BSM Higgs Searches in ATLAS and CMS (part 1)

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On Behalf of the ATLAS and CMS Collaborations

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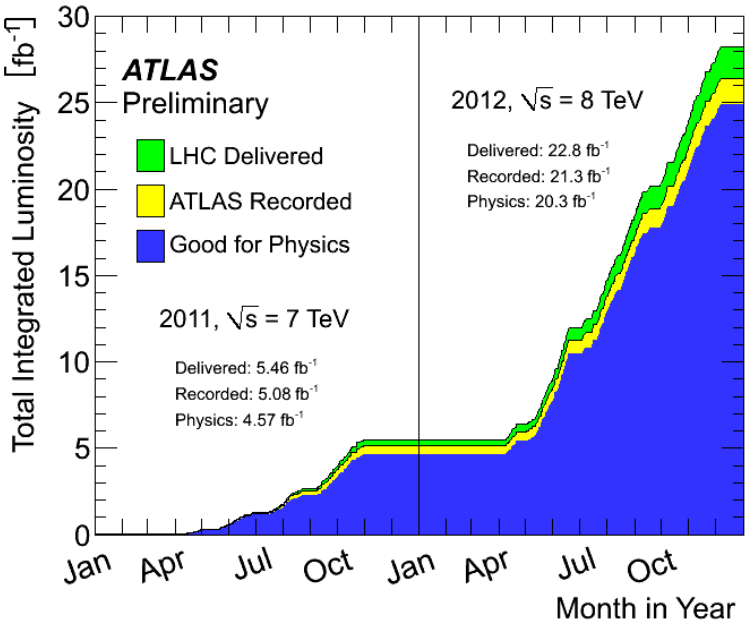
Outline

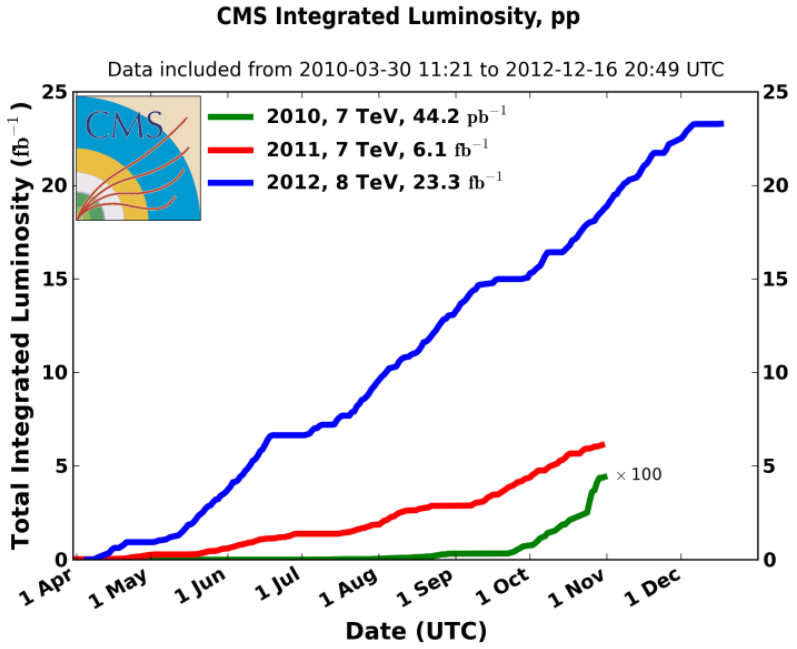
- Introduction
- Constraints on New Physics via Higgs Couplings
- Search for Flavor-Changing Neutral Currents
- SM-like Higgs bosons at high masses
- Charged Higgs Boson Searches
- Neutral (N)MSSM Higgs Boson Searches

searches including invisible decay modes, di-Higgs, Higgs cascades etc. are covered by L. Soffi in the following talk

Introduction

- Extended Higgs sector predicted in many BSM theories
  - ➢ additional Higgs bosons
- Search strategies:
  - additional charged or neutral Higgs bosons
  - Higgs production in Flavor-Changing Neutral Currents
  - re-interpretation of measured properties of SM-like Higgs boson
- results based on run1 data sets from ATLAS and CMS





Introduction

Two-Higgs-Doublet Model (2HDM)

- 2 Higgs doublets (Separate Vacuum Expectation Values: $\tan\beta = v_2/v_1$)
- 5 Higgs bosons: 3 neutral h^0,H^0 (CP even), A^0 (CP odd), 2 charged ($H^{\pm}$)
- α = mixing angle between h^0 and H^0

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	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

- Type I: One Higgs doublet couples to bosons, the other to fermions
- Type II: One doublet couples to up-type quarks, the other to down-type quarks + leptons
- Type III: 'Lepton-specific', quark couplings like Type I, but lepton couplings like Type II
- Type IV: 'flipped Type III'

Minimal Supersymmetric Standard Model (MSSM): 2HDM Type II + SUSY sector

Next-to-Minimal Supersymmetric Standard Model (NMSSM)

- MSSM + 1 additional singlet
- 7 Higgs bosons: 5 neutral h^1, h^2, h^3 (CP even), a^1, a^2 (CP odd), 2 charged ($H^{\pm}$)

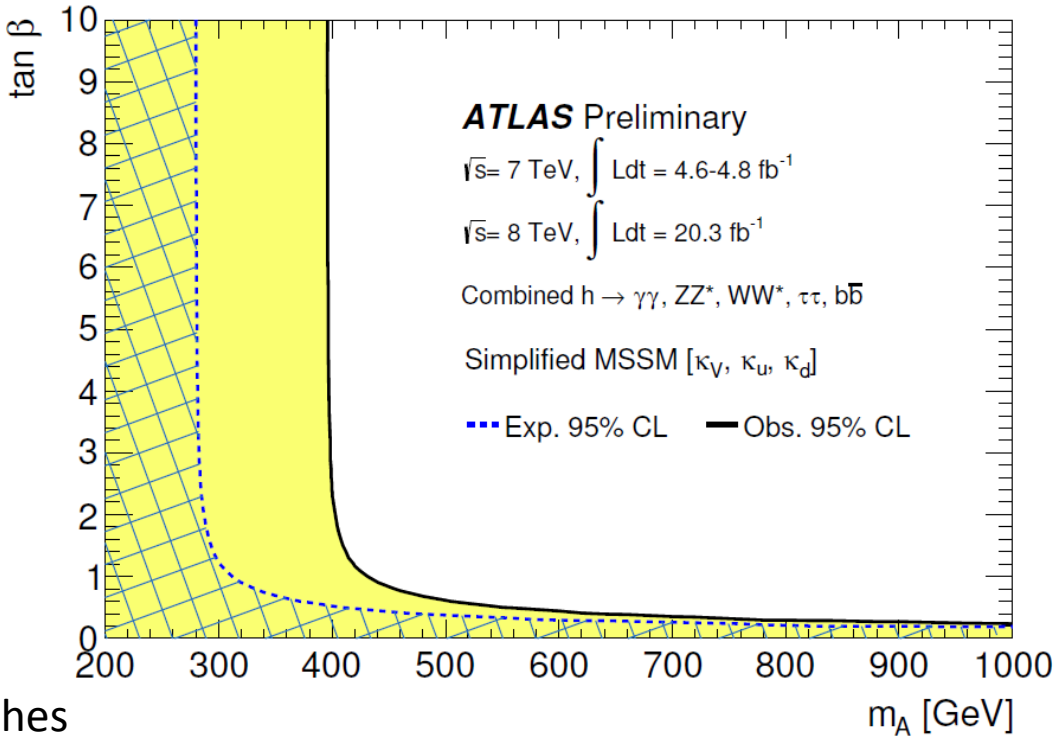
ATLAS-CONF-2014-010

Simplified MSSM†

- light Higgs couplings measured by combination of various channels (7+8 TeV)
- using SM higgs boson mass $m_h \approx 125.5$ GeV
- MSSM: Higgs sector defined by m_A and tanβ
- simplified: effects of sparticles not included

- Constrain m_A and tanβ via Coupling measurements:
  95% CL, $2 < \tan\beta < 10$
  $m_A > 400\ (290)$ GeV obs. (exp)

- observed limits stronger than exp. due to higher $h \to \gamma\gamma$ and ZZ* rates than predicted by SM



- complementary to direct MSSM searches

† see e.g. arXiv:1405.2241

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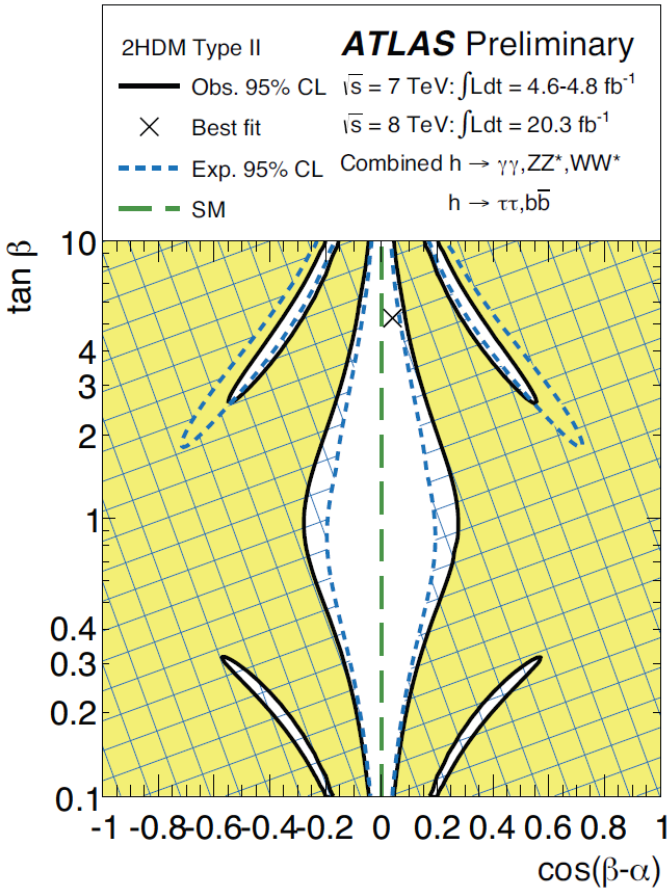
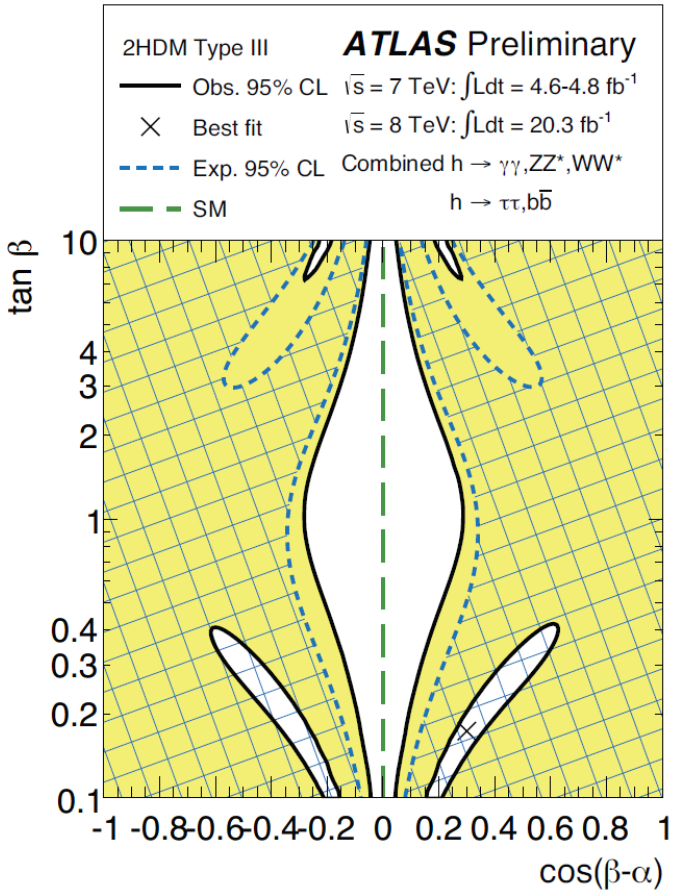
2HDMs

- express SM couplings in context of the four types of 2HDMs
- observed 95% exclusion limits in $(\cos(\beta-\alpha), \tan\beta)$ plane
- data consistent with SM-like alignment at $\cos(\beta-\alpha)=0$ within 1-2σ for all models



