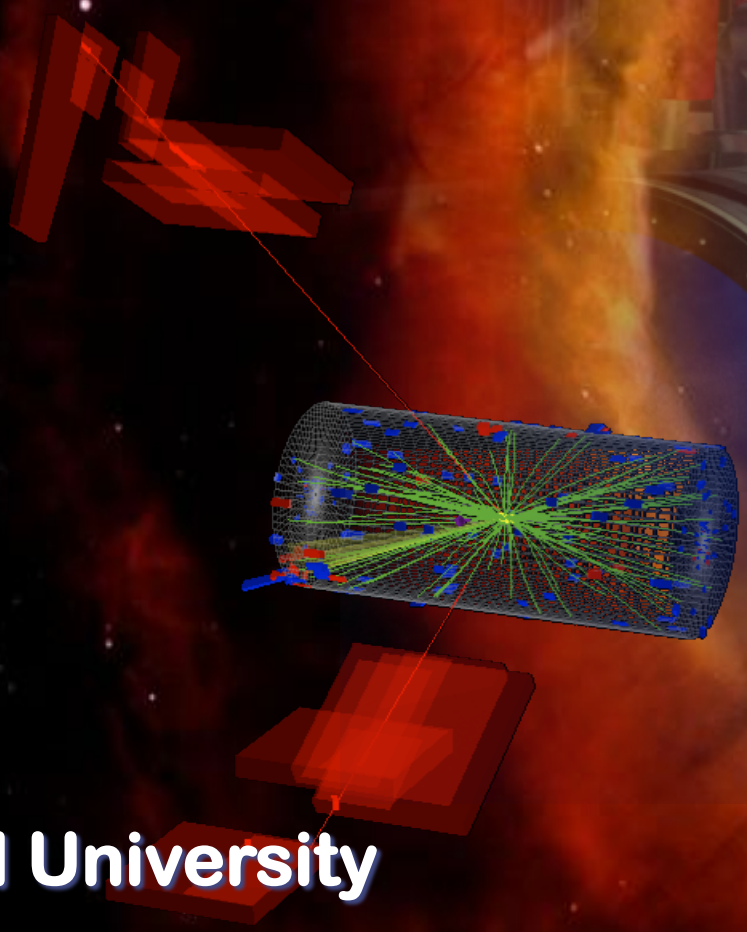
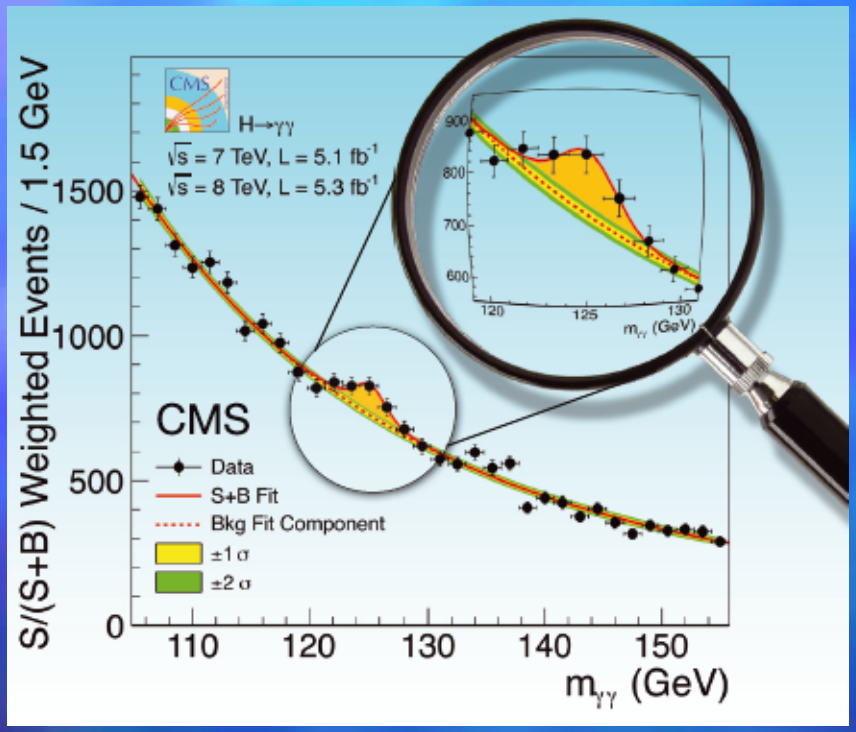
Search for BSM Higgs at the LHC

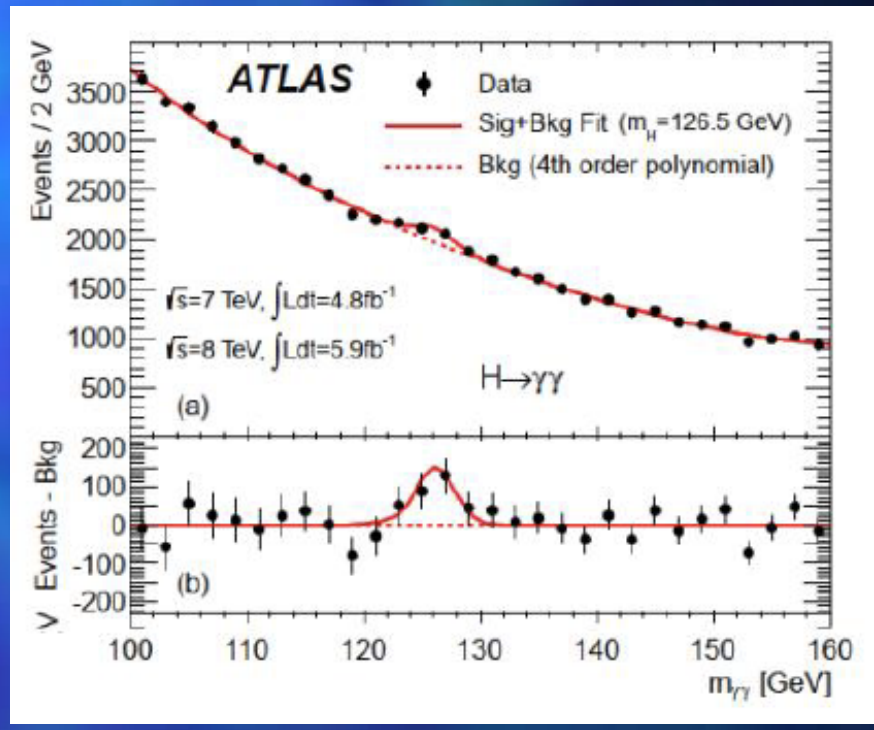


Un-ki Yang
Seoul National University

2023 Chung-Ang University BSM Workshop, Feb. 20~24, 2023

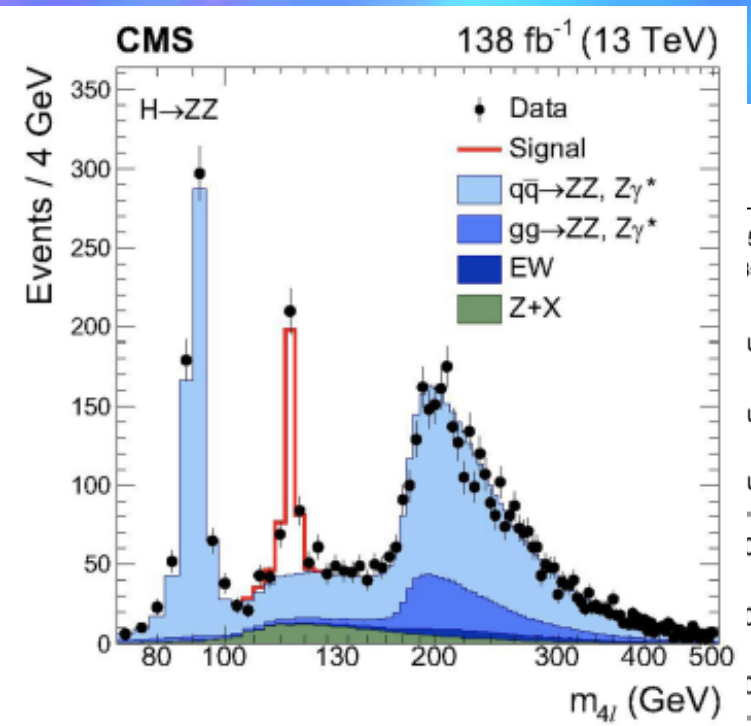
Discovery of a Higgs boson in 2012



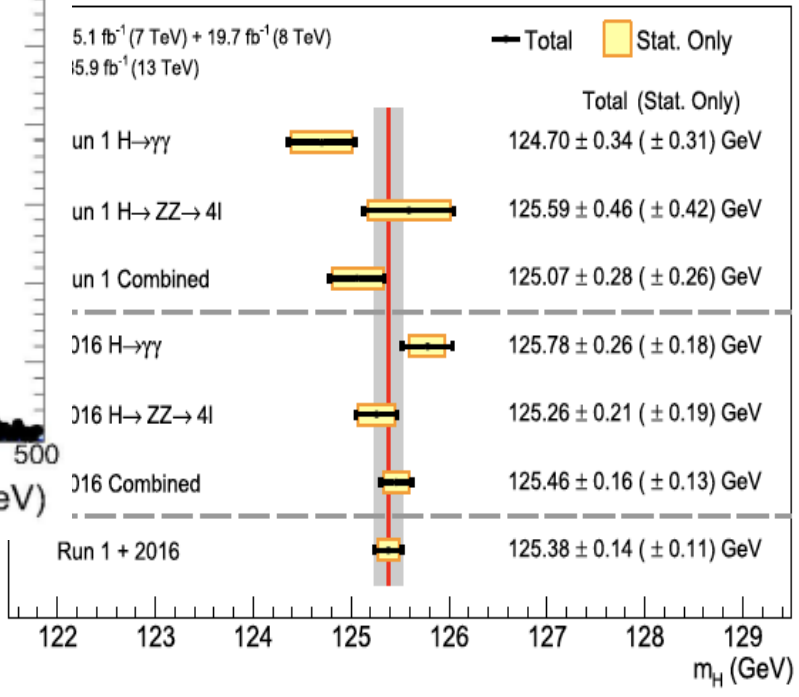


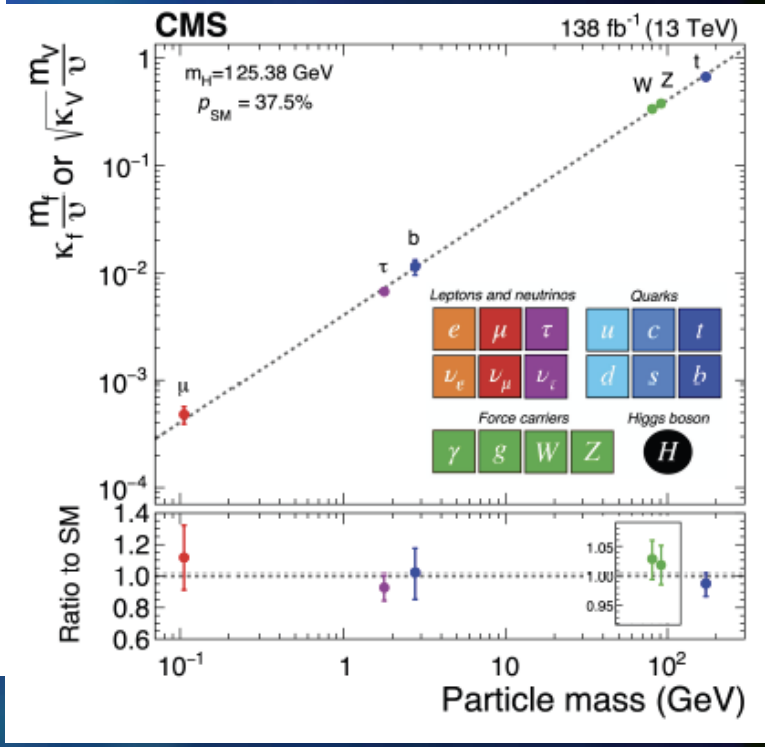
- In 2012 SUSY people were happy to say that h(125) can be the first discovered SUSY particle

