BSM Higgs Searches with ATLAS

New Physics

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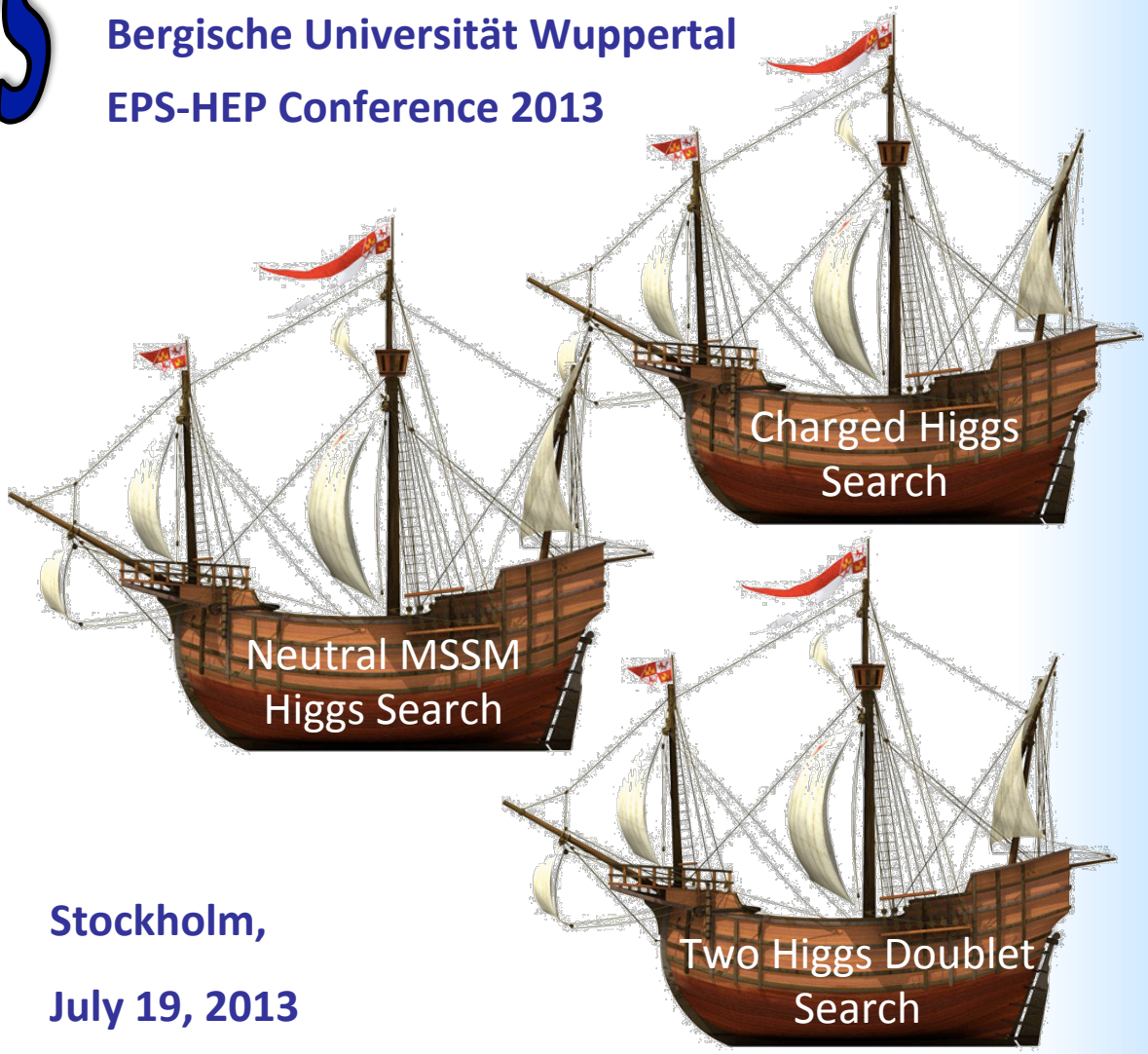
EPS-HEP Conference 2013

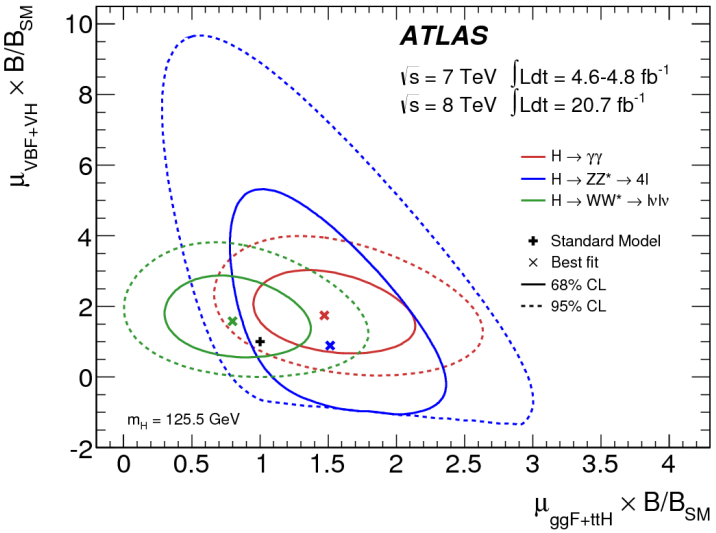


Stockholm,

July 19, 2013

Standard Model

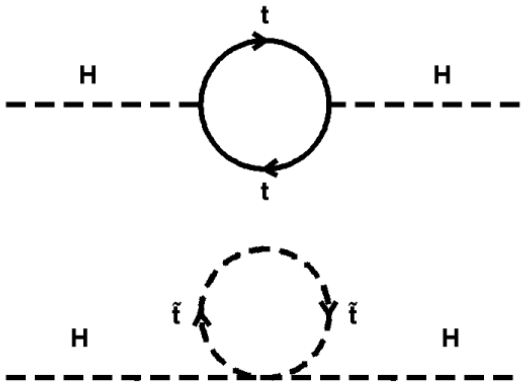
Extending the Standard Model



- Higgs boson discovered at LHC
- Couplings and quantum numbers appear SM-like
- SM is complete
- Measurements of coupling strengths narrow parameter space of new physics models.
  ➔ talk by Oscar Stal

Remaining open questions:

- CP violation in the early universe
- Dark Matter
- Hierarchy problem, naturalness, fine-tuning
- Relation between lepton and quark charges
- …



➔ solution by extending SM
most prominent: supersymmetry

Most theories beyond SM include an extended scalar sector.

Extended Higgs Sectors

Two Higgs Doublet Models (2HDMs)

for a review, see for example:
Branco et al. arXiv: 1106.0034

- The softly broken Z_2 symmetric 2HDM potential:

$$\mathcal{V} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - [m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}] + \tfrac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \tfrac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2$$

$$+\lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \left\{ \tfrac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \text{h.c.} \right\} ,$$

- Two complex Higgs doublets ➔ five physical states:
  h (light neutral CP even), H (heavy neutral CP even), A (CP odd), $H^\pm$
- Minimal Supersymmetric Model (MSSM) is specific type-II 2HDM (at tree level).
  Not using Z_2 symmetry.

Adding one singlet

- add one electroweak singlet H

nMSSM model

- adds a superfield resulting in 7 physical states: h_1, h_2, h_3, a_0, a_1, $H^\pm$

Triplet models

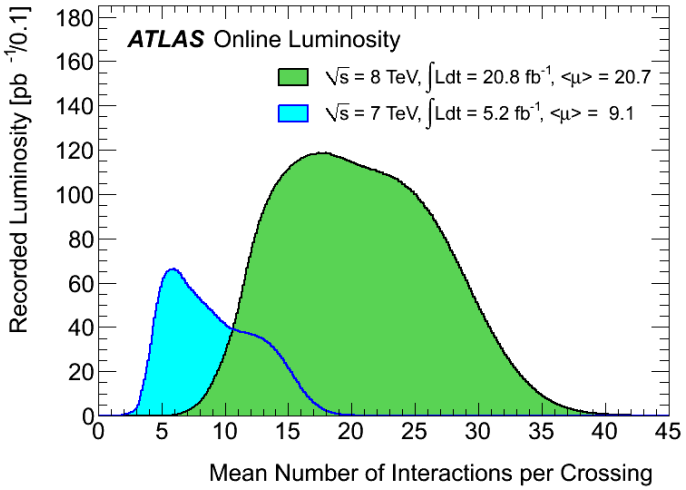
- Use complex triplet instead of doublet: h^0, $H^\pm$, $H^{\pm\pm}$
- Explains neutrino masses and mixing

