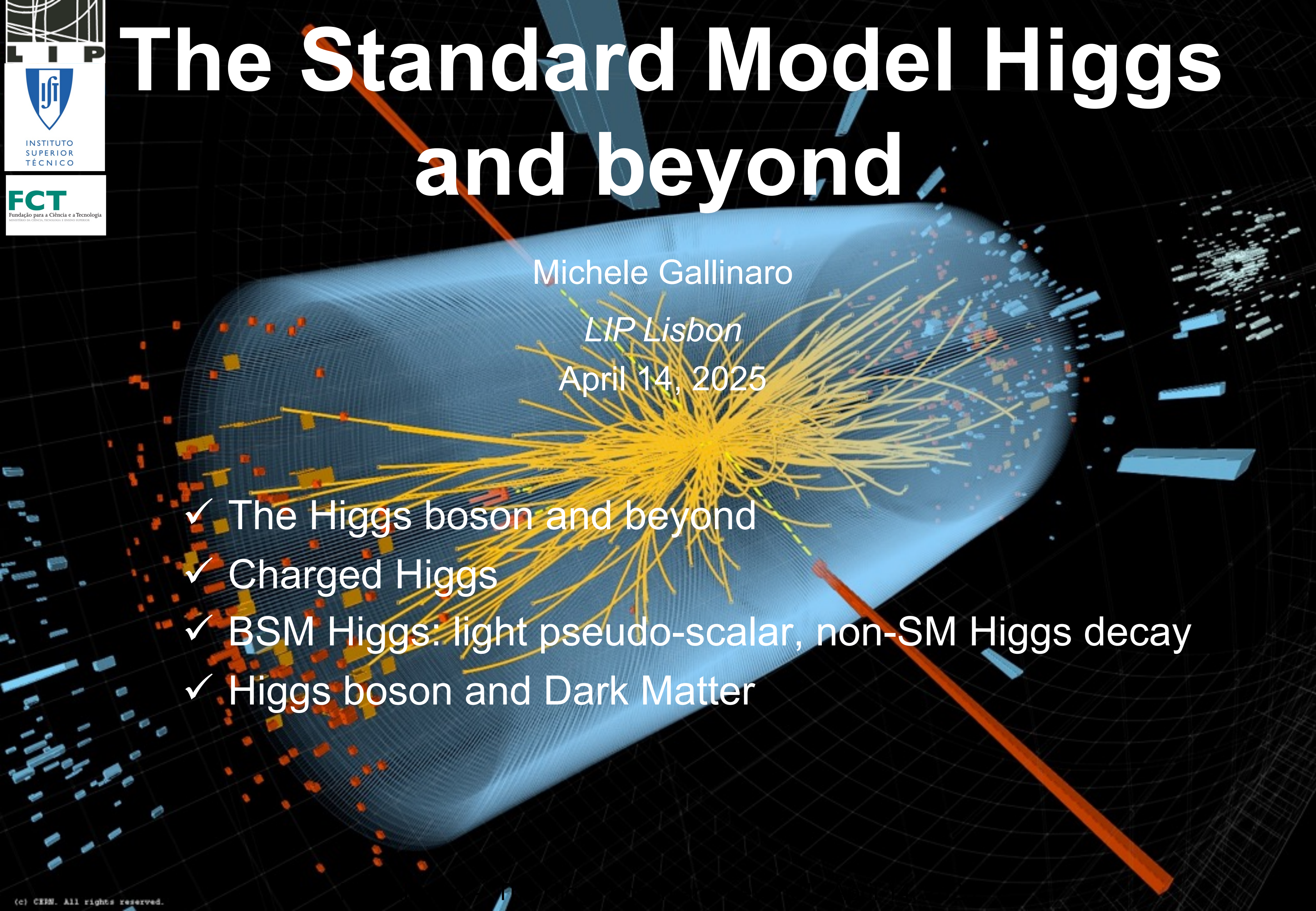
The Standard Model Higgs and beyond

Michele Gallinaro

LIP Lisbon

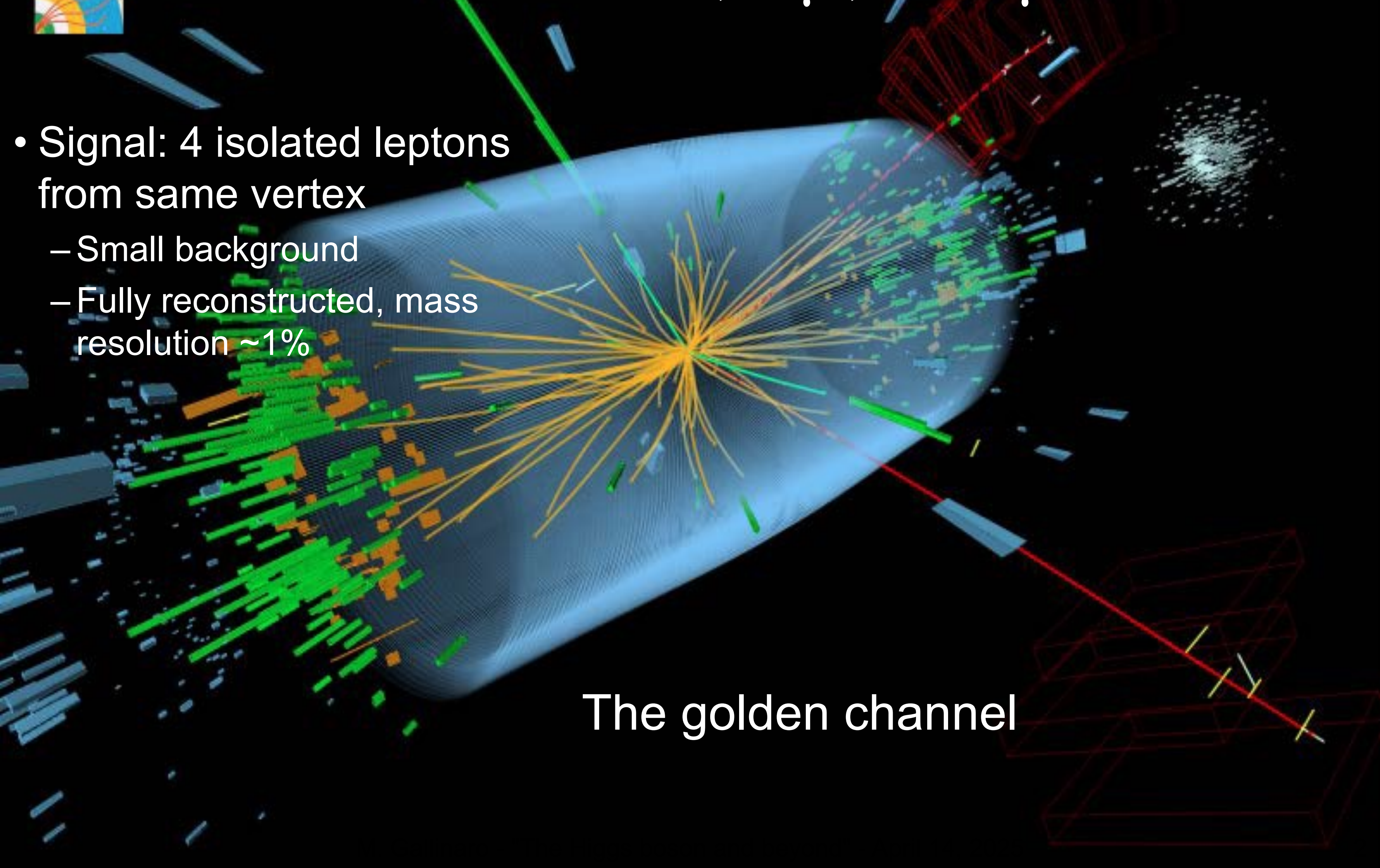
April 14, 2025

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



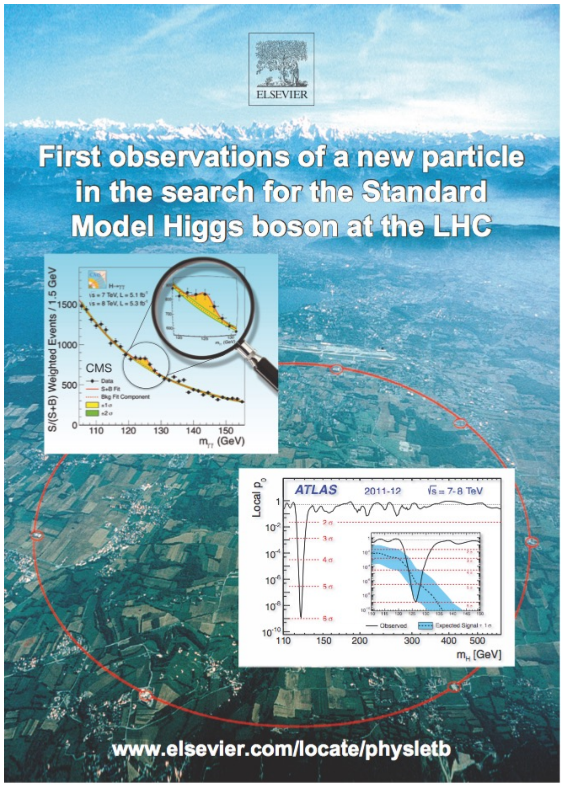
$H \rightarrow ZZ \rightarrow 4e,\ 4\mu,\ 2e2\mu$

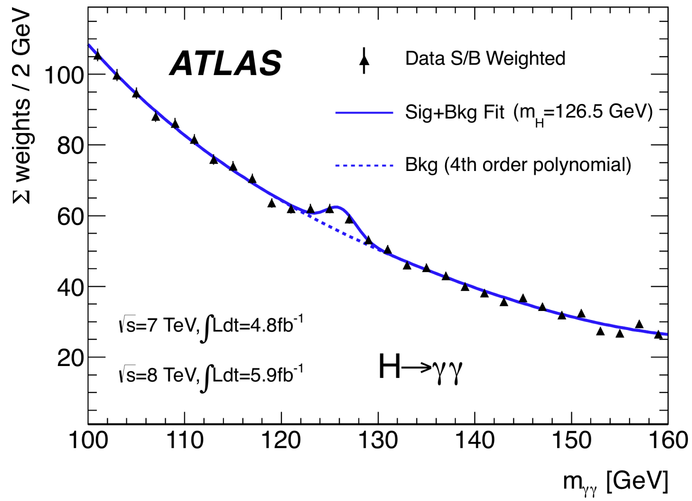
- Signal: 4 isolated leptons from same vertex
  - Small background
  - Fully reconstructed, mass resolution ~1%

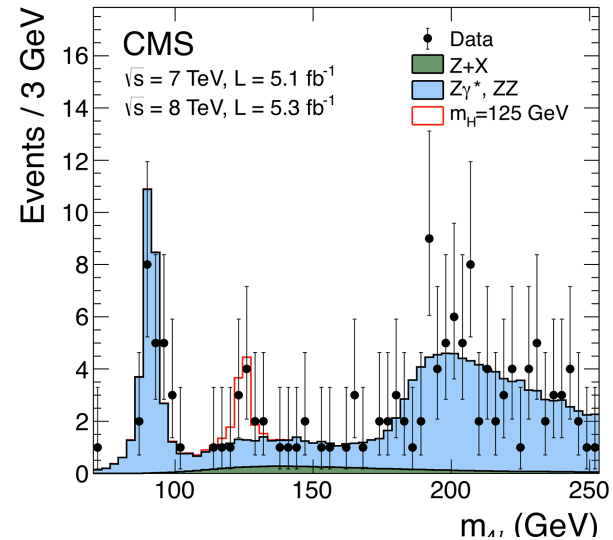


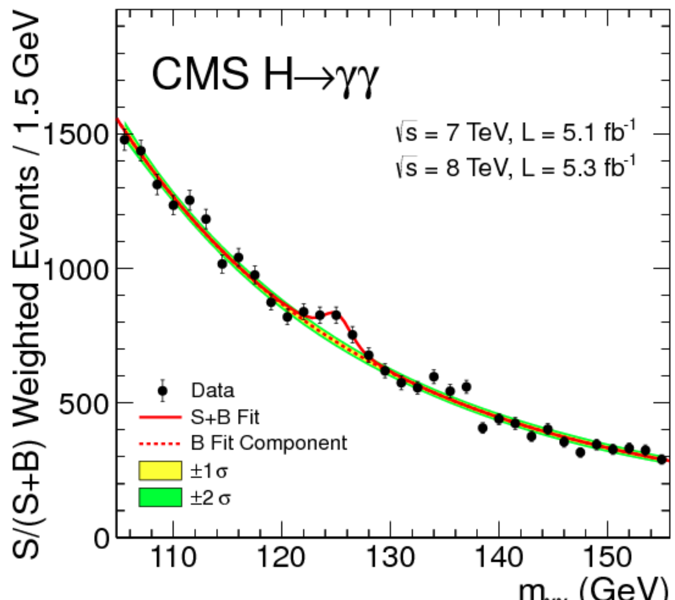
The golden channel

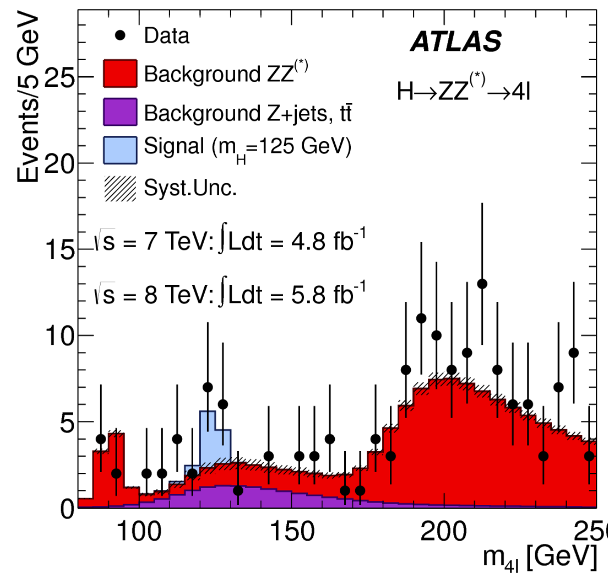
July 4th, 2012: A Higgs boson







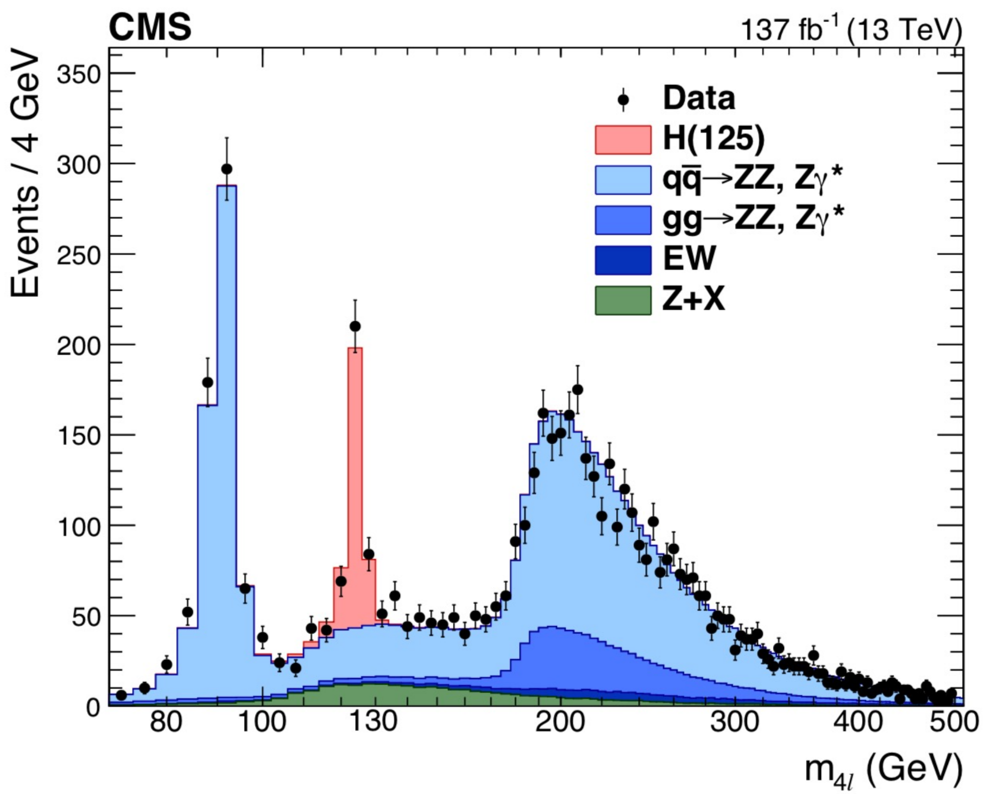


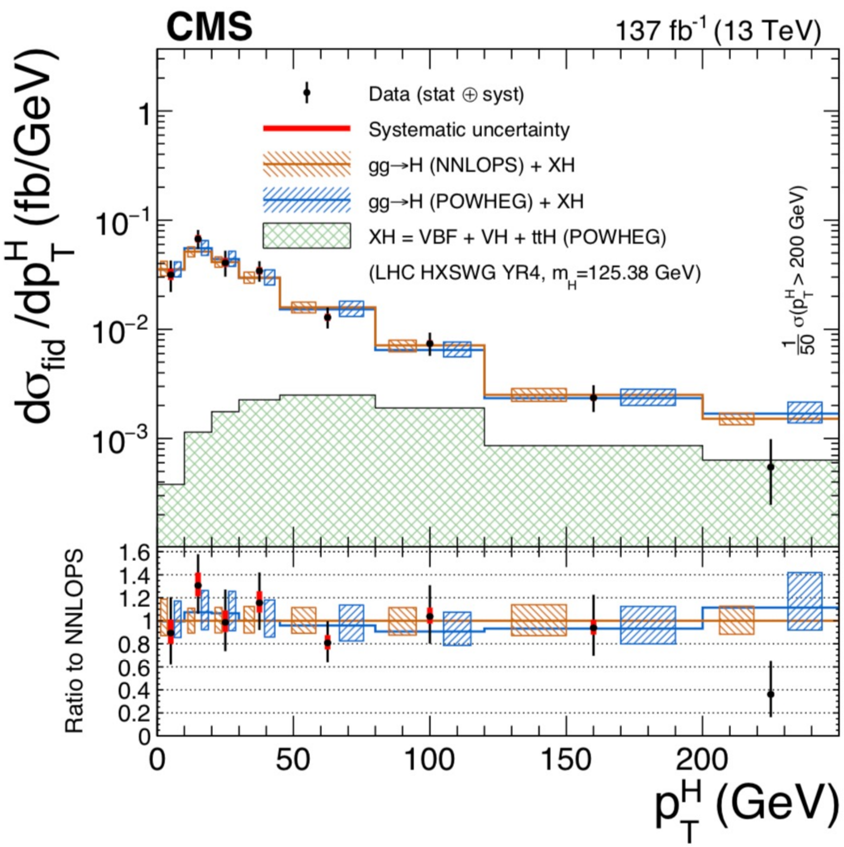


Higgs and ZZ

EPJC 81(2021)200, arXiv:2103.04956

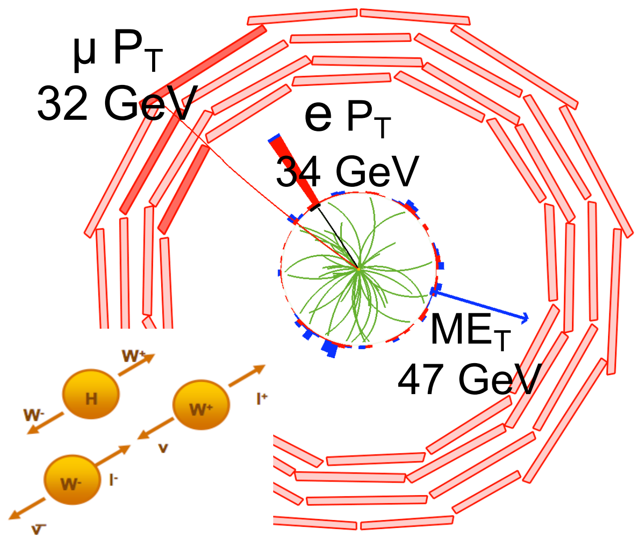
- Study of SM ZZ production, and Higgs decay to ZZ
  - ~98% of Run2 data
- SM cross section measured with 3% precision

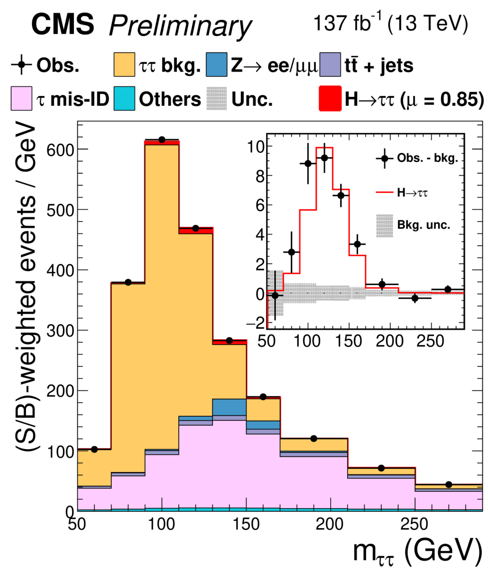


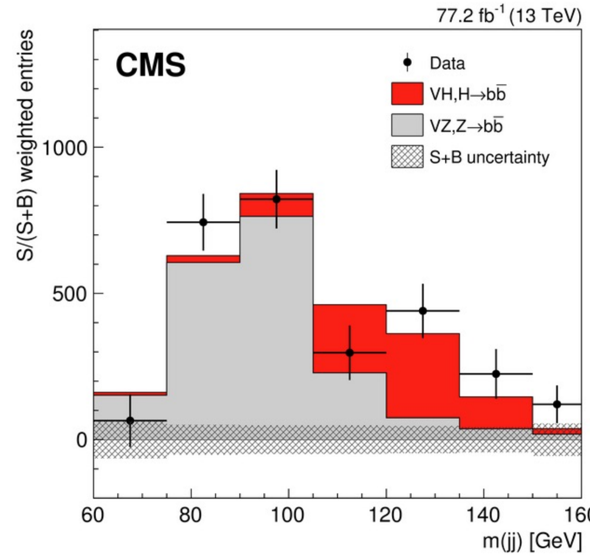


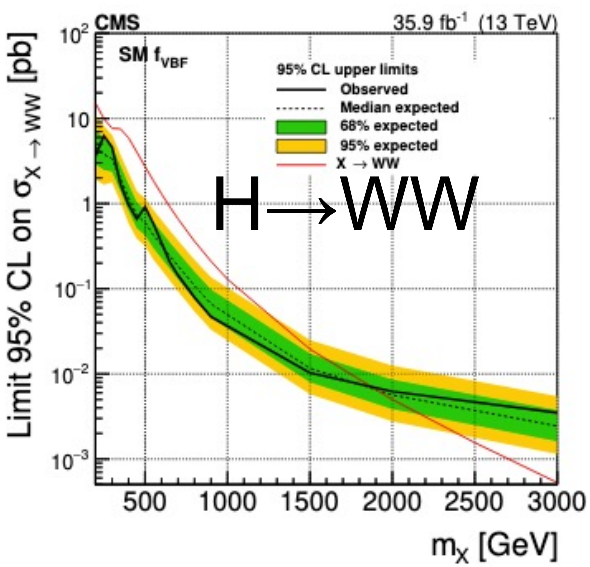
Low mass-resolution channels

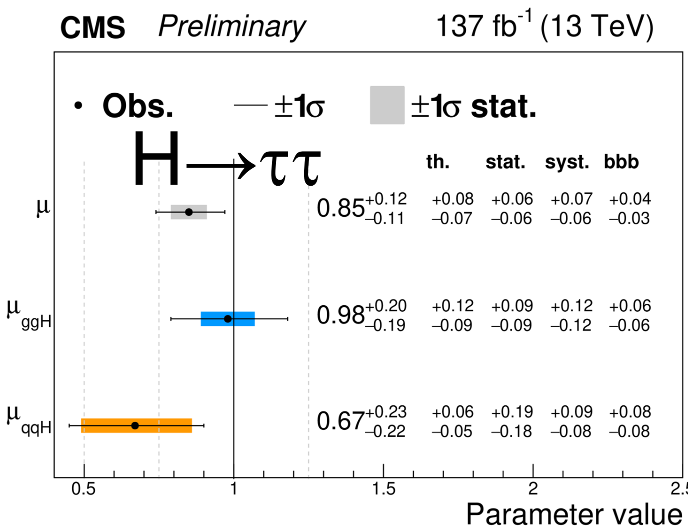
JHEP 03(2929)034, HIG-19-010, PRL 121(2018)121801

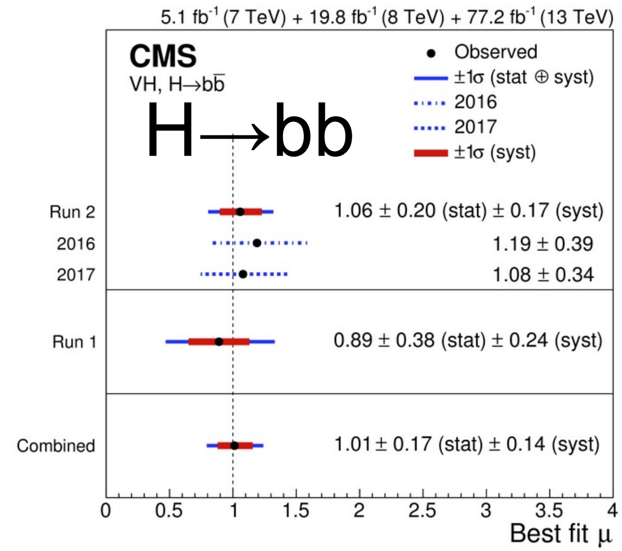








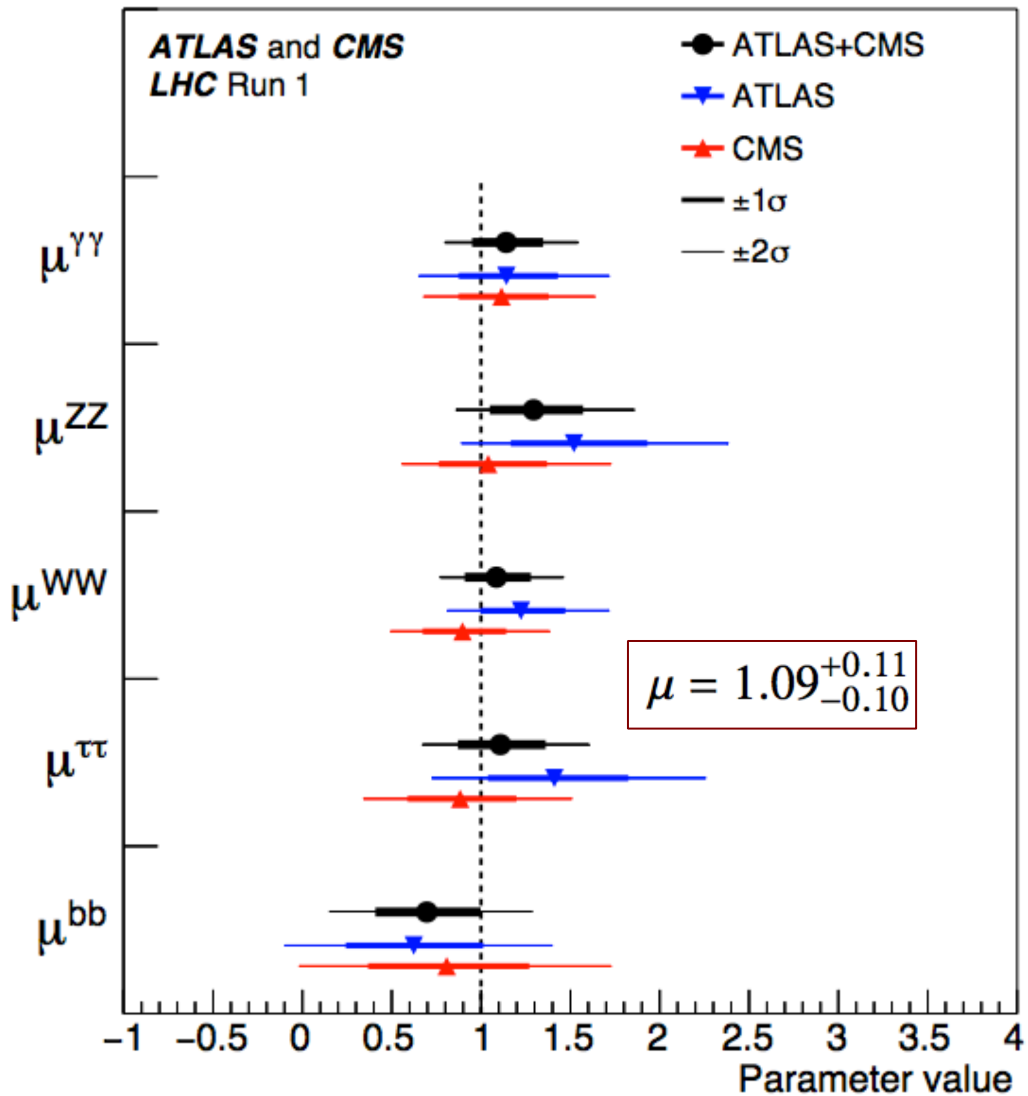




Couplings: individual channels

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

Results based on the full Run 1 data samples



Rare decays: H→μμ, cc

JHEP 01(2021)148, arXiv:2205.0550, arXiv:2211.14181

Study couplings to 2nd generation

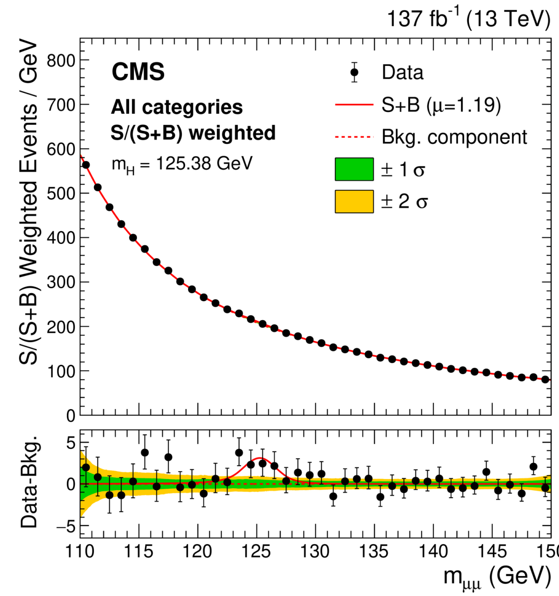
- H→μμ
  - Most sensitive category is VBF channel
  - Obs.(exp.): 3.0 σ (2.5σ)
- H→cc
  - Low cross section, need c-tagging
  - Use resolved (2jets) and merged (1jet),
  - Use ML and large jet substructure for tagging and classification
  - Validate using VZ production:

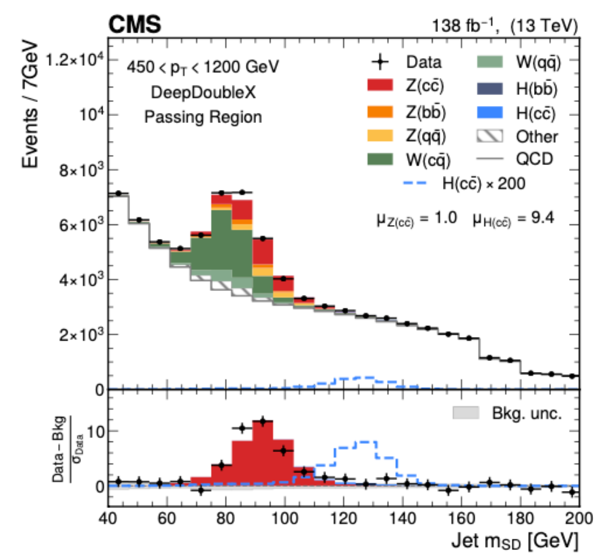
$$\mu_{VZ(cc)} = 1.01^{+0.23}_{-0.21}\ (5.7\sigma)$$

  - Set limits

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

$$\boxed{1.1 < |\kappa_c| < 5.5\ (|\kappa_c| < 3.4)}$$

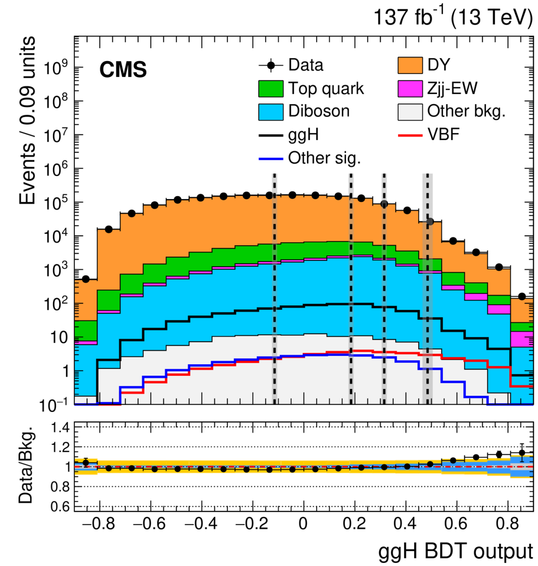


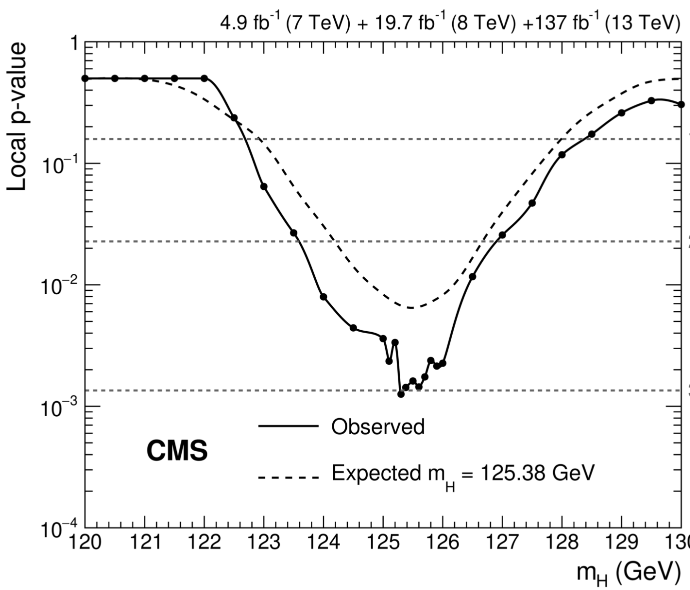


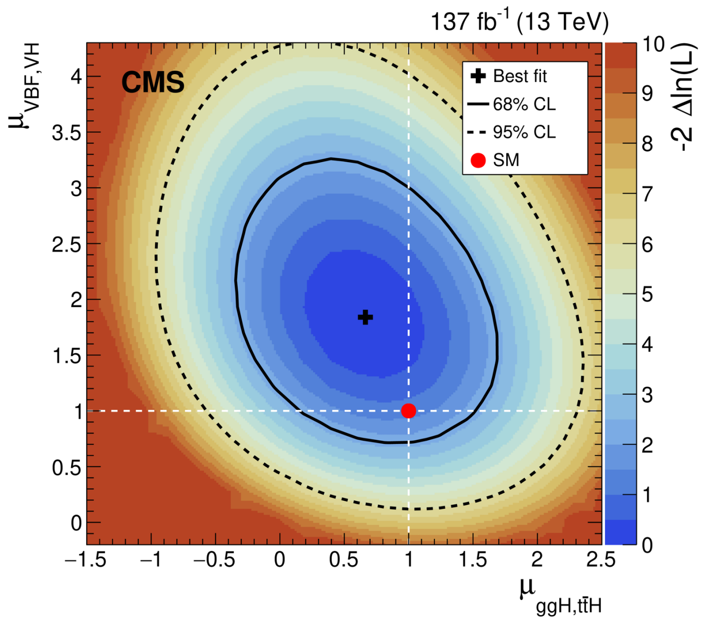
Search for SM H→μμ

JHEP 01(2021)148

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

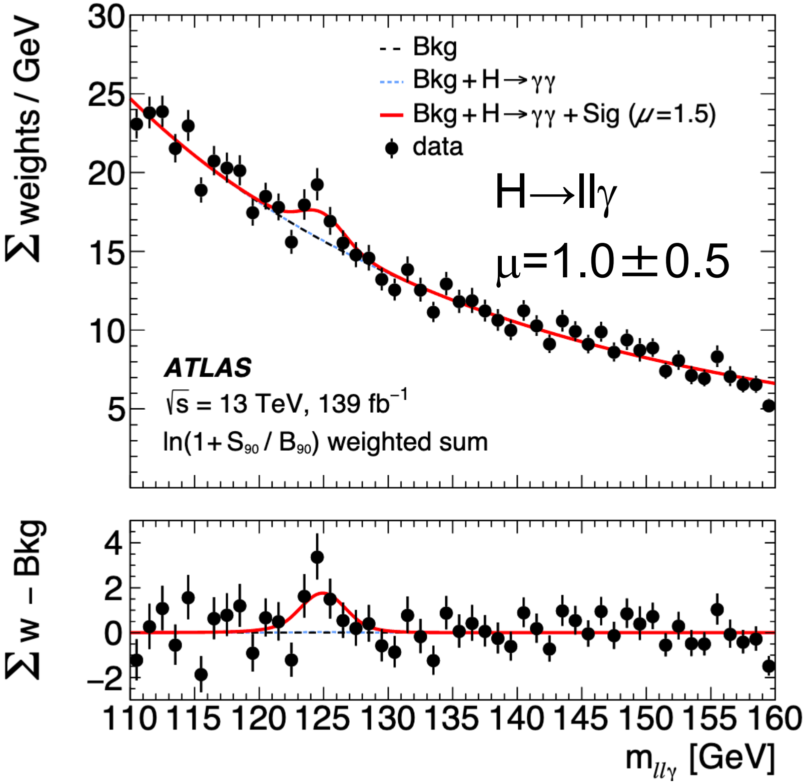


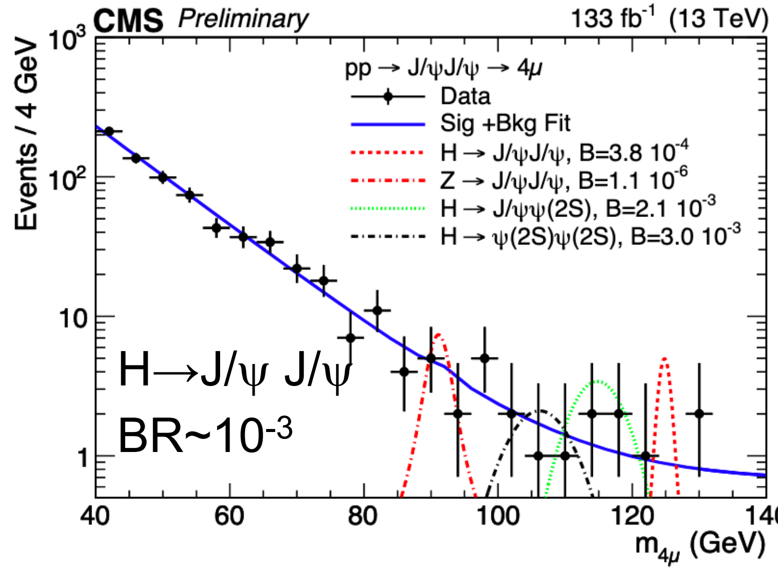


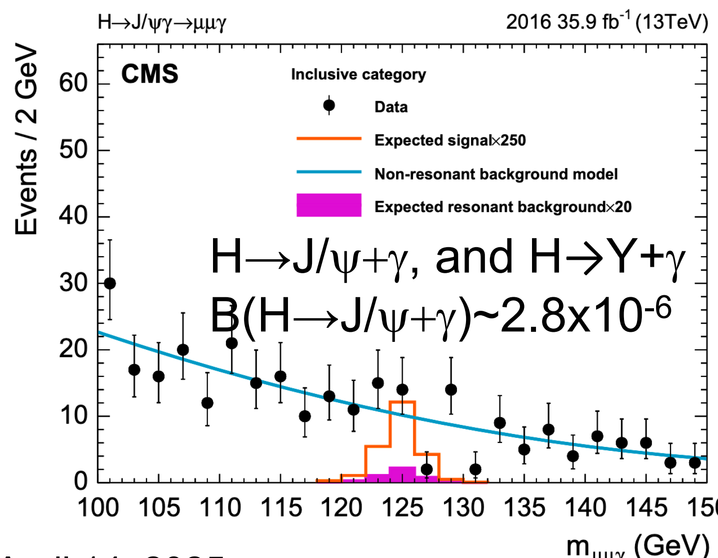


Search for rare decays

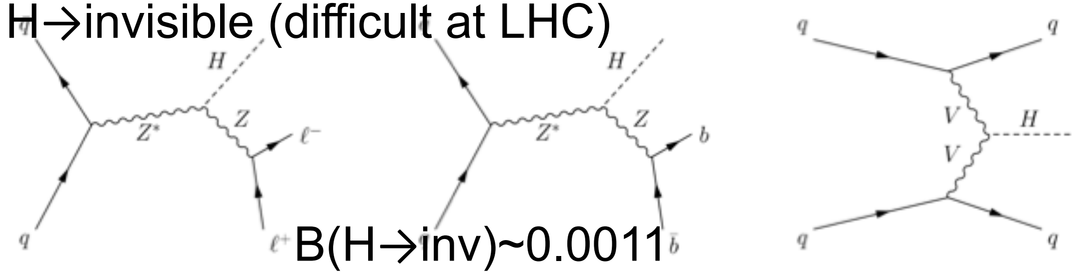
PLB 797(2019)134811, arXiv:2103.10322, EPJC 79(2019)94, PLB 793(2019)520, CMS-HIG-20-008







H→invisible (difficult at LHC)

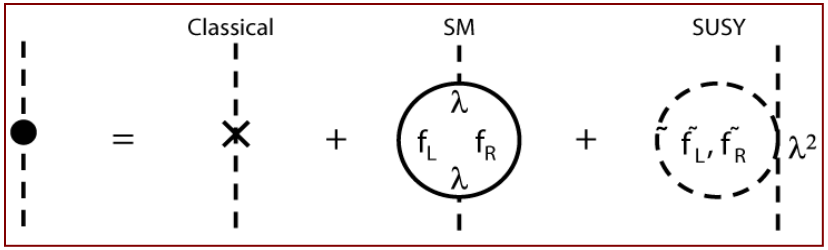


B(H→inv)~0.0011

Higgs and the SM

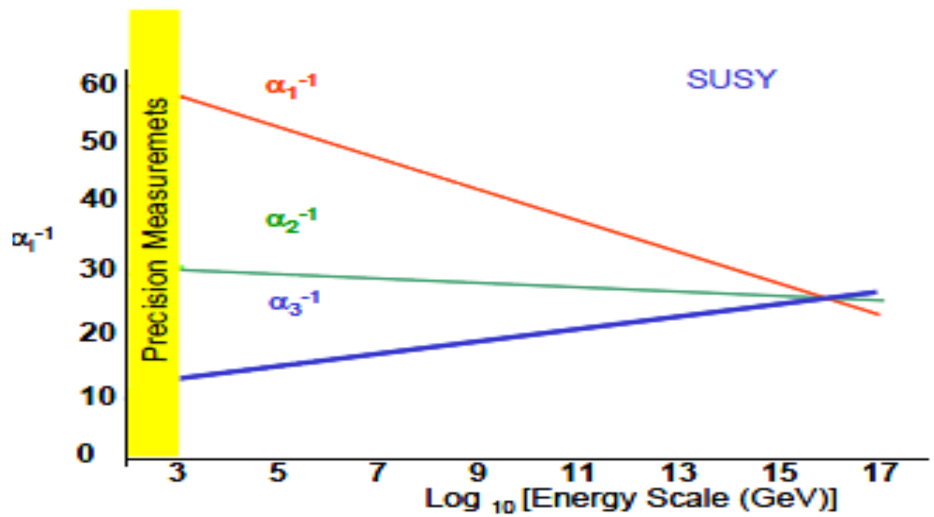
- SM is a successful theory
- Nothing prevents the SM to survive up to the Planck scale. However, it is unnatural.
- Virtual particles in quantum loops contribute to the Higgs mechanism
  - contributions grow with Λ (upper scale validity of the SM)
  - Higgs mass depends quadratically on Λ: $m^2 = m_0^2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

cancelation?



Higgs and the SM (cont.)

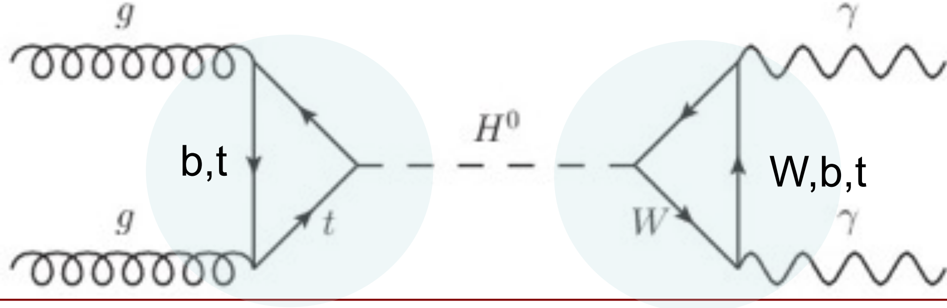
- SUSY postulates a new symmetry between fermions and bosons
  - Loops of particles and their SUSY partners have the ability to cancel the quadratic divergences in the Higgs field self-couplings, solving the naturalness problem
  - SUSY foresees unification of couplings at large energy scales ~10^{15} 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

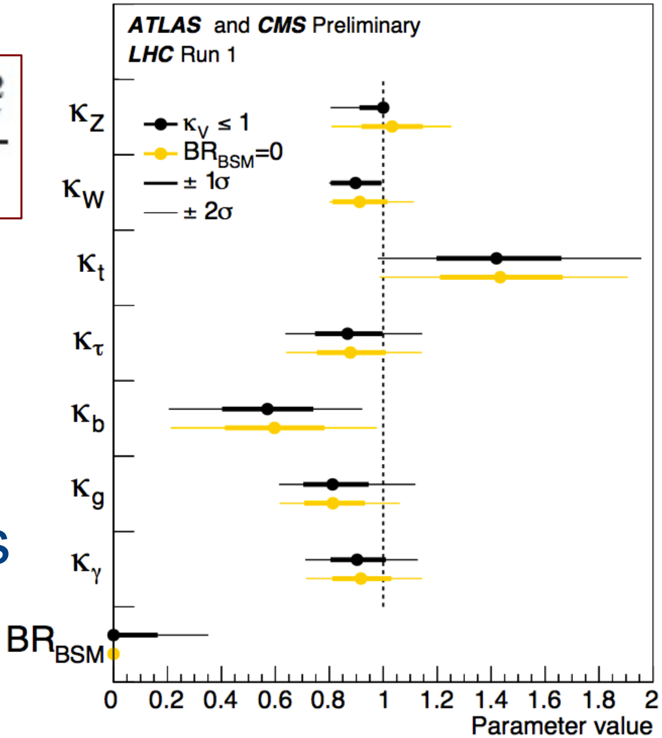
ATLAS-CONF-2015-044, CMS-HIG-15-002

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



$$(\sigma \cdot \mathrm{BR})\,(gg \to H \to \gamma\gamma) \;=\; \sigma_{\mathrm{SM}}(gg \to H) \cdot \mathrm{BR}_{\mathrm{SM}}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

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



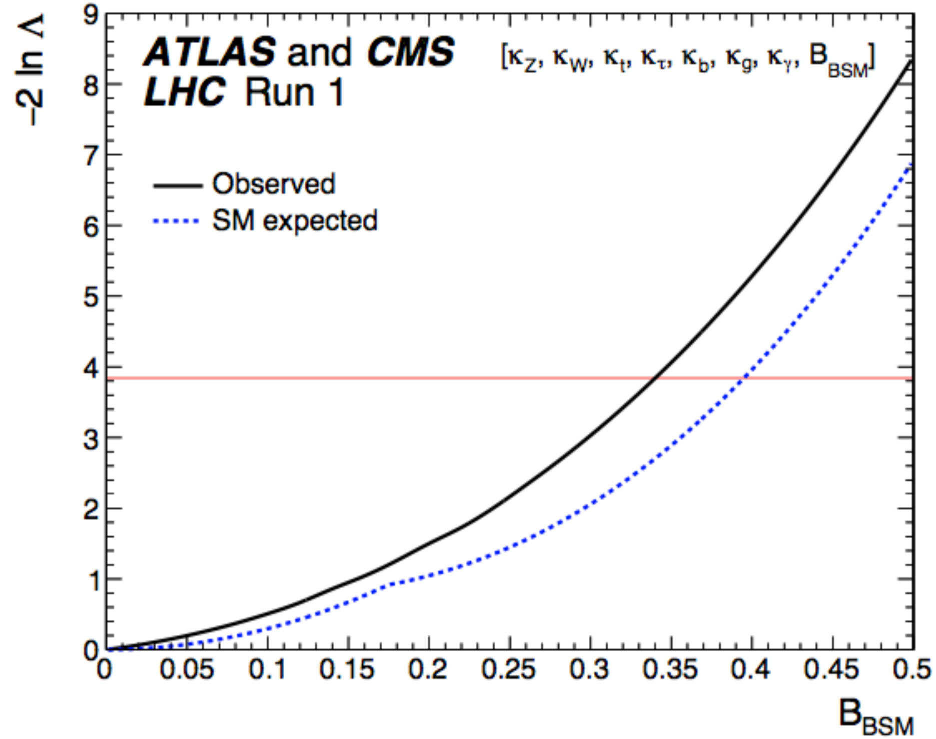
Experimental approach

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

Looking for new particles

JHEP08(2016)045

- Constrain BR_{BSM} in a scenario with free parameters
- $\Gamma_{tot}=\Gamma_{WW}+\Gamma_{ZZ}+\Gamma_{bb}+\ldots+\Gamma_{BSM}$
- 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

obs.(exp.) @95%CL:
$\Gamma_H < 5.4(8.0)\Gamma_H^{SM}$
$\Gamma_H < 22(33)$MeV

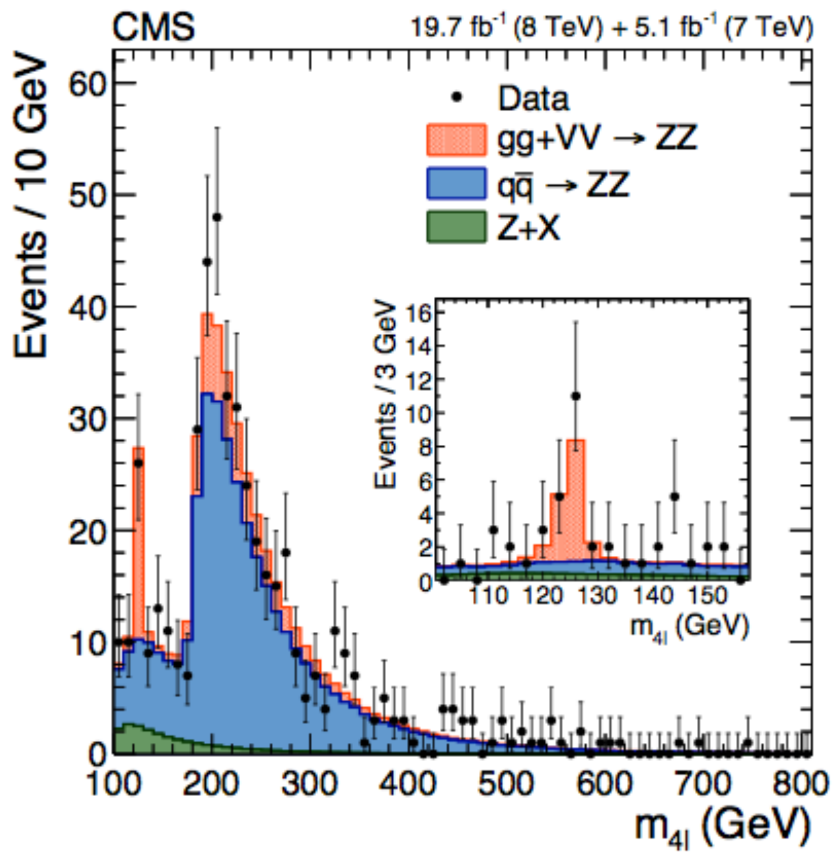
- couplings and width sensitive probes to BSM
- indirectly constrained in coupling fits
- off-peak to on-peak ratio proportional to Γ_H
- constrain Higgs boson width by using off-shell production/decay
- measure ratio of $\sigma^{\text{off-peak}}$ to $\sigma^{\text{on-peak}}$

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

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



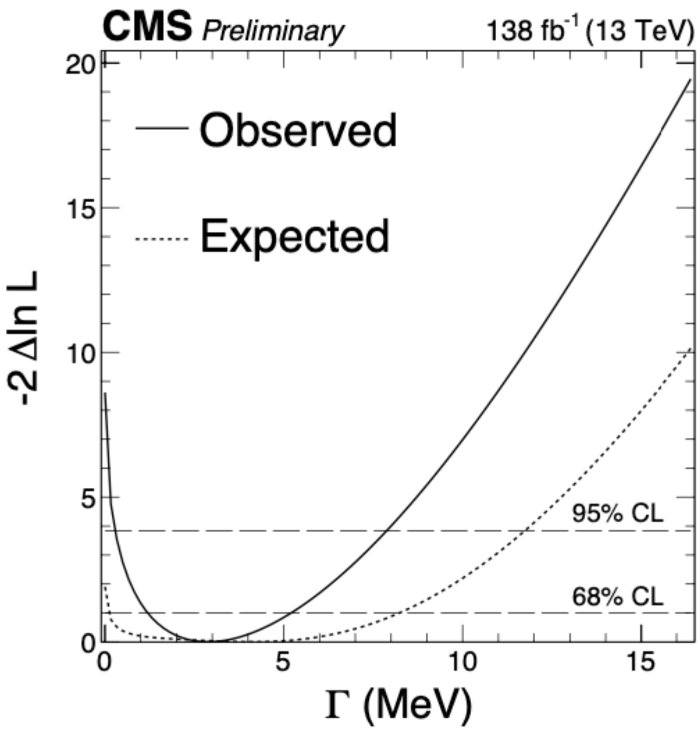
Higgs mass and width (cont.)

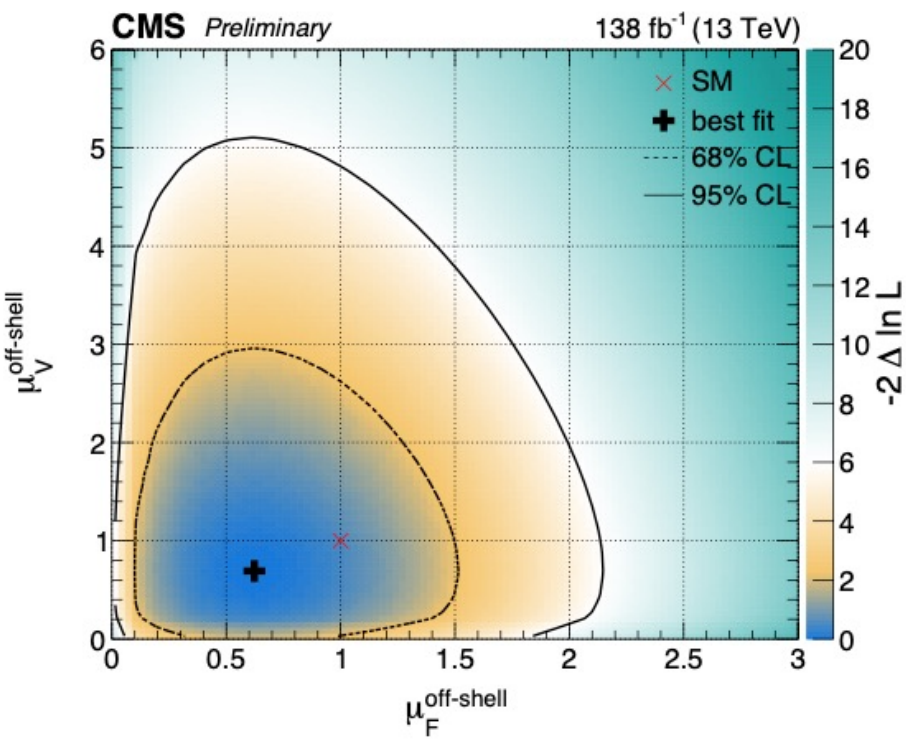
arXiv:2202.06923, CMS-HIG-21-019

- 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

$$\frac{\sigma^{\text{off-shell}}_{\text{vv}\to\text{H}\to4\ell}}{\sigma^{\text{on-shell}}_{\text{vv}\to\text{H}\to4\ell}} \propto \Gamma_\text{H}$$

$$\boxed{\Gamma_\text{H} = 2.9^{+2.3}_{-1.7}\,\text{MeV}}$$

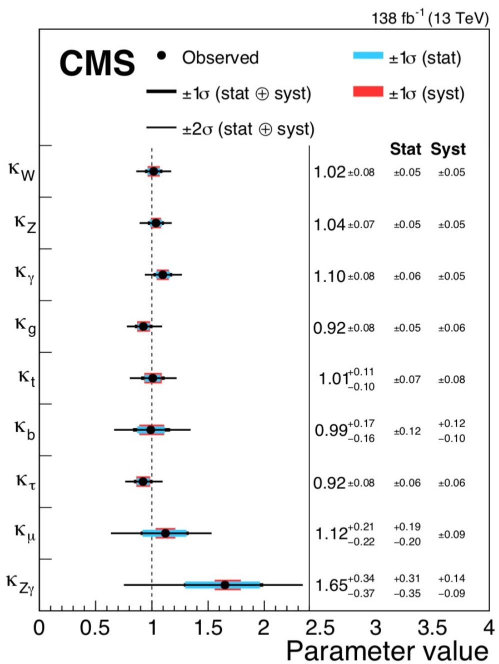


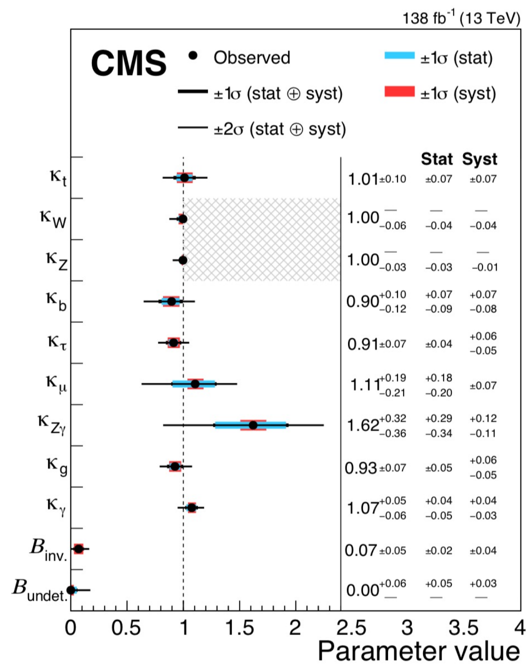


Couplings: decays

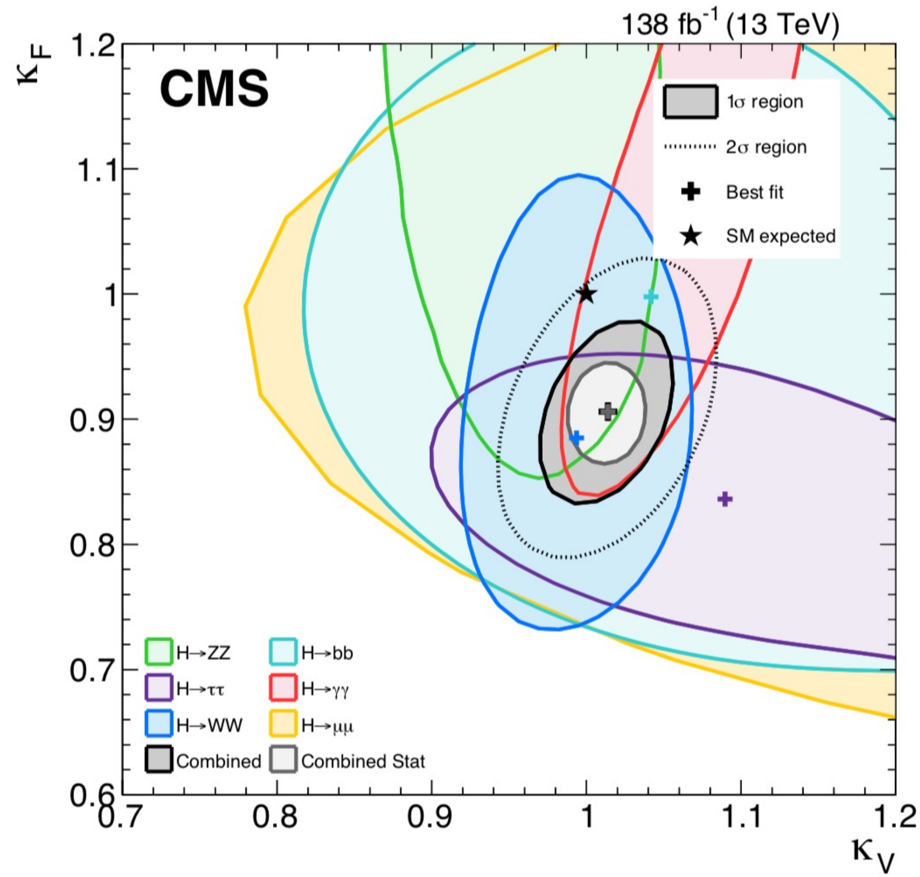
ATLAS-CONF-2015-044, CMS-HIG-15-002, JHEP08(2016)045, CMS-HIG-22-001, Nature 607(2022)60