10 years after the Higgs discovery



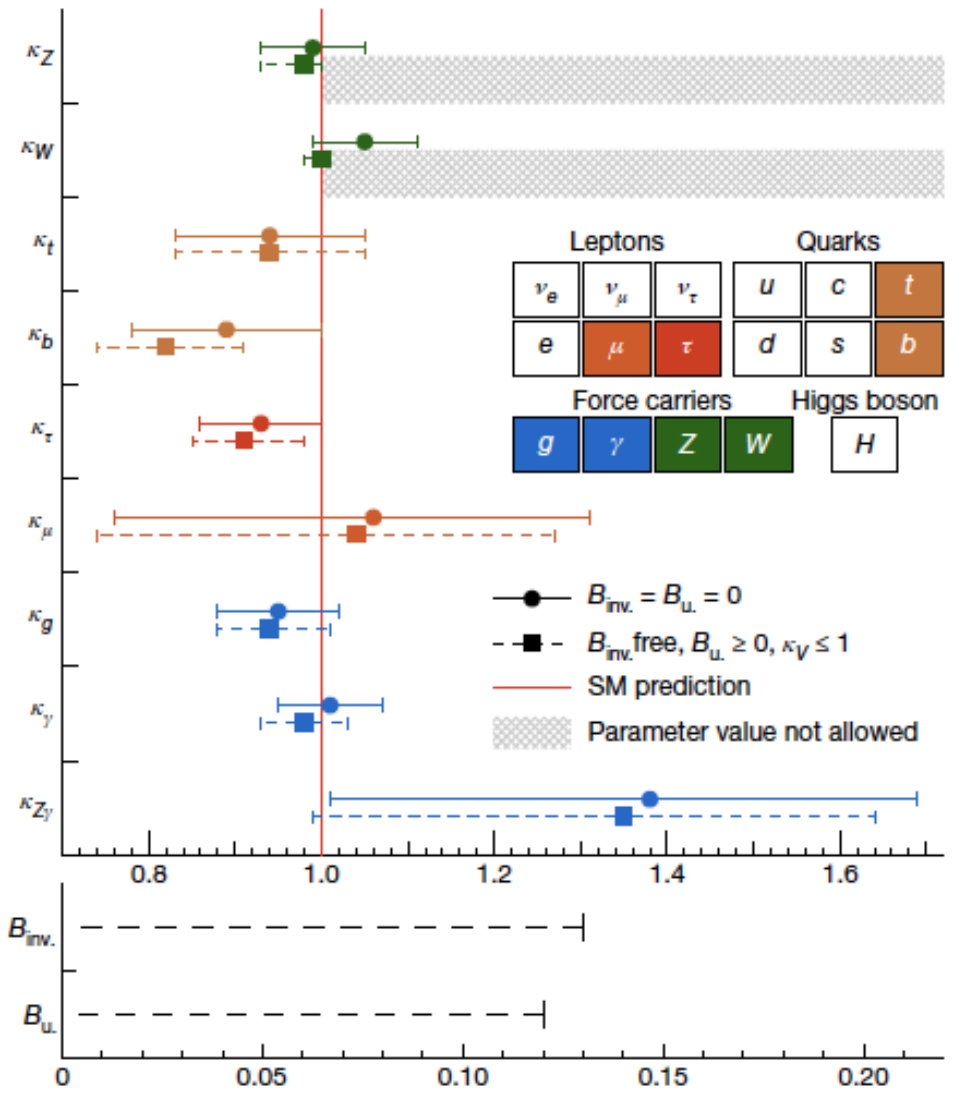
$m_H = 125.38 \pm 0.14\ GeV$





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

Room for new physics



- Higgs to invisible decay mode:< 13%
- Higgs to undetected decay mode: <12%

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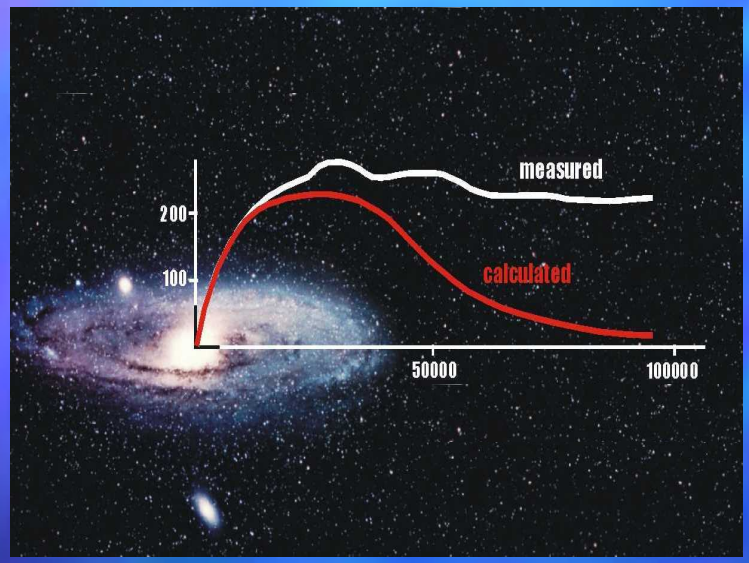
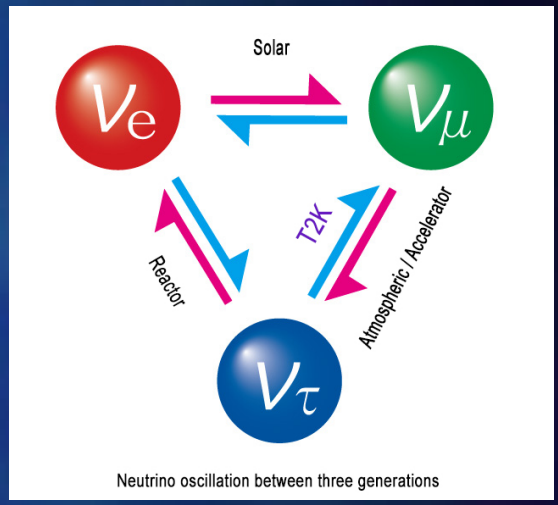
With the most successuful SM, why care for BSM?





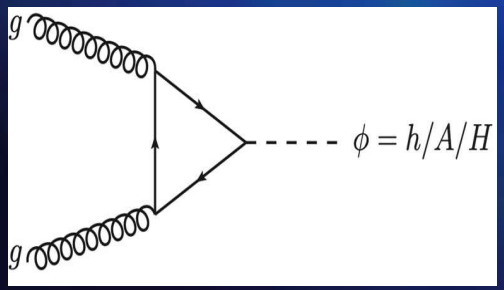
- Evidence for Beyond SM (BSM)
  - Dark matter, matter-antimatter asymmetry, neutrino mass
  - Naturalness

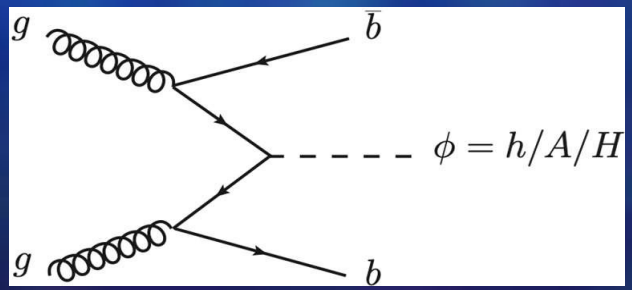
BSM Higgs

- 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 ($H^{+/-}$)
  - MSSM (m_A, $\tan\beta$): $h=h_{125}$, 2HDM Type-I/II : $h/H=h_{125}$
- **NMSSM: 2HDM + Singlet** : $h_1, h_2, h_3, a_1, a_2, h^{+-}$ (h_1 / h_2 = h_{125})
- Triplet model : double charged Higgs bosons ($H^{++/--}$)

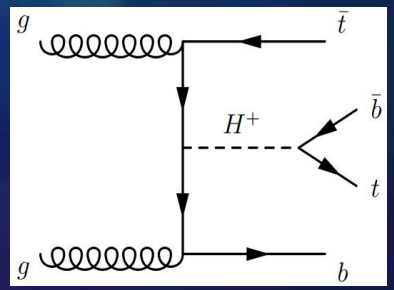
- **Find additional Higgs bosons**
- Find non-SM decay of h(125) particle
- Precision measurements of h(125) particle

Neutral Higgs Production





Charged Higgs Production



Searches for Heavy Neutral Higgs

- Recent Run 2 results on direct decays of H/A
- Mostly focused on MSSM and generic 2HDM

2020

A/H → ττ
A → μμ (+ b)
bb (φ → bb)
X → HH → WW(*)WW(*)
X → Z/W/H → qqγ/qqγ/bbγ
A → ZH → llbb
H → ZZ → 4l / llνν
A → Zh → llbb/ννbb
A → WW/WZ → lνqq

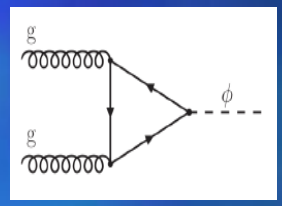
A → hZ → ττll
H → ZA → llbb
X → WW → 2l2ν / lν2q
A → μμ
H/A → tt
A → Zh
A/H → ττ
A/H →bb
X → ZZ → 4l / 2l2q / 2l2ν

