



BSM Higgs Searches at ATLAS

Martin zur Nedden

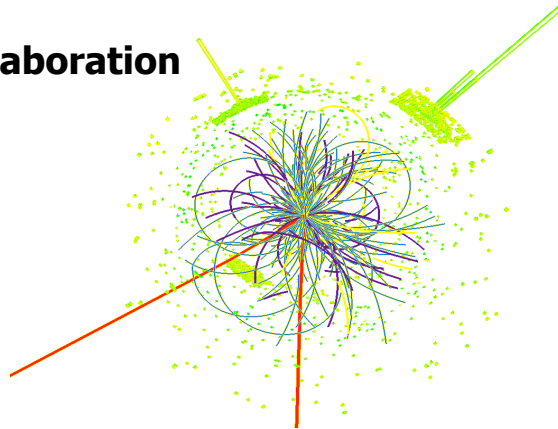
Humboldt-Universität zu Berlin

for the ATLAS Collaboration

GEFÖRDERT VOM



**Bundesministerium
für Bildung
und Forschung**



SUSY Conference 2014
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Introduction

- **Discovery of a scalar Boson consistent with SM Higgs**
 - $M(H) = 125 \text{ GeV}$
 - constraints on new phenomena via coupling measurements
 - new window for searches for physics beyond the SM
- **SM Higgs or something different?**
 - lot of room for non-SM interpretation
 - is this Boson part of an extended scalar sector?
 - large variety of models, as e.g. SUSY, composite Higgs,...
- **How to explore the Higgs sector for BSM physics?**
 - measurement of the properties (couplings, JPC, decays) of the Higgs
 - ❖ constraints to be in-compatible with the SM
 - search for additional Higgs bosons
 - ❖ heavier neutral scalars
 - ❖ charged Higgs bosons

Overview BSM Higgs

- **Large variety of models, two basic approaches**
 - consider simplest extensions of the SM
 - topological driven searches (model independent)
- **Considered models**
 - Two Higgs Doublet Model (2HDM)
 - ❖ additional doublet
 - ❖ four types based on coupling structure
 - Minimal Supersymmetric Standard Model (MSSM)
 - ❖ search for neutral and charged Higgs bosons
 - Minimal composite Higgs Model (MCHM)
 - Next-to-Minimal SUSY (NMSSM)
 - ❖ MSSM + complex singlets (S)
 - **2HDM and MSSM have a rich phenomenology, compatible with SM-like Higgs boson**
- **Only a small selection of a rich field can be shown in this talk!**

Two Higgs Doublet Models

- **2HDM:** adding a second EW doublet to the Higgs sector

- one of the simplest extensions of the SM
- 5 Higgs bosons:



- **2HDM Higgs sector described by:**

- 4 Higgs boson masses
- $\tan \beta$ (ratio of vacuum expectation values of the doublets)
- mixing parameter α (between two neutral CP even states h, H)

- **Four types**, type II is MSSM like (charged leptons along with d-type quarks)

Coupling Scale	Type I	Type II	Type III	Type IV
doublet 1	vector bosons	u-type q's	q's as type I	q's as type II
doublet 2	fermions	d-type q's	ℓ 's as type II	ℓ 's as type I

2HDM Coupling Limits

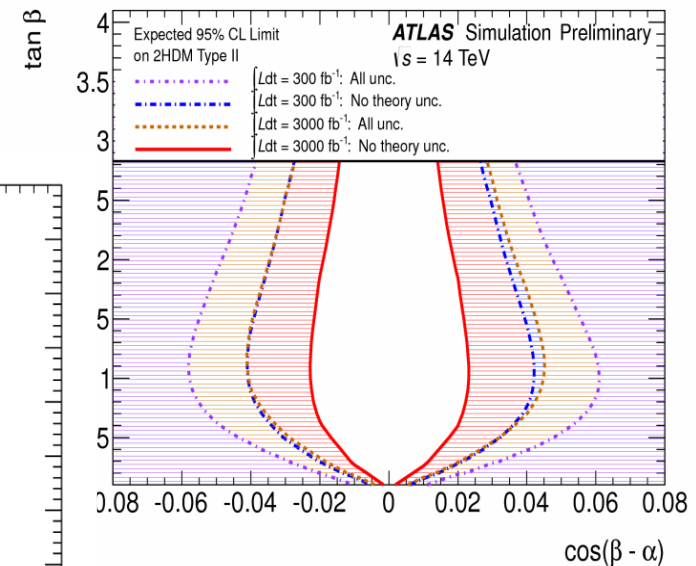
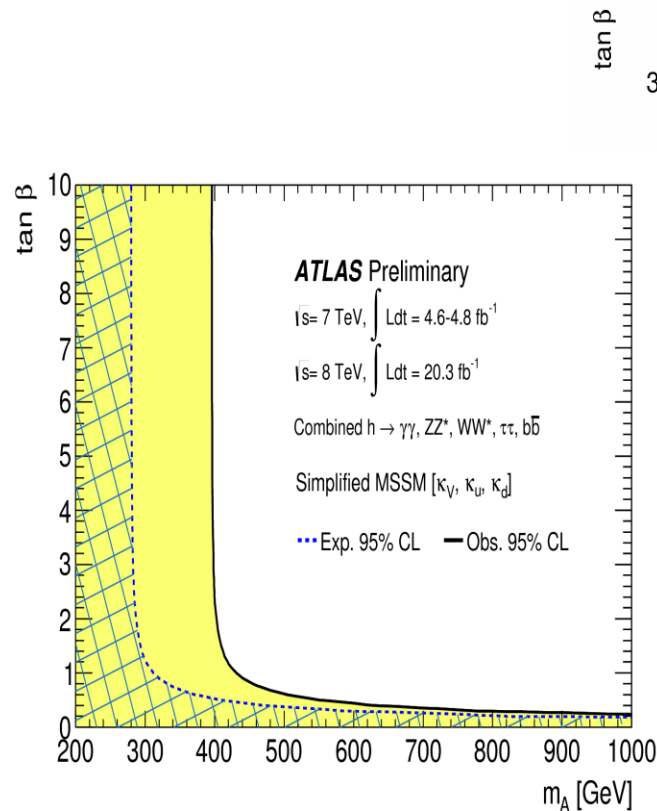
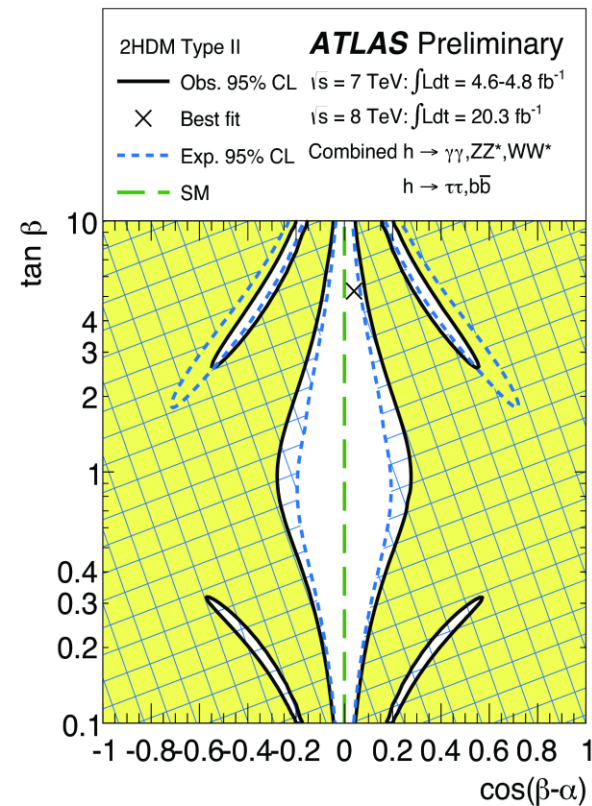
- Based on ATLAS SM Higgs coupling measurements
 - **ATLAS-CONF-2014-009** ($h \rightarrow \gamma\gamma$, $h \rightarrow ZZ'$, $h \rightarrow WW'$, $h \rightarrow \tau\tau$, $h \rightarrow bb$)
- Consistent with SM-like augment: $\cos(\beta-\alpha) \sim 0$
 - **ATLAS-CONF-2014-010**
- 2 HDM Coupling factors:

