Search for Additional Higgs Bosons in ATLAS

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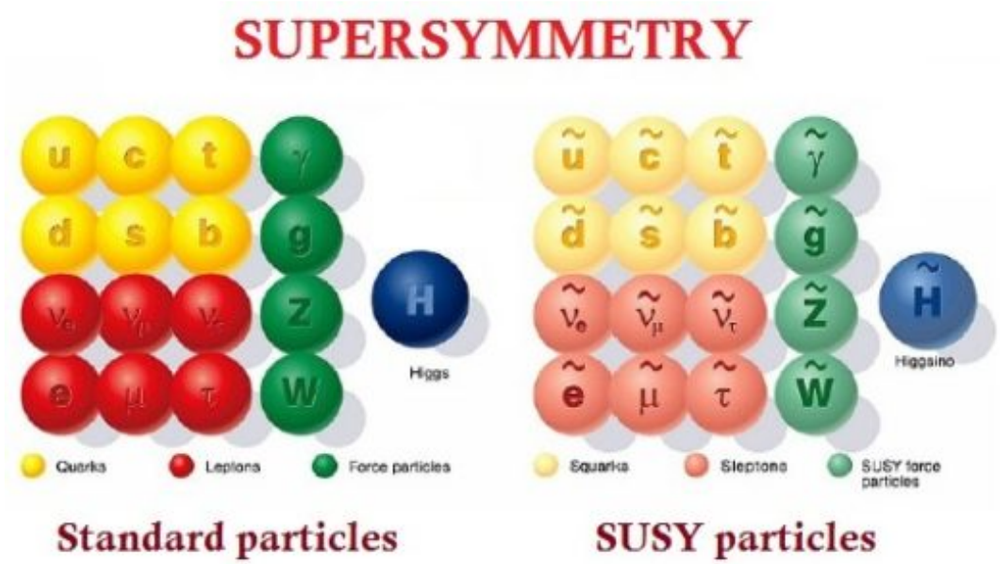
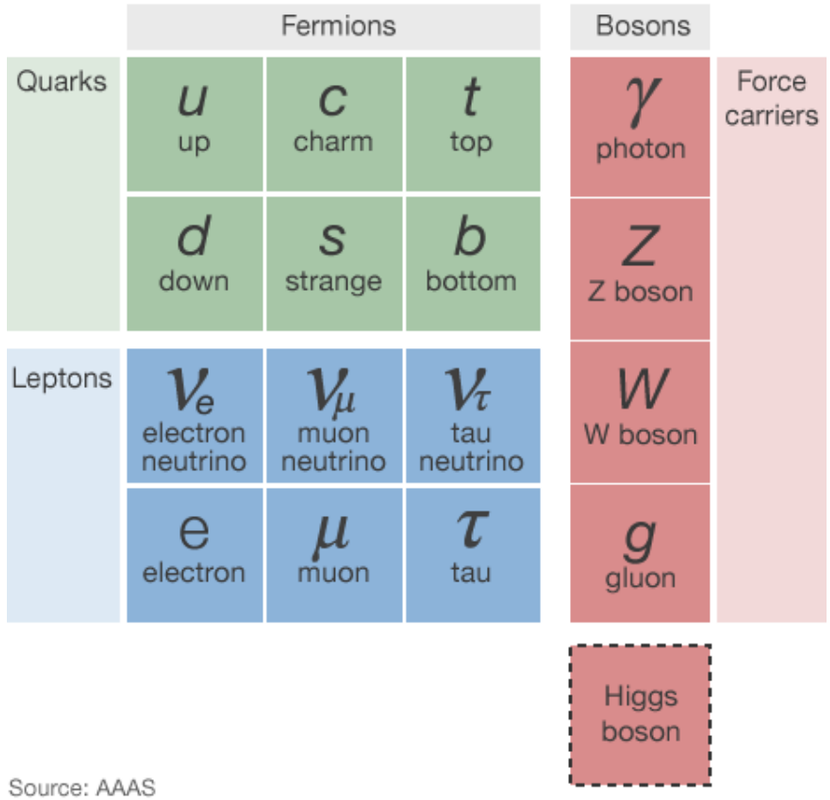
Beyond the Standard Model

- The Standard Model (SM) of particle physics is a very successful theory.
- But not perfect.
- For example, SM Lagrangian does not include:
  - Dark matter.
  - Neutrino mass term.
- Many ideas beyond the standard model exists.
  - Two Higgs Doublet Models (2HDM).
    - These models have dark matter candidates.
    - One example: Supersymmetric extension of SM (SSM).
  - Seesaw and radiative neutrino mass mechanisms.
    - These models explain the smallness of the neutrino masses.
  - Left-right symmetric models, and many more…



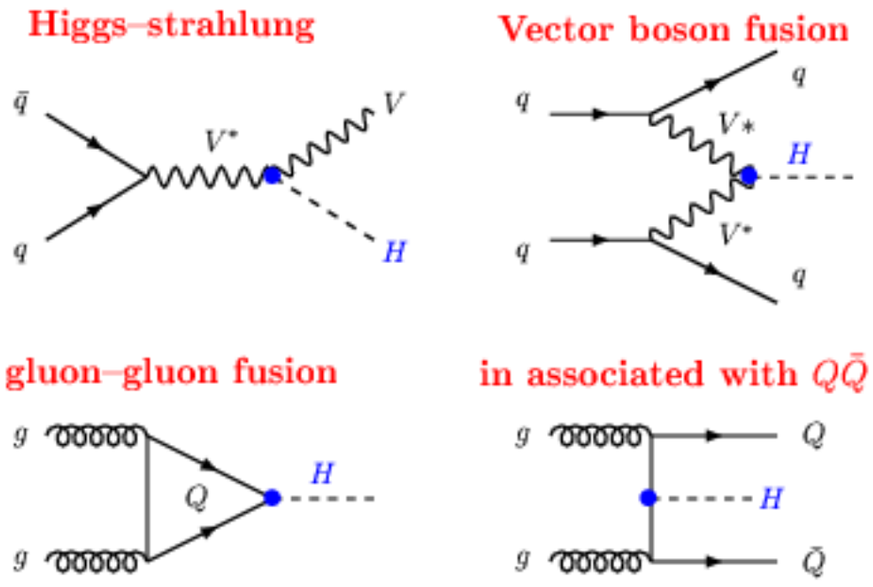
Two Higgs Doublet Models

- The Standard Model (SM) Lagrangian has 1 Higgs doublet.
  - 4 degrees of freedom
  - 3 weak gauge boson masses + 1 Higgs boson (h)
- 2 Higgs Doublet Models (2HDM) has additional Higgs Doublet
  - Additional 4 degrees of freedom.
  - Additional 4 Higgs Bosons.
    - Heavy scalar: H
    - Pseudo scalar: A
    - Charged scalars: H^+ and H^-
  - Additional parameter:
    - tanβ = the ratio of vacuum expectation values of the two Higgs doublets.



