Searches for physics beyond the Standard Model at the ATLAS experiment

Inaugural Symposium of TCHoU, March 26-27, 2018

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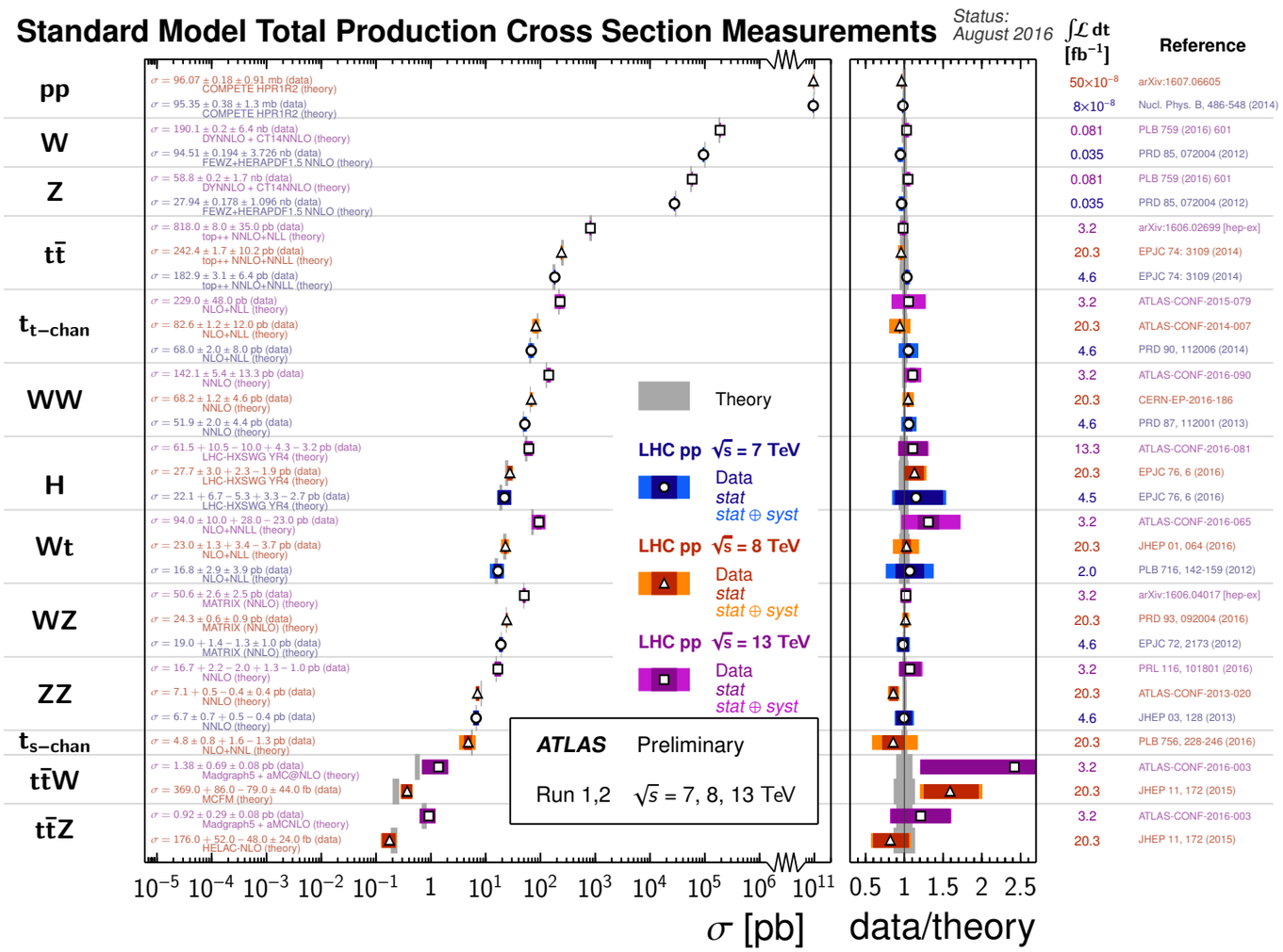
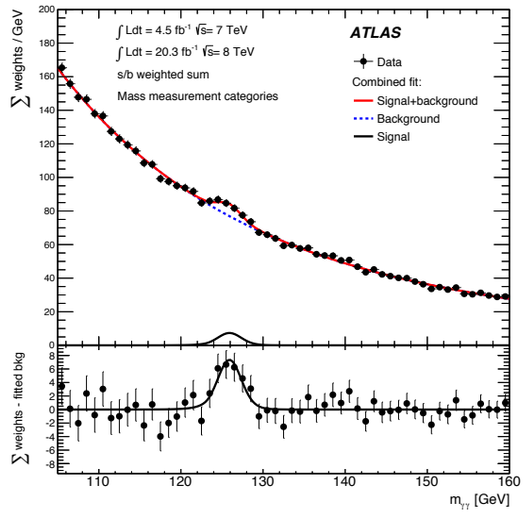
New Physics Searches

Outstanding success of Standard Model!

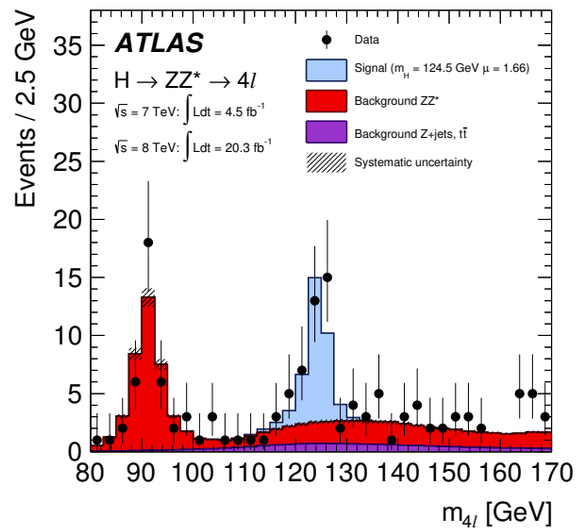


Standard Model agrees with experimental results for ~$\mathcal{O}(10^{12})$ of magnitude

Structure of the Higgs Sector is yet to be understood



Phys. Rev. D. 90, 052004 (2014)

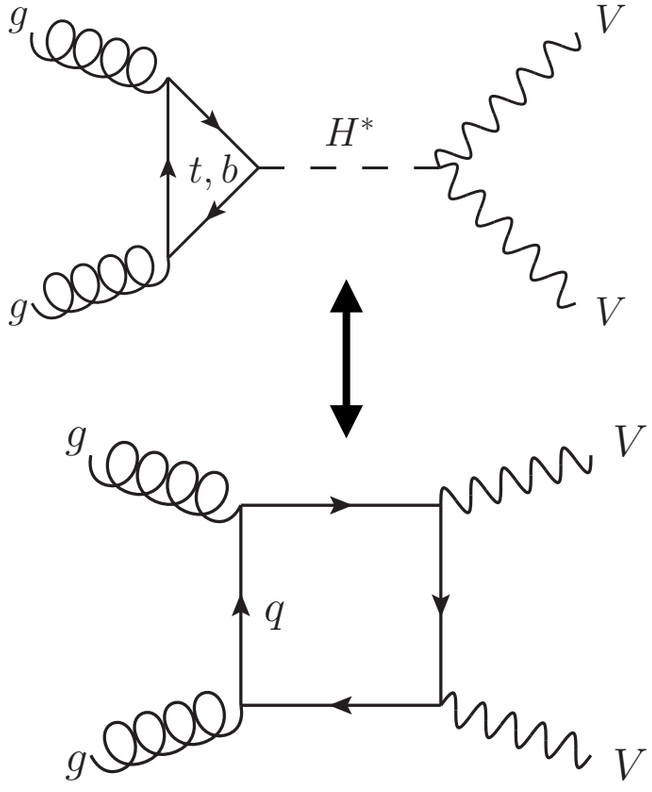


- **How many Higgs bosons do we have?**
- **Any other resonance that originate from physics beyond the Standard Model?**
- **Any connection to dark matter?**

Higgs Rare BSM Decays & Dark Sectors

Higgs Width & Rare Decays

- **The decay width of the Higgs boson is 4.1 MeV.** Unable to directly measure at the LHC due to the detector resolution ($\mathcal{O}$(GeV)).
- **Indirect constraint from the off-shell Higgs production & its interference still allows sizable BSM rare decays (Γ_H <~5 Γ_H^{SM}).**
- **Searches for rare Higgs decays (e.g. to dark matter)** will also provide another probe for new physics, and are motivated from various BSM models.



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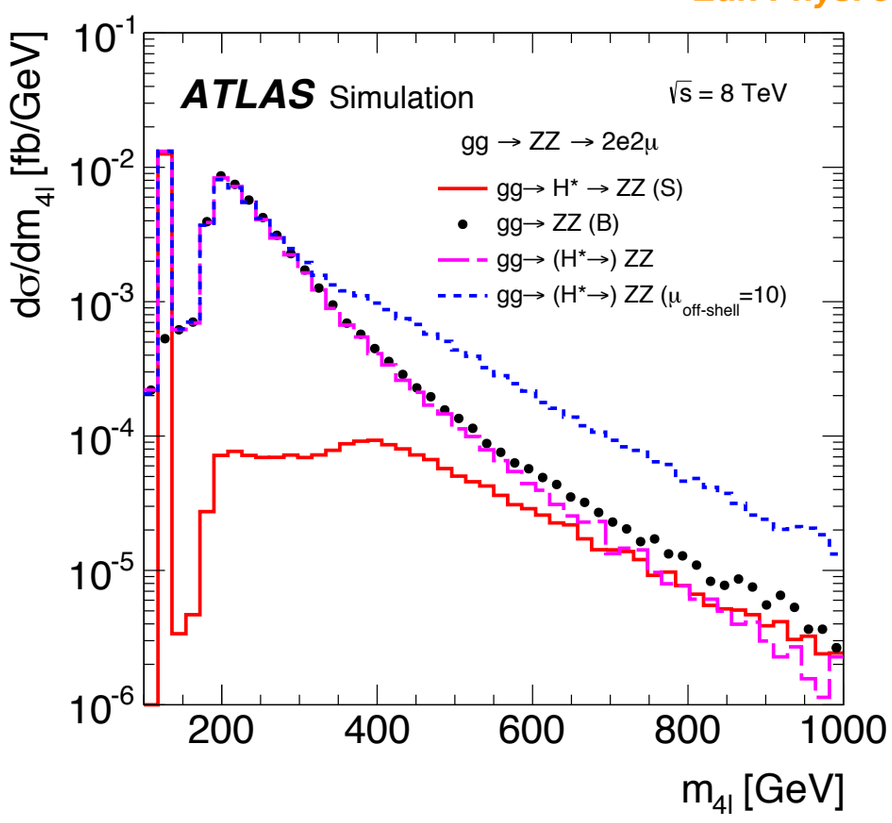
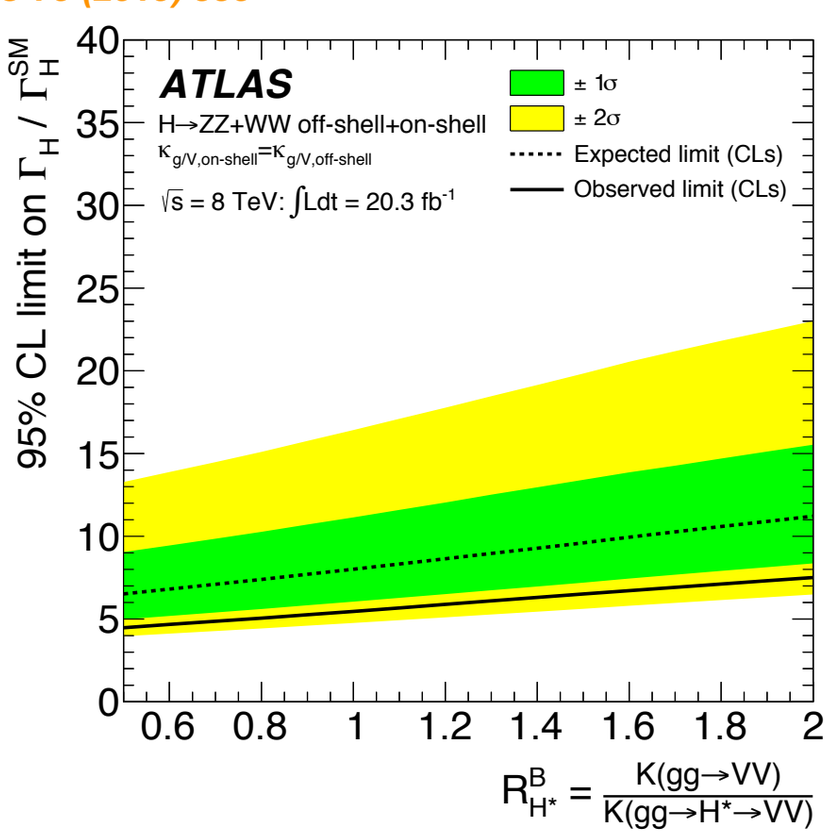
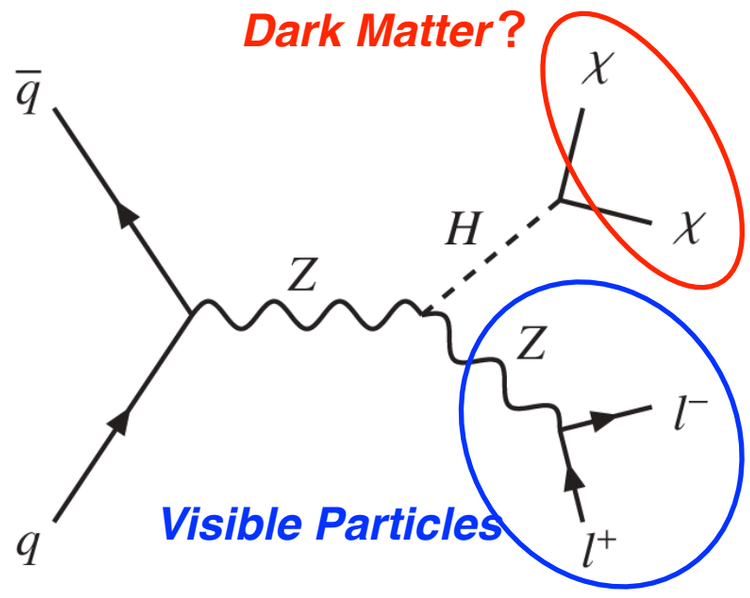




Invisible Decays

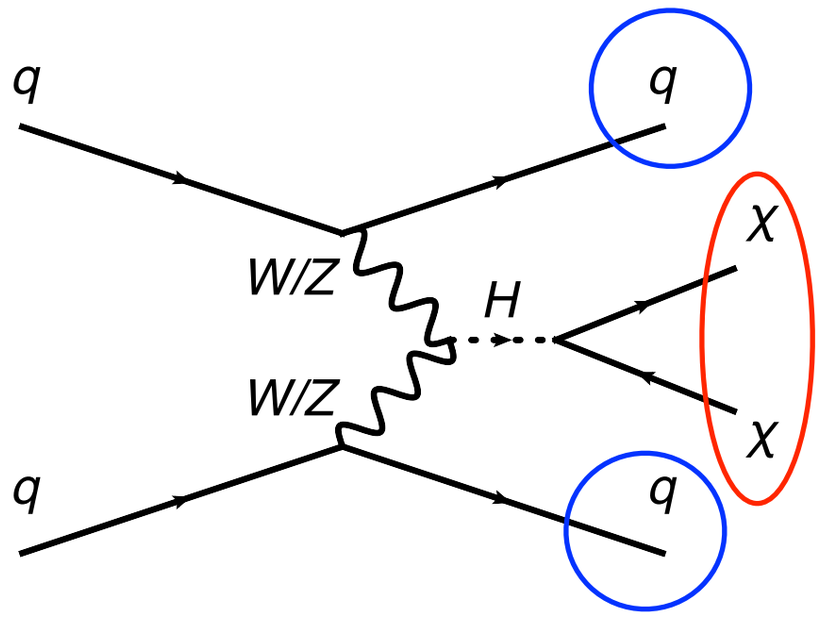
BSM decay of Higgs boson to dark matter. Expected from Supersymmetry, etc.