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

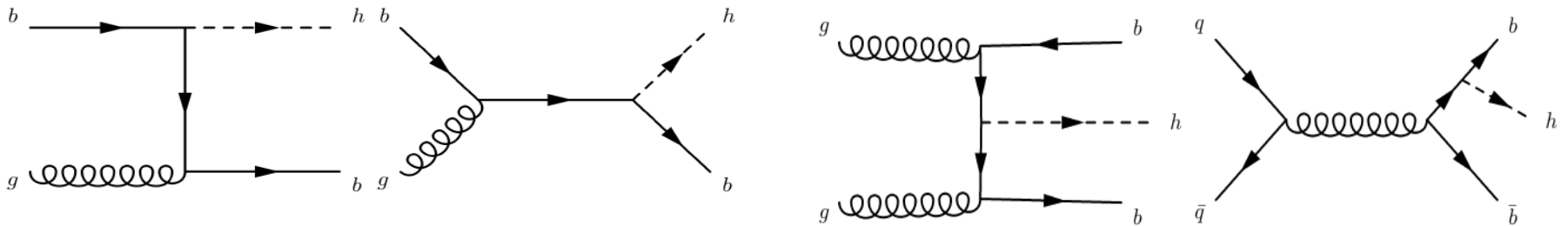
- Measurements of Higgs couplings to vector bosons, up- & down type fermions (combination of all channels)
 - set limits on all 2HDM models
- Higher sensitivity at 14 TeV expected
 - **ATL-PHYS-PUB-2013-015**

2HDM Coupling limits, Type 2

- Set limits on the 2HDM Type II with 7 / 8 TeV data (left)
- Mass dependence of the coupling compatible with SM Higgs boson (middle)
- Expected sensitivity for 14 TeV data (right)
- More results shown in the backup (Vector Boson coupling)

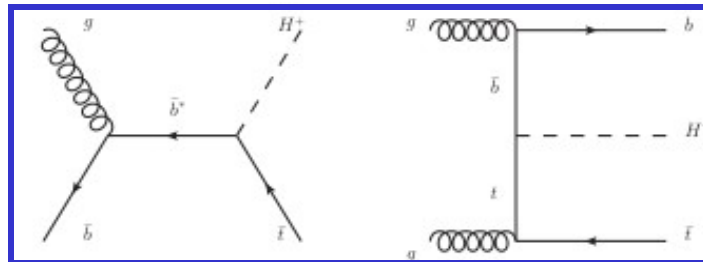
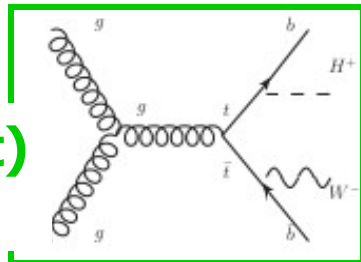


- **Higgs coupling to b-quarks and τ -lepton enhanced**
 - associated production with b-quarks ($h/H/A + b$) increasingly important
 - decays to $h/H/A \rightarrow bb / \tau\tau$ dominate



- **Charged Higgs production involves top-quarks**
 - decay via $H^+ \rightarrow \tau\nu / cs / tb$, depending on $m(H^+)$ and $\tan\beta$
 - $\tau / b / t$ reconstruction play a central role in this searches

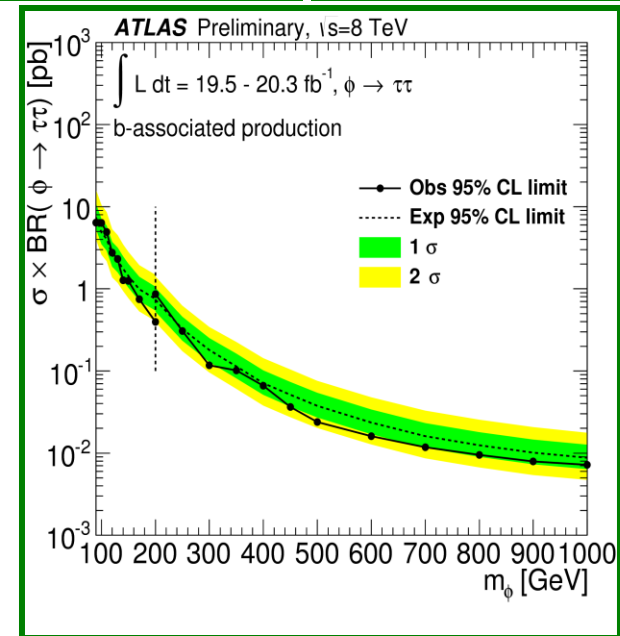
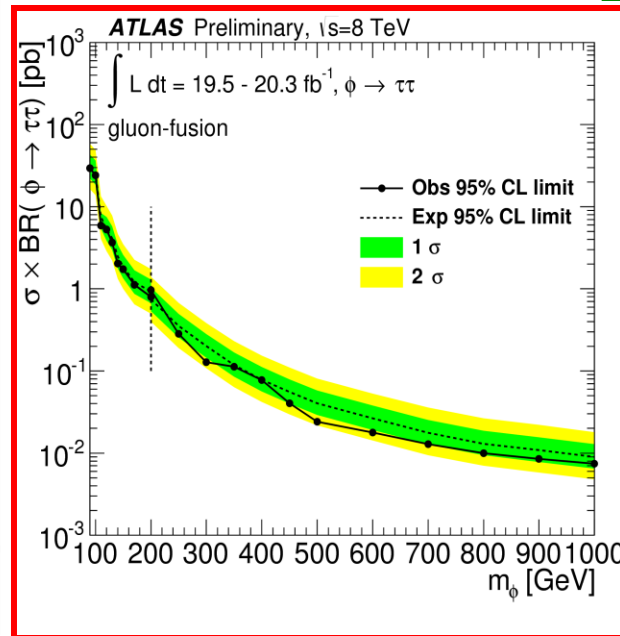
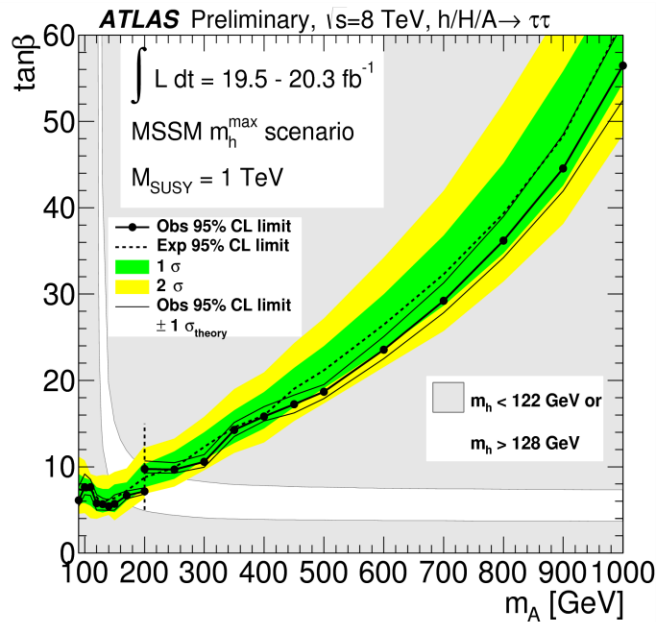
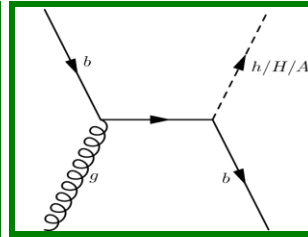
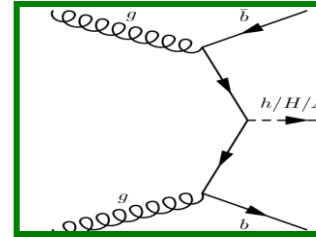
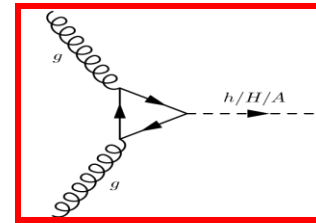
$m(H^+) < m(t)$
 $t \rightarrow bH^+$



