Searches for BSM Higgs at ATLAS

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On behalf of the ATLAS Collaboration

WIN2021 | University of Minnesota
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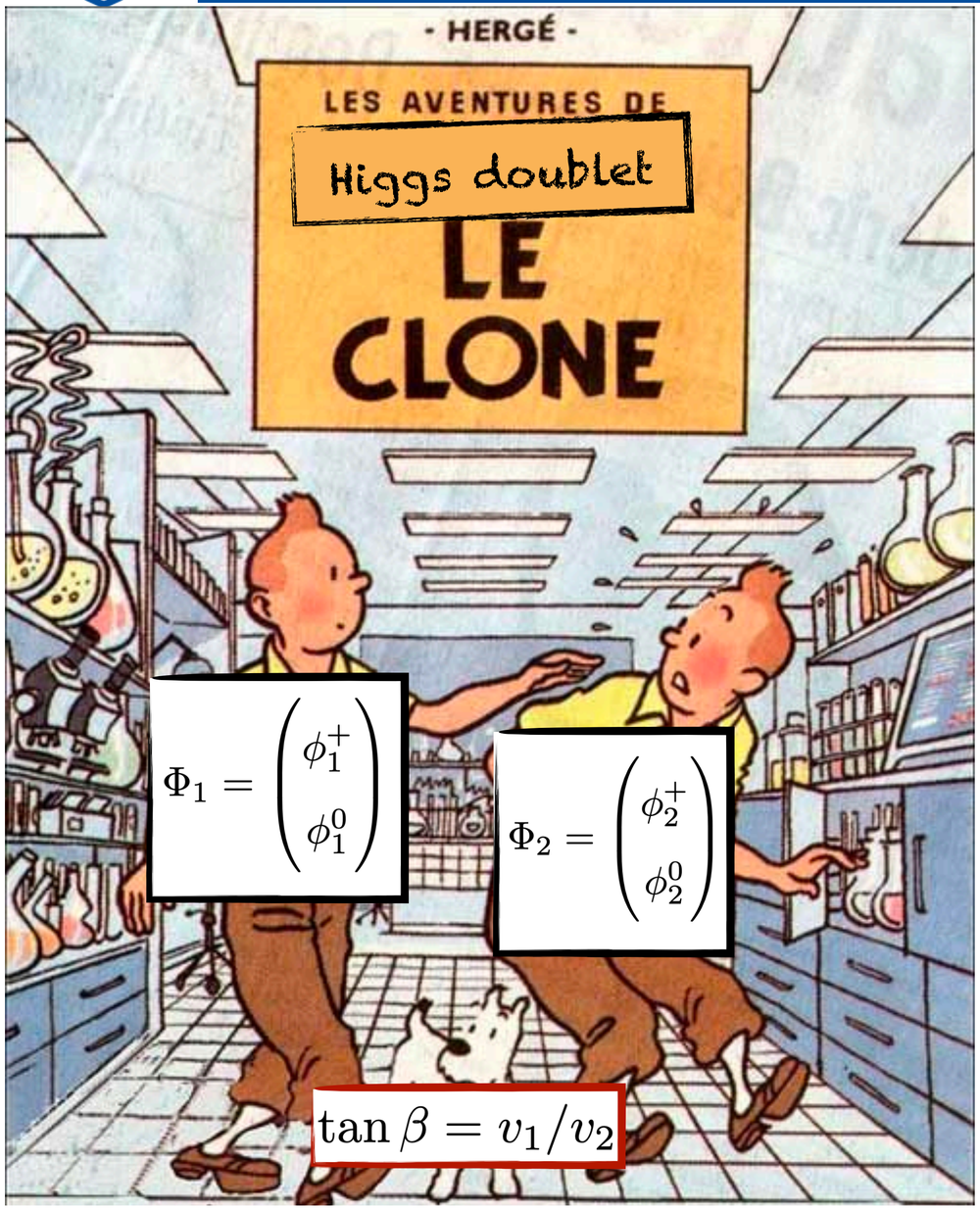
University of Pittsburgh

ATLAS EXPERIMENT

Direct searches for BSM Higgs



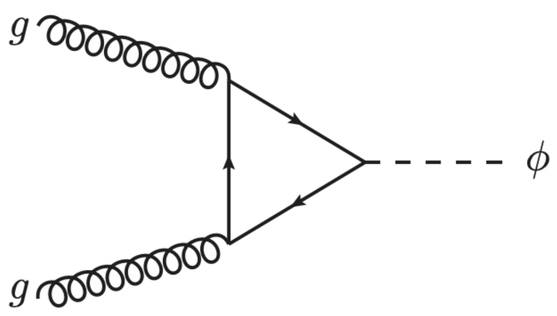
- In most extensions of the SM, the Higgs doublet must also be extended.
- Benchmark models: two Higgs doublet model (2HDM).
  - Minimal extension of the SM Higgs sector.
  - Predicting CP-even h and H, CP-odd A, and singly charged $H^{+/-}$.
  - Four ways/types(I, II, III, IV) for the doublet coupling to SM fermions.
- Other extensions: Higgs triplet models (HTM)
  - Appearance of doubly-charged Higgs bosons $H^{++/--}$.
- Rich phenomenology and final states.
  - Production and decay largely depending on: coupling types, targeting mass and tanβ...

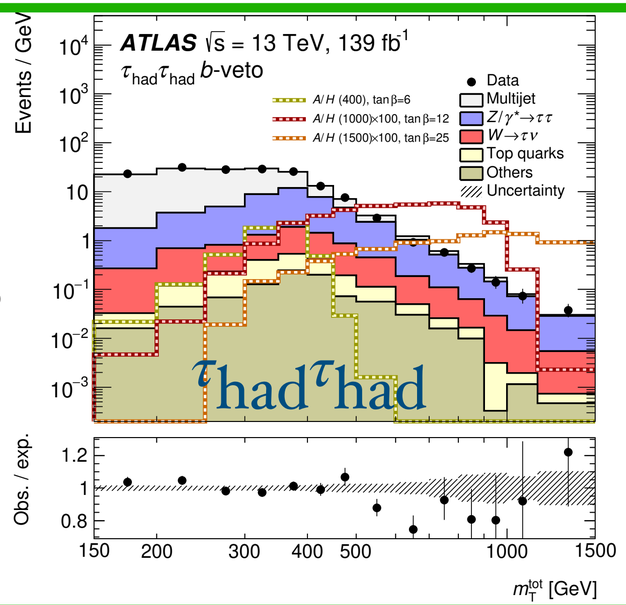
Neutral heavy Higgs $A/H \to \tau\tau$

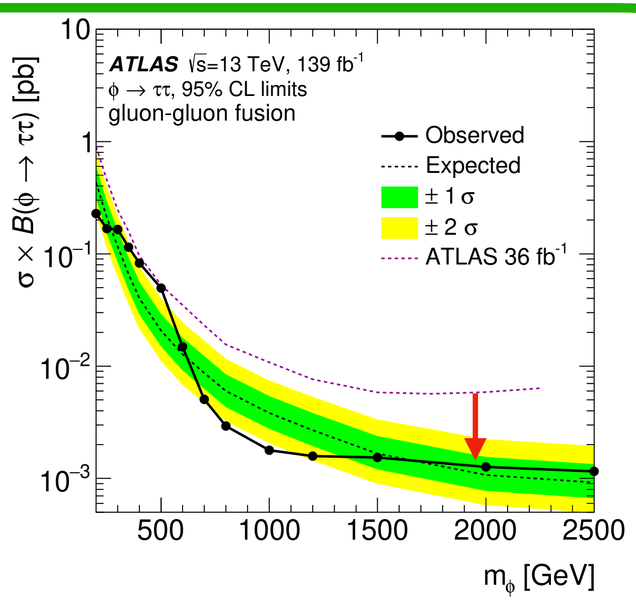
PRL 125(2020) 051801
139 fb^{-1}

- Dominant decay mode with large mass and large tan β.
- Consider both $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$ channels.