Source: AAAS

Searches in ATLAS



- Look for all major decay modes:
  - Neutral Higgs: ZZ, WW, Zγ, γγ, Zh, hh, $\tau^+\tau^-$, $t\bar{t}$, $b\bar{b}$
  - Charged Higgs: $t\bar{b}$, τν
  - Doubly Charged Higgs: l^+l^+ (l^-l^-), W^+W^+ (W^-W^-)

- I'll talk about only recent results:
  - $\tau^+\tau^-$ (New, first time shown to public) [No reference # yet]
  - t->bH^+, H^+-> $\tau^+\nu$: JHEP 09 (2018) 139, arXiv:1807.07915
  - pp->H$b\bar{b}$, H->$b\bar{b}$: submitted to Phys. Rev. D, arXiv:1907.02749

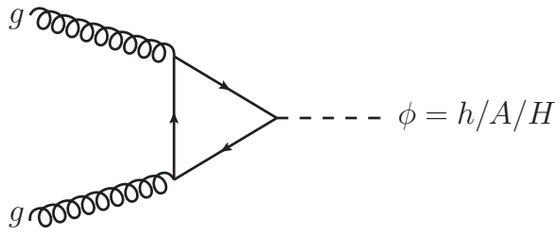
- 2HDM constraints:
  - Summary of limits in hMSSM scenario: ATL-PHYS-PUB-2019-034
    - hMSSM = Minimal Supersymmetric Standard Model (MSSM) + 125 GeV Higgs (h).
  - Summary of limits from dark matter searches: JHEP 1905 (2019) 142, arXiv:1903.01400
  - h(bb) dark matter search: ATLAS-CONF-2018-039

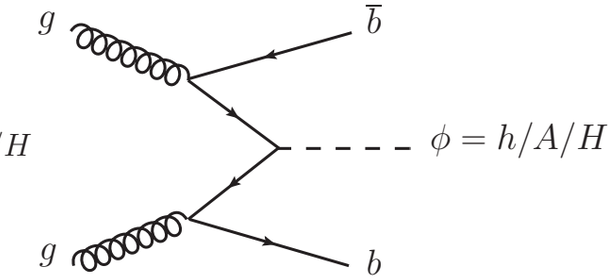
- In Nicolo's talk
  - hh->bbbb: submitted to JHEP, arXiv:2001.05178
  - WW+ZZ: Phys. Rev. D 98 (2018) 052008, arXiv:1808.02380

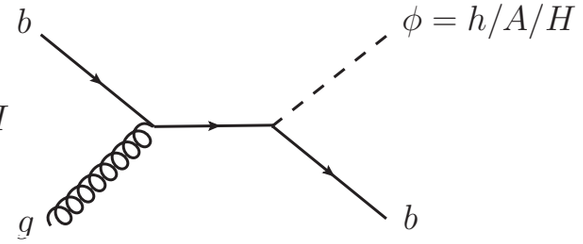
NEW

Neutral Higgs -> $\tau^+\tau^-$

- 13 TeV, 139 fb^{-1}.
- Production modes:
  - gluon-gluon fusion
  - b-associated production



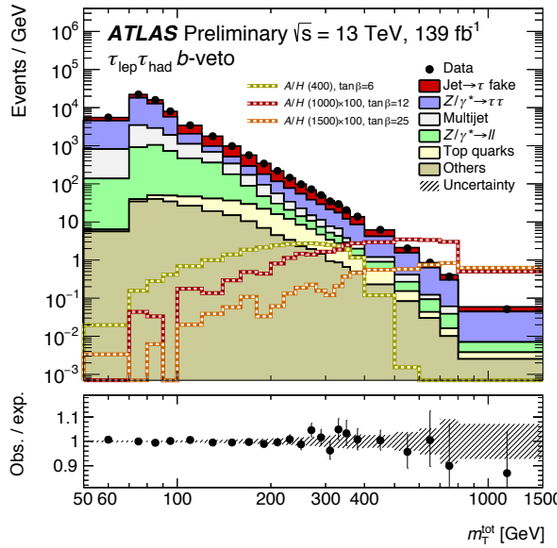


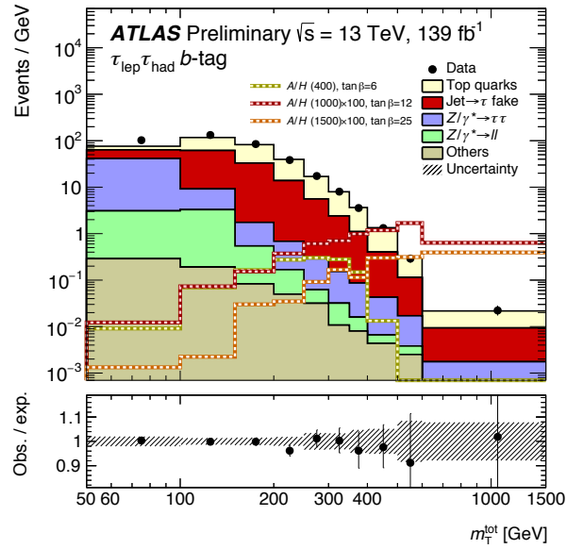


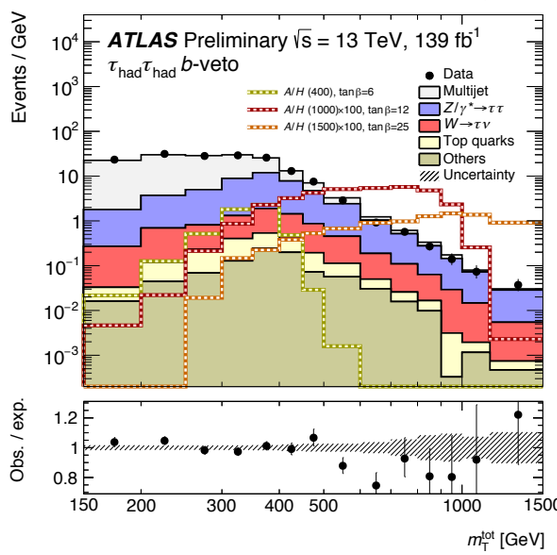
- The $\tau^+\tau^-$ mode is enhanced in supersymmetric models.
  - 2 $\tau^+\tau^-$ decay modes are considered:
  - lep-had: $\tau_e\tau_{had}$ + $\tau_\mu\tau_{had}$
    - Single electron and single muon triggers are used.
  - had-had
    - Single tau triggers are used.
    - Two τ_{had} and no electron or muon.

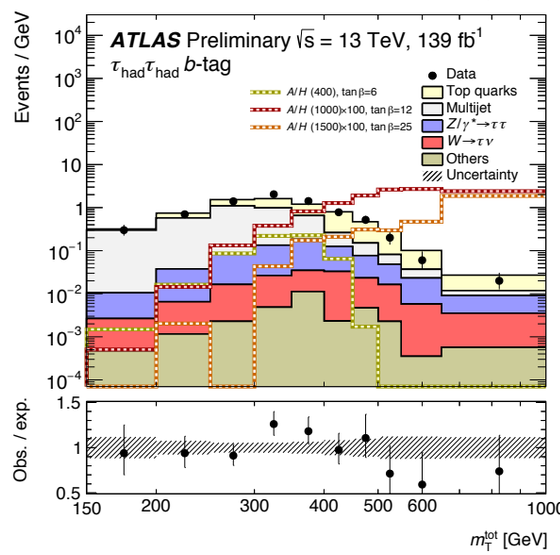
- Main backgrounds:
  - jet-τ fake, Muitlijet -> data-driven fake-factor method.
  - Top -> MC simulation.
  - Z/γ* -> ττ -> MC simulation.

