

The Standard Model Higgs and beyond

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LIP Lisbon

April 17, 2024

- ✓ The Higgs boson and beyond
- ✓ Charged Higgs
- ✓ BSM Higgs: light pseudo-scalar, non-SM Higgs decay
- ✓ Higgs boson and Dark Matter

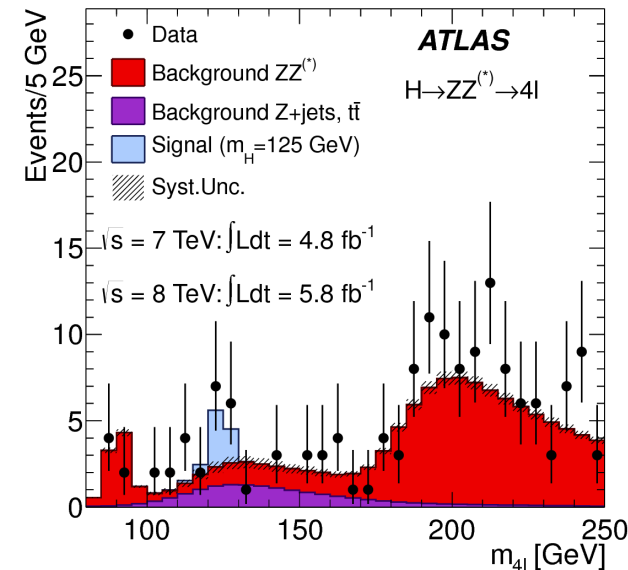
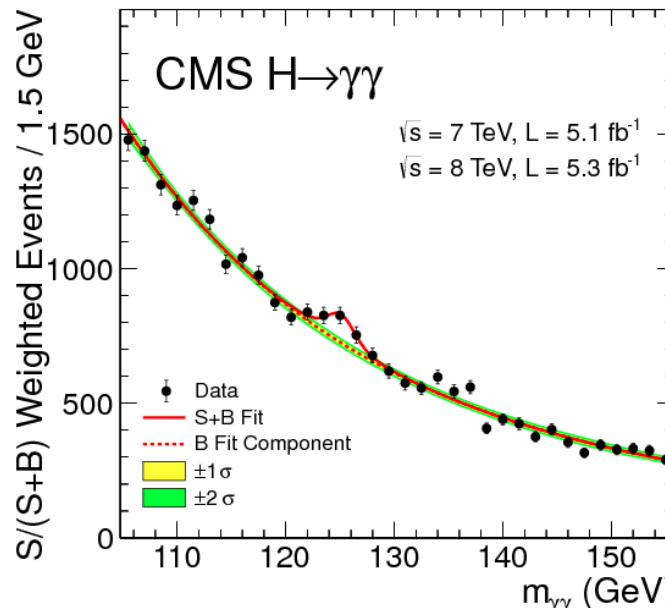
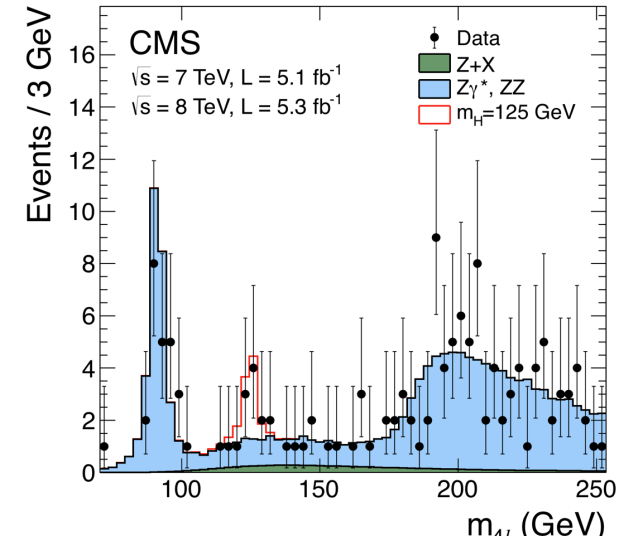
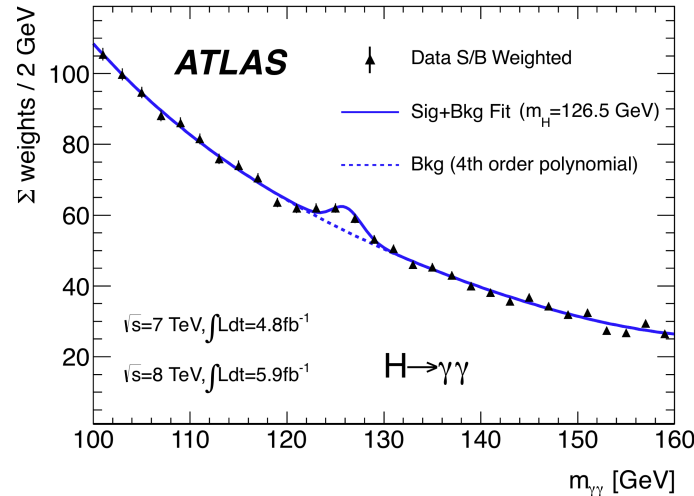
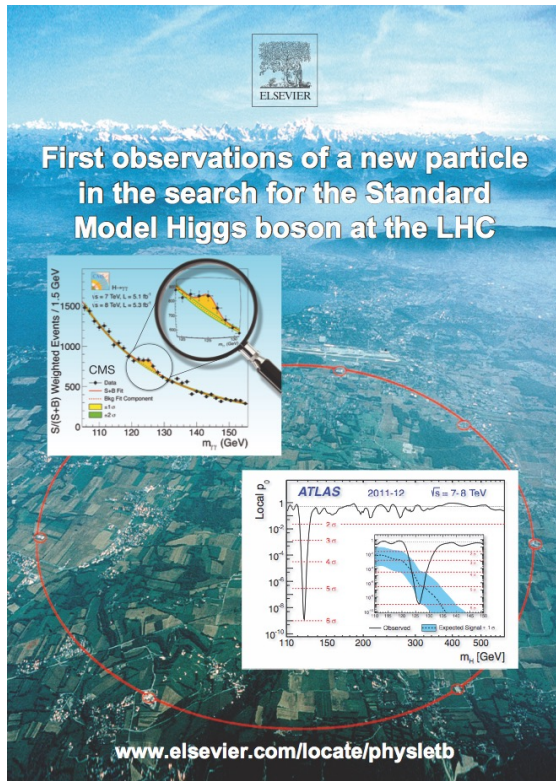


$$H \rightarrow ZZ \rightarrow 4e, 4\mu, 2e2\mu$$

- Signal: 4 isolated leptons from same vertex
 - Small background
 - Fully reconstructed, mass resolution $\sim 1\%$

The golden channel

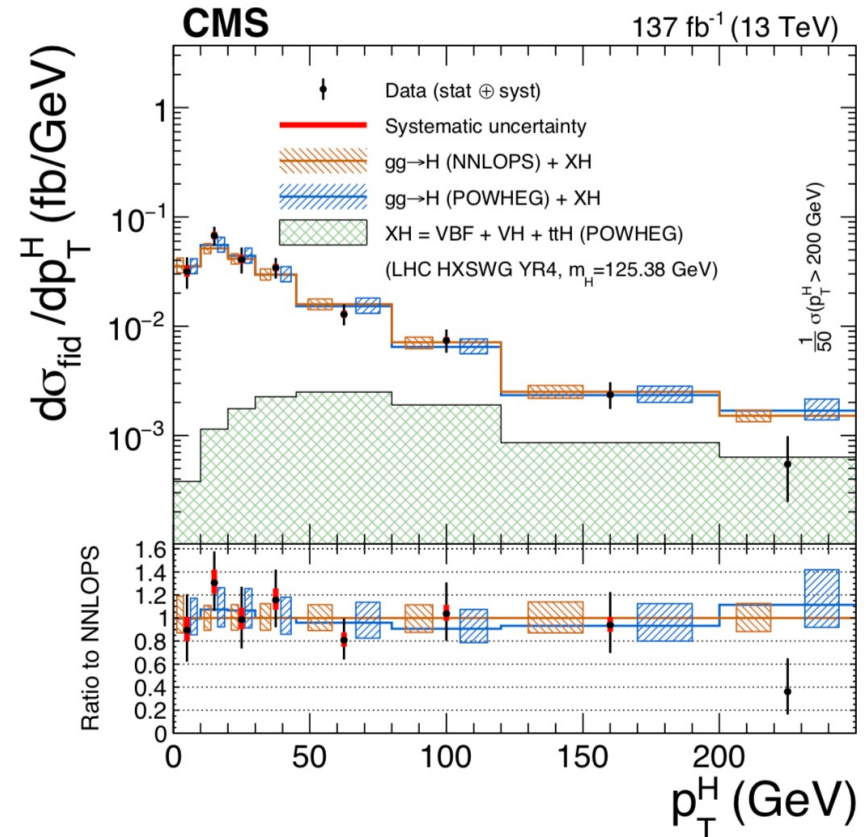
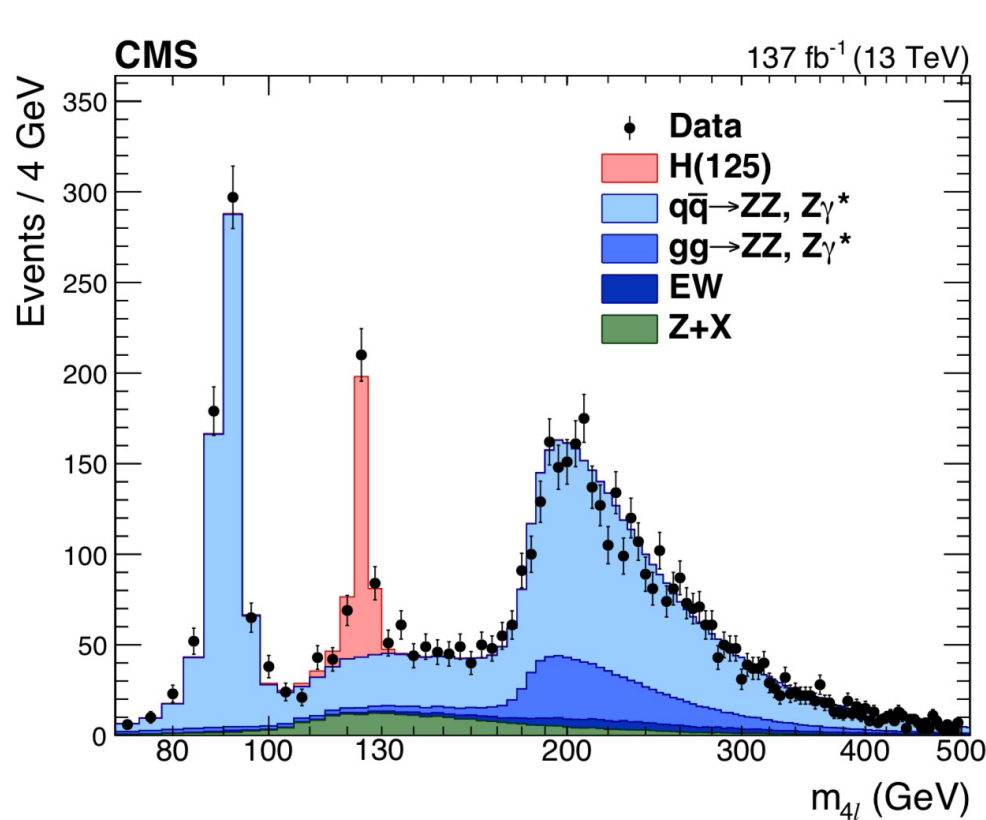
July 4th, 2012: A Higgs boson



Higgs and ZZ

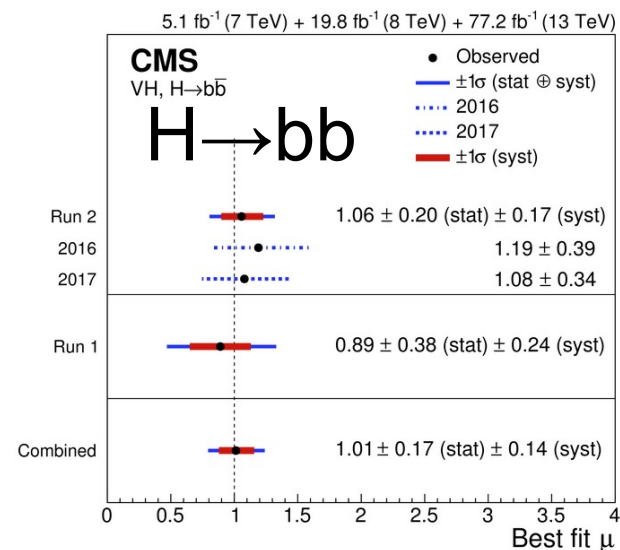
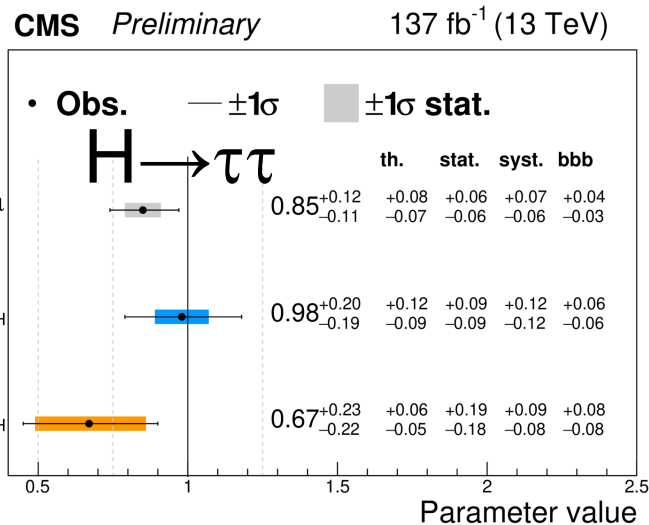
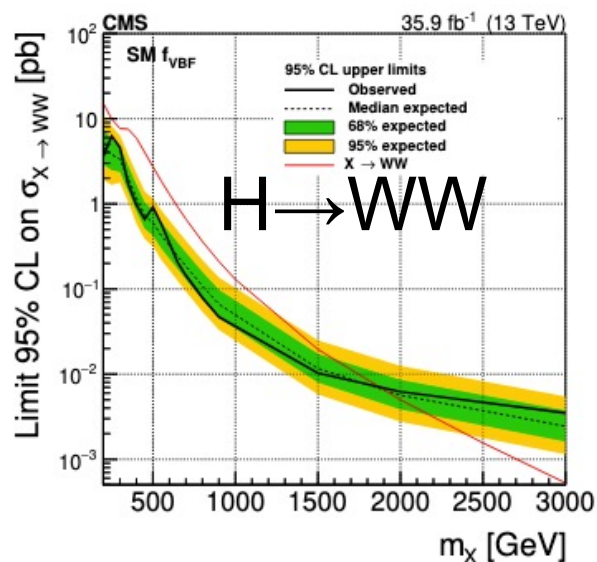
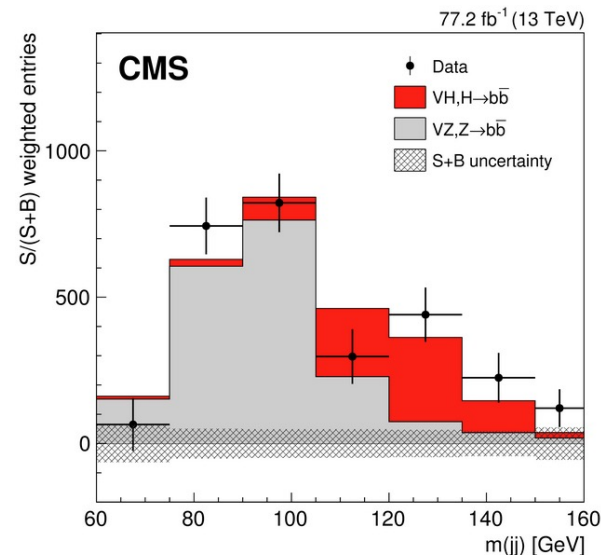
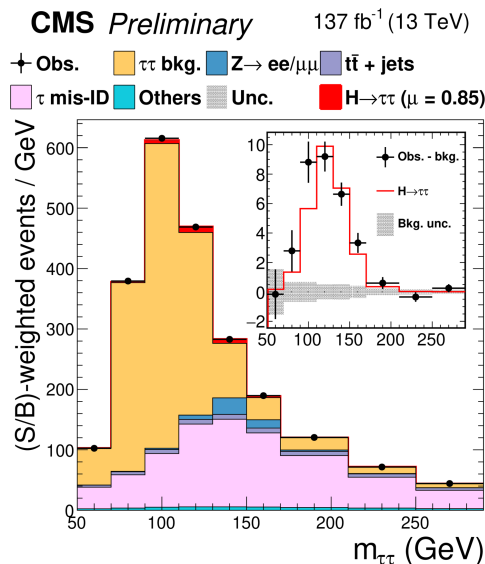
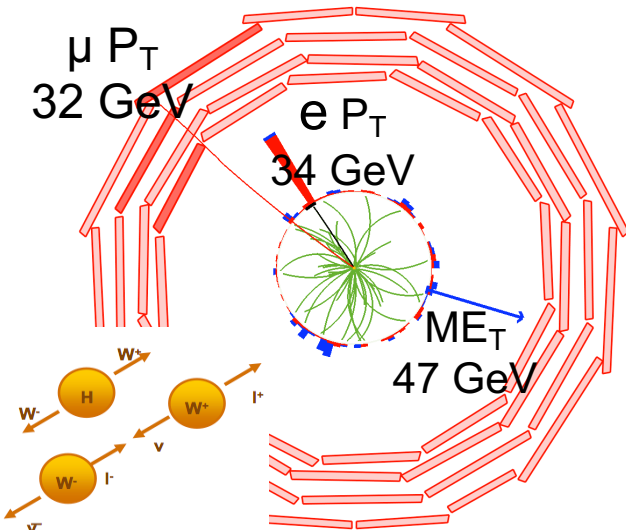
EPJC 81(2021)200, arXiv:2103.04956

- Study of SM ZZ production, and Higgs decay to ZZ
 - ~98% of Run2 data
- SM cross section measured with 3% precision



Low mass-resolution channels

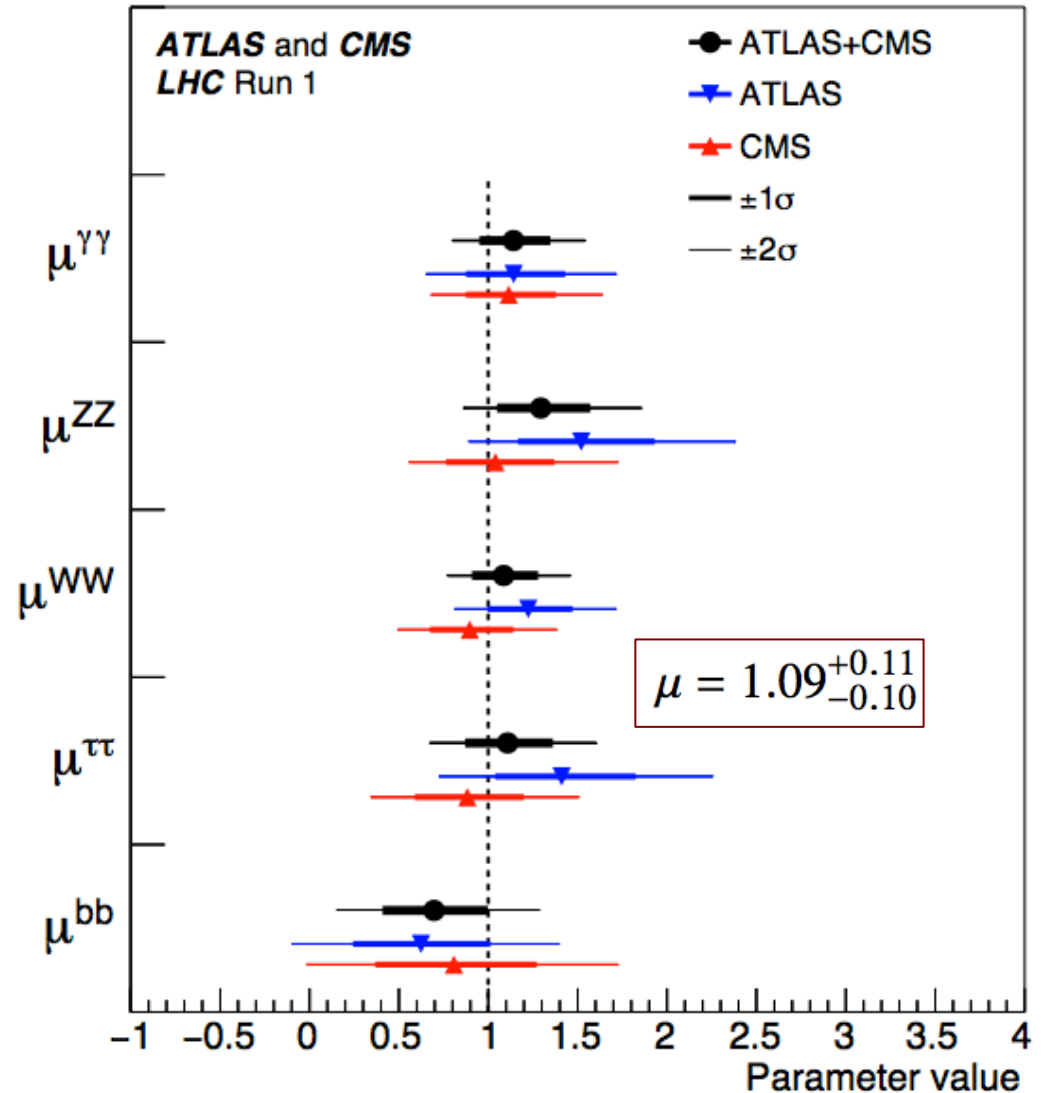
JHEP 03(2929)034, HIG-19-010, PRL 121(2018)121801



Couplings: individual channels

EPJC 75(2015)212, arXiv:1507.04548, arXiv:1606.02266

Results based on the full
Run 1 data samples



Rare decays: $H \rightarrow \mu\mu, cc$

JHEP 01(2021)148, JHEP 03(2020)131, arXiv:2205.05550, arXiv:2211.14181

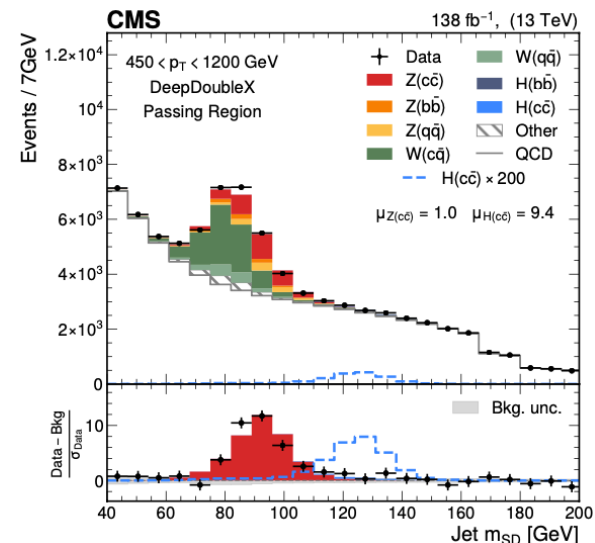
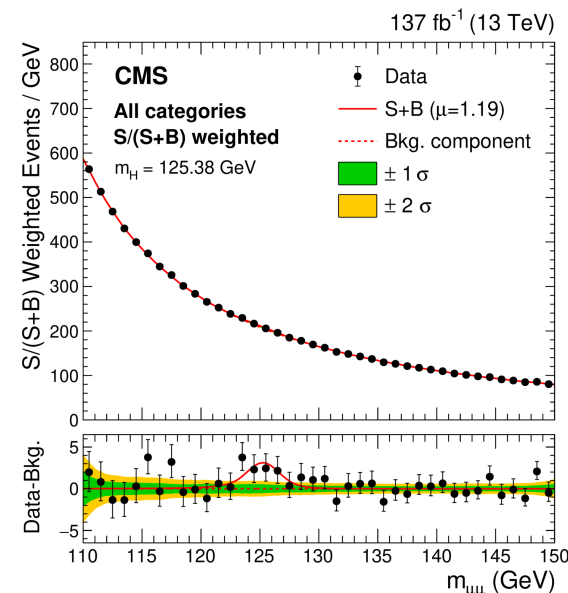
Study couplings to 2nd generation

