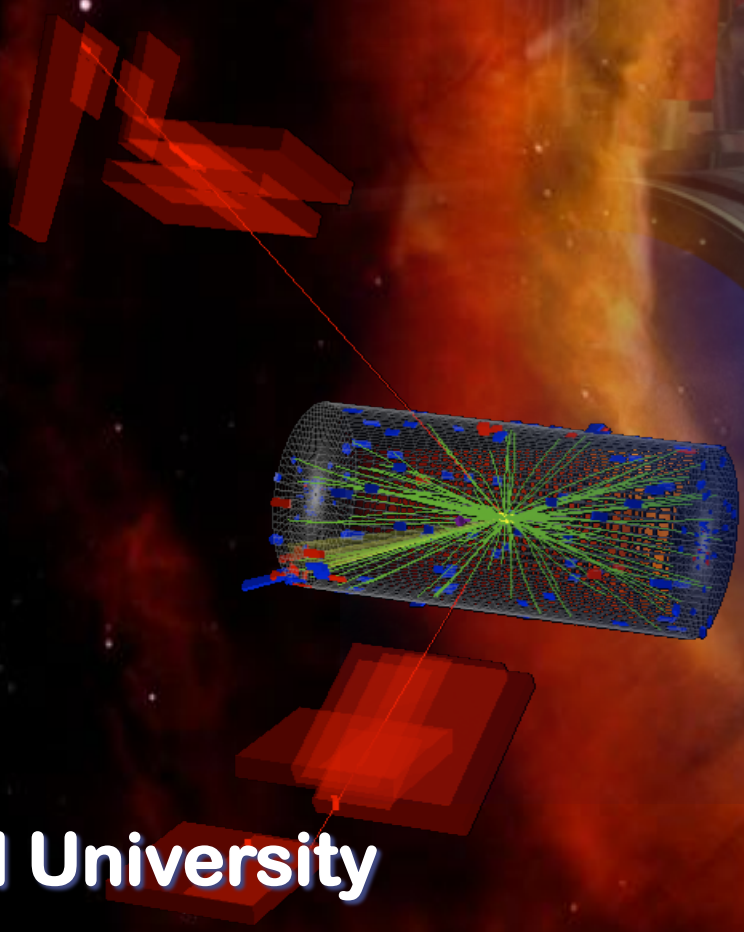
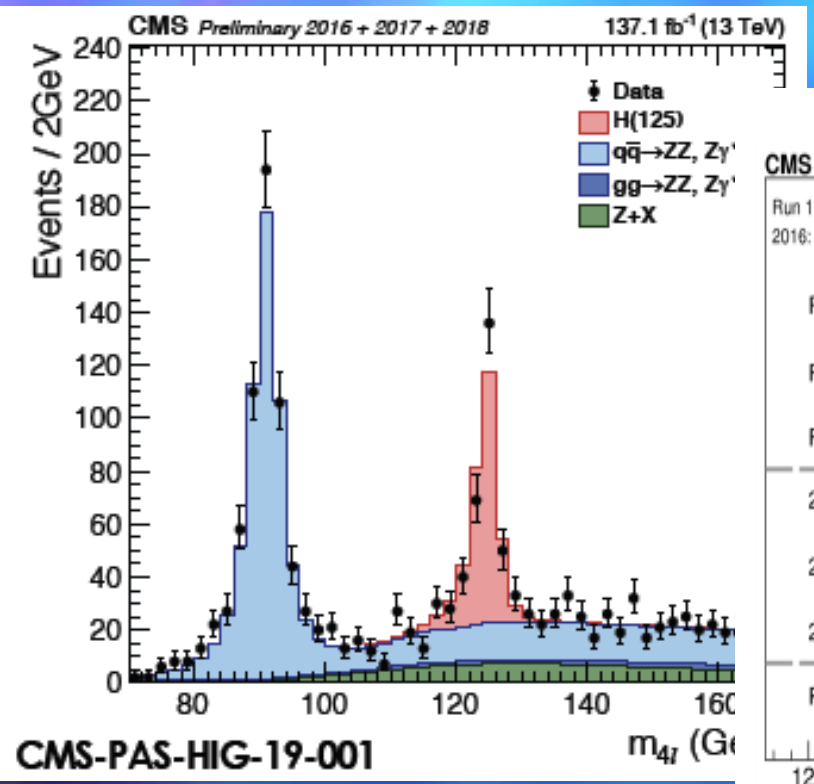
BSM Higgs Physics at the LHC