Main source of systematic errors







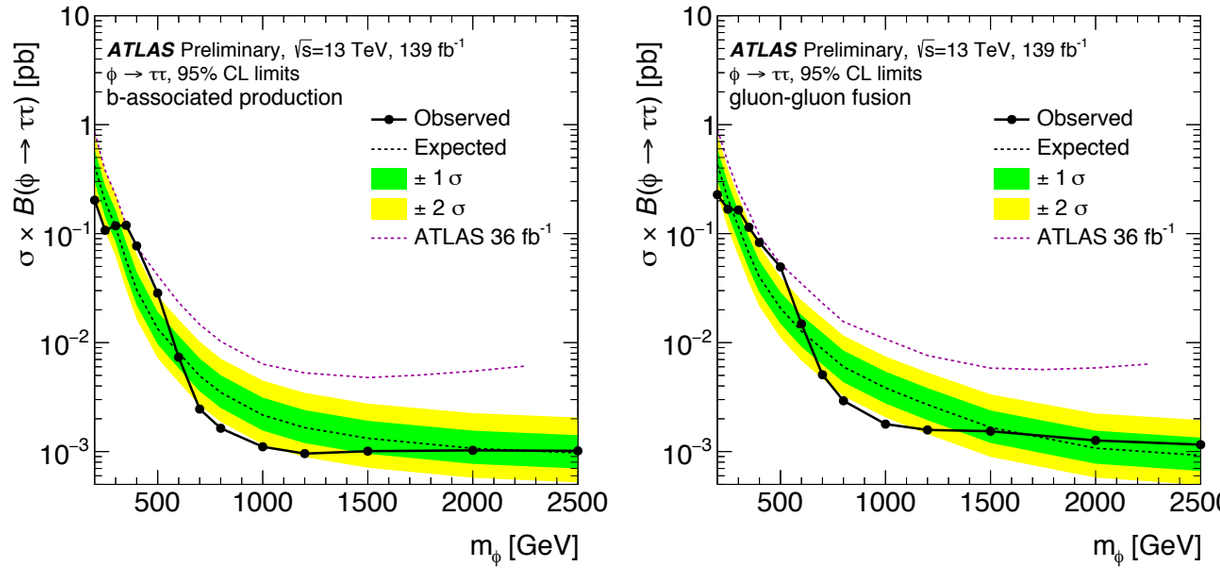


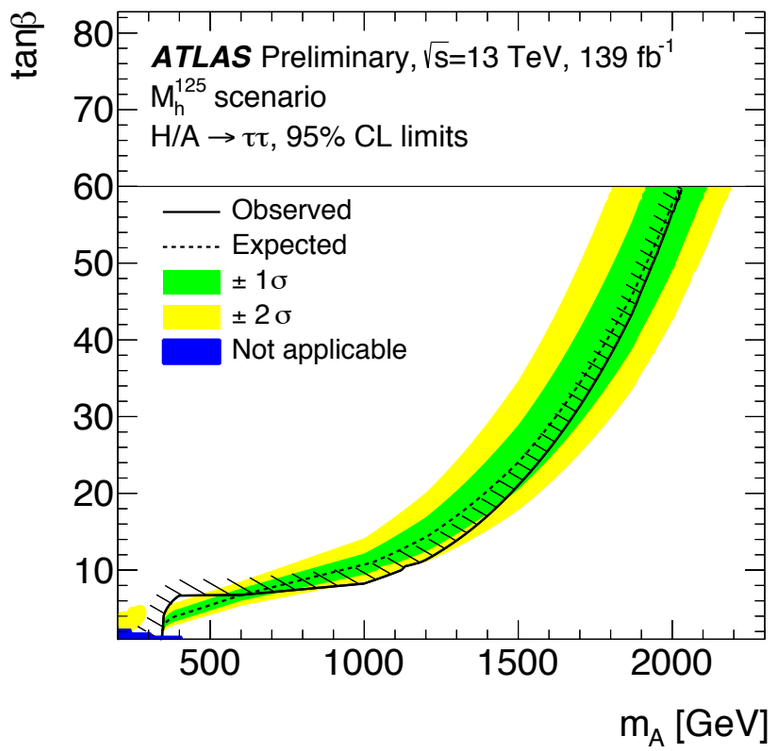
NEW

Neutral Higgs -> $\tau^+\tau^-$

- Model independent limit on the (cross section)*(branching fraction)
  - Significant improvement wrt the 2017 result (13 TeV, 36 fb^{-1}).

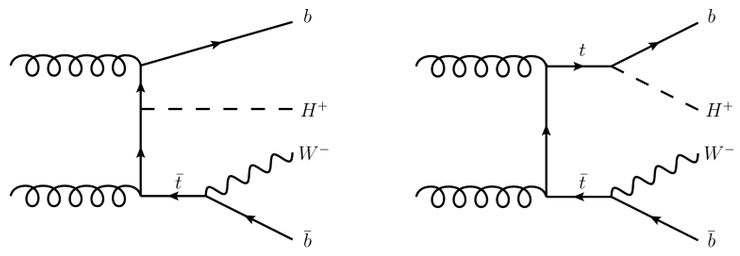
- Limits on A mass vs tanβ plain.
  - Interpreted in M_h^{125} scenario.
  - Aslo in hMSSM scenario.
    - Dominant contribution to the 2d exclusion (see p9).



