Beyond-the-Standard Model Higgs searches using the ATLAS experiment

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On behalf of the ATLAS Collaboration

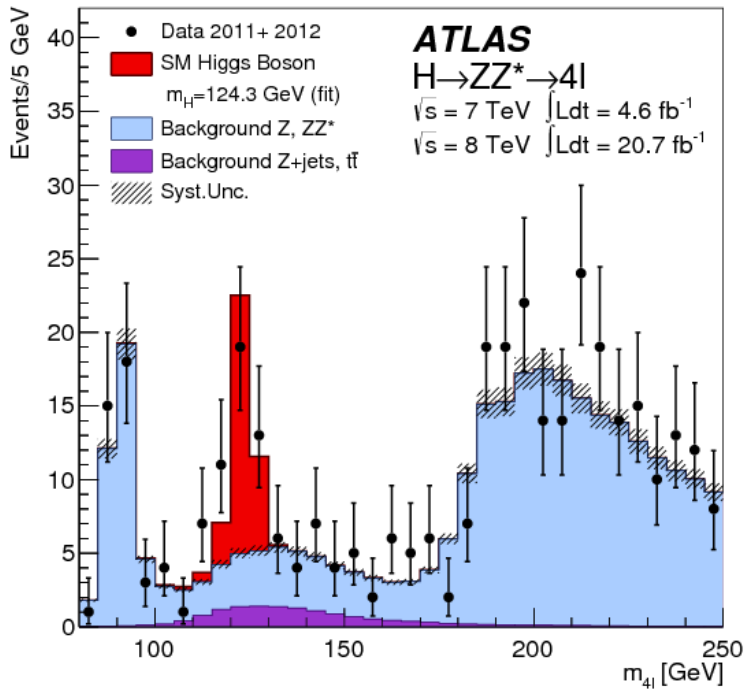
WORKSHOP ON DISCOVERY PHYSICS AT THE LHC, 1 December

Higgs discovery at CMS and ATLAS

- 2012: New boson discovered by CMS + ATLAS
- 2013: Mass and spin-parity studies revealed

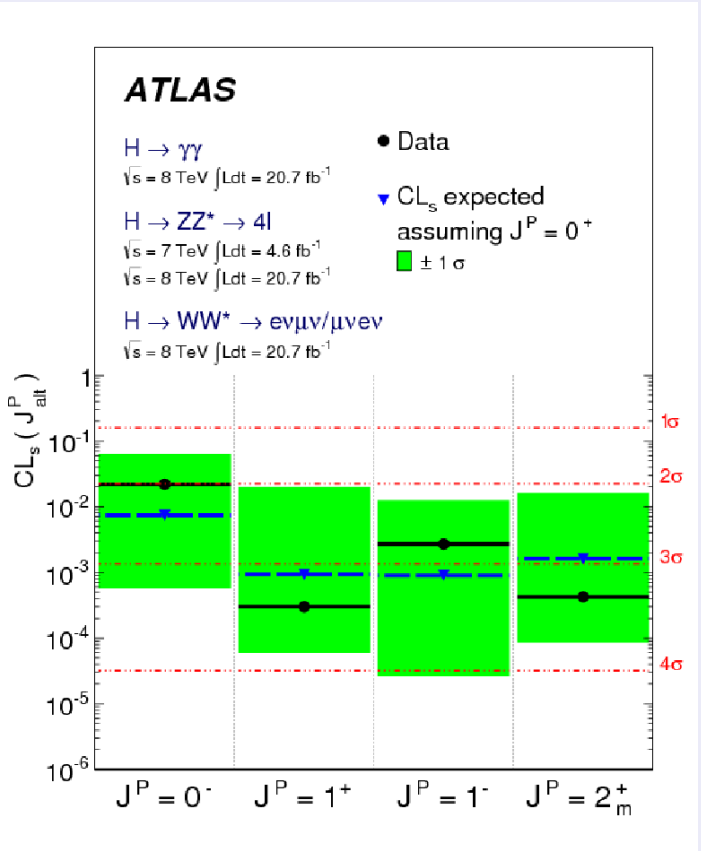
$m_H \approx 125.5$ GeV

CERN-PH-EP-2013-103



$J^P = 0^+$ compatible

CERN-PH-EP-2013-102



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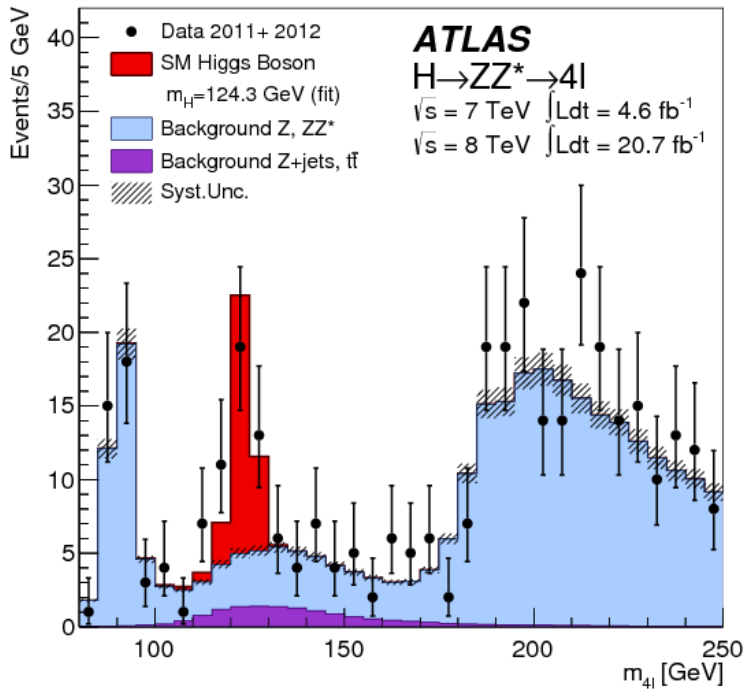

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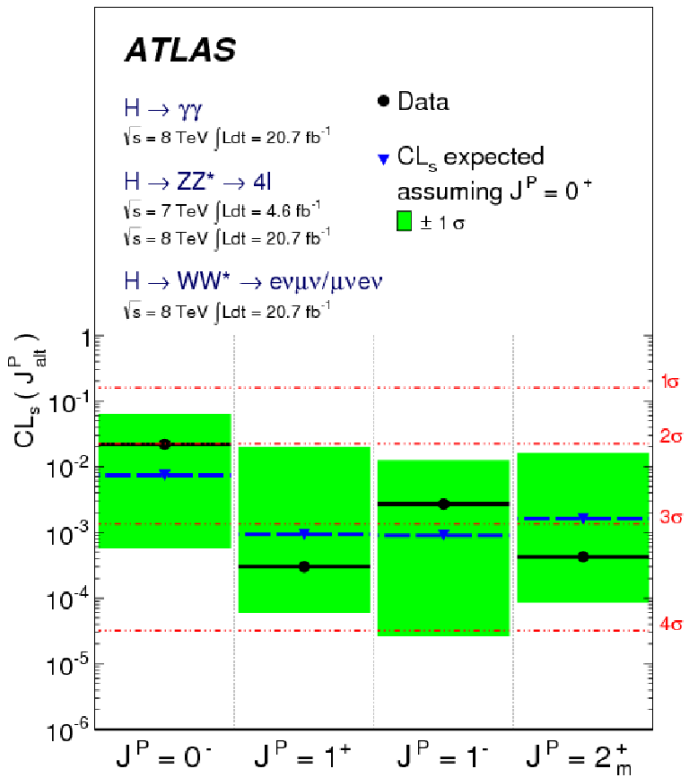

No deviations from SM

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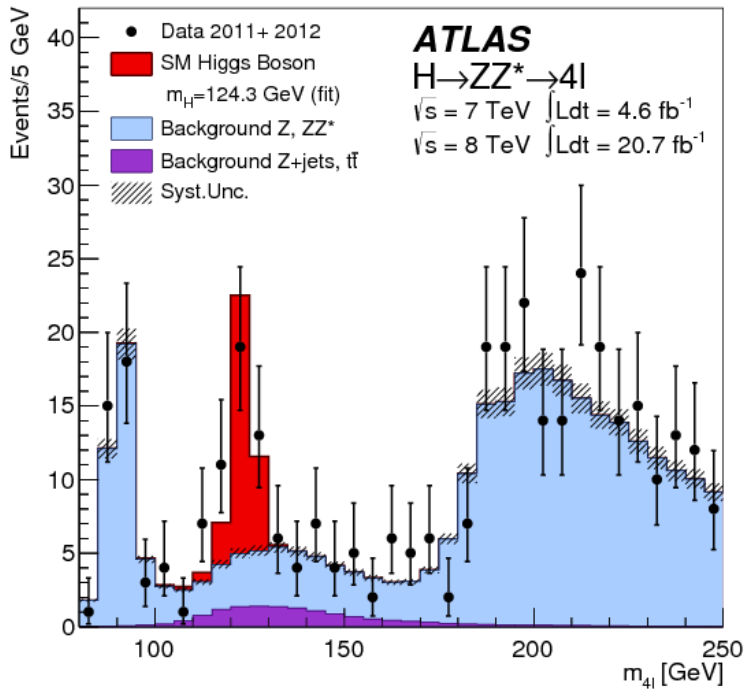

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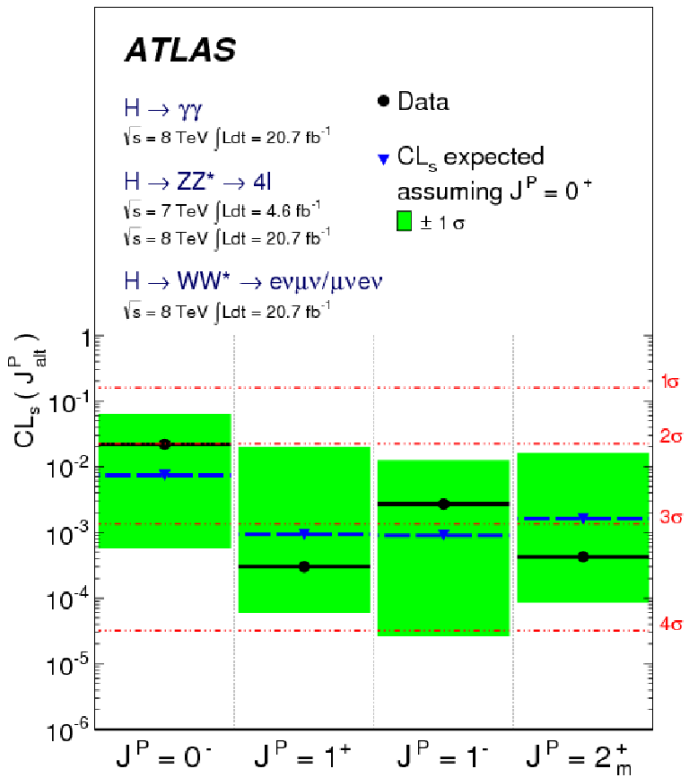

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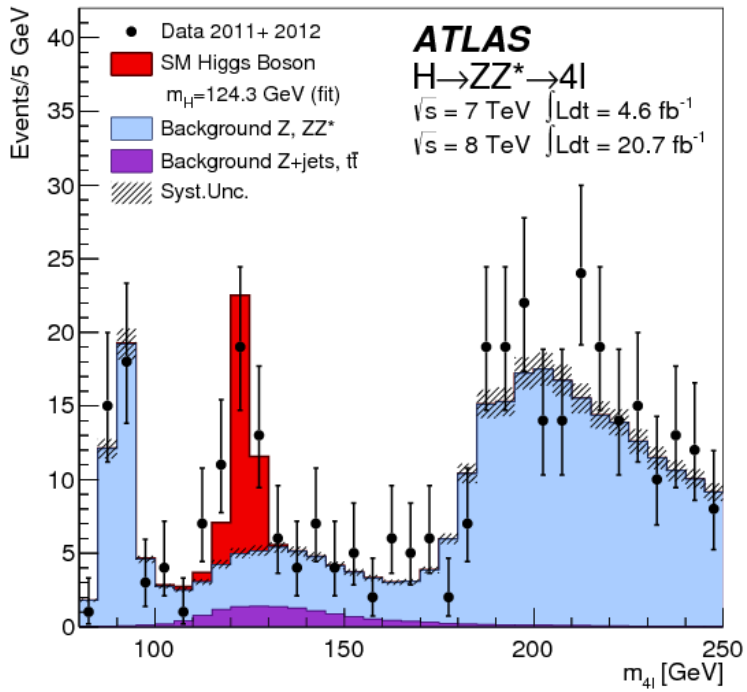

