ATLAS Searches for BSM Higgs

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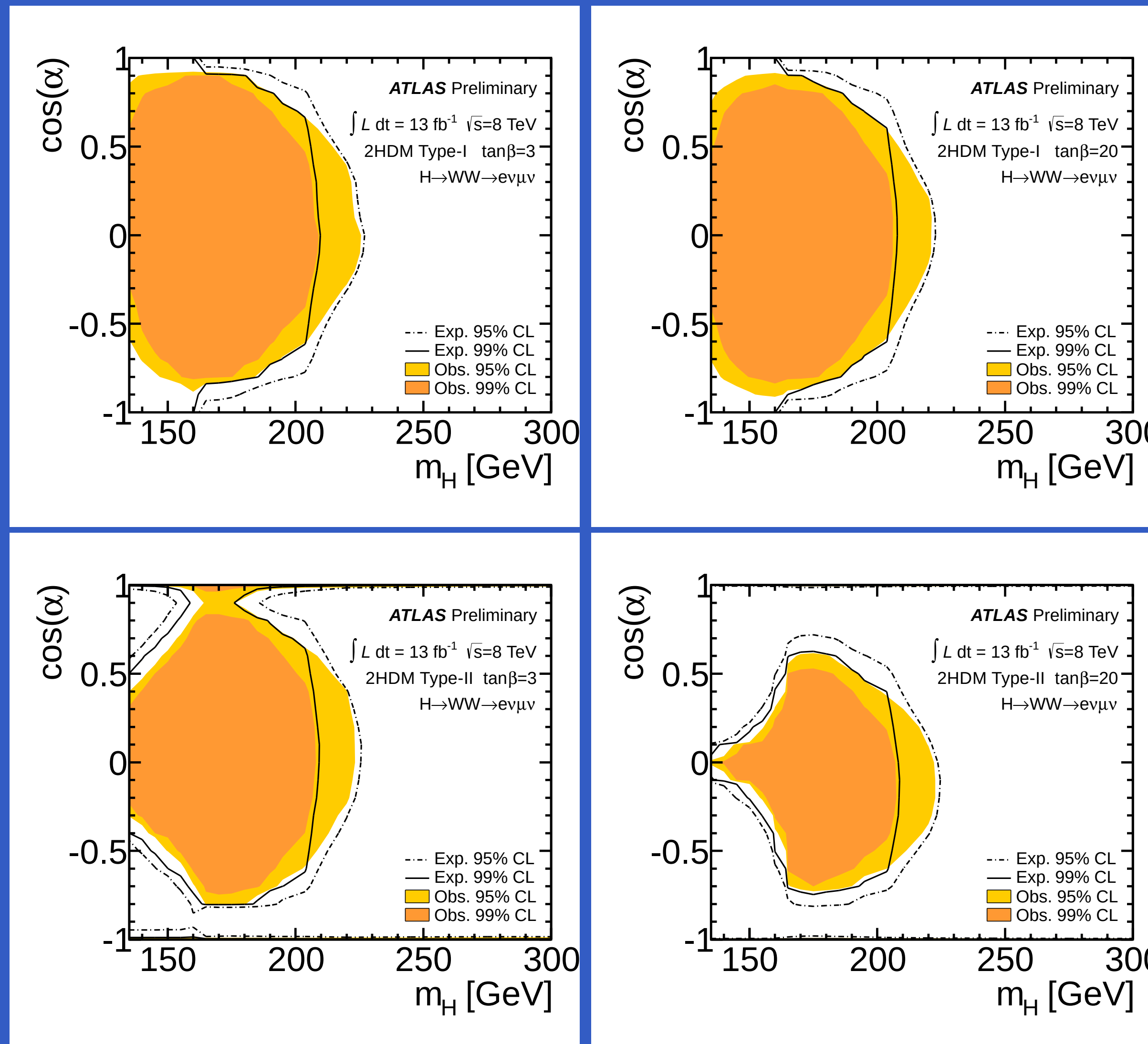
Higgs Sector Extensions: Beyond One Doublet

BSM Experimental Motivation: We know the SM cannot be complete. It does not explain gravity, dark matter, dark energy, the baryon asymmetry, or muon g-2. The SM Higgs mass blows up!

- Two Doublets (2HDM)
  - In a Type I 2HDM, only one of these doublets couples to fermions. The other doublet does not couple to fermions.
  - 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.
  - In Types III and IV 2HDM couplings to leptons differ.

  MSSM (SUSY) Theoretical Motivation: solve the hierarchy problem, gauge couplings unify at GUT scale. Not all parameter space is ruled out!
- Two Doublets and a Singlet
  Another typical SUSY scalar benchmark, the NMSSM, employs a 2HDM Type II and an additional singlet.
  NMSSM Theoretical Motivation: solve the μ-term problem of the MSSM. Phenomenology can be radically different from MSSM!
- Doublet and Singlet, Doublet and Triplet have been investigated by CMS.
- Exotic Higgs decays in invisible/undetected/not-looked-for decays.

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

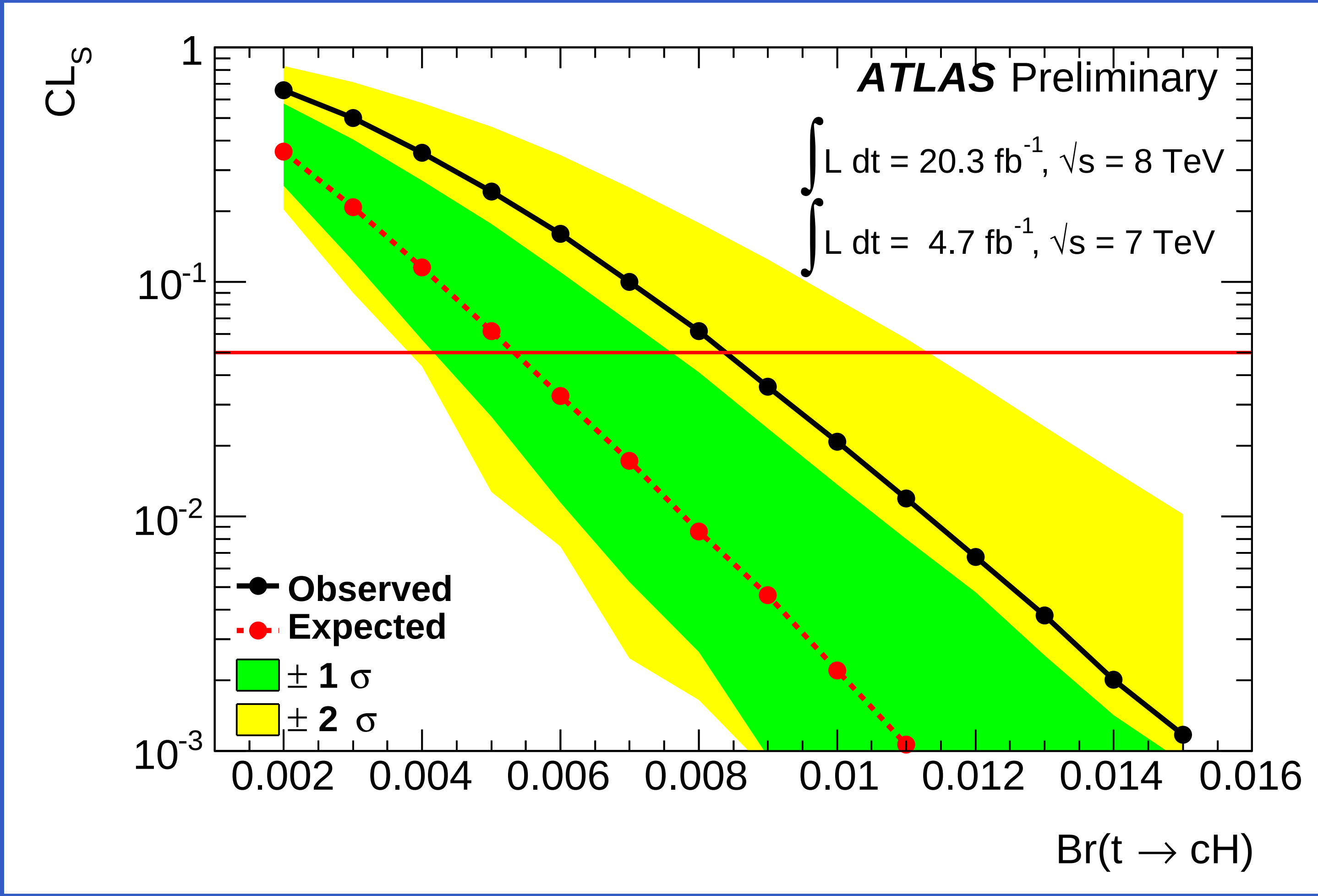


ATLAS-CONF-2013-027

At tree level, the only free parameters in a generic 2HDM are a Higgs mass (m_H), the ratio of doublet VEVS ($\tan\beta$) and an angle to diagonalize the mass matrix ($\cos\alpha$).

ATLAS Limits on (FCNC) $t \to cH \to c\gamma\gamma$

ATLAS-CONF-2013-081



Process	SM	QS	2HDM-III	FC-2HDM	MSSM
$t \to cH$	3×10^{-15}	4.1×10^{-5}	1.5×10^{-3}	10^{-5}	10^{-5}

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).

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)

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

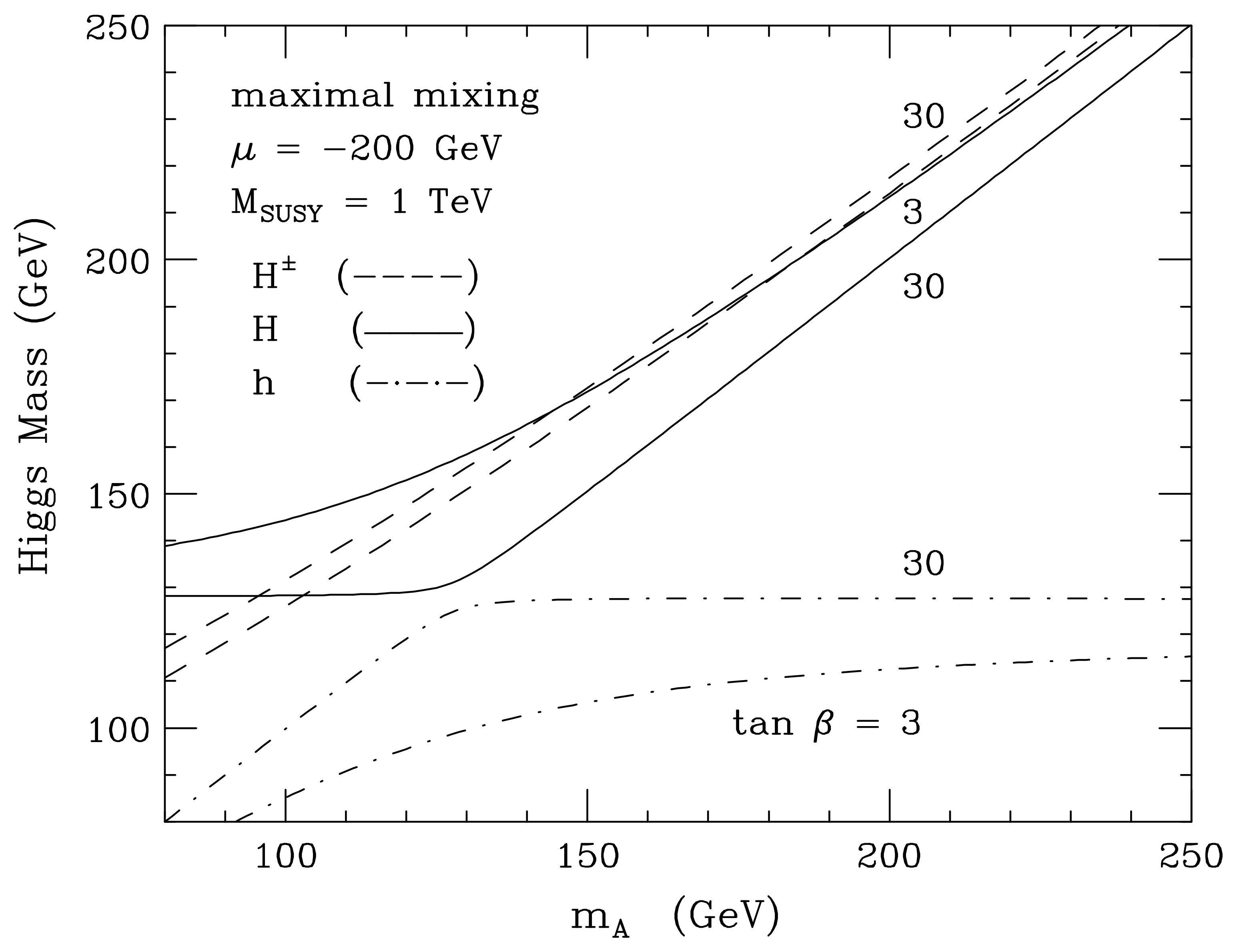
- MSSM Scalar Mass Spectrum at Tree Level

$$
\begin{aligned}
m_{H^\pm}^2 &= m_A^2 + m_W^2 \\
m_{H,h}^2 &= \frac{1}{2} m_A^2 + m_Z^2 \pm \sqrt{(m_A^2 + m_Z^2)^2 - 4 m_z^2 m_A^2 \cos^2 2\beta}
\end{aligned}
$$

- 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.

