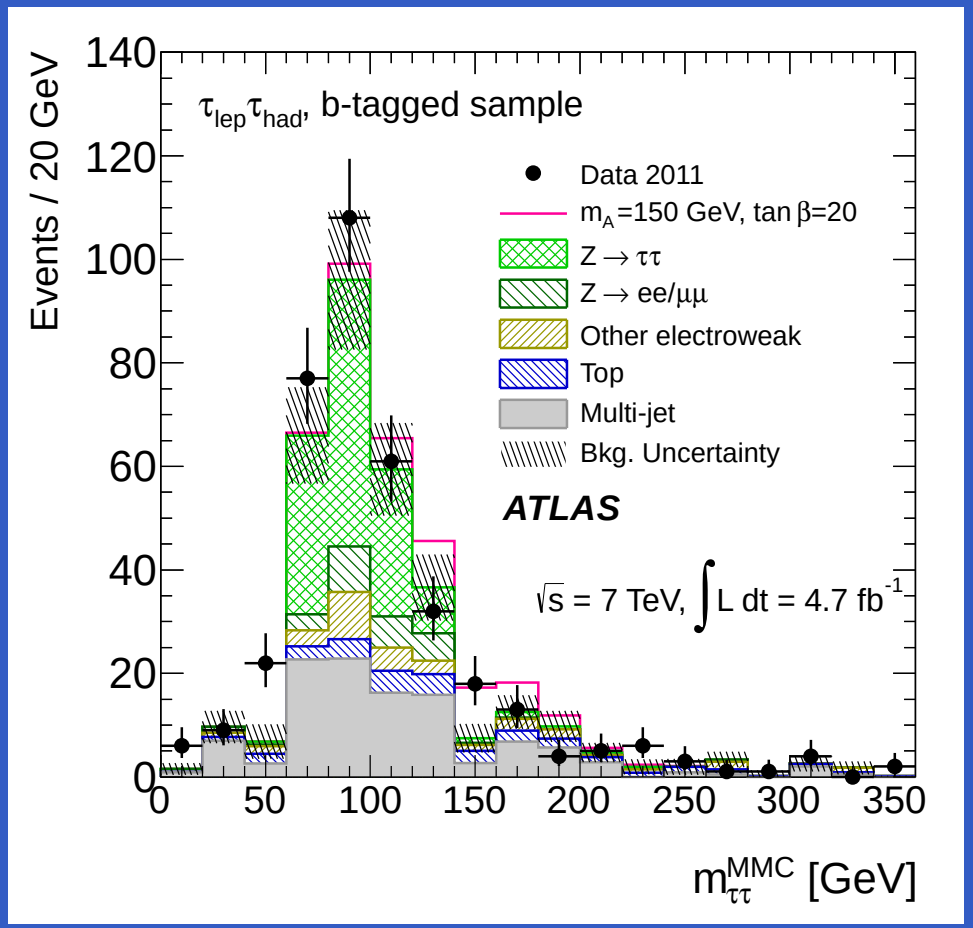


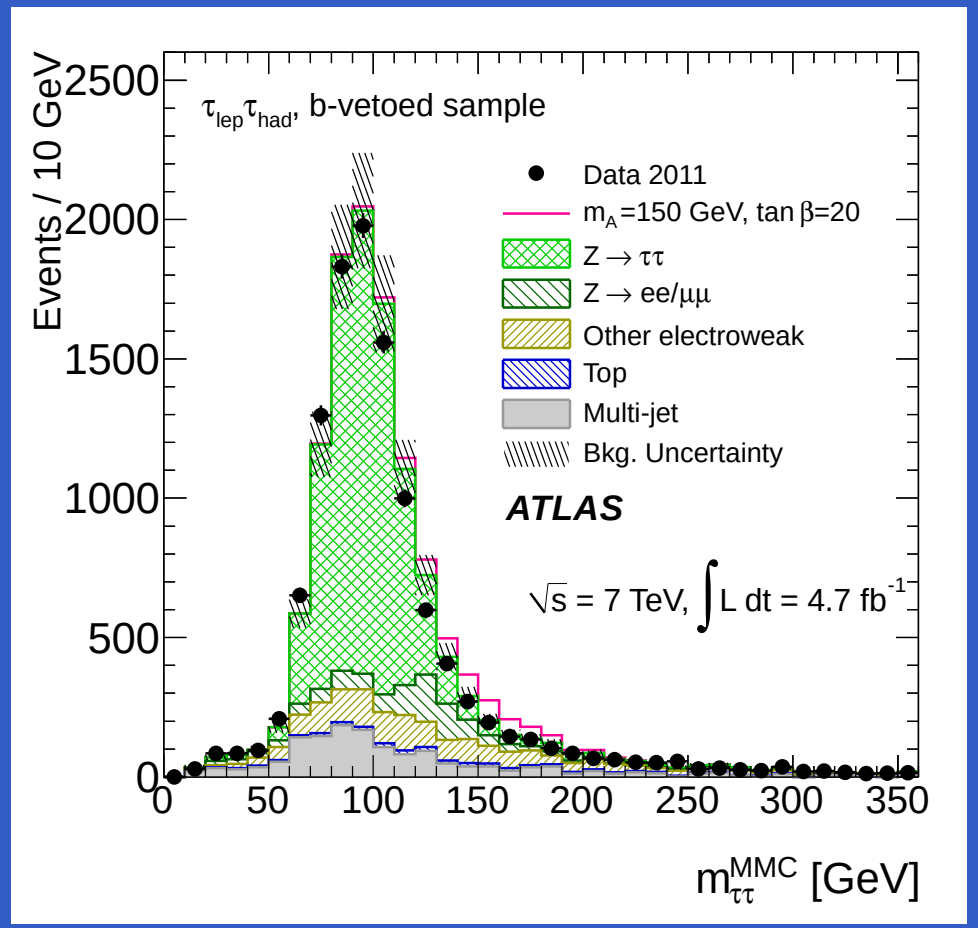


CMS-HIG-12-033

At left, dijet mass distribution in the medium-mass scenario including a signal template for a scalar with a mass of $200GeV/c^2$. At right, observed upper limits at 95% confidence level on $\tan\beta$ as a function of M_A, including the statistical and systematic uncertainties, in the m_h^{max} benchmark scenario with $\mu = -200GeV/c^2$ for the combined all-hadronic and semileptonic results.

ATLAS $h/H/A \to \tau^+\tau^-$ ($\int \mathcal{L}dt$ =4.8 fb^{-1})

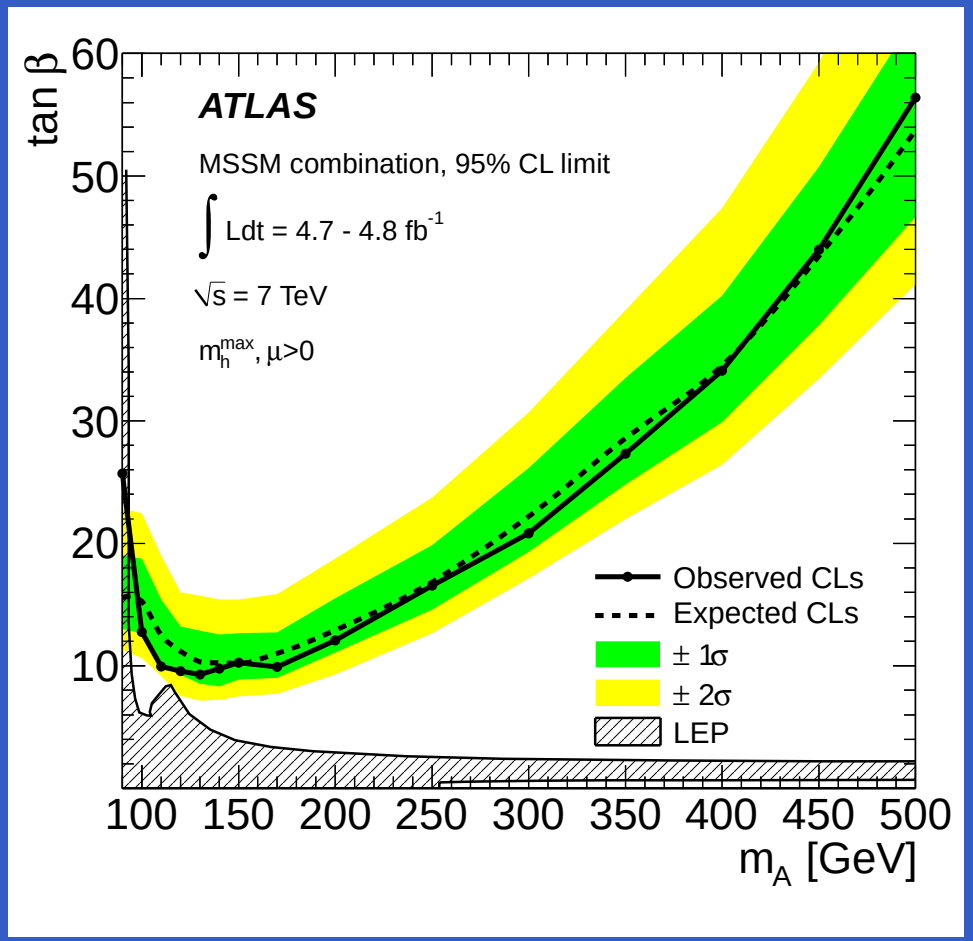


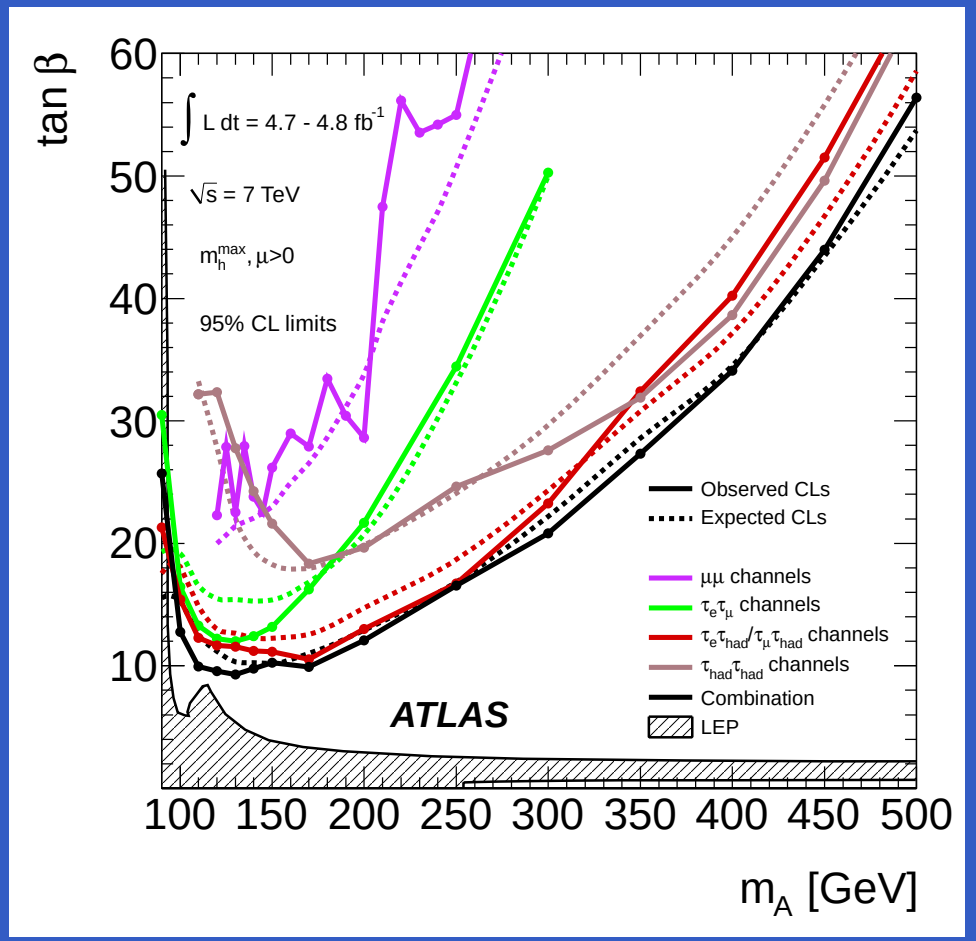


JHEP02(2013)095

Final mass distributions for the $h/A/H \to \tau_{lep}\tau_{had}$ final state. The MMC mass is shown for the b-tagged (left-hand side) and b-vetoed selections (right-hand side) for the combined $\tau_e\tau_{had}$ and $\tau_\mu\tau_{had}$ samples. The data are compared to the background expectation and a hypothetical MSSM signal with $m_A = 150$ GeV and $\tan\beta = 20$. The background uncertainties include statistical and systematic uncertainties.