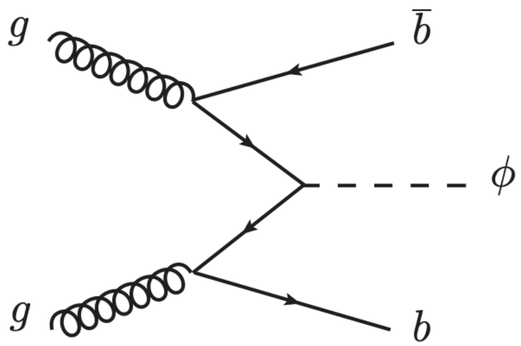
b-veto regions

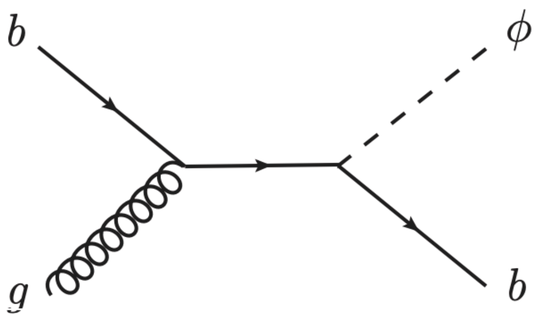


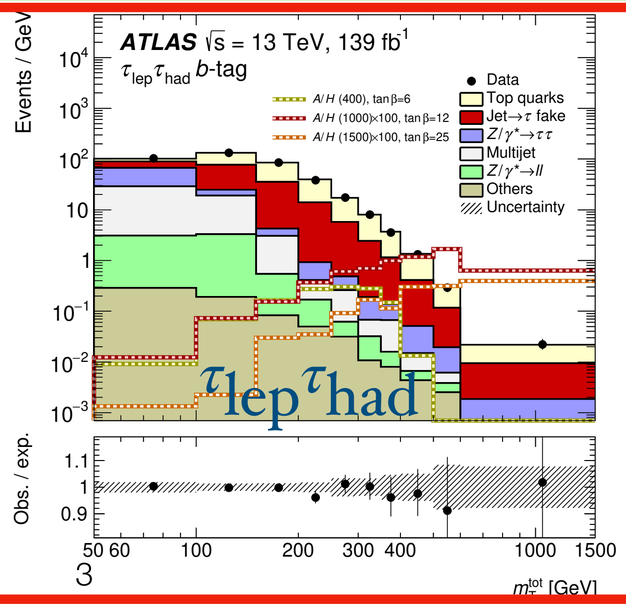


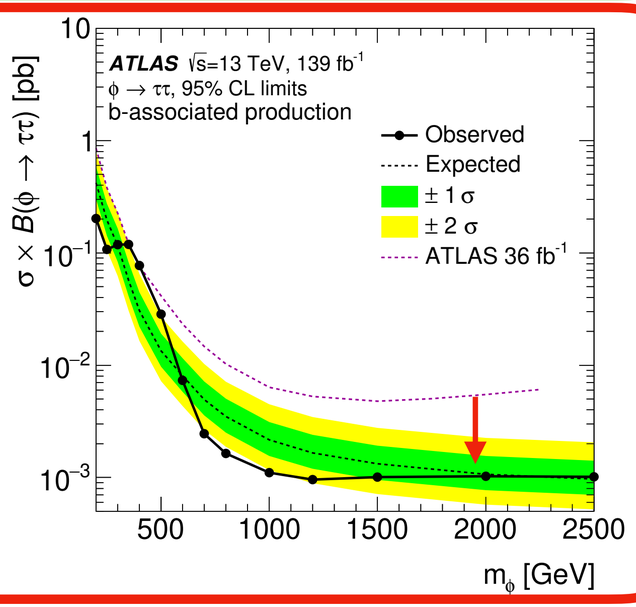


b-tag regions









Neutral heavy Higgs $A/H \to \gamma\gamma$

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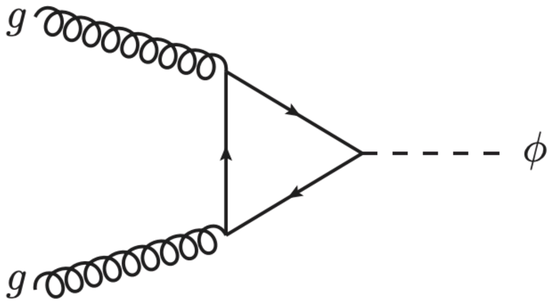
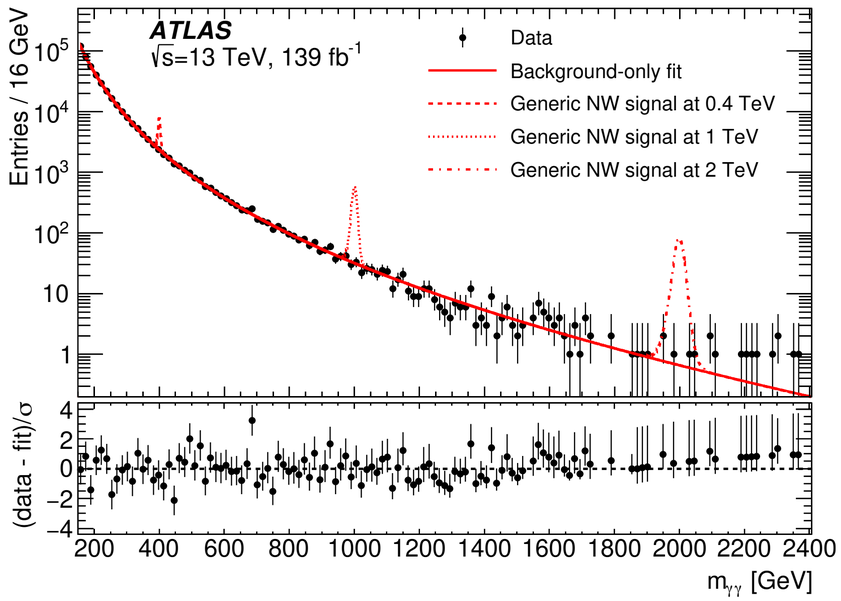
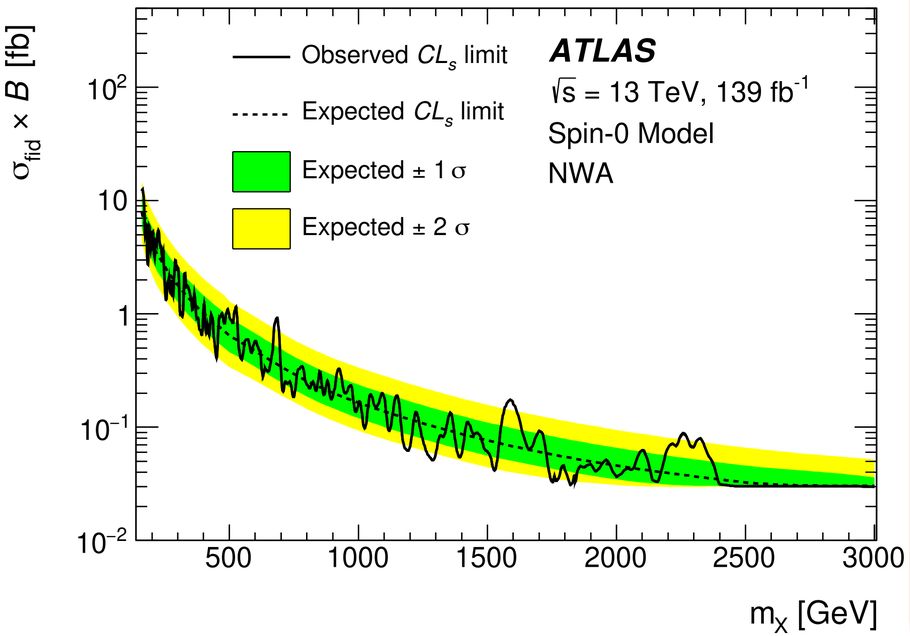
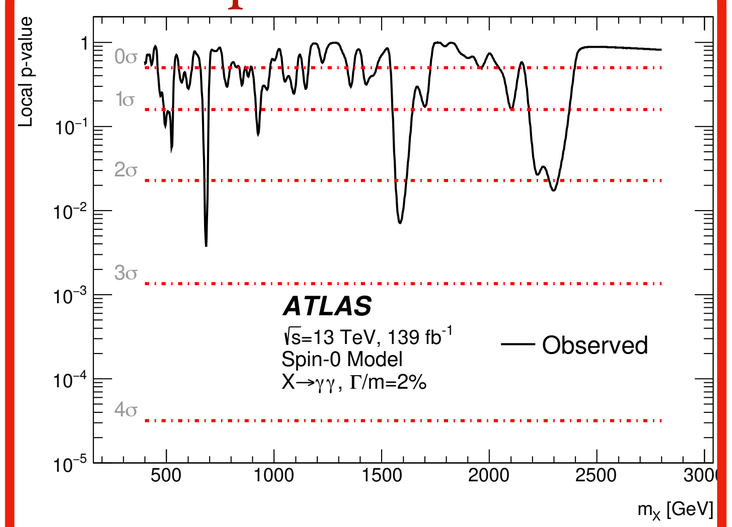
- Using diphoton invariant mass as discriminator.
  - Excellent resolution of diphoton pair.
- Limits provided in terms of fiducial cross-section.
- Sensitivity largely dependent on the decay width.

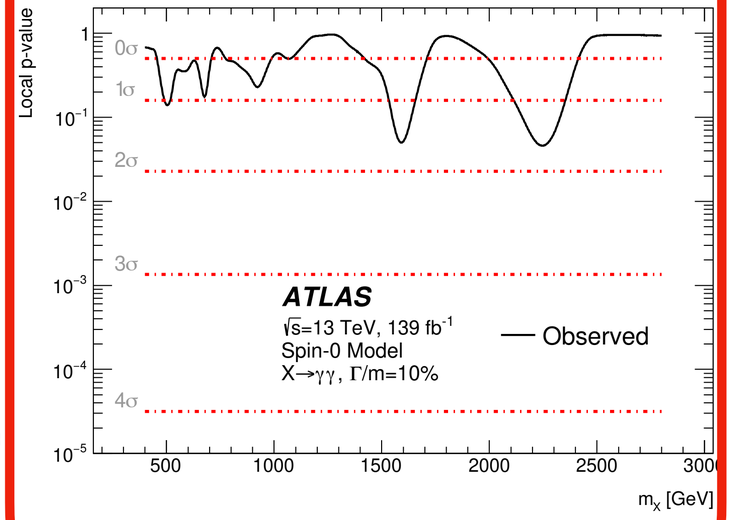






p-value scan





Singly-charged $H^+ \to tb$

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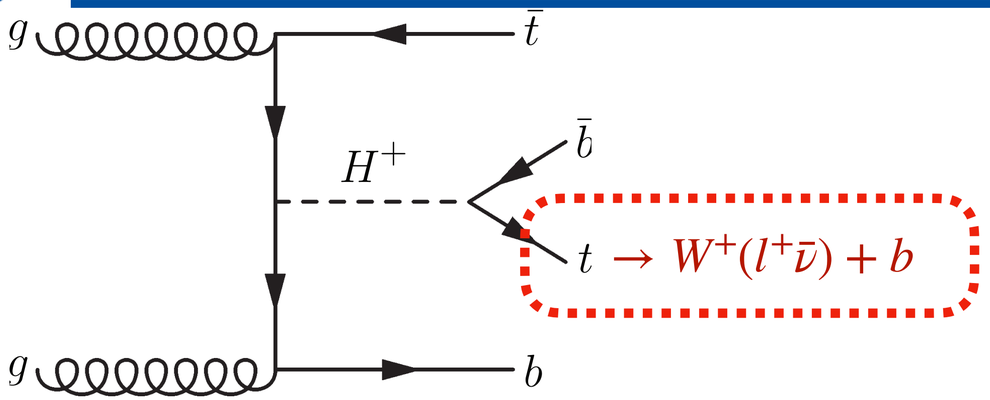
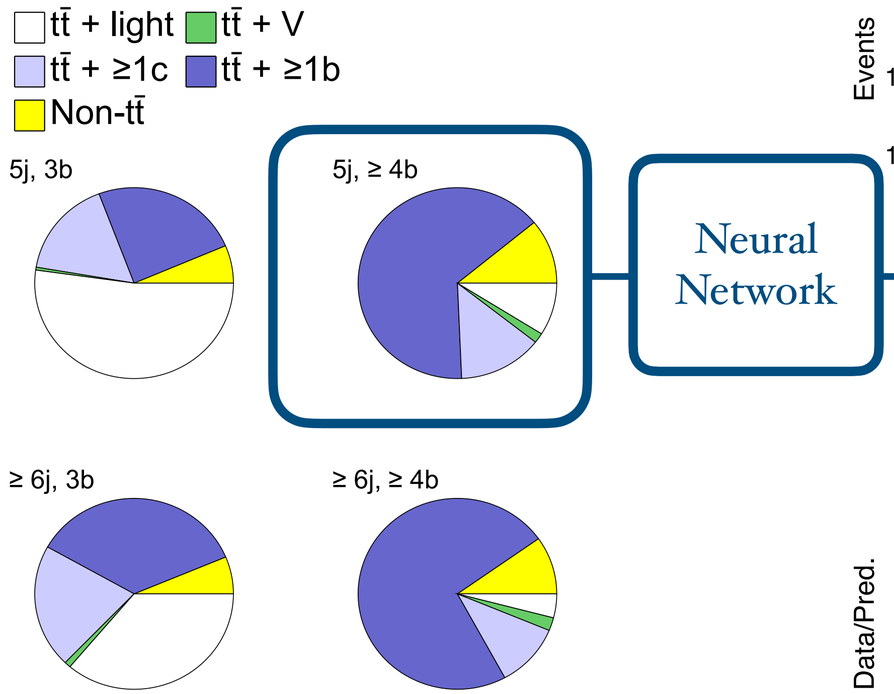
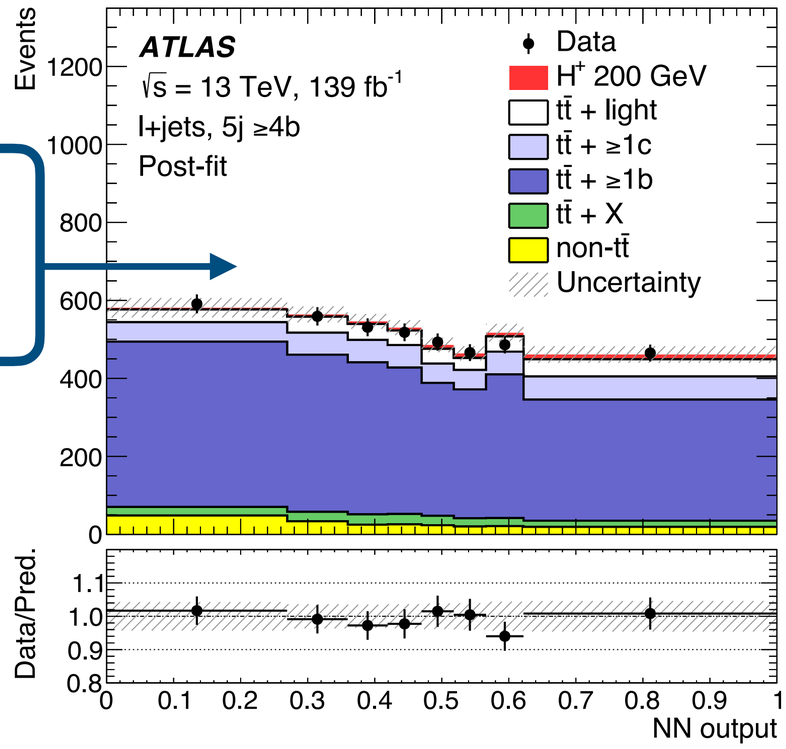


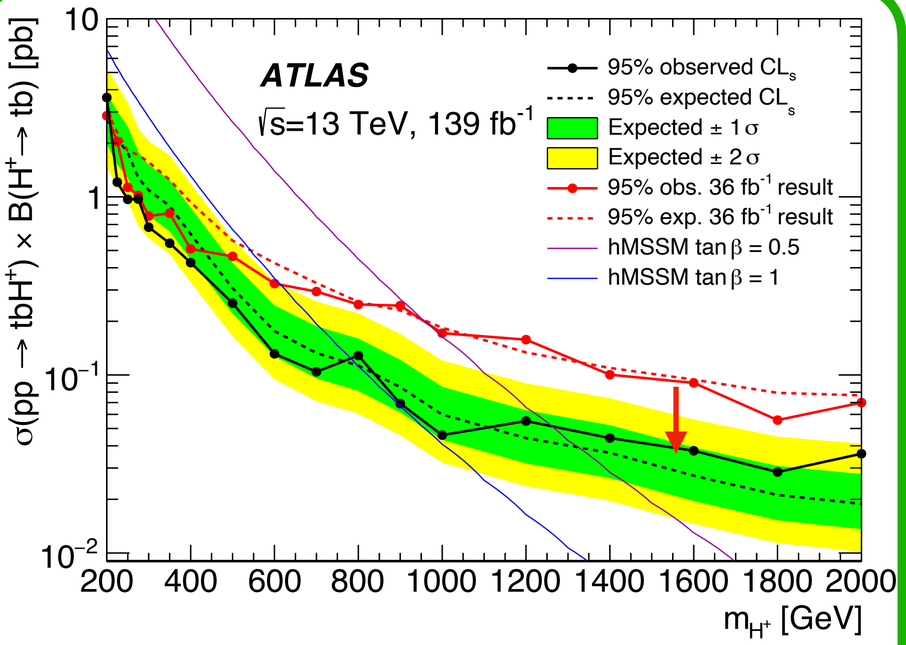
- Important channel for H^+ searches, especially high mass.
- Feature: one triggered lepton + many jets.
  - Categorised by the jet and b-jet multiplicities.
- Dedicated NN trained as final discriminant.



Neural Network



Main background: tt+jets



Much better sensitivity with larger dataset and analysis improvement.