MSSM Scalar Mass Spectrum

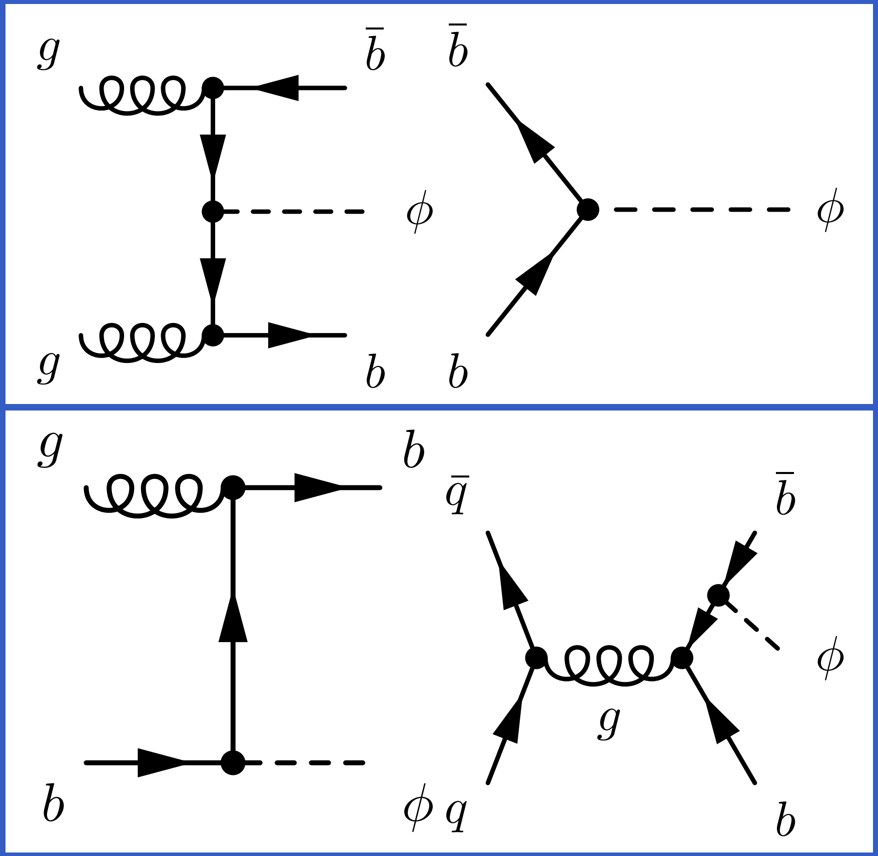
The MSSM h mass is bounded above by $m_h < 135$ GeV



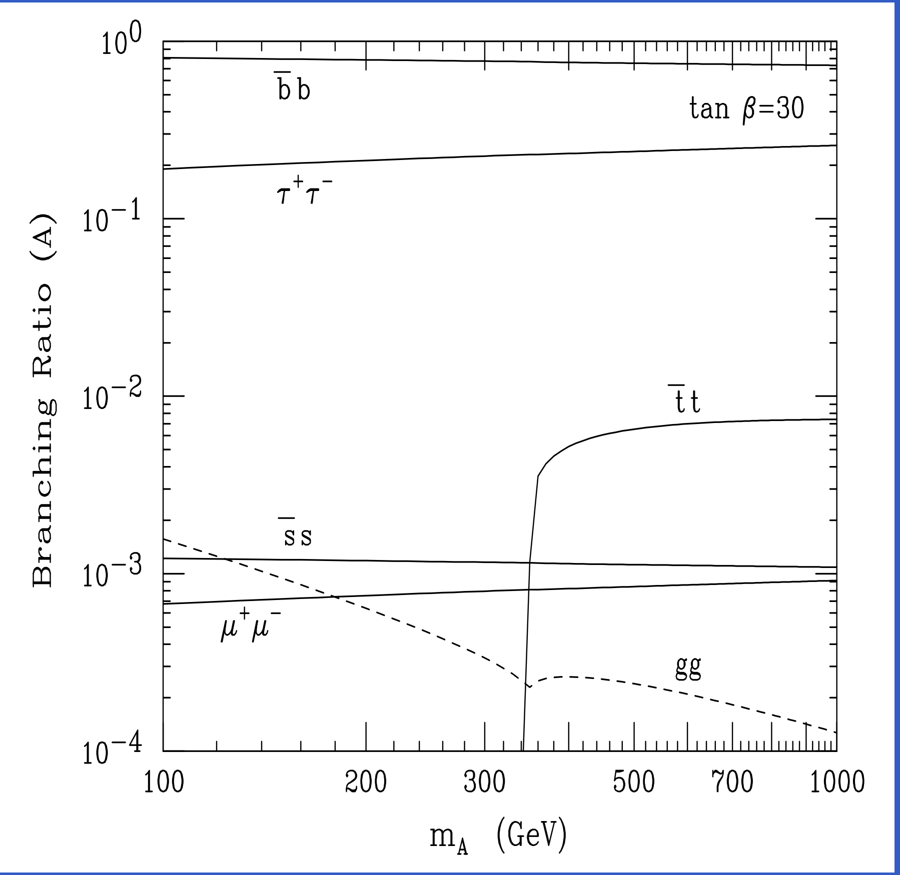
Prog.Part.Nucl.Phys.50:63-152,2003

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

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



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

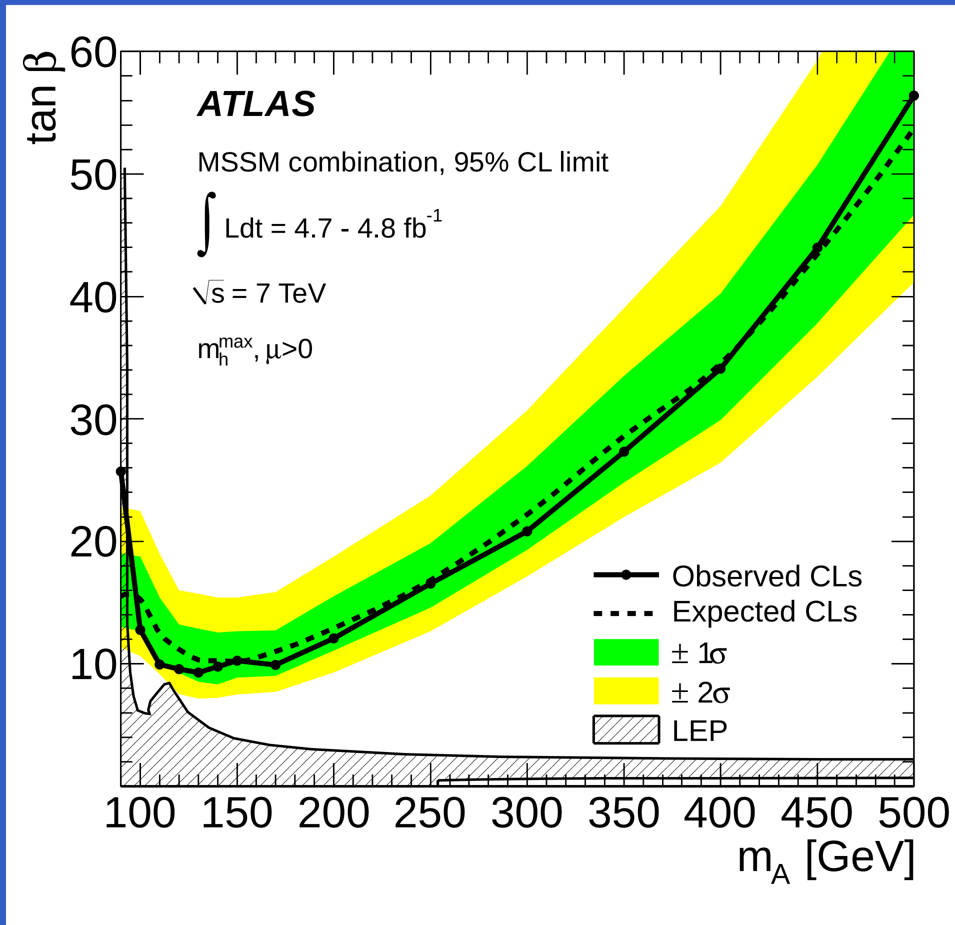


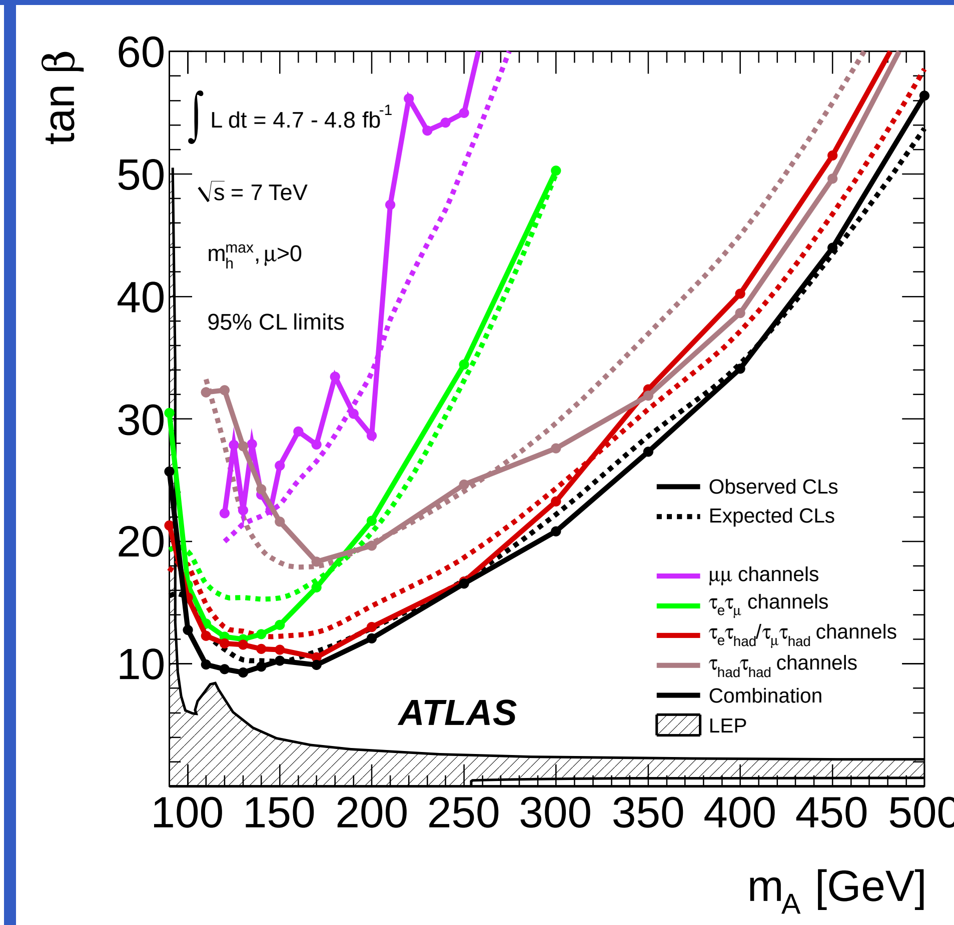
If $\tan\beta$ is large ($> \mathcal{O}(10)$), the coupling of down-type fermions is enhanced and to up-type fermions is suppressed. In the MSSM the coupling is $g_{\phi bb}^{MSSM} = \tan\beta \times m_b/v$. So

- 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.

