The Standard Model Higgs and beyond

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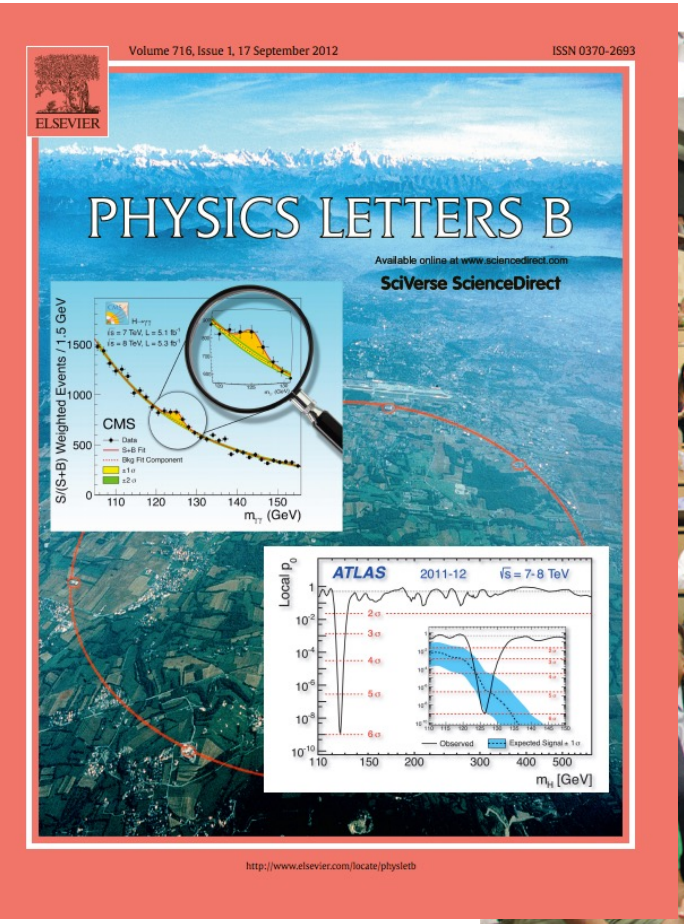
on behalf of the CMS Collaboration

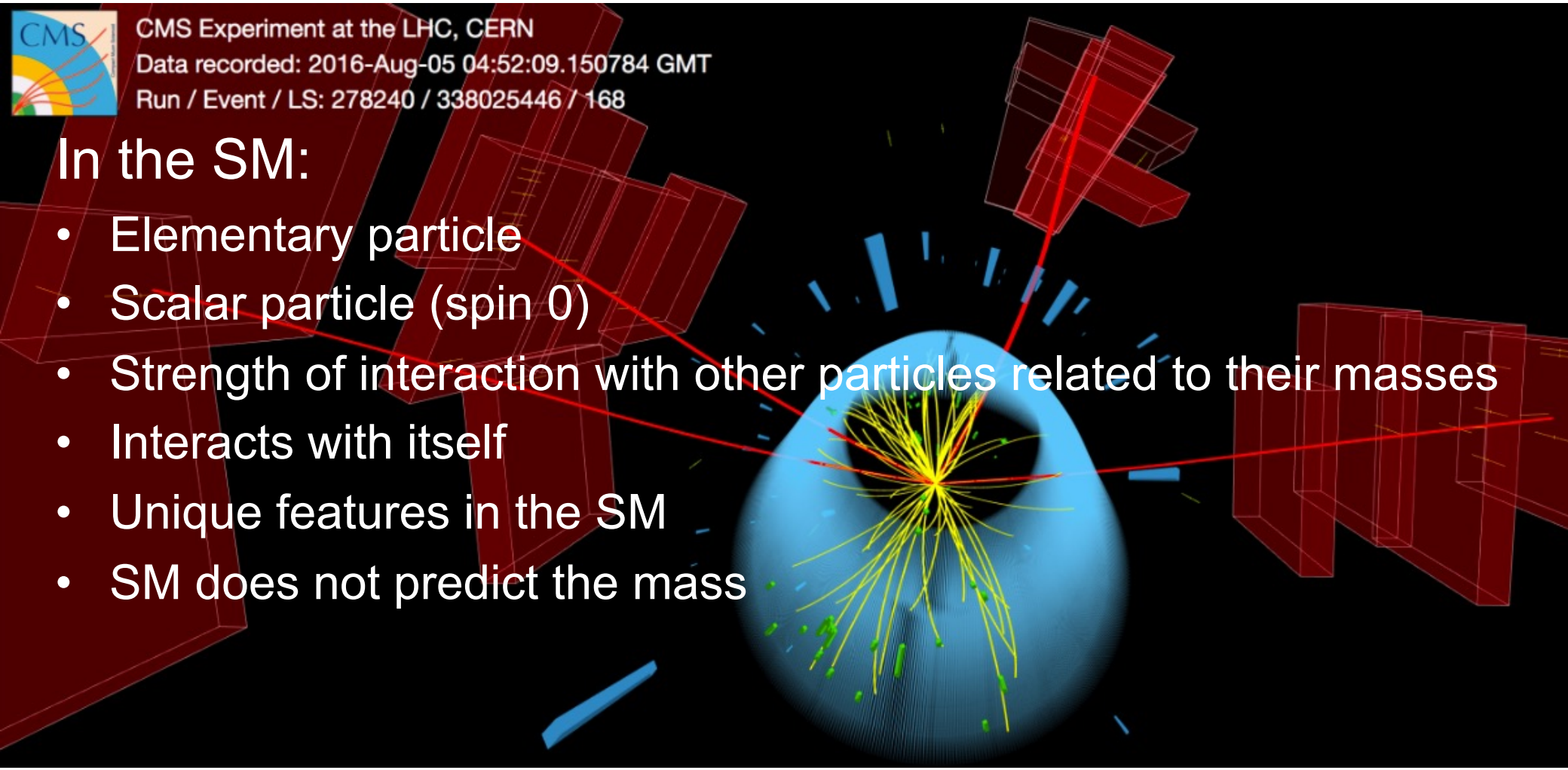
September 1, 2022

- ✓ Couplings, mass, width
- ✓ Pair production
- ✓ Higgs boson and Dark Matter
- ✓ BSM: light pseudo-scalar, non-SM decays, etc.

2012: A new boson discovery



The Higgs boson



In the SM:

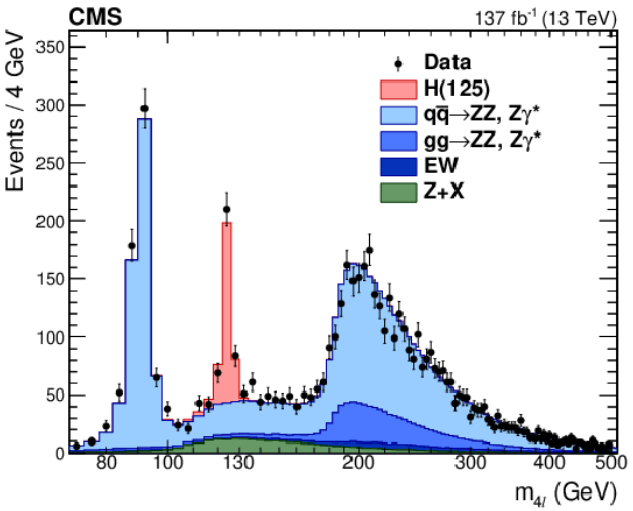
- Elementary particle
- Scalar particle (spin 0)
- Strength of interaction with other particles related to their masses
- Interacts with itself
- Unique features in the SM
- SM does not predict the mass

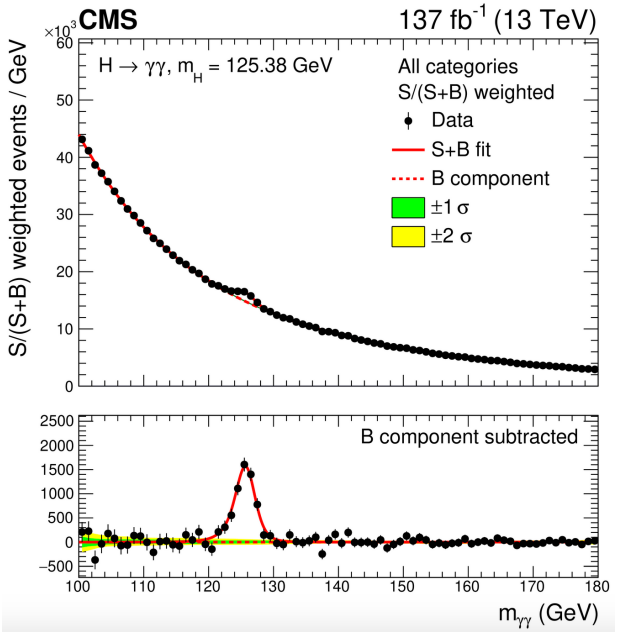
Only a few events ⇒ aim at exploring its properties

Higgs boson

arXiv:2103.06956, arXiv:2103.04956

- 5 main decay channels
  - ZZ, $\gamma\gamma$, WW, $\tau\tau$, bb
  - Most accurate measurements in $\gamma\gamma$ and ZZ
- Progress since Higgs discovery (July 2012)
  - Observation in boson and fermion channels
  - Precise mass measurement (~125 GeV)
  - Improving precision of coupling measurements
  - Differential distributions
  - 2nd generation fermions
  - Study of rare decays
- A long journey ahead



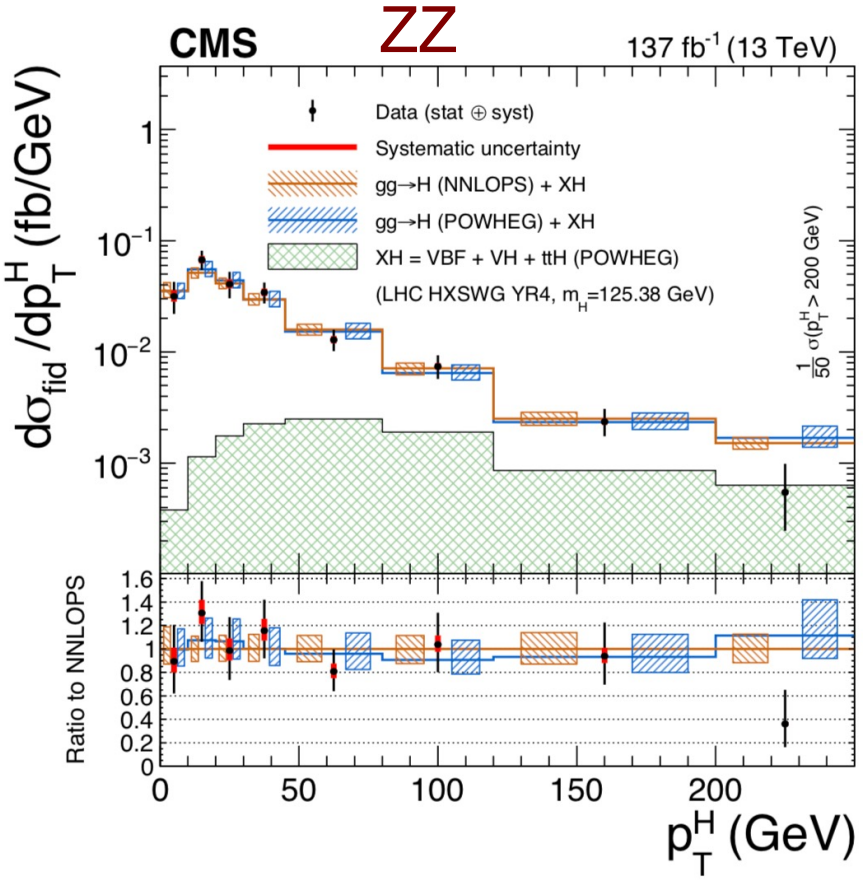


Differential distributions

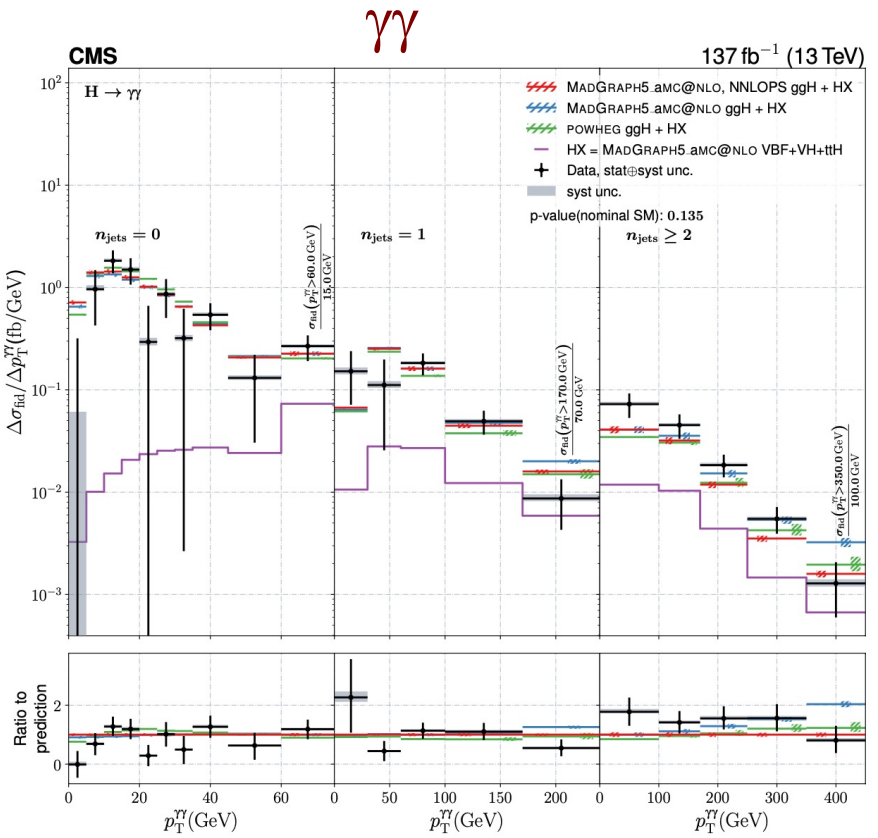
EPJC 81(2021)200, arXiv:2103.04956, arXiv:2208.12279

- Large range of variables measured in several channels
- BSM effects can be enhanced in tails of distributions
- Good agreement of data with predictions

ZZ

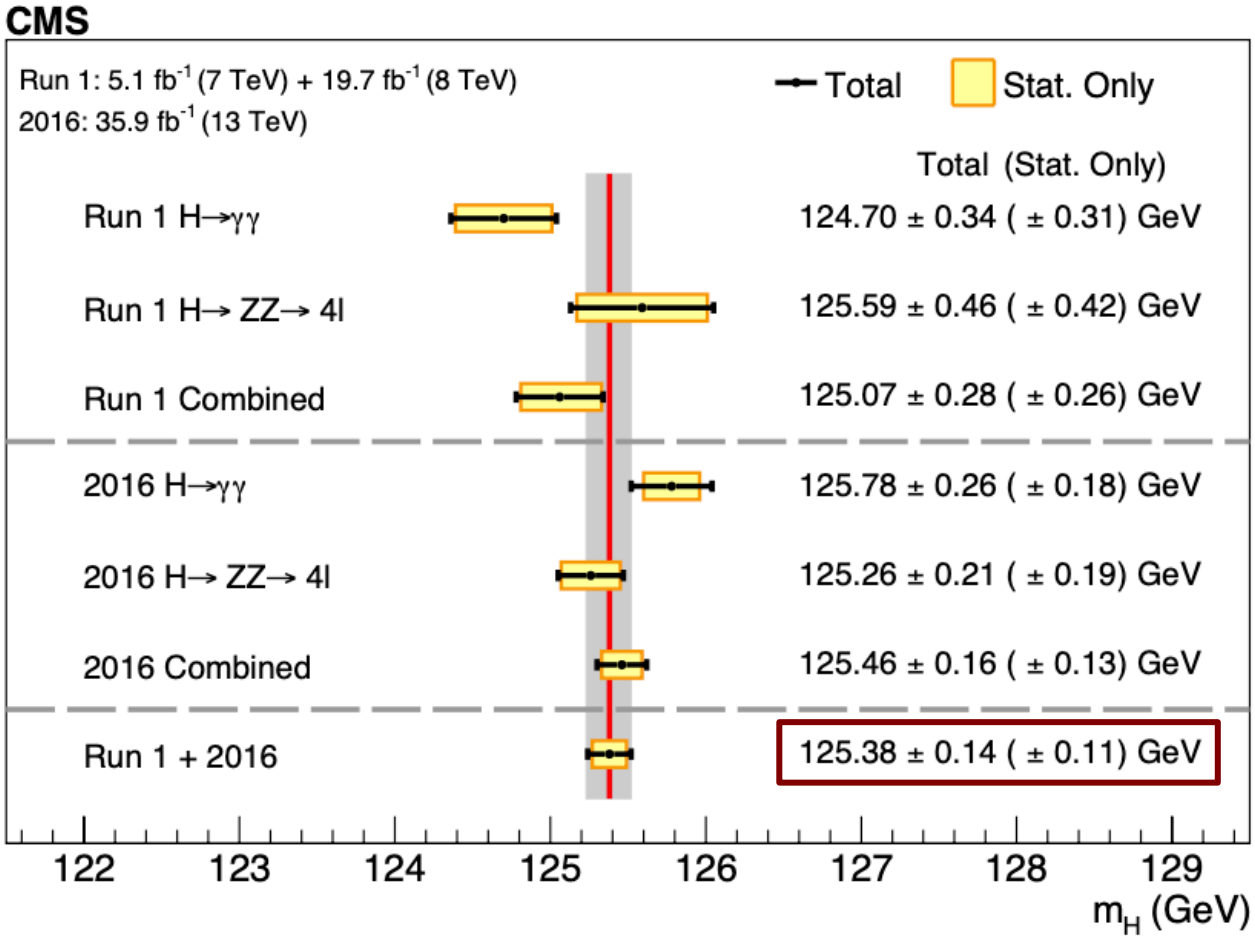


γγ



Higgs boson mass

PLB 805(2020)135425

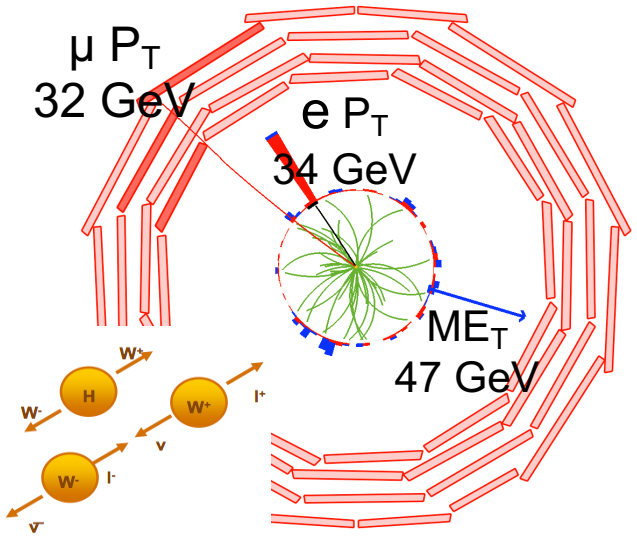


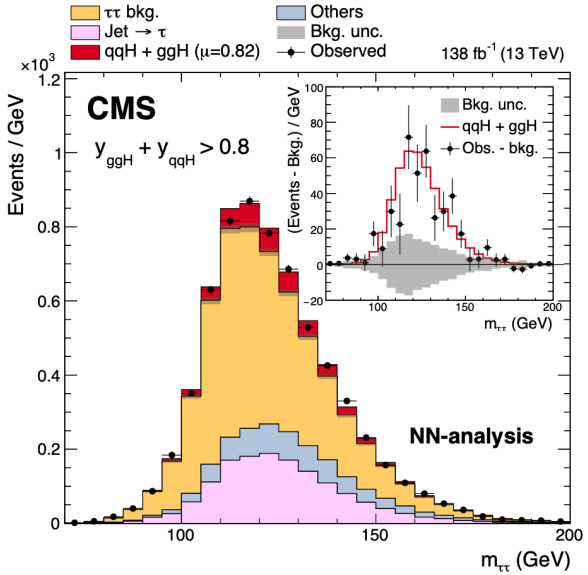
- Most accurate measurement in the $\gamma\gamma$ and 4ℓ channels
- Precision driven by statistics
  - soon energy scale and resolution systs will become dominant
- Some measurements still based on partial Run2 datasets

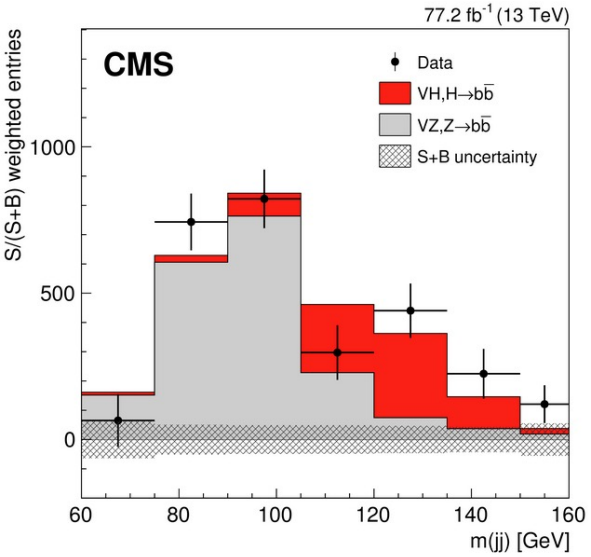
Uncertainty 140 MeV (0.11%)

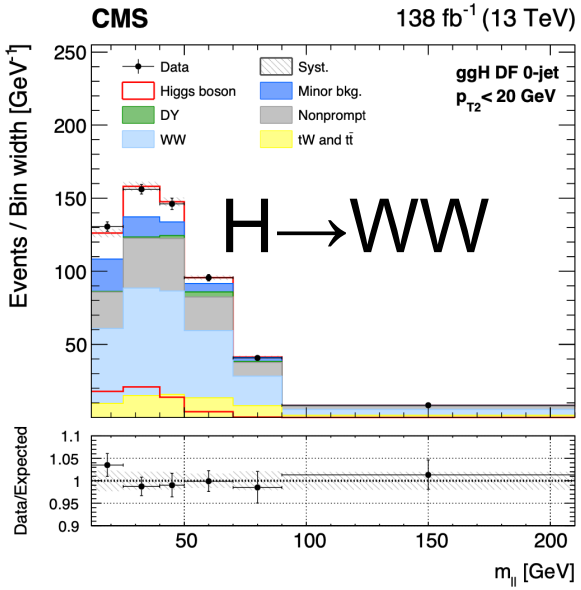
Low mass-resolution channels

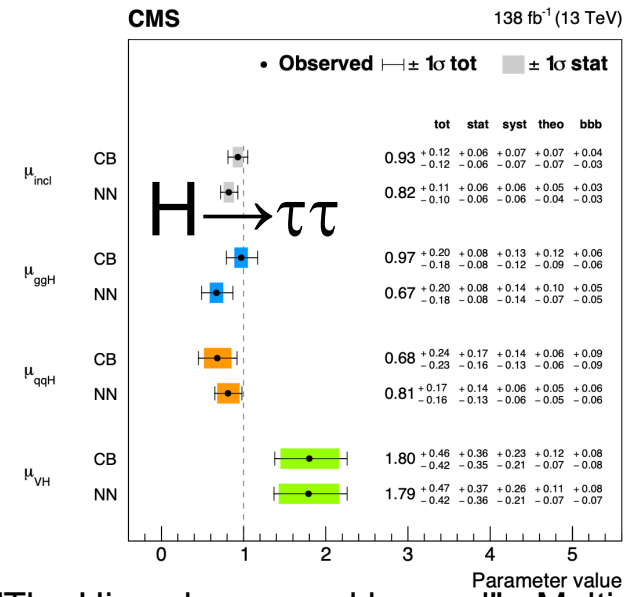
arXiv:2206.09466, arXiv:2204.12957, PRL 121(2018)121801