BSM Higgs Searches at ATLAS

Charged Higgs boson searches

- $H^{\pm} \rightarrow \tau\nu$ (important for tan β > 3) JHEP 1206 (2012) 039
- $H^{\pm} \rightarrow \tau\nu$ via violation of lepton universality in top-quark decays, JHEP (2013) 076
- $H^{\pm} \rightarrow cs^{bar}$ (important for tan β < 1) Eur. Phys. J. C 73 (2013) 2465
- pair production of $H^{\pm\pm}$ Eur. Phys. J. C 72 (2012)

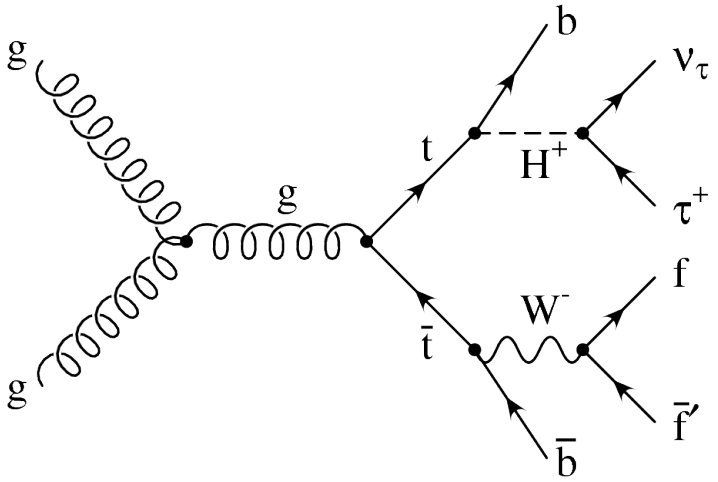
4.8 fb^{-1} @ 7 TeV



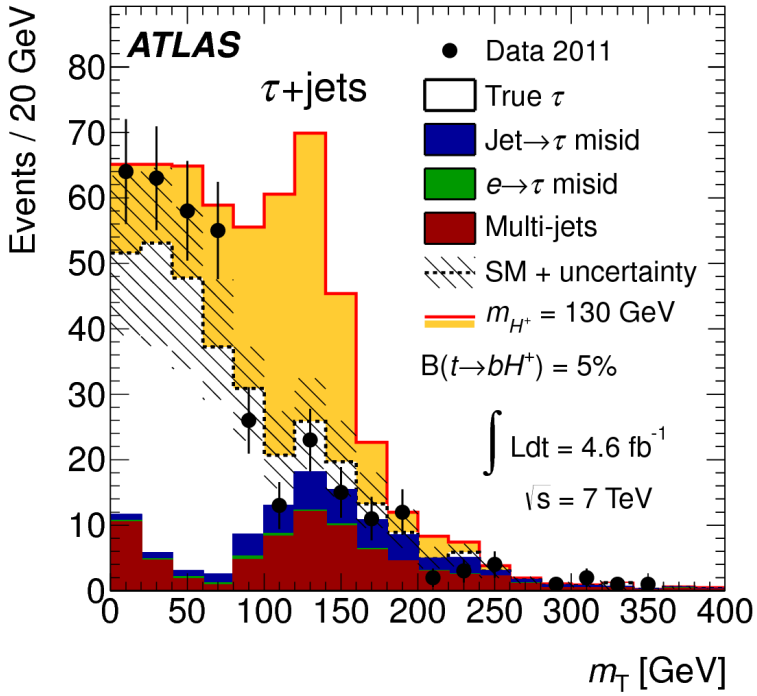
Neutral Higgs boson searches

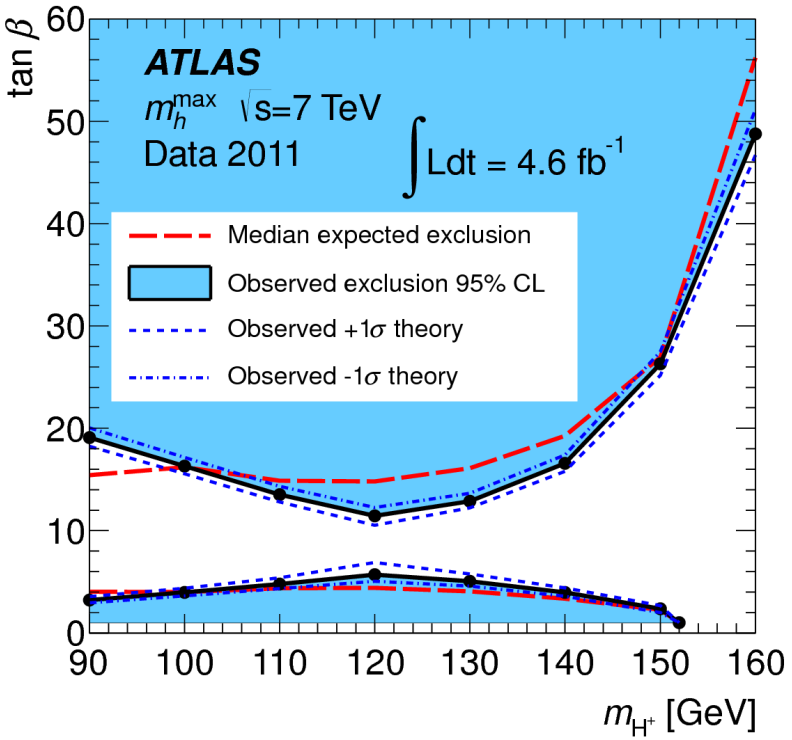
- MSSM A / H / h $\rightarrow \tau^+\tau^-$ / $\mu^+\mu^-$, JHEP02 (2013) 095 — 4.8 fb^{-1} @ 7 TeV
- Generic 2HDM in H $\rightarrow W^+W^- \rightarrow e\nu\mu\nu$, ATLAS-CONF-2013-027, 13 fb^{-1} @ 8 TeV
- ZH production with H $\rightarrow$ invisible, ATLAS-CONF-2013-011, 4.7 fb^{-1} @ 7 TeV / 13 fb^{-1} @ 8 TeV
  ➔talk by Johannes Elmsheuser
- nMSSM H $\rightarrow a^0a^0 \rightarrow \gamma\gamma\gamma\gamma$, ATLAS-CONF-2012-079, — 4.9 fb^{-1} @ 7 TeV
- nMSSM $a^1 \rightarrow \mu^+\mu^-$, ATLAS-CONF-2011-020, — 37 pb^{-1} @ 7 TeV
- Fermiophobic h $\rightarrow \gamma\gamma$, Eur. Phys. J. C (2012) 72:2157, — 4.9 fb^{-1} @ 7 TeV

$H^+ \rightarrow \tau\nu$ from Top-Quark Decay



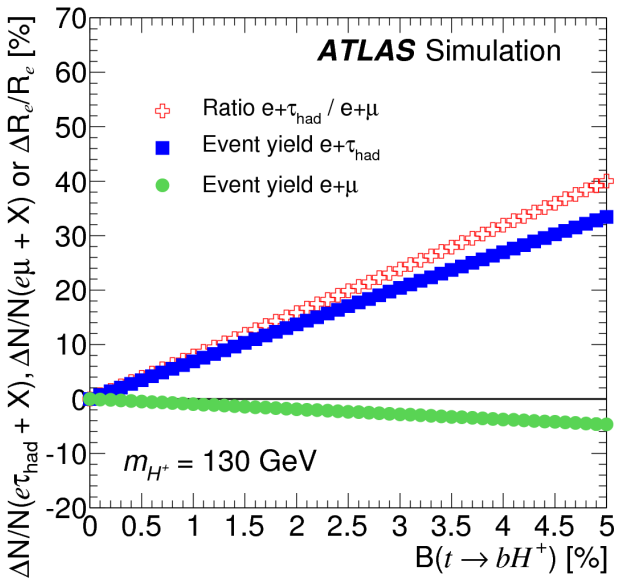
- light Higgs: $m(H^\pm) < m_t$
- Use leptonic and hadronic τ decays.
- Embedding method to estimate true τ backgrounds
- Interpretation in m_h^{max} scenario of MSSM