Doubly-charged $H^{++} \to W^+W^+$

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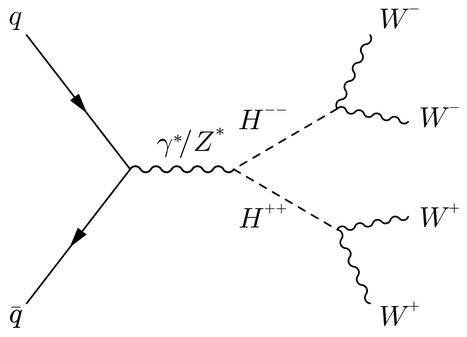
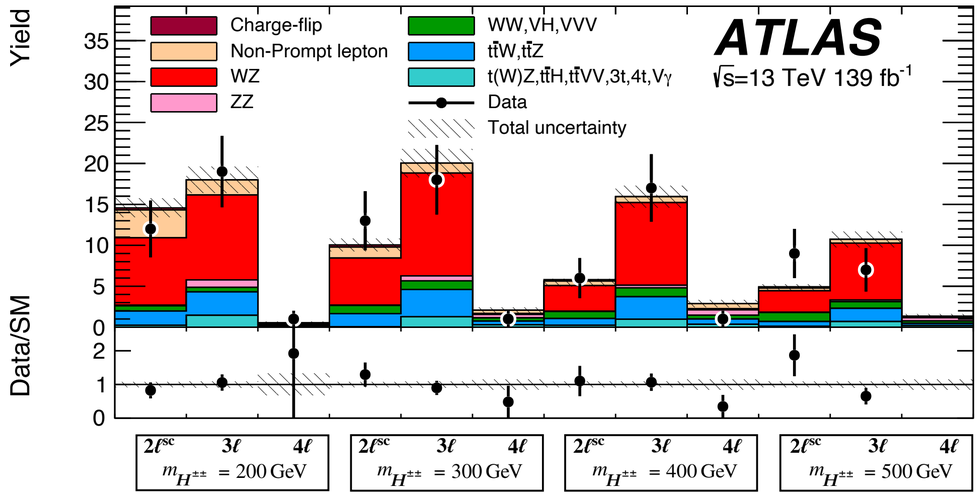
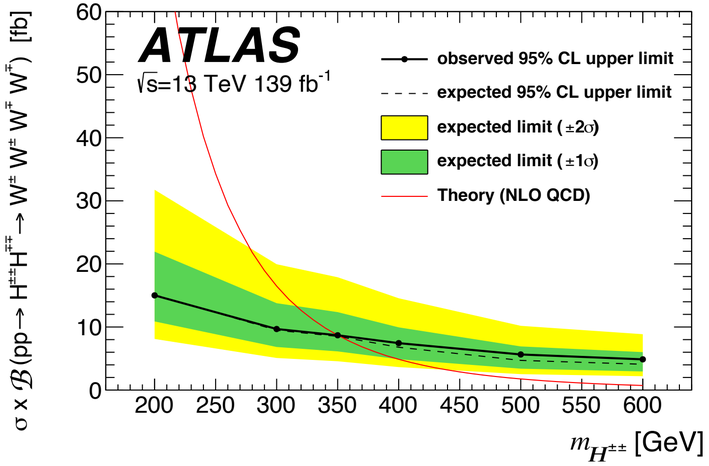
Pair production

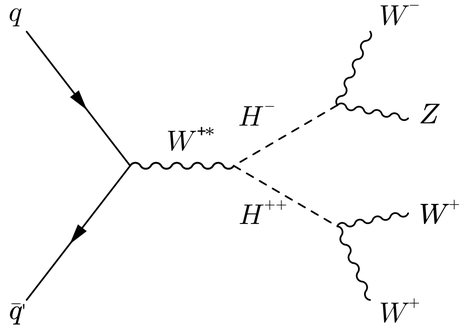


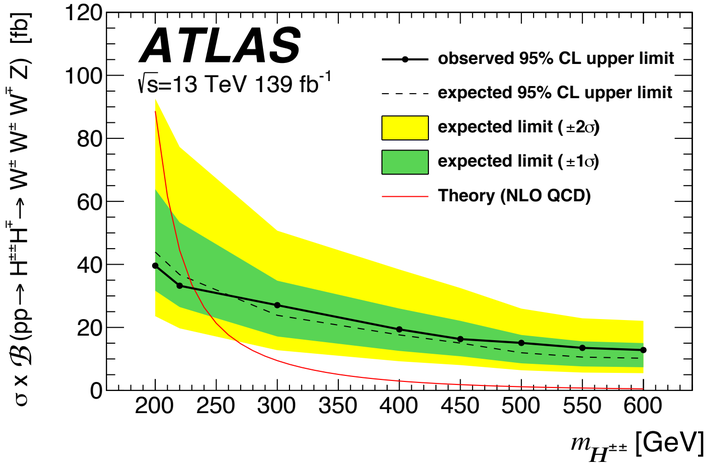
- Signal regions:
  - Three channels, based on lepton multiplicities: 2l same-sign charged, 3l,4l.
  - Further kinematic requirements for different signal mass target.





Associated production





Putting all pieces together..

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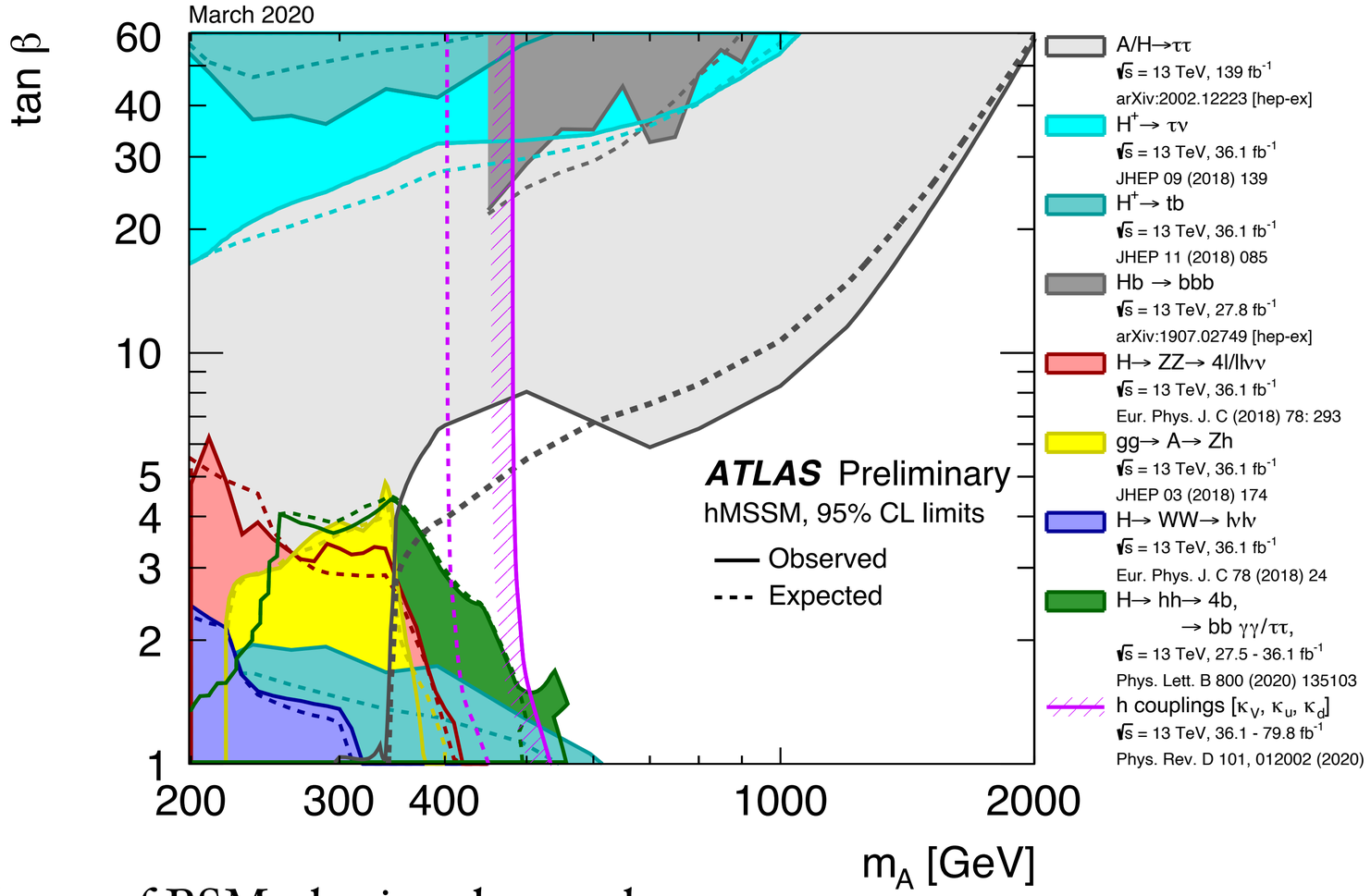
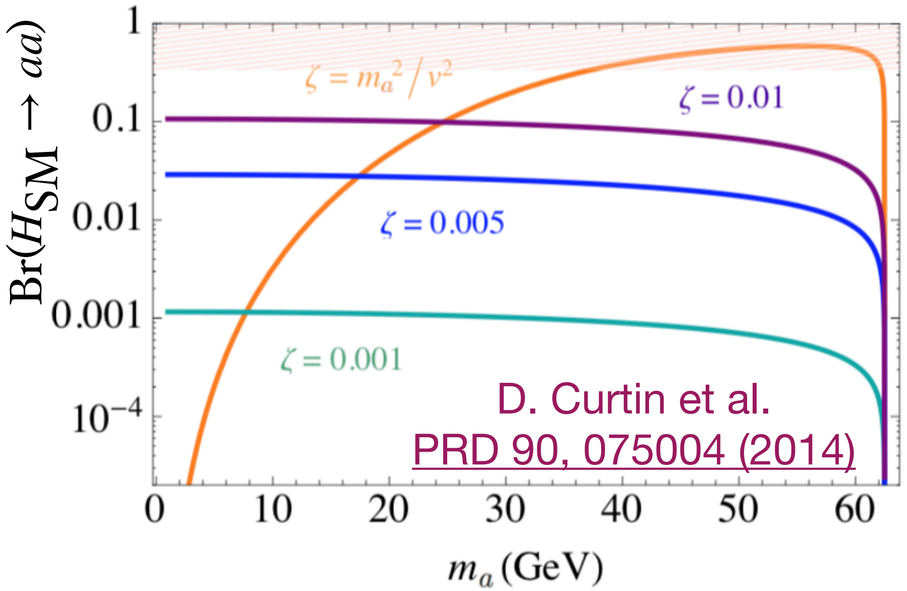


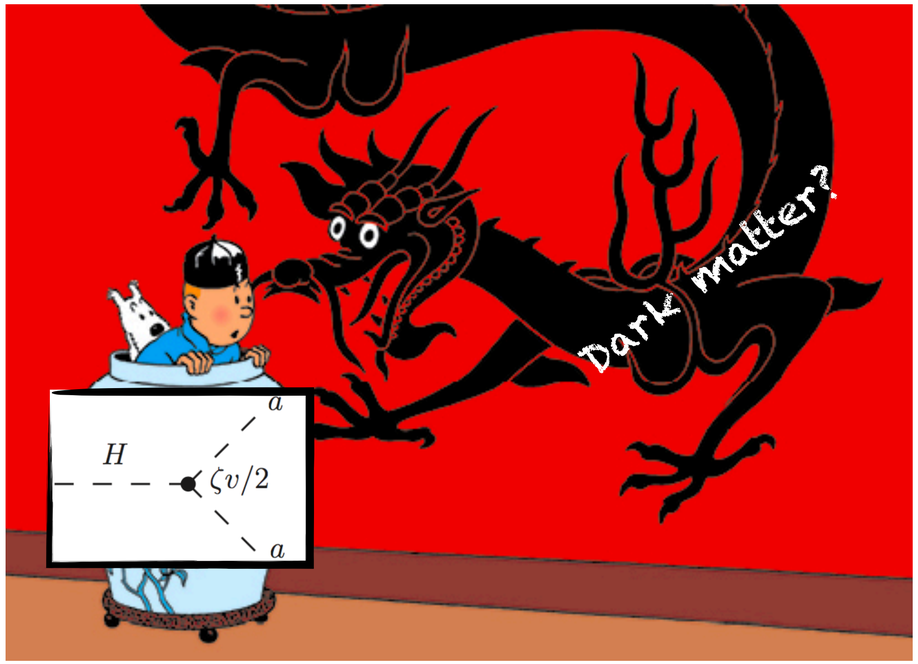
- So far no evidence of BSM physics observed...
- Large region of 2HDMs and HTPs parameter space $[m_A, \tan\beta]$ are now excluded.

Something hidden behind the SM Higgs?