BSM physics in the loop





Vector and fermion couplings



BR$_{BSM}$ can be measured

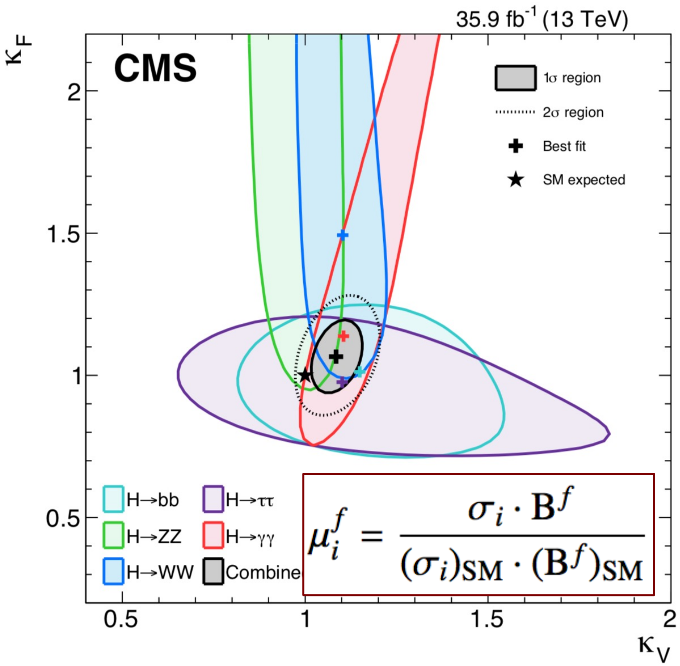
BR$_{BSM}$ < 0.18(010) at 95% C.L. (assuming $\kappa_V \leq 1$)

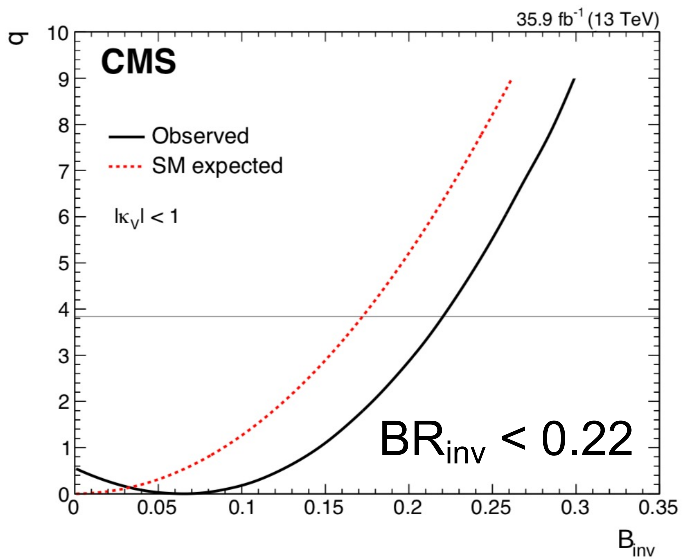
BR$_{BSM}$ includes non standard decays, visible or invisible

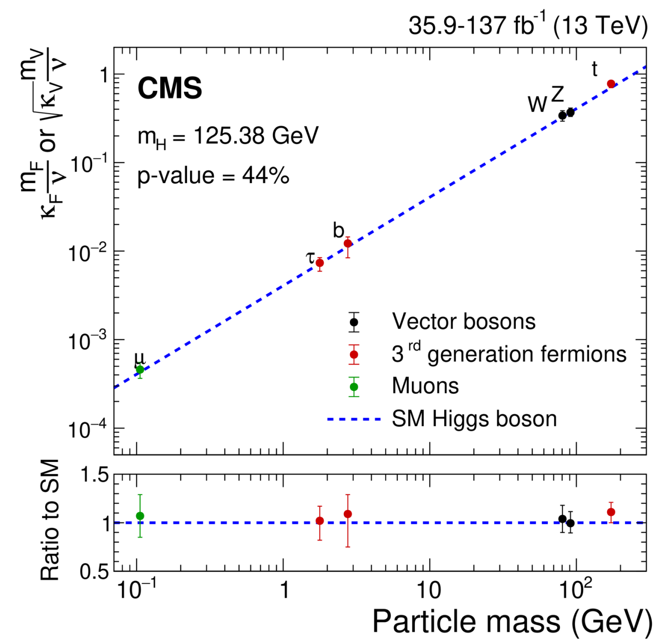
⇒Results in agreement with SM (k_V=k_F=1) within 1σ

Consistency with SM

arXiv:1809.10733, JHEP 01(2021)148

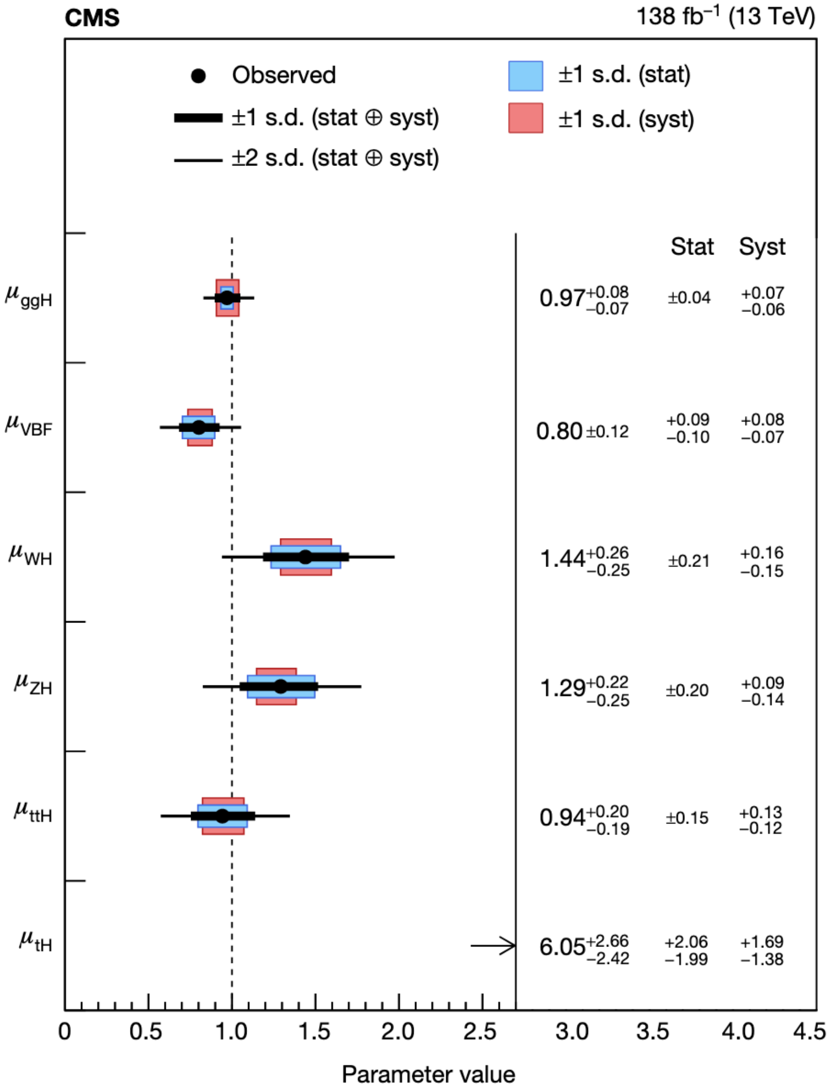


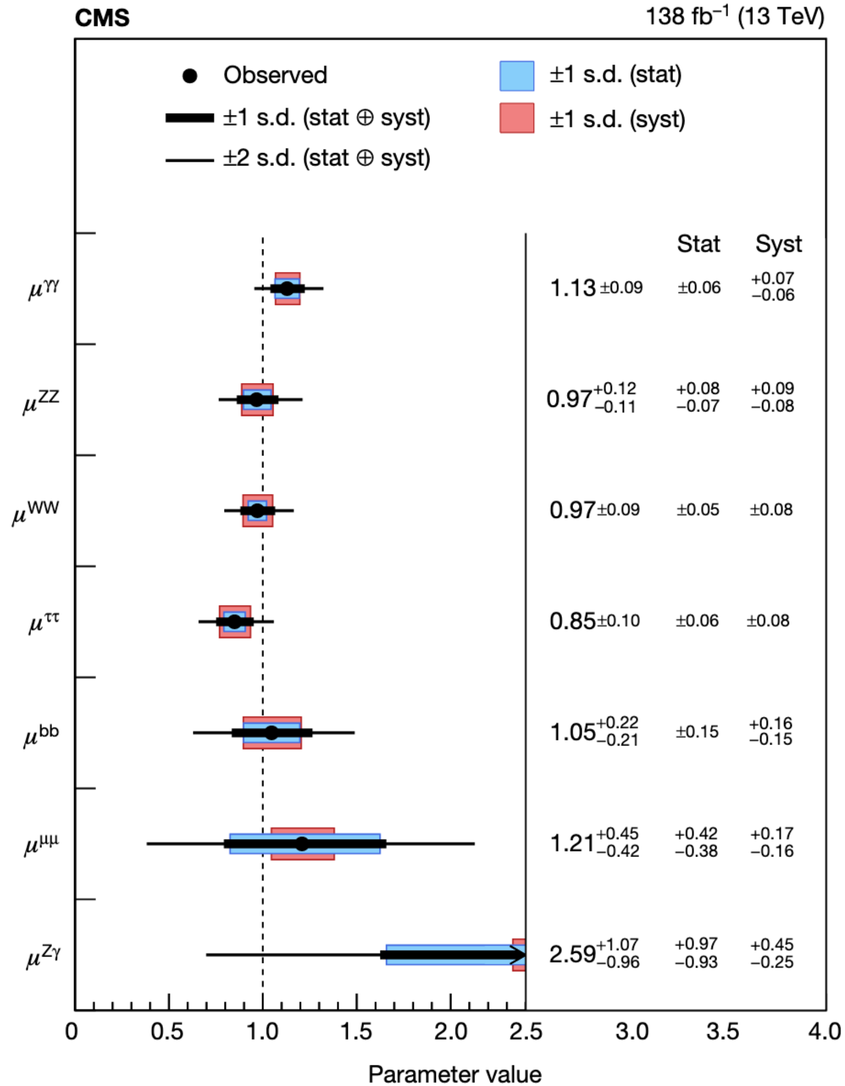




Consistency with SM

Nature 607(2022)60



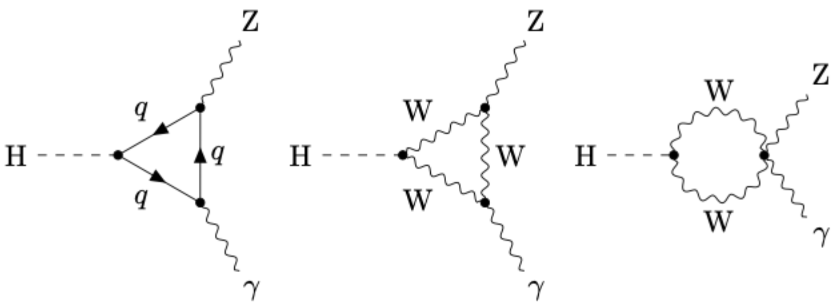


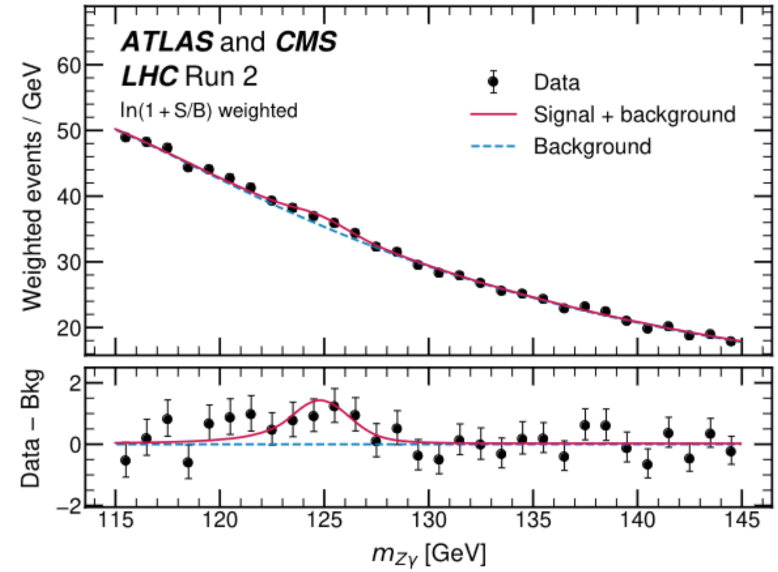
Rare decays: Z+photon

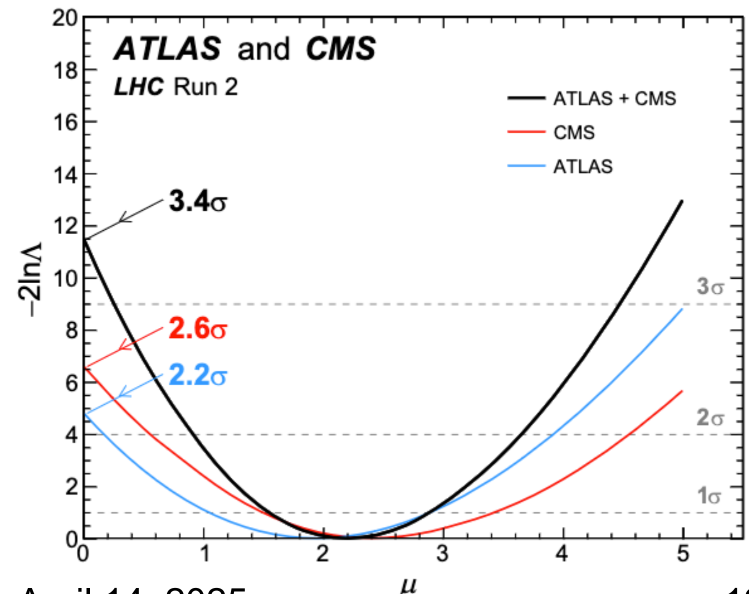
arXiv:2204.12945, PRL 132 021803

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

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





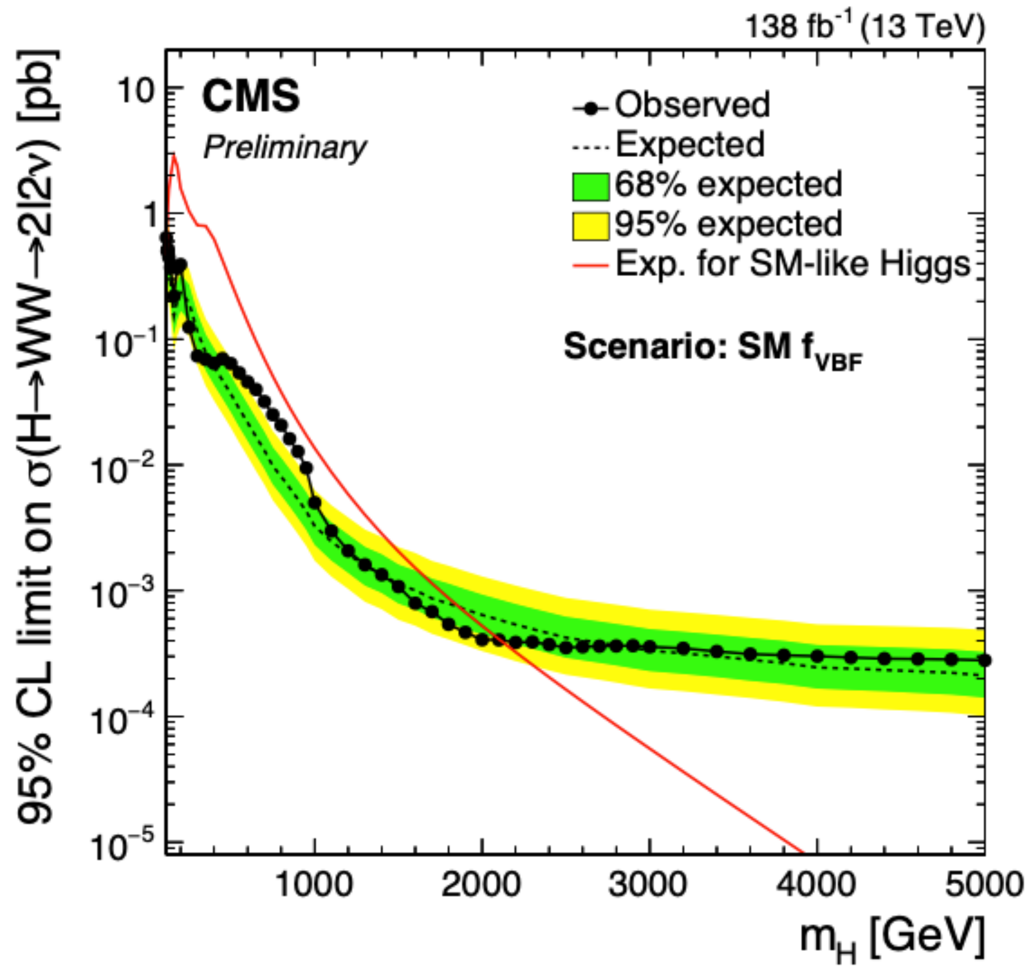


⇒ significance of 3.4σ (ATLAS+CMS)

High mass: H→WW/ZZ

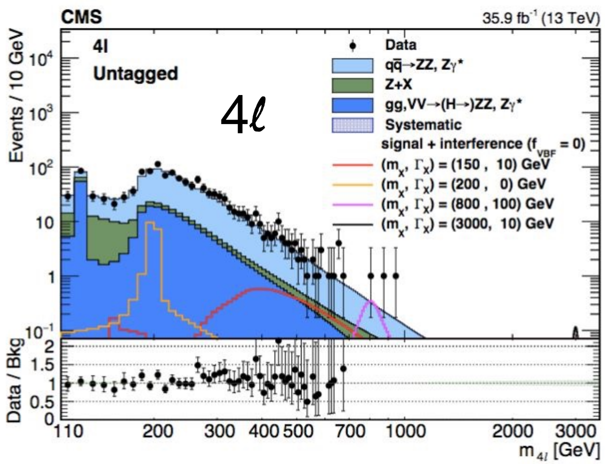
JHEP 10(2015)144, HIG-16-033, HIG-16-034, arXiv:1912.01594, HIG-20-016

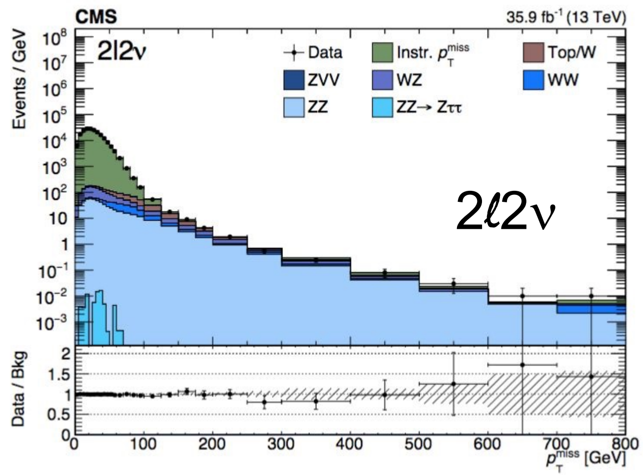
- Search for a heavy Higgs boson
  - H→ZZ→4ℓ, 2ℓ2ν, 2ℓqq
  - H→WW→2ℓ2ν, 2ℓqq
- Optimized separately for VBF and gluon fusion production processes
- Combined upper limits at 95% CL on the product of σ x BR exclude a heavy Higgs boson with SM-like couplings and decays up to 1870 GeV
- Search interpreted 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

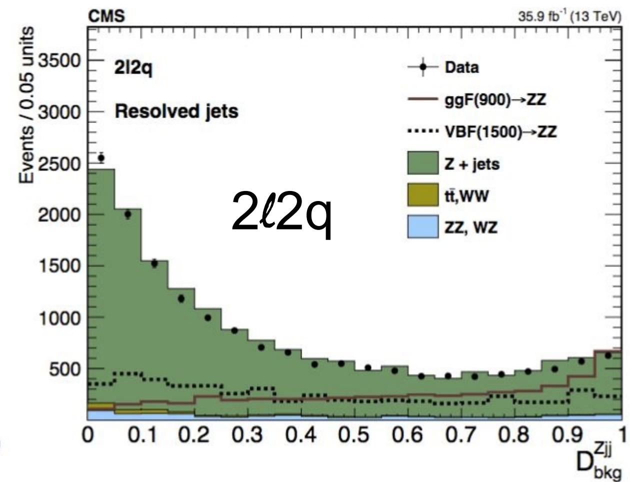


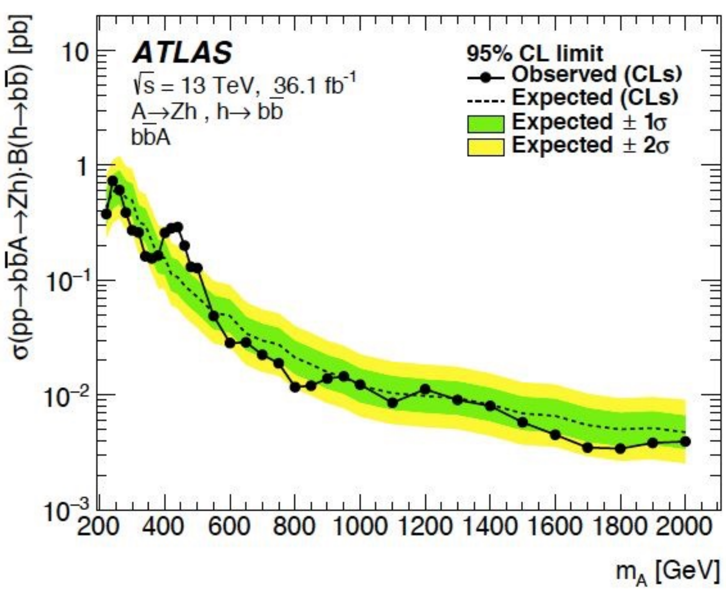
Heavy Higgs: dibosons

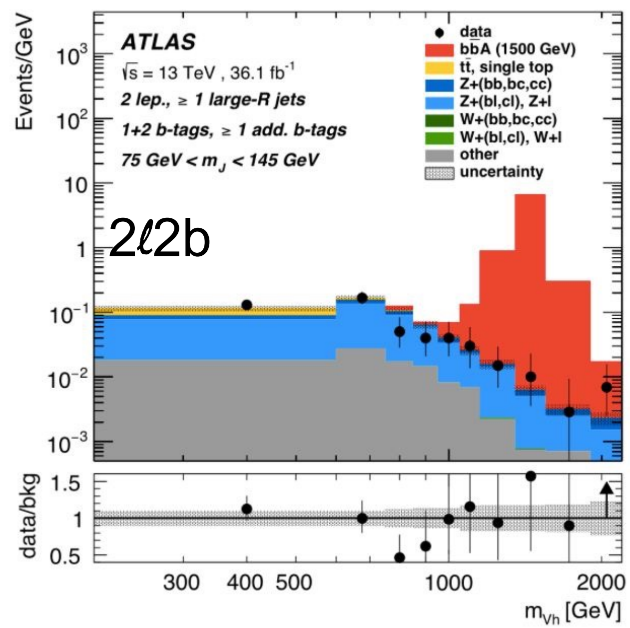
arXiv:1804:01939, JHEP03(2018)174, arXiv:1804.01126







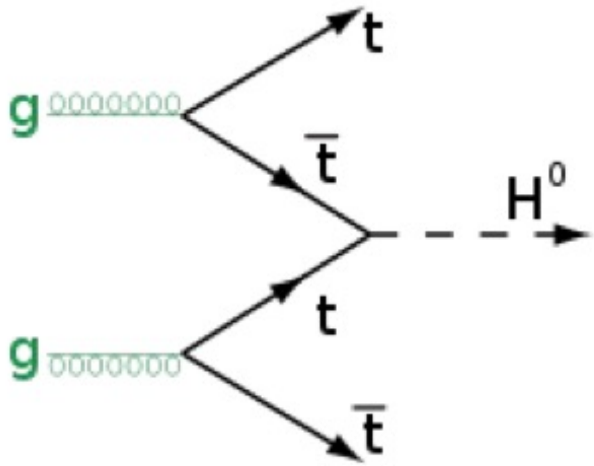




Hunting for a bump in the diboson mass spectrum

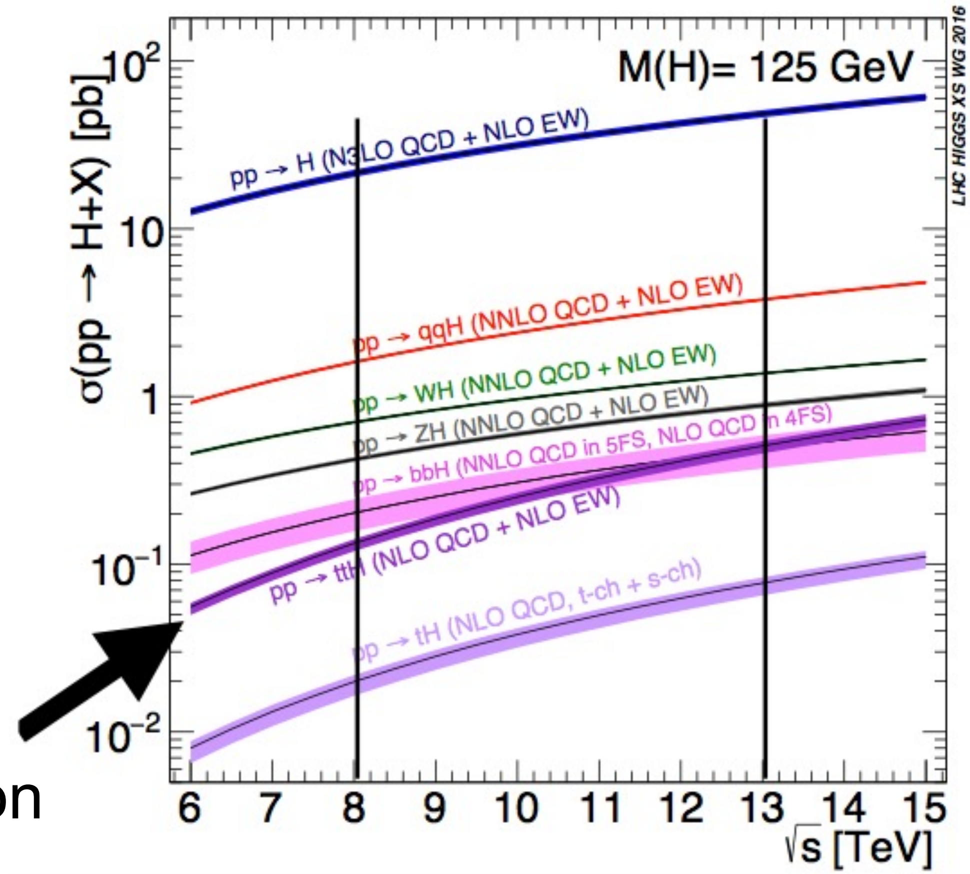
ttbar+Higgs

- ttbar 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)

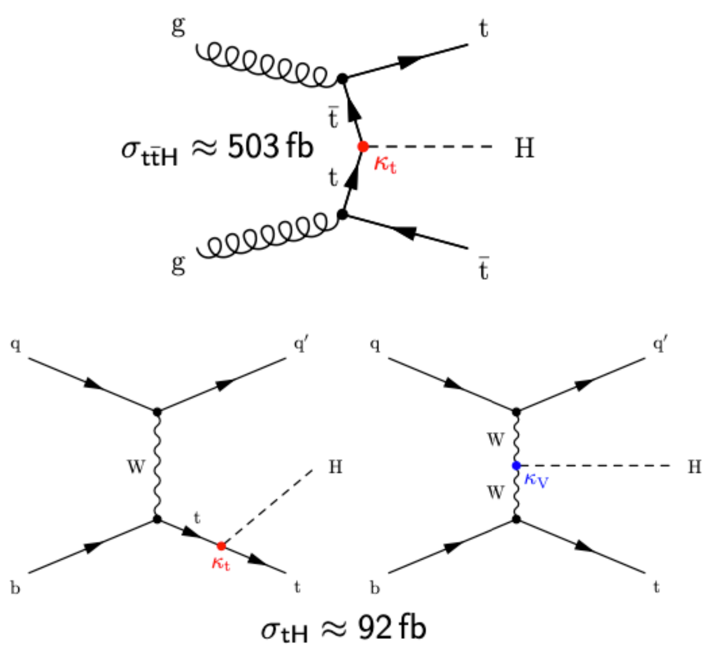
ttH ~1% of total Higgs cross section

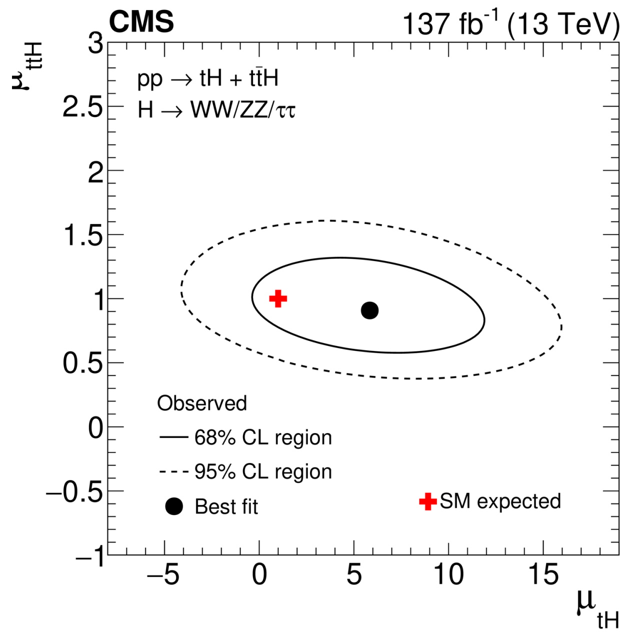


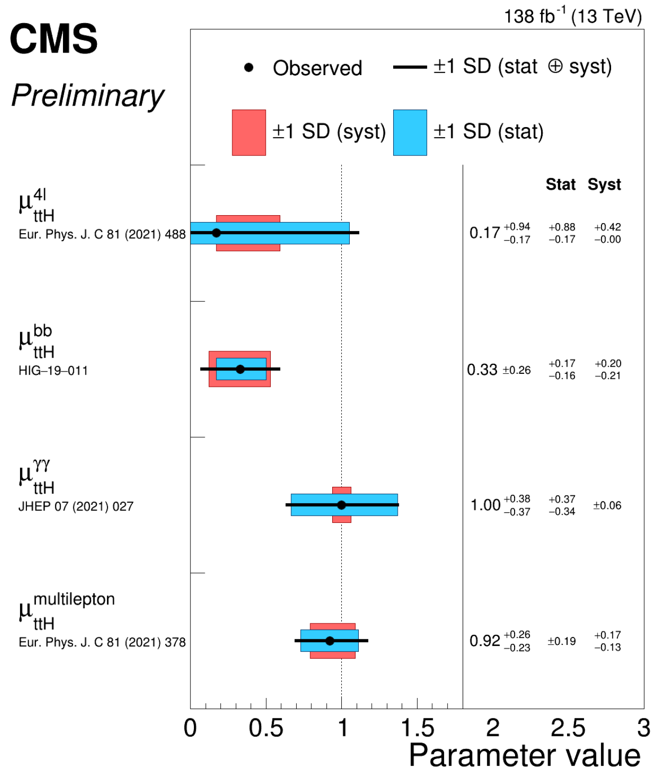
Higgs+Top: tH, ttH

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→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:

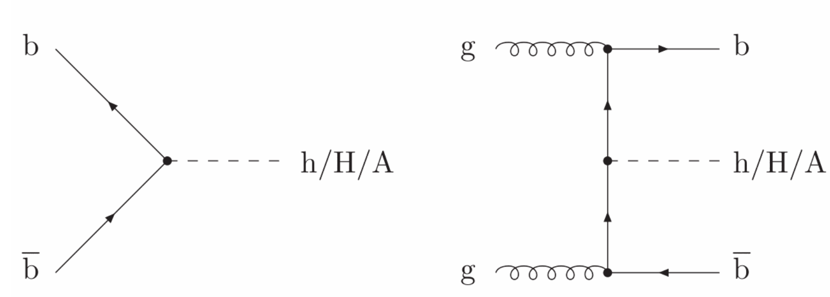
- 5 physical Higgs bosons
  - 3 neutral: CP-even ϕ=h,H CP-odd A
  - 2 charged $H^{\pm}$
- SM-like Higgs boson: h

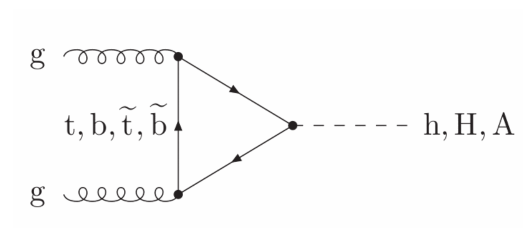
Neutral Higgs ϕ decay modes:

- BR($\phi\to$bbar)~90%
- BR($\phi\to\tau\tau$)~10%
- BR($\phi\to\mu\mu$)~0.1%

Two main production modes:

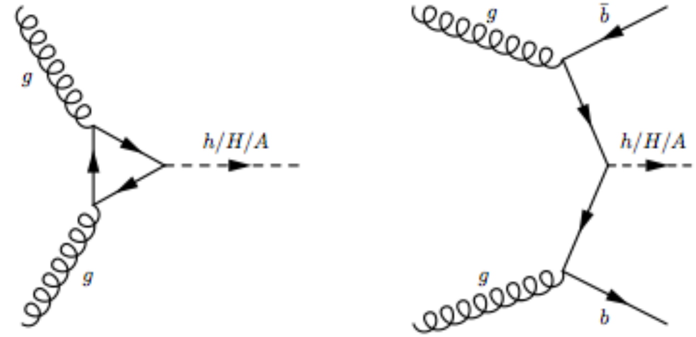
- gg$\to$H
- $b\bar{b}H$





Neutral MSSM Higgs

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

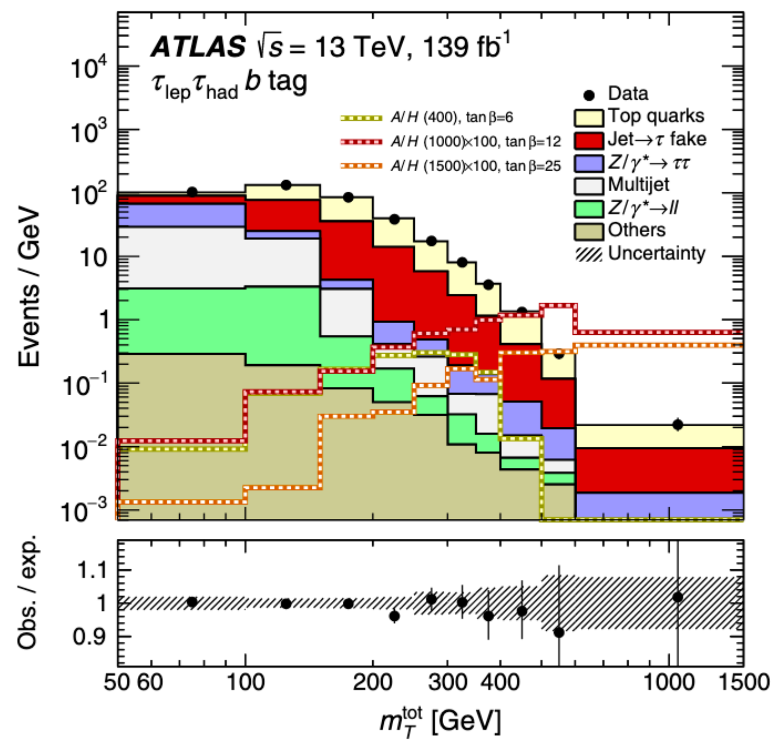


- Enhanced couplings of MSSM Higgs to down-type fermions (large tanβ)

⇒increased BR to τ leptons and b-quarks

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

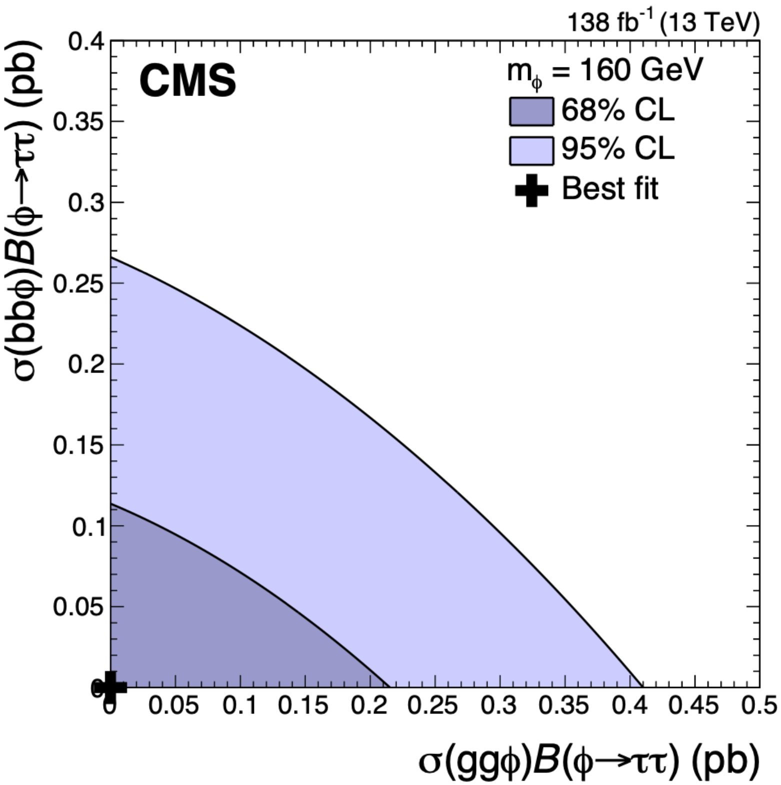
- Search for neutral MSSM Higgs boson
- 5 final states used: $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$, $e\mu$, $\mu\mu$
  - Reconstruct tau-pair invariant mass
  - Split in b-tag/no b-tag categories to enhance sensitivity
- Main backgrounds: Z→ττ, QCD/W+jets, DY,ttbar, dibosons



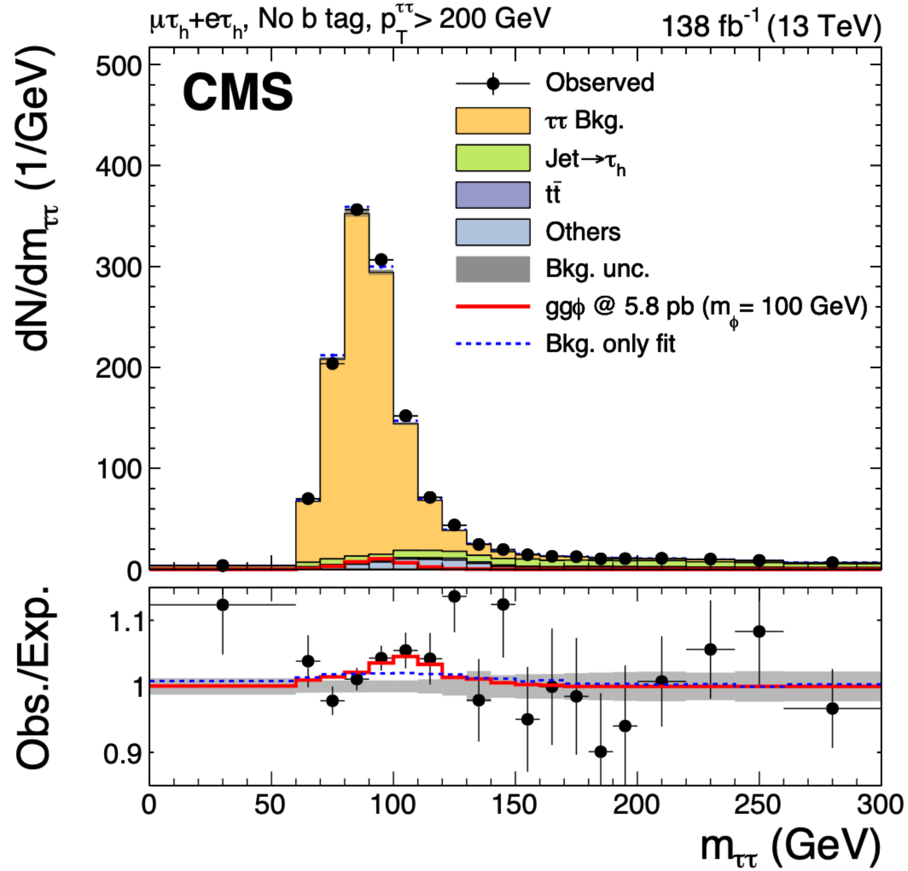
Neutral MSSM Higgs: $\phi \rightarrow \tau\tau$

arXiv:2208.02717

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



Model-independent limits by separating production modes

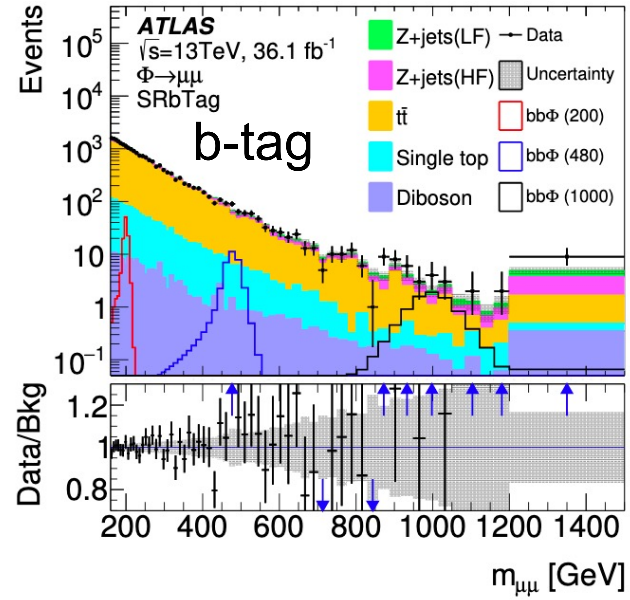


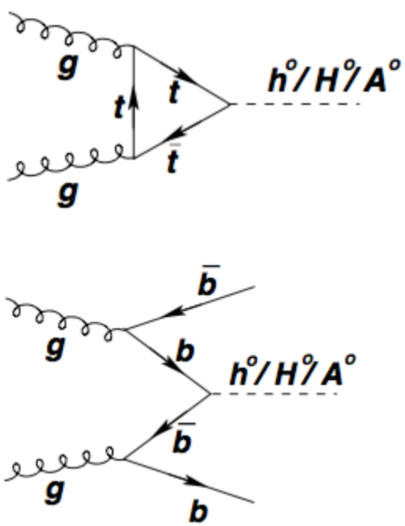
Some fluctuation over bkg expectations

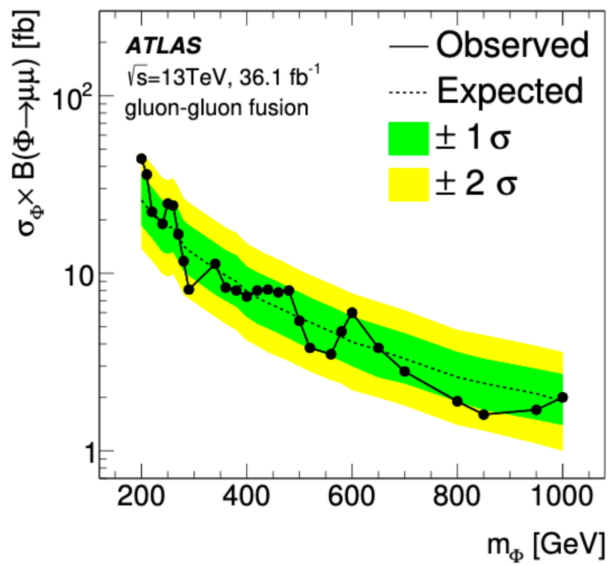
Neutral MSSM Higgs: $\phi \to \mu\mu$

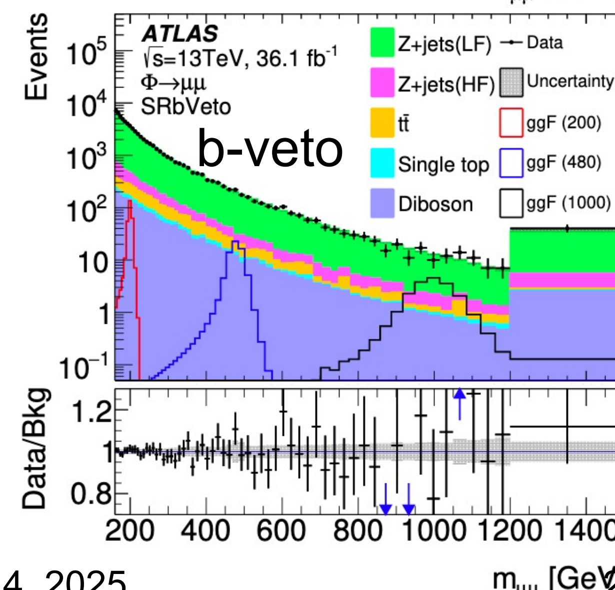
arXiv:1508.01437, JHEP07(2019)117

- 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 $gg \to \phi$ and $bb\phi$ production modes
- Main backgrounds: Z(bbar), ttbar, WW



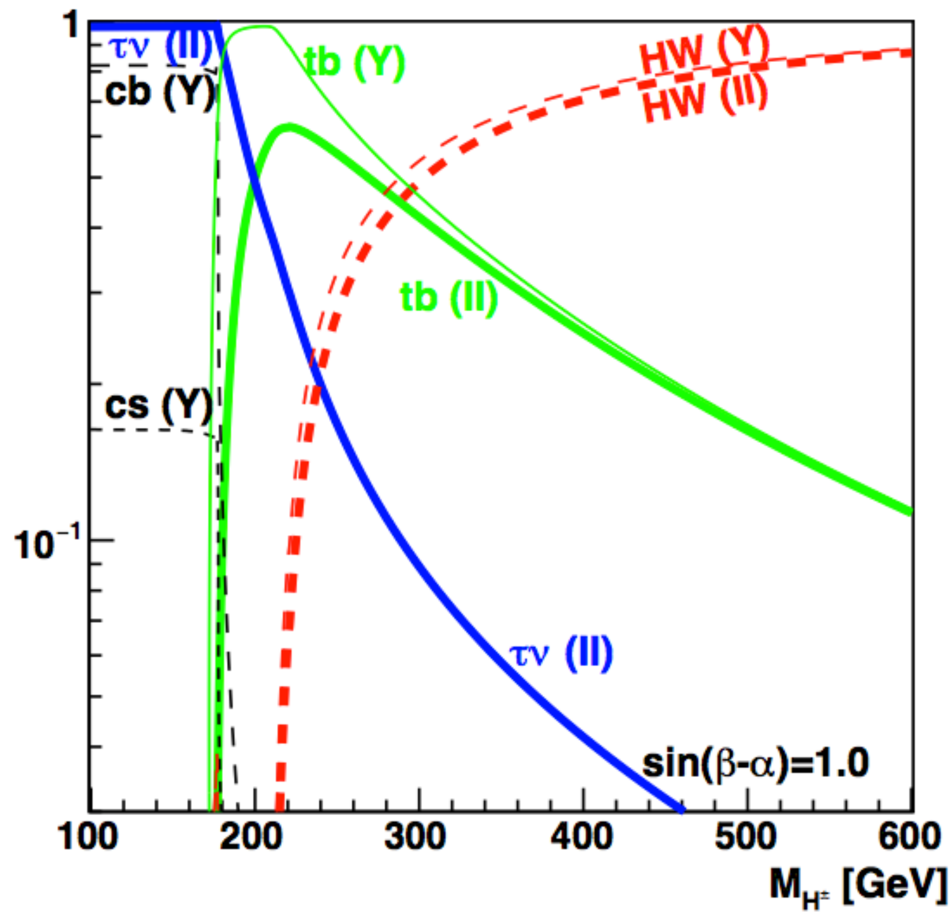






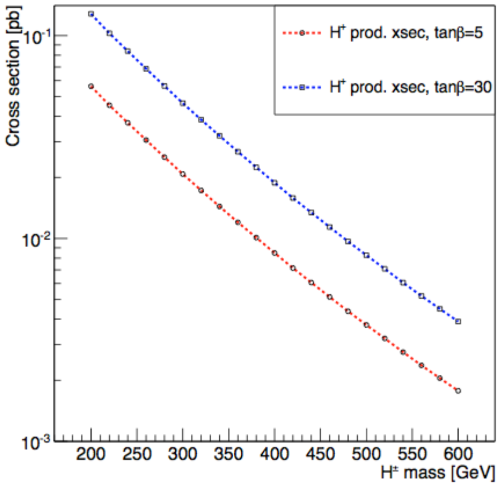
Charged Higgs

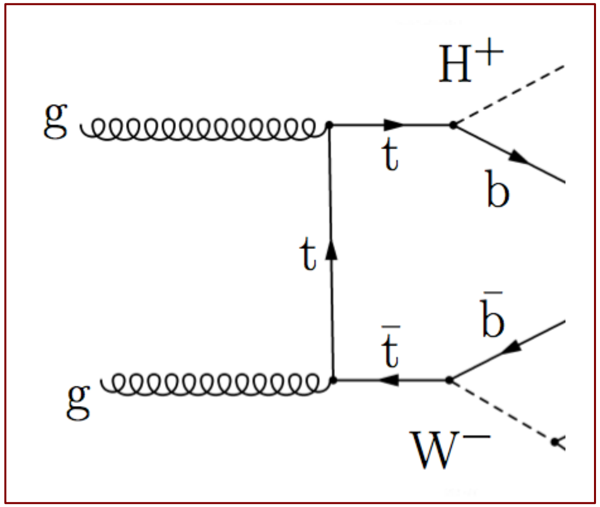
- If found, a clear indication of BSM
- Study non-SM Higgs in two mass regimes:
- $m_H < m_{top}$
  - Mostly produced in top quark decays
  - Large tanβ: $H^{\pm} \rightarrow \tau^+ \nu$
  - Small tanβ (<1): $H^+ \rightarrow c\bar{s}$
- $m_H > m_{top}$
  - Produced in gluon-gluon fusion
  - Main decays: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



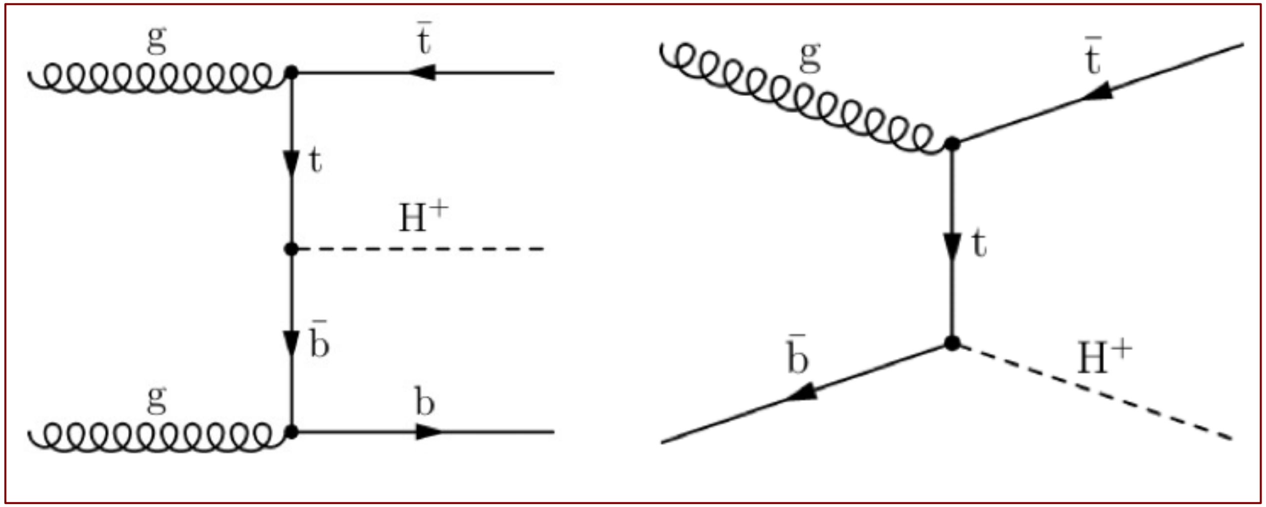
Charged Higgs (cont.)

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





$m_H < m_{top}$

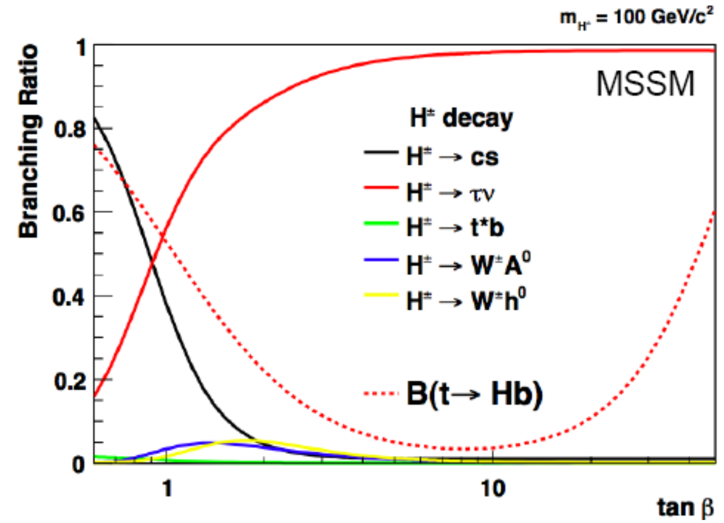


$m_H > m_{top}$

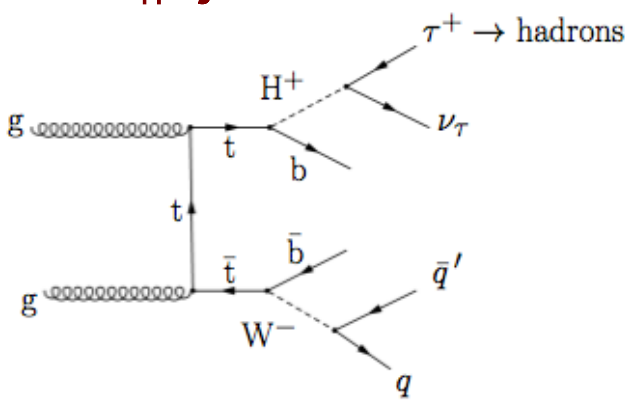
Charged Higgs and top quark decays

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

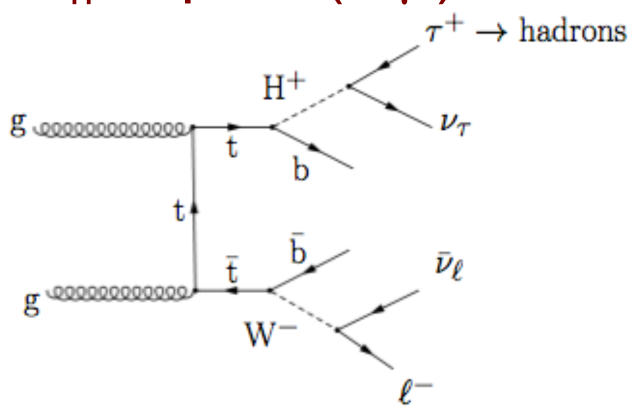
- Look for charged Higgs in four final states:
  - Tau+lepton (electron or muon)
  - Dilepton (tau decays leptonically)
  - lepton+jets
  - Fully hadronic: tau+jets



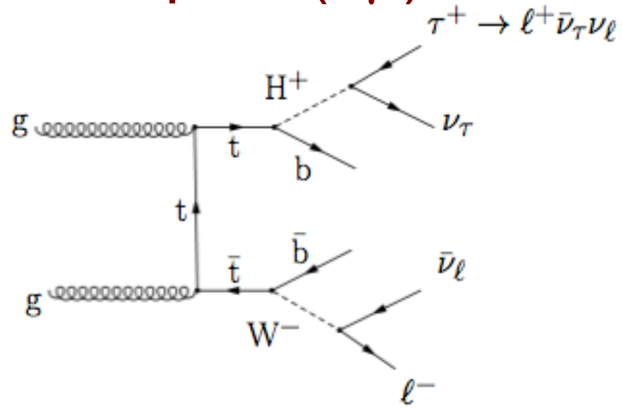
τ_h+jets



τ_h+lepton (e/μ)



di-lepton (eμ)



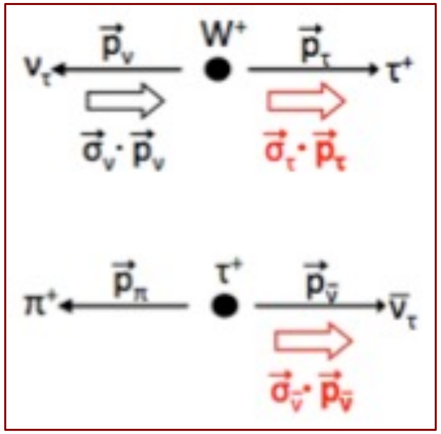
Looking at tau decays

CMS-HIG-12-052, arXiv:1903.04560

Low H$^+$ mass:

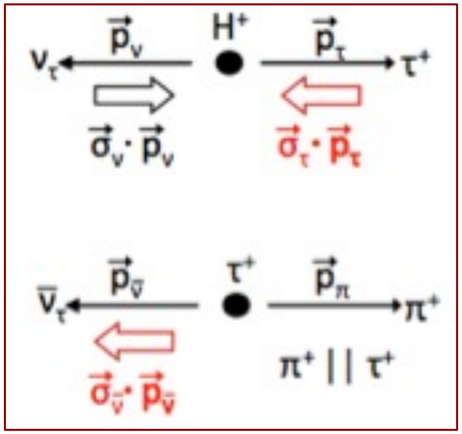
- Use R variable in the limit extraction: binned maximum-likelihood fit
- Tau fake component is data-driven, includes uncertainties

