Some ATLAS BSM Higgs results & Some notes about the LHC HXS WG3

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Prelude: BSM Higgs in Run-I

- The experimenter's view of BSM Higgs has changed a lot since the LHC started and has even more changed since the Higgs discovery. For instance remember:
  - 7 TeV run most work into
    - MSSM h/H/A → τ τ,
    - Charged Higgs H+ → τν (mostly influenced by MSSM)
    - light CP-odd a1 → μμ (NMSSM influenced)
  - Full run-I has given rise to a tendency to go beyond MSSM
    - In addition to the previous searches searches including h125 in the final state also appear, e.g. H → hh, h → invisible, with many of those motivated by generic 2HDM or dark matter models
    - This is also reflected in the LHC Higgs cross section group, where a lot of time was invested in 2HDM and other topics

Talk overview

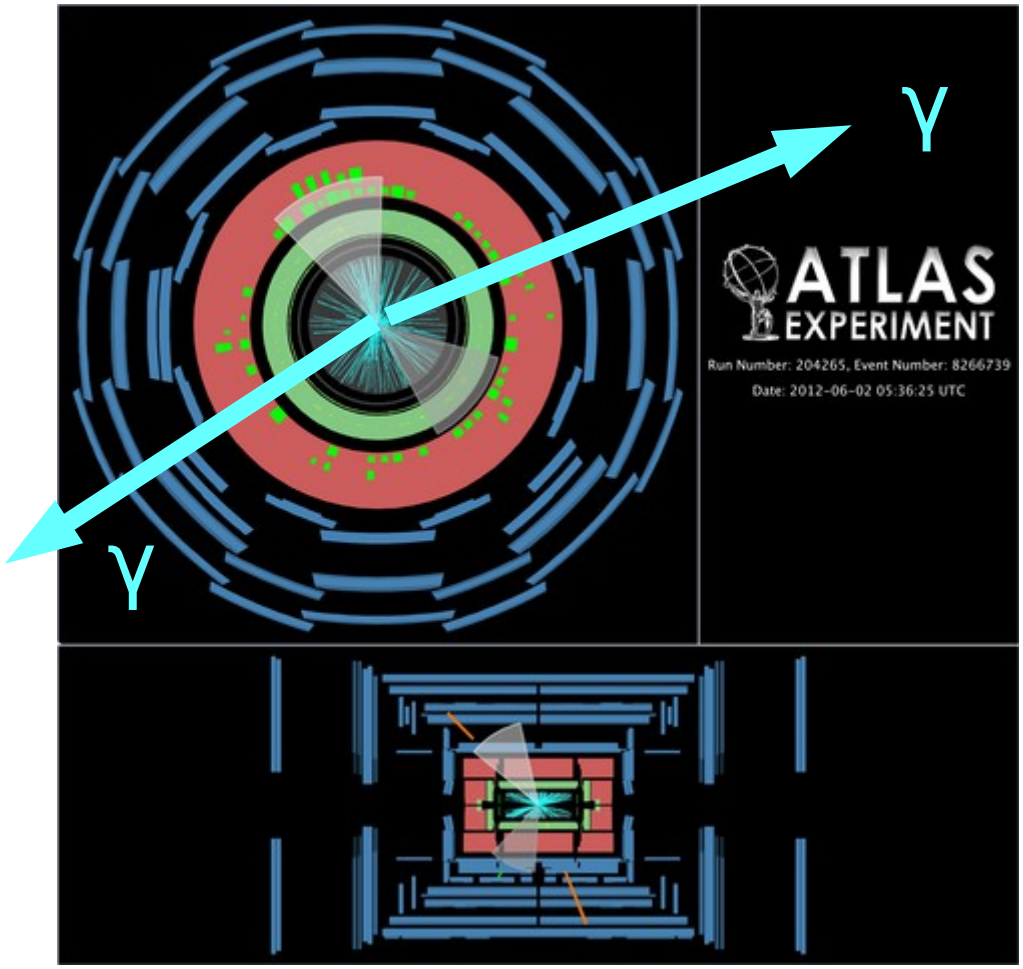
- I will show you here some ATLAS results that weren't shown in the last Higgs Days meeting of September 2013
  - Di-Higgs production
  - High mass $\gamma\gamma$ resonances
  - MSSM Higgs search
  - Flavour changing neutral currents
  - Higgs to invisible
- I will also discuss briefly the WG3 of the LHC HXSG and some items that are discussed among the experimenters and which are also relevant to theorists

Di-Higgs production: hh

- The discovery of a light CP-even Higgs boson, h, opens up the possibility to look for heavy particles decaying to it
- A heavy CP-even Higgs can decay to hh (m_h = 125 GeV)
- There is also interest in anomalous hh production, that can be enhanced in BSM Higgs models e.g. composite Higgs scenarios
- There are currently two public ATLAS results on that
  - "hh → bbγγ" arXiv:1406.5053
  - "hh → bbbb" ATLAS-CONF-2014-005

Di-Higgs production: hh → bbγγ

- Collect events with a loose di-photon trigger
- Event contains 2 b-jets (p_T > 55 GeV for leading, 35 GeV for the rest)
- 105 < m(γγ) < 160 GeV
- 95 < m(bb) < 135 GeV
- Use of techniques from the ATLAS SM h → γγ search



Example of a bb γγ event as recorded by the ATLAS detector.

This event has m(γγ) = 125 GeV and m(γγbb) = 265 GeV

Di-Higgs production: hh → bbγγ

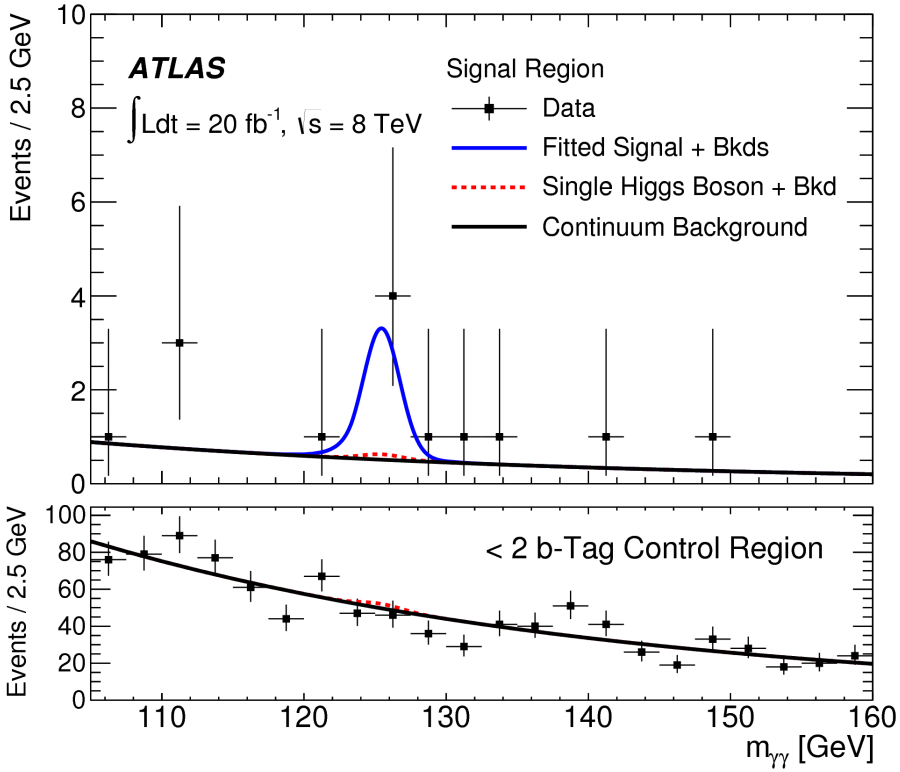
- Search for anomalous, non-resonant hh production

⎔ Fit the m(γγ) distribution: exponential for background and Crystal Ball+Gaussian for signal

⎔ Constrain the fit from a control region that contains less than 2 b-jets

⎔ **Obtained limit for anomalous non-resonant hh production: < 2.2 pb (Exp: 1.0 pb)**

(c.f. SM hh production ~ 10 fb)

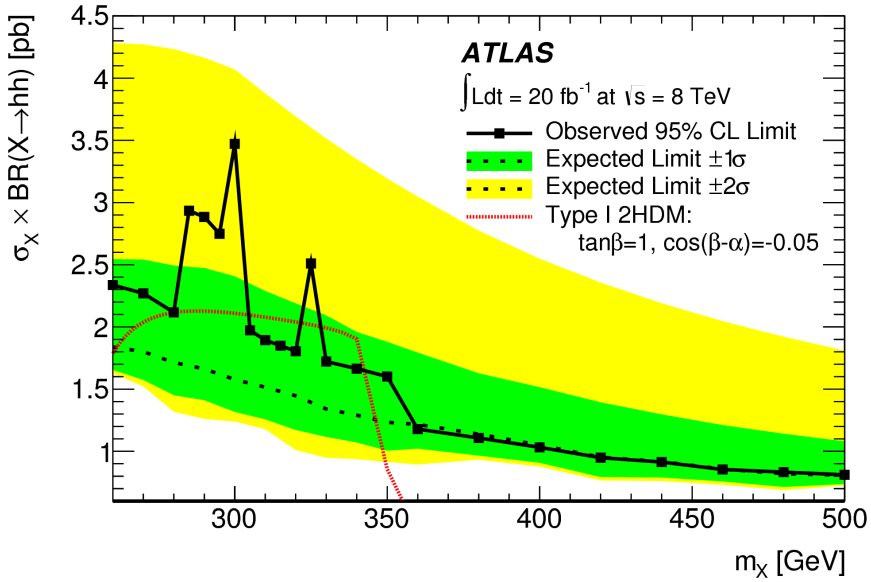


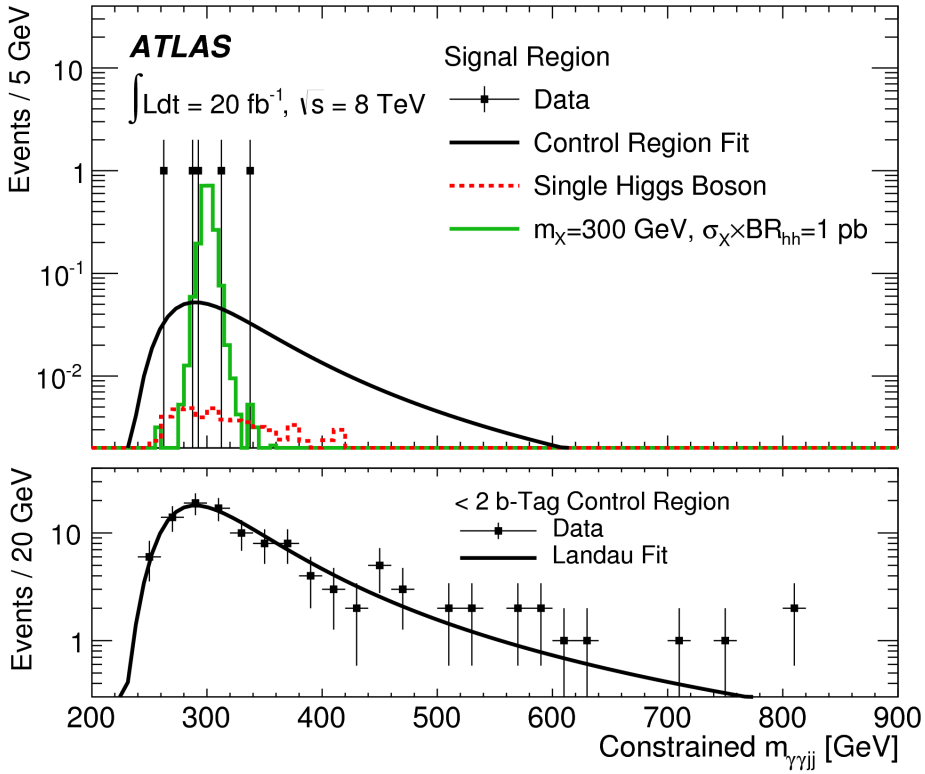
Di-Higgs production: hh → bbγγ

- Search for resonant hh production

⎔ Use of the same event as in the non-resonant search, but in addition a constraint in m(γγbb) mass is imposed

