Exotic Higgs decays at ATLAS

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Introduction

The discovery of a new particle consistent with the SM Higgs has opened an extremely interesting range of opportunities for discovery of possible "exotic" behaviours in the data collected by ATLAS

POST-DISCOVERY
BSM HIGGS PHYSICS
@ ATLAS/LHC

→ SEARCH FOR ANOMALOUS DECAYS

→ SEARCH FOR ANOMALIES IN THE HIGGS COUPLINGS

→ SEARCH FOR ANOMALOUS PRODUCTION MODES AND/OR ADDITIONAL SCALARS

Outline

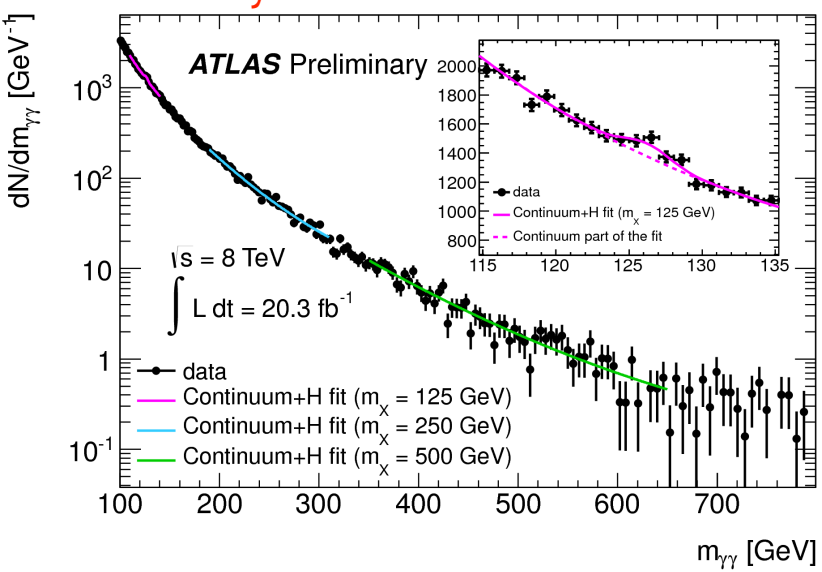
* exotic Higgs bosons decays and anomalies in the production of the Higgs boson:
  - higgs-like particles decaying in YY
  - multi-higgs cascades
  - di-higgs production: bbbb, bbγγ
  - flavor violating top decays: $t \rightarrow cH$ ($H \rightarrow YY$)
* decays of the Higgs in exotic particles:
  - higgs decays to dark-photons
  - higgs decays to invisible particles
* indirect constraints from Higgs coupling measurements
* summary

NOTE: not enough time to cover everything here. A full and daily updated list of all ATLAS results, with details on each analysis, is available here:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic

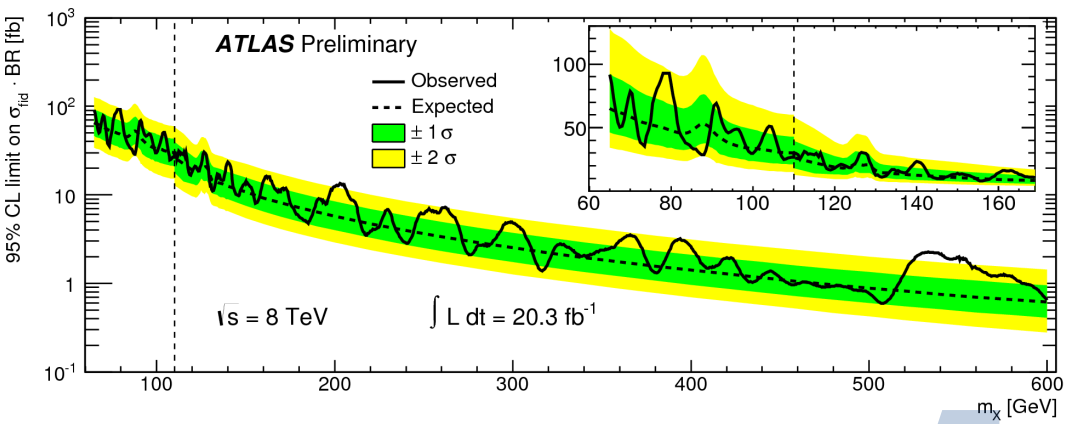
Scalar resonances to di-photon pairs

- extension of the techniques developed for the discovery of H(125)→γγ to search for additional Higgs-like states (A,H,…) in an extended mass range
  - predicted by several extensions of SM: ex. 2HDM → 2 higgs doublets → 5 bosons h, H, A, H^+, H^-
  - $m_{\gamma\gamma}$ spectrum, fitted with analytical descriptions of signal and background distributions (H(125) contribution included in BG)
  - background yield obtained from data by interpolation between the $m_{\gamma\gamma}$ sidebands
  - sensitivity increased by splitting the analysis in two mass ranges and in different categories according to the number of reconstructed converted photons

BG-only fit



95% CL UL on x-section×BR(X→γγ) VS m_X



x-section restricted to a fiducial volume chosen to reduce the dependence from event topology and production process

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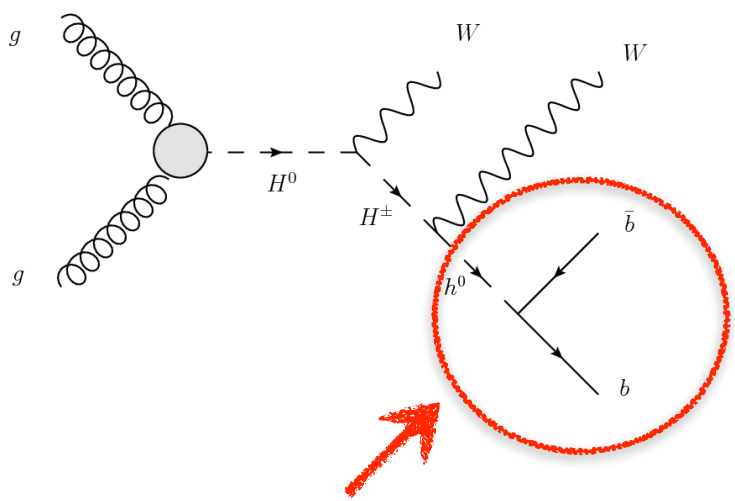
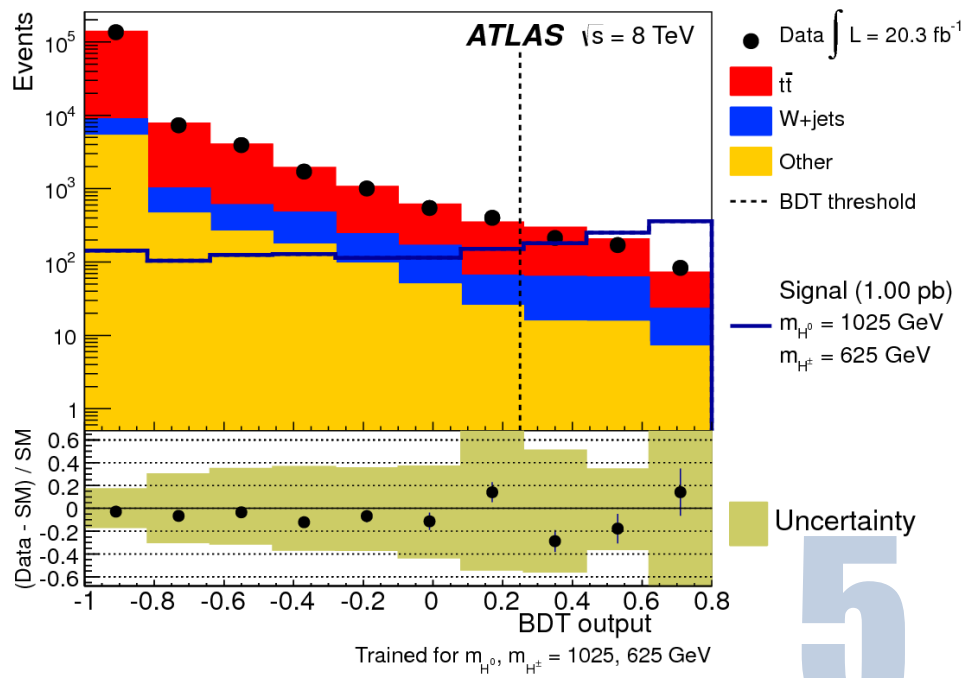
Higgs Cascades

- interesting signature: decays of heavier higgses in lighter ones
- example: $H \rightarrow WH^{\pm} \rightarrow WWh \rightarrow WWbb$ ← may just be hidden in ttbar events!
  - multivariate analysis techniques (BDT) to discriminate against ttbar using event kinematics
  - dominant systematics: b-tag eff., jet energy, ttbar normalisation