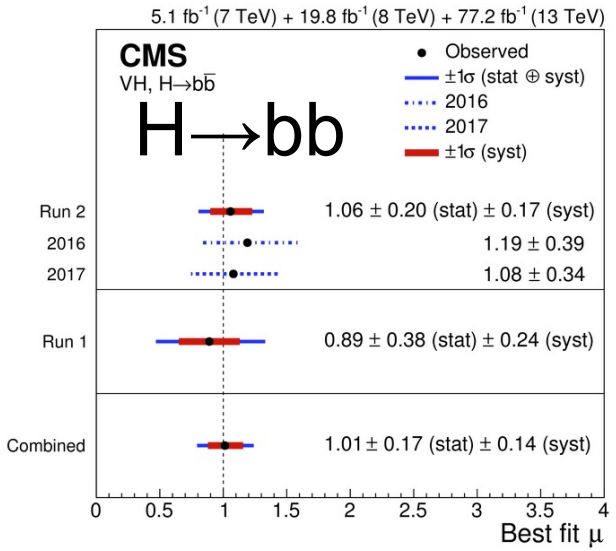






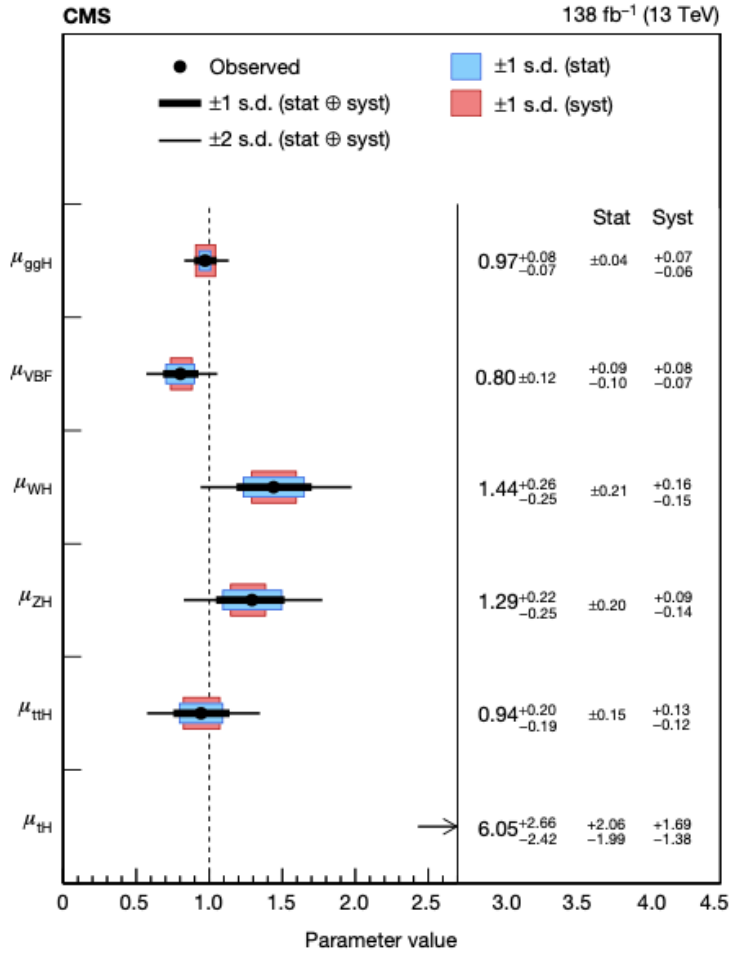


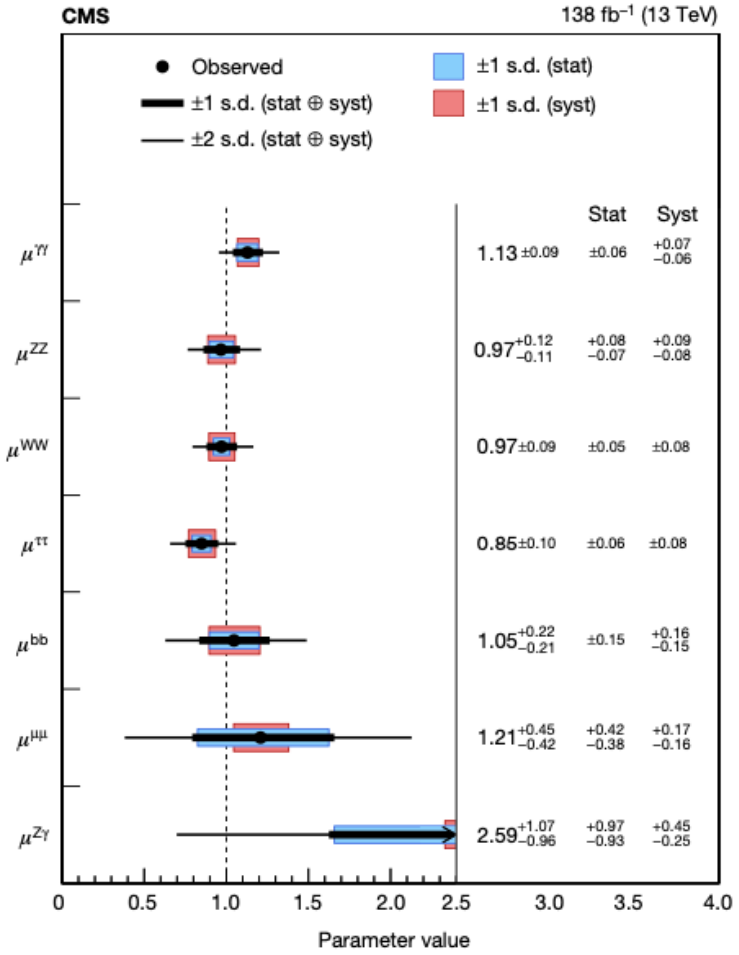




Consistency with SM

Nature 607(2022)60



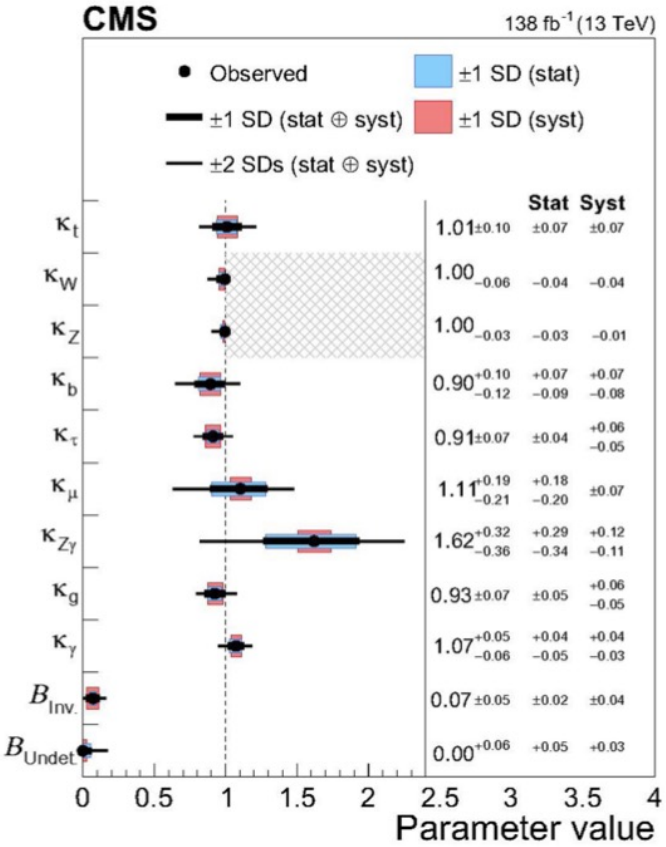


- Gluon-gluon fusion precision better than 10%
- 10-20% on other main production modes

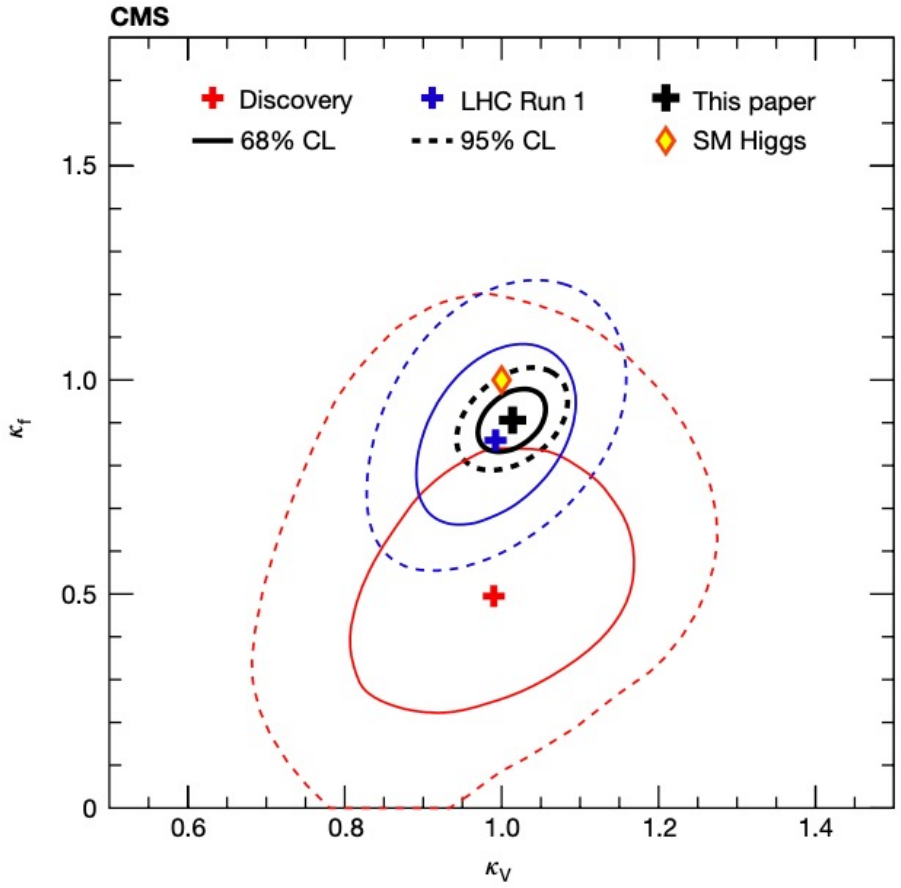
Couplings

Nature 607(2022)60

BSM physics in the loop



Vector and fermion couplings



BR_{inv} < 0.18 (0.10) at 95% C.L. (assuming $\kappa_V \leq 1$)

BR_{undet} includes non-standard decays, visible or invisible

⇒Results in agreement with SM (k_V=k_F=1) within 1σ

Rare decays: H→μμ, cc

JHEP 01(2021)148, arXiv:2205.0550, CMS-HIG-21-012

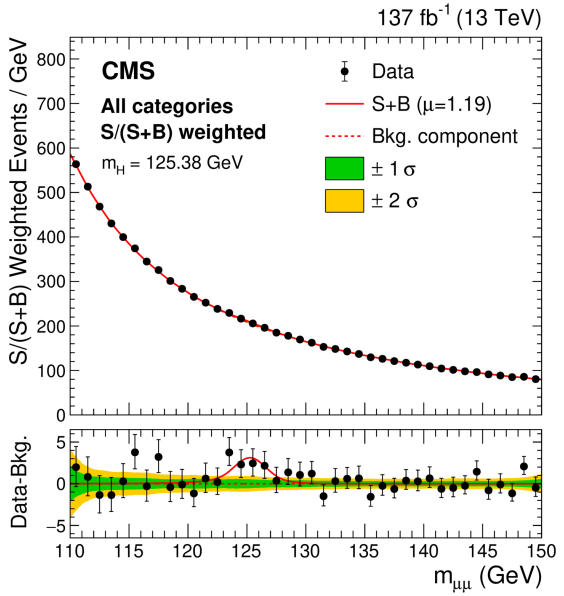
Study couplings to 2nd generation

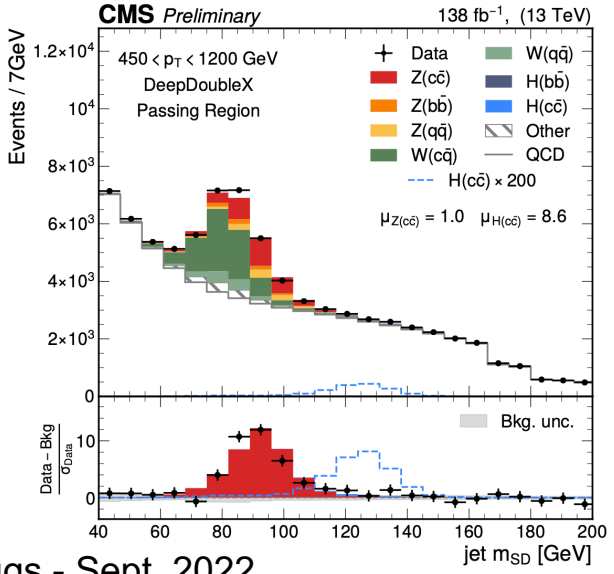
- H→μμ
  - Most sensitive category is VBF channel
  - Obs.(exp.): 3.0 σ (2.5σ)
- H→cc
  - Low cross section, need c-tagging
  - Use resolved (2jets) and merged (1jet),
  - Use ML and jet substructure for tagging and classification
  - Validate using VZ production:

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

  - Set limits

$$\sigma\,(\mathrm{VH})\,\mathcal{B}\,(\mathrm{H}\to\mathrm{c\bar{c}}) < 0.94\,\mathrm{pb}$$

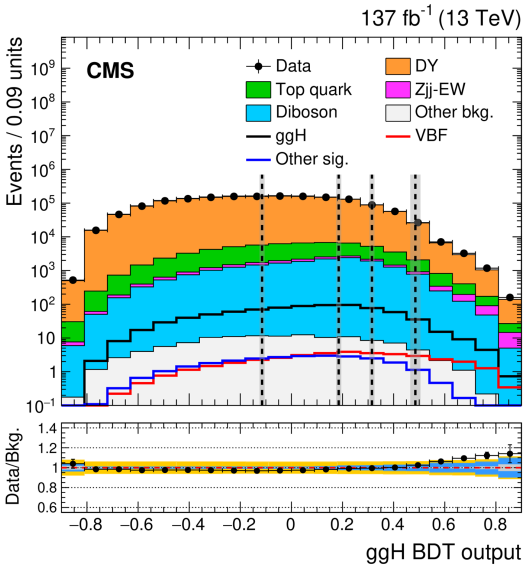


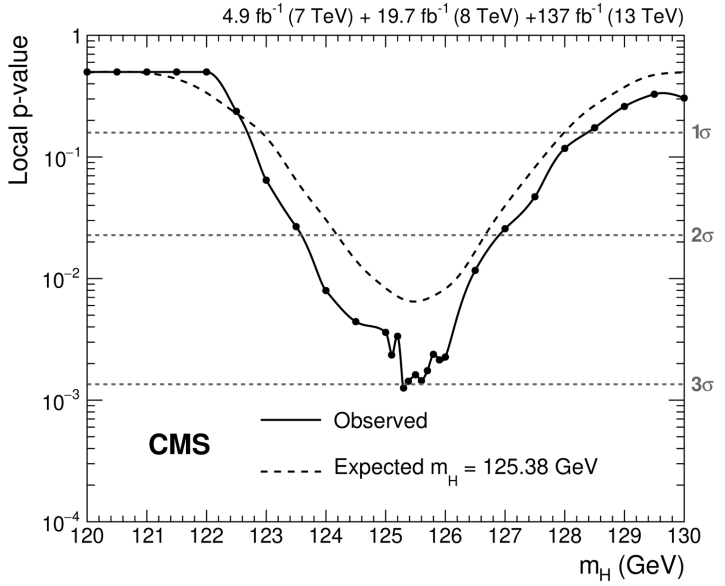


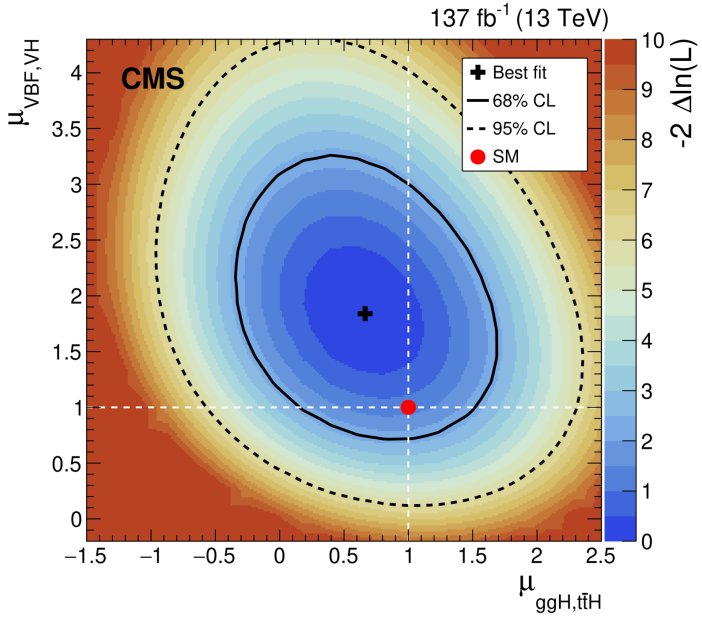
Search for SM H→μμ

JHEP 01(2021)148

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



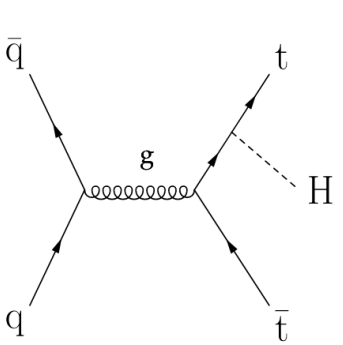


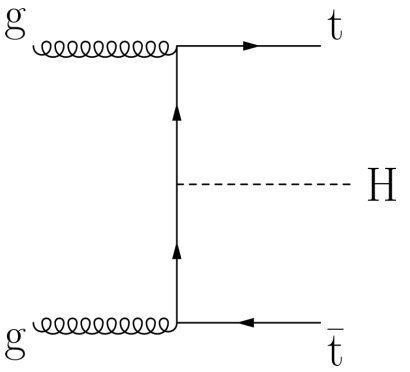


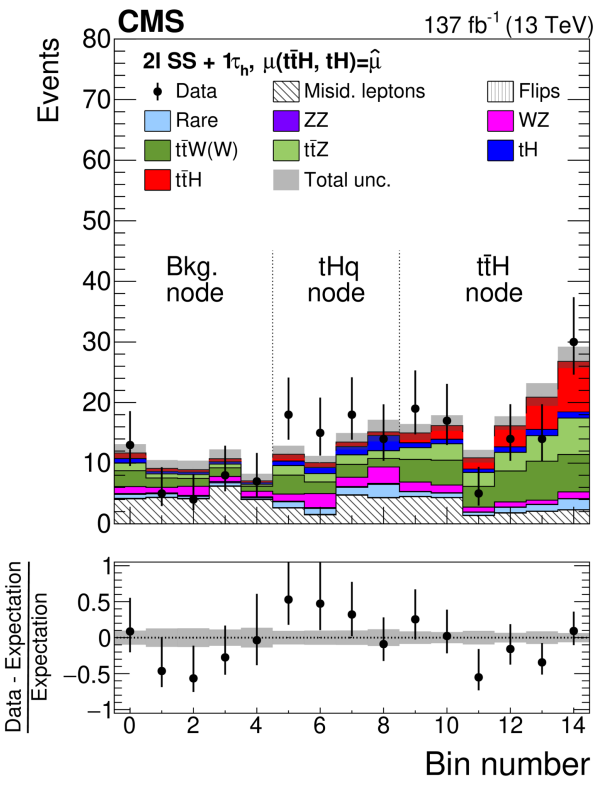
Higgs+Top: tH, ttH

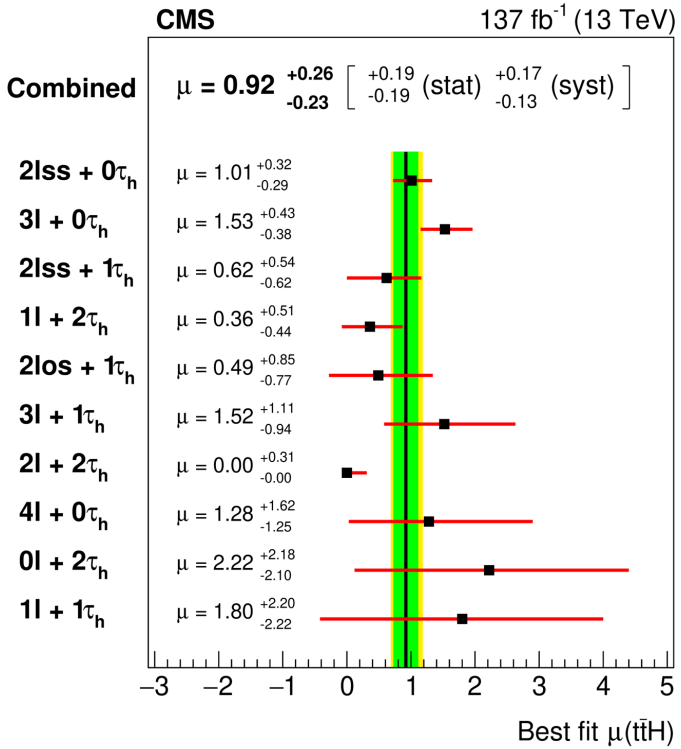
arXiv:2011.03652

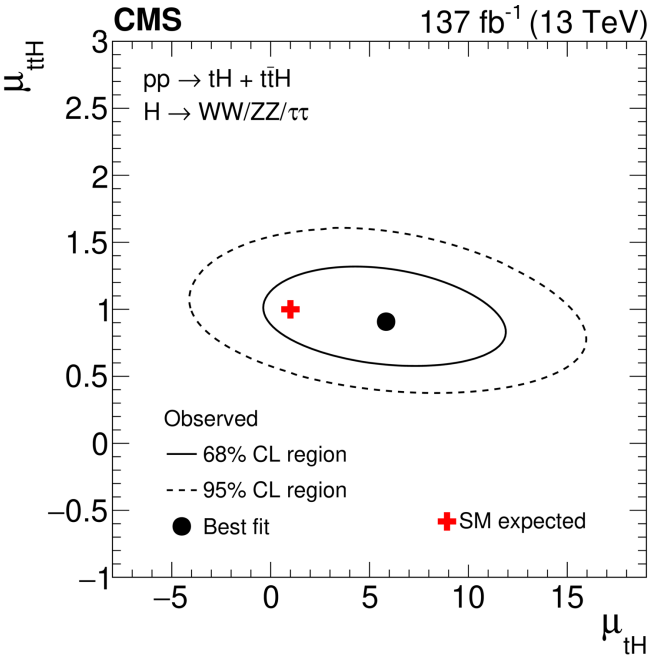
- Higgs (H) bosons production in association with one (tH) or two (ttH) top quarks in final states with electrons, muons, tau
- Study H→WW/$\tau\tau$/ZZ decays
- Model-independent, signature-based