- $H \rightarrow \mu\mu$
 - Most sensitive category is VBF channel
 - Obs.(exp.): 3.0σ (2.5σ)
- $H \rightarrow cc$
 - Low cross section, need c-tagging
 - Use resolved (2jets) and merged (1jet),
 - Use ML and jet substructure for tagging and classification
 - Validate using VZ production:

$$\mu_{VZ(cc)} = 1.01^{+0.23}_{-0.21} \quad (5.7\sigma)$$

- Set limits

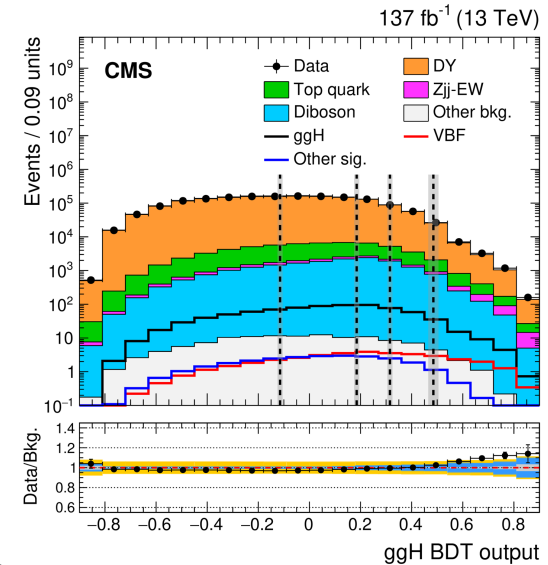
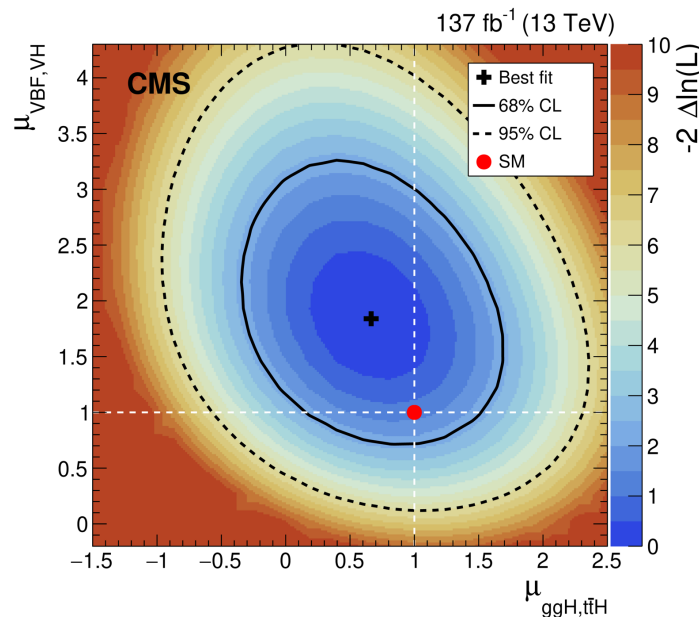
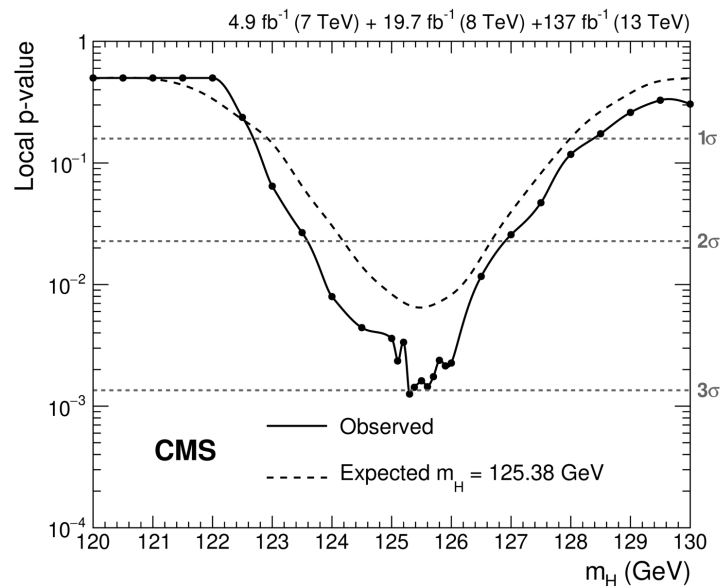
$$\sigma(VH) \mathcal{B}(H \rightarrow c\bar{c}) < 0.94 \text{ pb}$$



Search for SM $H \rightarrow \mu\mu$

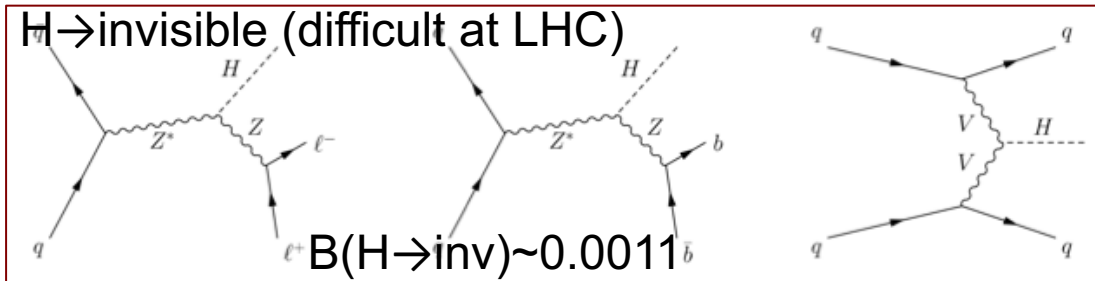
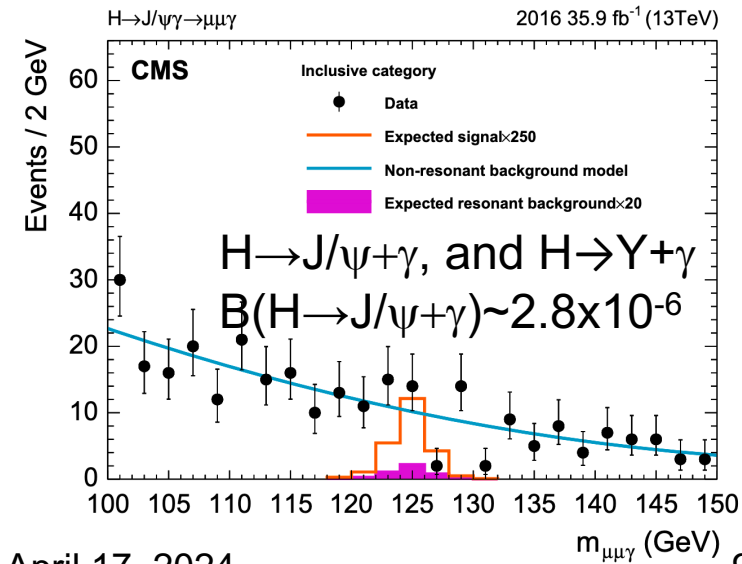
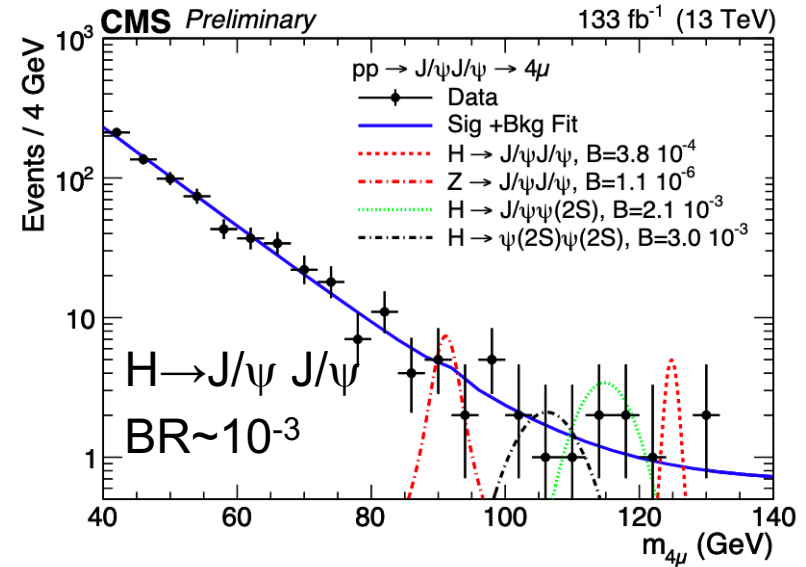
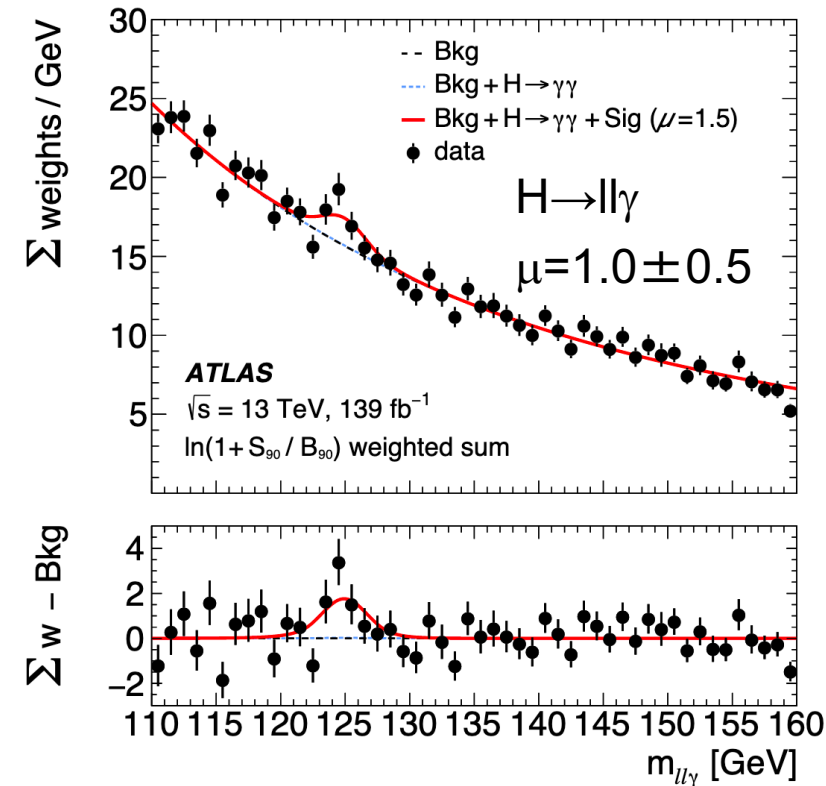
JHEP 01(2021)148

- Small rate: $\mathcal{B}(H \rightarrow \mu^+ \mu^-) = 2.18 \times 10^{-4}$
- Search based on BDT discriminant
 - Event categories based on BDT score
- Weighted sum of individual fits to each category
- Signal strength: $\mu = 1.19^{+0.40}_{-0.39} (\text{stat})^{+0.15}_{-0.14} (\text{syst})$



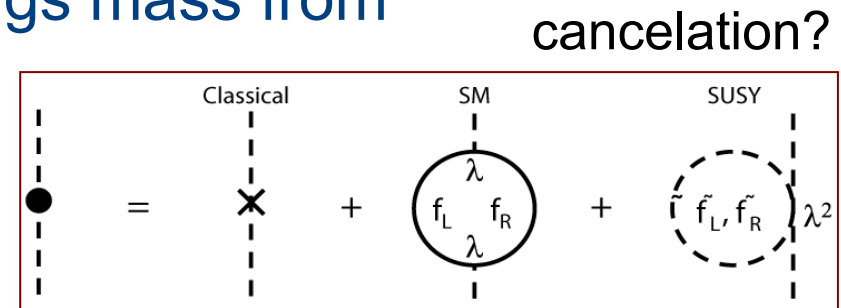
Search for rare decays

PLB 797(2019)134811, arXiv:2103.10322, EPJC 79(2019)94, PLB 793(2019)520, CMS-HIG-20-008



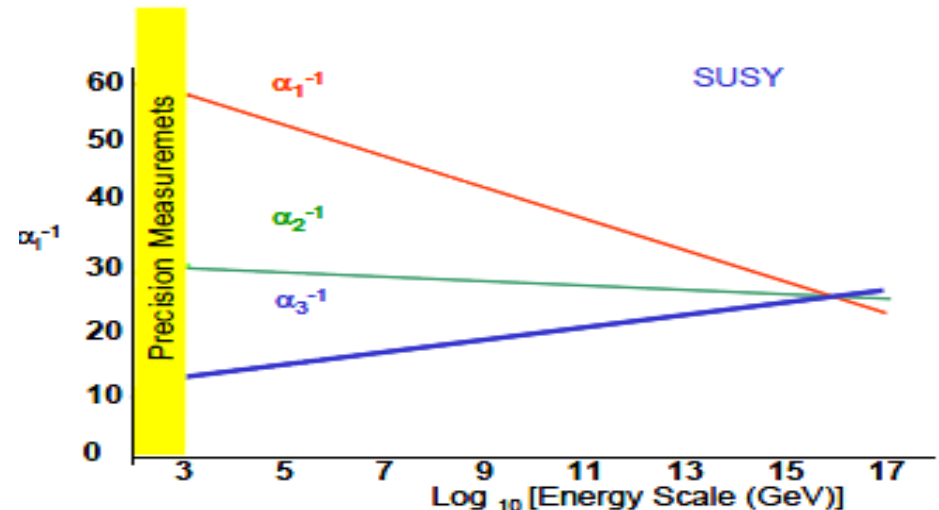
Higgs and the SM

- SM is a successful theory
- Nothing prevents the SM to survive up to the Planck scale. However, it is **unnatural**.
- Virtual particles in quantum loops contribute to the Higgs mechanism
 - contributions grow with Λ (upper scale validity of the SM)
 - Higgs mass depends quadratically on Λ : $m^2 = m_0^2 + g^2\Lambda^2$
- Miraculous cancellations are needed to keep $m_H < 1\text{TeV}$
- Is there a symmetry that protects the Higgs mass from receiving large corrections?



Higgs and the SM (cont.)

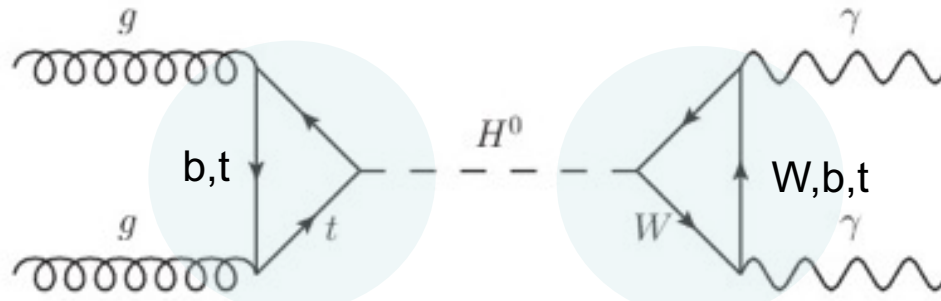
- SUSY postulates a new symmetry between fermions and bosons
 - Loops of particles and their SUSY partners have the ability to cancel the quadratic divergences in the Higgs field self-couplings, solving the naturalness problem
 - SUSY foresees unification of couplings at large energy scales $\sim 10^{15}$ GeV
 - Provides DM candidates (LSP)
- It suggests many options, but the LHC may not be able to find it
- # of experimental scenarios is large



Higgs and BSM

ATLAS-CONF-2015-044, CMS-HIG-15-002

- Is there BSM physics **hidden** in the “Higgs sector”?

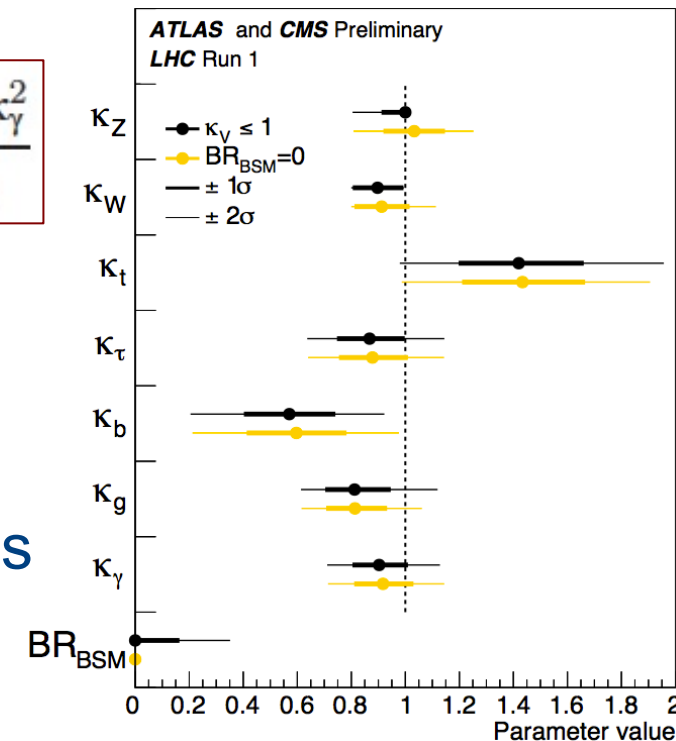


$$(\sigma \cdot \text{BR})(gg \rightarrow H \rightarrow \gamma\gamma) = \sigma_{\text{SM}}(gg \rightarrow H) \cdot \text{BR}_{\text{SM}}(H \rightarrow \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

Experimental approach

- Measure \$H(125)\$ properties
- Search for additional Higgs bosons
- Search for BSM in signatures with Higgs bosons
- Search for BSM Higgs decays

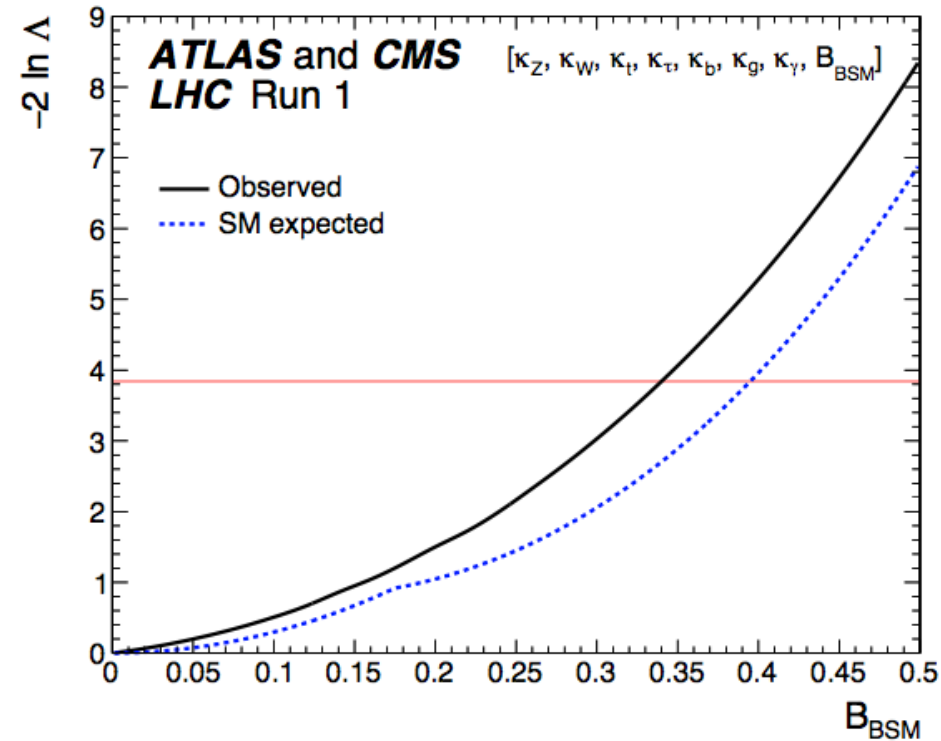
Strategy: parametrize deviations wrt SM in production and decay
 $\Rightarrow$ loops are sensitive to BSM physics



Looking for new particles

JHEP08(2016)045

- Constrain BR_{BSM} in a scenario with free parameters
- $\Gamma_{tot} = \Gamma_{WW} + \Gamma_{ZZ} + \Gamma_{bb} + \dots + \Gamma_{BSM}$
- Likelihood scan vs BR_{BSM}
- Assuming couplings bound by SM expectations ($k_v < 1$)
- $0 \leq BR_{BSM} \leq 0.34$ at 95%CL



Constraining Higgs width

PLB 736(2014)64

- couplings and width sensitive probes to BSM
- indirectly constrained in coupling fits
- off-peak to on-peak ratio proportional to Γ_H
- constrain Higgs boson width by using off-shell production/decay
- measure ratio of $\sigma^{\text{off-peak}}$ to $\sigma^{\text{on-peak}}$

$$\sigma_{\text{gg} \rightarrow \text{H} \rightarrow \text{ZZ}}^{\text{on-peak}} \propto \frac{g_{\text{ggH}}^2 g_{\text{HZZ}}^2}{\Gamma_H}, \quad \sigma_{\text{gg} \rightarrow \text{H} \rightarrow \text{ZZ}}^{\text{off-peak}} \propto g_{\text{ggH}}^2 g_{\text{HZZ}}^2$$

F. Caola, K. Melnikov PRD88(2013)054024
J. Campbell et al. arXiv:1311.3589

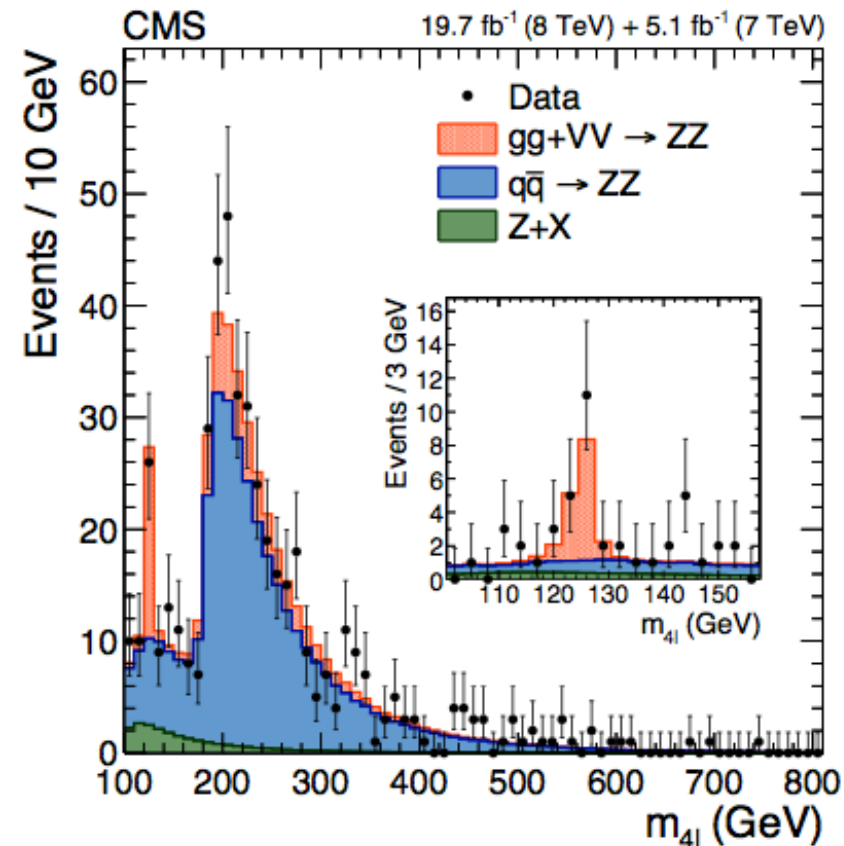
– g_{ggH} and g_{HZZ} : couplings to gluons and bosons

- measurement of Γ_H

obs.(exp.) @95%CL:

$$\Gamma_H < 5.4(8.0) \Gamma_H^{\text{SM}}$$

$$\Gamma_H < 22(33) \text{ MeV}$$

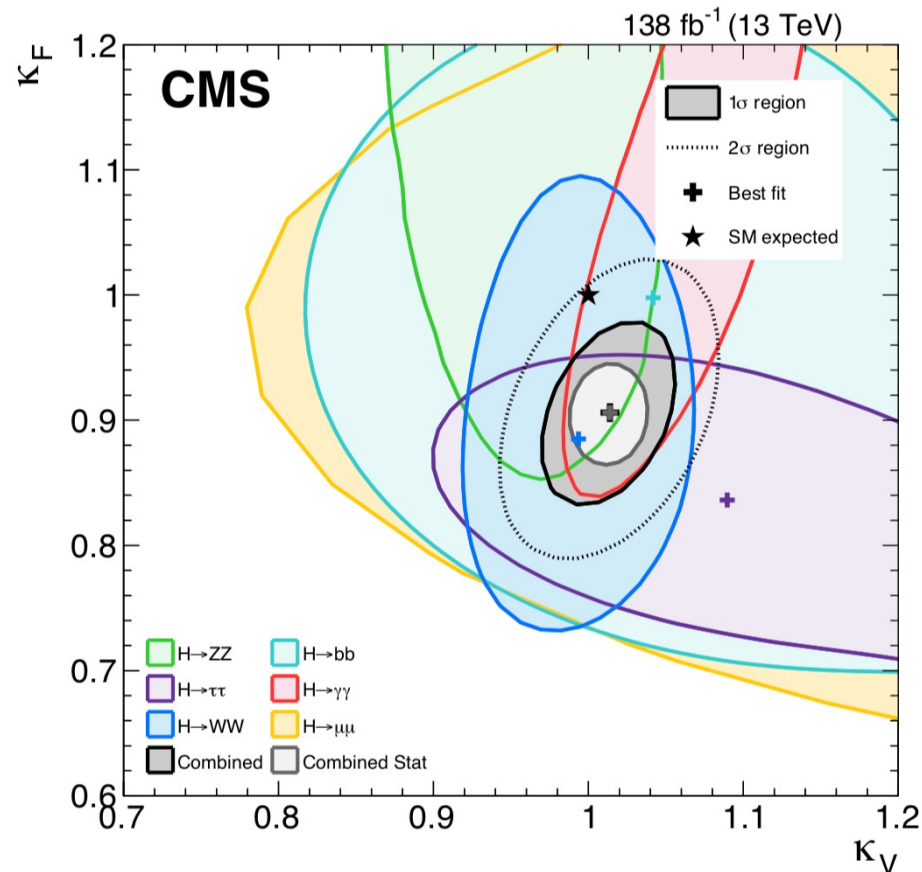
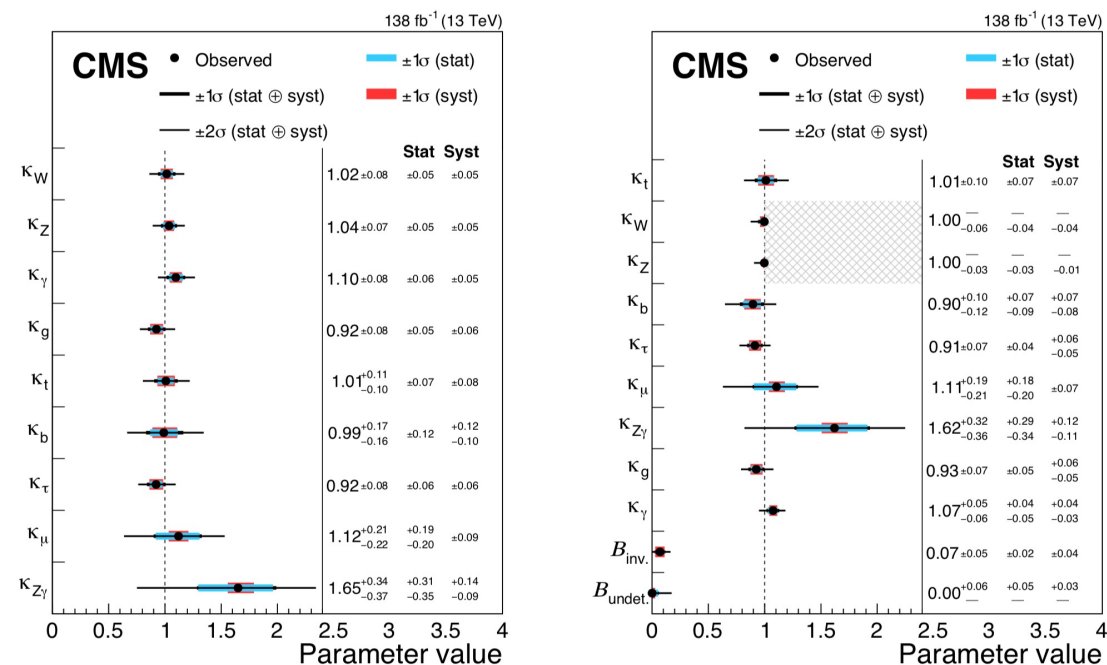