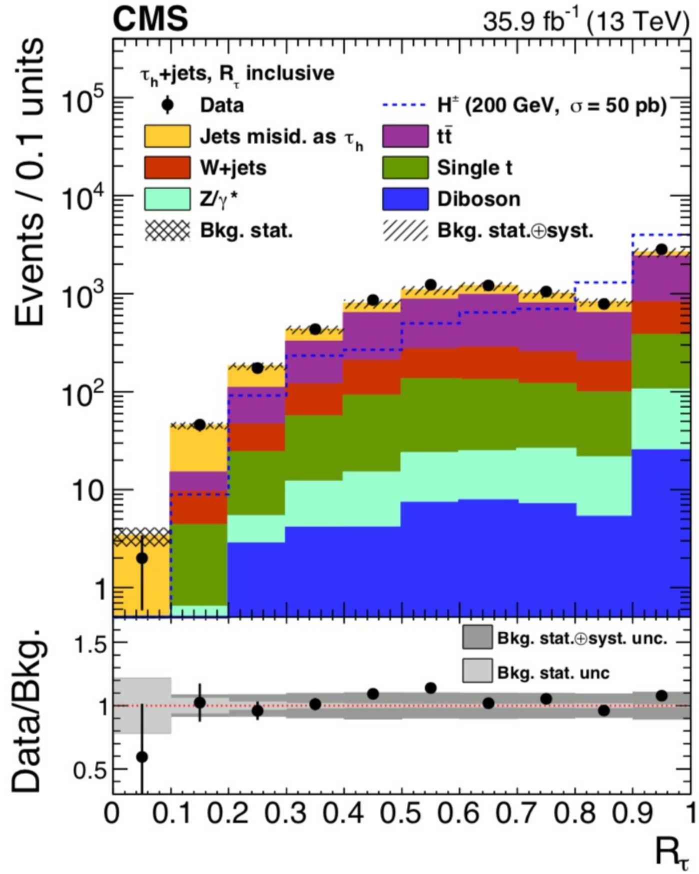
SM



VS

BSM

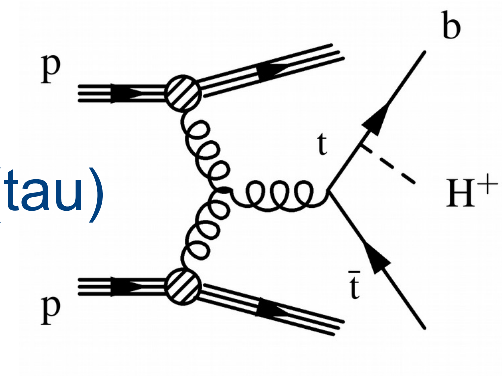


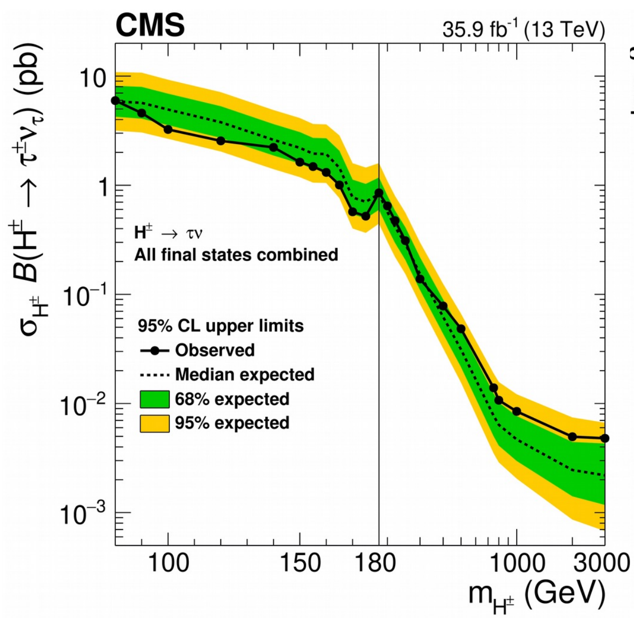


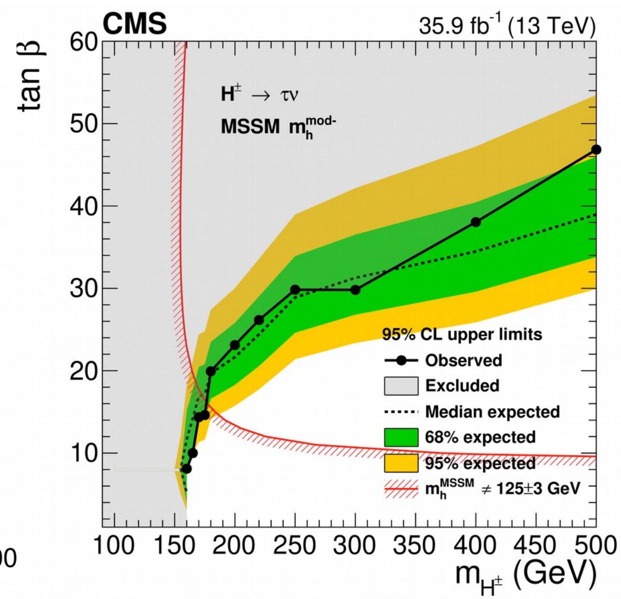
Charged Higgs: $H^+ \to \tau\nu$

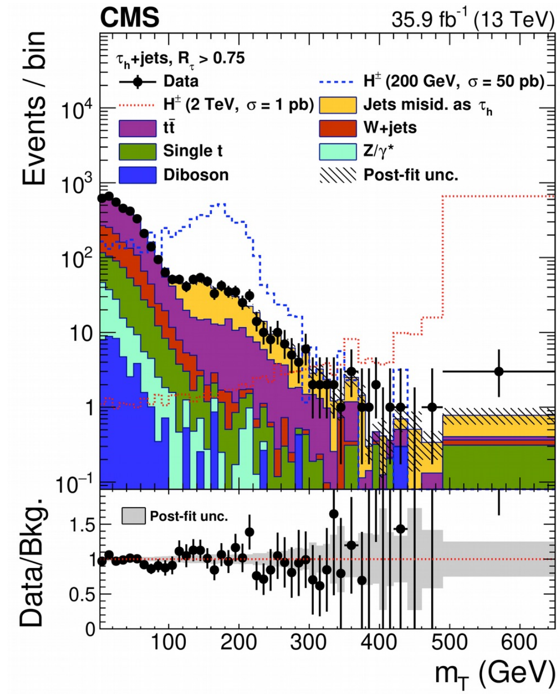
MSSM, high tanβ

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







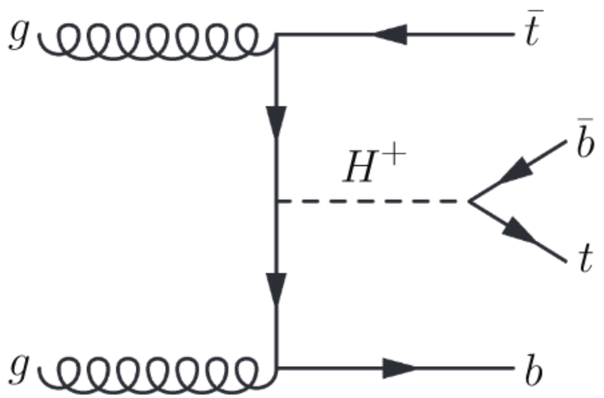


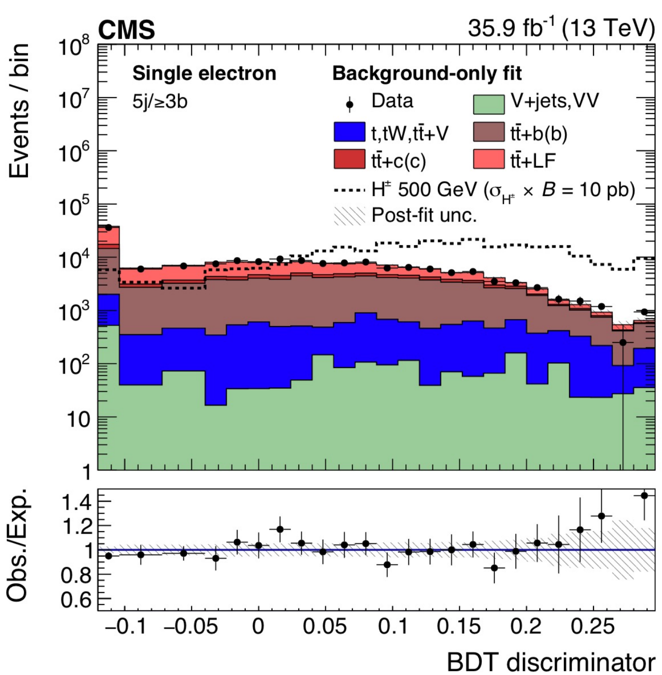
Charged Higgs: $H^+ \to tb$

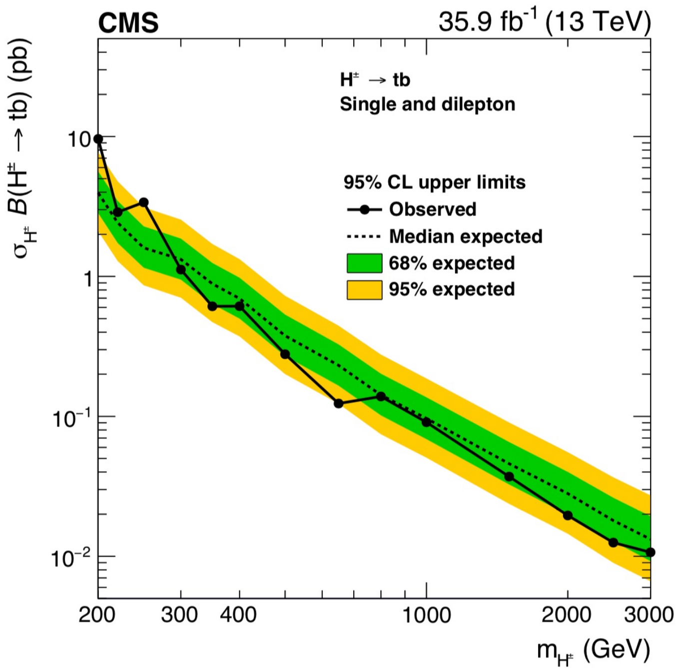
arXiv:1908.09206, arXiv:2102.10076

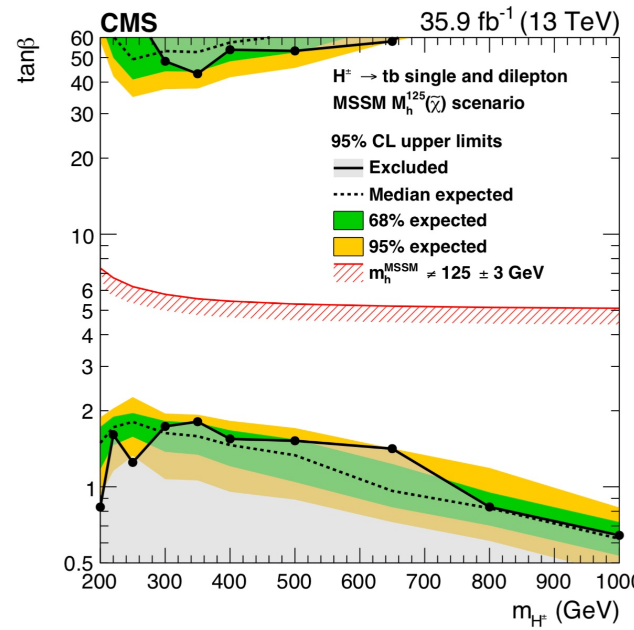
MSSM, low tanβ

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





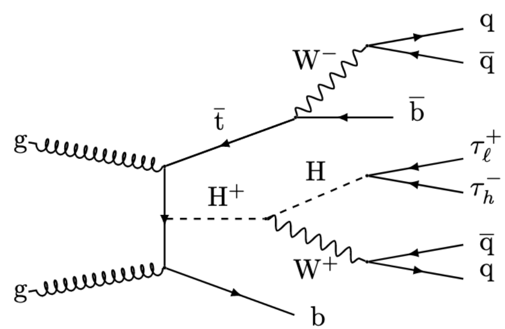


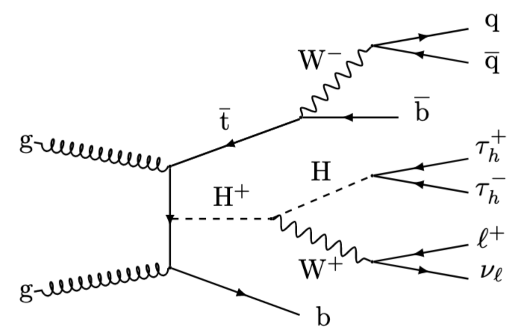


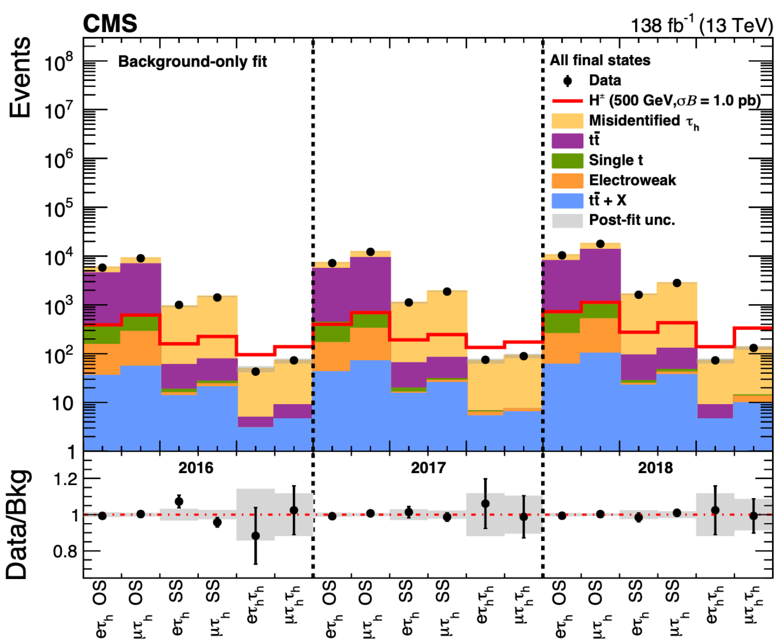
Charged Higgs: $H^+ \rightarrow tb$ (cont.)

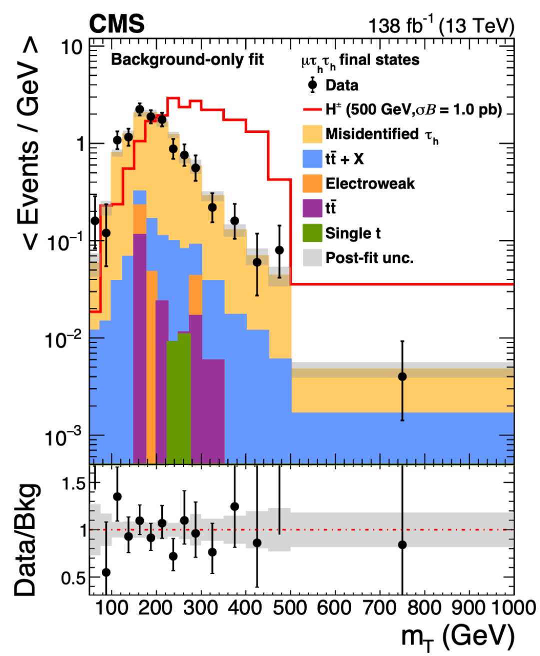
arXiv:2207.01046

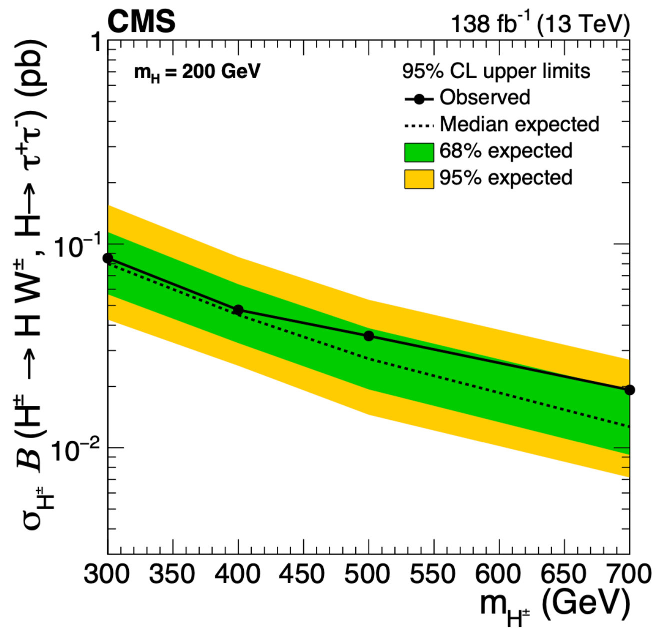
- Search for a $H^{\pm}$ decaying to a heavy neutral Higgs boson H and a W
- data consistent with SM expectations
- Set limits:
  - $H^{\pm}$ in the mass range 300-700GeV, assuming m_H=200 GeV
  - Cross-section limit from 0.08pb@300GeV to 0.013pb @700GeV







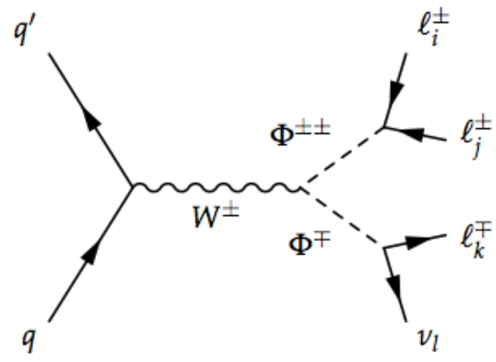


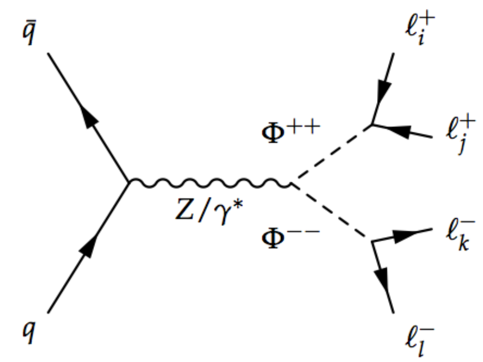


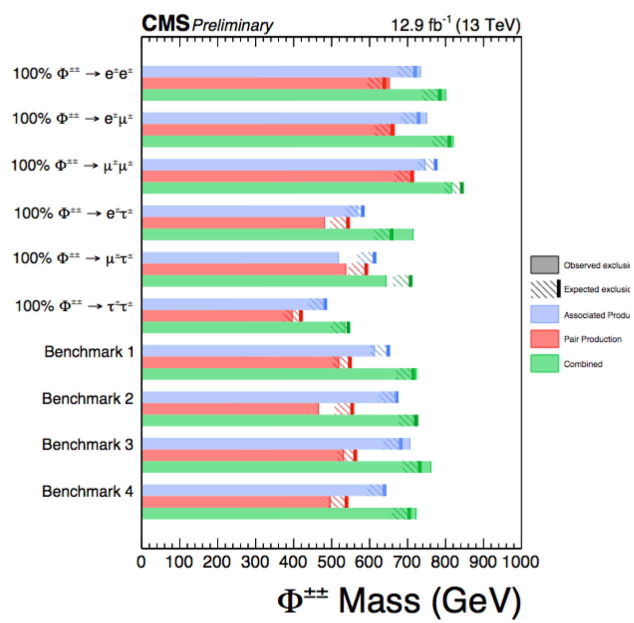
Doubly charged Higgs

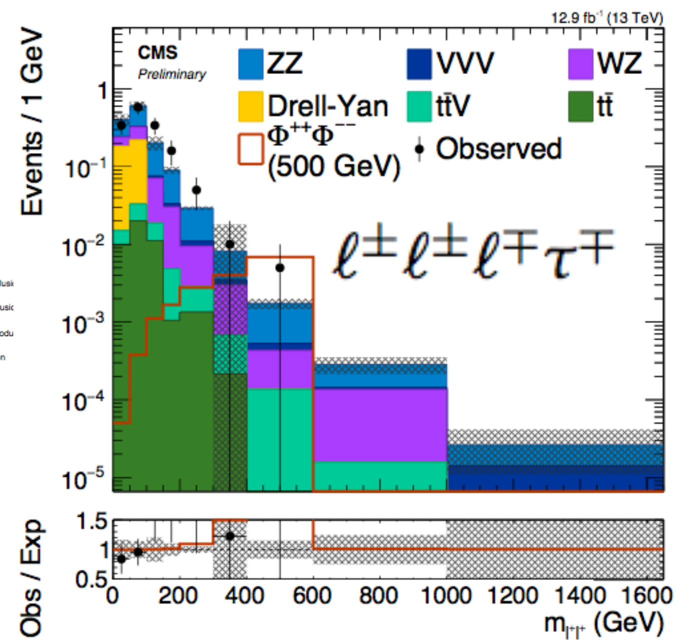
HIG-16-036, arXiv:1710.09748

- Model
  - SM extended with scalar triplet (Φ^{++}, Φ^{+}, Φ^{o})
  - 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





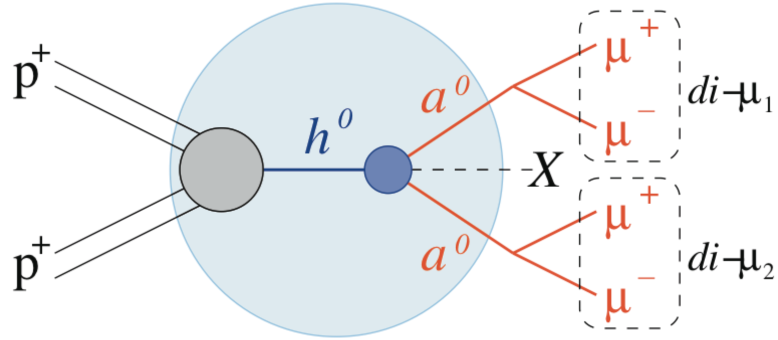




non-SM Higgs decay: h→aa→4X

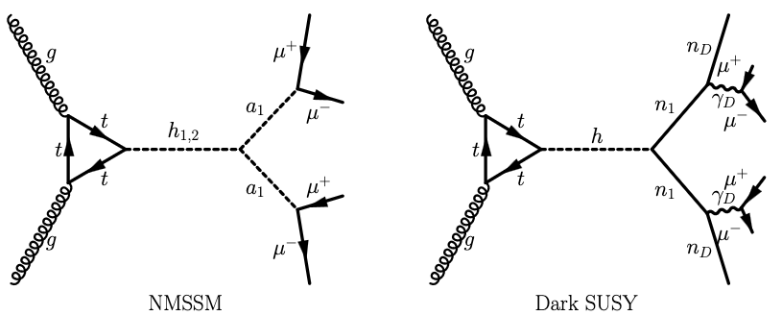
arXiv:2407.20425, arXiv:2403.10341

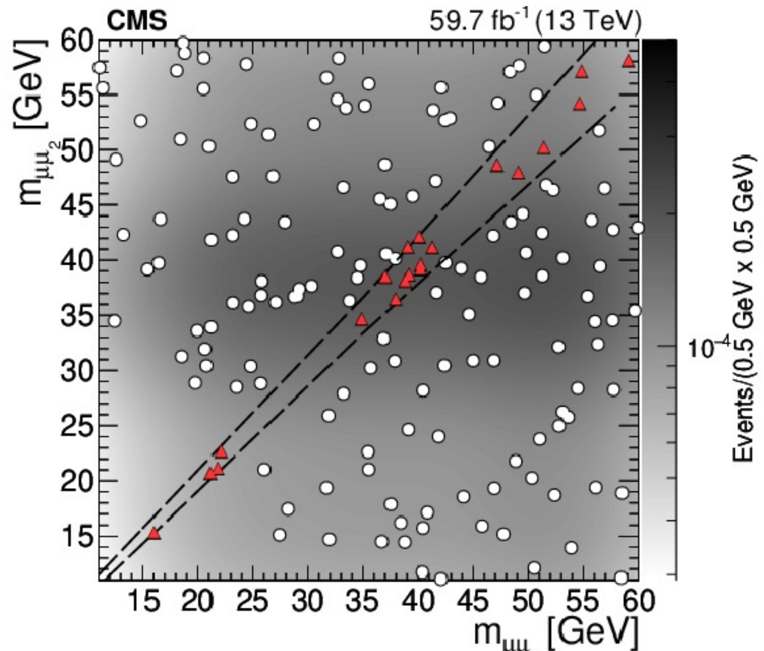
- Explore non-SM decays of a Higgs boson (h)
  - Higgs boson (h) can be SM or not
  - include production of two new light boson (a^0)
- Search for generic Higgs decays: $h \to 2a+X \to 4\mu+X$
  - Require two dimuon pairs with consistent masses
  - Limits on production rates, benchmark models
- (similar search: 4b final state)



Results interpreted in NMSSM and dark SUSY

- Dark SUSY: h decay to pair of neutralinos (n_1): LSP
- NMSSM: add a complex singlet field (1 CP-even+1 CP-odd boson)





NMSSM and Dark SUSY Limits

PLB 726(2013)564, arXiv:1506.00424

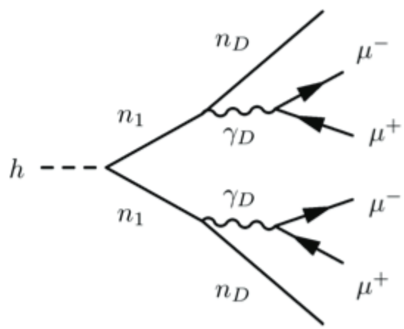
Results interpreted in NMSSM and dark SUSY

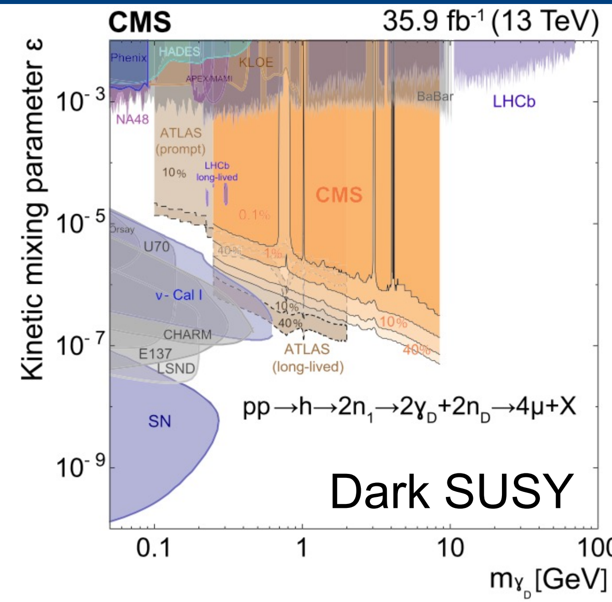
- Dark SUSY: h decay to pair of neutralinos (n_1): LSP

$\mu\mu$

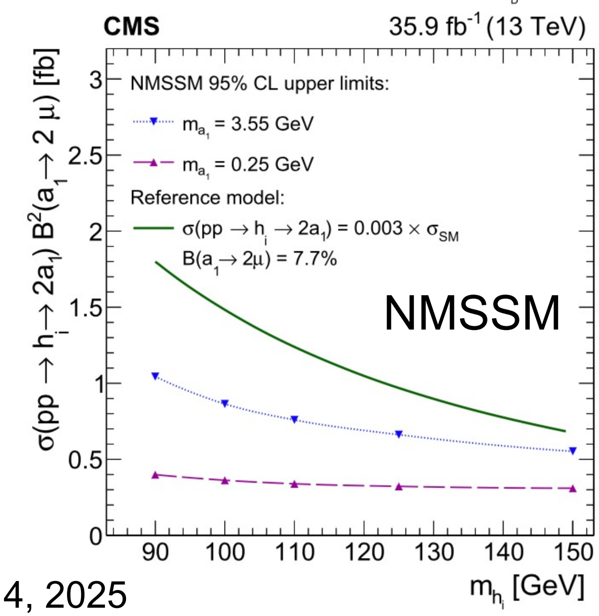
$n_1 \rightarrow n_D \gamma_D$ decays

invisible





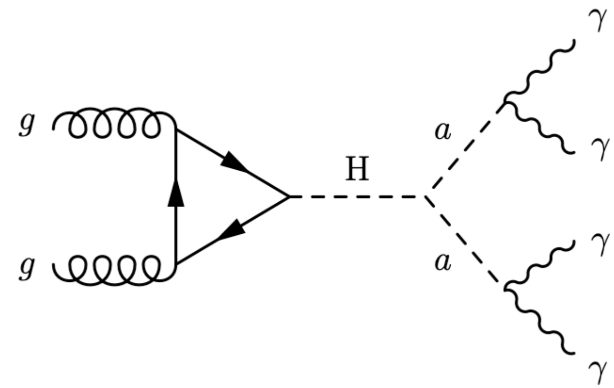
- NMSSM: Extend MSSM by adding a complex singlet field (1 CP-even+1 CP-odd boson)
- NMSSM: $h_{1,2} \rightarrow 2a_1$; $a_1 \rightarrow 2\mu$
- Compare to SM Higgs cross section