JHEP 1206 (2012) 039

$H^+ \rightarrow \tau\nu$ using Lepton Universality

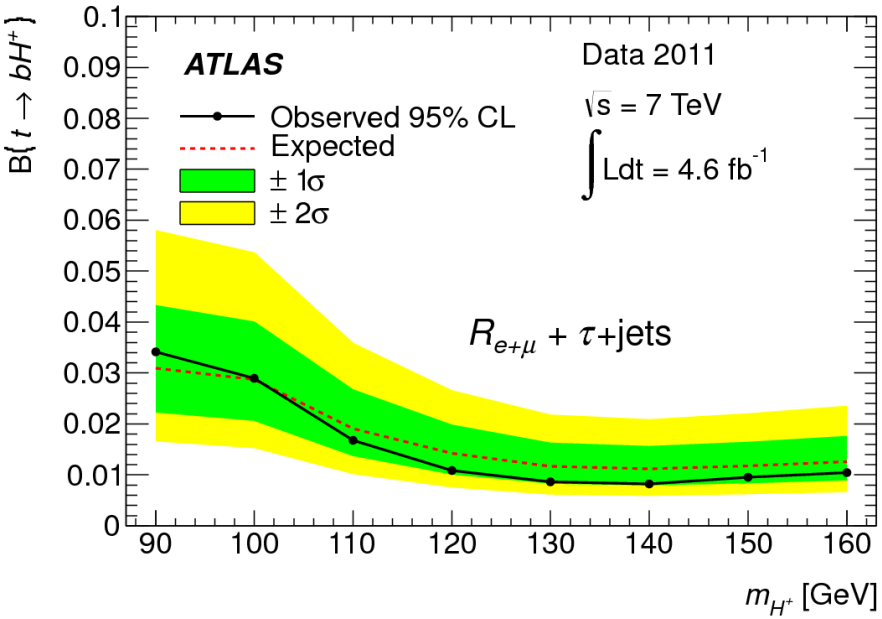


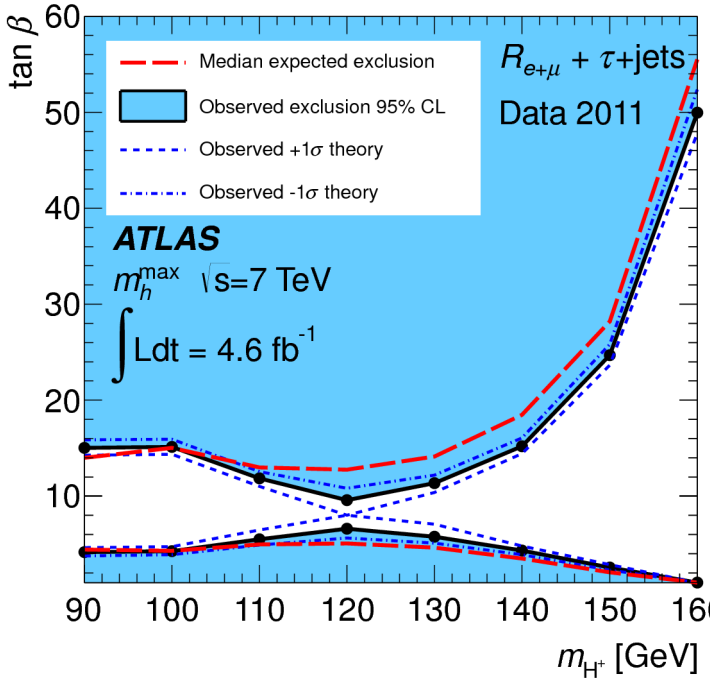
- Investigate lepton universality in top-quark decays to search for H±
- Ratio:

$$R_{e+\mu} = \frac{\mathcal{N}(e+\tau_{\mathrm{had}}) + \mathcal{N}(\mu+\tau_{\mathrm{had}})}{\mathcal{N}(e+\mu) + \mathcal{N}_{\mathrm{OR}}(\mu+e)}$$

depends on B (t → b + H±)

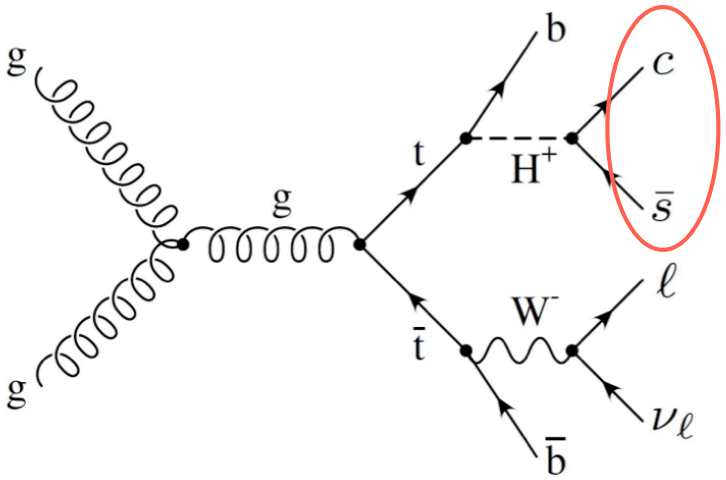
- Combination of $R_{e+\mu}$ and τ_{had} +jets analyses:





JHEP (2013) 076

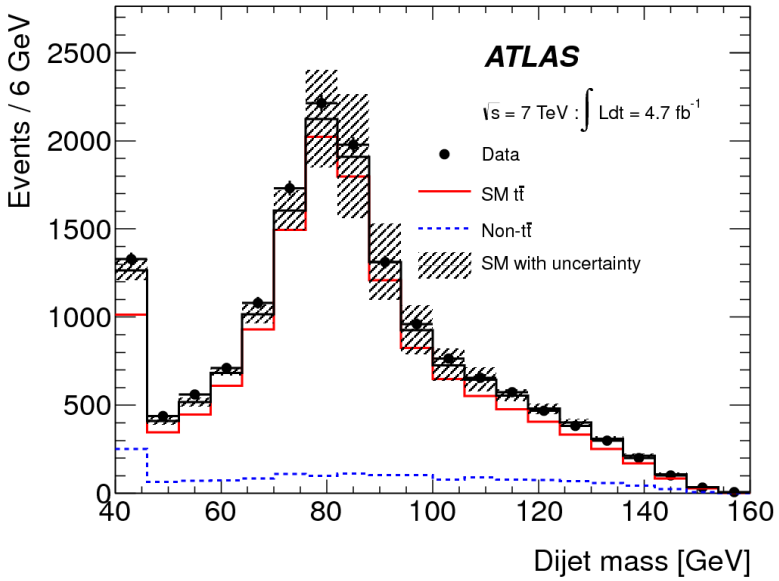
$H^+ \rightarrow c\bar{s}$ in Top-Quark Events

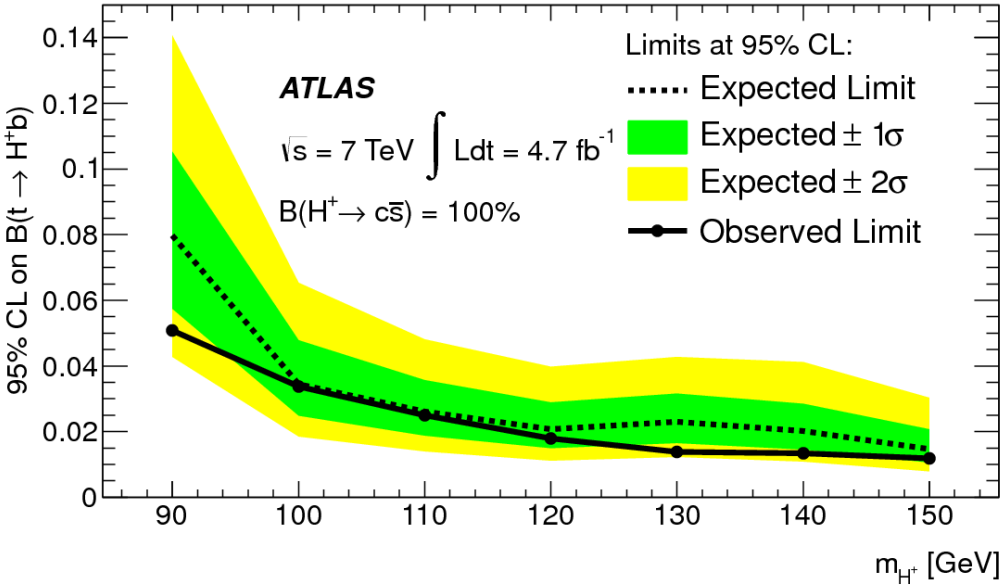


m(H^+)

- light Higgs: m($H^\pm$) < m_t
- $H^\pm \rightarrow cs^{bar}$ important for tan β < 1
- Top-quark-antiquark events reconstructed with kinematic fitter
- Search for additional bump in dijet mass distribution