ATLAS MSSM Limits on $\tan\beta$ from $h/H/A \to \tau^+\tau^-$



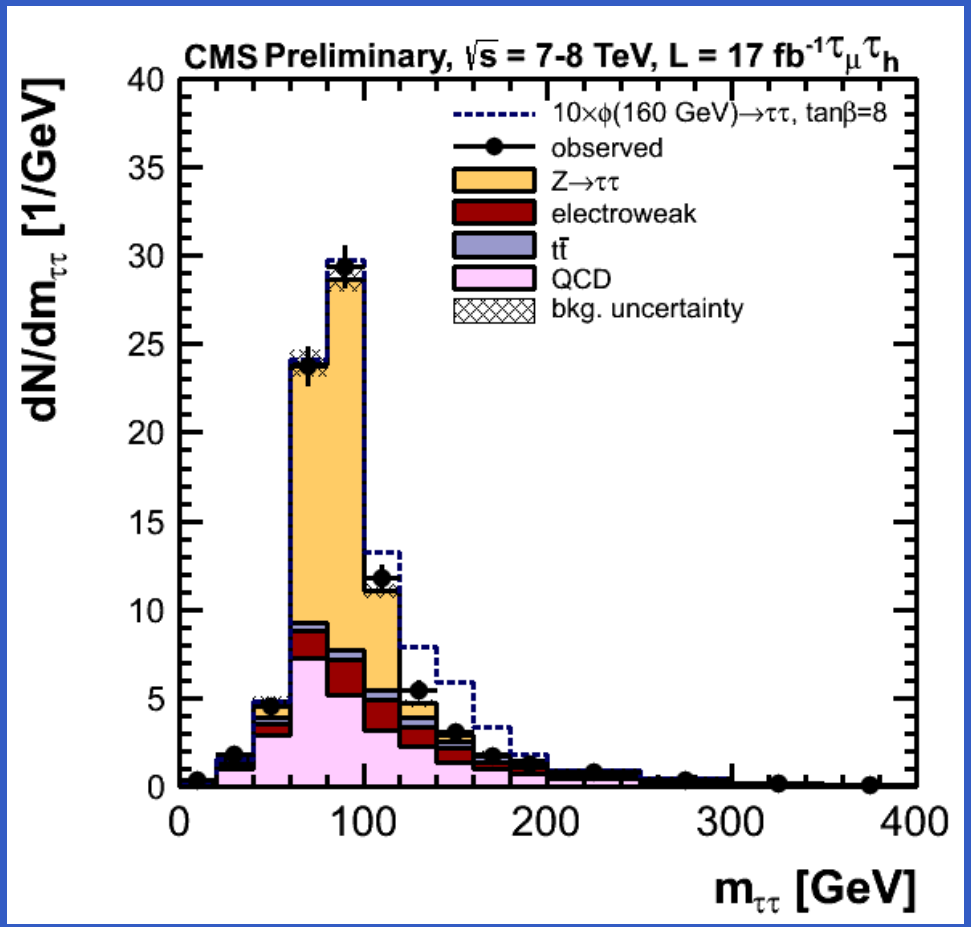


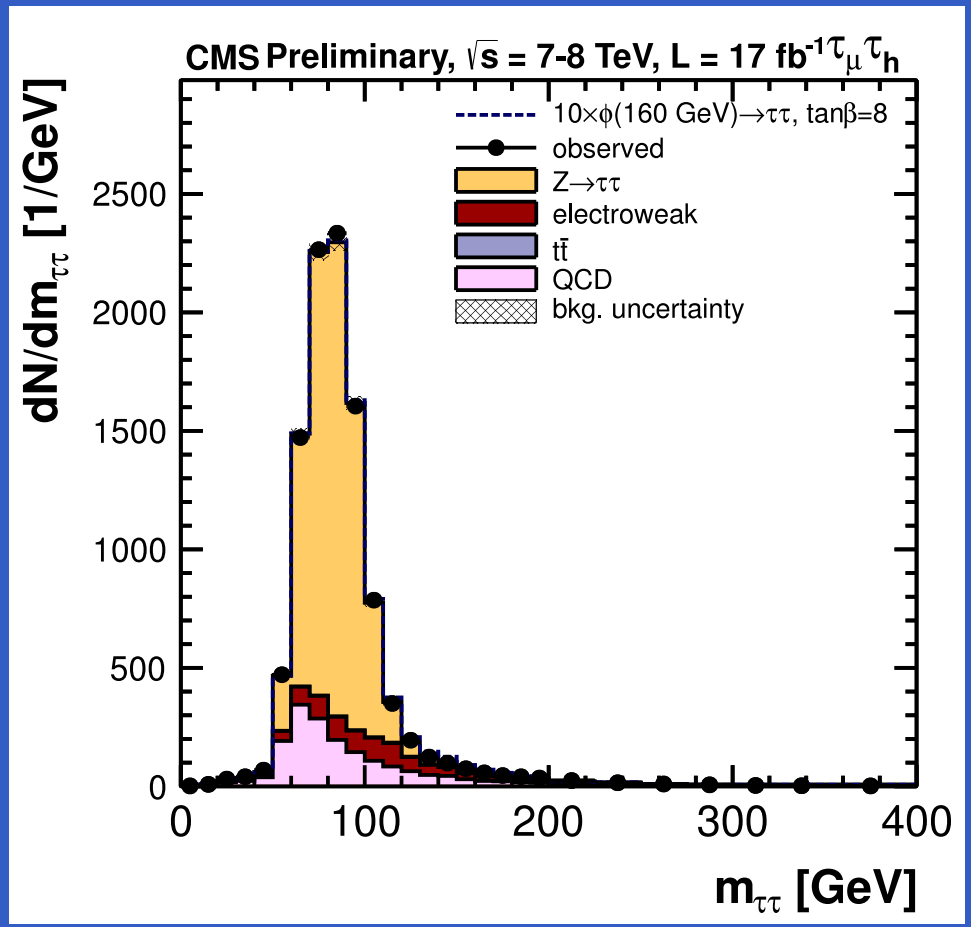
JHEP02(2013)095

Expected (dashed line) and observed (solid line) 95 % confidence level CLs limits on tanβ as a function of m_A for the statistical combination of all channels along with the $\pm 1\sigma$ (green) and $\pm 2\sigma$ (yellow) bands for the expected limit are shown on the left plot. The 95 % confidence level CLs limits along with the $\pm 1\sigma$ band for the expected limit for each of the $\mu\mu$, $\tau_e\tau_\mu$, $\tau_{lep}\tau_{had}$, and $\tau_{had}\tau_{had}$ final states are shown on the right plot.

CMS $h/H/A \to \tau^+\tau^-$ ($\int \mathcal{L}dt$ =17 fb^{-1})

CMS-PAS-HIG-12-050

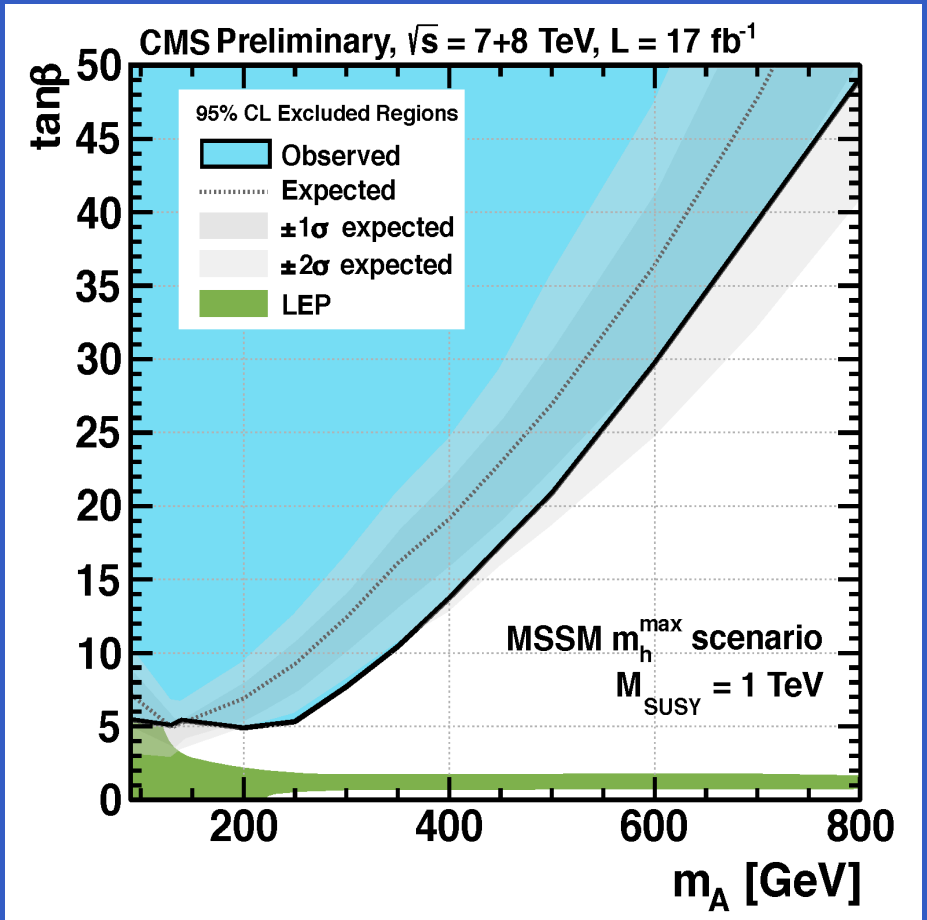


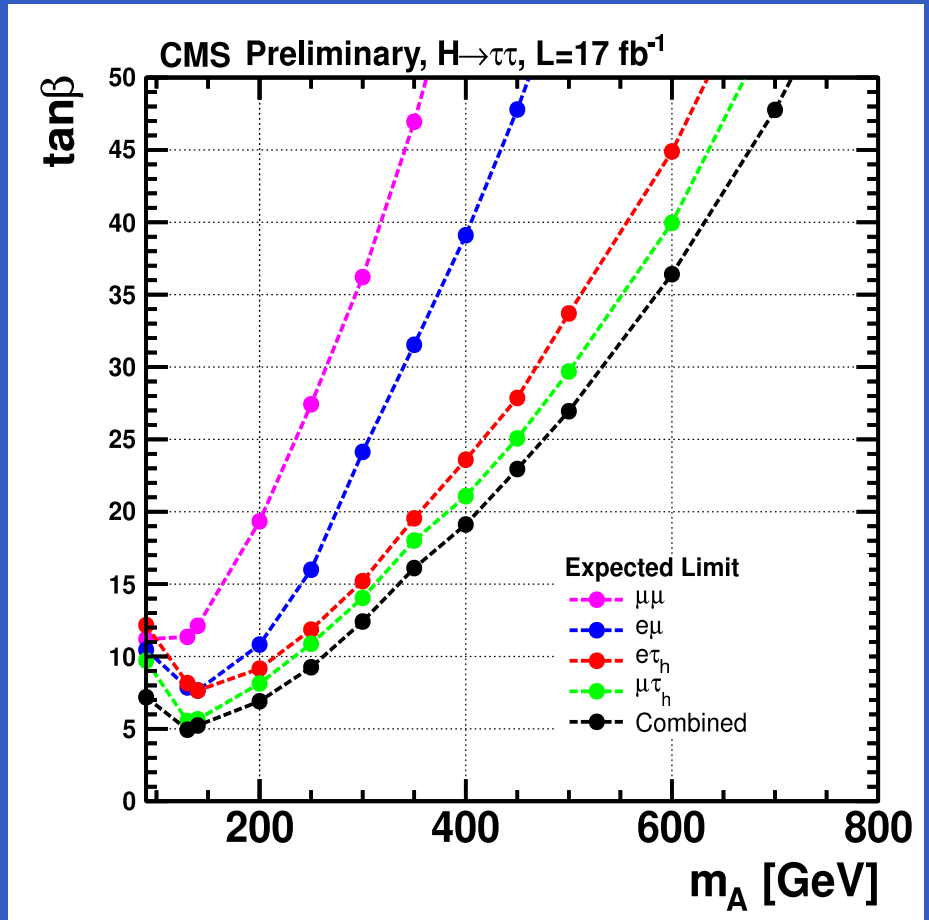


At left, di-tau mass, b-tag category. At right, di-tau mass, no b-tag category.

CMS MSSM Limits on $\tan\beta$ from $h/H/A \to \tau^+\tau^-$

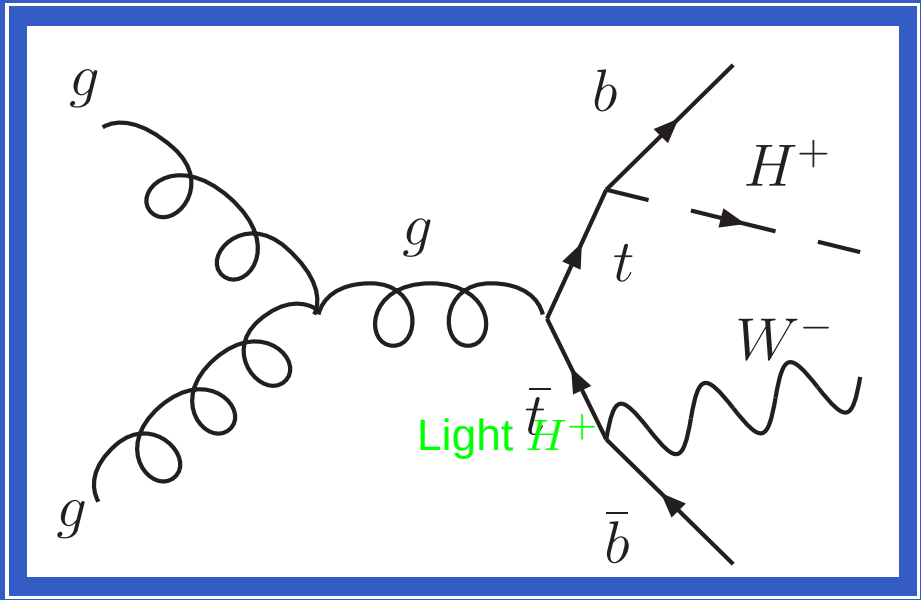
CMS-PAS-HIG-12-050

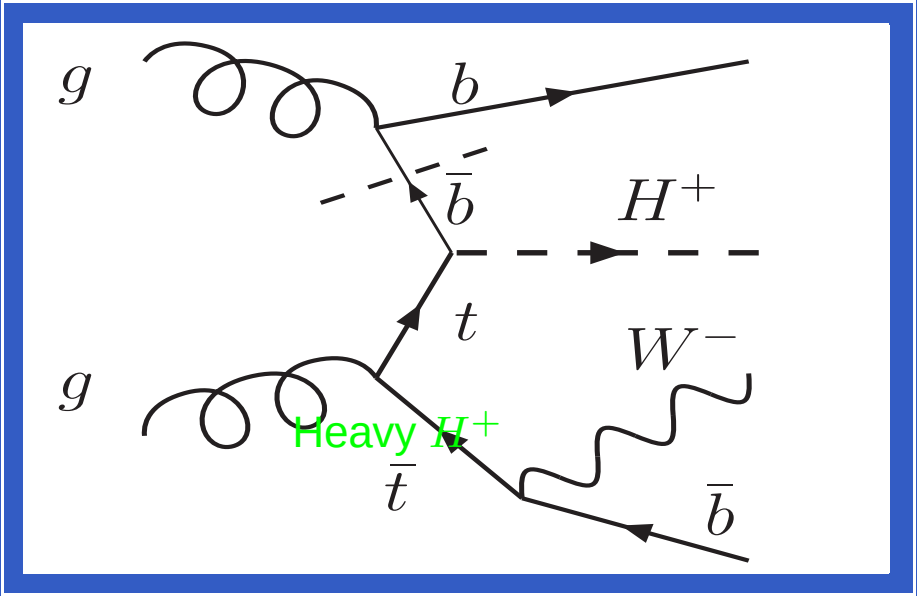


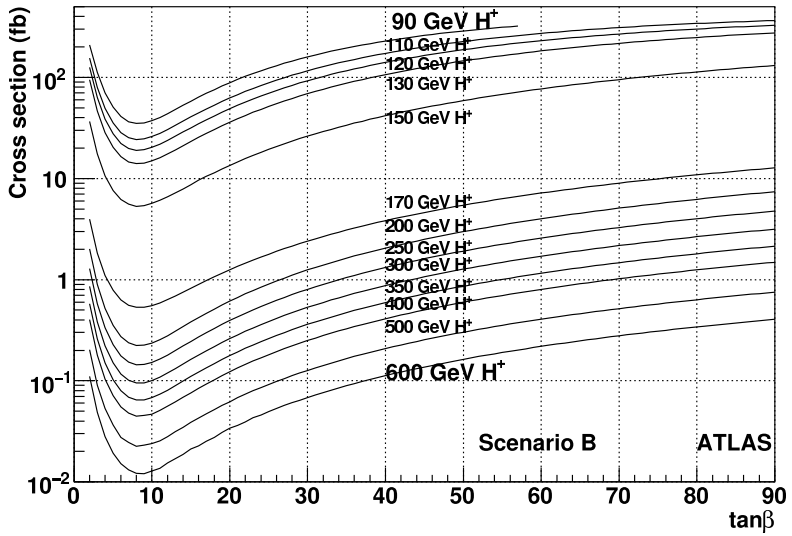


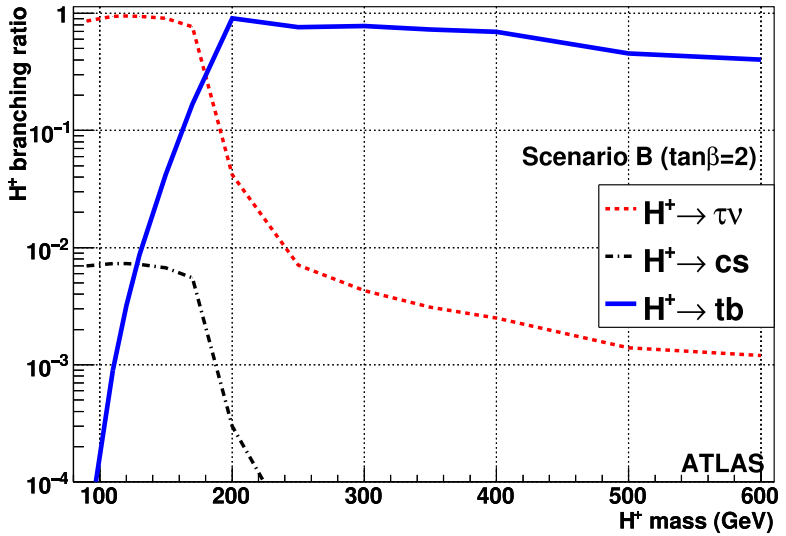
At left, 95% CL Exclusion limit. At right, expected exclusion limit for different final states.