ZH Associated Production

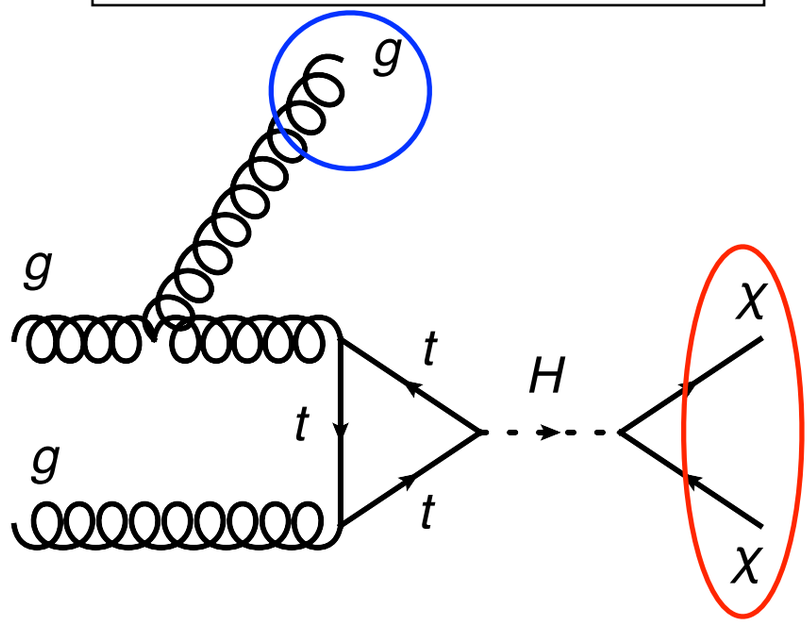


Run-2 results available

Vector-Boson Fusion



Gluon-Gluon Fusion



- To search for invisibly decaying Higgs boson, **we need "visible" particles produced along with the Higgs** to search for such phenomenon.
- **ZH associated & vector-boson fusion** channels are highly sensitive to the invisible Higgs decay. **ZH especially has a "clean" signature.**

Z(ll)H(inv) Results

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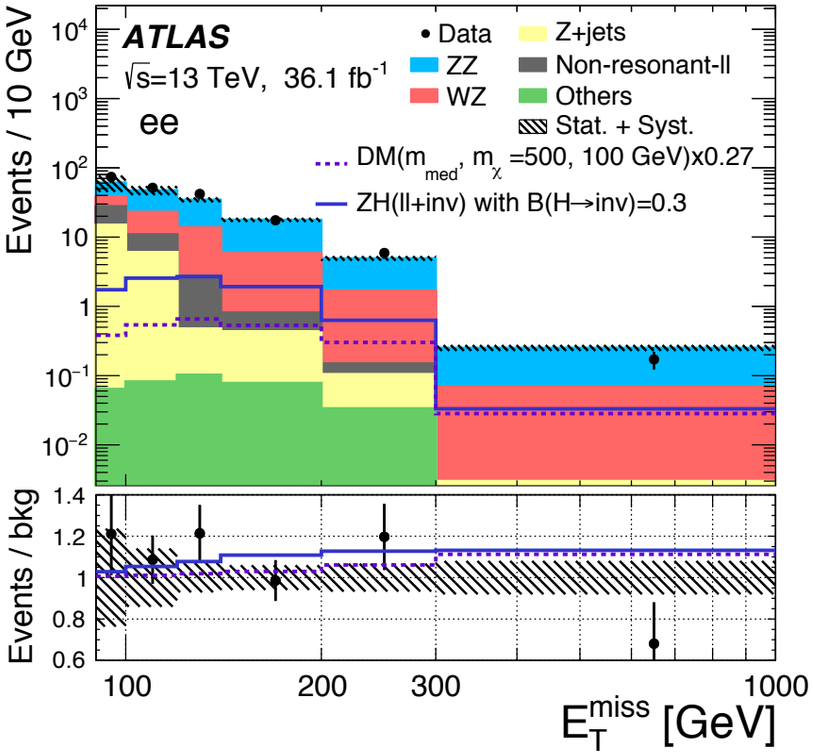
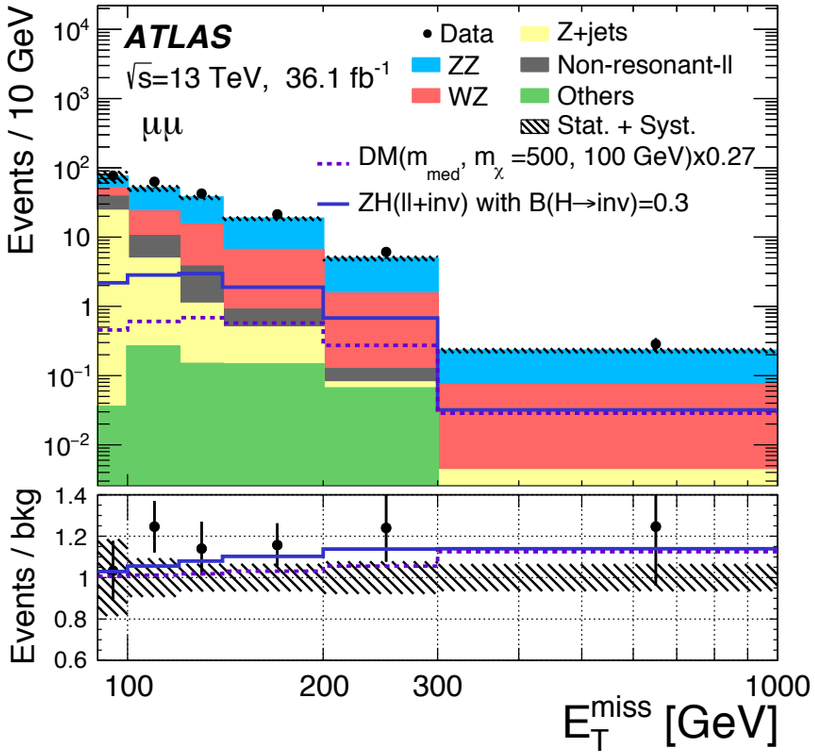
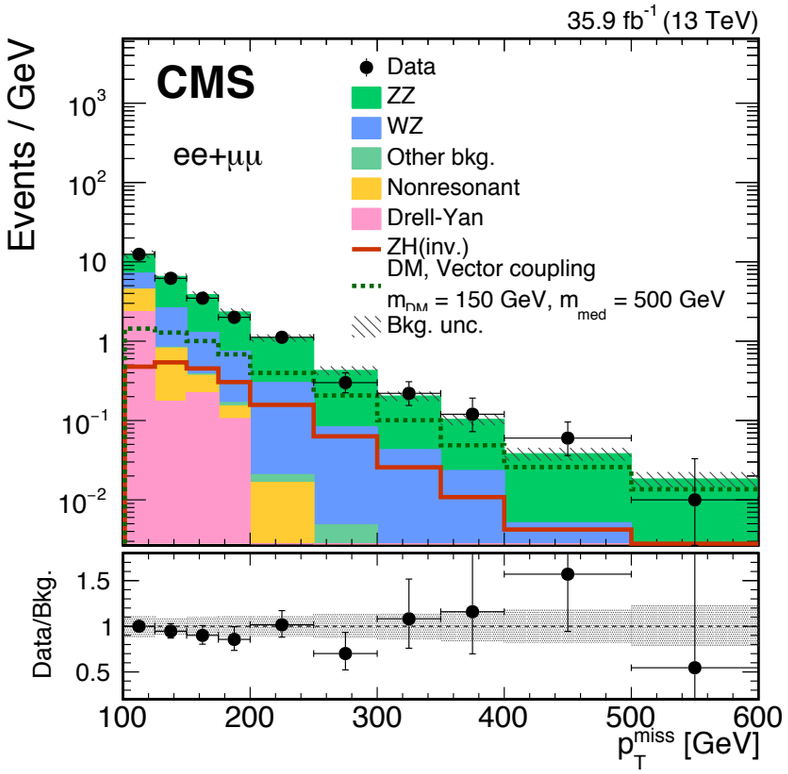






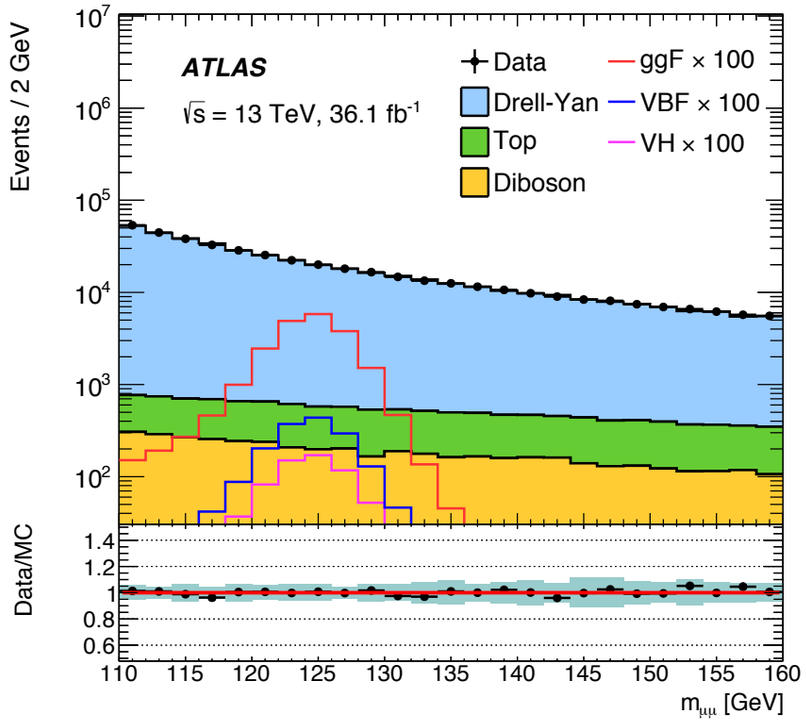
- 2.2σ excess observed in the μμ-channel.
- **BR(H→inv) < 67% obs. (39% exp.)@95%CL.**
  - Run-1: BR(H→inv) < 75% obs. (63% exp.)
- **Best fit value for BR(H→inv)=30±20%.**
  - Run-1 combination results: BR(H→inv) < 23%

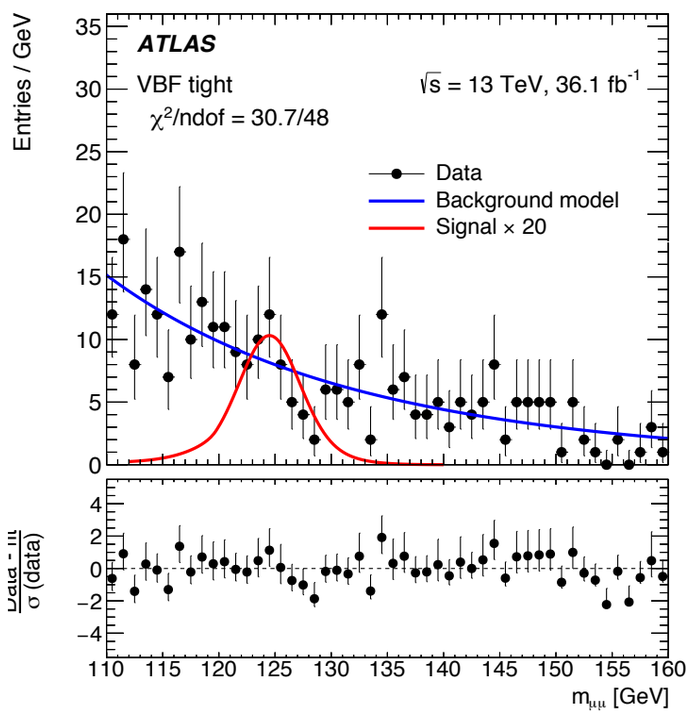
- CMS does not see visible excess.
- **BR(H→inv) < 40% obs. (42% exp.) @95%CL.** w/ MVA
- Main difference is that a quasi-data driven estimation is used for ZZ BG.

Other Rare Decay Searches

1st & 2nd generation Yukawa couplings

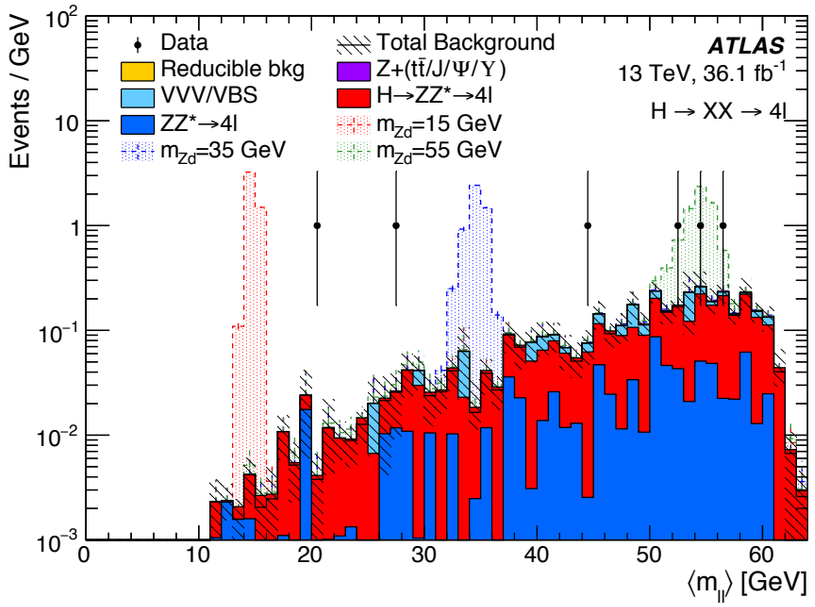
- Searches for 2nd generation coupling is pursued with $\mu^+\mu^-$ & cc.
- Meson+γ channels are considered for the 1st, 2nd generation Yukawa couplings.
- Observed (expected) upper limit of 2.8 (2.9) times the Standard Model prediction @95% CL.