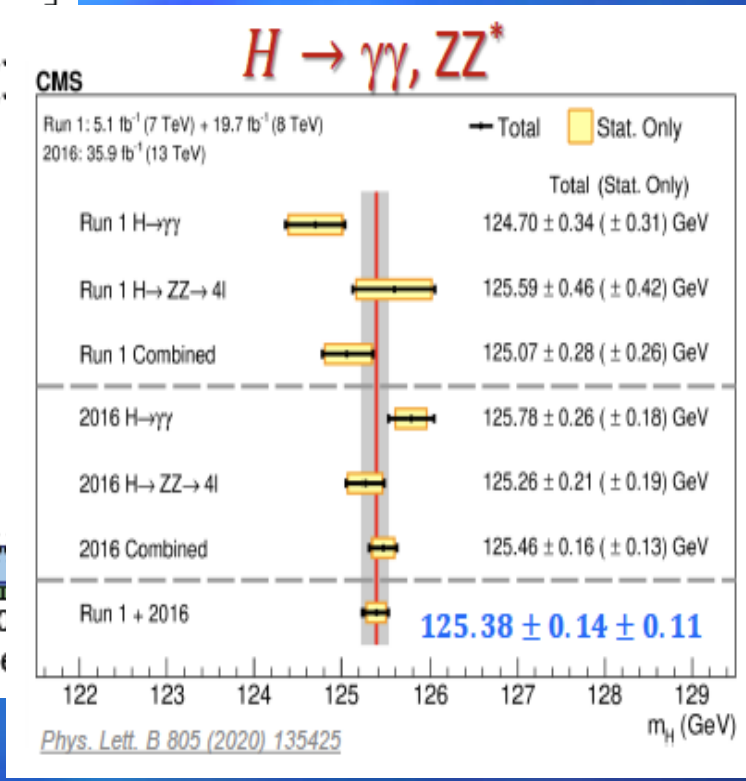


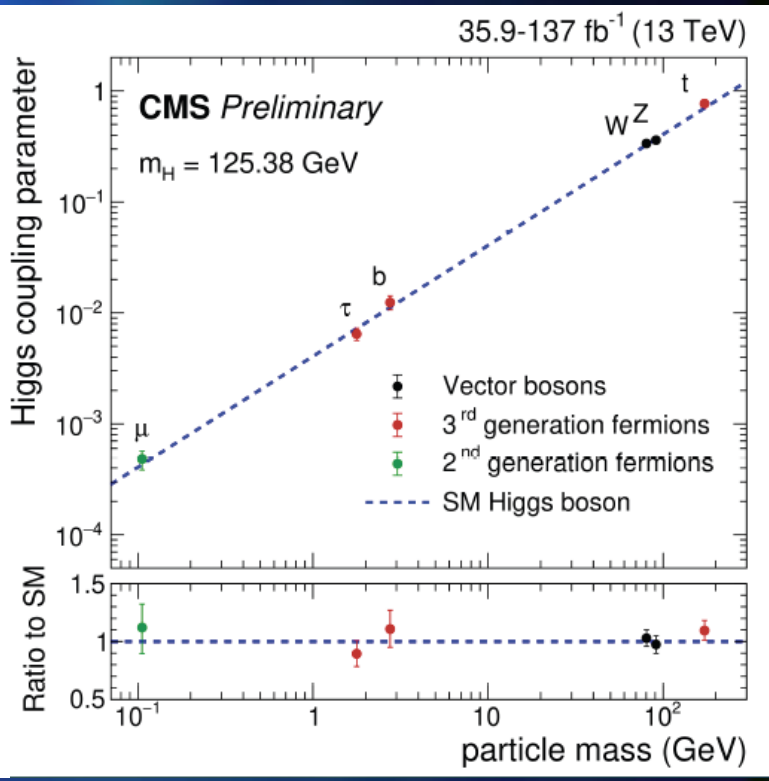
Un-ki Yang
Seoul National University

KCMS Collider Lecture Series, May 10, 2022

Since the discovery of Higgs

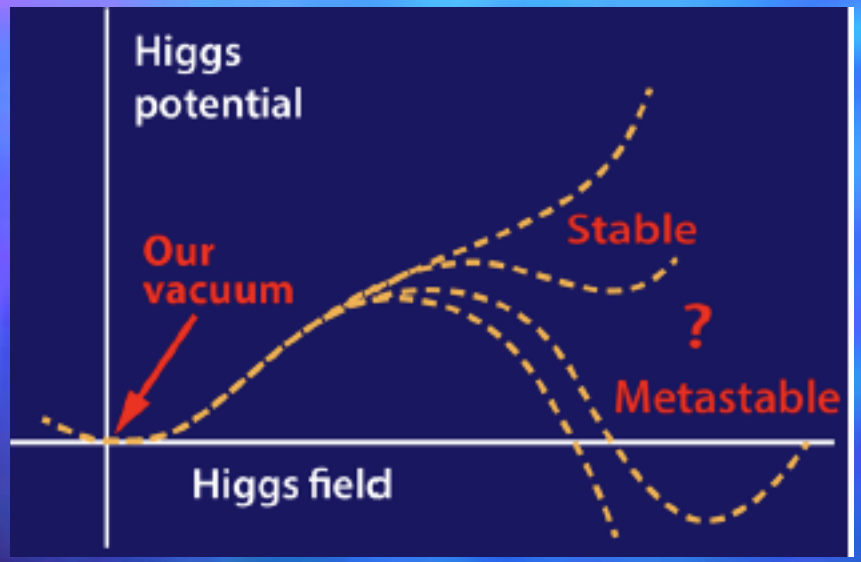


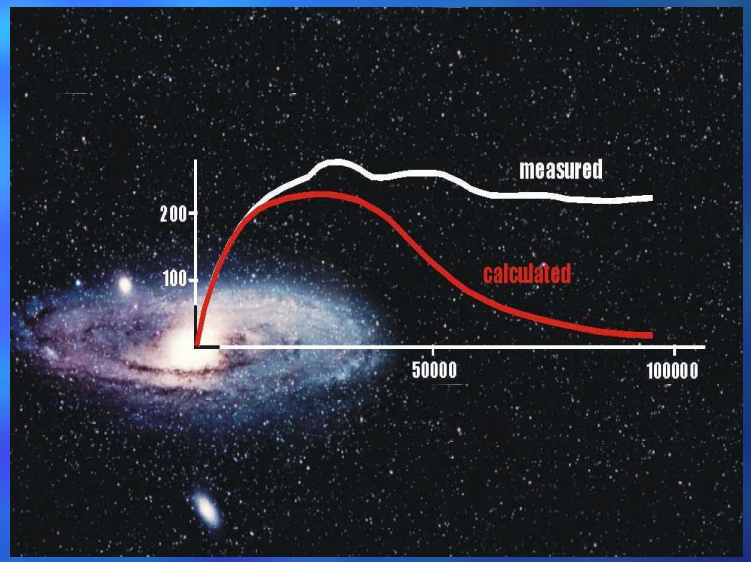


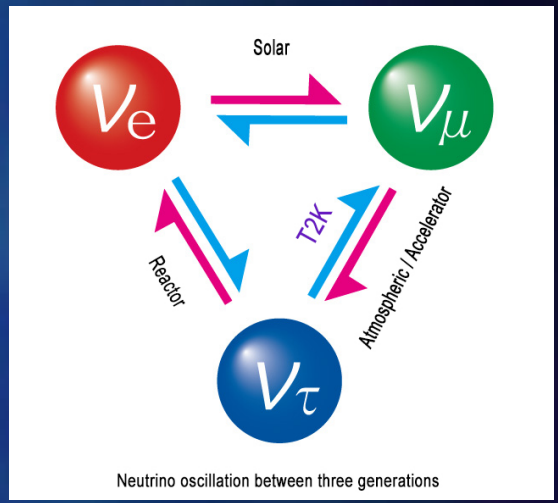


- Higgs mass: 125.38 GeV with 0.1% precision
- Couplings to the SM particles: consistent with the SM predictions
- All consistent with the SM Higgs world

But the real world ...
the BSM Higgs(?) world





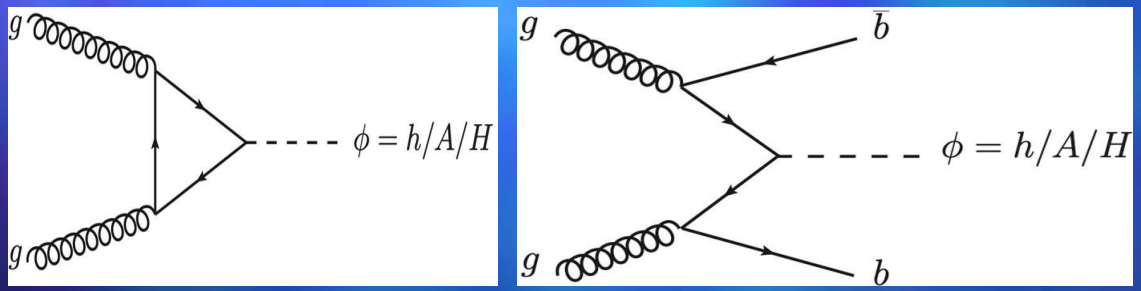


- Unstable Higgs mass, stability of our vacuum depending on Higgs potential
- BSM phenomena
  - Dark matter with gravitational interaction coupled to mass
  - Neutrino mass

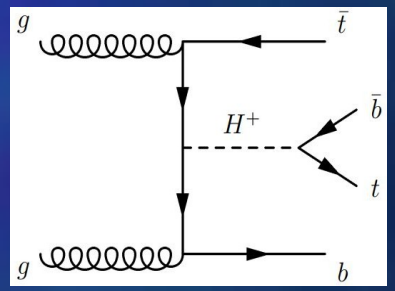
BSM Higgs

- Many BSM theories predict extended Higgs sector
- Two-Higgs-Doublet models (2HDM) such as in SUSY: five Higgs bosons
  - 2 neutral CP even (h, H), 1 neutral CP odd (A), 2 charged Higgs ($H^{+/-}$)
  - m_h, m_H, m_A, $m_{H+/-}$ (convention $m_H > m_h$) $\tan\beta$, mixing angle α
- Triplet model : double charged Higgs bosons ($H^{++/--}$)

Neutral Higgs Production



Charged Higgs Production



- **Production is enhanced by $\tan\beta^2$**
- **Look for bb, $\tau\tau$ (large coupling) by $\tan\beta$**

- **Higher sensitivity with top quark events**

Searches for Heavy Neutral Higgs

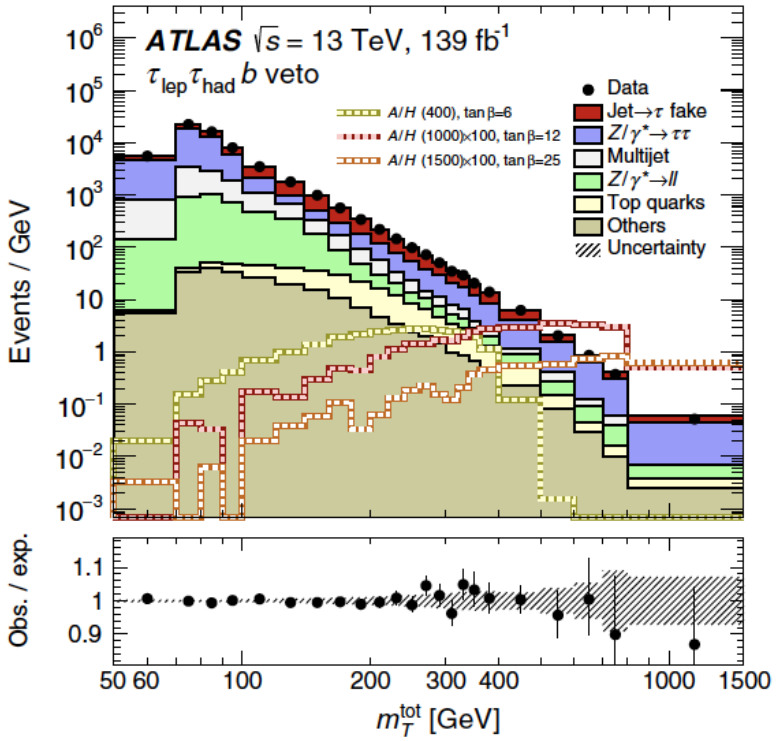
- Recent Run 2 results on direct decays of H/A
- Many channels have been explored

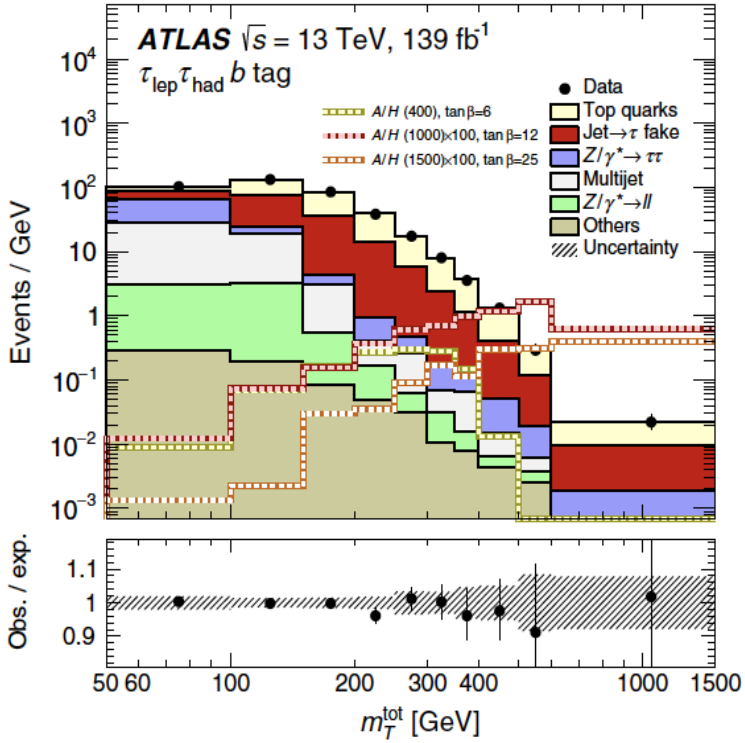
A/H → ττ	arXiv 2002.12223
A → μμ (+ b)	JHEP 07 (2019) 117
bb (φ → bb)	arXiv 1907.02749
X → HH → WW(*)WW(*)	JHEP 05 (2019) 124
X → Z/W/H → qqγ/qqγ/bbγ	Phys. Rev. D, 98, 032015
A → ZH → llbb	Phys. Lett. B, 783, 392-414 (2018)
H → ZZ → 4l / llνν	Submitted to EPJC)
A → Zh → llbb/ννbb	JHEP 03 (2018) 174
A → WW/WZ → lνqq	JHEP 03 (2018) 042