Coupling vs mass

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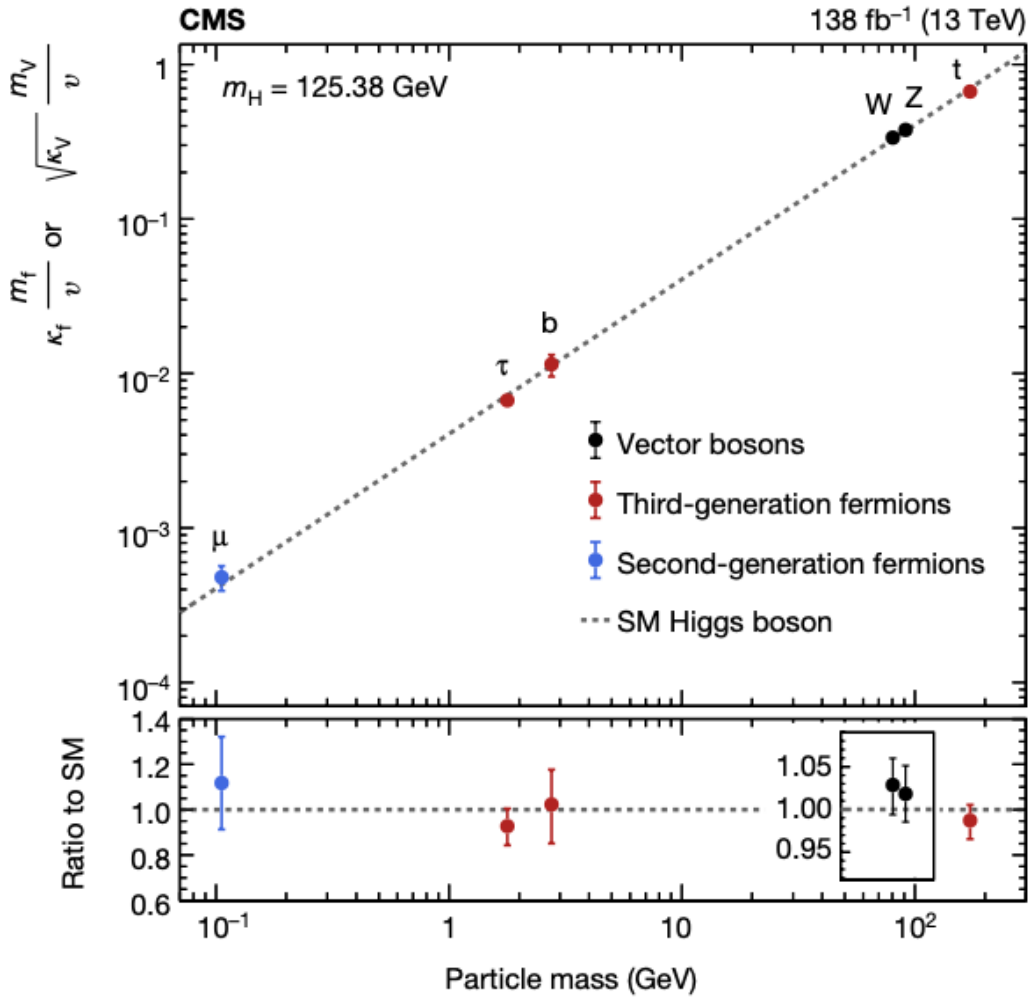
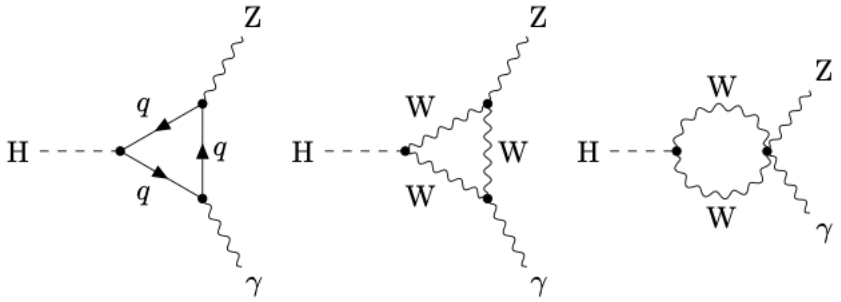


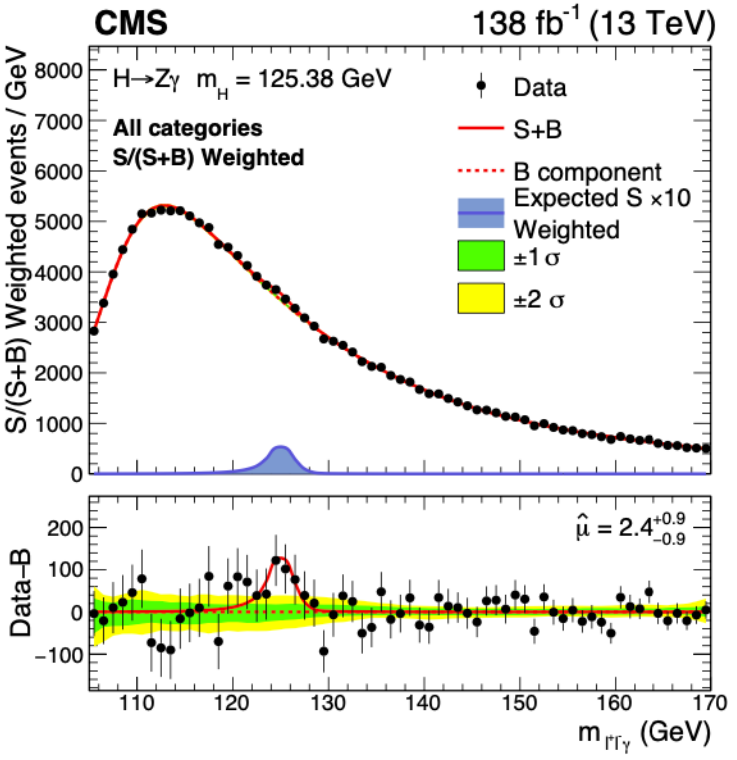
Rare decays: Z+photon

arXiv:2204.12945

- New particles may contribute to internal loops
- Exploit different production modes
  - Tag Z⟶ℓℓ (ℓ=e,μ): most accessible experimentally

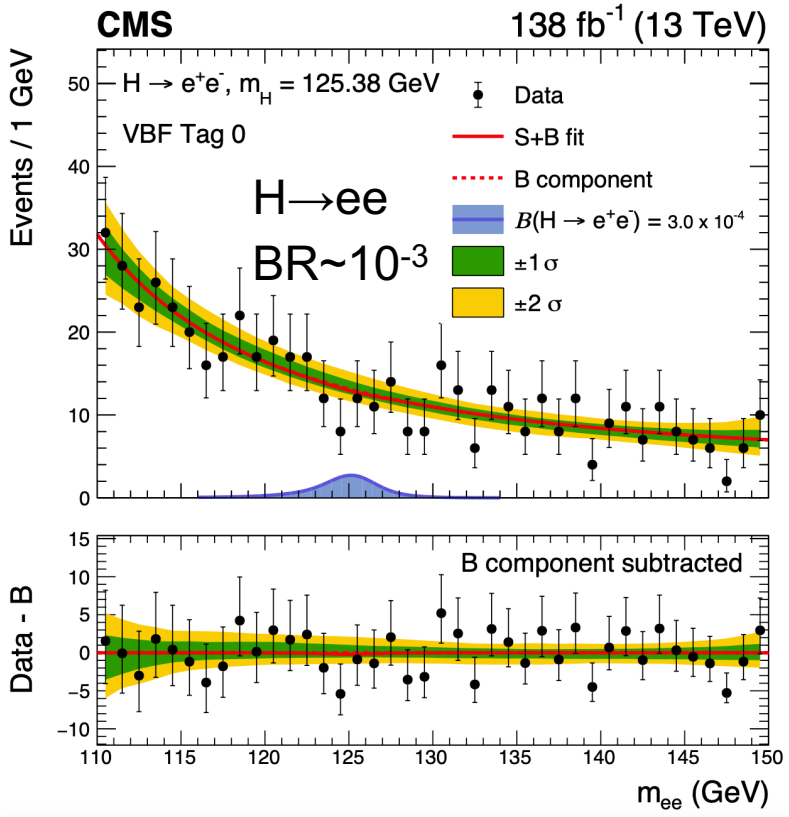
$$\sigma(\mathrm{pp} \rightarrow \mathrm{H})\mathcal{B}(\mathrm{H} \rightarrow \mathrm{Z}\gamma) = 0.21 \pm 0.08\,\mathrm{pb}$$

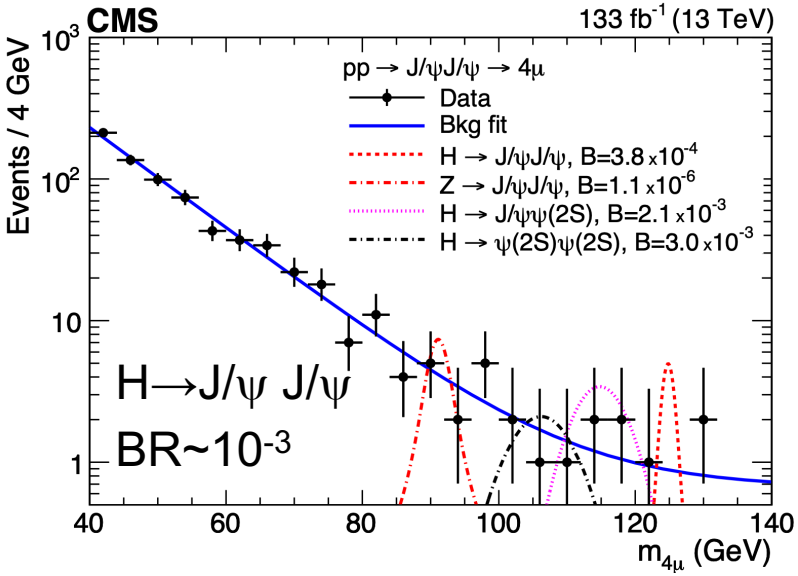


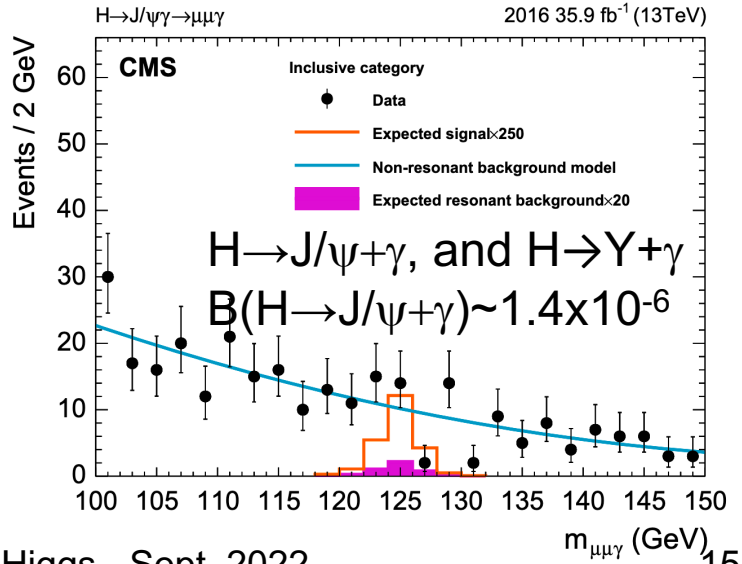


Search for rare decays

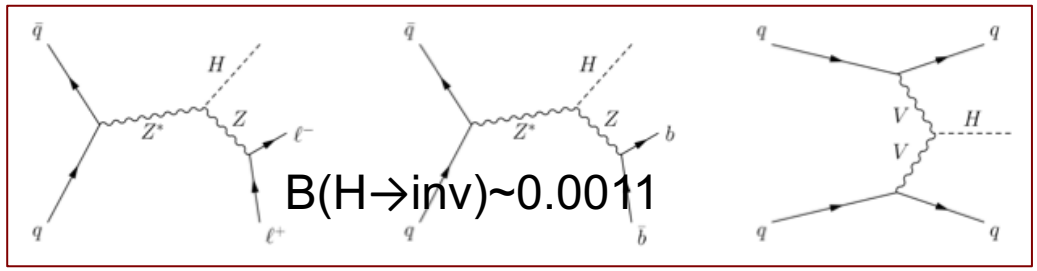
arXiv:2208.00265, arXiv:2206.03525, PLB 797(2019)134811, EPJC 79(2019)94, PLB 793(2019)520







H→invisible (difficult at LHC)



Higgs width

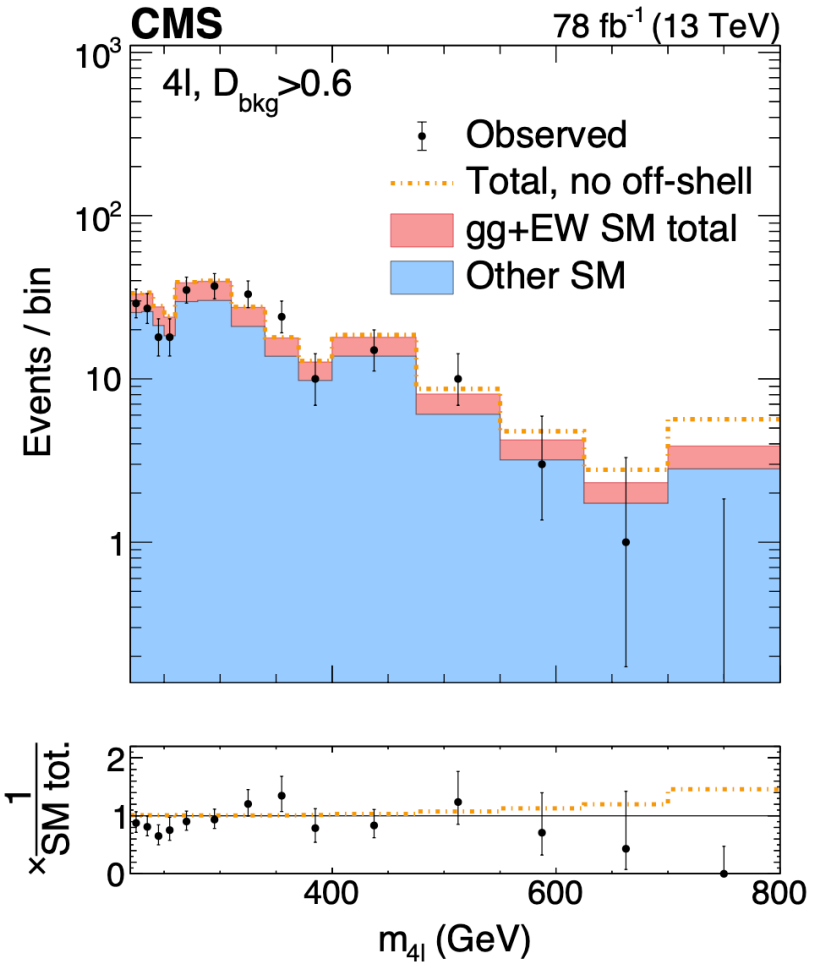
arXiv:2202.06923

- Couplings and width sensitive probes to BSM
  - Total width of 4.1MeV too small to measure directly
- Measure width by using off-shell production/decay: H(ZZ)
- Off-peak to on-peak ratio proportional to Γ_H
- Measure ratio of $\sigma^{\text{off-peak}}$ to $\sigma^{\text{on-peak}}$

$$\sigma^{\text{on-peak}}_{gg\to H\to ZZ} \propto \frac{g^2_{ggH} g^2_{HZZ}}{\Gamma_H}, \qquad \sigma^{\text{off-peak}}_{gg\to H\to ZZ} \propto g^2_{ggH} g^2_{HZZ}$$

$$\Gamma_H = 3.2^{+2.4}_{-1.7}\,\text{MeV}$$

$$\Longrightarrow 7.7\times10^{-23} < \tau_H < 1.3\times10^{-21}\,\text{s}$$

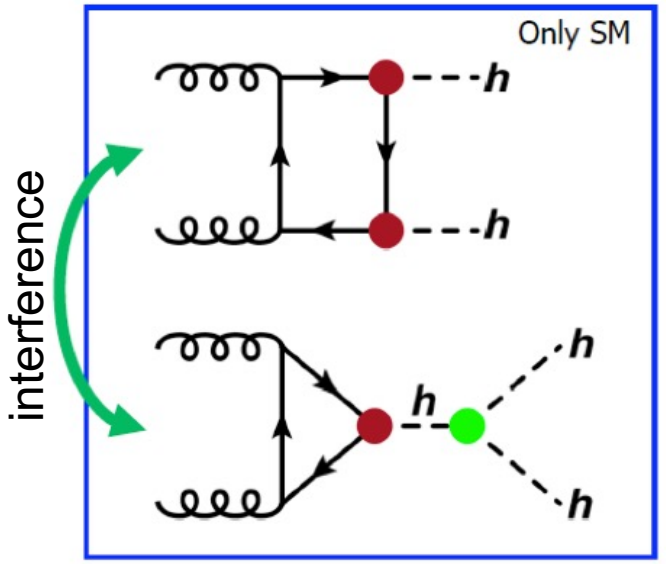


di-Higgs searches

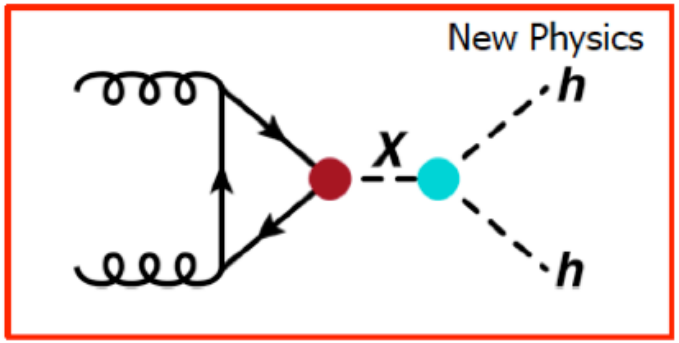
- Self-coupling measurement
- Destructive interference in SM
  - Could be altered in BSM
  - If constructive, it could be large enhancement
- In SM, only σ=31fb at 13 TeV
- Study different final states

(X→)hh→		BR	Mass scale
	bbbb	34%	High
	bbττ	7.3%	
	bbWW	27%	
	bbγγ	0.26%	Low

non-resonant production

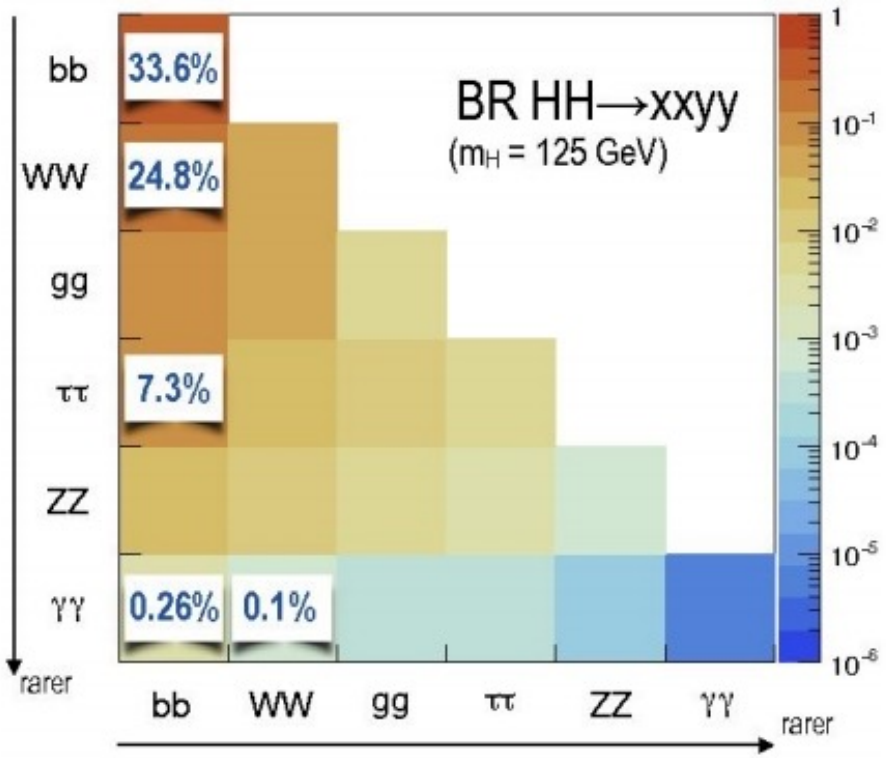


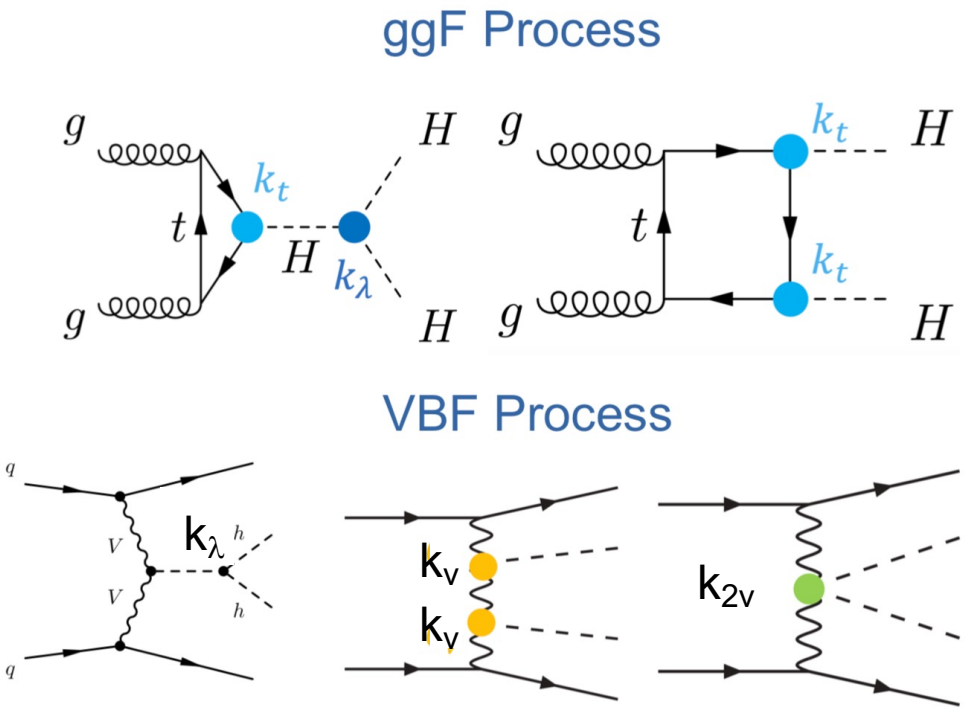
resonant production



HH: non-resonant production

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



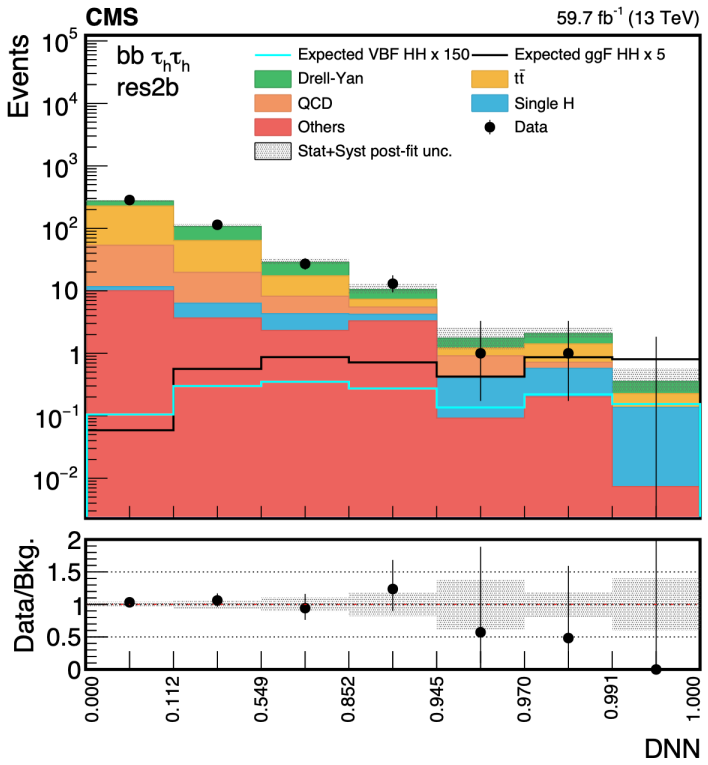


What is new in HH searches

arXiv:2206.09401, CMS-B2G-21-001

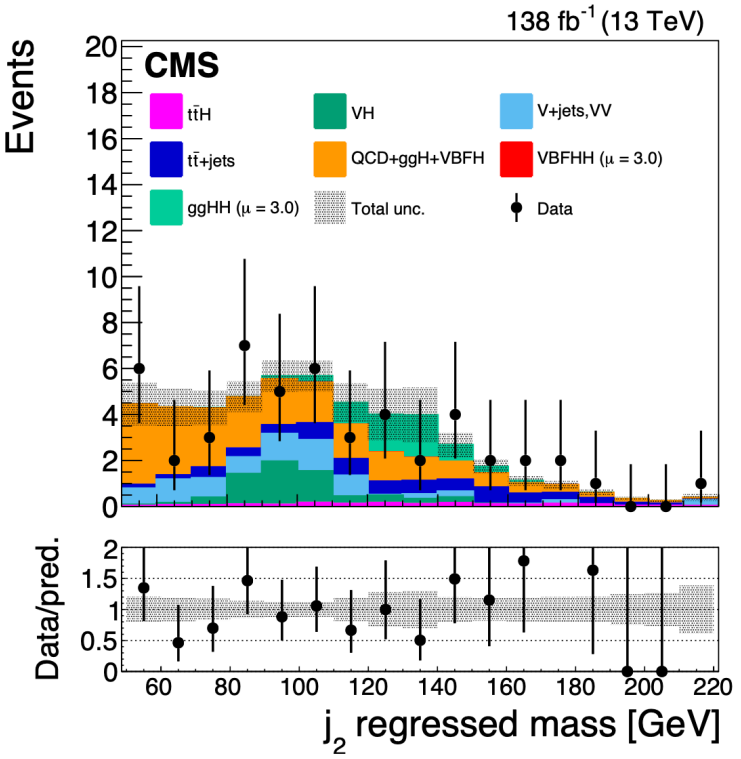
- Results are better (x2-3) than 2016 results alone after scaling for luminosity