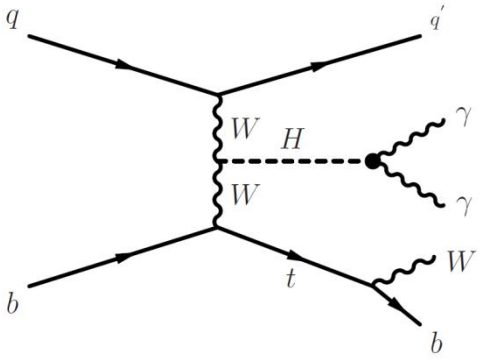


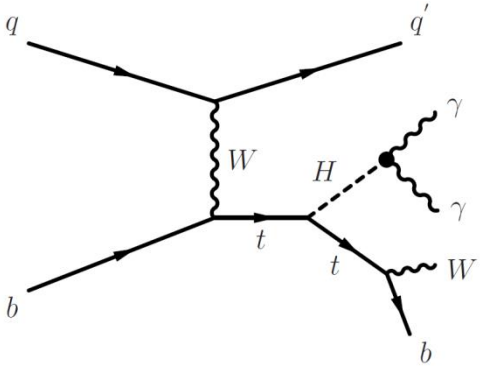
CMS-PAS-HIG-14-001

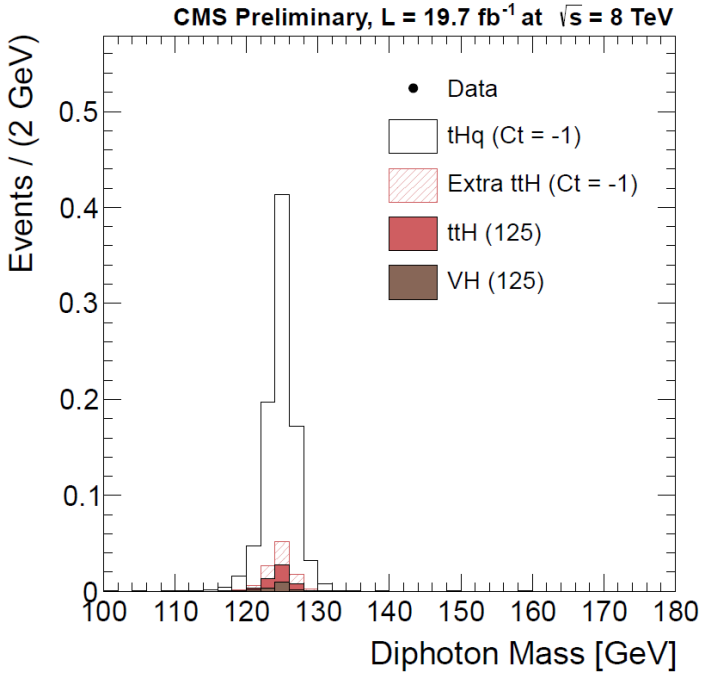
tHq

- SM: couplings Higgs to W (C_W) and top (C_t) suffer from destructive interference
- non-SM fits still allow $C_t = -1$ → increase of tHq cross section

- associated production of single top: $tHq \rightarrow b(W \rightarrow l\nu)\, q(H \rightarrow \gamma\gamma)$
- a cut-and-count analysis is performed
- no events seen in signal region
- 95% CLs upper limit: $4.1 \times \sigma_H(C_t = -1)$







Flavor-Changing Neutral Currents

CMS-PAS-HIG-13-034

$t \to cH$

- FCNC supressed in SM: $\mathrm{BR}(t \to cH) \sim 10^{-15}$
- Couplings increase in types of 2HDM models: ~0.15% (e.g. present at tree level)
- Study done by CMS (8 TeV, 19.5 fb^{-1}) using $t\bar{t}$ topology and various final states:

Higgs Decay Mode	observed	expected	1σ range
$H \to WW^*$ ($\mathcal{B} = 23.1\,\%$)	1.58 %	1.57 %	(1.02–2.22) %
$H \to \tau\tau$ ($\mathcal{B} = 6.15\,\%$)	7.01 %	4.99 %	(3.53–7.74) %
$H \to ZZ^*$ ($\mathcal{B} = 2.89\,\%$)	5.31 %	4.11 %	(2.85–6.45) %
combined multileptons (WW^*, $\tau\tau$, ZZ^*)	1.28 %	1.17 %	(0.85–1.73) %
$H \to \gamma\gamma$ ($\mathcal{B} = 0.23\,\%$)	0.69 %	0.81 %	(0.60–1.17) %
combined multileptons + diphotons	0.56 %	0.65 %	(0.46–0.94) %

- Limit on Branching Fraction:

$$\mathrm{BR}(t \to cH) < 0.56\ (0.65)\%$$ Observed (Expected)

- Limit on left- and right handed top Flavor-Changing Yukawa Couplings:

$$\sqrt{|\lambda^{\mathrm{H}}_{\mathrm{tc}}|^2 + |\lambda^{\mathrm{H}}_{\mathrm{ct}}|^2} < 0.14$$

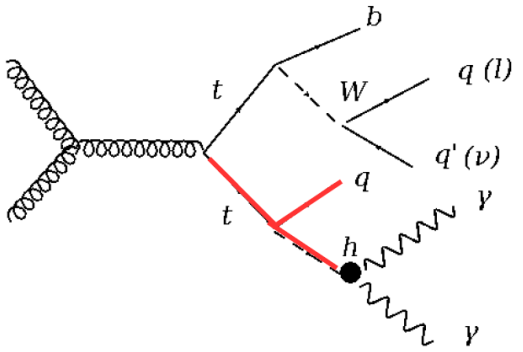
Flavor-Changing Neutral Currents

JHEP06(2014)008

$t \to qH$

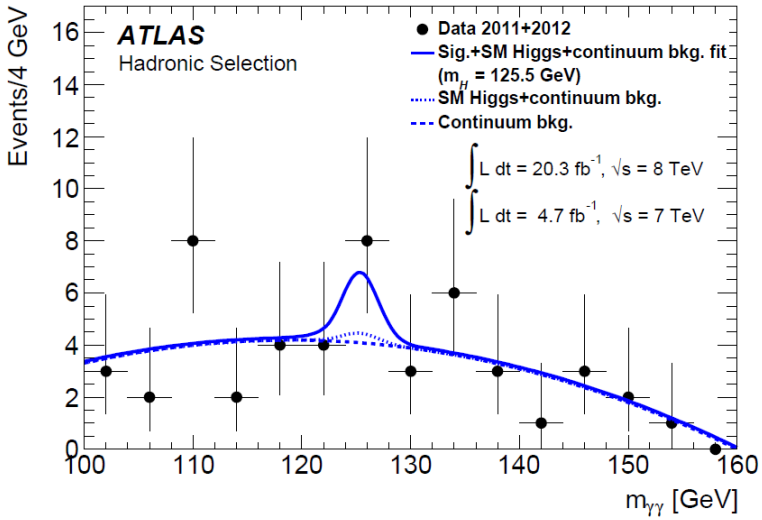
- search done in top-pair events: $t\bar{t} \to b(W \to ff)\, q(H \to \gamma\gamma)$
- Limits:

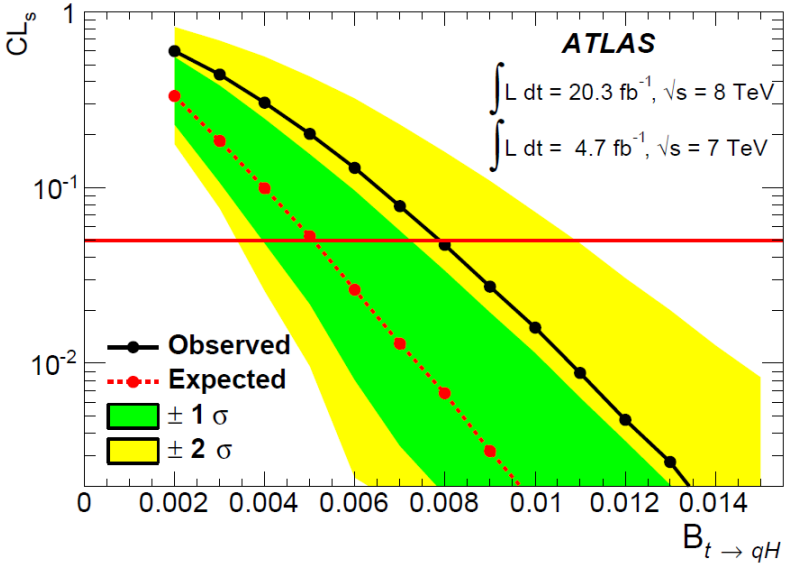
$$BR(t \to cH) < 0.79\%\ (0.51\%)$$
$$\lambda_{tcH} < 0.17\ (0.14)$$



- Equally sensitive to tuH and tcH:

$$\sqrt{\lambda_{tcH}^2 + \lambda_{tuH}^2} < 0.17$$

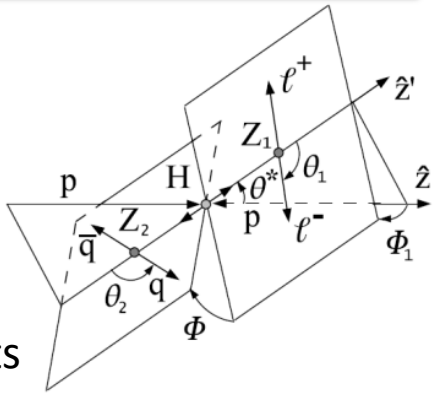




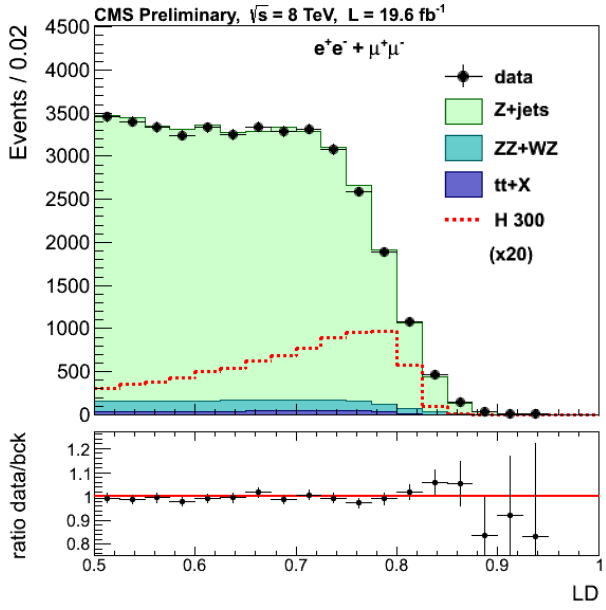
Search for SM-like Higgs in high-mass regions

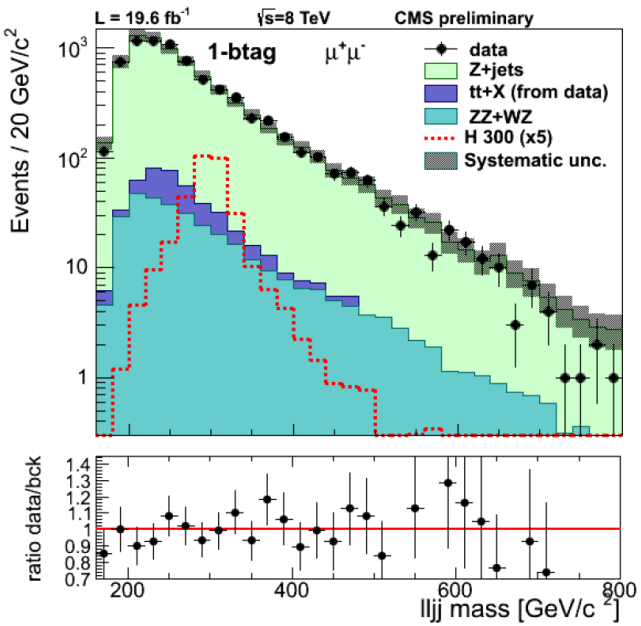
CMS-PAS-HIG-12-024

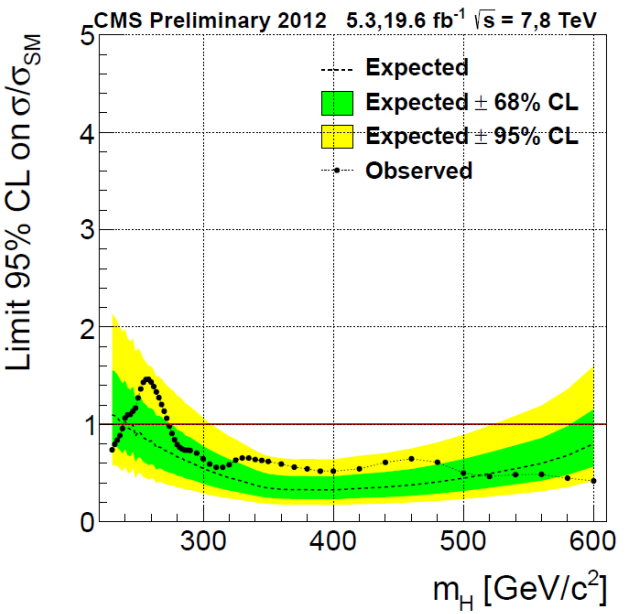
$$H \rightarrow ZZ \rightarrow l^+l^-q\bar{q} \qquad (l = e, \mu)$$



- angular observables fully describe kinematics in rest frame
- take advantage of discrimination power using likelihood discriminant
- 0,1,2 b-tag categories increase further significance via rejecting Z+jets
- for $m_H < 400\ GeV$ consider SM width and neglect interference effects
- effects on σ and mass shape taken into account for high mass (Complex-Pole Scheme)
- excluded resonance with SM Higgs boson properties in $275 < m_H < 600$ GeV