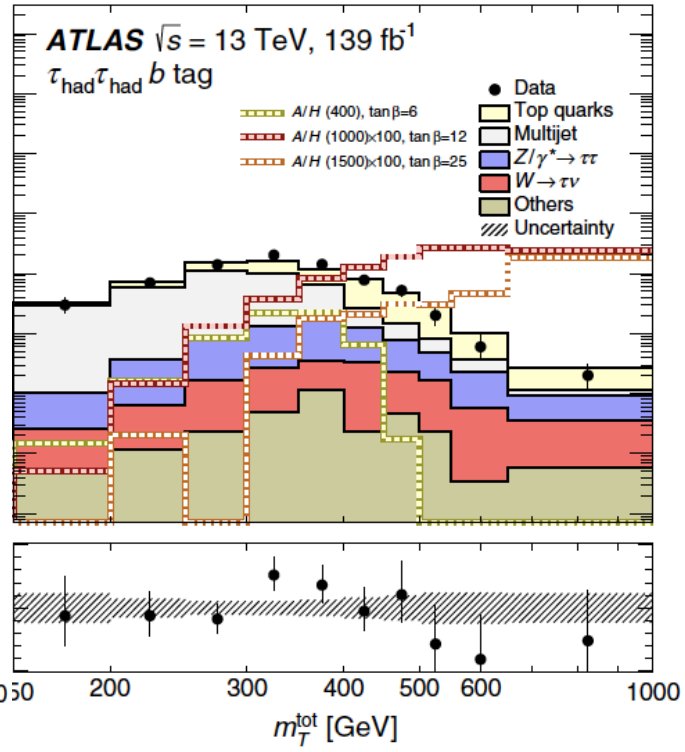
A → hZ → ττll	JHEP 03 (2020) 065
H → ZA → llbb	JHEP 03 (2020) 055
X → WW → 2l2ν / lν2q	JHEP 03 (2020) 034
A → μμ	Phys. Lett. B, 798, (2019) 134992
H/A → tt	arXiv 1908.01115
A → Zh	EPJC, 79, 564 (2019)
A/H → ττ	JHEP 09 (2018) 007
A/H →bb	JHEP 08 (2018) 113
X → ZZ → 4l / 2l2q / 2l2ν	JHEP 06 (2018) 127

Neutral Higgs, $\phi(H/A) \rightarrow \tau\ \tau$

- New ATLAS full Run 2 result with 139 fb^{-1}
- $\tau_{lep}\ \tau_{had}$ (e/μ trigger) and $\tau_{had}\ \tau_{had}$ (τ trigger) channels: b-veto and b-tag category
- BDT to distinguish jet from τ, or e/μ from τ
- Higher sensitivity due to increased luminosity, improved tau ID and optimization

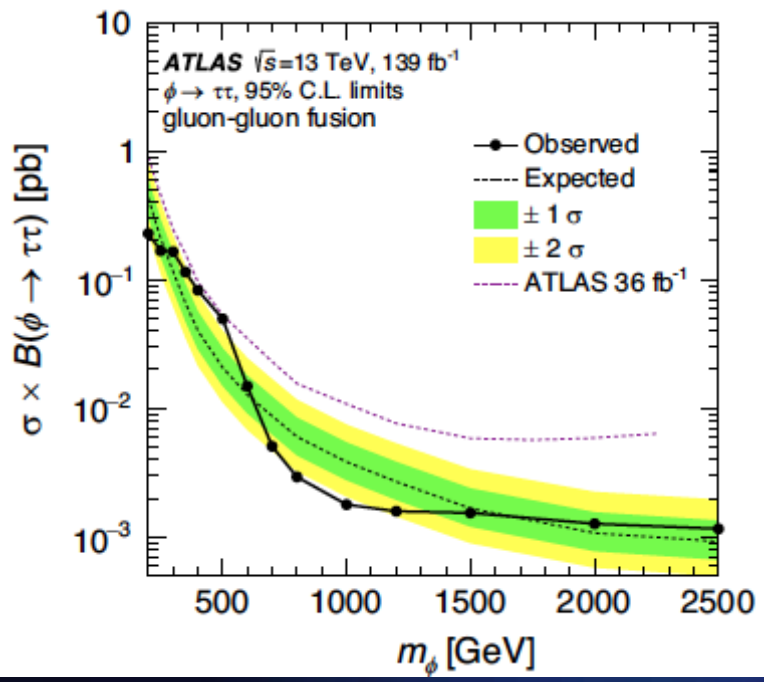


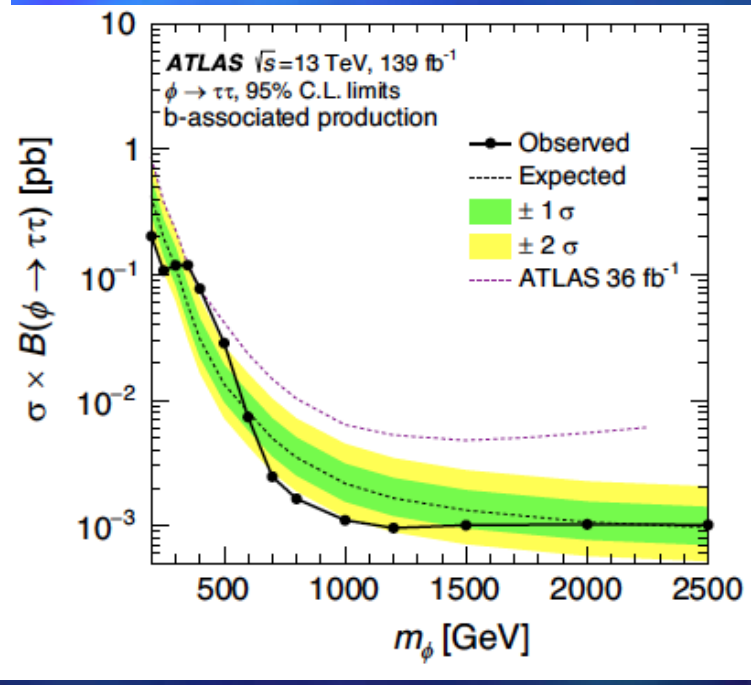


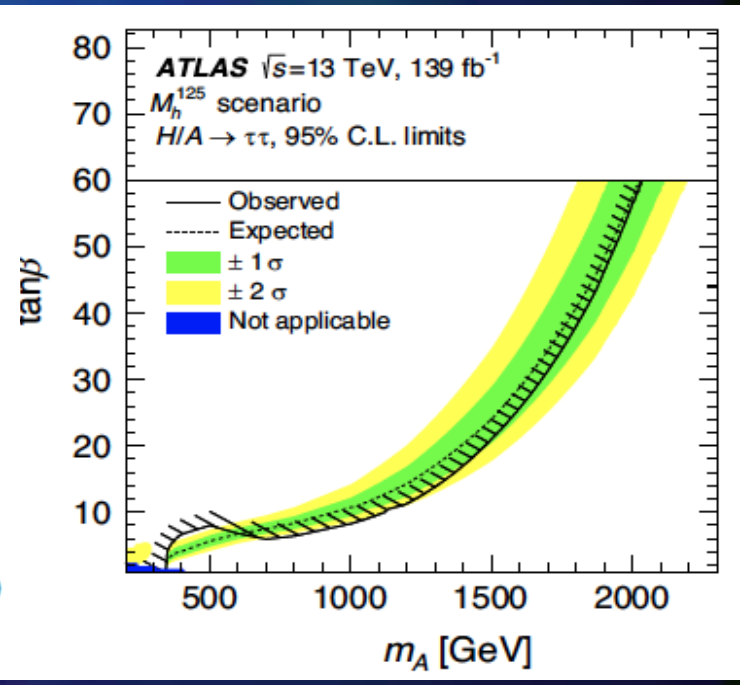


Neutral Higgs, $\phi(H/A) \rightarrow \tau\ \tau$

- The data are in good agreement with the background
- But small excess observed at m=400 GeV, in the data:
  2.2σ (ggF), 2.7σ (bbH) at m=400 GeV
- Set limits on σ x B and and m_A vs tanβ





