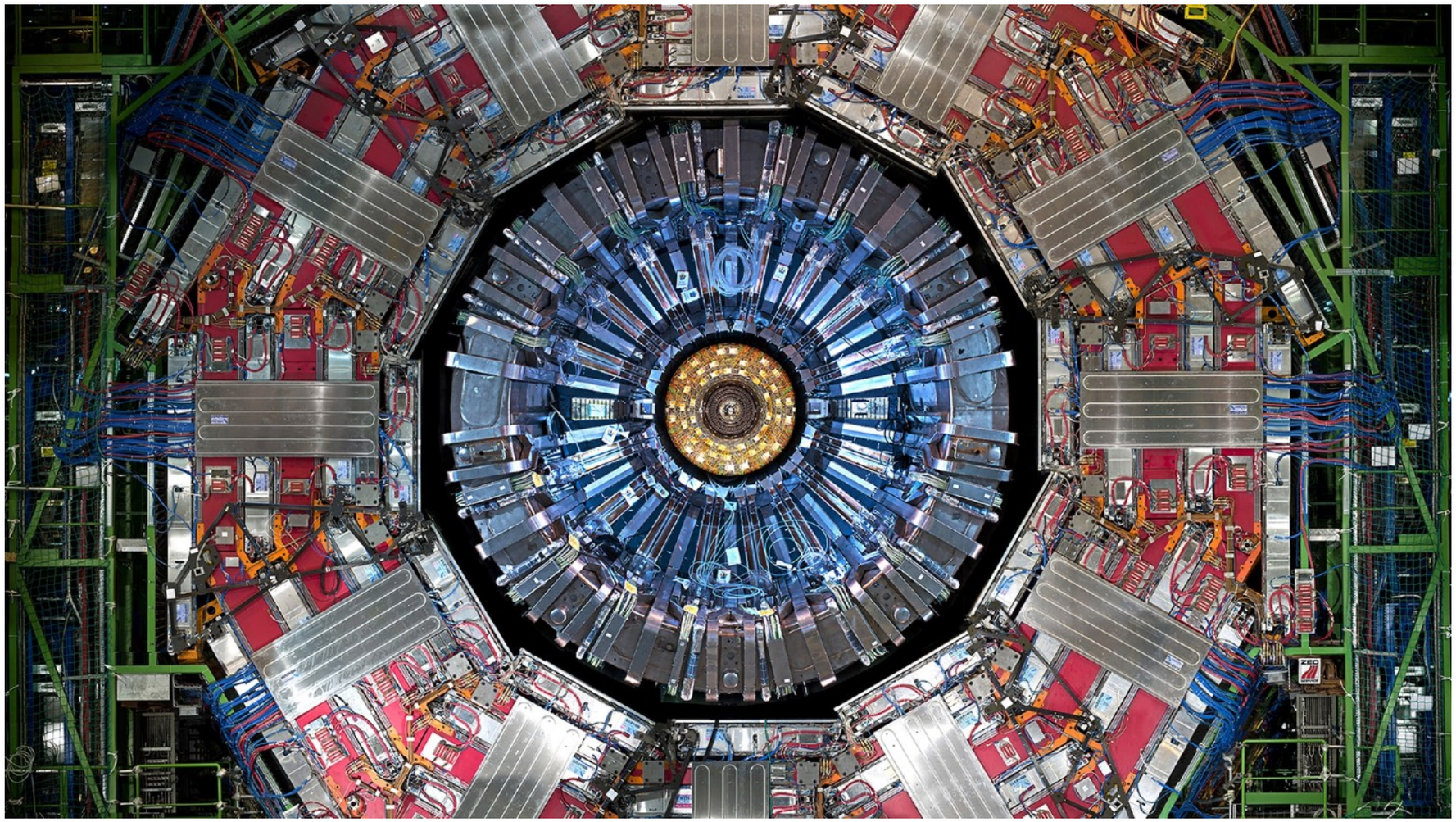
IMPERIAL

CMS Higgs Highlights



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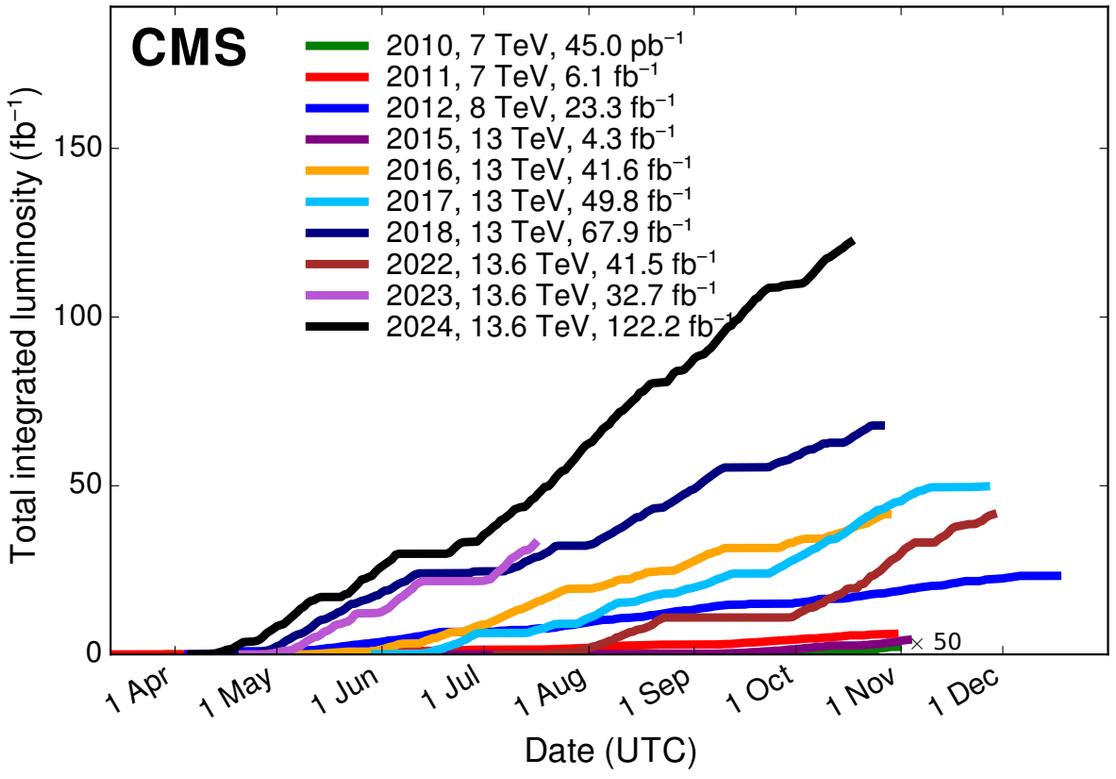
Overview

Today I will show highlights from CMS from the last year (since Higgs 2023)

First CMS Higgs analyses using Run-3 data