MSSM Charged Scalar H^+ Phenomenology



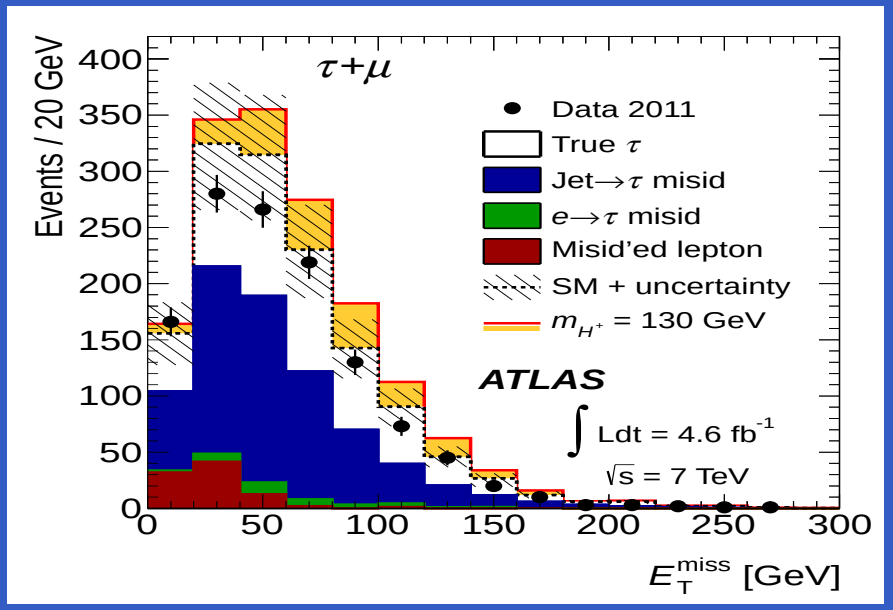


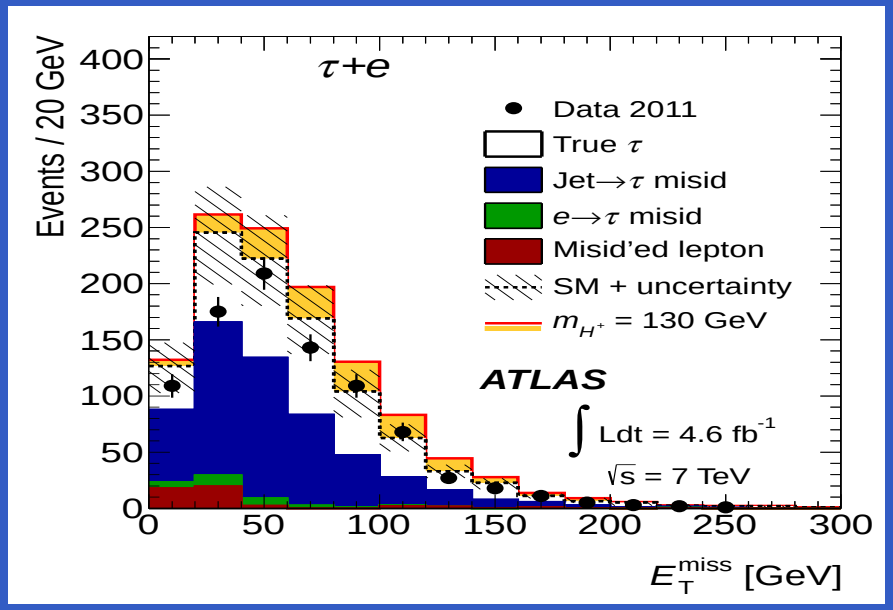


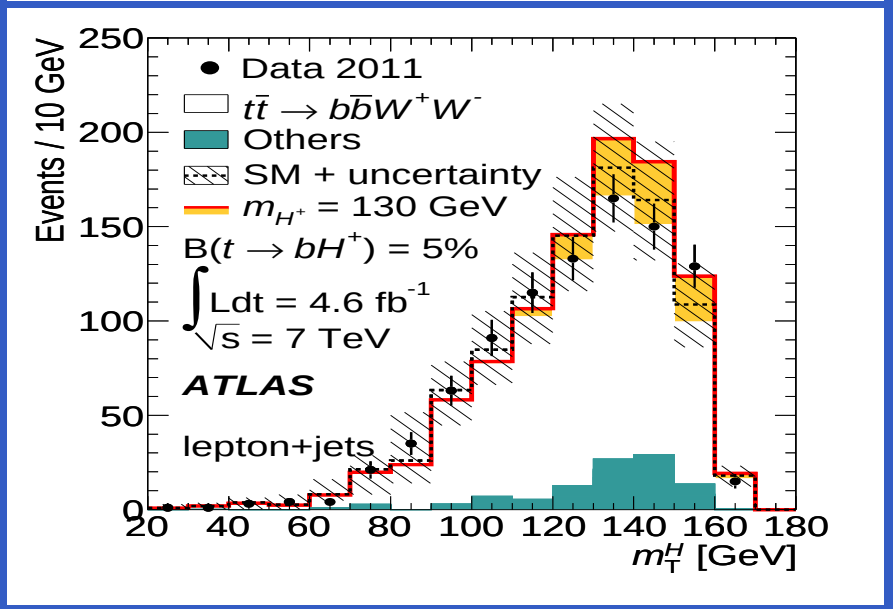


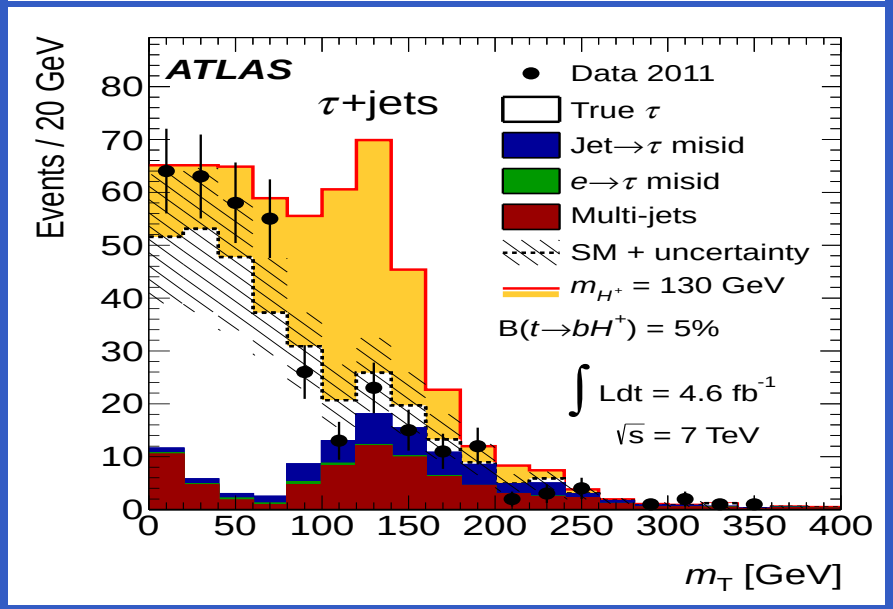
CERN-OPEN-2008-020

ATLAS $H^+ \to \tau^+\nu$ ($\int \mathcal{L}dt$ =4.6 fb^{-1})