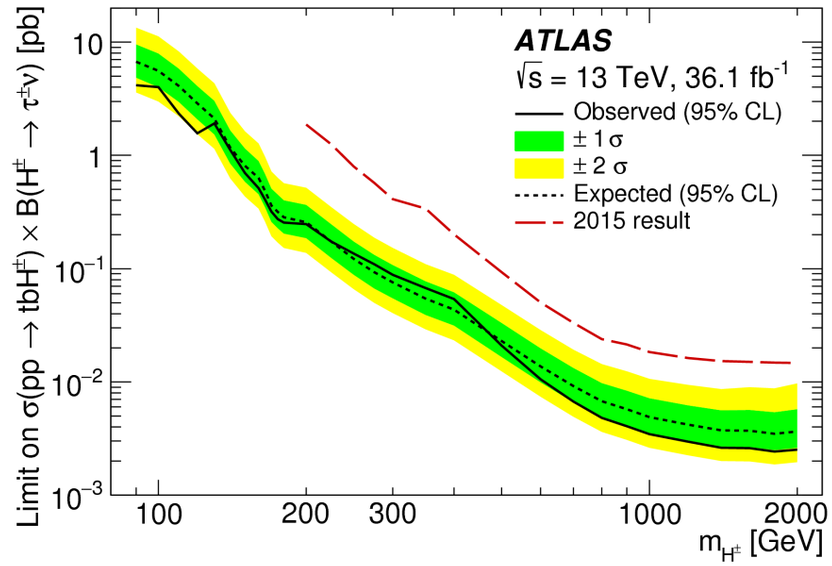


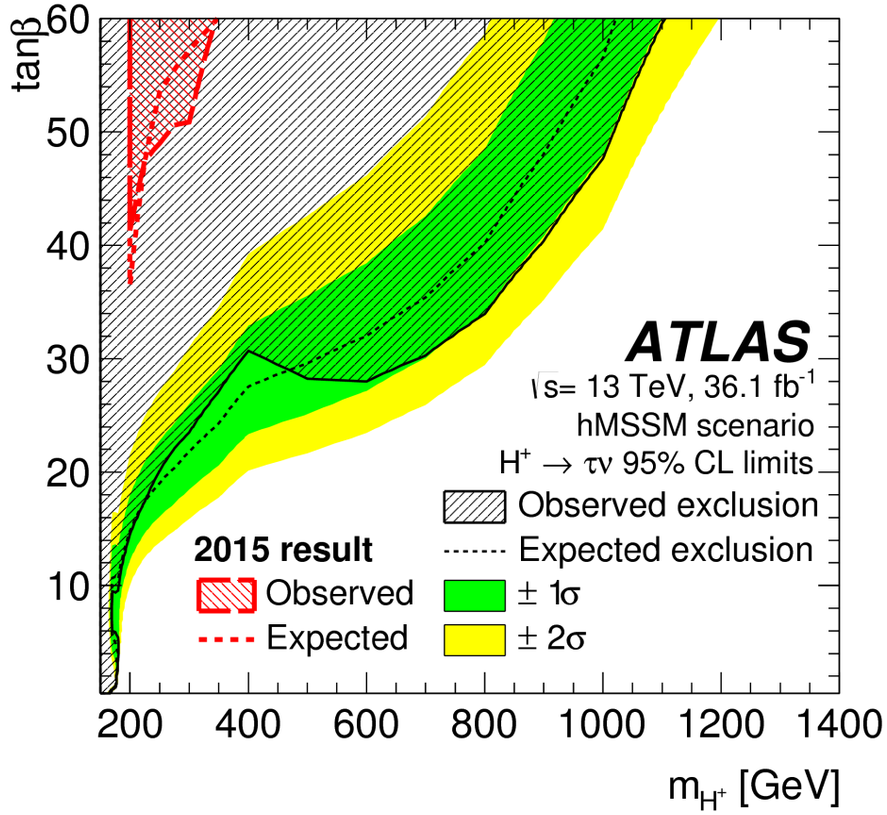
arXiv:1807.07915

$H^+ \to \tau^+ \nu$



- 13 TeV, 36.1 fb^{-1}.
- H^+ decay modes.
  - Leptonic τν: sensitive in high tanβ region.
  - Hadronic tb: sensitive in low tanβ region (arXiv:1808.03599).
- Main backgrounds:
  - $t\bar{t}$ -> MC simulation.
  - τ mis-ID -> fake factor method.
    - Main source of systematic uncertainty for low mass.
- Model independent limits on production cross section * decay branching fraction.
  - Significant improvement wrt the 2015 result.
- Interpreted in hMSSM scenario.
  - Limits on H^+ mass vs tanβ plain.
  - Significant improvement wrt the 2015 result.

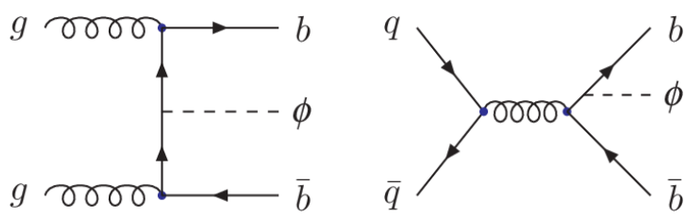




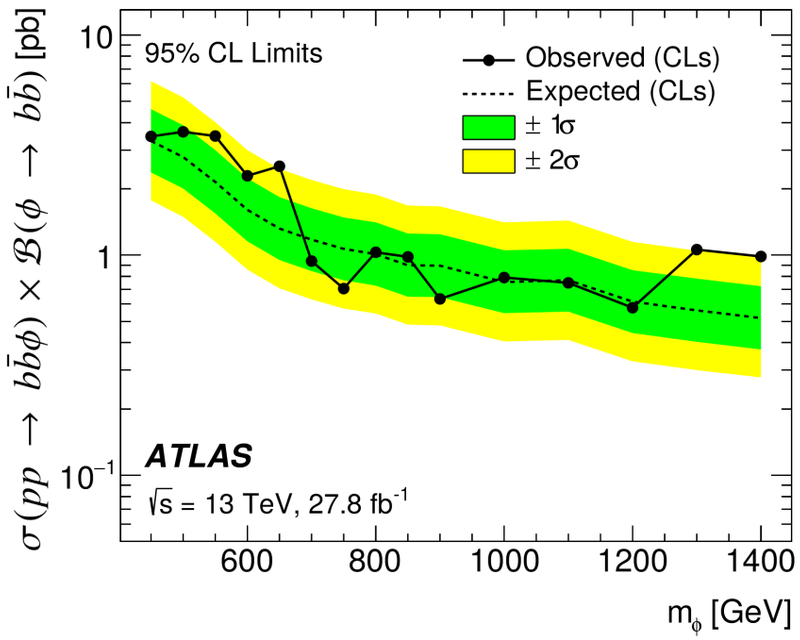
arXiv:1907.02749

Neutral Higgs -> bb

- 13 TeV, 27.8 fb^{-1}.



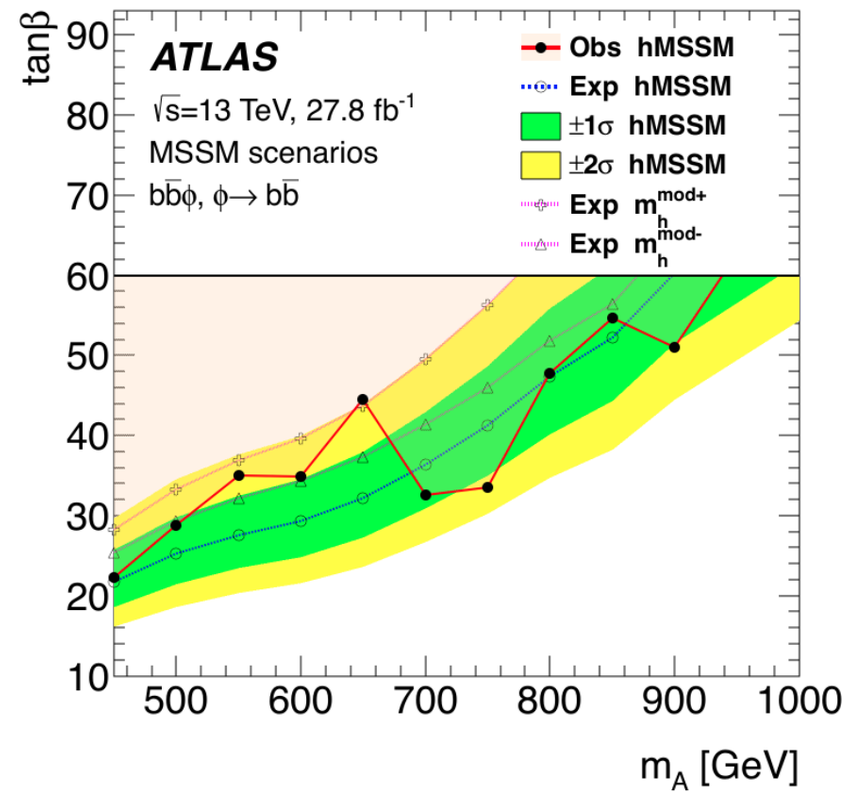
- Associate production with b-jets.
  - Decay to 2b.
  - Single or double b-jet trigger.



- Main backgrounds:
  - Multijet -> simulation.