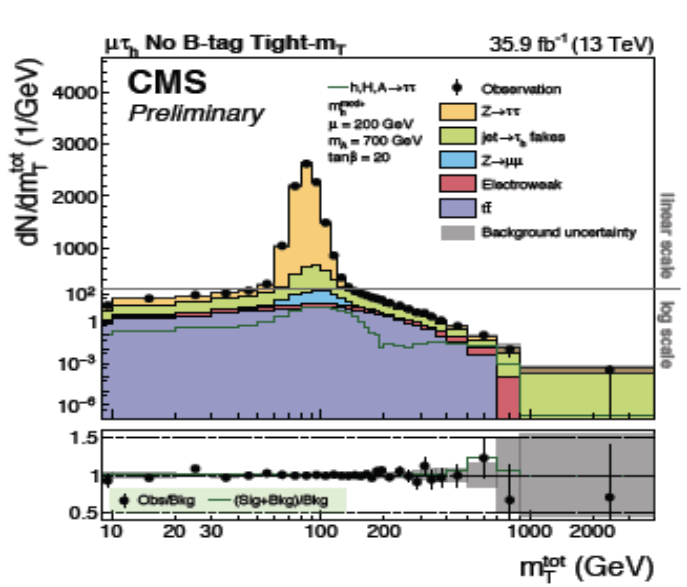


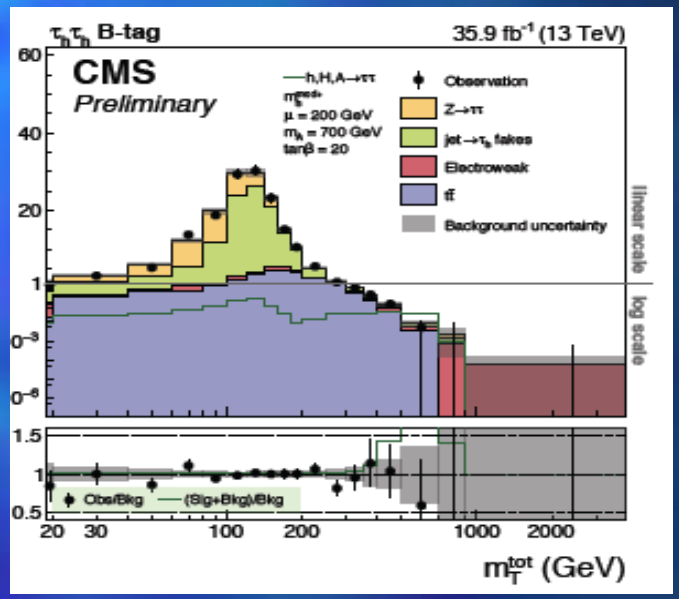
PRL 125 (2020) 051801

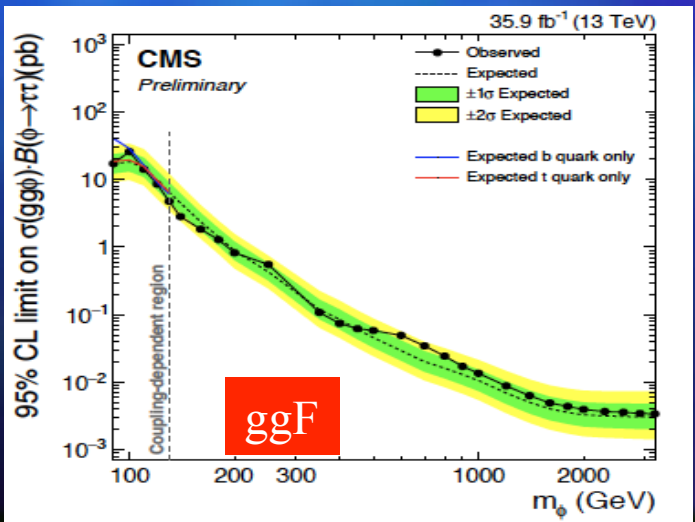
Neutral Higgs, $\phi(H/A) \rightarrow \tau\ \tau$

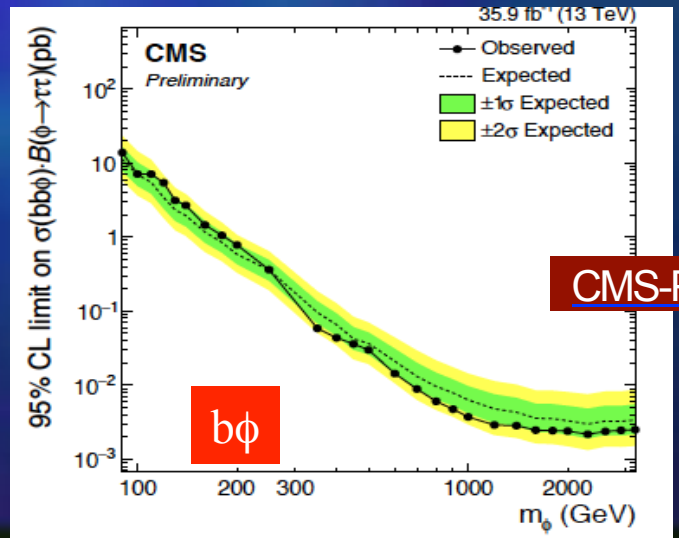
- The earlier CMS results with 2016 data (35.9 fb^{-1})
- No excess observed. Updated results with the full Run 2 data?