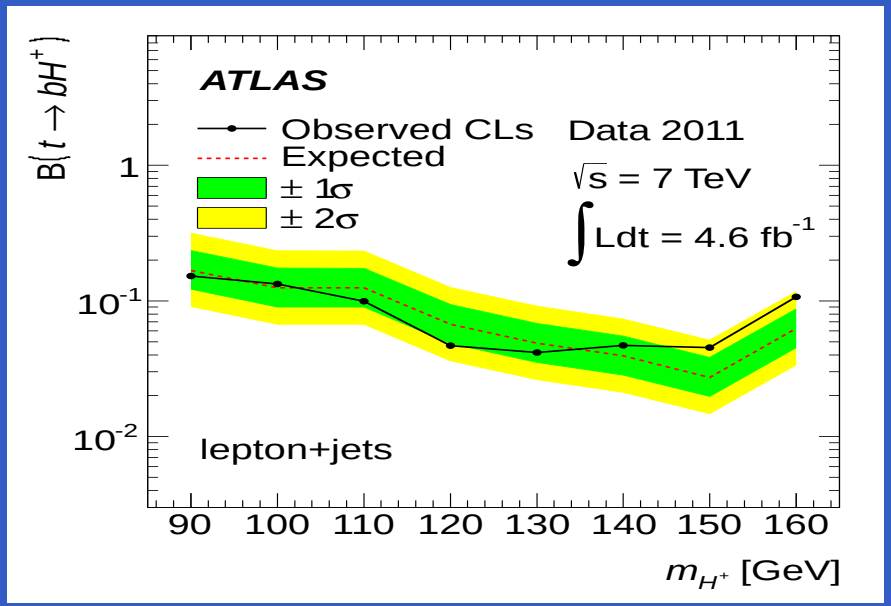


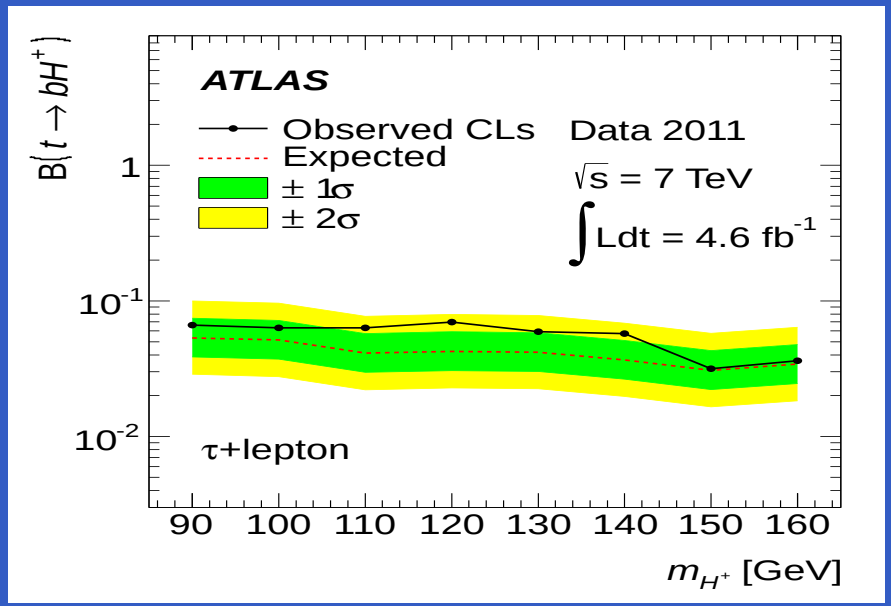


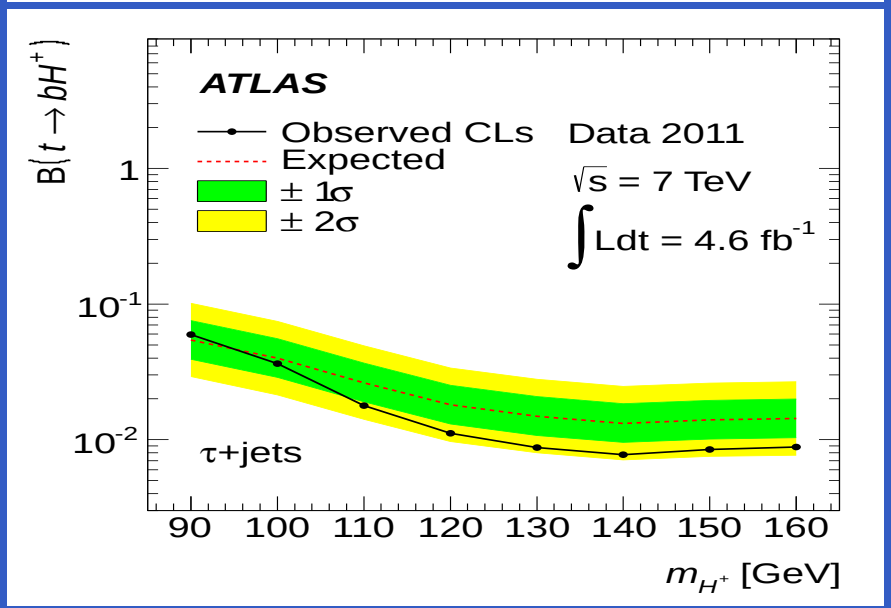


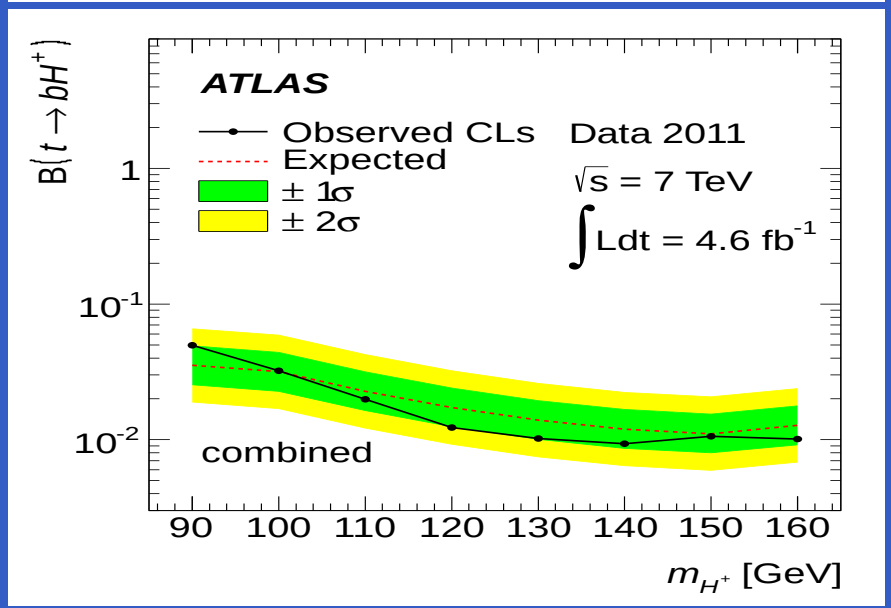
JHEP 1206 (2012) 039

ATLAS Limits on $t \to bH^+ \to b\tau^+\nu$



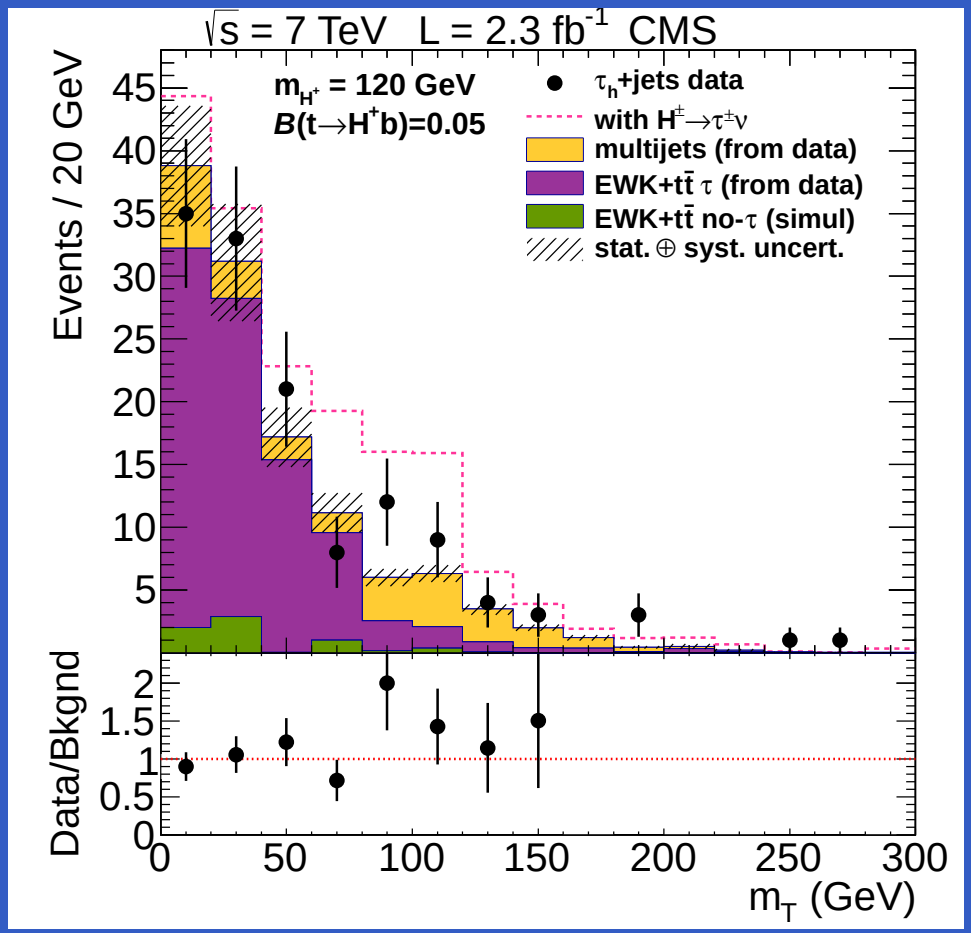


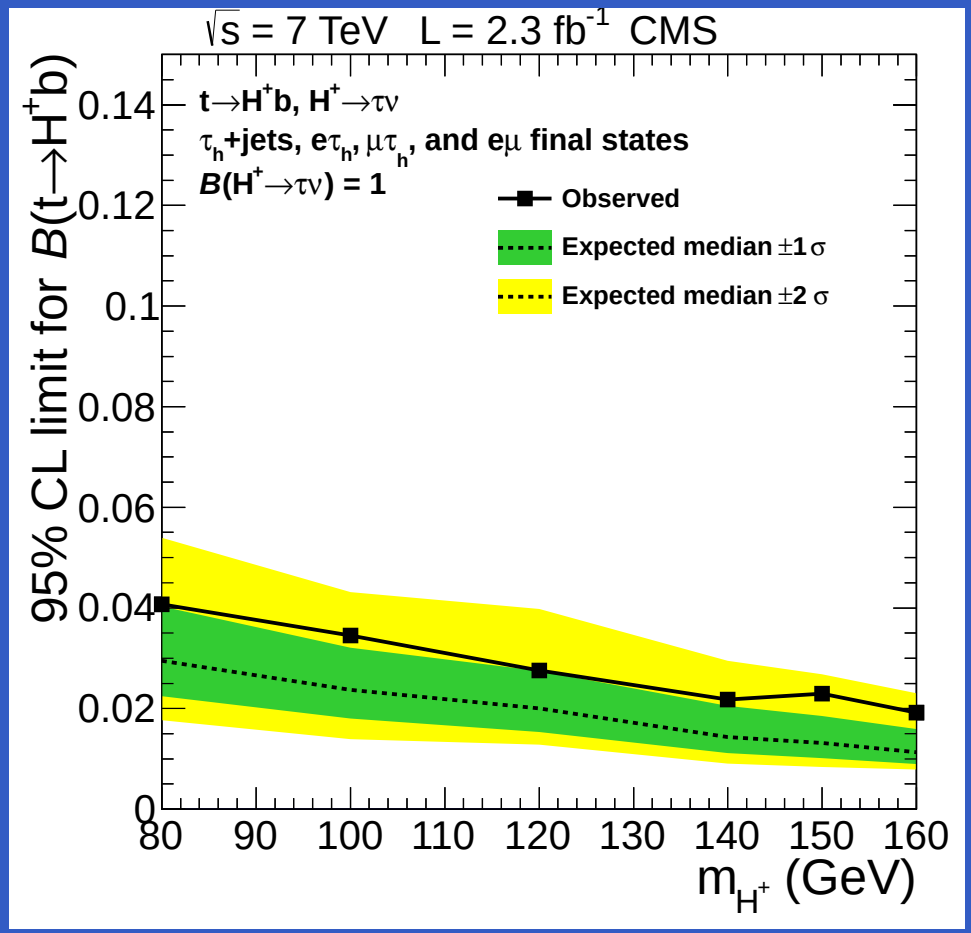




JHEP 1206 (2012) 039

CMS $H^+ \to \tau^+\nu$ ($\int \mathcal{L}dt$ =2.3 fb^{-1})

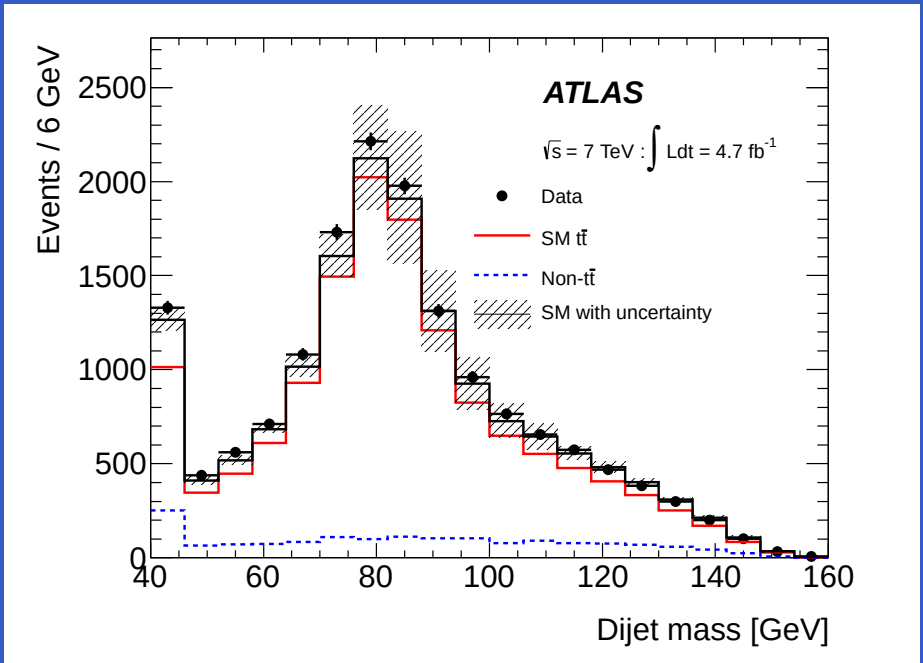


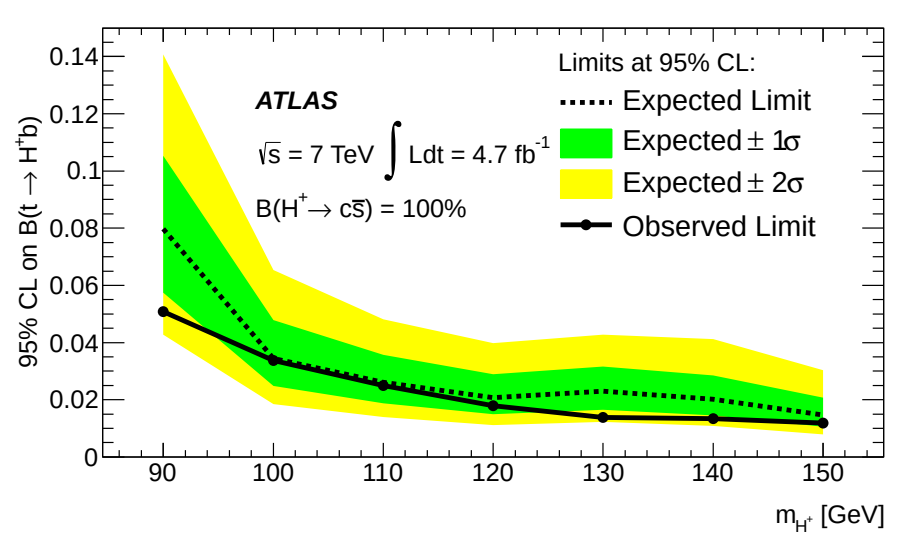


CMS-HIG-11-019

At left, the transverse mass of τ, jet and E_T^{miss} after full event selection for the τ+jets analysis. At right, the upper limit on $B(t \to H^+b)$ as a function of m_{H^+} obtained from the combination of the all final states.

ATLAS $H^+ \to c\bar{s}$ ($\int \mathcal{L}dt$ =4.7 fb^{-1})

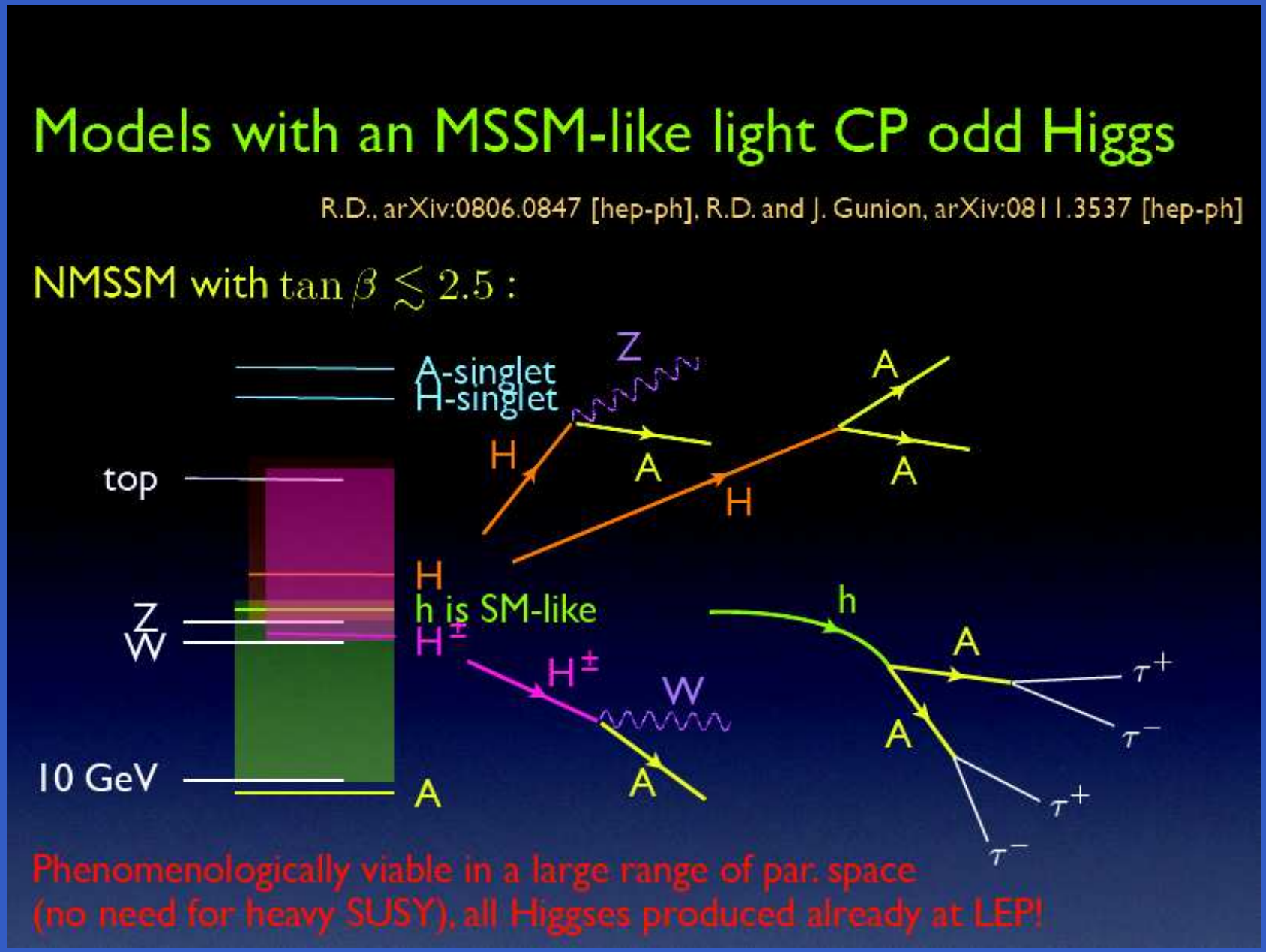




CERN-PH-EP-2012-338

- Above, the dijet mass distribution from data and the expectation from the SM (Br=0). The error bars represent the statistical uncertainty on the data. The uncertainty shown on the background estimate is the combination in quadrature of the $\pm 1\sigma$ systematic uncertainties, accounting for the constraint from the profile likelihood fit.
- Below, the extracted 95% C.L. upper limits on $\mathcal{B}(t \to H^+ b)$ are shown in the range of the charged scalar mass from 90 to 150 GeV. The limits shown are calculated using the CLs limit-setting.