Extensive use of ML tools



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

Boosted topologies

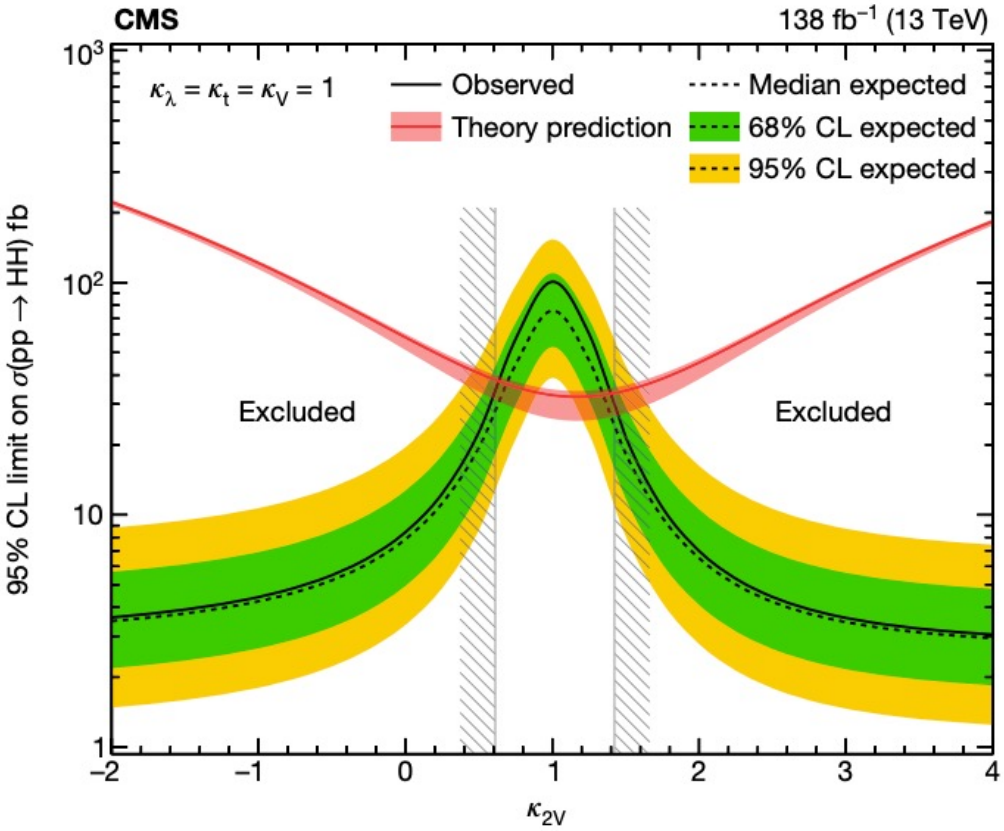


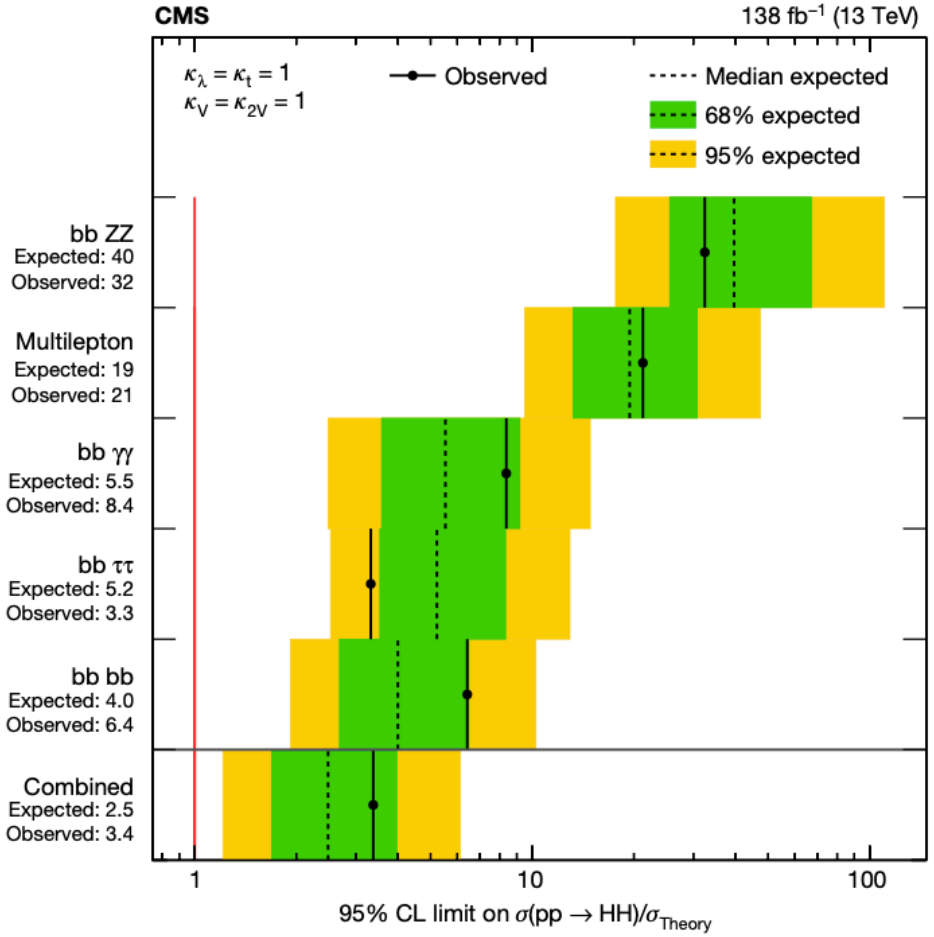
Regressed mass of one AK8 jet in a ggHH(4b) boosted category

HH: results

Nature 607(2022)60

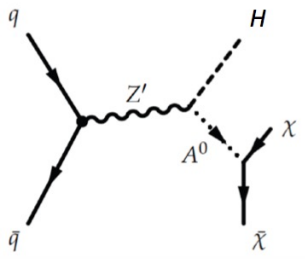
- Both resonant and non-resonant searches
- Background estimate and signal extraction



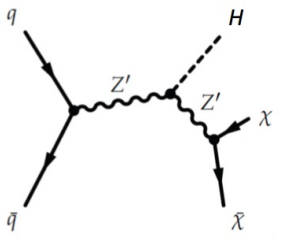


DM searches with Higgs bosons

- Higgs as portal to Dark sector
  - New massive particle mediates the Higgs-DM interaction
- H(125) may mix with new dark mediators
  - DM particles could get mass through Higgs mechanism
- Study scenarios where Higgs is involved

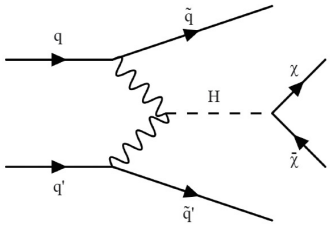


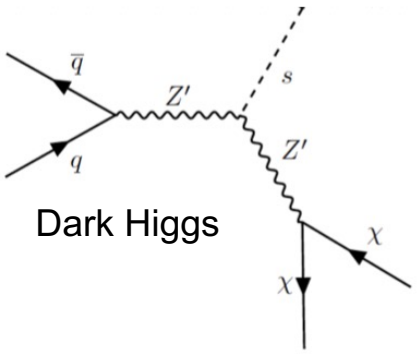
Z' – 2HDM



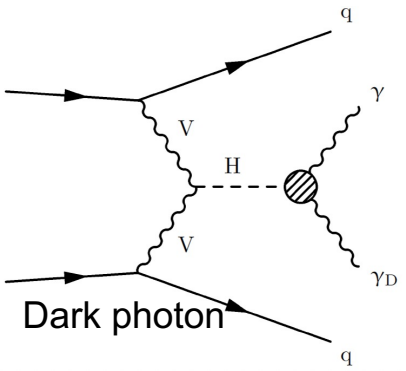
Z' – baryonic

Invisible Higgs





Dark Higgs



Dark photon

Mono-Higgs

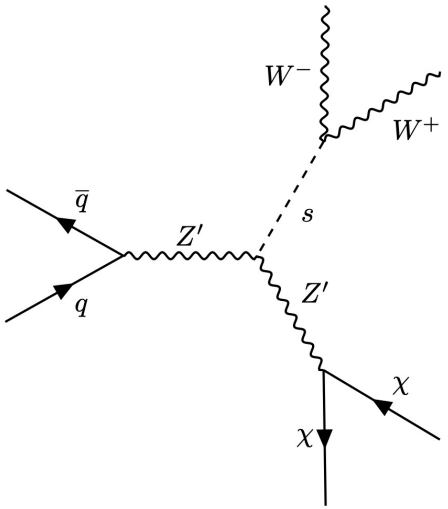
- Generic search: pp→H+MET
- ISR suppressed due to small coupling to H
- Signature: Higgs+MET ⇒ H used as a tag
- Final states (WW,ZZ,bb,ττ,γγ)

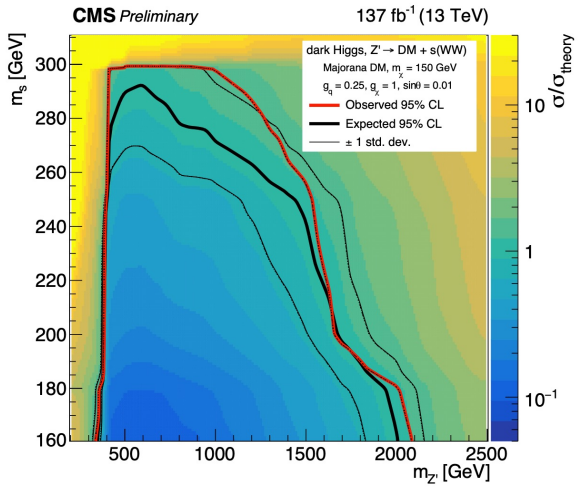
Dark Higgs & Dark photon

CMS-EXO-20-013, arXiv:2009.14009

Dark Higgs

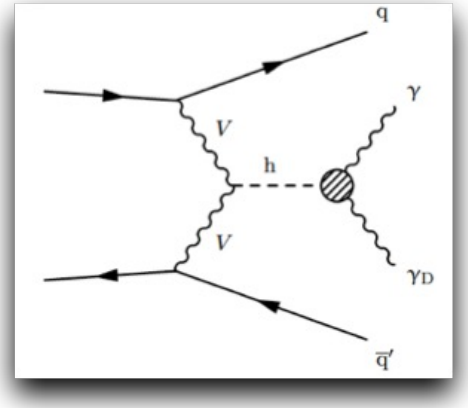
- DM particle acquire mass through interaction with a dark Higgs (s)
- WW decay dominates for m_s>160GeV
- Fully leptonic final state
- Observable: $m_T(\ell,MET)$

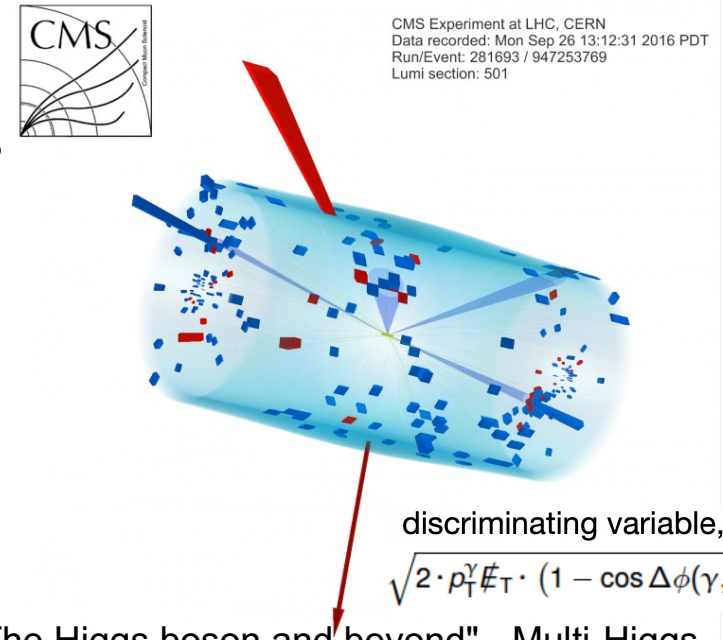




Dark photon

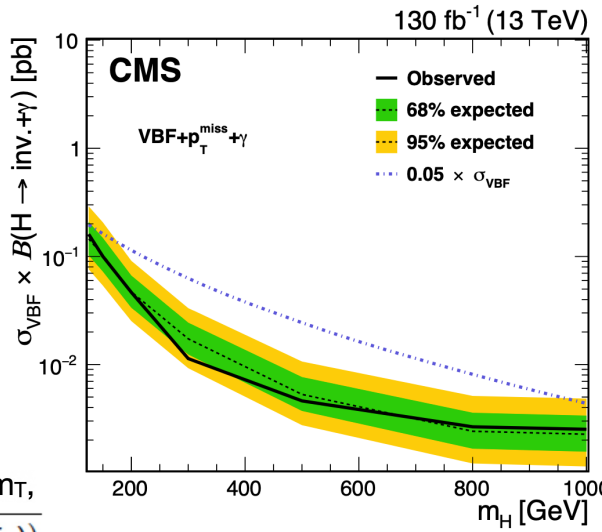
- Search in VBF Higgs events





discriminating variable, m_T,

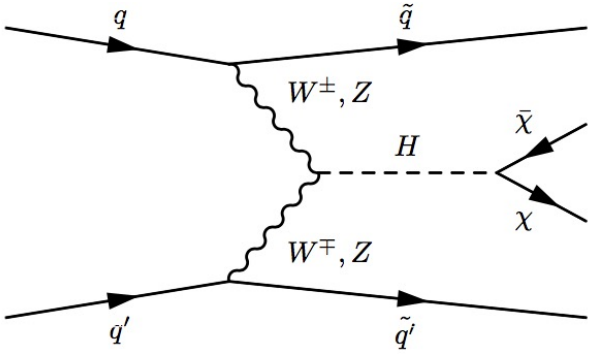
$$\sqrt{2 \cdot p_T^{\gamma} \not{E}_T \cdot (1 - \cos\Delta\phi(\gamma, \not{E}_T))}$$

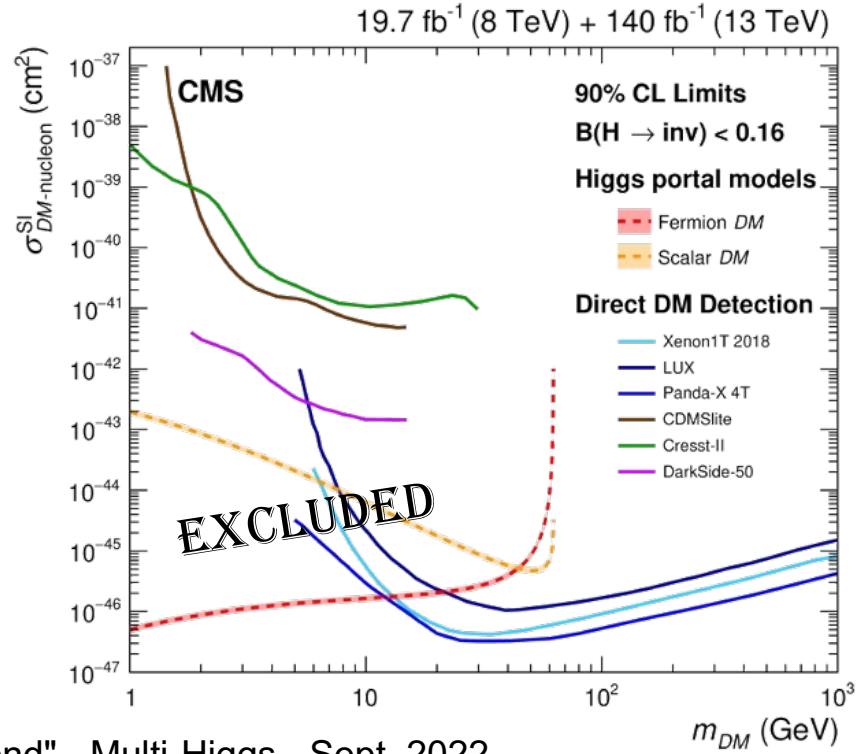


DM: Higgs invisible decays

arXiv:2201.11585

- In the SM, BR(H→inv) is ~0.1%
- Search for Higgs invisible decays in VBF process
  - 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($\ell\ell$)H production modes
- Set limits on DM models
  - Upper limits: 0.18(0.10exp)@95%CL
- Competitive limits for low-mass DM candidates





Extending searches

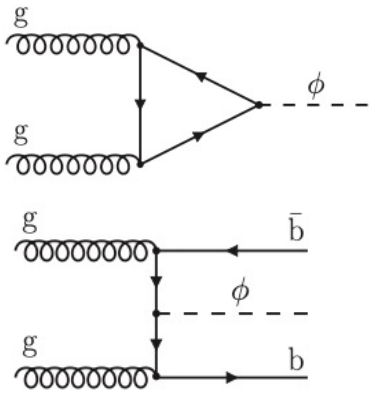
- Minimal Supersymmetric SM (MSSM)
  - Neutral Higgs: $\phi \to \tau\tau/bb/\mu\mu$
  - Charged Higgs, $H^{\pm}$
- Beyond MSSM
  - Light pseudoscalar: $h \to aa$
  - Non-SM decays
  - Heavy Higgs
  - Resonant production

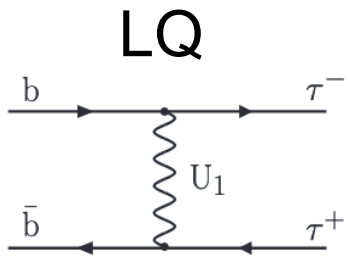
Neutral MSSM Higgs

PLB793(2019)320, arXiv:2208.02717

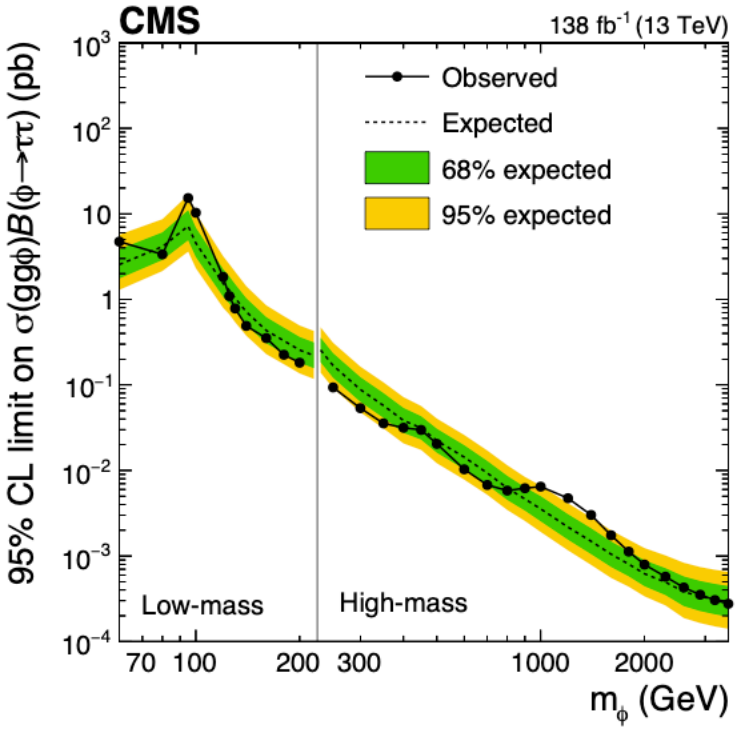
- Enhanced couplings of MSSM Higgs to down-type fermions (large tanβ)

⇒increased BR to τ leptons and b-quarks





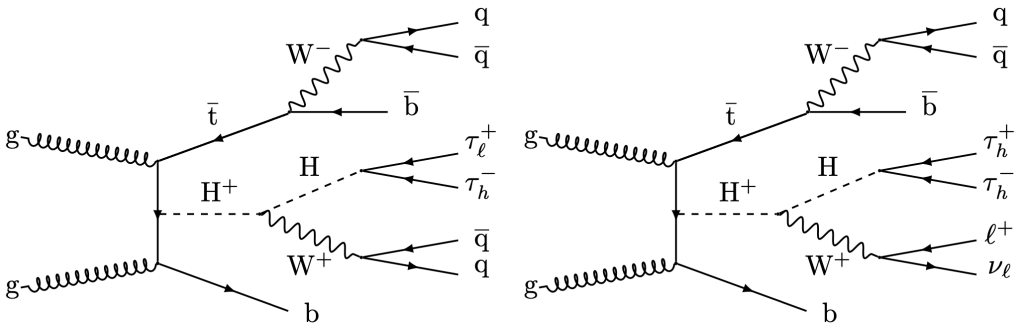
- Search for neutral MSSM Higgs boson
- 4 final states used: $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$, $e\mu$
  - Reconstruct tau-pair invariant mass
  - Signal extracted from m_T^{tot} distribution
  - Split in b-tag/no b-tag categories to enhance sensitivity
- Main backgrounds: $Z\rightarrow\tau\tau$, QCD/W+jets, DY, ttbar
- Some fluctuations over bkg expectations
  - Two excesses: 100GeV and 1.2TeV
  - Local(global) significance 3.1(2.7)σ@100GeV
  - 2.8(2.4)σ@1.2TeV