$\tau_{lep}\ \tau_{had}$
$\tau_{had}\ \tau_{had}$





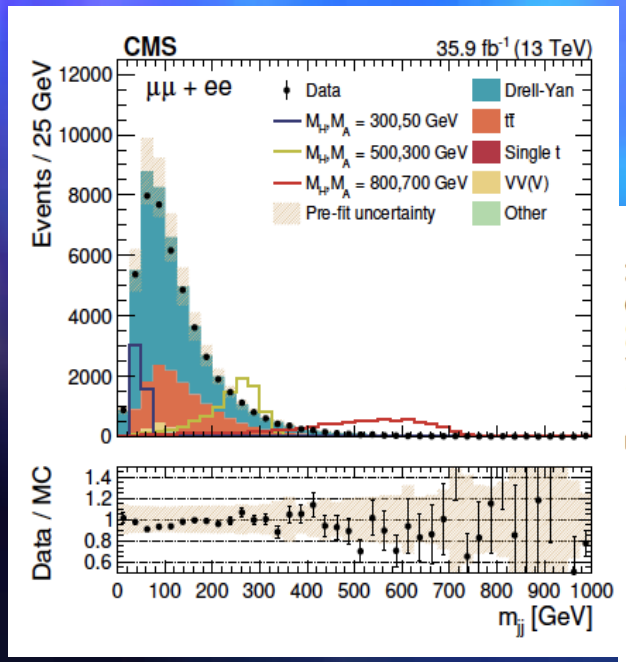


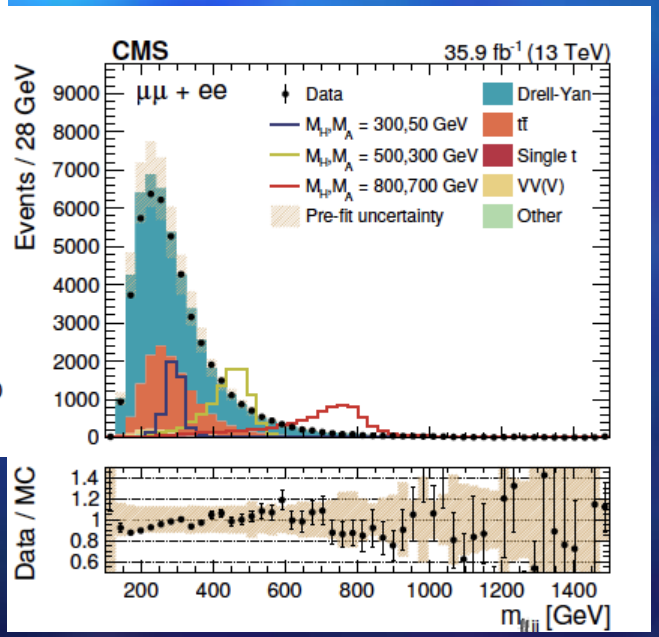


CMS-PAS-HIG-17-020

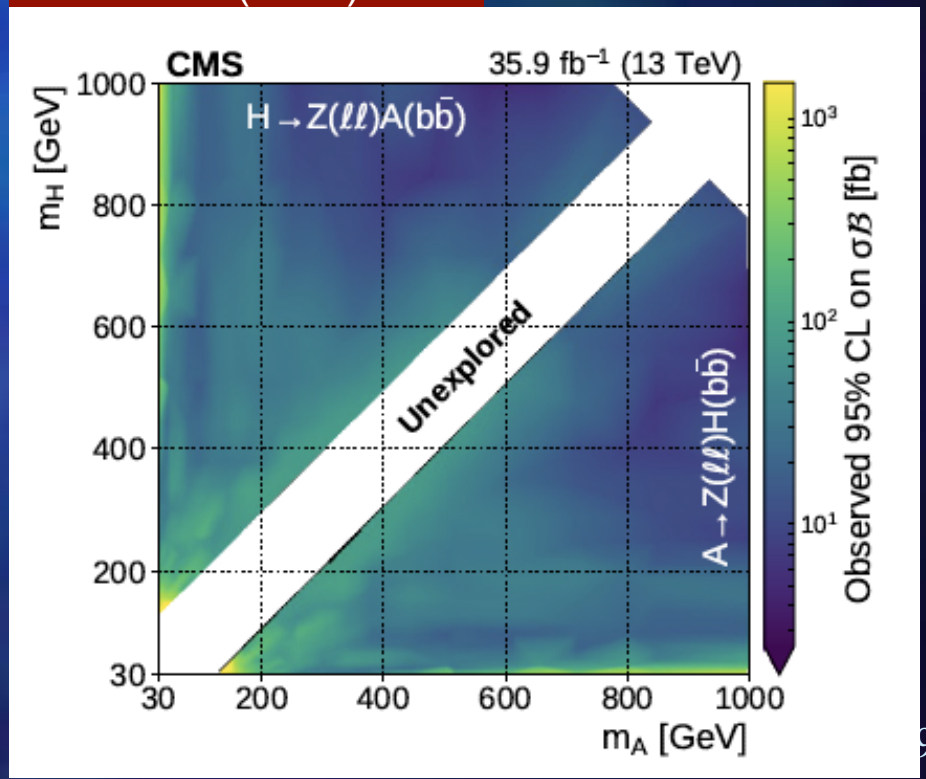
$H \rightarrow ZA \rightarrow llbb$

- CMS assumes $m_H > m_A$ scenario:
  In alignment limit (m_h = 125 GeV), branching of H to ZA is largest
- Dilepton + bb final state: $Z \rightarrow ll$ for clean, $A \rightarrow bb$ for large branching ratio
- Use m_{lljj} and m_{jj}



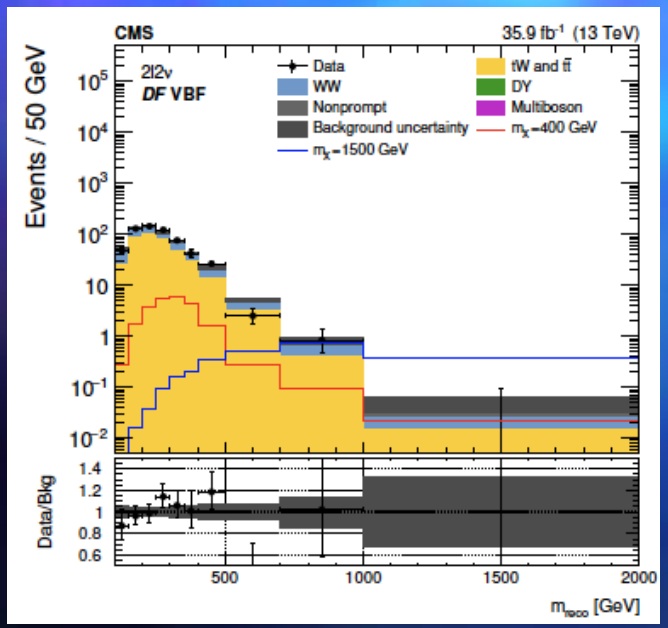


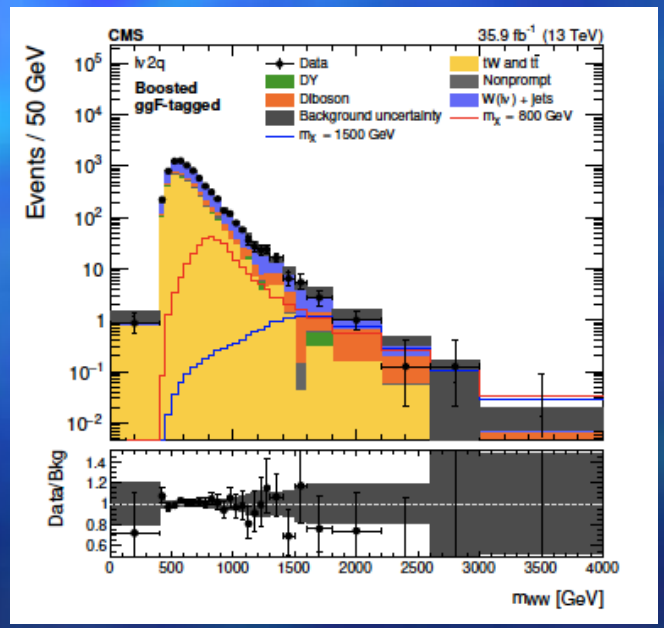
JHEP 03 (2020) 055

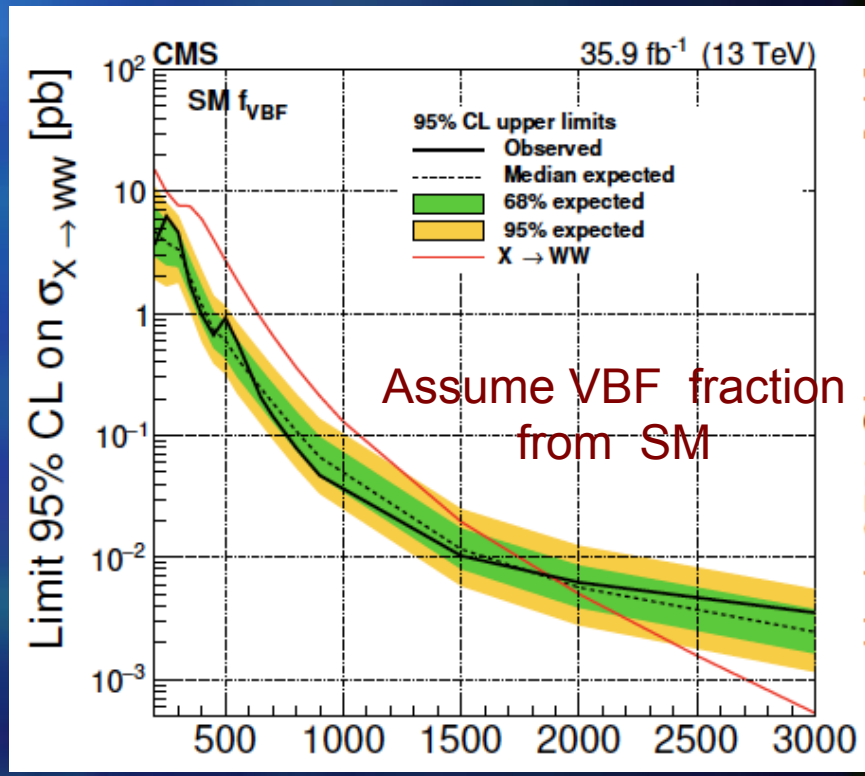


H→ WW (→2l 2ν , lν qq)

- ggF and VBF category
- Same flavor (SF) & different-flavor (DF) 2l (2l2ν)
- Resolved & boosted hadronic W (lν qq)
- Reco. Invariant mass m_{reco} (2l2ν) and H invariant mass m_{WW}(lν qq) as final discriminants







JHEP 03 (2020) 034

Searches for charged Higgs

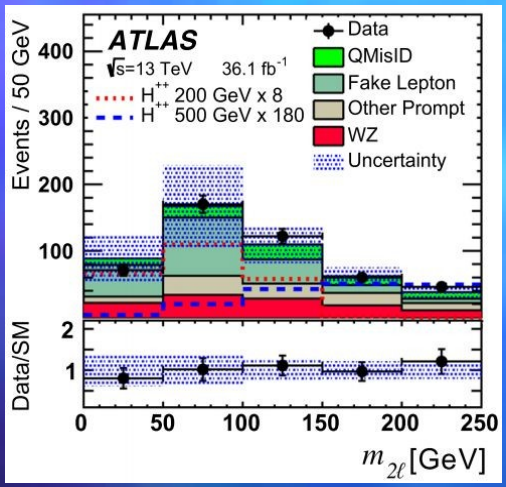
- Two single charged Higgs in 2HDM
- Other models extend to Higgs triplet: double charged Higgs

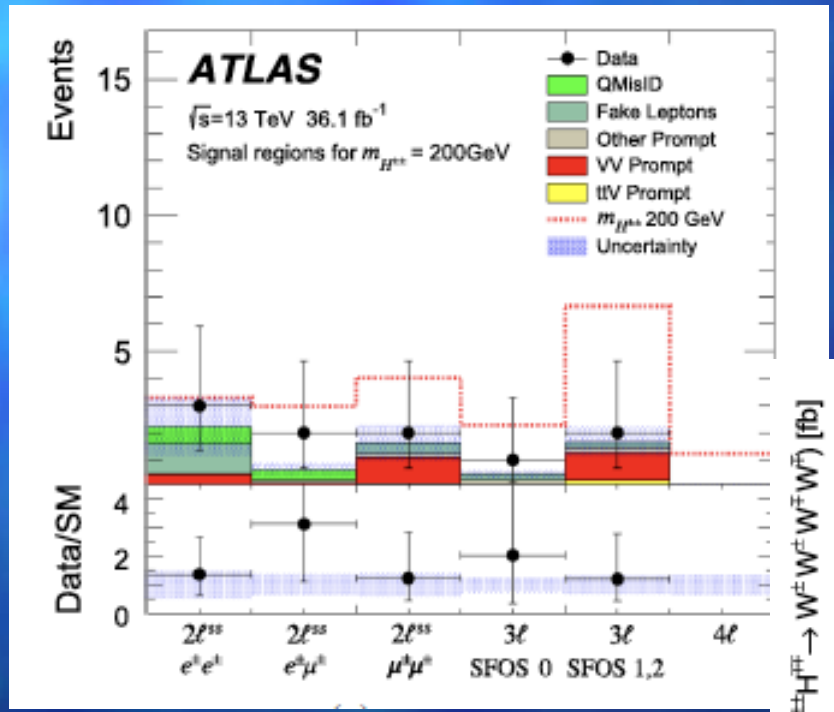
$H^{++}H^{--} \rightarrow 4W$	EPJC 79, 58 (2019)
$H^{+} \rightarrow tb$	JHEP 11 (2018) 085
$H^{+} \rightarrow \tau\ \nu$	JHEP 09 (2018) 139
$H^{++}H^{--} \rightarrow 4l$	EPJC 78 119 (2018)