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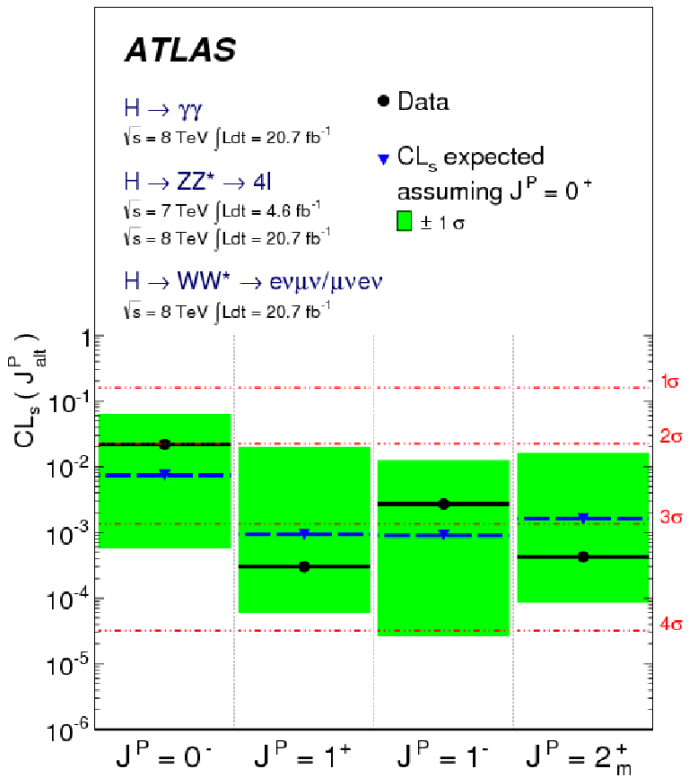

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- σ, BR and couplings of H show no deviation from SM within uncertainties
- Higgs doublet responsible for EW symmetry breaking?
- **Is Higgs sector minimal or extended? (BSM)**

Beyond the SM: 2HDMs

- SM Higgs sector has experimental constrains:

$$\rho \equiv m_W/(m_Z \cos\theta_W) \to 1$$

- 2HDM: Simple extension by adding complex Higgs doublet, SU(2).
- **Assumptions**:
  - CP-conservation
  - Softly broken $\mathcal{Z}_2$ symmetry ($\Phi_1 = -\Phi_1$)
  - Electroweak symmetry breaking, and $v_1 v_2 \neq 0$

8 fields

3 give mass to $W^{\pm}$ and Z bosons, 5 physical **scalar ("Higgs") fields**

The Big Five

Five most **difficult** *and* **elusive** *animals in Africa to hunt.*





h H A H^+ H^-

CP-even pseudo scalar CP-odd

2HDMs

Degrees of freedom

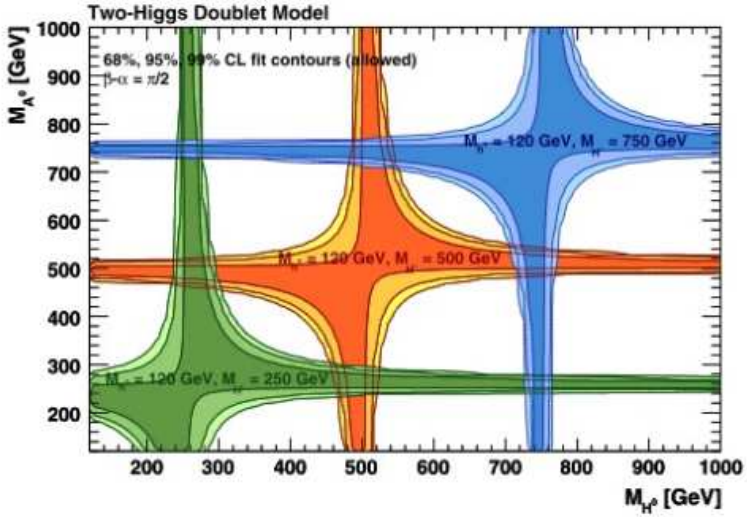
m_h m_H m_A m_{H^+} m_{H^-} $tan\beta$ $\cos(\beta-\alpha)$

Possible coupling

- Type-I (κ_V, κ_f)
- Type-II ($\kappa_u, \kappa_{d,\ell}$)
- Type-III (Lepton Specific)
- Type-IV (Flipped Lepton Specific)

Assumptions can be made

- $m_h = 125$ **GeV**.
- $m_A = m_H = m_{H^\pm}$



Eur. Phys. J. C (2012) 72:2003

Figure: Constraints in the 2HDM

Probing the 2HDM

h_{SM} coupling measurements

- Couplings of h_{2HDM} differs from h_{SM}
- 2HDM and MSSM, SM Couplings interpretation

Recent direct searches:

- $h/A/H \to \tau\tau$ (MSSM)
- $H^+ -> \tau\nu$+jets (2HDM + MSSM)
- Di-Higgs resonances: $hh \to \gamma\gamma bb, hh \to 4b$
- $H \to WW$ (2HDM)

SM Coupling Measurements

Higgs coupling limits 2HDM

Constrains on new physics via Higgs coupling [1]

H coupling scale factor: $\frac{2HDM}{SM}$

2HDM constrain

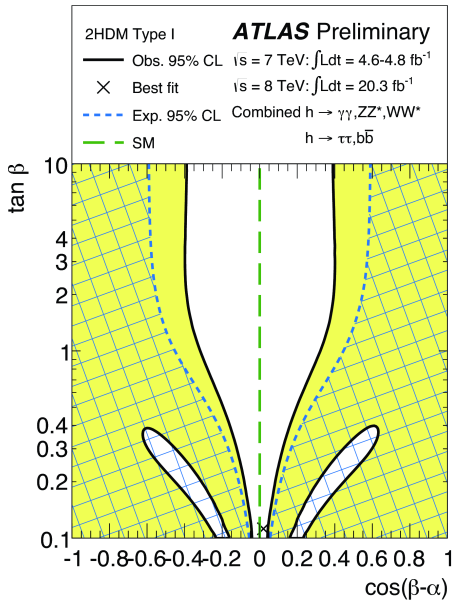
- Assume $m_h \approx 125.5$ GeV
- Production and decay rates rescaled (scale factors)
- Ratios $\frac{2HDM}{SM}$ cast as functions of β and α
- Assumed same production modes as in the SM

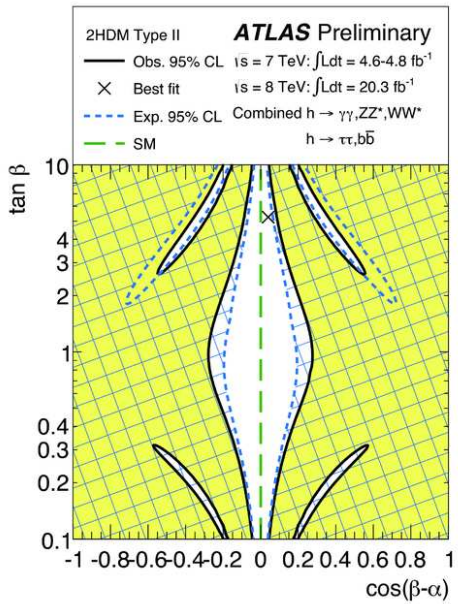
Coupling scale factor	Type I	Type II	Type III	Type IV
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

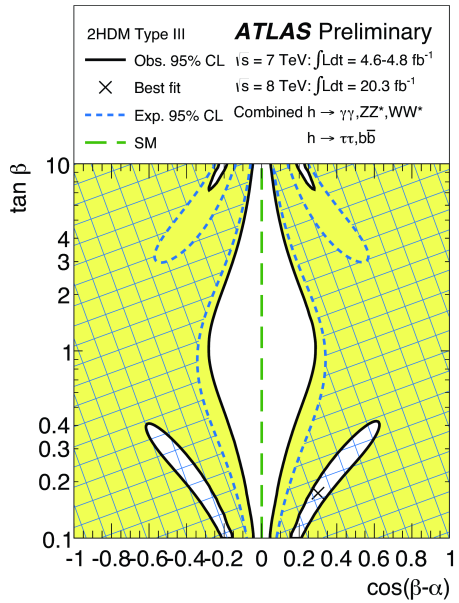
Likelihood limits

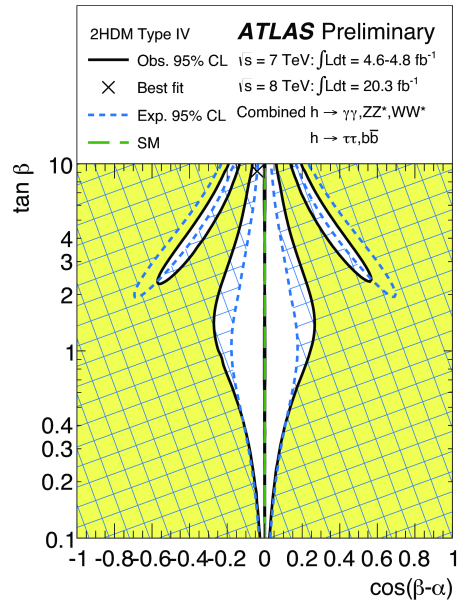
Obs & exp exclusion limits at 95% CL

ATLAS-CONF-2014-010









Higgs coupling limits Simplified MSSM

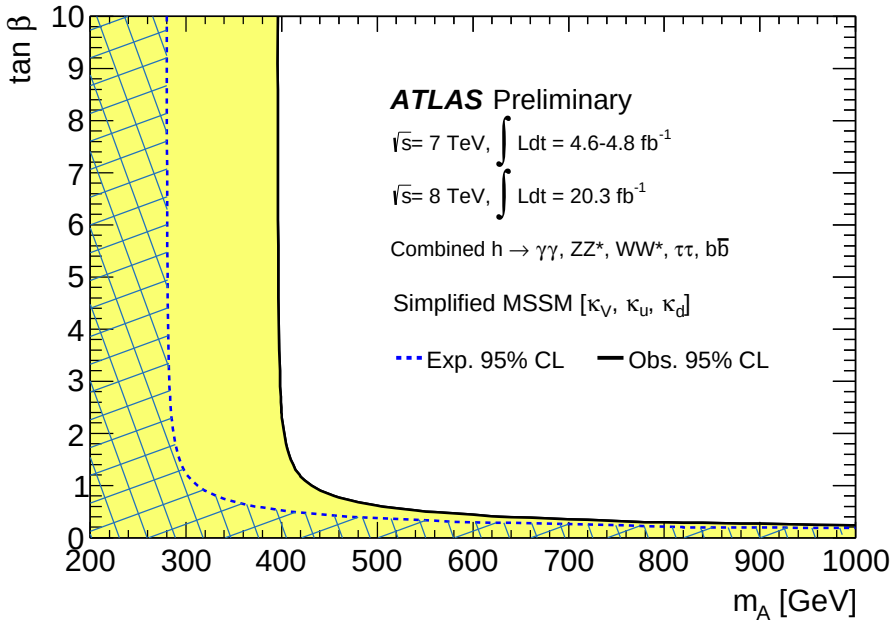
Constrains on new physics via Higgs coupling [1]
*MSSM is 2HDM Type-II

simplified MSSM constrain

- simplified MSSM is not general
- Assume $m_h \approx 125.5$ GeV
- Mass mixing matrix simplified s.t. Higgs couplings are functions of m_A and $\tan\beta$ only:
  - $\kappa_V = \frac{s_d + \tan\beta s_u}{\sqrt{1+\tan_2\beta}}$
  - $\kappa_u = s_u \frac{\sqrt{1+\tan_2\beta}}{\tan\beta}$
  - $\kappa_d = s_d \sqrt{1+\tan_2\beta}$

Likelihood scan (m_A ,$\tan\beta$)

Observed (expected) lower limit at 95% CL:
$m_A > 400$ (280) GeV for $2 \le \tan\beta \le 10$
Higher rate in boson decay than predicted by SM causing stronger limit.
Simplified MSSM limited by $\kappa \le 1$



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Direct searches

Charged H $H^{\pm} \rightarrow \tau^{\pm}\nu$ + jets

Search $H^{\pm} \rightarrow \tau^{\pm}\nu$ in hadronic final states: 19.5fb^{-1} p-p at $\sqrt{s}$ = 8 TeV ATLAS-CONF-2014-050 [2]