⎔ Simple event counting experiment



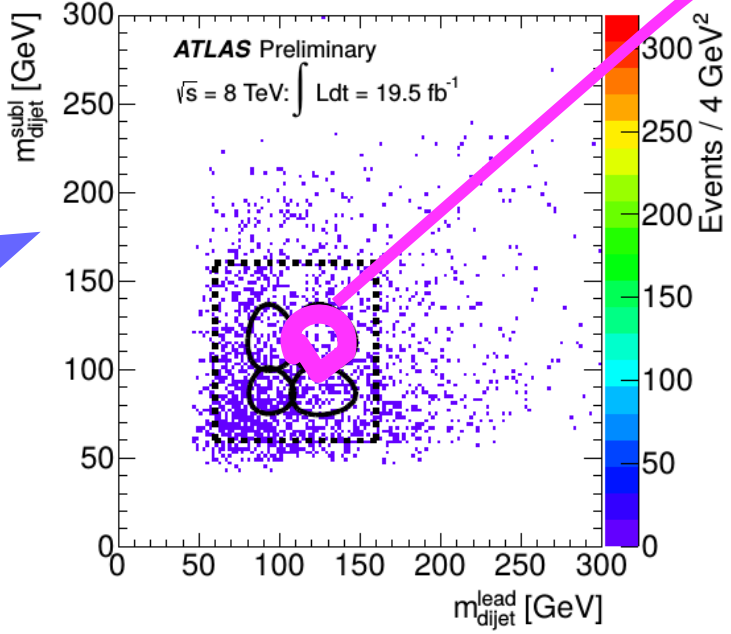


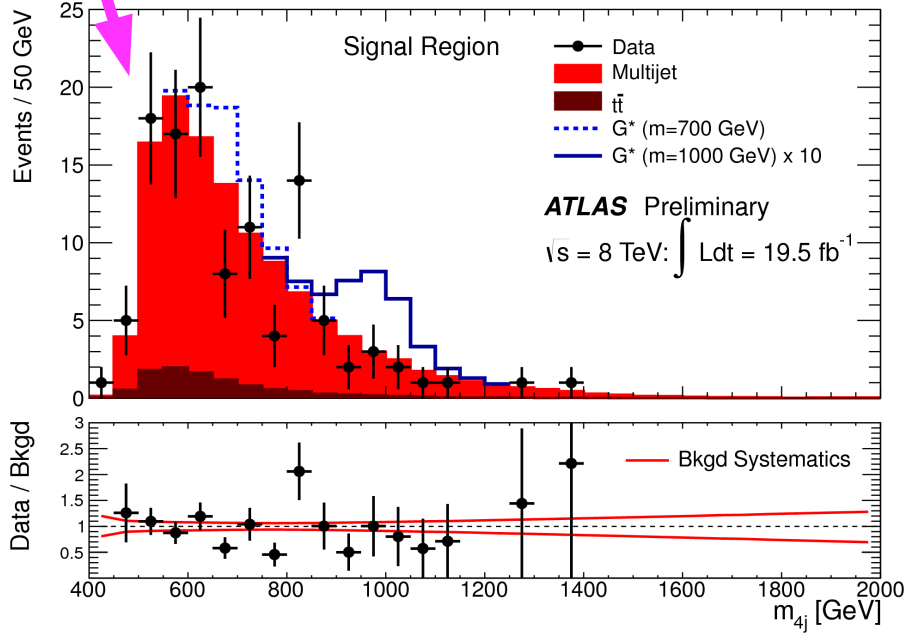
Cross section X BR limits for a **narrow scalar resonance** decaying to hh → bbγγ

Di-Higgs production: hh → bbbb

- Search for resonant hh production

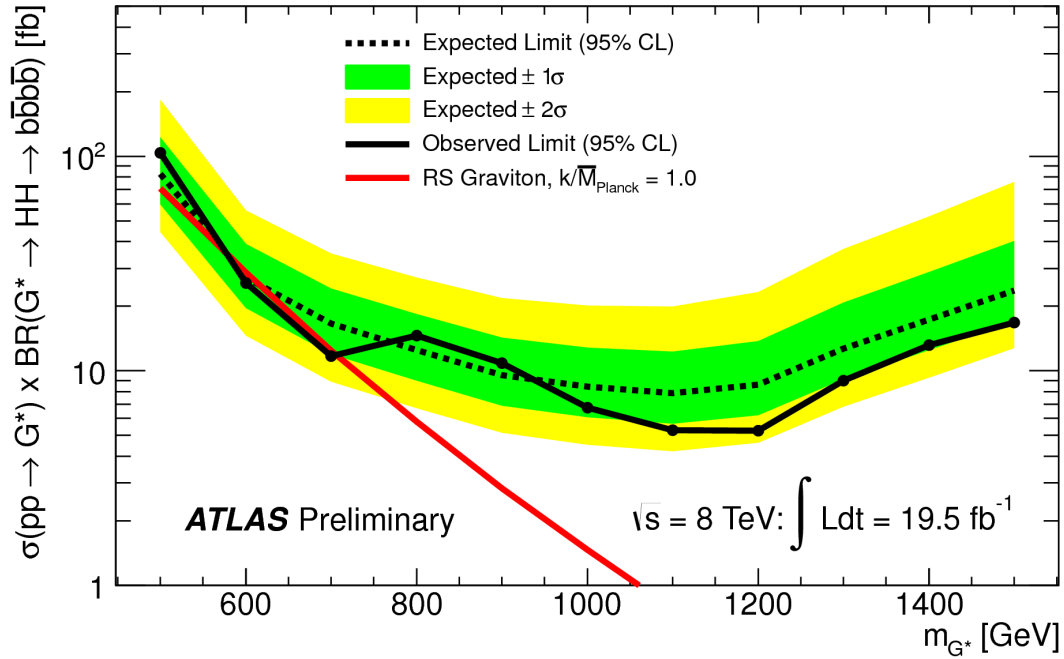
⎔ Events are selected by a set of jet triggers some of which trigger on b-jets
⎔ ≥ 4 b-jets (p_T > 40 GeV) forming two di-jet systems with p_T(bb) > 200 GeV
⎔ Dedicated tt veto
⎔ Constrain on di-jet mass system





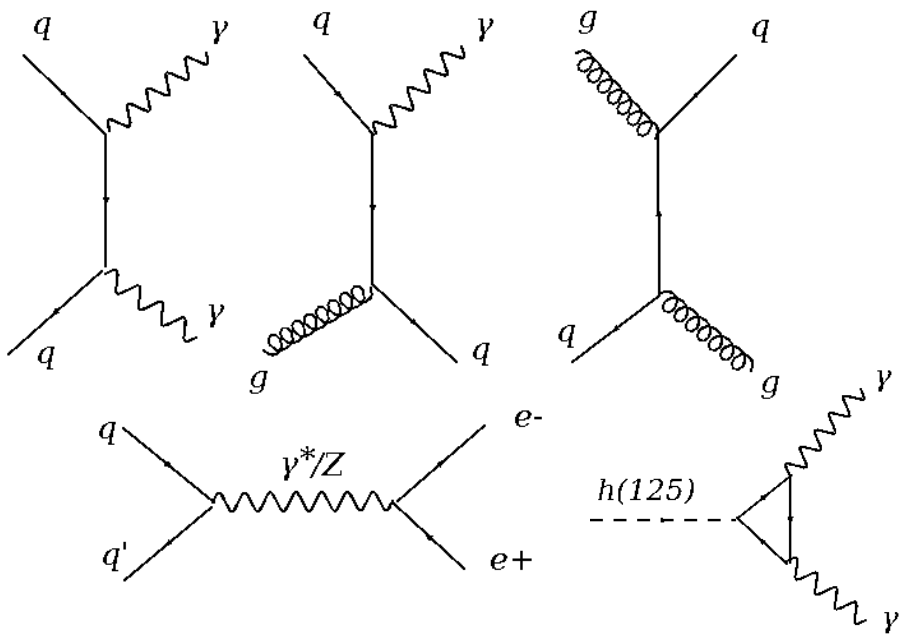
Di-Higgs production: hh → bbbb

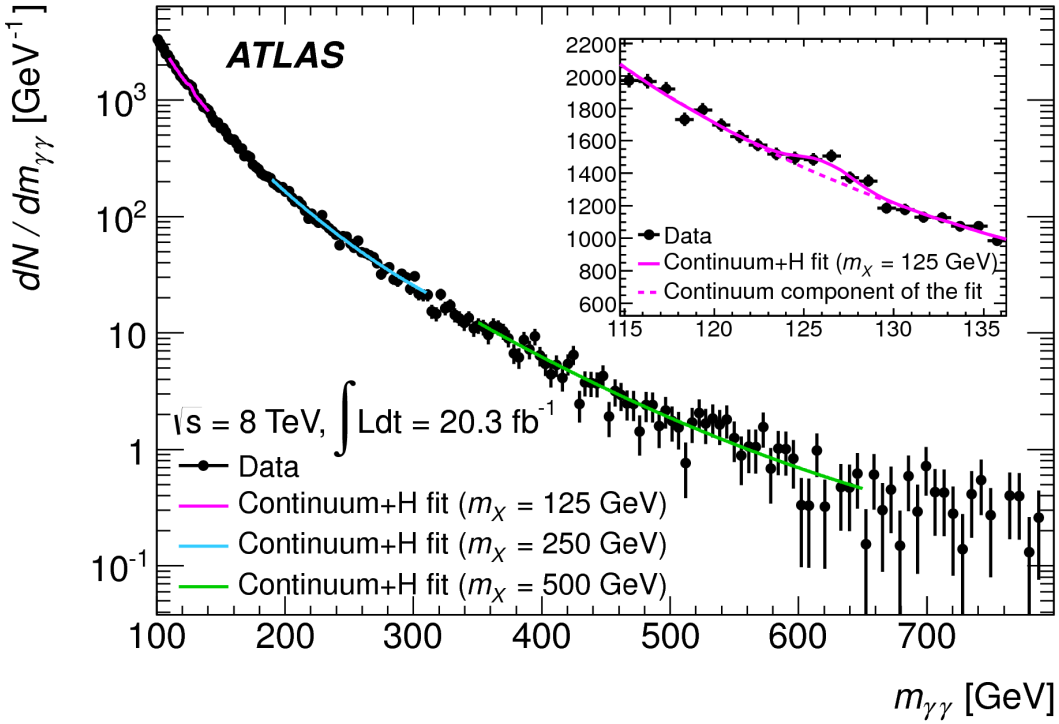
⎔ Interpretation of the result of this search using a Graviton model, but you can also get an idea what the limit would be on heavy Higgs production