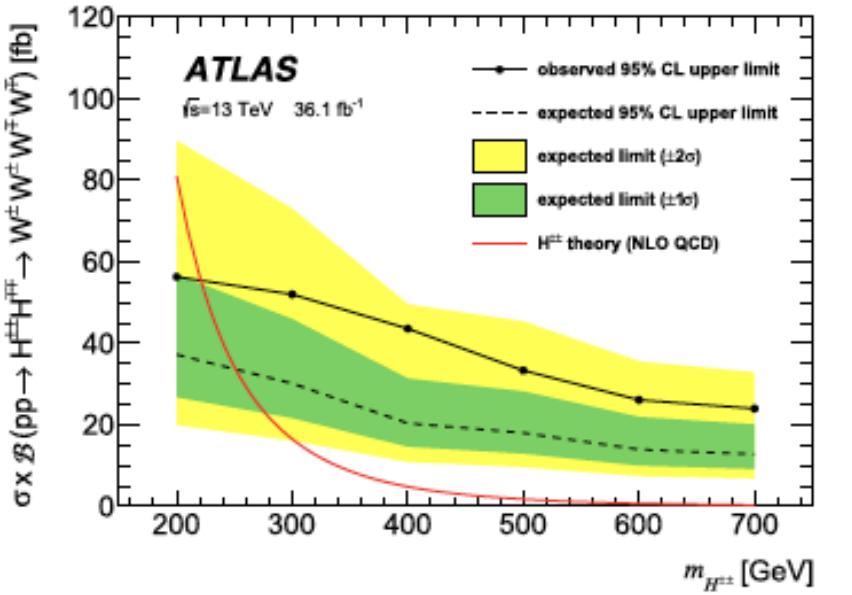
$H^{+} \rightarrow tb$ (hadronic)	arXiv 2001.07763
$H^{+} \rightarrow tb$	JHEP 01 (2020) 096
$H^{+} \rightarrow \tau\ \nu$	JHEP 07 (2019) 142
$H^{+} \rightarrow cb$	JHEP 11 (2018) 115
$H^{+} \rightarrow WA$	PRL 123 (2019) 131802
$H^{++}H^{--} \rightarrow 4l$	EPJC 78 199 (2018)

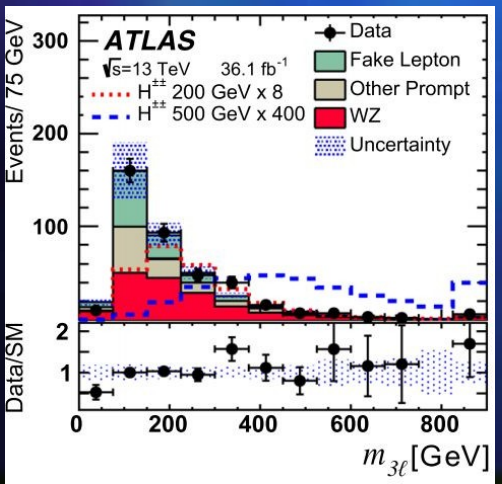
$H^{++/--} \rightarrow WW$

- Doubly charged H arise in Type II seesaw models
- With non-zero neutrino mass, H^{++} predominantly decay to WW
- Final states of leptons, MET and Jets (2l (same sign), 3l, 4l
- Exclude up to 220 GeV

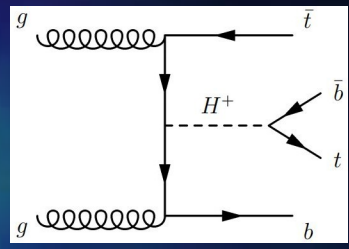




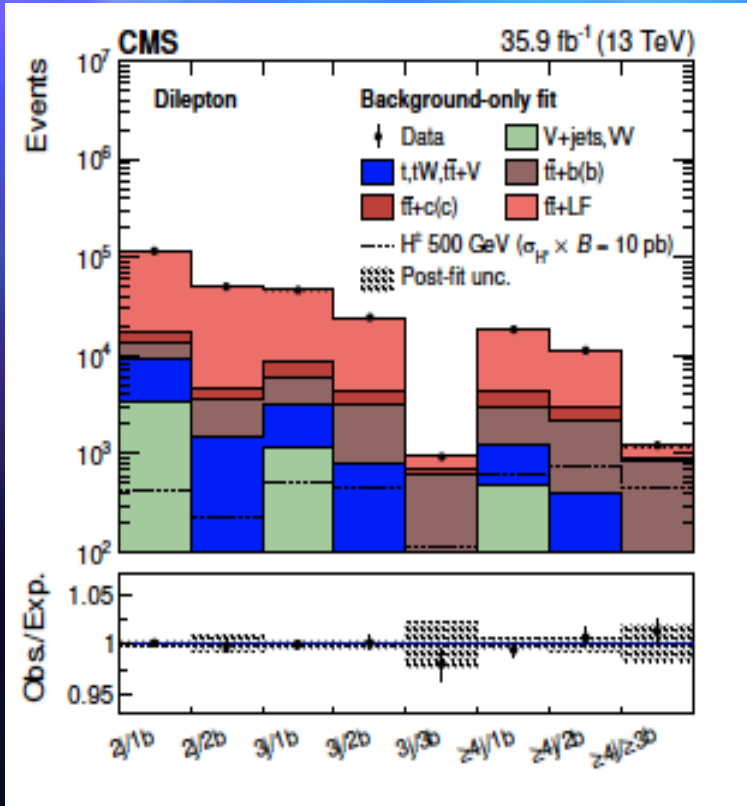


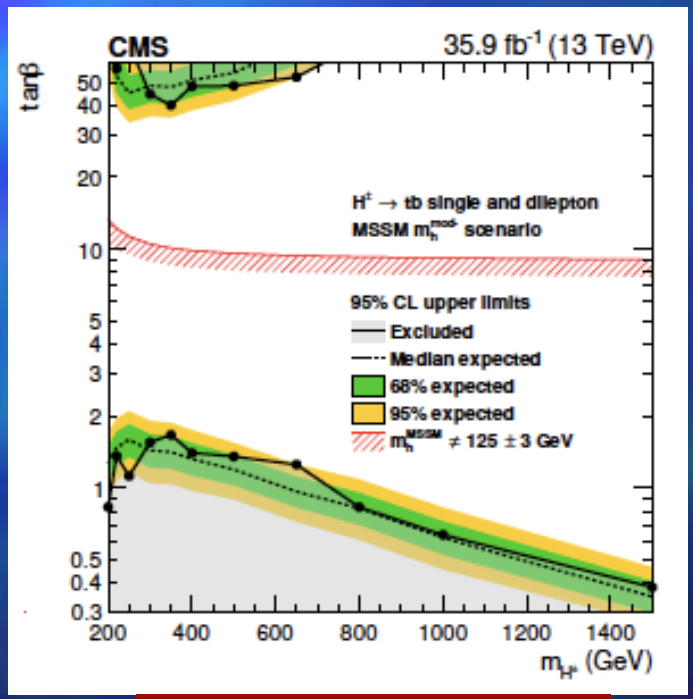


Heavy $H^+ \rightarrow tb$

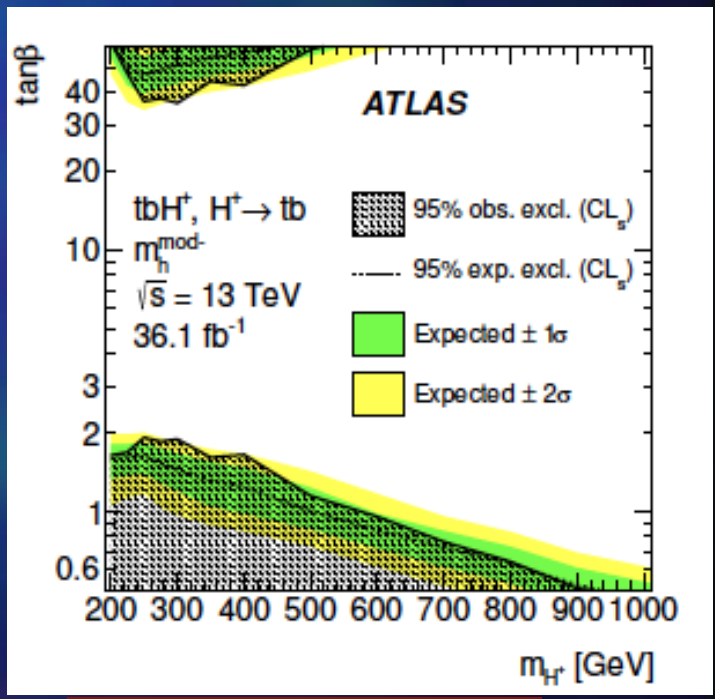


- H^+ to tb produced in association with tb
- Final state: leptons, jets, b-jets, MET
- ATLAS: BDT train for each signal mass in each signal region
- CMS: BDT train for single lepton in each signal, DNN for dilepton,