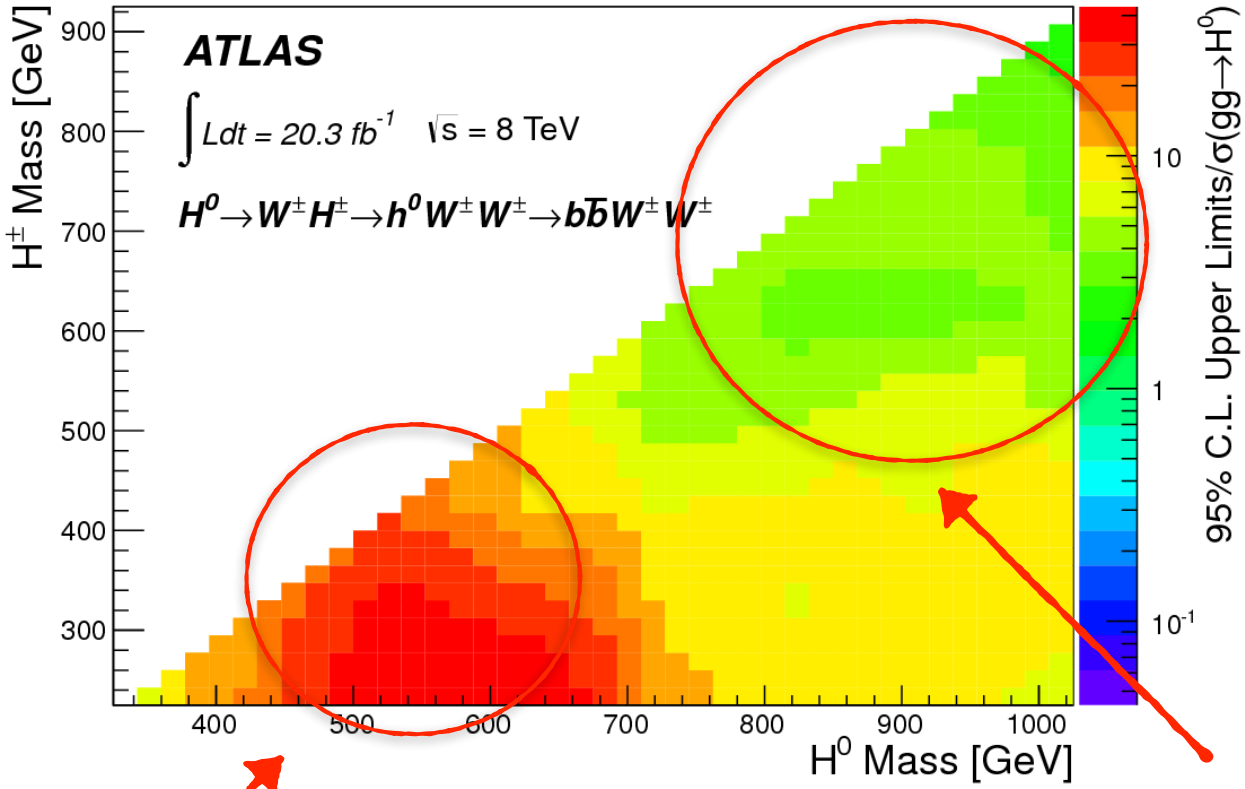
125 GeV SM-like Higgs decaying in bbar



Phys. Rev. D 89, 032002 (2014) arXiv:1312.1956

Higgs Cascades

95% CL Upper limit on x-section/σ^{TH}(SM)



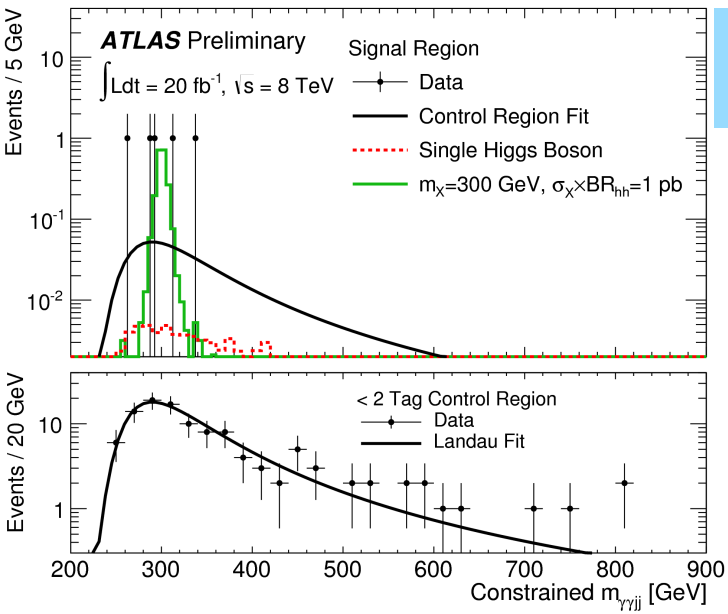
loss of sensitivity due to poorer separation from ttbar BG

sensitive to an Heavy Higgs produced via gg-fusion at SM rate

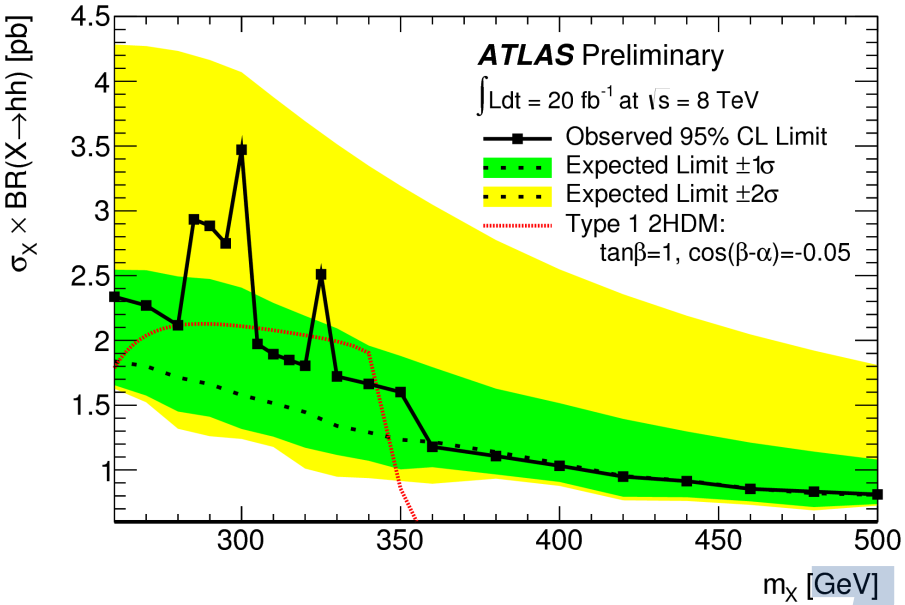
di-Higgs Production: hh→bbγγ

Search for anomalies in non resonant and resonant production of higgs pairs

- SM production (~10 fb) not observables with current statistic at LHC
- rate can be enhanced up to pb level in several extension of SM: 2HDMs, composite models, hidden valleys, gravitons, radions, …
  - examples: additional heavy higgs decay in two higgs bosons, alterations of the λ_{hhh} self-coupling …
- γγ signature provides high trigger efficiency, clean signature and low BG wrt 4b and 2b2τ decay modes



Resonant search



Public Note/Paper available soon …

- low event yield → counting experiment
- BG shape from $m_{bb\gamma\gamma}$ control region (<2 b-tag)
- BG normalisation from $m_{\gamma\gamma}$ side-bands in CR

X-section*BR UL at 95% CL for for a narrow scalar resonance decaying to hh→bbγγ

Resonant di-higgs production: hh→bbbb

… fully hadronic higgs decays can be exploited at higher masses where multi jet BG is strongly reduced: search for TeV-scale gravitons in higgs pairs

- experimental strategy:
  - two pairs of b-jets with inv. mass consistent with the 125 GeV Higgs
  - veto on events with extra jets looking like top decays
  - dominant BG: multi-jets, normalised with control regions