Couplings: decays

ATLAS-CONF-2015-044, CMS-HIG-15-002, JHEP08(2016)045, CMS-HIG-22-001

BSM physics in the loop

Vector and fermion couplings



BR_{BSM} can be measured

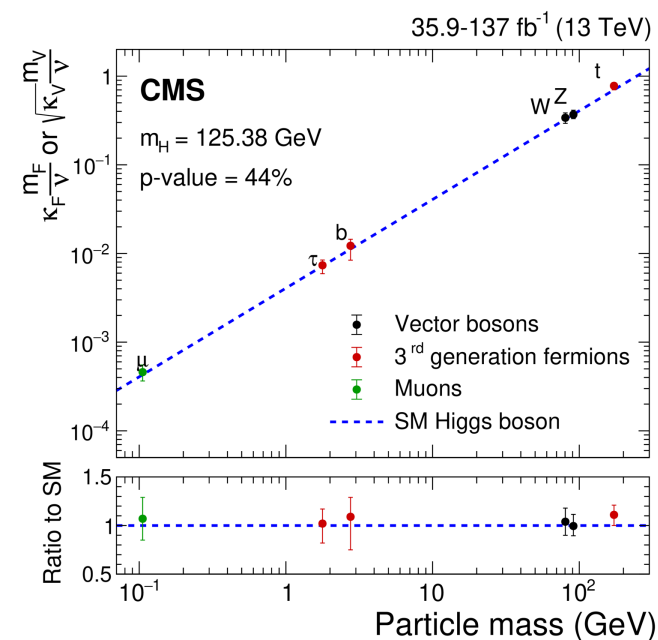
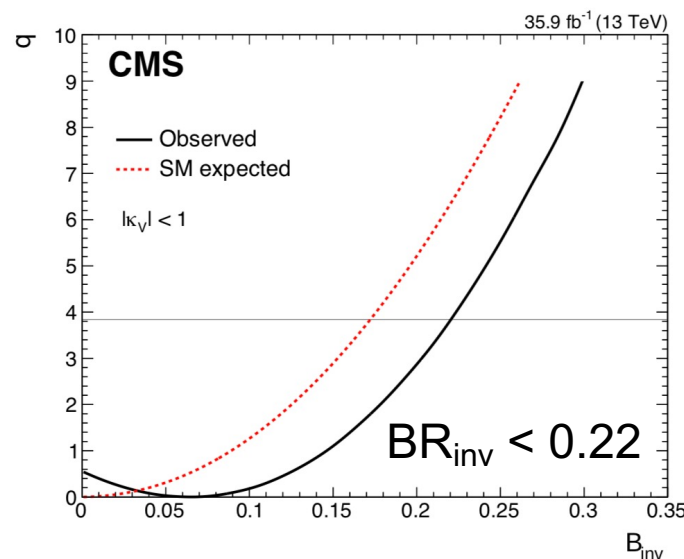
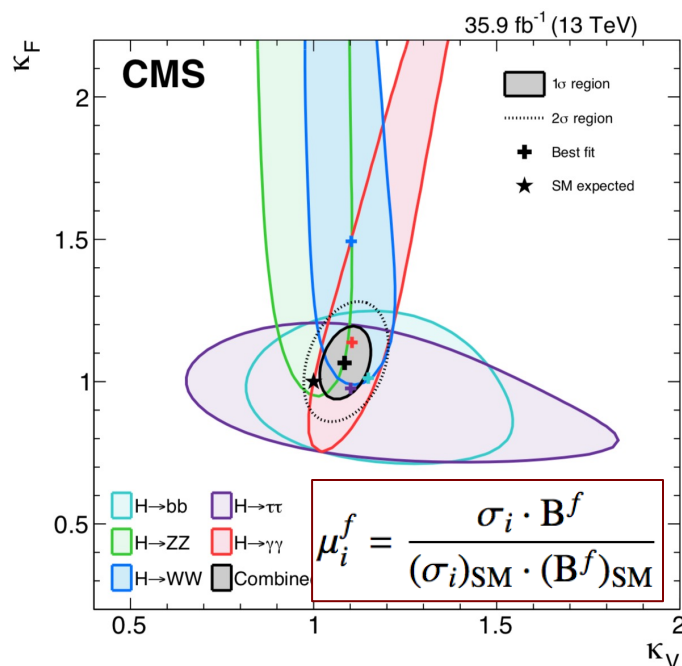
$BR_{BSM} < 0.34$ at 95% C.L. (assuming $k_V \leq 1$)

BR_{BSM} includes non standard decays, visible or invisible

$\Rightarrow$ Results in agreement with SM ($k_V=k_F=1$) within 1σ

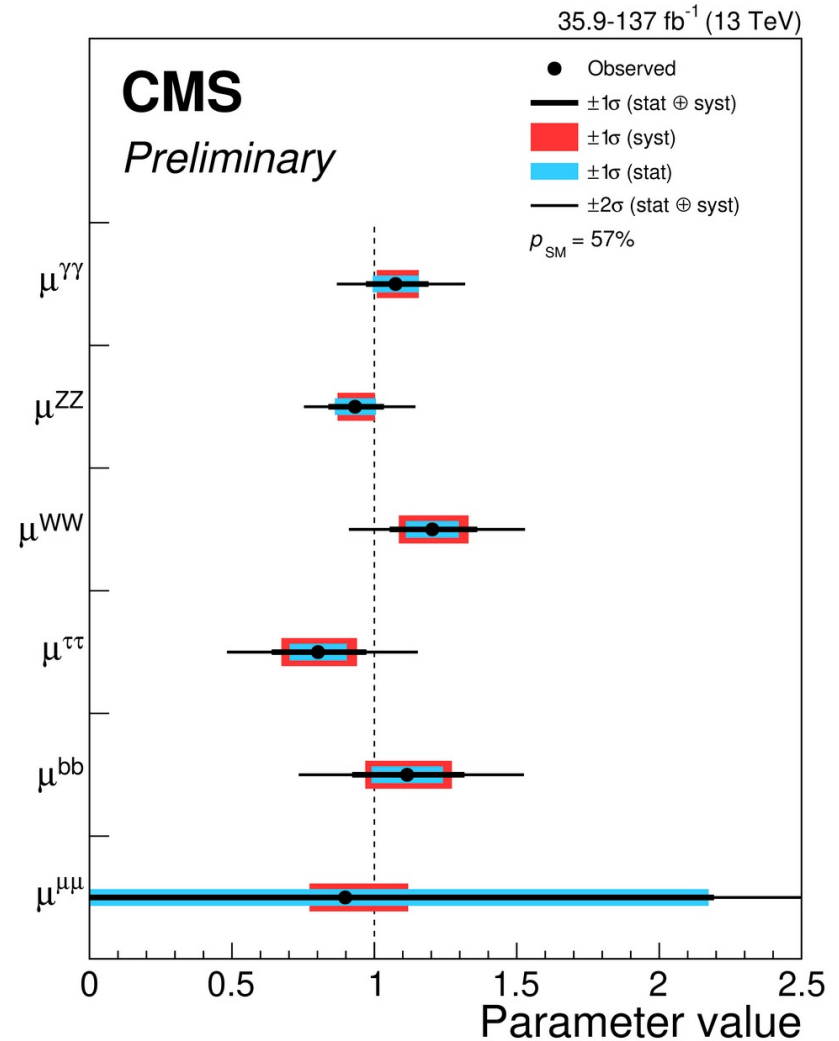
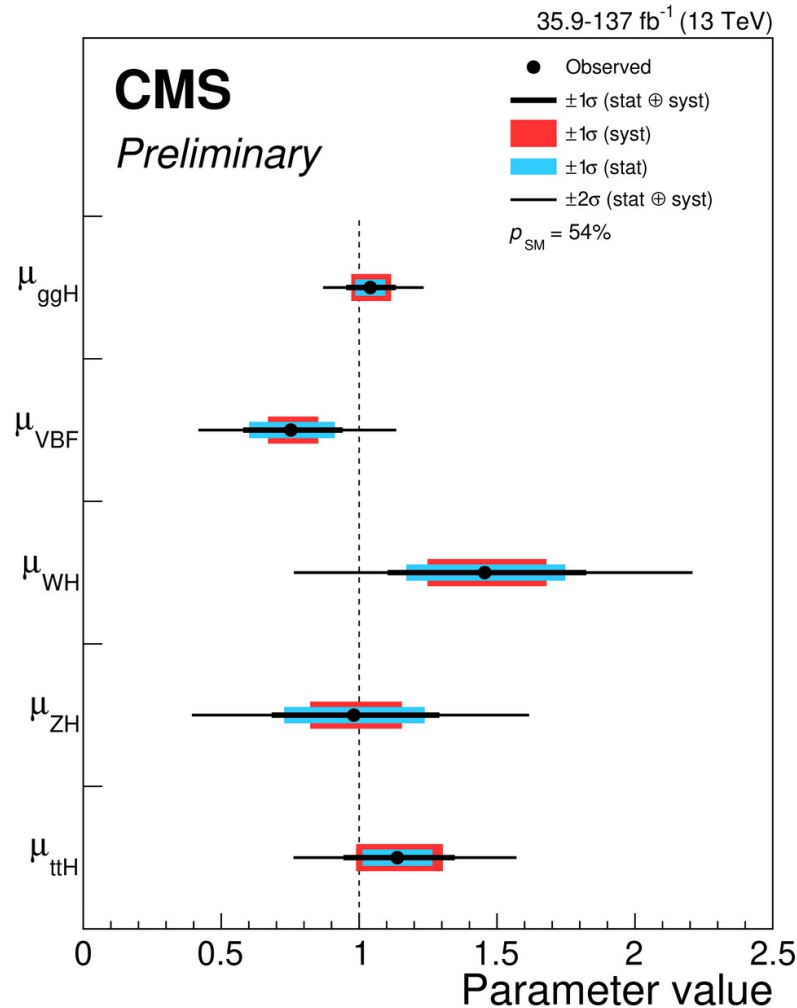
Consistency with SM

arXiv:1809.10733, JHEP 01(2021)148



Consistency with SM

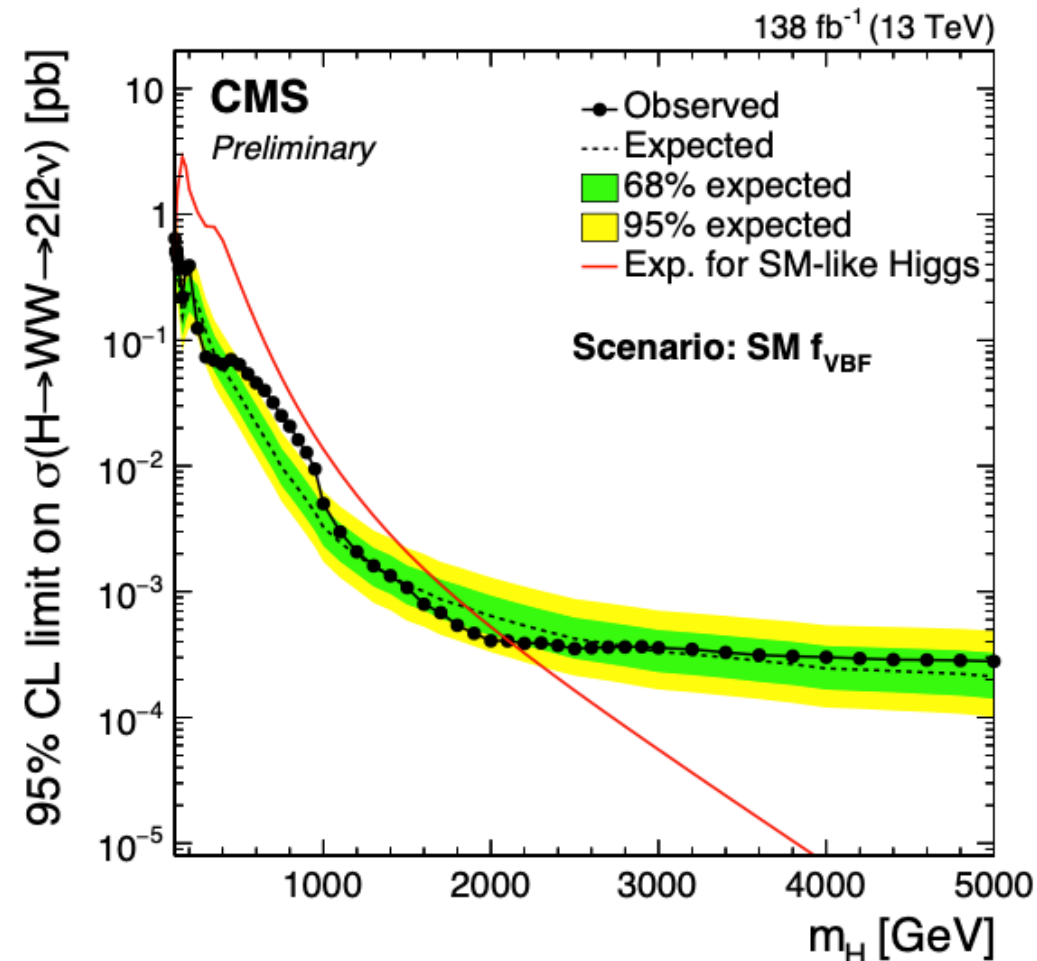
CMS HIG-19-005



High mass: $H \rightarrow WW/ZZ$

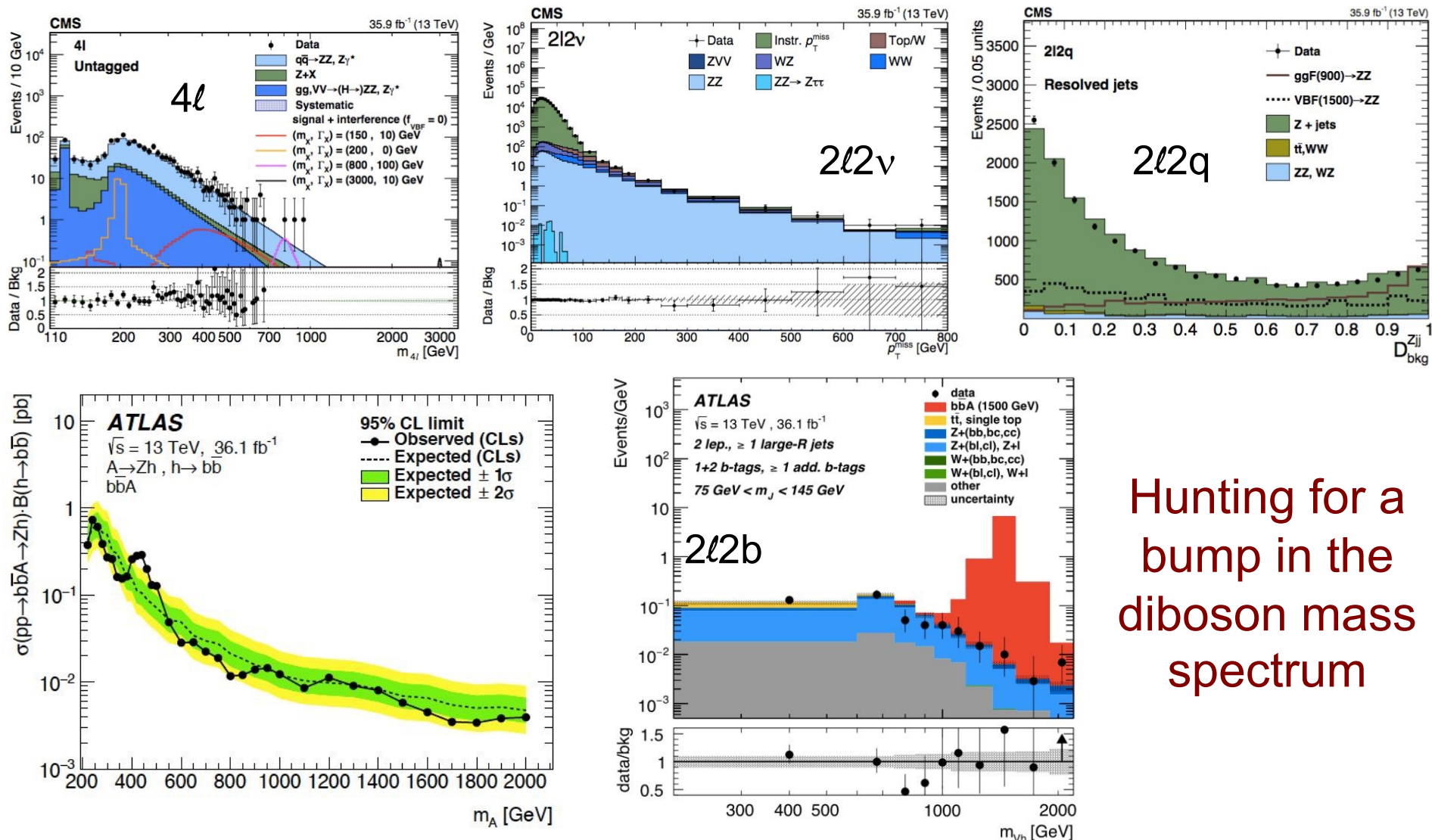
JHEP 10(2015)144, HIG-16-033, HIG-16-034, arXiv:1912.01594, HIG-20-016

- Search for a heavy Higgs boson
 - $H \rightarrow ZZ \rightarrow 4\ell, 2\ell 2\nu, 2\ell qq$
 - $H \rightarrow WW \rightarrow 2\ell 2\nu, 2\ell qq$
- Optimized separately for VBF and gluon fusion production processes
- Combined upper limits at 95% CL on the product of $\sigma \times \text{BR}$ exclude a heavy Higgs boson with SM-like couplings and decays up to 1870 GeV
- Search interpreted in BSM scenario (heavy Higgs, heavy EWK singlet state)
 - evolution of signal strength of the singlet state with modified couplings/width wrt SM.
 - assume new scalar does not decay to any new particle



Heavy Higgs: dibosons

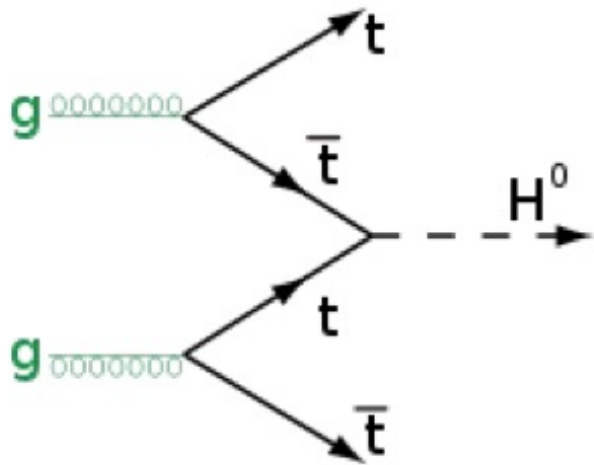
arXiv:1804.01939, JHEP03(2018)174, arXiv:1804.01126



Hunting for a bump in the diboson mass spectrum

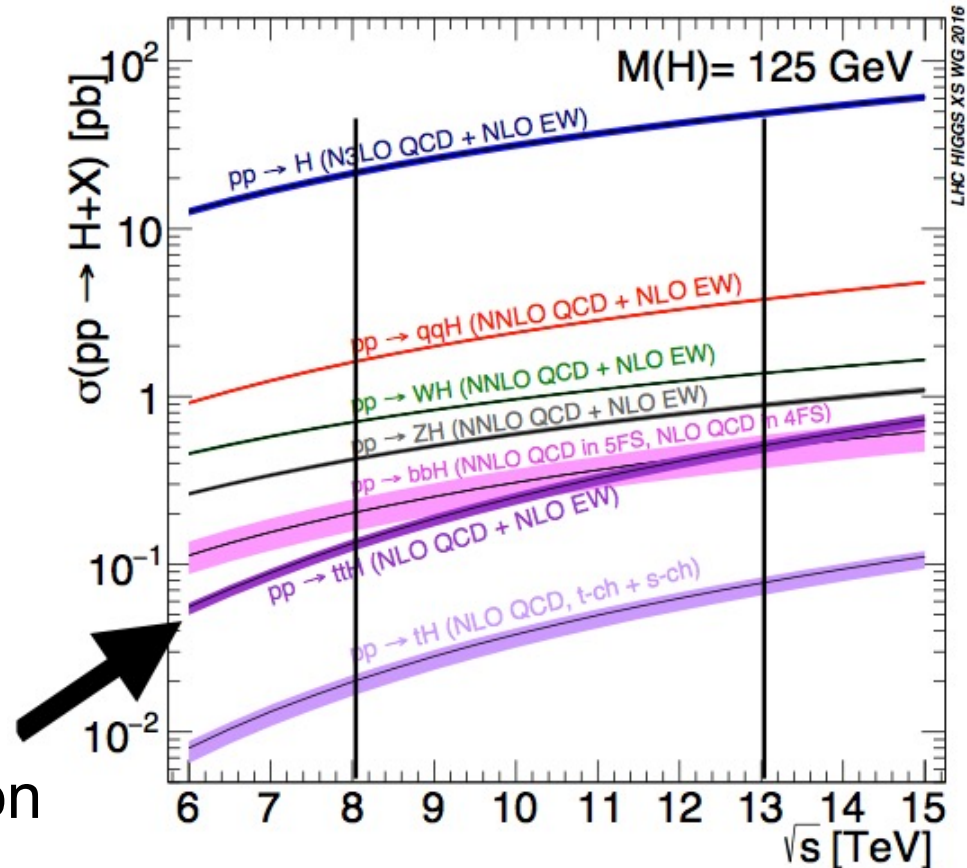
$t\bar{t}$ +Higgs

- $t\bar{t}$ produced in association with Higgs boson



Cross section for $t\bar{t}H$ at the LHC:
0.13 pb (8 TeV)
0.61 pb (14 TeV)

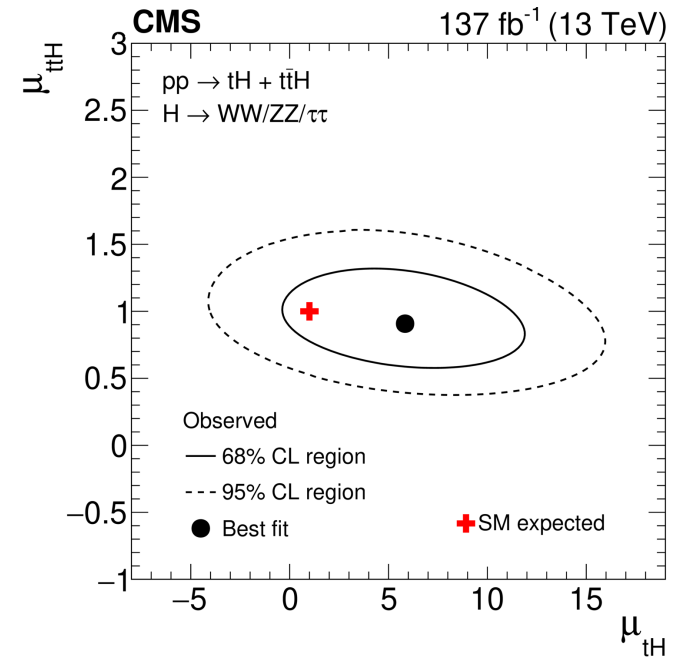
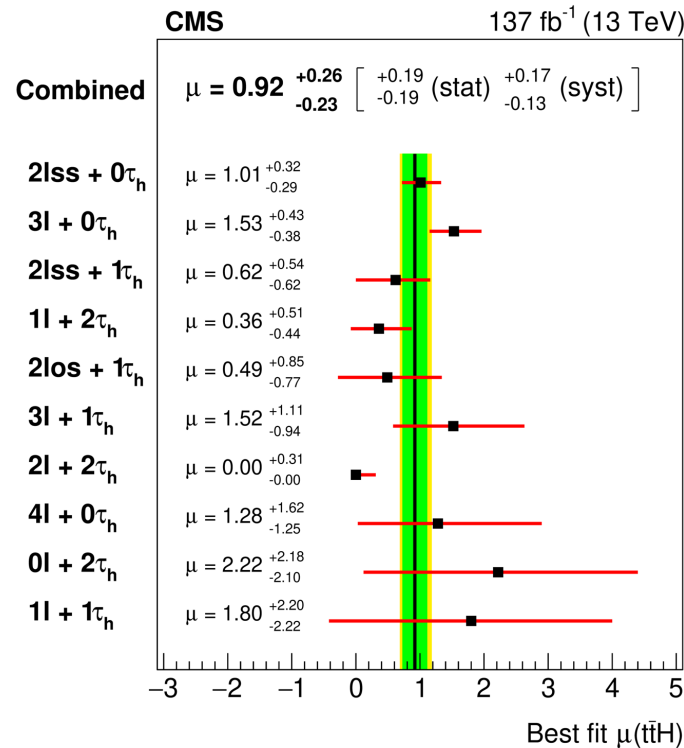
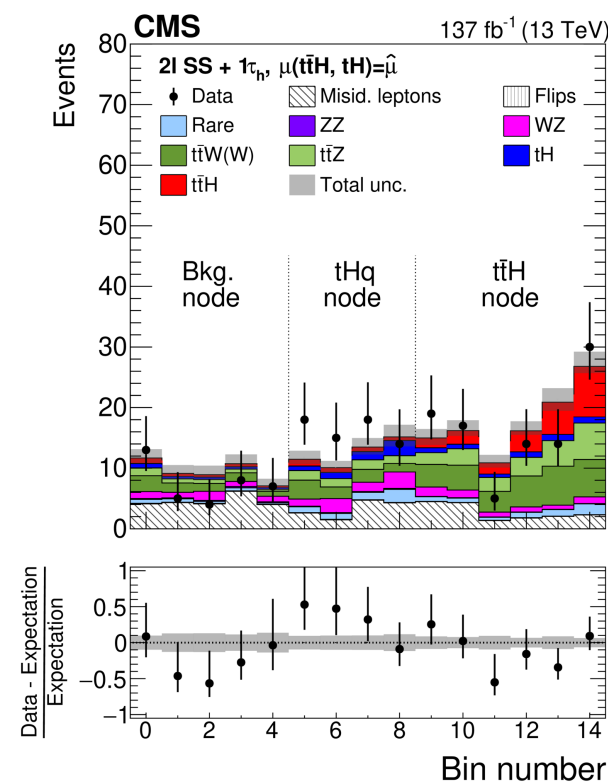
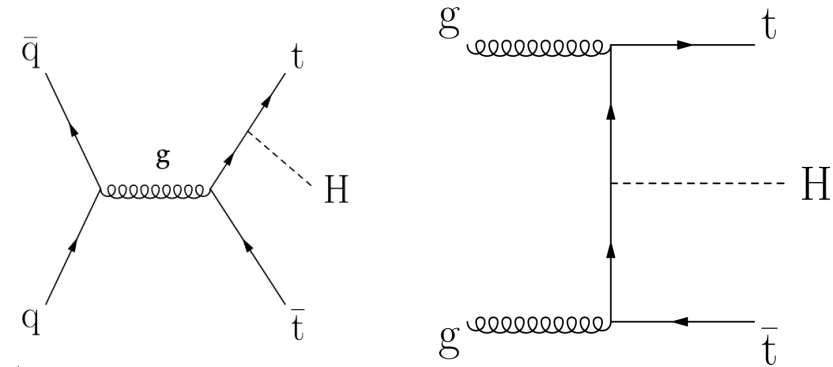
$t\bar{t}H \sim 1\%$ of total Higgs cross section