Split at $m_{top} \approx 173.3$ GeV

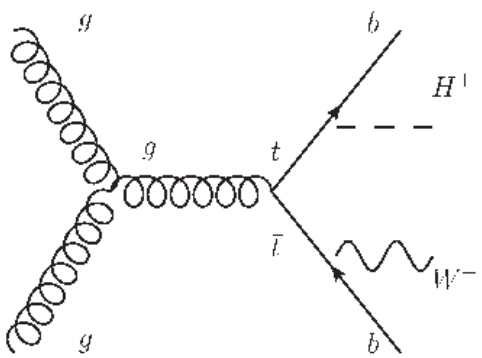
Low mass: $m_{H^+} < m_{top}$

$t \rightarrow bH^+$ $(m_{H^+} \in (80, 160))$

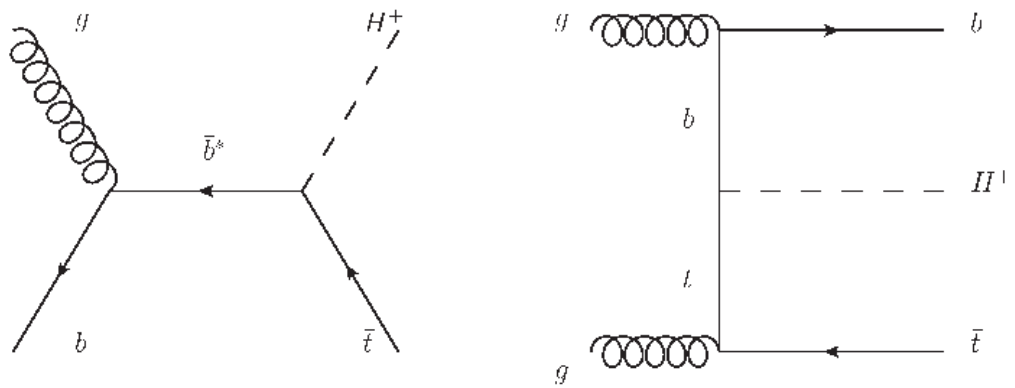
High mass: $m_{H^+} > m_{top}$

t associated $(m_{H^+} \in (180, 1000))$

$\tan\beta > 2$, $1 < \tan\beta < 2$



Large $\tan\beta$



Decay:

- $H^+ \rightarrow \tau^+\nu$
- $W \rightarrow q\bar{q}$

Final States:

- τ_{had}, E_T^{miss}
- 2 b-jets (at least 1 for $m_{H^+} > m_{top}$)
- 2 q-jets from W_{had}
- no additional leptons

Data driven:

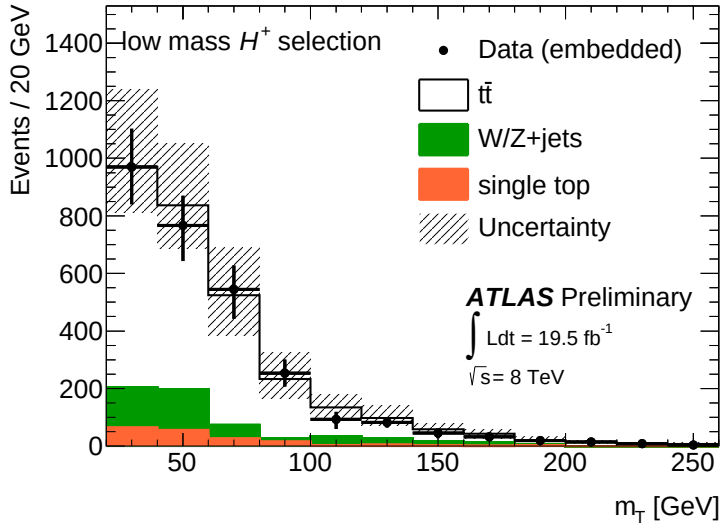
- True τ_{had} (embedding method)
  - μ+jets data events ('loose' selection)
  - μ REPLACED with MC τ_{had} decay (TAUOLA)
  - Distribution is normalized
- Misidentified jets
  - Fake τ_{had} calculated from: ID (miss-ID) efficiency from $t\bar{t}$ signal (W+jets control)
  - m_T distribution fit for 200-800 GeV

Simulated:

- Misidentified e/μ contribute 1—2% BKG

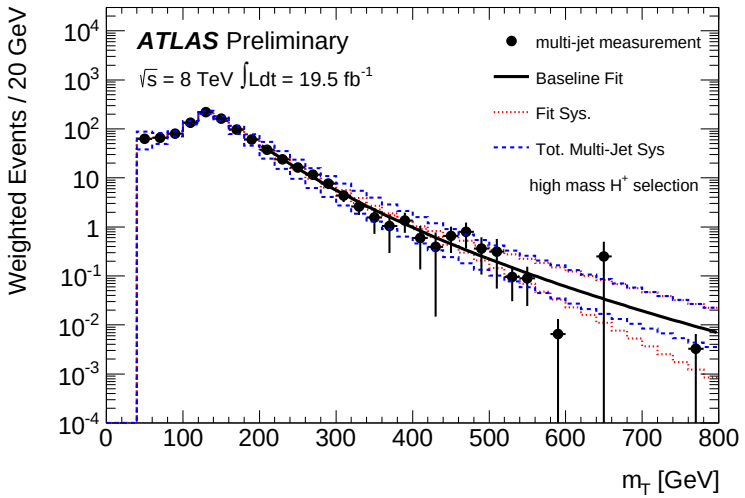
Final Event Selection

Sample	Low mass H^+ selection	High mass H^+ selection
True τ_{had} (embedding method)	2900 ± 60 ± 500	3400 ± 60 ± 400
Misidentified jet → $\tau_{\text{had-vis}}$	490 ± 9 ± 80	990 ± 15 ± 160
Misidentified e → $\tau_{\text{had-vis}}$	15 ± 3 ± 6	20 ± 2 ± 9
Misidentified μ → $\tau_{\text{had-vis}}$	18 ± 3 ± 8	37 ± 5 ± 8
All SM backgrounds	3400 ± 60 ± 500	4420 ± 70 ± 500
Data	3244	4474
H^+ (m_{H^+} = 130 GeV)	230 ± 10 ± 40	
H^+ (m_{H^+} = 250 GeV)		58 ± 1 ± 9



ATLAS-CONF-2014-050

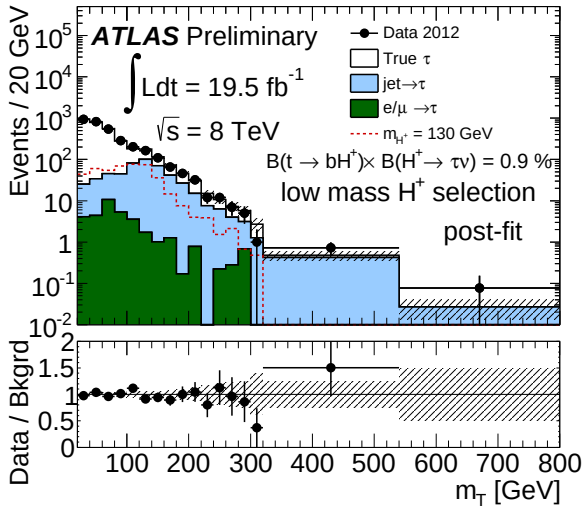
High Mass

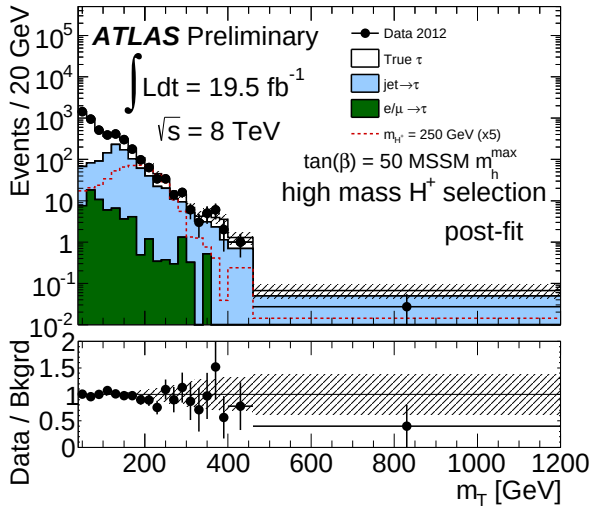


Charged H $H^{\pm} \rightarrow \tau^{\pm}\nu$ + jets

ATLAS-CONF-2014-050

- Expected limits derived with asymptotic approximation
- Limits reject 95% CL
- Expected and observed limits agree within systematics
- Agreement with SM



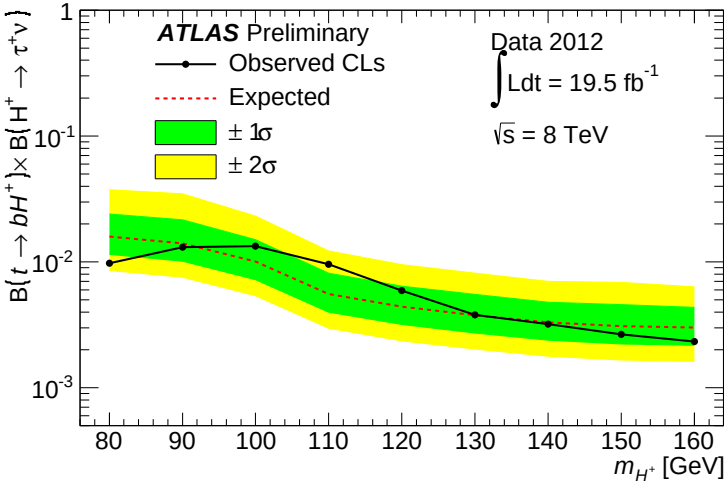


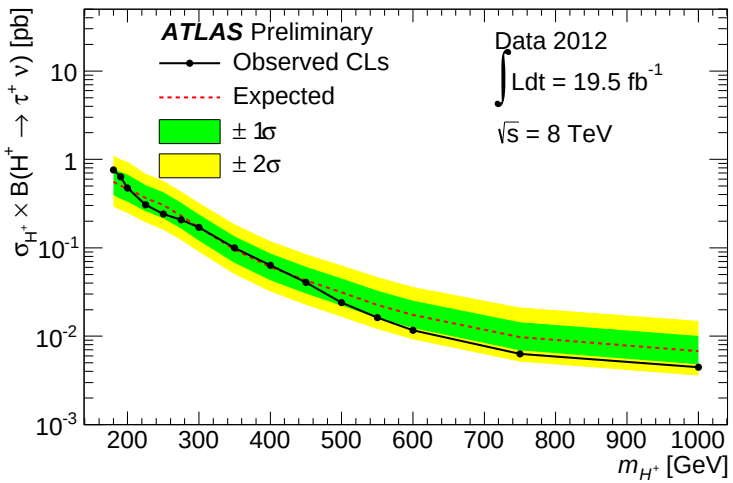
$B(t \rightarrow bH^+) \times B(H^+ \rightarrow \tau^+\nu)$

between 0.23% and 1.3% (m_{H^+} = 80-160 GeV)

$\sigma(pp \rightarrow tH^+ + X) \times B(H^+ \rightarrow \tau^+\nu)$

between 0.76 pb and 4.5 fb (m_{H^+} = 180-1000 GeV)





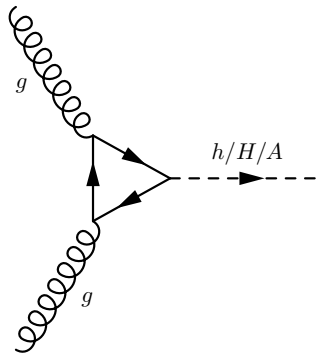
Search for neutral Higgs bosons (MSSM) JHEP11(2014)056 [3]

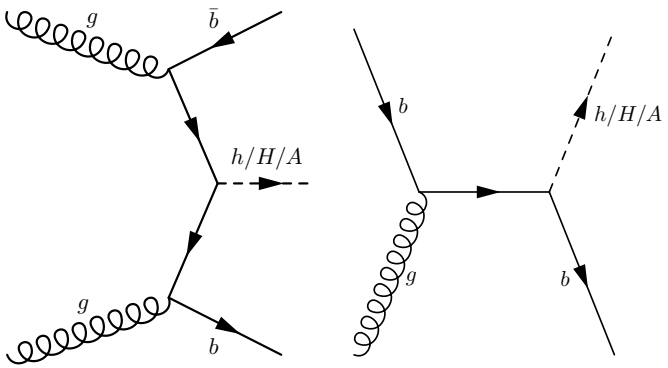
MSSM contains two Higgs doublets (2HDM)

- Upper bound $m_h \sim 135$ GeV
- $m_H \approx m_A \approx m_{H^\pm}$
- m_h properties similar to $m_{H_{SM}}$

Scenarios

- m_h^{max}: $m_h \lesssim 135$
- m_h^{mod-} & m_h^{mod+}: $m_h \lesssim 126$
- Two parameters: m_A, $\tan\beta$ increases parameter space