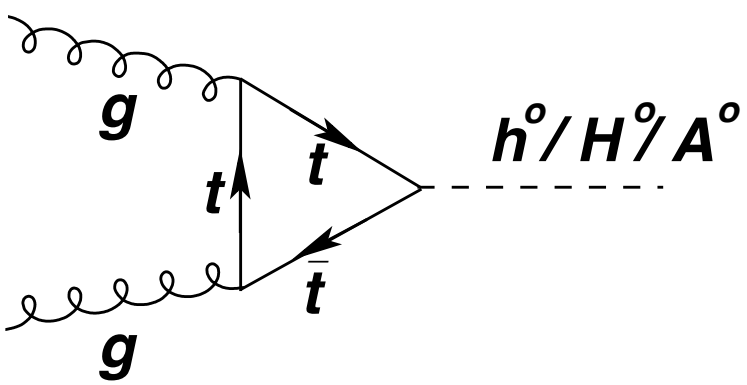
Eur. Phys. J. C 73 (2013) 2465

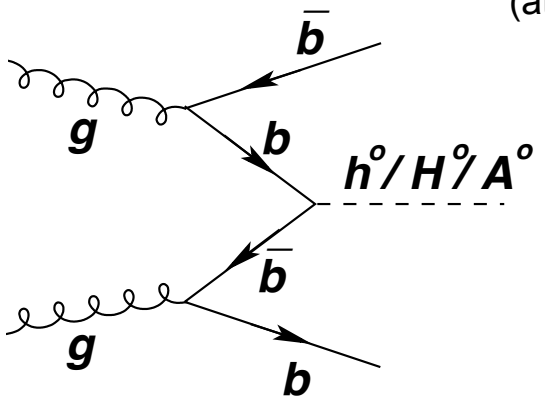




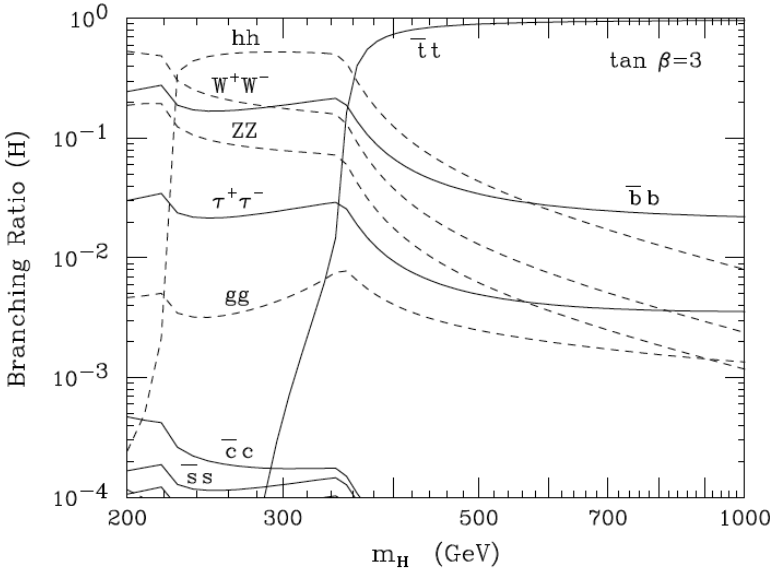
Neutral Higgs Bosons in the MSSM

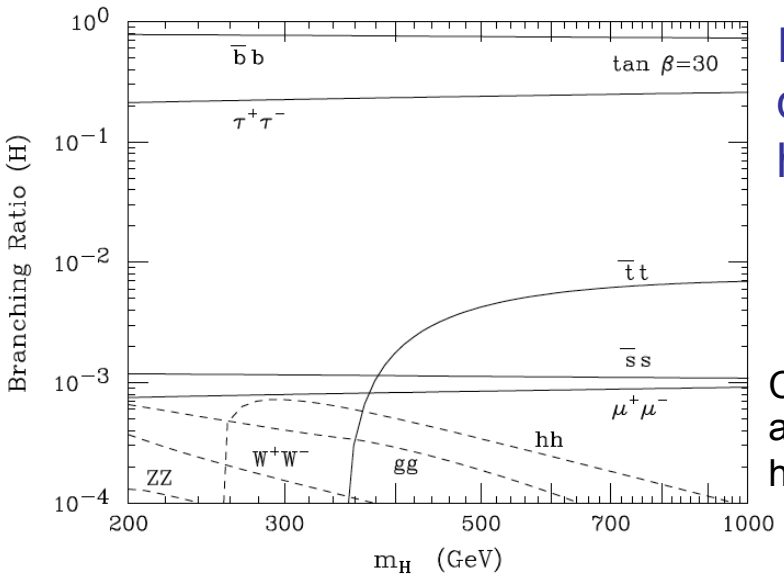
- Type II 2HDM describes Higgs sector of the MSSM.
- In the MSSM the Higgs sector is defined by 2 parameters: tan(β) and m_A (at tree level)





enhanced by $\tan^2(\beta)$





Investigated decays:
h/H/A → $\tau^+\tau^-$
→ $\mu^+\mu^-$

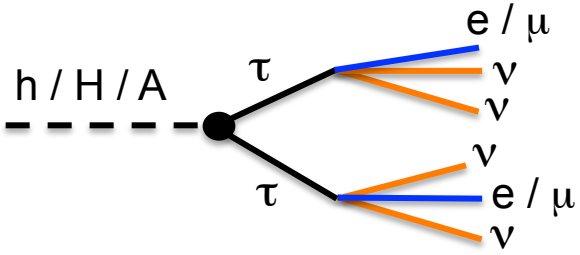
Carena and Haber, arXiv: hep-ph/0208209

h / H / A → $\tau^+\tau^-$

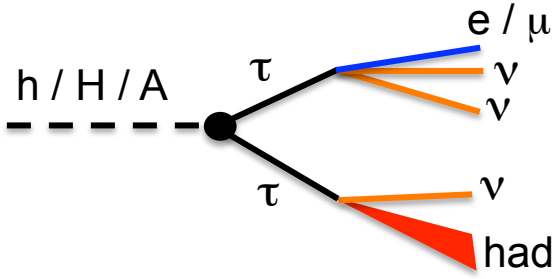
JHEP 02 (2013) 095

analysis channels

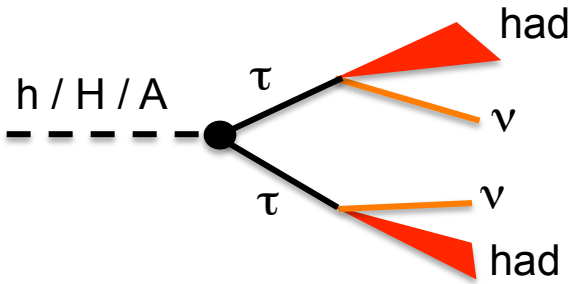
lepton-lepton



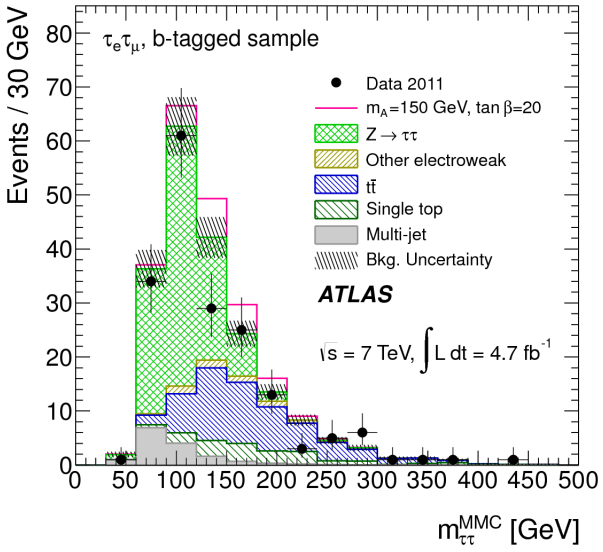
lepton-hadron

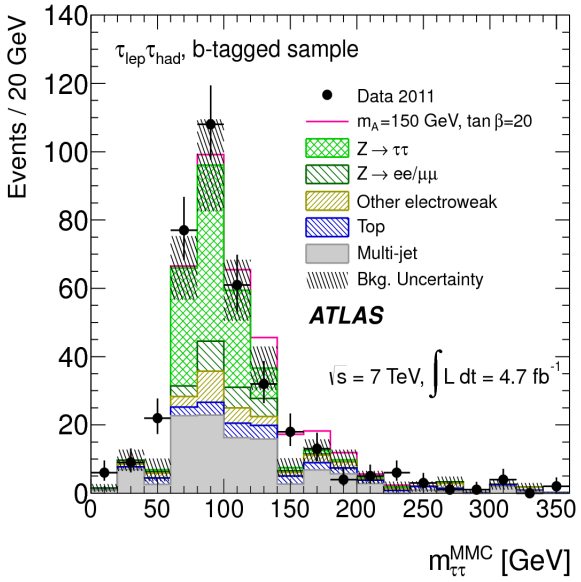


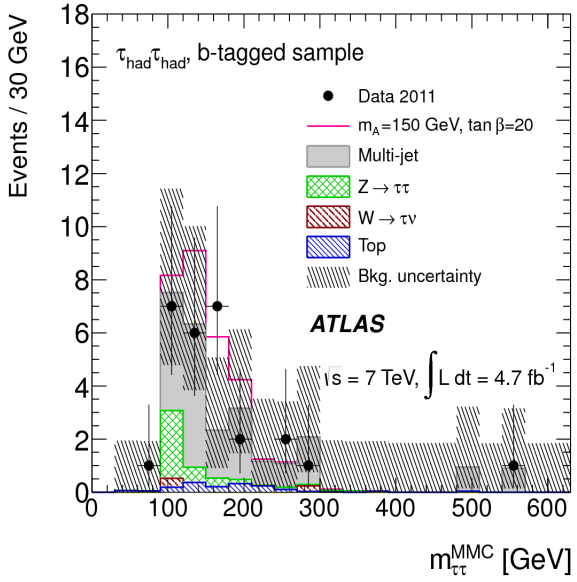
hadron-hadron



Use q_μ-value test statistics based on max. likelihood fit to $m_{\tau\tau}^{MMC}$ calculated with Missing Mass Calculator technique to scan M_A and tan(β) parameter space.