Higgs+Top: tH, ttH

arXiv:2011.03652

- Higgs (H) bosons production in association with one (tH) or two (ttH) top quarks in final states with electrons, muons, tau
- Study $H \rightarrow WW/\tau\tau/ZZ$ decays
- Model-independent, signature-based



Extending searches

- Minimal Supersymmetric SM (MSSM)
 - Neutral Higgs: $\phi \rightarrow \tau\tau/bb/\mu\mu$
 - Charged Higgs
- Next-to-MSSM
 - Light pseudoscalar: $h \rightarrow aa$
 - Non-SM decays: $h \rightarrow 2a \rightarrow 4\tau/4\mu$
 - Heavy Higgs: $H \rightarrow h_{125}h_{125}$ or $A \rightarrow Zh_{125}$
- FCNC: $t \rightarrow cH$

Higgs sector in the MSSM

Higgs sector in SUSY contains two scalar doublets:

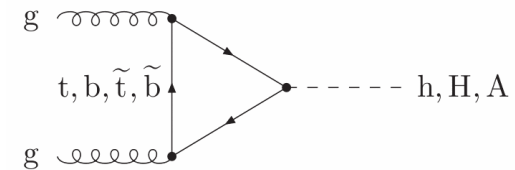
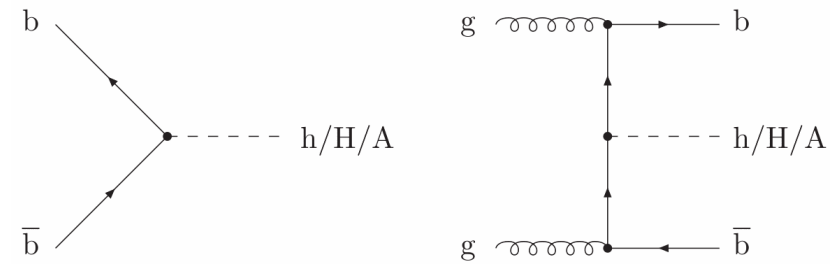
- 5 physical Higgs bosons
 - 3 neutral: CP-even $\phi=h, H$ CP-odd A
 - 2 charged $H^\pm$
- SM-like Higgs boson: h

Neutral Higgs ϕ decay modes:

- $\text{BR}(\phi \rightarrow b\bar{b}) \sim 90\%$
- $\text{BR}(\phi \rightarrow \tau\tau) \sim 10\%$
- $\text{BR}(\phi \rightarrow \mu\mu) \sim 0.1\%$

Two main production modes:

- $gg \rightarrow H$
- $b\bar{b}H$



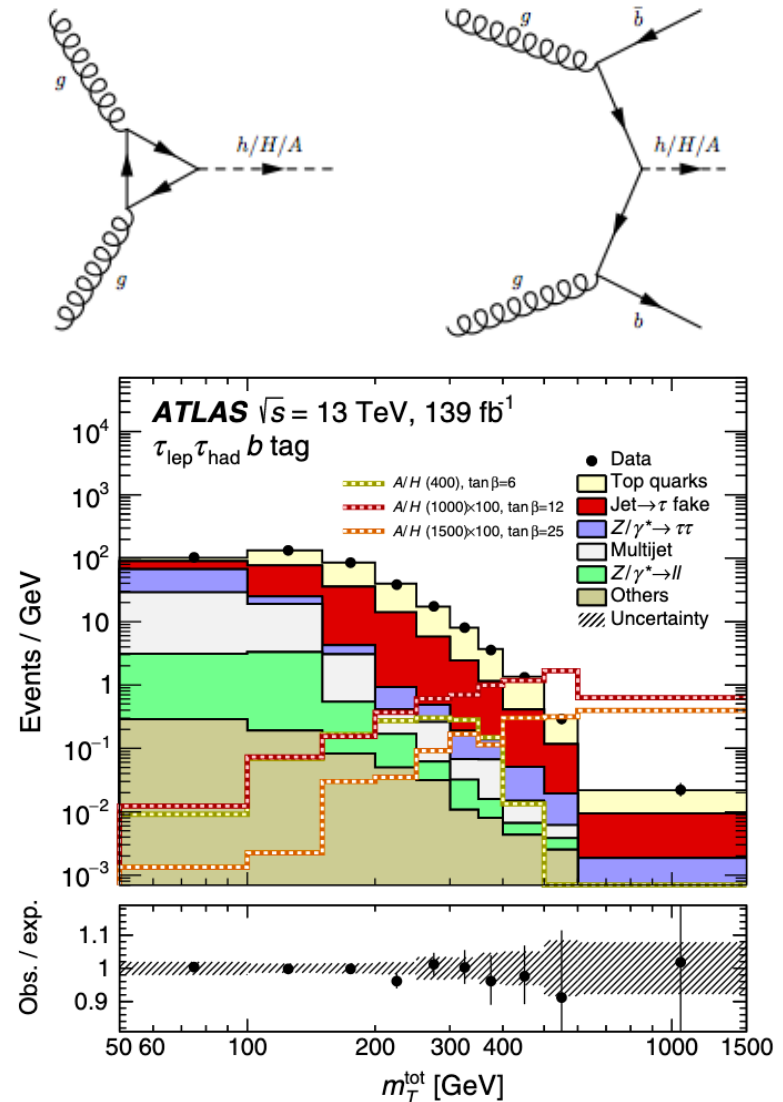
Neutral MSSM Higgs

JHEP 10(2014)212, arXiv:1803.06553, PRL 125(2020)051801

- Enhanced couplings of MSSM Higgs to down-type fermions (large $\tan\beta$)
 $\Rightarrow$ increased BR to τ leptons and b-quarks

$$m_T^{\text{tot}} = \sqrt{m_T^2(p_T^{\tau_1}, p_T^{\tau_2}) + m_T^2(p_T^{\tau_1}, p_T^{\text{miss}}) + m_T^2(p_T^{\tau_2}, p_T^{\text{miss}})},$$

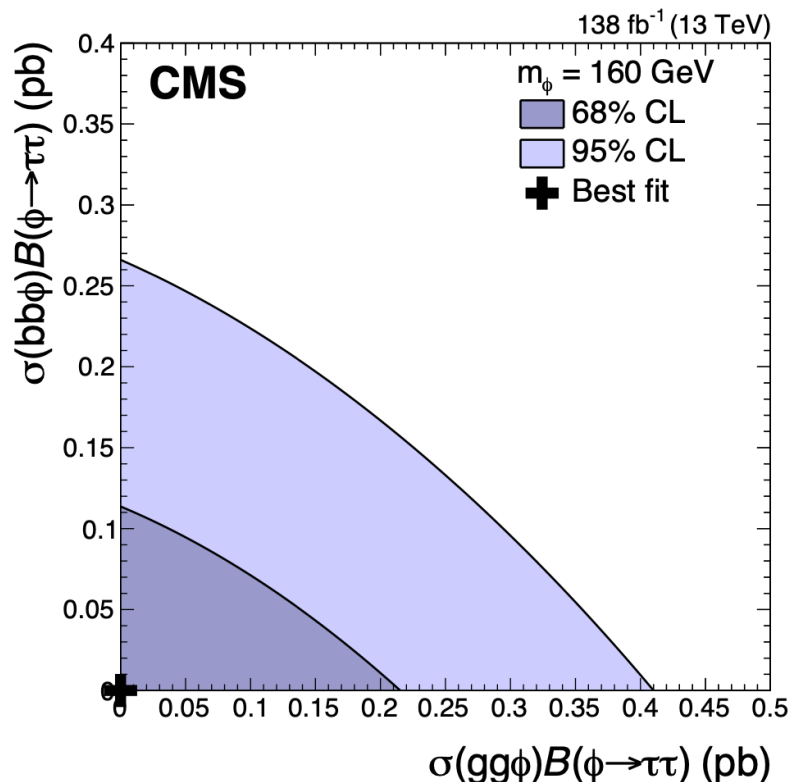
- Search for neutral MSSM Higgs boson
- 5 final states used: $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$, $e\mu$, $\mu\mu$
 - Reconstruct tau-pair invariant mass
 - Split in b-tag/no b-tag categories to enhance sensitivity
- Main backgrounds: $Z \rightarrow \tau\tau$, QCD/W+jets, DY, ttbar, dibosons



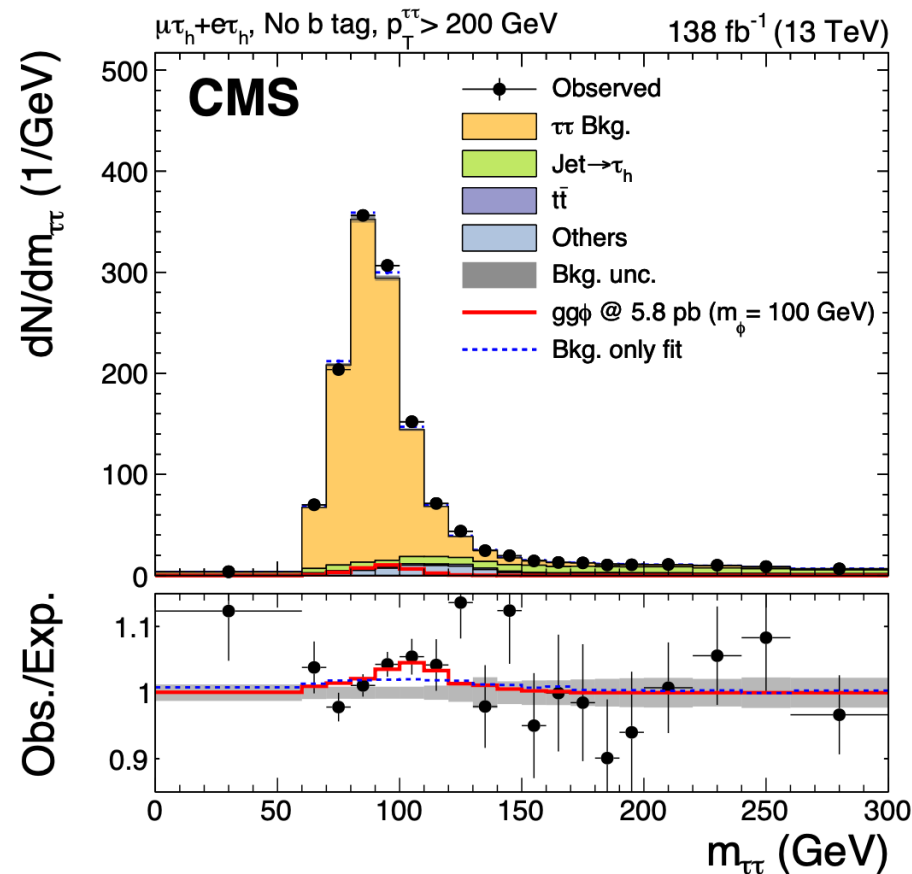
Neutral MSSM Higgs: $\phi \rightarrow \tau\tau$

arXiv:2208.02717

- Direct search: inclusive and b-tagged
- τ in both leptonic and hadronic decays



Model-independent limits by separating production modes

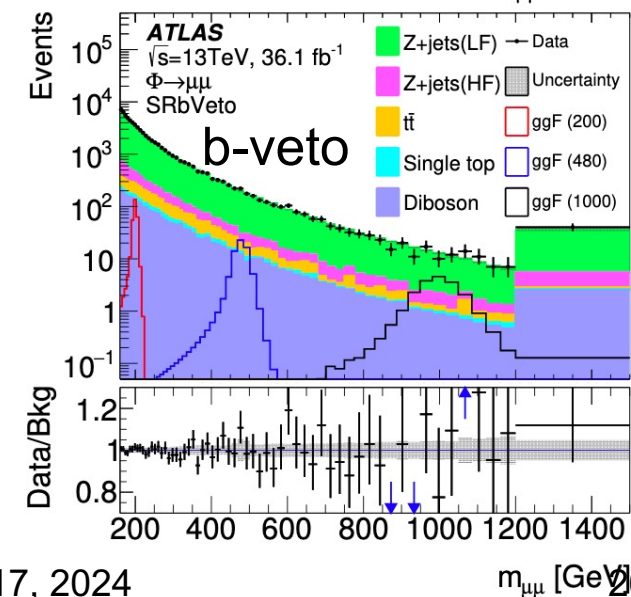
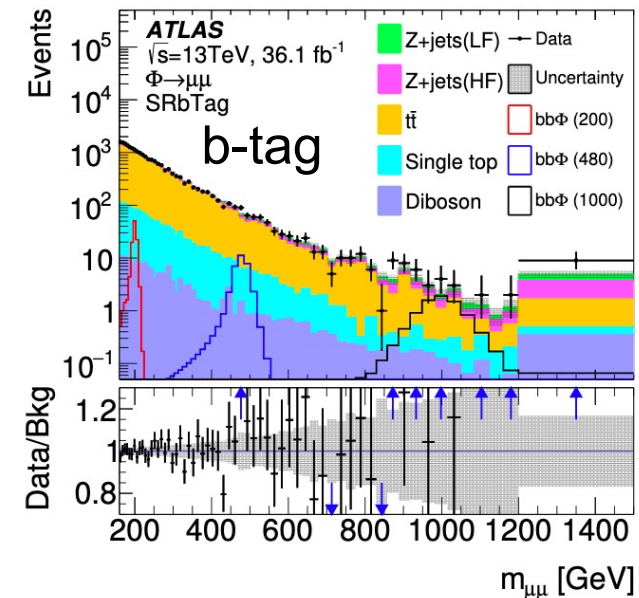
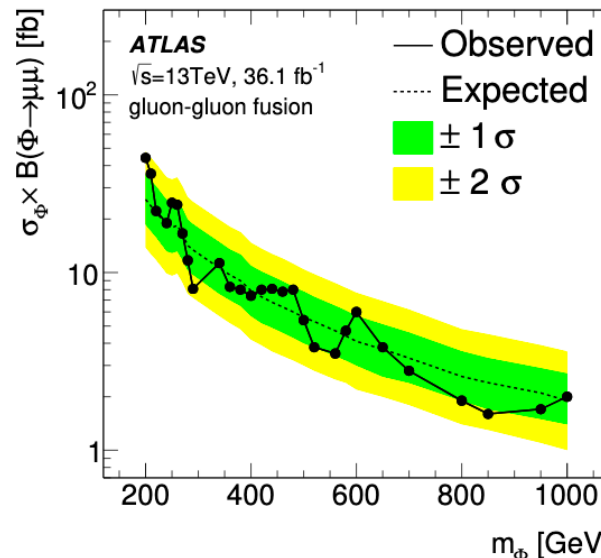
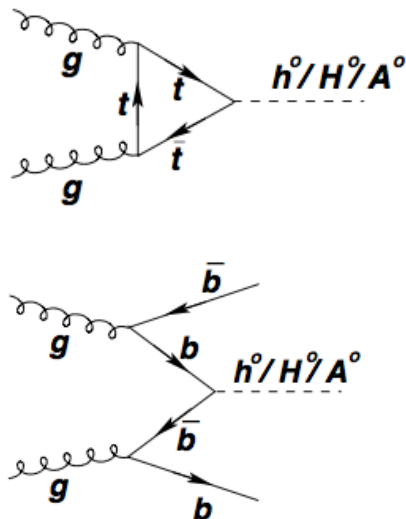


Some fluctuation over bkg expectations

Neutral MSSM Higgs: $\phi \rightarrow \mu\mu$

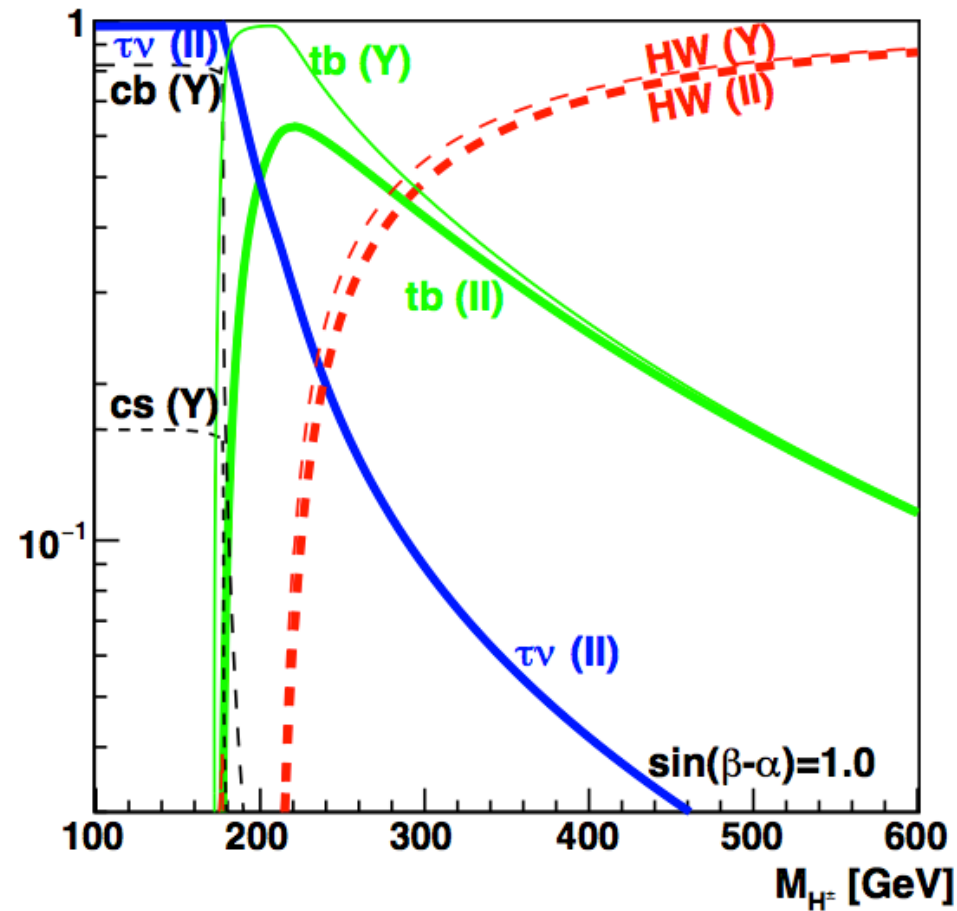
arXiv:1508.01437, JHEP07(2019)117

- Search for a $\mu\mu$ mass resonance
- Good mass resolution
 - full and clean reconstructed final state
- Split in b-tagged and non b-tagged categories to be sensitive to $gg \rightarrow \phi$ and $bb\phi$ production modes
- Main backgrounds: $Z(b\bar{b})$, $t\bar{t}$, WW



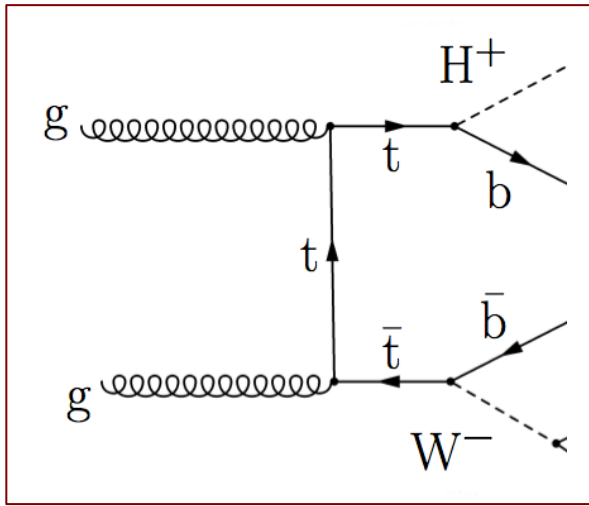
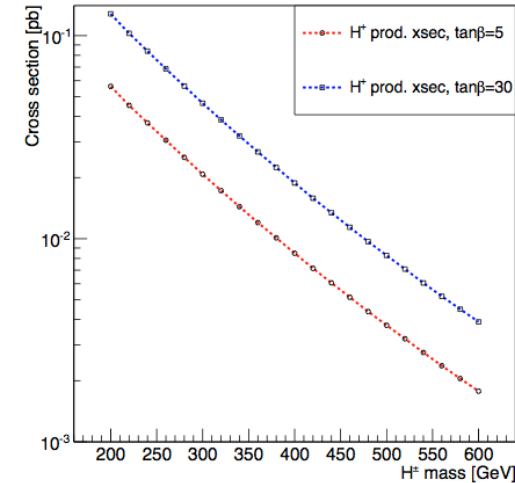
Charged Higgs

- If found, a clear indication of BSM
- Study non-SM Higgs in **two mass regimes**:
- $m_H < m_{\text{top}}$
 - Mostly produced in top quark decays
 - Large $\tan\beta$: $H^\pm \rightarrow \tau^\pm \nu$
 - Small $\tan\beta$ (< 1): $H^+ \rightarrow c\bar{s}$
- $m_H > m_{\text{top}}$
 - Produced in gluon-gluon fusion
 - Main decays: $H^+ \rightarrow tb$, $H^+ \rightarrow \tau^\pm \nu$
- Main backgrounds: $t\bar{t}$, W +jets

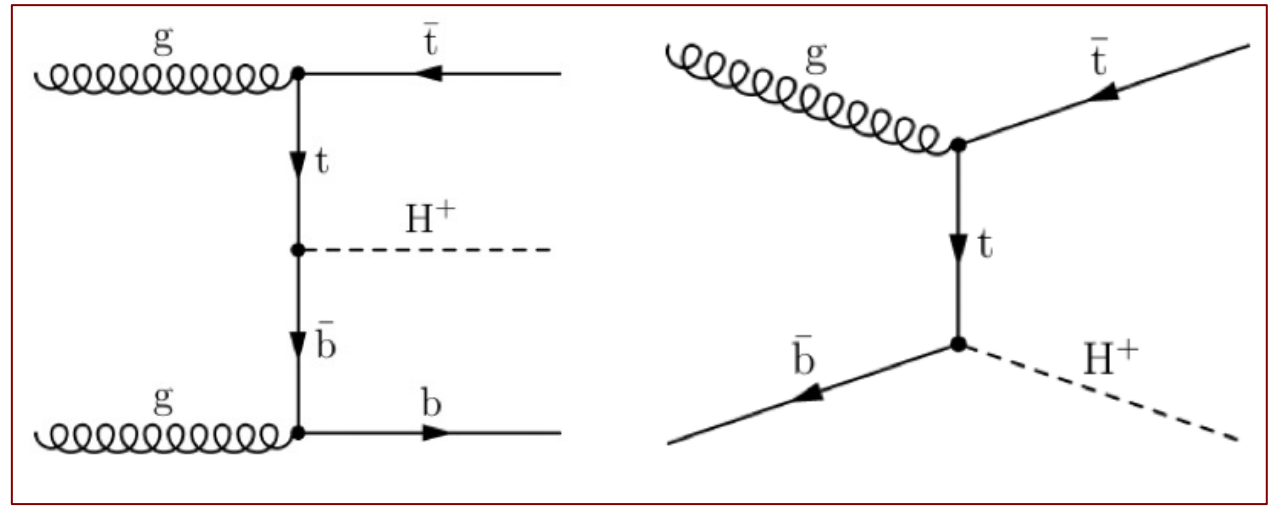


Charged Higgs (cont.)