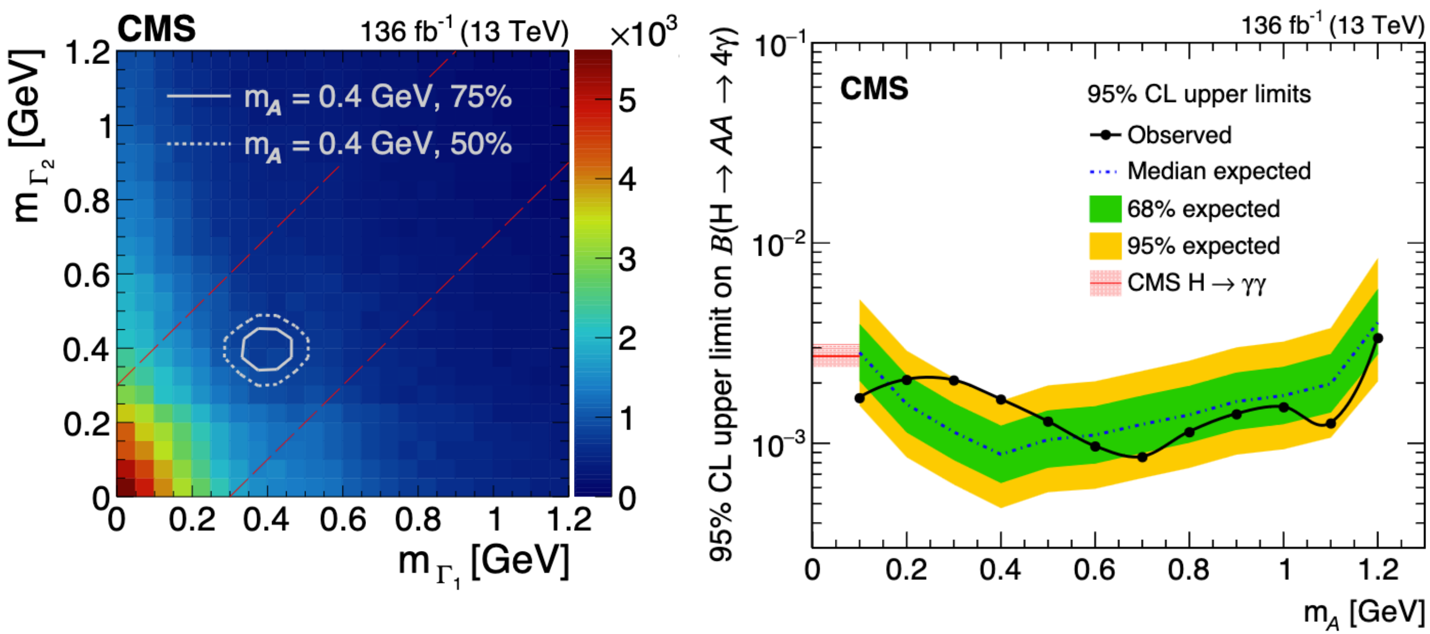
Exotic: H→AA→4γ

arXiv:2209.06197, arXiv:2208.01469

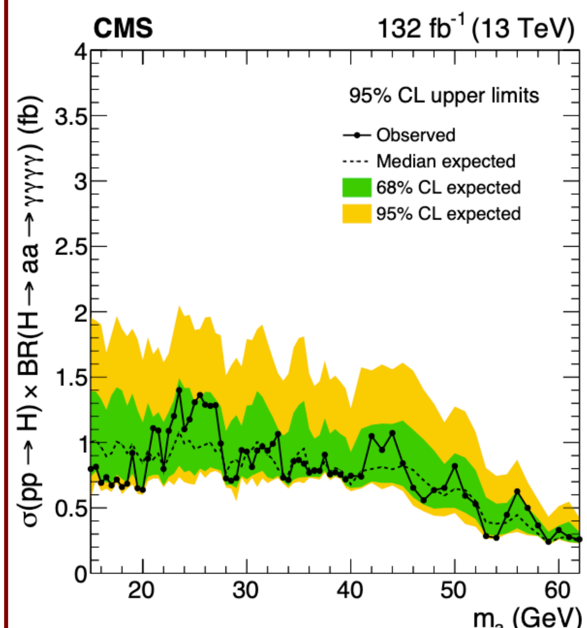
- Exotic Higgs decay to light pseudo-scalar A
  - Motivated in BSM extensions (ALPs, DM, etc)
  - Merged γγ reconstructed as single γ-like object
  - Resolved and boosted topologies
- Model-independent search



boosted



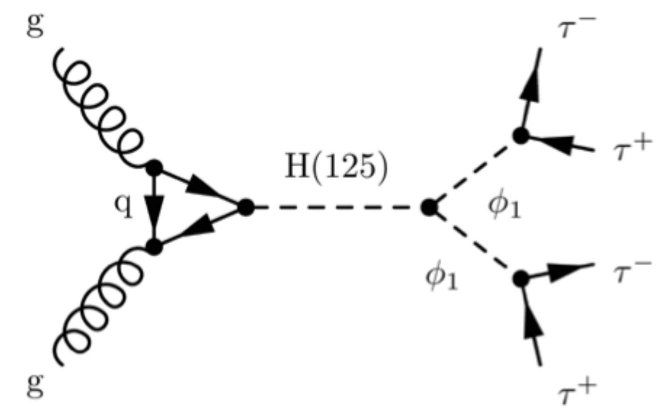
resolved

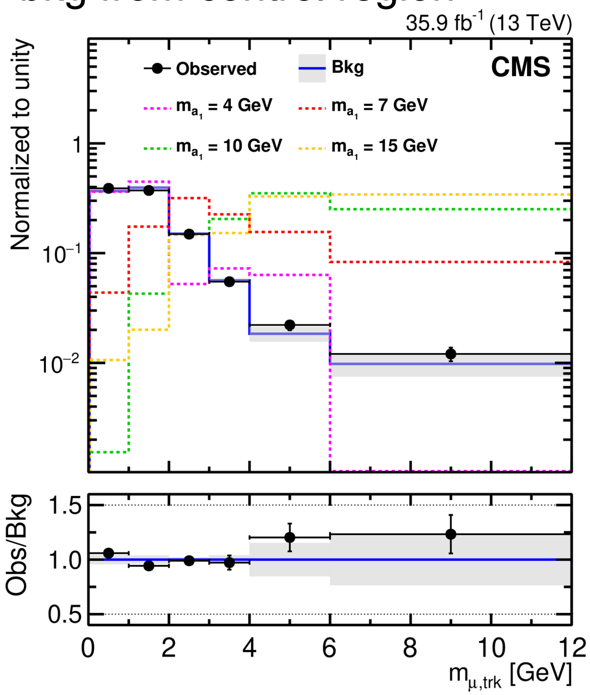


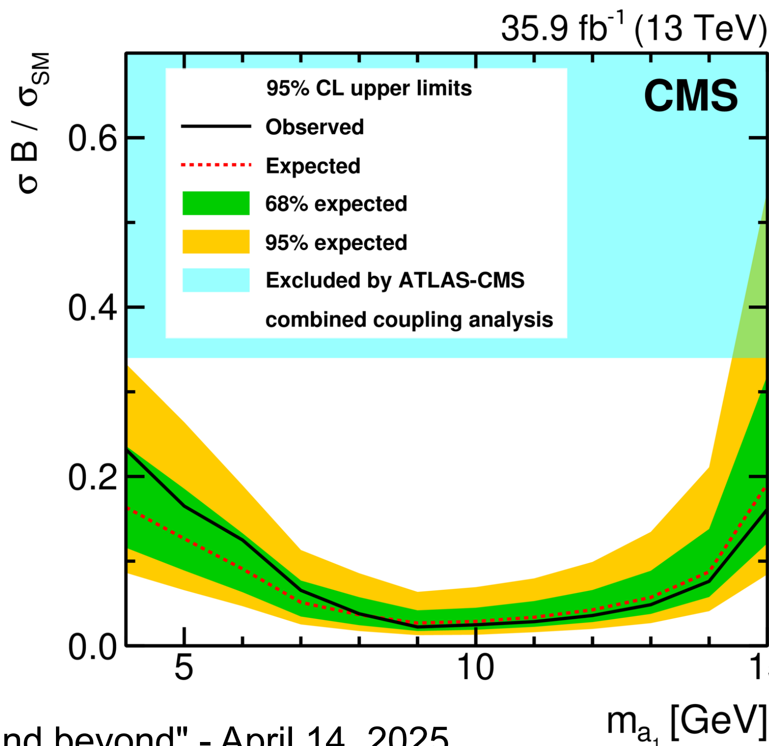
non-SM Higgs decay: $H_{125} \rightarrow 2h(a) \rightarrow 4\tau$

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

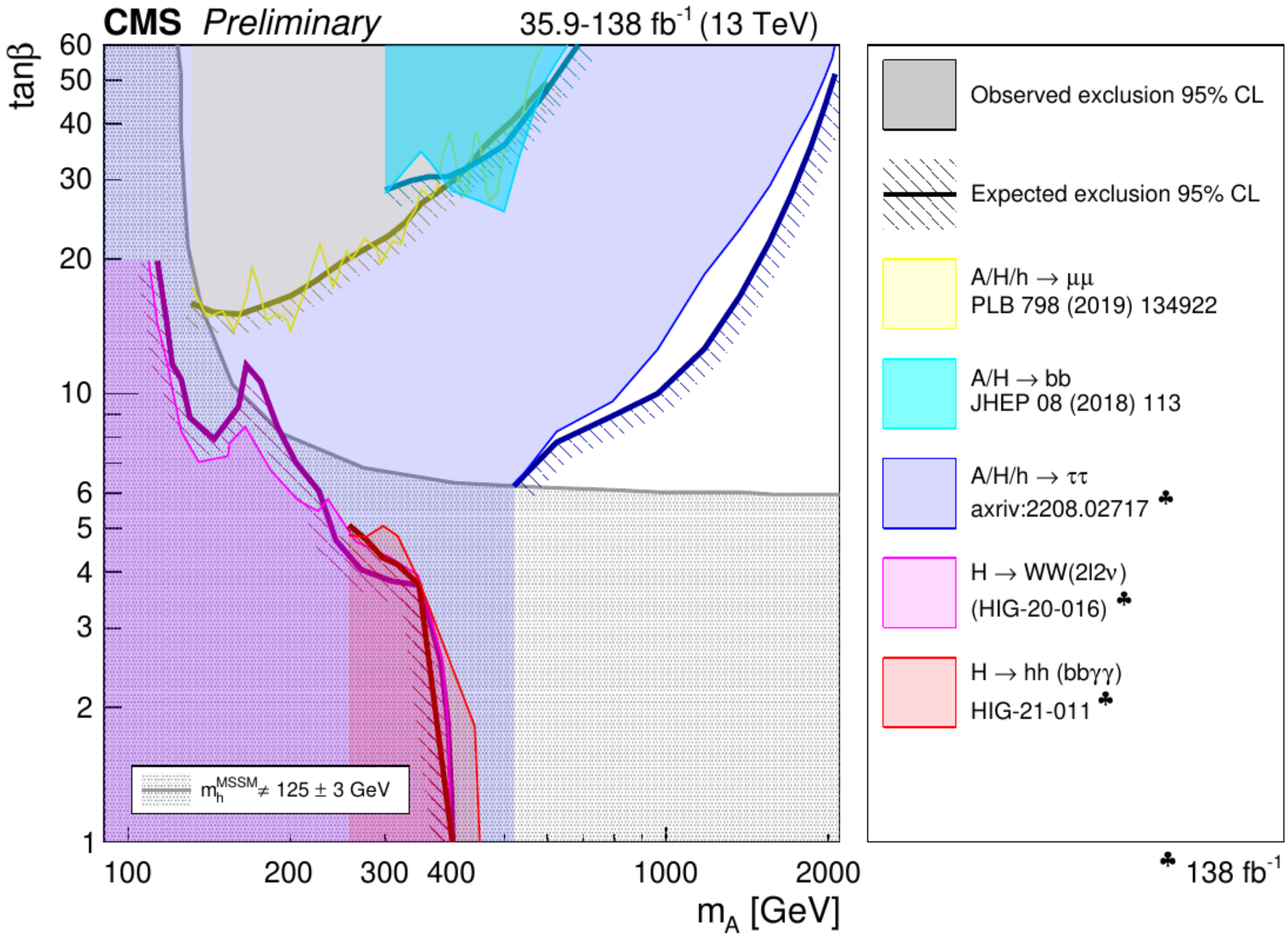
- Search for very light Higgs in NMSSM
  - H(125)⟶light pseudoscalar (ϕ) bosons
  - One ϕ decays to a τ pair, the other to τ/μ pair
- Reconstruct μ-track invar. mass (m_1,m_2)
  - SS dimuon sample (removes DY)
  - bin in 2-dim distribution, fit signal and bkg
  - QCD bkg from control region







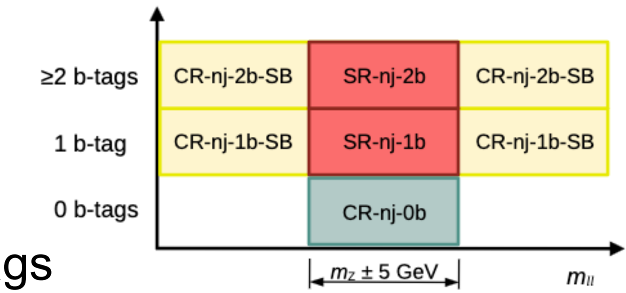
Summary for Higgs exotic decays



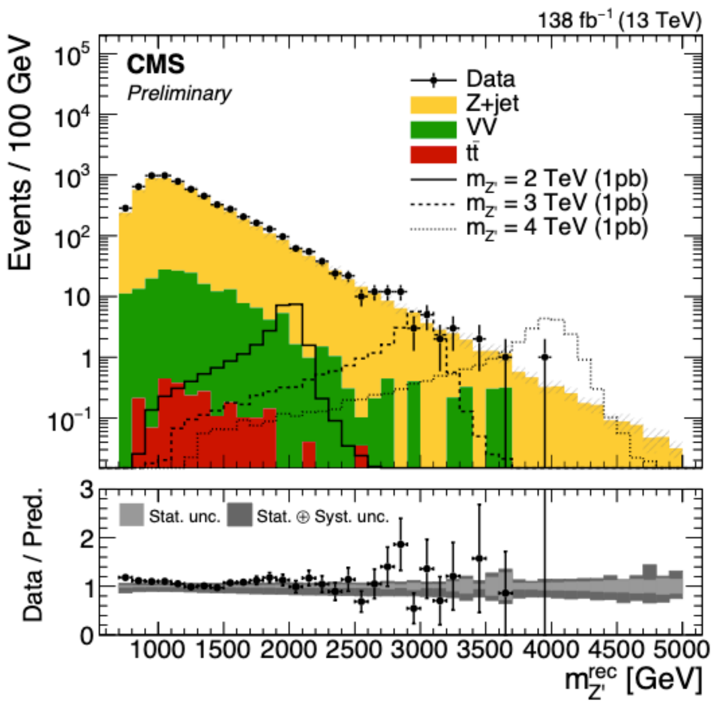
Heavy resonance search: ZH

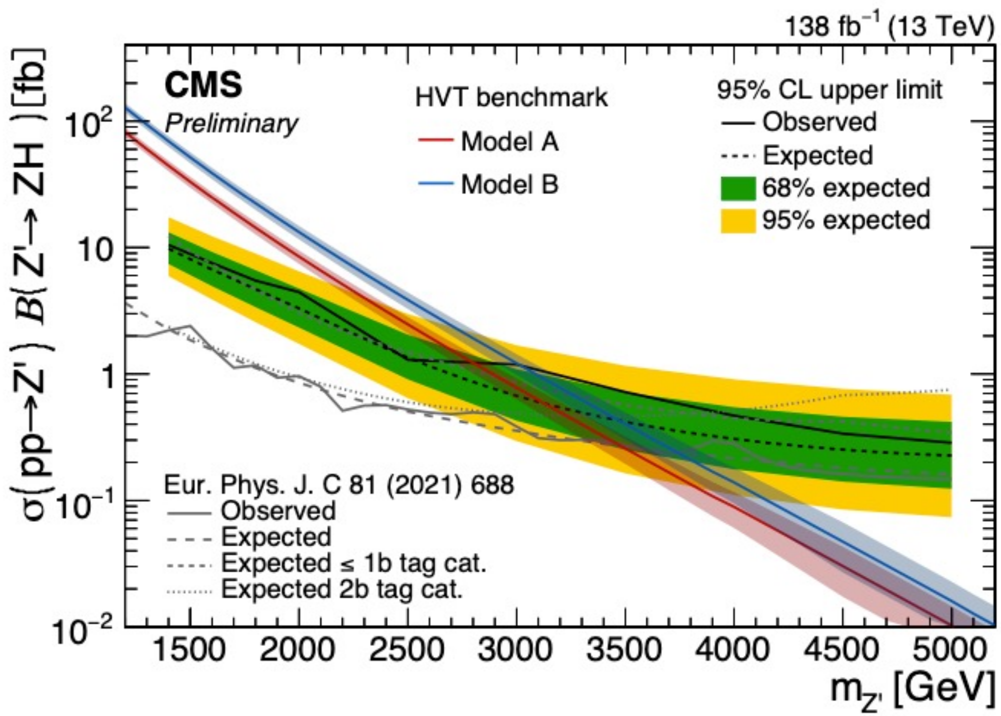
CMS-B2G-23-008, B2G-23-006

- Search for heavy resonance: Z($\ell\ell$)H
  - H → cc or VV(4q)
  - H as AK8 jet recoiling against Z
  - Jet substructure to discriminate vs bkg (DNN)
  - H→ttbar
  - Event categories: leptons, b-tags



- Reconstruct invariant mass of ZH system

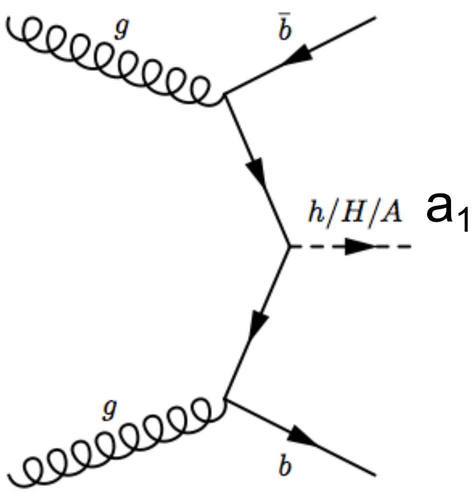


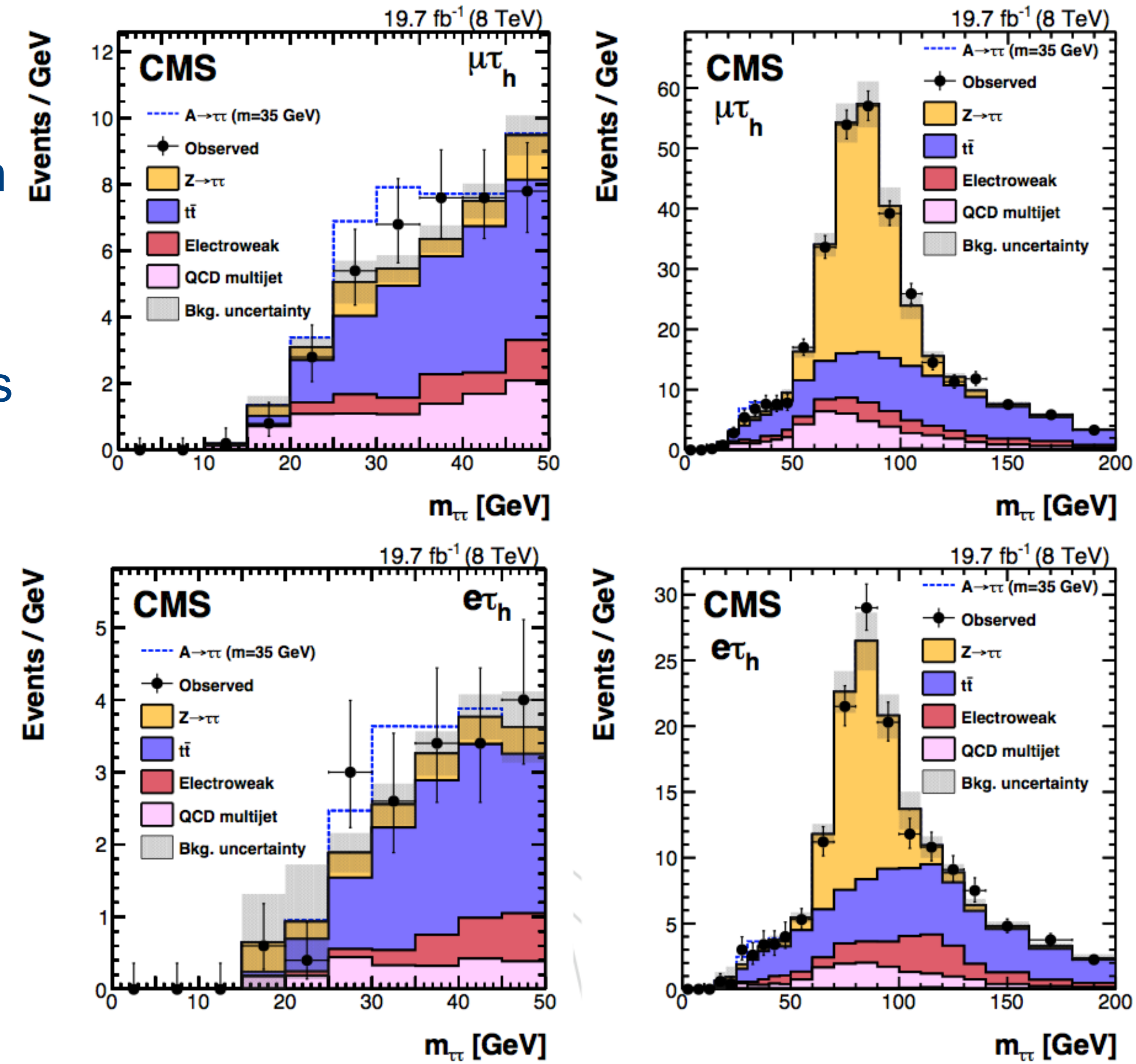


Low mass Higgs: a(→ττ)bb

arXiv:1511.03610, JHEP05(2019)210

- Low mass Higgs in the NMSSM
- Low mass pseudo-scalar ($a_1 \rightarrow \tau\tau$) in association with bbar: $a_1 bb \rightarrow \tau\tau$ bb
- Similar strategy to $H \rightarrow \tau\tau$
- Search for a_1 masses below Z mass
- No evidence for signal
- Set limits: σxB~9-39 pb

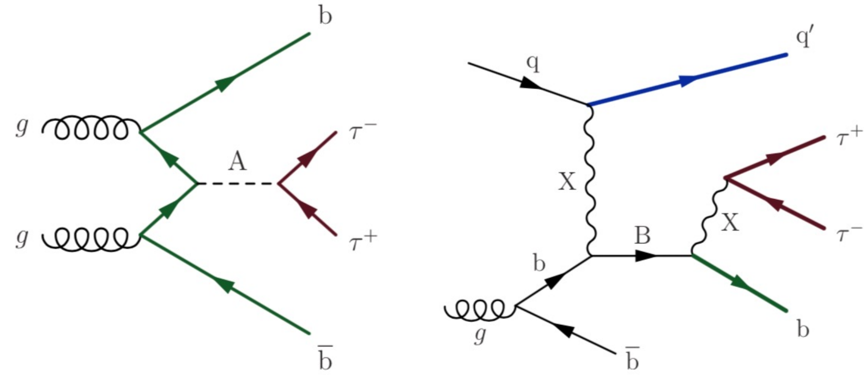


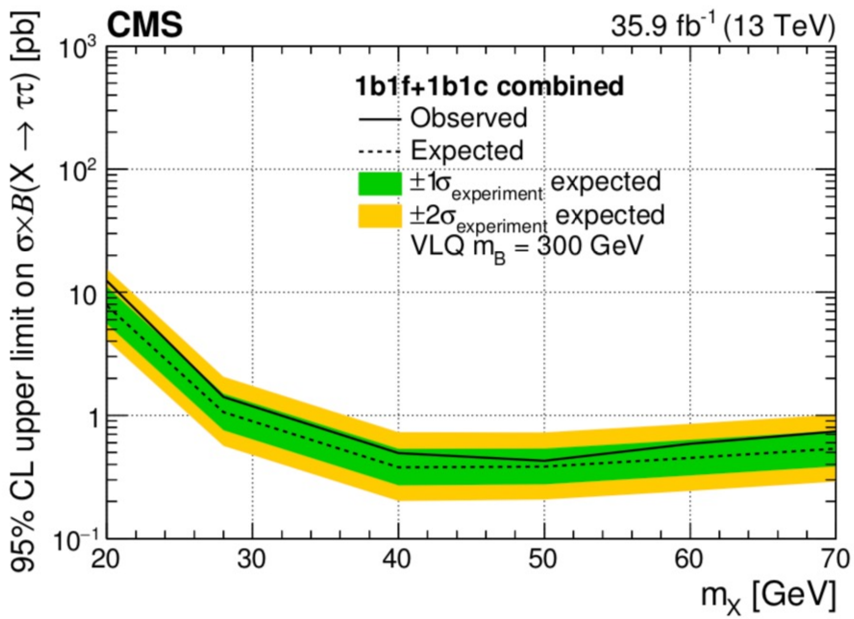


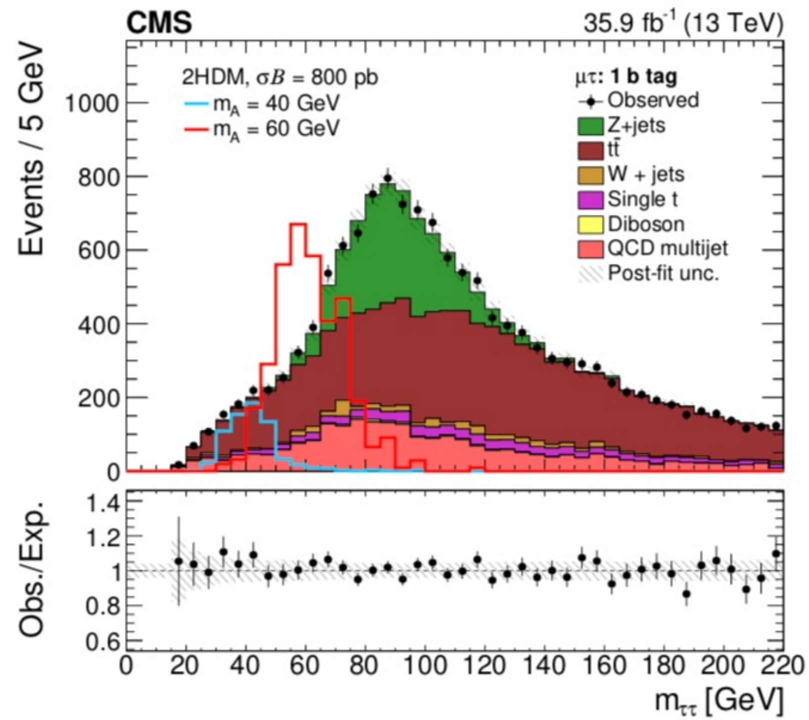
Low mass Higgs: a(→ττ)bb

arXiv:1511.03610, JHEP05(2019)210

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



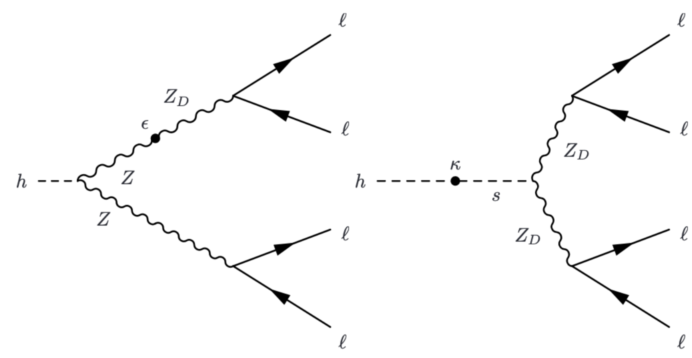


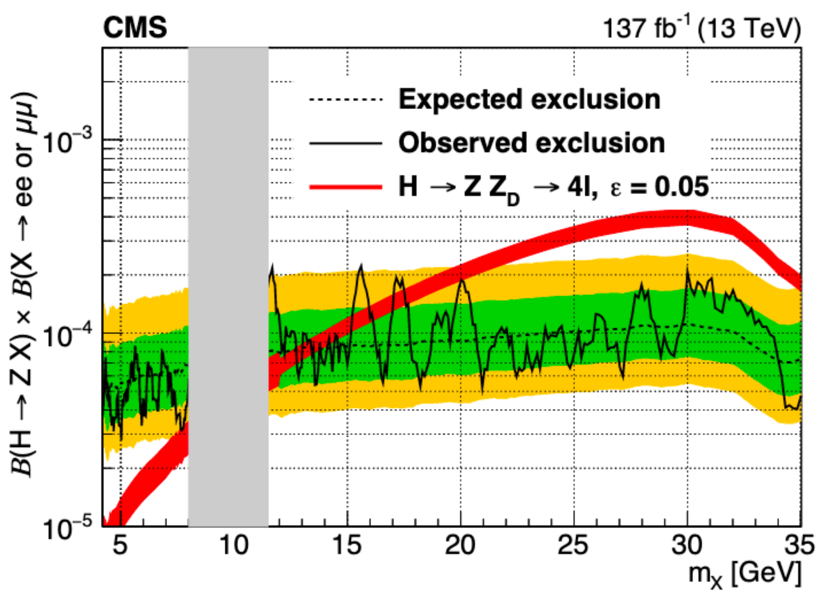


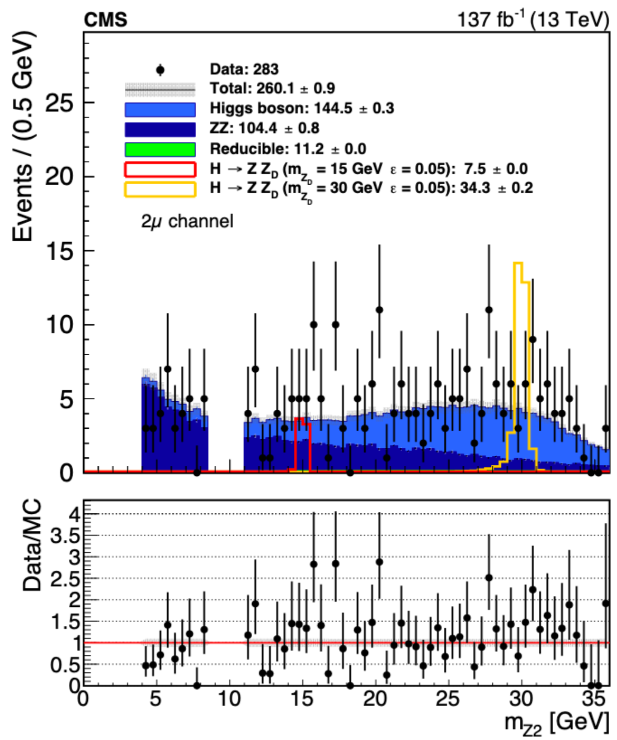
Low mass dilepton resonance

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



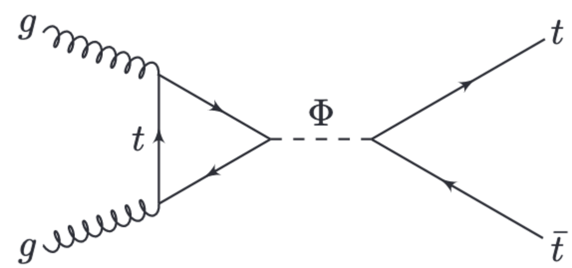


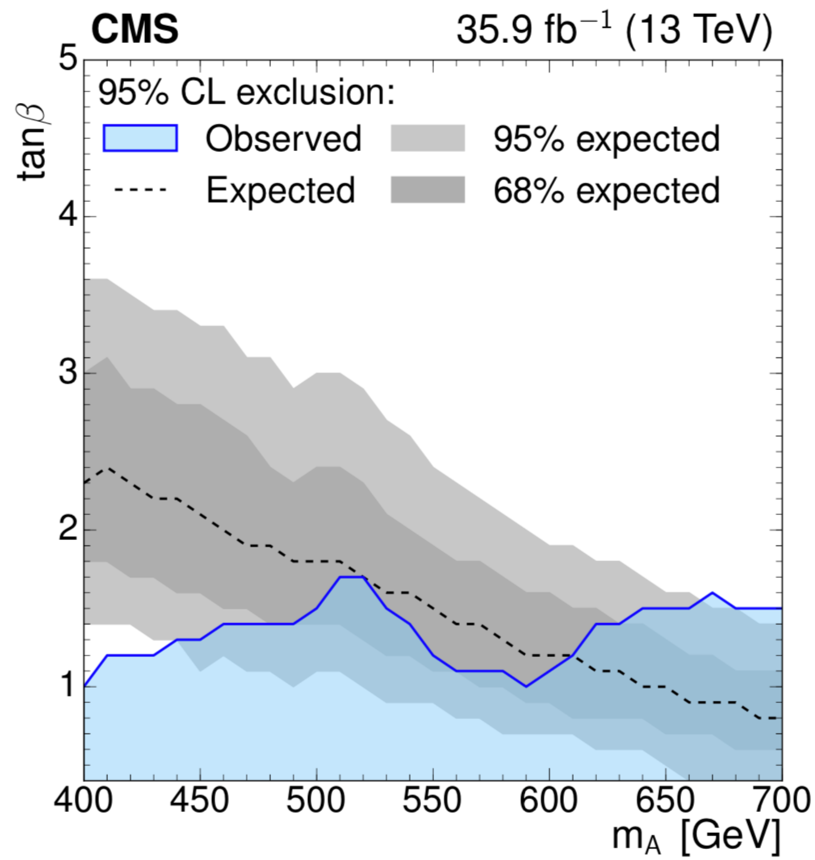


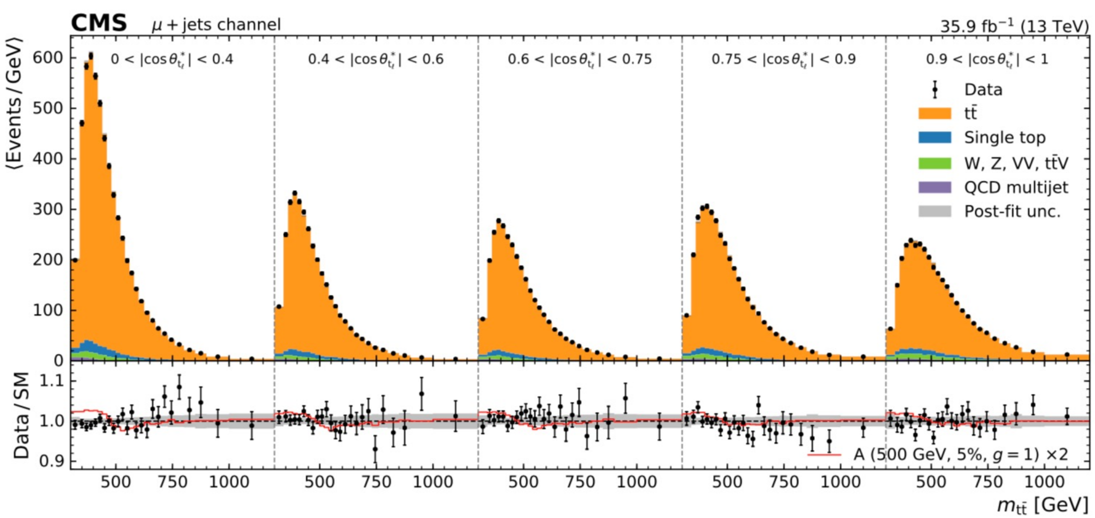
Heavy Higgs: H→ttbar

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)