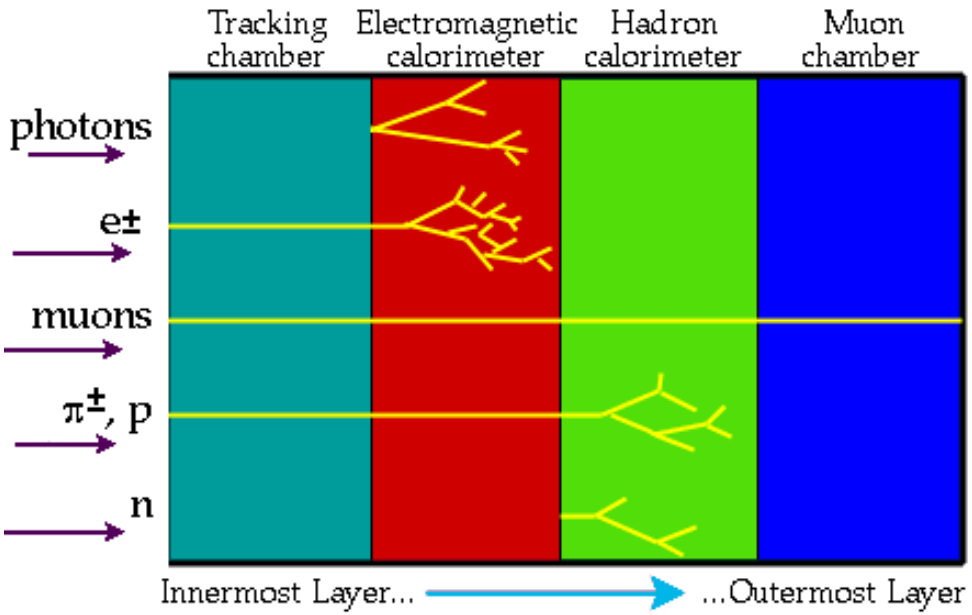


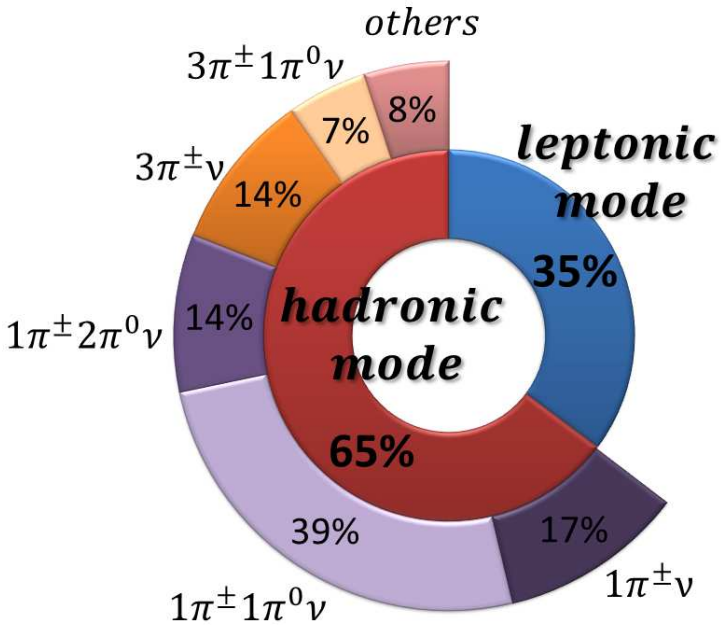


- Increased BR in $\tau\tau$ and bb decay.
- Higher b-associated cross section.
- Search channels:
  - $\tau_e\tau_\mu$ (6%) at 20.3 fb^{-1}
  - $\tau_{lep}\tau_{had}$ (46%) at 20.3 fb^{-1}
  - $\tau_{had}\tau_{had}$ (42%) at 19.5 fb^{-1}

mod ± different in $\frac{X_t}{M_{SUSY}}$.
M_{SUSY} — soft-SUSY-breaking squark mass
X_t — stop mixing parameter

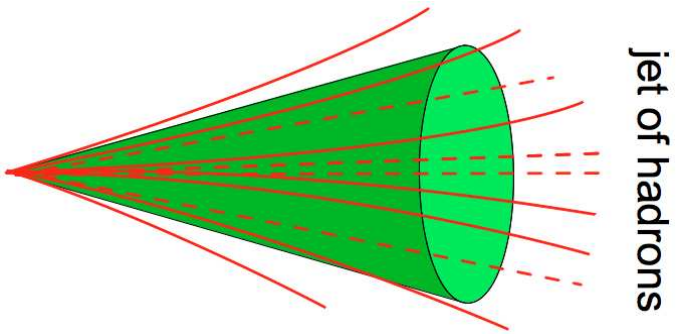
Different decays in ATLAS detector:



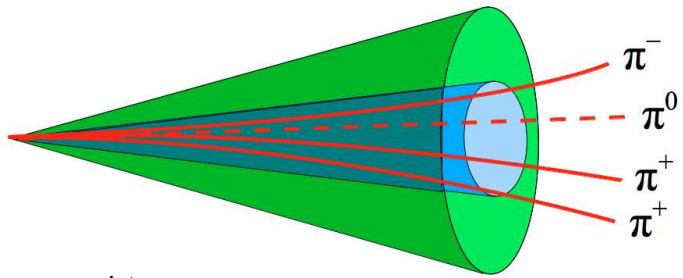


Taus never make the inner-detector (can only look at decays) ATLAS-CONF-2013-064

Non-Tau Jet



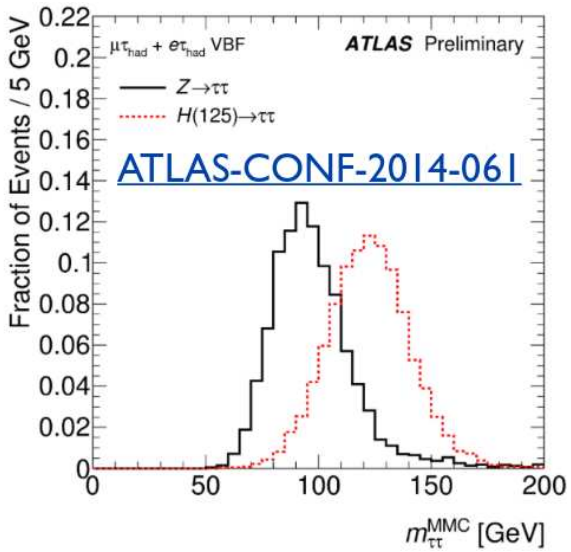
Tau Jet



- Narrow cone jet
- 1- or 3- prong jet

$m_{\tau\tau}$ reconstruction uses **Missing Mass Calculator**
Assume non-zero angle between τs and νs
System of equations with 6-8 unknowns
Most likely solution chosen (likelihood)

Nucl. Instrum. Methods,A654,p481-489



$m_{\tau\tau}^{\mathrm{MMC}}$ is final discriminating variable for $\tau_{lep}\tau_{lep}$ and $\tau_{lep}\tau_{had}$

$h/A/H \to \tau_e\tau_\mu$ and $\tau_{lep}\tau_{had}$

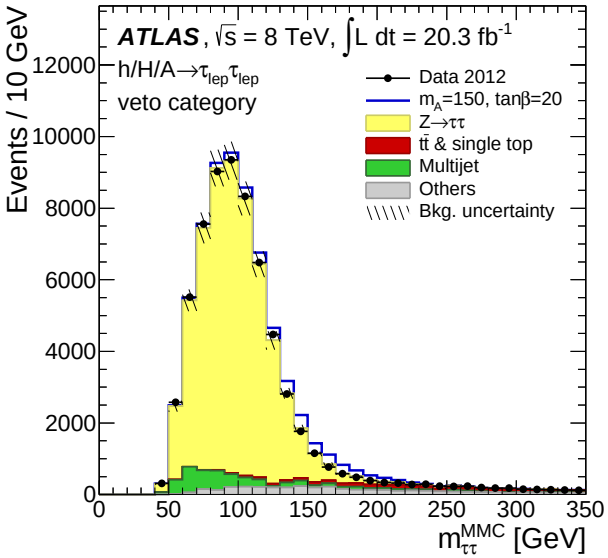
$\tau_e\tau_\mu$ and $\tau_{lep}\tau_{had}$ Backgrounds

- True bkg: $Z/\gamma* \to \tau\tau$
  - Estimated from τ embedded $Z/\gamma* \to \mu\mu$ data
  - Normalized using NNLO $Z/\gamma*$+jets cross section
- Multi-jet
  - two dimensional sideband (A-BCD)

	opposite charge	same charge
lep iso	**A**	**B**
fail iso	**C**	**D**

$$n_A = \frac{n_C}{n_D} n_B$$

- Other bkg taken from simulation
  Di-boson, W+jets, $t\bar{t}$, single t



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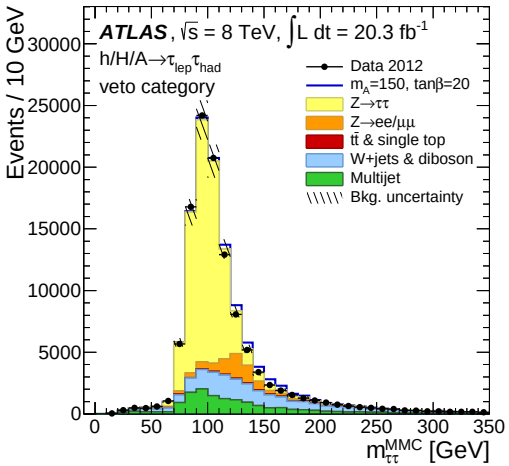
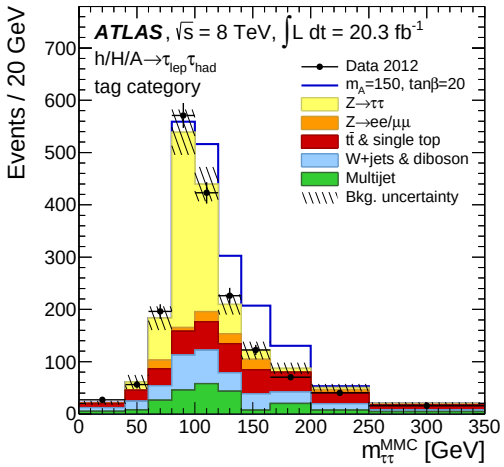
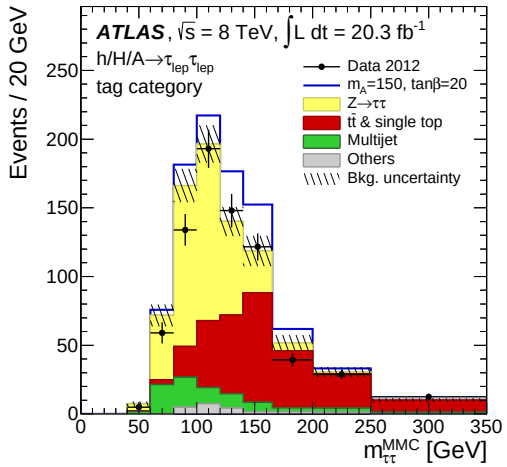






$h/A/H \rightarrow \tau_{had}\tau_{had}$

Multi-Jet is dominant background

- Total $\tau\tau$ transverse mass

$$m_T^{total} = \sqrt{m_T^2(\tau_1,\tau_2) + m_T^2(\tau_1, E_T^{miss}) + m_T^2(\tau_2, E_T^{miss})}$$

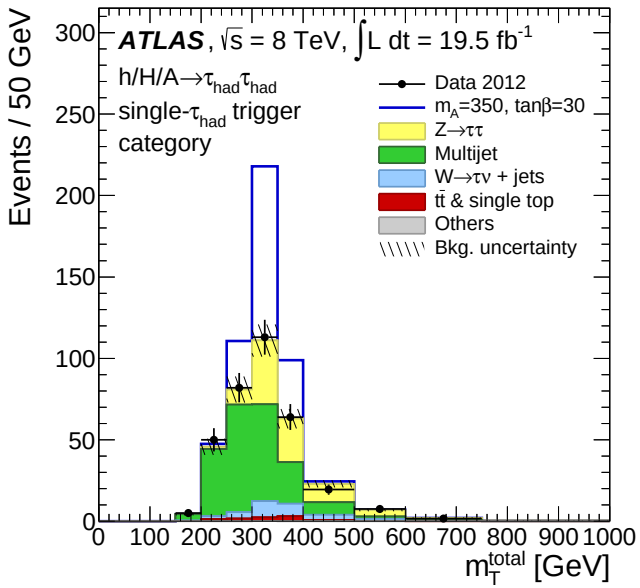
- Simulation used for remaining Bkg.