JHEP 01 (2020) 096

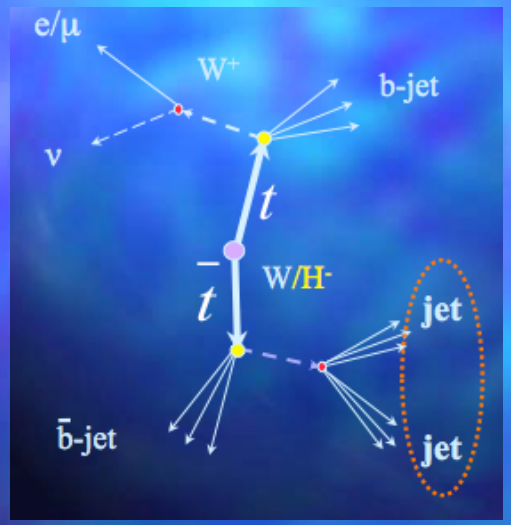


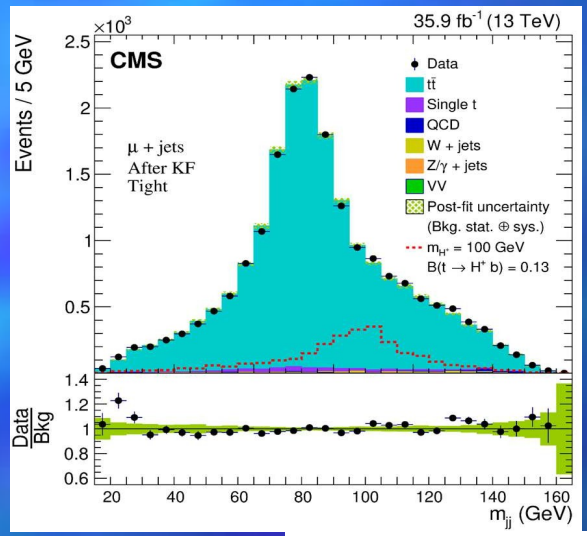
JHEP 11 (2018) 085

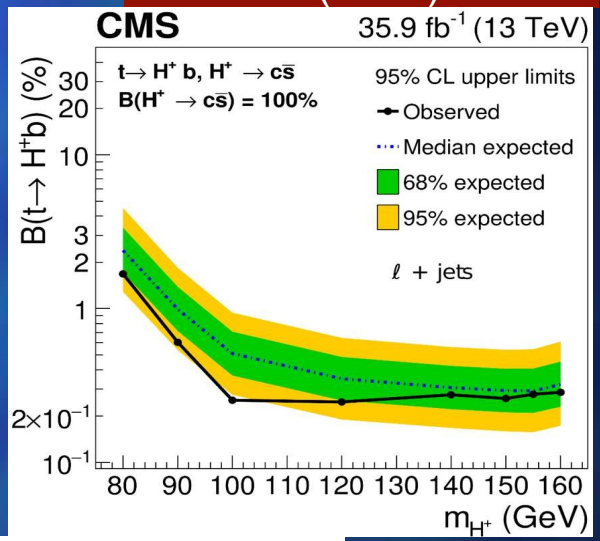
Light $H^+ \to \tau\nu$, cb, WA

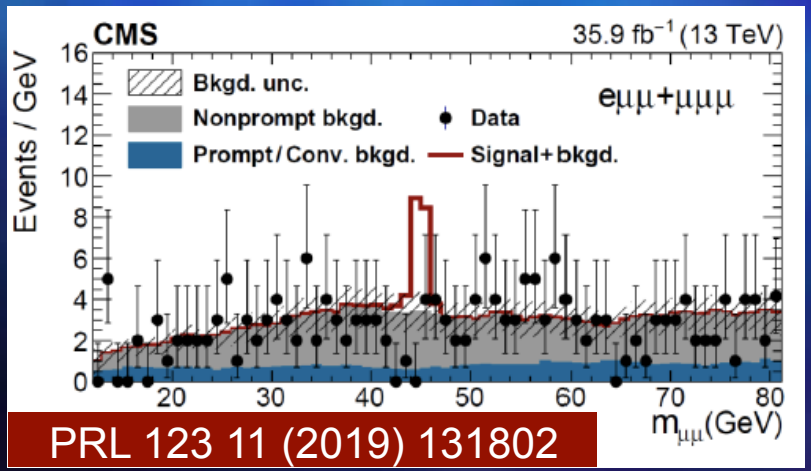
- Search for $H^+ \to \tau\nu$, cs, cb, WA($\to \mu\mu$) from top quark decays in tt events
- Look for a second peak in dijet system (cs, cb) using top kinematic fitter
- Look fro additional peak in dimuon invariant mass for A