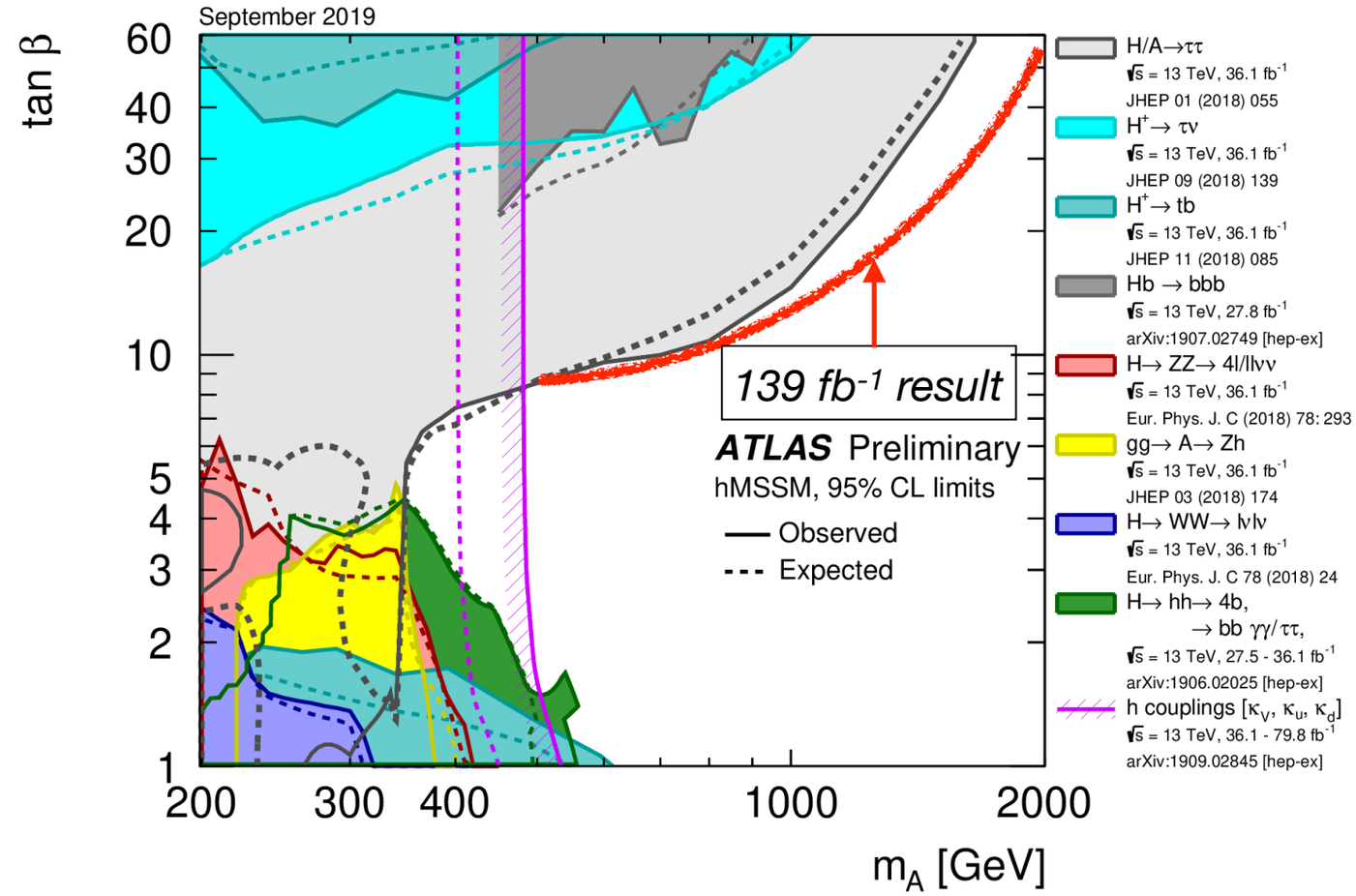
- Limits on (cross section)*(branching fraction).

- Interpreted in hMSSM scenario.
  - Limits on A mass vs tanβ plain.



Summary of hMSSM limits

- 13 TeV, 36 fb^{-1}.

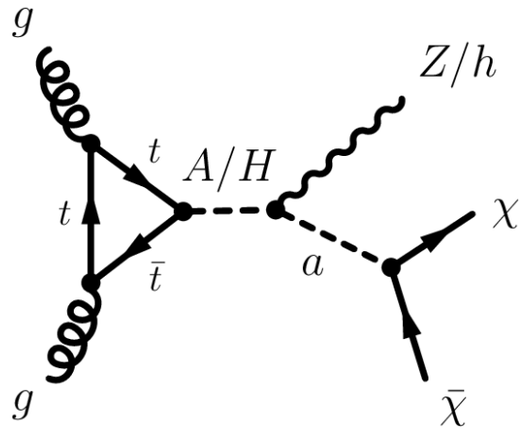


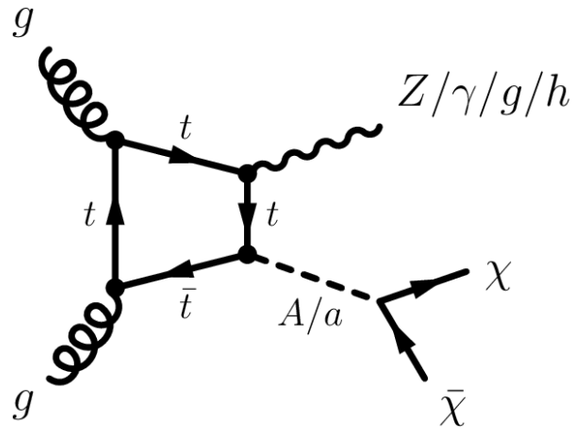
- 8 analyses are interpreted in hMSSM scenario.
  - Limits on A mass vs tanβ plain.
- Higher tanβ: dominated by $\tau^+\tau^-$.
  - New 139 fb^{-1} result is just a rough draw by hand (not official).
- Lower tanβ: dominated by hh->4b.