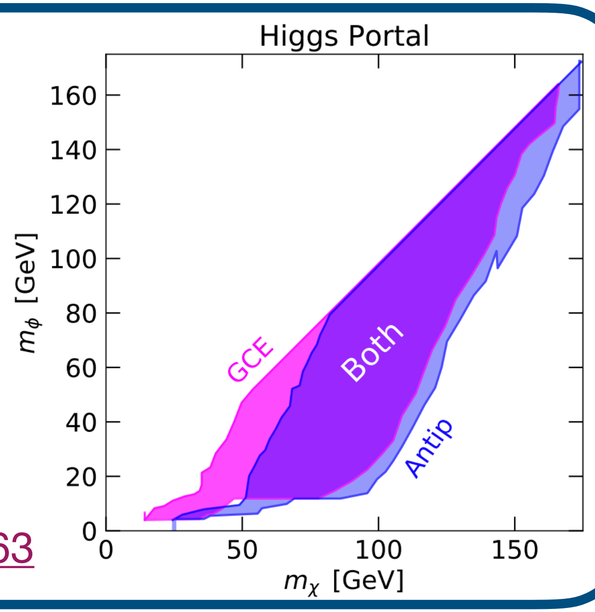
- A hidden sector that can decay SM through mass mixing with the SM Higgs boson.
- Simple example: two-Higgs-doublet plus singlet model (2HDM+S).
  - Predicting light pseudoscalar a with mass range in 0 to $\frac{m_h}{2}$.
  - Four types of coupling to SM fermions, just as 2HDM.
  - Candidate of dark matter mediator.



D. Curtin et al.
PRD 90, 075004 (2014)



- Explanation of anomalous observed in astrophysics:
  - Fermi-LAT observed gamma-ray excess at the galaxy center (GCE).
  - Anti-proton access in cosmic rays (Antip).



D. Hooper et al.
JHEP 2020 (2020) 163

Higgs to 4*b*

PRD 102 (2020) 112006
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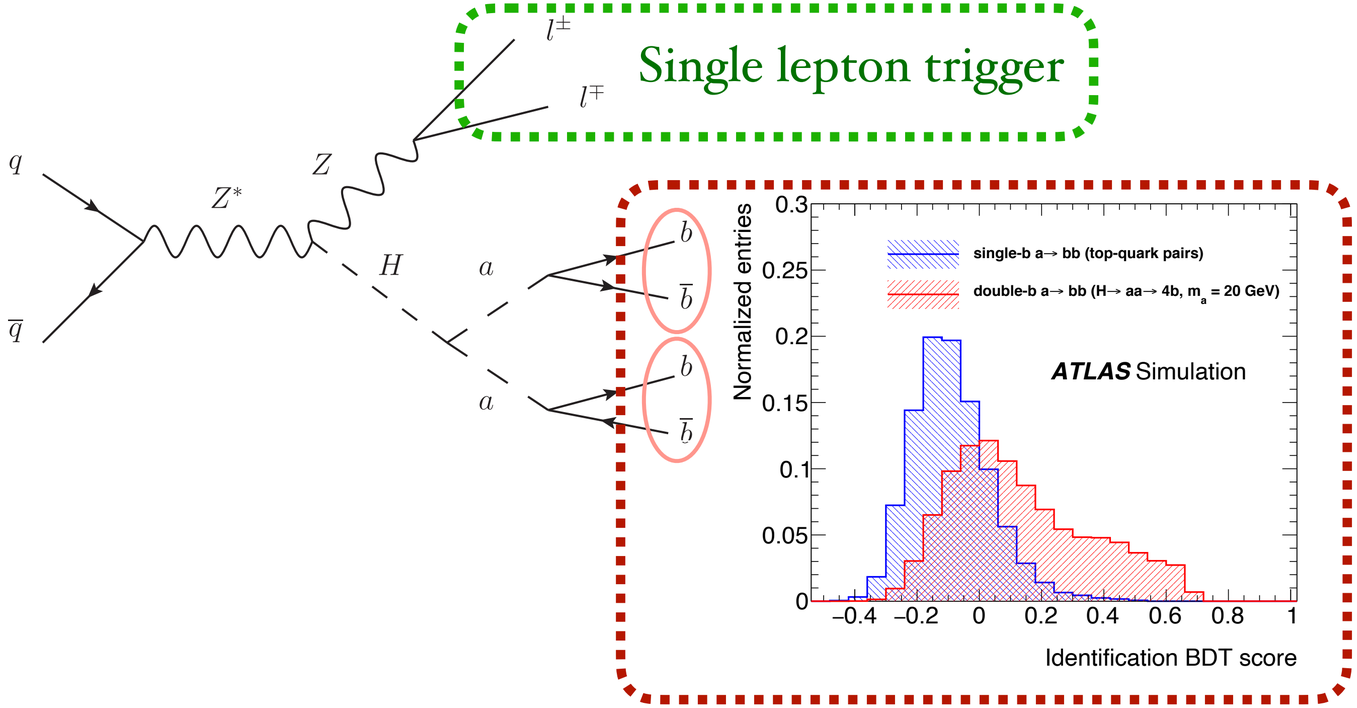

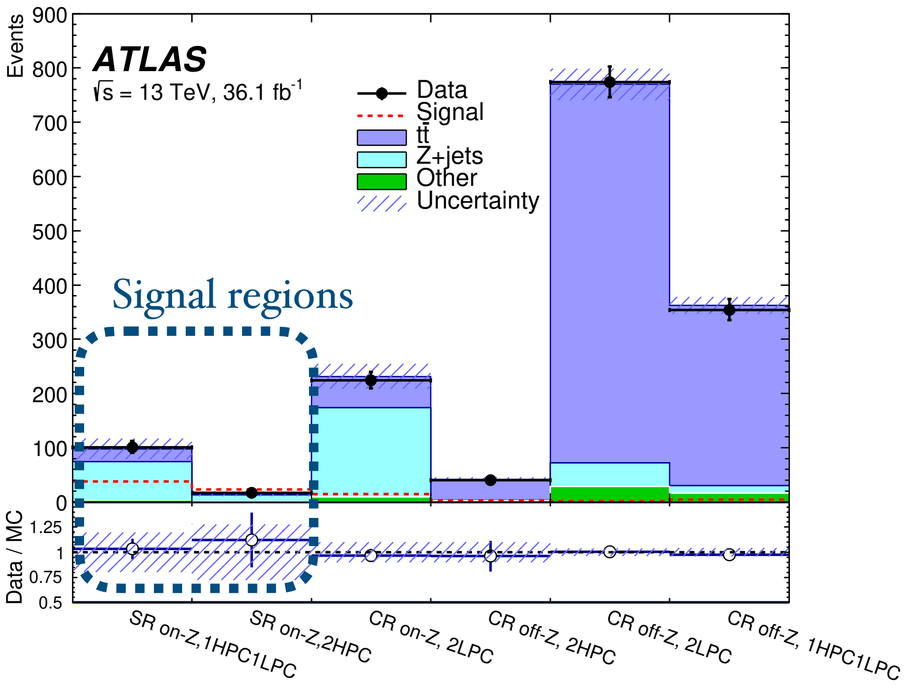

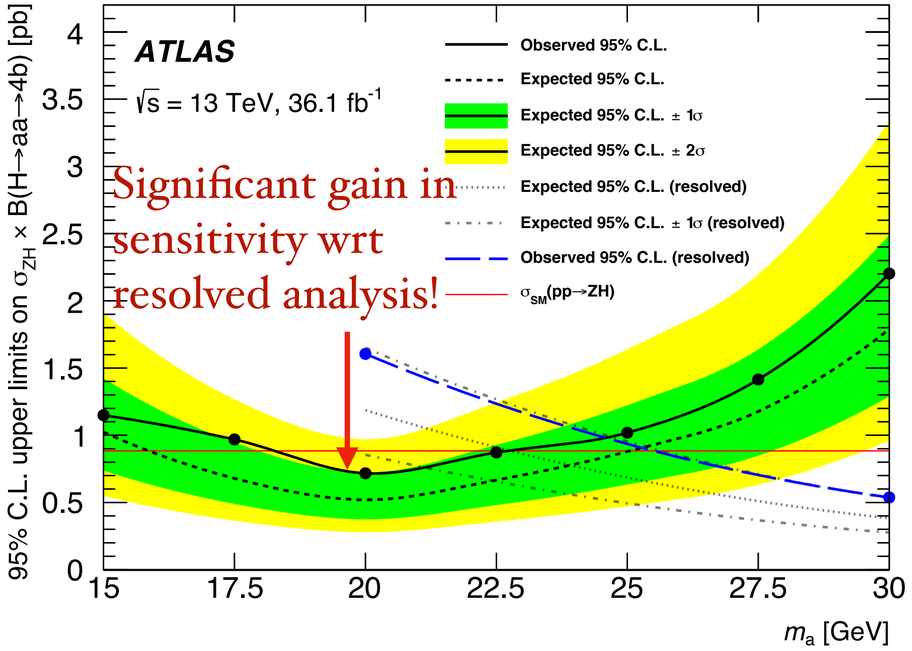

- Largest branching ratio for many scenarios.
- Focusing on ZH production mode.
  - Able to trigger by leptons.
- Dedicated strategy for low p_T $a \to bb$ tagger using multivariable BDT.
  - Two signal regions (high/low purity category HPC/LPC) designed for two different BDT working points.

Higgs to $bb\mu\mu$

ATLAS-CONF-2021-009
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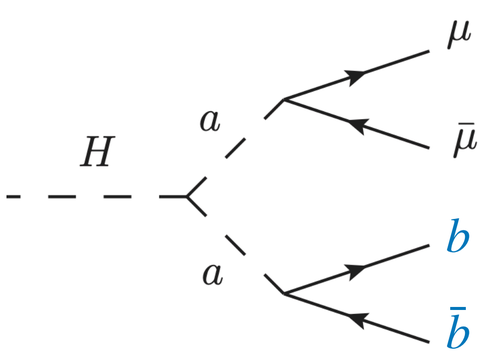
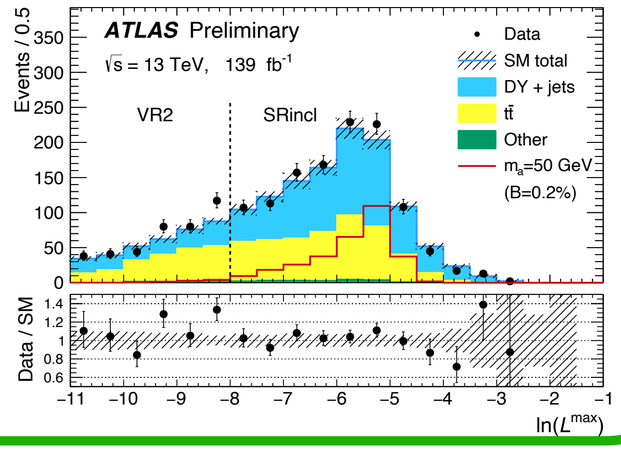
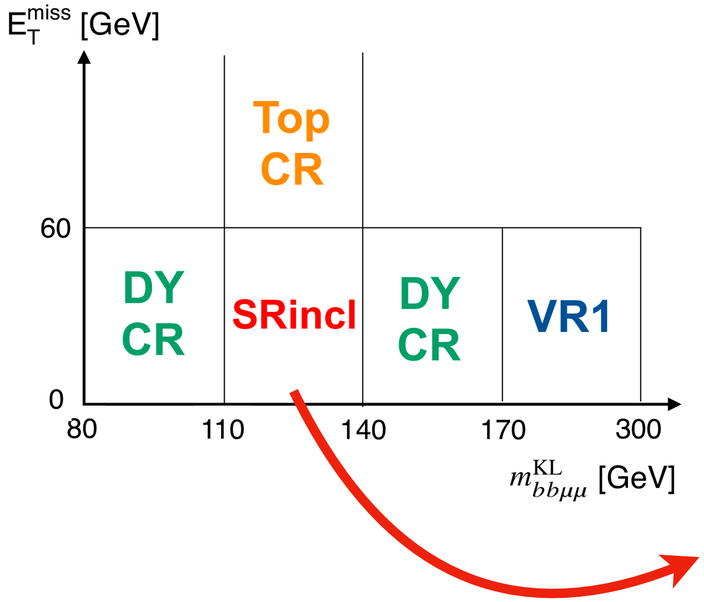
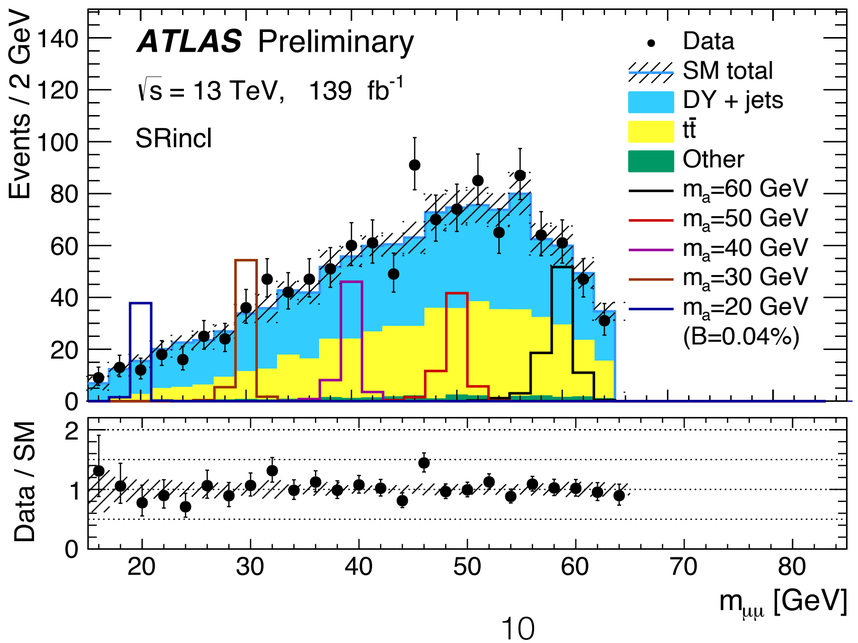
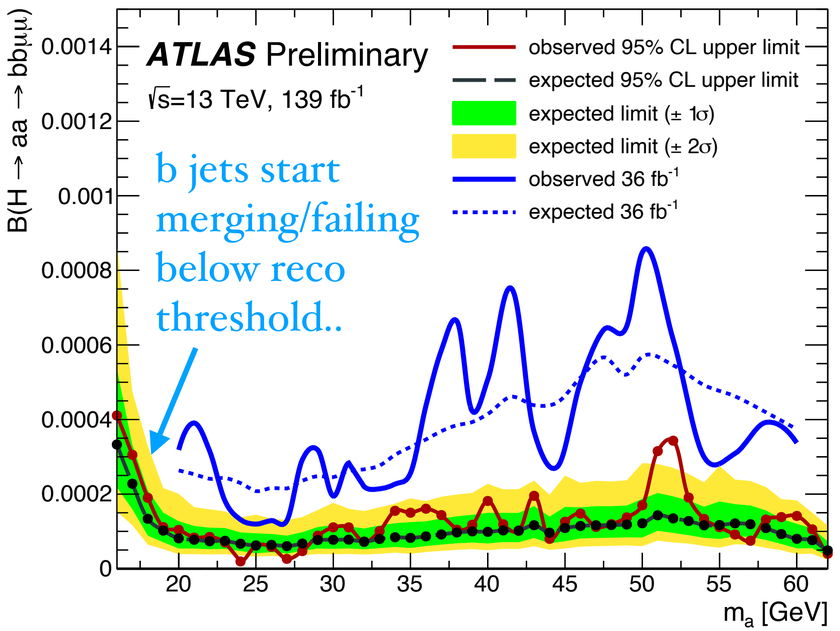
- Benefit from large Br($a \to bb$) and clean $a \to \mu\mu$ signature.
- Using m_{bb} and $m_{\mu\mu}$ in a kinematic-likelihood (KL) fit.
  - Cut on $\ln(L^{\max}) > -8$ to select event with $m_{bb} \approx m_{\mu\mu}$.