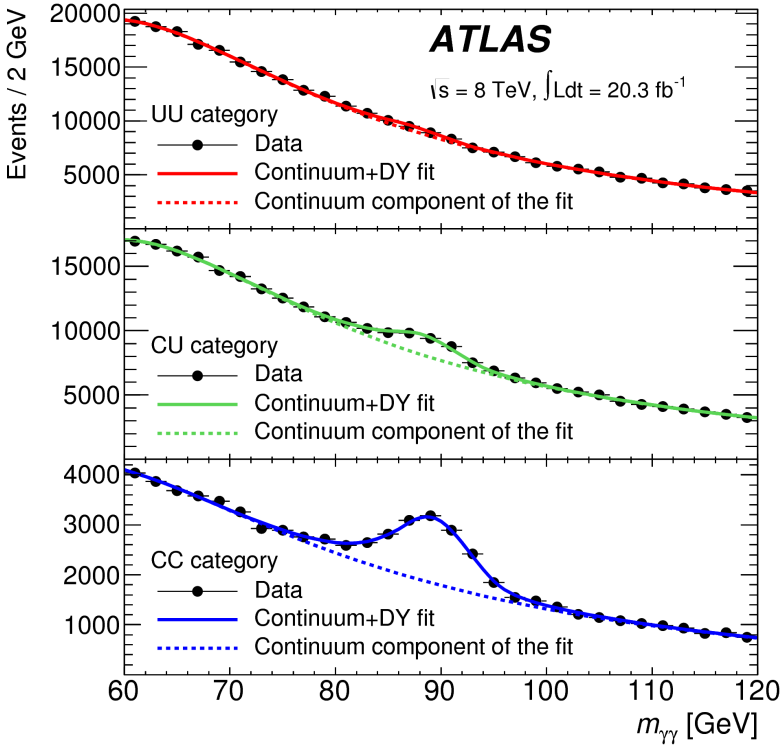
Scalar resonances to di-photon pairs

- Another Higgs boson, other than the one at ~125 GeV, is still phenomenologically viable
- ATLAS has looked for A/H → γγ at a mass range from 65–600 GeV extending the techniques mastered in the SM Higgs → γγ search



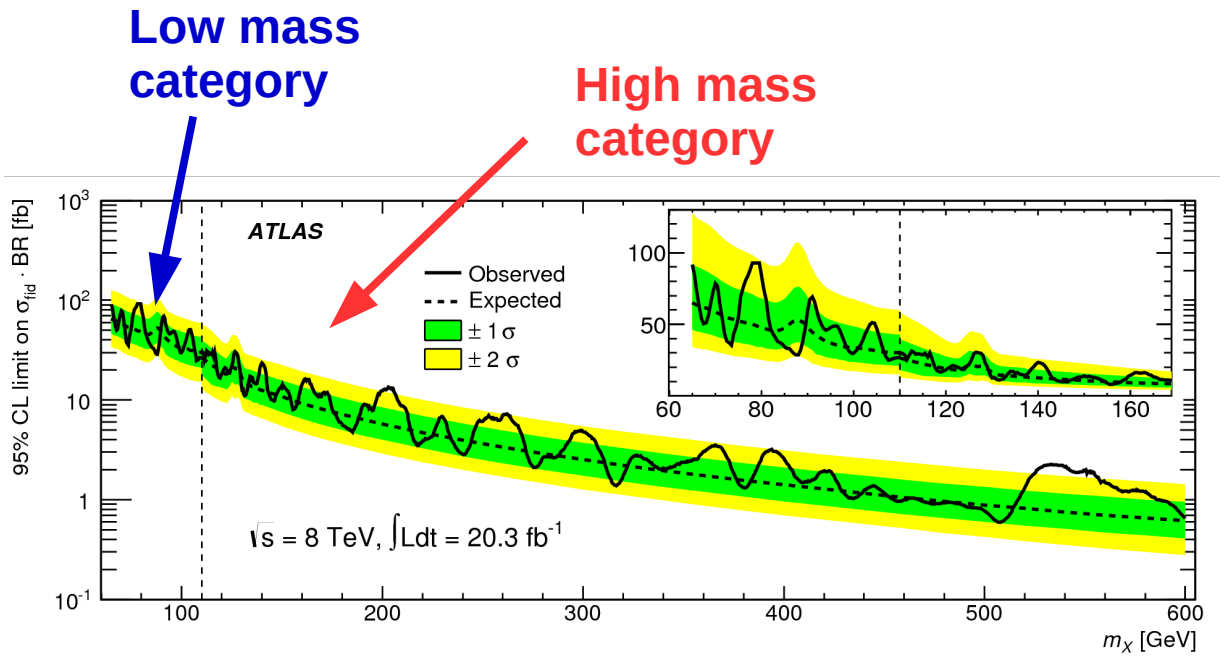


Scalar resonances to di-photon pairs



Background estimation from m(γγ) sidebands interpolation
Analytical functions used for shapes of signals and backgrounds

UU: unconverted-unconverted
UC: unconverted-converted
CC: converted-converted



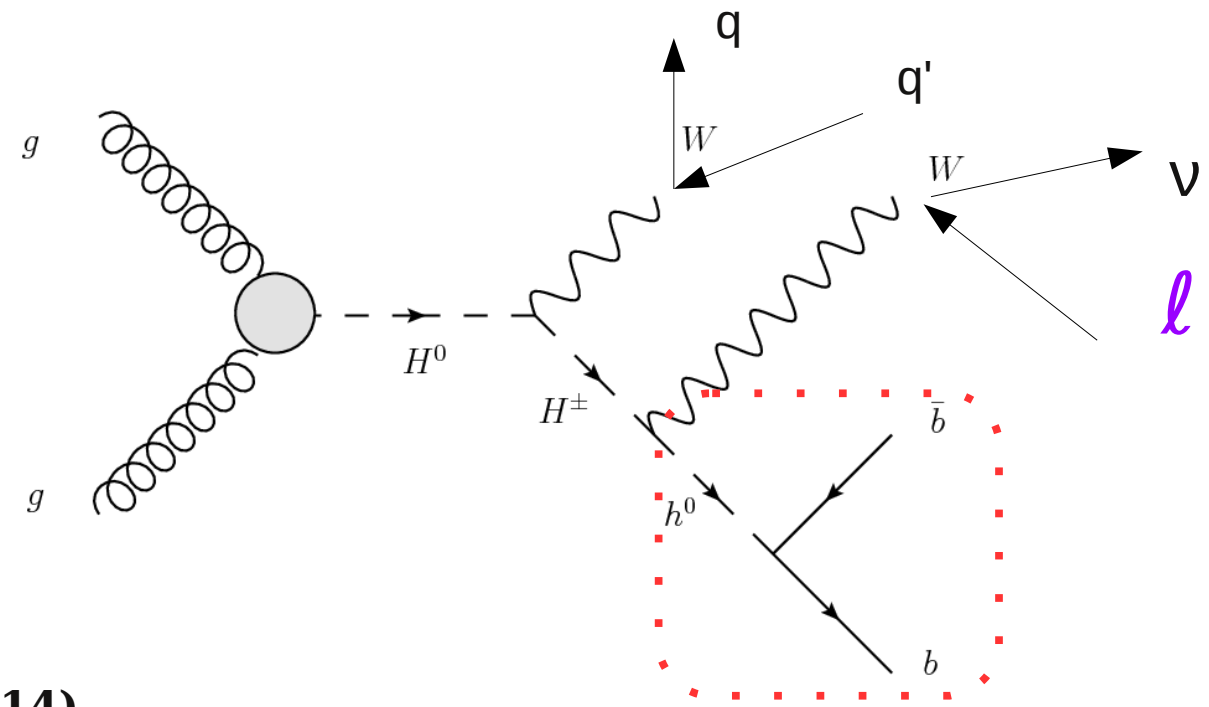
Limit on the fiducial cross section as a function of the assumed resonance mass

Higgs cascades: $H^0/A \to H^+ W^- \to W^+ W^- h$

- An interesting possibility when more than one Higgs bosons appear in the model includes decays of Heavy Higgses into lighter ones

Electron or muon to trigger the event

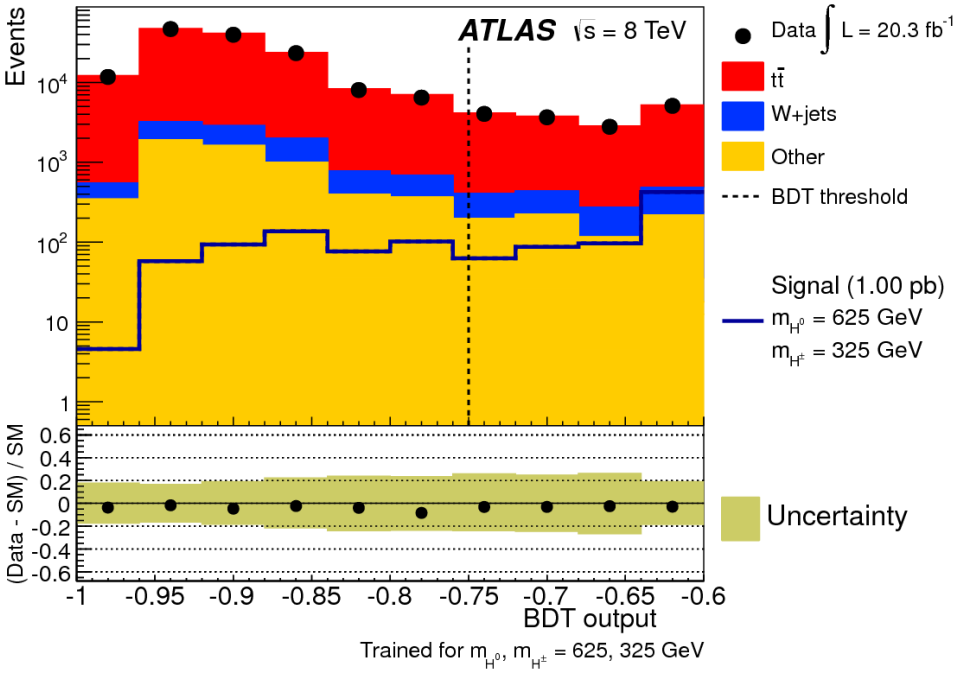
Example of a cascade decay: this final state may be simply hidden in ttbar events!

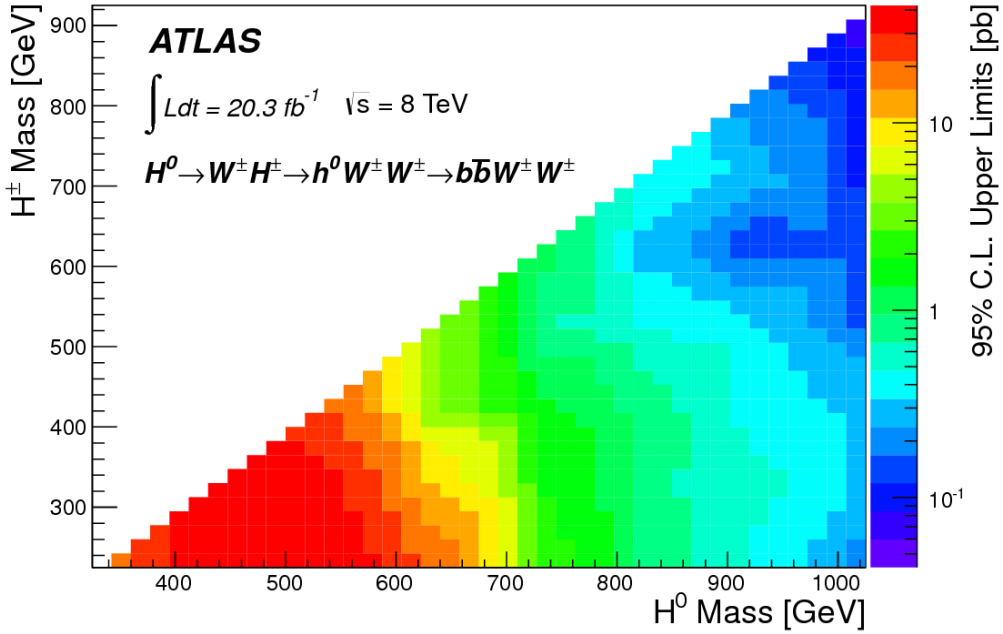


Phys. Rev. D 89, 032002 (2014)