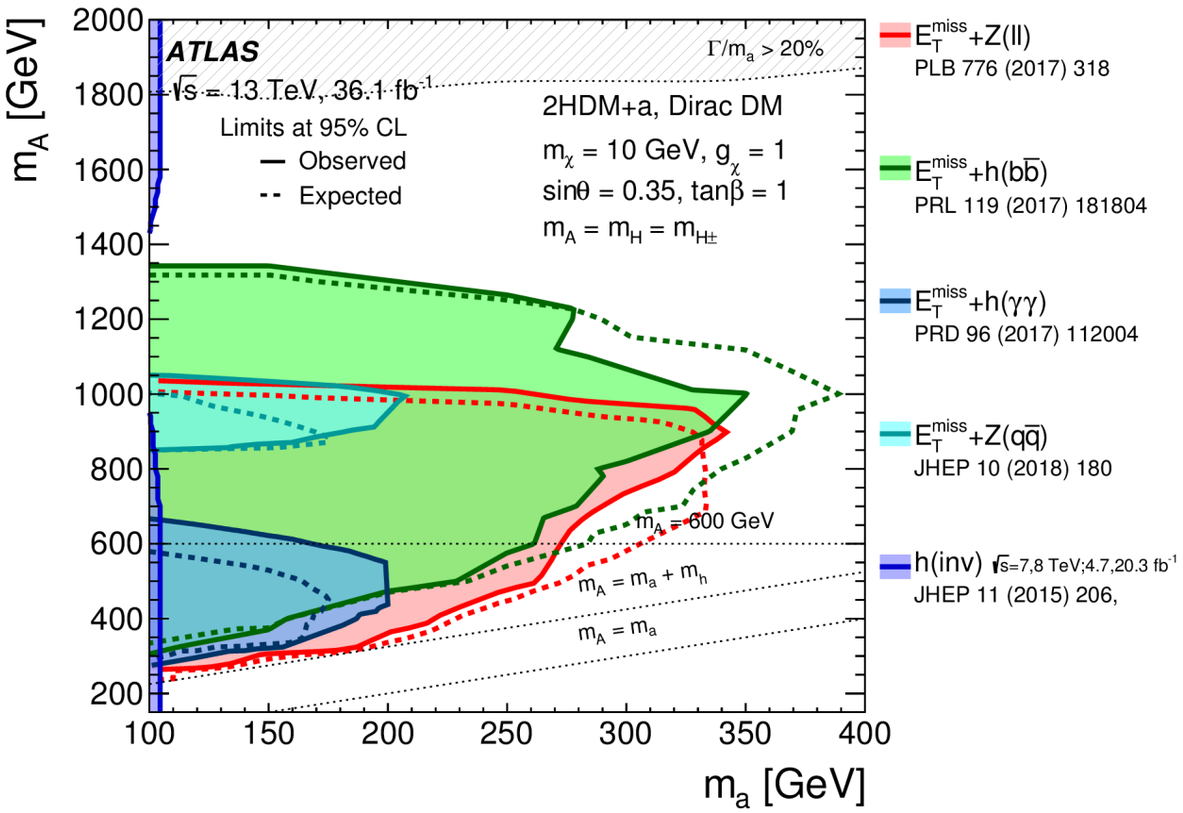
arXiv:1903.01400

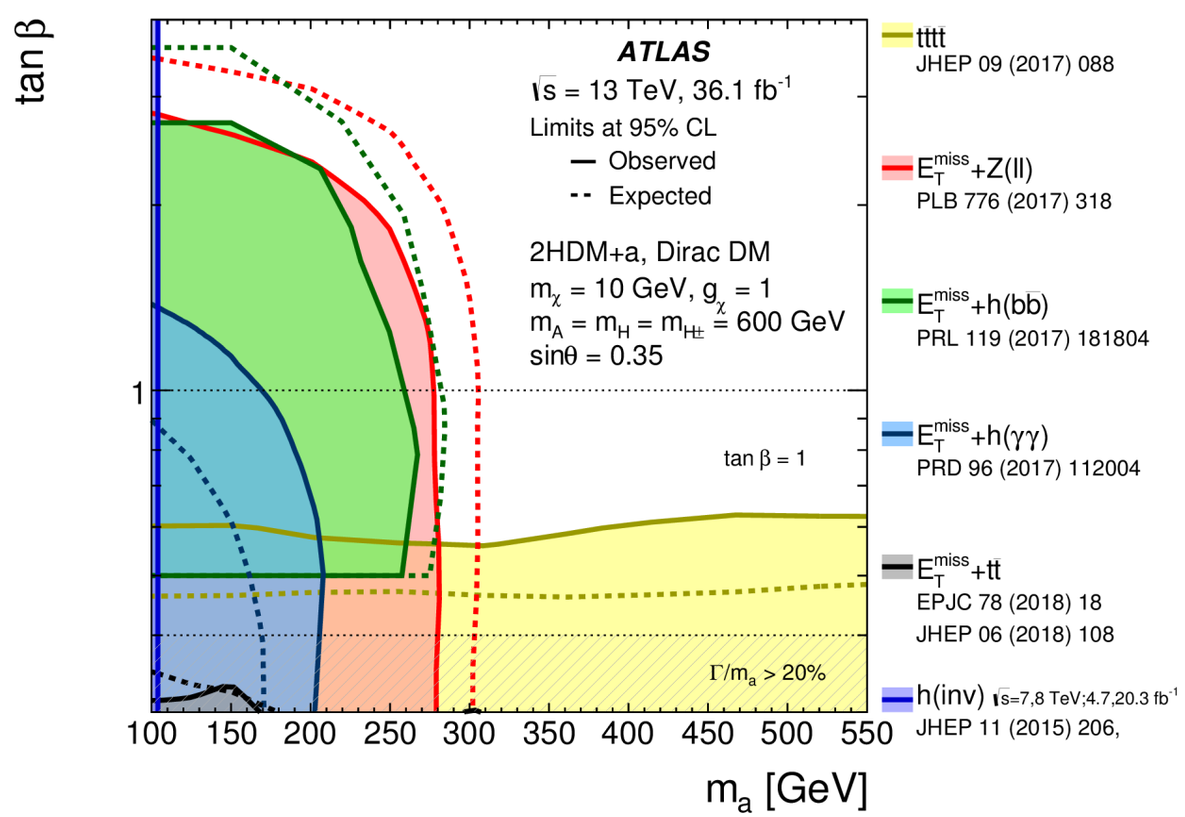
Summary of dark matter searches

- 13 TeV, 36.1 fb^{-1}.
- 2HDM + pseudo-scalar mediator model.
  - a = dark matter mediator (pseudo-scalar).
  - χ = dark matter particle.
- Limits on mass and tanβ.
  - mono-Z and mono-h channels dominate the limits.