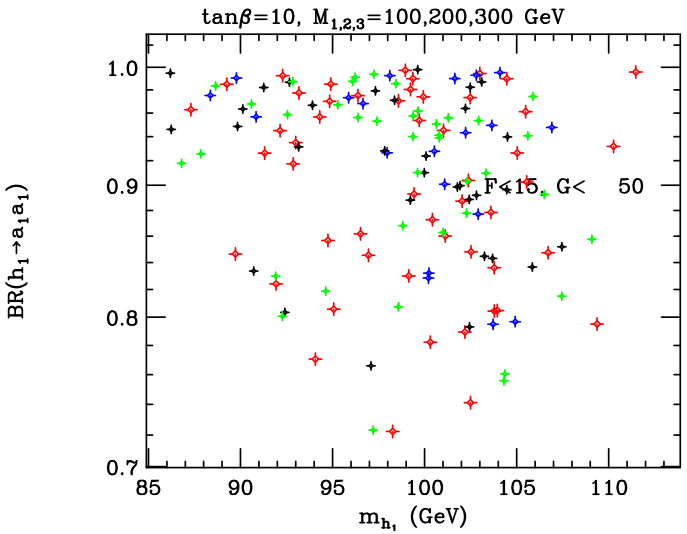
NMSSM Scalar Mass Spectrum and Decays

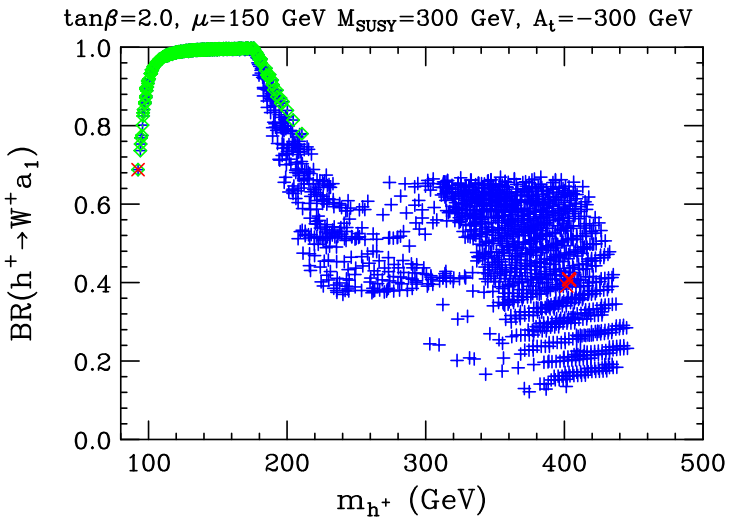


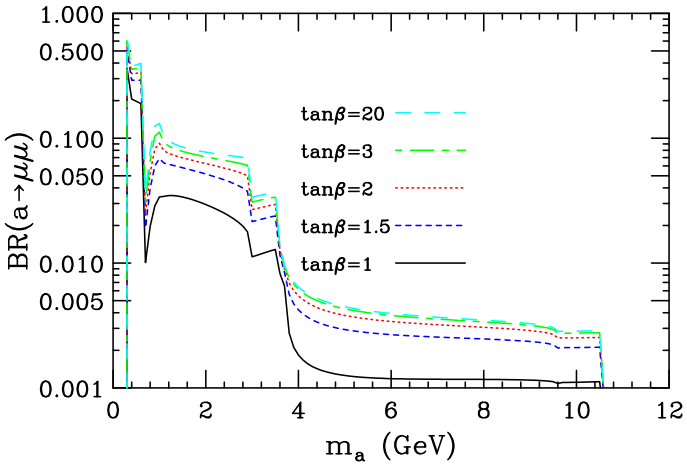
R. Dermisek talk at CERN Theory Group, 20 Aug. 2009.

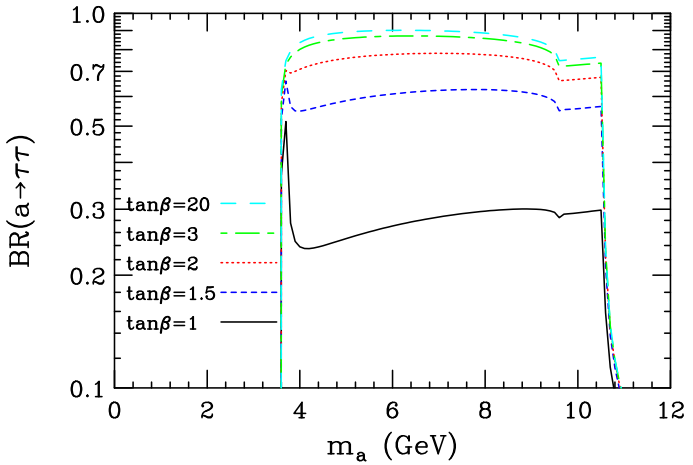
NMSSM Ideal Scenario: $m_{a_1} < 2m_B$

Phys.Rev.D79:055014,2009



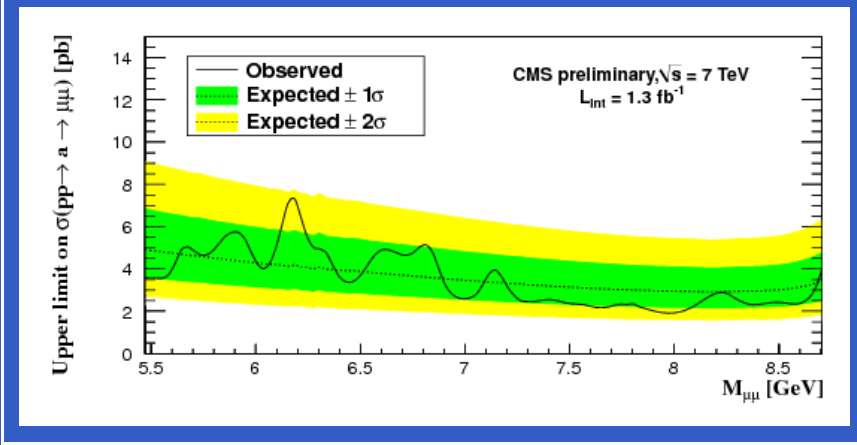


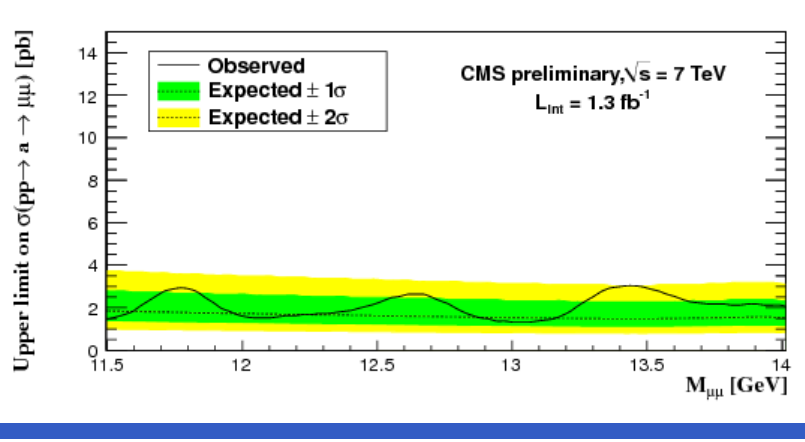


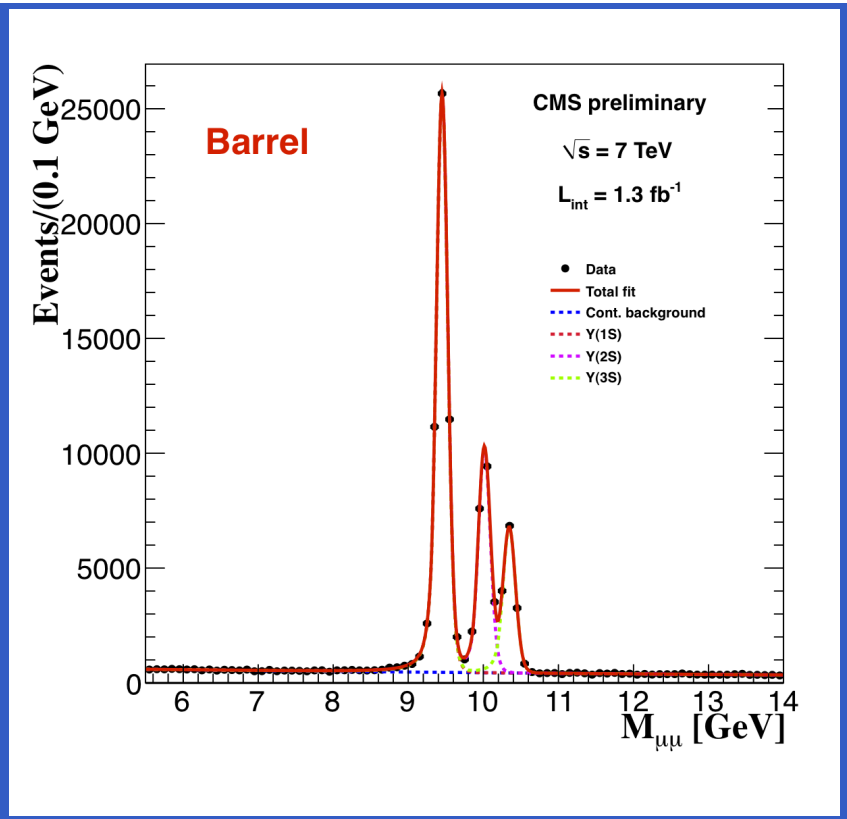


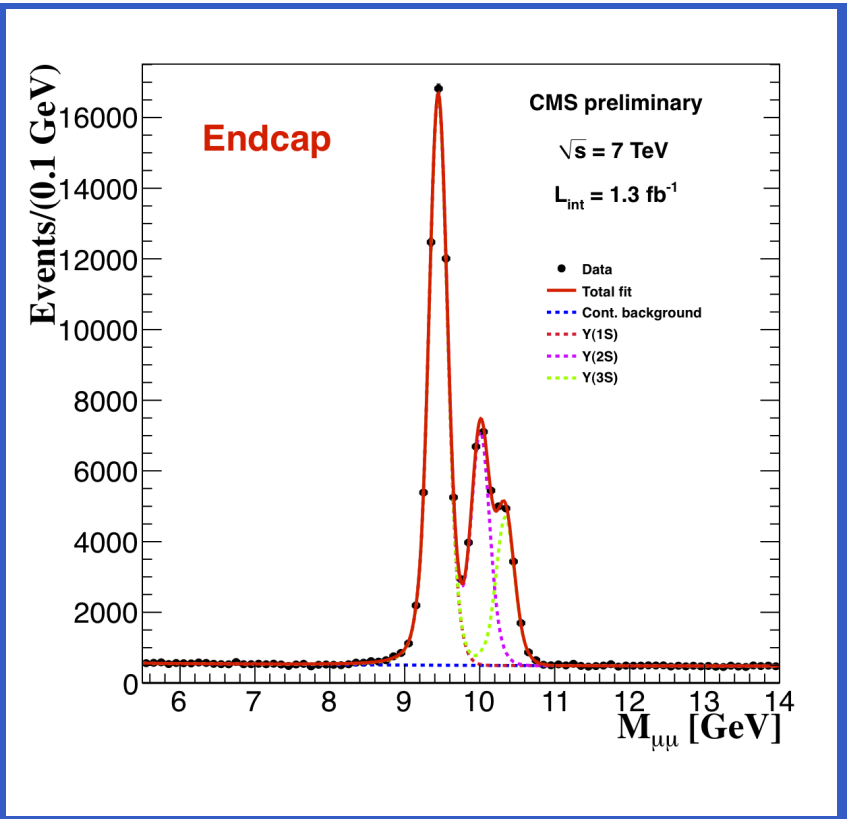
Phys.Rev.D81:075003,2010

CMS NMSSM $gg \to a_1 \to \mu^+\mu^-$ ($\int \mathcal{L}dt$ =1.3 fb^{-1})