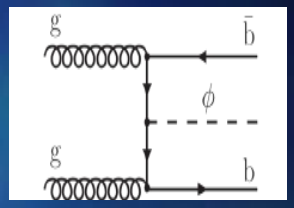
2023

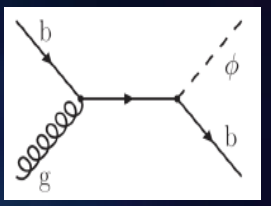
$H \to$ multilepton	ATLAS
$H/A \to \tau\tau$	CMS
$VH/ttH \to \ell\ell\tau\tau$	CMS
$ttH/A \to tttt$	ATLAS
FCNC $t \to qX \to qbb$	ATLAS
$A \to ah \to \chi\chi\tau\tau$	ATLAS
$A \to Zh \to Zbb$	ATLAS
$H \to WW \to \ell\nu\ell\nu$	CMS
$H \to WW \to e\nu\mu\nu$	ATLAS
$WH \to WWW$	ATLAS
$VH \to \ell\ell hh/\ell\nu hh$	ATLAS
$H \to hh \to bb\gamma\gamma$	CMS
$H \to hh \to bbbb$	CMS
$H \to \phi\phi \to bbbb$	CMS
$H \to hh \to WW/WW\tau\tau/\tau\tau\tau\tau$	CMS
$H \to hh \to bbWW/bb\tau\tau$	CMS
$X \to \gamma\gamma$	ATLAS

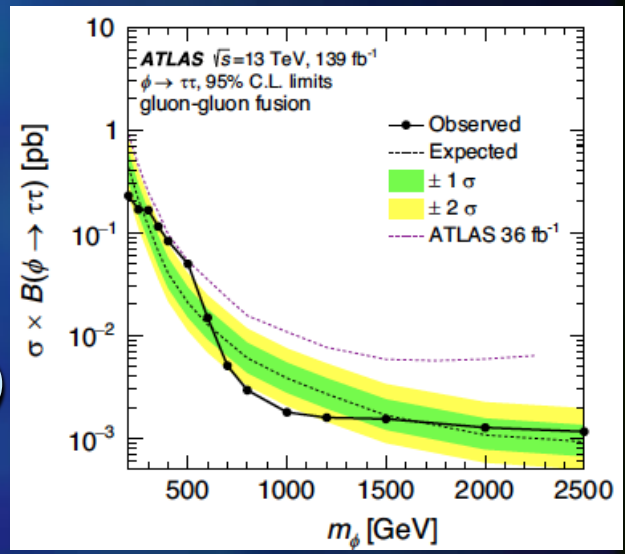
Neutral Higgs, $\phi(H/A) \rightarrow \tau\ \tau$

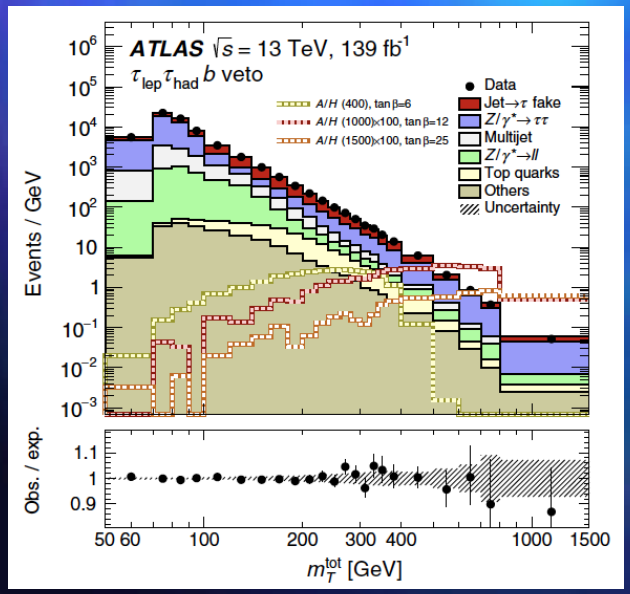
- ATLAS full Run 2 result with 139 fb^{-1}
- $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ channels: b-veto and b-tag category
- BDT to distinguish jet from τ, or e/μ from τ (improved tau ID and optimization)
- Small excess observed at m=400 GeV: 2.2σ (ggF), 2.7σ (bbH) at m=400 GeV
- But no excess from '16 CMS data (full results?)

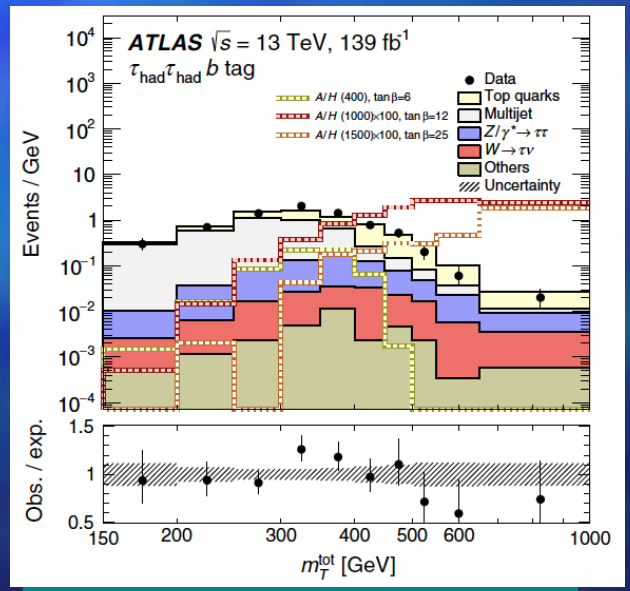


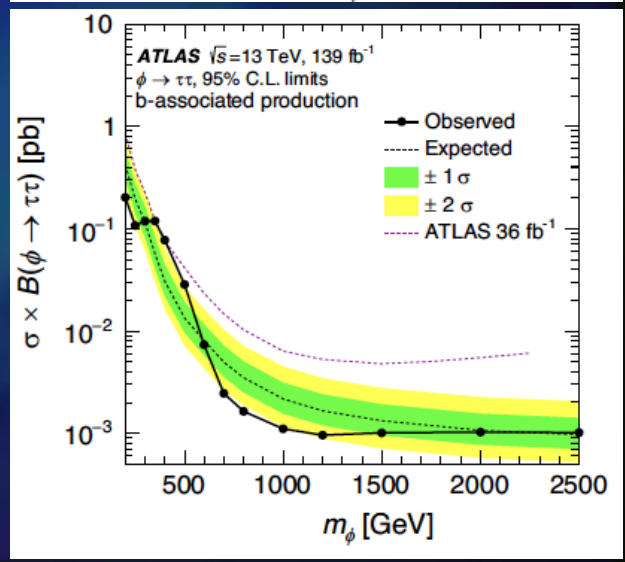








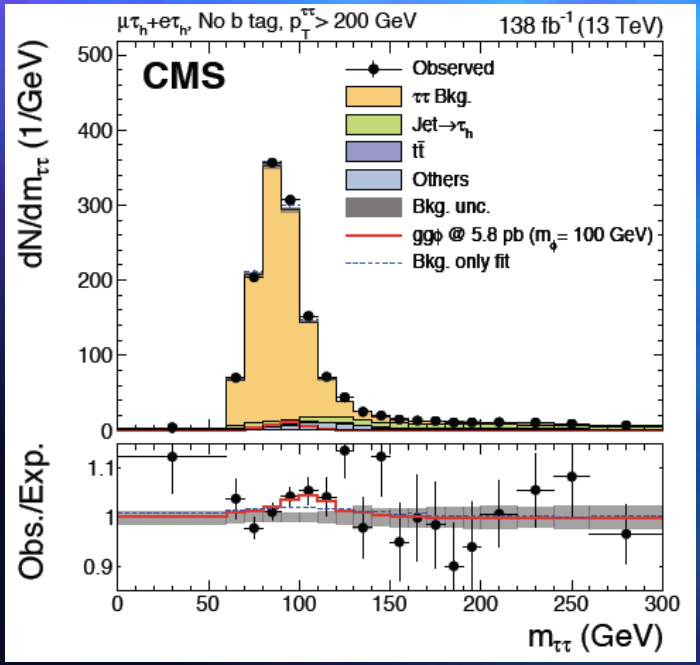


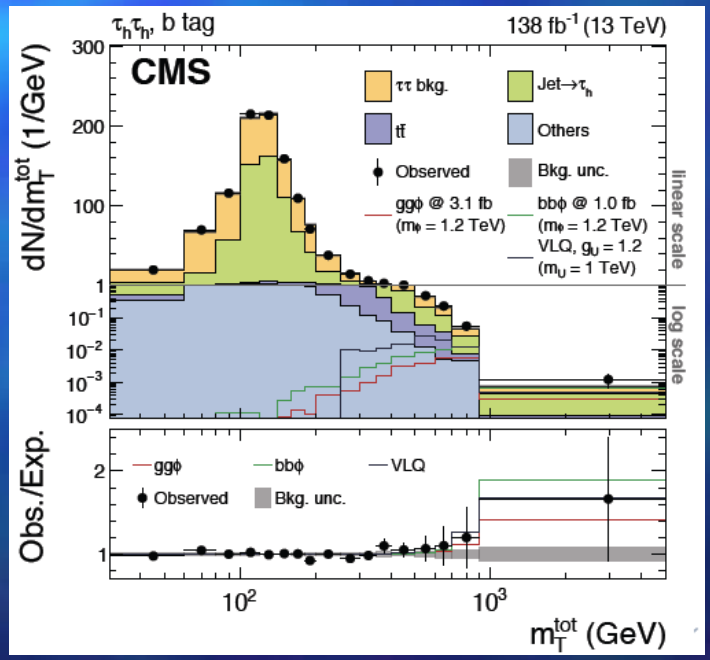


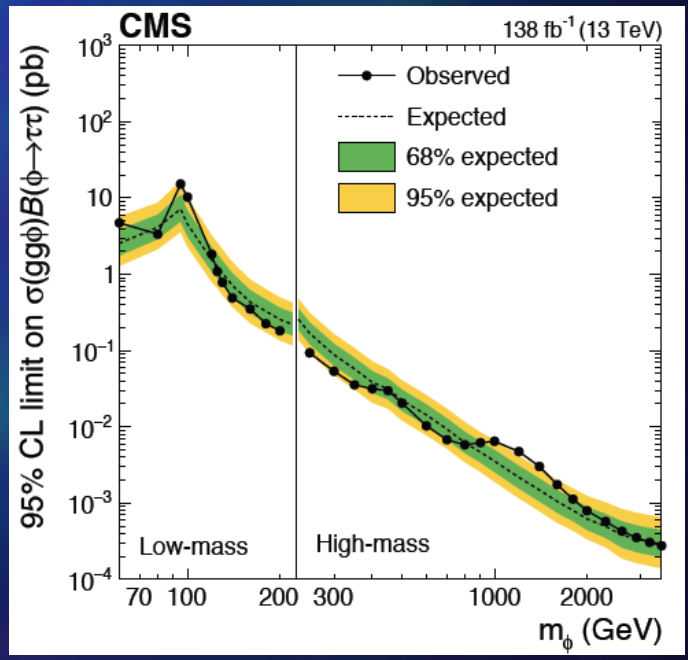
PRL 125 (2020) 051801

Updated results on $\phi(H/A) \rightarrow \tau\ \tau$

- Include $\tau_e \tau_\mu$, $\tau_{lep} \tau_{had}$, $\tau_{had} \tau_{had}$ channels:
- Use number of *b*-tagged jets
- Low / High mass search: $m_{\tau\tau}$, m_T^{tot}
- No ATLAS excess shown at 400 GeV, but two excesses:
  at 3.1 σ 100 GeV and 2.8 σ at 1.2 TeV
- Limits are interpreted in the MSSM scenarios and heavy Higgs boson below 350 GeV excluded.