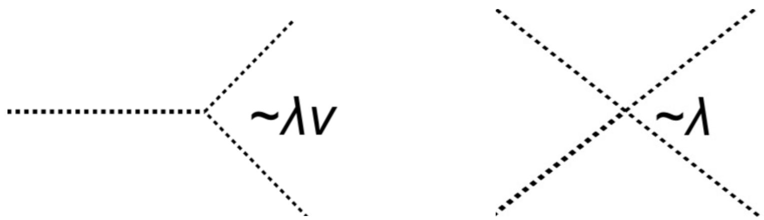






Higgs self-coupling

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

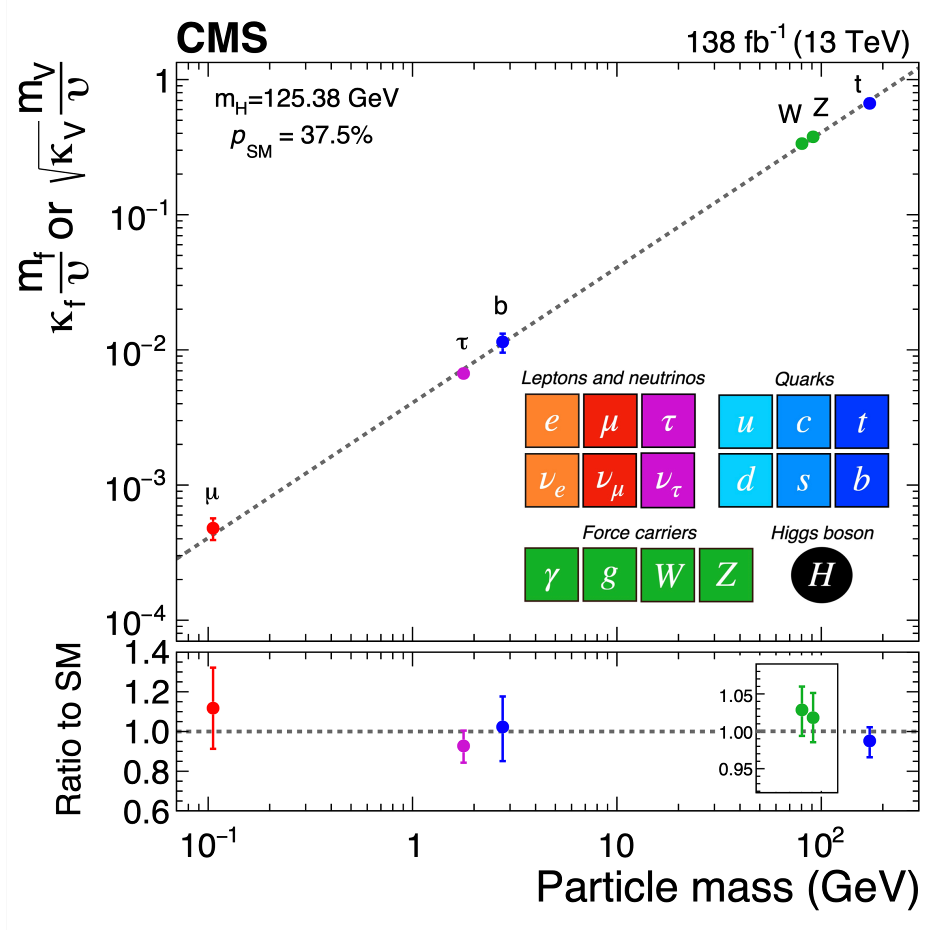


H trilinear coupling

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

Use coupling modifiers:

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



di-Higgs searches

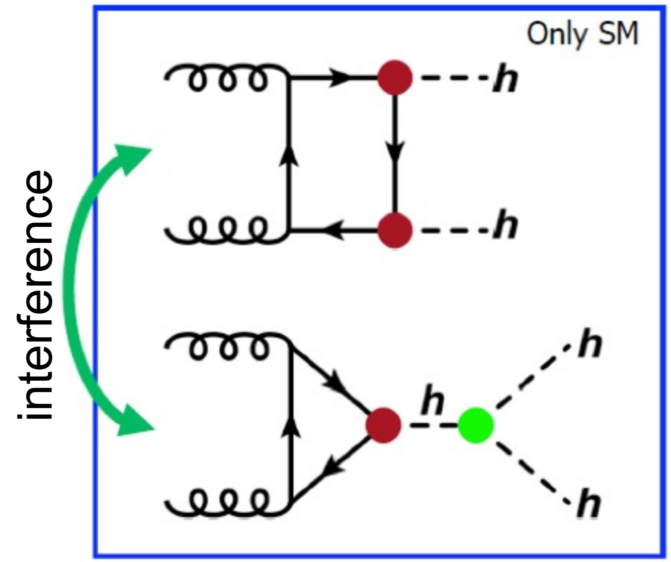
- Self-coupling measurement
- Destructive interference in SM
  - Could be altered in BSM
  - If constructive, it could be large enhancement
- In SM, only σ=31fb at 13 TeV
- Study different final states

$(X\rightarrow)hh\rightarrow$

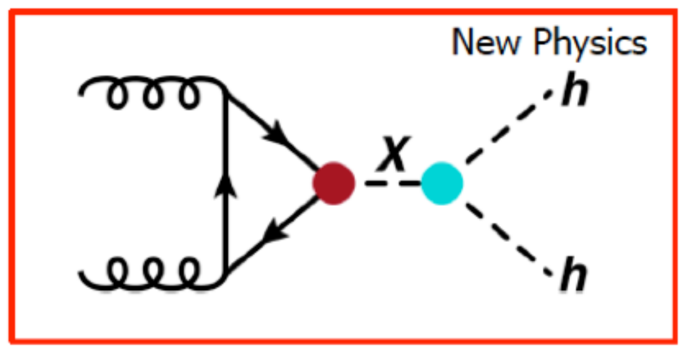
	BR	Mass scale
$bbbb$	34%	High
$bb\tau\tau$	7.3%	High
$bbWW$	27%	High
$bb\gamma\gamma$	0.26%	Low

$$V(h) = \underbrace{V_0 + \frac{1}{2}m_H^2h^2}_{\text{Mass Term}} + \underbrace{\lambda_{hhh}vh^3}_{\text{HH production}} + \underbrace{\frac{1}{4}\lambda_{hhhh}h^4}_{\text{HHH production}}$$

non-resonant production

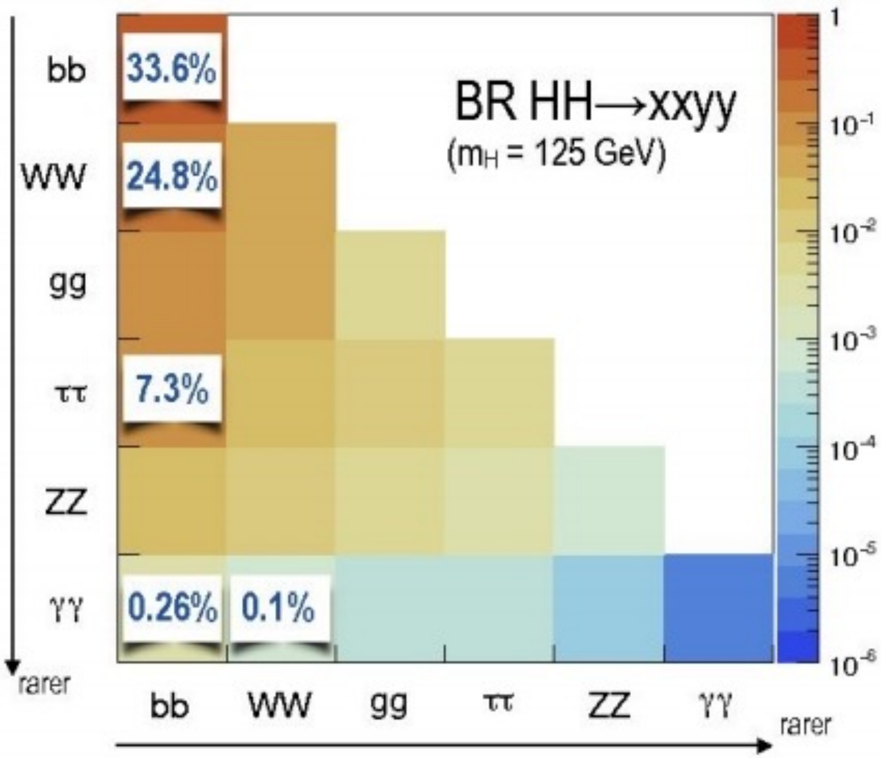


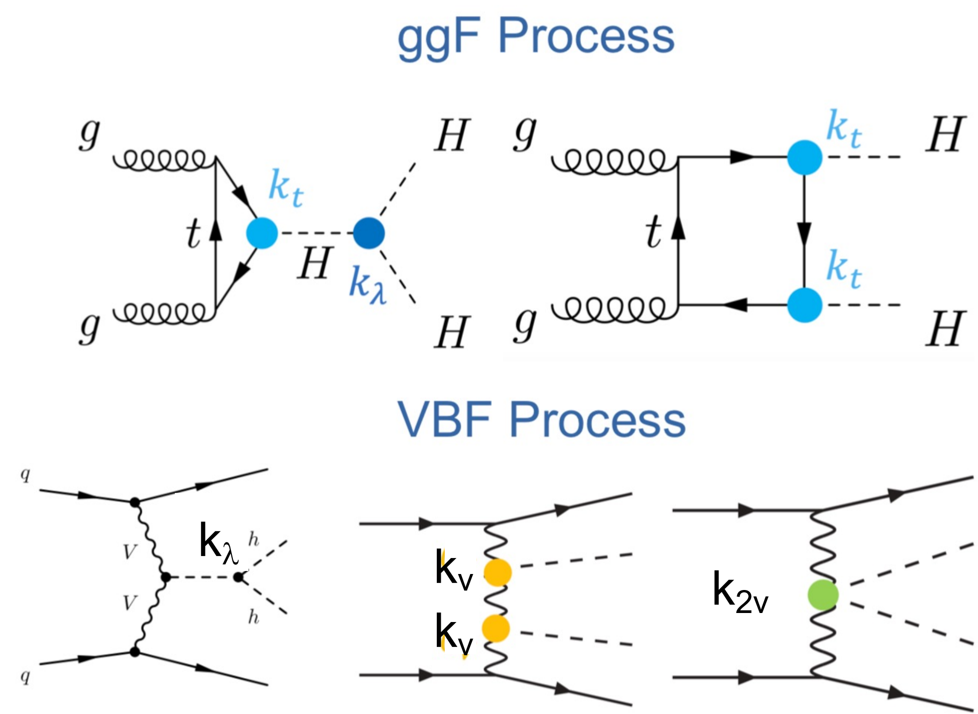
resonant production



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



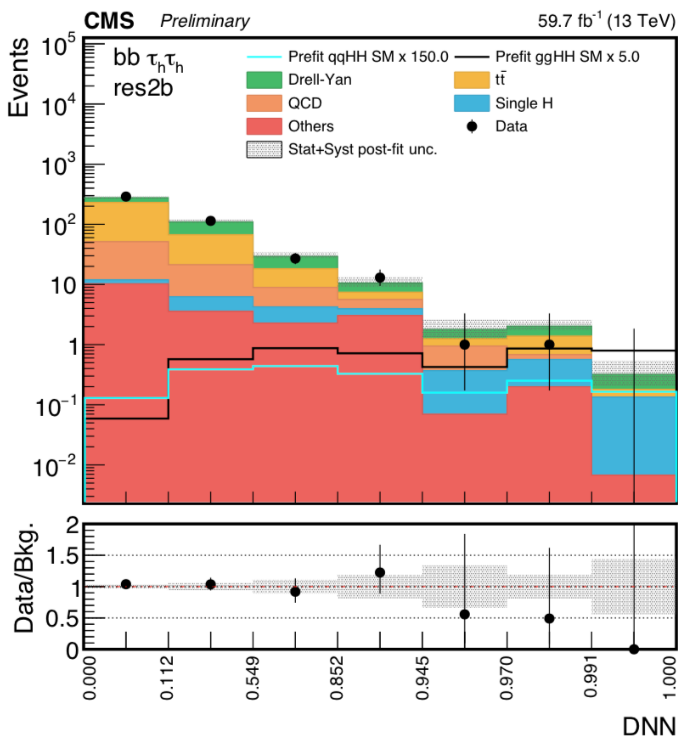


What is new in HH searches

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

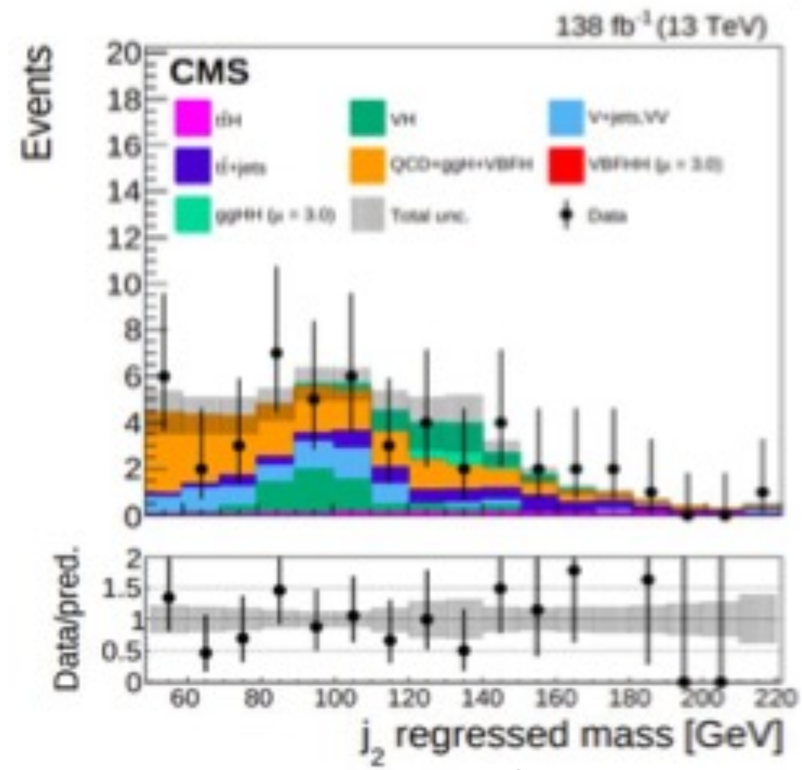
- Results are better (x2-3) than 2016 results alone after scaling for luminosity

Extensive use of ML tools



DNN score for resolved ggHH(bbττ) category

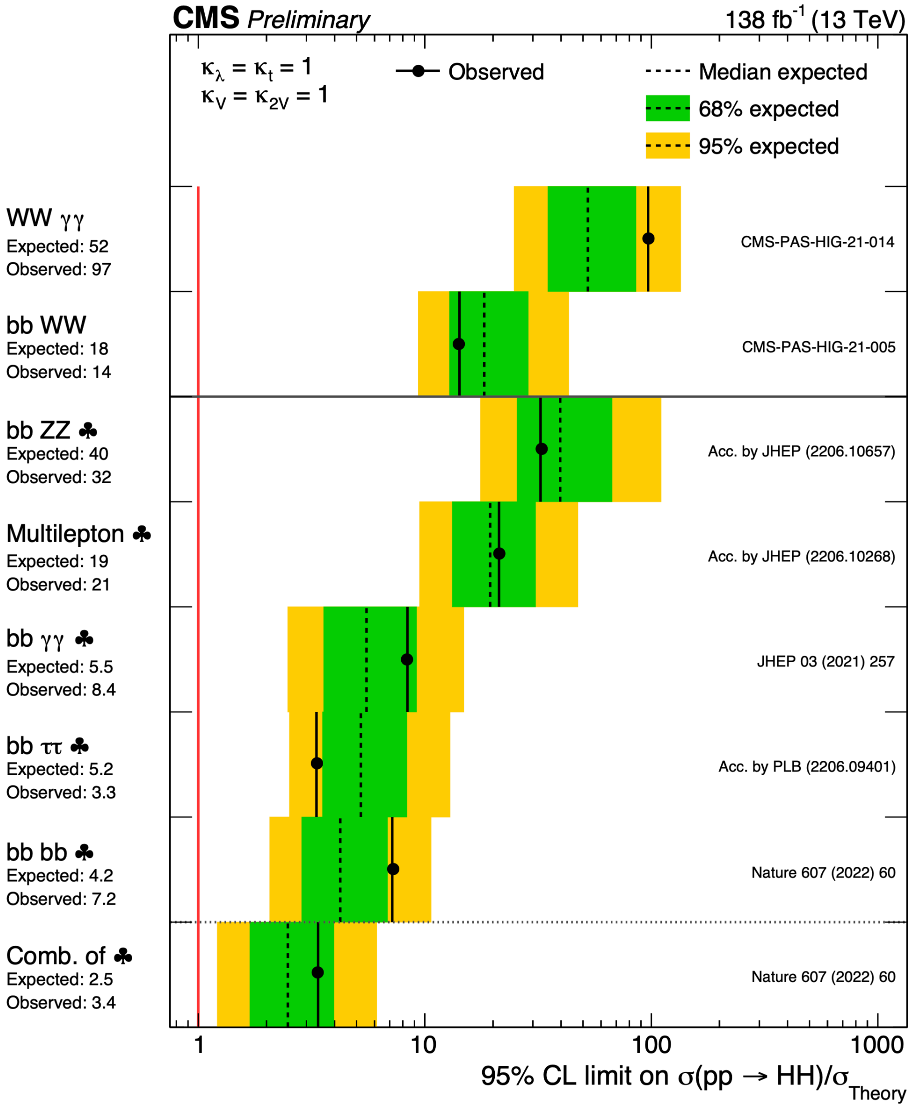
Boosted topologies

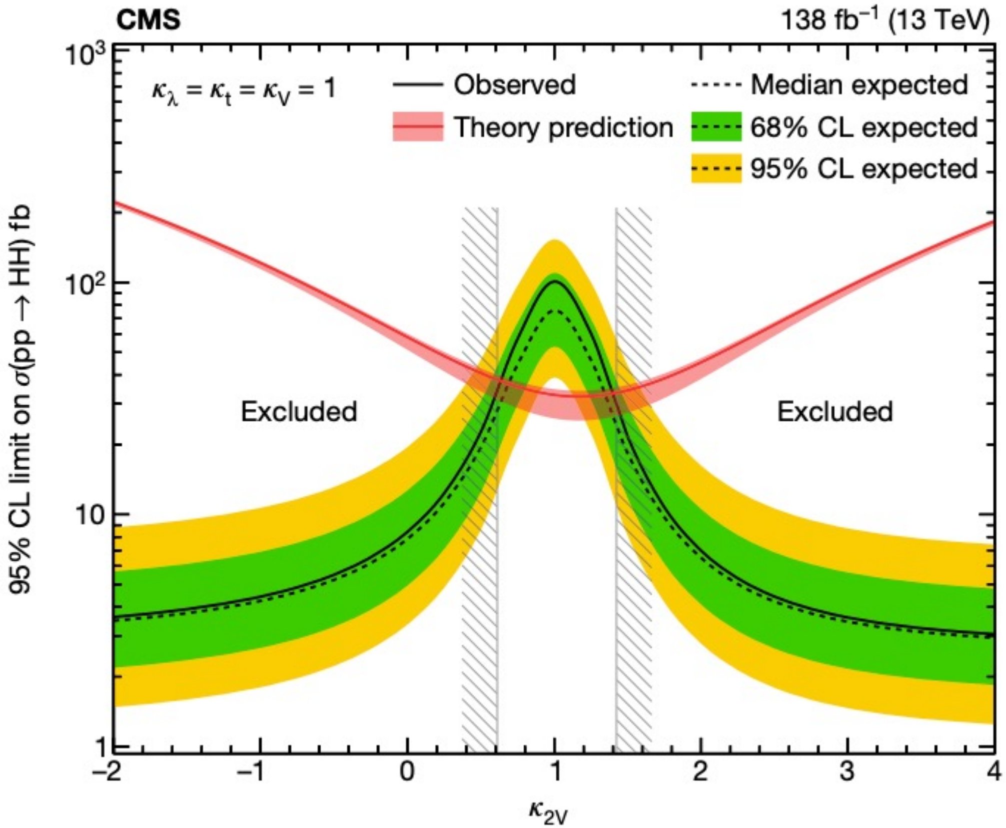


Regressed mass of one AK8 jet in a ggHH(4b) boosted category

HH: Results

Nature 607(2022)60



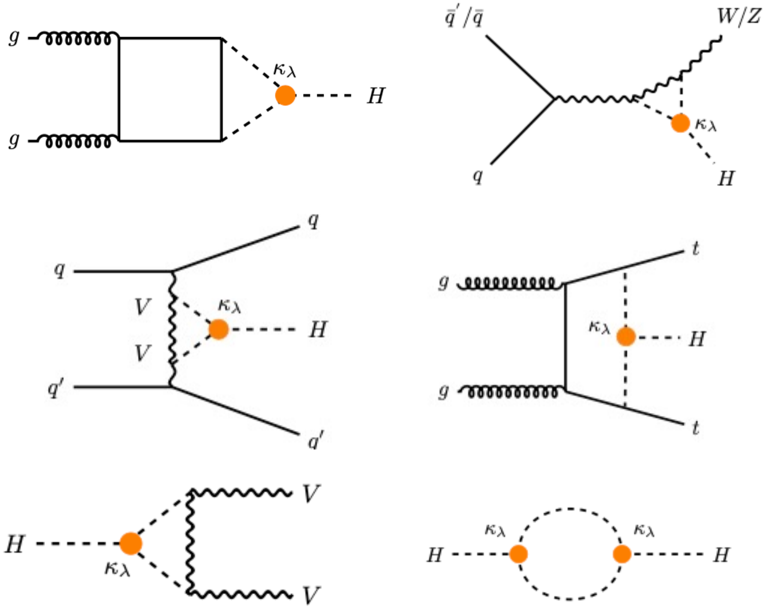


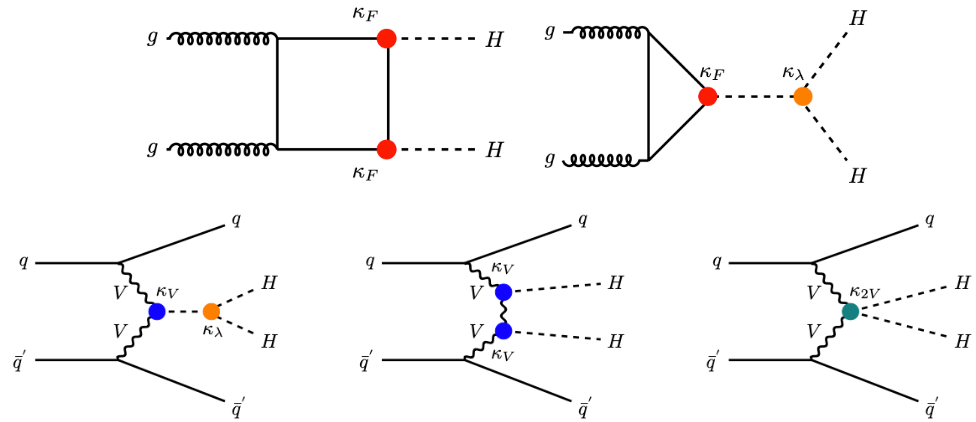
Combined sensitivity:

- $k_\lambda \in [-1.24, 6.49]$
- $k_{2V} \in [0.67, 1.38]$

Self-coupling: H and HH

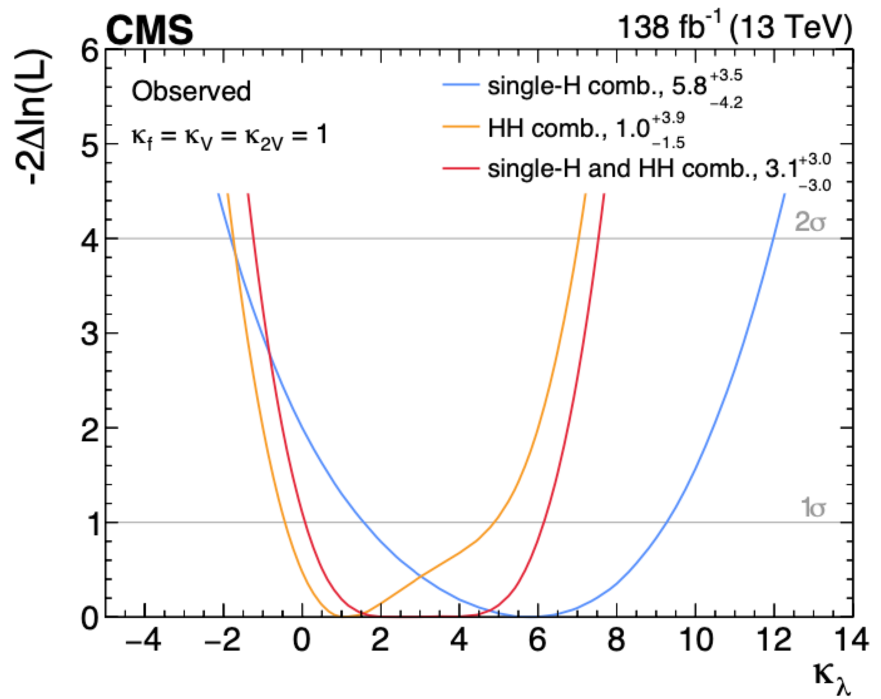
arXiv:2407.13554





- Set constraints on H self-coupling
- Use H and HH results:
  - HHVV coupling (k_{2V}) affects VBF HH mechanism
  - H: Use NLO EWK corrections

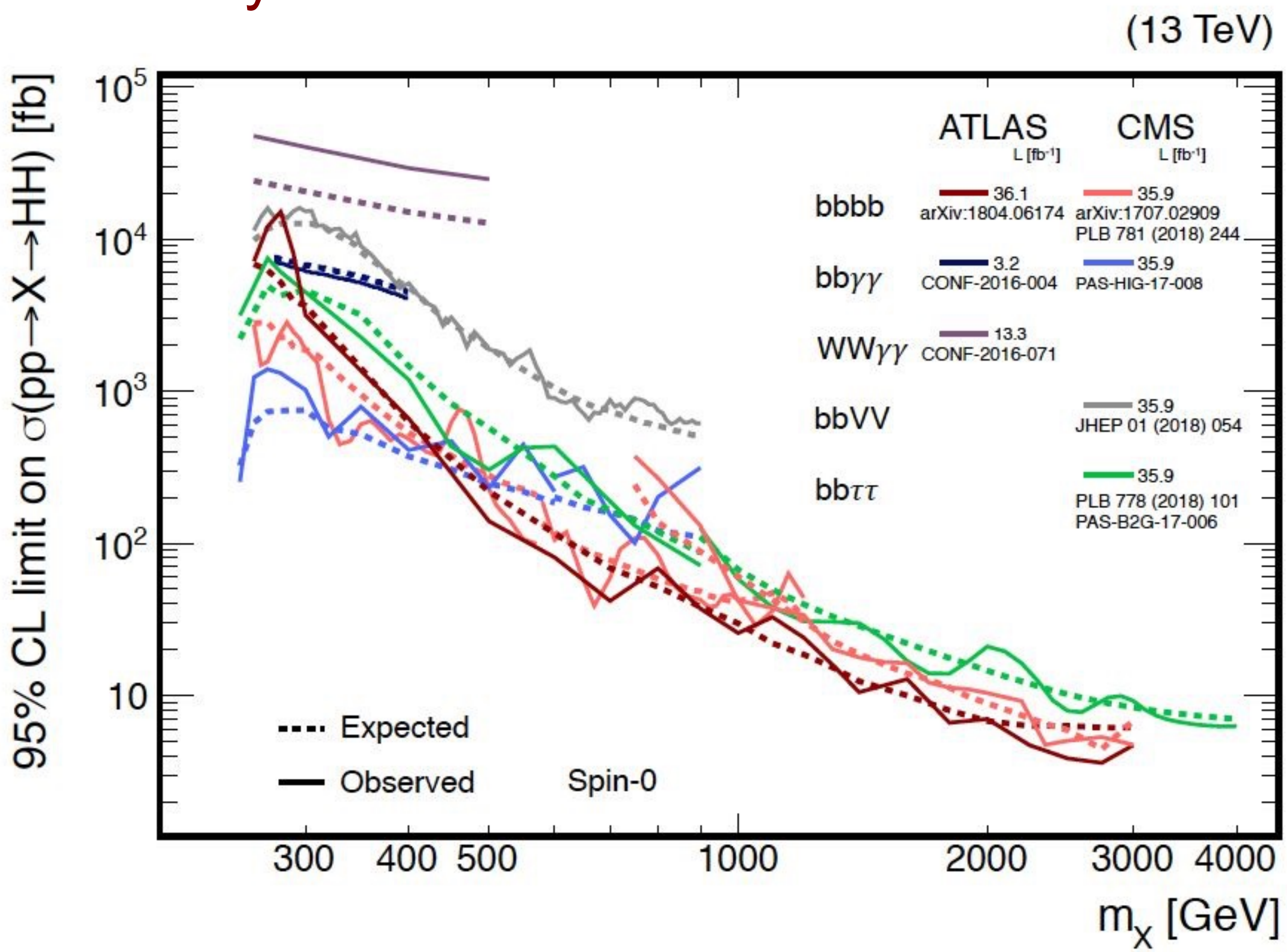
$\Rightarrow k_\lambda \in [-1.2, 7.5]$ @95%CL