125-GeV SM-like Higgs decaying to bb

Higgs cascades: $H^0/A \rightarrow H^+ W^- \rightarrow W^+ W^- h$





Example of a BDT output: the kinematic differences between a Higgs cascade and top pair production is exploited to improve sensitivity

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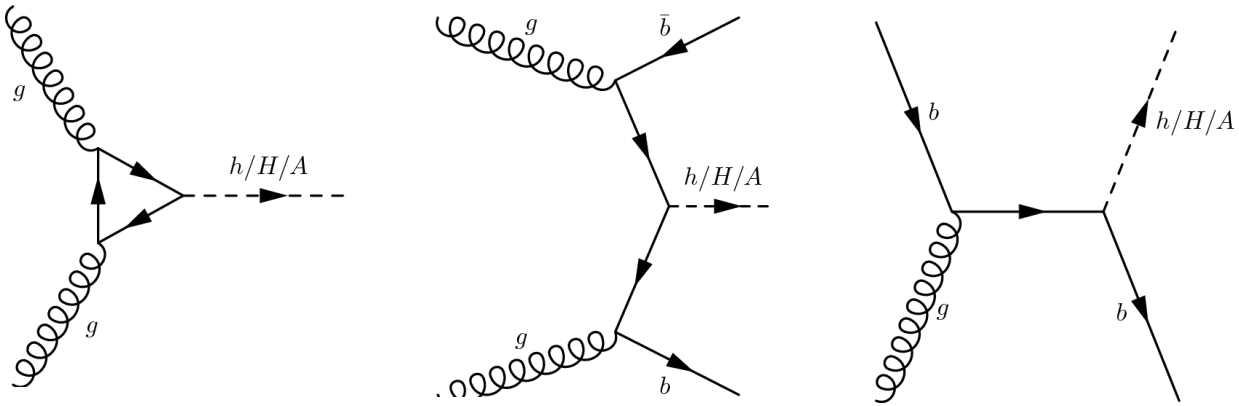
MSSM Higgs search

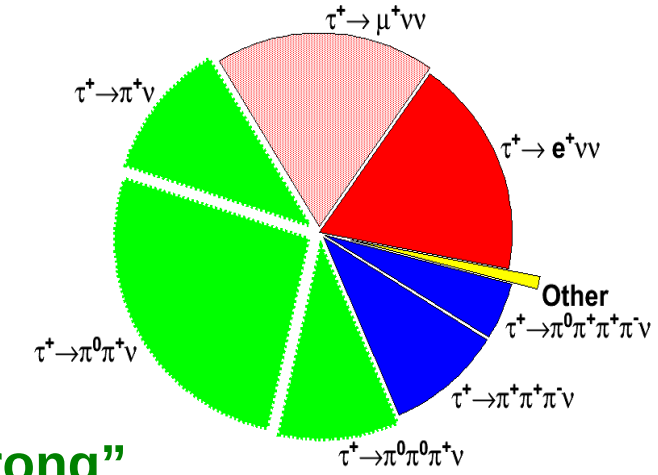
ATLAS-CONF-2014-049

- Search for MSSM Higgs bosons
- Production mechanism:
  - Gluon-fusion or in association with b-quarks



- Higgs bosons decay to a τ τ pair
  - The τ leptons may decay hadronically or leptonically

Leptonic τ decays (~35%)

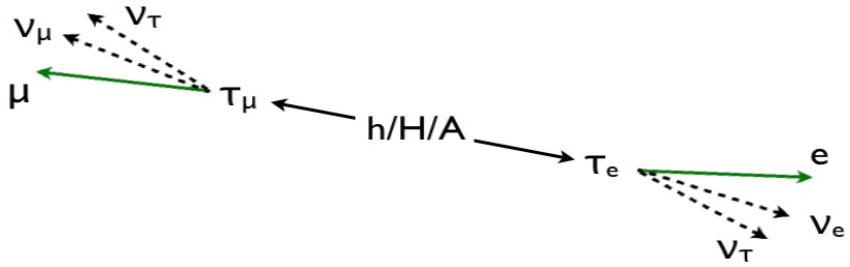


"1-prong" hadronic τ decays (~50%)

"3-prong" hadronic τ decays (~15%)

MSSM Higgs search: τ(lep)τ(lep)

- LepLep final state is optimized for low mass (m_A < 200 GeV)



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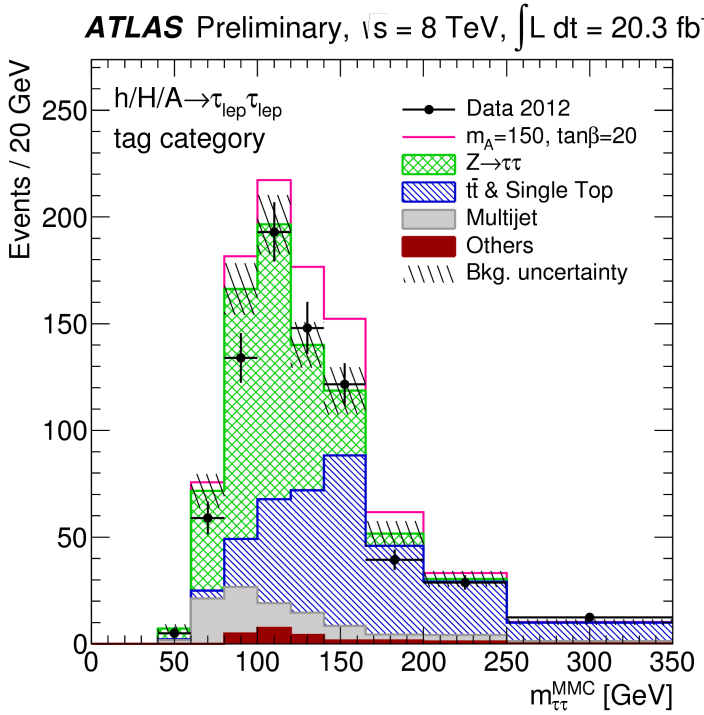

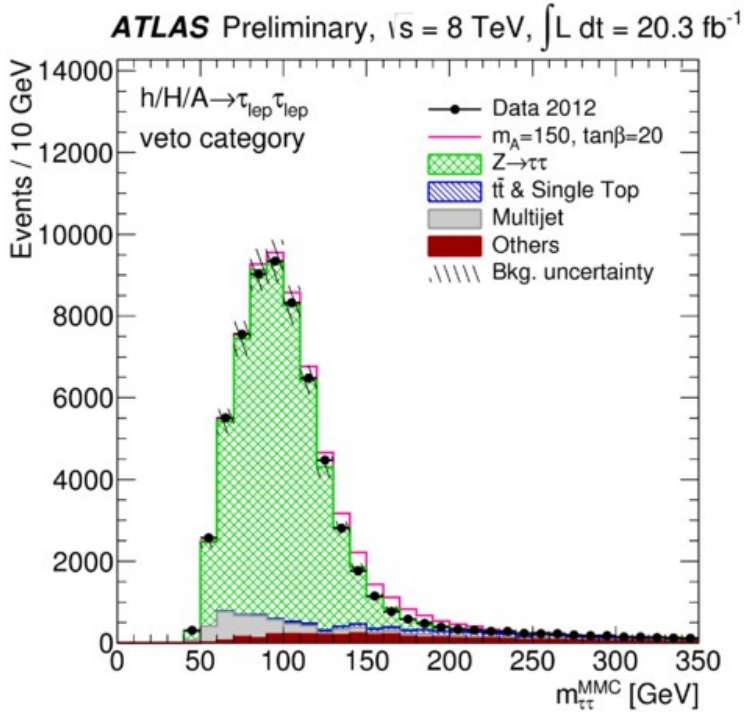

MSSM Higgs search: τ(lep)τ(had)

- LepHad channel is separately optimized for two mass regimes: low mass (m_A<200 GeV) and high mass (m_A > 200 GeV)

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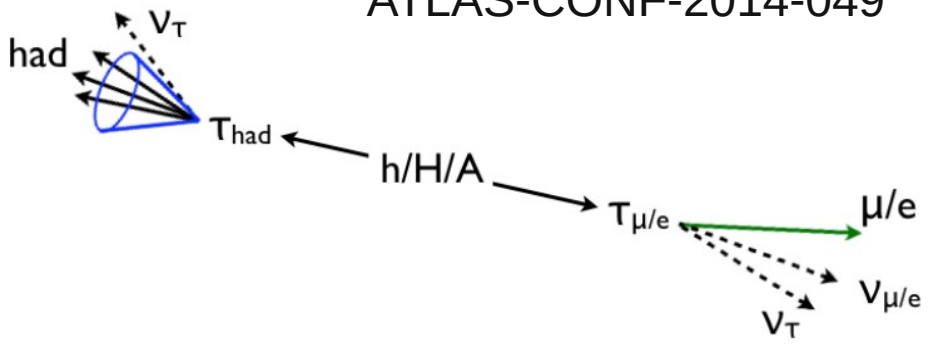
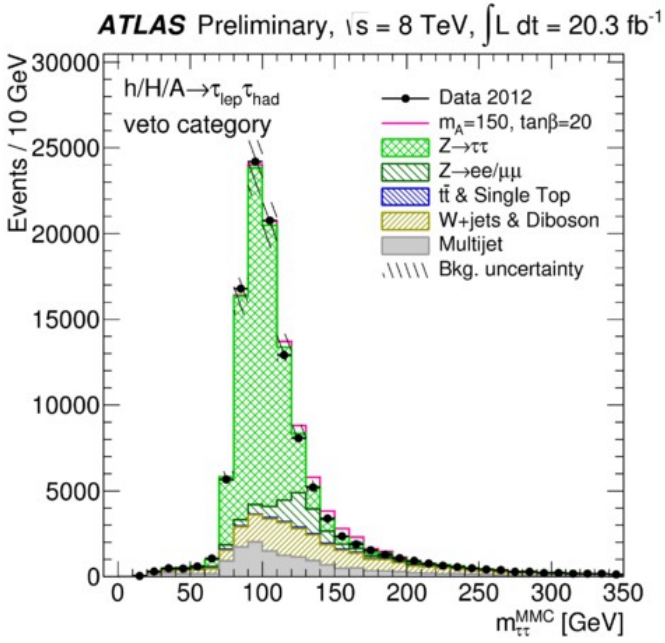
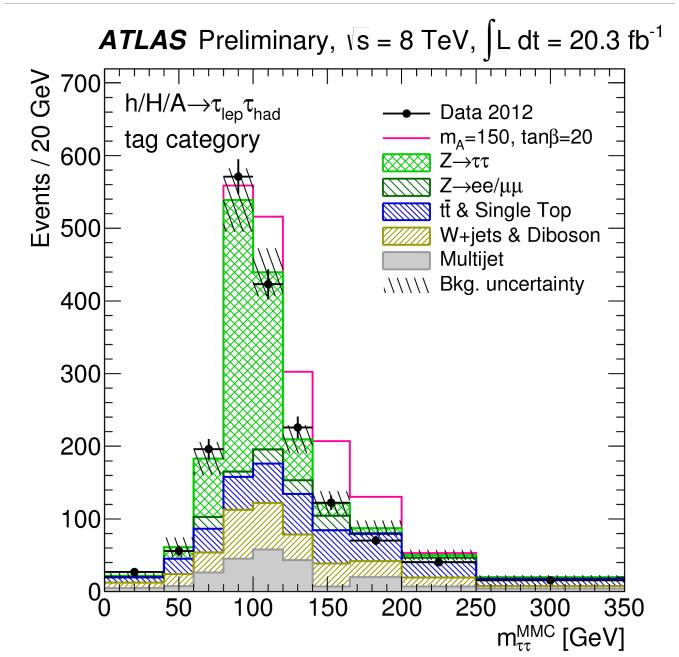
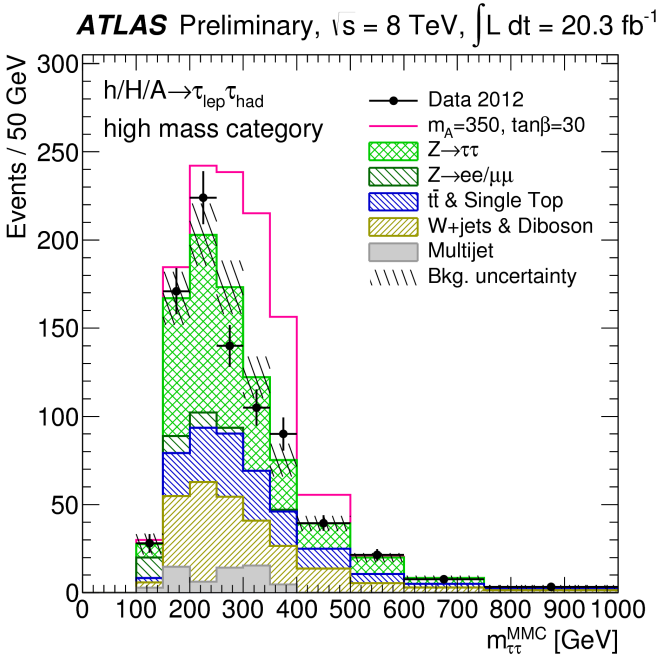