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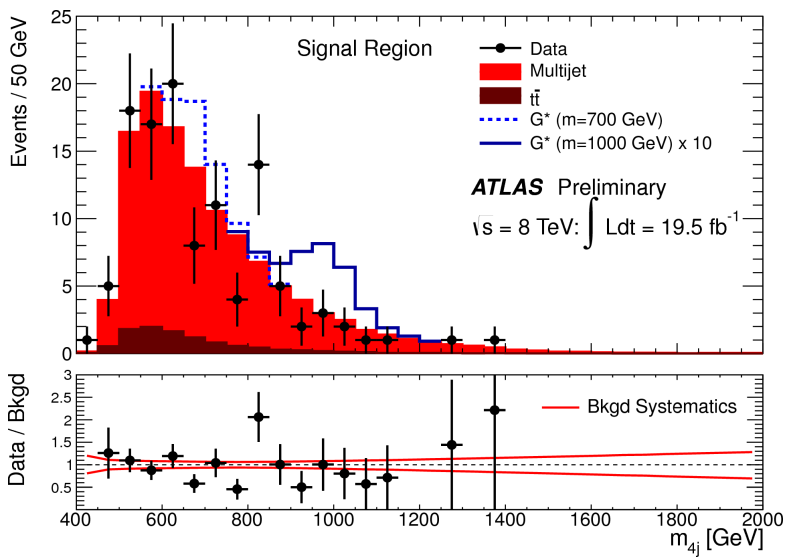
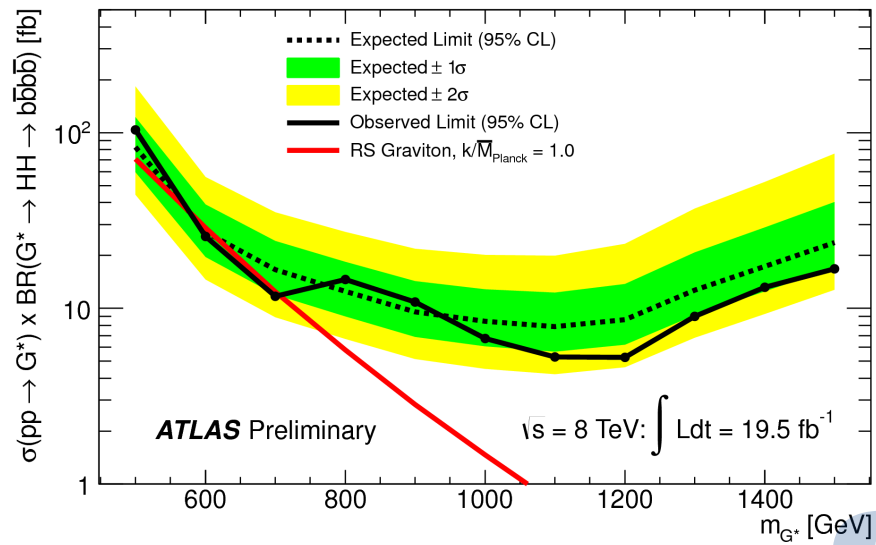


4b invariant mass after selection



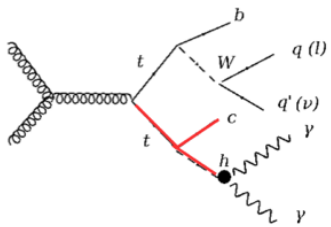
x-section UL interpreted in the context of the bulk RS model with $k/M_{Pl} = 1$

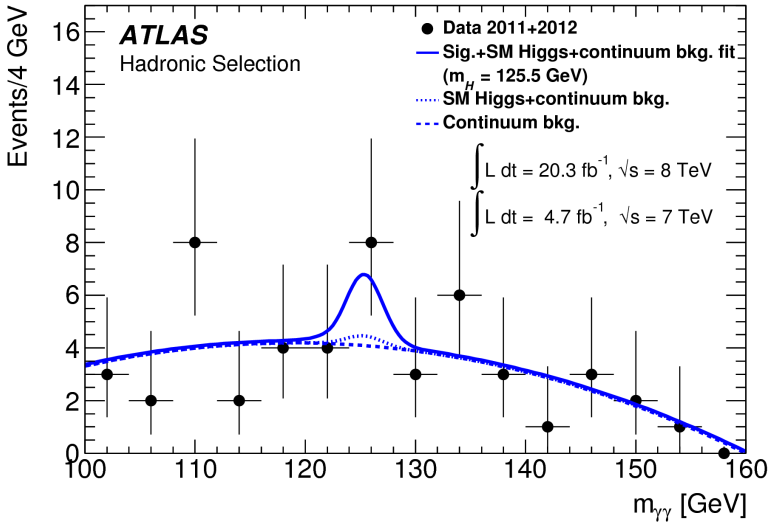
- benchmark excluded for $590 < m_{G^*} < 710$ GeV @95% CL

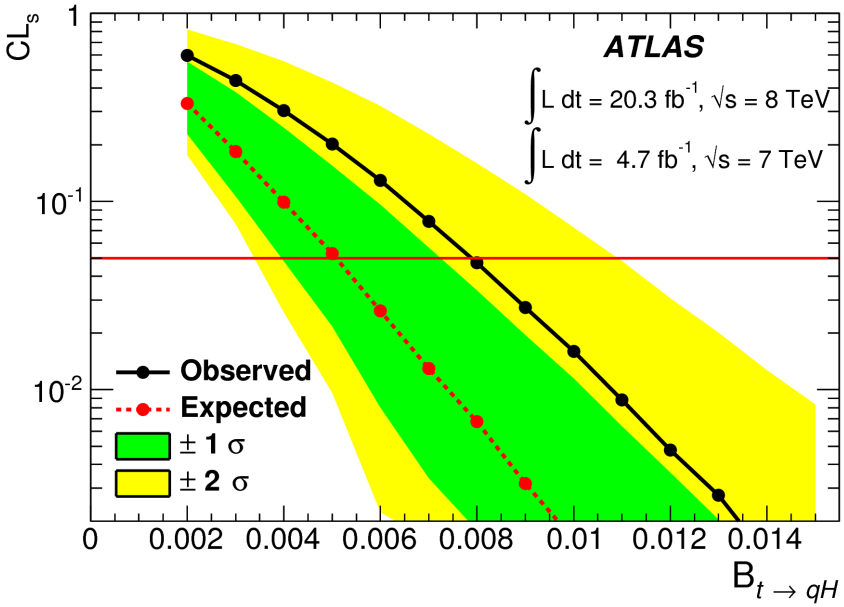
FCNC decays: t→Hc

FCNC highly suppressed in the SM (BR~10^{-15}) but may be greatly enhanced in BSM models

- example: type III 2HDM allows for tch and tuh couplings with sizeable effects of the rate (up to 10^{-3} level)
- ATLAS analysis: look for t→Hc and Hu in ttbar events with H→γγ + hadronic/leptonic decays of the other top







BR(t→Hq) < 0.79% @95% CL (expected <0.51%)

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

Run2 prospects:

BR~0.1%

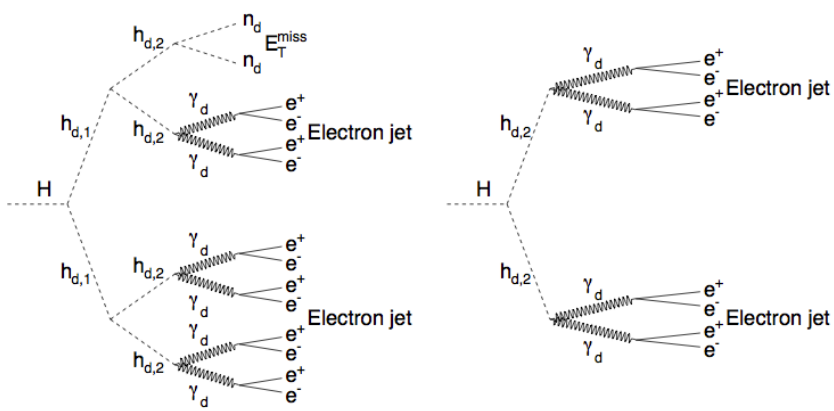
arXiv:1403.6293

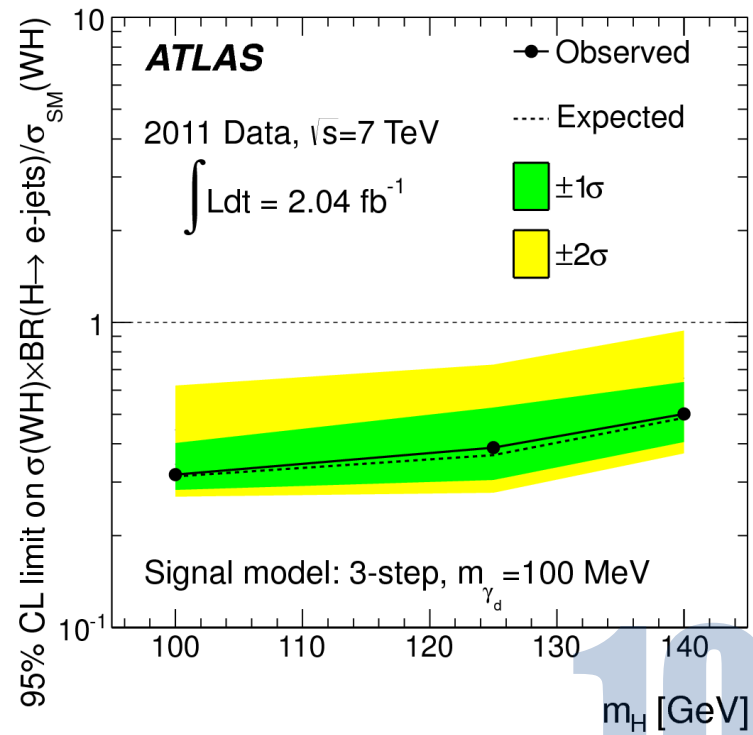
Higgs to dark photons: electron jets

ATLAS search for prompt electron jets:

- predicted in many extensions of the SM with Hidden sectors
- connection to the hidden sector through kinetic mixing
- predict massive dark photons decays to pair of electrons/muons/hadrons
- experimental signature: collimated jets of leptons (or hadrons)
- SM-HS strength determines lifetime of dark photons

NJP 15, 043009 (2013) arXiv:1302.4403





pp→W(→lν)+H

provides high p_T lepton for triggering

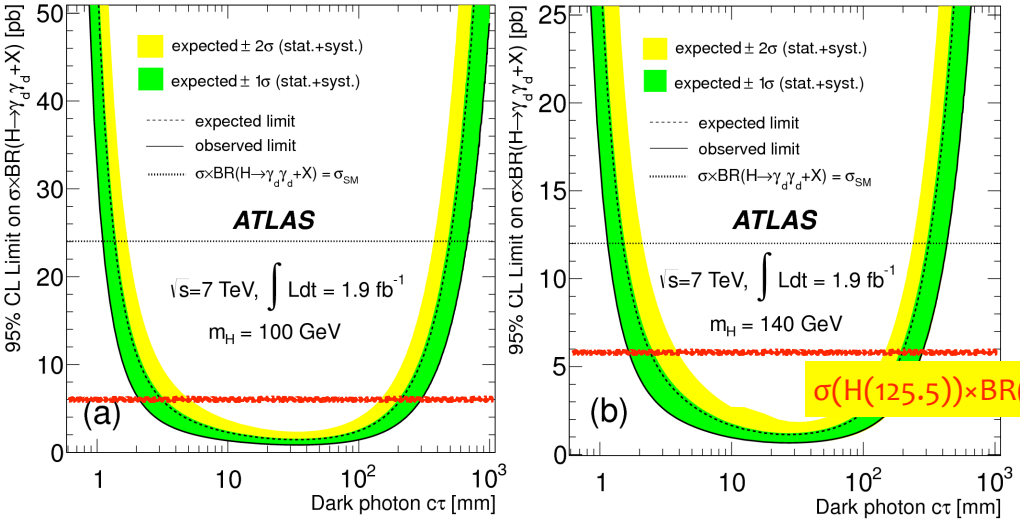
updated analysis with full Run 1 statistic ongoing …

Higgs to dark photons: displaced muon-Jets

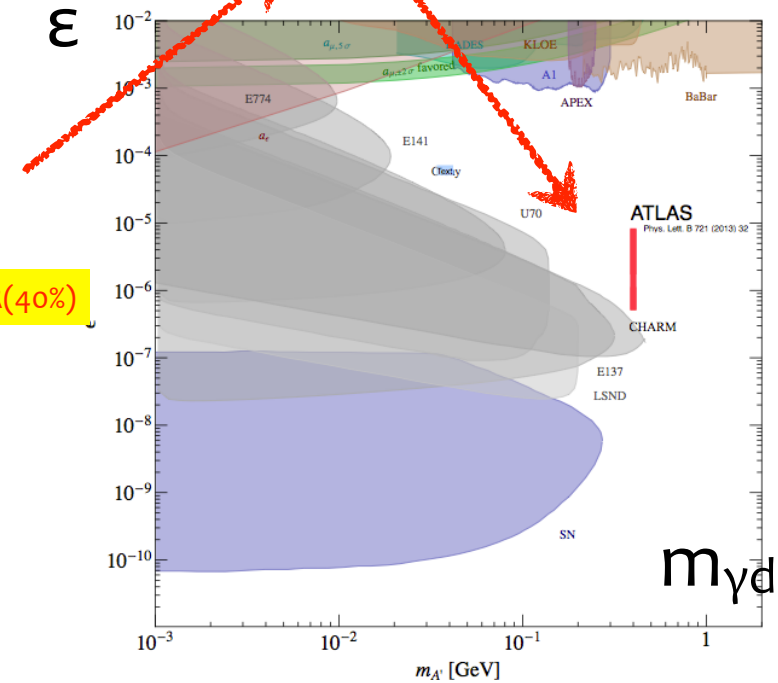
ATLAS search for displaced muon jets:

lifetime depends on the size of kinetic mixing

$$\Gamma = \frac{1}{3}\alpha\,\epsilon^2\, m_{\gamma_d}\sqrt{1-\frac{4m_l^2}{m_{\gamma_d}^2}}\left(1+\frac{2m_l^2}{m_{\gamma_d}}\right)$$



σ(H(125.5))×BR(40%)



Higgs boson mass [GeV]	Excluded cτ[mm] BR(100%)	Excluded cτ[mm] BR(10%)
100	1 ≤ cτ ≤ 670	5 ≤ cτ ≤ 159
140	1 ≤ cτ ≤ 430	7 ≤ cτ ≤ 82

my extrapolation in the (ε,$m_{\gamma d}$) plane
assume: BR(40%), m_H=125 GeV, $m_{\gamma d}$=400 MeV

new analysis with full Run 1 statistic and extended dark-photon mass range ready soon …

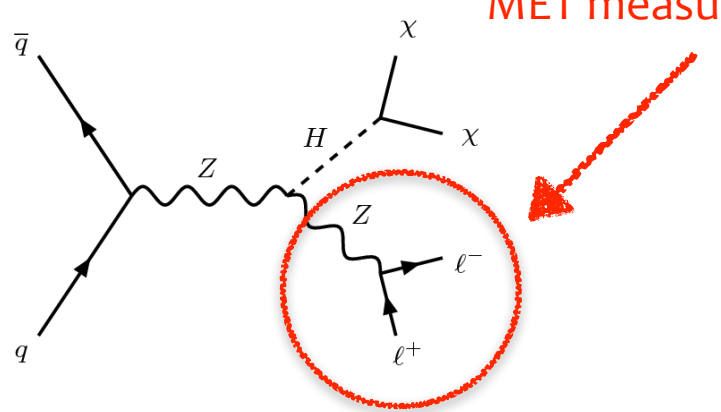
Phys. Lett. B 721 (2013) 32-50 arXiv:1210.0435

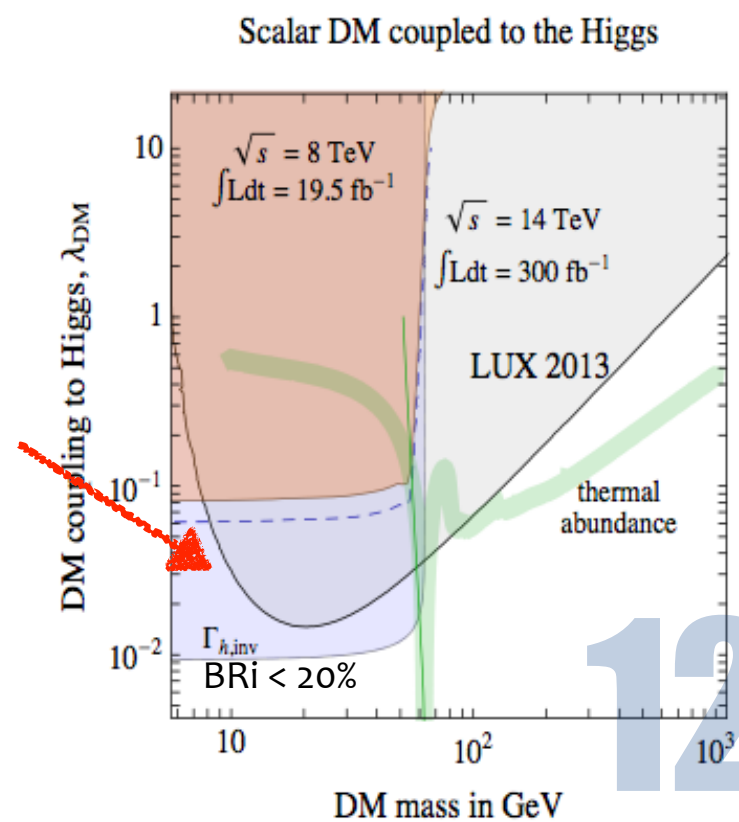
Higgs to Invisible

Search for Higgs decaying into WIMPs:

- connection to hidden sectors via scalar or Higgs portals
- SM B(H→ZZ→4ν)~0.12%

Exp. signature:
MET measured from recoiling Z→ll



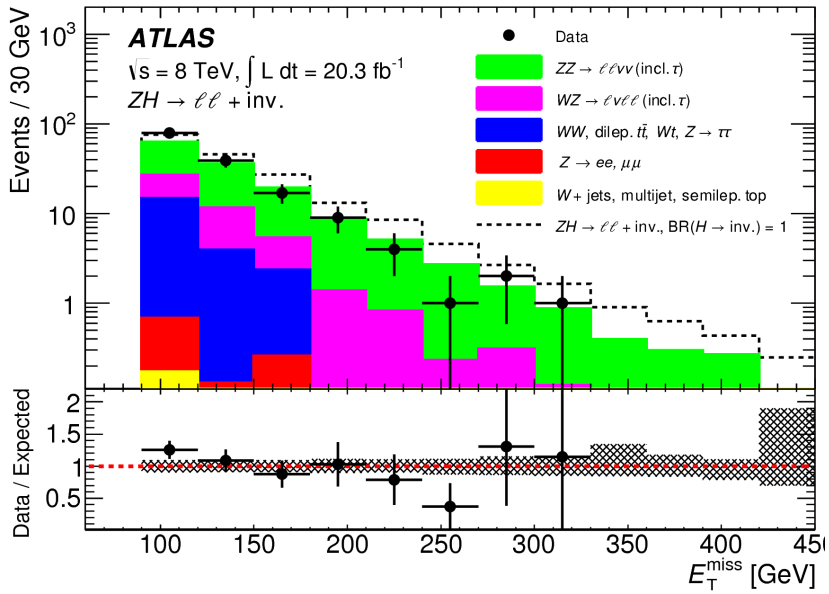


- provides an interesting possibility to search for DM signals at LHC, competitive and complementary to:
  - indirect limits on BR(H→inv) from higgs coupling measurements → see next slides
  - inclusive searches from mono-objects (jets, Z/W) → see Steven's talk today

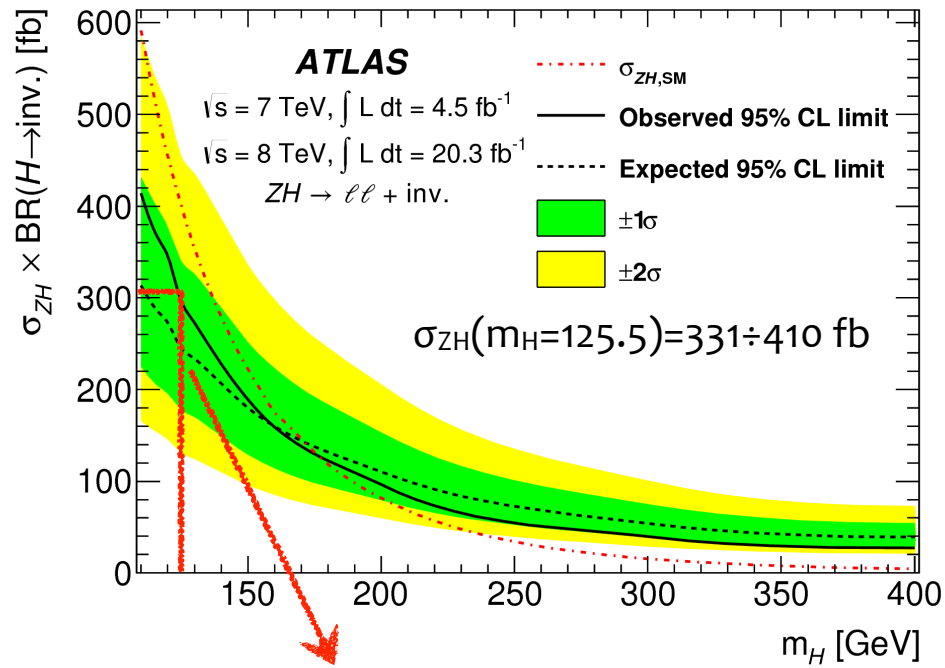
De Simone, Giudice, Strumia: arXiv:1402.6287v3

Higgs to Invisible

MET Distribution after full selection



95% CL UL on $\sigma_{ZH} \times BR(H \rightarrow inv)$



dominant BGs:

- ZZ→llνν & WZ→lllν
- estimated from simulation and validated in data control regions

BR limit @95% CL (2011+2012 stat.)

- BR(H→inv) < 75% (expected <62%)
- BR(H→inv) < 37% (expected <39%) when combined with the results from higgs couplings

Phys. Rev. Lett. 112, 201802 (2014) arXiv:1402.3244

Probing BR_i with higgs couplings

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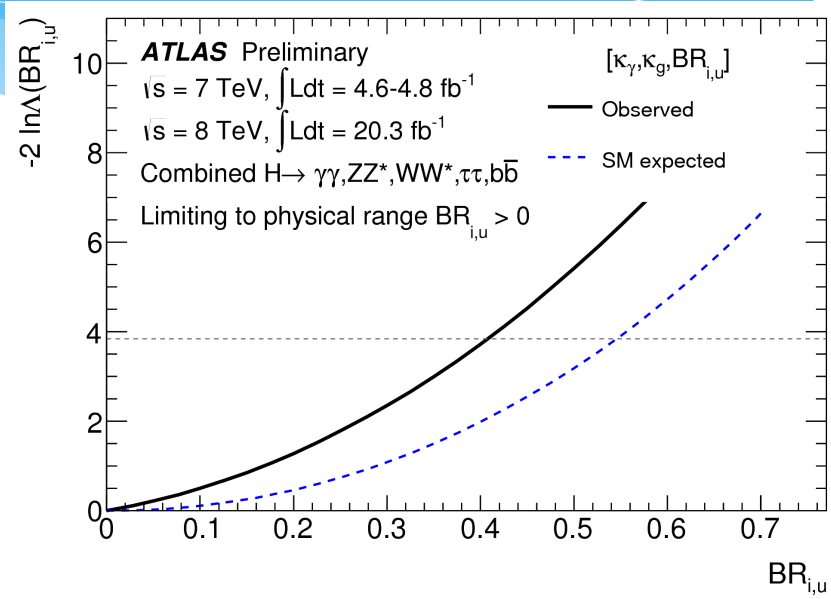
- fit with k_g, k_γ and observed width as free parameters
- tree-level couplings of the new boson to SM particles fixed to SM values

$$\frac{\Gamma_h}{\Gamma_{h,SM}} = \frac{\sum k_i^2(k_g^2, k_\gamma^2)}{(1 - BR_i)}$$

$BR_i < 0.41$ @95% CL (w/o)
$BR_i < 0.37$ @95% CL (w/ Zh->ll+MET)