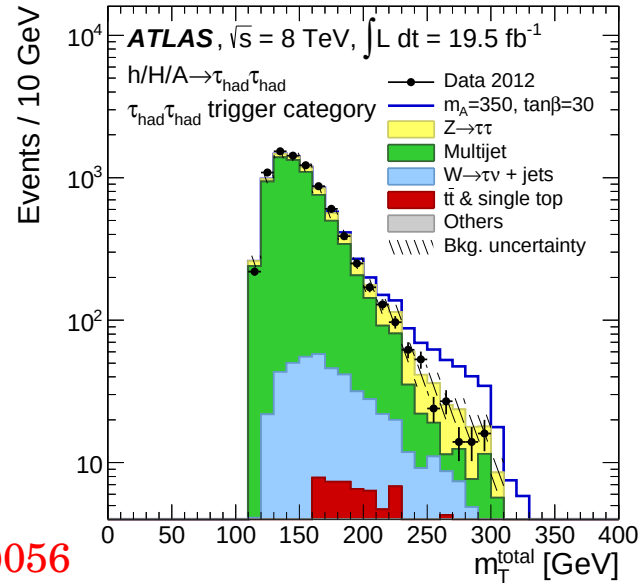
Single τ_{had} trigger

- τ_2 fail selection (Control Region)
- Normalized with fake efficiencies (QCD)

$\tau_{had}\tau_{had}$ trigger

Sideband method:
$\tau\tau$ charge, E_T^{miss}





JHEP11(2014)056

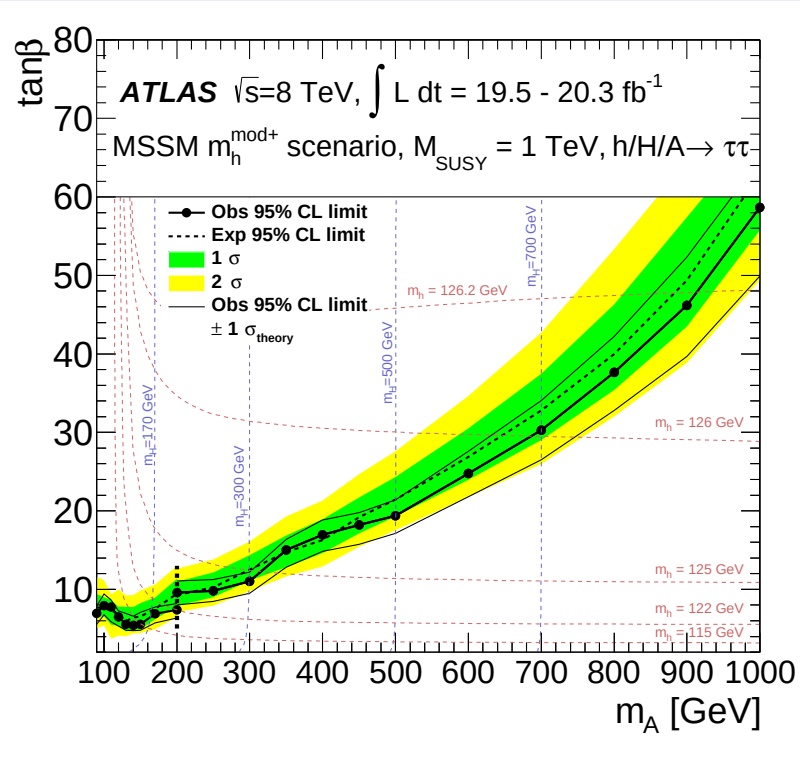
Exclusion limits:
calculated with asymptotic approximation

- $\tau_e\tau_\mu + \tau_{lep}\tau_{had}$ $(90 \leq m_A < 200$ GeV) Sensitive to h,H, A
- $\tau_{lep}\tau_{had}$ (high mass) + $\tau_{had}\tau_{had}$ $(m_A \geq 200$ GeV) Sensitive to H, A

$m_h^{mod\pm}$ scenario

- MSSM $(m_h^{mod}) \notin [m_A < 200] \cup [\tan\beta < 5.5]$

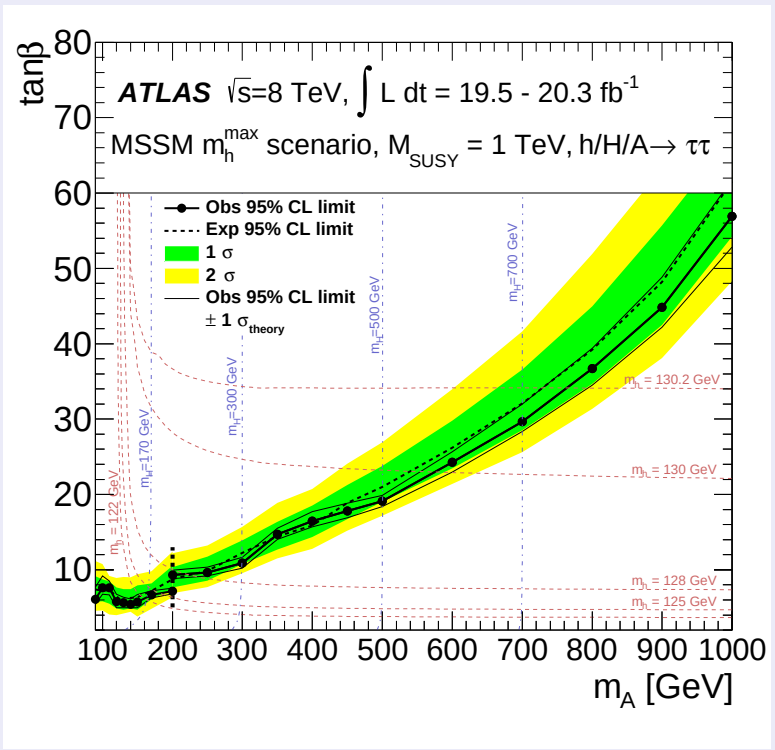
JHEP11(2014)056



m_h^{max} scenario

- If $m_h \equiv m_{h_{SM}}$ $(125.5 \pm 3$ GeV)
- MSSM (m_h^{max}) $\notin [m_A < 160] \cup [\tan\beta < 4] \cup [\tan\beta > 10]$

JHEP11(2014)056

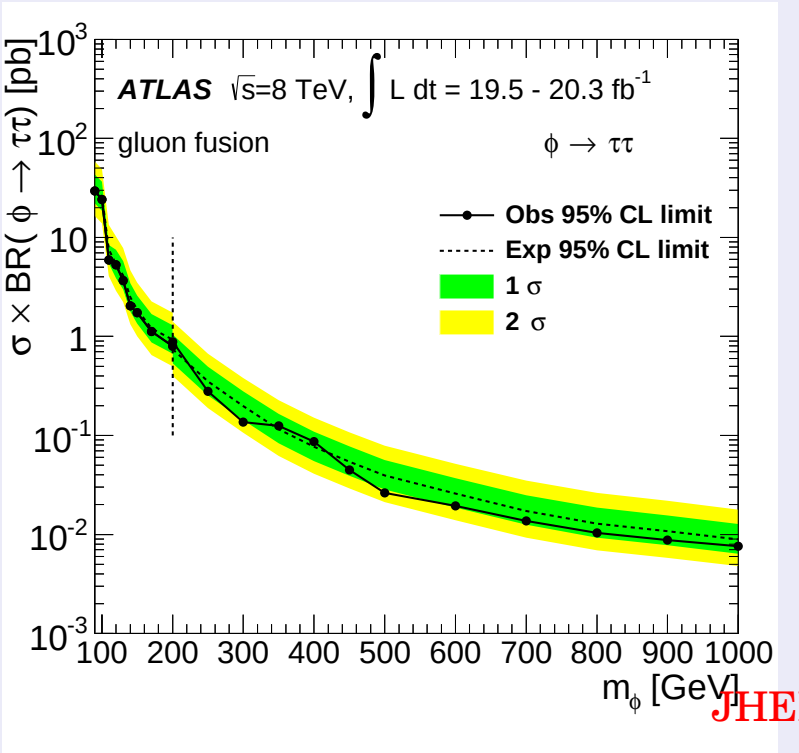


Exclusion of single scalar boson ϕ

ggF or b-associated $\to \tau\tau$ — 95% upper limit CL

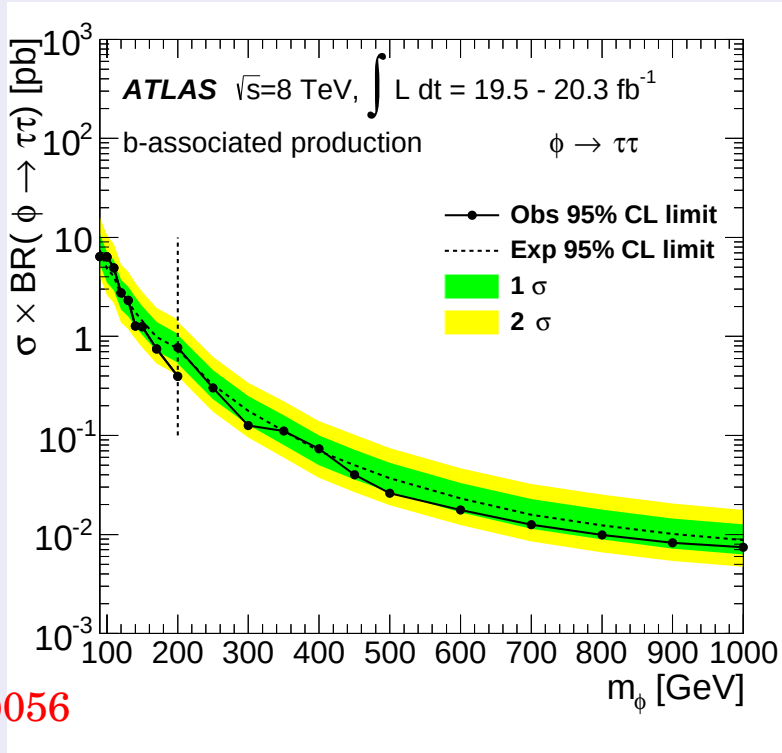
ggF exclusion

- $\sigma \times BR > 29$ pb $(M_\phi = 90\text{GeV})$
- $\sigma \times BR > 7.4$ pb $(M_\phi = 1\text{TeV})$



b-associated exclusion

- $\sigma \times BR > 6.4$ pb $(M_\phi = 90\text{GeV})$
- $\sigma \times BR > 7.2$ pb $(M_\phi = 1\text{TeV})$

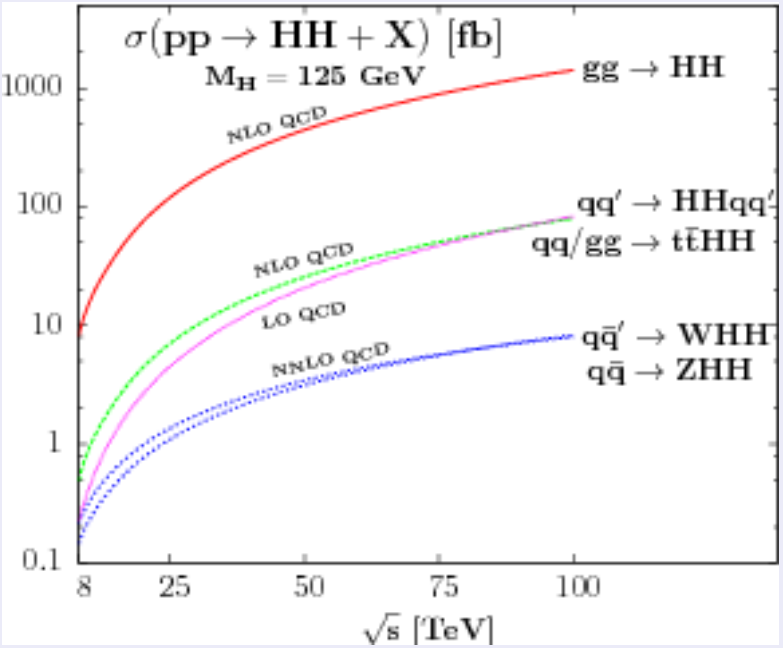


JHEP11(2014)056

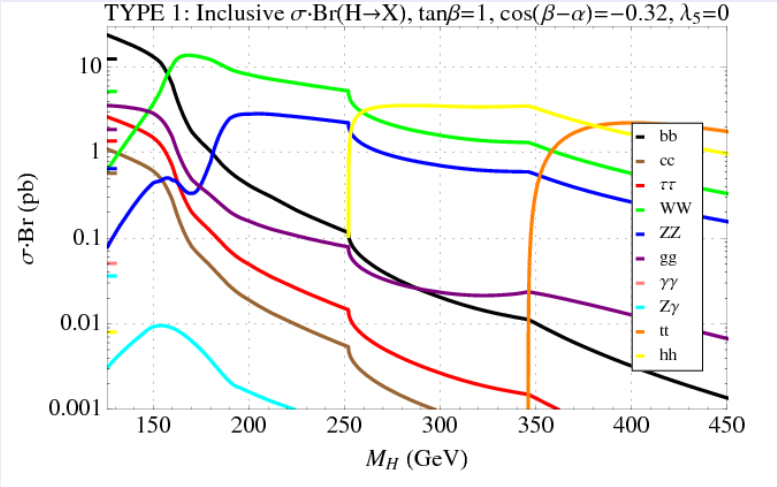
Di Higgs Resonant Searches

Di-Higgs SM rate too low to be observed at current LHC lumi [6]

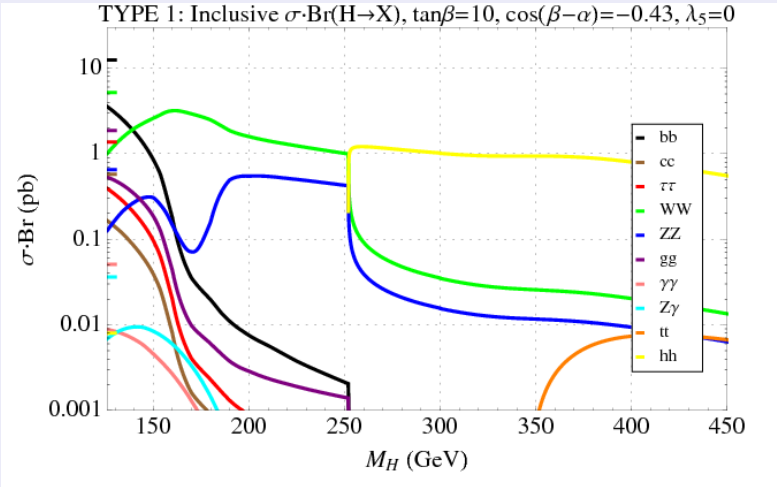
JHEP 1304 (2013) 151



2HDM XS can be greater than 1 pb [7]