$m(H^+) > m(t)$,
 associated
 production

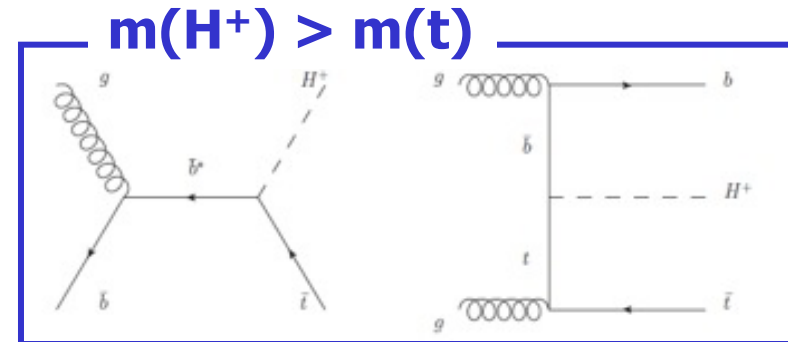
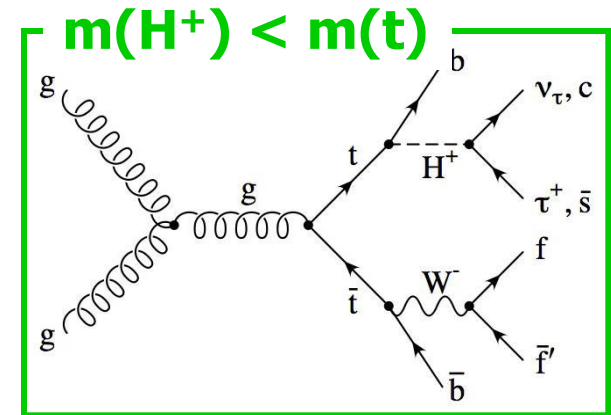
Neutral Higgs Boson Searches

- Decay of MSSM neutral Higgs bosons in τ -pairs
- **ATLAS-CONF-2014-049**
- Limits for the **MSSM m_h^{\max} scenario**
- Exclusion limits for the production cross section $\Phi \rightarrow \tau\tau$
 - **gluon-fusion** and **b-associated** production
 - extended mass range up to 1000 GeV, no significant excess found

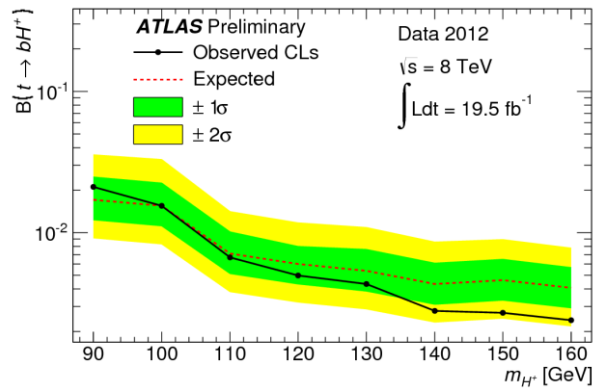


Charged Higgs Searches

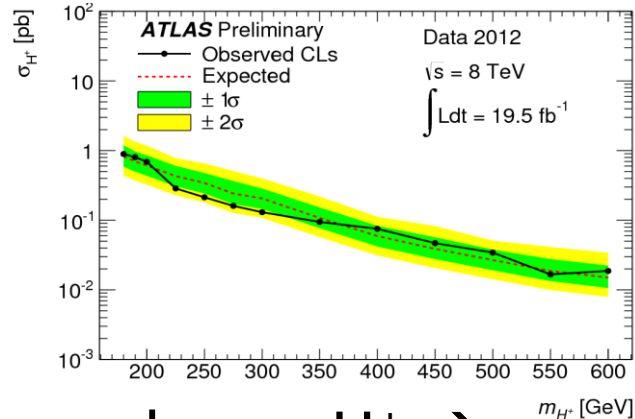
- Observation of a charged Higgs would be a clear hint for BSM physics
- Production mode dependent $m(H^+)$ relative to $m(t)$
- **Light charged Higgs**
 - $\tan \beta < 1$: $H^+ \rightarrow sc$ dominant / $\tan \beta > 1$: $H^+ \rightarrow \tau\nu$ dominant
- $H^+ \rightarrow cs$ measurement (**light H^+**)
 - reconstruction using a kinematic fit
 - [Eur.Phys.J.C 736\(2013\)2465](#)
- $H^+ \rightarrow \tau\nu$ measurement (**light and heavy H^+**)
 - [JHEP06\(2012\)039](#) (**light H^+**)
 - [ATLAS-CONF-2013-090](#) (**heavy H^+**)
 - using $\tau_{had} + jets$ channels
 - at least one b-tagged jet
- **No evidence of a H^+ signal**
 - set limits



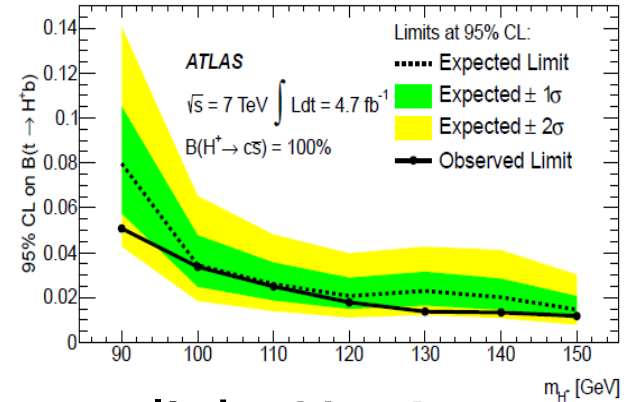
Charged Higgs Boson Searches



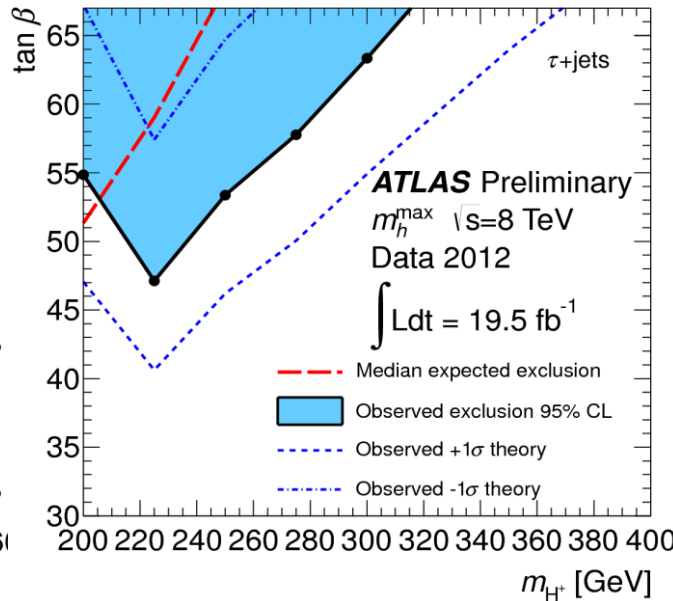
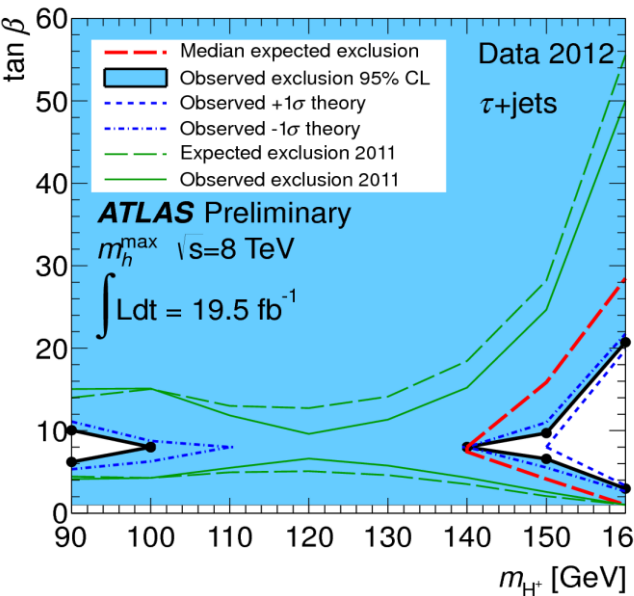
light $H^+ \rightarrow \tau\nu$