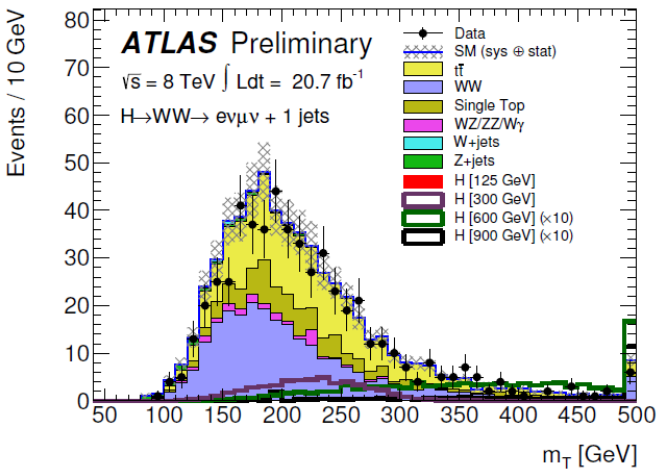


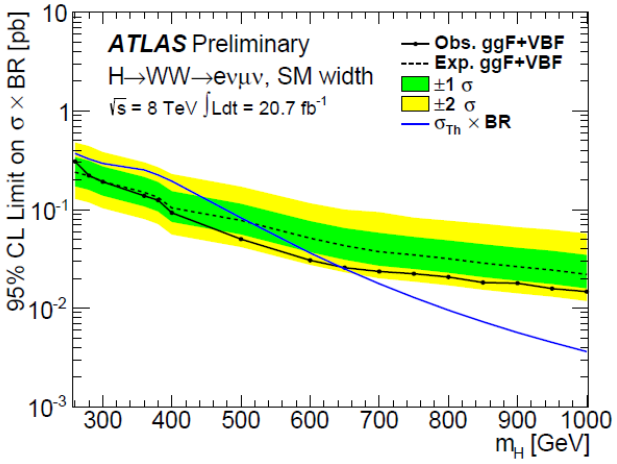
Search for SM-like Higgs in high-mass regions

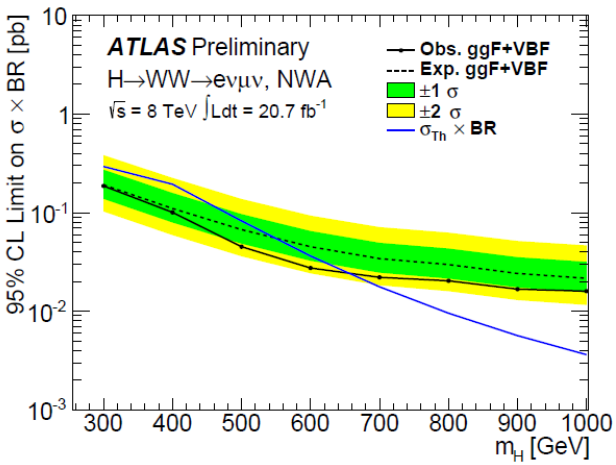
ATLAS-CONF-2013-067

$H \to WW \to l\nu l\nu$

- only different lepton-flavour final state used ($l_1 \neq l_2$), no hadronic τ decay mode
- optimized for 0, 1 and ≥2 additional jets, sensitive to ggF or VBF production
- contribution from $m_H \sim 125$ GeV treated as background
- analysis performed for Higgs bosons with SM width and a narrow width
- SM-like Higgs boson excluded at 95% CLs in mass range $260 < m_H < 642$ GeV

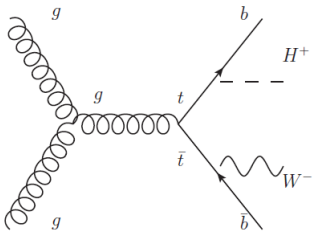


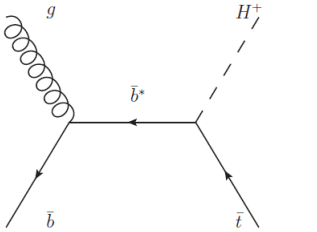


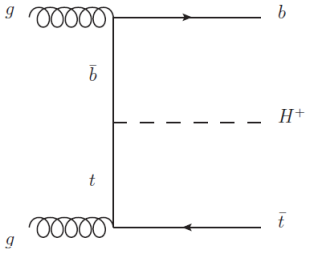


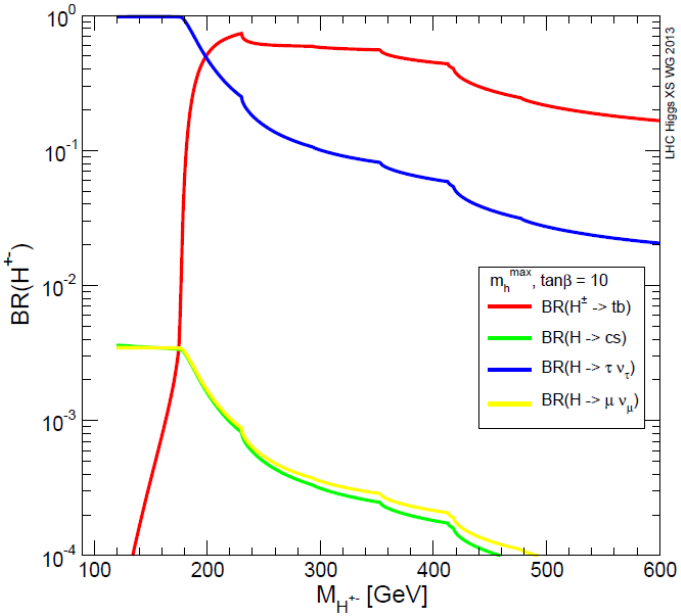
Charged Higgs Boson searches

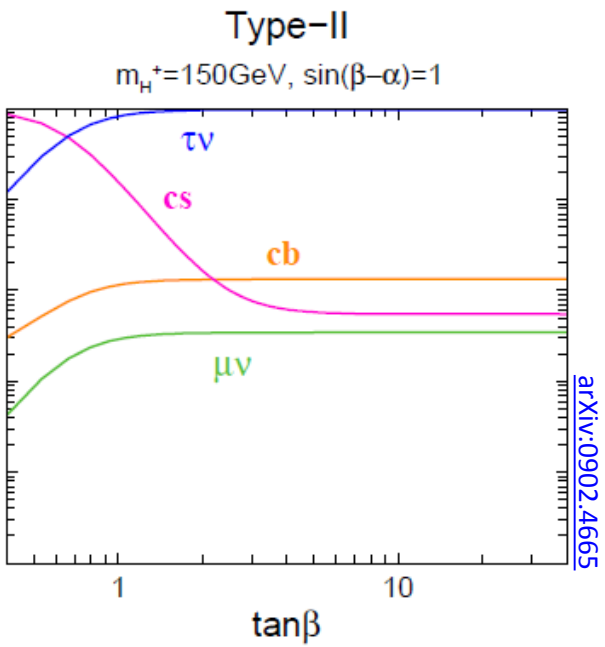
- charged Higgs bosons predicted by many BSM theories
- dominant modes in 2HDM type-II:
  $t \to H^+ b$ for $m_{H^+} < m_t$ (light charged Higgs)
  assoc. production (tH^+) for $m_{H^+} > m_t$ (heavy charged Higgs)
- $H^+ \to \tau\nu$ important decay channel for tanβ>3
- $H^+ \to c\bar{s}$ get dominant for tanβ<1 in specific models

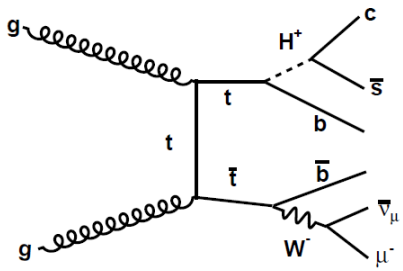










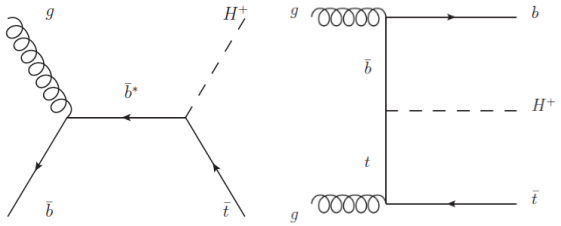


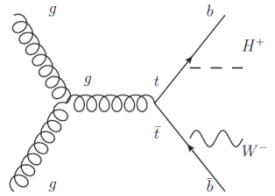
Charged Higgs Boson searches

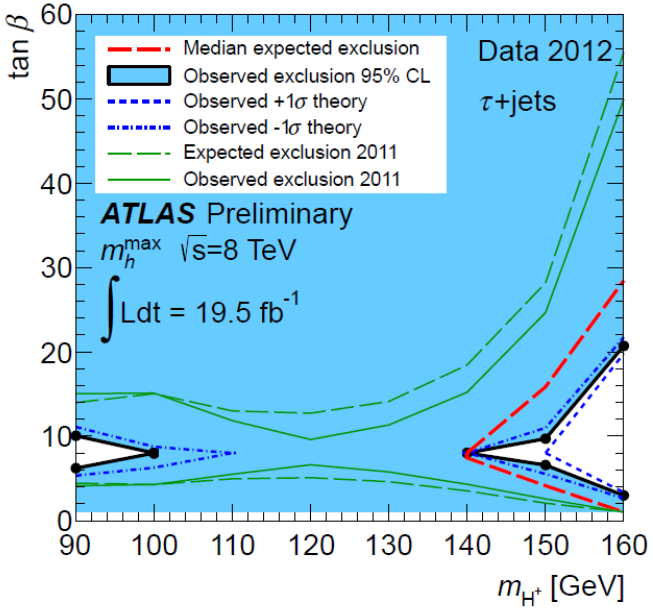
ATLAS-CONF-2013-090

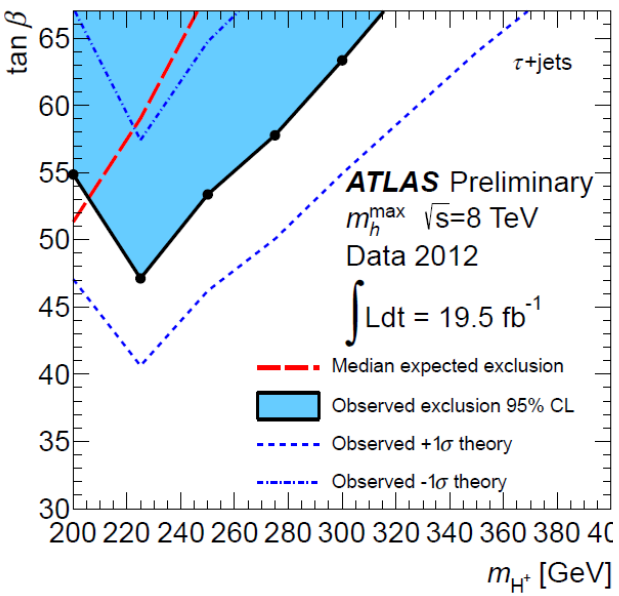
$H^+ \to \tau\nu$

- assume $\mathrm{BR}(H^+ \to \tau\upsilon) = 1$
- model-independent limits:
  $\mathrm{BR}(t \to H^+ b) = 0.24 - 2.1\%$ for $90 < m_{H^+} < 160$ GeV
  $\sigma(H^+) = 0.017 - 0.9$ pb for $180 < m_{H^+} < 600$ GeV
- results interpreted in MSSM mhmax scenario

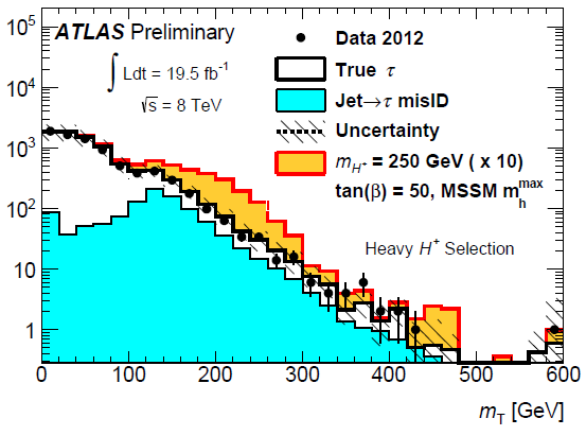








$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\tau} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \Delta\phi_{\tau,\mathrm{miss}})}$$