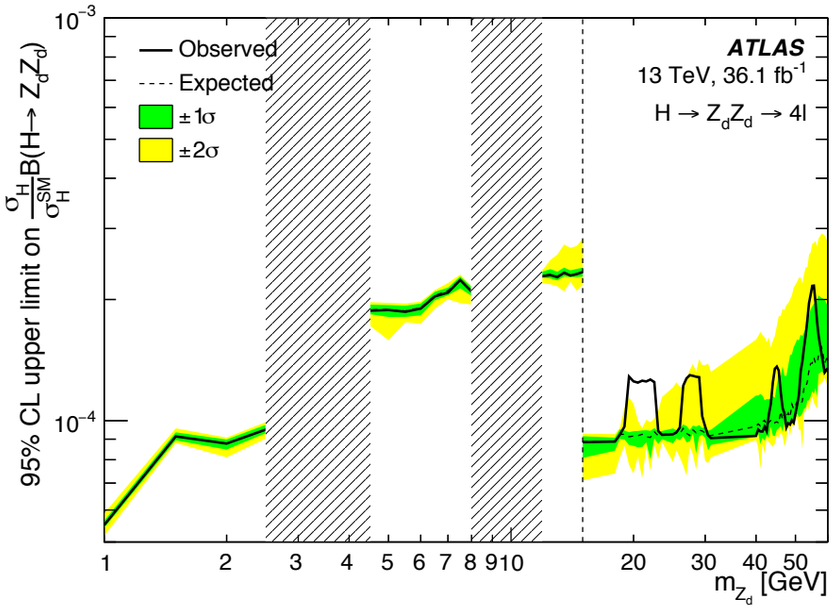




Couplings to exotic bosons

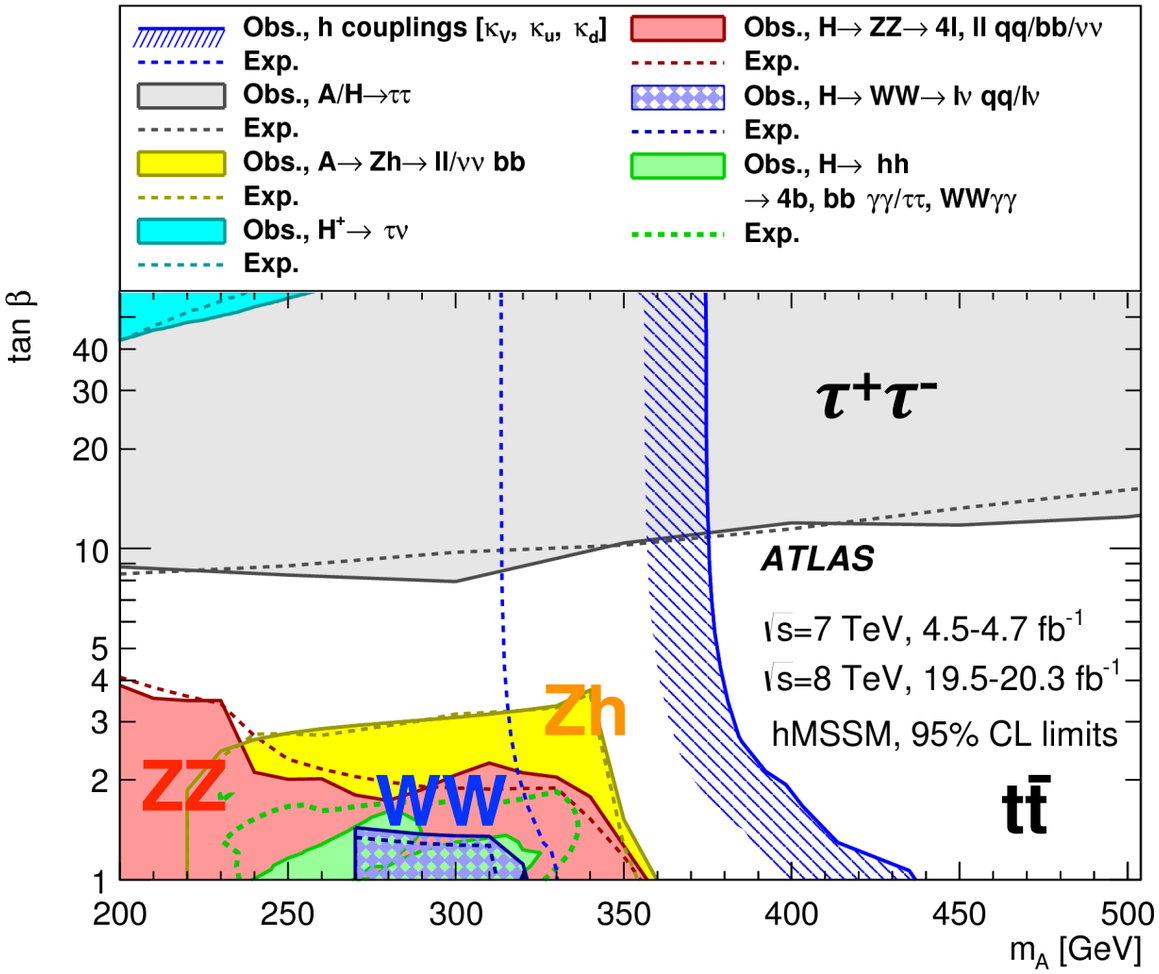
- Searched for Higgs couplings to exotic dark bosons with 4l.
- No excess in the $H \to ZZ_d \to 4l$ channel, but 3σ excess for $H \to Z_dZ_d \to 4l$ with 2l2e (but not for 2l2μ).





Heavy Higgs &
Other Resonance Searches

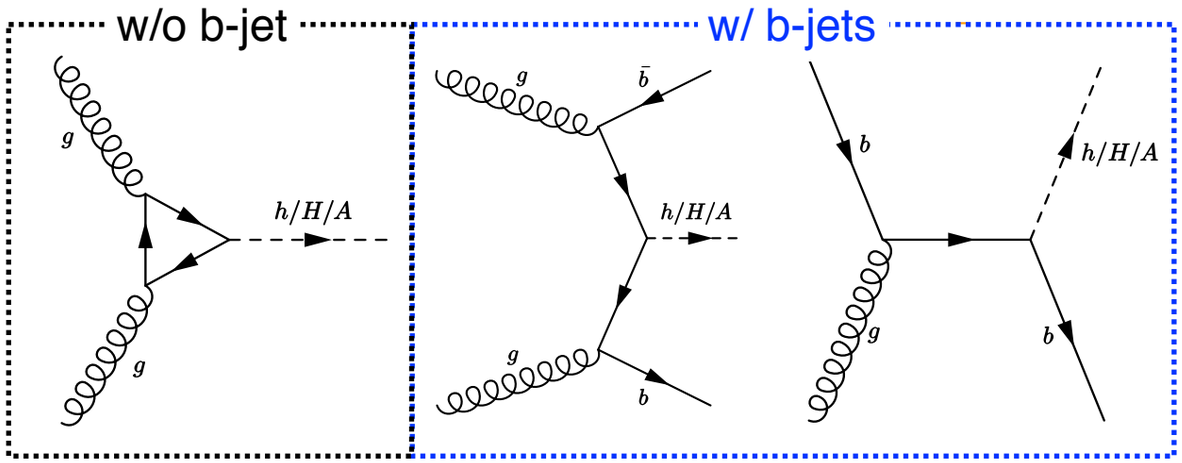
Heavy Higgs Searches

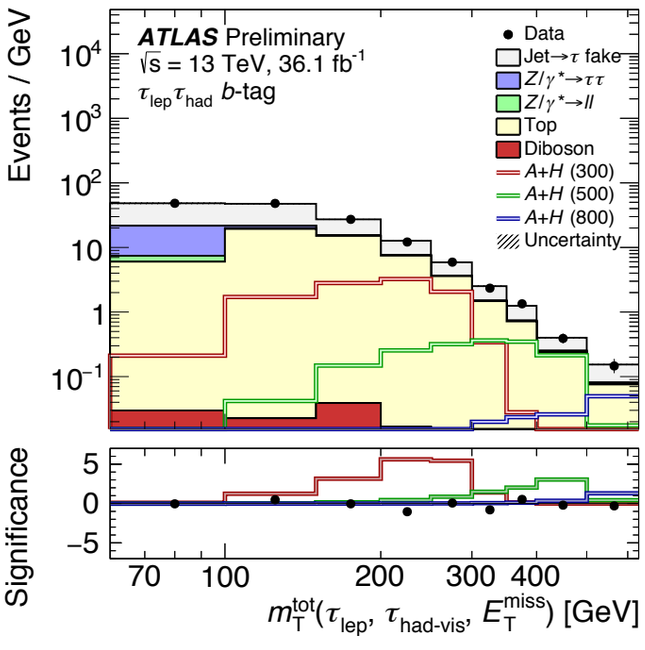


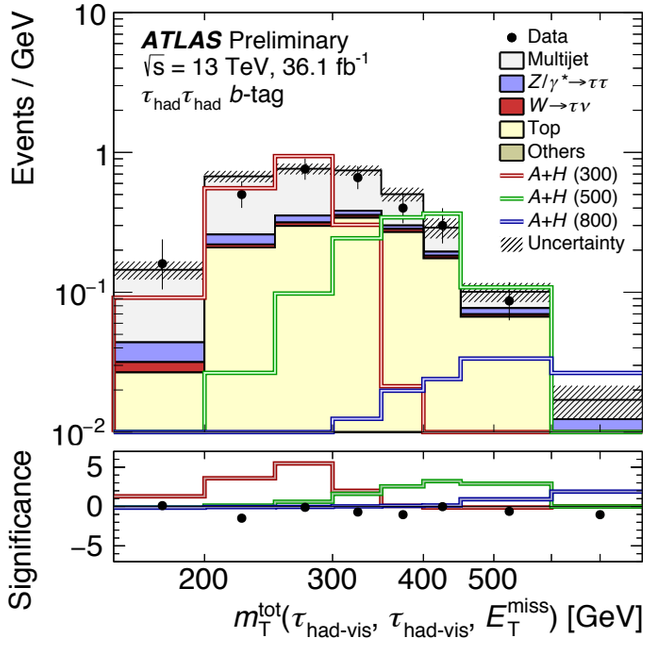
- **If the Higgs sector is extended by another doublet (Two Higgs Doublet Model; 2HDM), the decay modes depend on the heavy Higgs mass & tan β.**
- Neutral Heavy Higgs (H/A) searches:
  - High tan β: $\tau^+\tau^-$
  - Low tan β: ZZ,Zh,WW ($m_{H/A} < \sim 2m_t$)
    $t\bar{t}$ ($m_{H/A} > \sim 2m_t$)
- Charged Higgs ($H^{\pm}$) searches (dominated by tb, $\tau^{\pm}\nu$)
- If the Higgs sector is extended by a triplet, there could also be doubly-charged Higgs ($H^{\pm\pm}$).
- If the Higgs is composite, there could be diboson resonances in the TeV region?
- **It is crucial to perform diverse searches assuming various scenarios.**

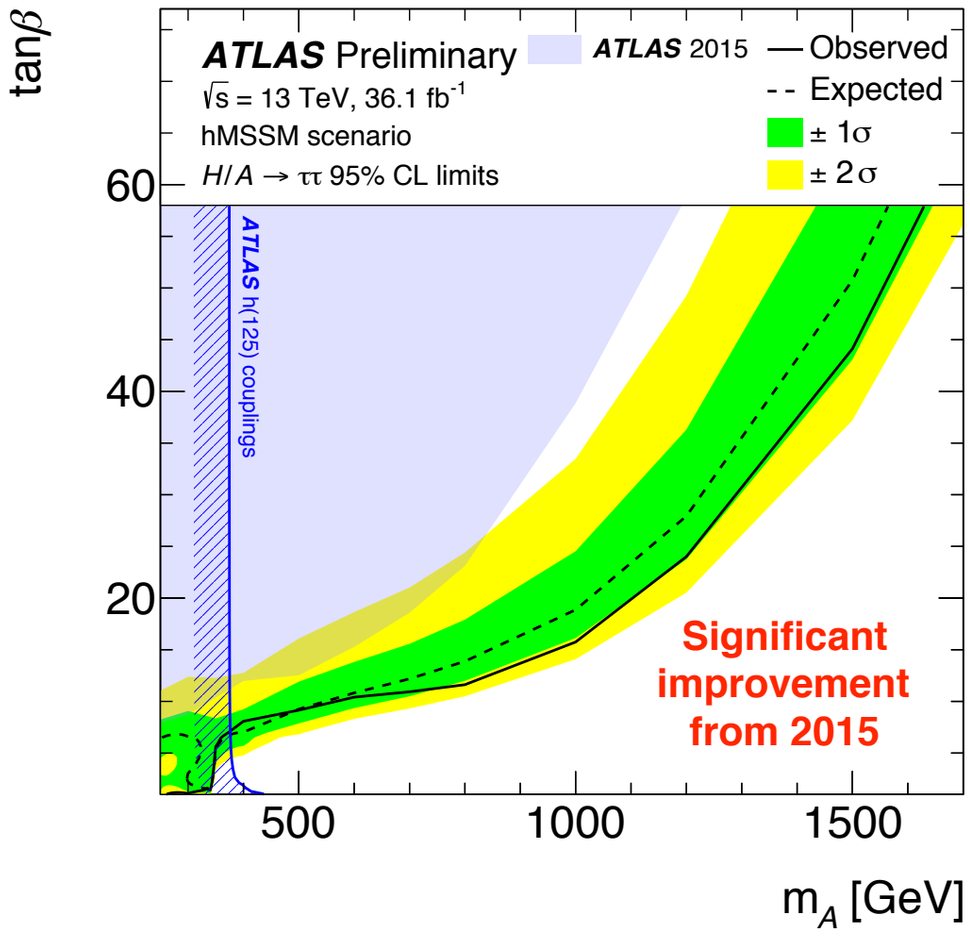
h/H/A → $\tau^+\tau^-$

- Particularly important for high tan β scenarios.
- Search for $\tau\tau$ resonances, at least with one hadronic τ ($\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$) b-tagged, b-veto categories.
  - $\tau_{had}\tau_{had}$ is more sensitive in the high mass region.
- Categorized into b-veto & b-tag regions to search for gluon fusion & bb-associated processes respectively.