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

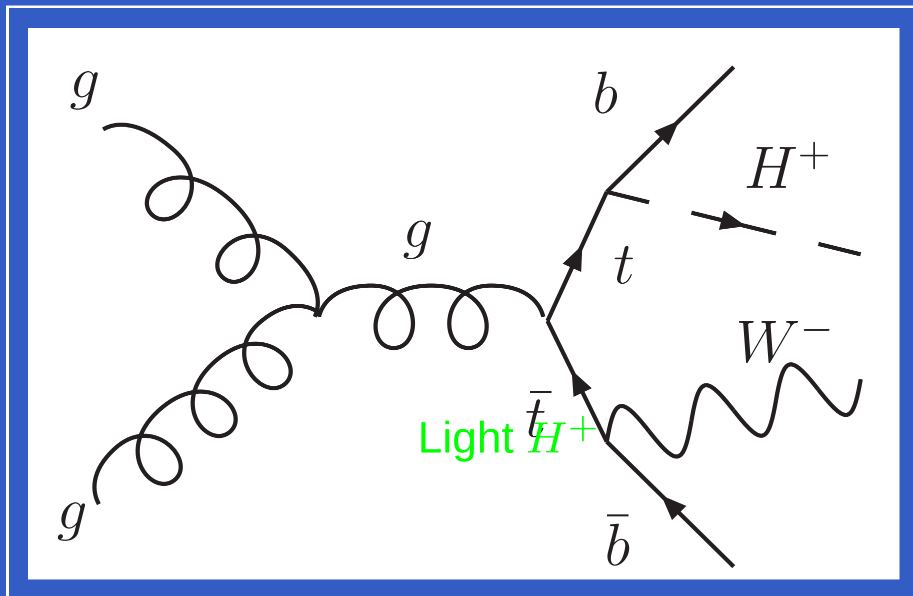


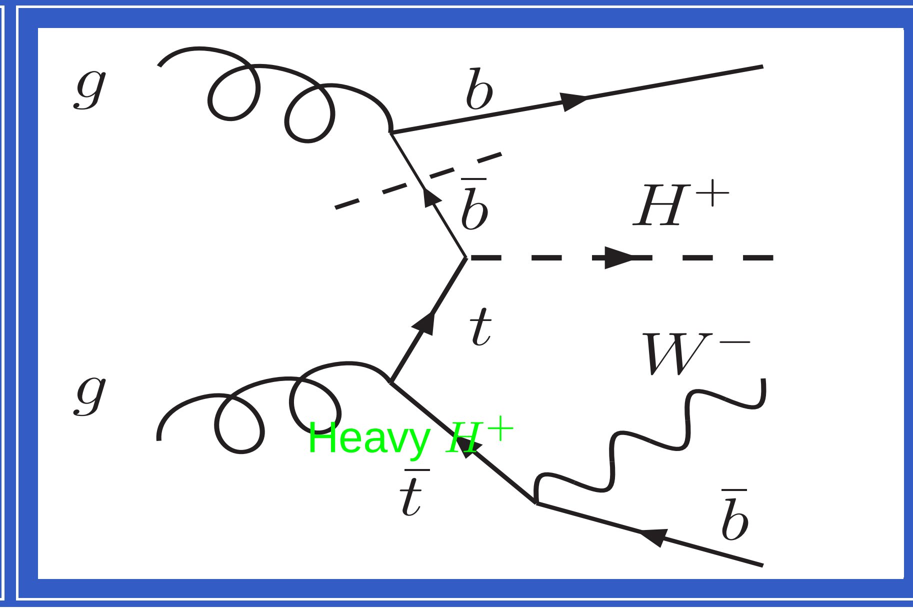


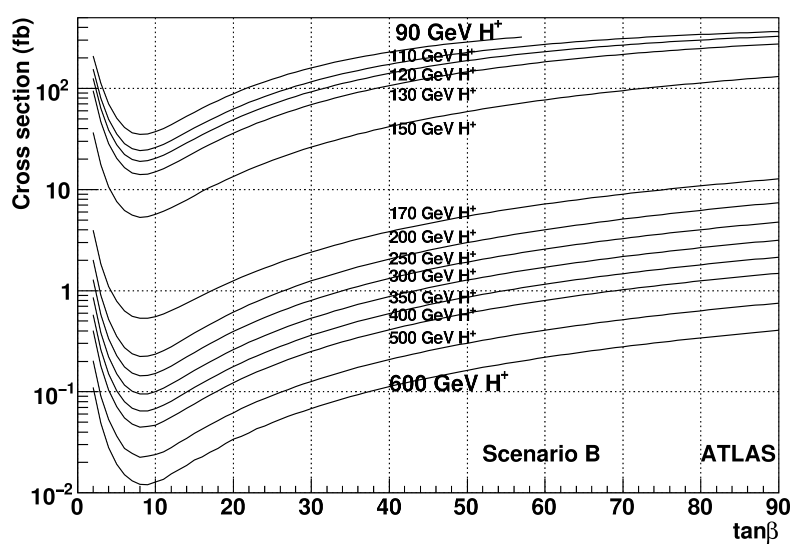
JHEP02(2013)095

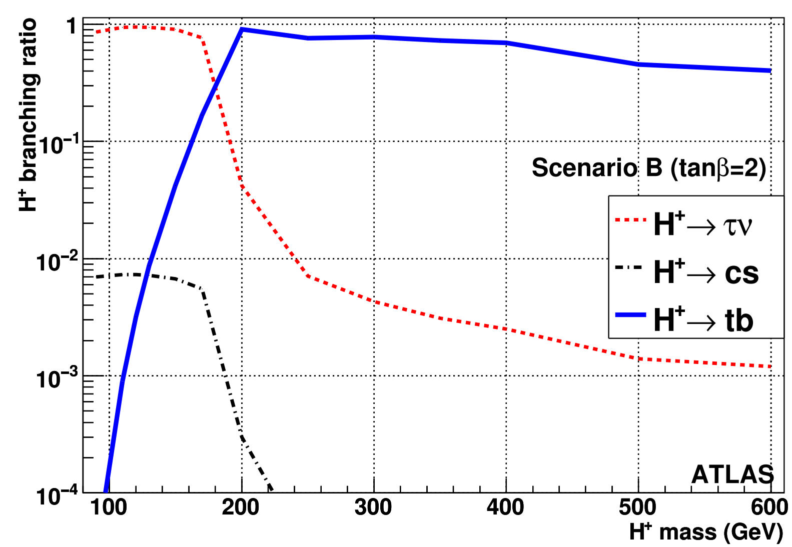
Expected (dashed line) and observed (solid line) 95 % confidence level CLs limits on tanβ as a function of m_A for the statistical combination of all channels along with the $\pm 1\sigma$ (green) and $\pm 2\sigma$ (yellow) bands for the expected limit are shown on the left plot. The 95 % confidence level 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.