- Different strategies for low- and high-mass searches
- tau+lepton, lep+jets, and $e\mu$ final states
- b-tagged jet categorization
- limited by statistics at high-mass



$$m_H < m_{\text{top}}$$



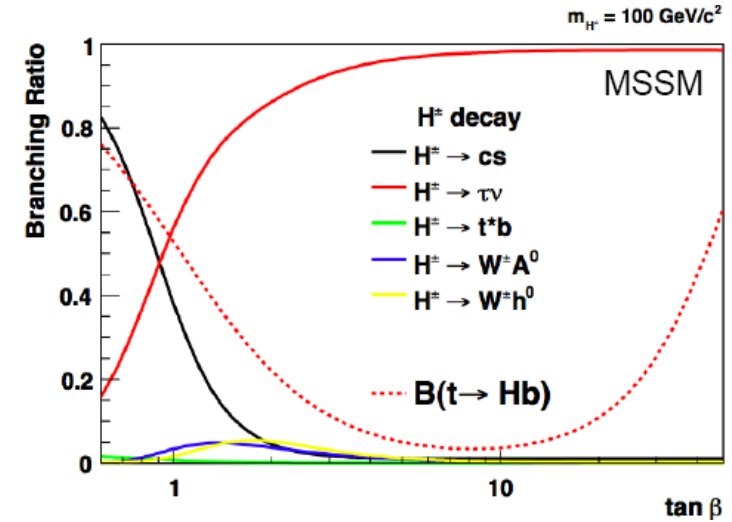
$$m_H > m_{\text{top}}$$

Charged Higgs and top quark decays

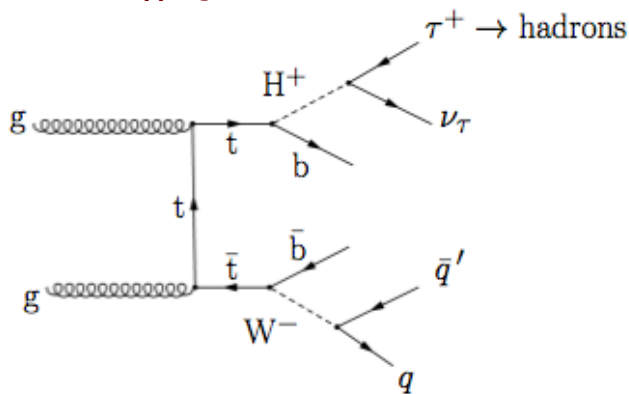
JHEP 07(2012)143, arXiv:1508.07774, HIG-16-031

- Look for charged Higgs in four final states:

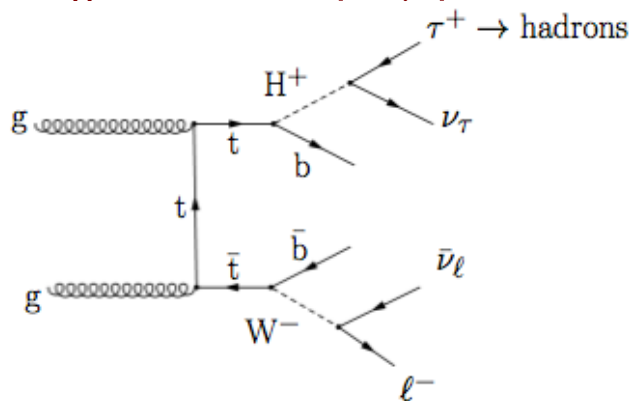
- Tau+lepton (electron or muon)
- Dilepton (tau decays leptonically)
- lepton+jets
- Fully hadronic: tau+jets



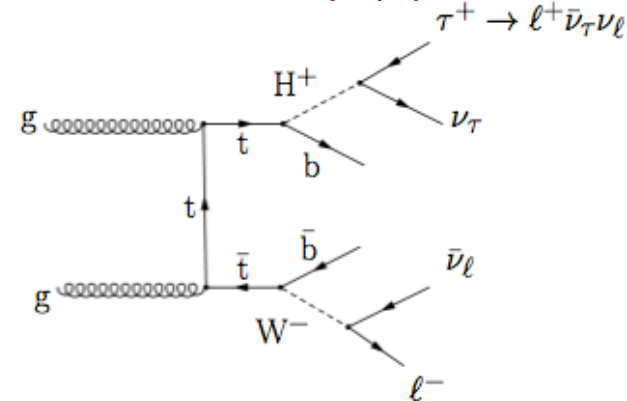
τ_h +jets



τ_h +lepton (e/ μ)



di-lepton (e μ)



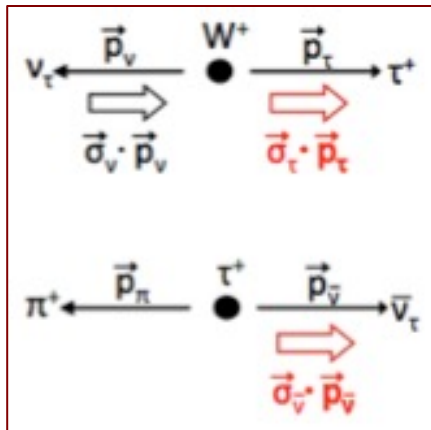
Looking at tau decays

CMS-HIG-12-052, arXiv:1903.04560

Low H^+ mass:

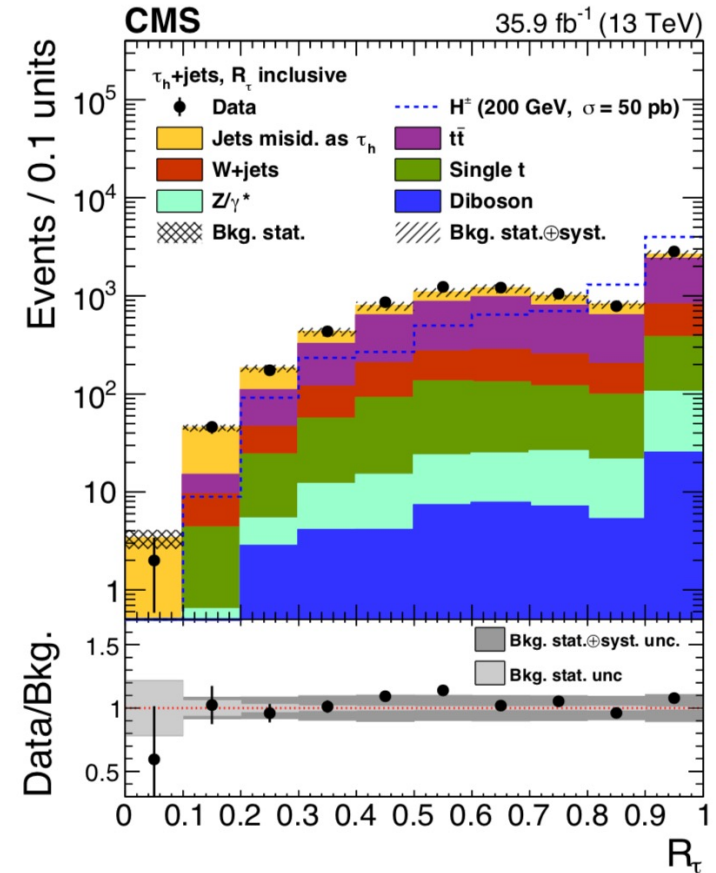
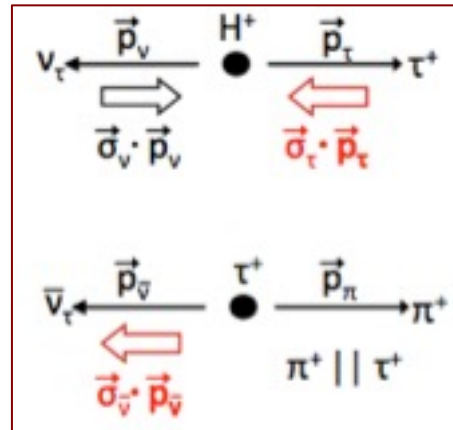
- Use R variable in the limit extraction: binned maximum-likelihood fit
- Tau fake component is data-driven, includes uncertainties

SM



VS

BSM

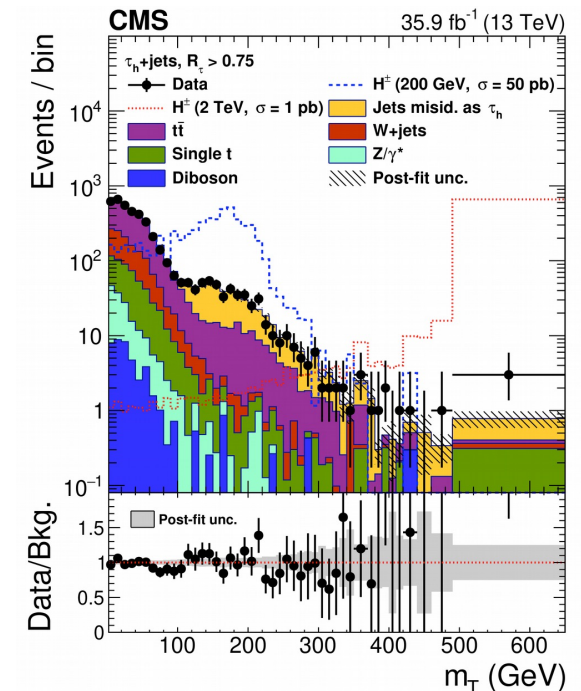
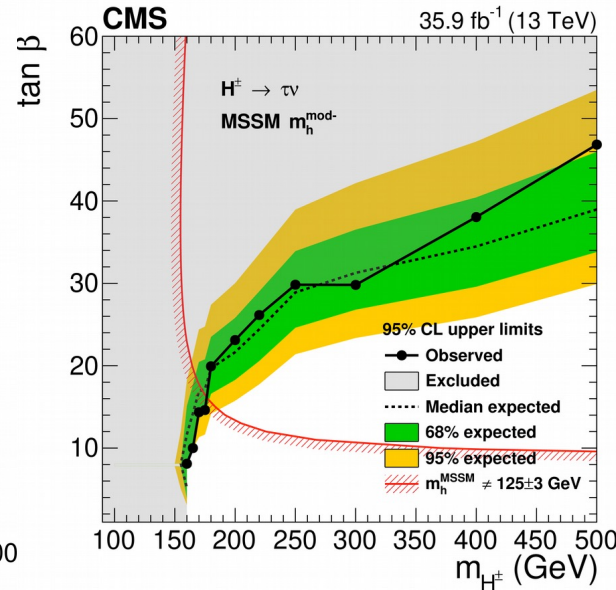
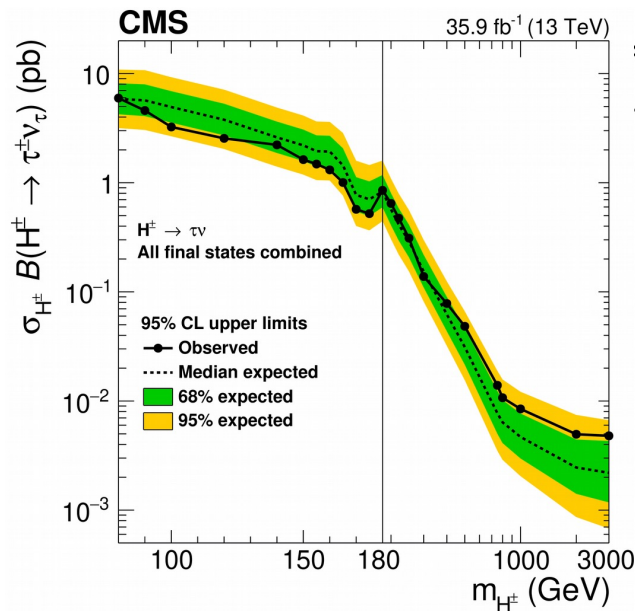
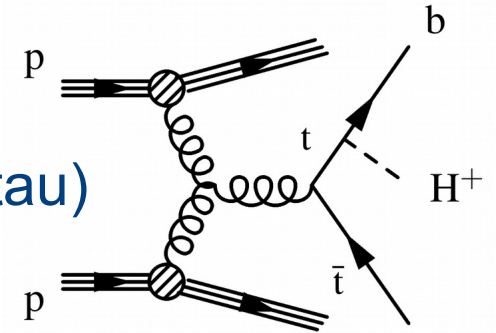


Charged Higgs: $H^\pm \rightarrow \tau \nu$

arXiv:1903.04560

MSSM, high $\tan\beta$

- Final states: τ +jets, τ + $\ell\ell$, 0τ + $\ell\ell$
- 36 categories: incl. #jets, polarization $R=p_T(t\bar{t})/p_T(\tau)$
- Cross section limits: 80-3000 GeV

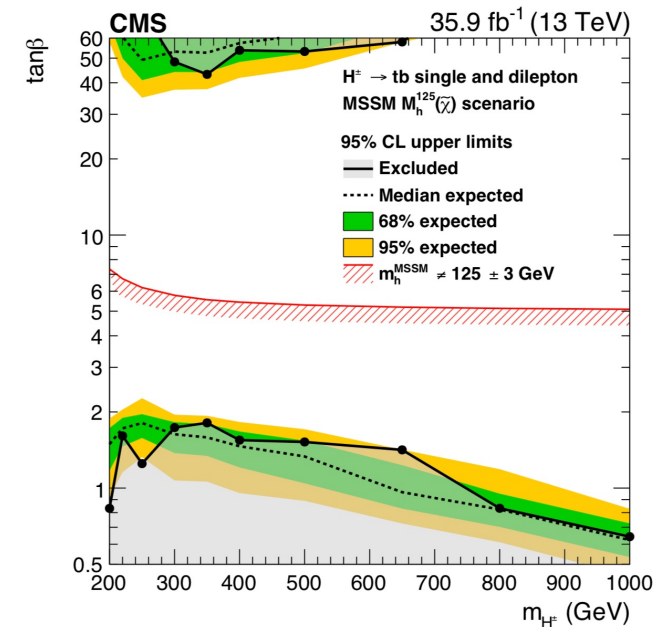
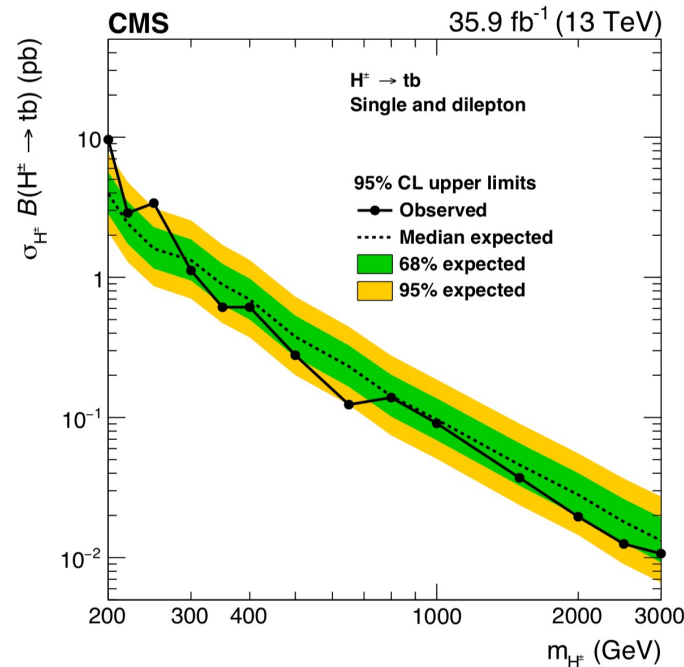
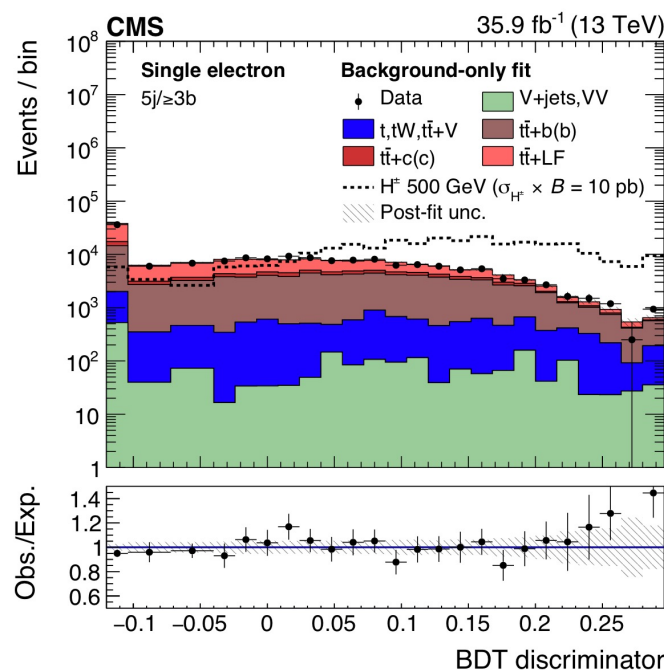
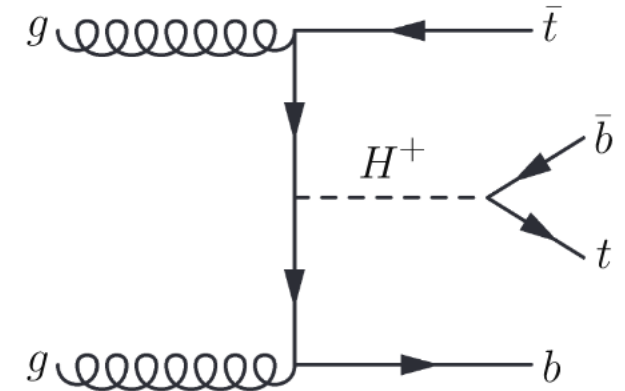


Charged Higgs: $H^+ \rightarrow t\bar{b}$

arXiv:1908.09206, arXiv:2102.10076

MSSM, low $\tan\beta$

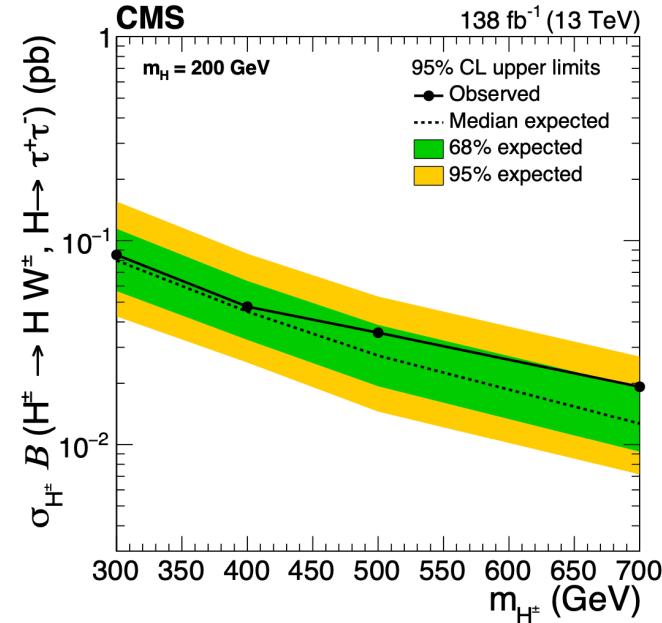
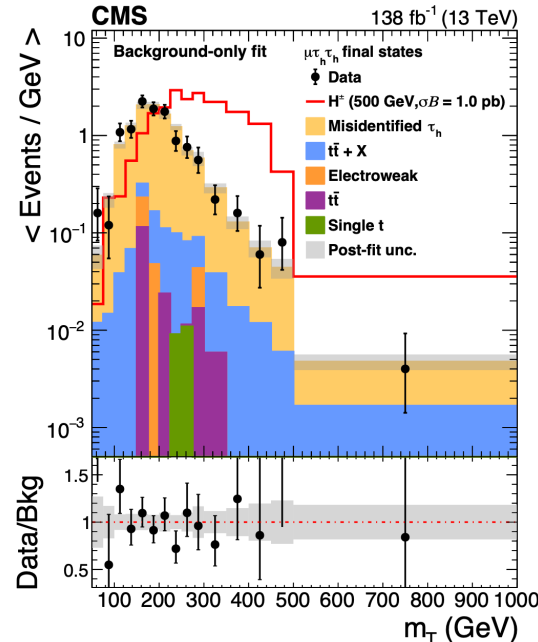
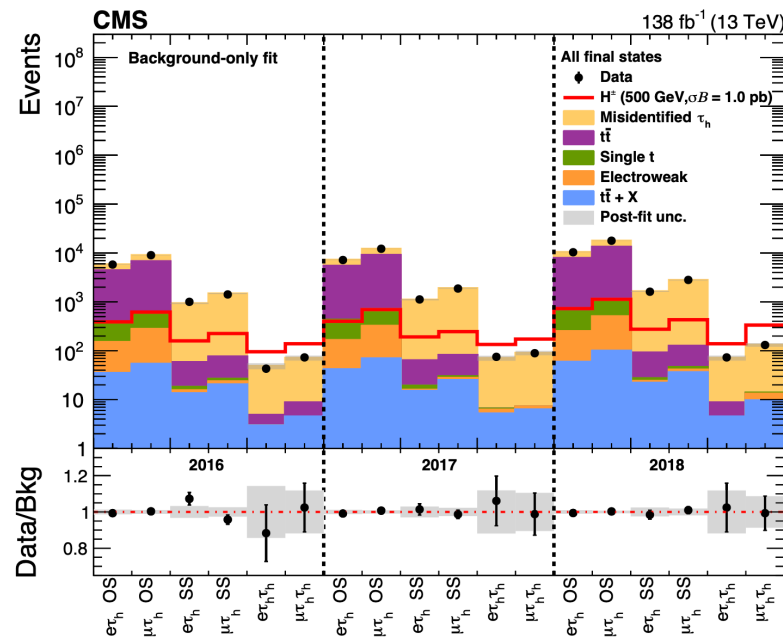
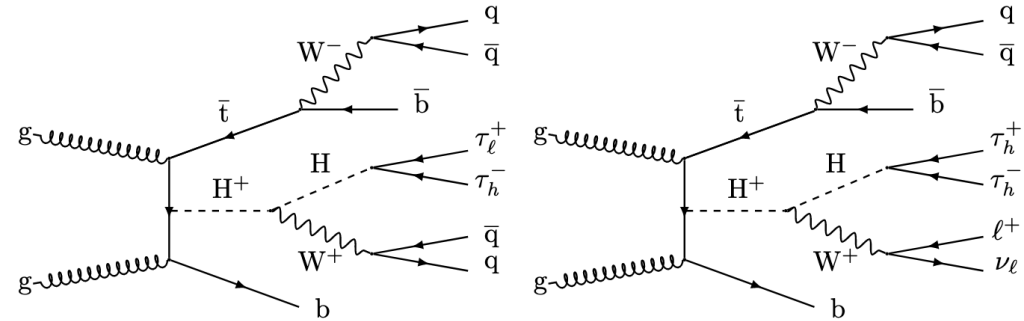
- Final states: 1ℓ and 2ℓ
- Categories (incl. #jets, #bjets)
- Discriminant vs $t\bar{t}b\bar{b}$ (BDT and DNN)
- Mass range: 200-3000 GeV



Charged Higgs: $H^\pm \rightarrow tb$ (cont.)

arXiv:2207.01046

- Search for a $H^\pm$ decaying to a heavy neutral Higgs boson H and a W
- data consistent with SM expectations
- Set limits:
 - $H^\pm$ in the mass range 300-700 GeV, assuming $m_H=200$ GeV
 - Cross-section limit from 0.08 pb @ 300 GeV to 0.013 pb @ 700 GeV



Doubly charged Higgs

HIG-16-036, arXiv:1710.09748

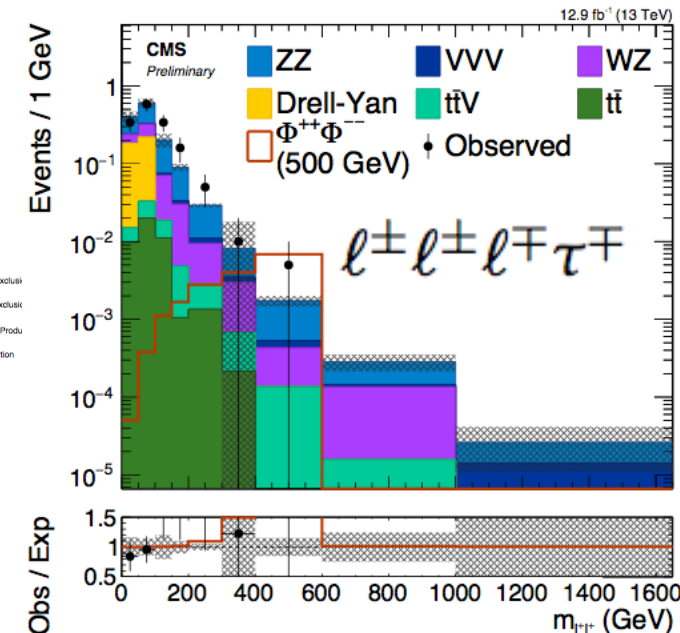
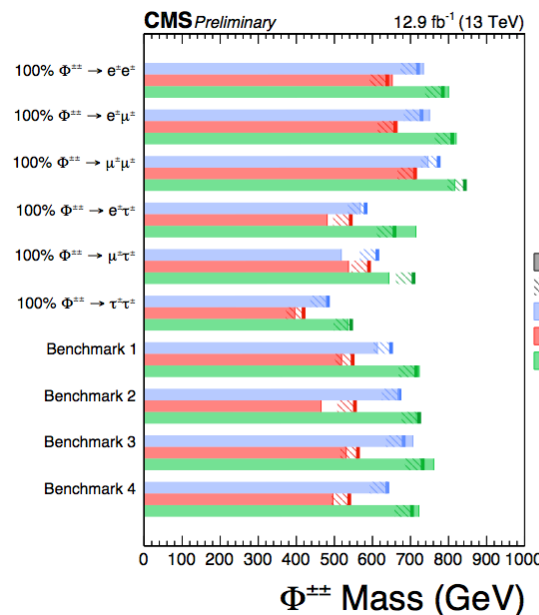
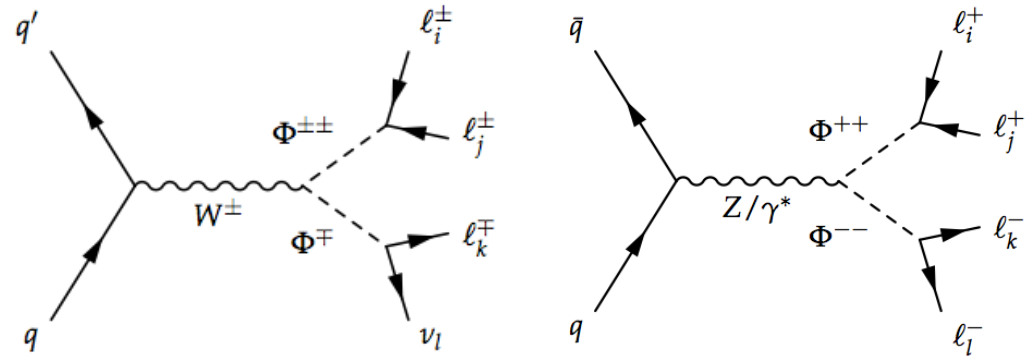
• Model

- SM extended with scalar triplet (Φ^{++} , Φ^+ , Φ^0)
- Triplet responsible for neutrino masses
- Search for doubly- and singly-charged
- DY pair production is most common
- SS lepton pair of any flavor combination

• Search with ≥ 3 leptons of any flavor

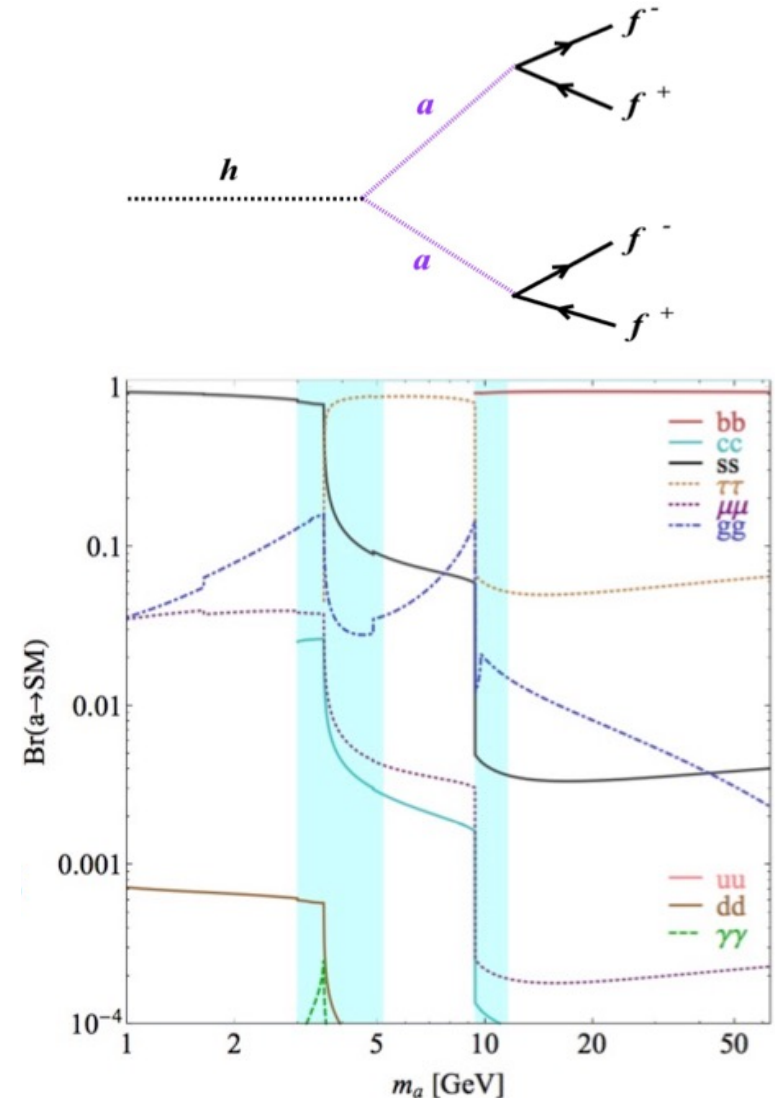
- Search for excess of events in one or more flavor combinations of SS lepton pairs