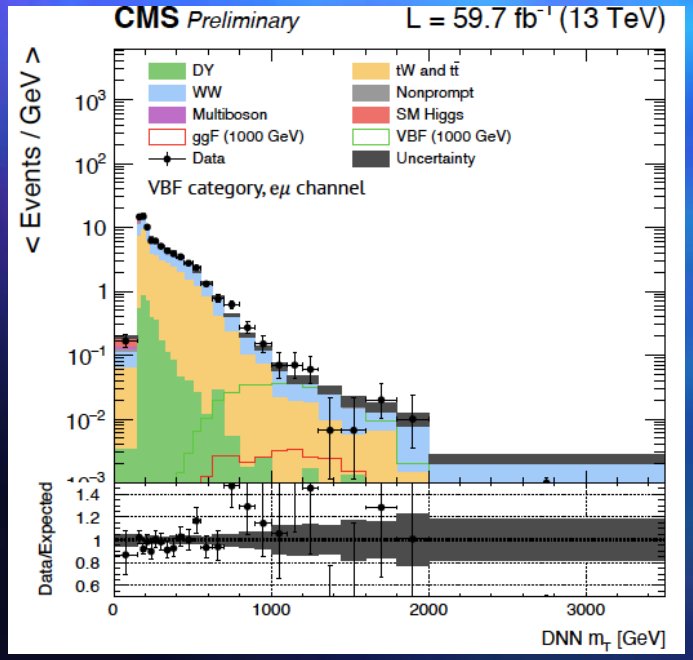


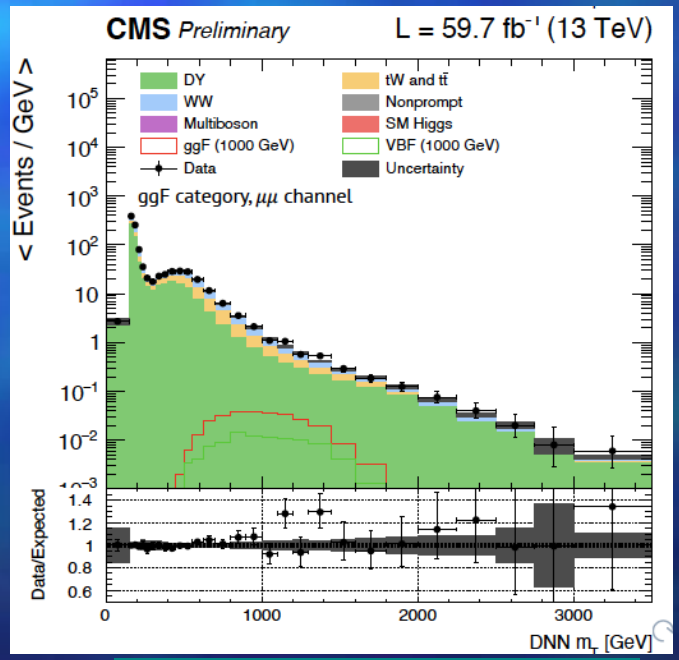


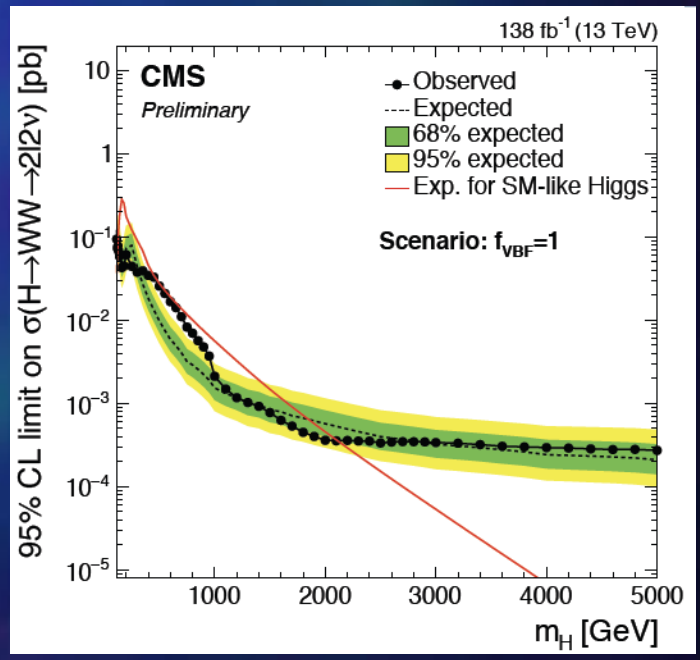
arXiv:2208.02717

H→ WW (→2l 2 ν)

- Search for heavy Higgs in ggF and VBF production in a mass range:150-5000 GeV
- Dilepton channels (ee,$\mu\mu$. eμ + MET): updated to Run2 from '16 data
- Dominant bkgds: top, DY, WW
- Use two DNNs to classify signal ggF, VBF, and bkgds and to regress H mass (DNN m_T) that is fitted
- No significant excess over SM predictions, exclusion limit on σ x B
- Largest excess 3.8 σ at 650 GeV (only VBF) and 2.6 σ (ggF) at 950 GeV



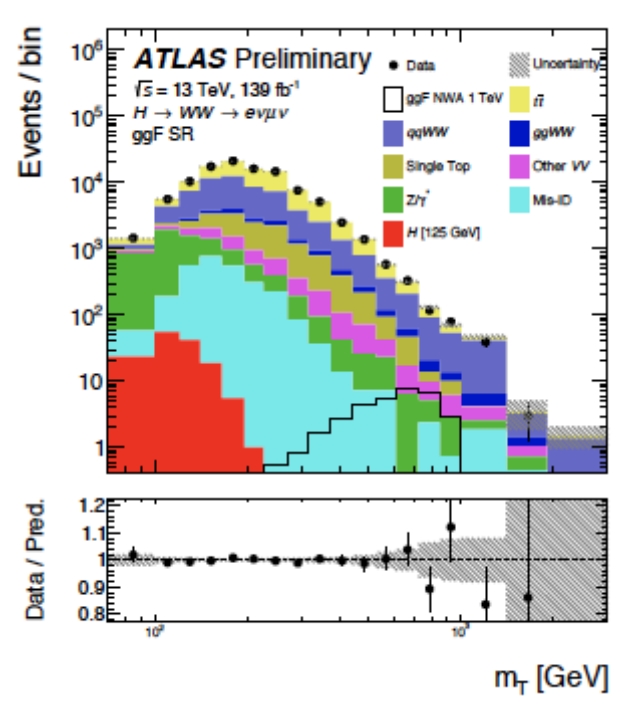


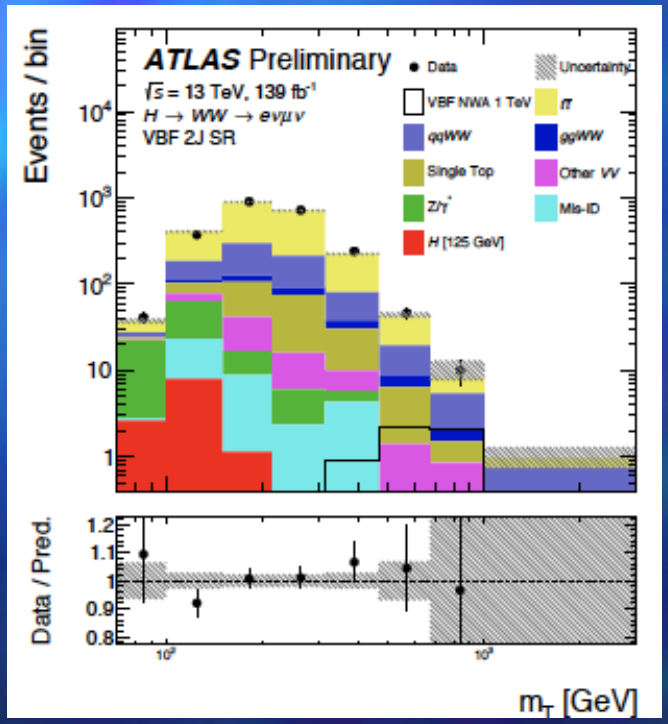


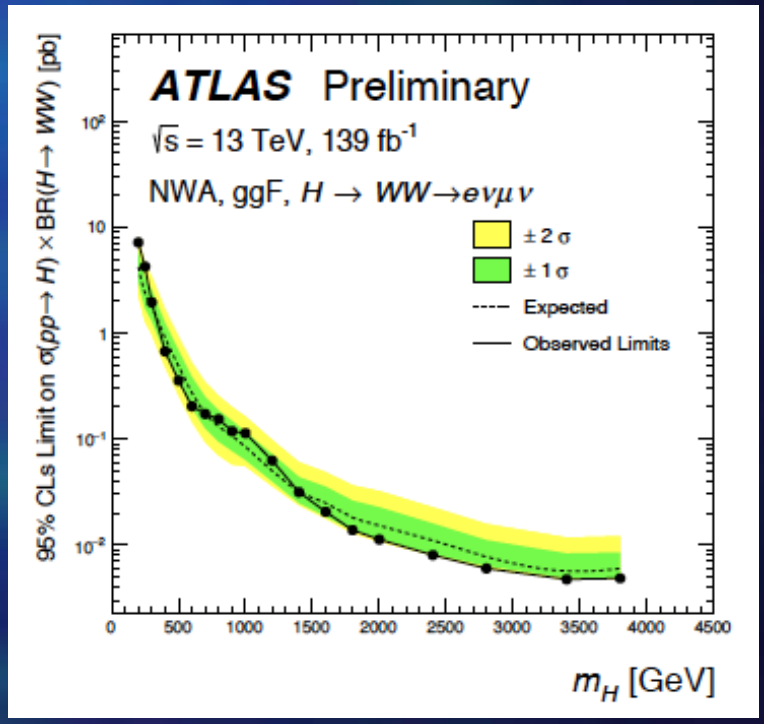
CMS-PAS-HIG-20-016

H→ WW (→2l 2 ν)