Mass distributions for the various categories:







MSSM Higgs search: τ(had)τ(had)

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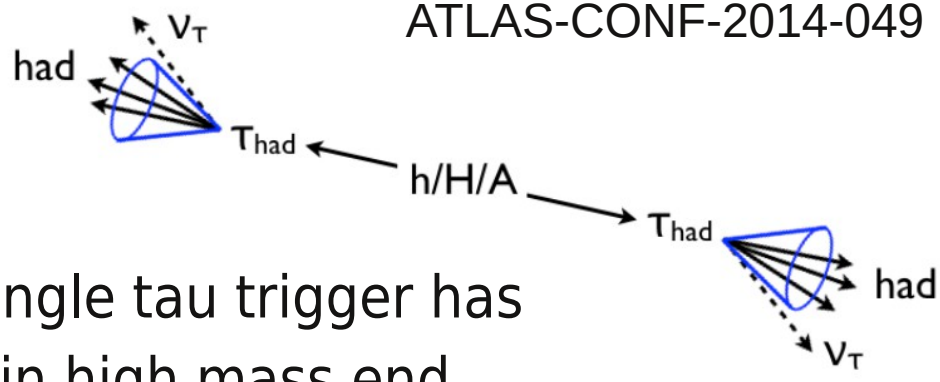
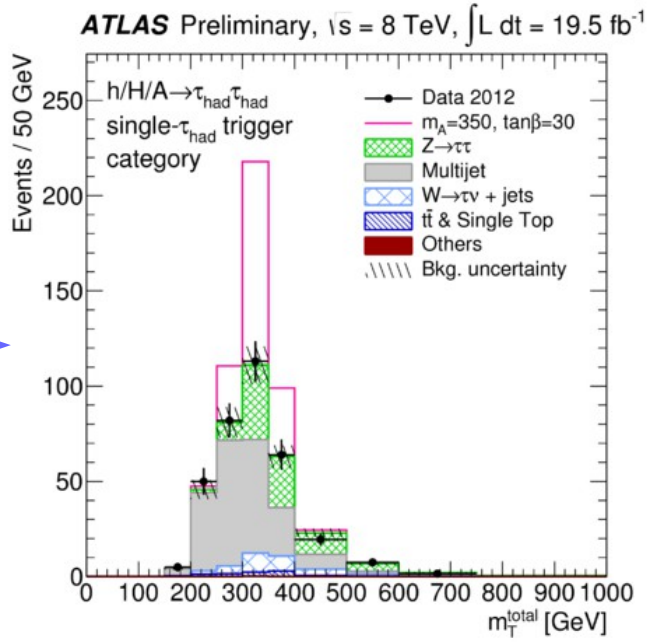
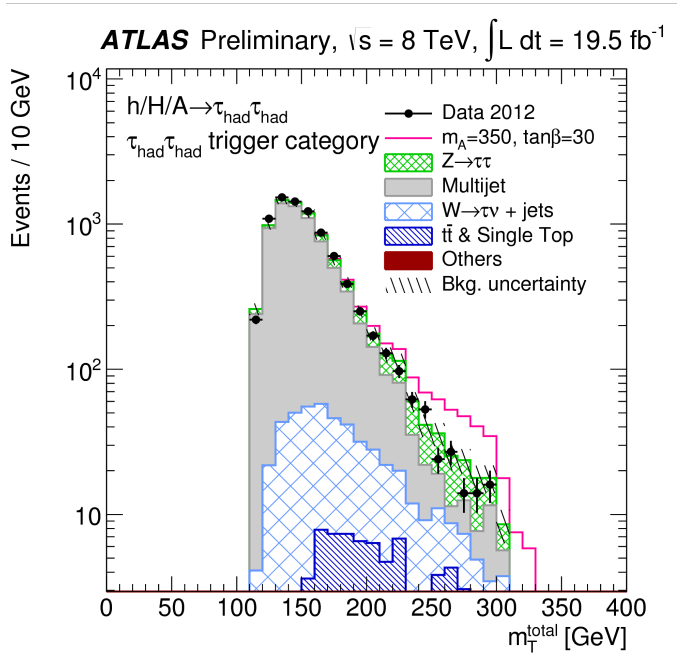
- HadHad channel is optimized for high mass only (m_A > 200 GeV)
- Single tau (p_T > 125 GeV) and di-tau triggers (p_T > 38 GeV): the use of single tau trigger has highly improved the sensitivity especially in high mass end



Largest background is multi-jet





MSSM Higgs search: Limits

- Exclusion limits: cross section limits for a single boson production with different production cross section mechanisms

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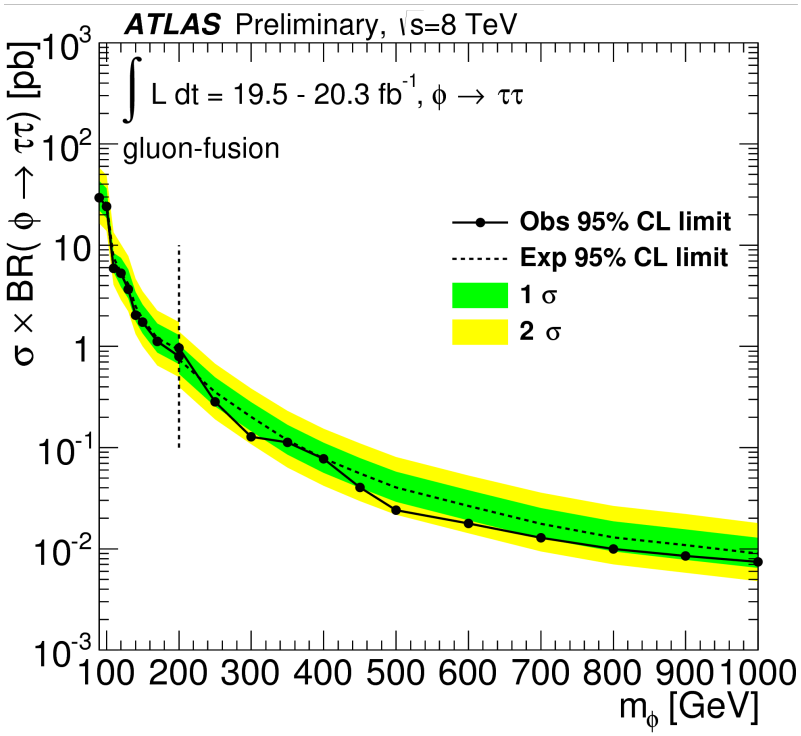

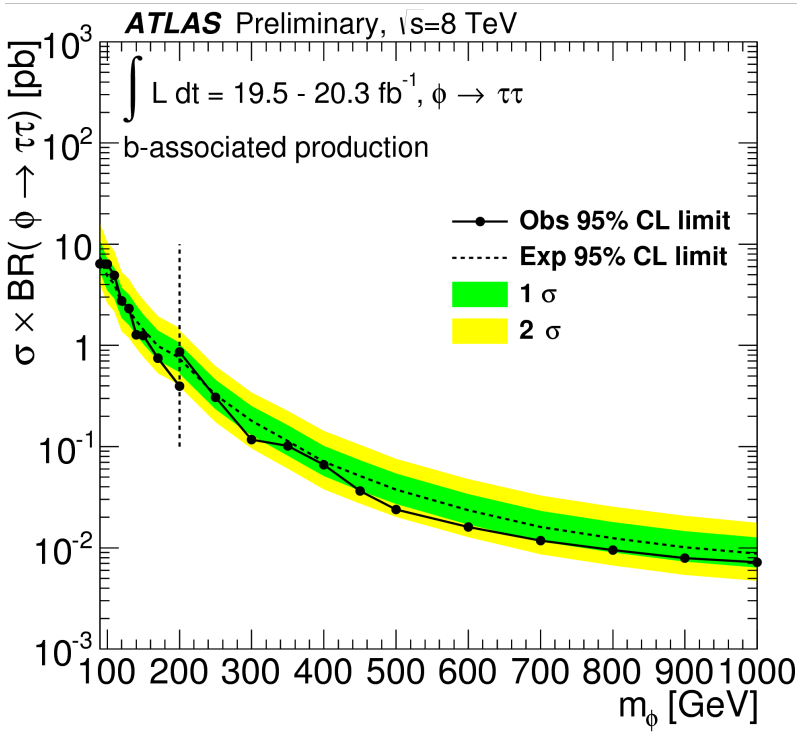

MSSM Higgs search: Limits

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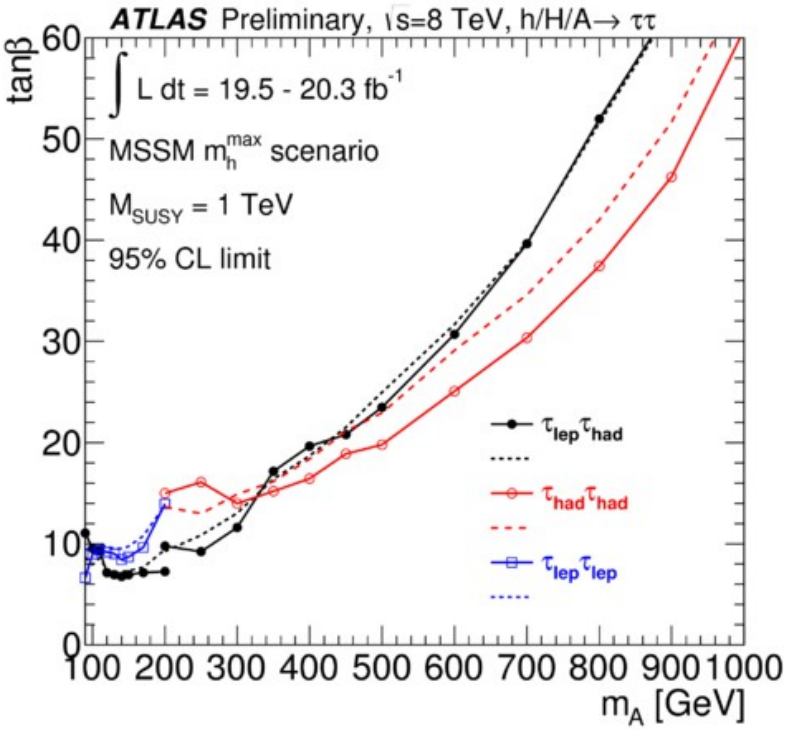
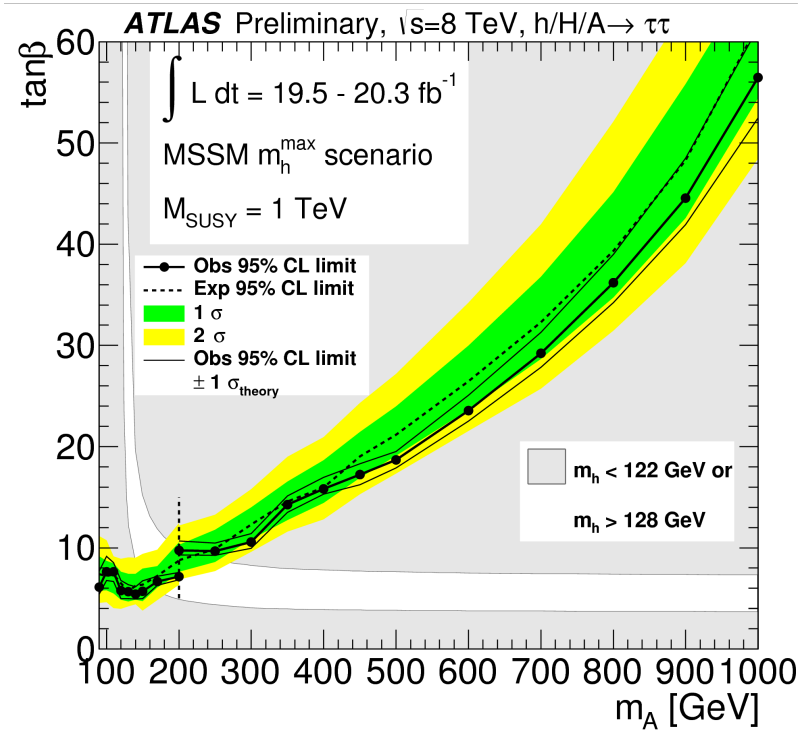
- Exclusion limits for MSSM scenarios