h / H / A → $\mu^+\mu^-$

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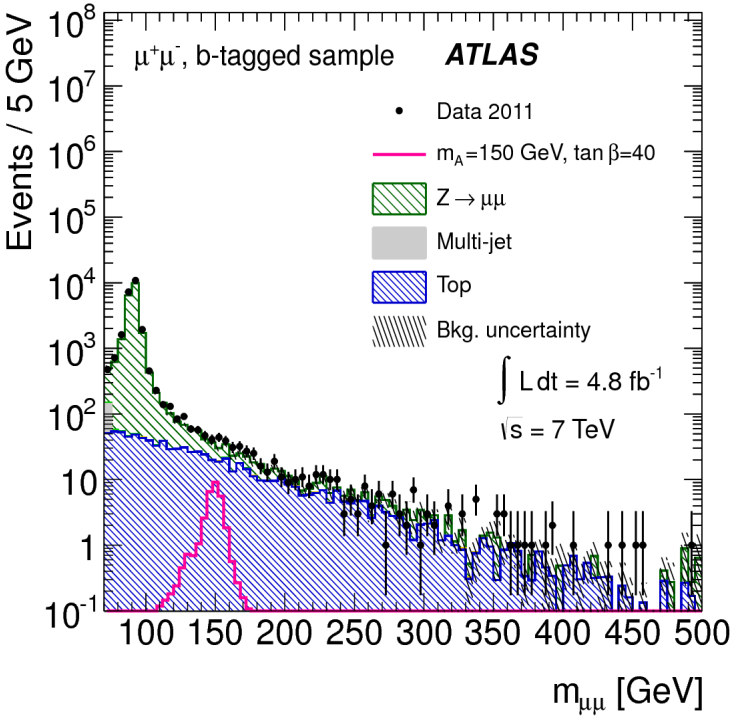
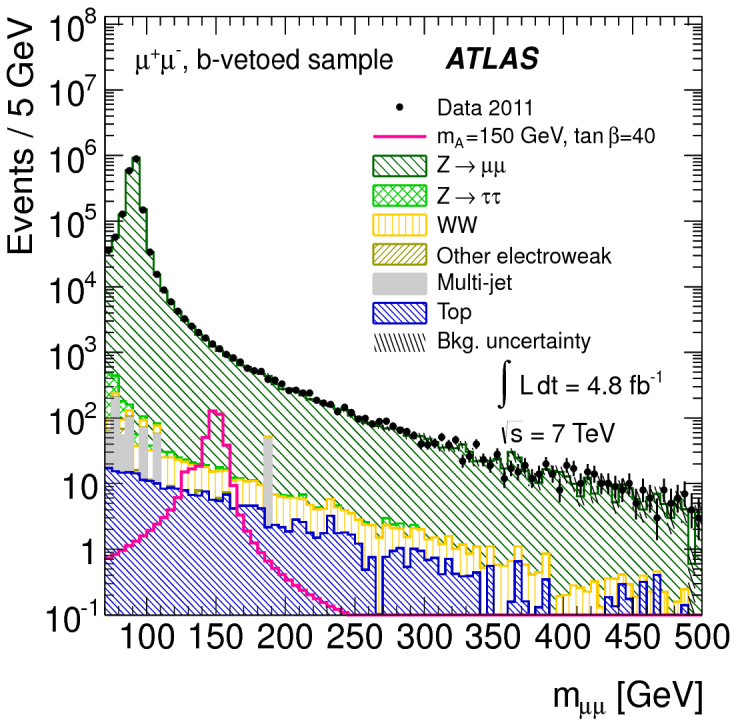
- Small branching ratio
- clean signal:
  narrow peak (2.5% to 3% resolution) in $m_{\mu\mu}$ distribution
- Divide in b-tagged and b-vetoed samples.

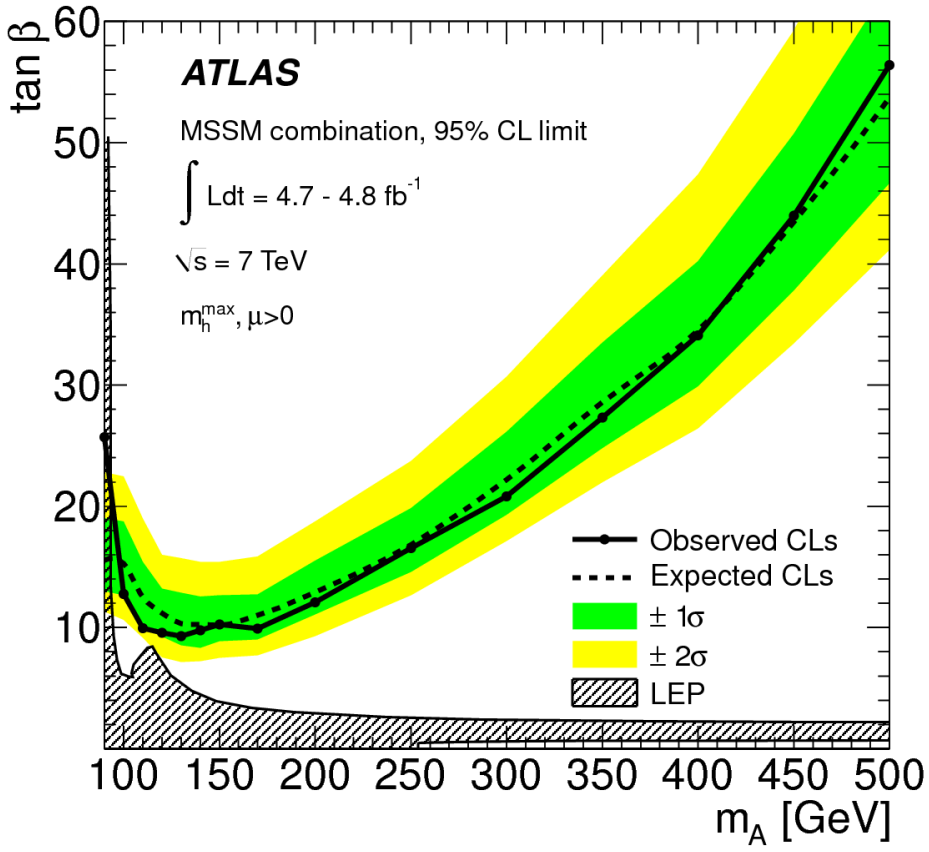
	b-tagged sample	b-vetoed sample
Mass Point	$m_A = 150\,\text{GeV}$	
Fit Range	110–200 GeV	
Background	980 ± 50	35900 ± 600
Signal $m_A = 150\,\text{GeV}, \tan\beta = 40$		
$b\bar{b}(h/A/H \to \mu\mu)$	$28 \pm 2\ ^{+3}_{-4}$	$271 \pm 22\ ^{+31}_{-40}$
$gg \to h/A/H \to \mu\mu$	$2.3 \pm 0.3 \pm 0.4$	$141 \pm 10\ ^{+22}_{-20}$
Data	985	36044