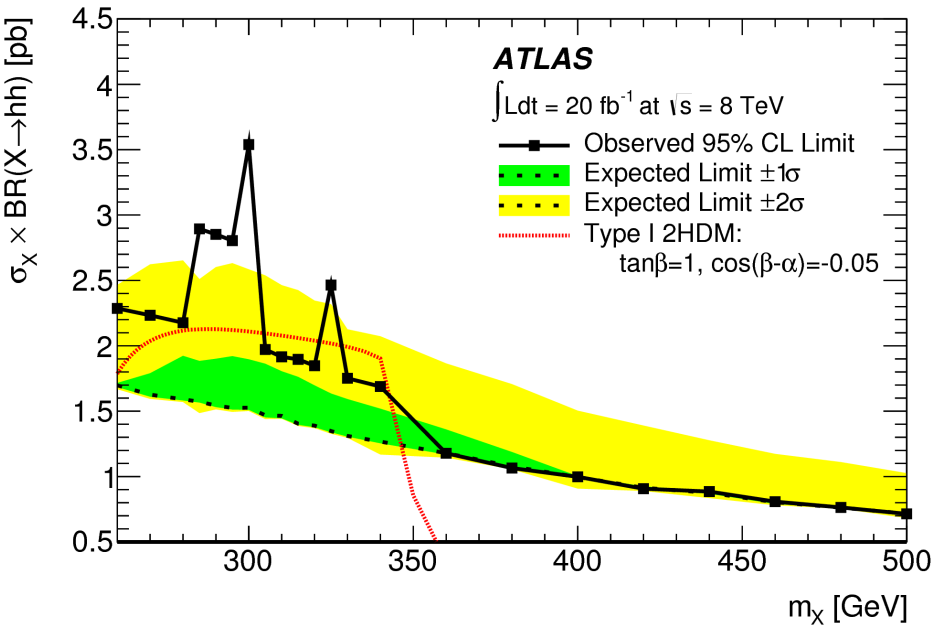
RU-NHETC-2013-07

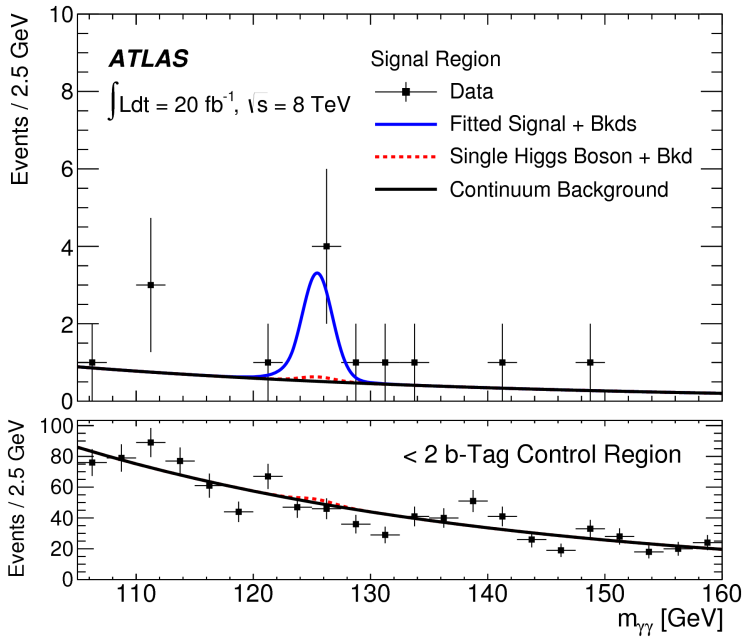


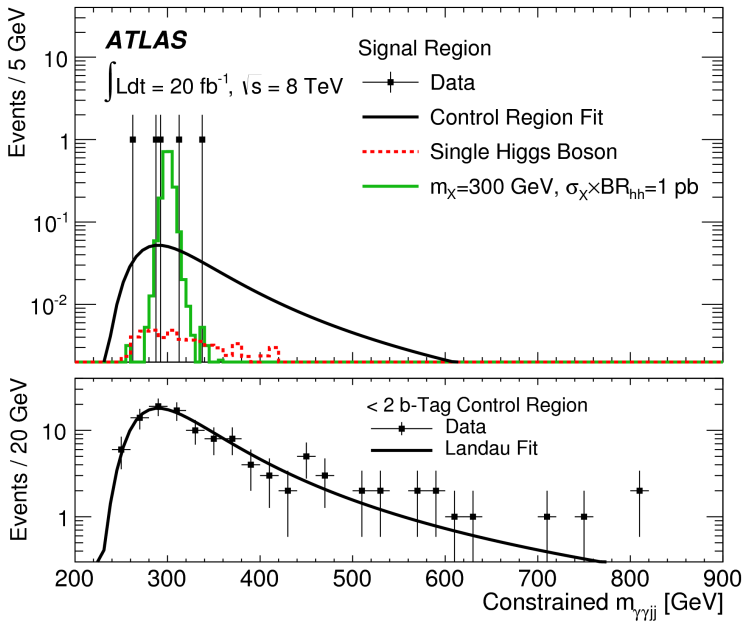
Di Higgs Resonant Searches $hh \rightarrow bb\gamma\gamma$

HIGG-2013-29

- **Non-resonant** search expected **1.5 events** (1.3 ± 0.5 fitted bkg and 0.17 ± 0.04 H_{SM})
  Observed **5 events** (2.4σ)
- Resonant search:
  $min\{p_0\} = 0.002$ at $m_X = 300$ GeV (3σ)
  Chance of fluctuation within range is 0.019 (2.1σ)



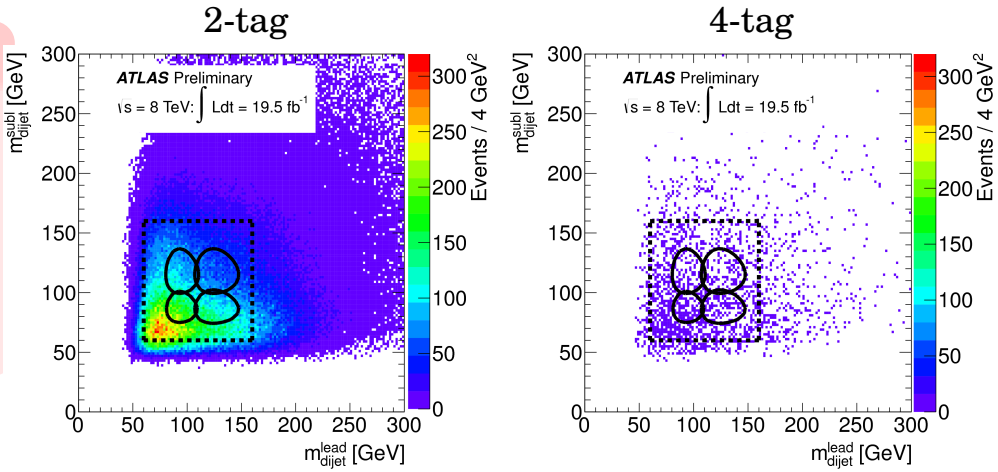




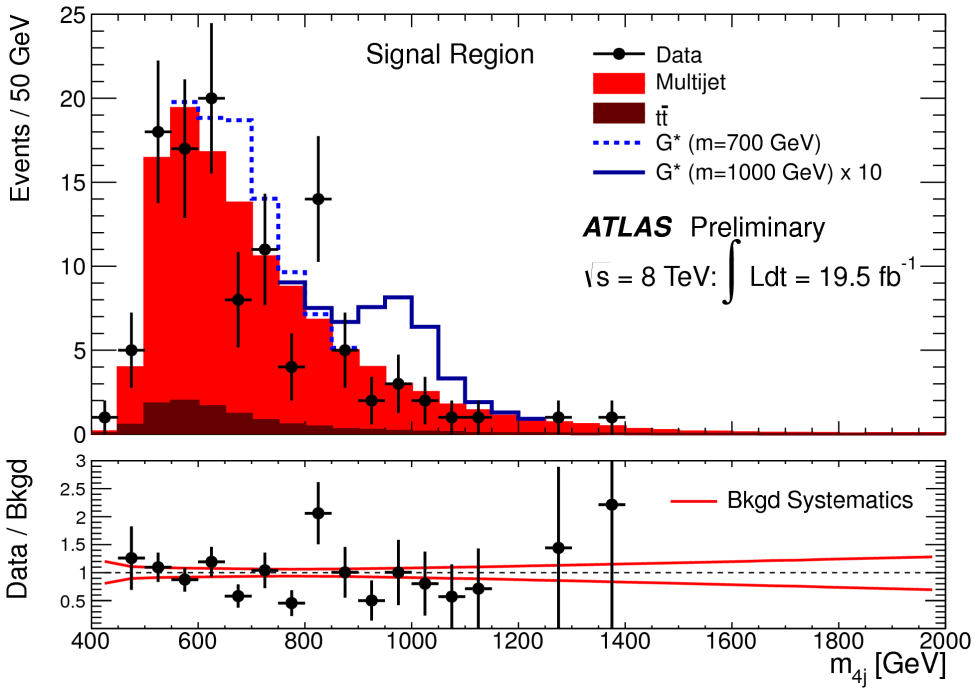
Di Higgs Resonant Searches $hh \to bbbb$

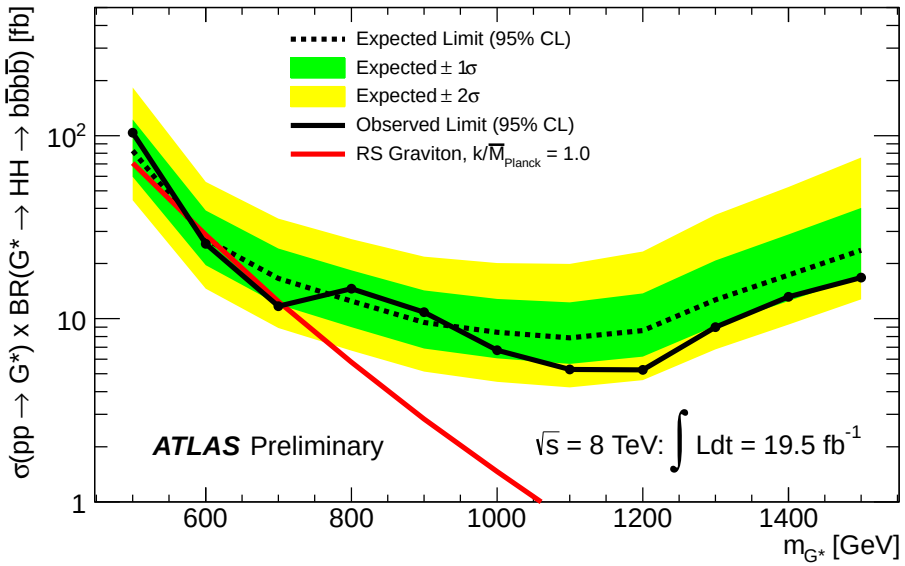
multi-jet bkg ≈ 90% total

- Signal Region 4 b-tagged jets
- 2-tag sample used to predict bkg
- Side Region to normalize 2-tag sample
- Control region tests multi-jet modelling



ATLAS-CONF-2014-005



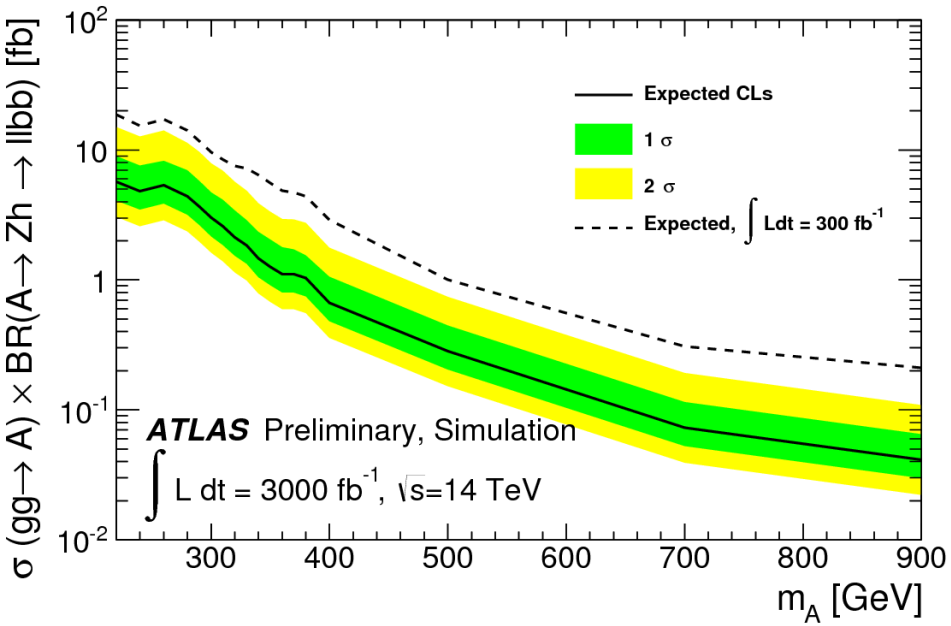


Randall-Sundrum (RS)

Conclusion

- Searches for BSM physics are currently taking place in ATLAS.
- Higgs coupling measurements and direct searches are used.
- ATLAS has performed various searches for BSM (2HDM/MSSM), the most recent of which where shown today.
  - $h/A/H \rightarrow \tau\tau$ (MSSM)
  - $H^{+} -> \tau\nu$+jets (2HDM + MSSM)
  - Di-Higgs resonances.
- Where no signal is observed:
  - Mode independent UL have been placed on XS and BR.
  - UL have been placed on XS and BR for specific bosons.
  - Phasespace exclusions (2HDM/MSSM).
- Run-II approaching with higher center of mass providing sensitivity improvements in near future.