- Search in e-μ channel only in a mass range: 200 – 6000 GeV
- 3 event category: ggF (2l), VBF (2l+ 1 jet), VBF (2l+ 2 jets)
- Dominant bkgds in tt,Wt, WW
- Use transverse mass, m_T for signal extraction
- No significant excess over SM predictions, exclusion limit on σ x B



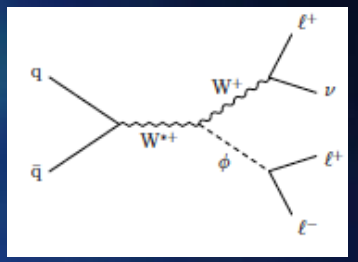


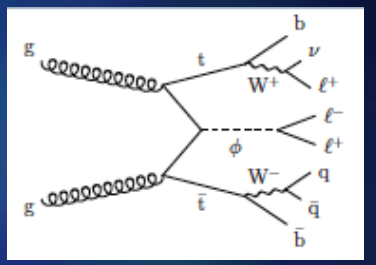


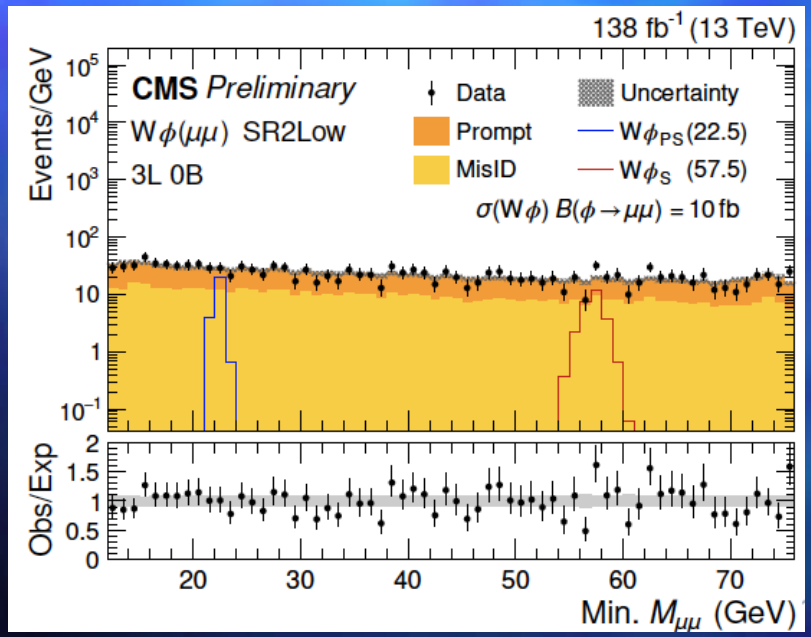
ATLAS-Conf-2022-066

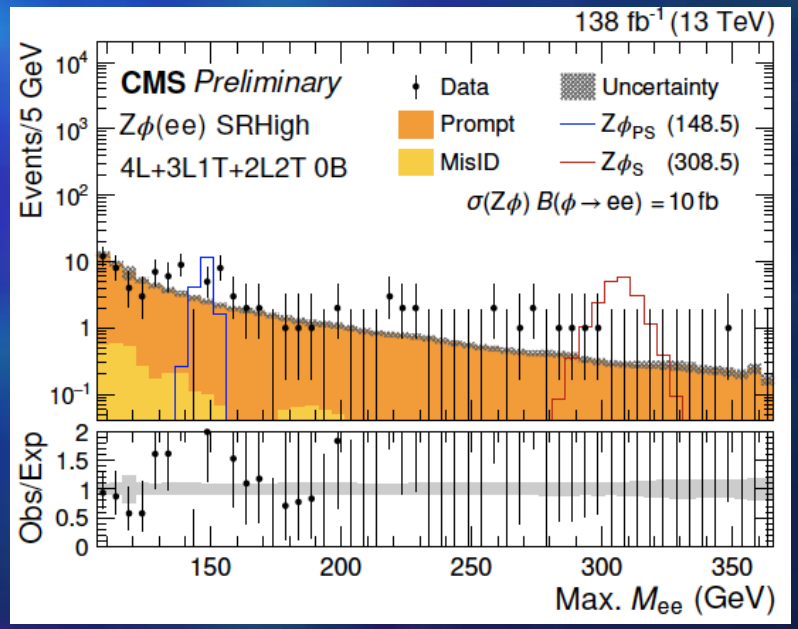
VH/ttH (H→ll/ττ)

- Search for high mass H in ZH, WH, ttH in dielepton channels
- Use 3l or 4l (e,μ,τ)
- Dilepton channels (ee,μμ. eμ + MET)
- Dominant bkgds: WW, WZ, ZZ, ttZ,
- Discriminating variable: min M_{ll} (low), max M_{ll} (high)
- No significant excess over SM predictions





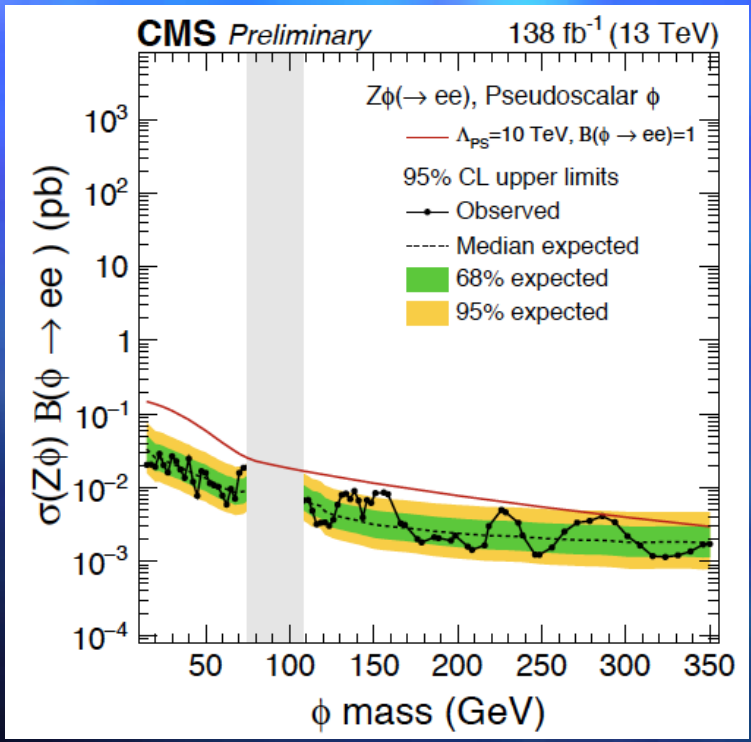


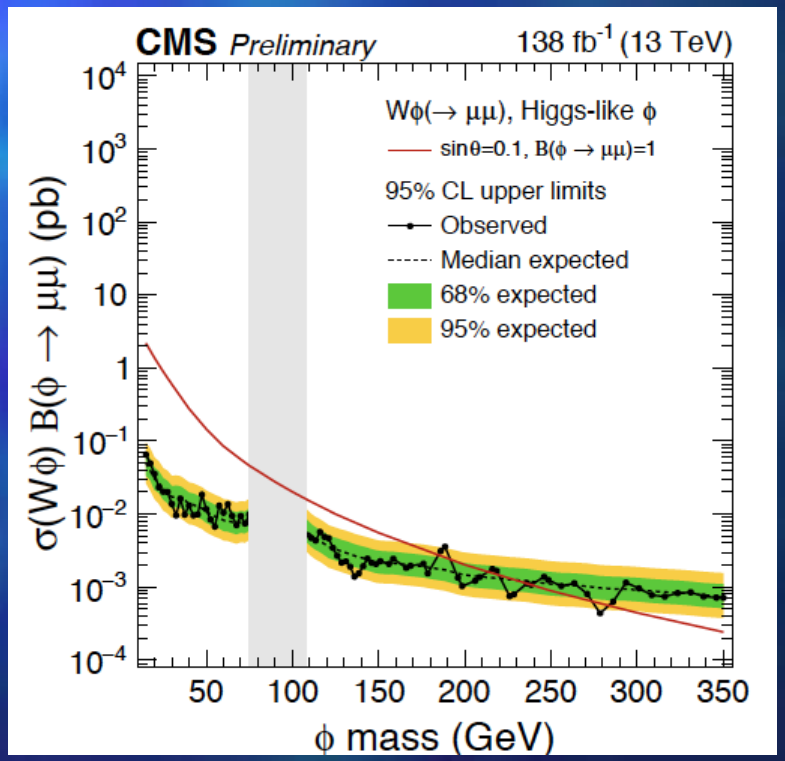


CMS-PAS-EXO-21-018

VH/ttH (H→ll/ττ)

- No significant excess over SM predictions
- Set on exclusion limit on σ x B
- Largest excess 2.9 σ at 156 GeV in ee channel