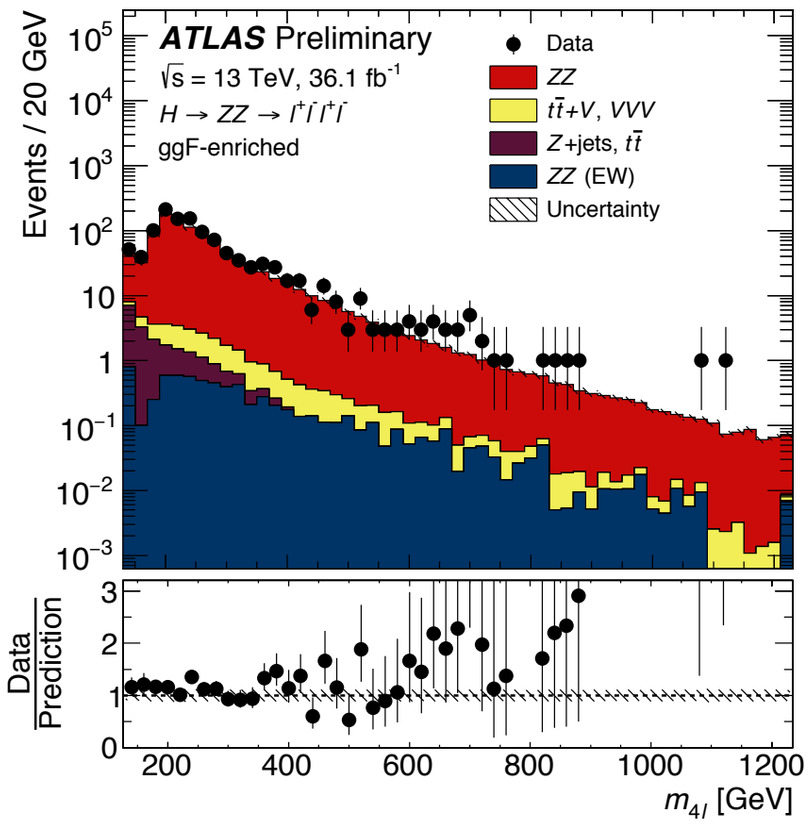




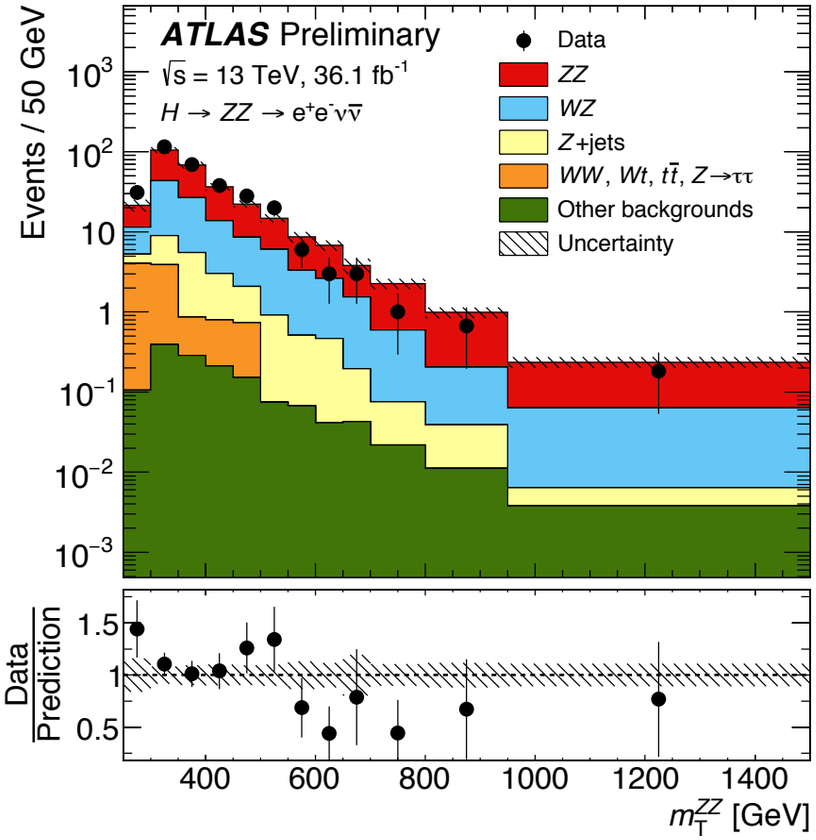
$$m_{\mathrm{T}}^{\mathrm{tot}} = \sqrt{m_{\mathrm{T}}^2(E_{\mathrm{T}}^{\mathrm{miss}}, \tau_1) + m_{\mathrm{T}}^2(E_{\mathrm{T}}^{\mathrm{miss}}, \tau_2) + m_{\mathrm{T}}^2(\tau_1, \tau_2)}$$

X(→ZZ)

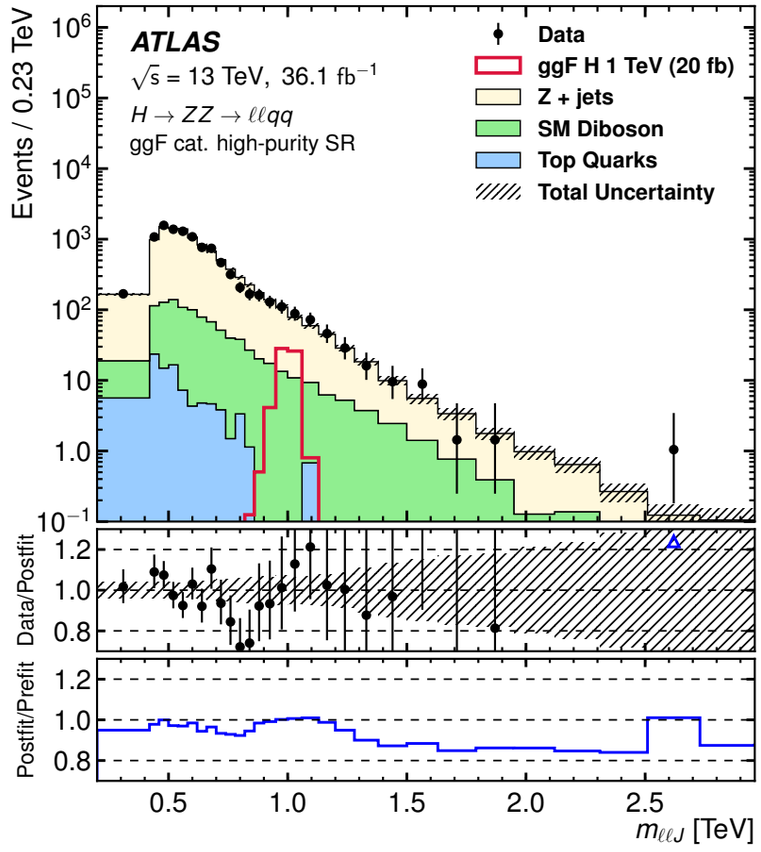
X→ZZ→4ℓ



X→ZZ→ℓℓνν



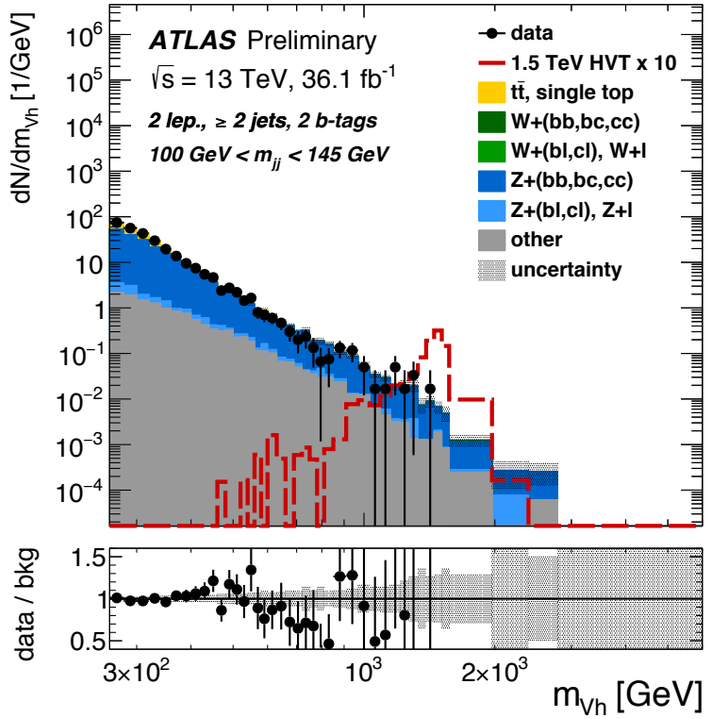
X→ZZ→ℓℓqq

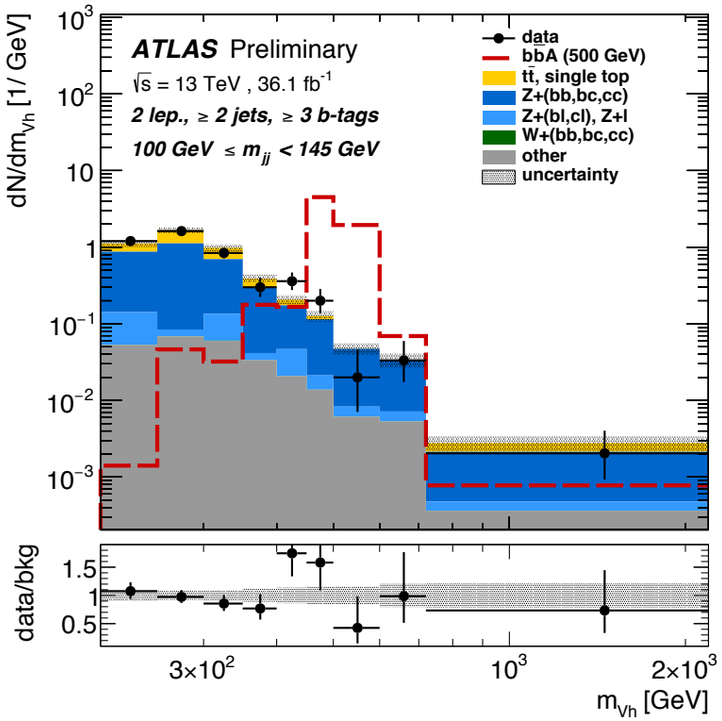


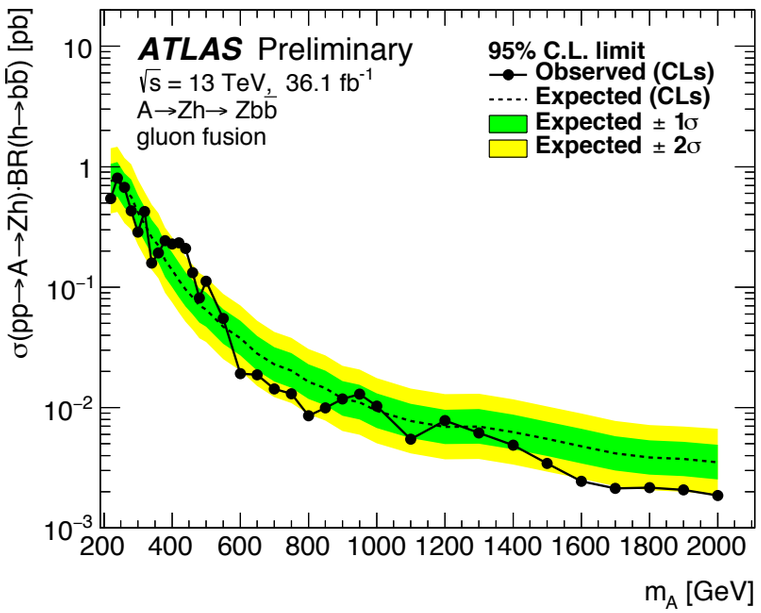
- **Visible excess of 3.6σ** (global 2.2σ) at 240 & 700 GeV. Mainly 4e for 240 GeV.
  - **700 GeV is not expected from the 2HDM.**
- 700 GeV excess not observed in $\ell\ell\nu\nu$, $\ell\ell$qq (deficit in the latter..)
- Need improvement on the ZZ BG estimation for 4ℓと$\ell\ell\nu\nu$ (currently fully relying on MC w/ NNLO QCD & NLO EW precision).

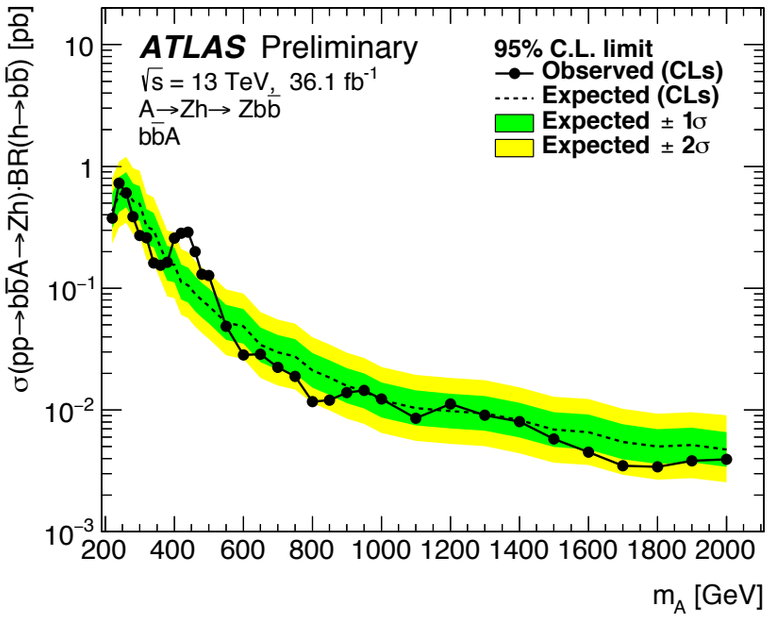
A(→Zh)

- **Important for low tanβ & $m_A<2m_t$ cases.**
- Similar strategies as the Vh(→bb) measurement.
- **Visible excess ~440 GeV (3.6σ local, 2.4σ global).**
  - **In both gluon fusion & bbA production modes.**
- If it is form 2HDM, there might also be $t\bar{t}$ resonances.
  - Though, challenging due to the negative interference.