heavy $H^+ \rightarrow \tau\nu$



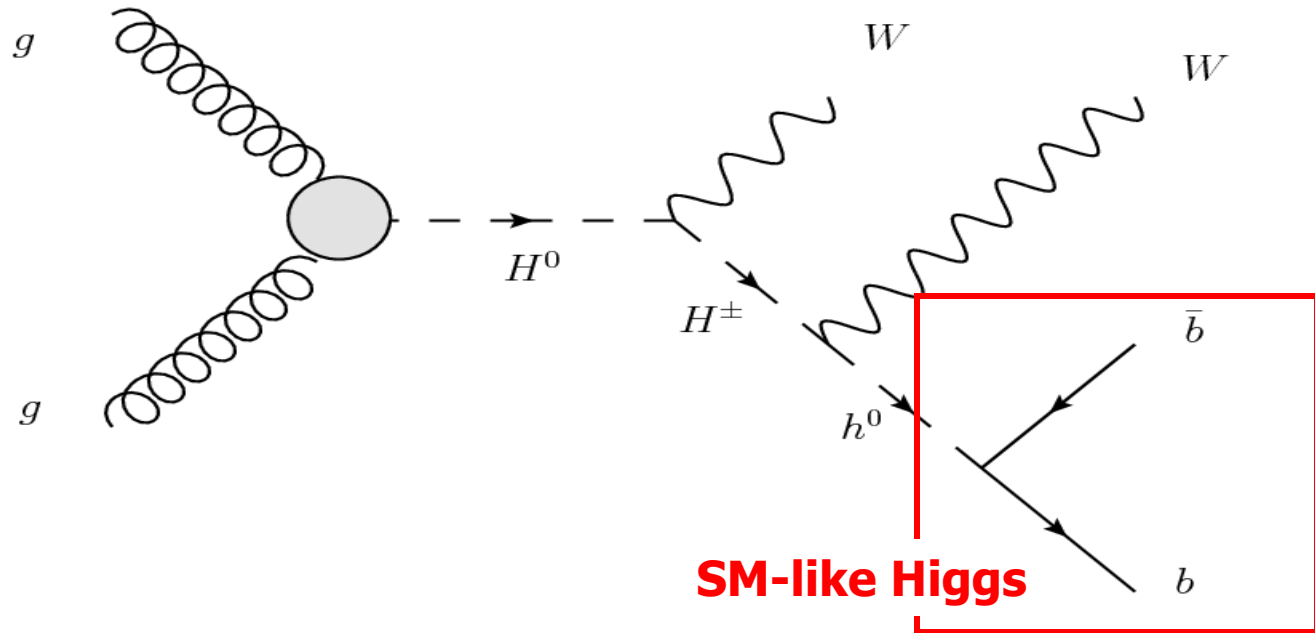
light $H^+ \rightarrow cs$



- **light H^+ :** exclusion of most of parameter space
- **heavy H^+ :** first limits in a high mass range
- **ongoing searches** heavy $H^+ \rightarrow tb$

2HDM multi-Higgs Cascade

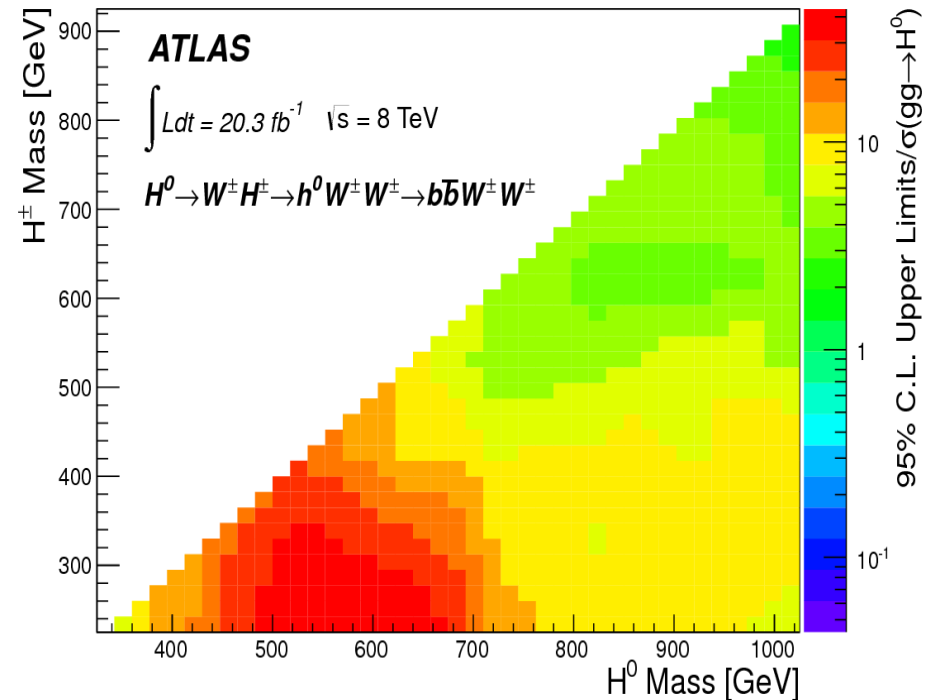
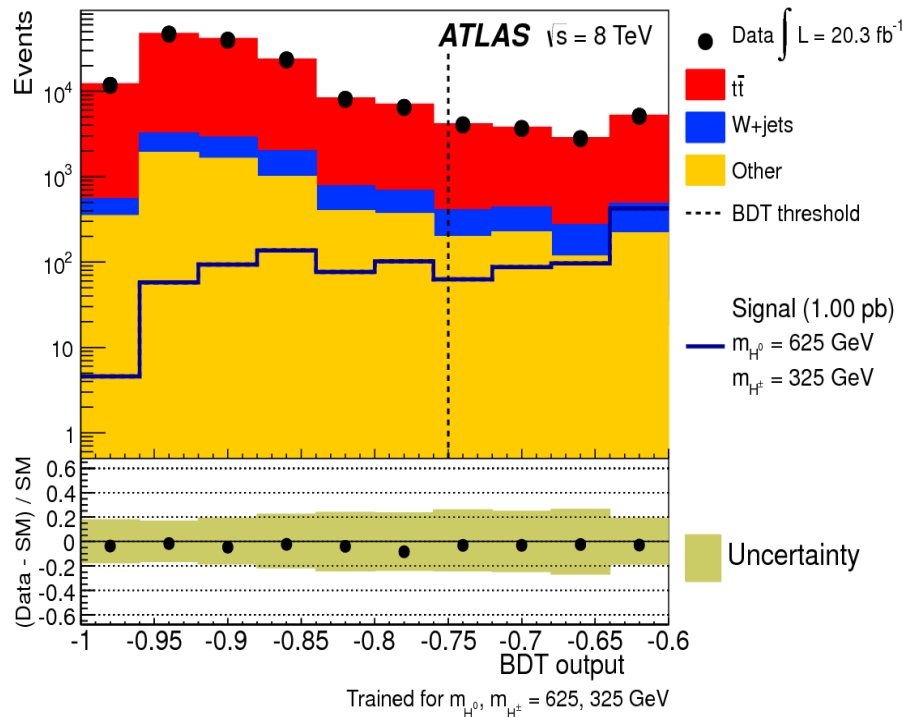
- Search for **cascade decay** $H^0 \rightarrow WH^+ \rightarrow WW h^0 \rightarrow WW b\bar{b}$
 - **Phys.Rev.D89(2014)032002**



- **search ranges**
 - $225 \text{ GeV} < m(H^+) < 925 \text{ GeV}$
 - $325 \text{ GeV} < m(H^0) < 1025 \text{ GeV}$
- same topology as top-pair events

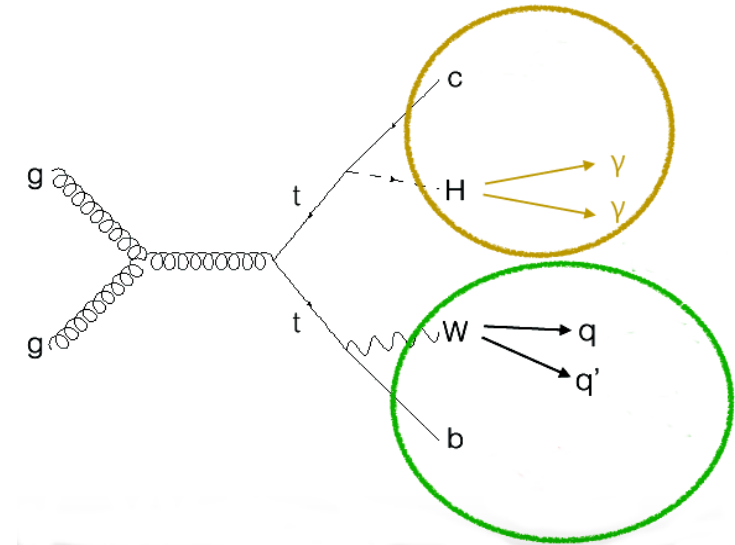
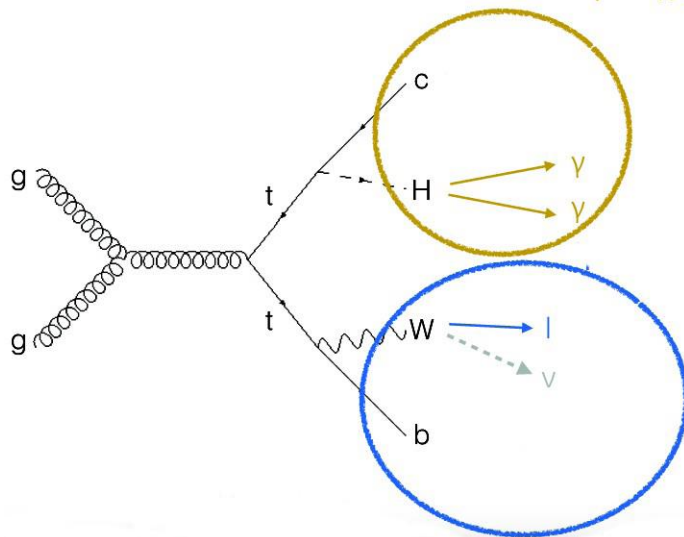
2HDM multi-Higgs Cascade