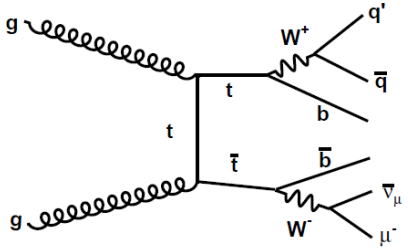


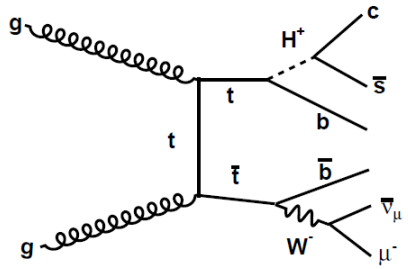
Charged Higgs Boson searches

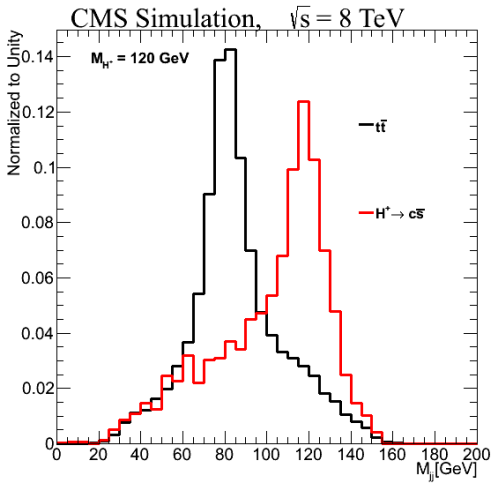
CMS-PAS-HIG-13-035

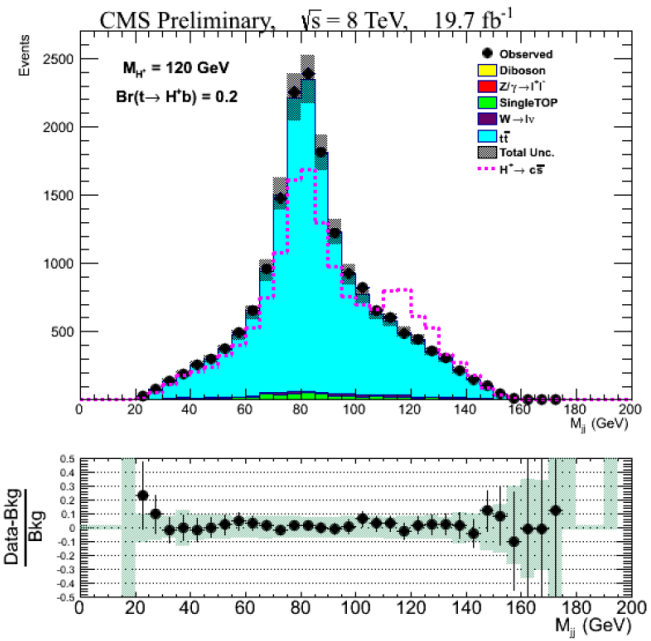
$H^+ \to c\bar{s}$

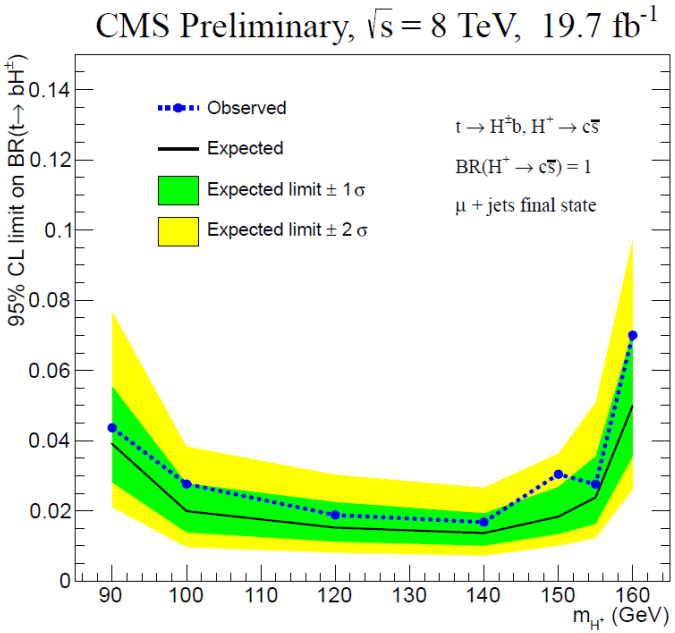
- search performed in $t\bar{t} \to W^{\pm} b H^{\mp} \bar{b} \to \mu + \text{jets}$
- kinematic fit used to improve separation of W/H mass
- assume $\mathrm{BR}(H^+ \to c\bar{s}) = 1$
- model-independent limits set:
  $\mathrm{BR}(t \to H^+ b) = 2 - 7\%$ for $90 < m_{H^+} < 160$ GeV







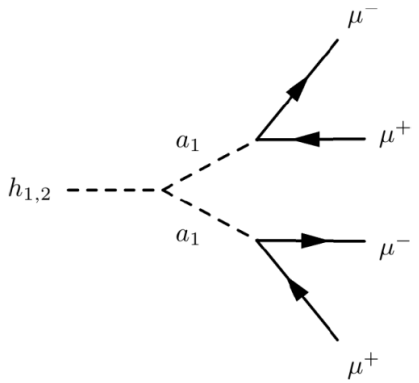




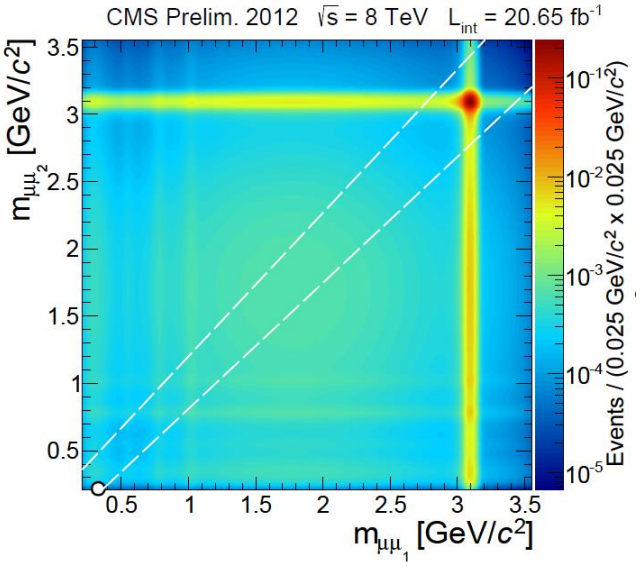
Neutral NMSSM Higgs Boson searches

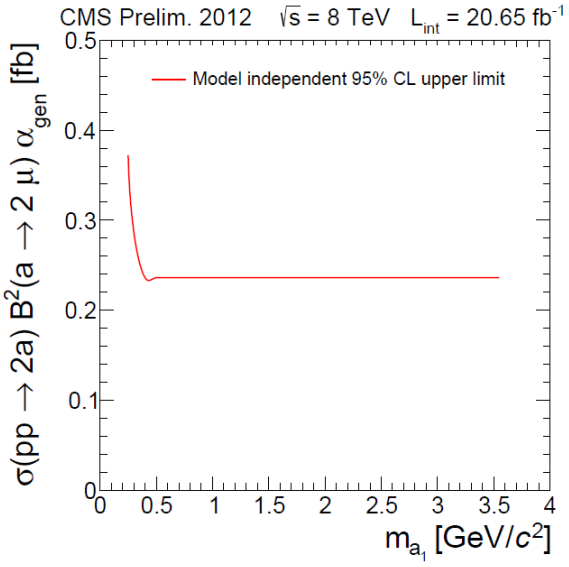
CMS-PAS-HIG-13-010

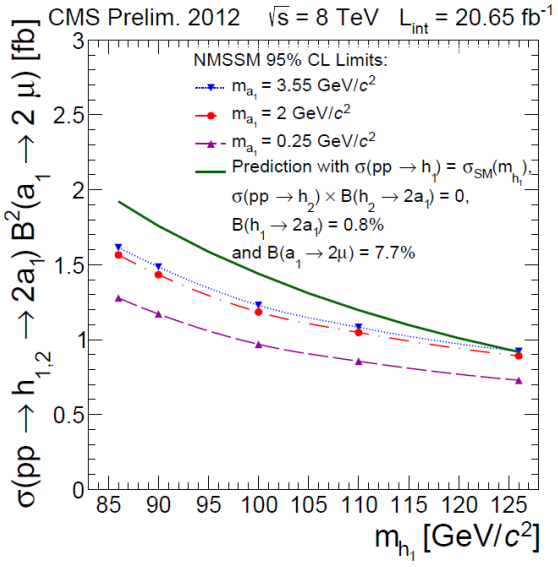
$$h \to 2a + X \to 4\mu + X$$



- non-SM decay of h including two new light bosons
- NMSSM: substantial BR $a \to \mu\mu$ if $2m_\mu < m_a < 2m_\tau$
- background dominated by $b\bar{b}$ and J/ψ pair production
- 1 event observed in signal region, compatible with bkg. prediction 3.8 ± 2.1
- limit obtained for $0.25 < m_a < 3.55$ GeV, $m_h > 86$ GeV
- search interpreted for dark-SUSY models as well as model-independent







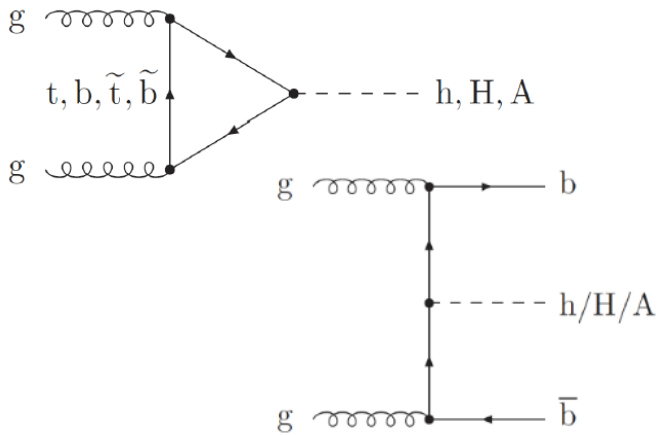
Neutral MSSM Higgs Boson searches

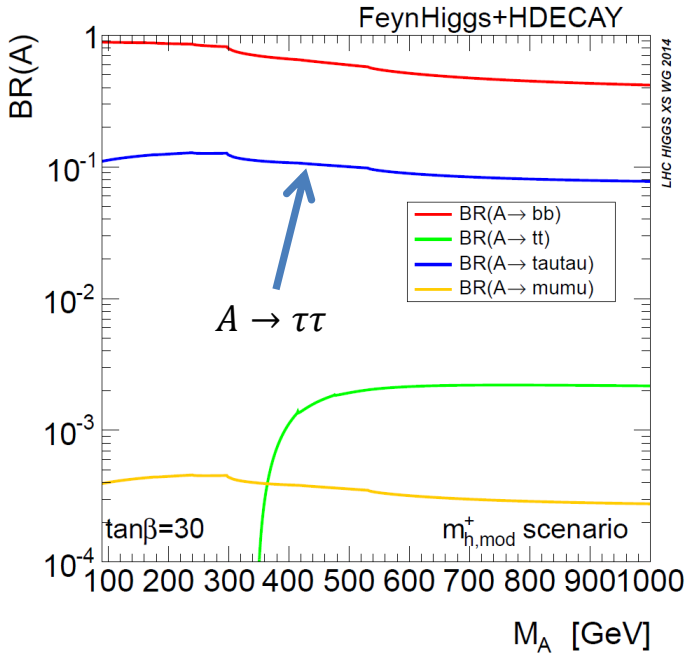
CMS-PAS-HIG-13-021
ATLAS-CONF-2014-049

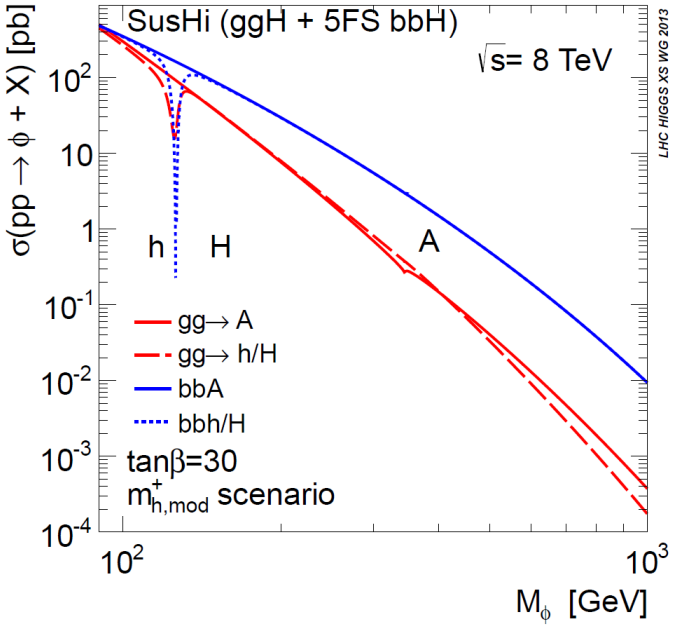
$\phi \to \tau\tau$

- tau decay modes are most dominant (10%) next to b-quarks modes
- two production modes:

  gluon-fusion → dominant for small tanβ
  b-associated production → dominant for large tanβ







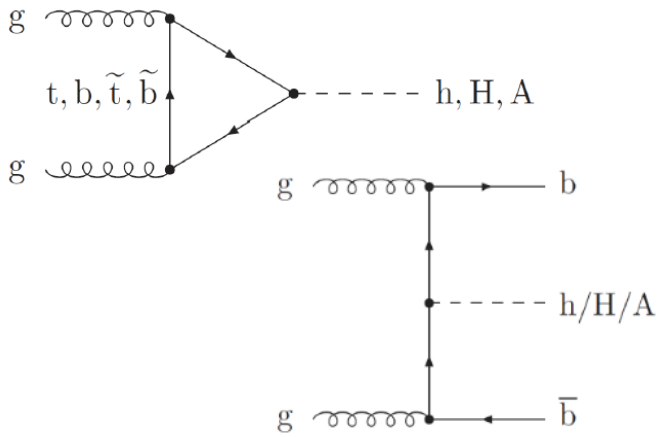
Neutral MSSM Higgs Boson searches

CMS-PAS-HIG-13-021
ATLAS-CONF-2014-049

$\phi \rightarrow \tau\tau$

- tau decay modes are most dominant (10%) next to b-quarks modes
- two production modes:

  gluon-fusion → dominant for small tanβ
  b-associated production → dominant for large tanβ
  and at high mass



- overview about analyses channels:

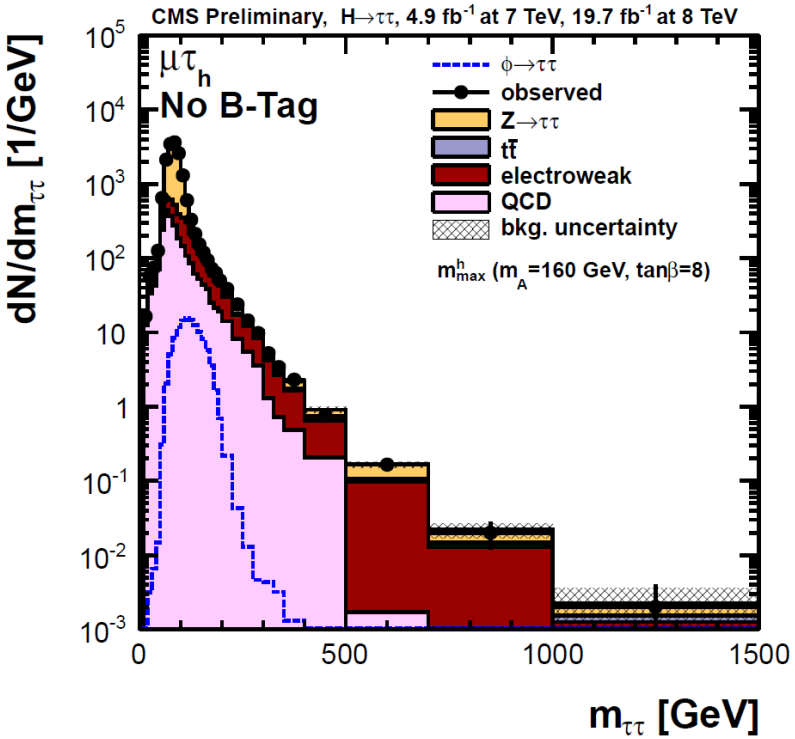
	ATLAS	CMS
Channels	$\tau_h\tau_h, e\tau_h, \mu\tau_h, e\mu$ (94%)	$\tau_h\tau_h, e\tau_h, \mu\tau_h, e\mu, \mu\mu$ (97%)
Categories	ll, lh: b-tag / b-veto lh high-mass: incl. hh: single-/di-tau trigger	all channels: b-tag / no b-tag
Discriminant	ll, lh: di-tau mass taking missing energy into account (MMC) hh: total transverse mass	all channels: di-tau mass taking missing energy into account (SVFit)

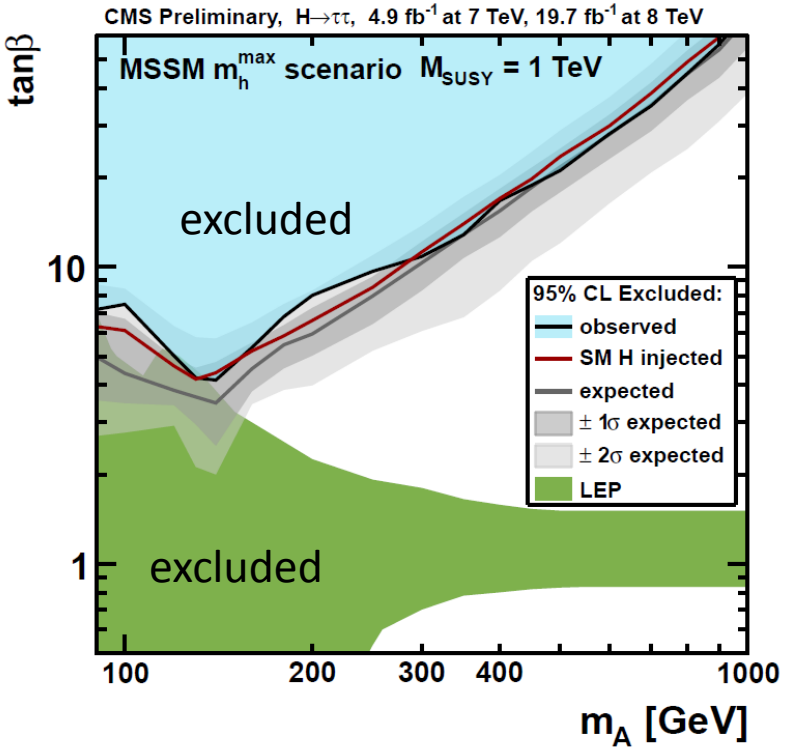
Neutral MSSM Higgs Boson searches

CMS-PAS-HIG-13-021

$\phi \rightarrow \tau\tau$

- di-tau mass reconstruction method (SVFit) based on likelihood method using e/μ/τ momenta and missing E_T information (see J.Phys.Conf.Ser. 513 (2014) 022035 for details)
- no evidence for signal beyond SM found
- interpretation of results on new MSSM benchmark scenarios in preparation





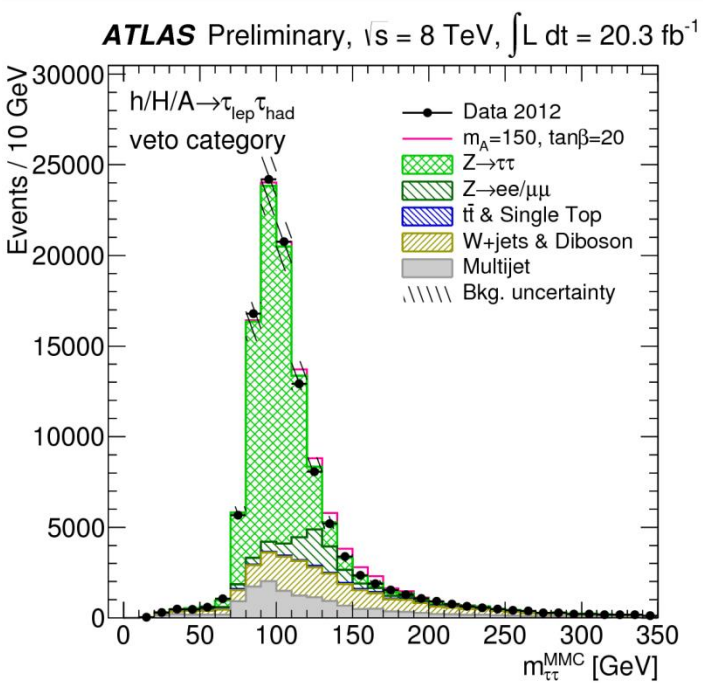
Neutral MSSM Higgs Boson searches

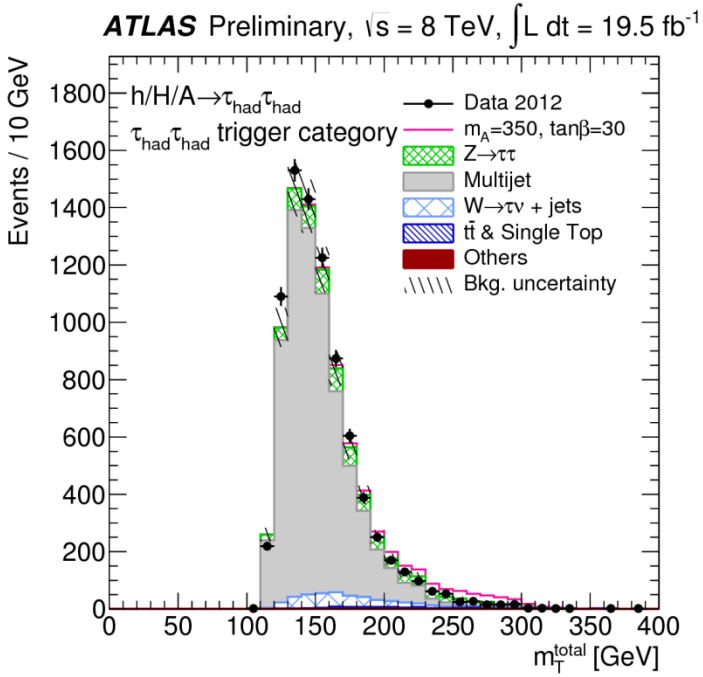
ATLAS-CONF-2014-049

$\phi \rightarrow \tau\tau$

MMC: *Nucl.Instrum.Meth.* A654 (2011) 481–489, [arXiv:1012.4686]

- MMC-mass based on lepton/tau momenta and missing energy information
- total transverse mass used in had-had due to better separation from multijet background
- lep-lep and lep-had channels combined for $m_A < 200$ GeV
- lep-had and had-had channels combined for $m_A \geq 200$ GeV
- limits for various MSSM benchmark scenarios calculated
- see also talk by F. Scutti tomorrow afternoon





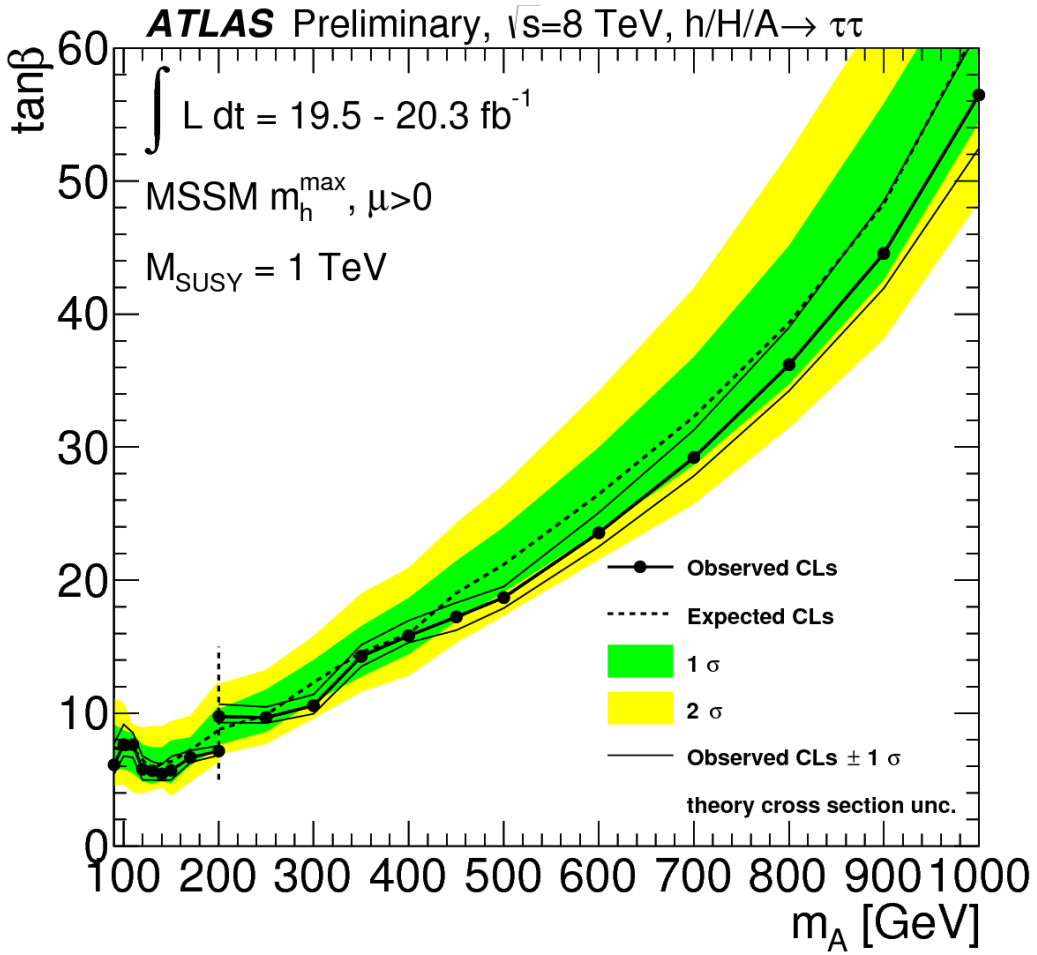
Neutral MSSM Higgs Boson searches

ATLAS-CONF-2014-049

$\phi \rightarrow \tau\tau$

first time shown at a conference

- very competitive exclusion limits at high m_A masses
- no evidence found for physics beyond SM