Limits in the mh-max scenario. The area that is incompatible with the assumption that the h125 Higgs is the lighest CP-even Higgs of the MSSM is shown as well (grey region).

MSSM Higgs search: Limits

- Exclusion limits for other MSSM scenarios

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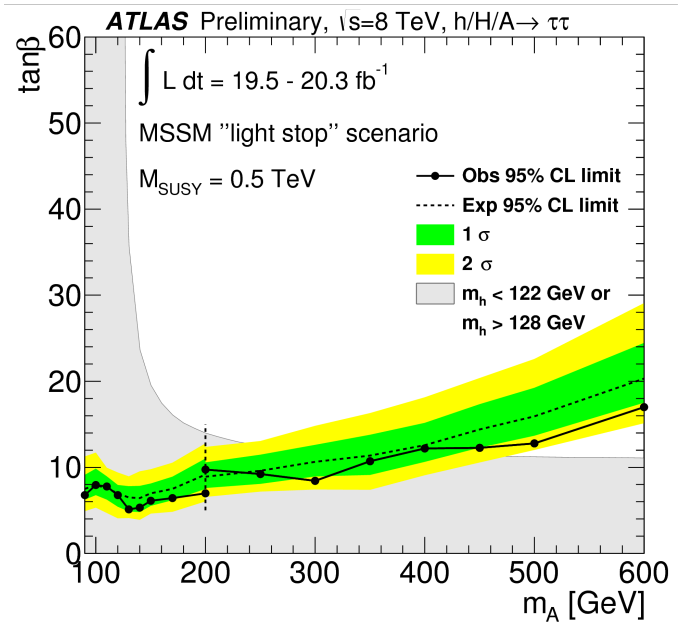
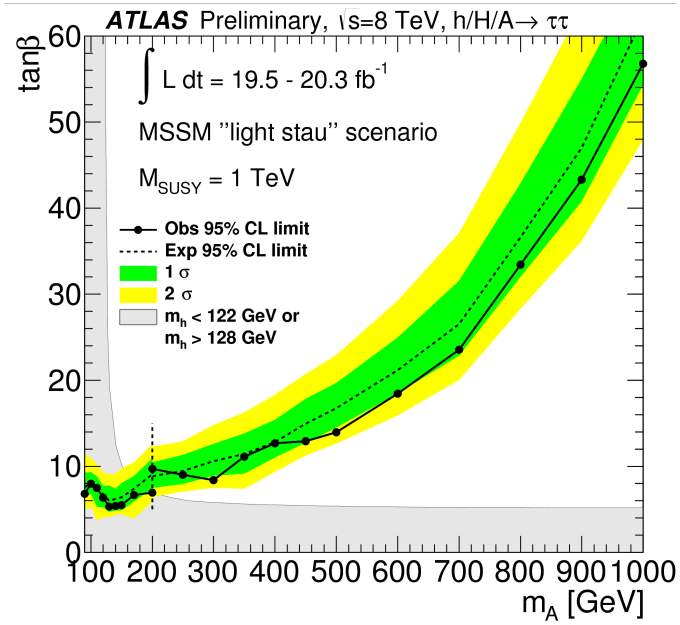
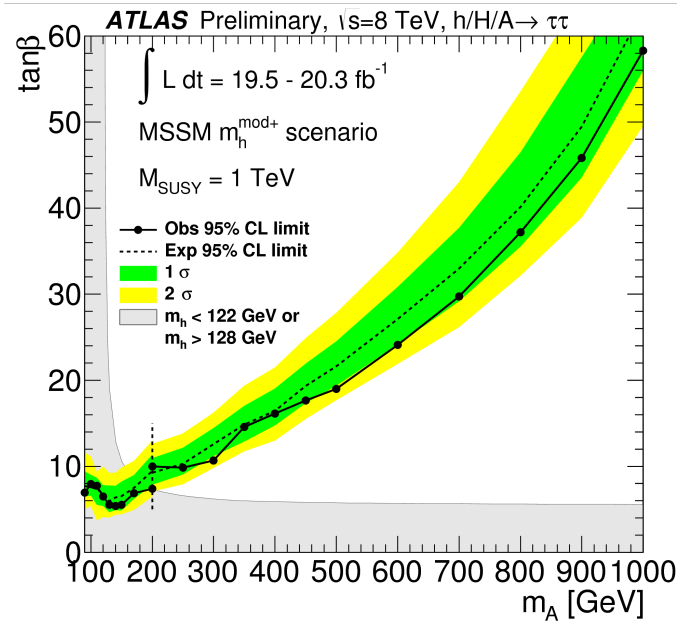


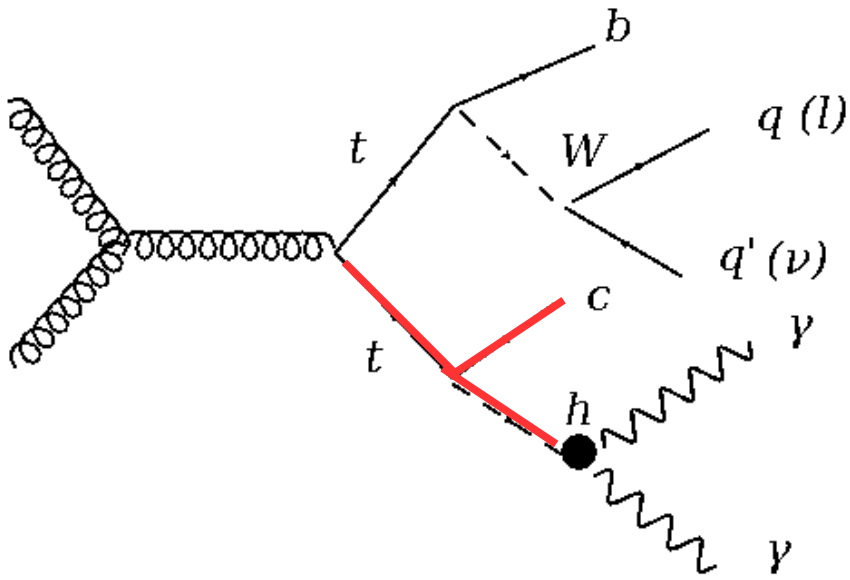




See the conference note for more plots; also the forthcoming publication for even more plots

Exotic Higgs sectors: Flavour violation

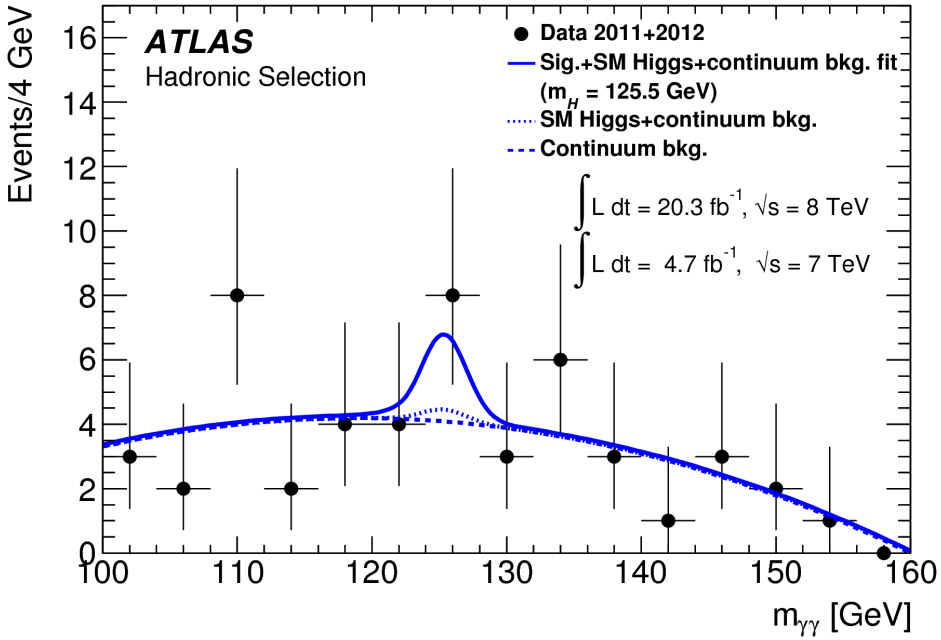
- Flavour changing (FC) neutral currents appear in many BSM theories
  - In type-III 2HDM, for instance, FC couplings **tch** (and tuh) exist and can have sizeable effects for LHC searches
- ATLAS has looked for FC decay **t → ch**/uh in ttbar events with h → γγ



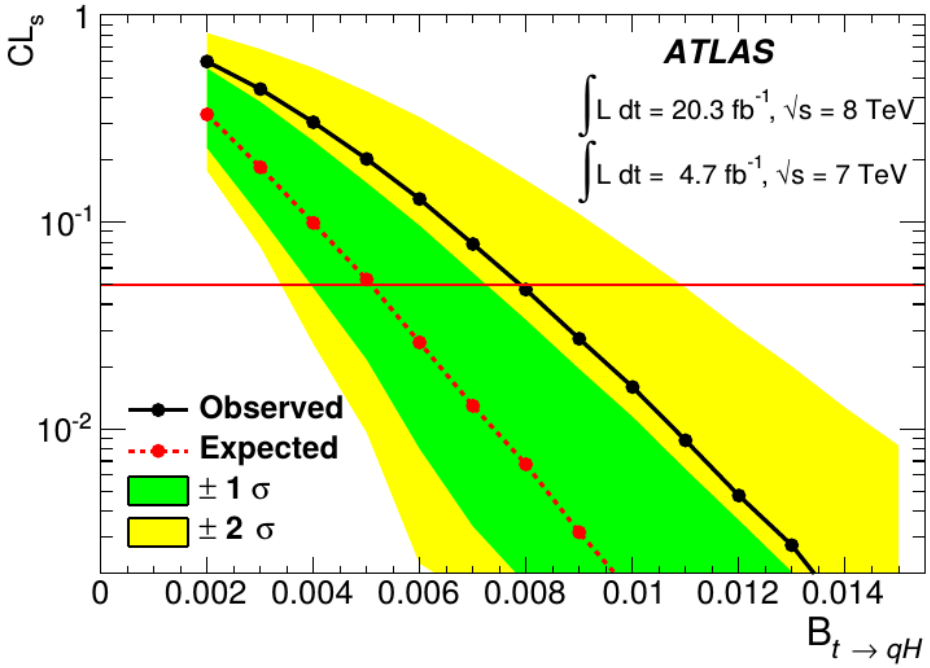
◇ 2 isolated photons, ET>40, 30 GeV to form a Higgs boson candidate
◇ Two channels: the other top decays hadronically or leptonically

Flavour violating top decays: t → ch

Example from the “hadronic top quark” channel: final distribution of events.