- Usage of Boosted Decision Trees
 - trained at 36 different mass points for $m(H^0)$ and $m(H^\pm)$
- **BDT output:**
 - kinematic difference between Higgs cascade and top-pair production
- **Upper limits:** larger as theoretical (SM-like) H^0 cross section

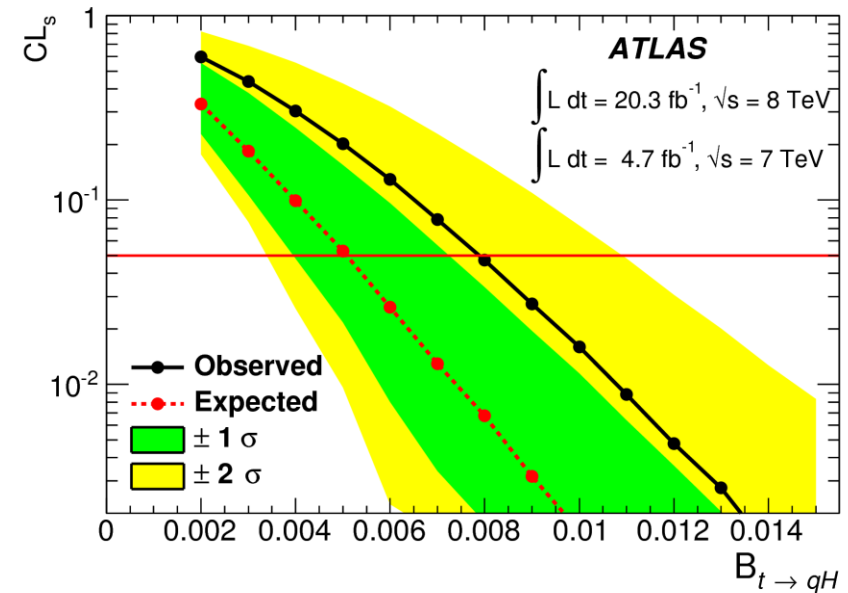
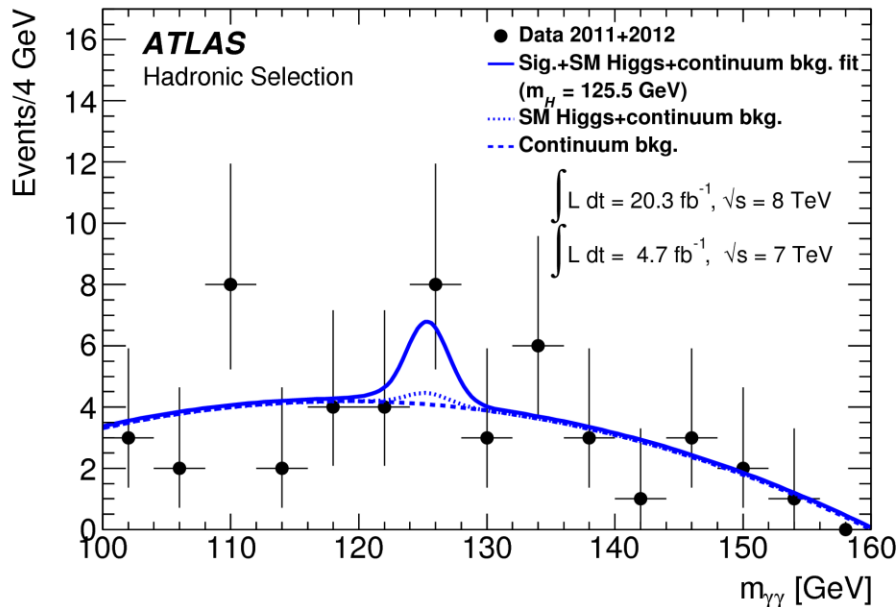


2HDM Higgs and FCNC top Decays

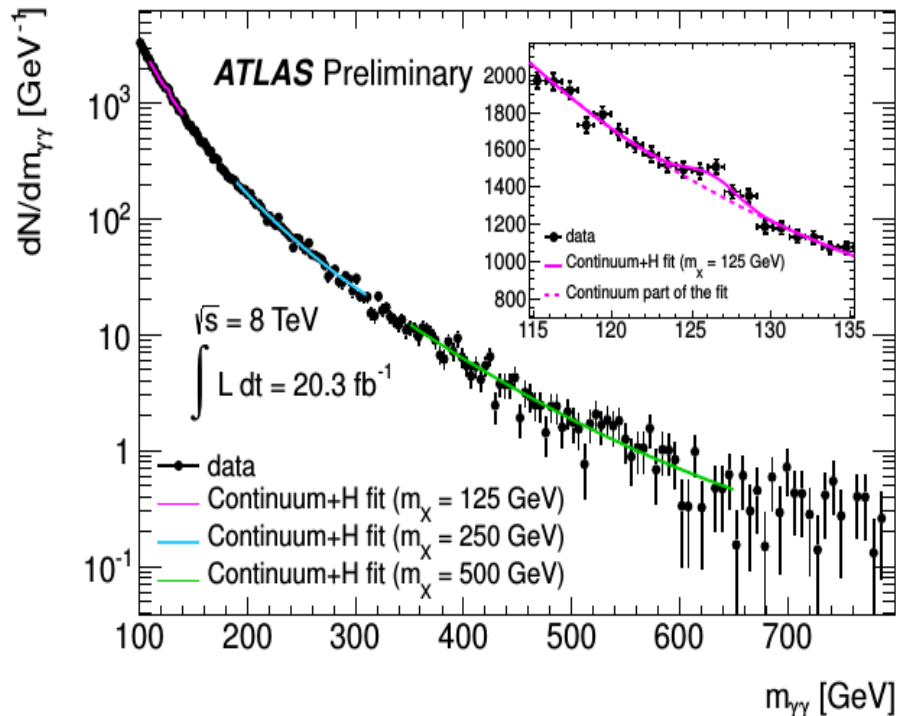
- Search for **FCNC** $t \rightarrow qH$ ($H \rightarrow \gamma\gamma$), q : up-type quark
 - suppressed by GIM mechanism (e.g. $BR \sim 3 * 10^{-33}$ for $t \rightarrow cH$)
 - observation of FCNC: clear signal of new physics
 - [arXiv:1403.6293\[hep-ex\]](https://arxiv.org/abs/1403.6293)
- **two channels**
 - other top decaying **leptonically** or **hadronically**
 - Higgs decay to **two photons**



- Example for “hadronic top quark” channel
 - final distribution of events of $m_{\gamma\gamma}$
 - CLs as a function of the FCNC branching ratio
- **Final constraints**
 - $\text{BR}(t \rightarrow qH) < 0.79$ (0.51)% observed (expected) @95%CL
 - for a SM Higgs boson at 125.5 GeV