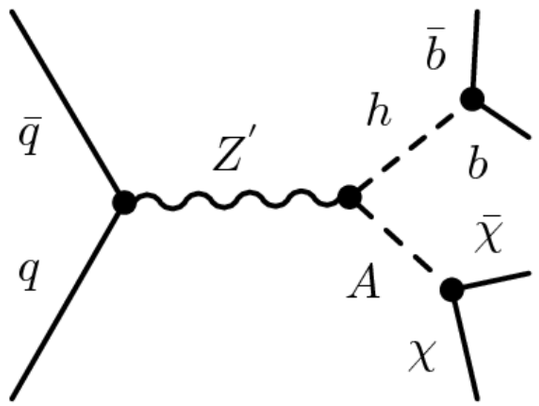


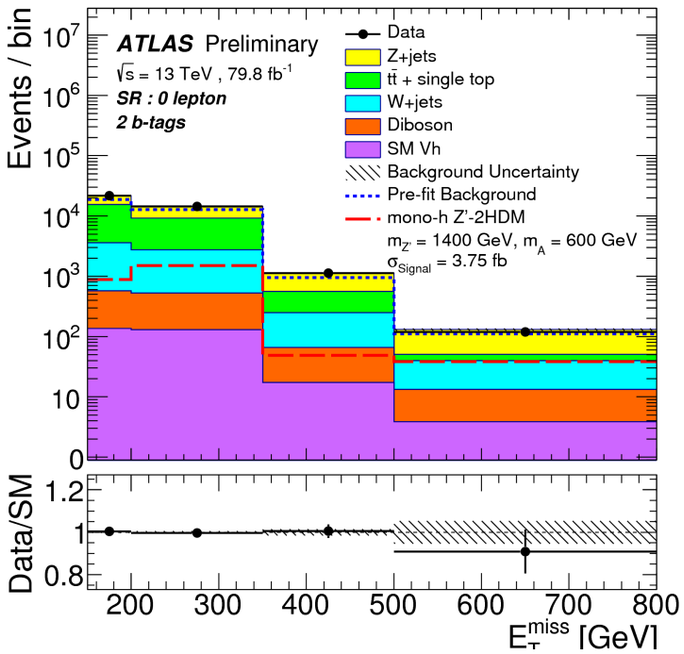


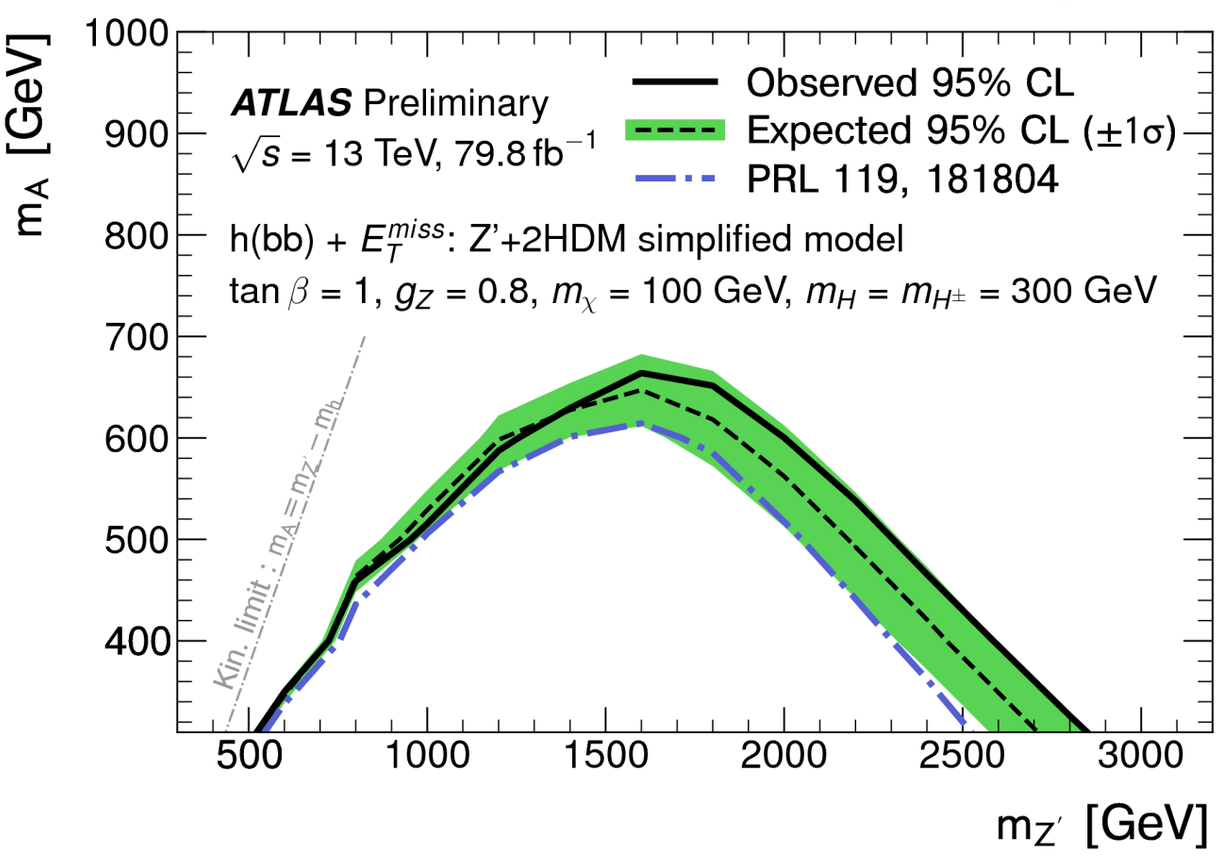
ATLAS-CONF-2018-039

Mono-H(bb) dark matter search

- 13 TeV, 79.8 fb^{-1}.
- 2HDM + vector mediator model.
  - Z’ = dark matter mediator (vector).
  - χ = dark matter particle.
- Higgs (2 b-jets) + Missing momentum (dark matter) final states.
  - Missing transverse momentum trigger.
- Limits on Z’ mass vs A mass.







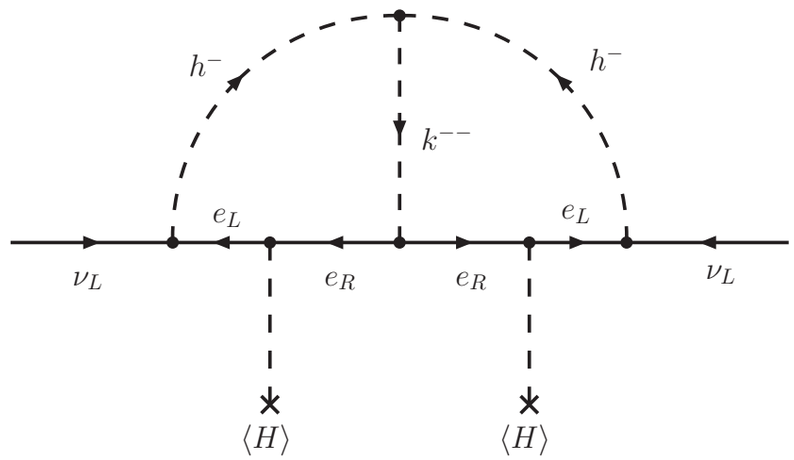
Conclusions

- Additional Higgs bosons are well motivated.
  - Dark matter, neutrino mass etc.
  - 2HDM are mainly used in ATLAS searches.
- Many decay modes were explored.
  - No additional Higgs has been found so far.
  - Limits on cross sections, branching fractions, parameter values were set.
- Only recent results were presented in details.
  - Significant improvements from previous results were achieved.

Backup: Doubly Charged Higgs

- Seesaw mechanisms:
  - Large mass of additional particles explains the smallness of neutrino masses like seesaw.
  - Type II seesaw model:
    - Additional scalar triplet -> singly and doubly charged scalars.

- Radiative neutrino mass models:
  - Generate neutrino mass by loop diagram
  - Zee-Babu model:
    - Additional singly and doubly charged scalars.

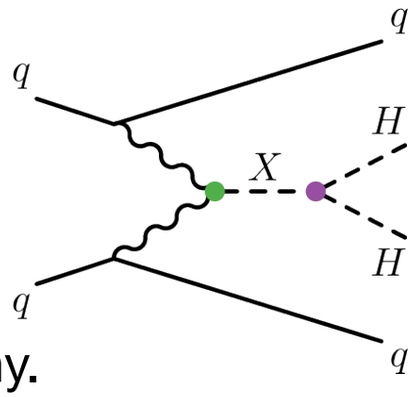


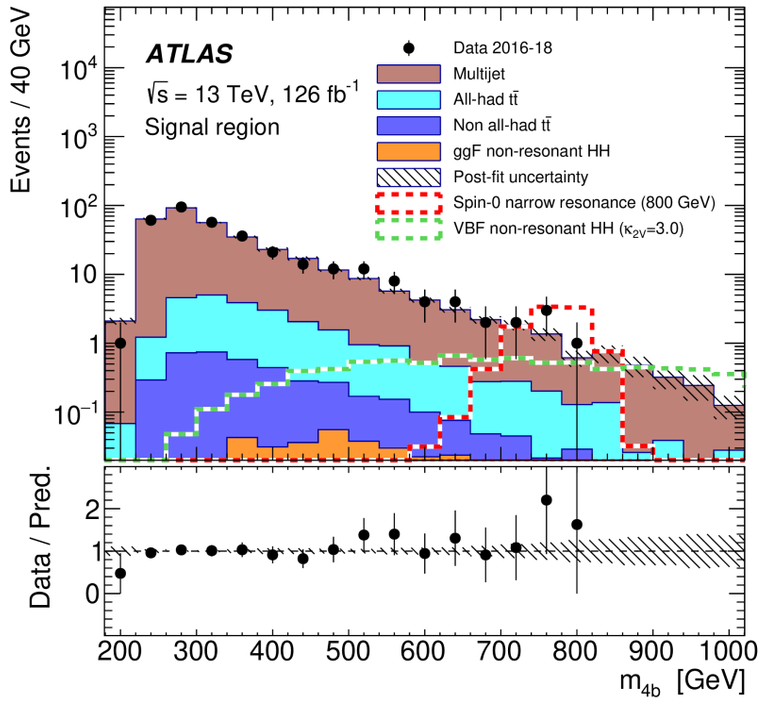
arXiv:0711.0483 [hep-ph]