MSSM Charged Scalar H^+ Phenomenology



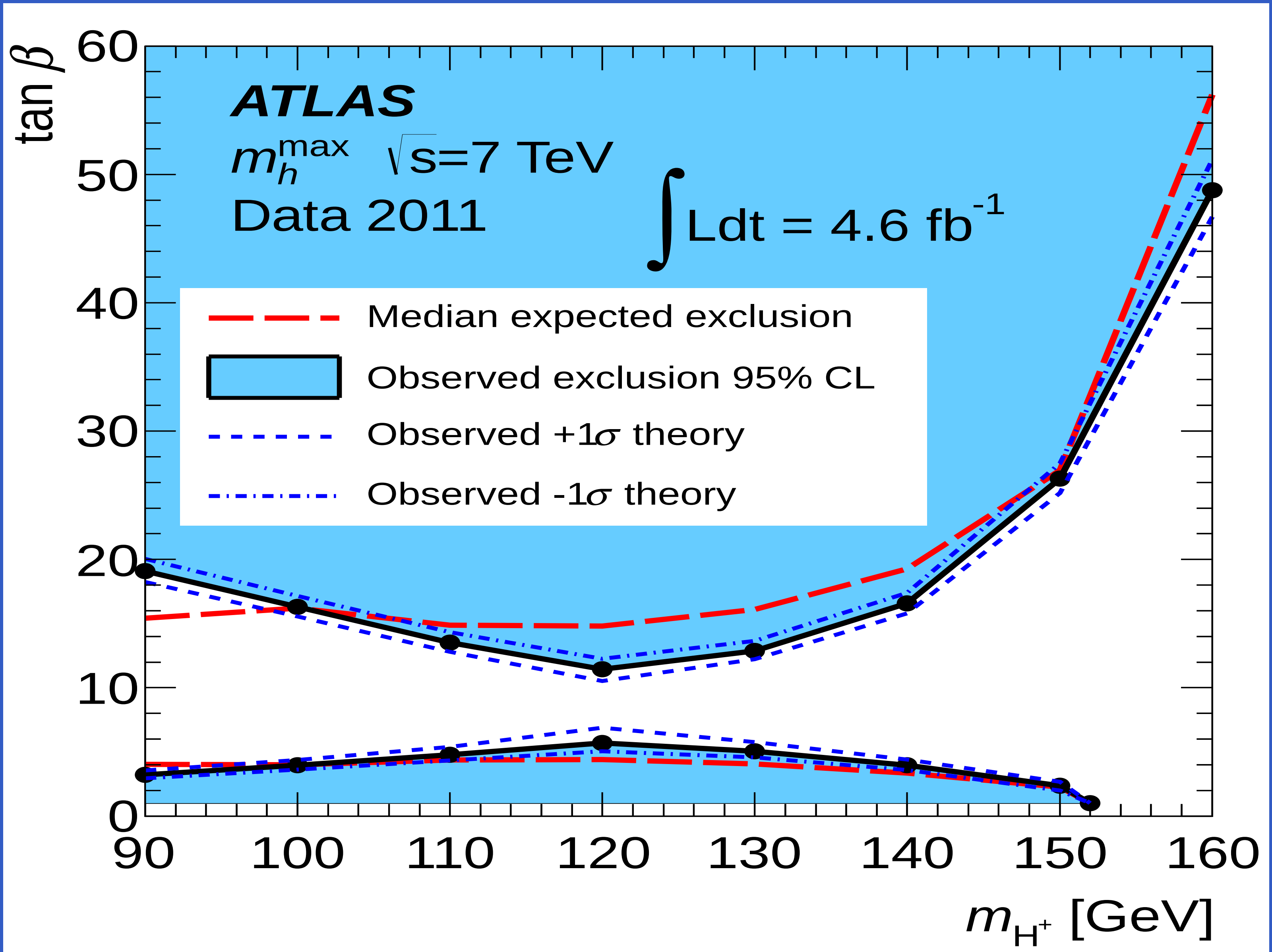






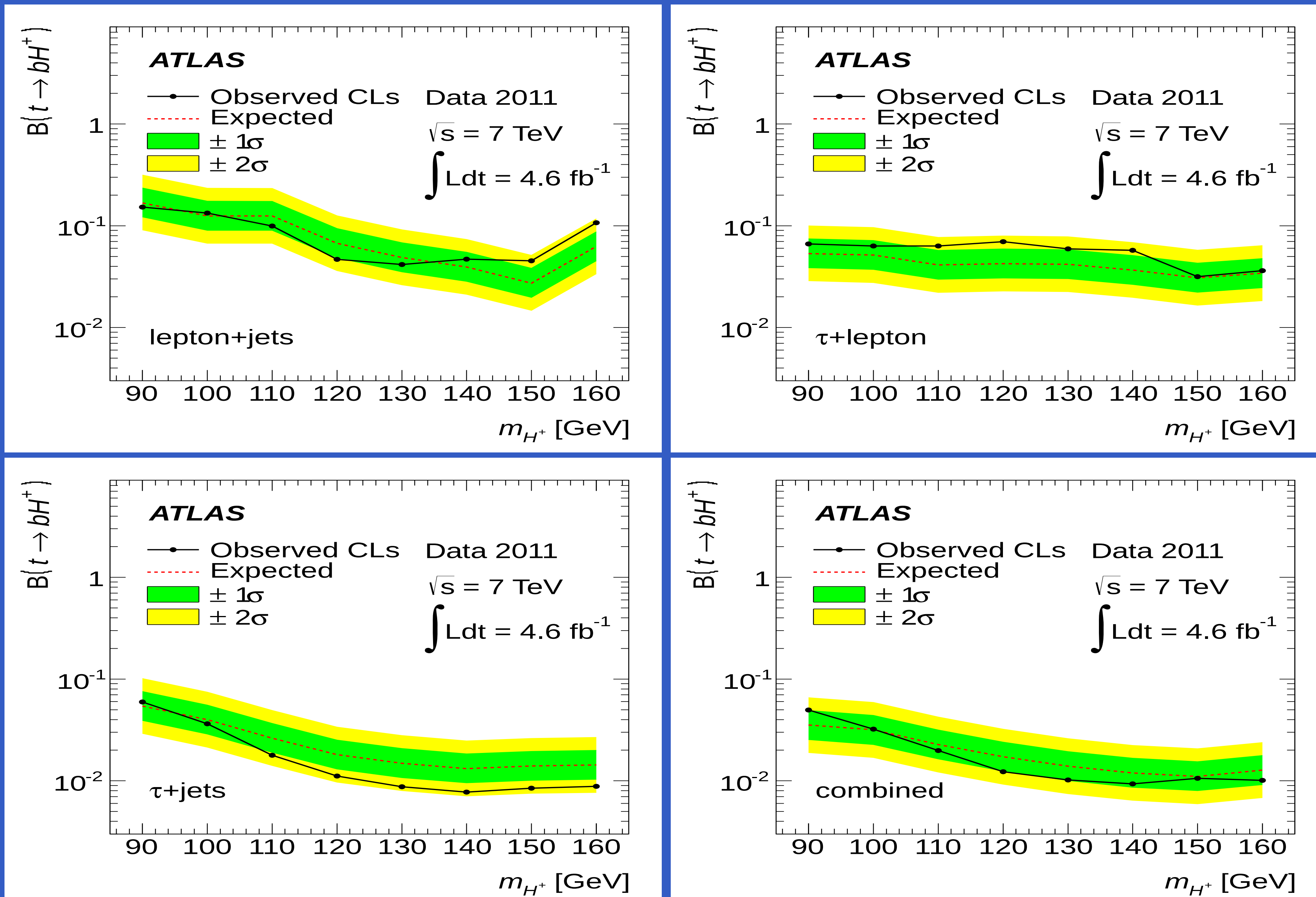
CERN-OPEN-2008-020

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



JHEP 1206 (2012) 039

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



JHEP 1206 (2012) 039

Next-to-Minimal Supersymmetric Model (NMSSM)

- The Next-to-Minimal Supersymmetric Model (NMSSM) is motivated to reduce the fine-tuning required for the term $\mu \hat{H}_u \hat{H}_d$ in the MSSM superpotential.
- One singlet superfield $\hat{S}$ is introduced to the MSSM. The NMSSM superpotential is

$$W_{NMSSM} = \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{\kappa}{3} \hat{S}^3 + W_{MSSM}$$

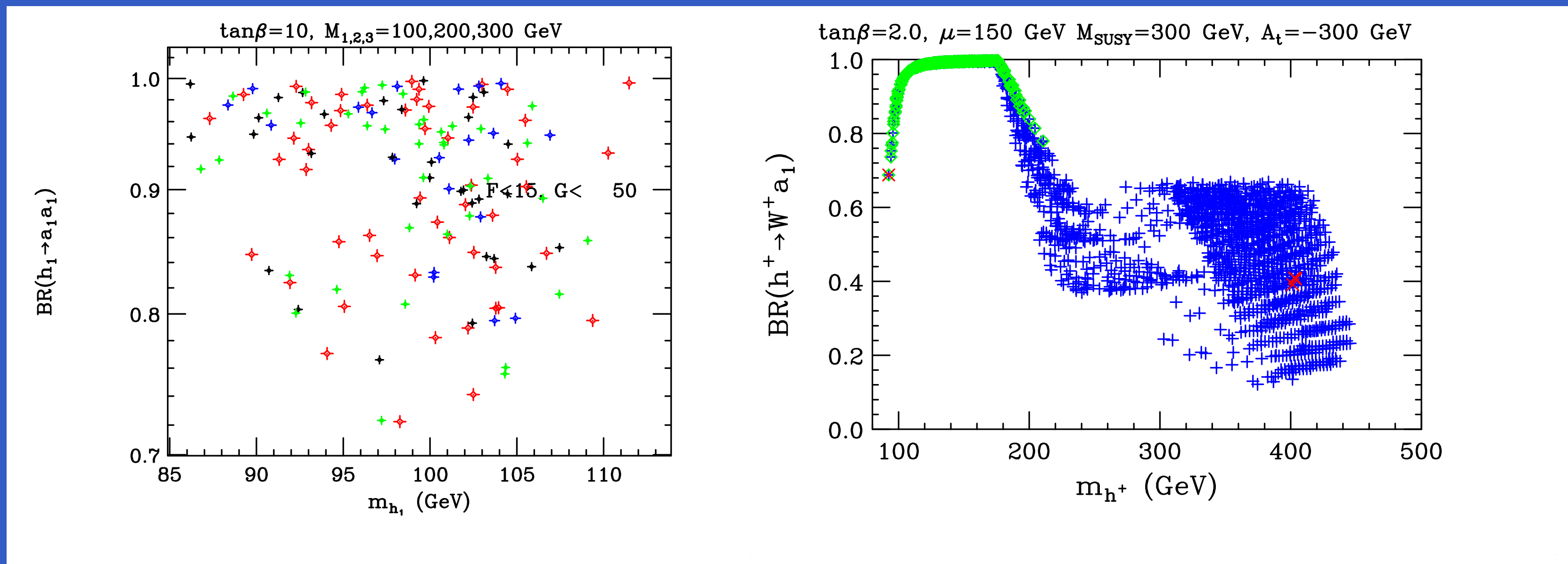
- An effective μ term is generated $\mu_{eff} = \lambda < \hat{S} >$ at a natural scale.
- The trilinear soft SUSY breaking terms in the NMSSM Lagrangian are

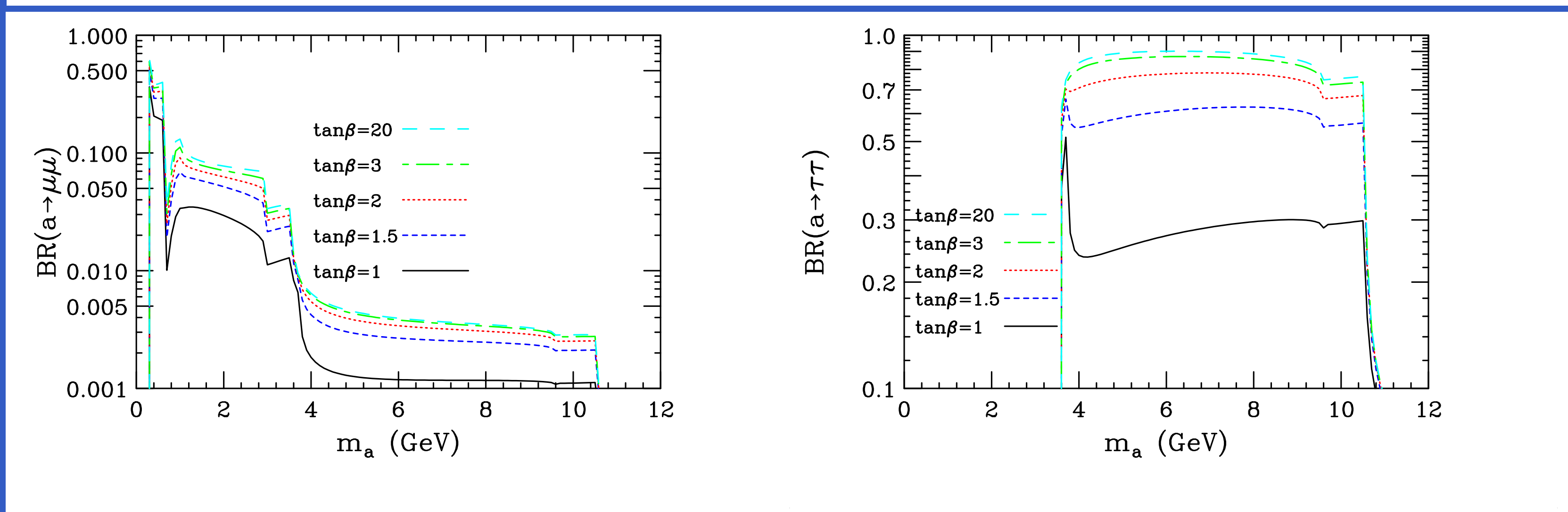
$$\mathcal{L}^{trilinear}_{soft} = \lambda A_\lambda S H_u H_d + \frac{\kappa}{3} A_\kappa S^3 .$$

- Six parameters determine NMSSM Higgs sector at tree level: $\lambda, \kappa, A_\lambda, A_\kappa, \tan\beta$ and μ_{eff}.
- The NMSSM Higgs sector includes neutral CP-odd a_1, a_2, neutral CP-even h_1, h_2, h_3 and charged H^+, H^-.