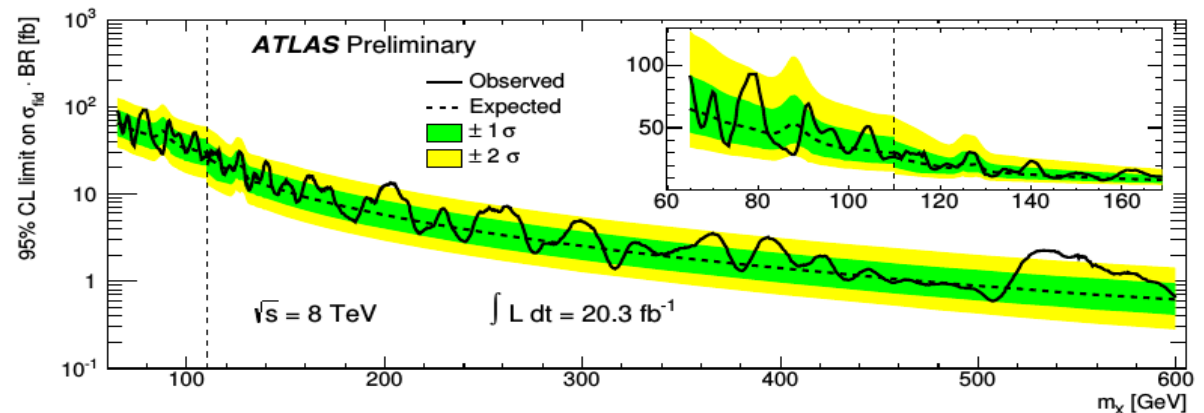
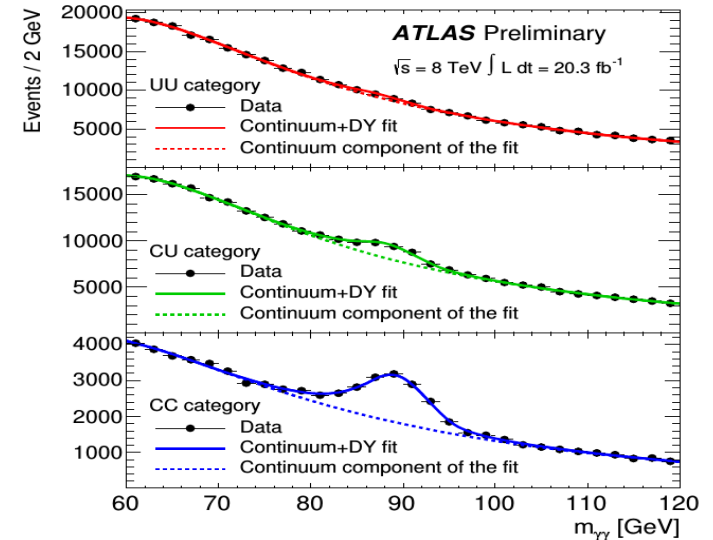


- Search for **heavy scalar particle** other than the SM Higgs
 - extensions of the SM (e.g. models featuring an extended Higgs sector) predict new scalar resonances
 - search for di-photon resonance within $65 < m_X < 600$ GeV
- SM $H \rightarrow \gamma\gamma$ treated as BG
 - same techniques as for SM di-photon Higgs analysis
- **ATLAS-CONF-2014-031**
- **No signal evidence found**
 - model independent limit at 95% CL on production cross section
 - wider mass range



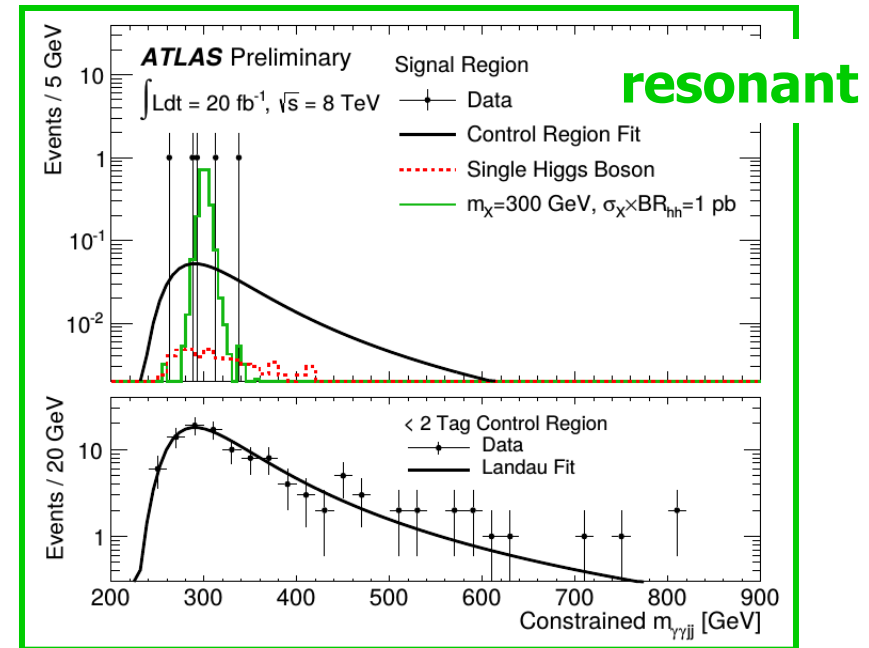
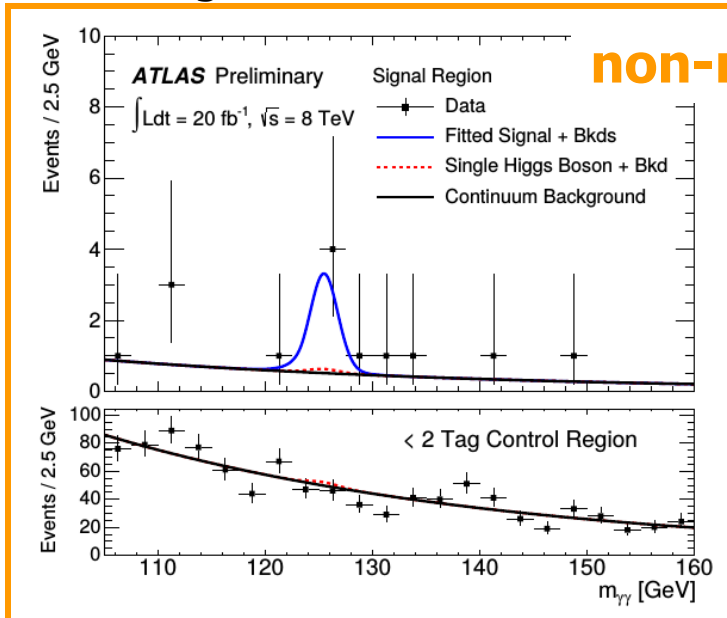
Heavy Scalar resonances in $\gamma\gamma$ Pairs

- Background estimation from $m_{\gamma\gamma}$ sideband interpolation
- Split in two mass ranges
 - $65 < m_X < 110$ GeV
 - $110 < m_X < 600$ GeV
- Categories according to (un)converted photon candidates:
 - UU / UC / CC
 - background only fits
- Limit on fiducial cross section as a function of m_X