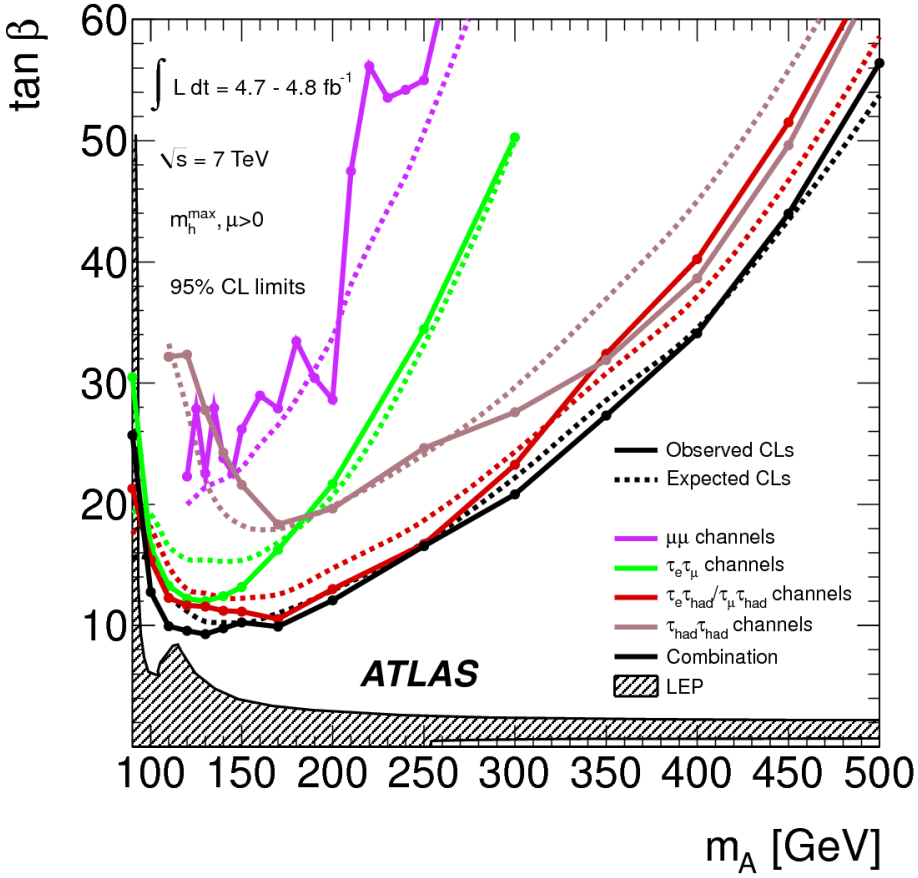




Combined h/H/A Exclusion Limits

- Exclusion limits in the MSSM parameter space of M_A and tan(β).
- Using cross sections in the m_h^{max} scenario with $\mu > 0$.
- Tightest constraint at m_A =130 GeV: tan(β) > 9.3





Generic Two-Higgs-Doublet Models

Two types of 2HDMs with natural flavour conservation:

- type I 2HDM: all quarks couple to just one of the Higgs doublets
- type II 2HDM: Q = +2/3 right-handed quarks couple to one Higgs doublet and Q = −1/3 right-handed quarks couple to the other.

Relevant couplings

$y_{\mathrm{2HDM}}/y_{\mathrm{SM}}$	Type I	Type II
ξ_h^{V}	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
ξ_h^{u}	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^{d}	$\cos\alpha/\sin\beta$	$-\sin\alpha/\sin\beta$
ξ_H^{V}	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
ξ_H^{u}	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^{d}	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$

Tree-level couplings of neutral Higgs bosons to vector bosons, up-type and down-type quarks in type I and type II 2HDMs.

Neural Network Discriminants

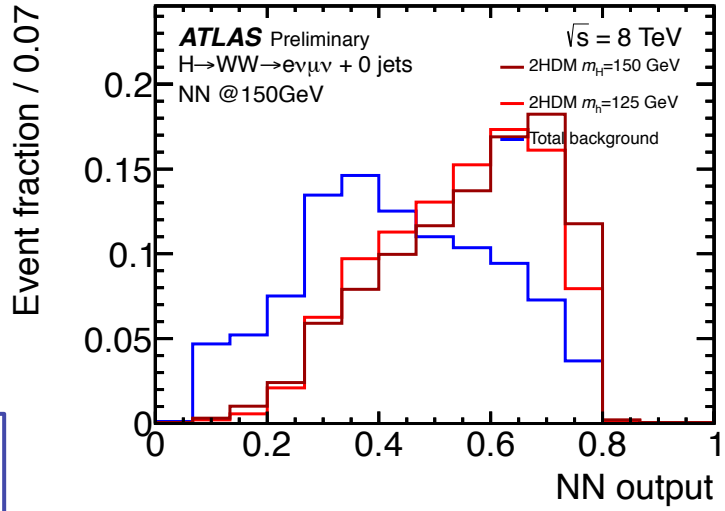
NN trained @ m_H = 150 GeV

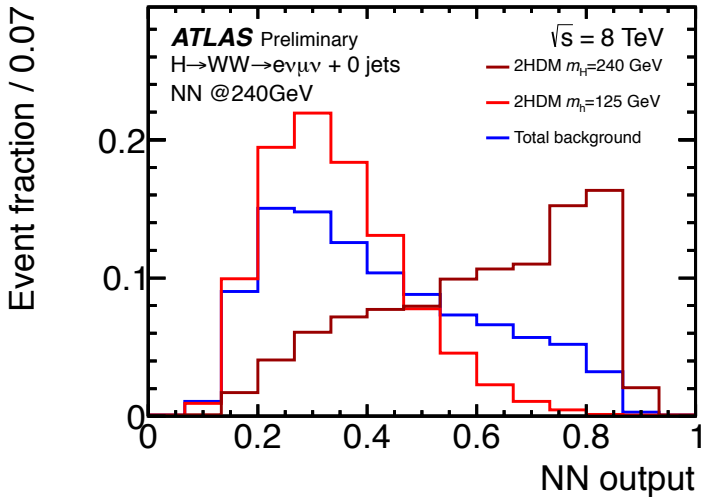
NN trained @ m_H = 240 GeV

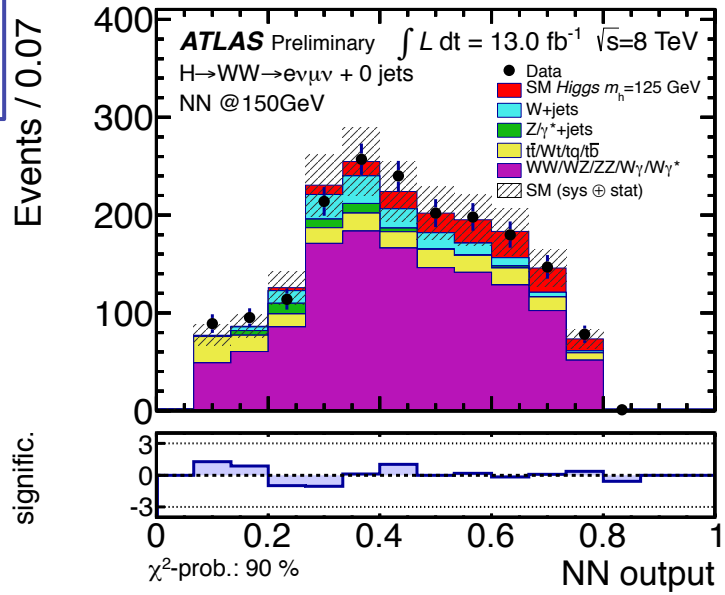
Legend:

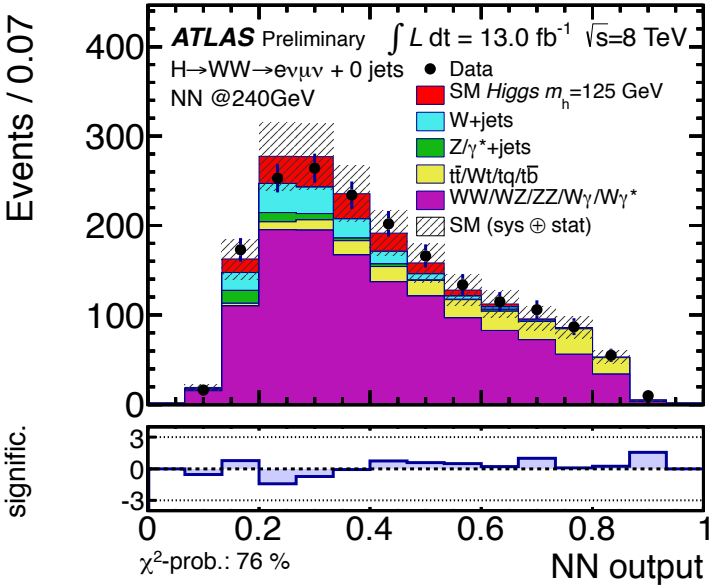
- Heavy Higgs
- Light Higgs
- Total background

Low and High mass Higgses can be well separated





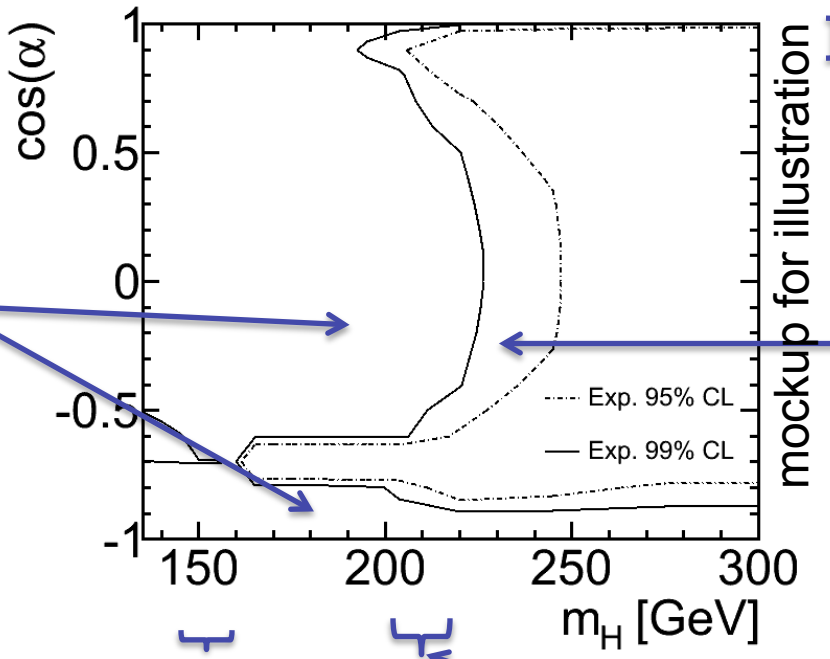




Exclusion Limits in the cos α vs. m_H Plane

- Use CL_s method to compute confidence level for each triplet (tan β, cos α, m_H)
- Plot exclusion contours in the cos α vs. m_H plane

expected limits only



y bin width = 0.1

Expected exclusion limit at 99% C.L.