The CLs as a function of the FC branching ratio



Final constrain on the FC branching ratio:
BR(t → qh) < 0.79 (0.51) % observed (expected) @ 95% CL

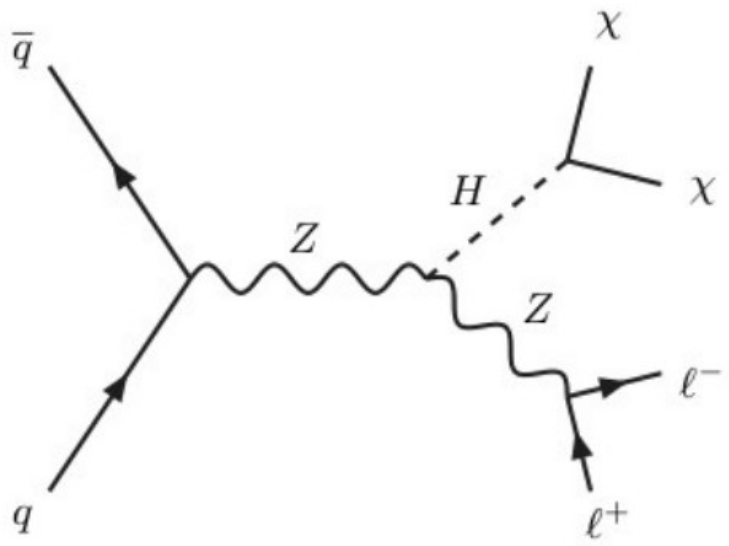
Higgs to Invisible

The SM Higgs boson has decays to (LHC detector) invisible particles, e.g., **h → ZZ → vvvv**, which has **BR ~ 1/1000** and hence it is beyond our current sensitivity.

BSM Physics may enhance this BR, e.g. Higgs portal models with Higgs decaying to dark matter particles.

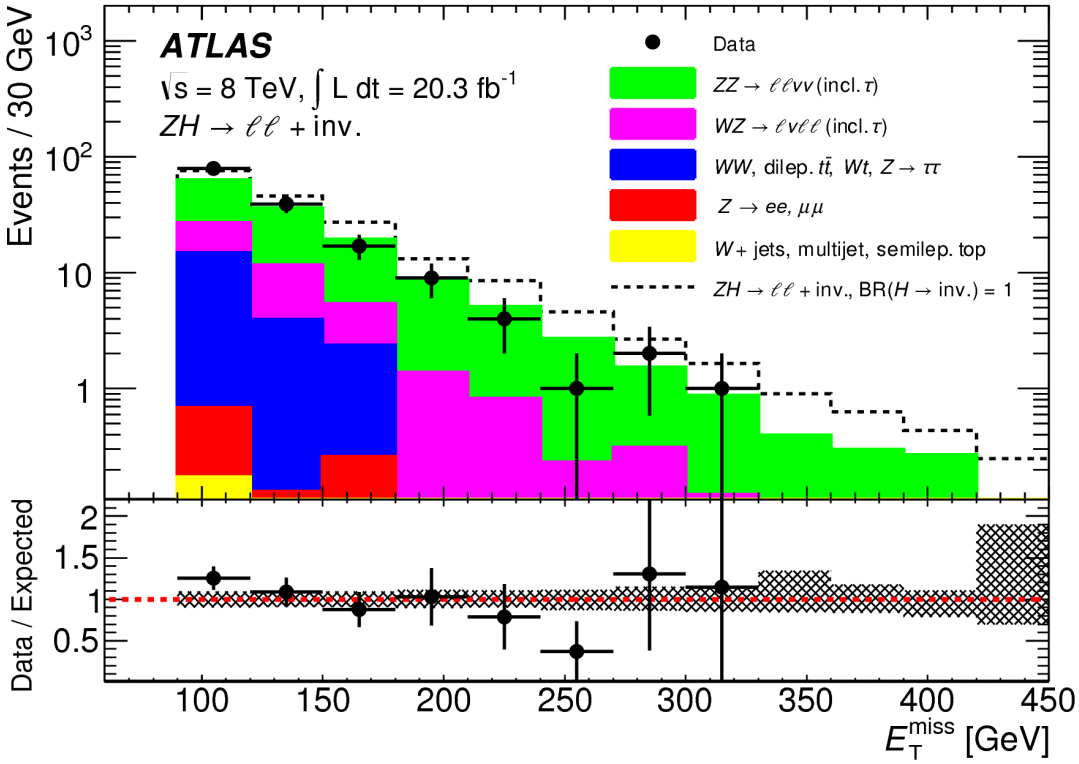
ATLAS has looked for
Zh → $\ell\ell$ inv

arXiv:1402.3244



Higgs to Invisible

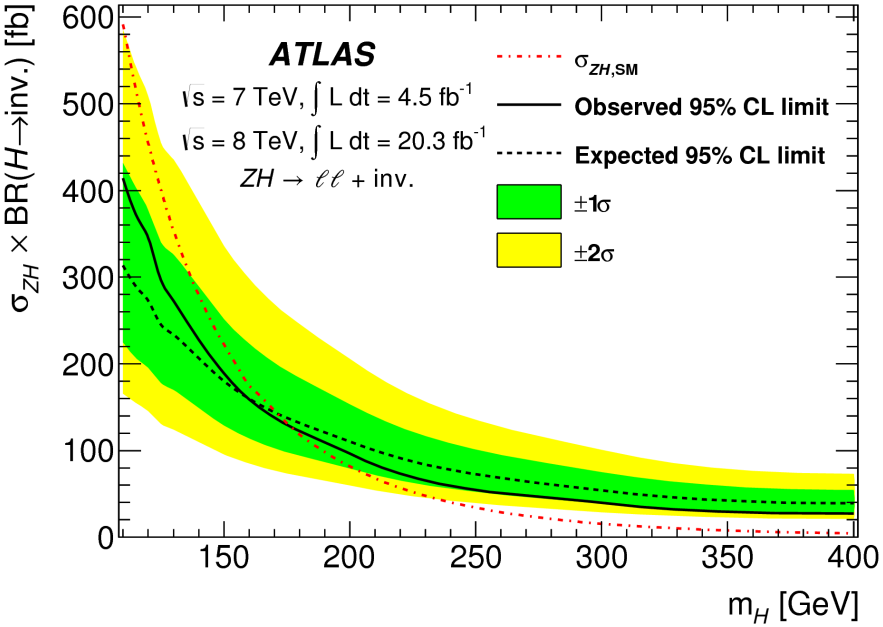
- Data collected with single lepton and di-lepton triggers
- $76 < m(\ell\ell) < 106$ GeV
- MET > 90 GeV
- $\Delta\phi(\text{MET}, p_T^{\text{miss}}) < 0.2$,
- $\Delta\phi(\text{MET}, p_T^{\ell\ell}) > 2.6$
- $\Delta\phi(\ell\ell) < 1.7$
- $|\text{MET} - p_T^{\ell\ell}| / p_T^{\ell\ell} < 0.2$
- veto of additional jets



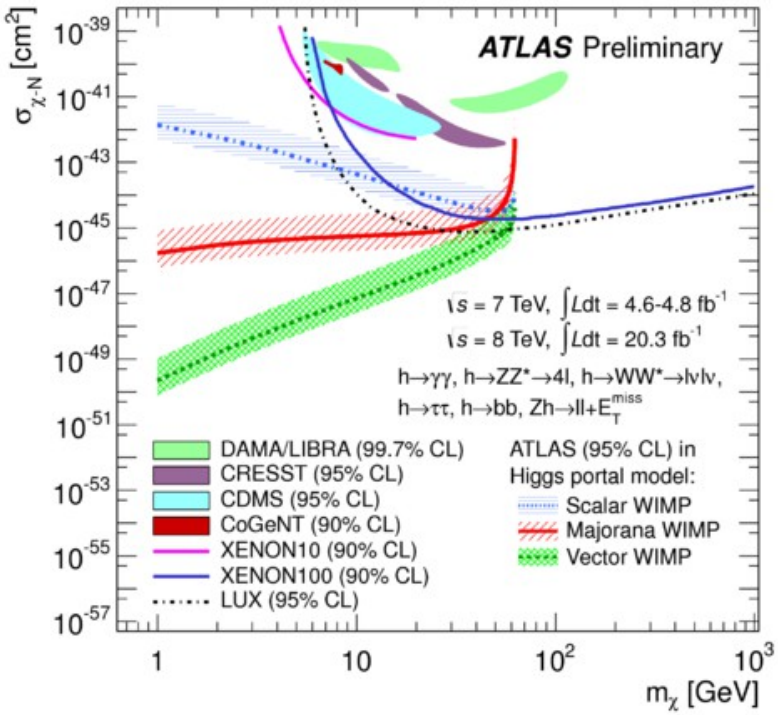
Examine the MET distribution for discrepancies

Higgs to Invisible

arXiv:1402.3244



ATLAS-CONF-2014-010



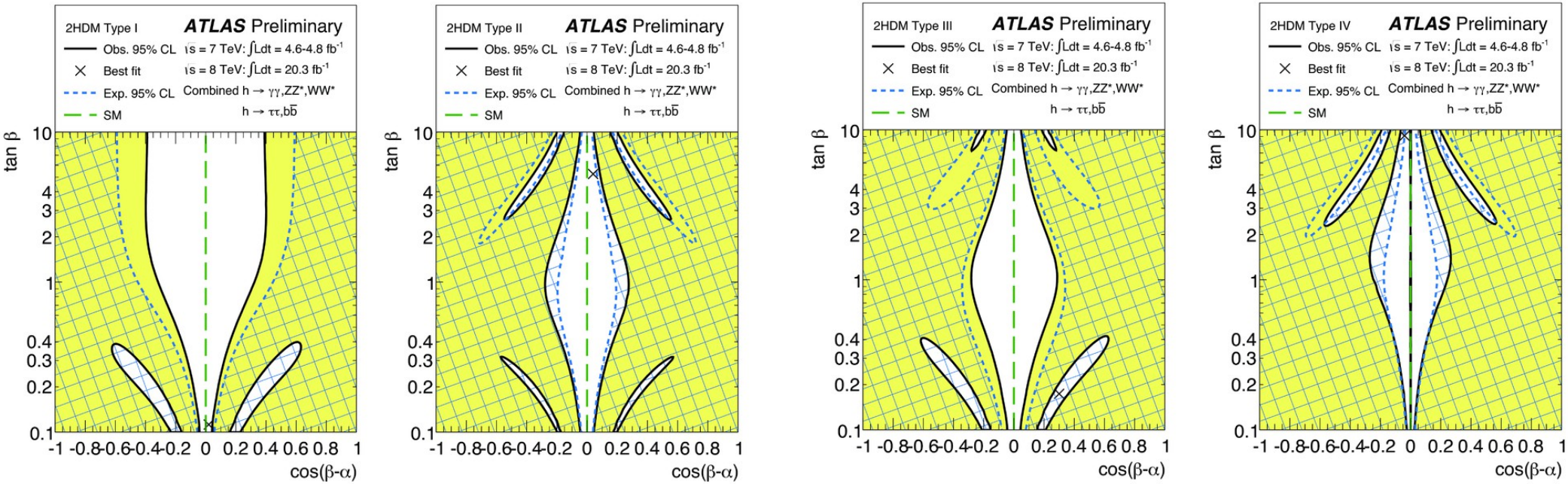
Constrains for the discovered Higgs boson:
BR(h → inv) < 75% (observed) (62% expected)

- The Zh → ll inv constrain on the BR(h→ inv) can be combined with the direct measurements of the Higgs couplings giving a combined result
  - BR(h→ inv) < 37 % (observed) (39% expected); the result can also be interpreted in terms of the dark matter-nucleon scattering cross section

Higgs couplings re-interpretation

ATLAS-CONF-2014-010

An attempt to interpret the Higgs coupling measurements to BSM Higgs scenarios can be found in ATLAS-CONF-2014-010



Examples of the 2HDM plots; many other models can be found in the note

BSM Higgs @ LHC HSXG

- Theoretical predictions, uncertainties, as well as advice on how to use them and how to interpret the experimental results is provided by the LHC Higgs Cross Sections group
- From this year forward it has been restructured:
  - WG3 is devoted to BSM Higgs

Meetings agenda: http://indico.cern.ch/category/5849/

Organization: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG#Organization

Mailing lists: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG#Mailing_List

Next meeting will take place on October 7th

Everyone is welcome to connect to the meetings and join the effort!