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

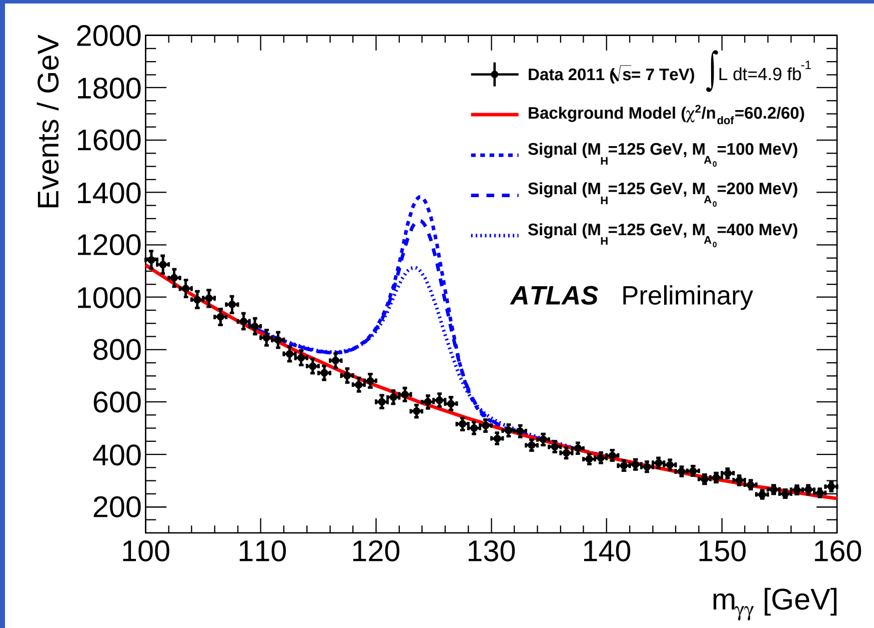
Phys.Rev.D79:055014,2009

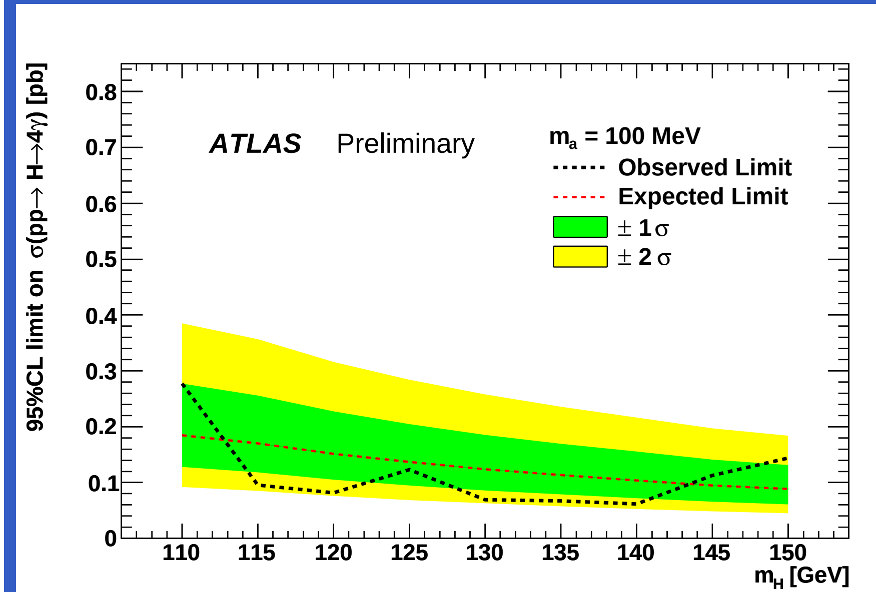


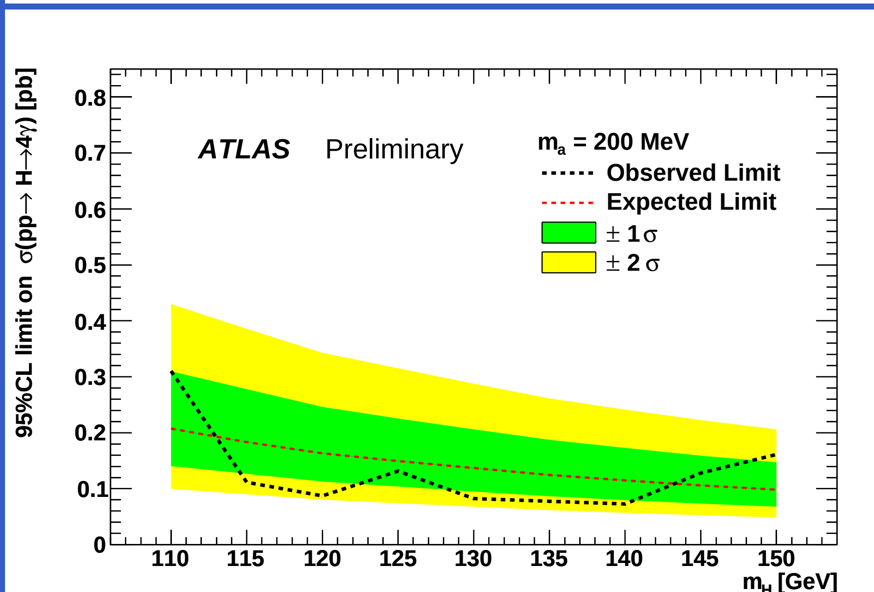


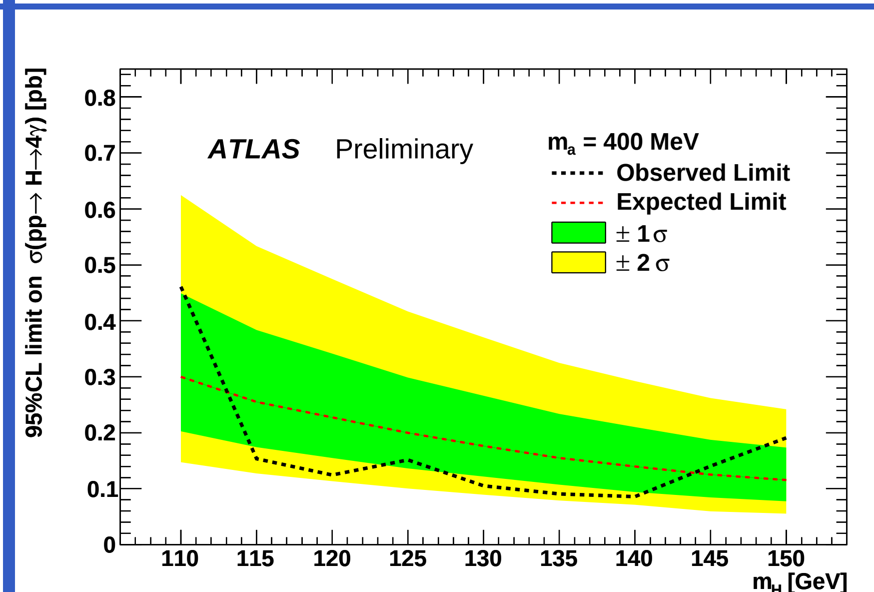
Phys.Rev.D81:075003,2010

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



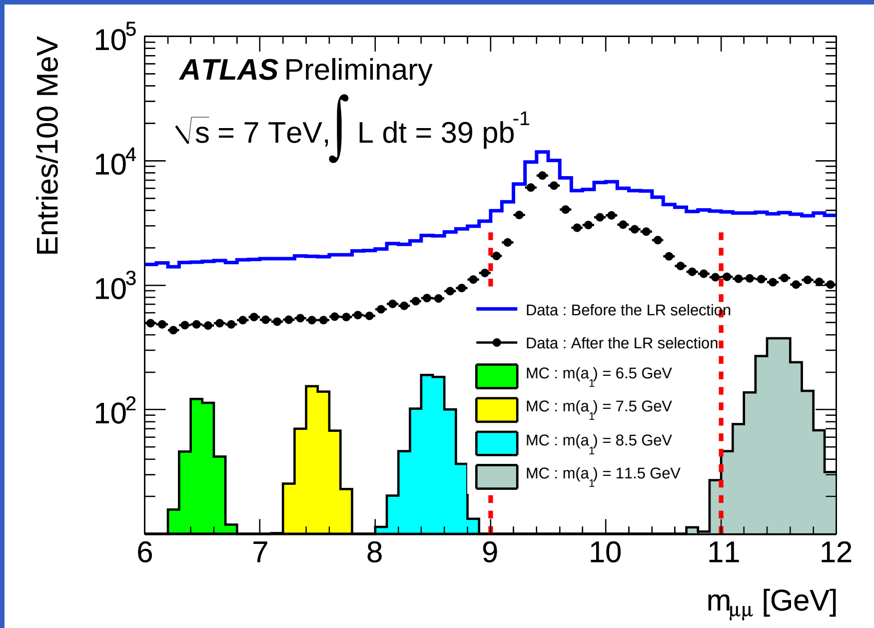


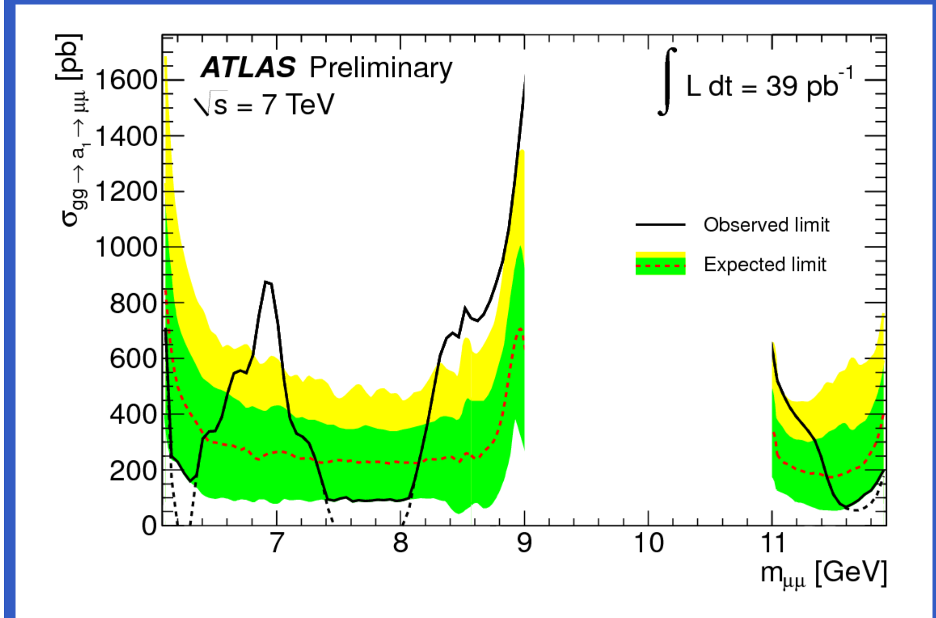




ATLAS-CONF-2012-079

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



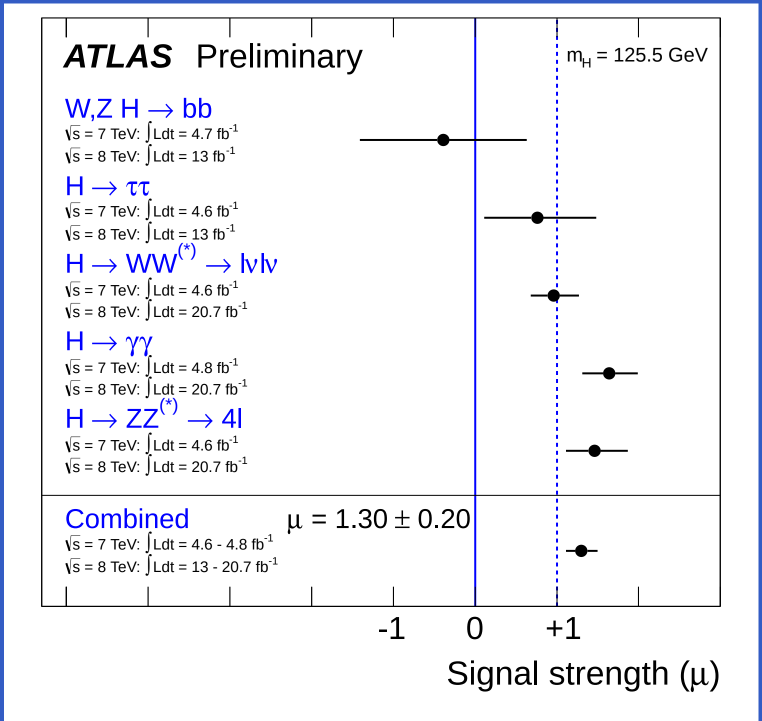


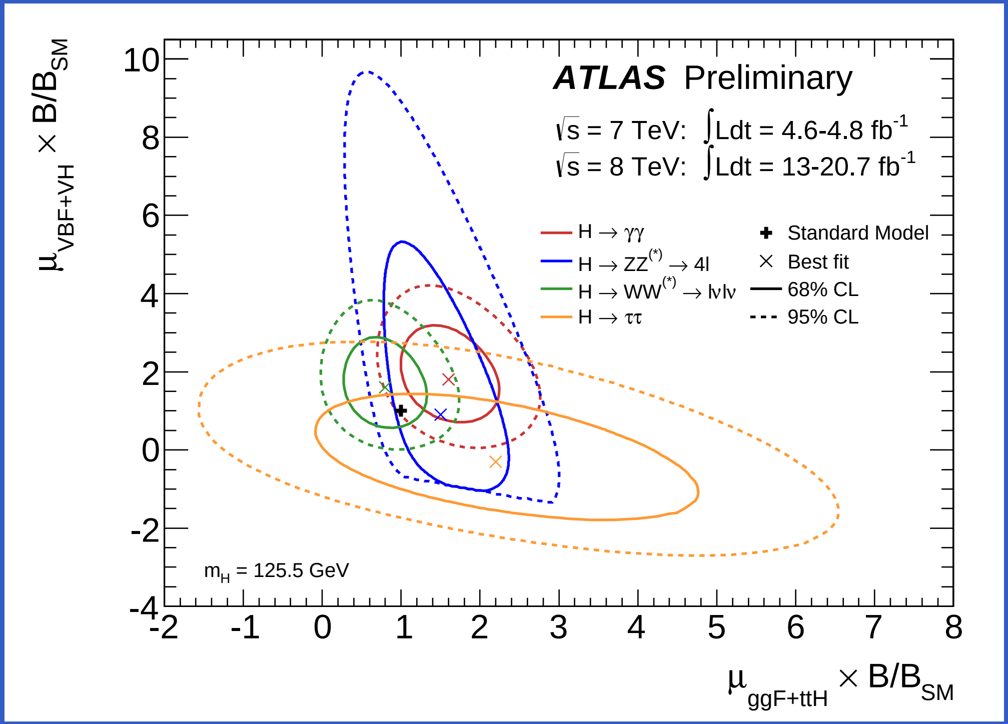
ATLAS-CONF-2011-020

- 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 $a_1 \to \mu^+\mu^-$ spectra (with arbitrary normalization) for various a1 masses.
- At right, upper limits on $\sigma(gg \to a_1) \times \mathcal{B}(a_1 \to \mu^+\mu^-)$ 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.