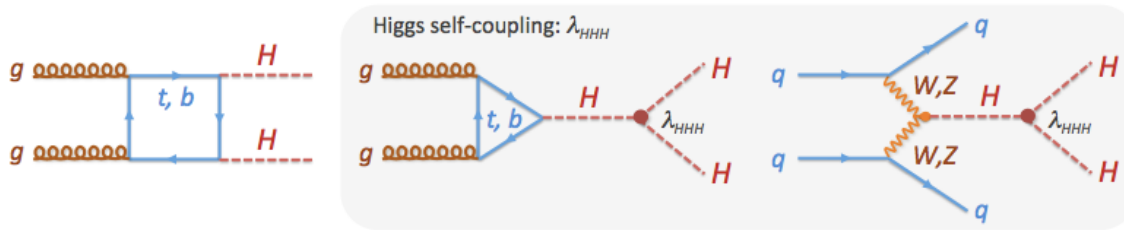


Higgs Boson Pair Production

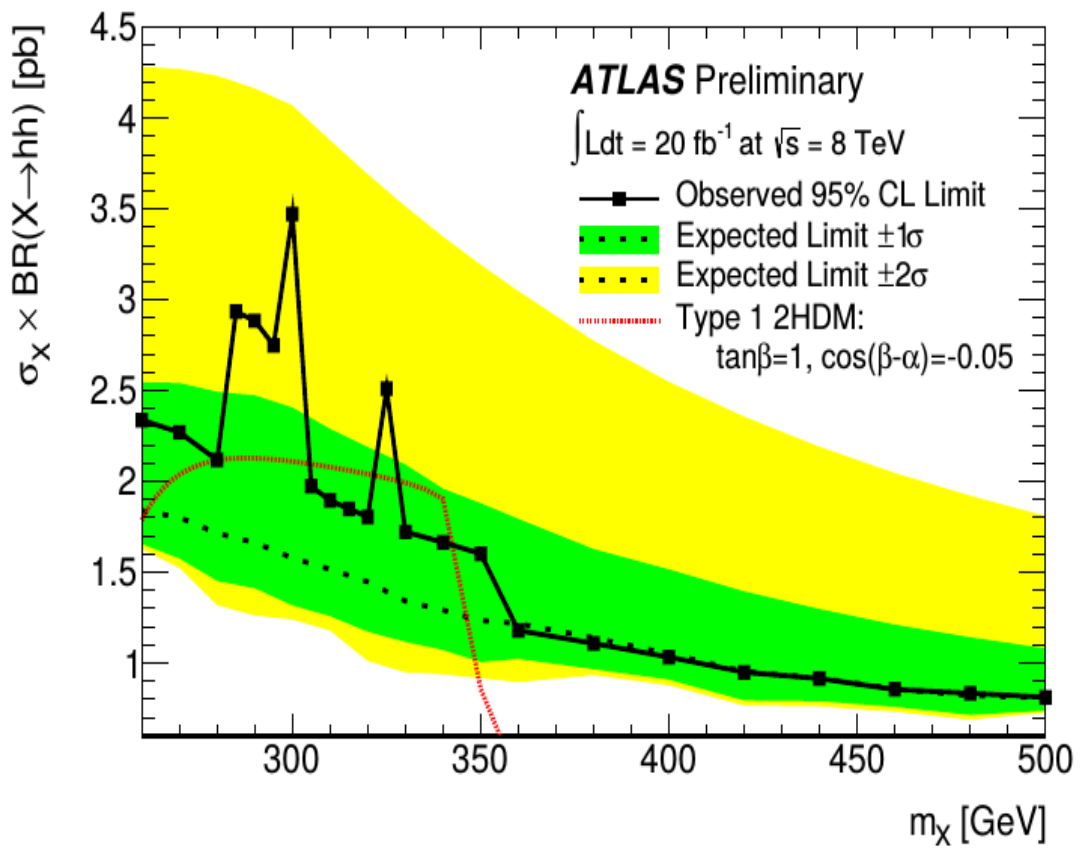
- Search for non SM with either **resonant** ($X \rightarrow hh$) or **non-resonant** pair production of Higgs bosons
 - $hh \rightarrow \gamma\gamma$ bb channel
 - [arXiv: 1406.5053\[hep-ex\]](https://arxiv.org/abs/1406.5053)
- Predicted rates in SM for hh several orders of magnitude smaller than for the single h production
 - variety of extensions of SM could enhance hh production
 - e.g. 2HDM: $H \rightarrow hh$



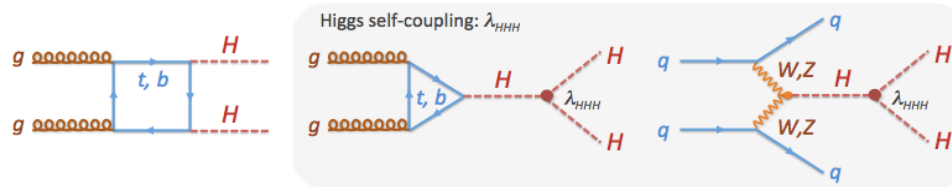
Higgs Boson Pair Production



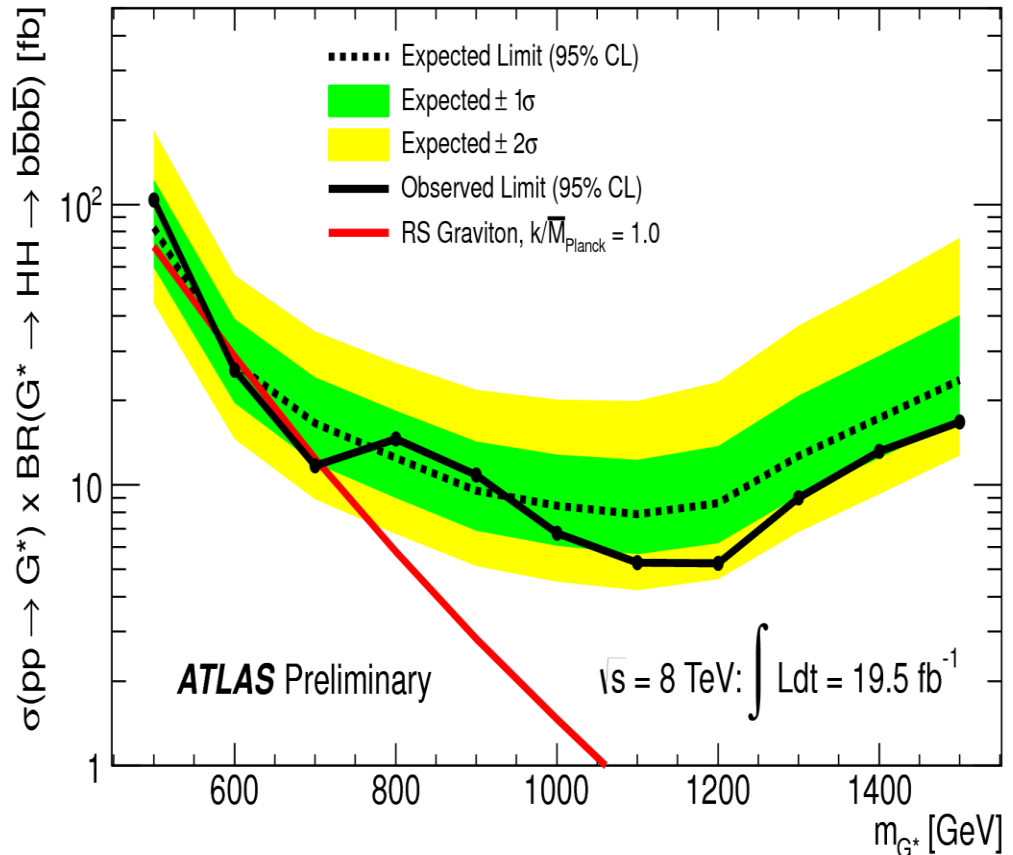
- **Decay channel $hh \rightarrow \gamma\gamma bb$**
- upper limit for anomalous non resonant hh production
 - **observed 2.2 pb,**
 - **expected 1.0 pb**
 - (SM hh production ~ 10 fb)
- 95%CL upper limit on cross section times BR as a function of m_X for a narrow scalar resonance



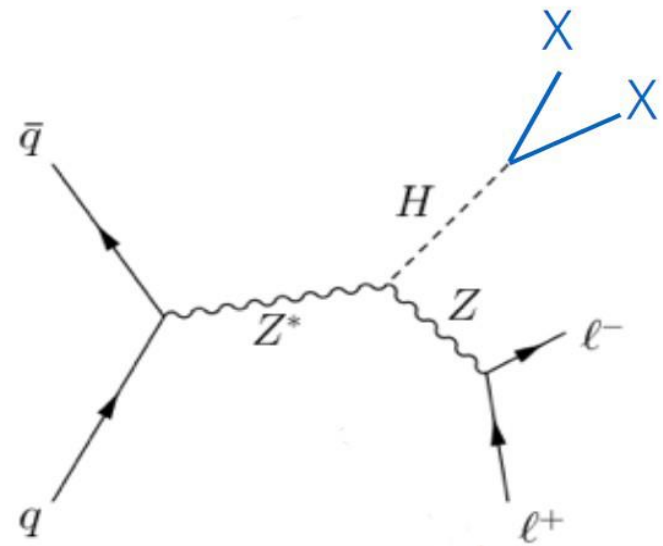
Higgs Boson Pair Production



- **Decay channel**
 $X \rightarrow HH \rightarrow bbbb$
- **ATLAS-CONF-2014-005**
- Search for TeV resonance decaying into SM Higgs bosons
- Result interpreted with first KK excitation of Graviton G^* as signal (in a Randall-Sundrum model)
- Upper limit at 95% CL derived as a function of $m(G^*)$
- KK Graviton **excluded** between **590 and 710 GeV**