PRD 102 (2020) 072001

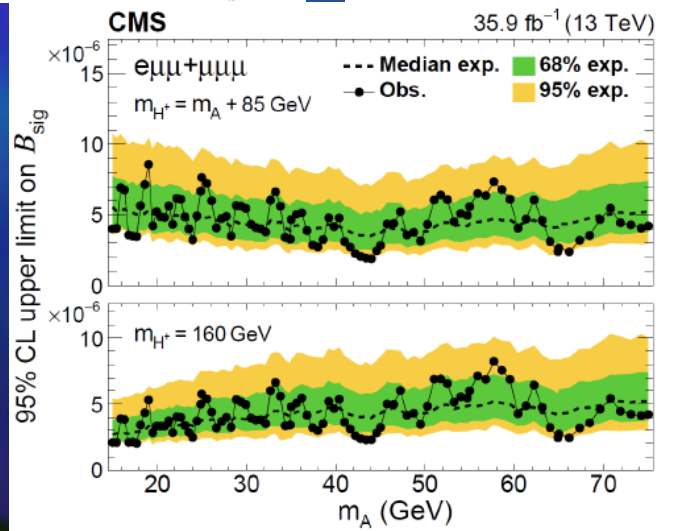






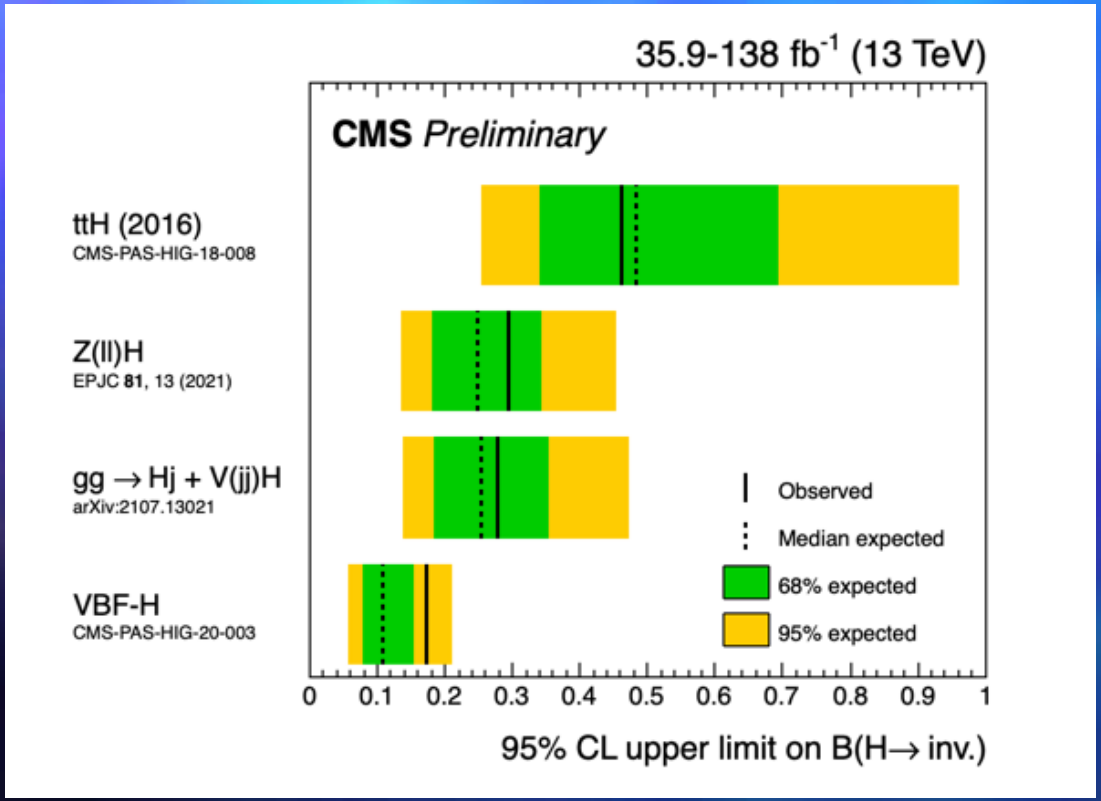


PRL 123 11 (2019) 131802

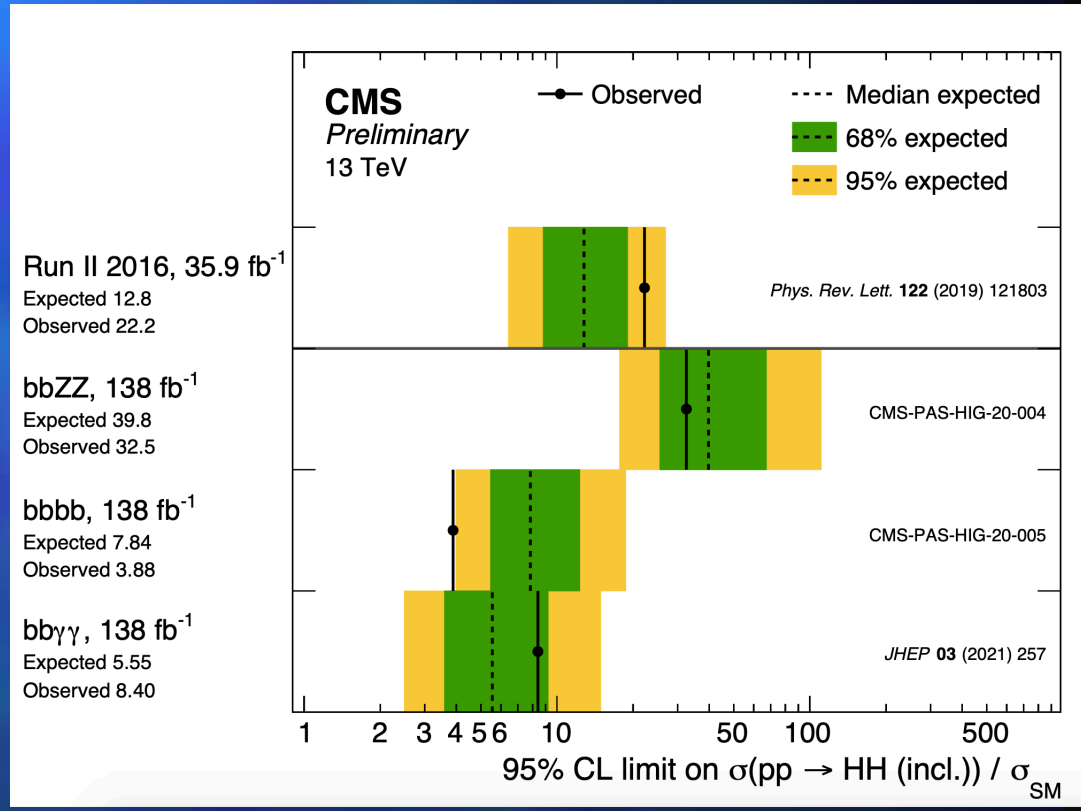


BSM Higgs

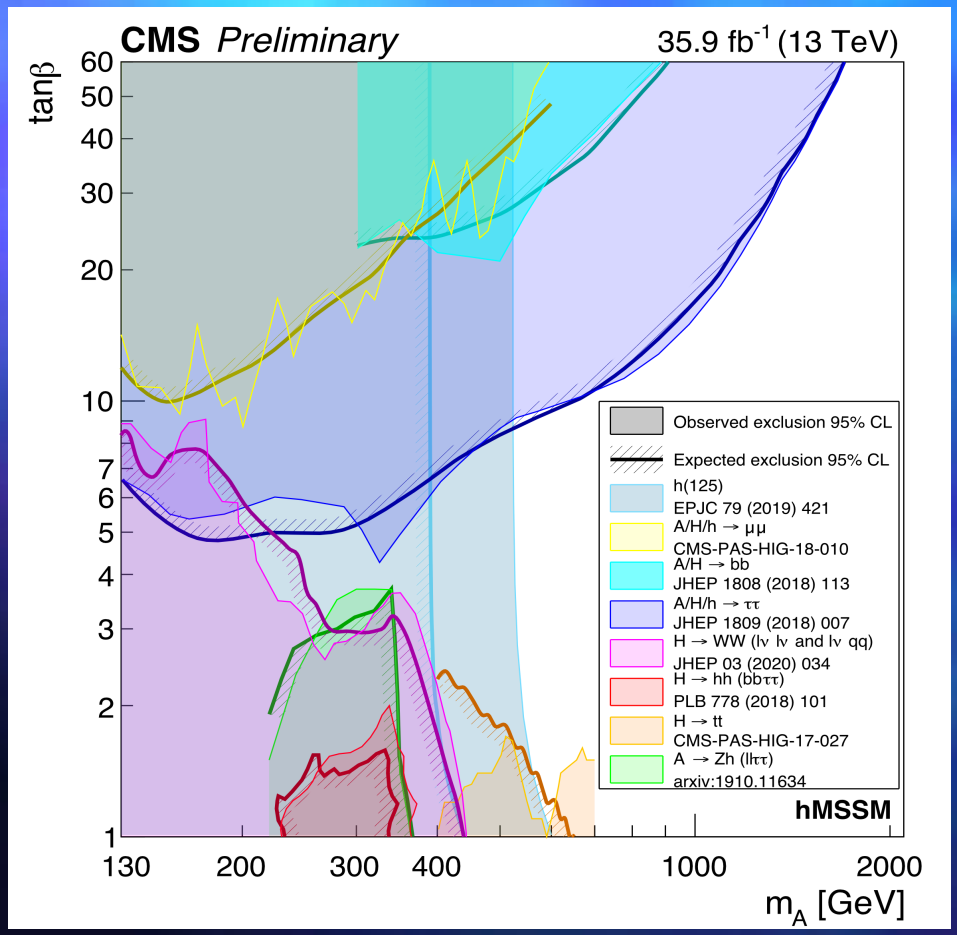
Higgs → Invisible (DM)

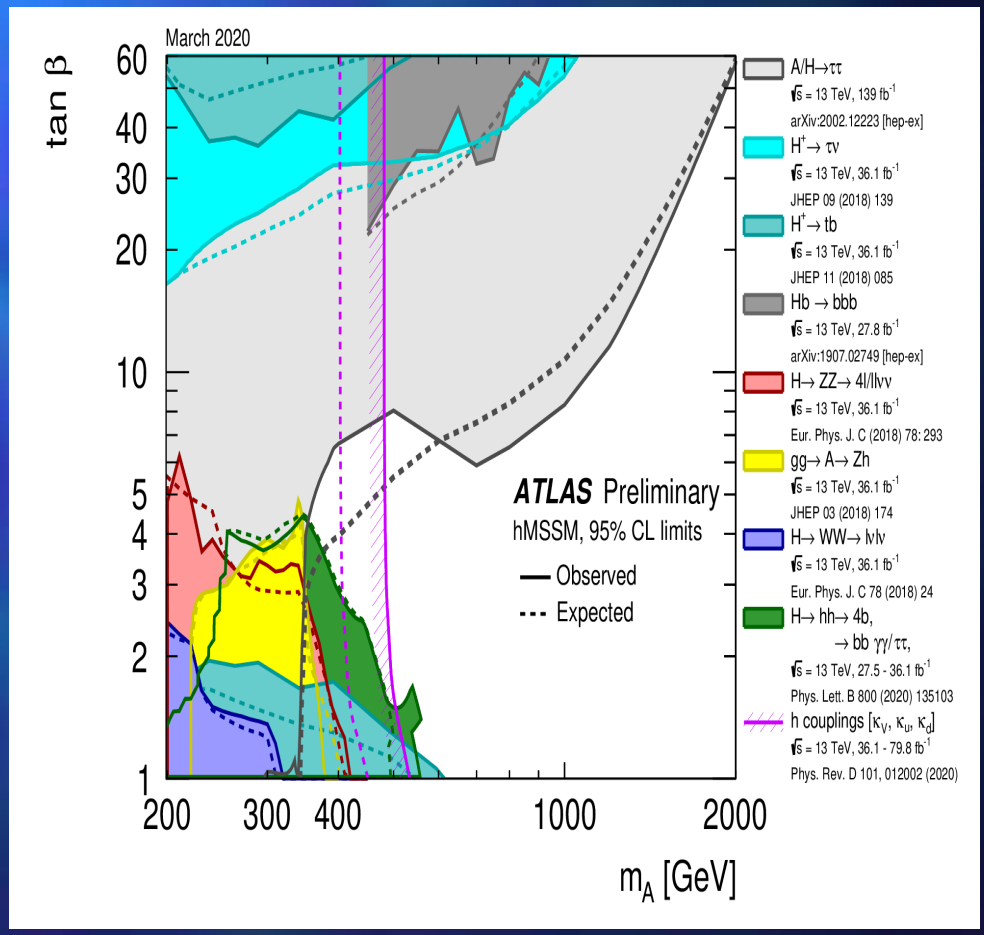


DiHiggs Production?



Summary of BSM Higgs Searches





Summary

- Hunting BSM Higgs boson at the LHC have been extensively and vigorously done in many different channels.
- So far, no evidence of BSM Higgs. Expect to get results using the full Run 2 data with improved sensitivities in many different channels
- LHC Run 3 will be started from Feb 2022, with expected data of 170~190 fb^{-1} (6 month delay due to Covid-19)
- Higgs potential at LHC in many ways is GREAT.