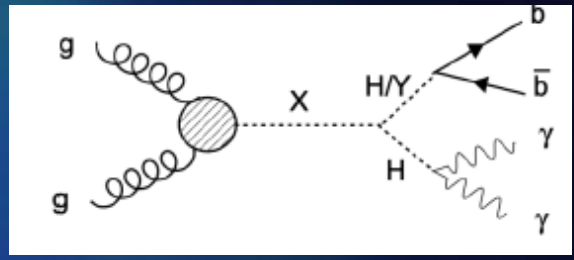




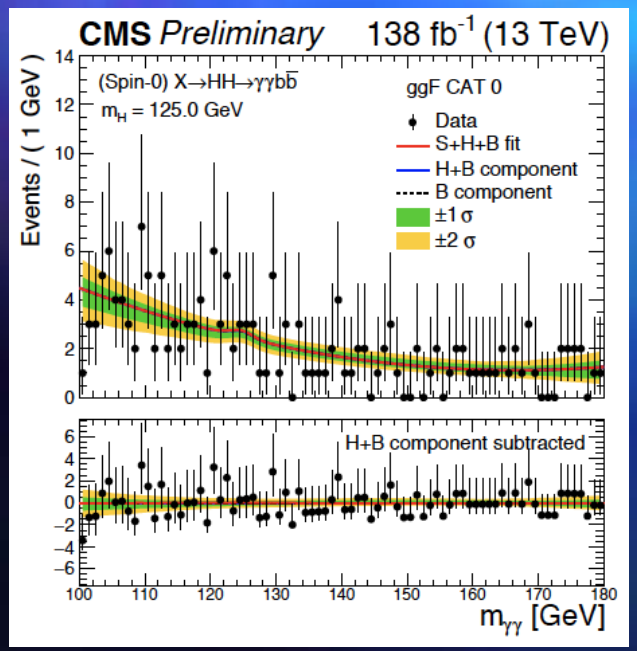
CMS-PAS-EXO-21-018

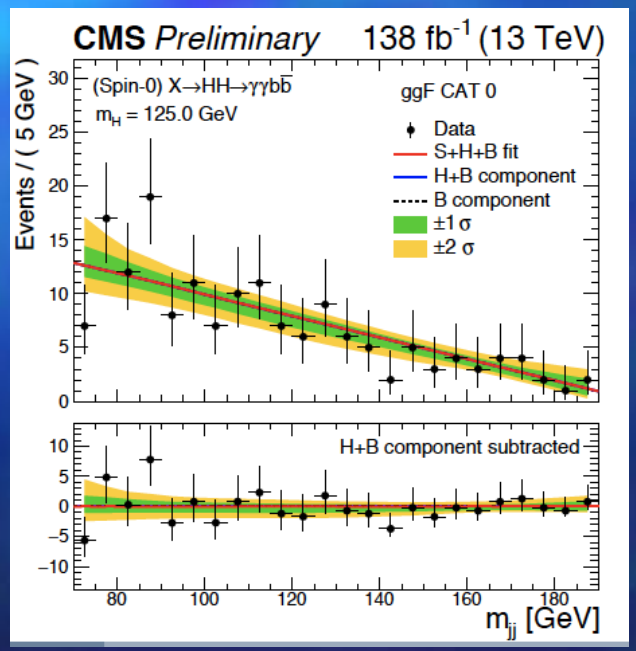
H(A)→ah$_{125}$→bbγγ

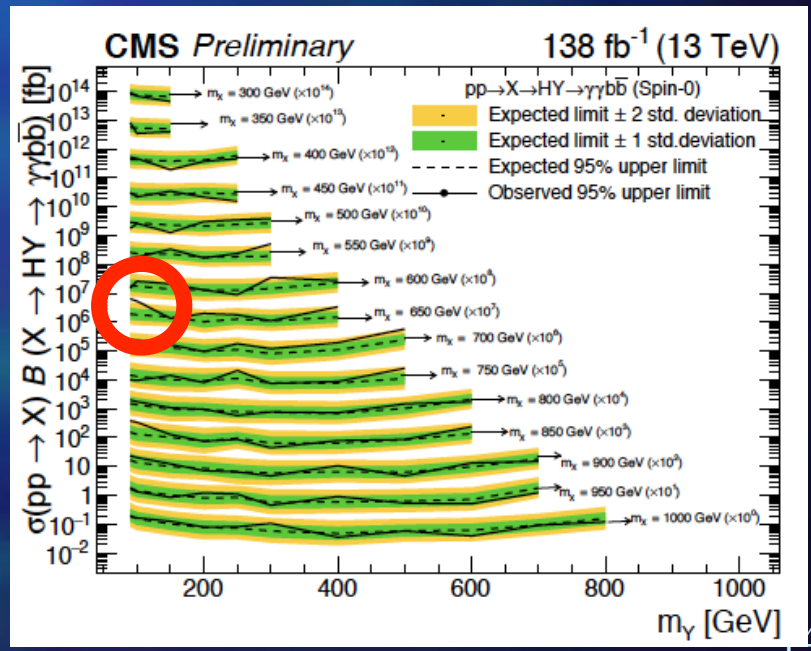
- Search for heavy Higgs decaying to a light Higgs and SM Higgs boson in NMSSM: 2HDM+S
- Dominant bkgds in ttH, bbH, γ+jets
- Use BDT and MX variable to categories events
- A parametric fit in the ($m_{\gamma\gamma}$, m_{jj})
- No significant excess over SM predictions
- Largest excess 3.8 σ at (m_H, m_a) = (650, 90) GeV



CMS-PAS-EXO-21-011

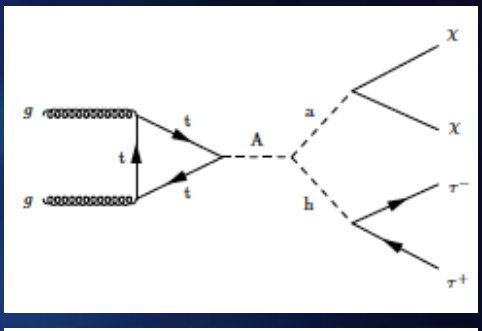


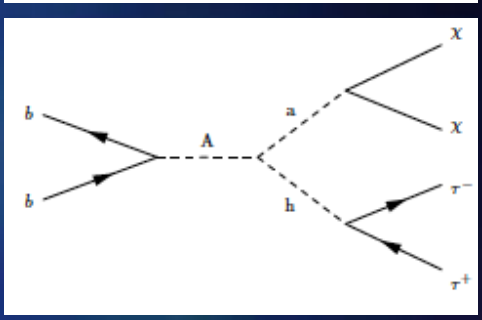


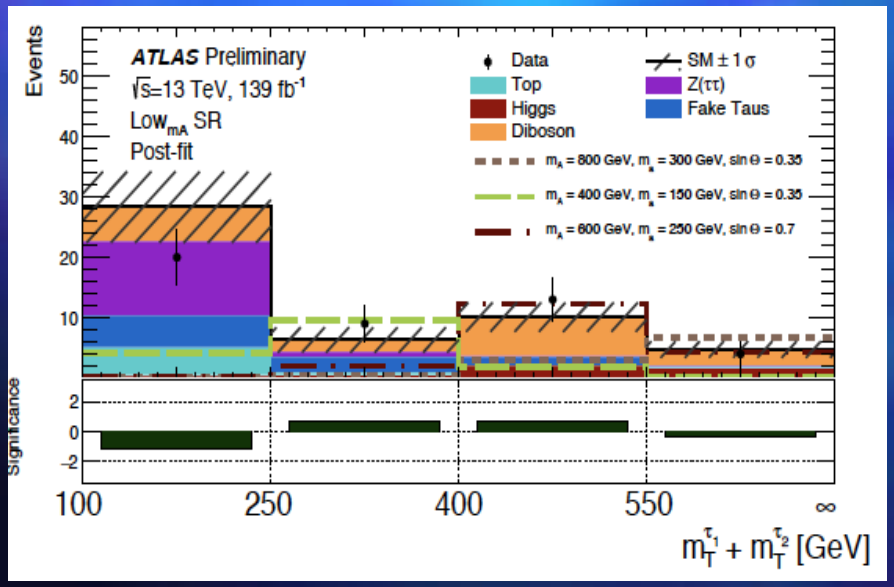


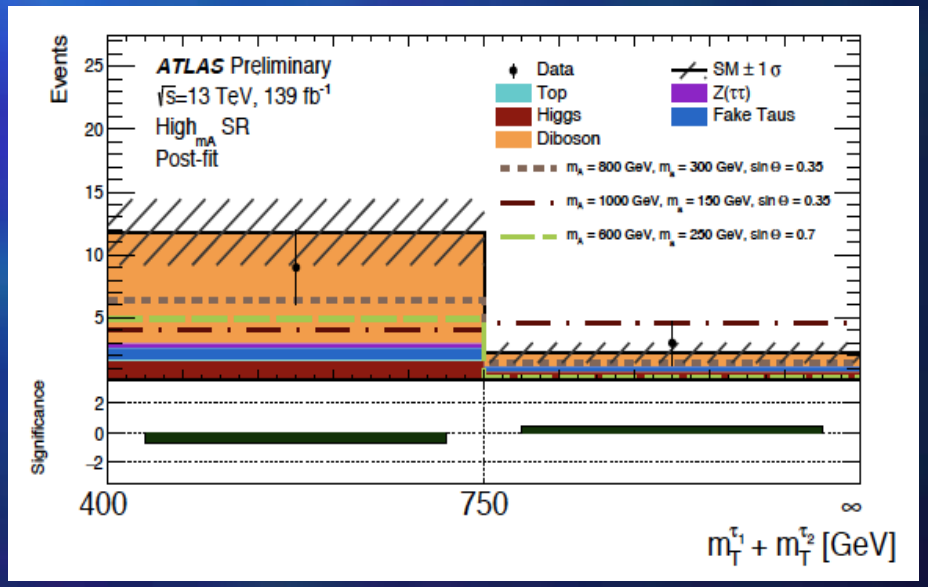
$A \rightarrow a h_{125} \rightarrow \chi\chi\tau\tau$

- Search for high mass H in dark matter decay channels with two tau leptons
- Additional pseudo-scalar singlet couples to DM candidate (m_χ=10 GeV) in 2HDM+S model
- Dominant bkgds in $\tau\tau$ and multi-jets
- Discriminating variable: transverse mass $m_T^{\tau 1}$ + $m_T^{\tau 2}$
- No significant excess over SM predictions