Higgs to $Z(ll)a(jj)$

PRL 125 (2020) 221802
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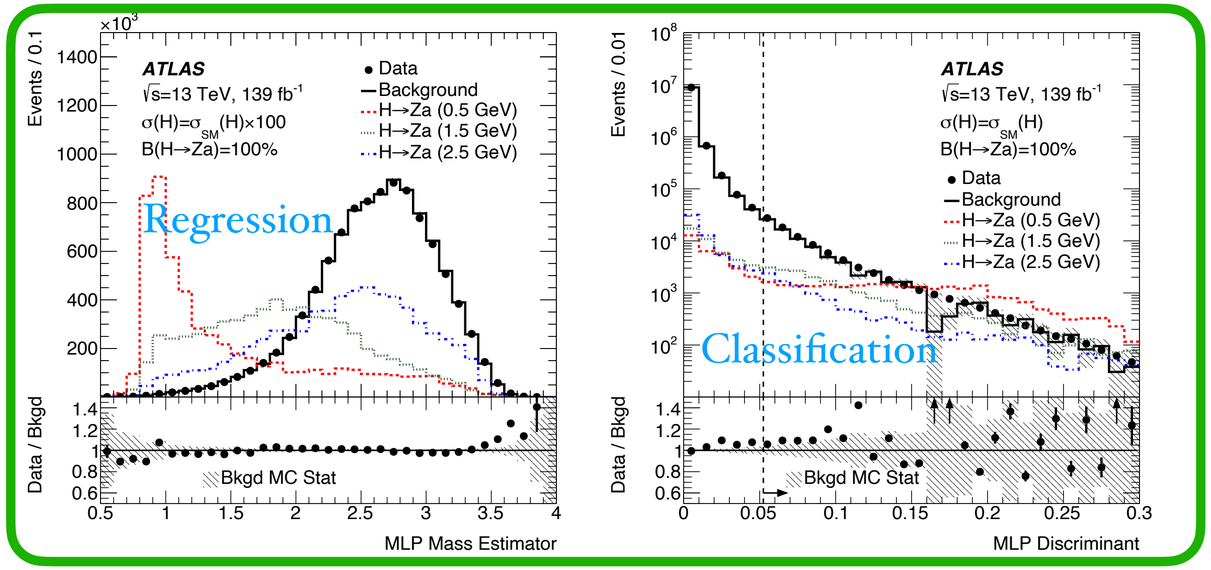
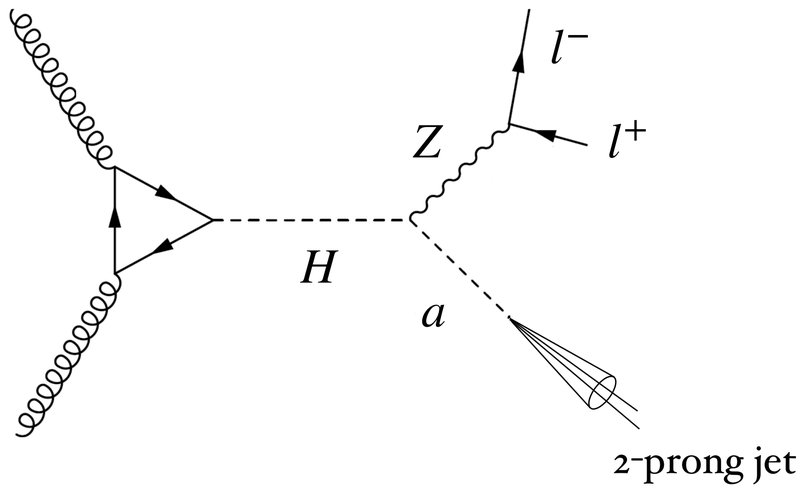
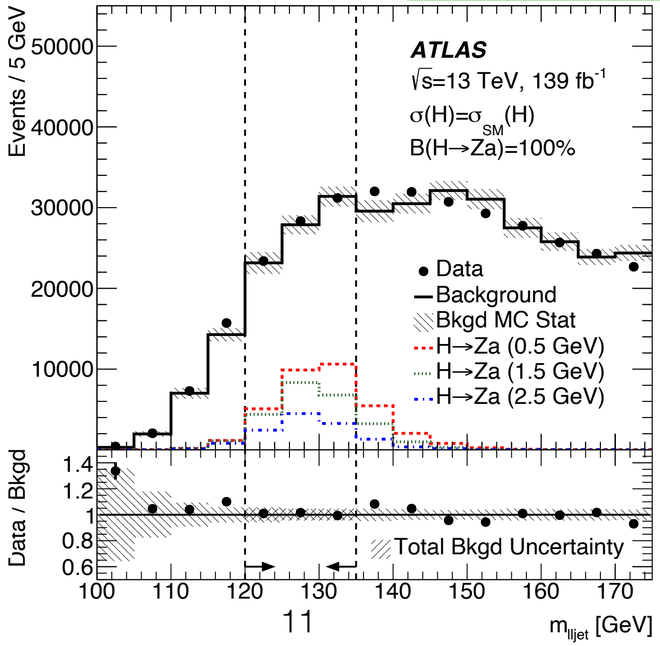
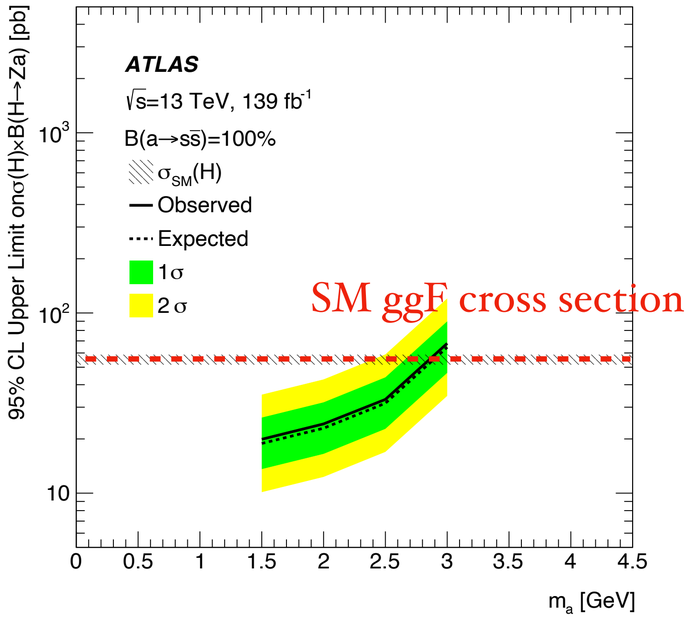
- Significant Br($H \to Za$) in some scenarios of 2HDM+S.
  - Targeting very light mass $m_a < 4$ GeV.
  - Where a primary decays to gluon pairs or light-flavour quark pairs.
- Using a 2-tiered Deep Neural Network (DNN):
  - Regression DNN to guess signal mass.
  - Classification DNN to distinguish signal and background (mainly Z+jets).
- Major background estimated by ABCD method from DNN score.