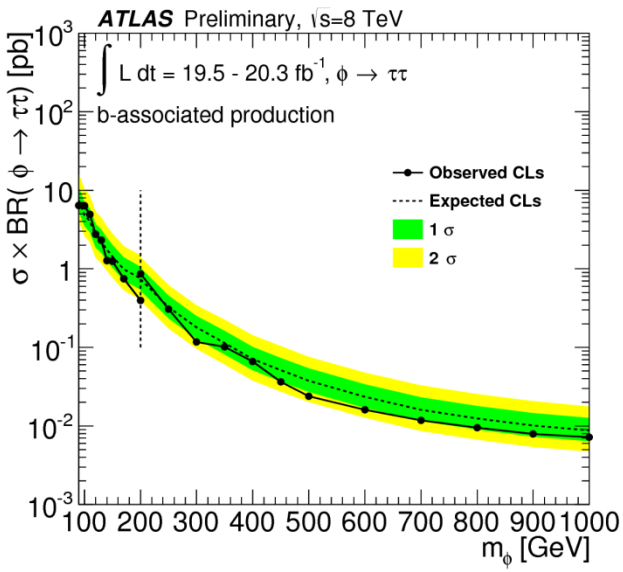


Neutral MSSM Higgs Boson searches

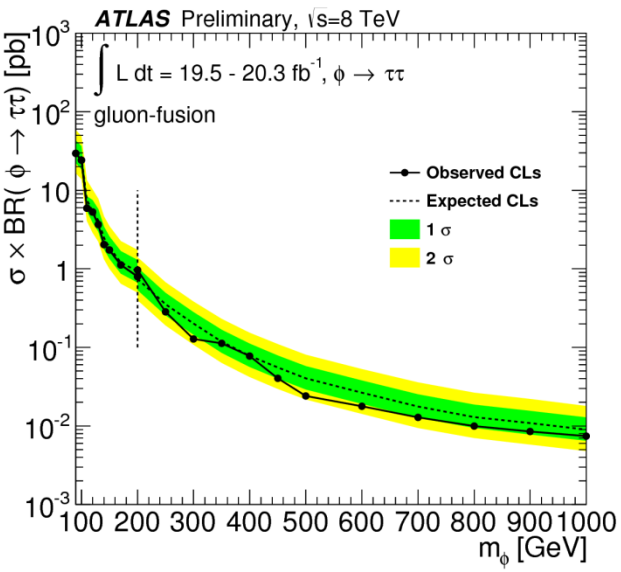
CMS-PAS-HIG-13-021, ATLAS-CONF-2014-049

$\phi \rightarrow \tau\tau$

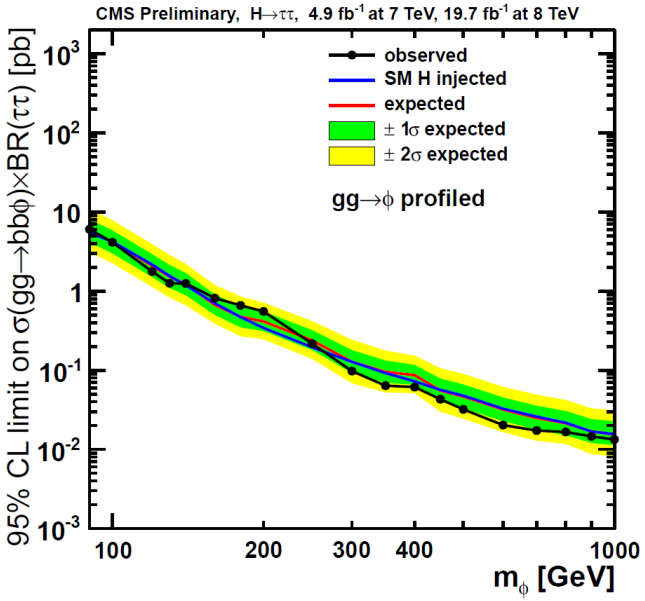
b-associated production

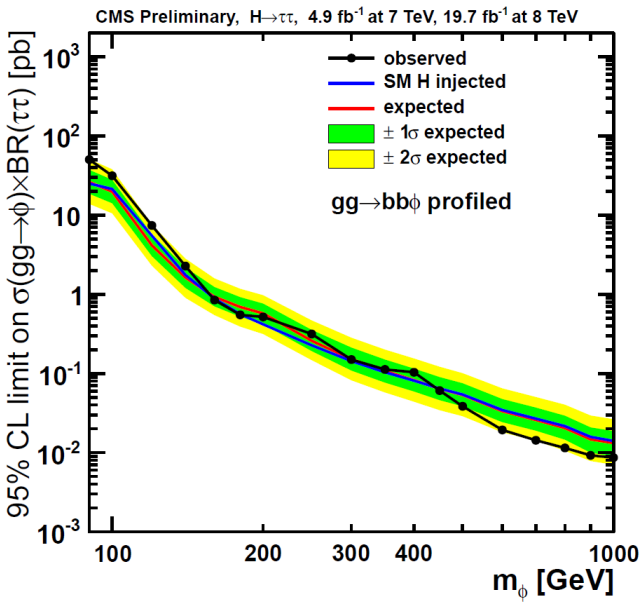


gluon-fusion



ATLAS





CMS

Conclusion

- Observation of SM-like Higgs boson excludes large regions of MSSM parameter space
- Still room left for BSM models to be compatible with observed Higgs boson
- Search for new Higgs bosons performed in various channels and with different strategies
- No evidence found
- Many BSM analyses with 8 TeV data still on-going in ATLAS + CMS

- Run-II with 13(14) TeV will enhance discovery potential of Beyond Standard Model searches
- New challenges for the analyses (e.g. detector, trigger)

Backup

ATLAS-CONF-2014-010

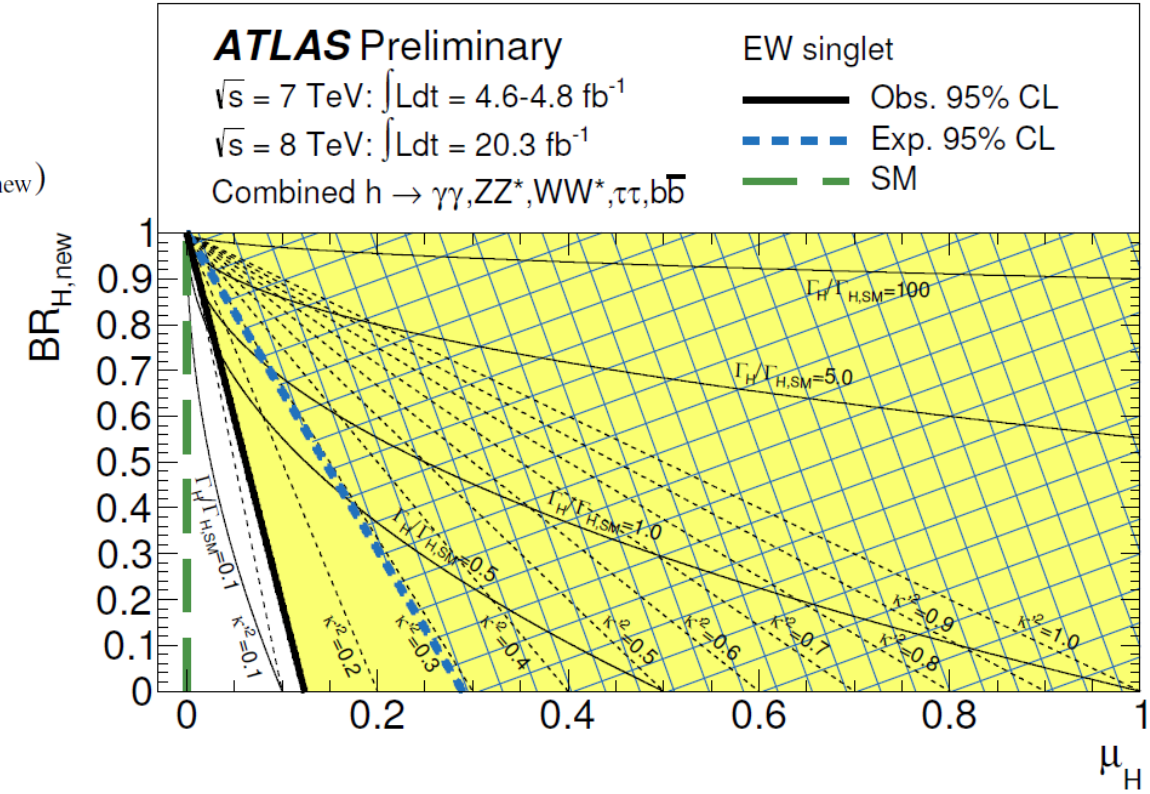
Electroweak Singlet

- mixing of singlet and one state of doublet → two CP-even Higgs bosons h,H
- new decay modes possible for H: H→hh ($BR_{H,new}$)
- couplings of h(H) reduced by κ(κ')
- cross section, width, signal strength modified wrt SM accordingly

$$\mu_h = \frac{\sigma_h \times \mathrm{BR}_h}{(\sigma_h \times \mathrm{BR}_h)_{\mathrm{SM}}} = \kappa^2$$

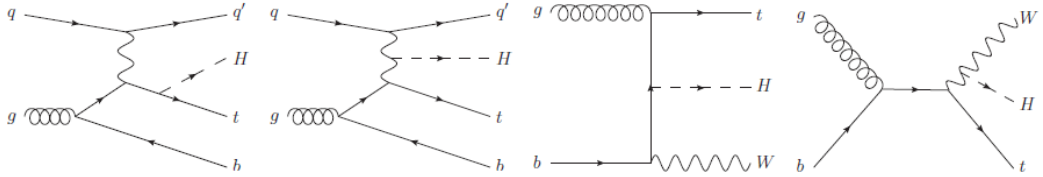
$$\mu_H = \frac{\sigma_H \times \mathrm{BR}_H}{(\sigma_H \times \mathrm{BR}_H)_{\mathrm{SM}}} = \kappa'^2\,(1 - \mathrm{BR}_{H,\mathrm{new}})$$

- EW singlet: physical boundary
  $\kappa'^2 \geq 0$ (SM: $\kappa'^2 = 0$)
- ignoring boundary, H coupling
  $\kappa'^2 = 1 - \mu_h = -0.30^{+0.17}_{-0.18}\ (0.00^{0.15}_{-0.17})$
- 95% CL upper limit
  $\kappa' < 0.12$ (0.29) obs (exp)

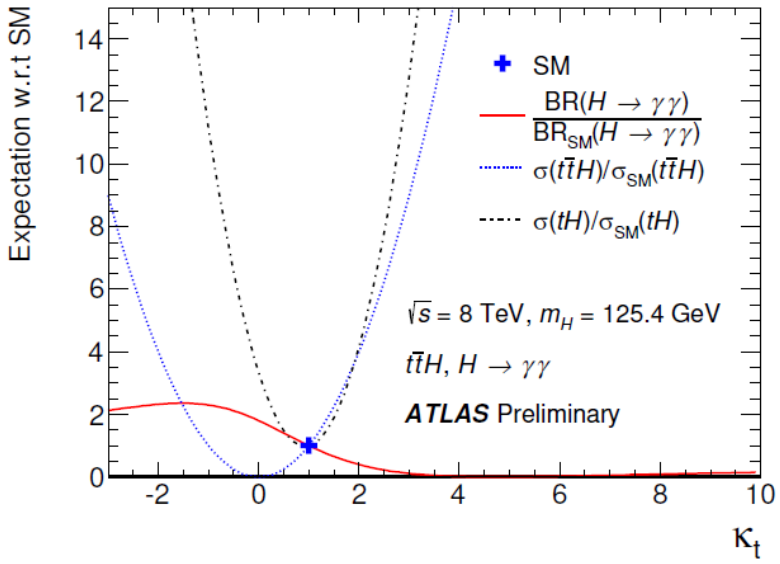


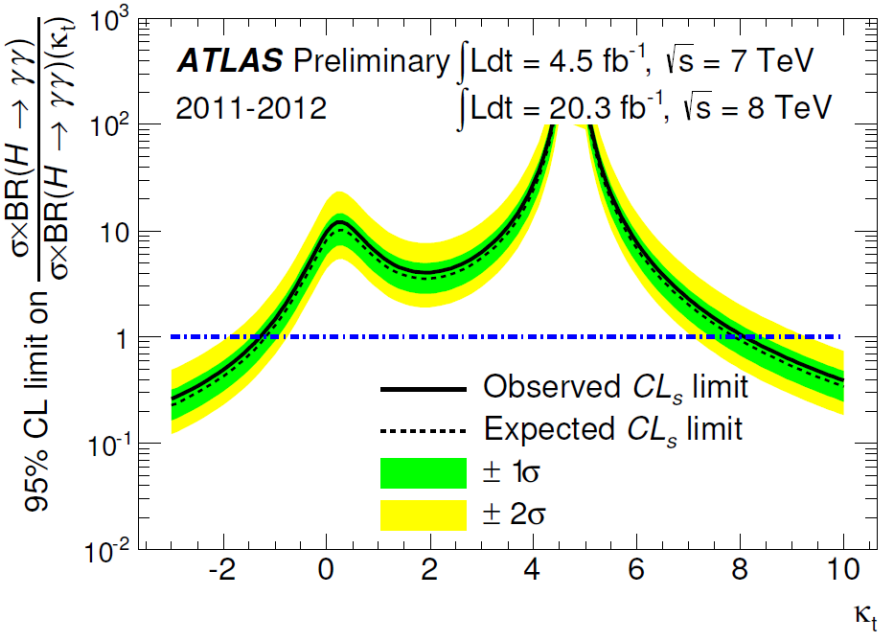
ATLAS-CONF-2014-043

tH $(tHqb, WtH)$

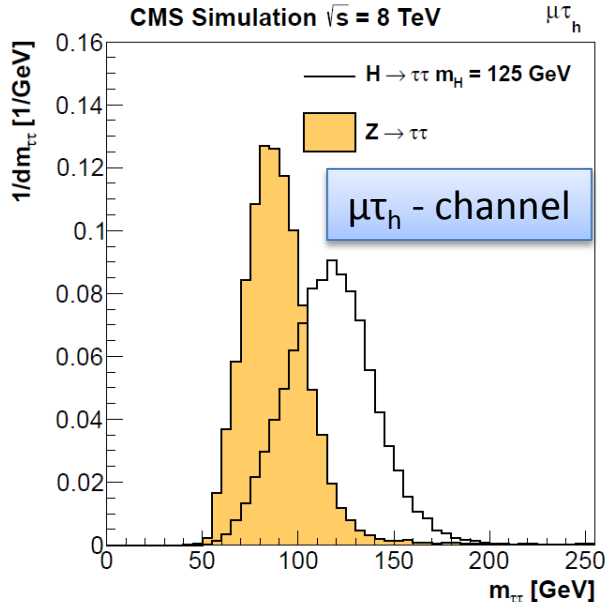


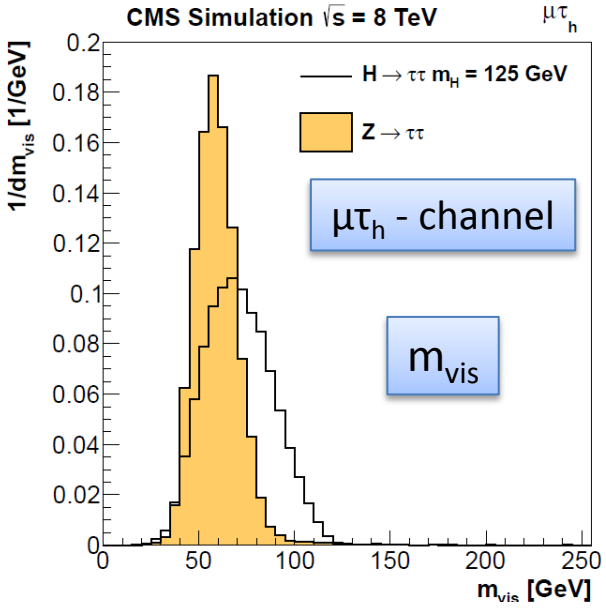
- Y_t = top quark-Higgs boson Yukawa coupling; can be different in BSM theories
- $\kappa_t = Y_t / Y_t^{SM}$
- analysis performed in $H \to \gamma\gamma$ channel, optimized for ttH production
- requirements kept loose enough to have high efficiency for tH as well
- σ(ttH), σ(th) and BR($H \to \gamma\gamma$) depend on κ_t, BR($H \to \gamma\gamma$) has minimum at $\kappa_t = +4.7$
- 95% CL lower(upper) limit: $-1.3 < \kappa_t < +8.1$