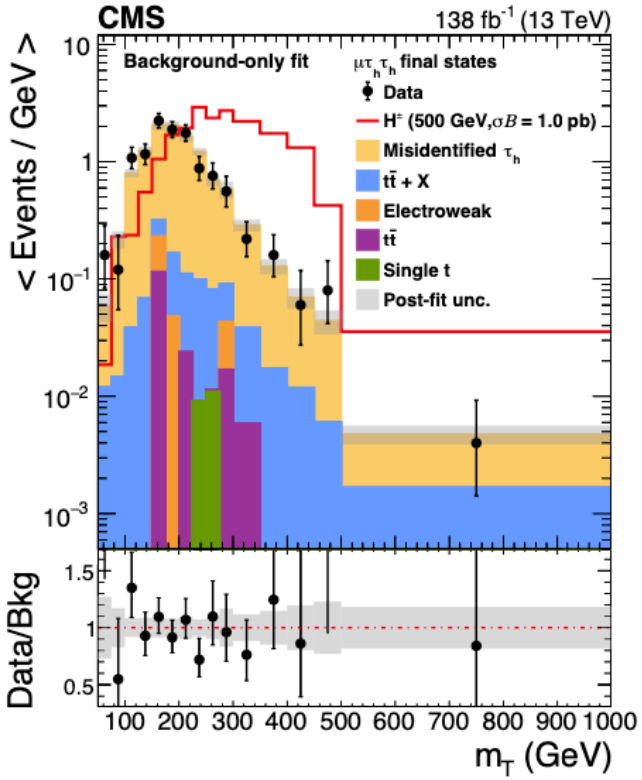


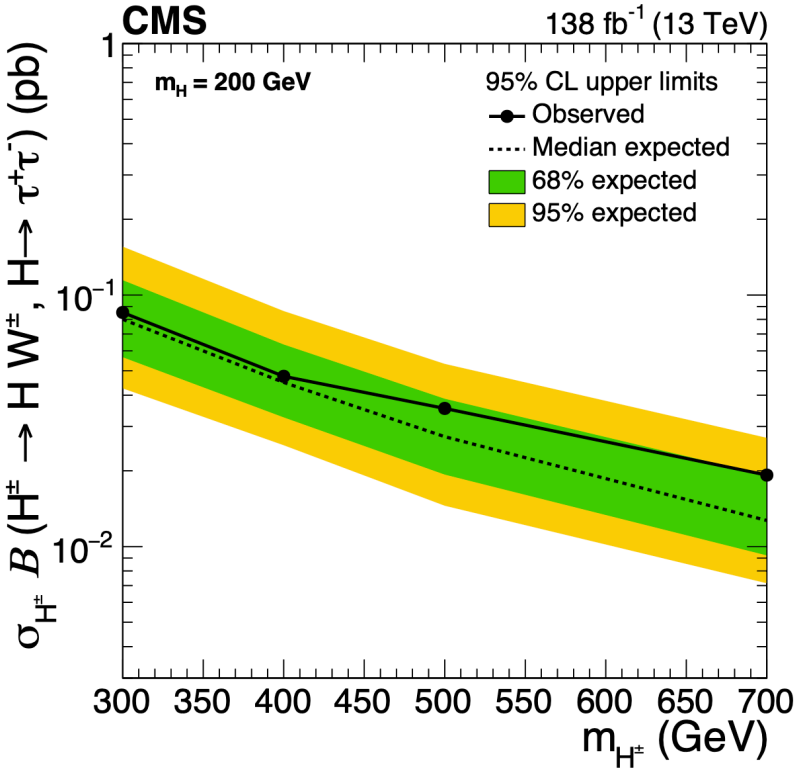
Charged Higgs

arXiv:2207.01046

- Search for a $H^{\pm}$ decaying to a heavy neutral Higgs boson H and a W
- Produced in association with top quark
  - discriminating variables: m_T, BDT discr.
- Data consistent with SM expectations



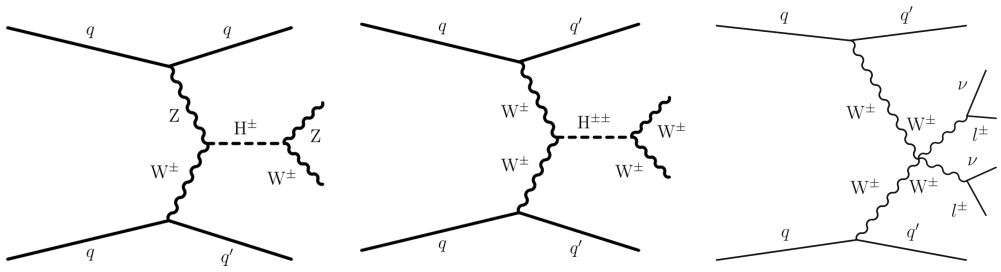


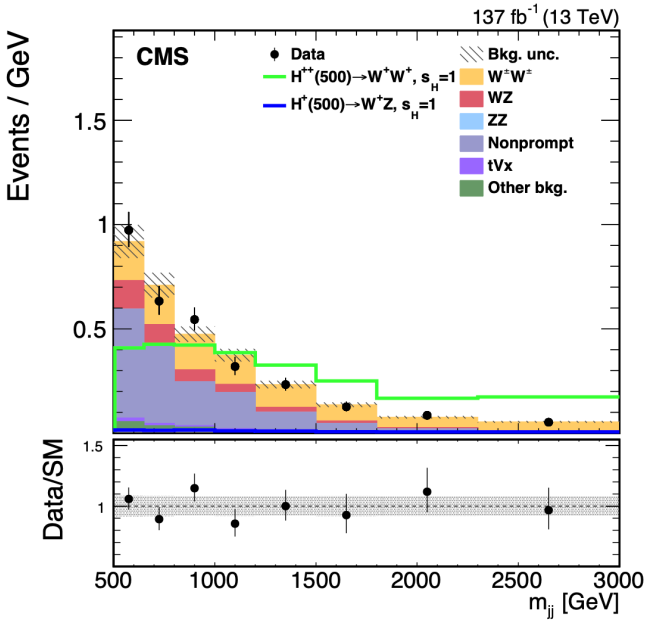


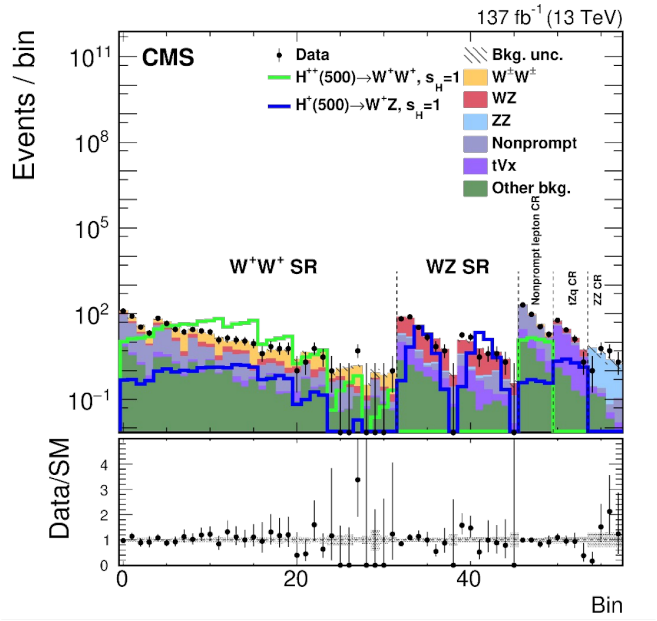
Charged Higgs (cont.)

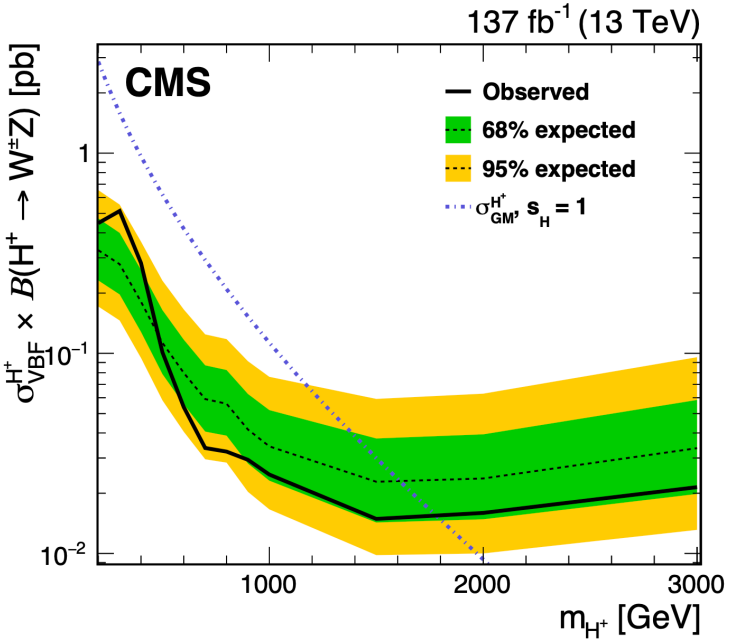
EPJC 81(2021)723

- Search for charged Higgs in GM model: H^+ and H^{++}
- Search for resonant production
  - Only fermiophobic H^+ considered
  - Require 2/3 leptons
  - Good bkg description of data in SR







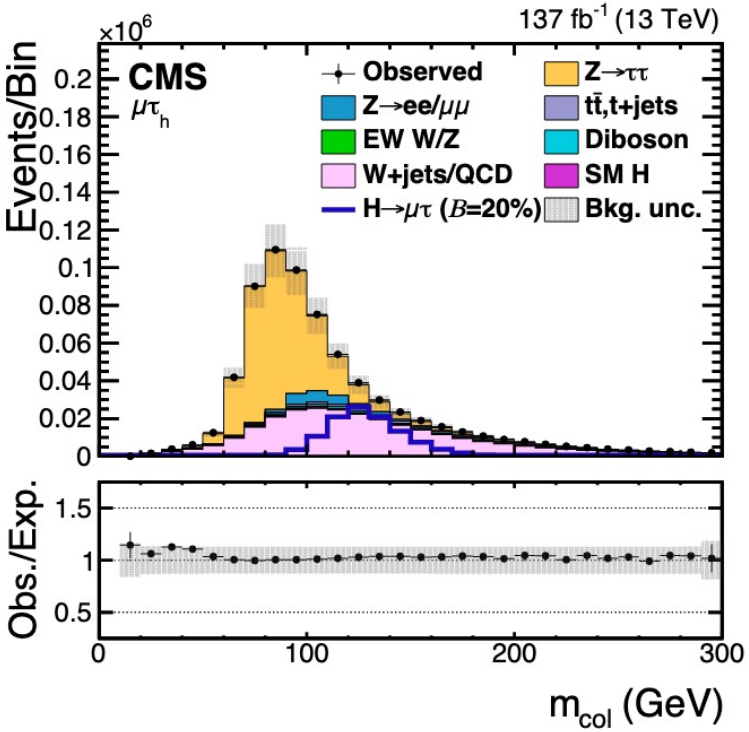


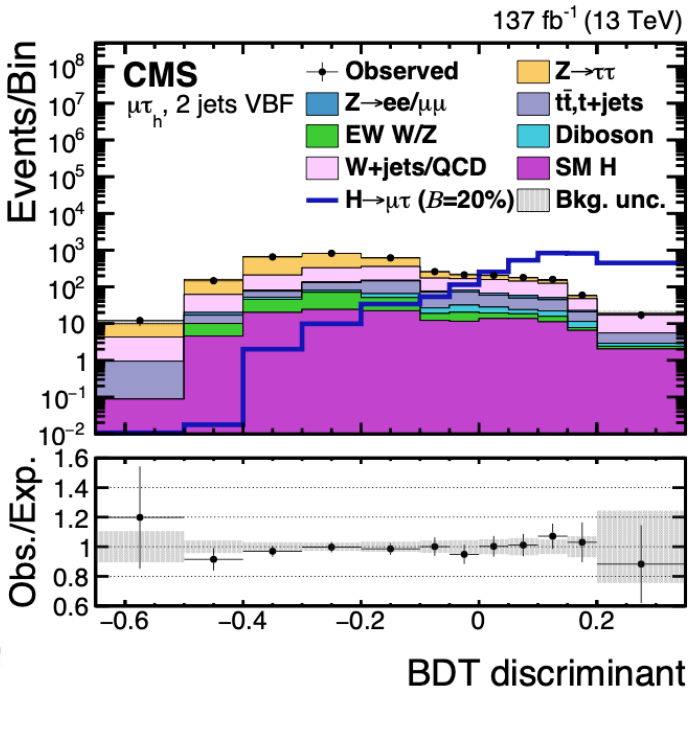
LFV in Higgs decays

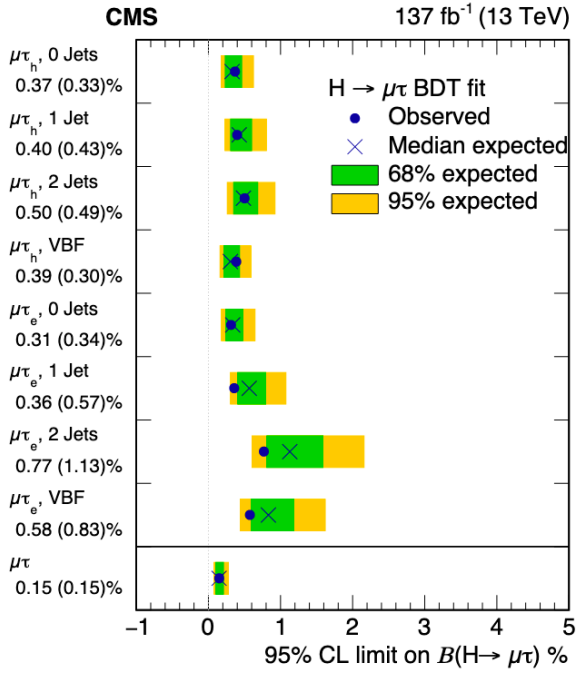
arXiv:2105.03007

- Some BSM models allow for LFV Higgs decays
- Search for H→eτ, eμ, μτ final states
- Categories: N_{jet}, lepton kinematics
  - N_{jet} to target ggH and VBF production
- Main background from DY, ttbar, WW

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

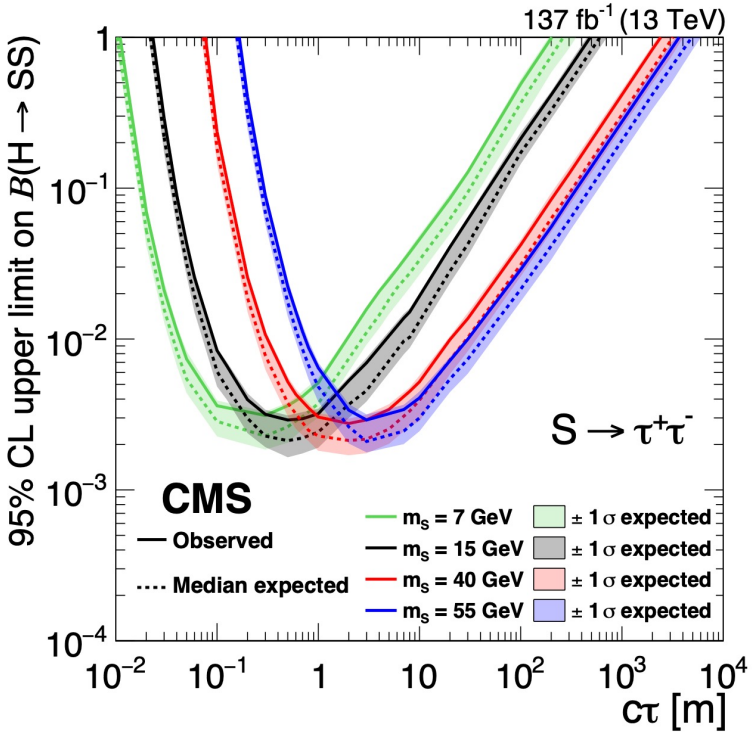


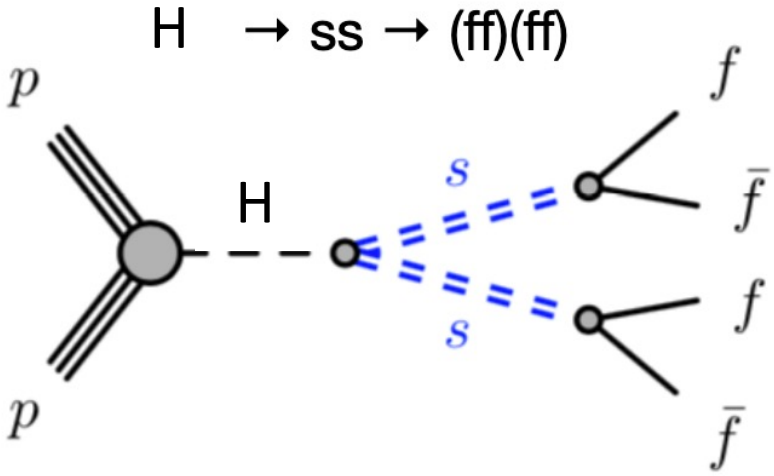




Long-lived: Higgs decays

arXiv:2107.04838



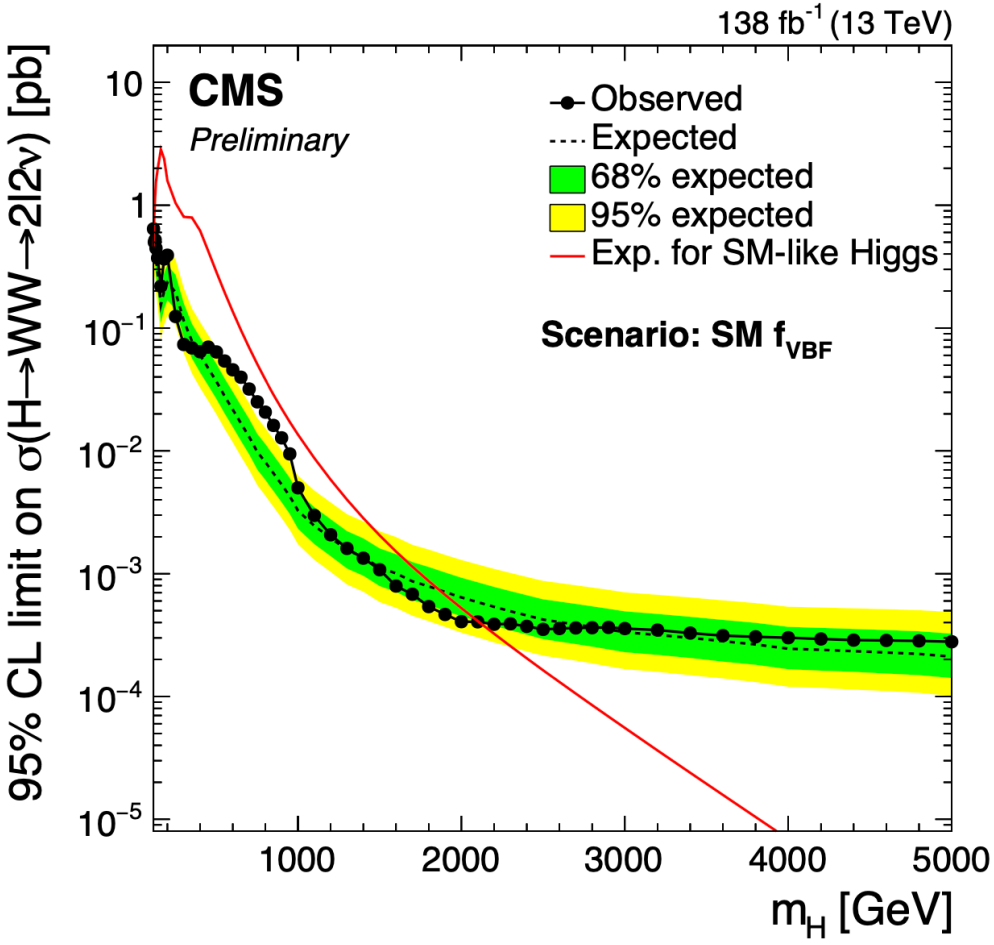


- Higgs decaying to long-lived scalars
  - Scalars decay to fermion final states in the muon chambers
- Resulting bounds are interpreted in context of LL decays
  - Missing energy trigger

High mass: H→WW

HIG-20-016

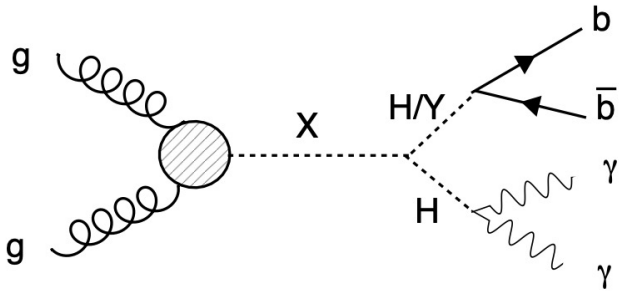
- Search for a heavy Higgs boson
  - Fully leptonic final state
- Optimized separately for VBF and gluon fusion production processes
- Search interpreted in BSM scenario (heavy Higgs, heavy EWK singlet state)
- Deviation of ~2σ around 500-900GeV



Resonant: X→HH→bbγγ

HIG-21-011

Search for a resonance decaying to two scalars

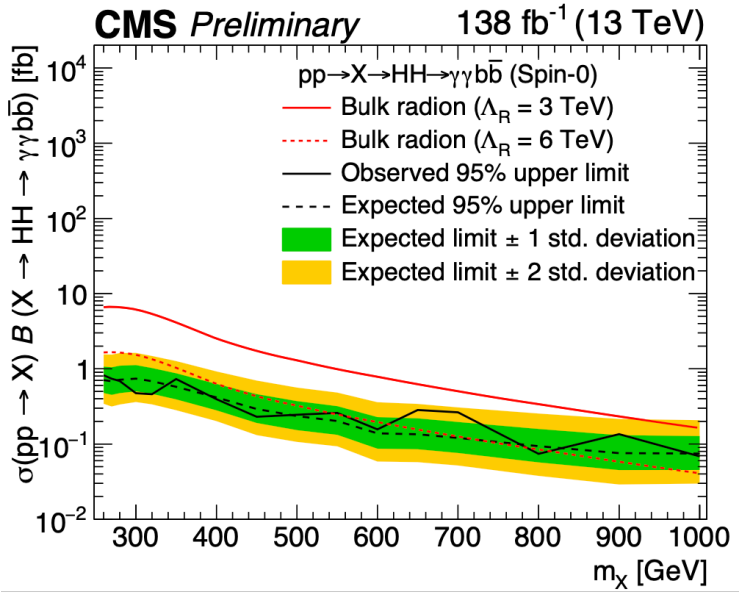


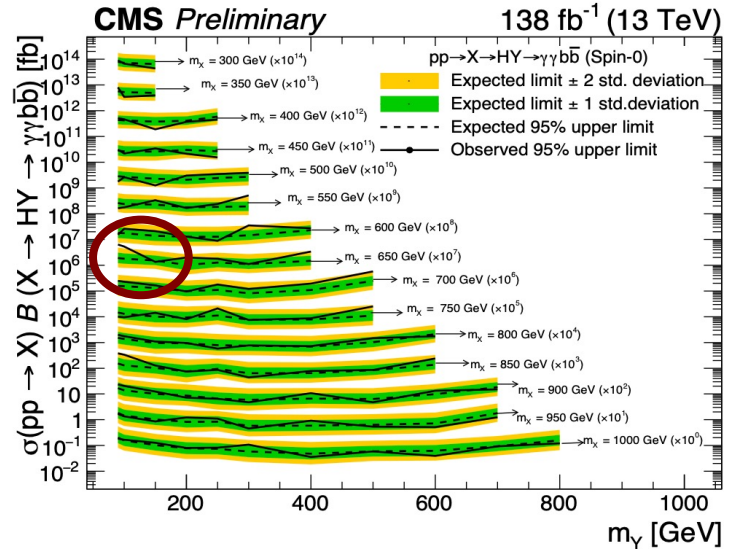
HH

- BDT to reject non-resonant γ(γ)+jets bkg
- b-jets tagged using DNN
- 2D fit of $m_{\gamma\gamma}$ vs m_{jj}
- No significant excess observed

HY

- Consider H→γγ and Y→bb
- Largest excess for m_Y=90GeV, m_X=650GeV
- Local(global) significance 3.8(2.8)σ