Invisible Higgs Decays

ATLAS-CONF-2013-034





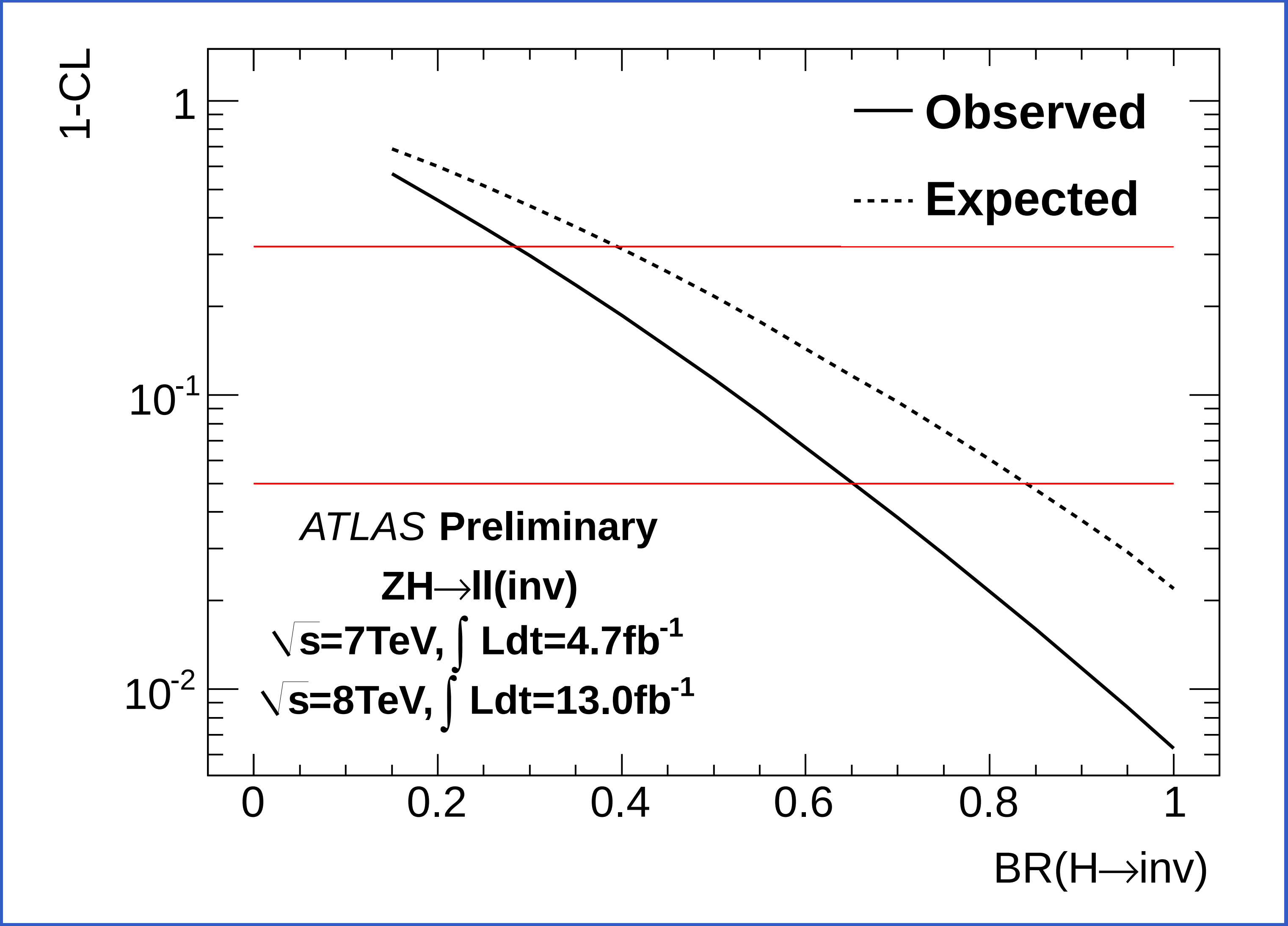
- At the LHC, we measure signal strength against the expected SM signal strength μ/μ_{SM}.
- The measured and SM-expected signal strengths in decays channel i are

$$\mu = \frac{\sigma \times \Gamma_i}{\Gamma} \times \frac{\Gamma^{SM}}{\sigma_{SM} \times \Gamma_i^{SM}}$$

- Are there invisible/unsearched-for/exotic decays of the 125 GeV Higgs?

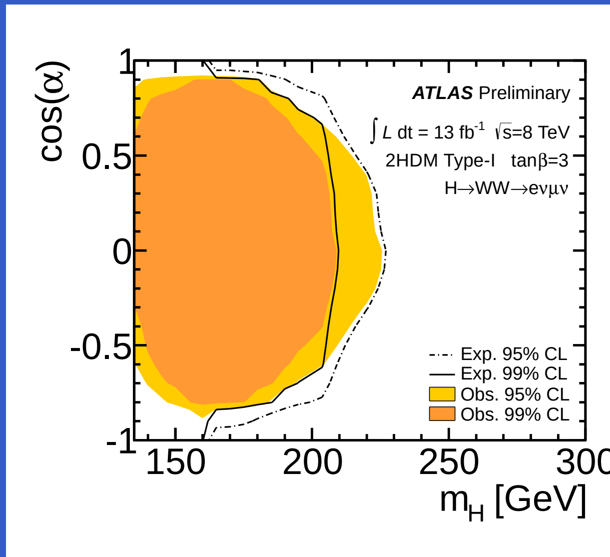
ATLAS Limits on $H \rightarrow INV$ ($\int \mathcal{L}dt$ =4.7+13.0 fb^{-1})

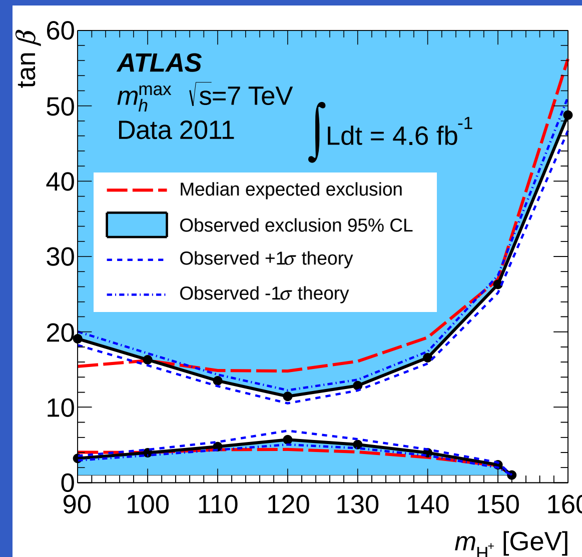
ATLAS-CONF-2013-011

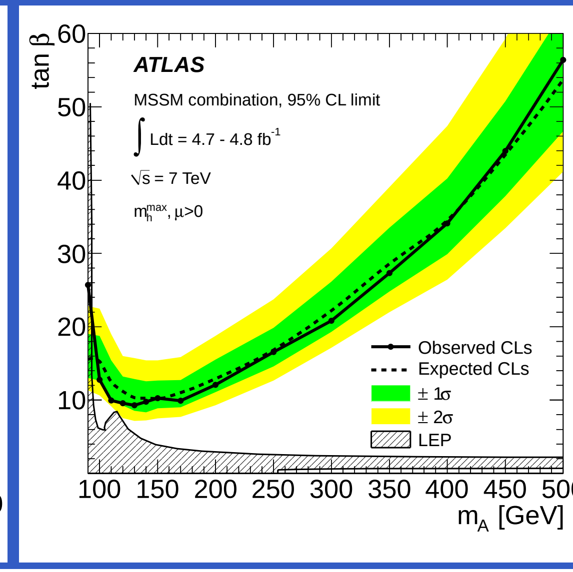


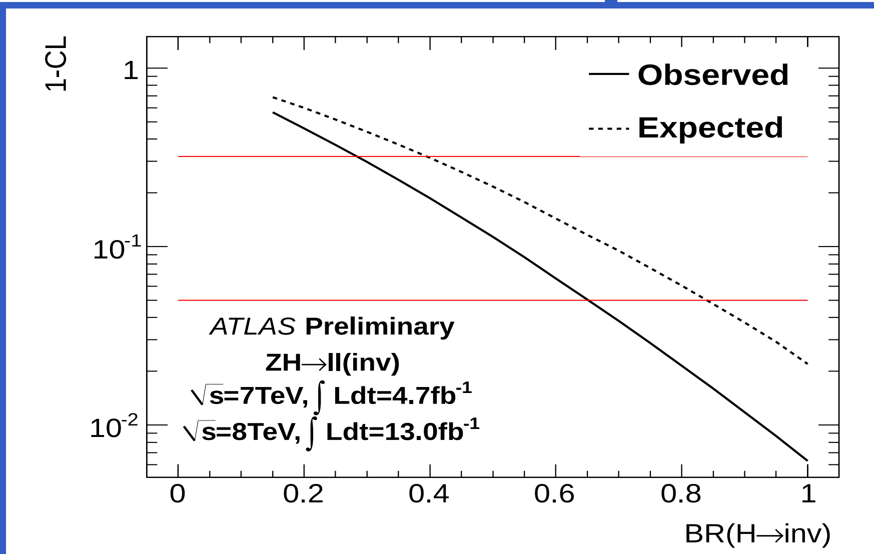
1 - Confidence level (CL) for the SM scalar with 125 GeV mass. The red solid lines indicate the 68% and 95% CL for (a). The expected 95% C.L. upper limit on $\mathcal{B}(H \rightarrow INV)$ at 125 GeV is 84%, the observed limit is 65%.