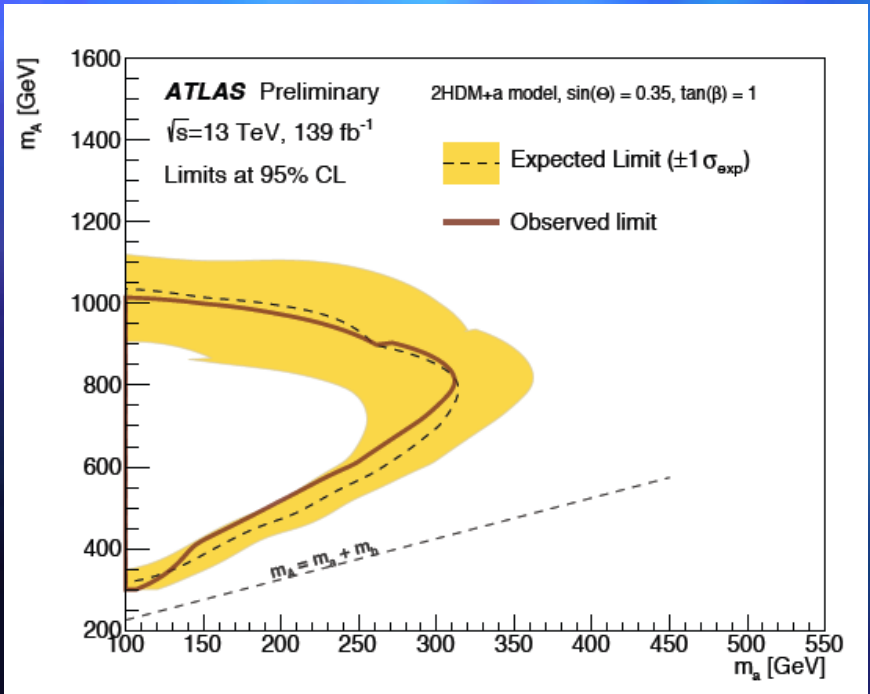


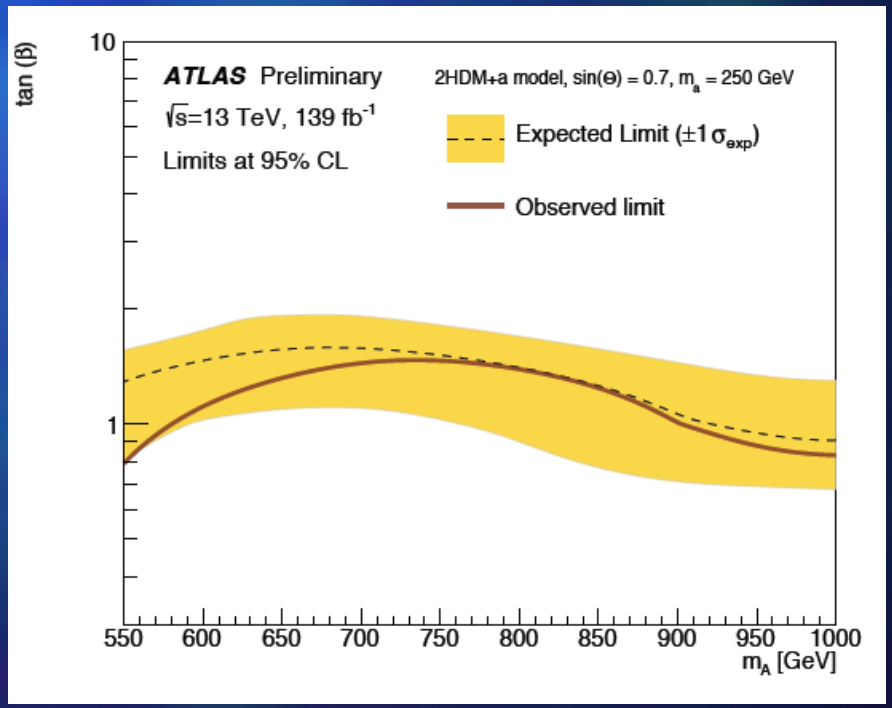


ATLAS-Conf-2022-069

$A \rightarrow ah \rightarrow \chi\chi\tau\tau$

- No significant excess over SM predictions
- Set on model independent limit on σ : <0.04~0.08 fb
- Limits interpreted in 2HDM+a model scenario
- Pseudo-scalar singlets with masses up to 300 GeV are excluded for m_A=800 GeV
- Signals in tan β <1 are excluded for m_A=900 GeV

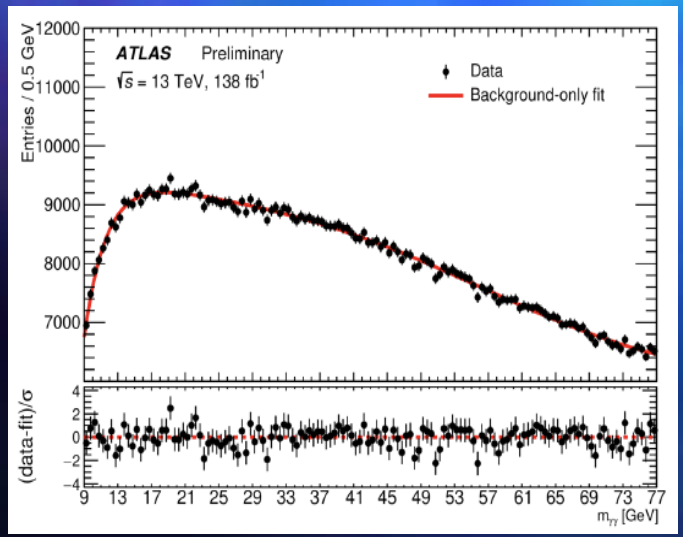


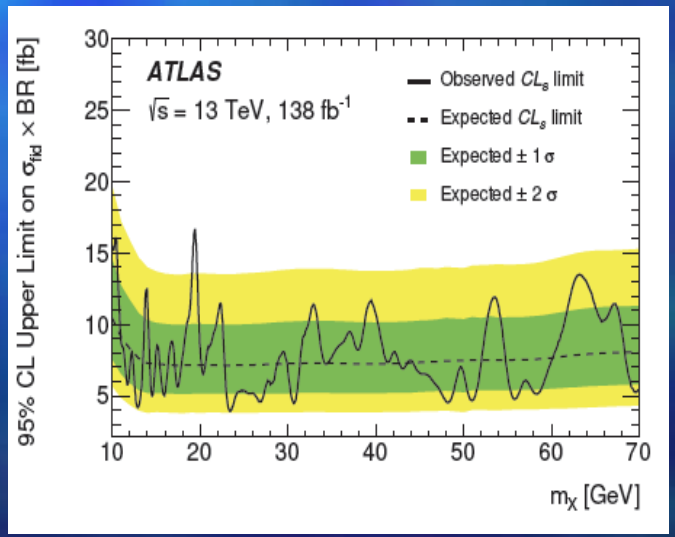


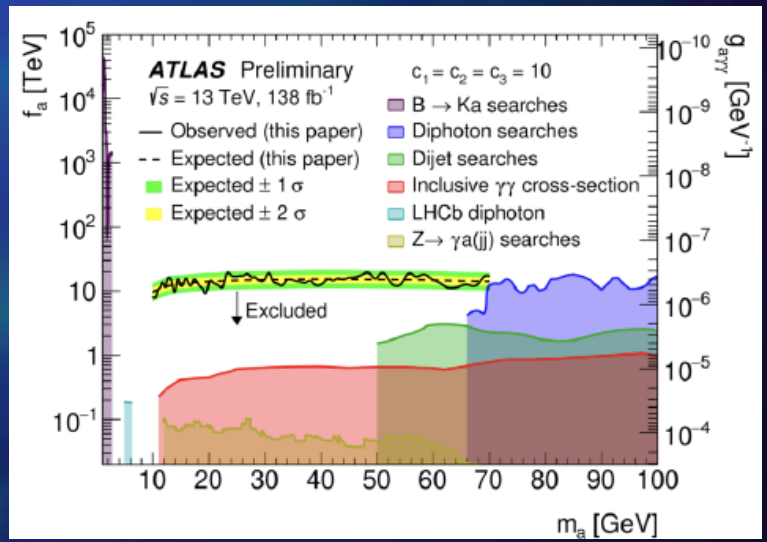
ATLAS-Conf-2022-069

H → γγ (boosted)

- First LHC search for generic γγ resonance in the mass range from 10 to 70 GeV
- Use special type of events with pt(γγ)>50 GeV to reach down to 10 GeV
- Complex analytic function to model bkgds (low mass turn-on & falling region)
- Discriminating variable: $m_{\gamma\gamma}$
- No significant excess over SM predictions
- Largest excess 3.1 σ at 19.4 GeV shown
- Observed limits are interpreted as a limit for axion-like-particle







arXiv:2211.04172

Searches for charged Higgs

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

2020

$H^{++}H^{--} \to 4W$
$H^{+} \to tb$
$H^{+} \to \tau\ \nu$
$H^{++}H^{--} \to 4l$

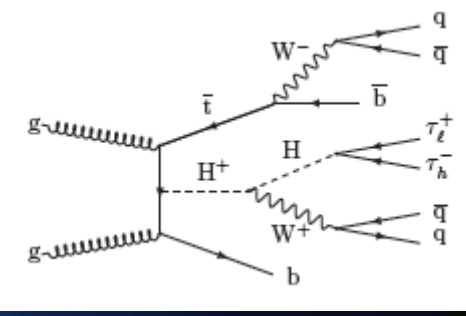
$H^{+} \to tb$ (hadronic)
$H^{+} \to tb$
$H^{+} \to \tau\ \nu$
$H^{+} \to cb$
$H^{+} \to WA$
$H^{++}H^{--} \to 4l$

2023

$H^{\pm} \to WZ \to \ell\ell\ell\nu$	ATLAS
VBF $H^{\pm} \to WZ \to \ell\ell\ell\nu$	CMS
$H^{\pm} \to HW \to \tau\tau\ell\nu/\tau\tau qq$	CMS

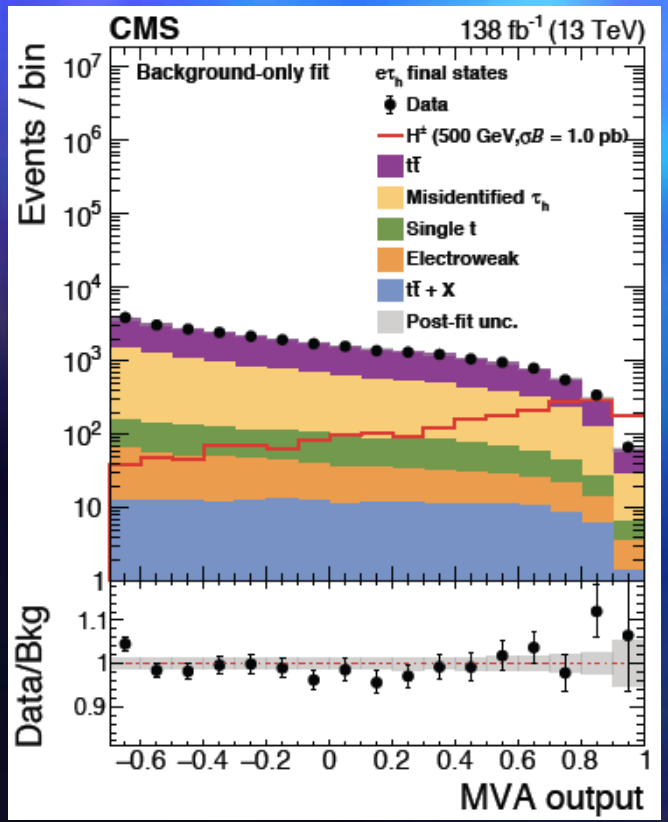
$H^{\pm\pm}H^{\mp\mp} \to \ell\ell\ell\ell$	ATLAS
VBF $H^{\pm\pm} \to WW \to \ell\nu\ell\nu$	CMS