Expected exclusion limit of 95%

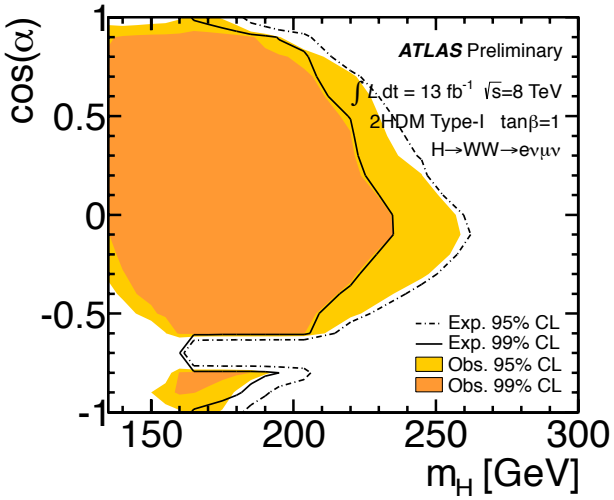
x bin width = 5 GeV from 135 to 200 GeV

x bin width = 20 GeV from 200 to 300 GeV

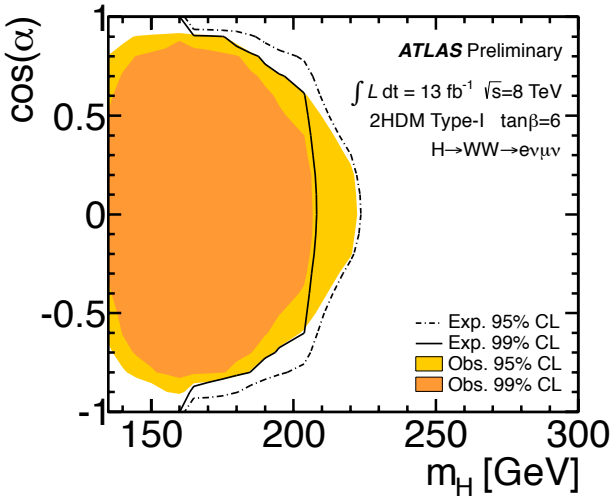
Exclusion Limits for 2HDMs

y_{2HDM}/y_{SM}	Type I	Type II
ξ_h^V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\sin\beta$
ξ_H^V	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$

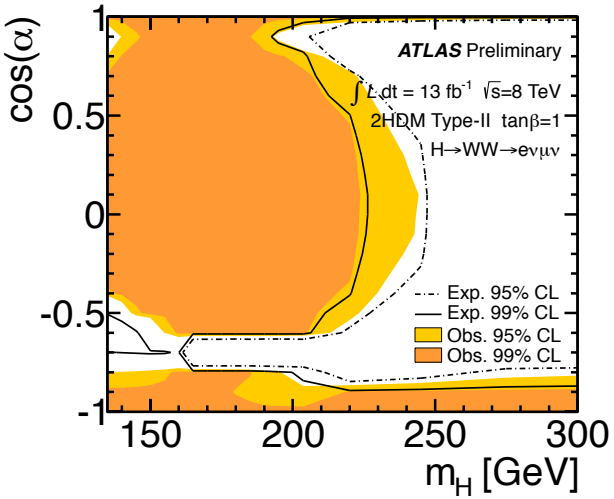
tan β = 1

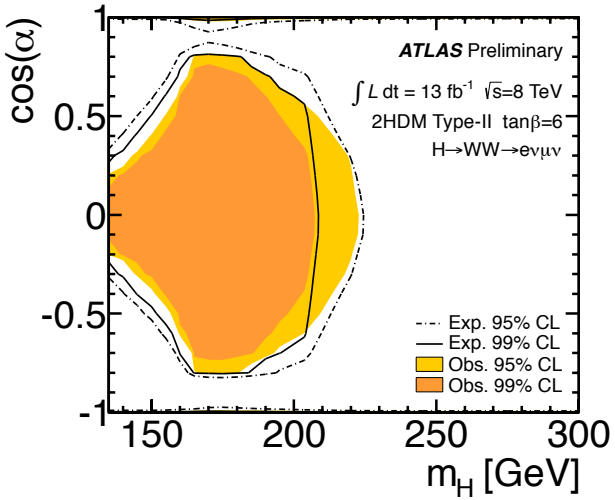


tan β = 6



y_{2HDM}/y_{SM}	Type I	Type II
ξ_h^V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\sin\beta$
ξ_H^V	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$

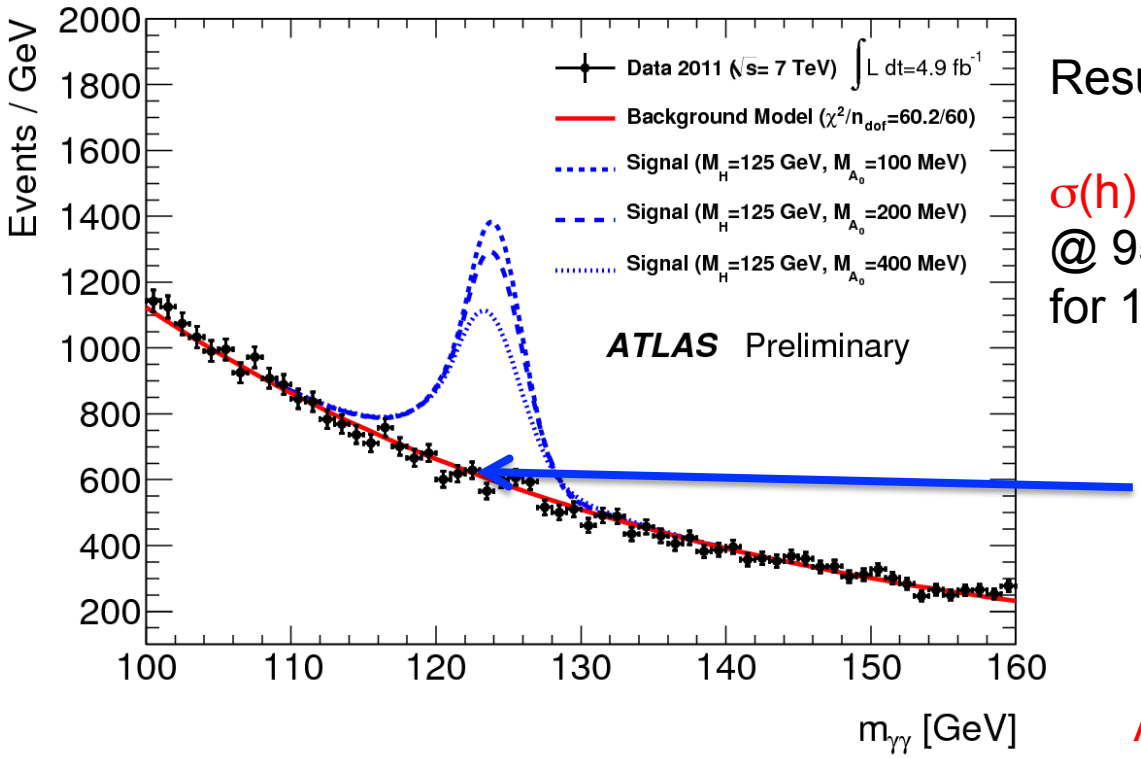




ATLAS-CONF-2013-027

Ultra-light CP-odd Higgs in nMSSM

- Consider: $h \rightarrow a^0a^0 \rightarrow \gamma\gamma\gamma\gamma$ decay chain
- a^0 assumed to be ultra-light: 100 – 400 MeV
- Photons from a^0 decay are collimated ➔ $m_{\gamma\gamma}$ discriminant
- Event selection is close to, but looser than SM $h \rightarrow \gamma\gamma$ analysis.