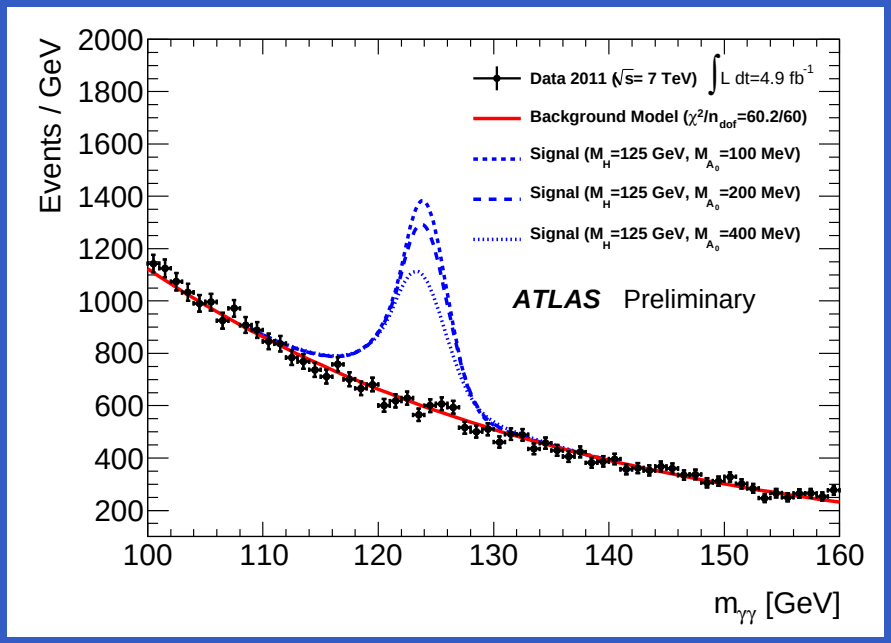


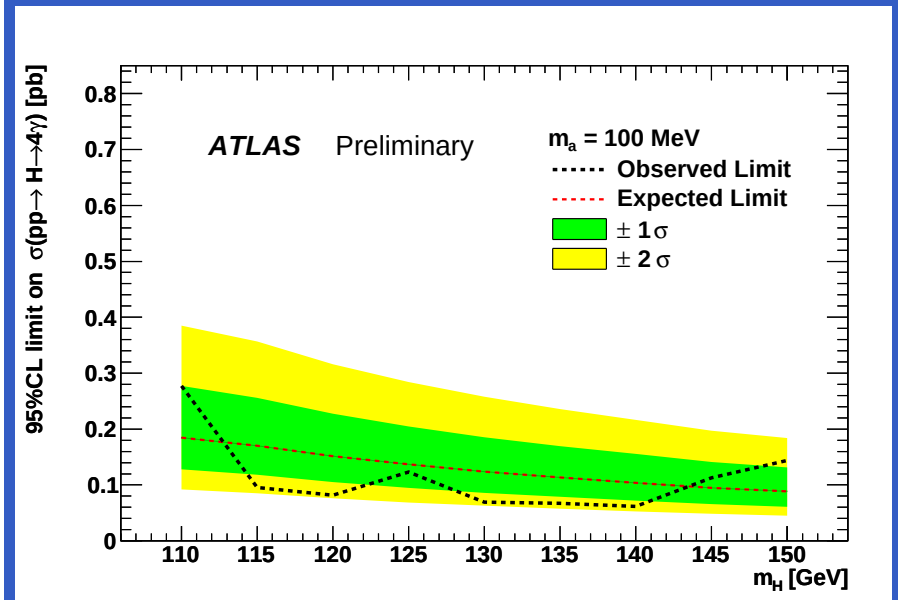


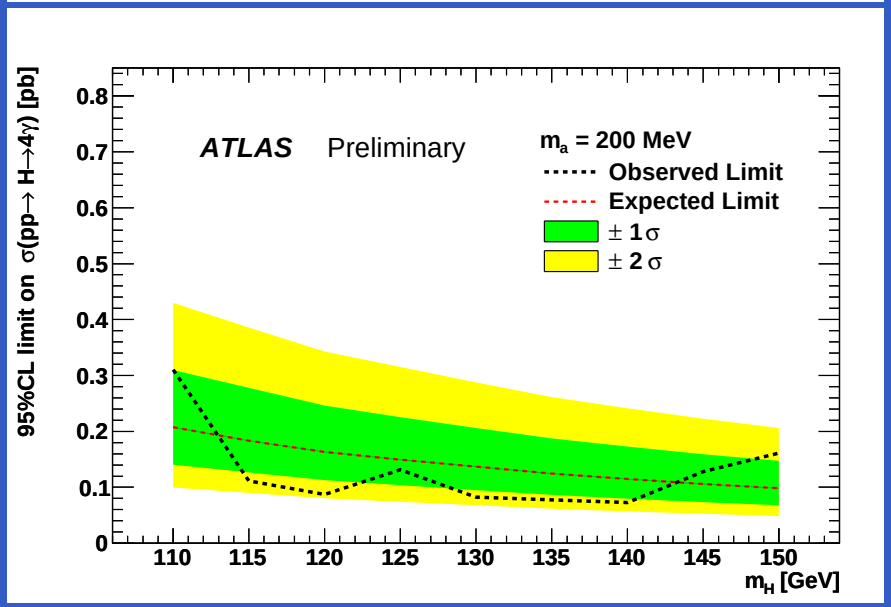


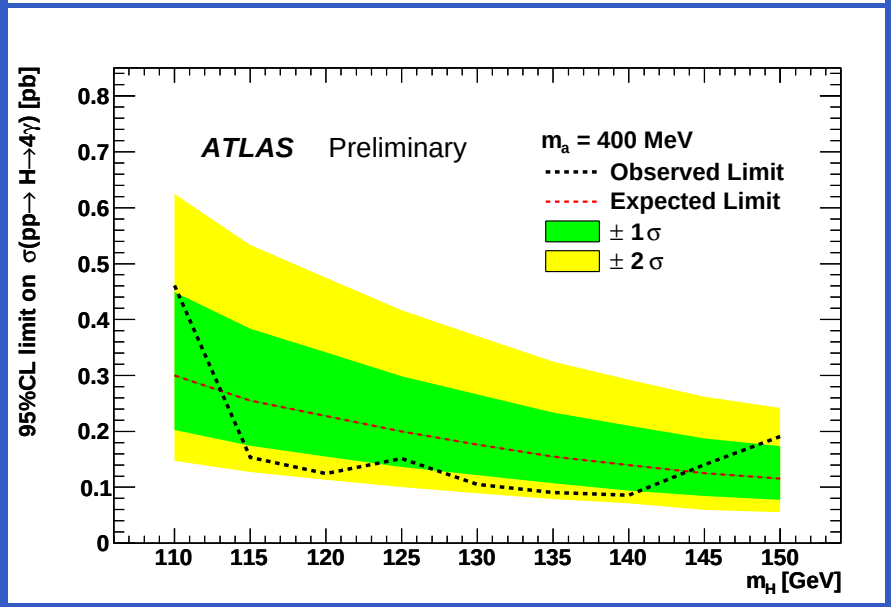
CMS-HIG-12-004

ATLAS NMSSM $h_1 \to 2a_1 \to 4\gamma$ ($\int \mathcal{L}dt$ =4.9 fb^{-1})



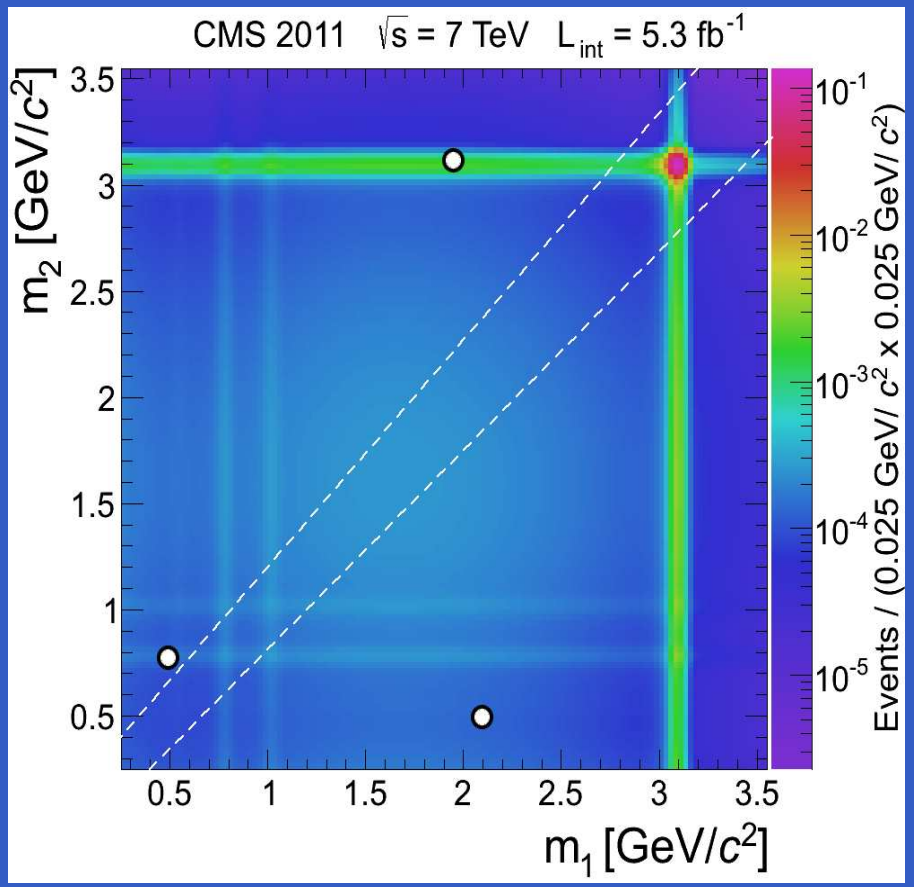


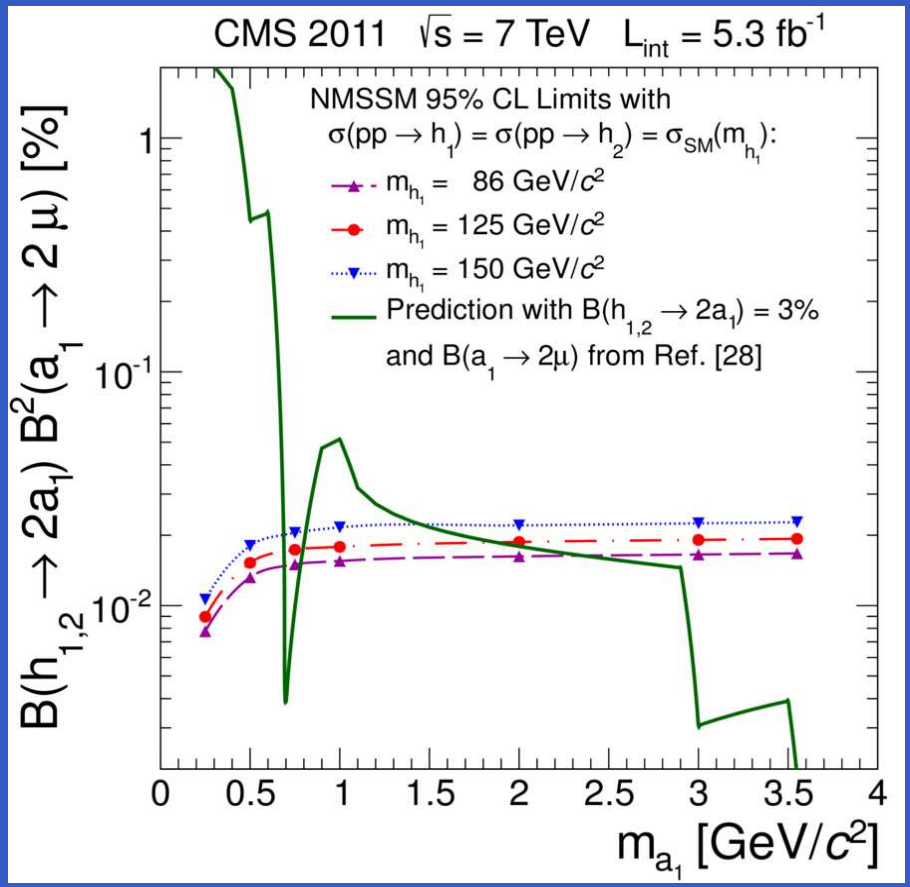




ATLAS-CONF-2012-079

CMS NMSSM $h_1 \to 2a_1 \to 4\mu$ ($\int \mathcal{L}dt$ =4.9 fb^{-1})

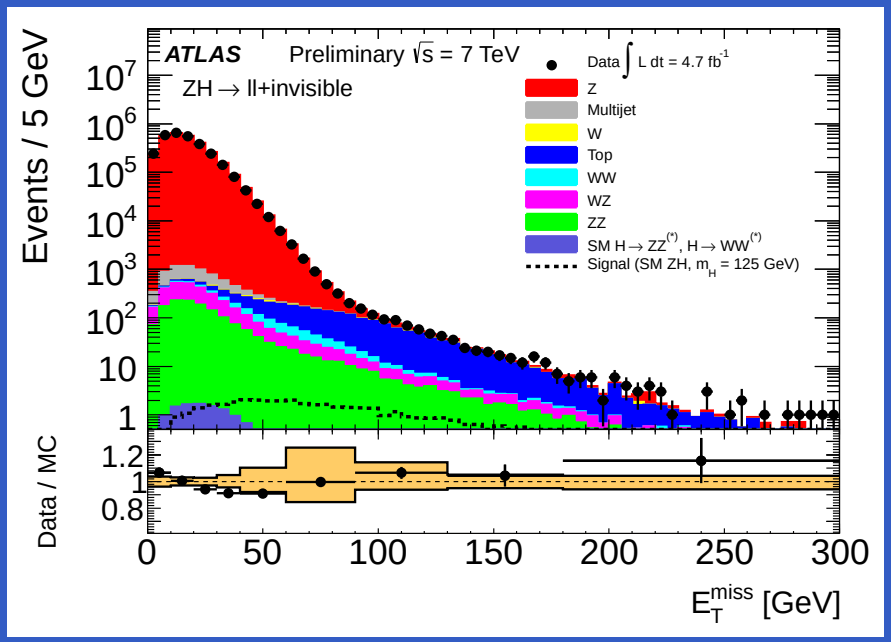


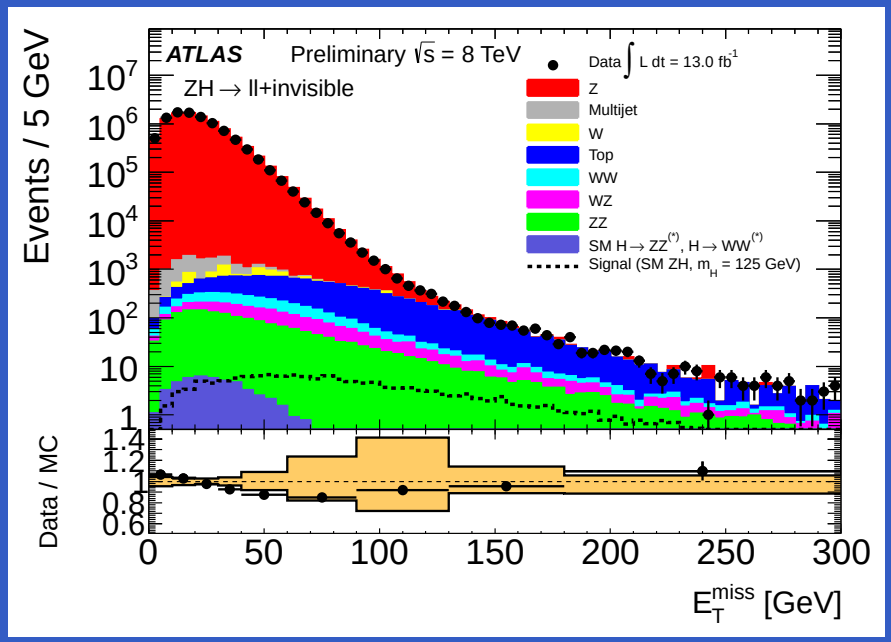


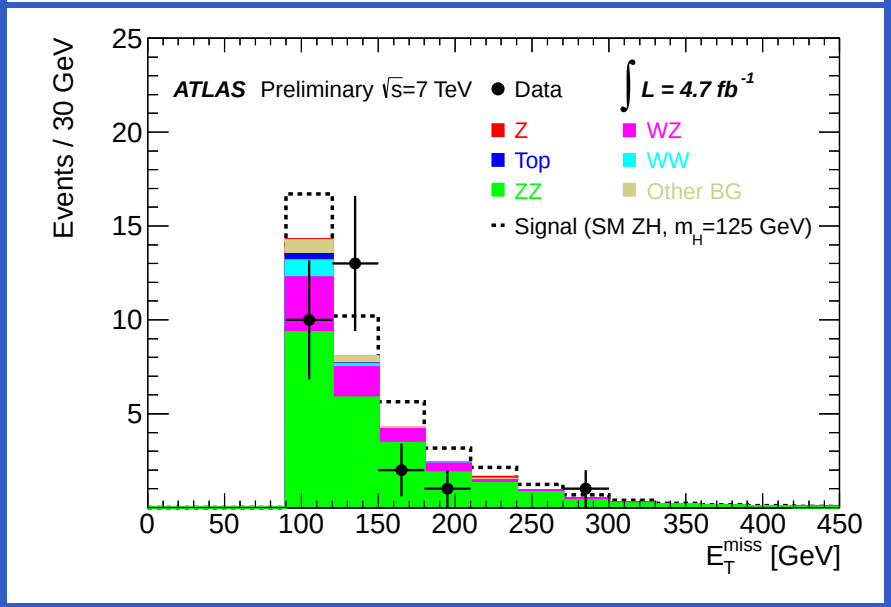
CMS-EXO-12-012

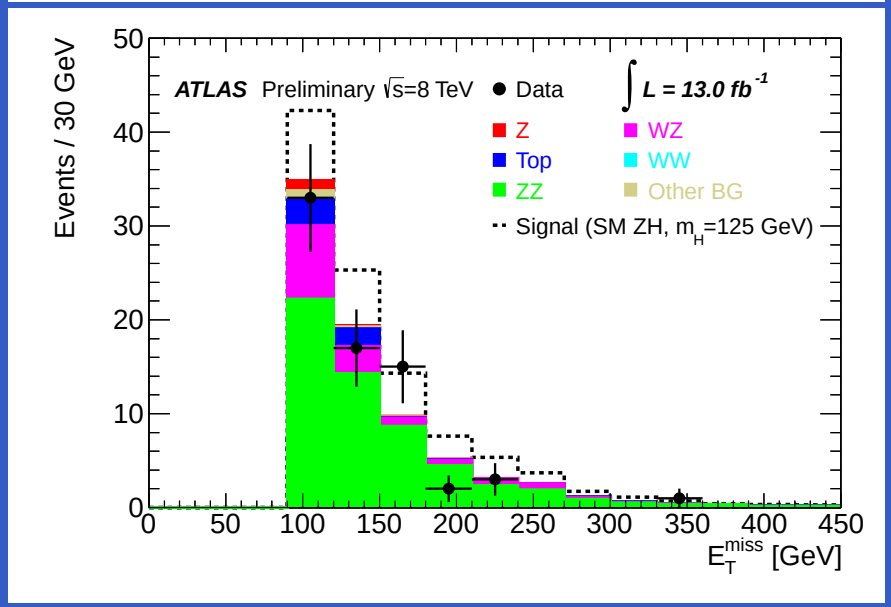
At left, the distribution of the invariant masses m_1 vs. m_2 for the isolated dimuon systems for the three events in the data (shown as empty circles) surviving all selections except the requirement that these two masses fall into the diagonal signal region (outlined with dashed lines). At right, 95% C.L. upper limits on the branching ratio for $h_1 \to 2a_1 \to 4\mu$ vs. m_{a_1} for masses $h_! = 86, 125$ and 150 GeV.