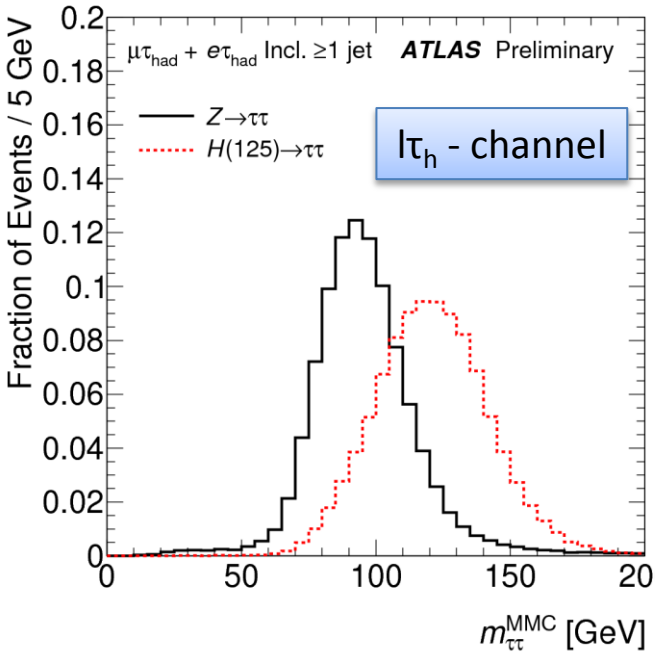
Di-Tau Mass Reconstruction Methods

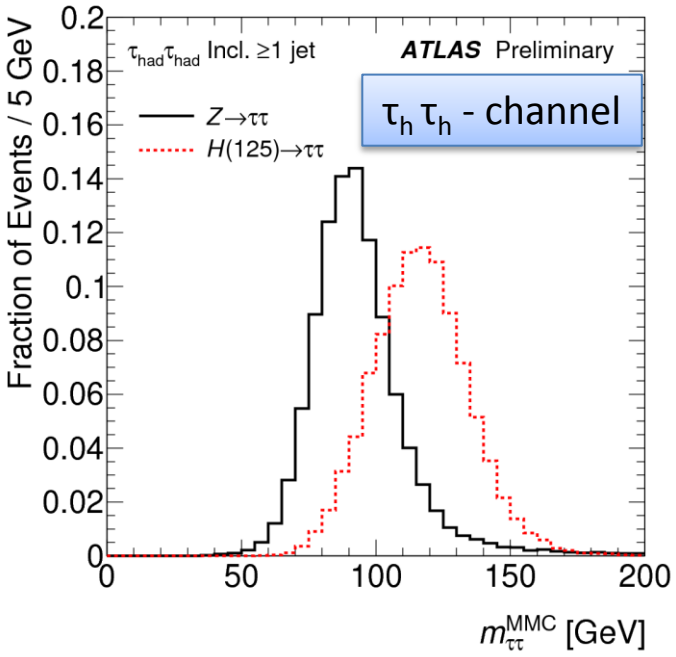




SVFit algorithm

J.Phys.Conf.Ser. 513 (2014) 022035





MMC algorithm

Nucl.Instrum.Meth. A654 (2011) 481–489, [arXiv:1012.4686]

ATLAS-CONF-2013-108

Di-Tau Mass Reconstruction Methods

- total transverse mass

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

- transverse mass between two particles

$$m_T = \sqrt{2 p_{T1} p_{T2} (1 - \cos \Delta\phi)}$$

Charged Higgs Boson searches

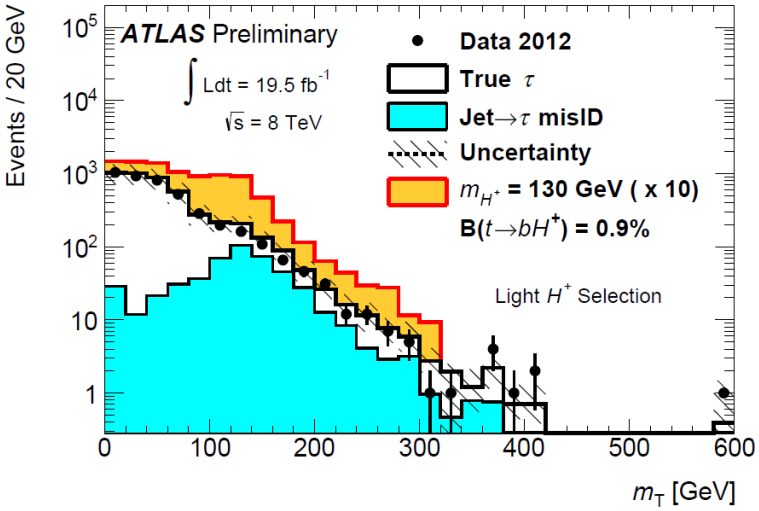
ATLAS-CONF-2013-090

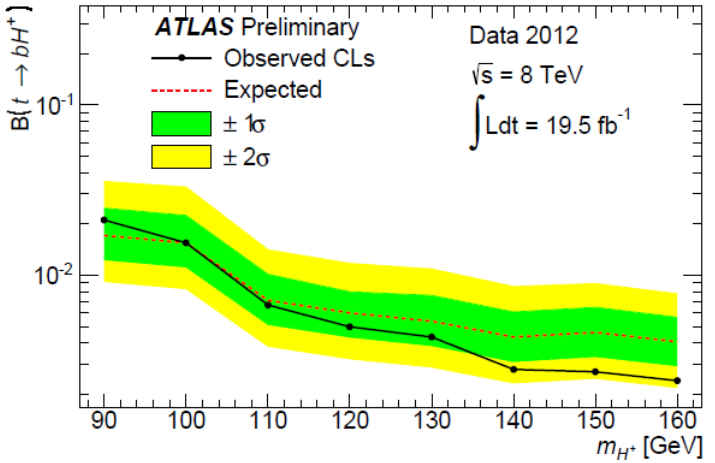
$H^+ \to \tau\nu$

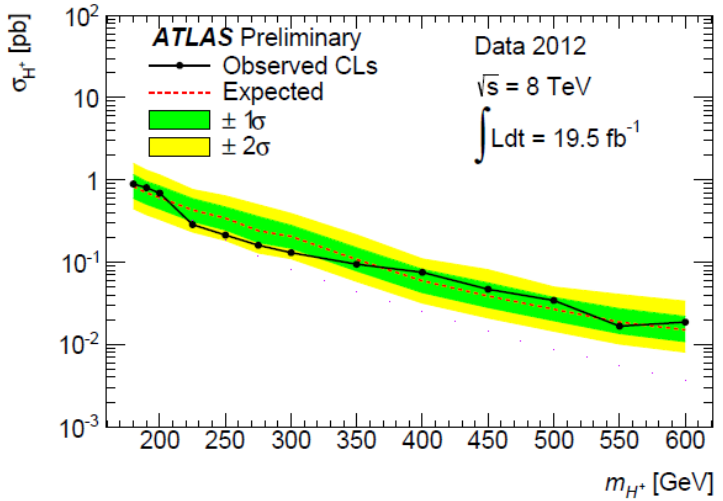
Analysis details:

- ≥ 4(3) jets with pT> 25 GeV, |η|<2.5 for light (heavy) signal selection
- ≥ 1 b-tagged jet
- 1 tau with pT > 40 GeV, matched to trigger
- no e/μ with pT>25 GeV or τ with pT>20 GeV
- Etmiss > 65 (80) GeV, $\frac{E_{\mathrm{T}}^{\mathrm{miss}}}{0.5\cdot\sqrt{\sum p_T^{\mathrm{PV\ trk}}}} > 13\ (12)\ \mathrm{GeV}^{1/2}$
- final discrimination done on mT

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\tau} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos\Delta\phi_{\tau,\mathrm{miss}})}$$







Charged Higgs Boson searches

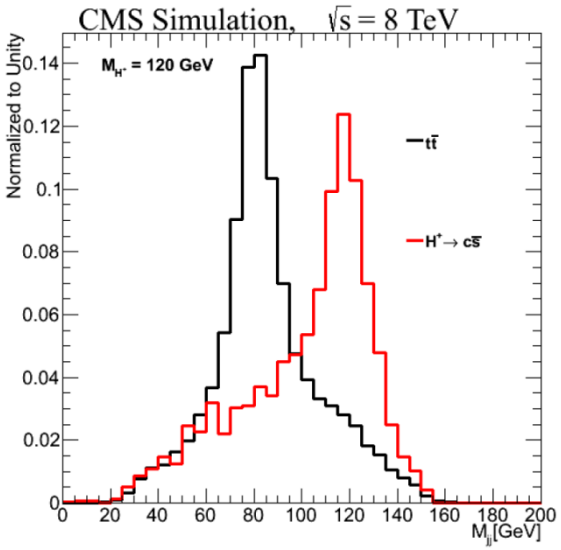
CMS-PAS-HIG-13-035

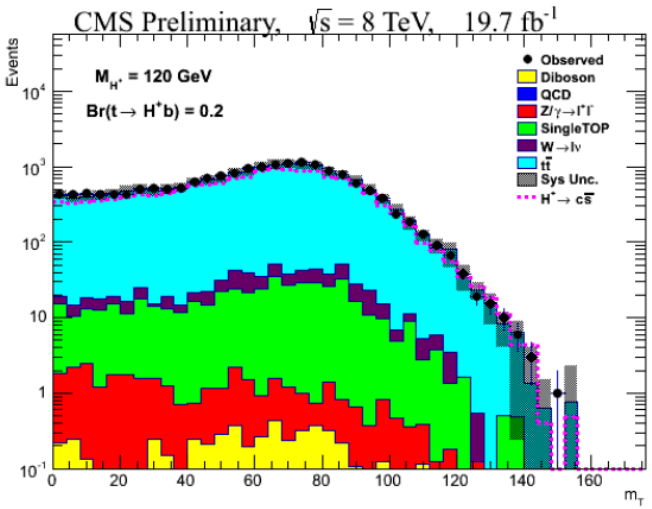
$H^+ \rightarrow c\bar{s}$

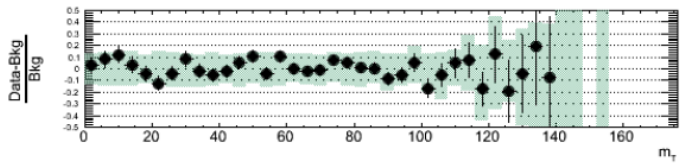
Analysis details:

- at least 1 isolated muon, pT>25 GeV, |η|<2.1
- reject events with additional e/μ with pT>10 GeV |η|<2.5 and looser isolation
- ≥ 4 jets, pT> 30 GeV, |η|<2.5
- ≥ 2 b-tagged jets
- Etmiss>20GeV

- kinematic fit constrains events using $m_t = 172.5\ GeV$ for each of the top quarks