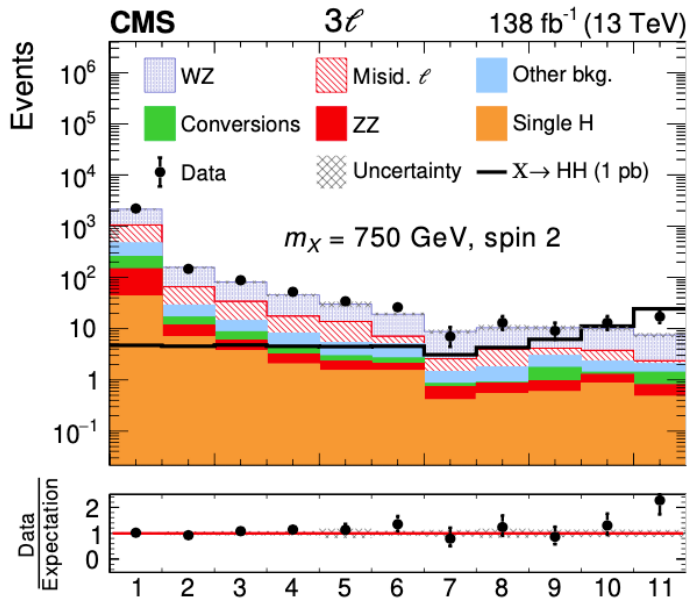


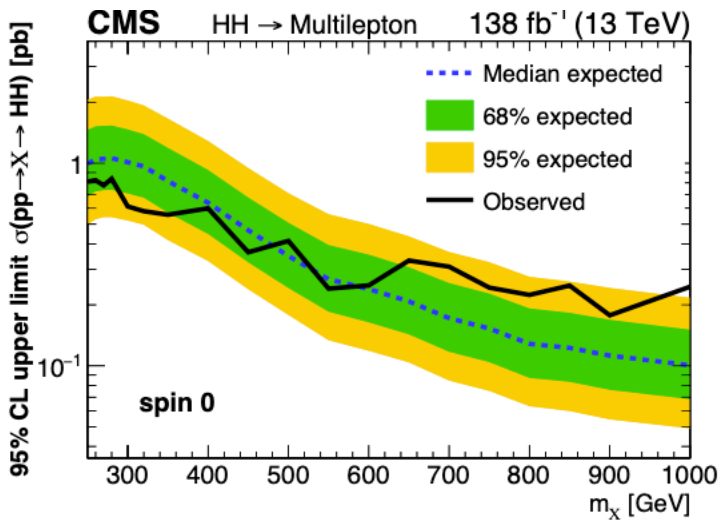
Resonant: X→HH→multileptons

arXiv:2206.10268

Search for resonant production

- Target decay modes: HH→4W/2W2τ/4τ (approx 7.7% of all HH decays)
- Split events depending on #light leptons, #τ_h in final state
- BDT to separate signal and bkg
- Data consistent with background-only hypothesis

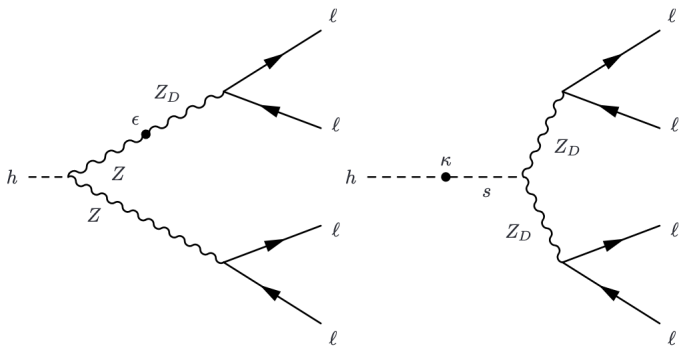


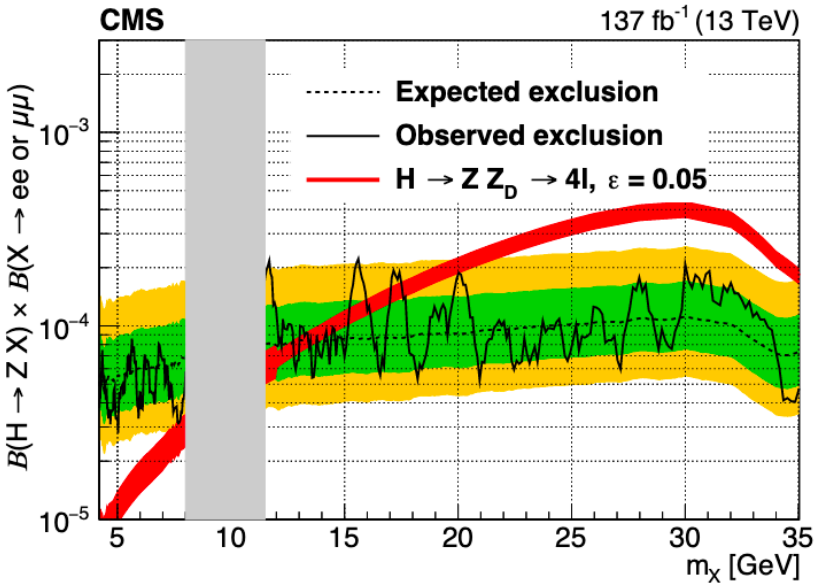


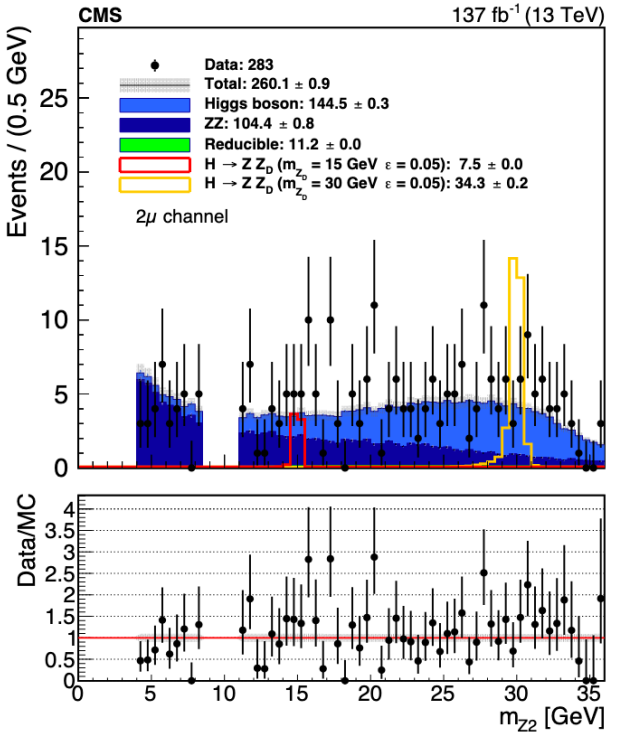
Low mass dilepton resonance

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



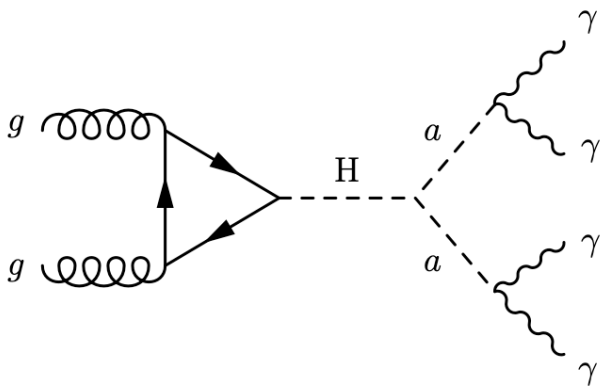


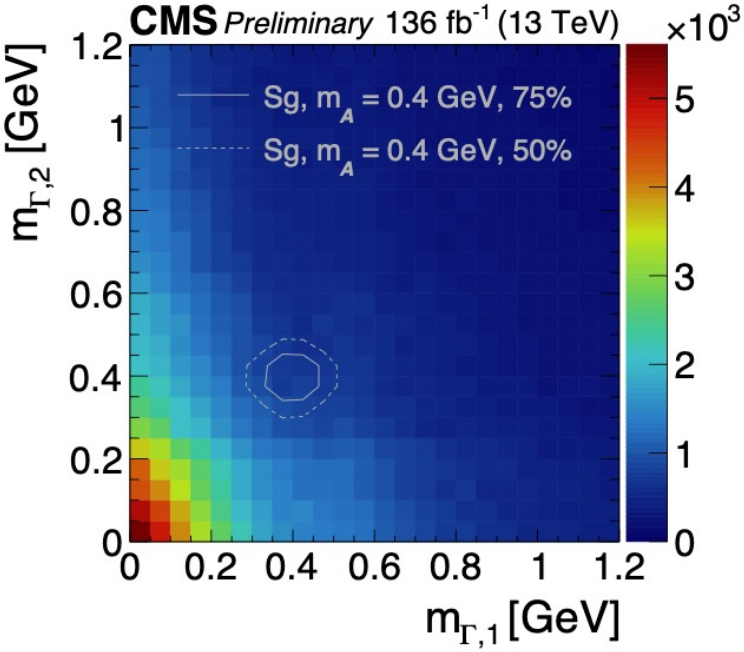


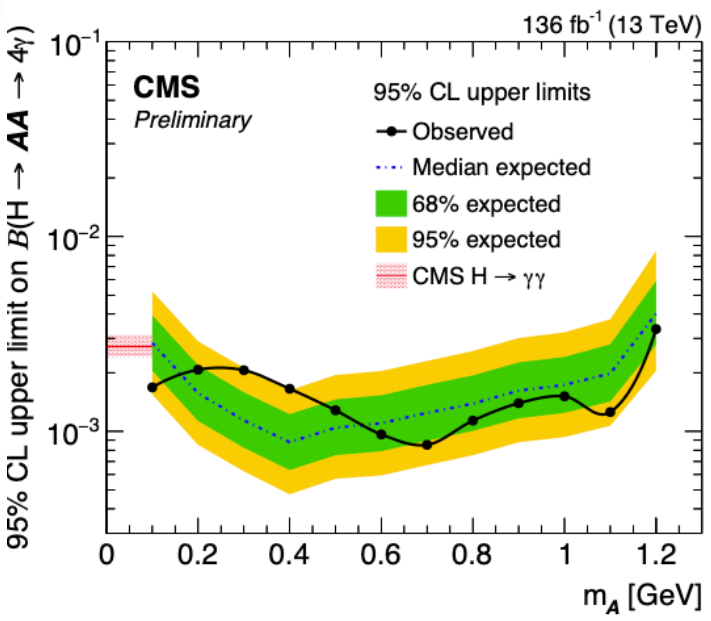
Exotic: H→AA→4γ

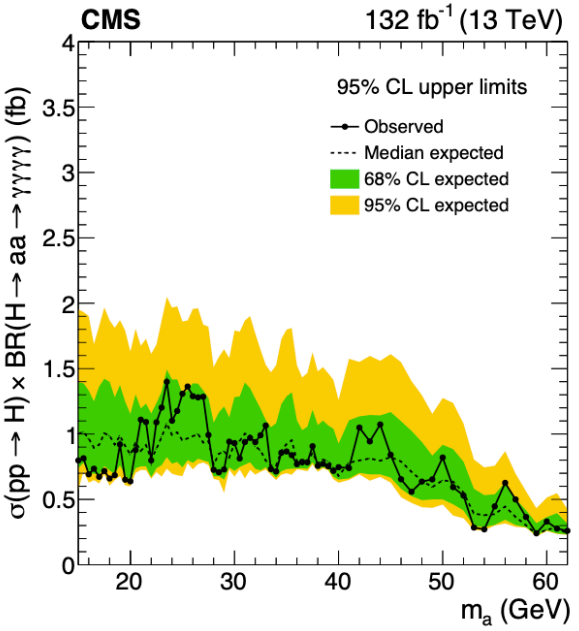
HIG-21-016, arXiv:2208.01469

- Exotic Higgs decay to light pseudo-scalar A
  - Upper limits ~20% to undetected states
  - Motivated in BSM extensions
  - Resolved and boosted topologies
- Model-independent search
  - Improves indirect constraints from BR(H→γγ)







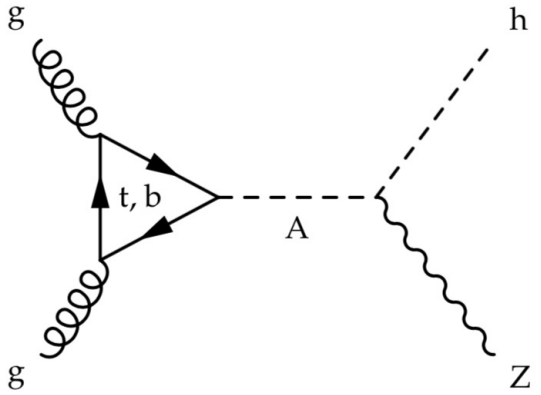


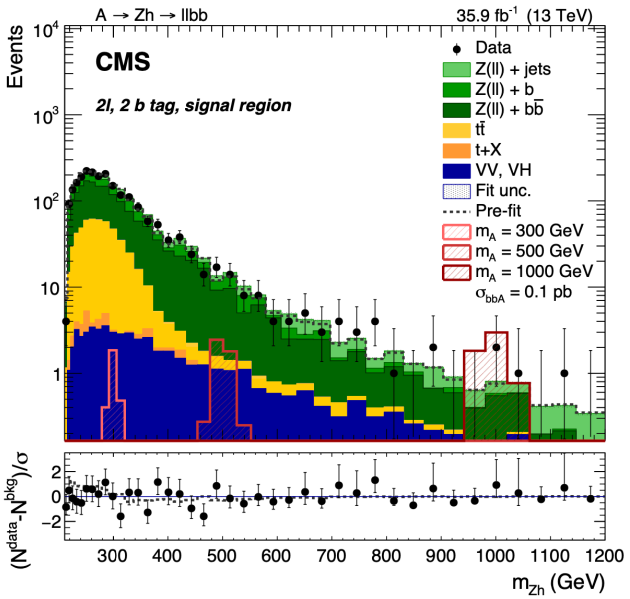
A→Z (ℓℓ)H(ττ,bb)

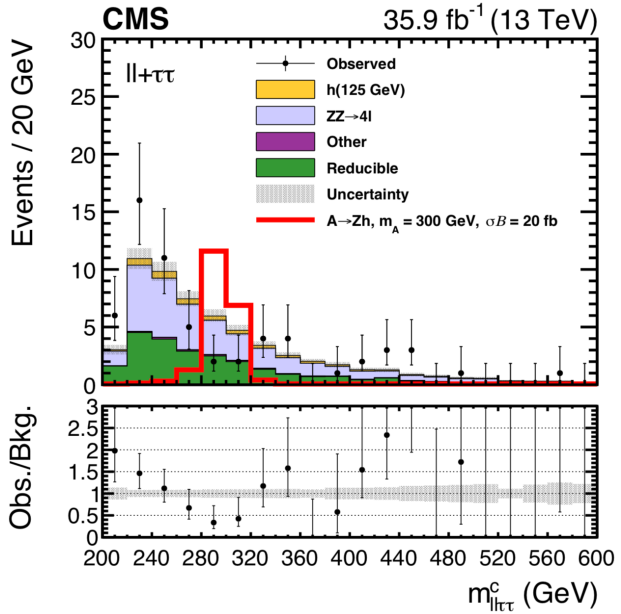
arXiv:1910.11634, arXiv:1903.00941

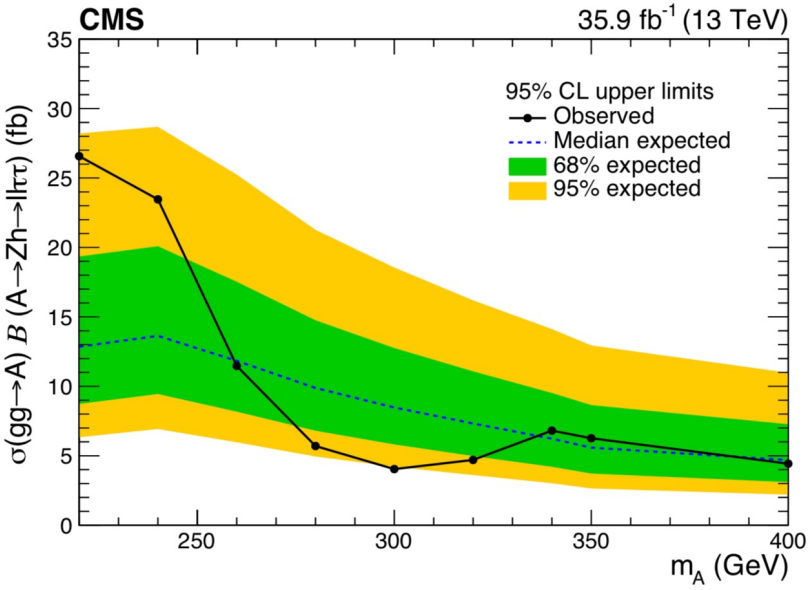
What if A is too light to decay to ttbar?

- MSSM: B(A→Zh)=1, low tanβ, m_A~200-350GeV
- Final state: Z(ℓℓ)h(ττ,bb)
- Reconstruct m_A with h_{125} constraint
- Results consistent with bkg expectations





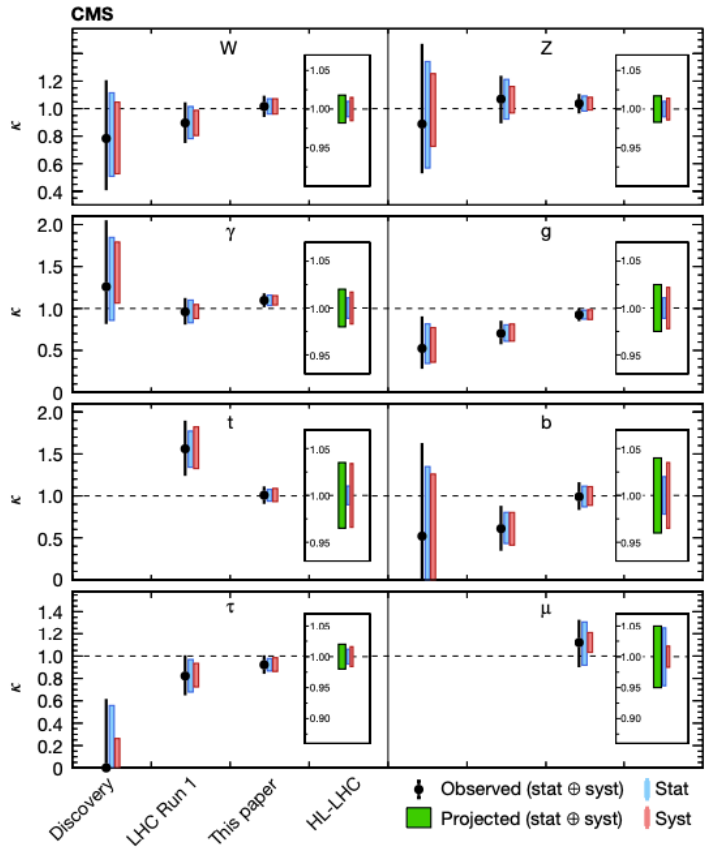


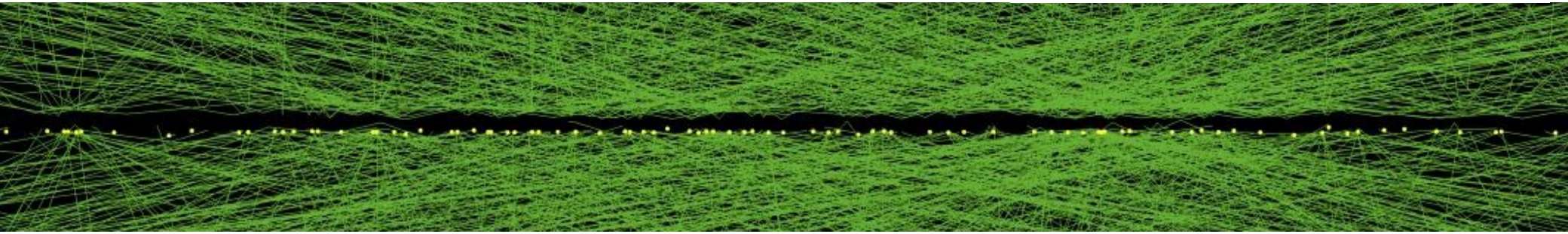


Looking ahead

Nature 607(2022)60

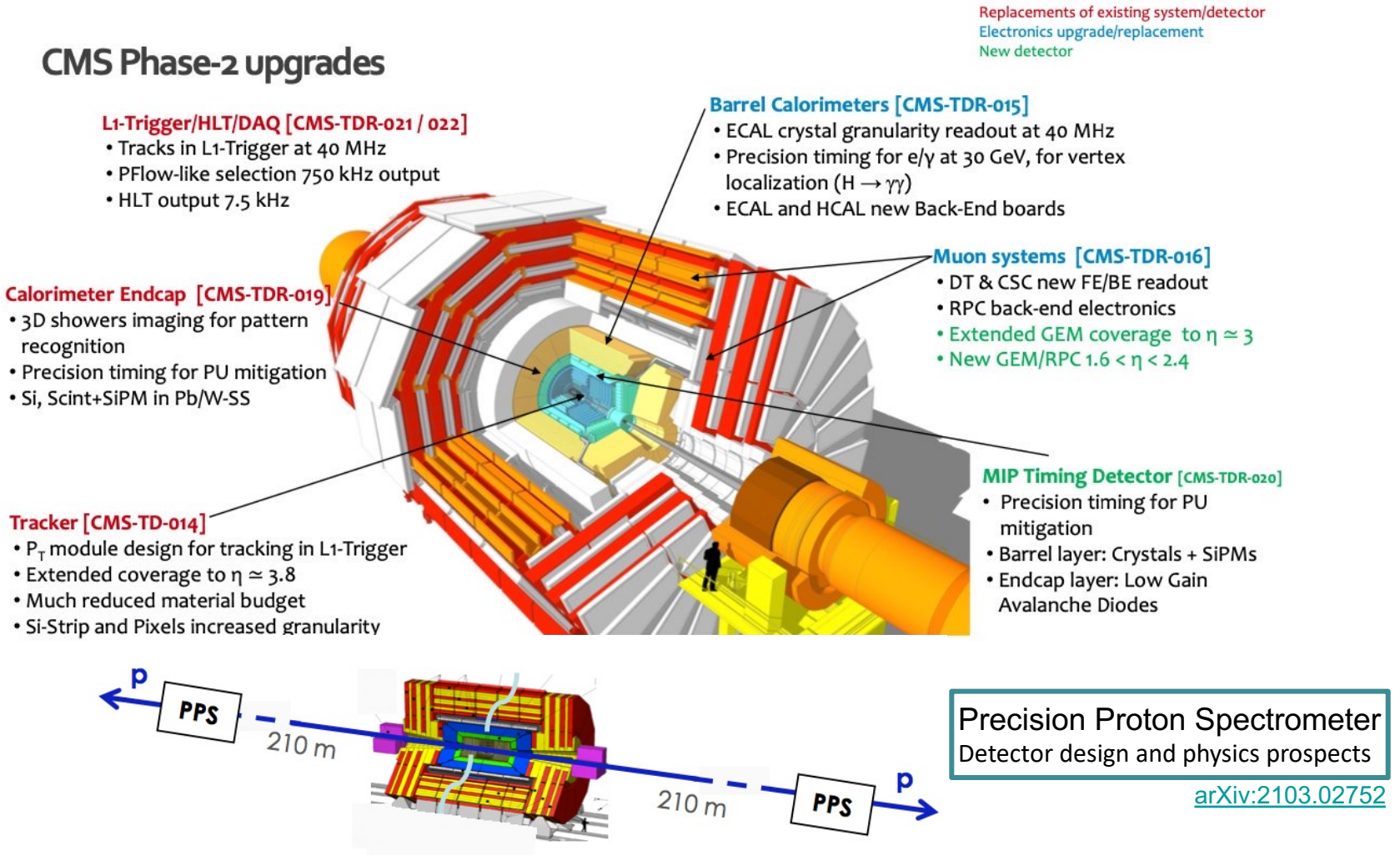
- Precision of measurements improved
- BSM scenarios may provide only small deviations
- More Higgs bosons expected in Run3 and HL-LHC
  - harsher experimental conditions
  - Improved/new detectors





Detector Upgrades

The HL-LHC will provide an integrated luminosity of 3000 fb^{-1} over 10 years of operation. It will present many technological challenges. Preparing new detectors and upgrading current ones.