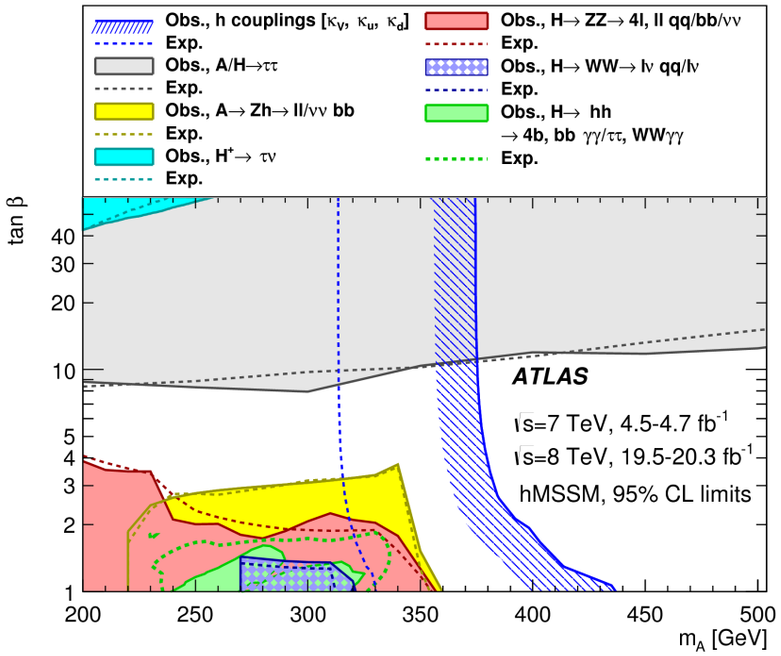


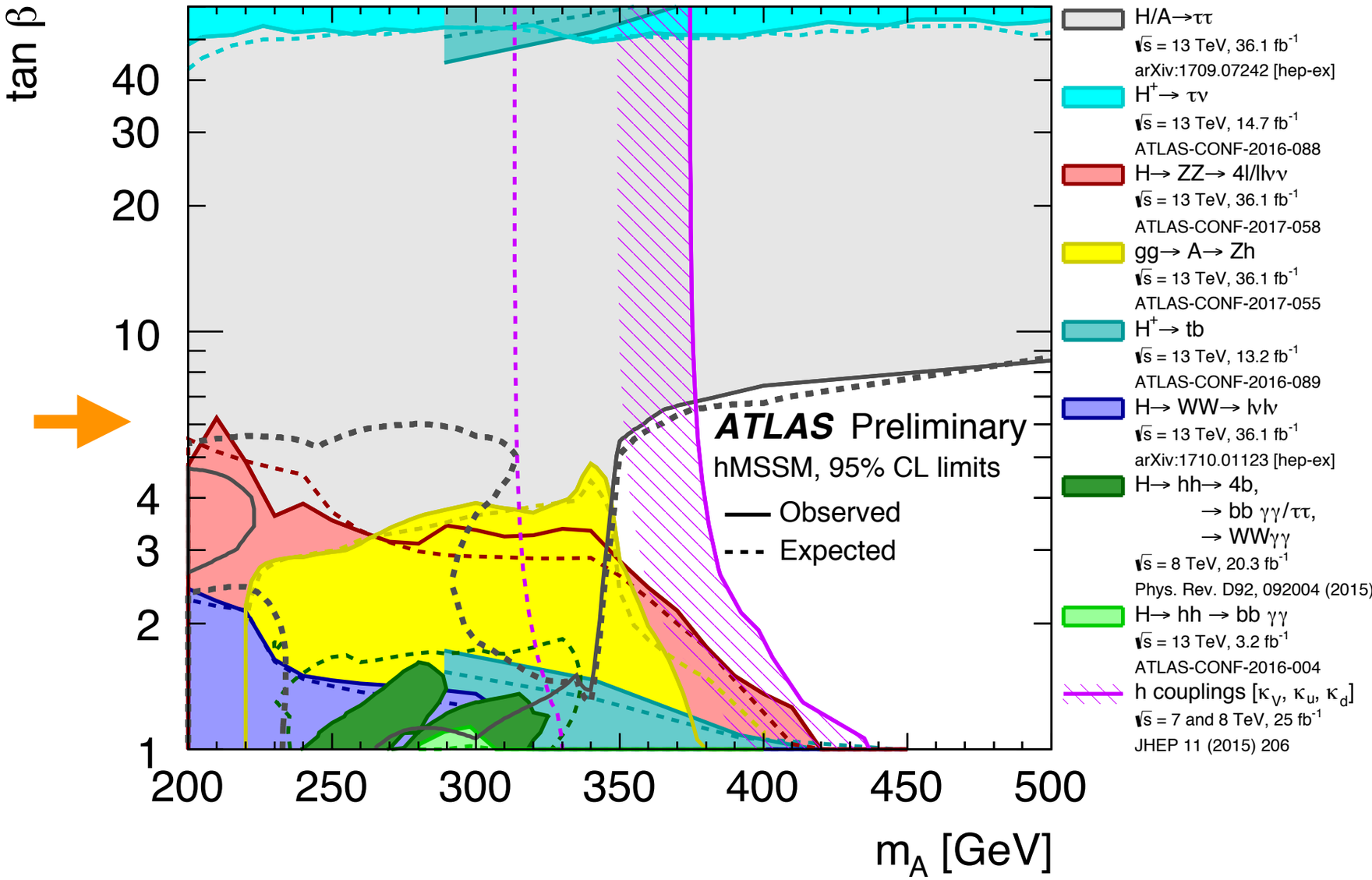






Heavy Higgs Summary

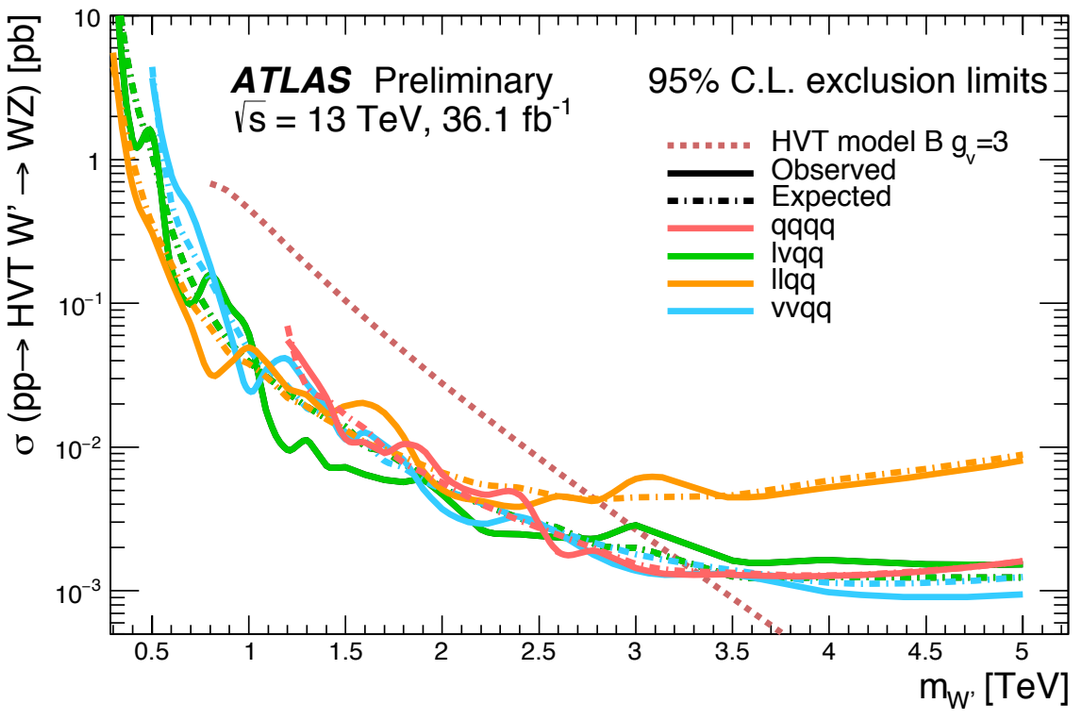




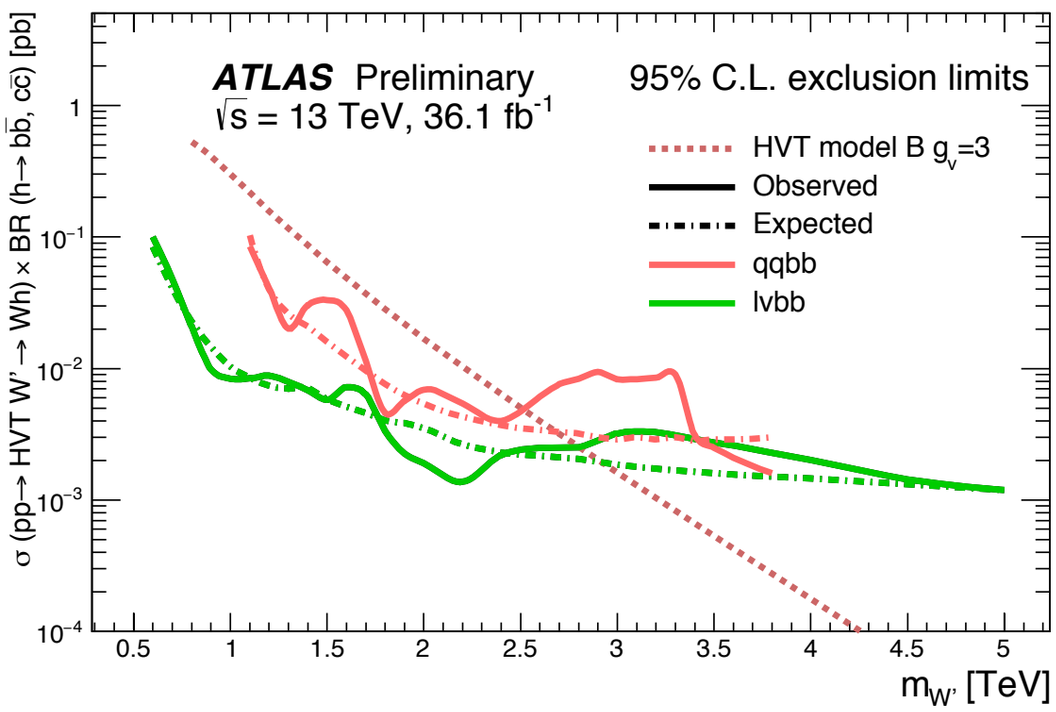
- Exclusions from heavy Higgs searches are summarized in the m_A-tanβ plane for hMSSM.
- Significant improvement in Run-2.

TeV-Scale Resonances

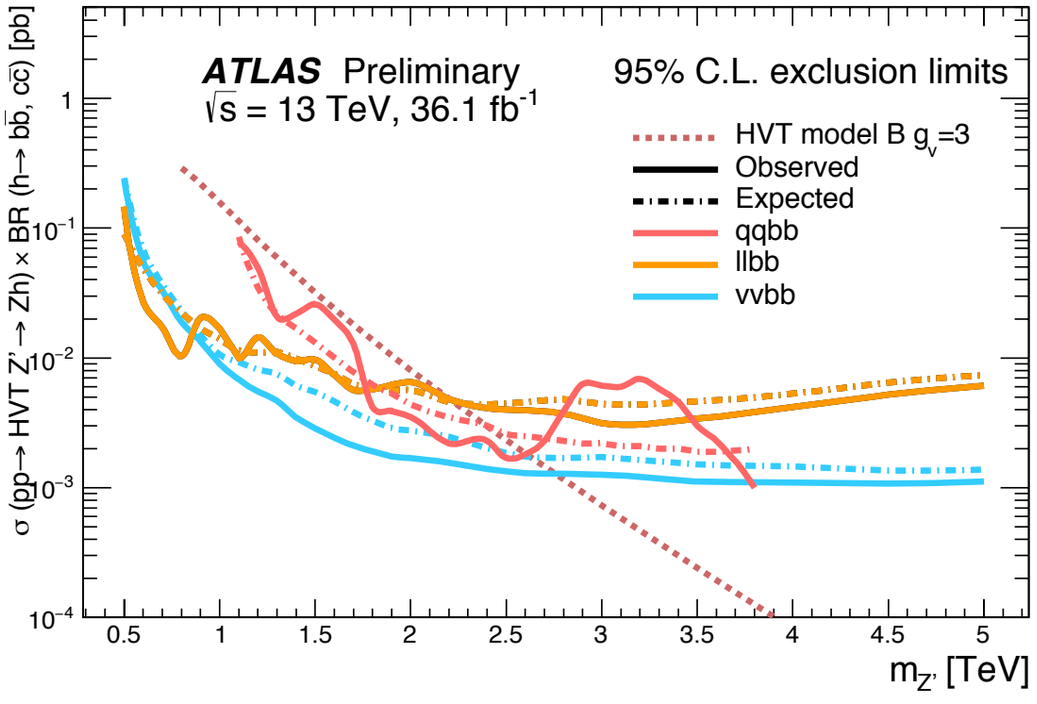
Searches w/ Boosted W/Z Tagging



Searches w/ Boosted Higgs Tagging



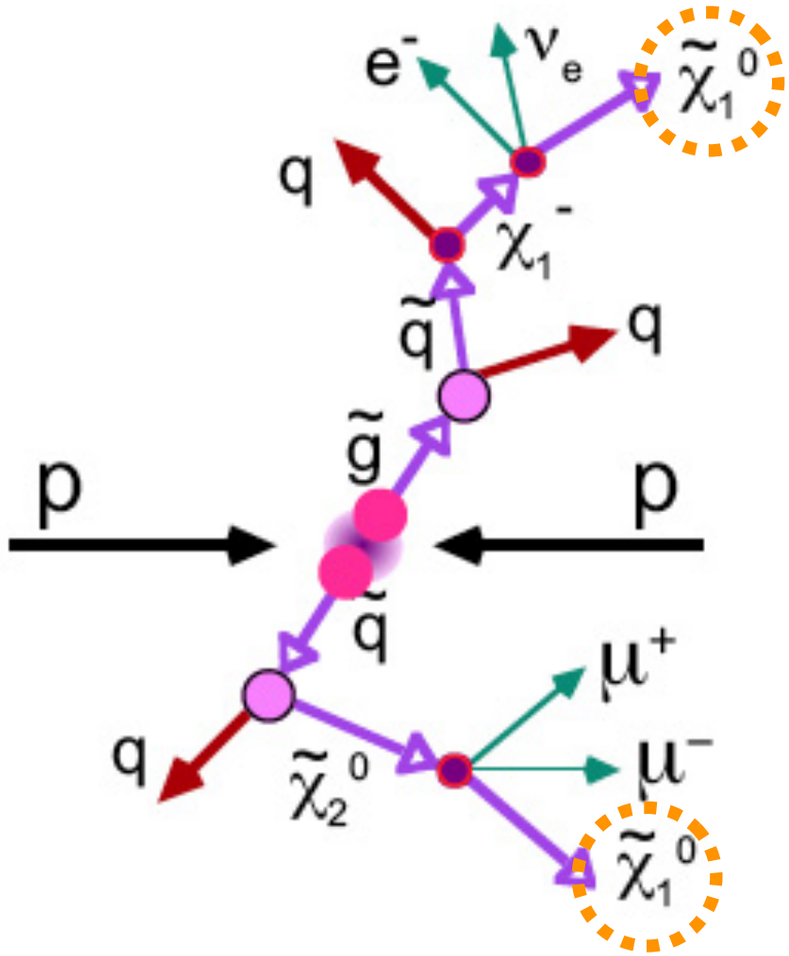
- Hadronic decays from boosted vector or Higgs bosons will be highly collimated & may only be reconstructed as single large-R jets.
- Such boosted-boson tagging techniques have been used for resonance searches at the TeV scale.