Double Higgs production

PRL 122(2018)121803

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

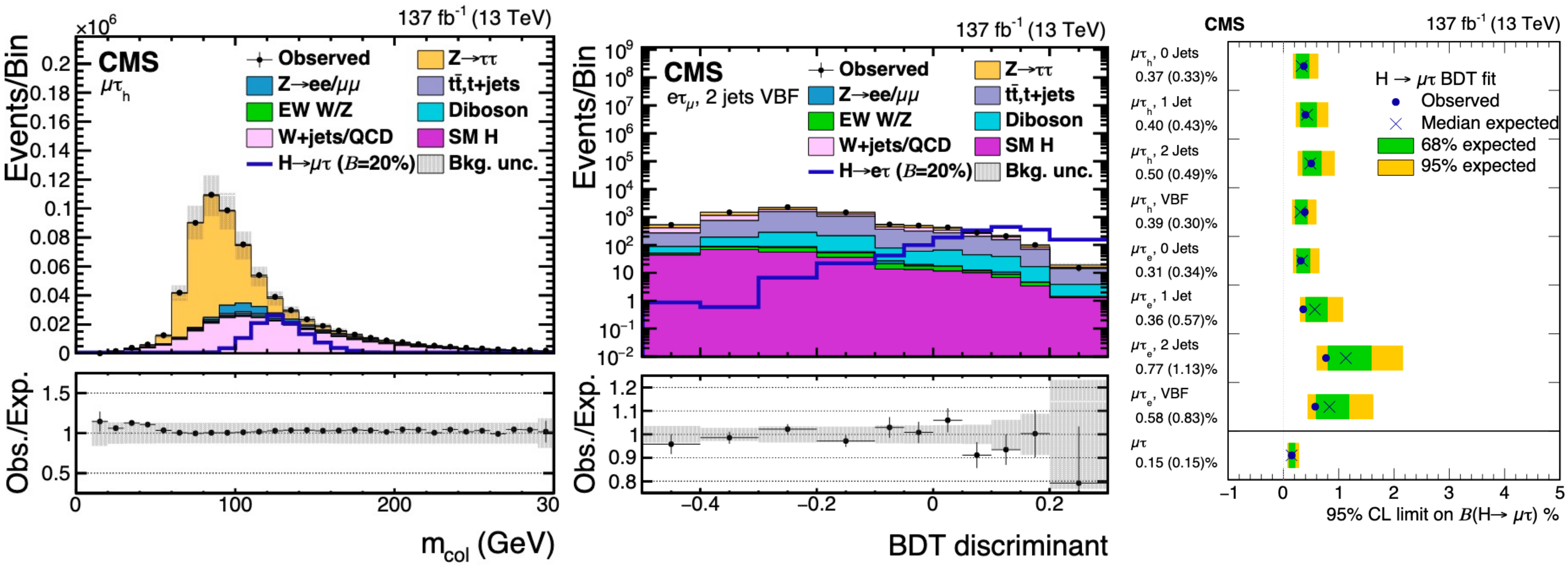


LFV in Higgs decays

arXiv:1911.10267, arXiv:2105.03007

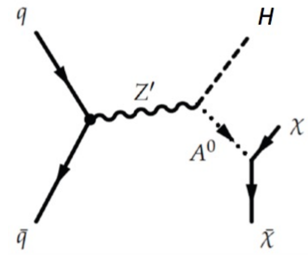
- Some BSM models allow for LFV Higgs decays
- Search for $H \to e\tau$, $e\mu$, $\mu\tau$ final states
- Categories: N_{jet}, lepton kinematics
  - N_{jet} to target ggH and VBF production
- Main background from DY, ttbar, WW

	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	$< 1.35\,(1.14) \times 10^{-3}$

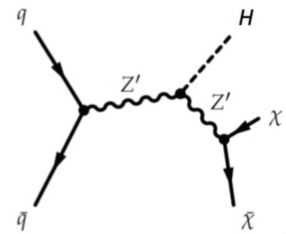


DM searches with Higgs bosons

- 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

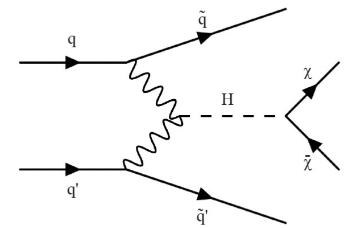


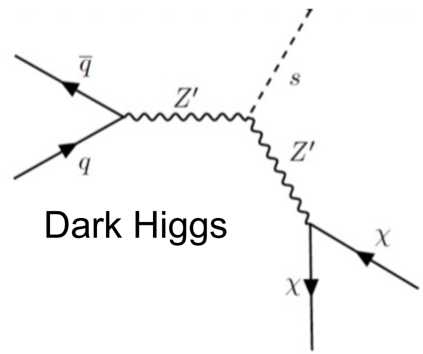
Z' – 2HDM



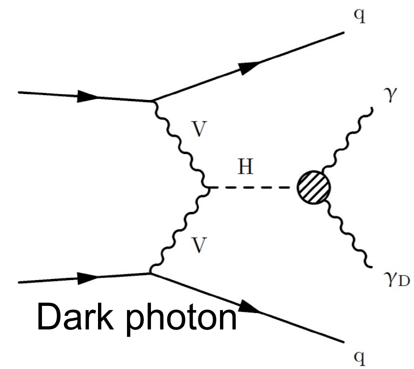
Z' – baryonic

Invisible Higgs





Dark Higgs



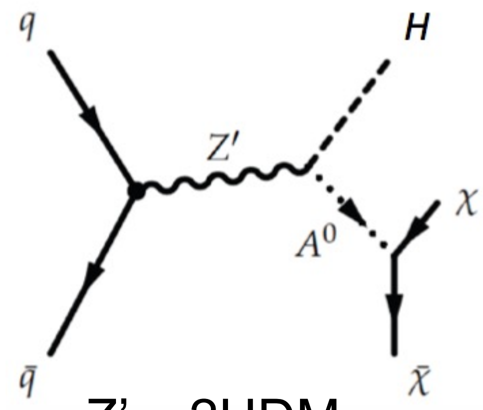
Dark photon

Mono-Higgs

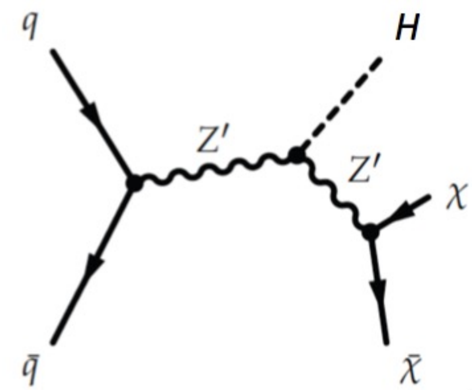
- Generic search: pp→H+MET
- ISR suppressed due to small coupling to H
- Signature: Higgs+MET ⇒ H used as a tag
- Final states (WW,ZZ,bb,$\tau\tau$,$\gamma\gamma$)

DM searches with Higgs bosons

- H(125) may mix with new dark mediators
- Signature: Higgs+MET ⇒ H used as a tag
- Final states:
  - H → bb ~58%, large bkg
  - H → WW ~21%, moderate bkg
  - H → $\tau\tau$ ~6%, lower bkg
  - H → $\gamma\gamma$ ~0.2%, clean final state



Z' – 2HDM

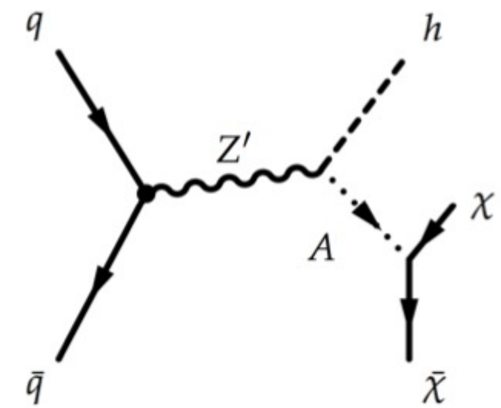


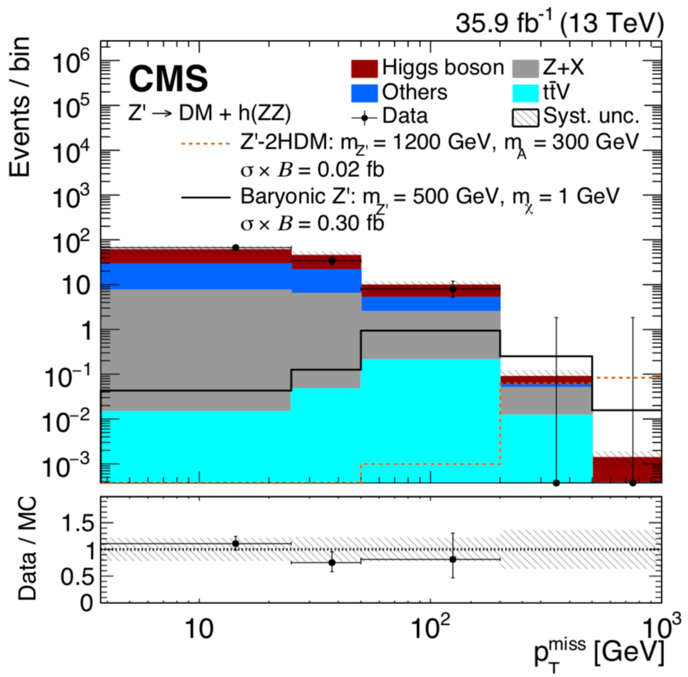
Z' – baryonic

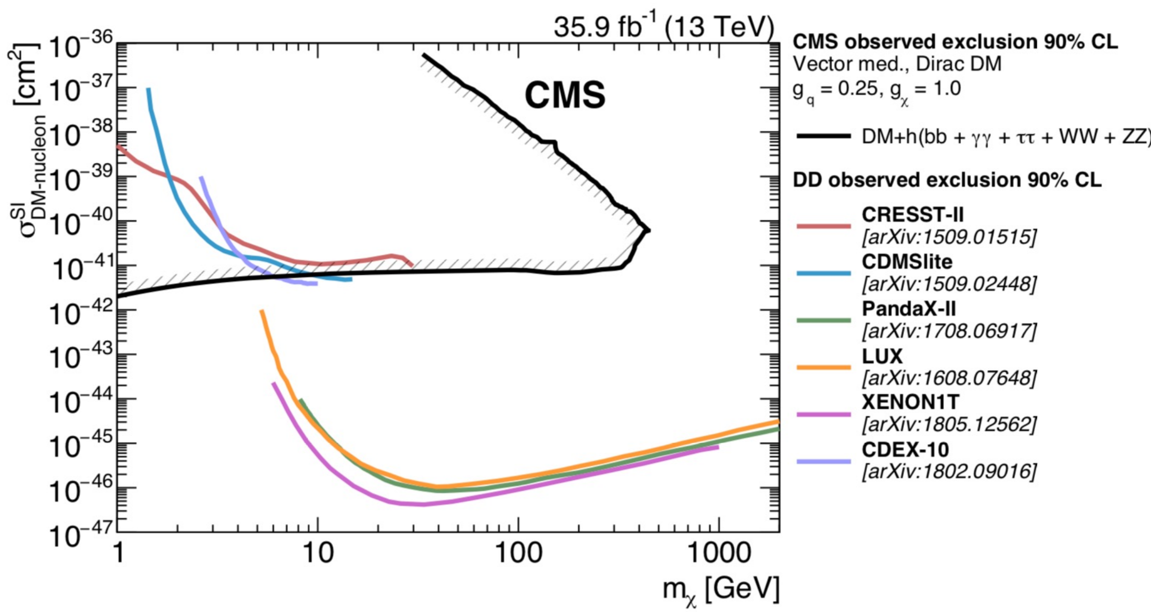
Higgs + Dark Matter

arXiv:1908.01713

- Generic search: pp→H+MET
  - ISR suppressed due to small coupling to H
  - In the context of simplified models
- DM search with H(→bb,γγ, ZZ,WW,ττ)
- Signal events at large MET





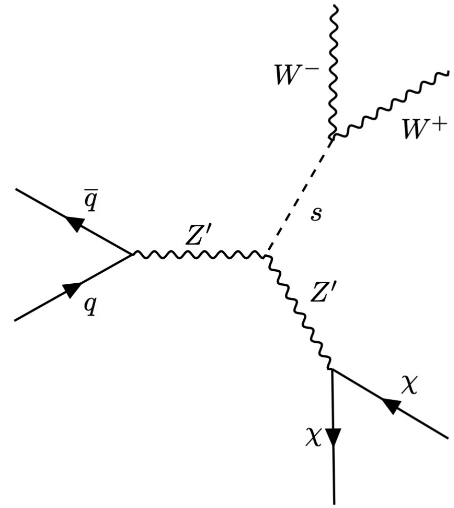


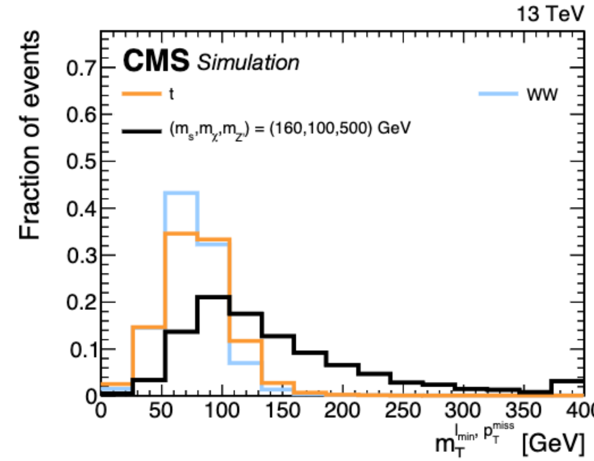
Dark Higgs & Dark photon

arXiv:2310.12229, arXiv:1908.02699, arXiv:2009.14009, arXiv:2405.13778

Dark Higgs

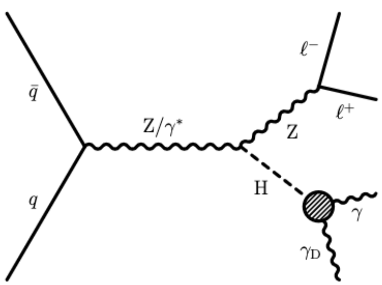
- DM particle acquire mass through interaction with a dark Higgs (s)
- WW decay dominates for m_s>160GeV
  - leptonic final state ($2\ell2\nu$, $2\ell2q$)
- Observable: $m_T(\ell,\mathrm{MET})$

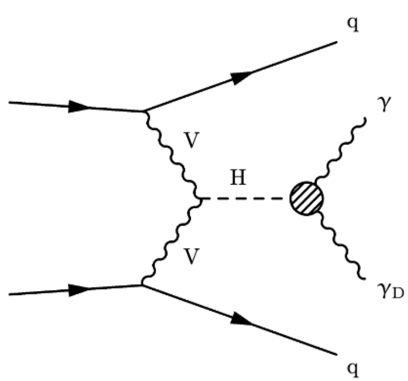


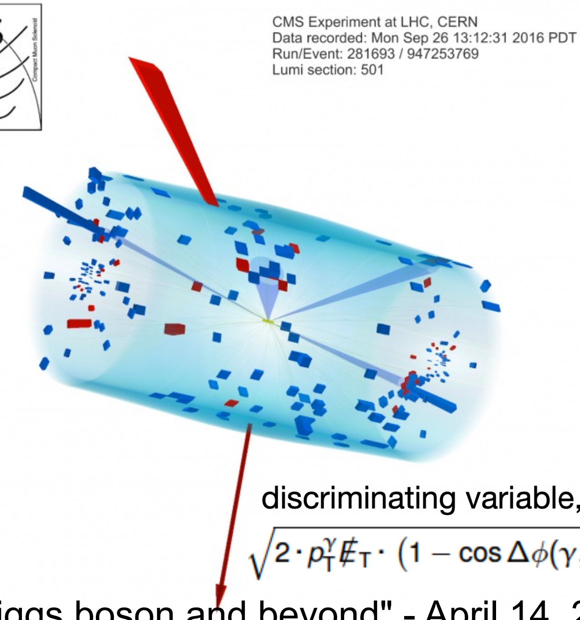


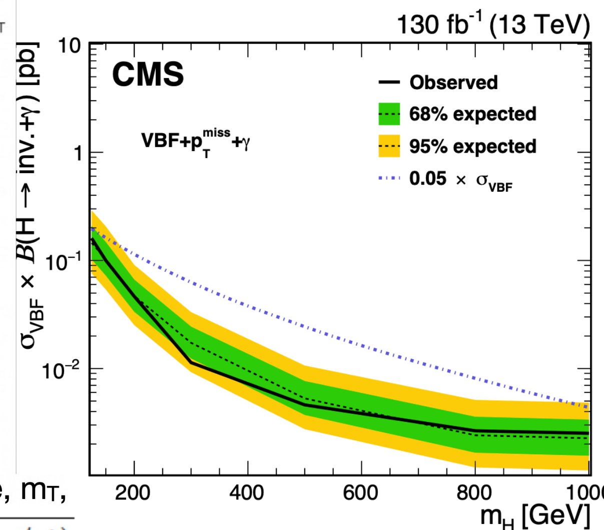
Dark photon

- Search in ZH & VBF events









discriminating variable, m_T,

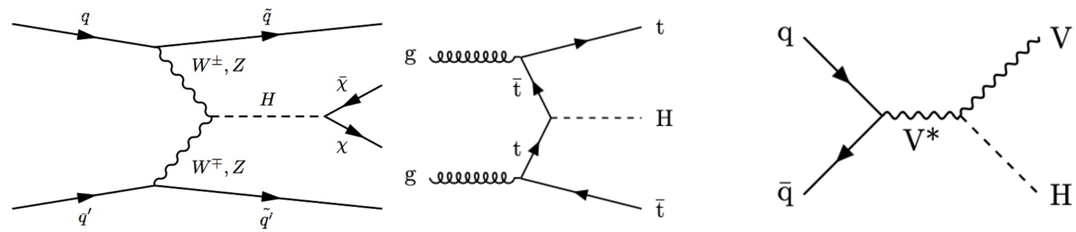
$$\sqrt{2 \cdot p_T^{\gamma} \not{E}_T \cdot (1 - \cos\Delta\phi(\gamma, \not{E}_T))}$$

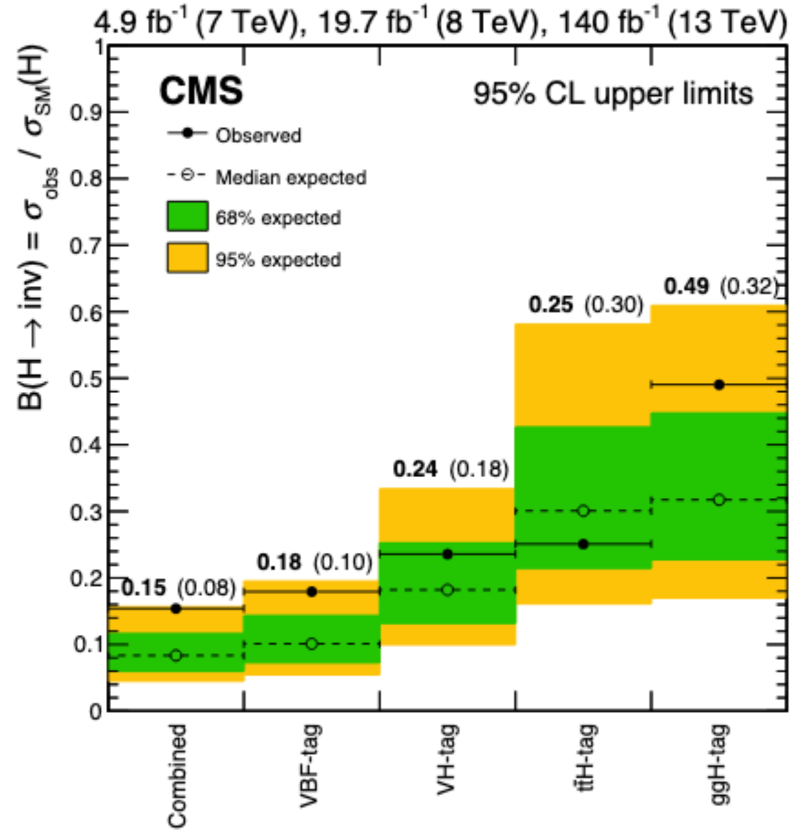
DM: Higgs invisible decays

arXiv:2201.11585, arXiv:2303.01214

- In the SM, BR(H→inv) is ~0.1%
- Search for Higgs invisible decays in VBF and associated production
  - 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, ttH production modes
- Set limits on DM models
  - Upper limits: 0.15(0.08exp)@95%CL
- Limits interpreted in the context of Higgs portal models

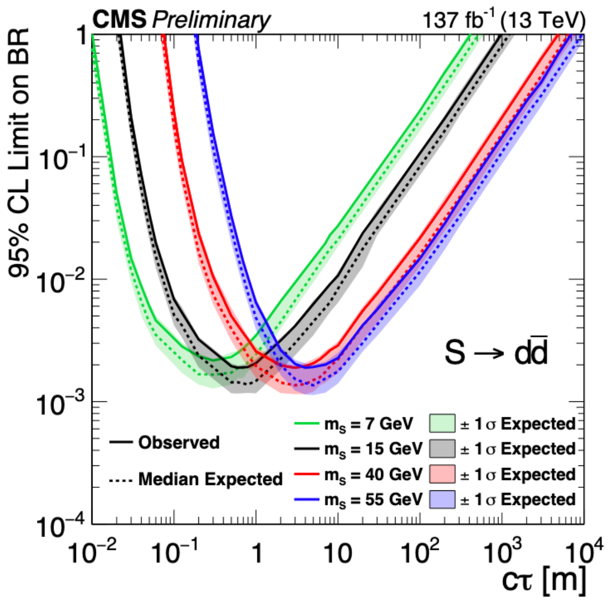
⇒ Competitive limits for low-mass DM candidates

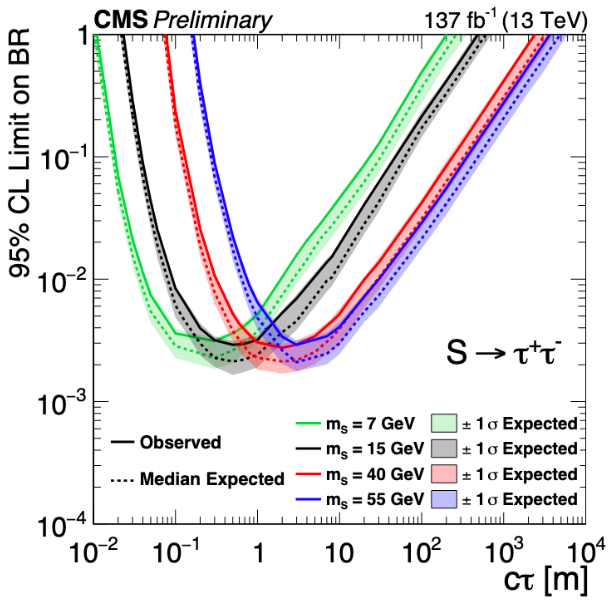


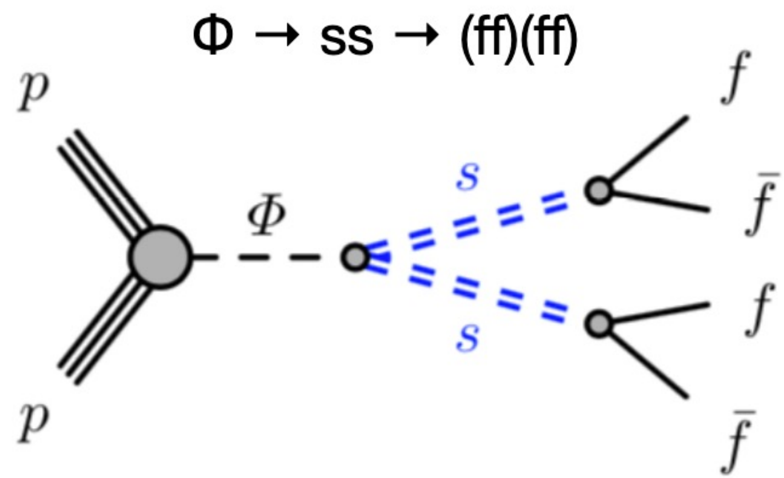


Long-lived: Higgs decays

CMS-EXO-20-015





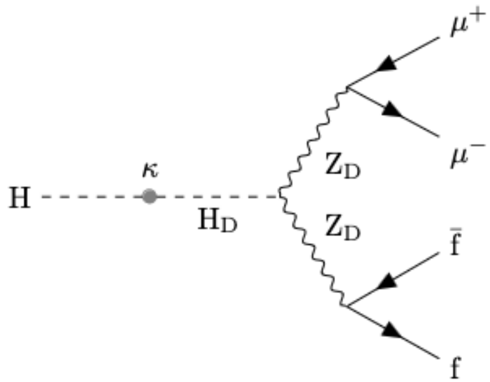


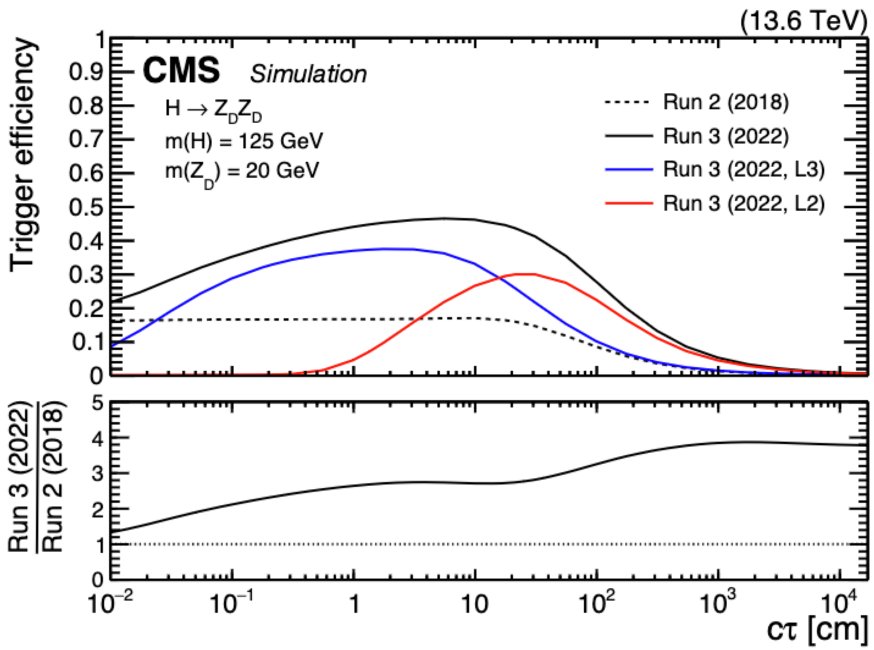
- Higgs decaying to long lived scalars
  - Scalars decay to quark final states in the muon chambers
- Resulting bounds are interpreted in context of LL decays
  - Missing energy trigger

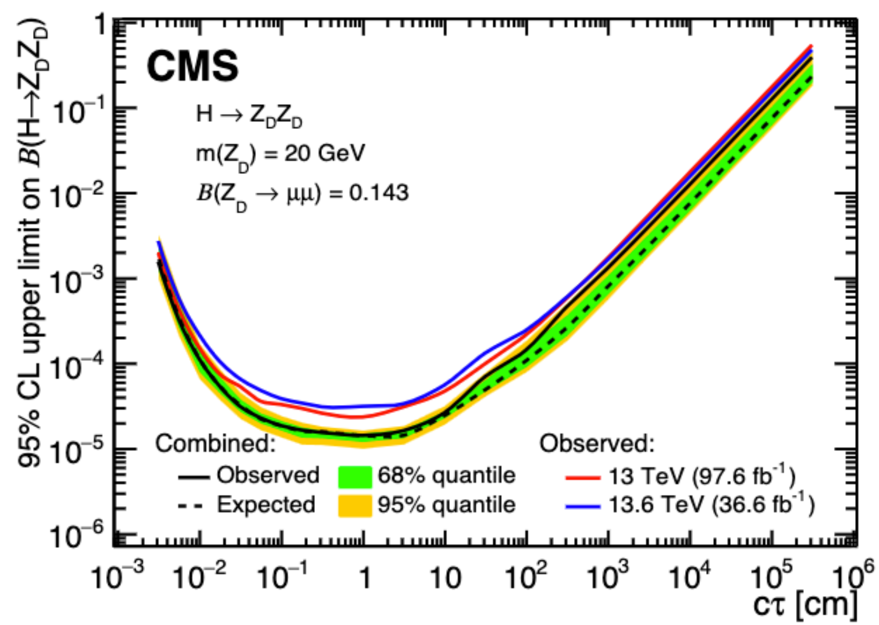
Long-lived: Higgs portal

arXiv:2402.14491

- Production of long-lived dark photons Z_D via Higgs portal
- H-H_D mixing with parameter κ
- Higgs decaying to long-lived scalars
  - Scalars decay to fermion final states in the muon chambers
  - Displaced dimuon originating from secondary vertex
- Resulting bounds are interpreted in context of LL decays







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