ATL-PHYS-PUB-2013-016



Further Reading I

The ATLAS Collaboration

Constraints on New Phenomena via Higgs Boson Coupling Measurements with the ATLAS Detector

ATLAS-CONF-2014-010, 2014.

The ATLAS Collaboration

Search for charged Higgs bosons decaying via $H^{\pm} \to \tau^{\pm}\nu$ in hadronic final states using pp collision data at sqrts = 8 TeV with the ATLAS detector.

ATLAS-CONF-2014-050, 2014.

The ATLAS Collaboration

Search for neutral Higgs bosons of the minimal supersymmetric standard model in pp collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector

JHEP11(2014)056, 2014.

The ATLAS Collaboration

Search For Higgs Boson Pair Production in the $\gamma\gamma b\bar{b}$ Final State using pp Collision Data at $\sqrt{s} = 8$ TeV from the ATLAS Detector

HIGG-2013-29, 2014.

The ATLAS Collaboration

A search for resonant Higgs-pair production in the $b\bar{b}b\bar{b}$ final state in pp collisions at $\sqrt{s} = 8$ TeV

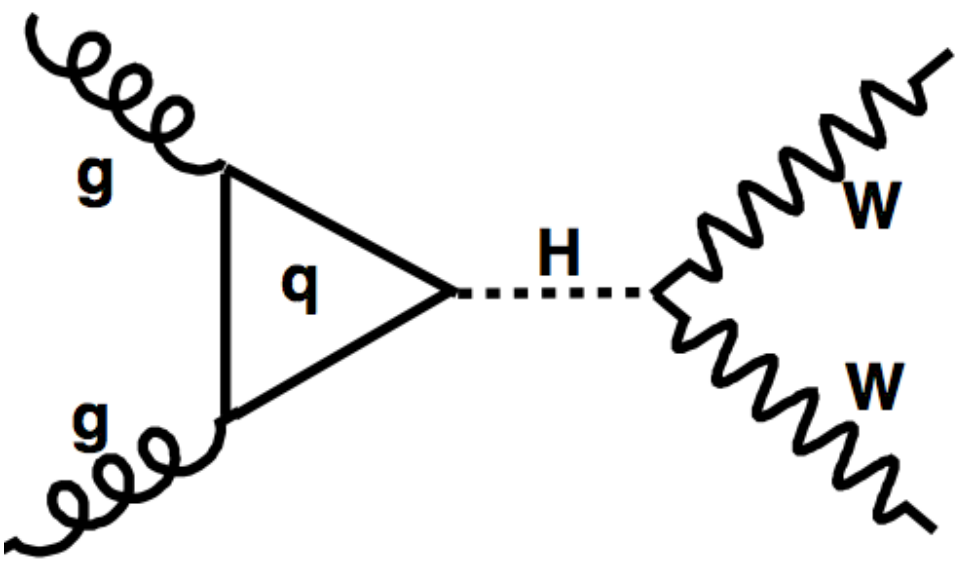
ATLAS-CONF-2014-005, 2014.

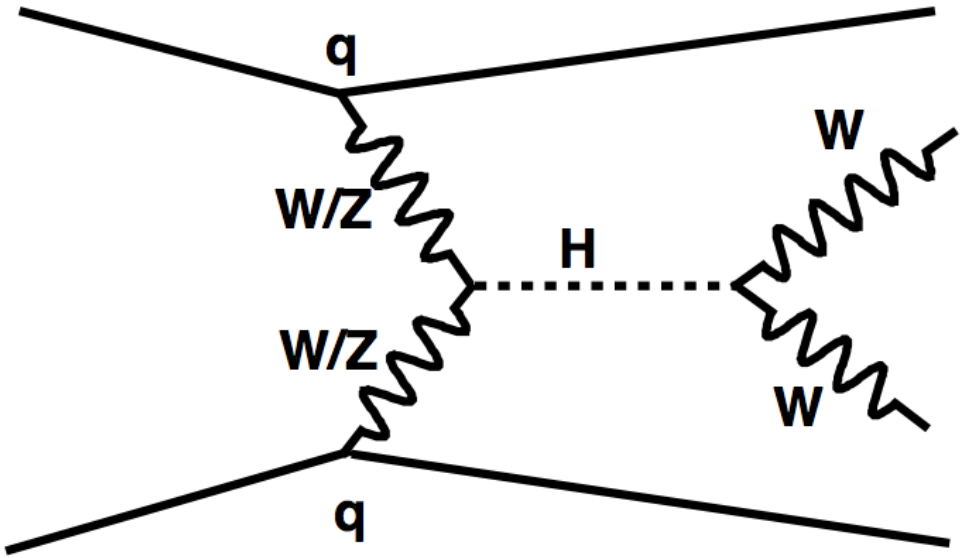
Further Reading II

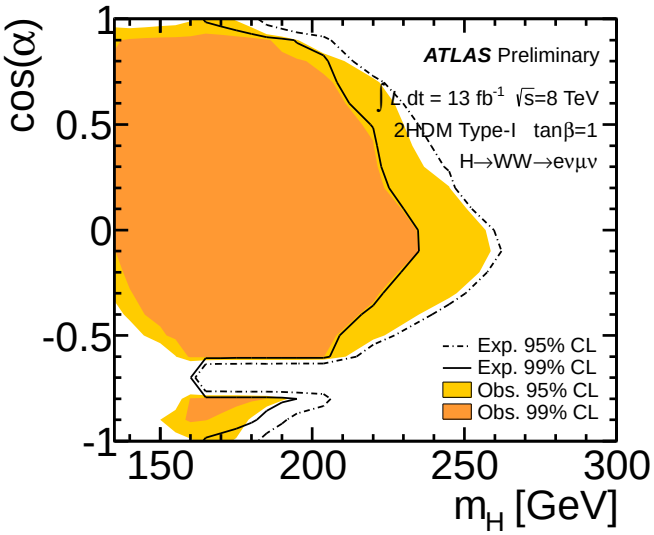

Baglio, J. and Djouadi, A. and Grober, R. et al.
The measurement of the Higgs self-coupling at the LHC:theoretical status
JHEP 1304 (2013) 151, 2013.

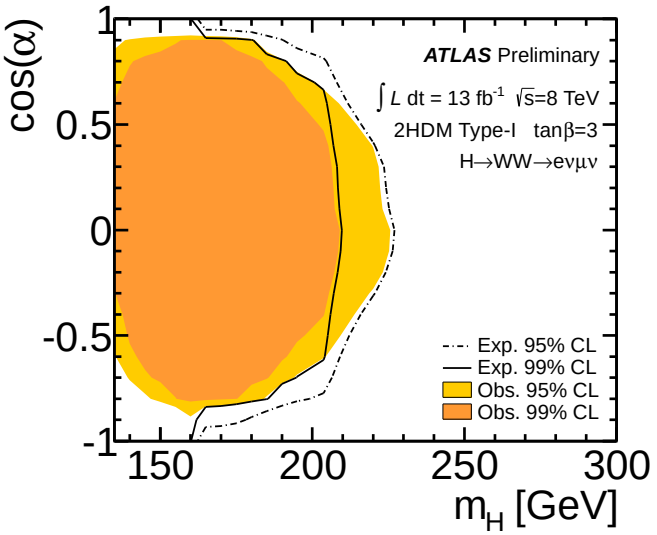

Nathaniel, C. and Jamison, G. and Scott, T.
Searching for Signs of the Second Higgs Doublet
RU-NHETC-2013-07, 2013.

Final state $e\nu\mu\nu$
Production via:






ATLAS Preliminary
∫ L dt = 13 fb-1 √s=8 TeV
2HDM Type-I tanβ=1
H→WW→eνμν
Exp. 95% CL
Exp. 99% CL
Obs. 95% CL
Obs. 99% CL
cos(α)
mH [GeV]


ATLAS Preliminary
∫ L dt = 13 fb-1 √s=8 TeV
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Exp. 99% CL
Obs. 95% CL
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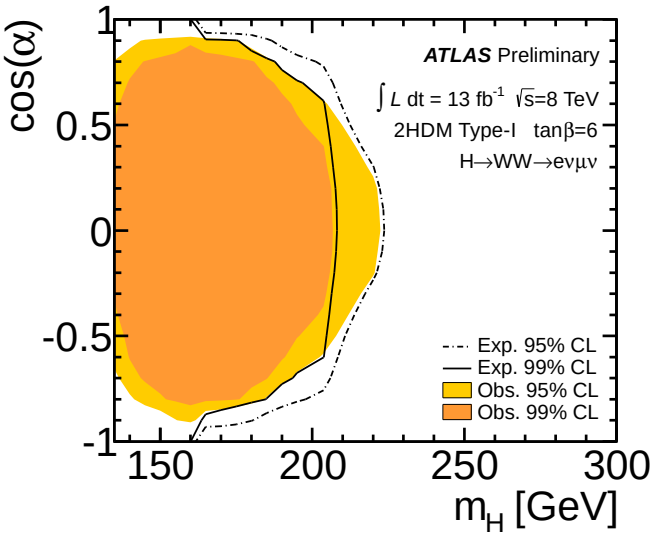
ATLAS Preliminary
∫ L dt = 13 fb-1 √s=8 TeV
2HDM Type-I tanβ=6
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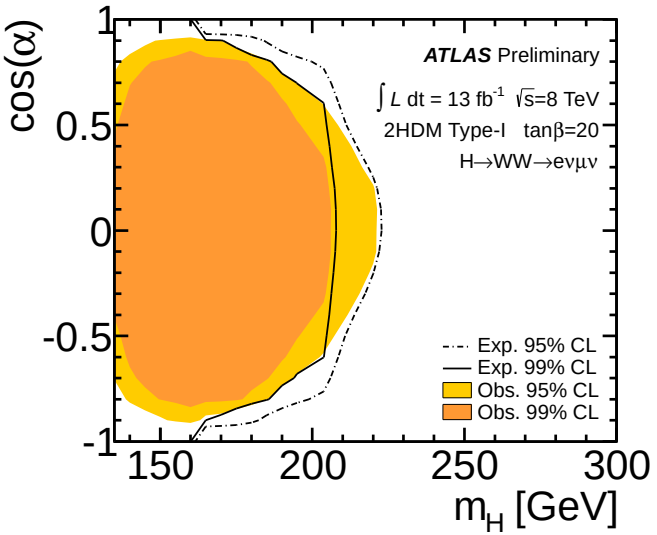
Exp. 95% CL
Exp. 99% CL
Obs. 95% CL
Obs. 99% CL
cos(α)
mH [GeV]