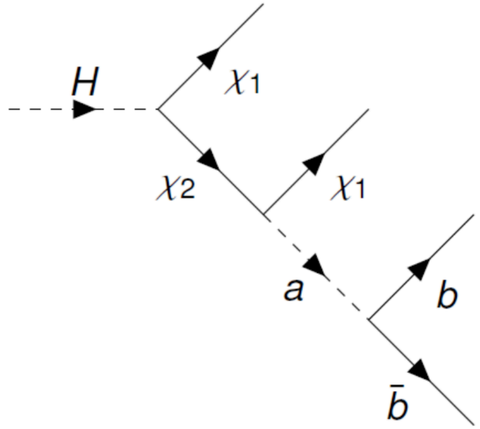


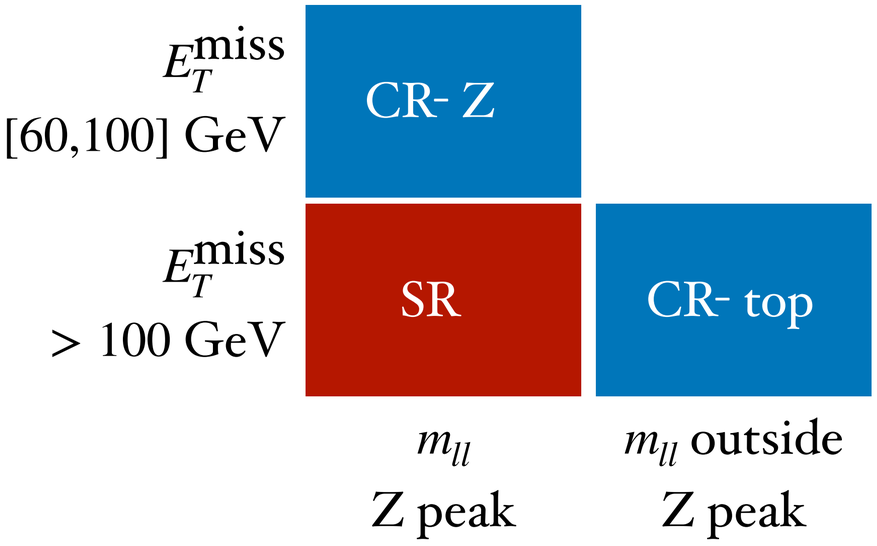


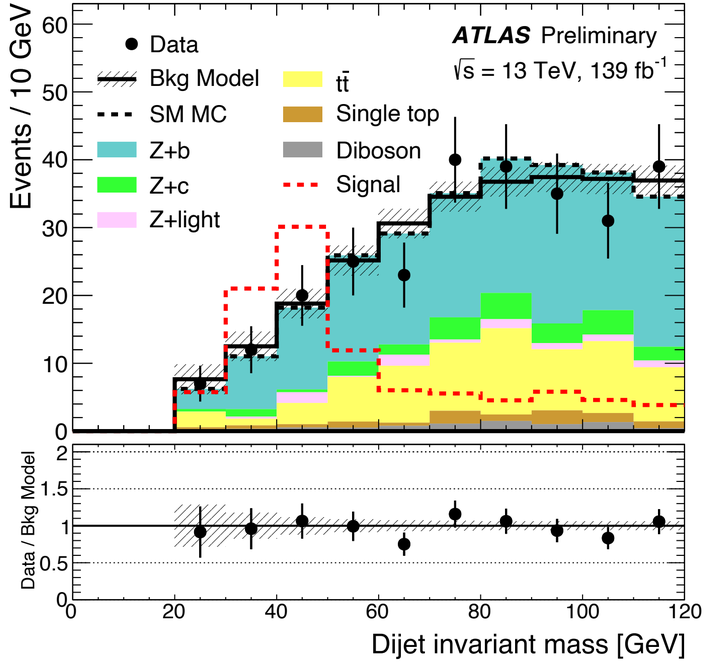


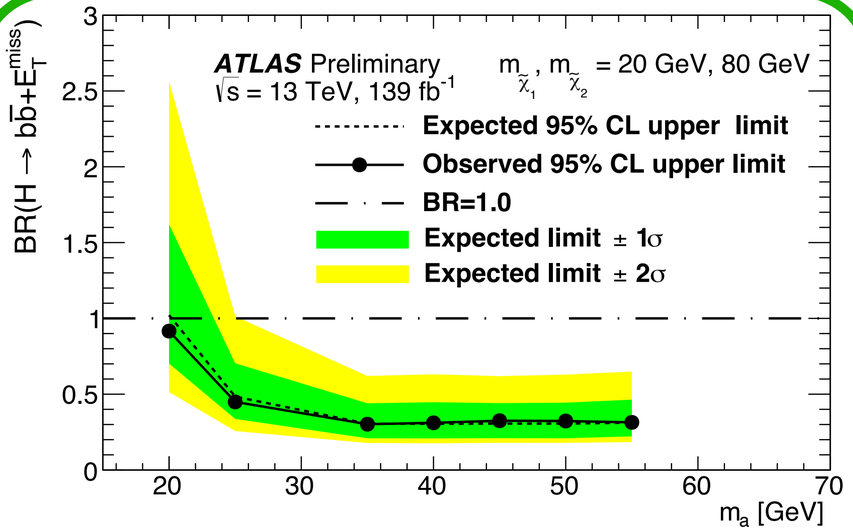
Higgs to $bb + E_T^{miss}$

- Targeting the phase space near the Peccei-Quinn (PQ) symmetry limit (NMSSM).
- Focus on the ZH associated production.
  - Where Z decays to a pair of electrons or muons.
- Select events with OS/SS lepton pair, large E_T^{miss} and at least one b-tagged jet.
- Search in the m_{jj} spectrum to see if any excess over the bkg. estimation.





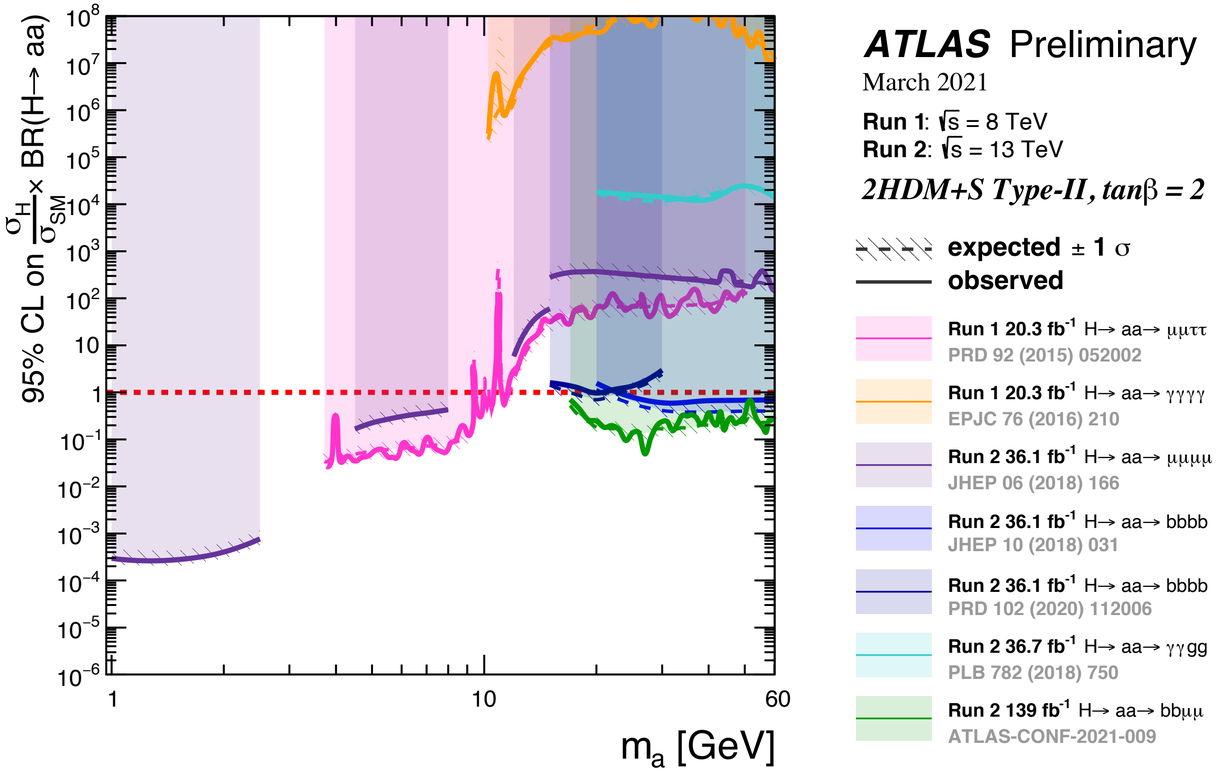


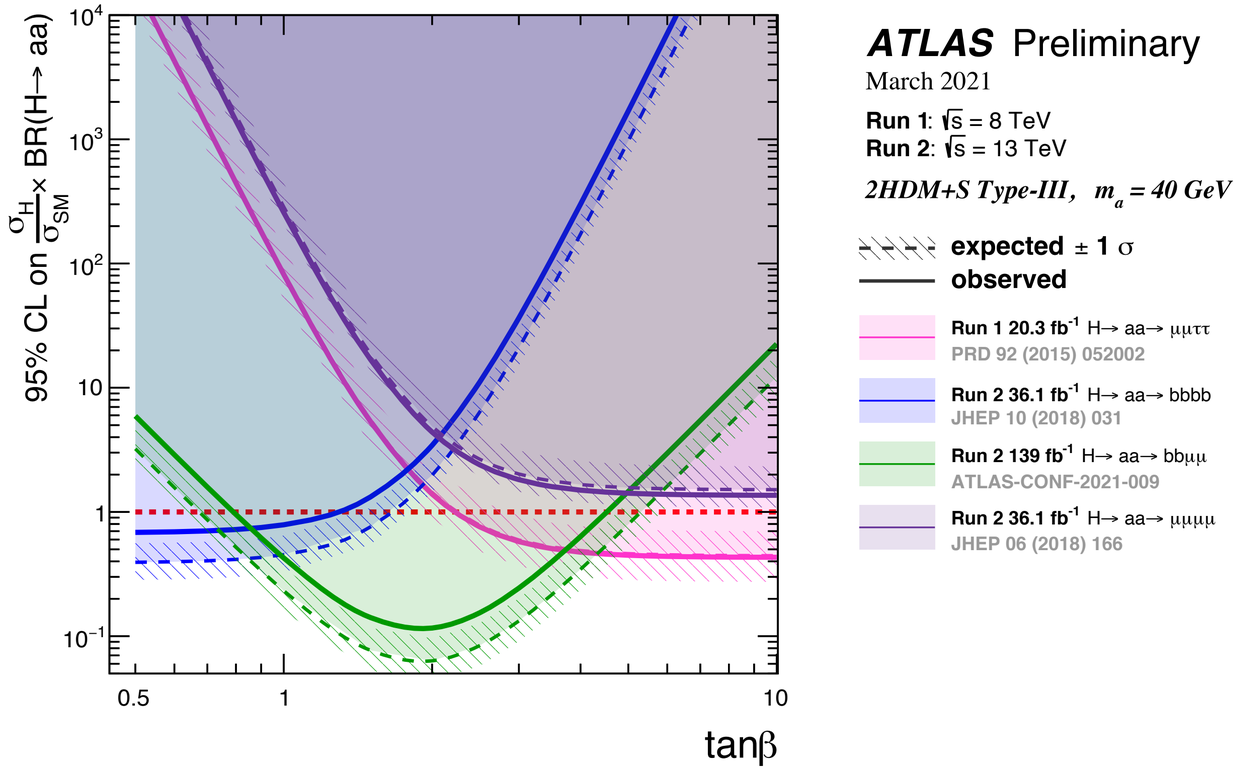


Branching ratio limit set for different (χ_1, χ_2) combinations.

Summary of 2HDM+S

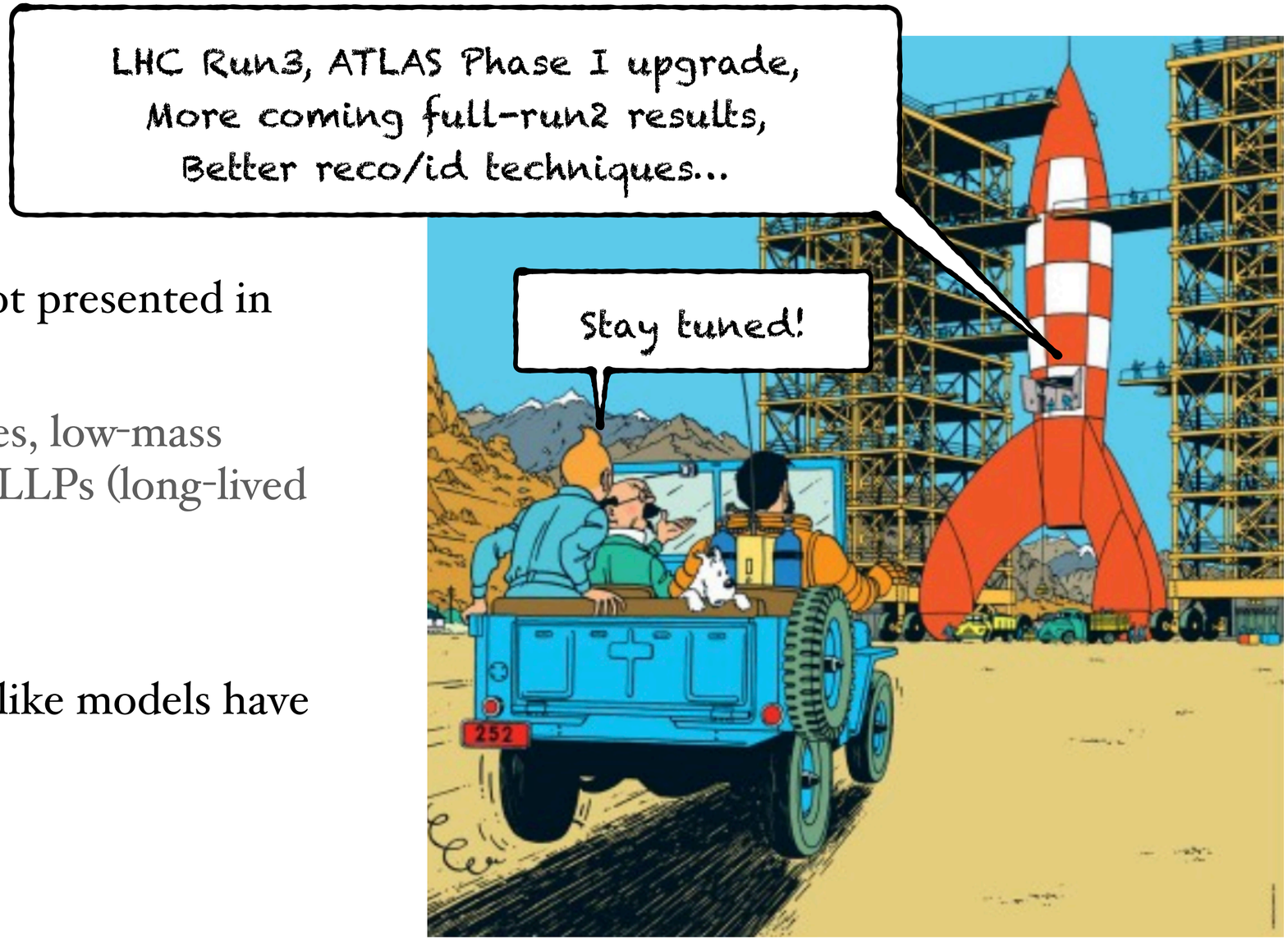
ATL-PHYS-PUB-2021-008





- Model independent limits translated to limits of Br($H \to aa$) under the assumption of each particular 2HDM+S scenario.
- Exclusion power differs by channels/analyses at different tan β.