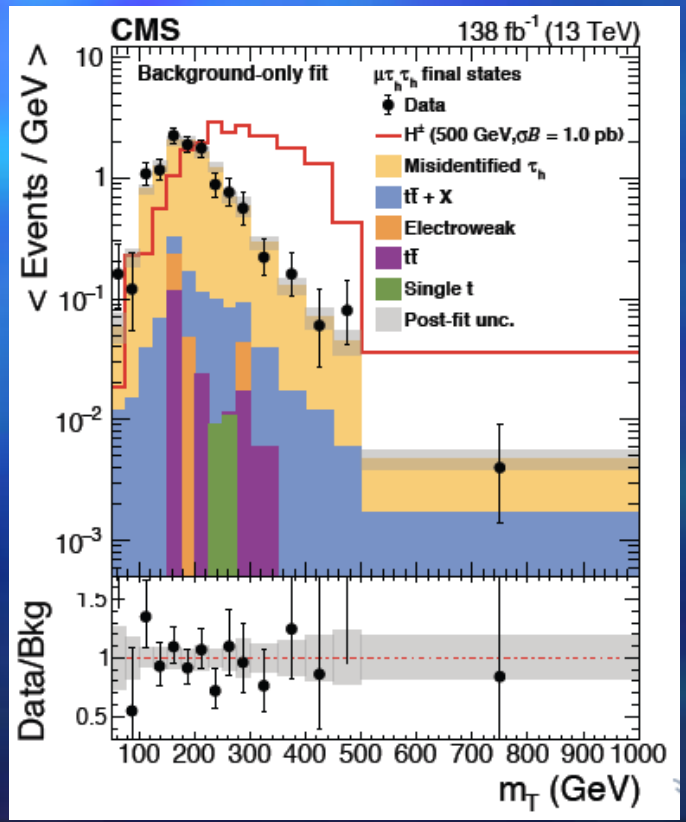
Heavy $H^+ \rightarrow h_{125} W$, $(h \rightarrow \tau\tau)$

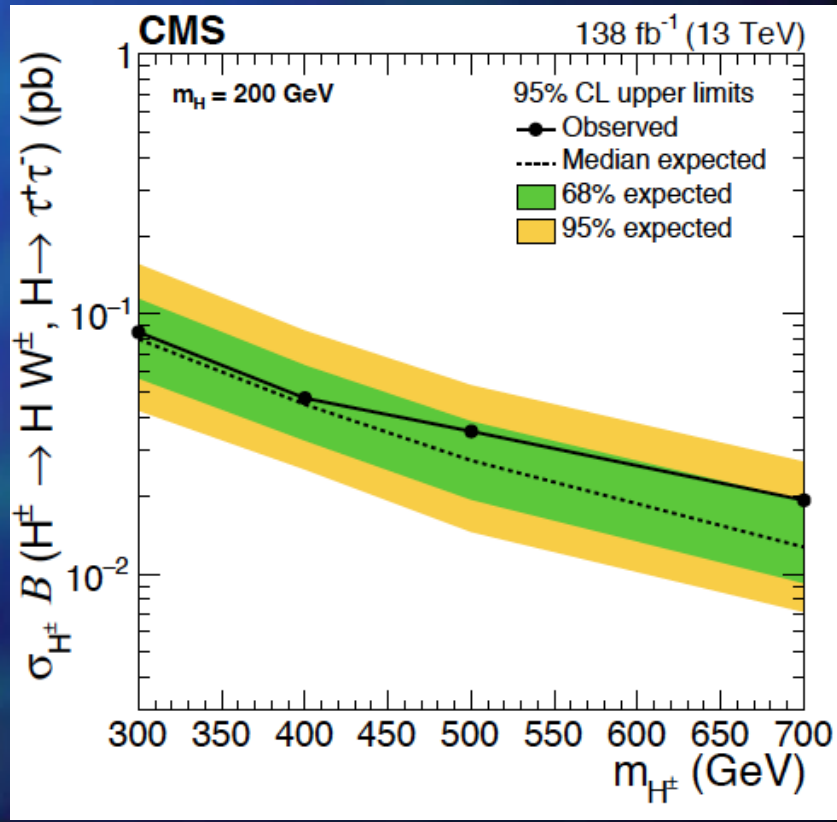


- Search for heavy Higgs in the region of 300-700 GeV
- Use e/μ τ_{had} ,e τ_{had} τ_{had} , μ τ_{had} τ_{had} channels
- Hadronic top decays identified using NN-based tagger
- Dominant bkgds in tt, V+jets
- Discriminating variable: e/μ τ_{had} (BDT:MVA output), e/μ τ_{had} τ_{had} (m_T)
- No significant excess over SM predictions

arXiv:2207.01046

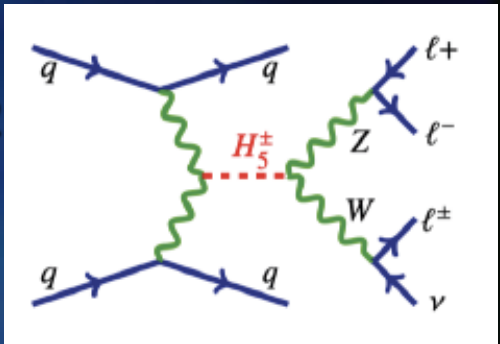




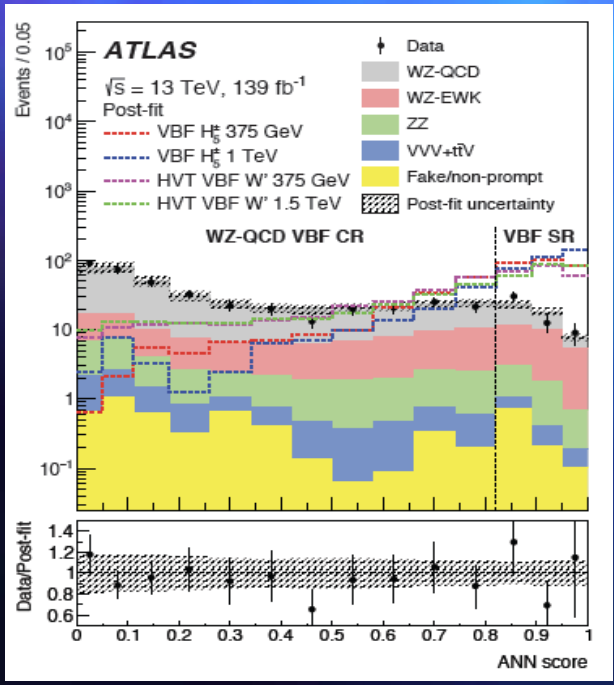


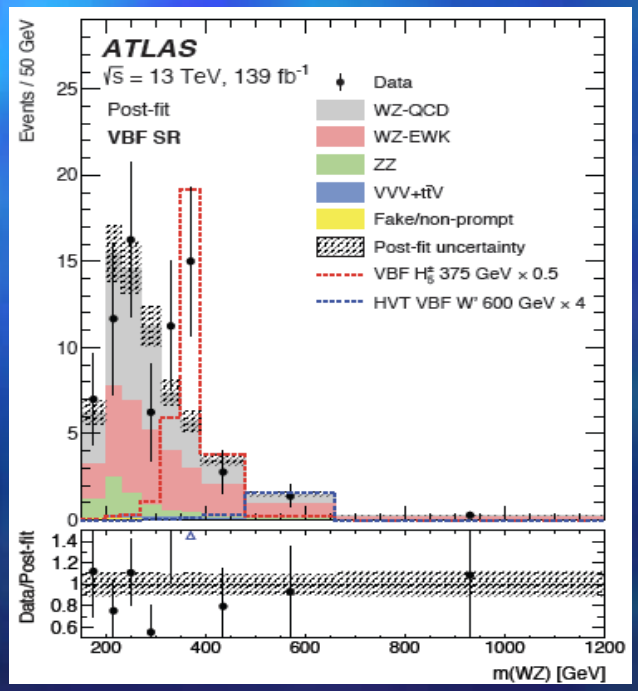
Heavy $H^+ \rightarrow WZ \rightarrow l\nu ll$

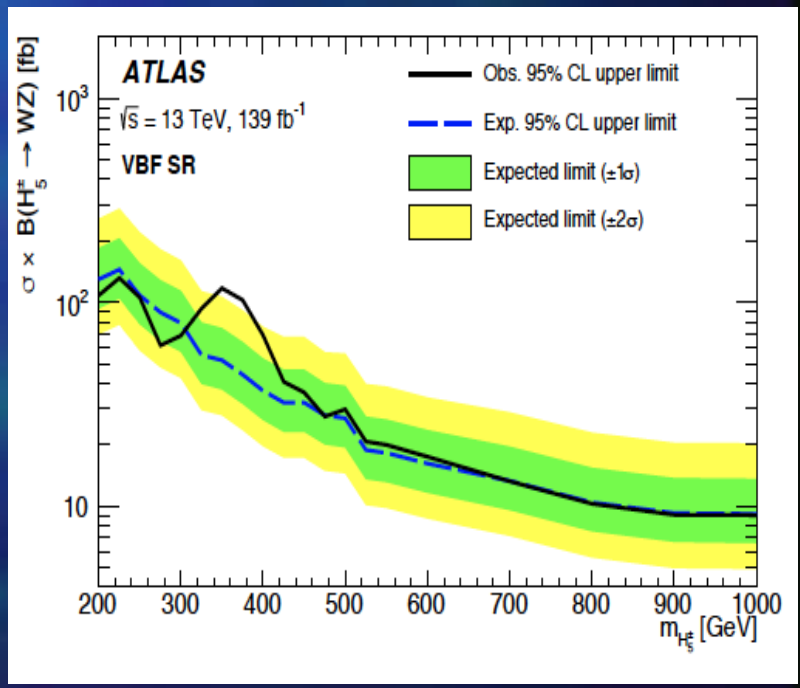
- Search for heavy Higgs to WZ decay in fully leptonic channel
- This channel is more sensitive for mass < ~ 1 TeV
- SR selection: 3l, MET, 2 VBF jets, m_{jj}>100 GeV, ANN>0.82
- Discriminating variable: m(WZ)
- No significant excess over SM predictions
- Largest excess 2.8 σ at 375 GeV



arXiv:2207.03925







Summary

- LHC CMS, ATLAS experiments have done much better than expected in understanding detector and analysis technique
- So far, no evidence of BSM Higgs in extensive and vigorous searches.
- LHC stated new run, Run 3 from Feb 2022, with expected data of $300fb^{-1}$
- We expect to have an another discovery after h_{125} with Run II, Run III and HL-LHC data

- So, Higgs potential is still GREAT!