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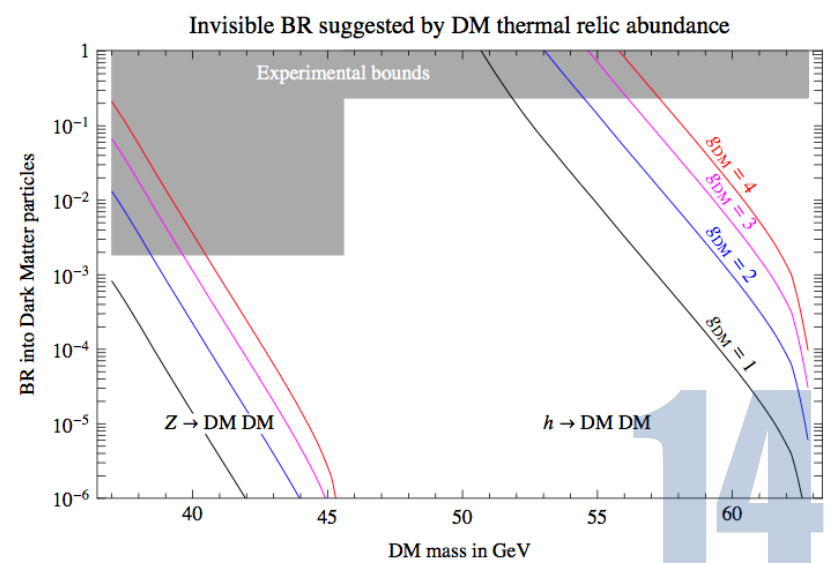
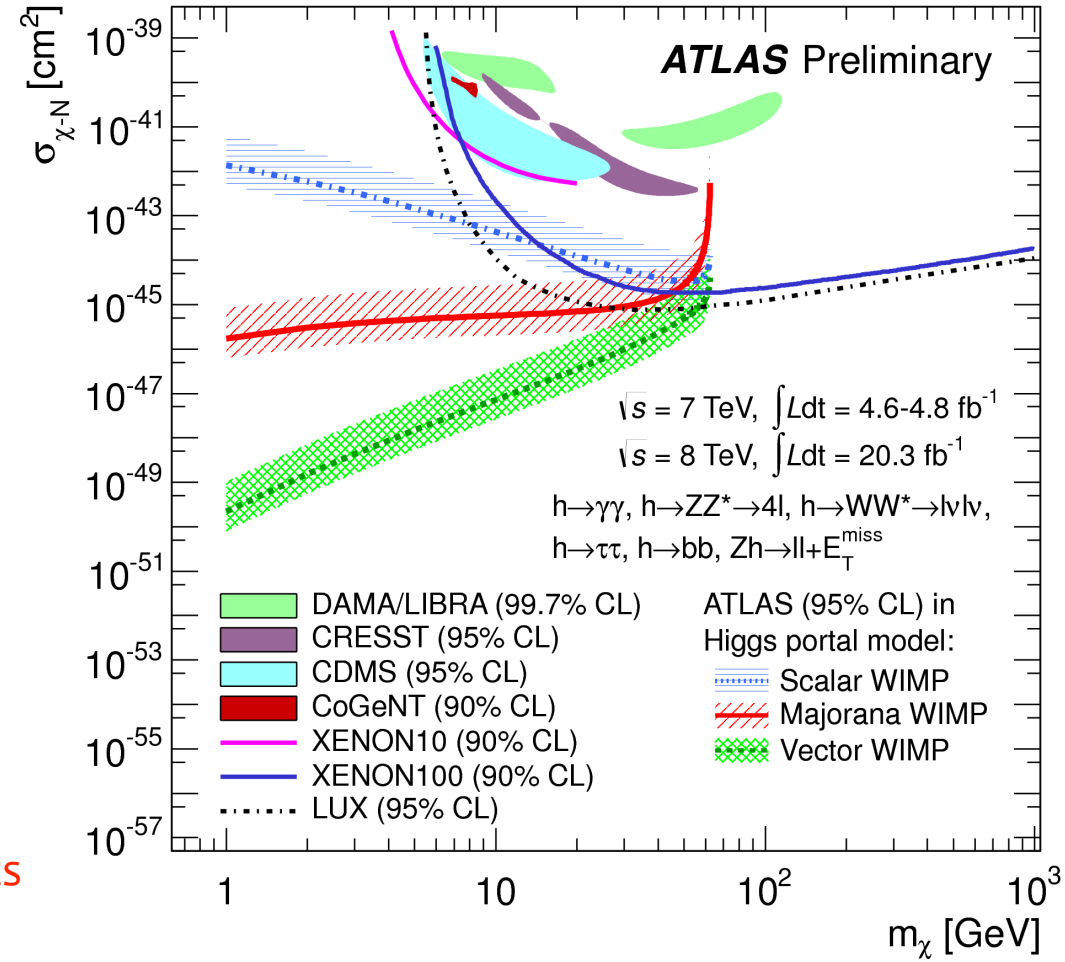
- start to explore invisible BR ranges suggested by DM relic abundance via thermal freeze-out of decays
- with 300/3000 fb^{-1} ATLAS able to exclude $BR_{i,u}$~20%,~8% respectively



De Simone, Giudice, Strumia: arXiv:1402.6287v3

Higgs Portal Model Interpretation

Constraints to the DM-nucleon scattering x-section in the context of Higgs Portal Models



Higgs to Invisible combined with coupling measurements

Summary

* Search for BSM effects in the Higgs sector is one of the most active research fields in ATLAS
* Excellent progress in analysis techniques and interpretative tools achieved, resulting in tight constraints on NP effects at LHC

* The exploration of new signatures and predictions from non-minimal models has just started exploiting the full potential of the statistics collected in Run I

…and the 13 TeV are just around the corner

Backup Slides

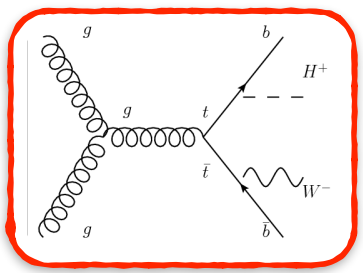
2HDM/MSSM: charged higgs

2HDM: 2 higgs doublets → 5 bosons h, H, A, H^+, H^-

- in MSSM (type II) spectrum governed by only 2 parameters M_A and tanβ
- for tanβ>1 coupling to b and τ enhanced (decays to muon pair also interesting)
- Search channels: neutrals: H/A→bb,ττ,μμ charged: $H^{\pm}$→τν,cs