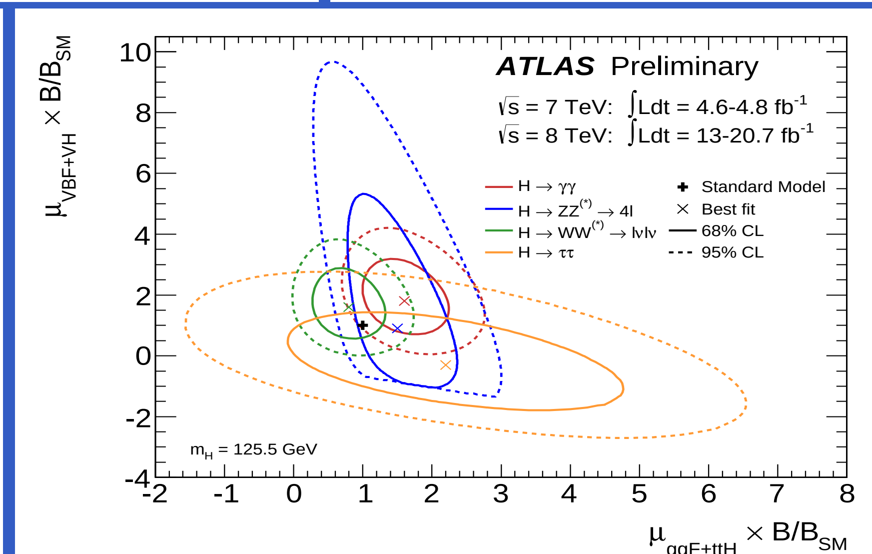
Conclusions and Outlook









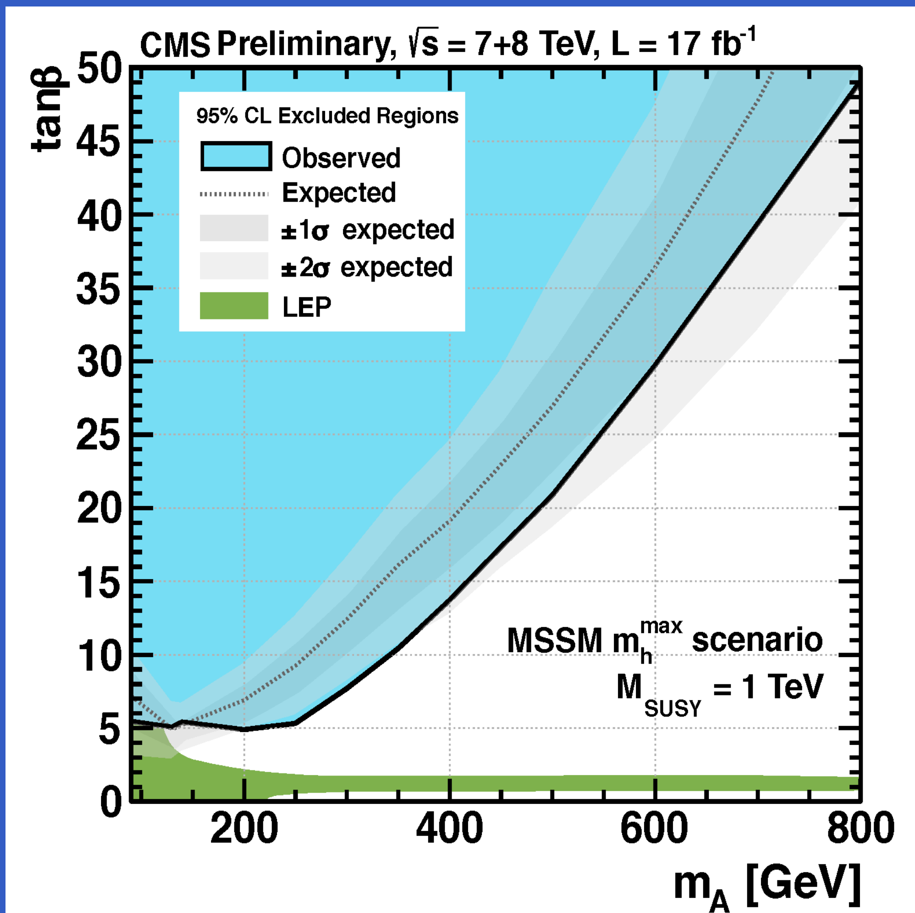


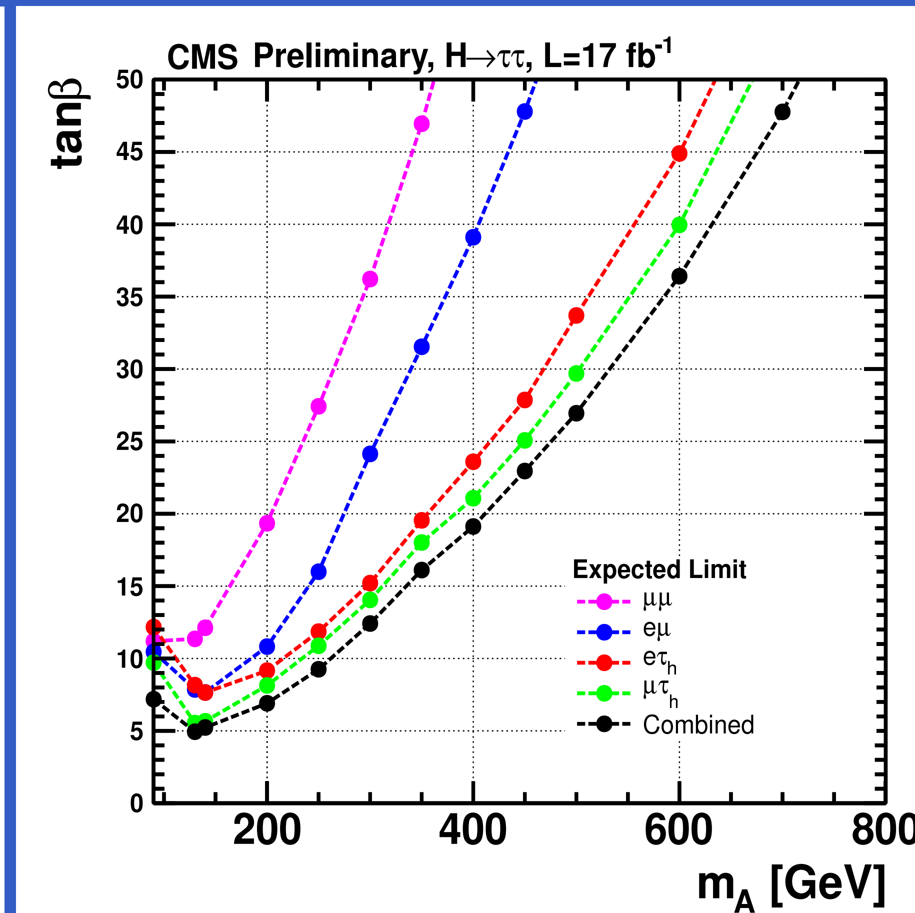
Some searches are not public yet. No searches described here have released results on the entire dataset. We have not yet begin to constrain NMSSM parameter space. Stay tuned!

Supplemental Slides

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

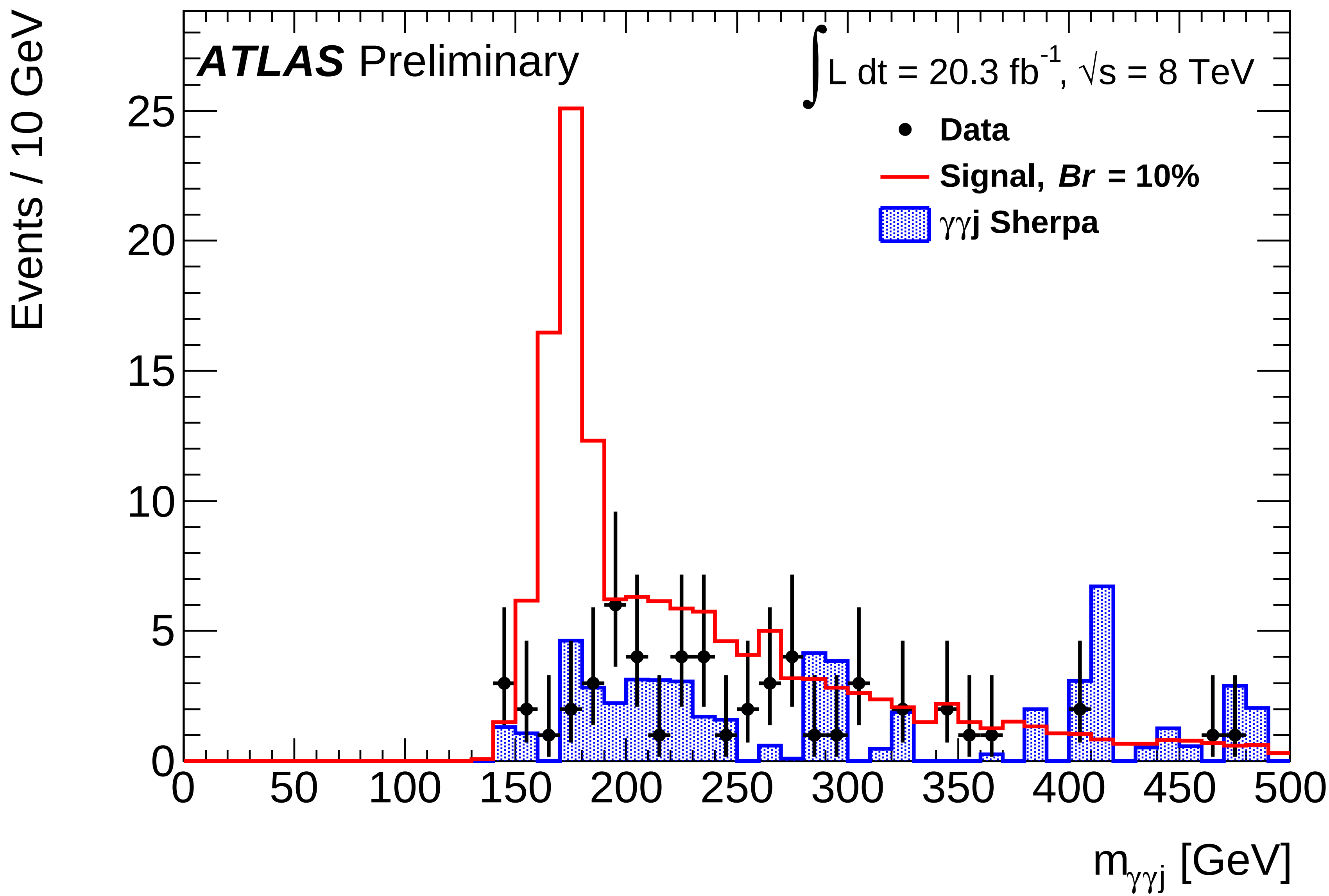
CMS-PAS-HIG-12-050





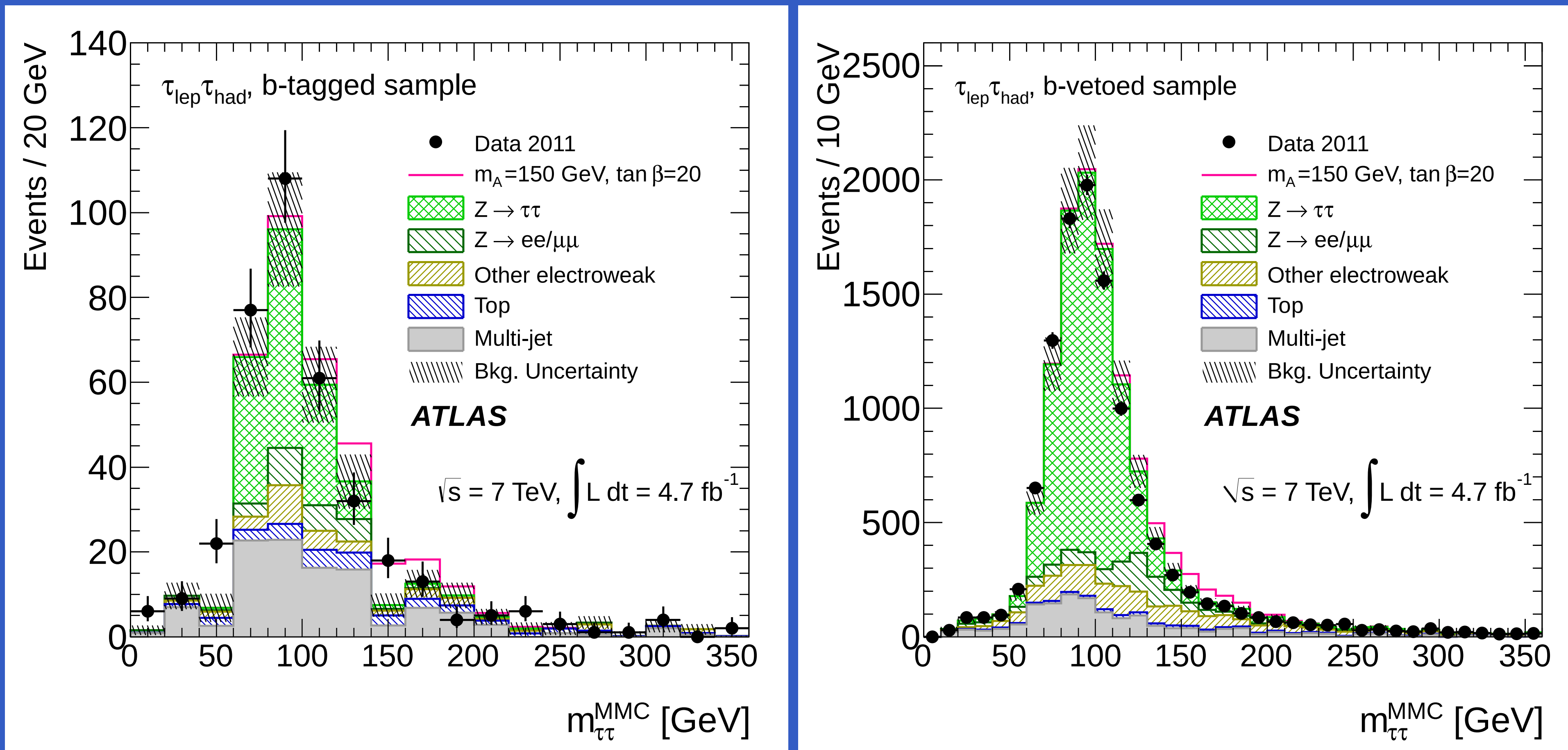
At left, 95% CL Exclusion limit. At right, expected exclusion limit for different final states.