Results:

$\sigma(h) \cdot BR(h \rightarrow a^0a^0 \rightarrow \gamma\gamma\gamma\gamma) < 0.1$ pb
@ 95% C.L.
for 115 GeV < m_h < 140 GeV

SM Higgs not seen because of looser selection criteria

ATLAS-CONF-2012-079

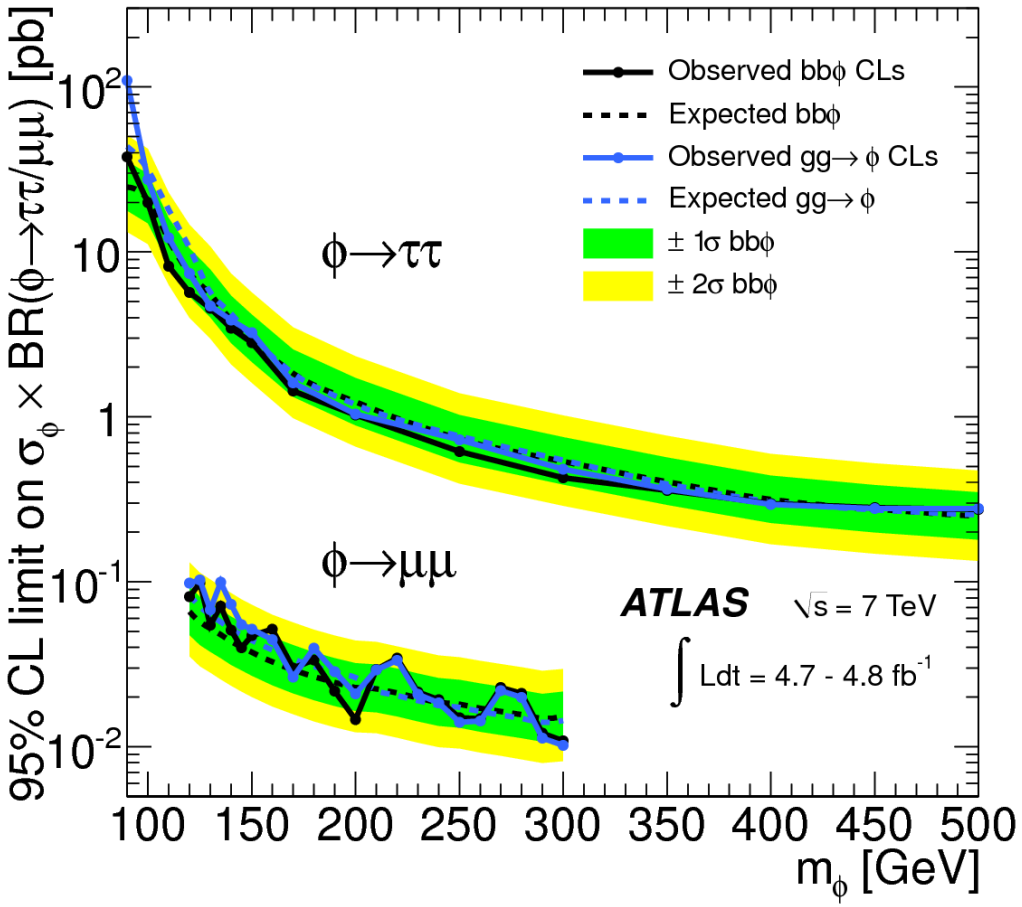
Conclusions

- Higgs Boson discovery at the LHC prompts deeper investigations of the nature of the new particle.
- Searches for additional neutral and charged Higgs bosons.
- Large regions of MSSM parameter space are excluded, but there are still open regions of parameter space compatible with the observed Higgs at 125 GeV.
- Searches beyond the MSSM:
  - Generic 2HDM
  - nMSSM
- Stay tuned! Analyses with full Run I data set are ongoing.

BACKUP

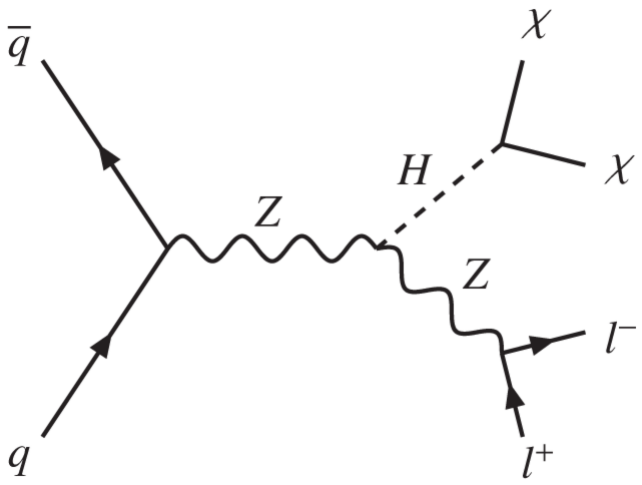
Limits on Generic Scalar

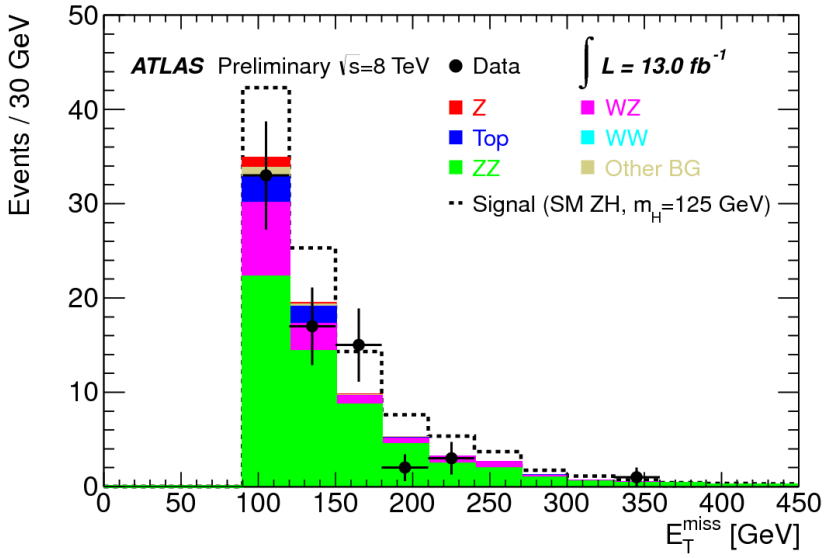
Generic case of a single scalar boson ϕ.



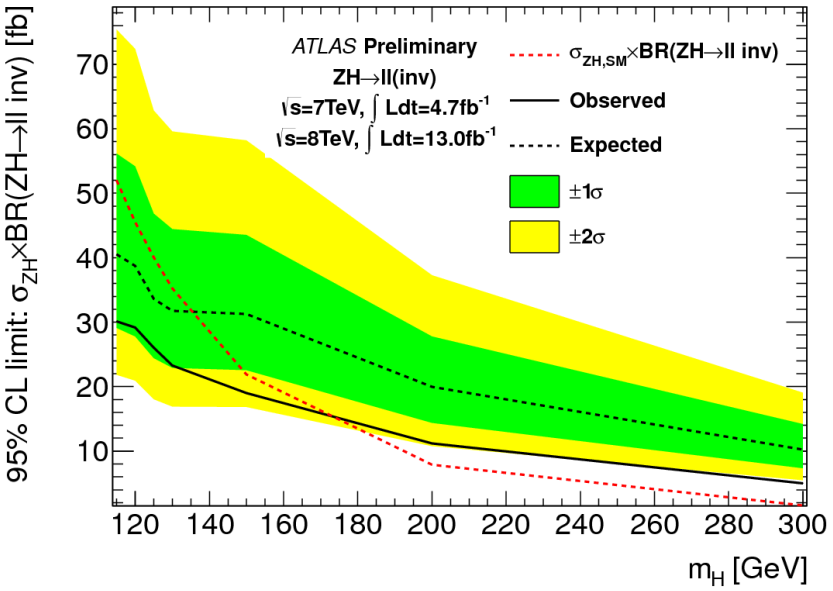
Produced either in gluon-fusion or b-associated production.

Higgs to Invisible Particles





- Conjecture: decay to stable or long-lived weakly interacting particles, e.g. dark matter particles
- Main background: ZZ → llνν continuum production
- ML fit to E_T^{miss} distribution
- Investigate 2 scenarios:
  1) Observed Higgs at m_H = 125 GeV decays to invisible particles
     Observed limit: BR(H → invisible) < 65%
  2) An additional Higgs boson decays invisibly



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