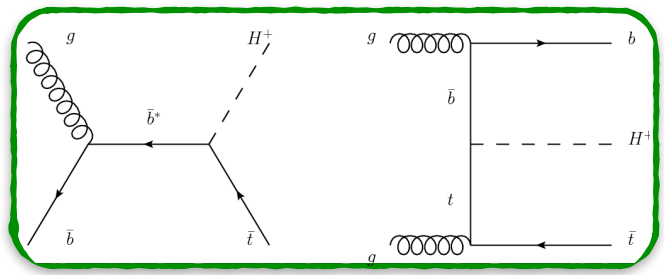
light H^+: $m_{H+} < m_t$

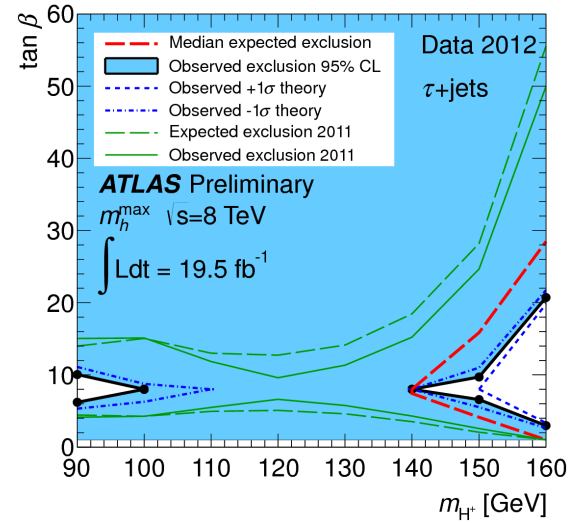
$t \rightarrow H^+b$

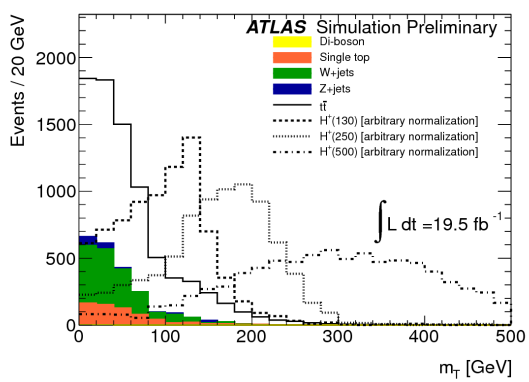


heavy H^+: $m_{H+} > m_t$

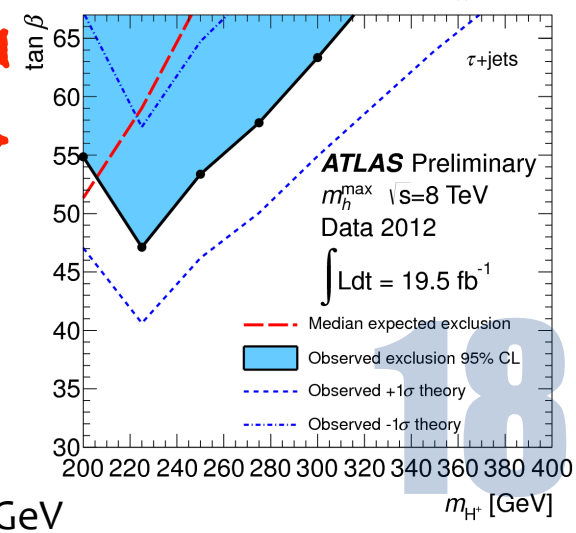
associate production H^+t/H^+tb







No evidence of signal interpreted in the context of the m_h^{max} MSSM



exclusions: of tanβ>1 for 100<mH<140 GeV

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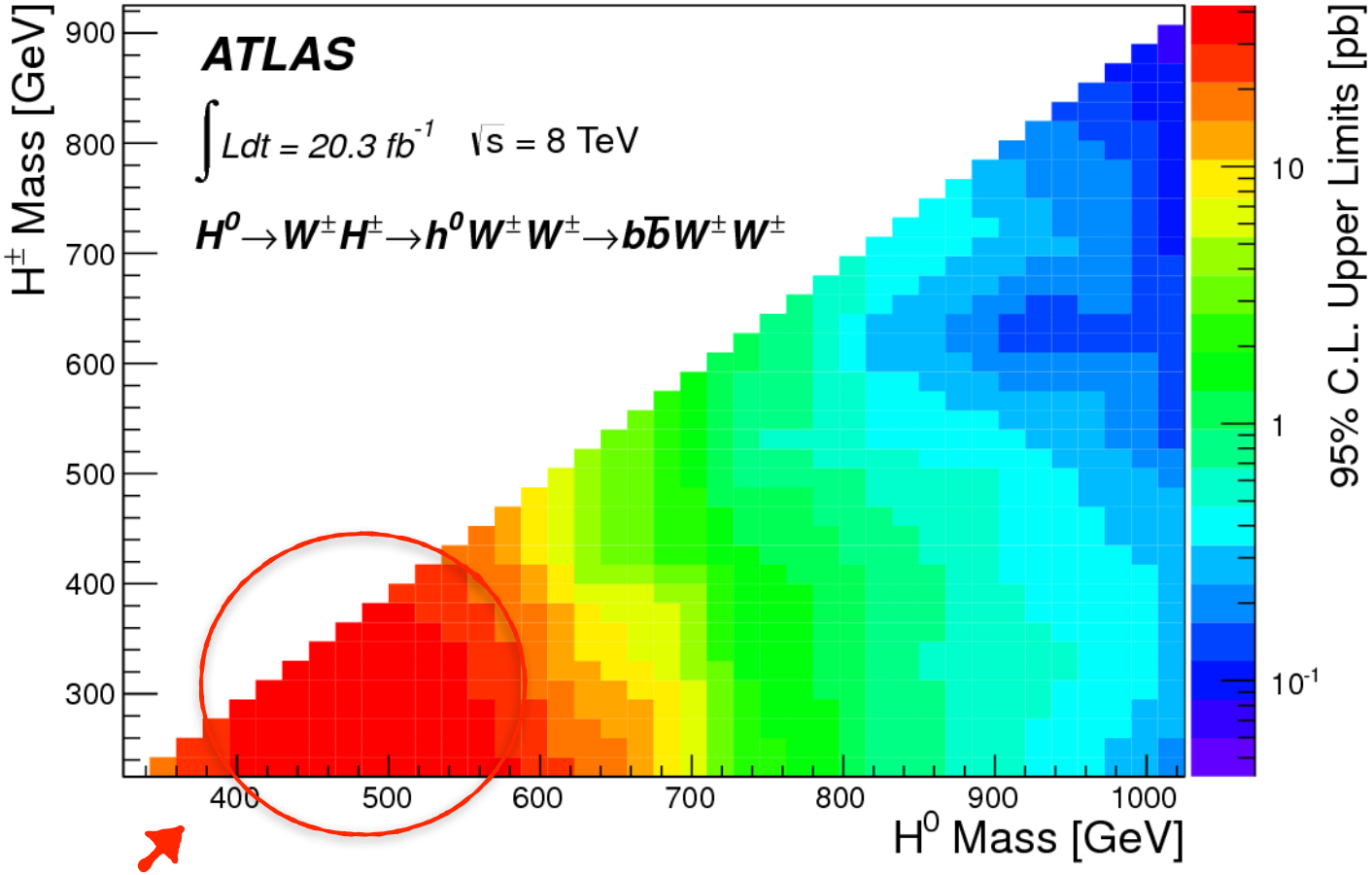
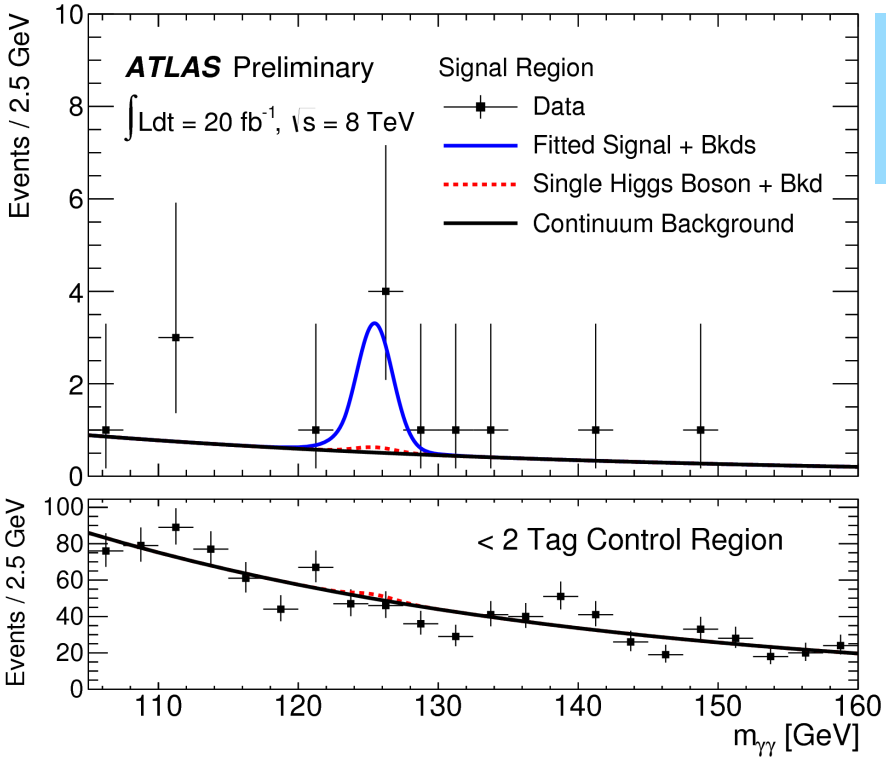
Higgs Cascades

95% CL Upper limit on x-section



loss of sensitivity due to poorer separation from ttbar BG

di-Higgs Production: hh→bbγγ



NON Resonant search

- m_{bb} consistent with the decay of a Higgs boson
- simultaneous fit in two $m_{\gamma\gamma}$ regions: signal + control region (<2 b-tag)

Non resonant hh production:
observed upper limit: <2.2 pb @ 95% CL (expected <1.0 pb)

Public Note/Paper available soon …

Constraint BSM effects from Higgs couplings

* Methodology:
  * tree level (LO) motivated framework recommended as benchmark by LHC XSWG
  * assume the observed signals originated from a single resonance with m=125.5 GeV
  * narrow-width approximation: $\sigma \times BR(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$
  * tensor structure of the lagrangian same as in the SM (J^{CP} = 0+)
    * only modification of the coupling strength are allowed

* deviations from SM prediction encoded in multiplicative scale factors k:

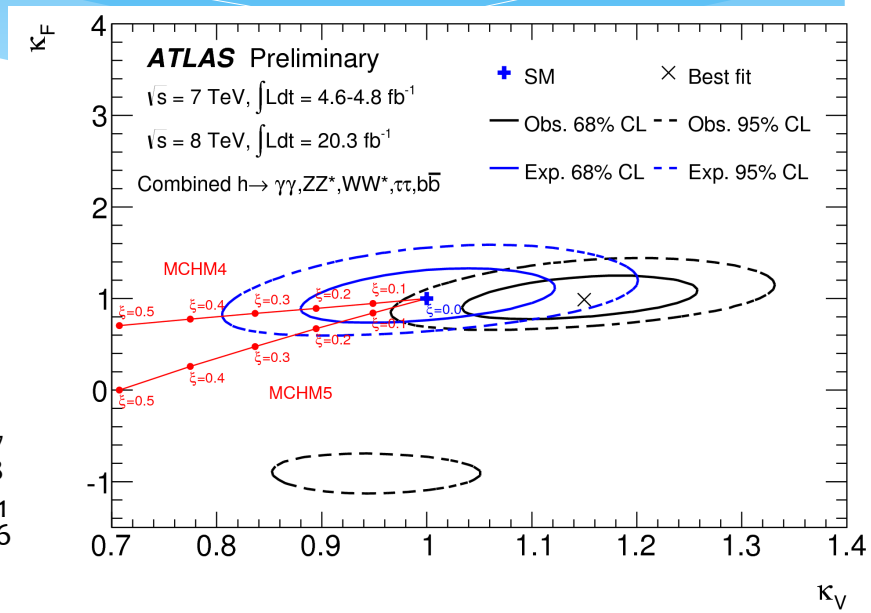
ex: gg-fusion H→γγ: $$\frac{(\sigma \times BR)(gg \to H \to \gamma\gamma)}{\sigma_{SM}(gg \to H) \cdot BR_{SM}(H \to \gamma\gamma)} = \frac{k_g^2 \cdot k_\gamma^2}{k_H^2}$$

* allow possible BSM contributions in:
  * gluon and photon vertex loops
  * the total Higgs decay width