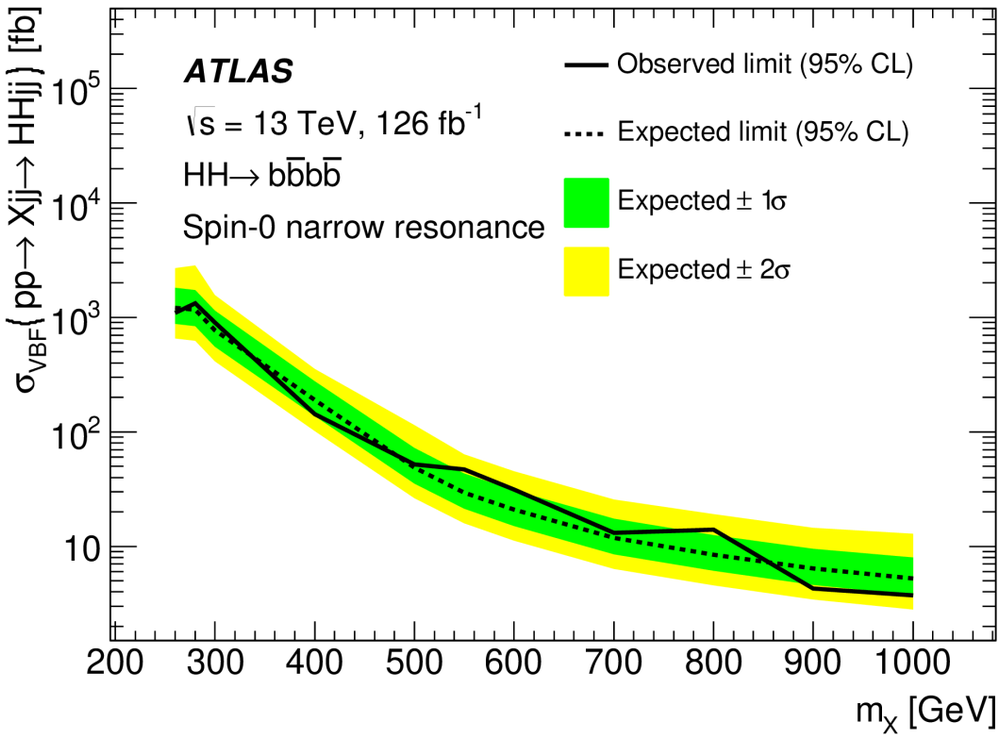
arXiv:2001.05178

Backup: Neutral Higgs -> hh -> 4b

- 13 TeV, 126 fb^{-1}.
- Higgs -> hh is rare in SM.
  - BSM contribution can be significant if any.
  - This analysis consider only VBF production.
    - b-jet triggers are used.
  - ggF production was done in arXiv:1906.02025 with 36.1 fb^{-1}.
- Main backgrounds:
  - Multijet (95%) -> data-driven. Derived from 2b+2j control region.
    - m(2b) vs m(2b) distributions are used to suppress this background.
    - Dominant source of the systematic uncertainty.
  - $t\bar{t}$ (5%) -> MC simulation.
- Limits on the cross section is set.



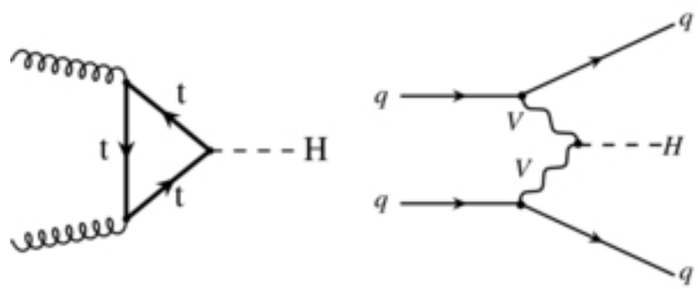




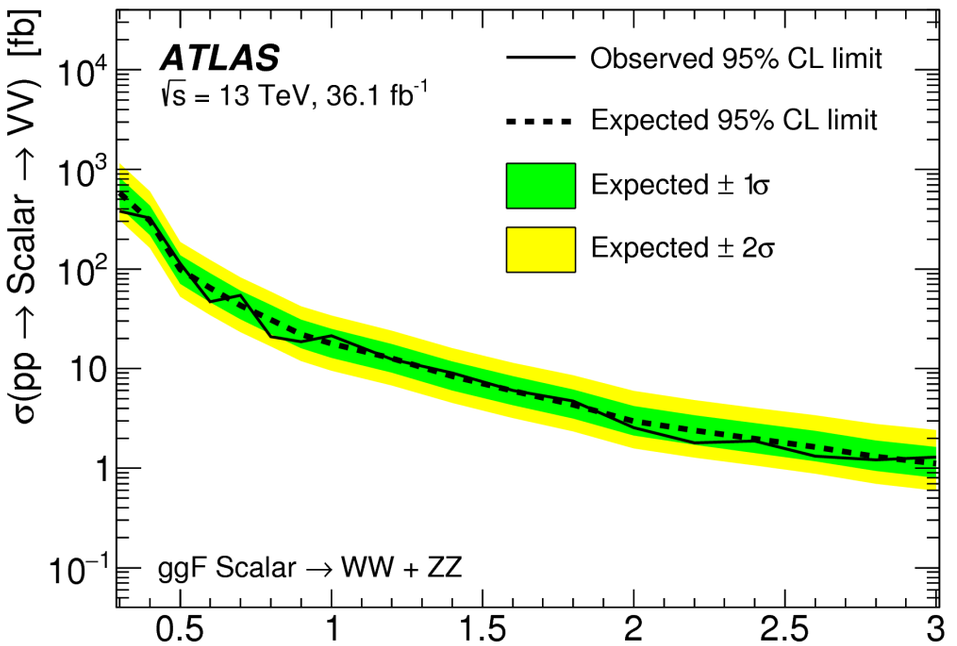
arXiv:1808.02380

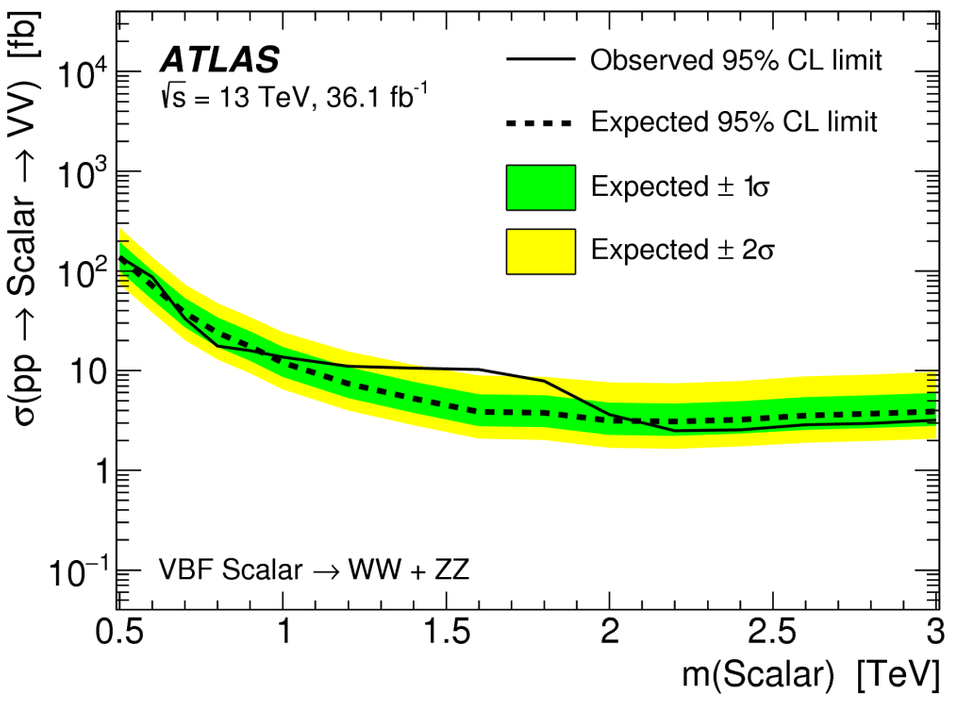
Backup: Neutral Higgs -> ZZ, WW

- 13 TeV, 36 fb^{-1}.



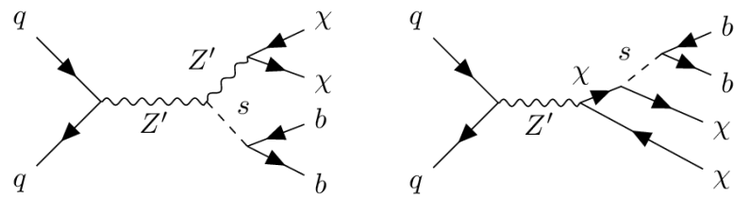
- Combine 8 ZZ and WW resonance searches.
  - WW -> qqqq, lvqq, lvlv
  - ZZ -> qqqq, vvqq, llqq, llvv, llll
- Set limits on cross sections.





Backup: Dark Higgs search

- 13 TeV, 79.8 fb^{-1}.



- RECAST: Apply a new model to an existing analysis
  - Original analysis (ATLAS-CONF-2018-039):
    - Mono-H(bb) dark matter search.
  - New model:
    - Dark Higgs boson s -> 2b.
      - Dominant decay mode at low mass (m_s < 150 GeV).
    - Vector mediator Z' -> 2χ.
- Limits on (cross section)*(branching fraction).
- Limits on mediator mass vs dark Higgs mass.