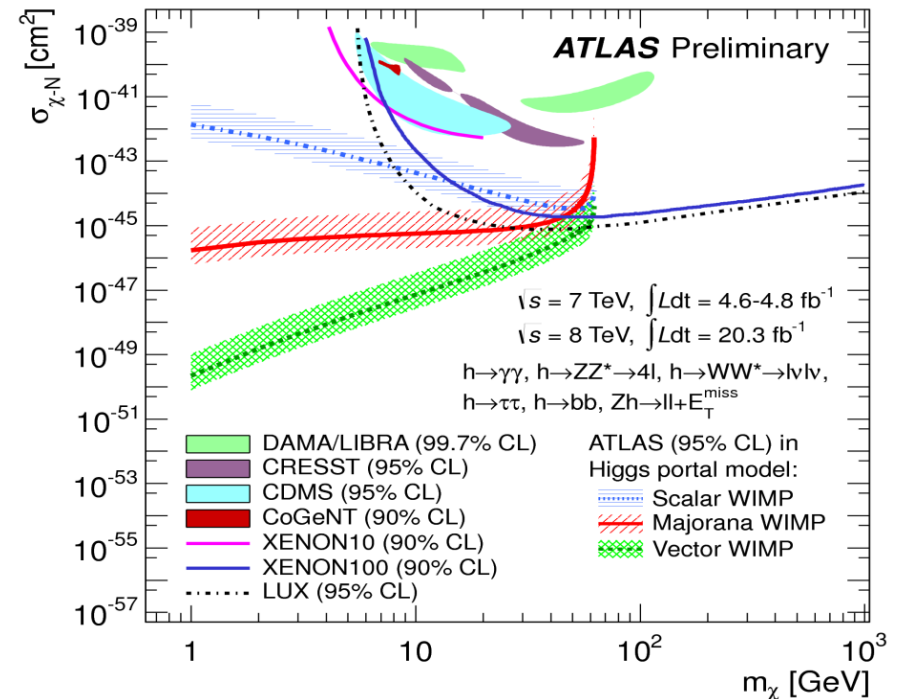
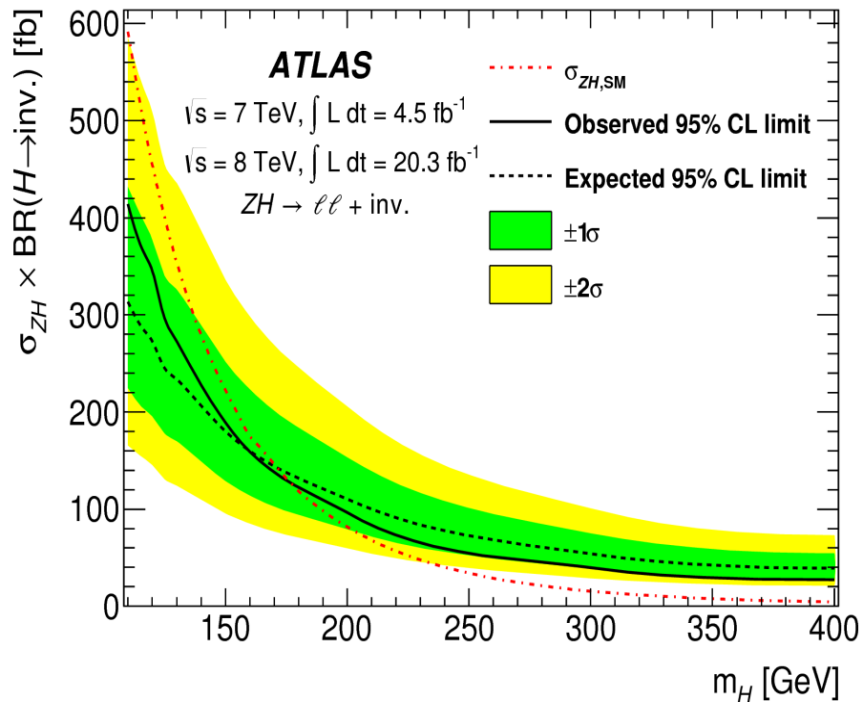


- Search for **evidence of invisible Higgs decay** modes
 - produced in association with a Z-boson
 - **Phy.Rev.Lett 112(2014)201802**
 - extensions of the SM allow higgs decays into long-lived particles
 - ❖ e.g. DM candidates
 - use LHC data to constrain the BR of invisible Higgs decays
- Assuming SM rate for ZH:
 - upper limit on BR set
 - interpreted in term of upper limit on allowed DM-nucleon scattering (Higgs Portal DM scenario)
 - mass range: $110 < m_H < 400$ GeV



Invisible Higgs Decay

- Constrain for the discovered Higgs boson:
 - **BR(h → inv.) < 75% (observed)** [$< 62\%$ (expected)] at 95%CL
- Limit on **DM-nucleon scattering** cross section (function of DM mass)
 - upper limit at 95% on the WIMP-nucleon scattering (Higgs portal model)
 - shown separately for scalar, majorana fermion or vector boson WIMP



Conclusions

- **BSM Higgs search very active field**
 - large variety of analyses
 - large potential to make a discovery
- **Large progress made in the last year**
 - tight constraints to neutral and charged Higgs
 - explore FCNC searches
 - limits on invisible Higgs decays
- **Still ongoing analyses on 8TeV**
- **Large physics potential expected of Run 2 with 13 TeV**



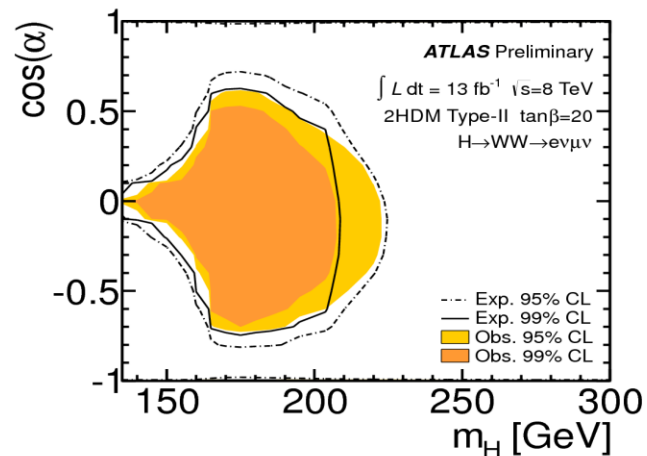
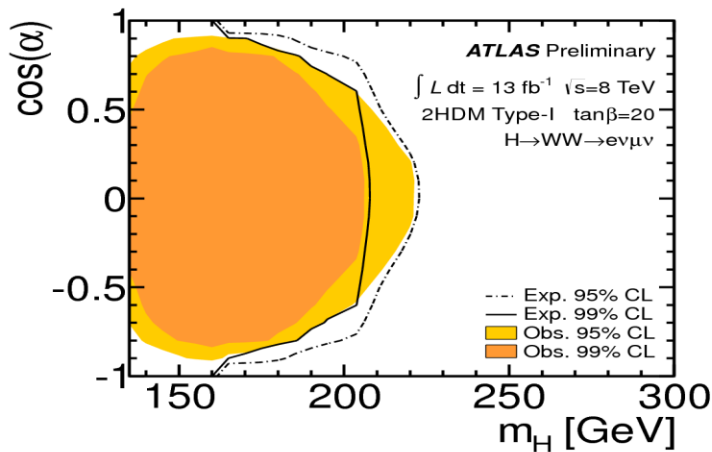
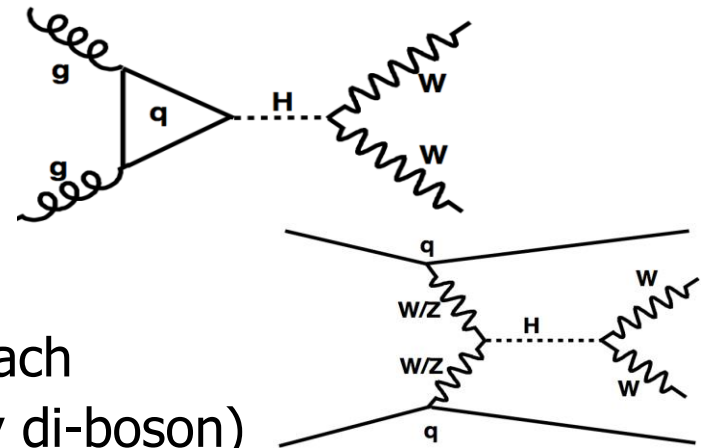
Backup Slides



- 2HDM Vector Boson Couplings
- Old neutral MSSM Higgs search with 7 TeV data

2HDM and Vector Bosons

- Search for heavy scalar CP-even Higgs
 $H \rightarrow WW \rightarrow e\nu \mu\nu$
- **ATLAS-CONF-2013-027**
- No evidence found in the region
 $135 < m_H < 300 \text{ GeV}$
- Analysis based on a neural network approach
 - signal / background separation (mainly di-boson)
- Exclusion limits for $\tan \beta = 20$ for 2HDM, type I / II



Heavy neutral Higgs Searches

- **Generic production of a neutral Higgs Boson $h / H / A$**
 - gluon fusion ($gg \rightarrow \Phi$) or b-associated ($\Phi b(b)$)
 - decay via $\Phi \rightarrow \tau\tau$ ($\sim 10\%$) or $\Phi \rightarrow \mu\mu$ ($\sim 0.04\%$)
 - analysed final states $\mu\mu, \tau_e\tau_\mu, \tau_e\tau_{had}, \tau_{had}\tau_{had}, \tau_\mu\tau_{had}$
 - split into b-tagged and b-vetoed samples
- **JHEP 02(2013)095**