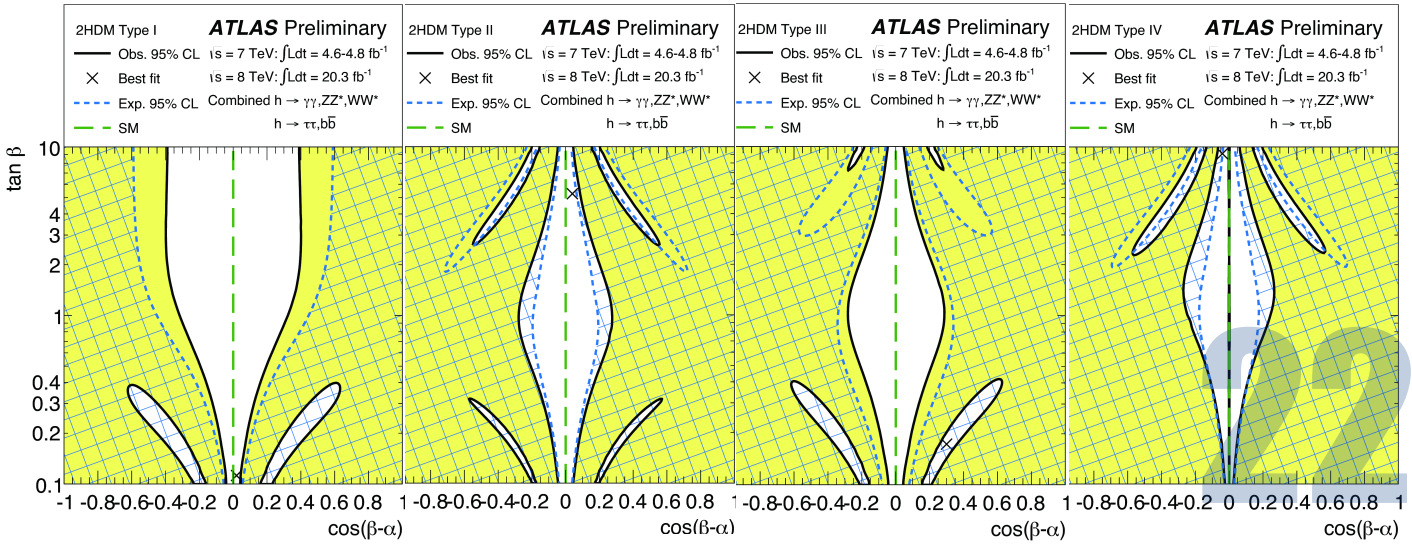
arXiv:1307.1347

Couplings: other specific BSM model constraints

- BSM models modify the couplings of the Higgs boson to SM particles as a function of the BSM model parameters:
  - example minimal composite Higgs model: couplings to f and V modified by compositeness scale f:
    - scaling parameter $\xi = v^2/f^2$ (SM: $\xi=0$)
    - MCHM4: $k_V = k_f = \sqrt{(1-\xi)}$ ← obs. $-0.30^{+0.17}_{-0.18}$
    - MCHM5: $k_V = \sqrt{(1-\xi)}$, $k_f * k_V = 1-2\xi$ ← obs. $-0.08^{+0.11}_{-0.16}$



Exclusions for 2HDM type I,II,III,IV



Couplings: probing mass scale

- probe the mass dependence of the Higgs boson couplings to other particles using the measured couplings to SM particles
- coupling scale factors can be expressed in terms of a mass scaling parameter (ε) and M (vev):

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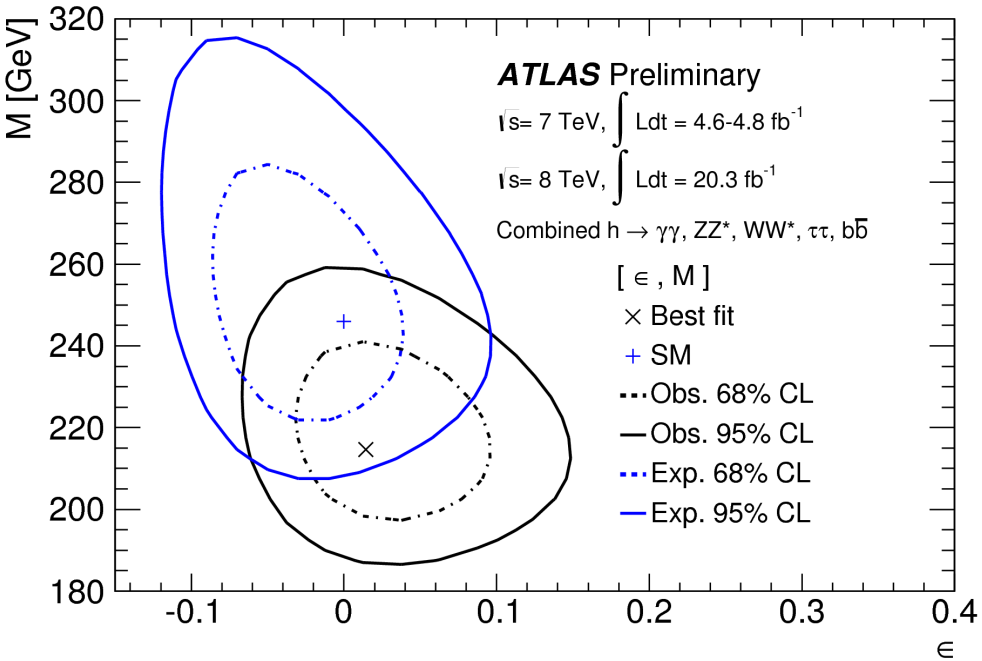
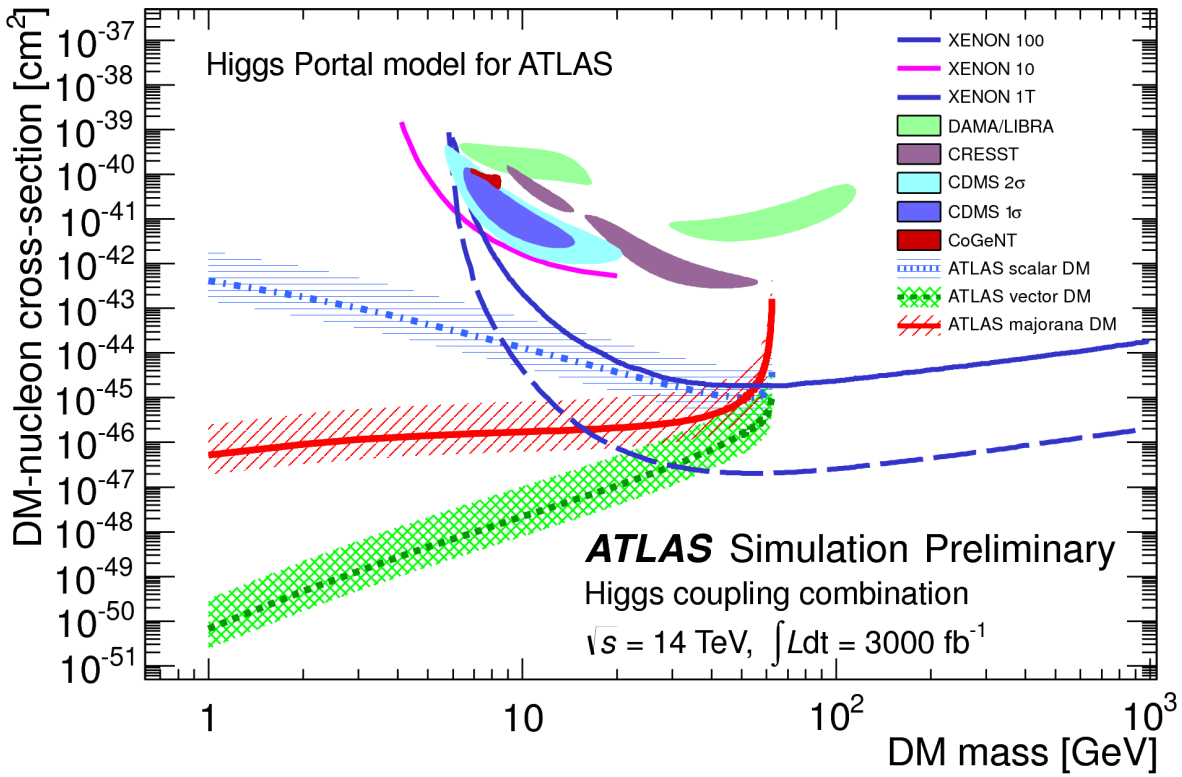


$$k_{f,i} = v\frac{m_{f,i}^{\epsilon}}{M^{1+\epsilon}}$$

$$k_{V,j} = v\frac{m_{V,j}^{2\epsilon}}{M^{1+2\epsilon}}$$

SM: ε=0, M=246 GeV

Best fit consistent with SM within 1.5σ, M<246 due to μ_h>1

Higgs Portal Model Interpretation

prospects with 3 ab^{-1}