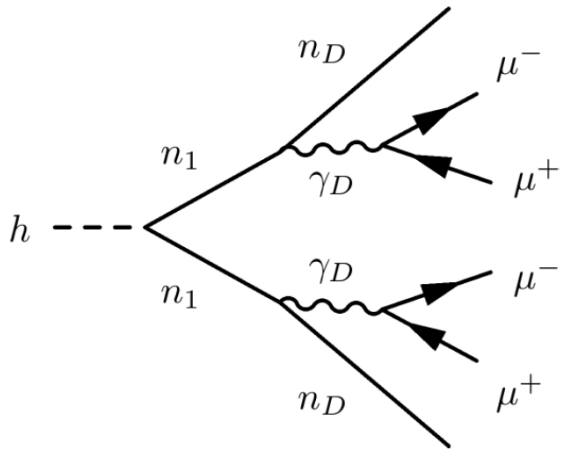




Neutral (N)MSSM Higgs Boson searches

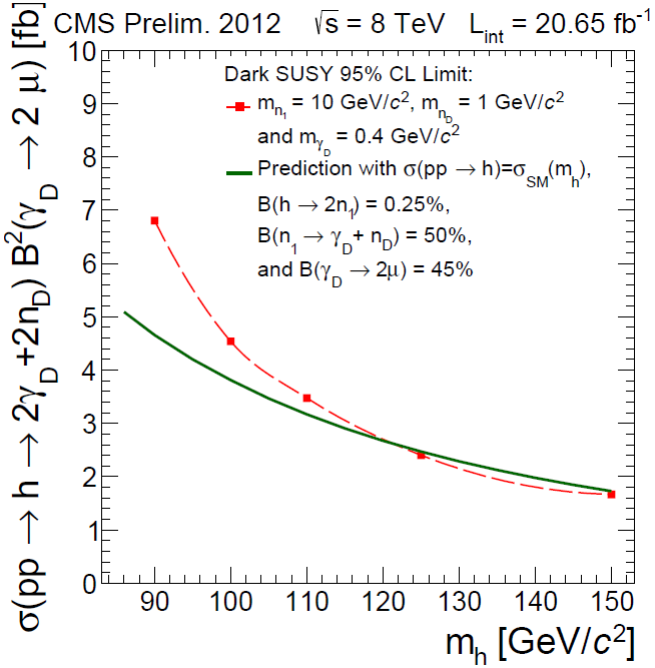
CMS-PAS-HIG-13-010

$$h \rightarrow 2a + X \rightarrow 4\mu + X$$



Analysis details:

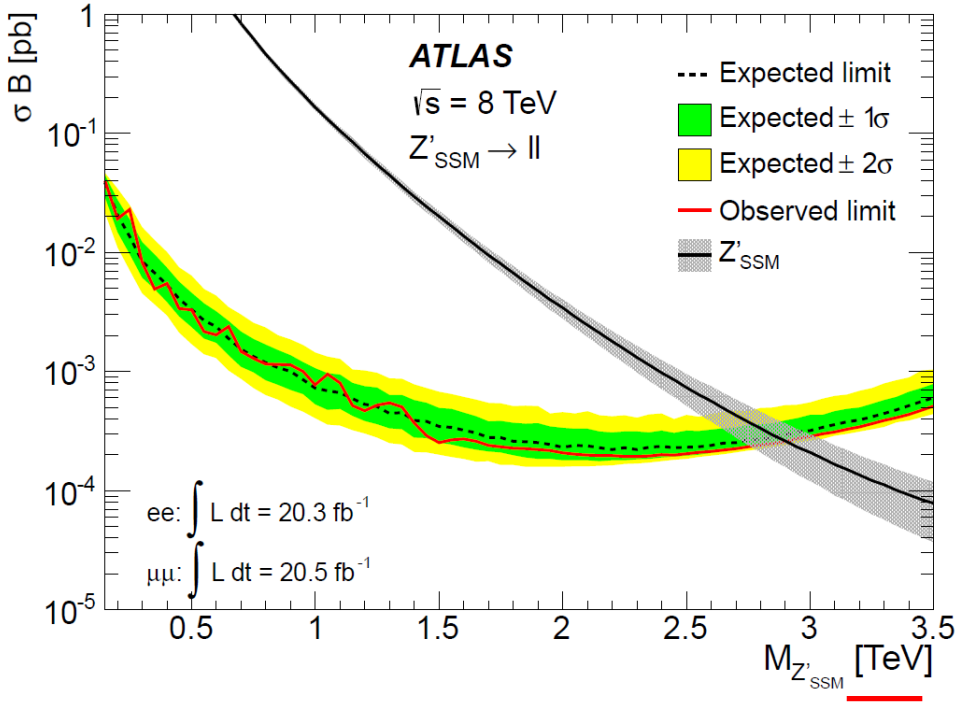
- at least 4 muons, pT>8GeV, |η|<2.4
- at least 1 muon with pT>17, |η|<0.9
- 2 isolated di-muons pairs with $m_{\mu\mu} < 5\ GeV$ and be compatible among both

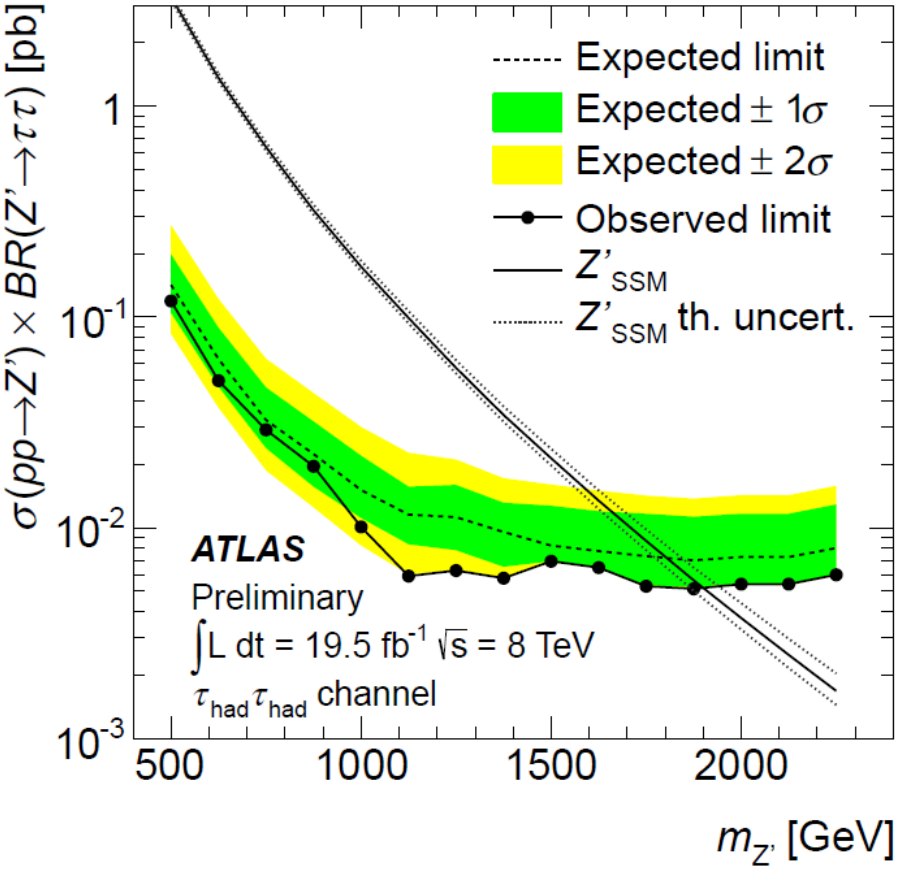


arXiv:1405.4123
ATLAS-CONF-2013-066

$Z' \rightarrow ll$ at high mass

- complementary studies to ATLAS high mass Higgs boson searches
- Sequential Standard Model (SSM)
- setup of full hadronic tau channel very similar to $\phi \rightarrow \tau_{had}\tau_{had}$
- no evidence of new physics found

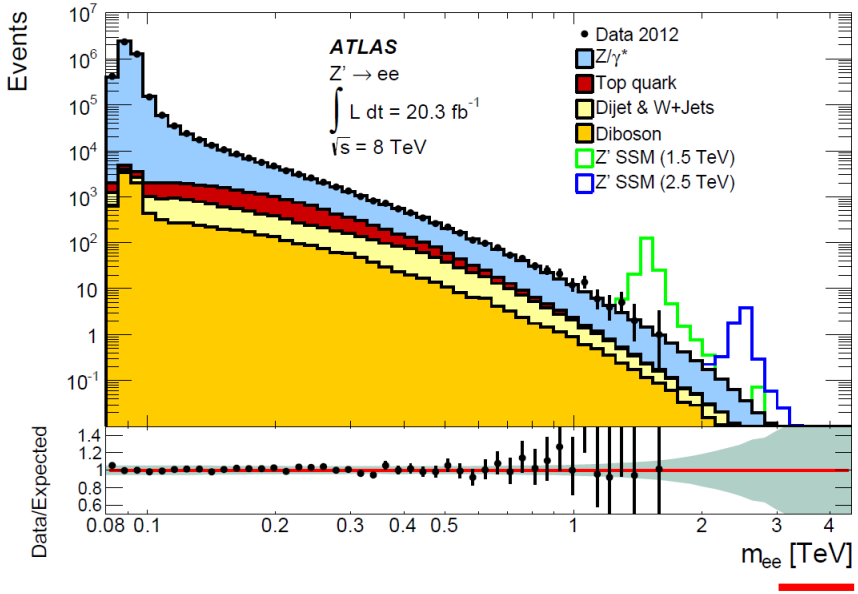


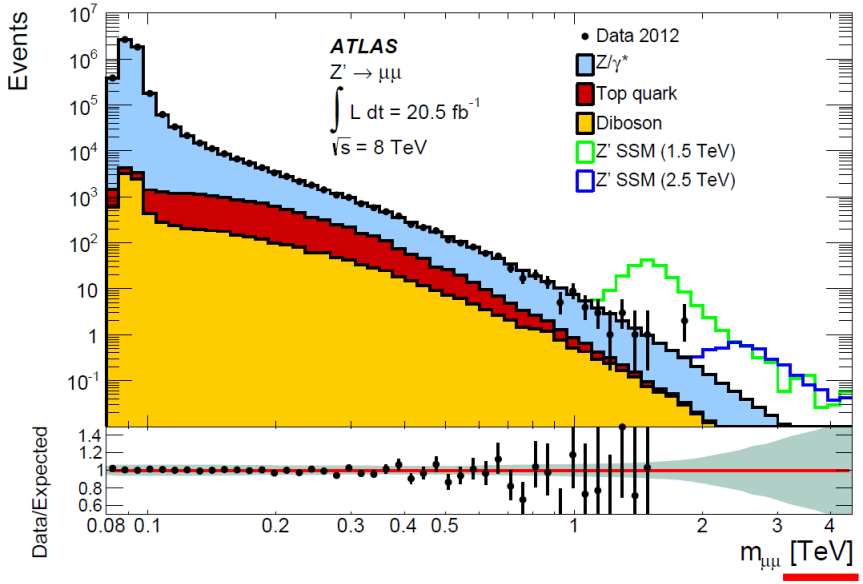


arXiv:1405.4123
ATLAS-CONF-2013-066

$Z' \rightarrow ll$ at high mass

- Sequential Standard Model (SSM)

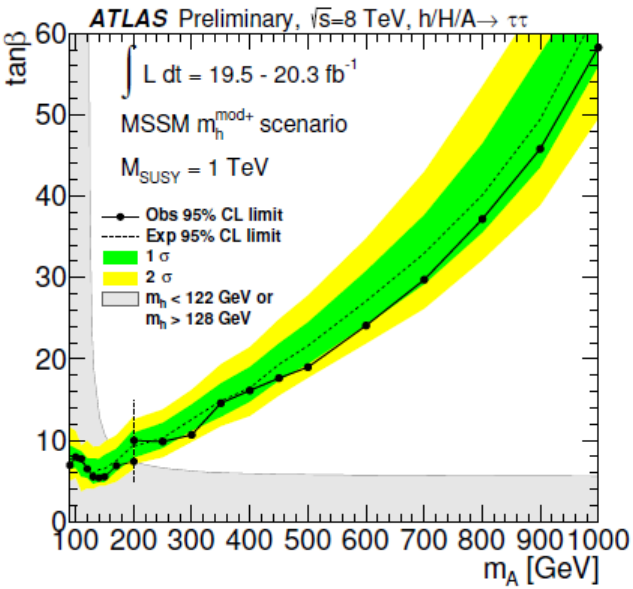


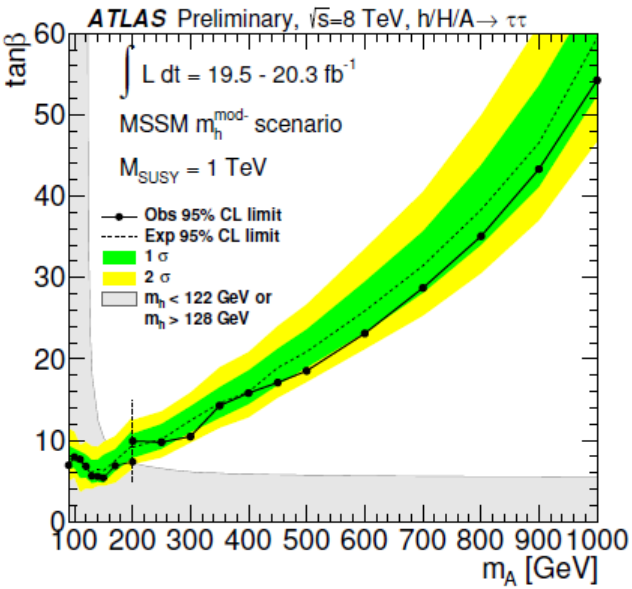


see also ATLAS-CONF-2014-030 for constraints on contact interactions and large extra dimensions using the same search channel

Neutral MSSM Higgs Boson searches

ATLAS-CONF-2014-049





$\phi \rightarrow \tau\tau$