• Dilepton invariant mass as discriminant



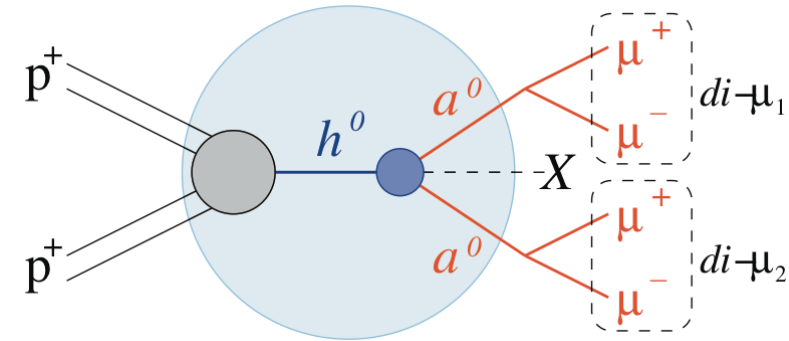
non-SM Higgs decay: $h \rightarrow aa \rightarrow 4X$

- Standard search for light (pseudo)- scalar Higgs with $m_a < m_h/2$
 - generic prediction of BSM theories (extended Higgs sector, NMSSM, etc)
 - Final states go to fermions ($b, \tau, \mu, \dots$)
 - BR depends on boson mass, model parameters

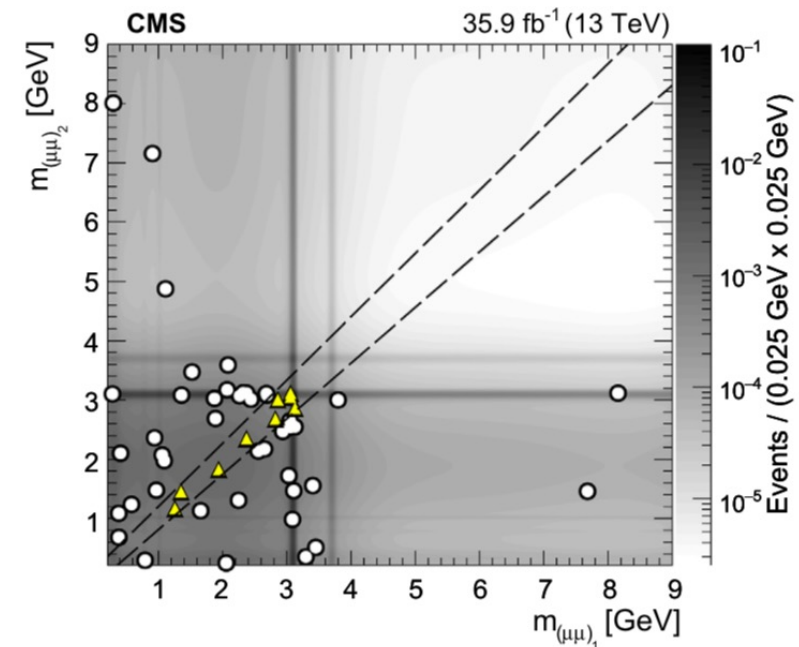


non-SM Higgs decay: $h \rightarrow aa \rightarrow 4\mu$

PLB796(2019)131



- Explore non-SM decays of a Higgs boson (h)
 - Higgs boson (h) can be SM or not
 - include production of two new light boson (a^0)
- Search for generic Higgs decays: $h \rightarrow 2a + X \rightarrow 4\mu + X$
 - Require two dimuon pairs with consistent masses
 - Signal region: **9 event** ($\sim 8 \pm 2$ bkg)
 - Limits on production rates, benchmark models



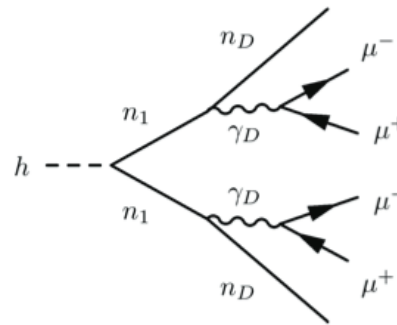
NMSSM and Dark SUSY Limits

PLB 726(2013)564, arXiv:1506.00424

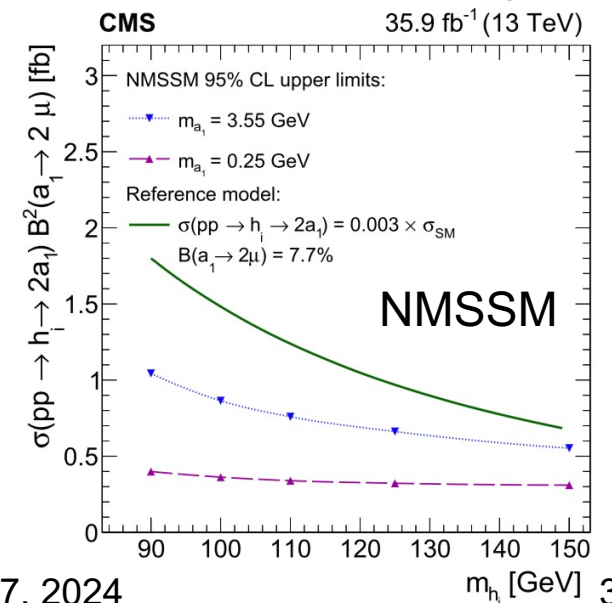
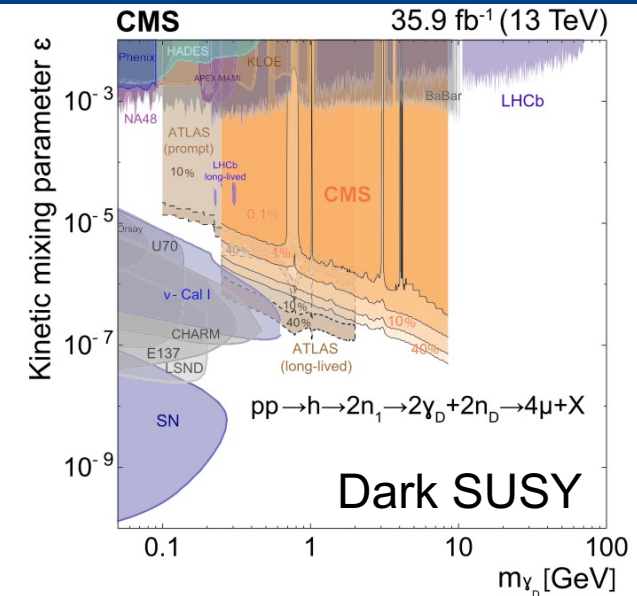
Results interpreted in NMSSM and dark SUSY

- Dark SUSY: h decay to pair of neutralinos (n_1): LSP

$n_1 \rightarrow n_D \gamma_D$ decays
 $\rightarrow \mu\mu$
 $\rightarrow$ invisible



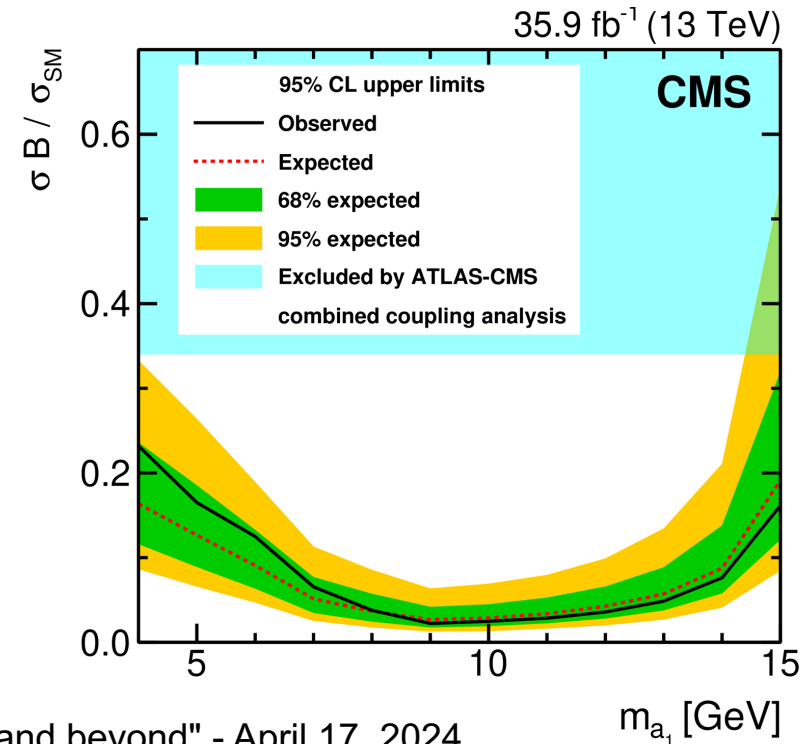
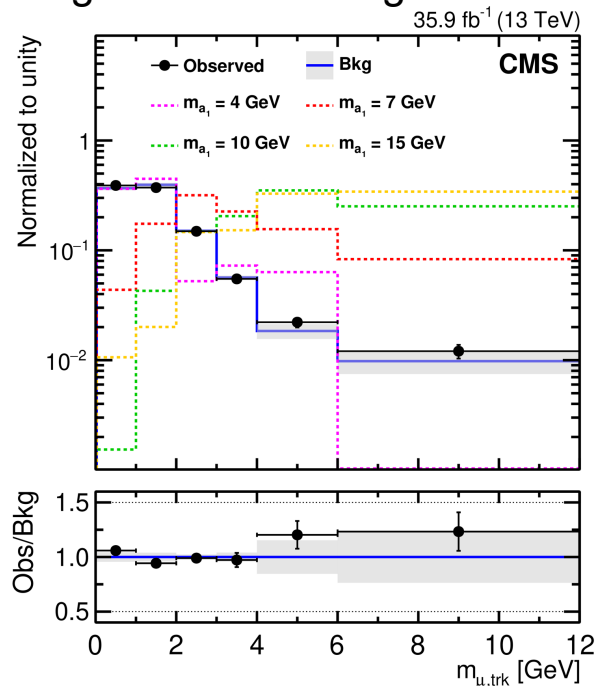
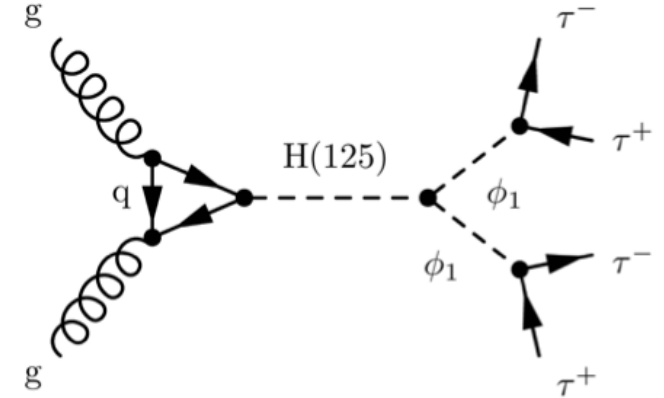
- NMSSM: Extend MSSM by adding a complex singlet field (1 CP-even+1 CP-odd boson)
- NMSSM: $h_{1,2} \rightarrow 2a_1$; $a_1 \rightarrow 2\mu$
- Compare to SM Higgs cross section



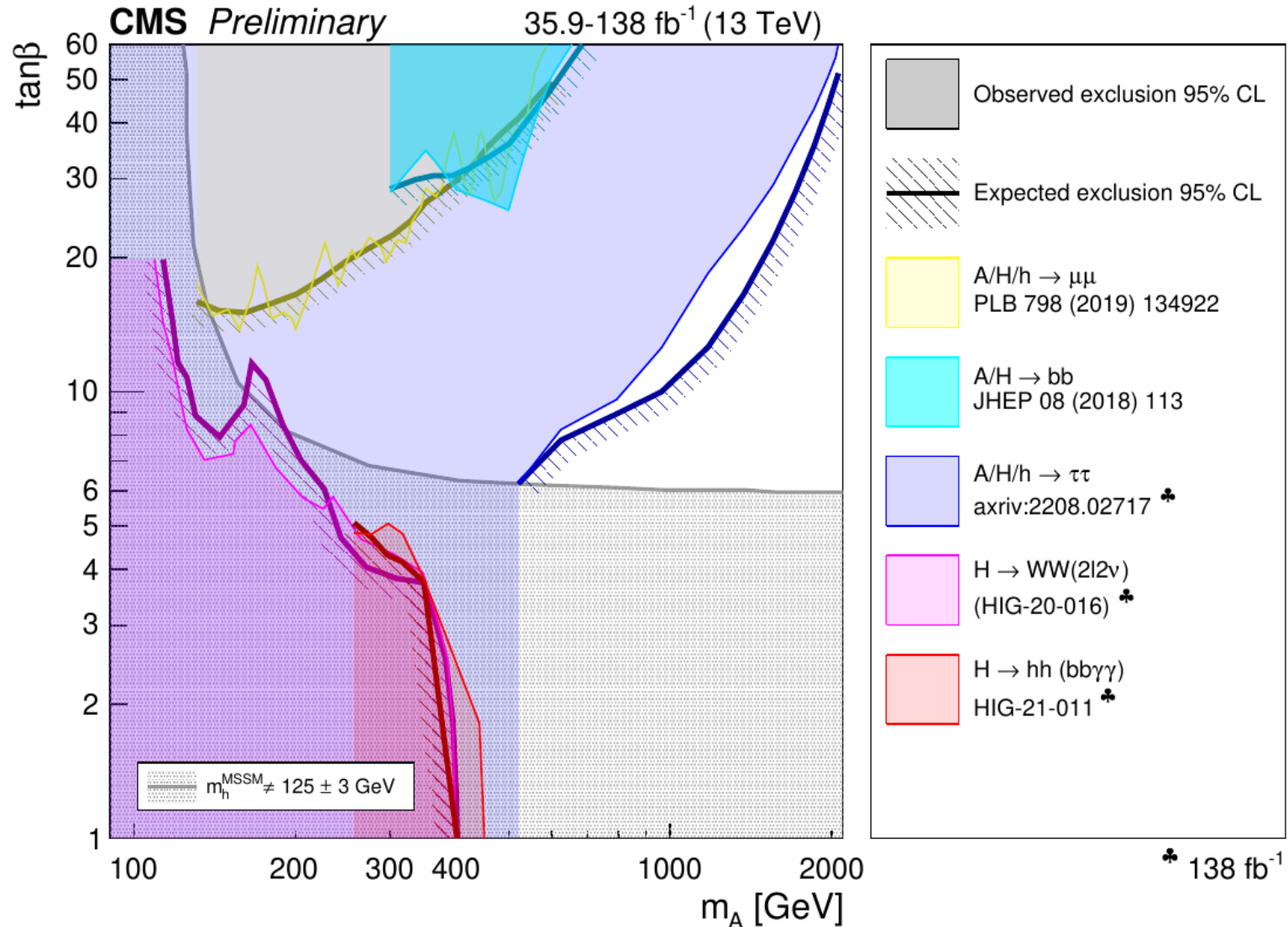
non-SM Higgs decay: $H_{125} \rightarrow 2h(a) \rightarrow 4\tau$

JHEP01(2016)079, PLB 800(2019)135087

- Search for **very light Higgs** in NMSSM
 - $H(125) \rightarrow$ light pseudoscalar (ϕ) bosons
 - One ϕ decays to a τ pair, the other to τ/μ pair
- Reconstruct μ -track invar. mass (m_1, m_2)
 - SS dimuon sample (removes DY)
 - bin in 2-dim distribution, fit signal and bkg
 - QCD bkg from control region



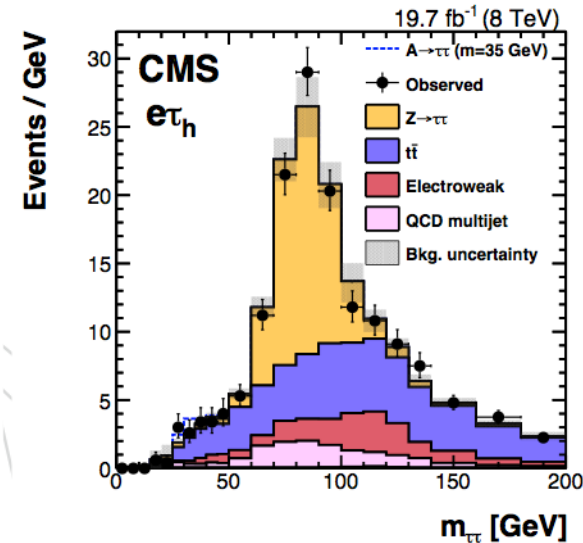
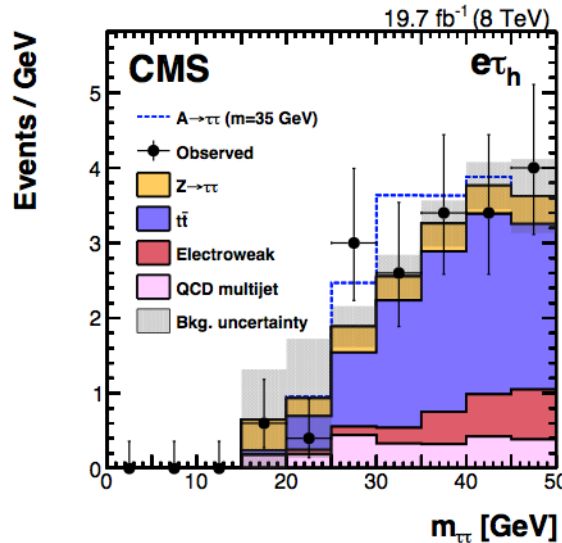
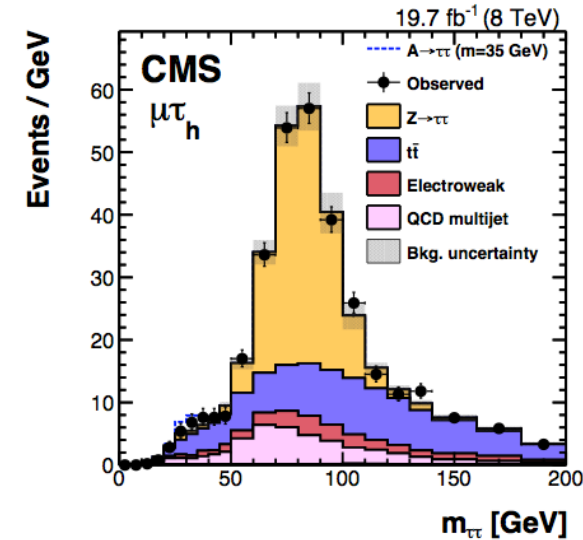
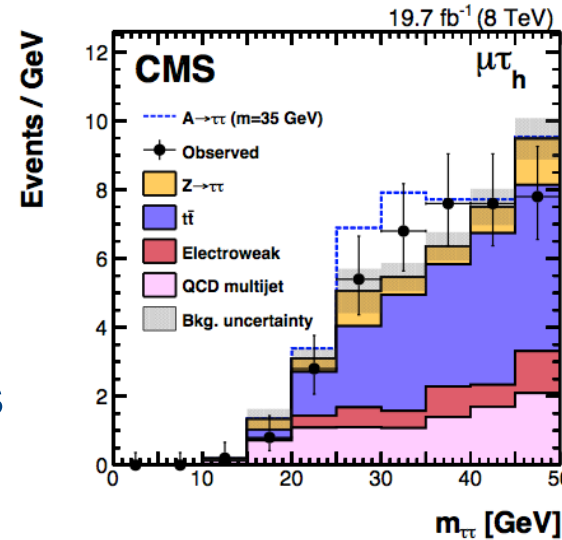
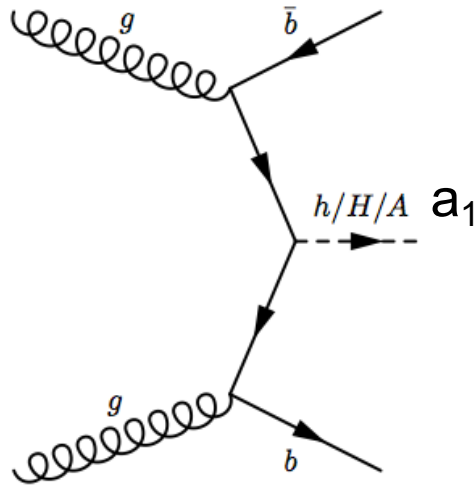
Summary for Higgs exotic decays



Low mass Higgs: $a(\rightarrow\tau\tau)bb$

arXiv:1511.03610, JHEP05(2019)210

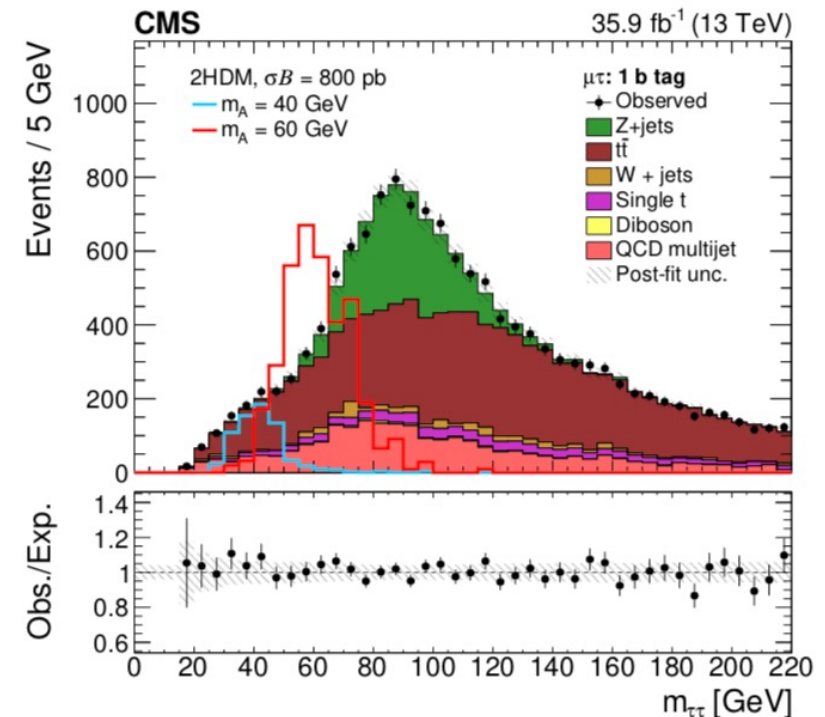
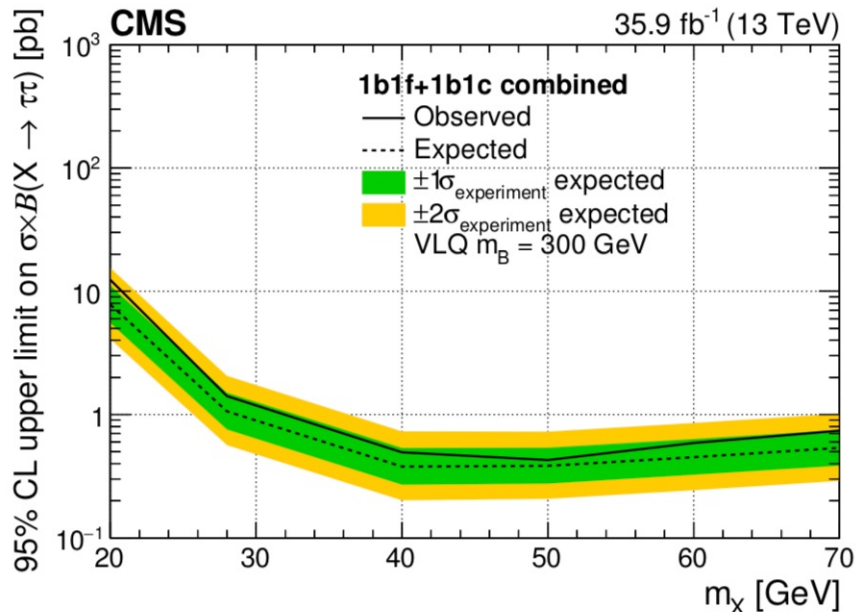
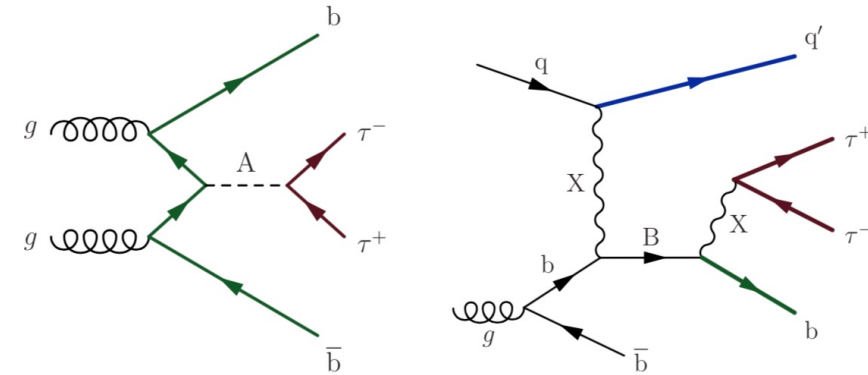
- Low mass Higgs in the NMSSM
- Low mass pseudo-scalar ($a_1 \rightarrow \tau\tau$) in association with $b\bar{b}$: $a_1 b\bar{b} \rightarrow \tau\tau b\bar{b}$
- Similar strategy to $H \rightarrow \tau\tau$
- Search for a_1 masses below Z mass
- No evidence for signal
- Set limits: $\sigma \times B \sim 9\text{--}39 \text{ pb}$