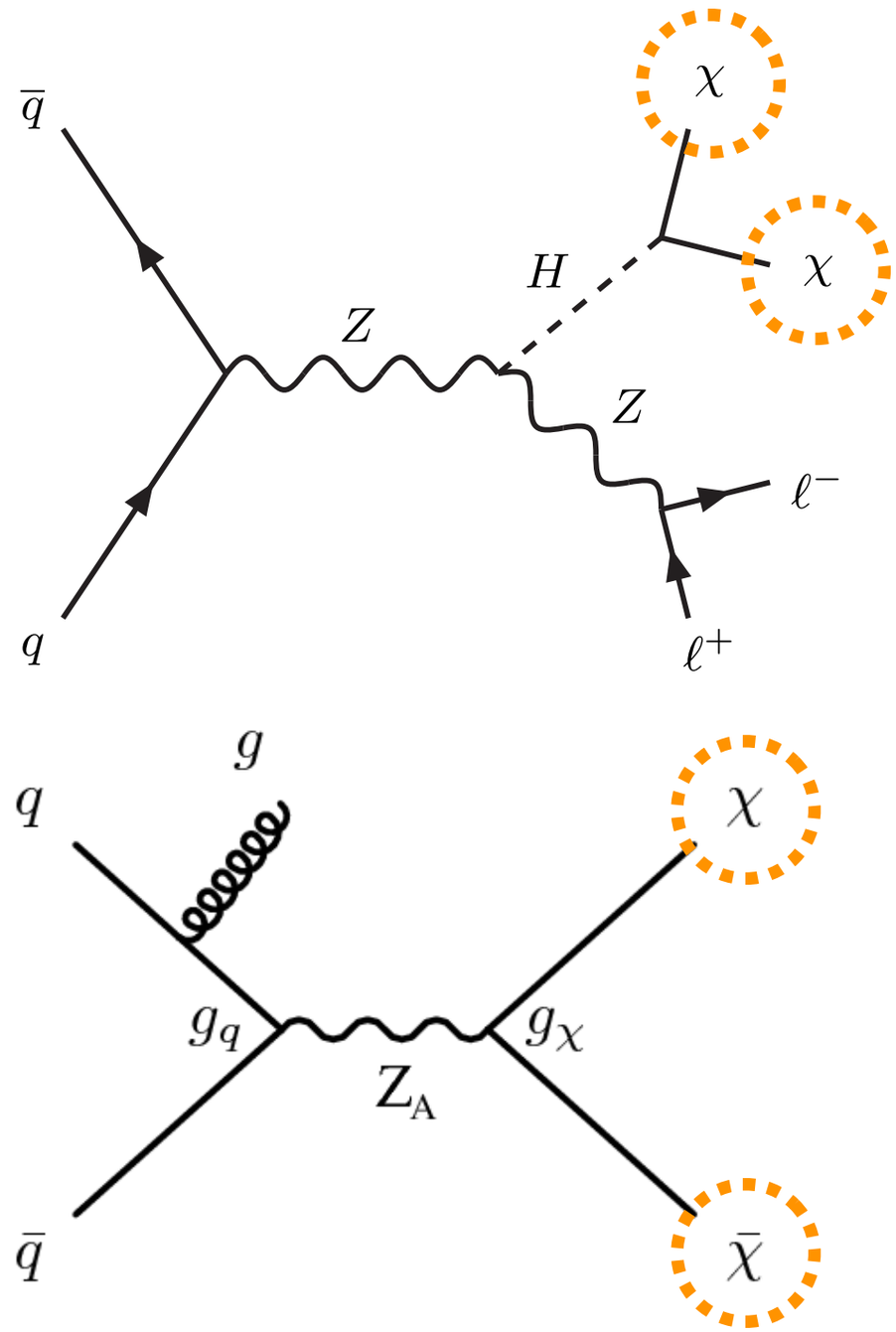
Dark Matter & Supersymmetry

Dark Matter@LHC

Dark matter from cascade decays from Supersymmetric particles

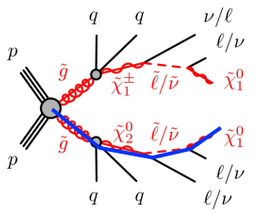


Dark matter directly produced via mediators

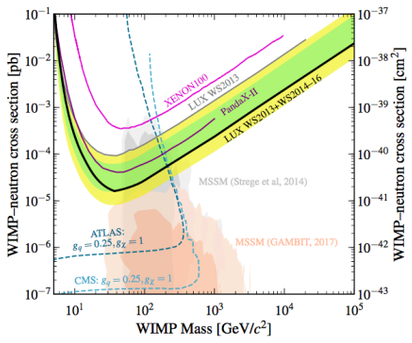


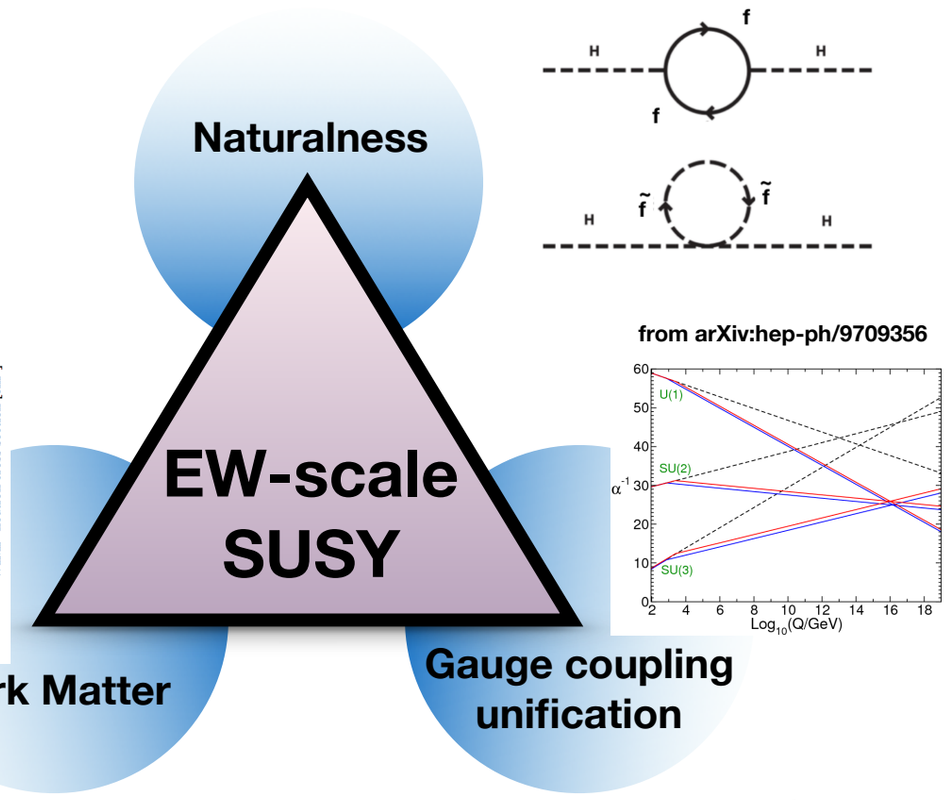
Dark matter could be produced through cascade decays from new particles (e.g. supersymmetric partners) or directly via mediator.

Supersymmetry



R-parity conservation

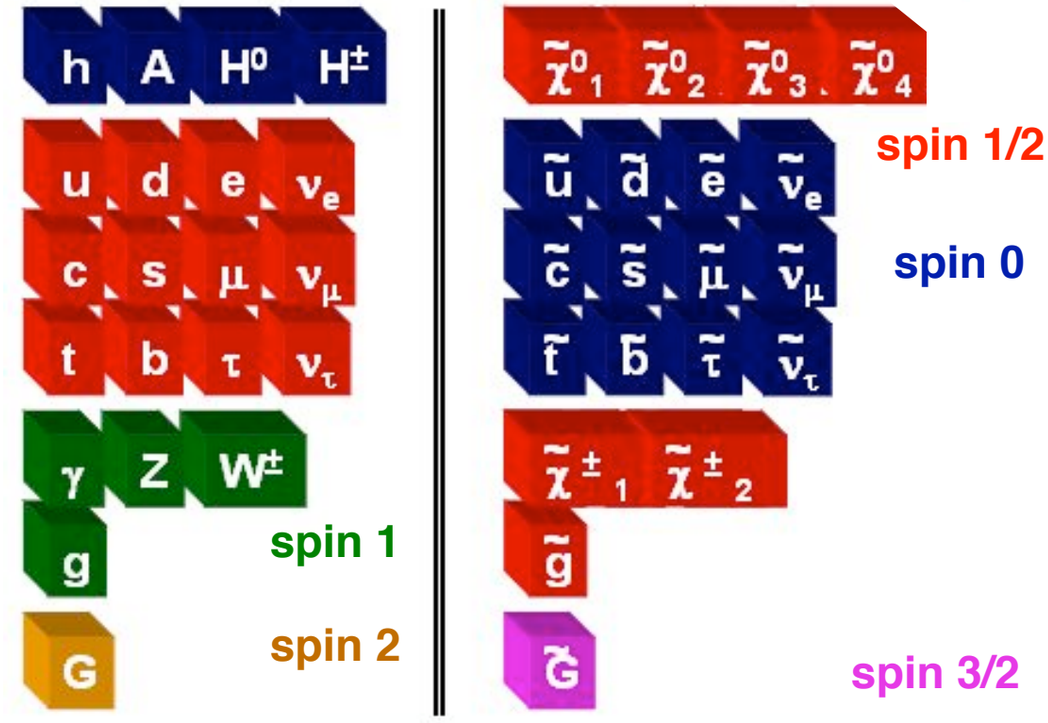




from arXiv:hep-ph/9709356

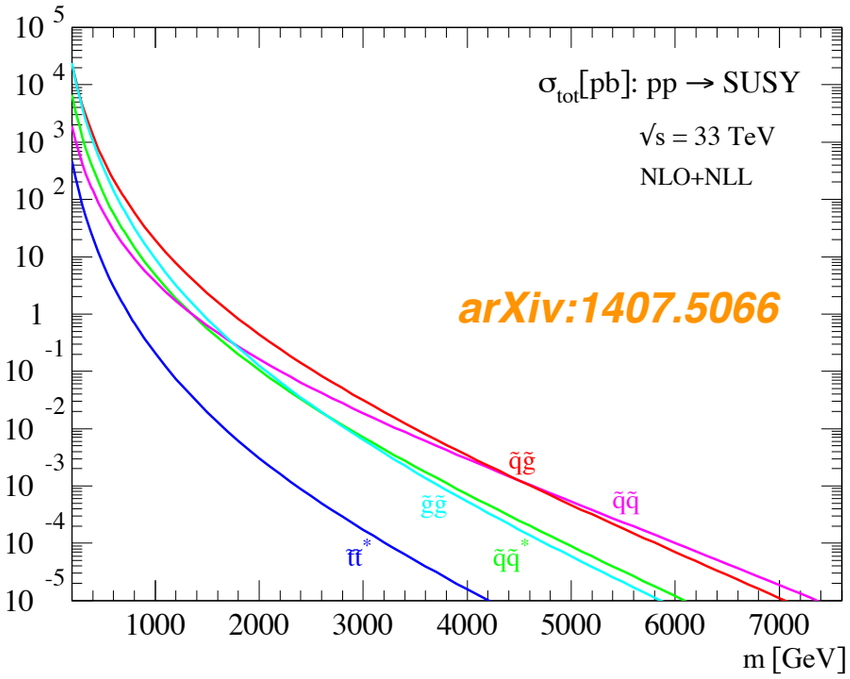
Thanks to N. Craig for the idea

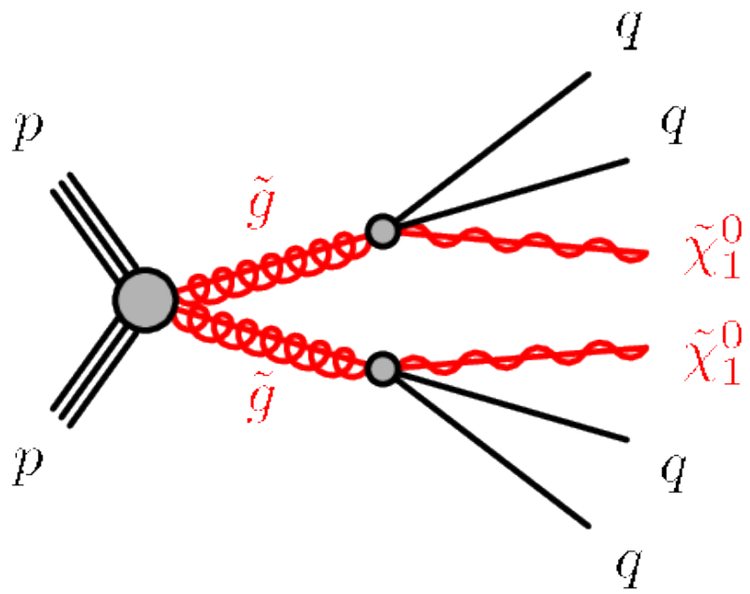
I. Vivarelli

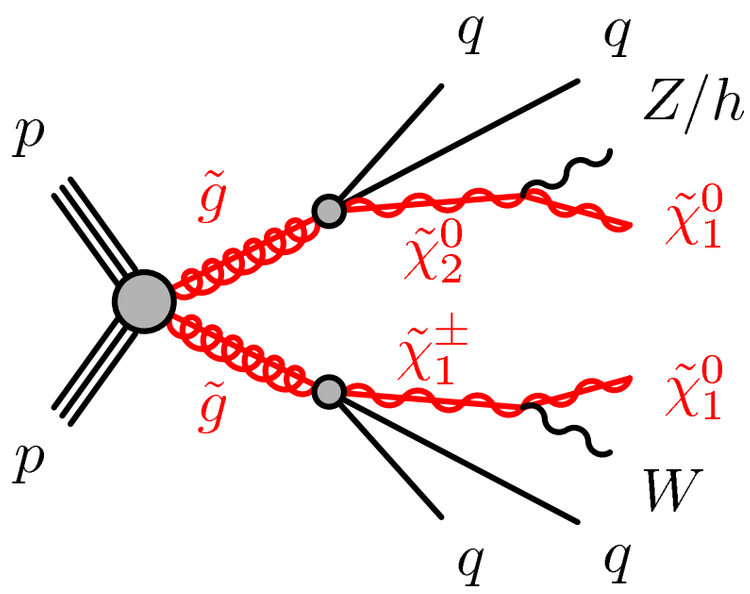


- EW-scale Supersymmetry (SUSY) is motivated by three outstanding points (though naturalness is becoming less compelling now due to the lack of low mass SUSY particles).
- Supersymmetry predicts existence of a new set of partner particles (“sparticles”) to the Standard Model ones.