ATLAS Preliminary
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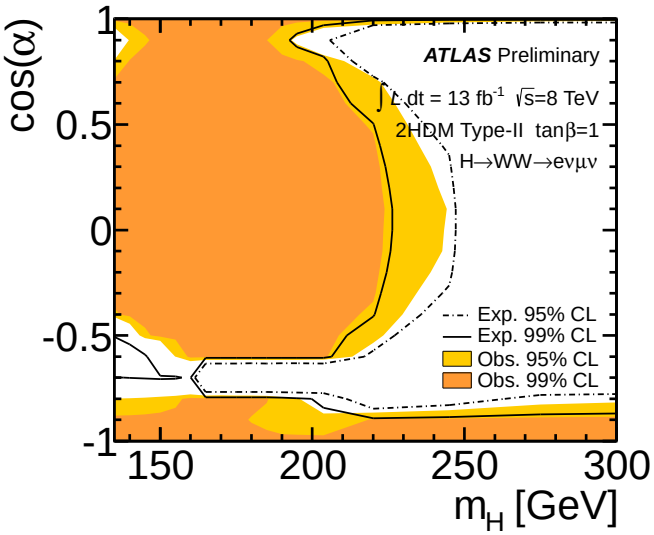
2HDM Type-I tanβ=20
H→WW→eνμν
Exp. 95% CL
Exp. 99% CL
Obs. 95% CL
Obs. 99% CL
cos(α)
mH [GeV]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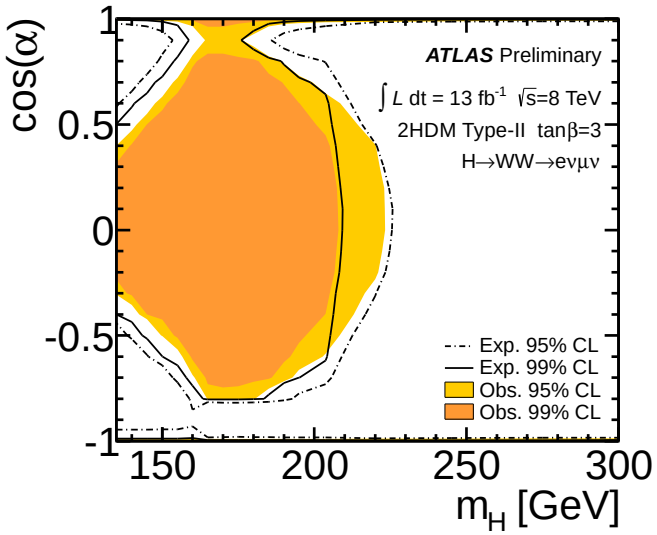
mH [GeV]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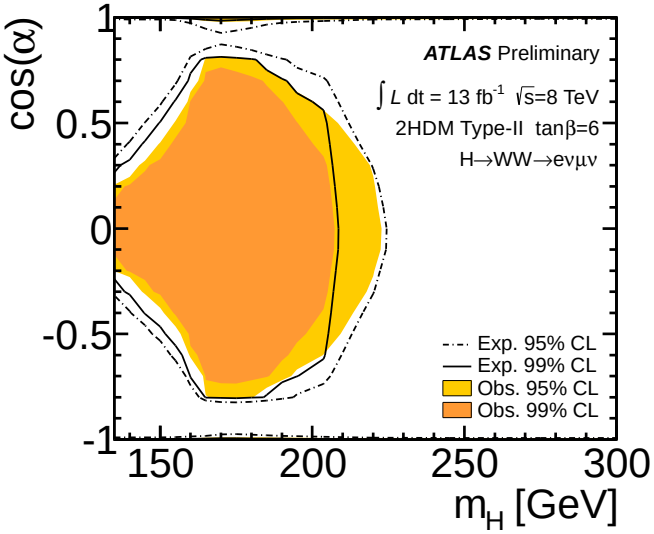
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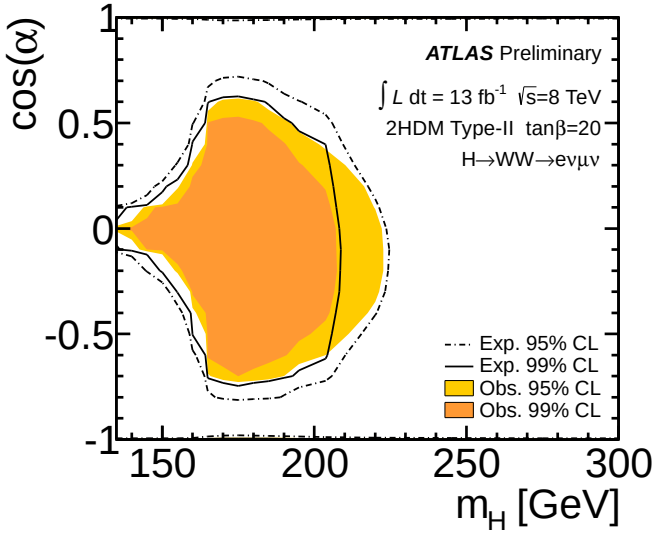
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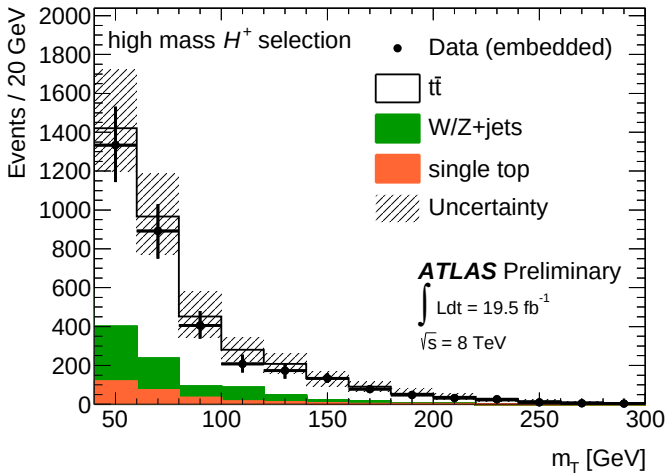
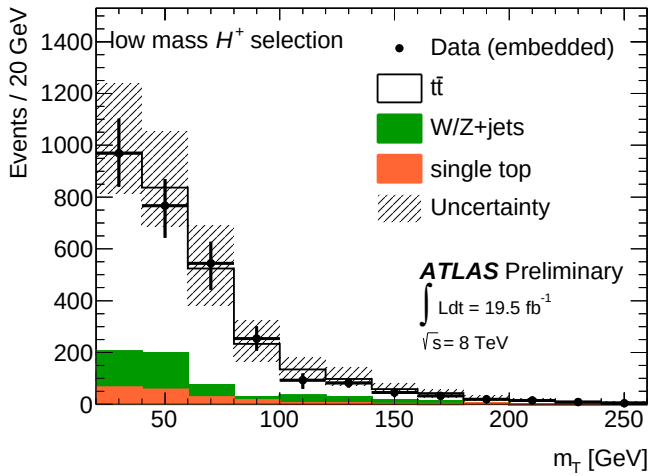
2HDM Type-II tanβ=20
H→WW→eνμν
Exp. 95% CL
Exp. 99% CL
Obs. 95% CL
Obs. 99% CL
cos(α)
mH [GeV]

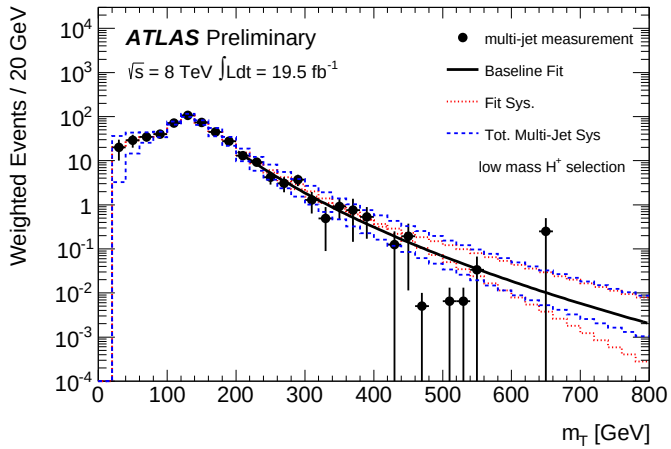
$H^{\pm} \rightarrow \tau^{\pm}\nu$ + jets



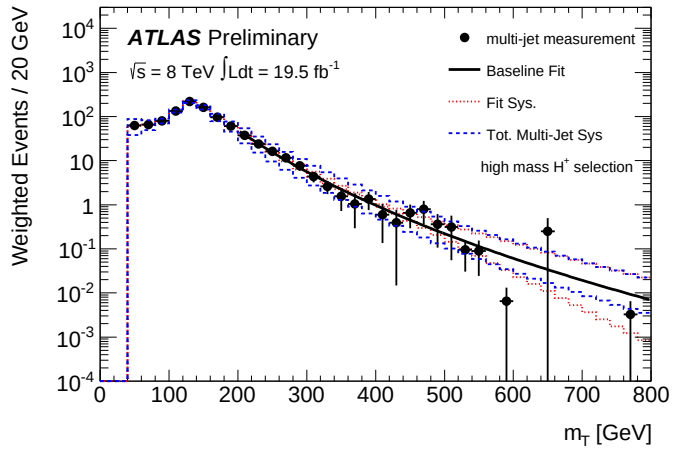


$$N_\tau = N_{\text{embedded}} \cdot \left(1 - c_{\tau\to\mu}\right) \frac{\epsilon^{\tau+E_{\text{T}}^{\text{miss}}-\text{trigger}}}{\epsilon^{\mu-\text{ID,trigger}}} \times \mathcal{B}(\tau \to \text{hadrons} + \nu),$$

Low mass

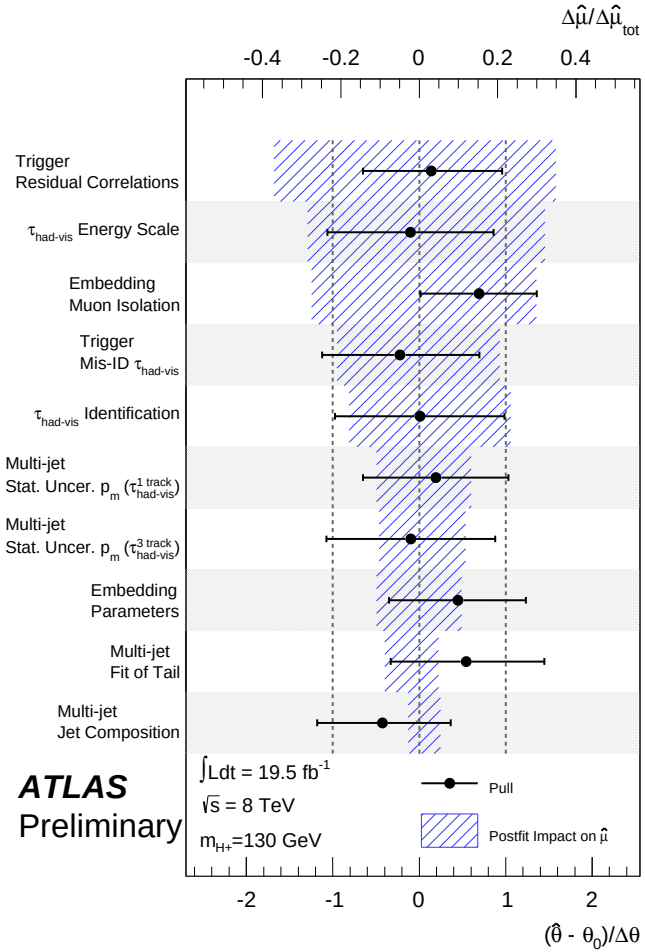


High mass

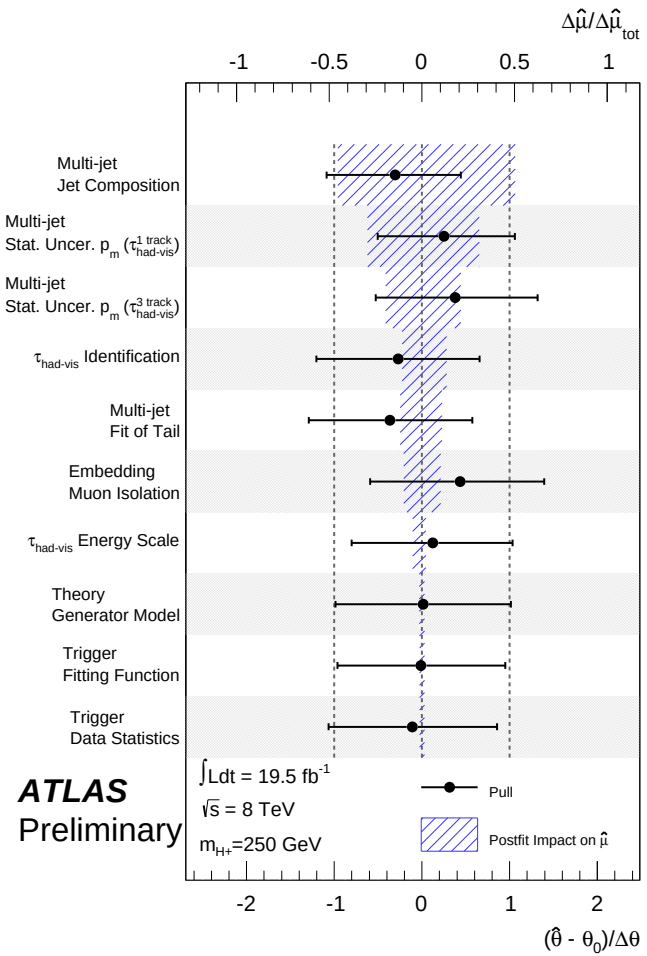


$$m_T^2 = 2p_T^{\tau} E_T^{miss}(1 - \cos\Delta\Phi_{\tau}^{miss})$$

Low Mass



High Mass



MSSM tau tau

Result of m_h^{mod-}