ATLAS $ZH \to \ell^+\ell^-\chi\chi$ ($\int \mathcal{L}dt$ =4.7+13.0 fb^{-1})





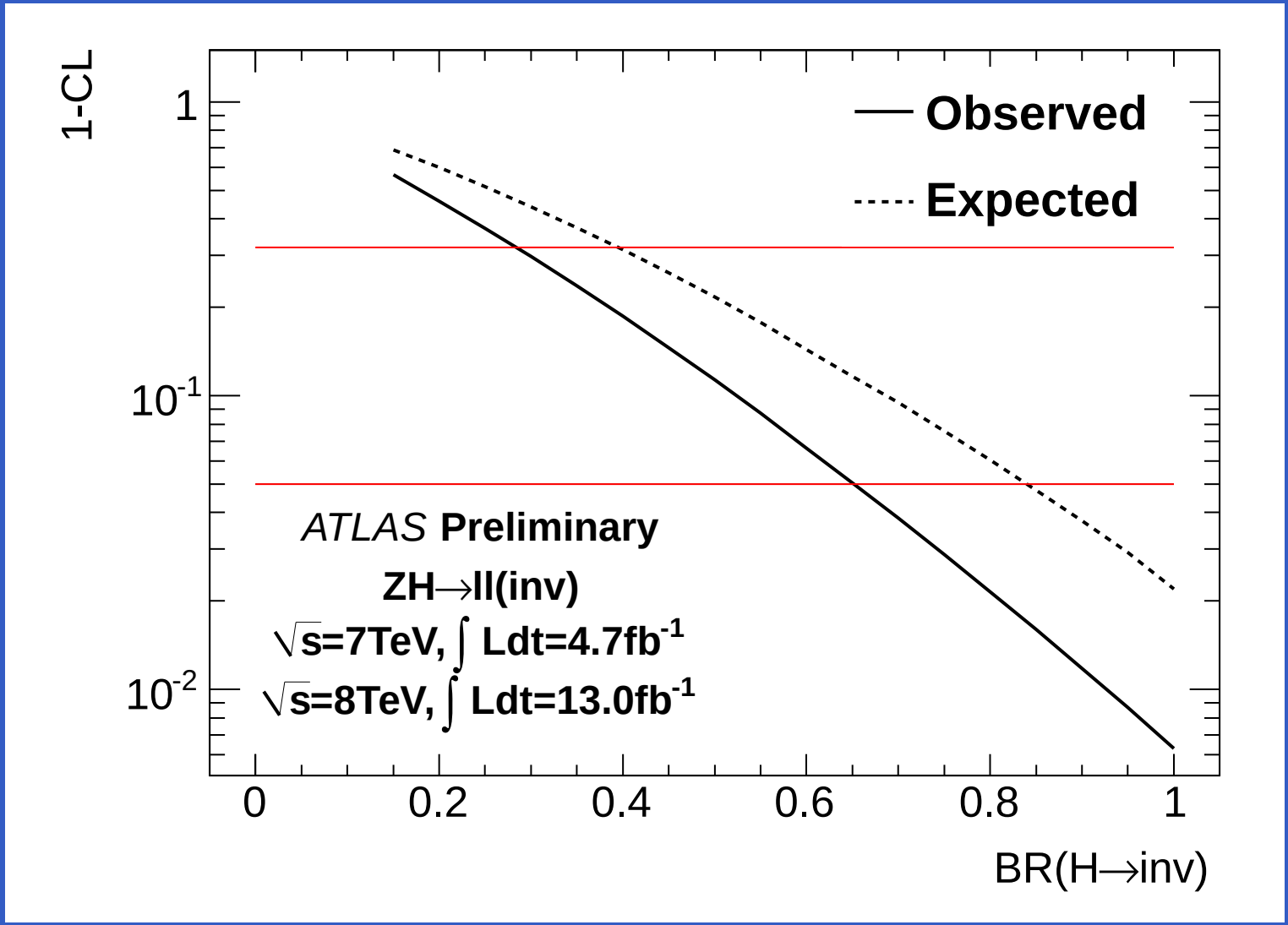




ATLAS-CONF-2013-011

ATLAS Limits on $H \to \chi\chi$ ($\int \mathcal{L}dt$ =4.7+13.0 fb^{-1})

ATLAS-CONF-2013-011



1 - Confidence level (CL) for the SM scalar with 125 GeV mass. The red solid lines indicate the 68% and 95% CL for (a). The expected 95% C.L. upper limit on $\mathcal{B}(H \to inv.)$ at 125 GeV is 84%, the observed limit is 65%.

Conclusions and Outlook

- Non-SUSY Extensions
  - CMS Singlet Extension: For $m_H > 600$ GeV, limits on $\sigma \times BR_{WW}$ are approaching theoretical predictions (19.3 fb^{-1}).
  - ATLAS 2HDM: For $m_H < 200$ GeV most points are excluded for Type I, space available in Type II depending on $\tan\beta$ and $\cos\alpha$ (13 fb^{-1}).
  - CMS Triplet Extension: For $m_\phi < 400$ GeV several benchmarks are excluded (4.6fb^{-1}).
- SUSY Extensions
  - ATLAS+CMS MSSM: $\phi \to \tau^+\tau^-$ excludes large regions in $\tan\beta - m_A$ plane (17.0 fb^{-1}).
  - ATLAS+CMS MSSM: $H^+ \to \tau^+\nu$ constrains $t \to bH^+$ below few % level (4.6 fb^{-1}).
  - ATLAS+CMS NMSSM: constraints are now in place on $\sigma \times BR$ for $gg \to a_1 \to \mu^+\mu^-$ and $gg \to h_1 \to 2a_1 \to 4\gamma$ (2.3,4.9 fb^{-1}).
- Outlook
  - Some searches underway have not been made public yet. These include:
    - ATLAS [+CMS?] Heavy $H^+ \to \tau\nu$
    - ATLAS [+CMS?] Heavy $H^+ \to t\bar{b}$
  - No searches described here have releases results on the entire dataset. Stay tuned!

Supplementary Slides

Scalar Sector of the MSSM

- The MSSM Scalar Sector
  - The MSSM scalar sector contains two complex doublets of scalar fields ϕ_u (coupling only to up-type fermions) and ϕ_d (coupling only to down-type fermions), with vacuum expectation values v_u and v_d related by $v^2 = v_d^2 + v_u^2$.
  - Three massless Goldstone bosons become the gauge bosons, and the remaining five components of the doublets ϕ_u and ϕ_d become the $h, H, A, H^\pm$.
- MSSM Scalar Couplings (not exhaustive)

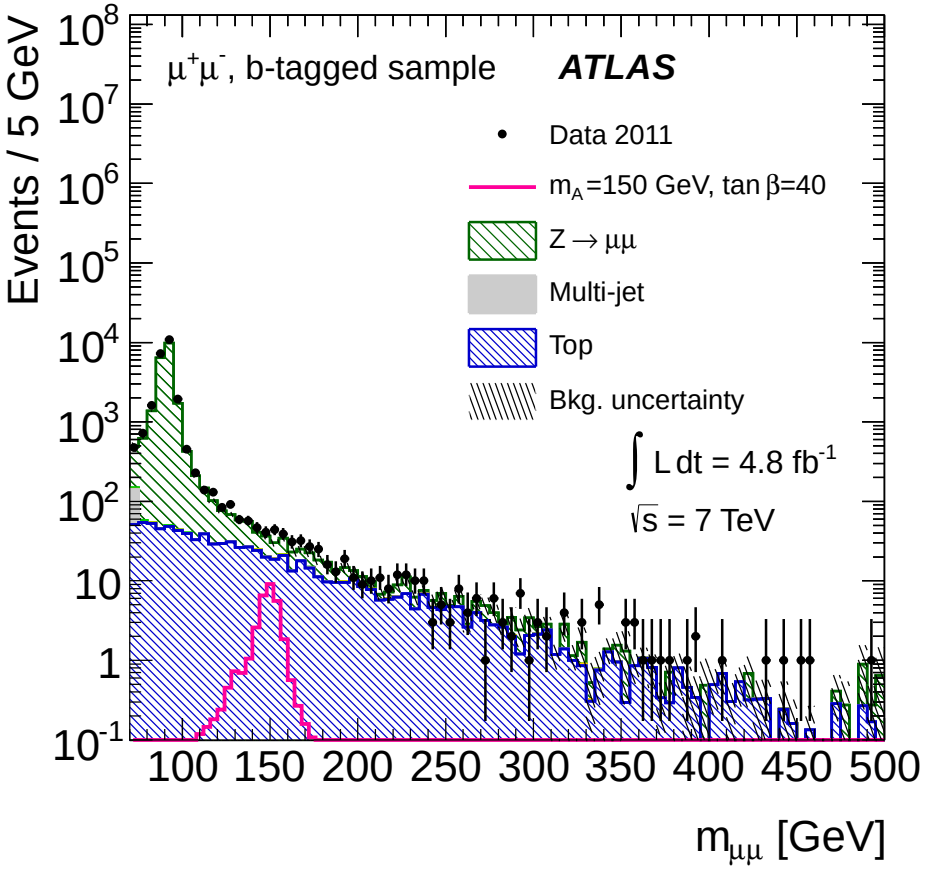
$$\begin{aligned} g_{Abb,A\tau\tau} &= m_{b,\tau} \tan\beta \Gamma_5 / v \\ g_{H^+tb,H^+\tau\nu} &= \sqrt{2} \left[m_{t,\nu} \cot\beta P_R + m_{b,\tau} \tan\beta P_L \right] / v \end{aligned}$$

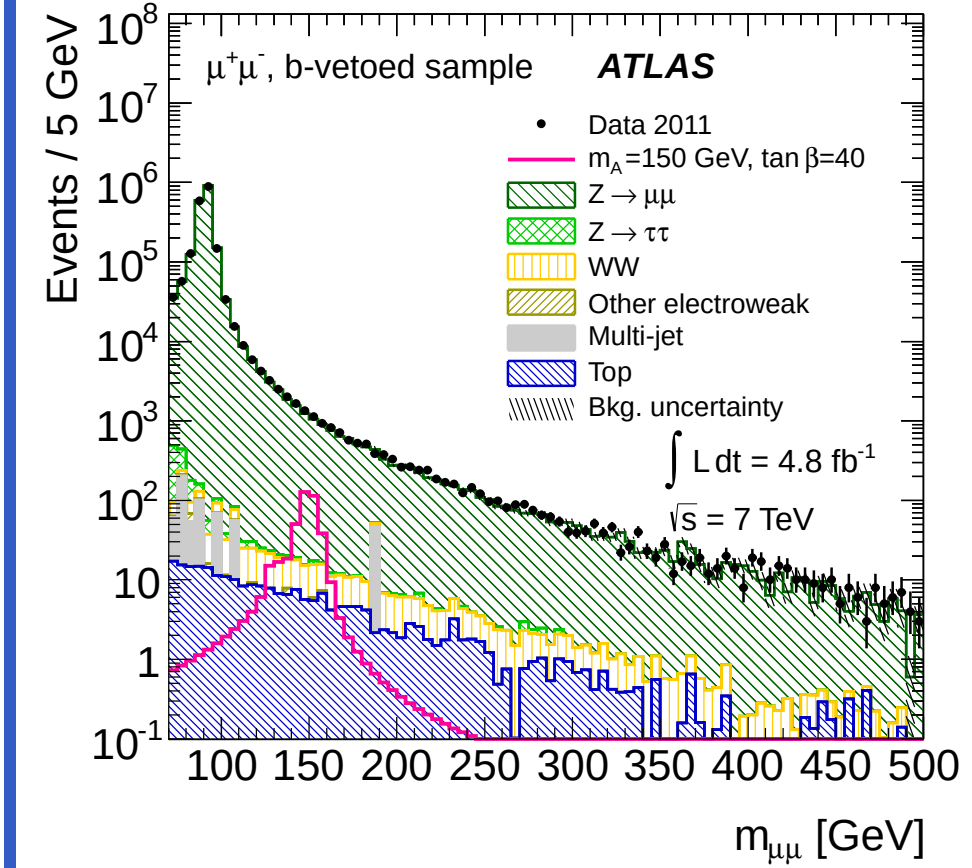
- MSSM Scalar Mass Spectrum at Tree Level

$$\begin{aligned} m^2_{H^\pm} &= m^2_A + m^2_W \\ m^2_{H,h} &= \frac{1}{2} m^2_A + m^2_Z \pm \sqrt{(m^2_A + m^2_Z)^2 - 4 m^2_z m^2_A \cos^2 2\beta} \end{aligned}$$

- In the *decoupling limit* $m_A \gg m_Z$, $A, H, H^\pm$ become mass degenerate and the couplings of the h are the same as the SM H.