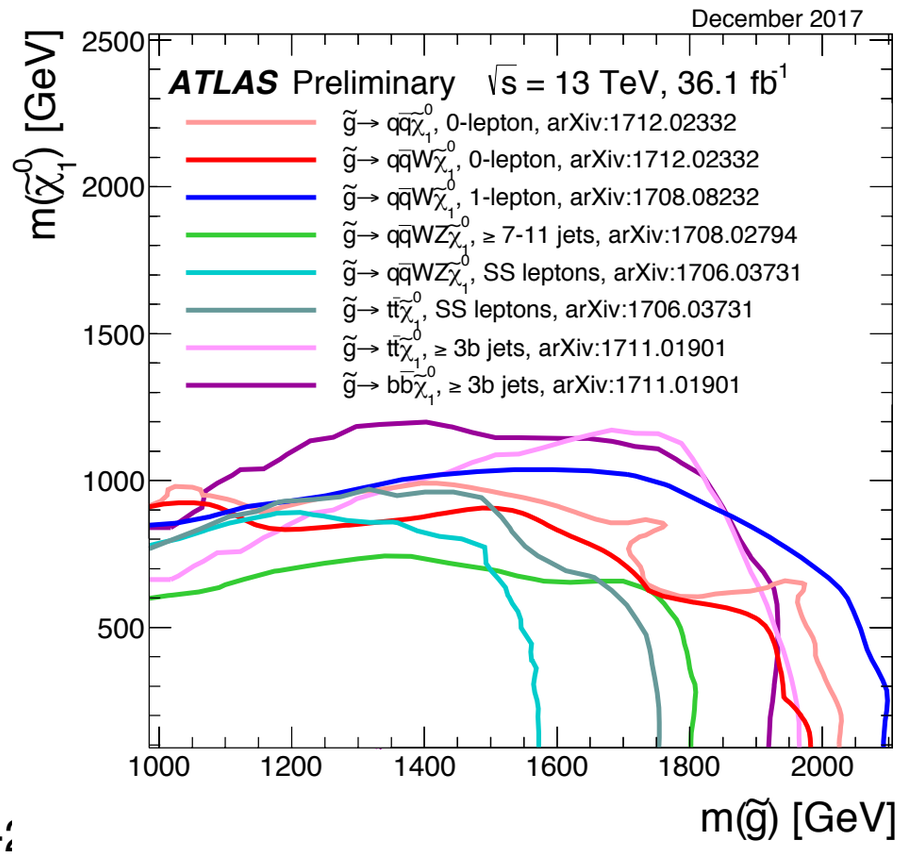
Gluino Searches



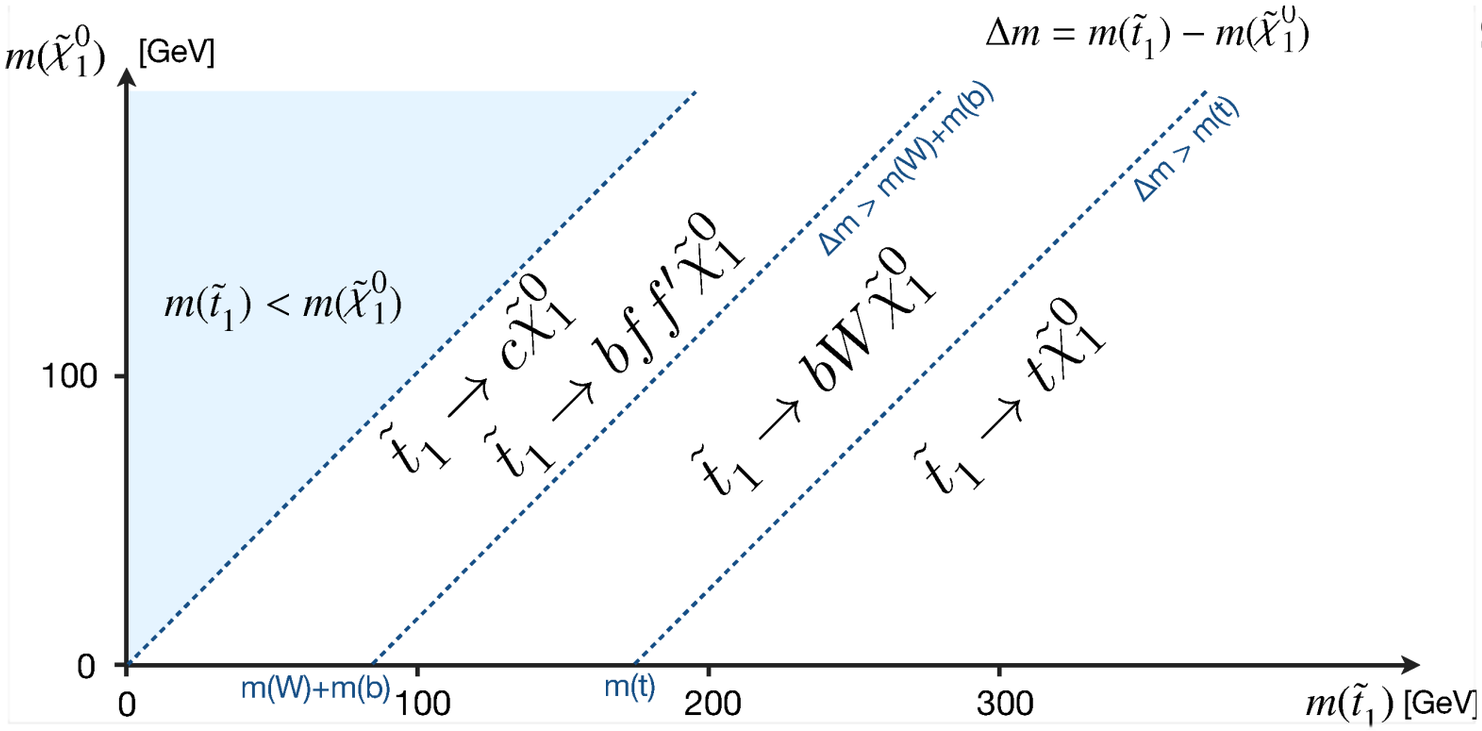


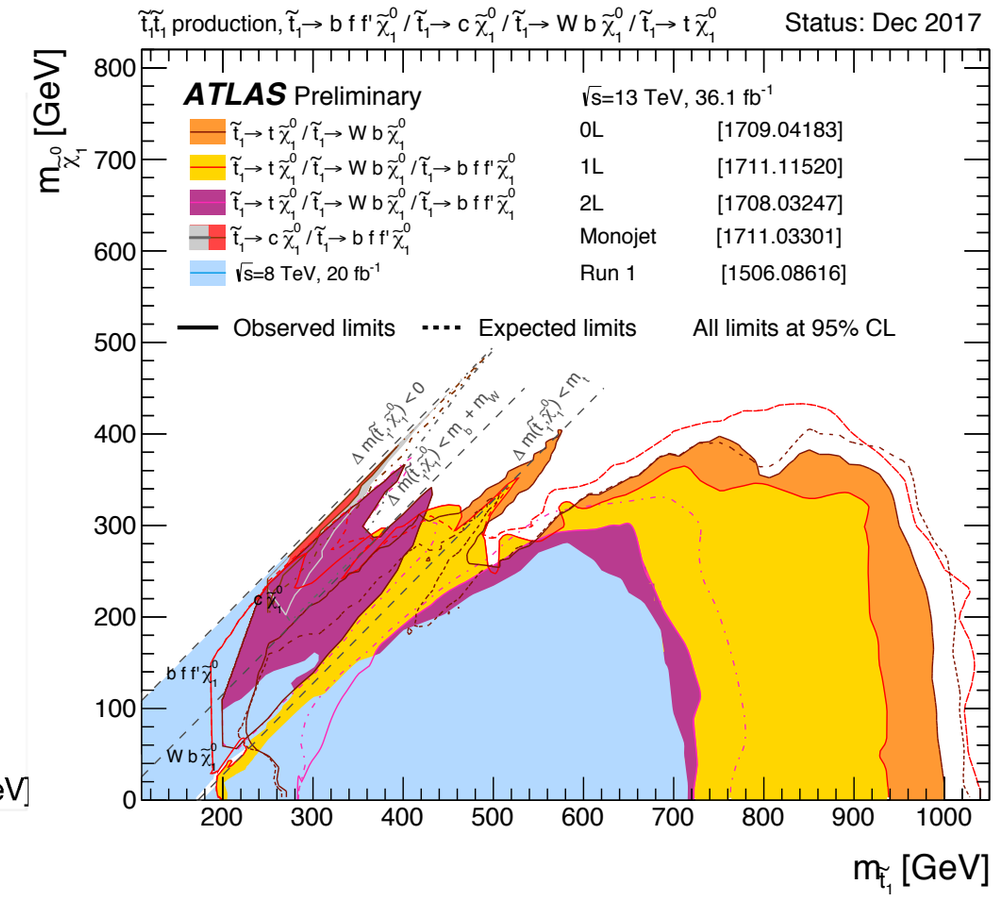


- **Gluino pairs could be one of the most-largely produced sparticles for a specific mass.**
- Jet multiplicity depends on the number of cascade decays & boson decays. b-jets exist in many cases.
- **m_{gluino} ~ 2 TeV is excluded in generic phase space; but much reduced in compressed scenarios.**



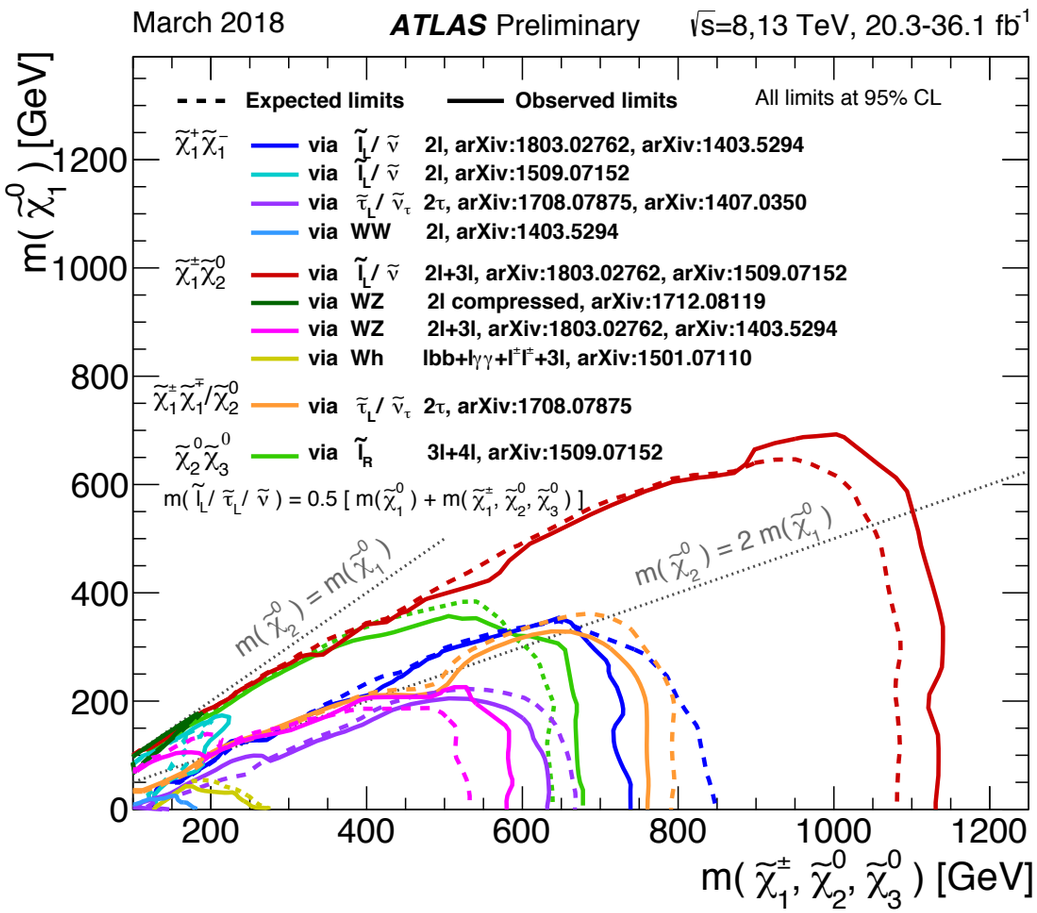
Stop Searches

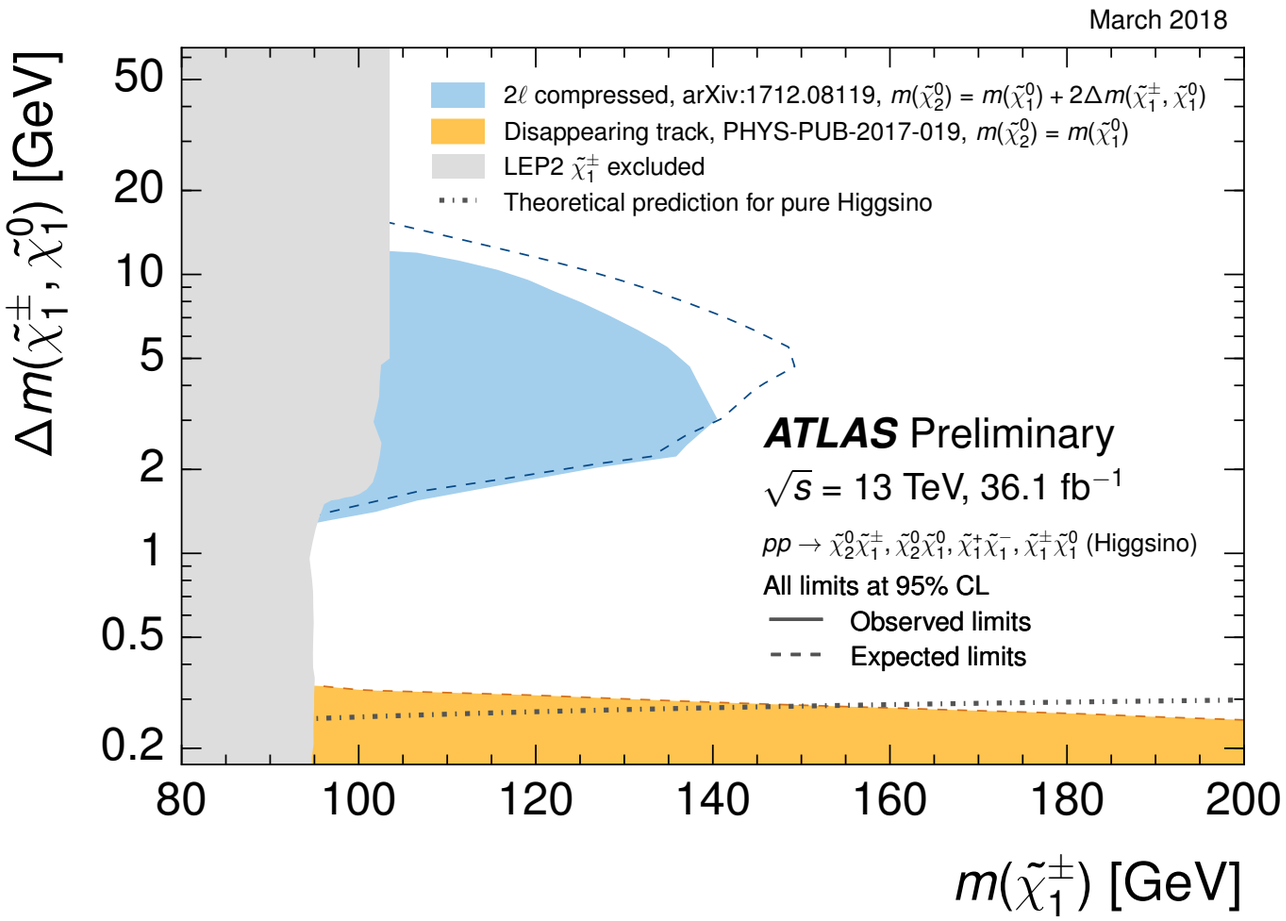




- **Top squarks (or "stop's")** could have relatively low masses (& possibly reachable by the LHC) due to naturalness.
- Its decay pattern depends on the mass difference between the lightest supersymmetric particles (LSP's) and stop's.
- **m_{stop} ~ 1 TeV is excluded for large phase space. Nature seems to be "fine-tuned" at some level.**