FCNC $t \to cH$ Signal Top Reconstruction



ATLAS-CONF-2013-081

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



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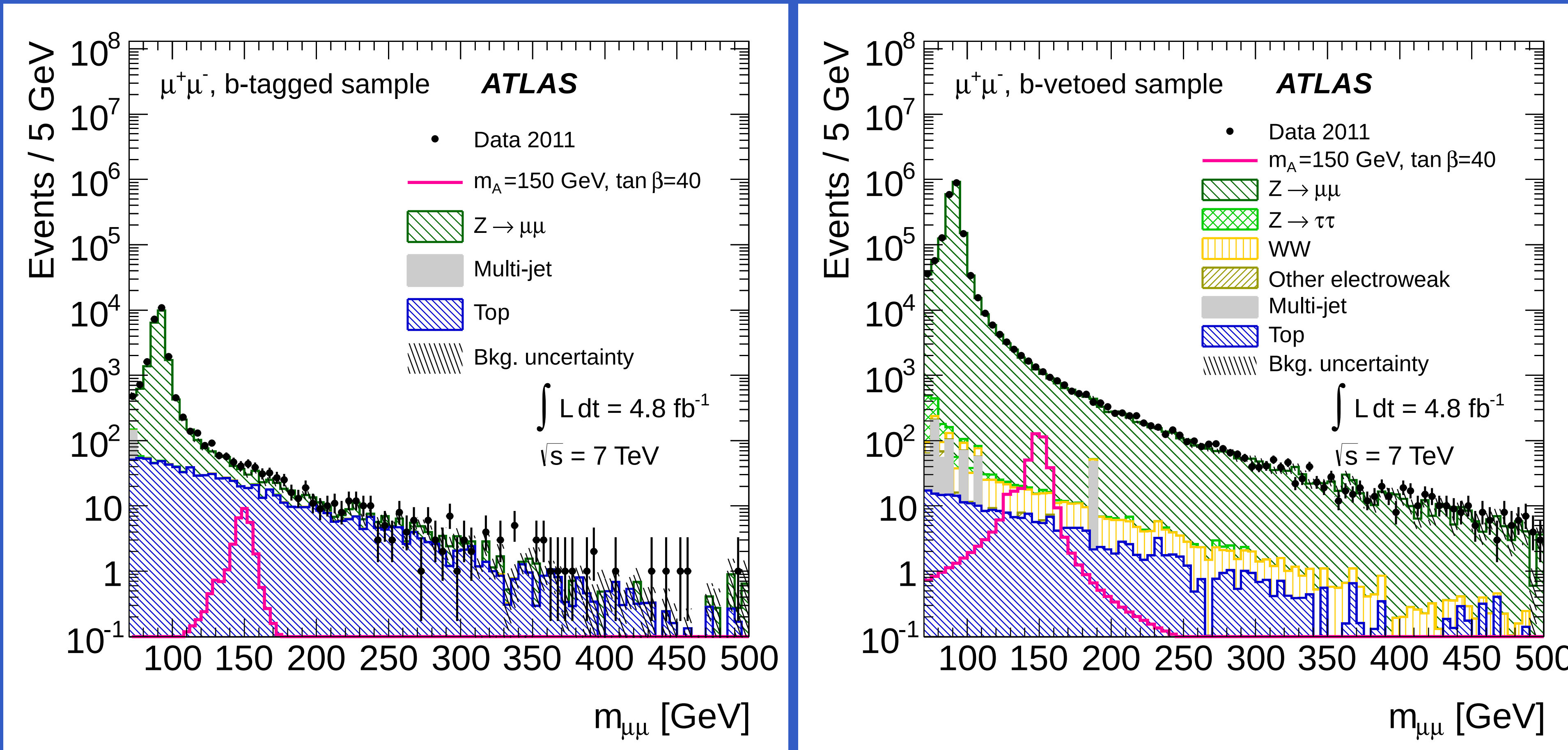
Final mass distributions for the $h/A/H \to \tau_{lep}\tau_{had}$ final state. The MMC mass is shown for the b-tagged (left-hand side) and b-vetoed selections (right-hand side) for the combined $\tau_e\tau_{had}$ and $\tau_\mu\tau_{had}$ samples. The data are compared to the background expectation and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

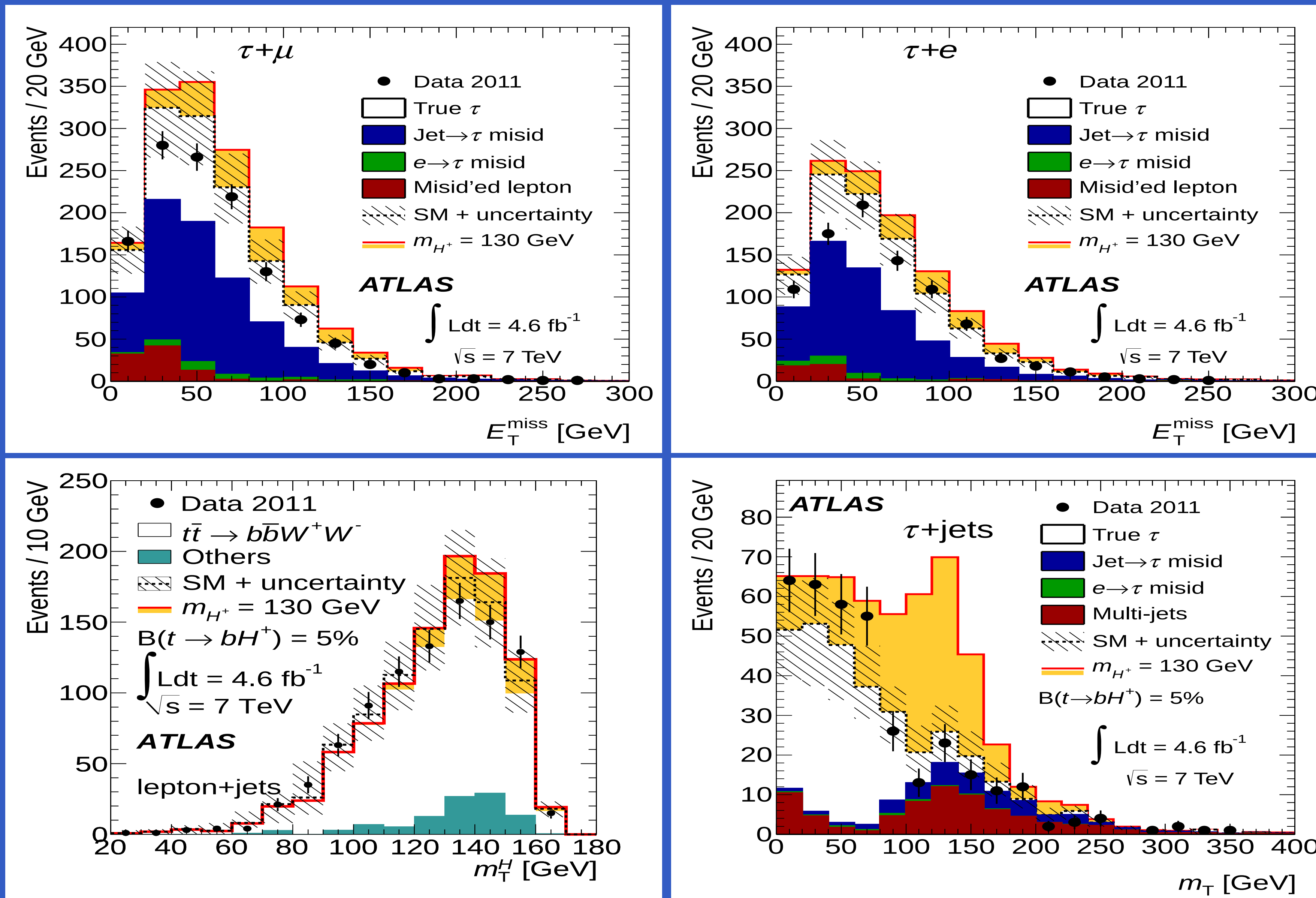
ATLAS $h/H/A \rightarrow \mu^+\mu^-$ ($\int \mathcal{L}dt$ =4.8 fb^{-1})



JHEP02(2013)095

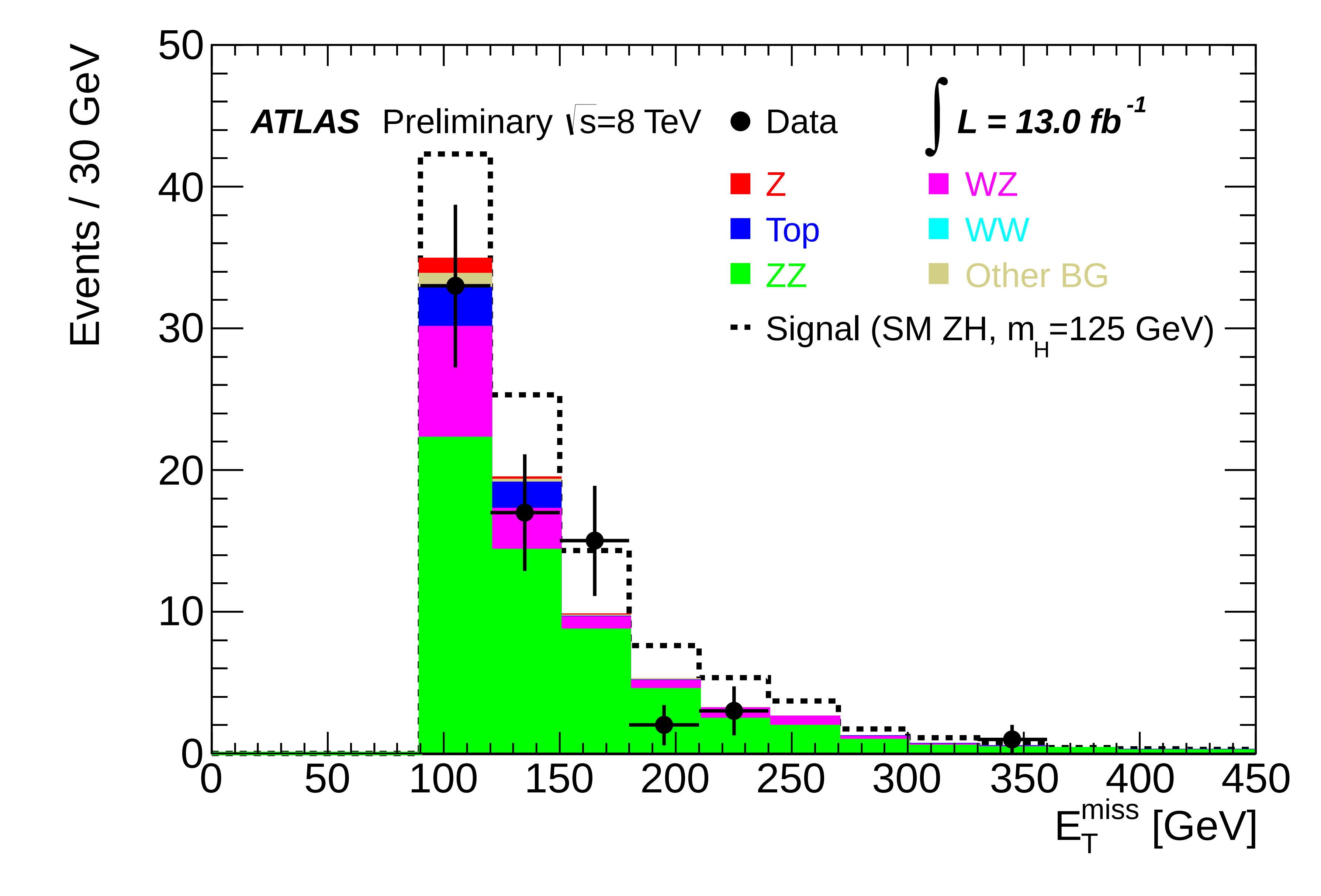
Final mass distributions for the mumu final state. The invariant mass distribution of the two muons is shown for the b-tagged (left-hand side) and the b-vetoed selection (right-hand side). The data are compared to the background expectation and an added hypothetical MSSM signal ($m_A = 150$ GeV, $tan\beta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

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



JHEP 1206 (2012) 039

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



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