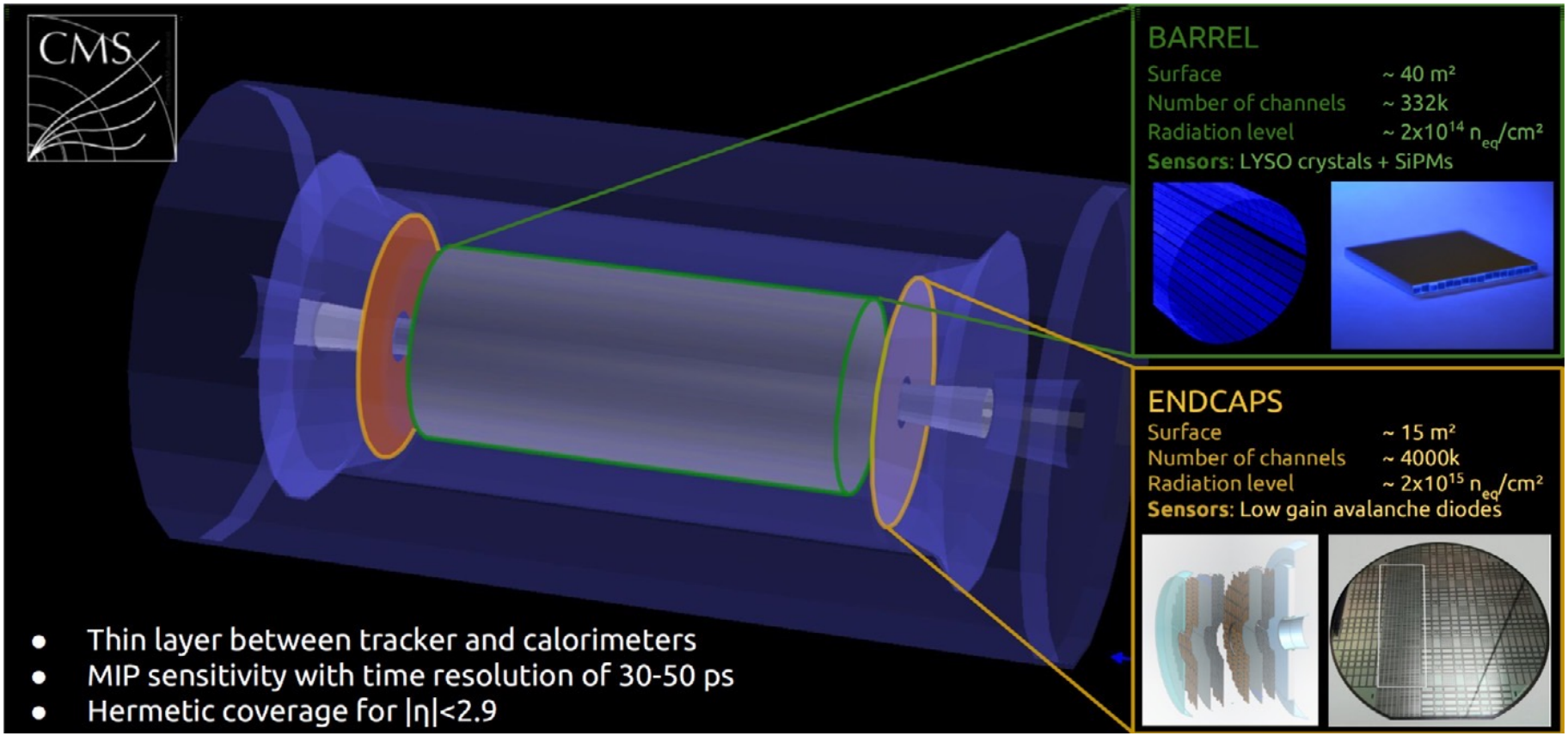


Precision Proton Spectrometer
Detector design and physics prospects
arXiv:2103.02752

Detector upgrades @ HL-LHC

CERN-CMS-TDR-020

- Timing detectors: a new paradigm in HEP for PU rejection
- Improve particle reconstruction/ID, reduce fake jet reconstruction
  - 10%-20% gain in S/B in many Higgs decay channels



Summary

- From discovery to precision
- Latest results on Higgs studies:
  - Properties, couplings, HH, BSM
  - Improved analysis techniques and new tools crucial to enhance sensitivity beyond statistics
  - No clear signal, a few deviations
- Great progress in the first 10 years
- Large samples to be collected
  - Run3 started, preparations for HL-LHC ongoing

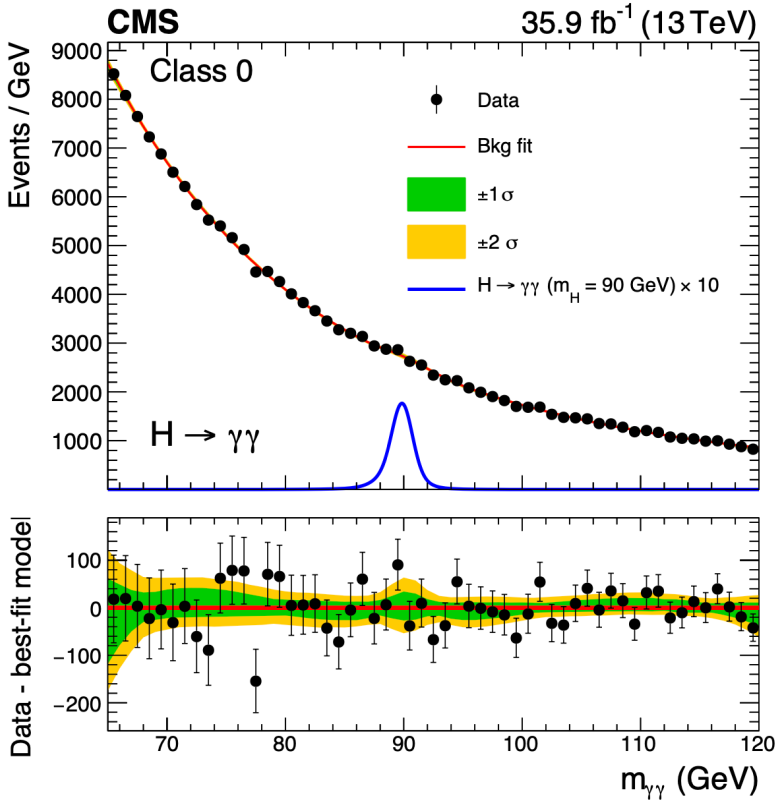
⇒ Rare processes and precise measurements as probe of New Physics

backup

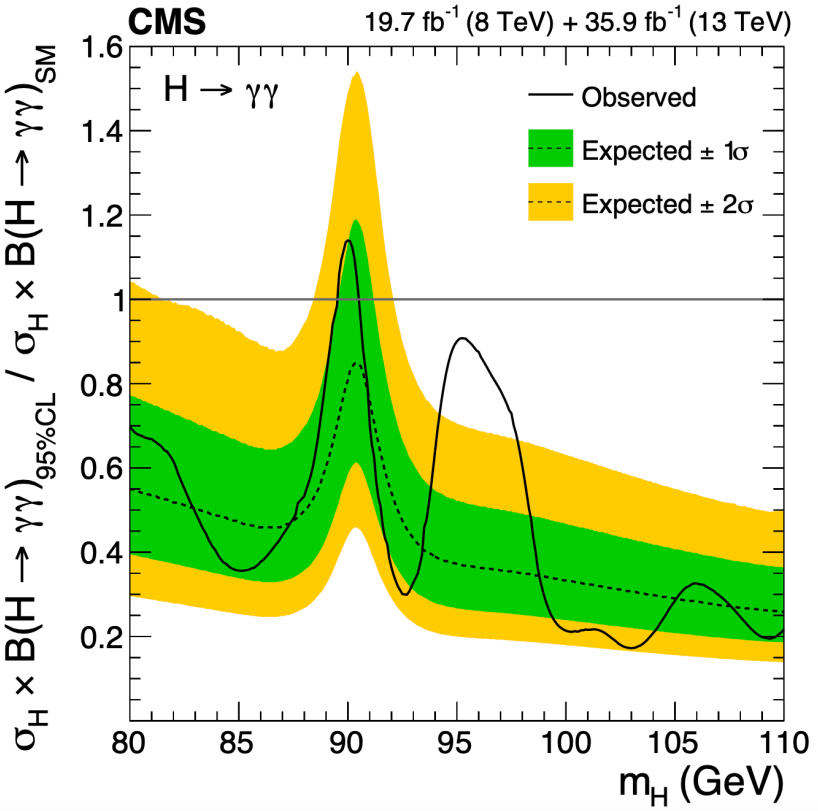
Higgs to diphotons

arXiv:1811.08459

- Search for low-mass H→γγ decay
  - Extended Higgs models
  - Clean final state, mass reconstructed w/high precision

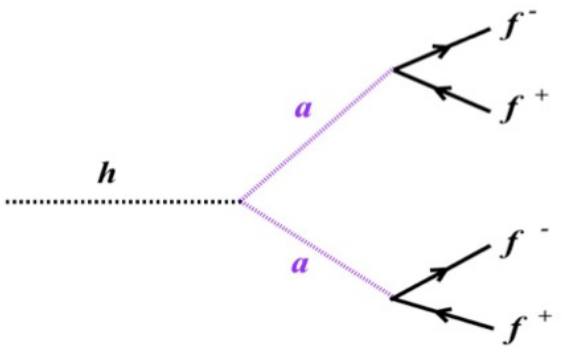


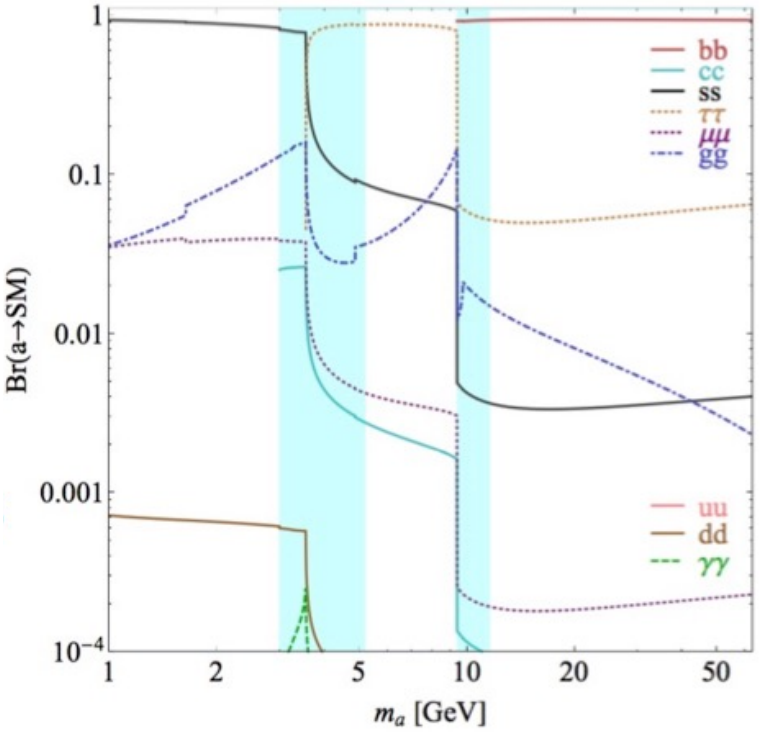
- Largest excess for m_H=95GeV
- Local(global) significance 2.8(1.3)σ



non-SM Higgs decay: h→aa→4X

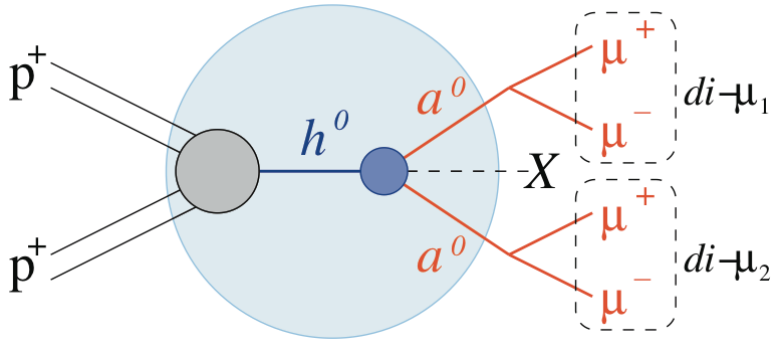
- Standard search for light (pseudo)- scalar Higgs with $m_a < m_h/2$
  - generic prediction of BSM theories (extended Higgs sector, NMSSM, etc)
  - Final states go to fermions (b, τ, μ, …)
  - BR depends on boson mass, model parameters



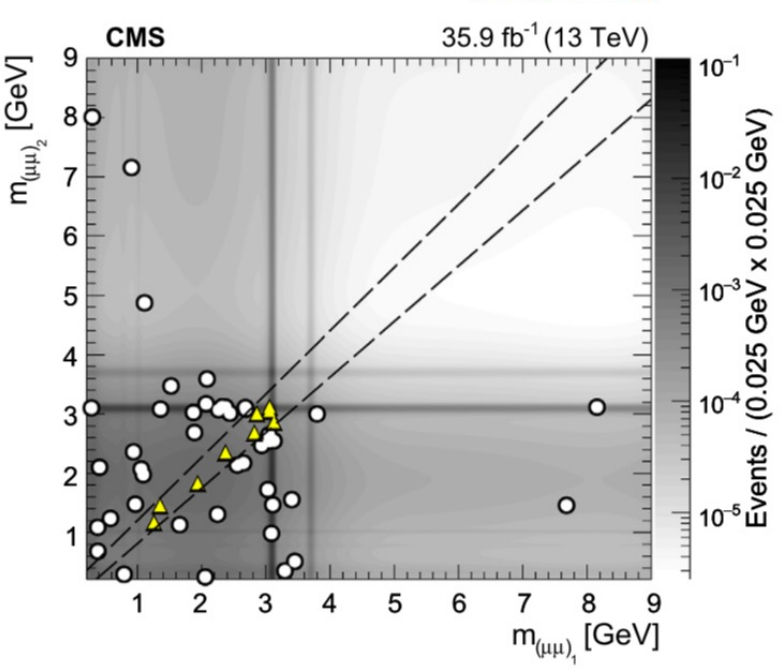


non-SM Higgs decay: h→aa→4μ

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→2a+X→4μ+X
  - Require two dimuon pairs with consistent masses
  - Signal region: 9 event (~8±2 bkg)
  - Limits on production rates, benchmark models



NMSSM and Dark SUSY Limits

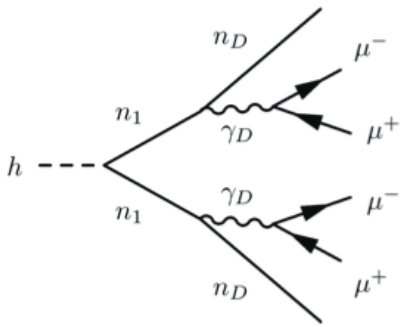
PLB 726(2013)564, arXiv:1506.00424

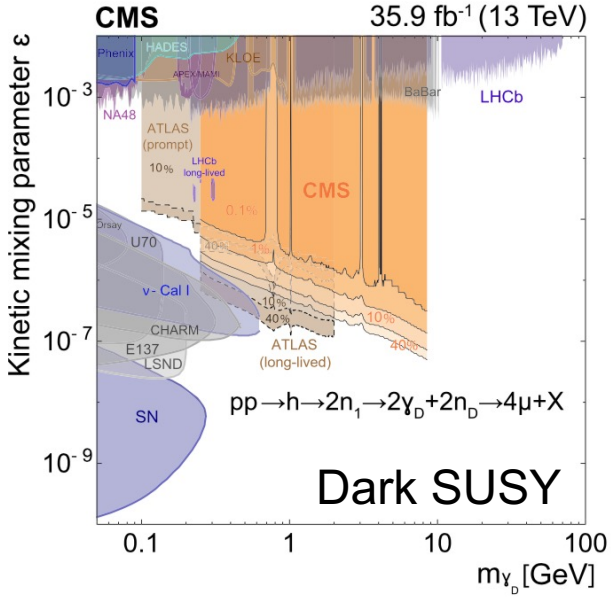
Results interpreted in NMSSM and dark SUSY

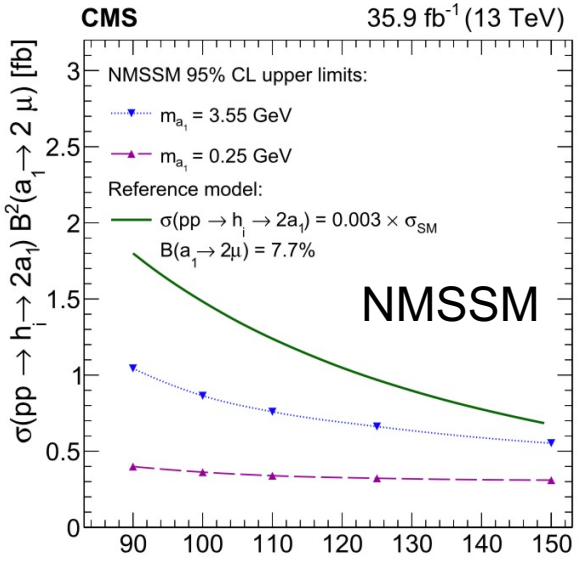
- Dark SUSY: h decay to pair of neutralinos (n_1): LSP

$n_1 \rightarrow n_D \gamma_D$ decays

- $\gamma_D \rightarrow \mu\mu$
- n_D → invisible





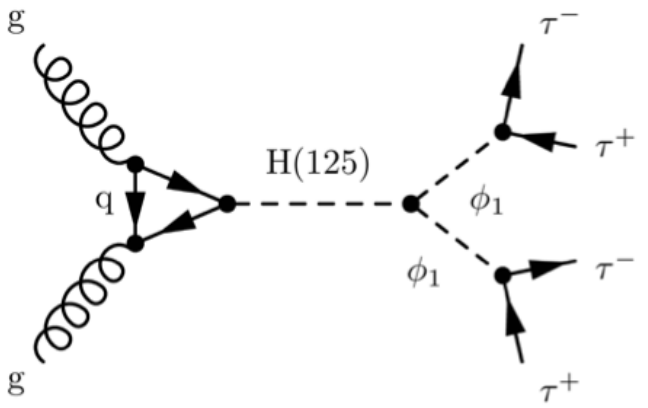


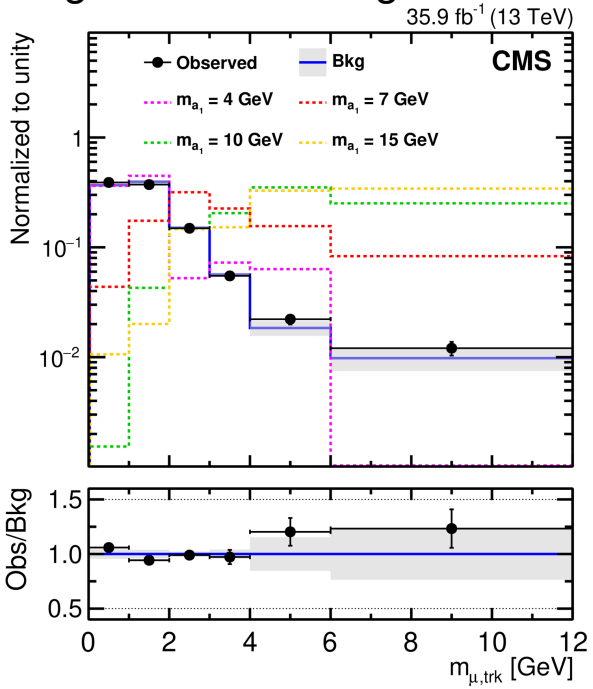
- NMSSM: Extend MSSM by adding a complex singlet field (1 CP-even+1 CP-odd boson)
- NMSSM: $h_{1,2} \rightarrow 2a_1$; $a_1 \rightarrow 2\mu$
- Compare to SM Higgs cross section

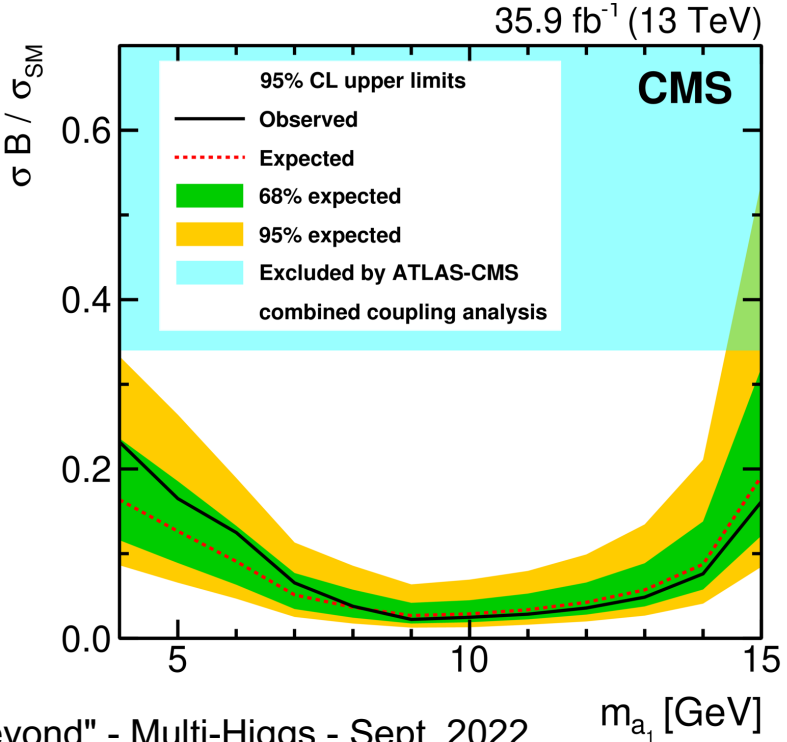
non-SM Higgs decay: $H_{125} \rightarrow 2h(a) \rightarrow 4\tau$

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

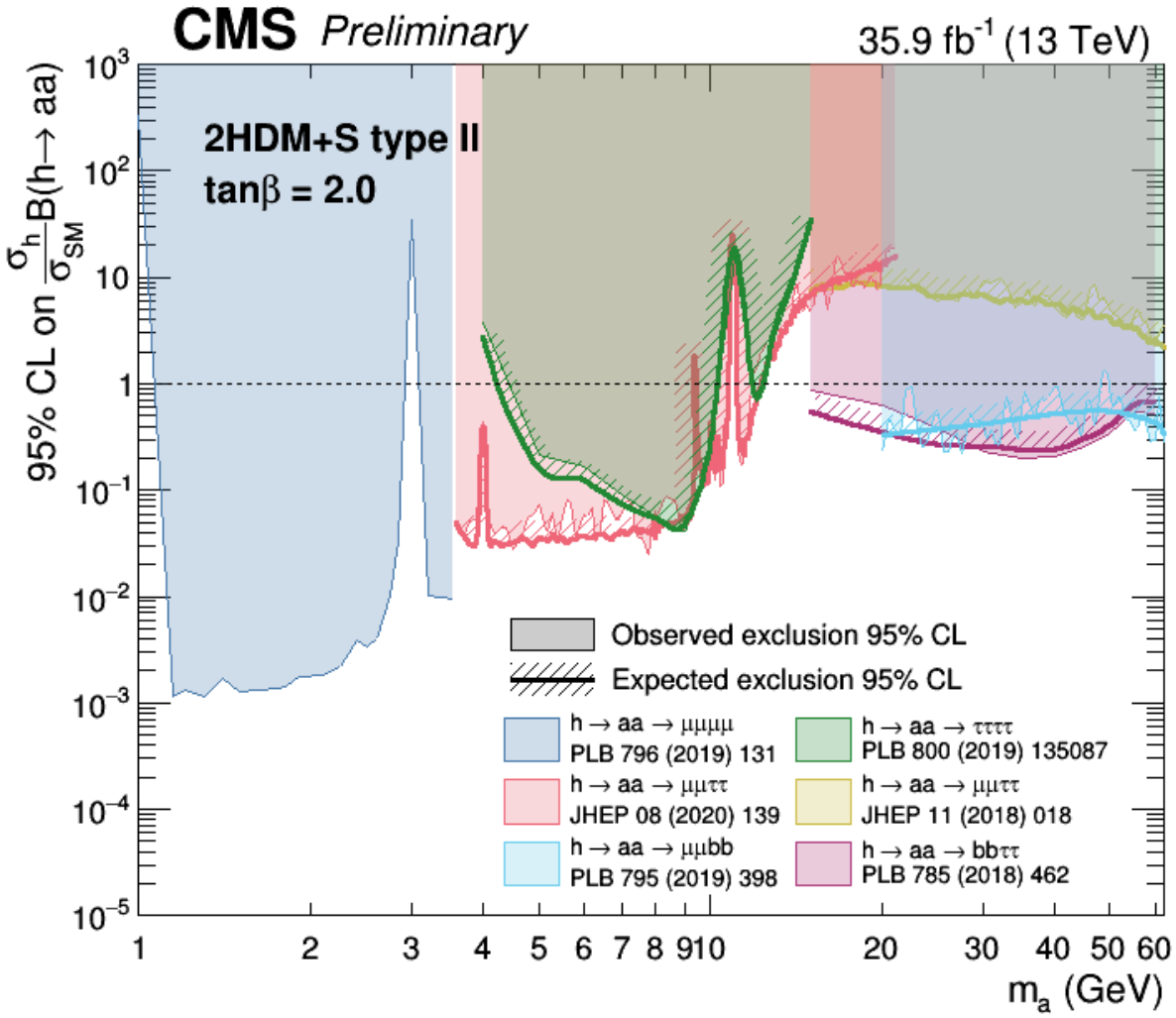
- Search for very light Higgs in NMSSM
  - H(125)⟶light pseudoscalar (ϕ) bosons
  - One ϕ decays to a τ pair, the other to τ/μ pair
- Reconstruct μ-track invar. mass (m_1,m_2)
  - SS dimuon sample (removes DY)
  - bin in 2-dim distribution, fit signal and bkg
  - QCD bkg from control region