ATLAS $h/H/A \to \mu^+\mu^-$ ($\int \mathcal{L}dt$ =4.8 fb^{-1})

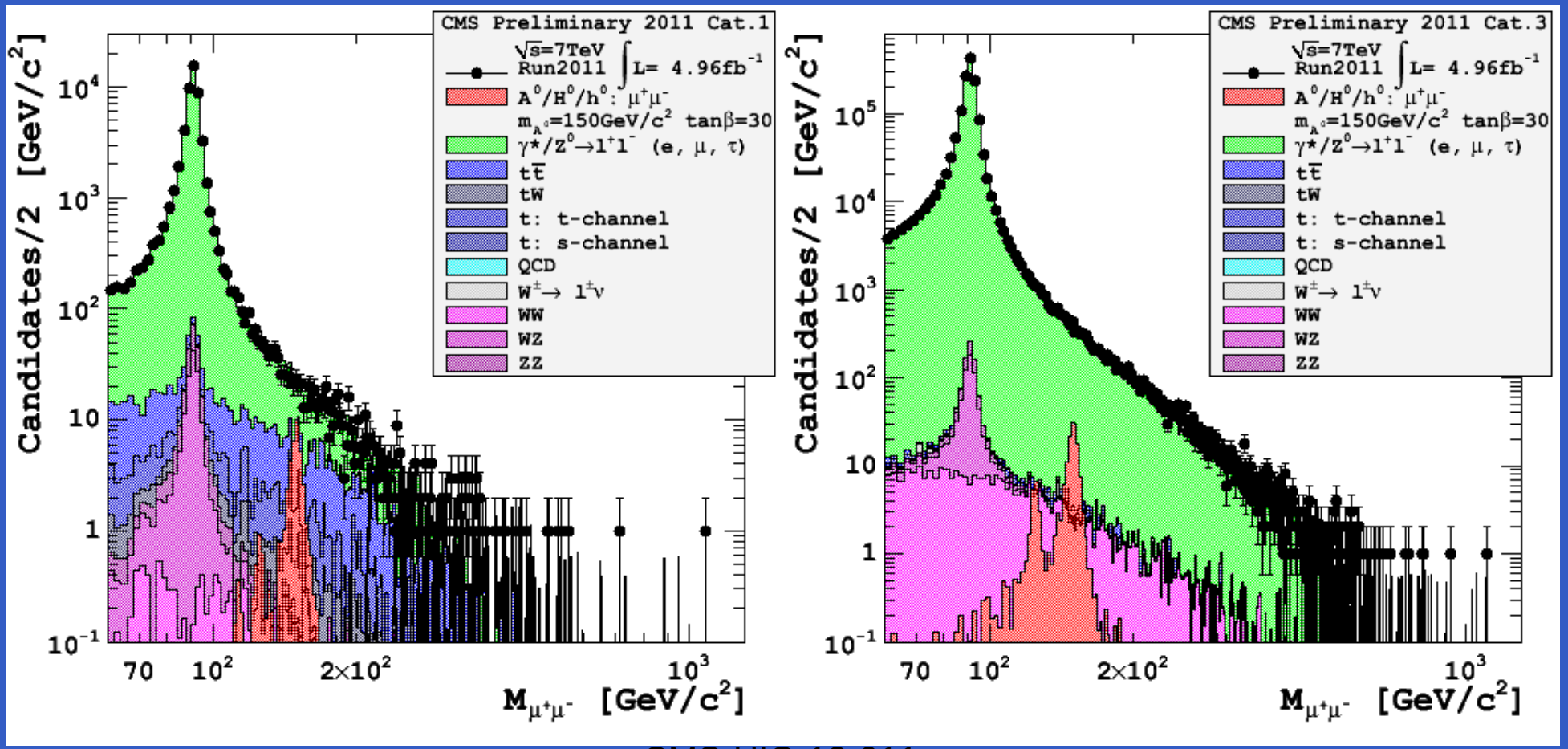




JHEP02(2013)095

Final mass distributions for the mumu final state. The invariant mass distribution of the two muons is shown for the b-tagged (left-hand side) and the b-vetoed selection (right-hand side). The data are compared to the background expectation and an added hypothetical MSSM signal ($m_A = 150$ GeV, $tan\beta = 40$). Simulated backgrounds are shown for illustration purposes, background is estimated from data sidebands. The background uncertainties include the statistical uncertainties only.

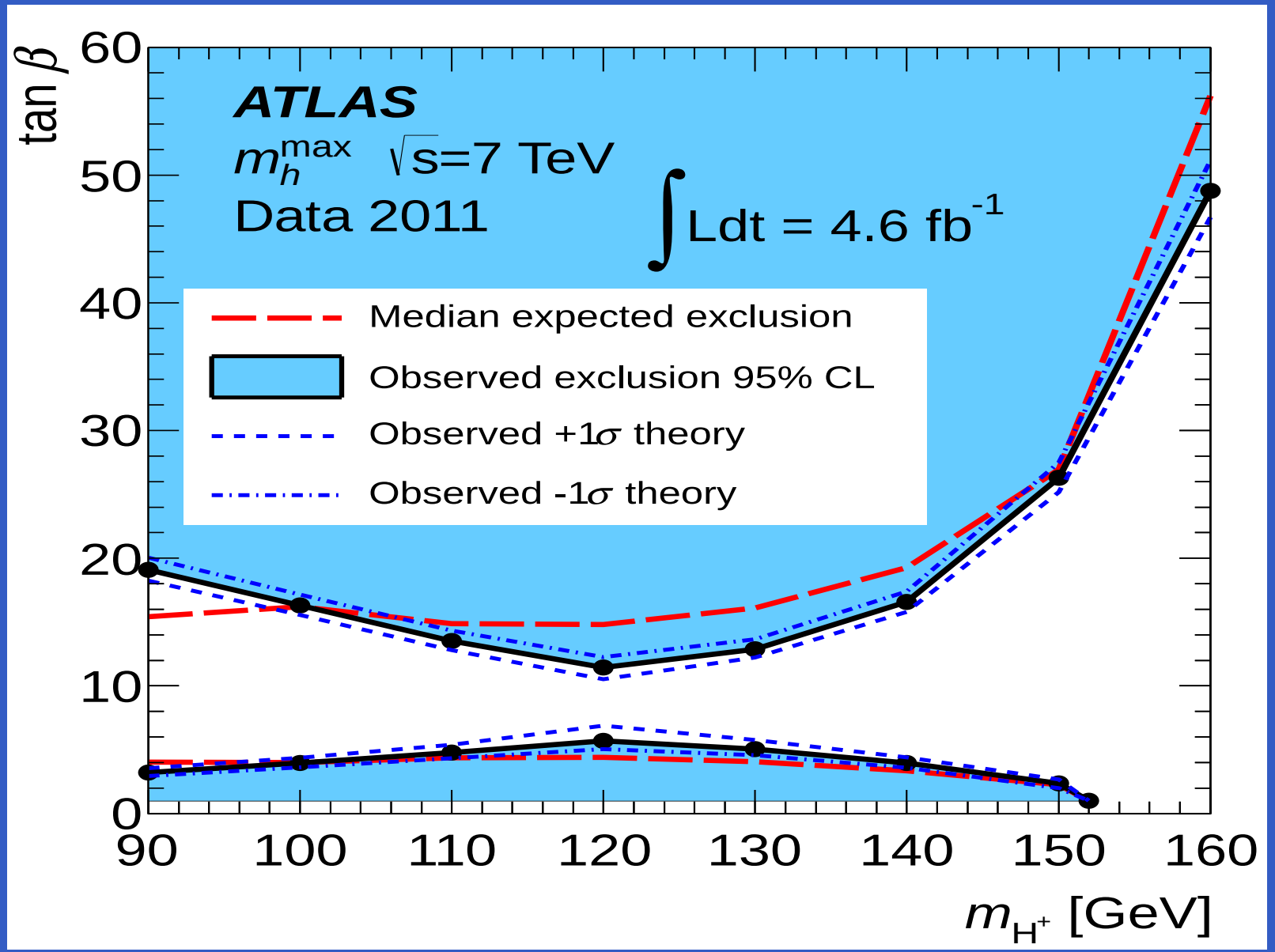
CMS $h/H/A \to \mu^+\mu^-$ ($\int \mathcal{L}dt$ =5 fb^{-1})



CMS-HIG-12-011

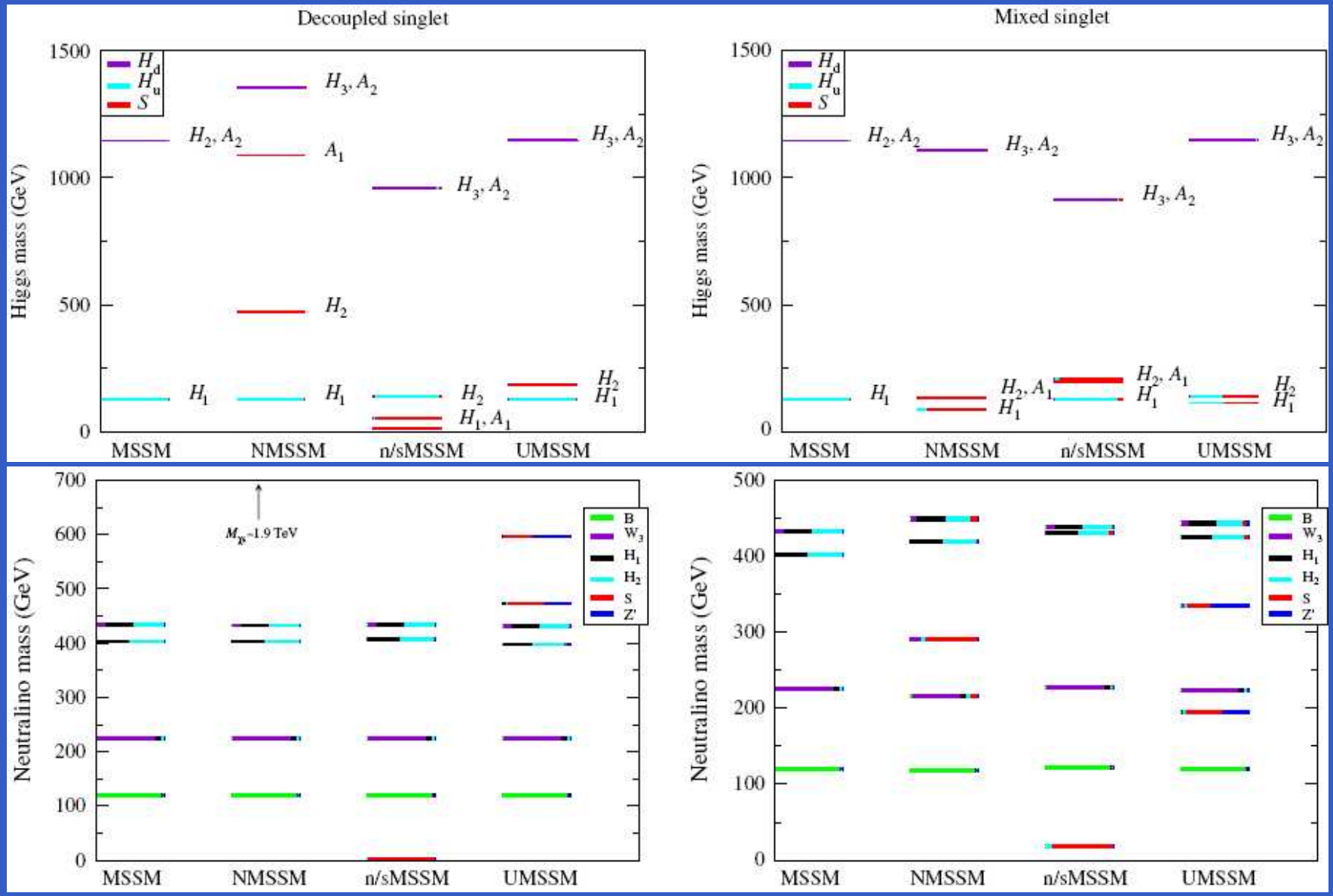
The first category (left) is focused on the enhanced b-associated production by looking for a tagged b-jet. The second category tries to recover events were the b-tagging fails and looks for an additional muon in the event from a b decay. The third category (right) recovers all events not falling in the first two categories, focusing on the gluon-gluon fusion component of the MSSM

ATLAS MSSM Limits on $\tan\beta$ from $H^+ \to \tau^+\nu$



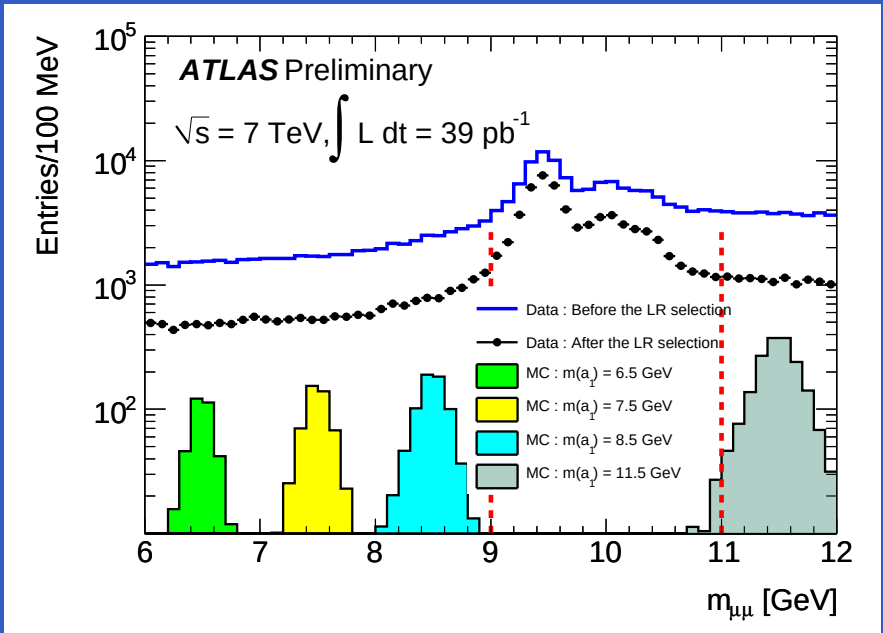
JHEP 1206 (2012) 039

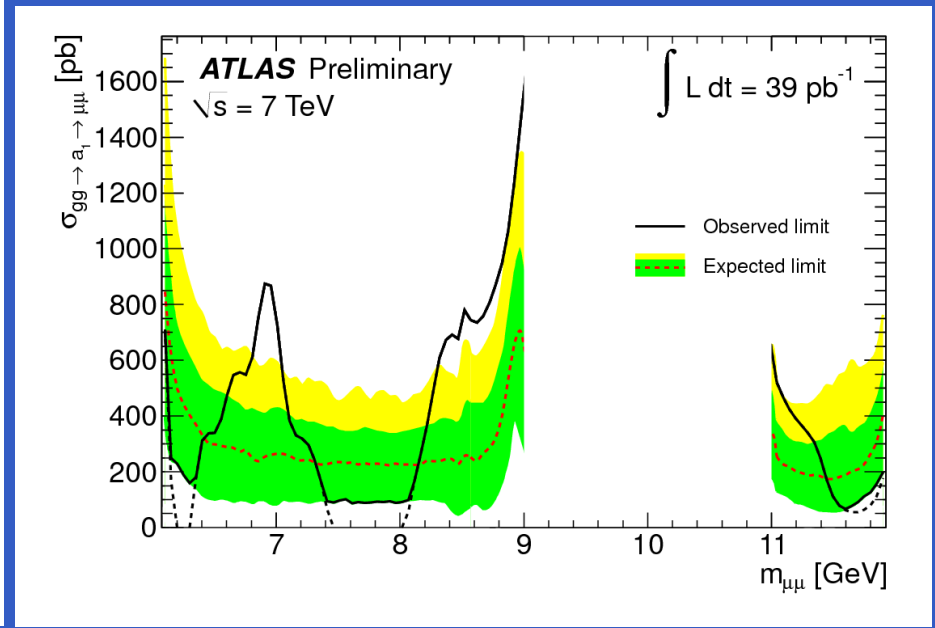
NMSSM Scalar (and χ^0) Mass Spectrum



New J. Phys. 9 (2007) 333

ATLAS NMSSM $gg \rightarrow a_1 \rightarrow \mu^+\mu^-$ ($\int \mathcal{L}dt$ =39 pb^{-1})





ATLAS-CONF-2011-020

- At left, the $m_{\mu^+\mu^-}$ spectrum after the dimuon selection (open histogram), and after the Likelihood Ratio selection (points). Also shown are the predicted $a_1 \rightarrow \mu^+\mu^-$ spectra (with arbitrary normalization) for various a1 masses.
- At right, upper limits on $\sigma(gg \rightarrow a_1) \times \mathcal{B}(a_1 \rightarrow \mu^+\mu^-)$ at 95% confidence level. The black solid line is the observed upper limit, presented as a 16% power constrained limit using asymptotic formulas, while the dashed red line corresponds to the expected limit, assuming absence of a signal. The green/yellow areas represent the $\pm 1 \times \sigma, \pm 2\sigma$ uncertainties on the expected limit.