Low mass Higgs: $a(\rightarrow\tau\tau)bb$

arXiv:1511.03610, JHEP05(2019)210

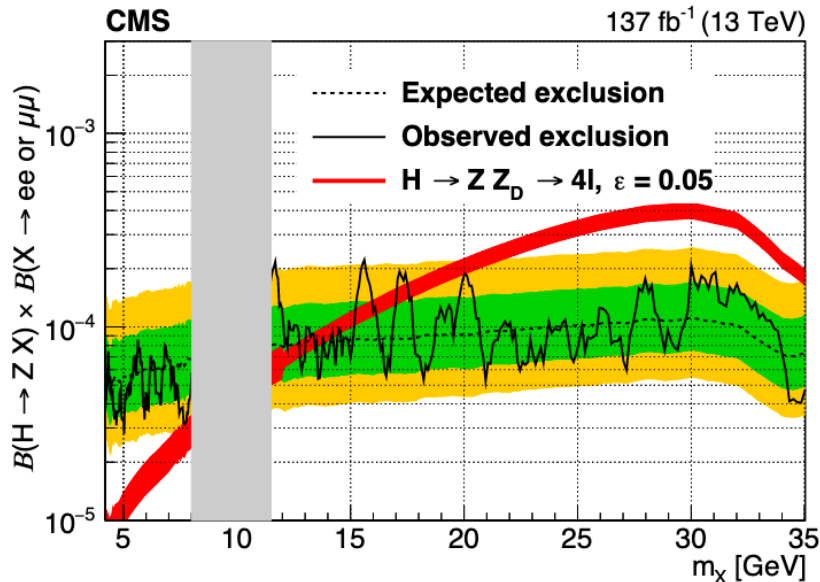
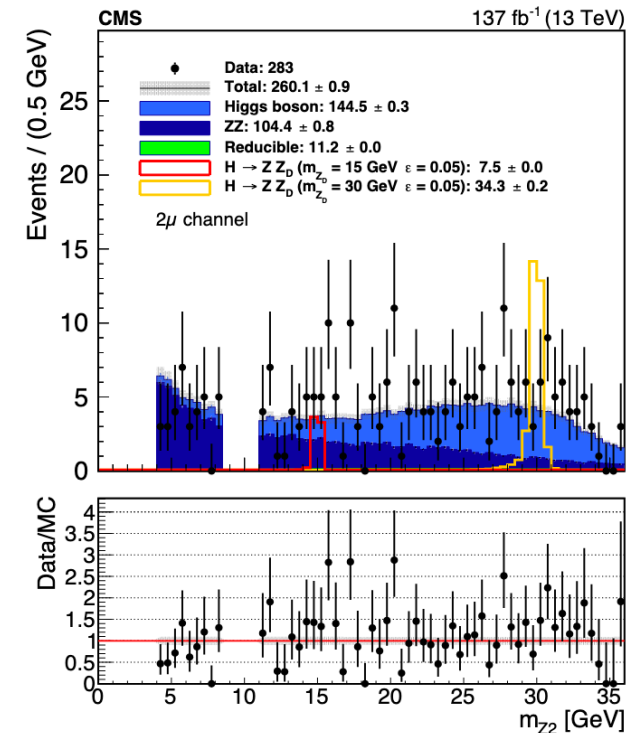
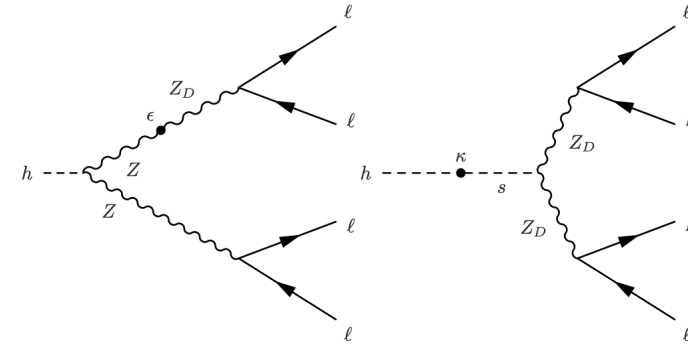
- Low mass Higgs in the NMSSM
- Low mass pseudo-scalar ($a_1 \rightarrow \tau\tau$) in association with $b\bar{b}$: $a_1 b\bar{b} \rightarrow \tau\tau b\bar{b}$
- Similar strategy to $H \rightarrow \tau\tau$
- Search for a_1 masses below Z mass
- No evidence for signal
- Set limits: $\sigma \times B \sim 20-0.3$ pb



Low mass dilepton resonance

arXiv:2111.01299

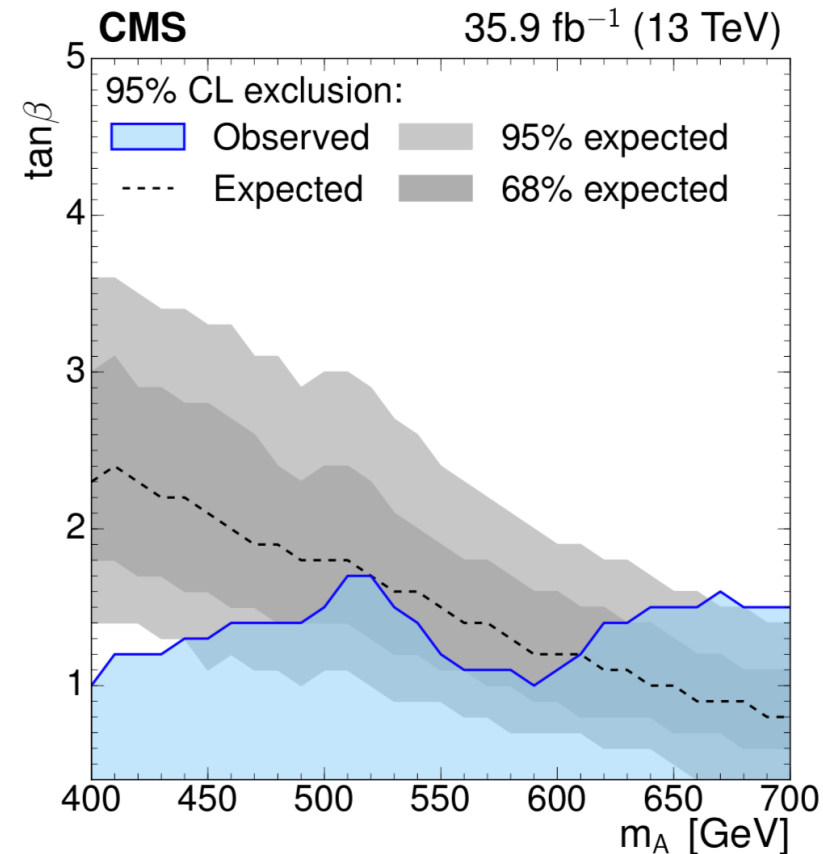
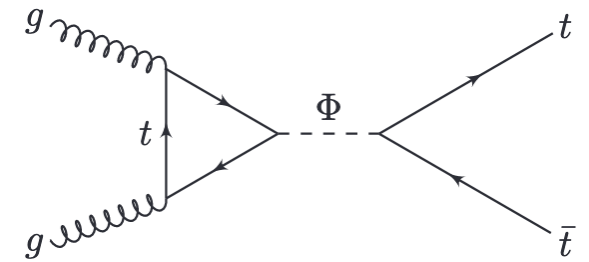
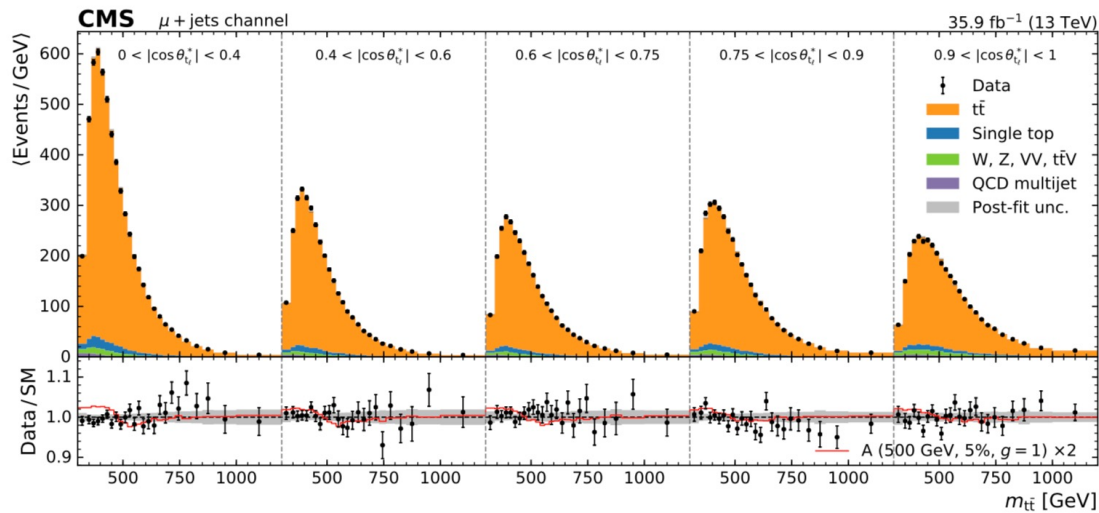
- Search for low-mass dilepton resonances in Higgs decays in the four-lepton final state
- Decay through a pair of BSM particles, or one is a Z boson
- Set limits
 - model-independent Higgs BRs.
 - dark photon and ALP production



Heavy Higgs: $H \rightarrow t\bar{t}$

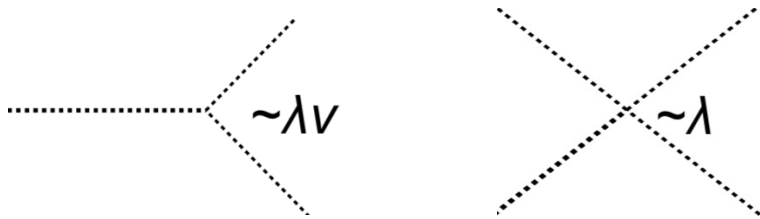
arXiv:1908.01115

- MSSM, low $\tan\beta$, $m(H) > 2 \times m(\text{top})$
- Search for $A/H \rightarrow t\bar{t}$
- Strong interference with SM $t\bar{t}$
- ℓ +jets and $\ell\bar{\ell}$ final states
- Kinematic reconstruction
 - $m(t\bar{t})$ and $\cos\theta^*$ (lepton angle in $t\bar{t}$ frame)



Higgs self-coupling

- Self-coupling measurements
- Improve measurements
- Include missing pieces:
 - H couplings to light fermions
 - HHVV (c_{2v}) and self-couplings

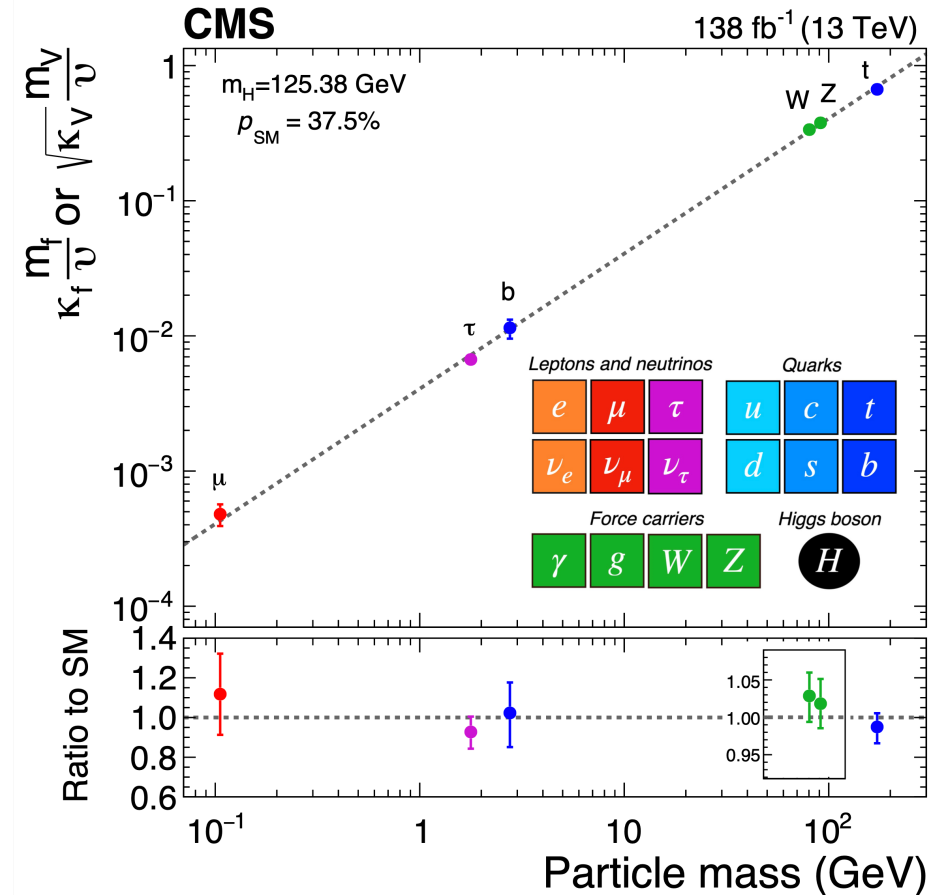


H trilinear coupling

$$\lambda = m_H^2/2v^2, \text{ where } v = \text{Higgs boson v.e.v}$$

Use coupling modifiers:

$$k_\lambda = \lambda/\lambda_{SM}; \quad k_{2v} = c_{2v}/c_{2v}(SM)$$

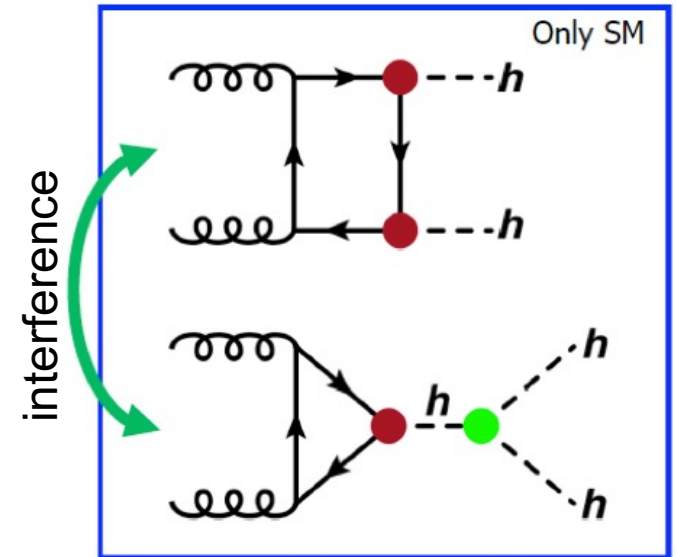


di-Higgs searches

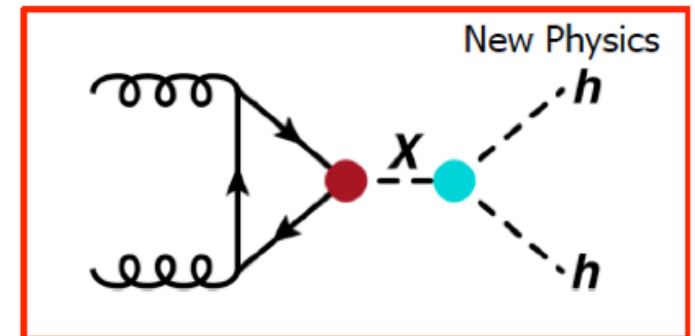
- Destructive interference in SM
- Could be altered in BSM
- If constructive, it could be large enhancement
- In SM, only $\sigma=31\text{fb}$ at 13 TeV
- Study different final states

	BR	Mass scale
$(X \rightarrow) hh \rightarrow$		
$bbbb$	34%	High
$bb\tau\tau$	7.3%	
$bbWW$	27%	
$bb\gamma\gamma$	0.26%	Low

non-resonant production

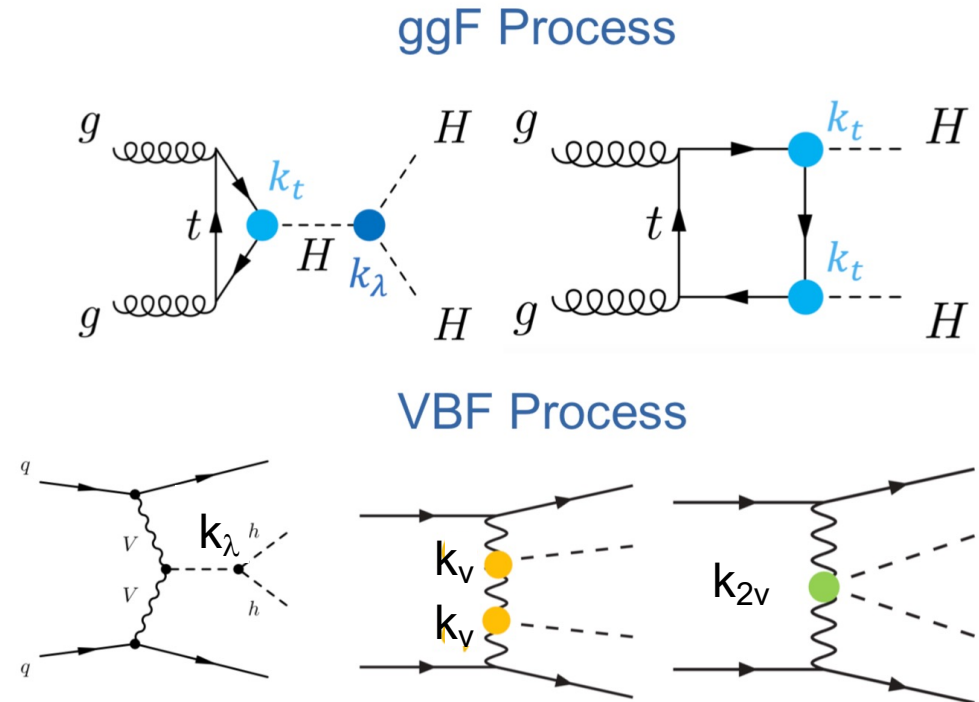
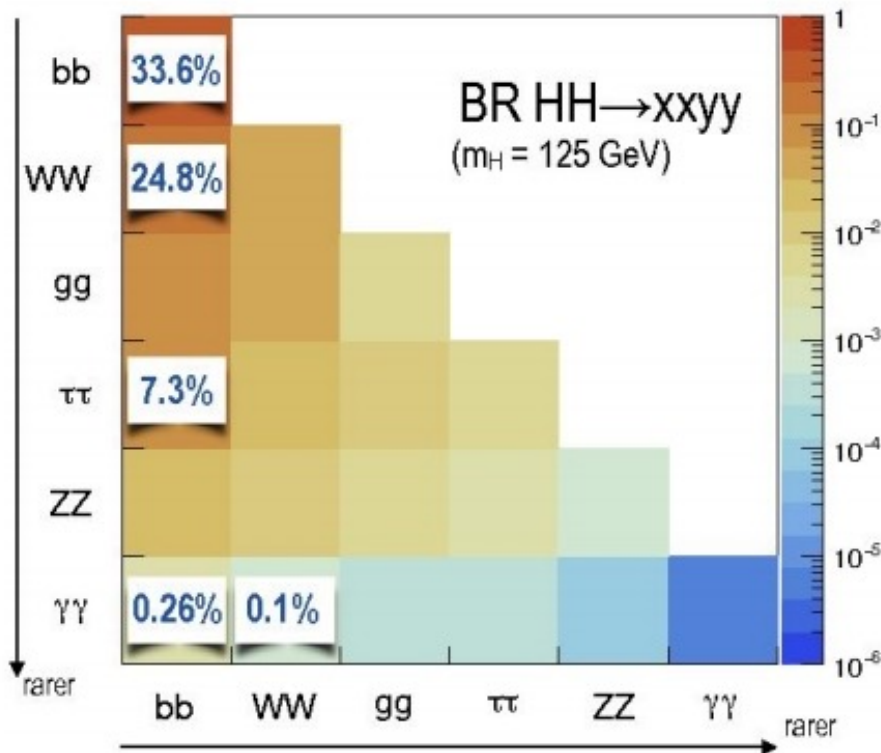


resonant production



HH: non-resonant production

- Higgs pair production @13 TeV
 - ggF $\sigma=31$ fb
 - VBF $\sigma=1.7$ fb
- Test non-resonant BSM models with anomalous couplings

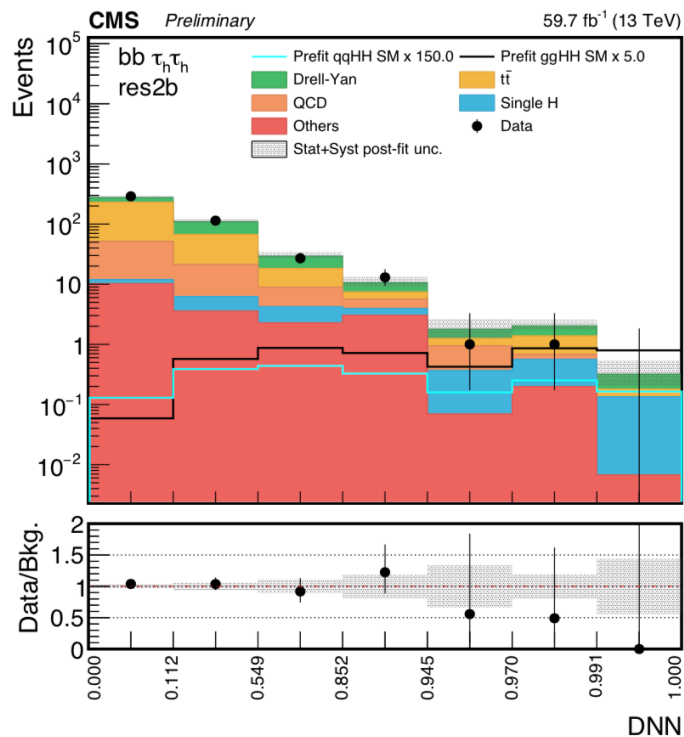


What is new in HH searches

CMS-HIG-20-010, CMS-B2G-21-001

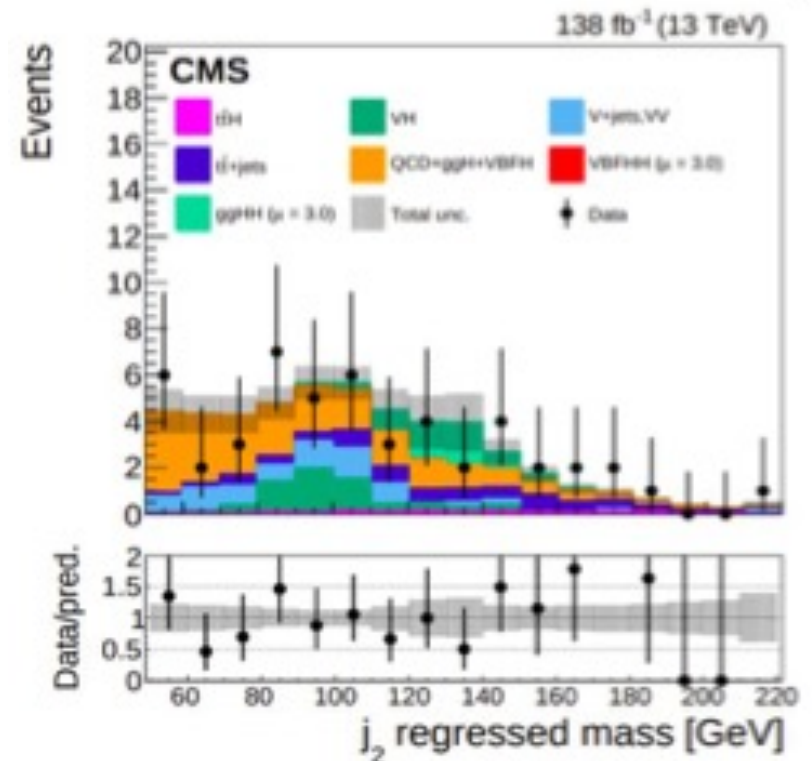
- Results are better (x2-3) than 2016 results alone after scaling for luminosity