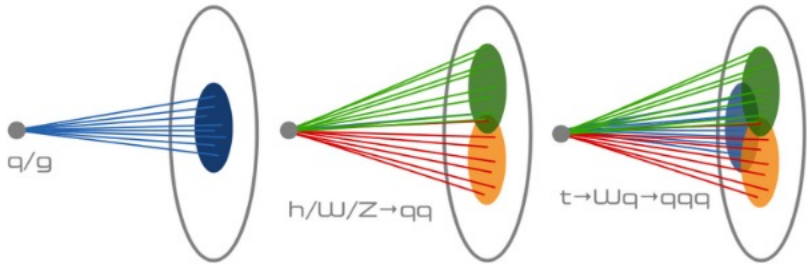
Summary of Higgs exotic decays

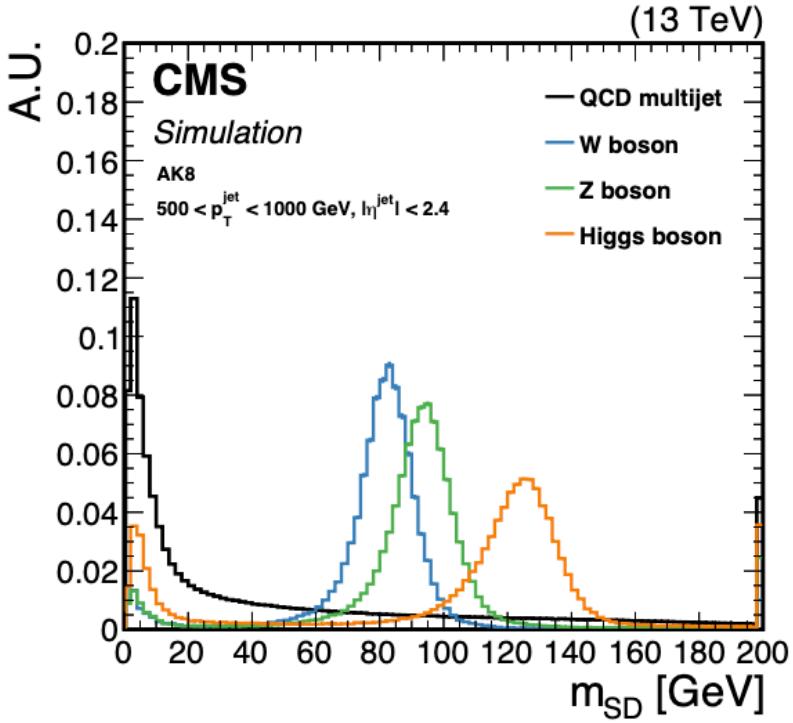


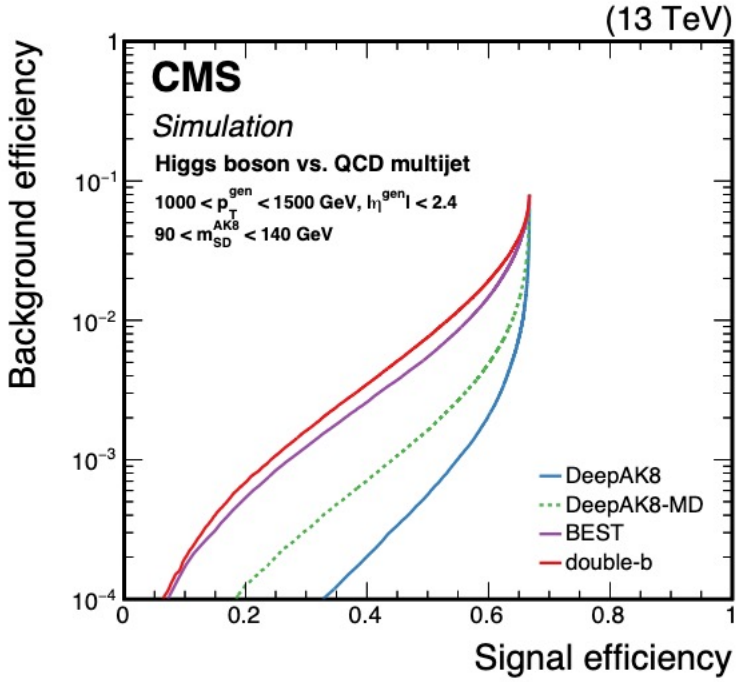
Boosted objects

arXiv:2204.08262

- Searches feature high-p_T W,Z,H bosons and/or top quarks
- At high p_T decay products merge into one large-radius jet
  - bkg rejection ~20-200 for p_T=1-1.5TeV
  - Factor of ~10 gain with DNN







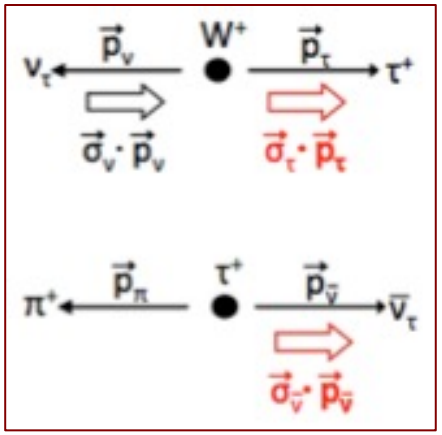
Looking at tau decays

CMS-HIG-12-052, arXiv:1903.04560

Low H^+ mass:

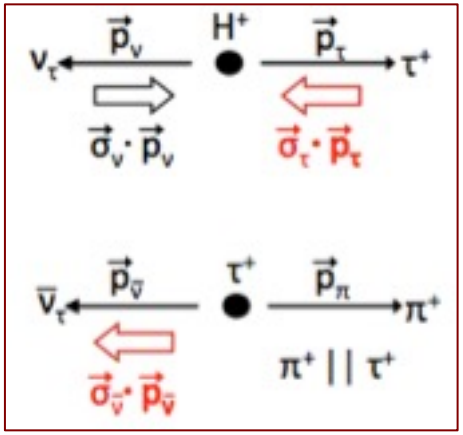
- Use R variable in the limit extraction: binned maximum-likelihood fit
- Tau fake component is data-driven, includes uncertainties

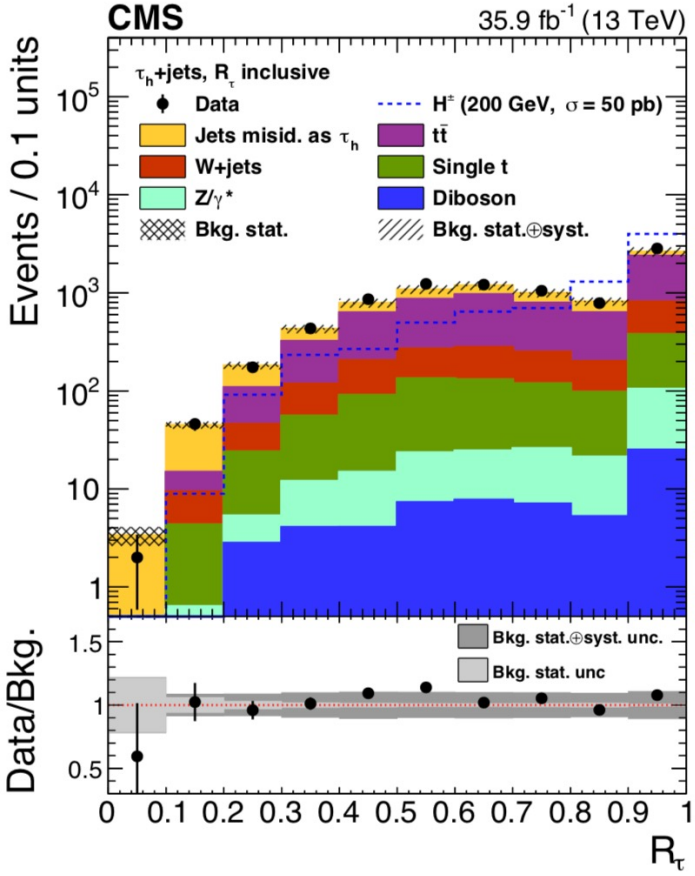
SM



vs

BSM



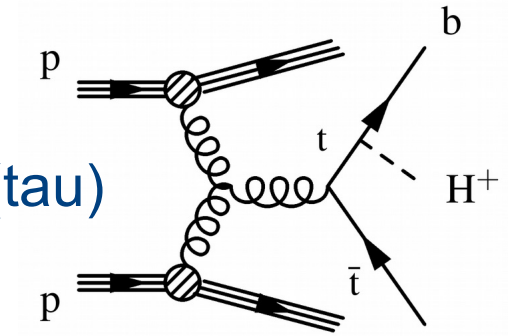


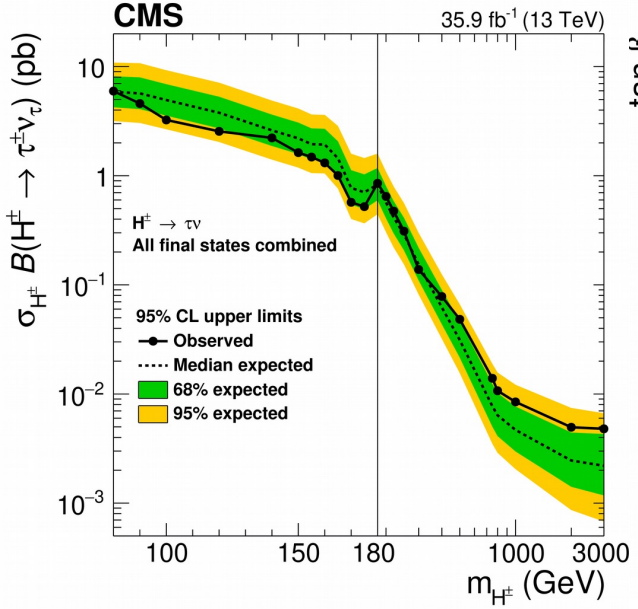
Charged Higgs: $H^+ \to \tau\nu$

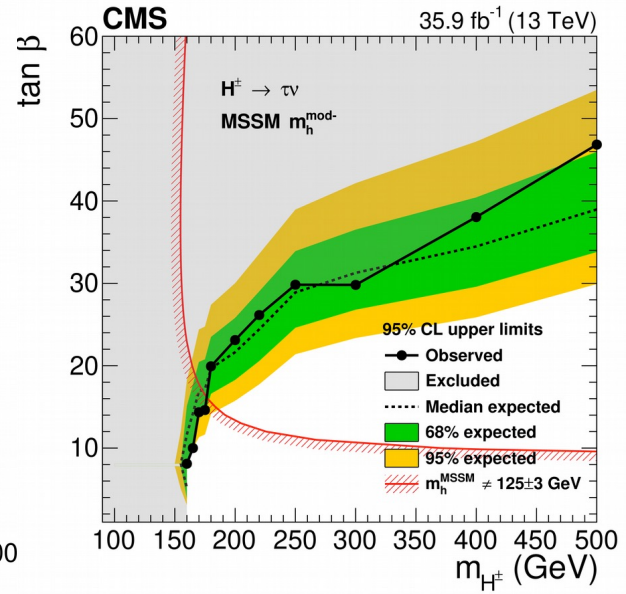
arXiv:1903.04560

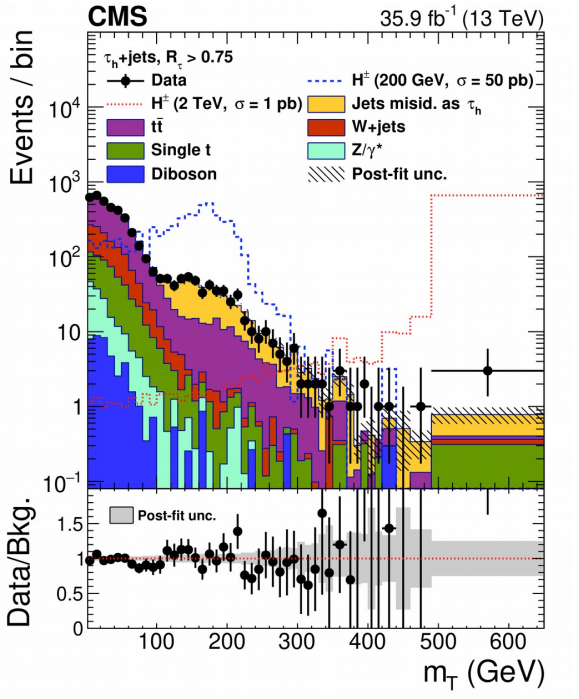
MSSM, high tanβ

- Final states: τ+jets, τ+ℓℓ, 0τ+ℓℓ
- 36 categories: incl. #jets, polarization $R=p_T(tk)/p_T(tau)$
- Cross section limits: 80-3000GeV







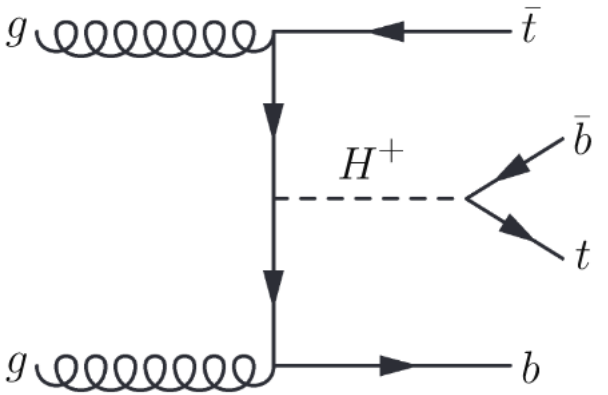


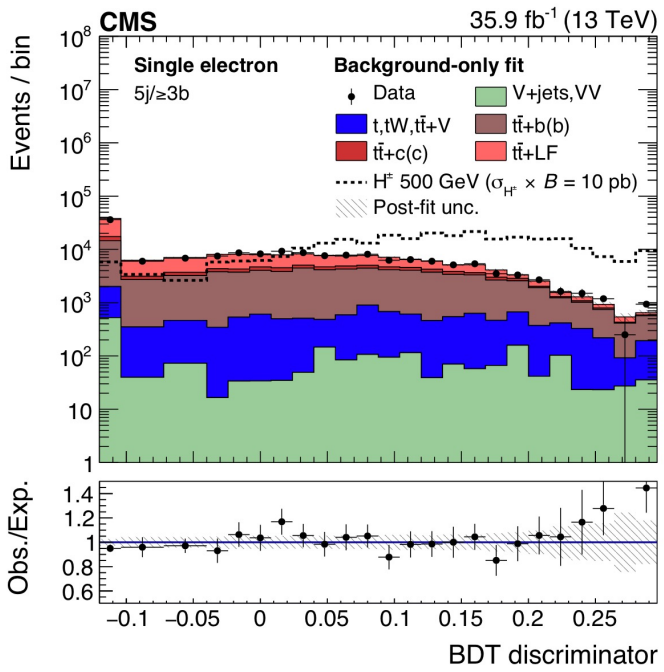
Charged Higgs: $H^+ \to tb$

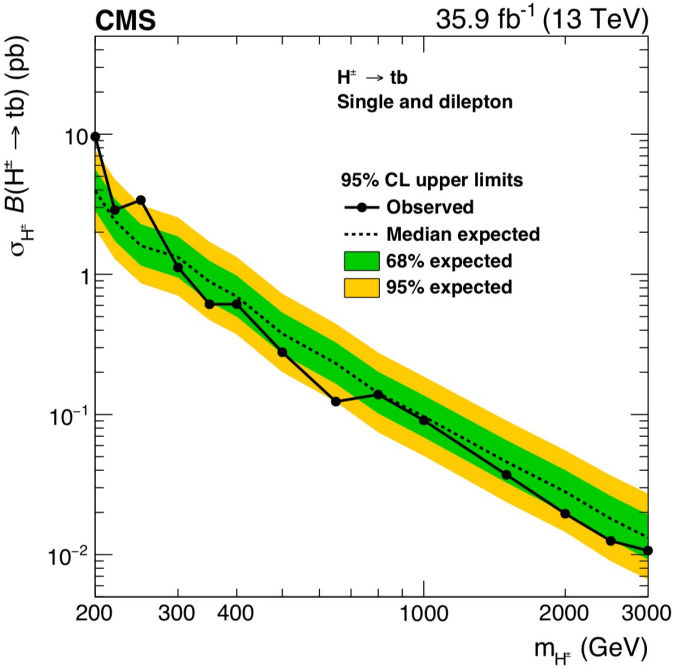
arXiv:1908.09206, arXiv:2102.10076

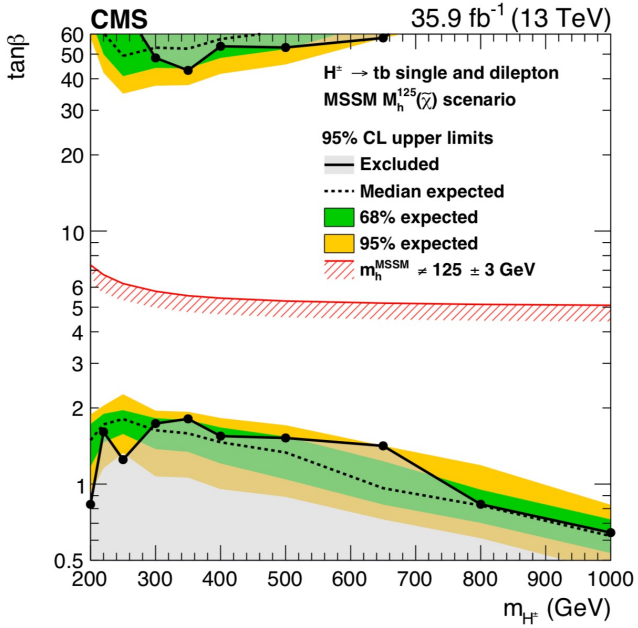
MSSM, low tanβ

- Final states: 1ℓ and 2ℓ
- Categories (incl. #jets, #bjets)
- Discriminant vs ttbar (BDT and DNN)
- Mass range: 200-3000 GeV





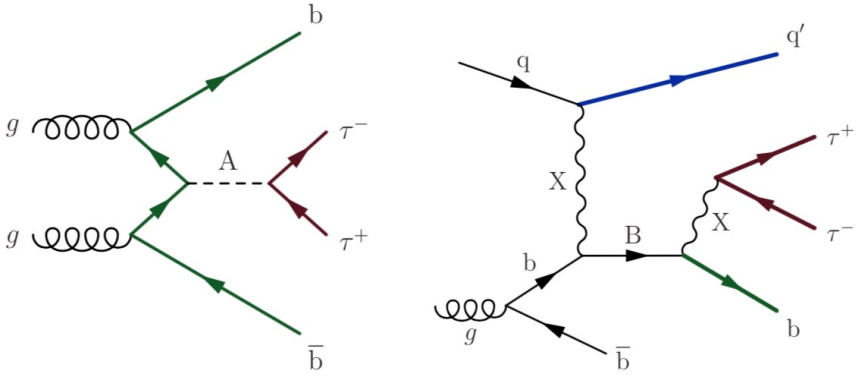


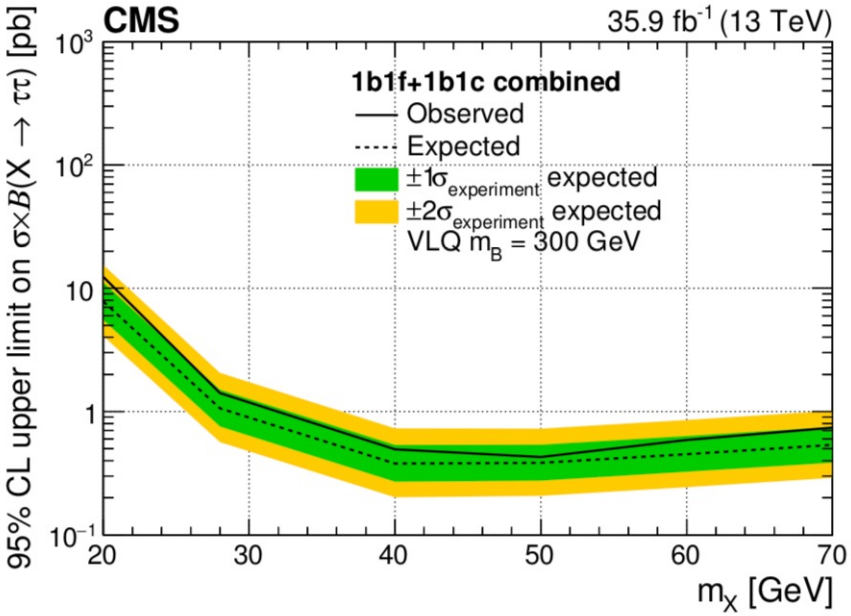


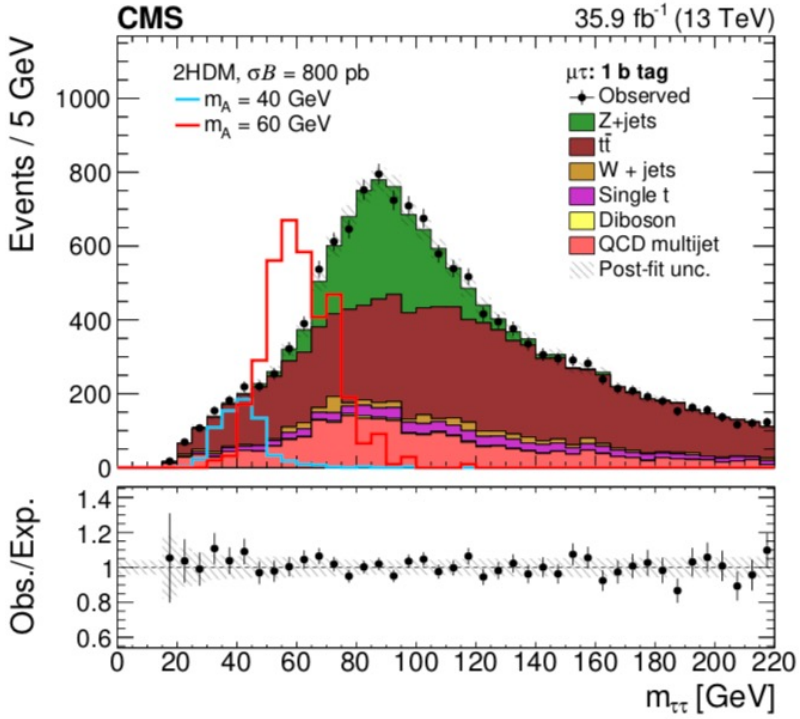
Low mass Higgs: a(→ττ)bb

arXiv:1511.03610, JHEP05(2019)210

- Low mass Higgs in the NMSSM
- Low mass pseudo-scalar ($a_1 \to \tau\tau$) in association with bbar: $a_1 bb \to \tau\tau$ bb
- Similar strategy to $H \to \tau\tau$
- Search for a_1 masses below Z mass
- No evidence for signal
- Set limits: σxB~20-0.3 pb







Heavy Higgs: H→ttbar

arXiv:1908.01115

- MSSM, low tanβ, m(H)>2 x m(top)
- Search for A/H→ttbar
- Strong interference with SM ttbar
- ℓ+jets and ℓℓ final states
- Kinematic reconstruction
  - m(ttbar) and cosθ* (lepton angle in ttbar frame)