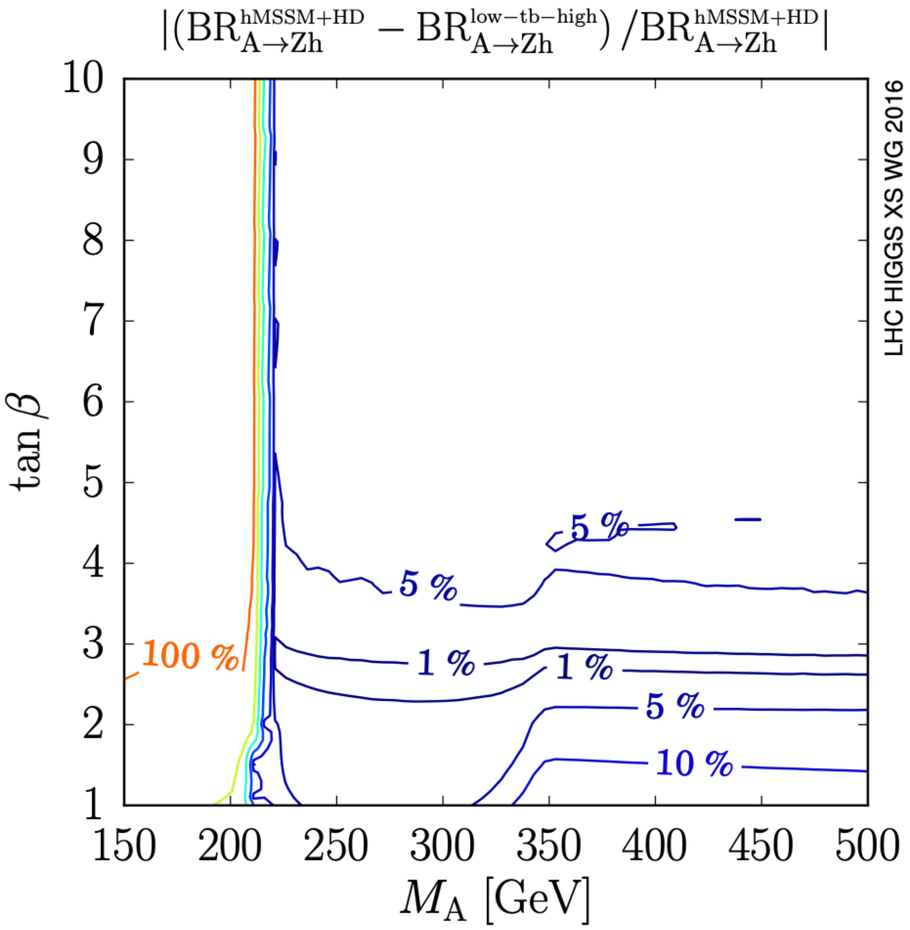
Conclusions and looking forward..

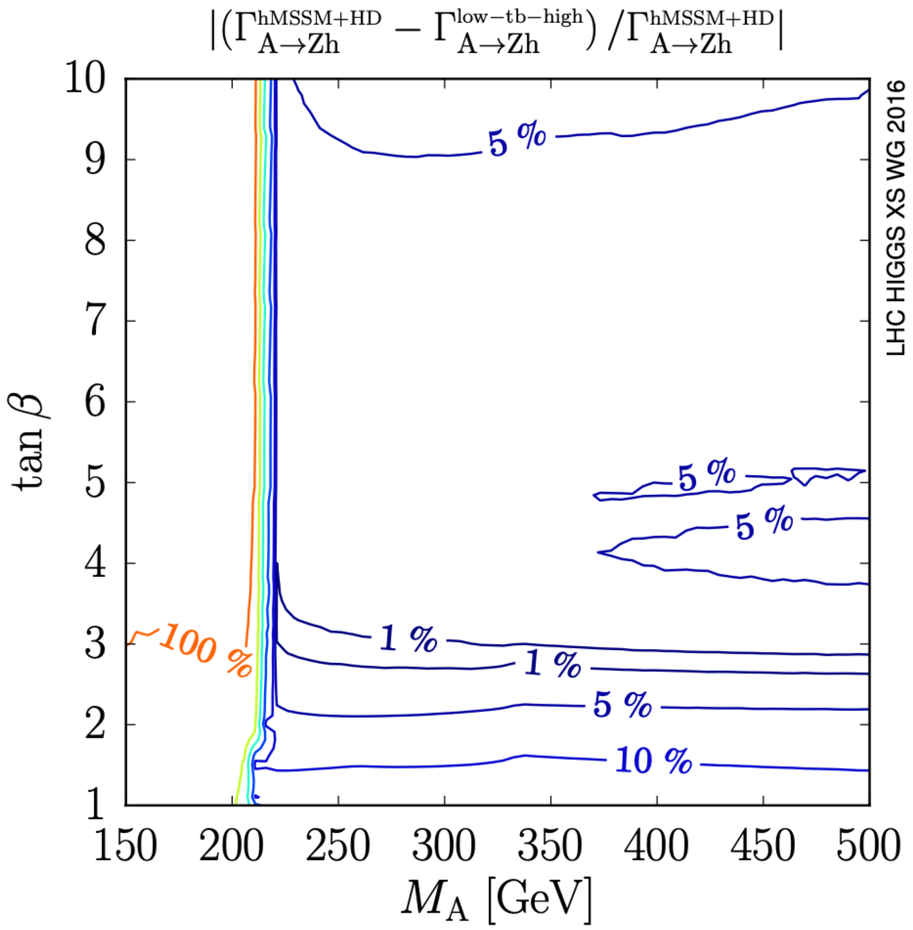


- Many more BSM Higgs searches not presented in this talk:
  - Such as BSM di-Higgs resonances, low-mass scalar searches, Higgs decays to LLPs (long-lived particles) etc.
  - See more results here.
- A large parameter space of 2HDM like models have been covered.
  - Still no sign of new physics yet...

Backup slides

Branching ratio of hMSSM $A \to Zh$

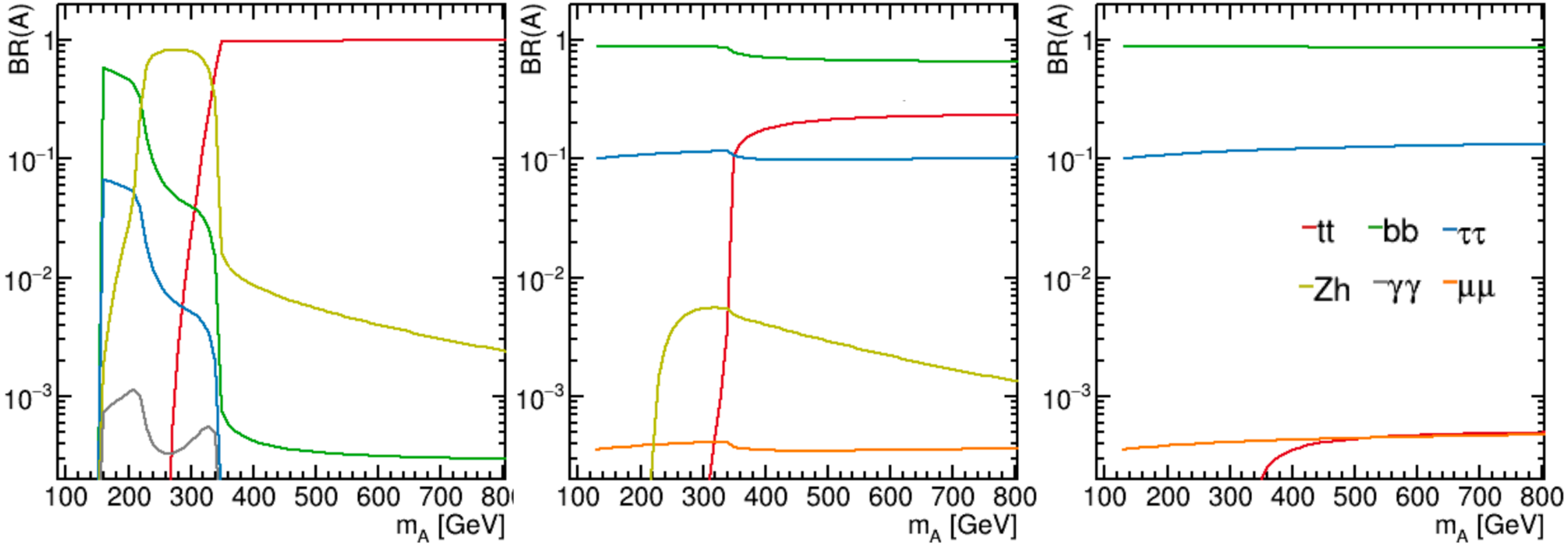




Handbook of LHC Higgs cross sections: 4. Deciphering the nature of the Higgs sector

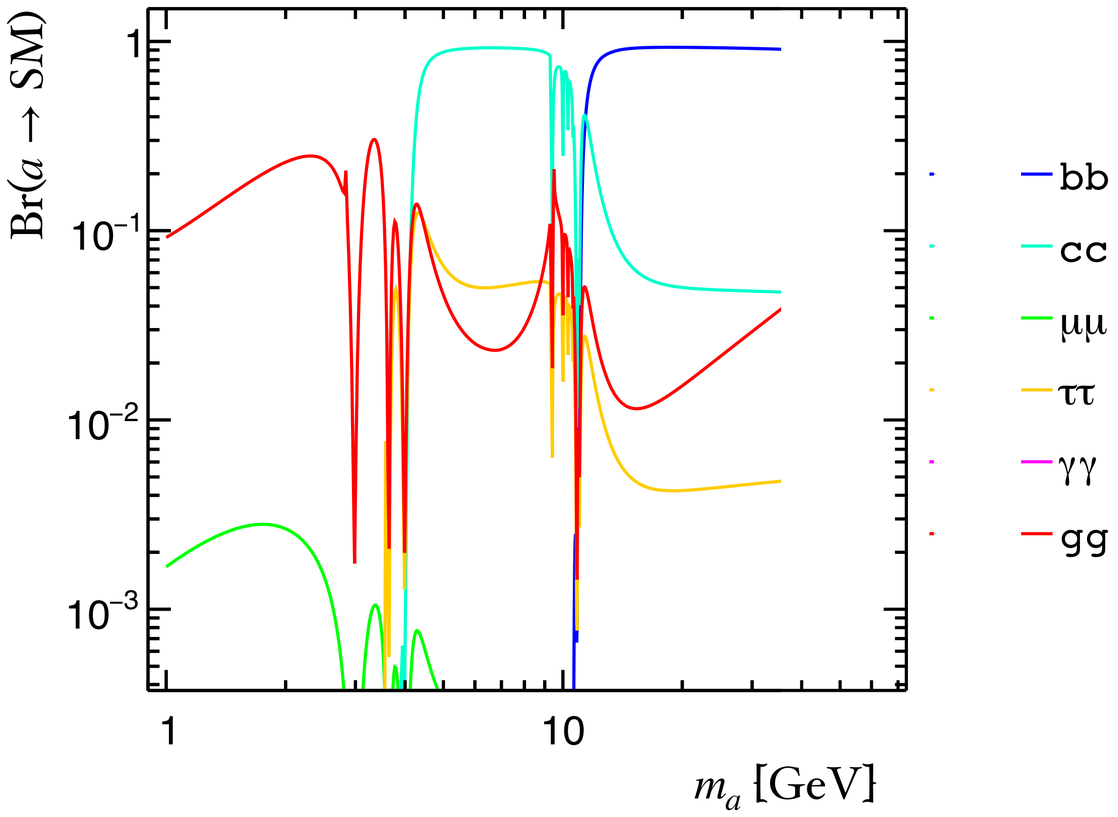
Branching ratio of heavy Higgs $A \rightarrow$ SM

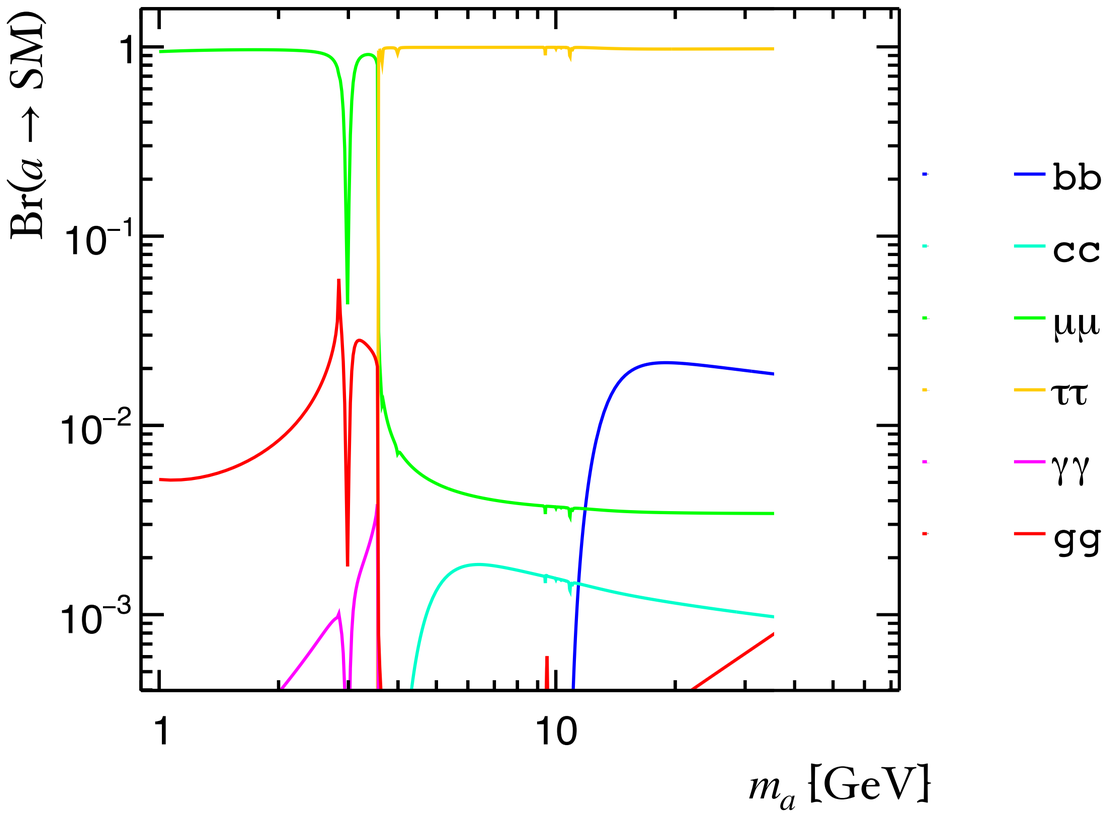
$\tan\beta = 1$ $\tan\beta = 10$ $\tan\beta = 50$