Extensive use of ML tools



DNN score for resolved $ggHH(bb\tau\tau)$ category

Boosted topologies

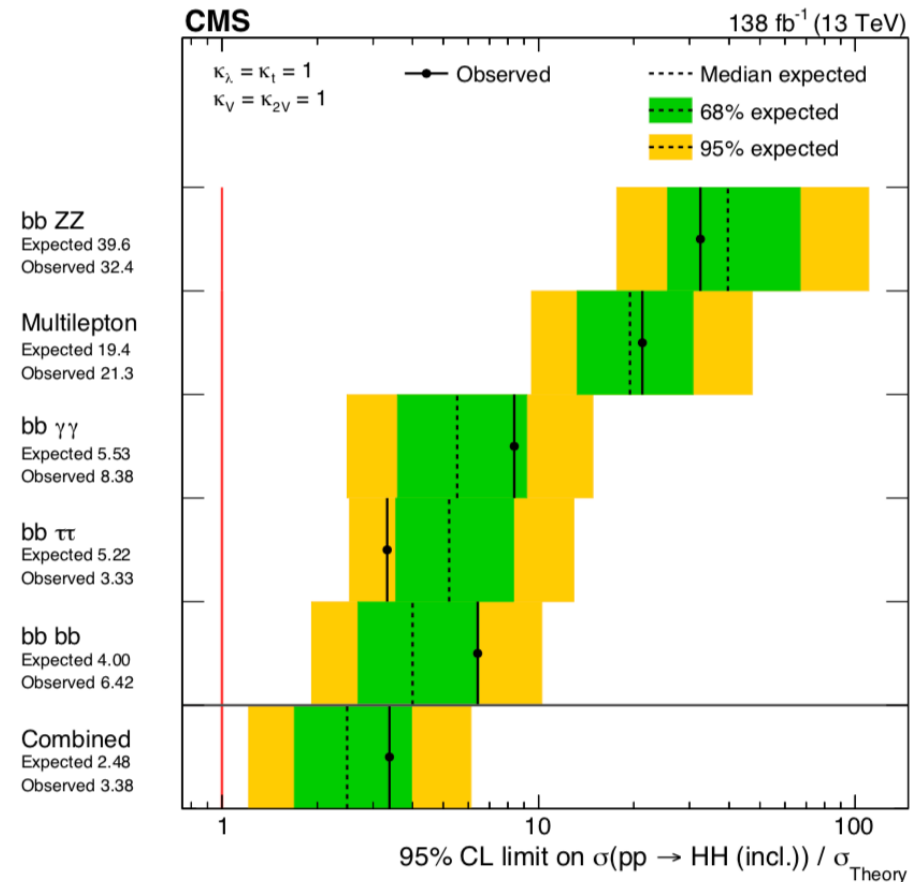
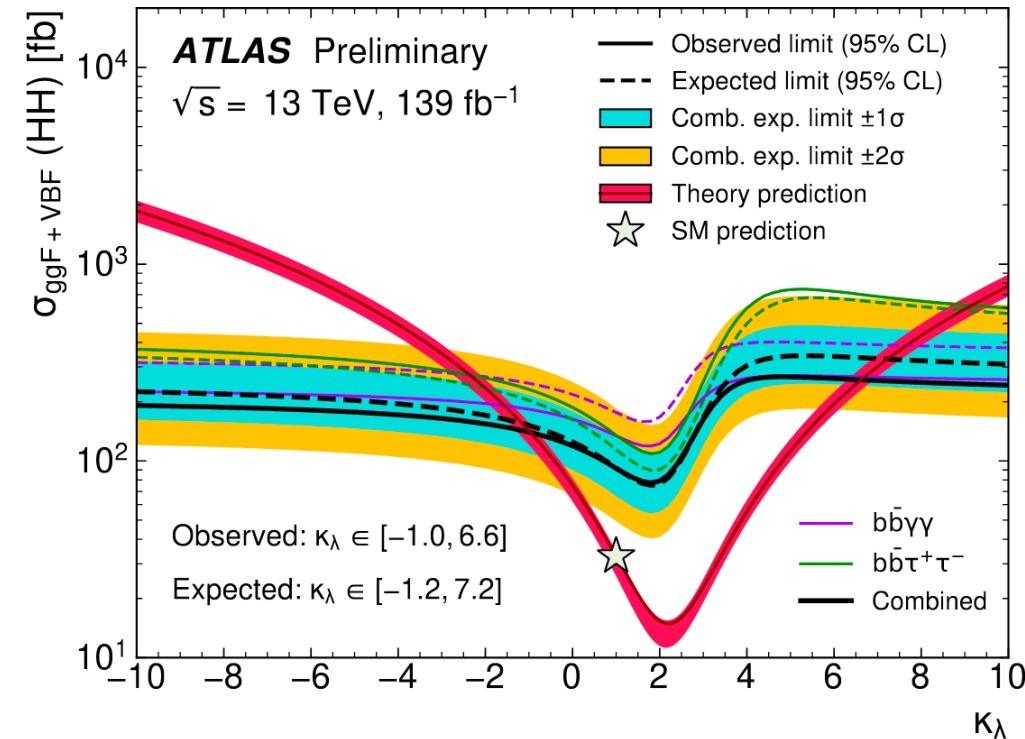


Regressed mass of one AK8 jet in a $ggHH(4b)$ boosted category

HH: results

ATLAS-CONF-2021-052, CMS-HIG-22-001

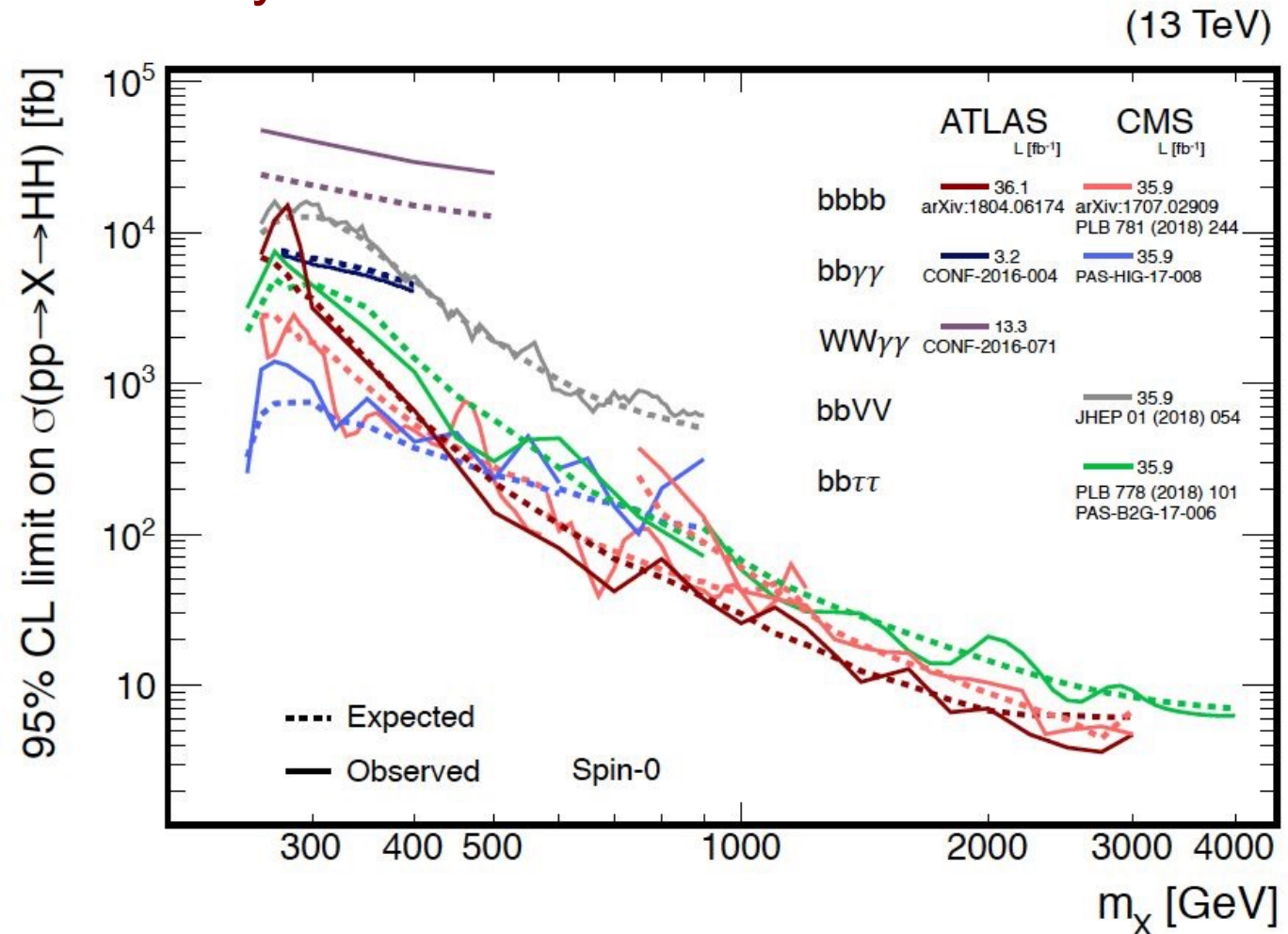
- Both resonant and non-resonant searches
- Background estimate and signal extraction



Double Higgs production

PRL 122(2018)121803

- Study different final states
- Not yet at the SM sensitivity

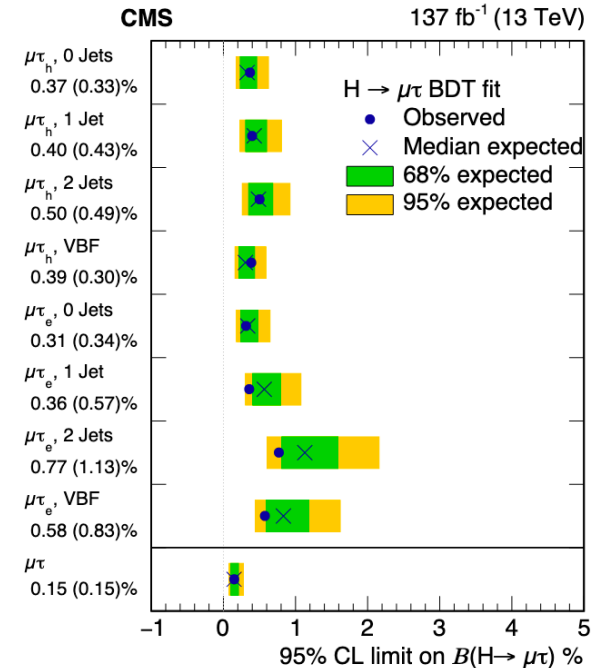
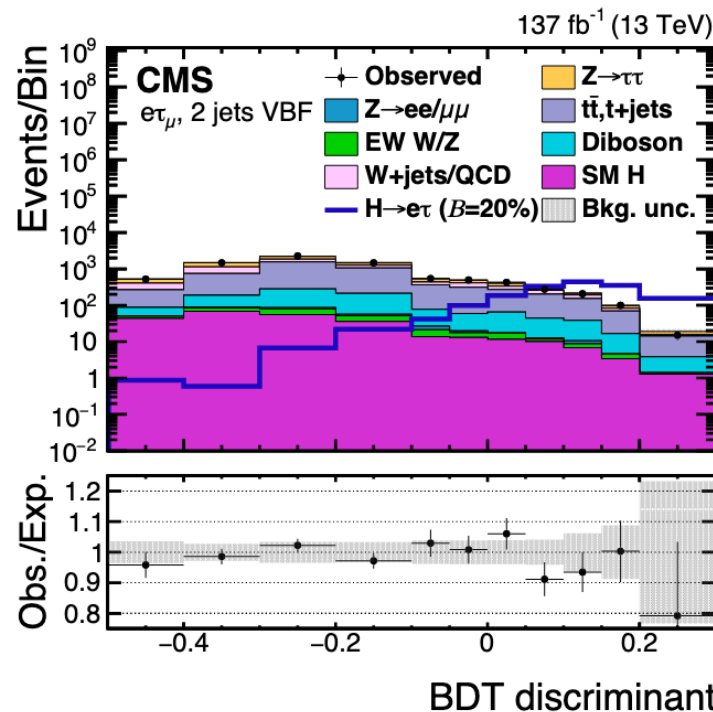
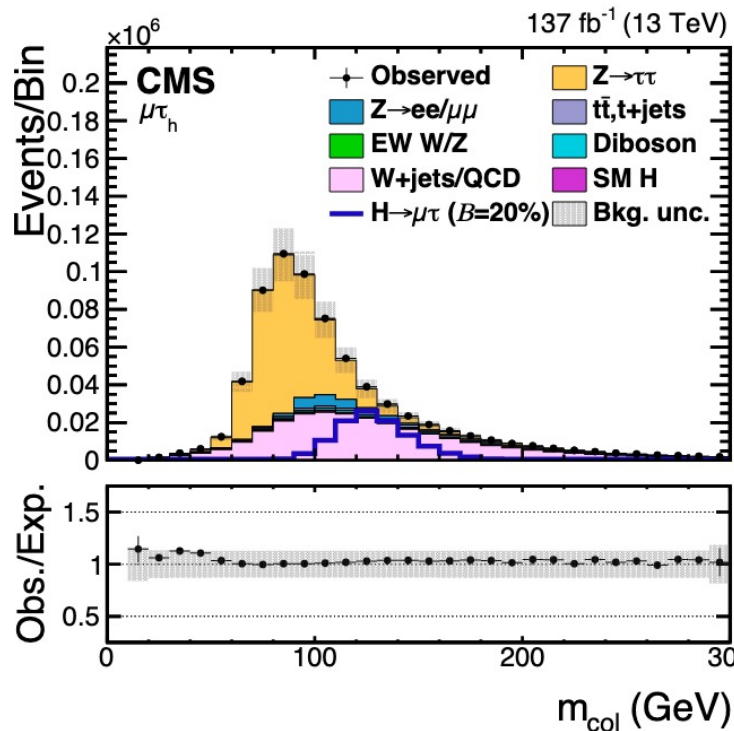


LFV in Higgs decays

arXiv:1911.10267, arXiv:2105.03007

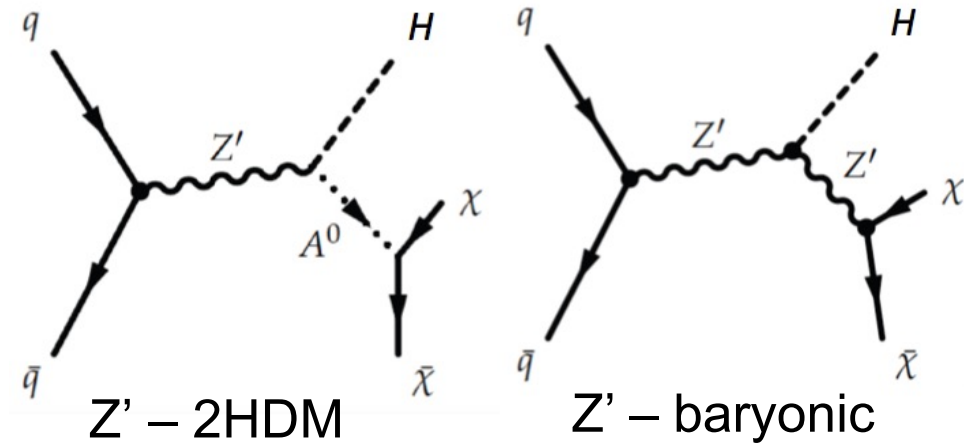
- Some BSM models allow for LFV Higgs decays
- Search for $H \rightarrow e\tau$, $e\mu$, $\mu\tau$ final states
- Categories: N_{jet} , lepton kinematics
 - N_{jet} to target ggH and VBF production
- Main background from DY, $t\bar{t}$, WW

	Observed (expected) upper limits (%)	Best fit branching fractions (%)	Yukawa coupling constraints
$H \rightarrow \mu\tau$	<0.15 (0.15)	0.00 ± 0.07	$< 1.11 (1.10) \times 10^{-3}$
$H \rightarrow e\tau$	<0.22 (0.16)	0.08 ± 0.08	$< 1.35 (1.14) \times 10^{-3}$



DM searches with Higgs bosons

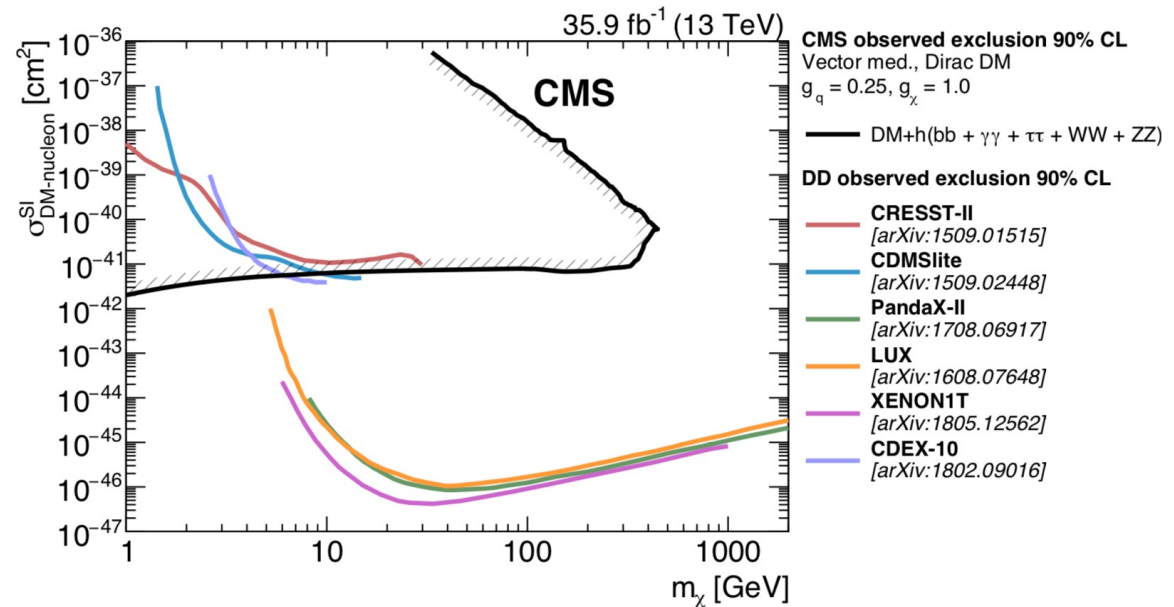
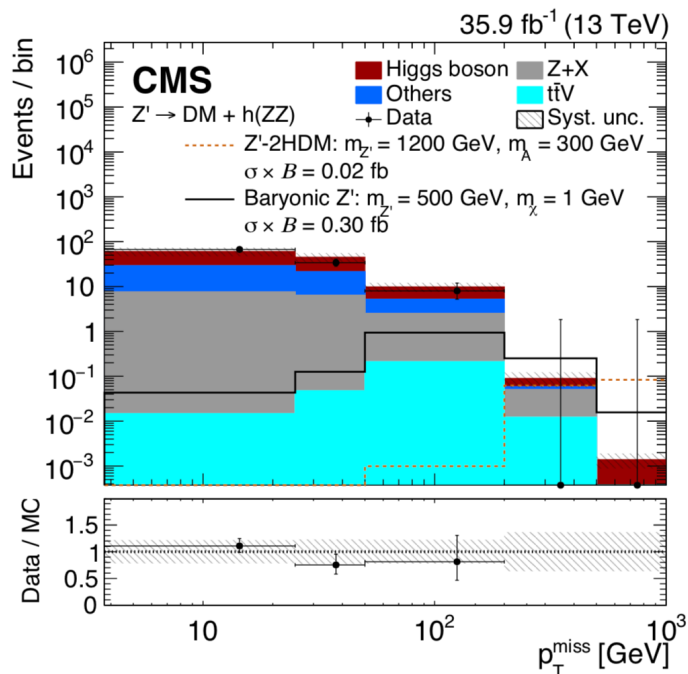
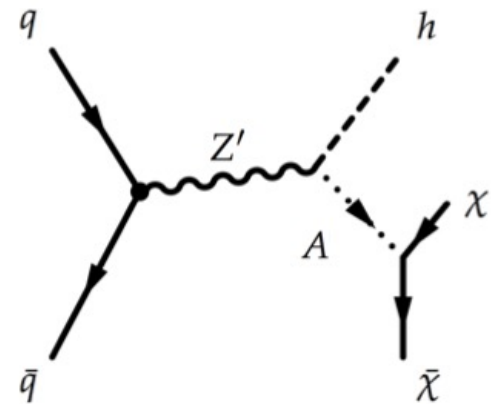
- H(125) may mix with new dark mediators
- Signature: Higgs+MET $\Rightarrow$ H used as a tag
- Final states:
 - $H \rightarrow b\bar{b} \sim 58\%$, large bkg
 - $H \rightarrow W^+W^- \sim 21\%$, moderate bkg
 - $H \rightarrow \tau^+\tau^- \sim 6\%$, lower bkg
 - $H \rightarrow \gamma\gamma \sim 0.2\%$, clean final state



Higgs + Dark Matter

arXiv:1908.01713

- Generic search: $pp \rightarrow H + \text{MET}$
 - ISR suppressed due to small coupling to H
 - In the context of simplified models
- DM search with $H(\rightarrow bb, \gamma\gamma, ZZ, WW, \tau\tau)$
- Signal events at large MET

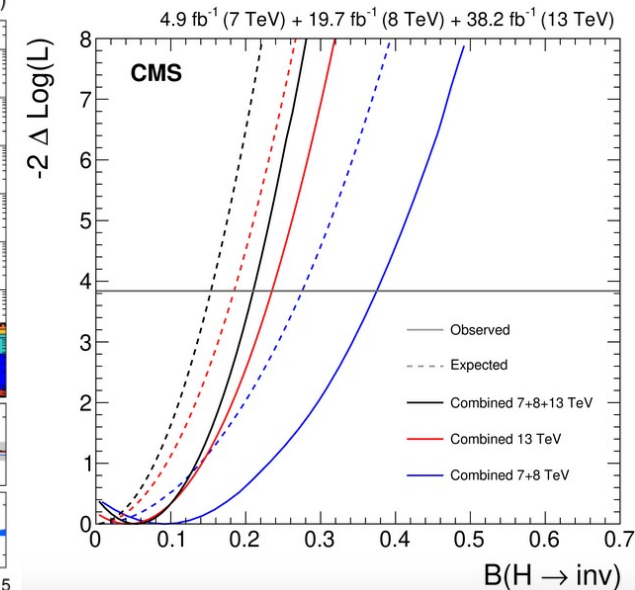
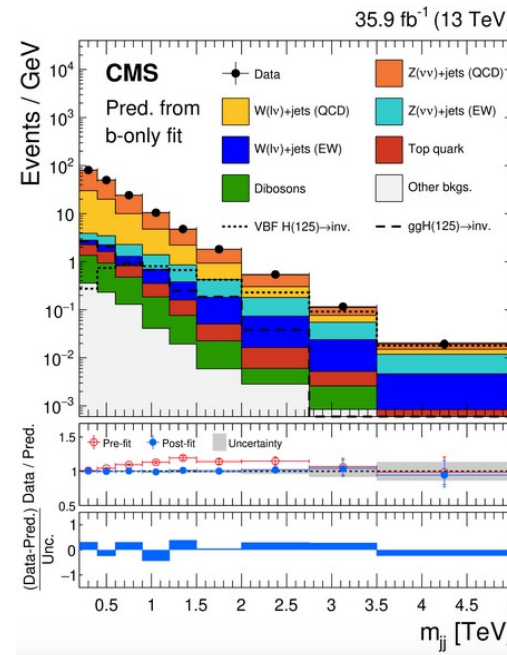
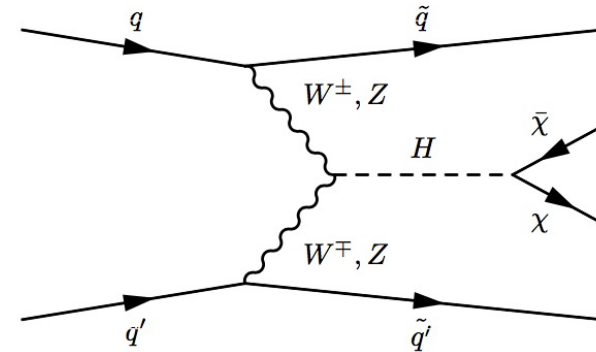


ttH production: Invisible decays

PLB 793(2019)520

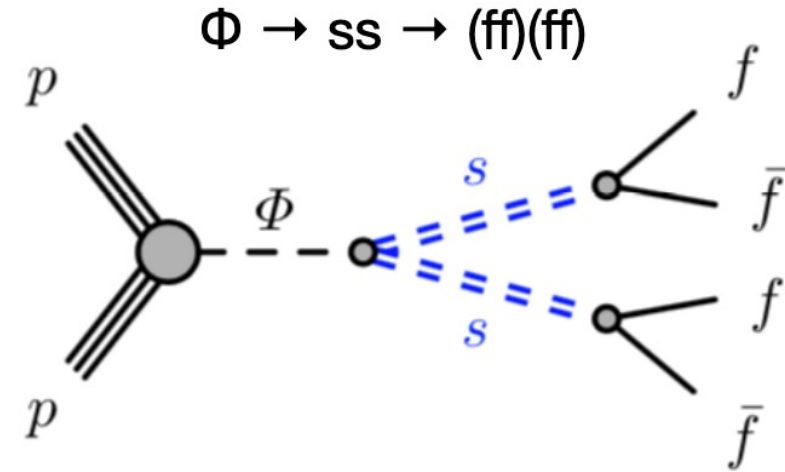
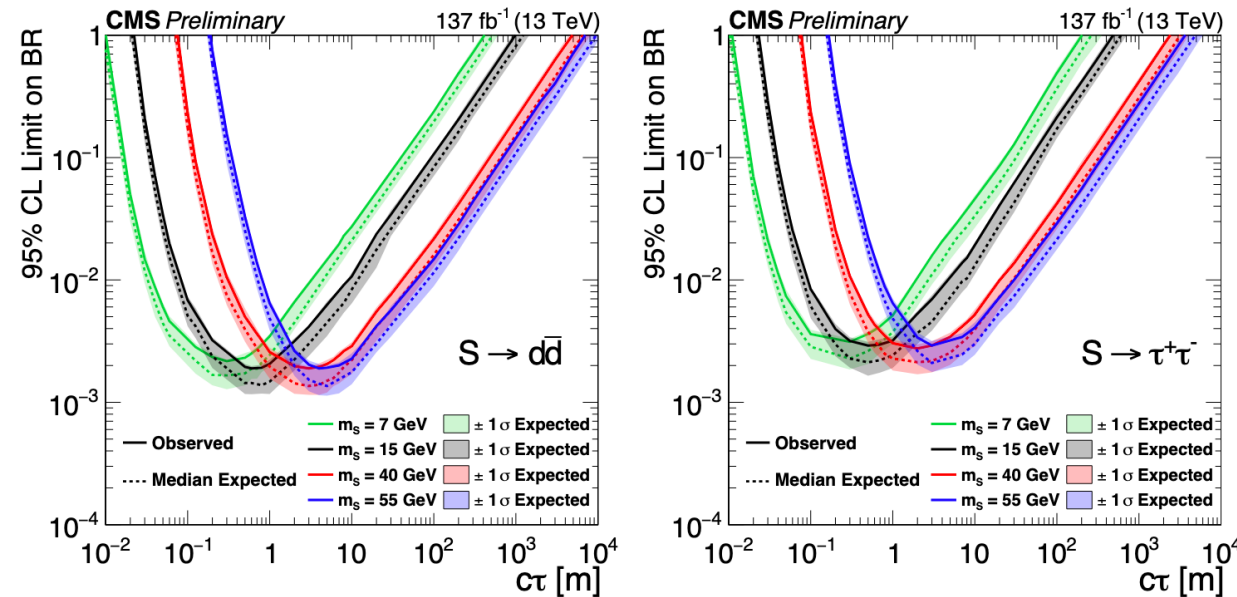
ttH → invisible

- Search for invisible decays in VBF
- Select large MET and 2-jet events with large $\Delta\eta(jj)$
- Fit to dijet invariant mass distributions
- Combination of ggH, V(jj)H, and Z(ll)H production modes
- Upper limits: 0.19@95%CL (0.15 exp.)



Long-lived: Higgs decays

CMS-EXO-20-015



- Higgs decaying to long lived scalars
 - Scalars decay to quark final states in the muon chambers
- Resulting bounds are interpreted in context of LL decays
 - Missing energy trigger

Summary

- Excellent consistency of SM but **SM is incomplete**
- Extensions foresee existence of additional bosons
- Searches for BSM bosons natural companion to precision SM Higgs boson measurements
 - Charged Higgs searches with top quark decays
 - Other BSM searches show no indication of deviations
- Searches provide **no hints for BSM yet**