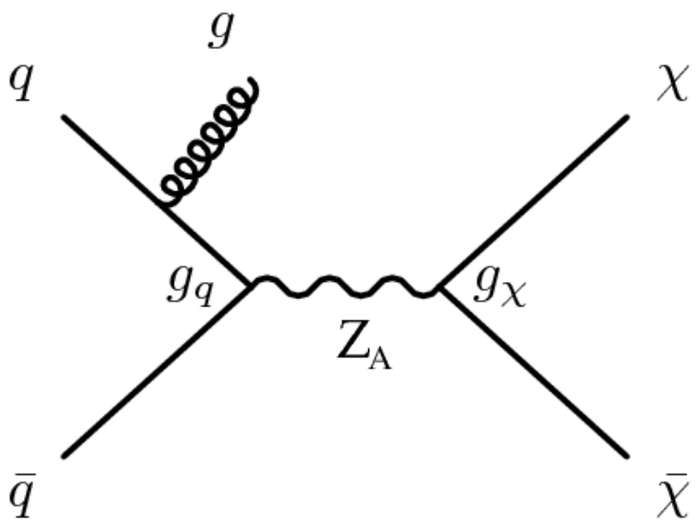
Electroweakino/Higgsino Searches



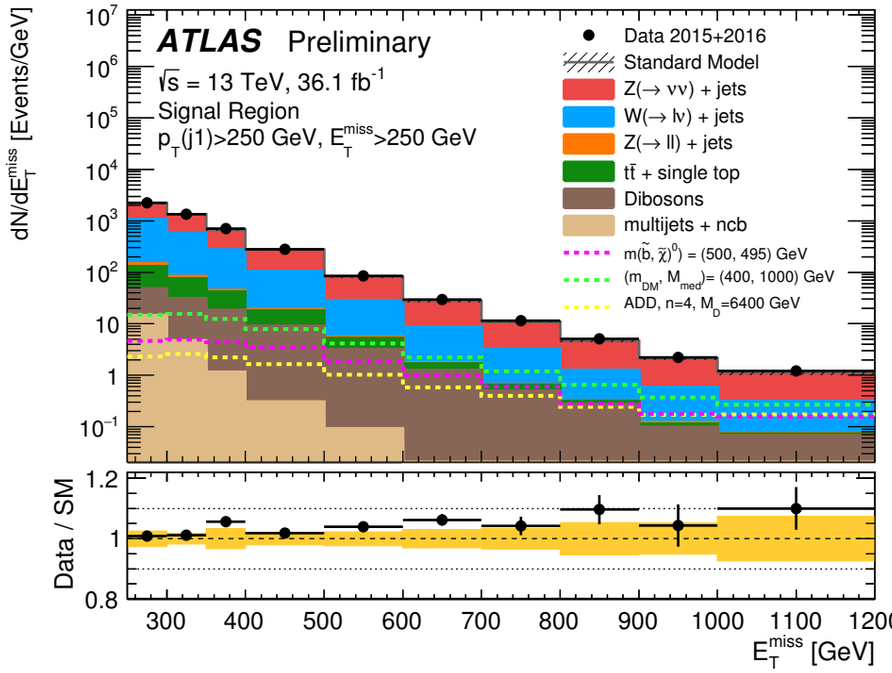


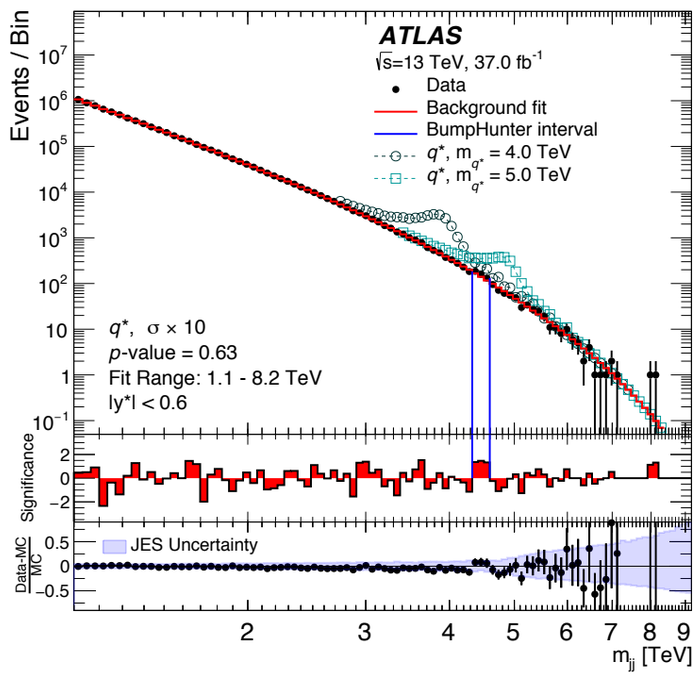
- Sensitivity to electroweakinos and higgsinos is improved due to large statistics.
- **Surpassed the LEP limit for higgsinos for the first time at the LHC!**

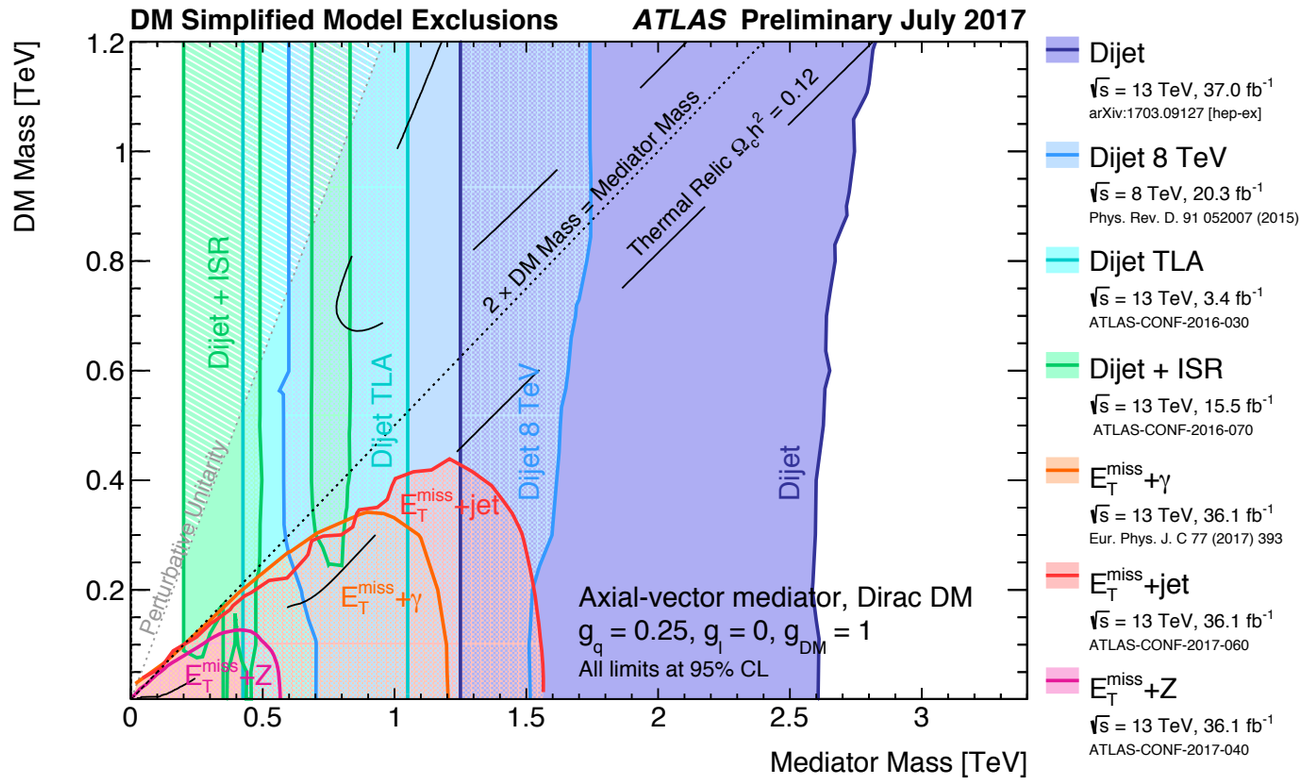
More Generic DM Searches



- Direct productions of DM are searched in "E_T^{miss} + ISR (jet,γ, W/Z, etc.)" final states.
- "Monojet" channel (ISR=jet) has the highest sensitivity for generic cases.
- Assuming the simplified model above, the dijet resonance searches can also be interpreted for DM models.

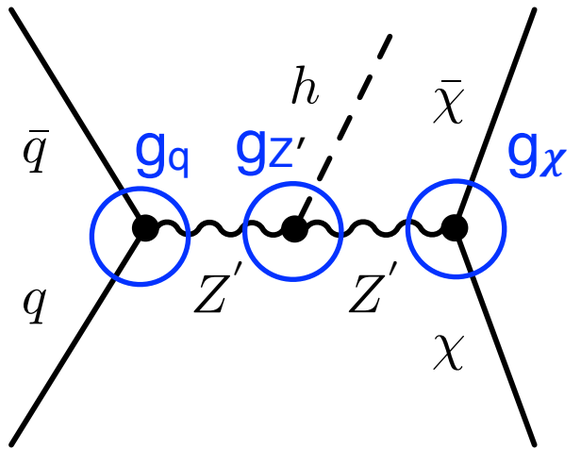




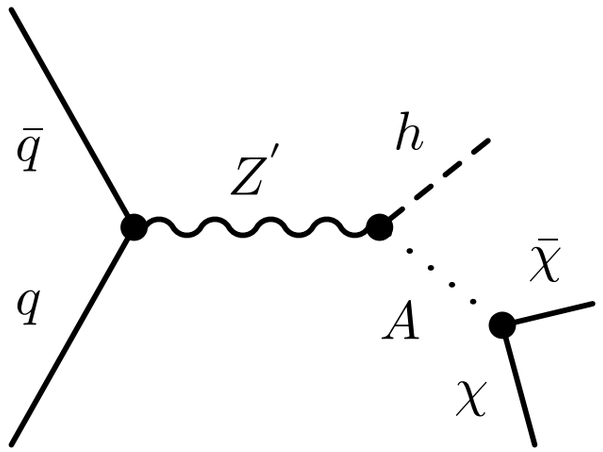


Mono-H DM Searches

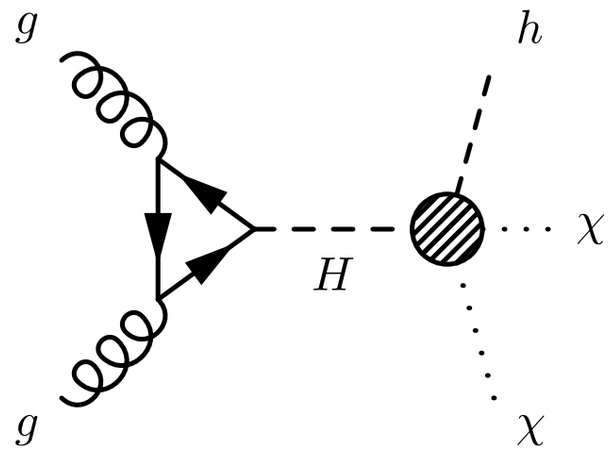
Vector Mediator Model



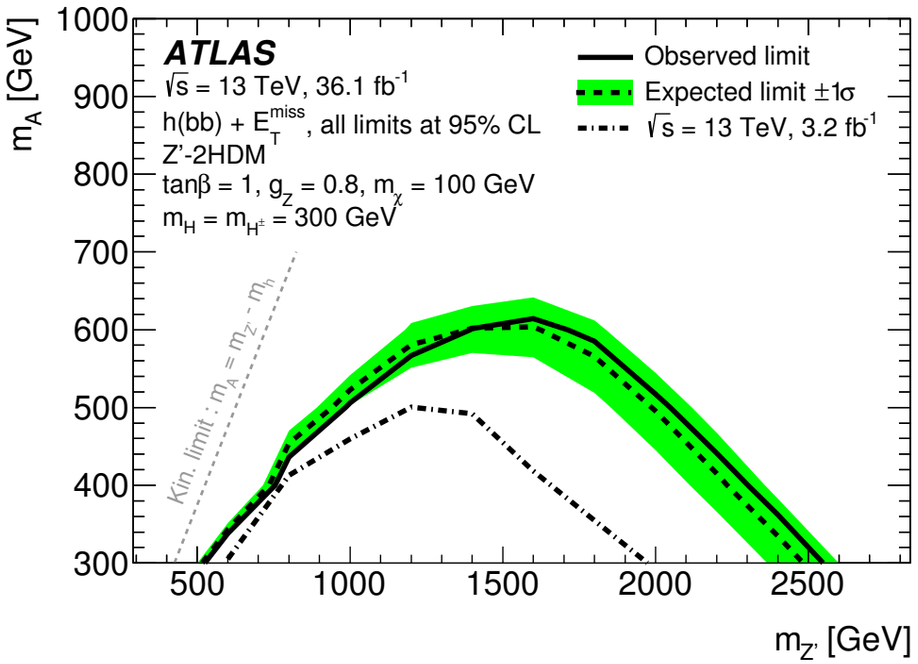
Z′-2HDM Model

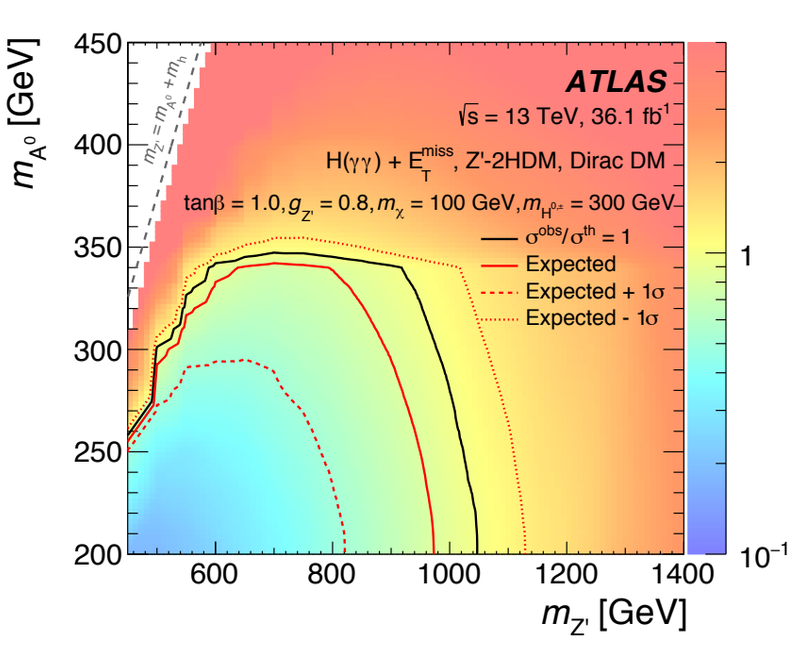


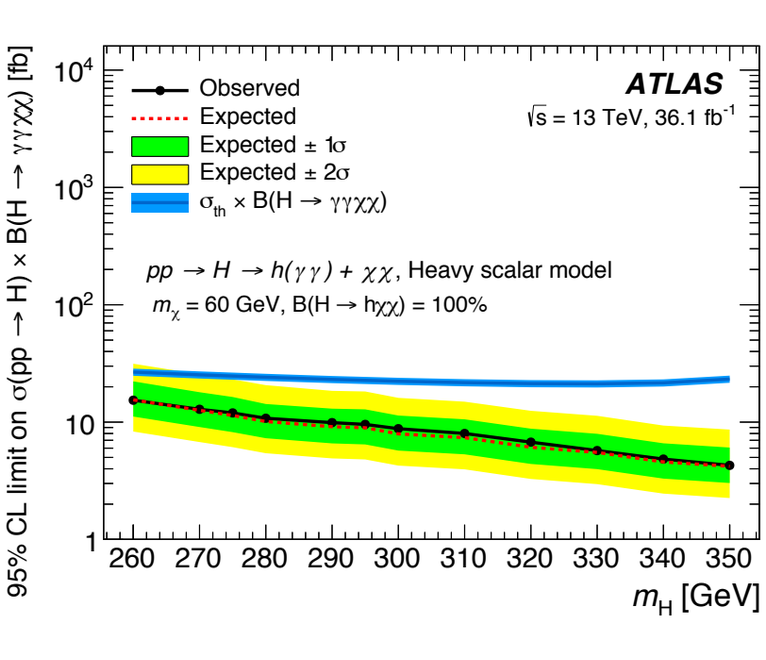
Heavy Scalar Model



- Higgs-strahlung from initial-state partons is suppressed by the Yukawa coupling.
- **Mono-H searches are direct probes for the DM interactions.**







Summary

- **Properties of the discovered Higgs boson is consistent with the Standard Model so far.**
- However, for new particle searches, there are a few excesses here and there, and they should be investigated further with more data.
- We will continue the precision measurements & searches with more data, and will also introduce various improvements and new methodologies to improve sensitivities to new phenomena.