Handbook of LHC Higgs cross sections: 4. Deciphering the nature of the Higgs sector

Branching ratio of pseudoscalar $a \to$ SM



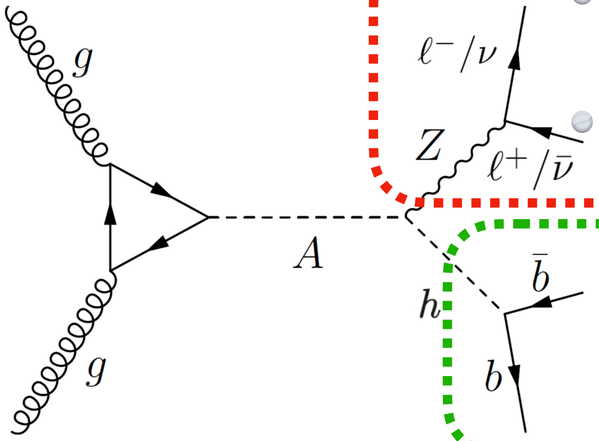


U. Haisch et al. JHEP 03 (2018) 178

Neutral heavy $A \to Z(2l/2\nu)h(2b)$

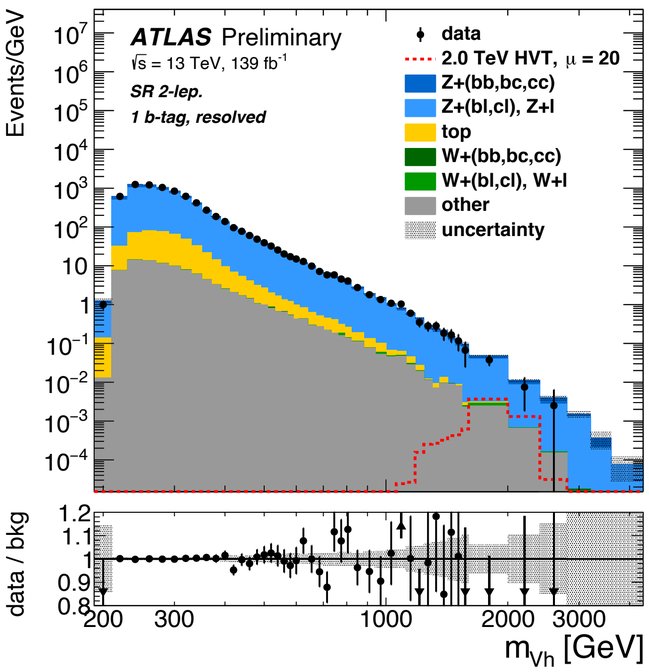
ATLAS-CONF-2020-043
139 fb^{-1}

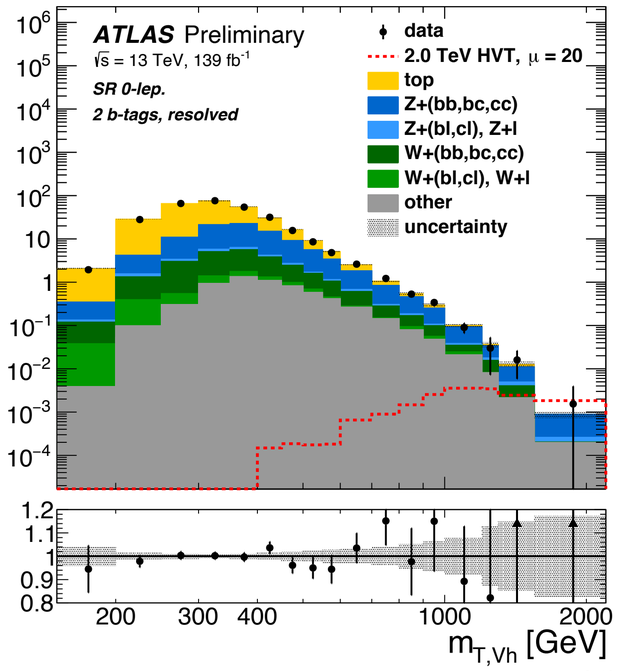
- Good sensitivity for small $tan\beta$ & MSSM like models.
- Signal discriminant:
  - Invariant mass m_{Vh} for $ee/\mu\mu$.
  - Transverse mass $m_{T,Vh}$ for $\nu\nu$.

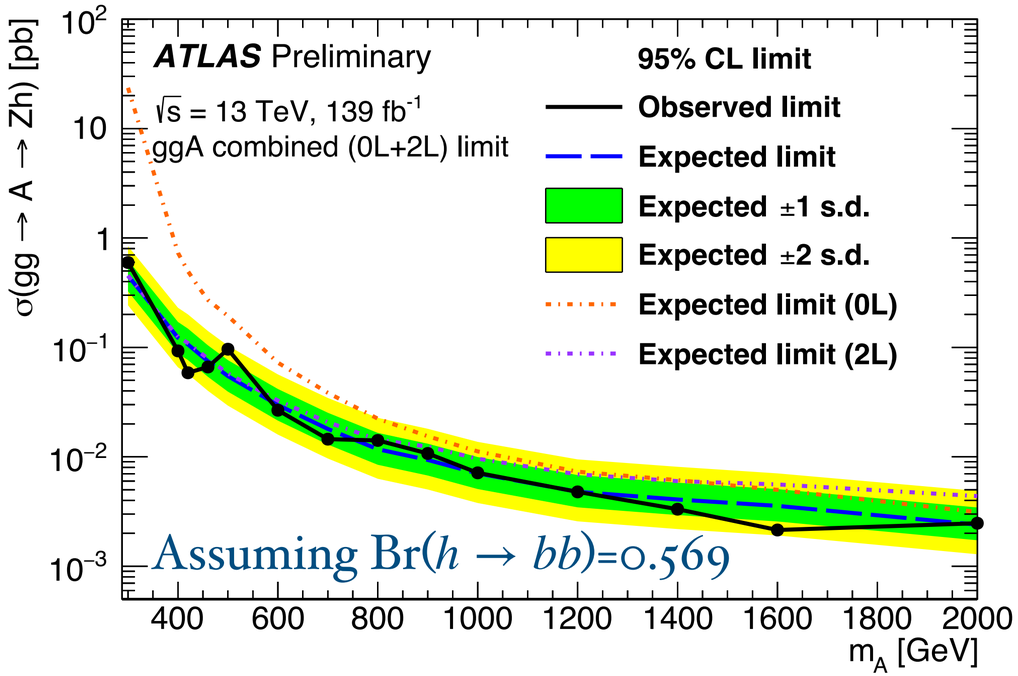


- $ee/\mu\mu$: single lepton trigger & two same-flavour opposite-charged leptons.
- $\nu\nu$: E_T^{miss} trigger & $E_T^{miss} > 150$ GeV.

Consider both resolved (2 b-tags) and merged (1 b-tag) bb pairs.



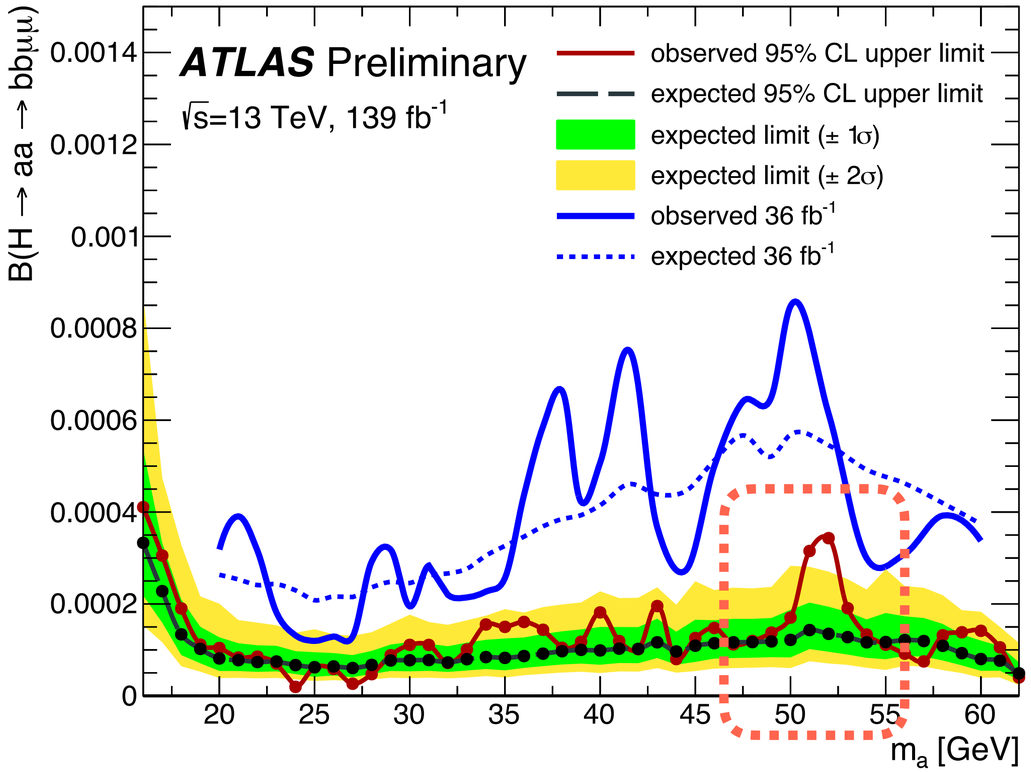




Assuming Br($h \to bb$)=0.569

Studies for the 52 GeV excess of $bb\mu\mu$

- Excess of 2.9σ local significance observed.
  - 3 GeV wide window around the central mass at 52 GeV.
- Multiple checks done to investigate the excess:
  - Looked at yields with different BDT modelling in SR, only seen on the dimuon mass distributions at BDT50.
  - No significant pull or constrains on bkg only and signal fit.
- Conclusions:
  - Looks like fluctuation in data.
  - Limits run with **toys** for points with very small number of events.



Higgs to 4μ

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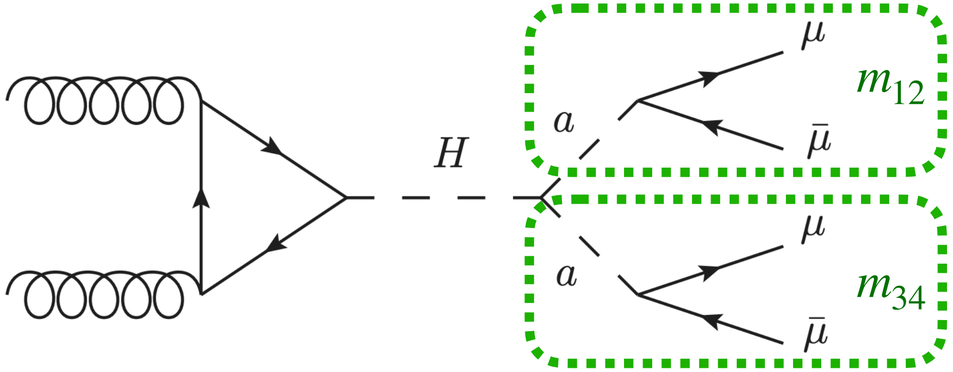
36.1 fb^{-1}



- Targeting a lower m_a, from 1 to 15 GeV.
  - For very low m_a, the two muons almost overlap.
  - Redefine the isolation criteria to account for extra muons in the isolation cone.
- Events selected with dimuon mass compatibility and Higgs mass window.
- Heavy flavour fake background ($b\bar{b}$ double semi-decay to muons) :
  - Estimated by a fully data-driven method using semi-leptonic b enriched template.