BSM Higgs @ LHC HSXG

- I cannot discuss here the future plans of WG3, since there will be dedicated discussion in a broad audience on October 7th : the meeting is public, so try to attend if you are interested
- Here, I will just mention some topics that are discussed in the experimental community and are relevant to the theory colleagues

The list had been prepared before the workshop and as you see lots of them have already been discussed!

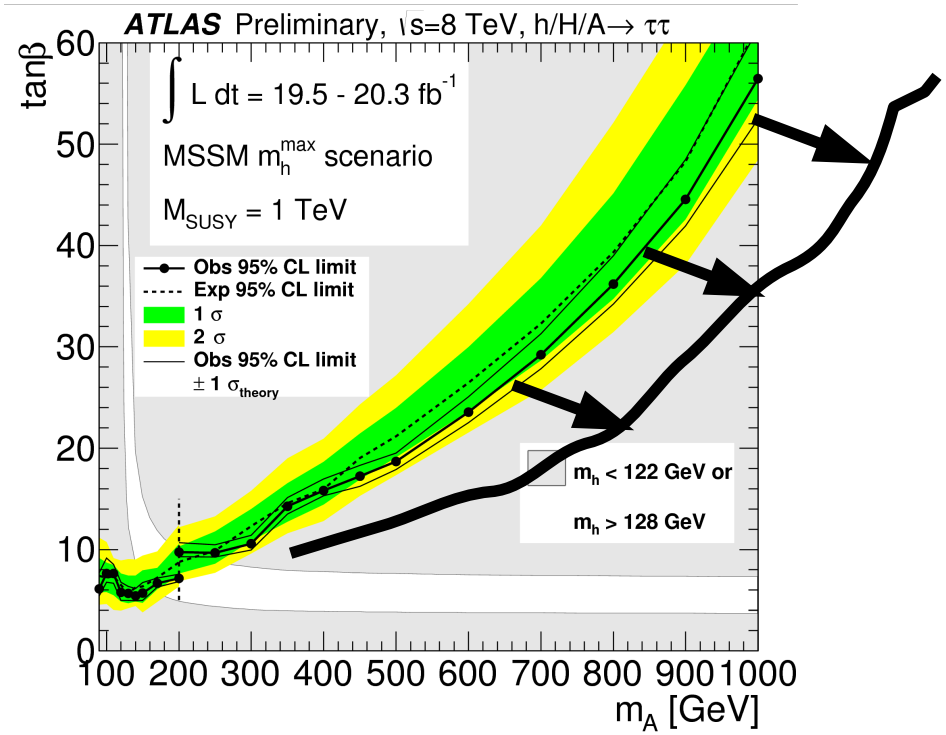
Higgs pT issues

- Higgs pT issues in MSSM and 2HDM
  - For gluon-fusion and b-associated production
  - Meetings for gluon-fusion already in the LHC HXSG

    http://indico.cern.ch/event/325226/
    - Need a recommendation for the resummation scale in Powheg; it will have a small effect in the experimental searches
  - b-associated production pT spectrum will have a larger effect. Is there anything we can do there?
    - Currently bbA signal is generated with Sherpa in ATLAS and Pythia6 in CMS; this is LO + PS. Is there need to move to NLO+PS?

MSSM Scenarios for Run-II

- Will be using the same scenarios with M_{susy} ~ 1 TeV in the new run?



In Run-2 we will start being sensitive to m_A > 1000 GeV. This is a critical value because popular scenarios like mh-max, mh-mod have m(stop) = m(sbottom) = m(gluino) = 1 TeV

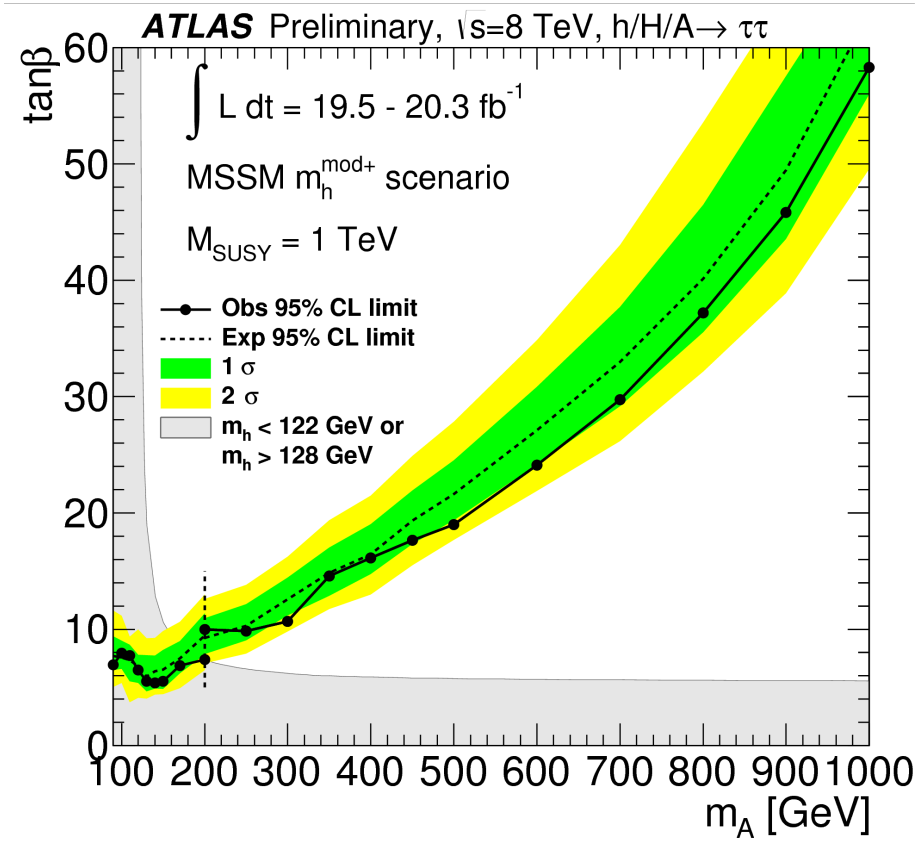
Calculations should be ok-ish as soon as we have sensitivity < 2 TeV, (at least I hope so, theorists should confirm that) but we may think of whether we need something else.

MSSM scenarios: predictions for h

- How much of the space compatible with mh ~ 125 GeV has an h with properties compatible to those measured experimentally?

Are we ready to do this comparison with the available MSSM calculations/numbers?

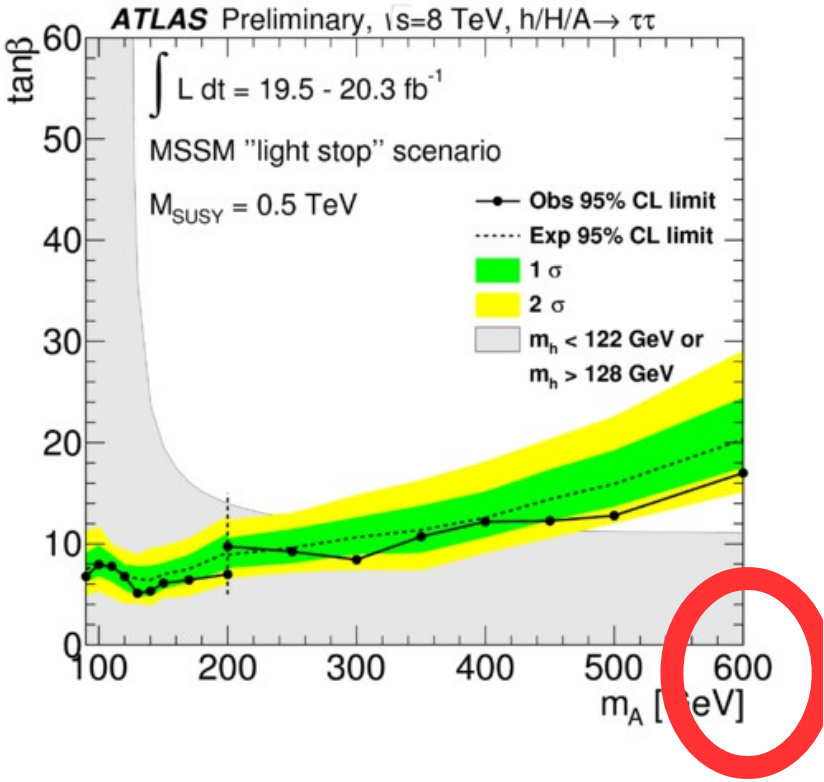
Notice that if you check the MSSM numbers for cross sections and BR currently provided by the LHC Higgs cross section group at the decoupling limit they do not converge to the SM Higgs values. (Different accuracy of the calculation?)



MSSM scenarios with light sparticles

- When we have light sparticles the predictions from the LHC HXSG don't hold

Light stop scenario: recommendation to be using only up to **mA = 600 GeV** (which is about 2m(stop))



Michael Spira's talk makes progress toward this direction.

Other topics

- Charged Higgs:
  - There is a request for s-channel production cross sections that have been requested since some time
    $qq' \rightarrow H^+$
  - Charged Higgs in the intermediate mass region: 160 – 200 GeV
  - MC for charged Higgs: 4FS and 5FS
- Heavy Higgs to WW/ZZ: lineshape discussion & interference
- Final states that we have forgotten?
- Other topics will be discussed more in detail on October 7th

Conclusions

- There was no discovery of a BSM Higgs boson at Run-I
  - But Nature gave us a light CP-even boson that is compatible with many BSM scenarios and can be used as a tool to go beyond SM
    - Searches for final states that include h125 are flourishing and they will continue to do so in Run-II
  - MSSM and charged Higgs searches will continue to play an important role
  - Theorist's input is needed both for cross section calculation but also for the identification of potentially interesting final states that we have neglected so far

Additional slides

BSM Higgs @ LHC HSXG

- What has been done so far
  - MSSM neutral Higgs: cross sections and branching ratios are provided for mh-max and many other scenarios
  - Charged Higgs: cross sections and branching ratios are provided for mh-max scenario
  - 2HDM
    - Neutral Higgs cross sections for g-fusion and b-associated production are available through SusHi; HIGLU can be also used for gluon-fusion
    - Branching ratios are available through 2HDMC or HDECAY
    - Charged Higgs production cross sections can be get from the type-II cross sections (available from MSSM charged Higgs study)
  - Electroweak singlet: recommendations in YR3 for the interpretation of the heavy Higgs search