Further exploration of Run-2 data:

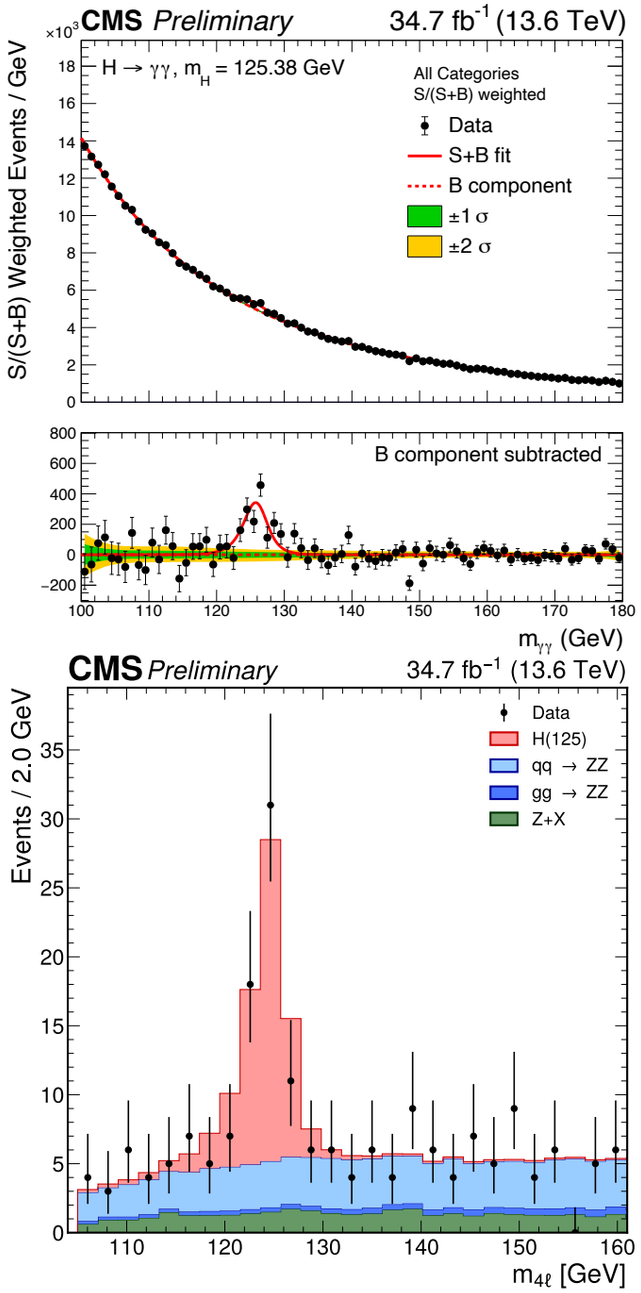
- EFT / anomalous coupling measurements
- Differential measurements
- Coupling and property measurements
- Rare decays
- di-Higgs
- Searches for additional Higgs bosons
- Note also CMS joker talk by A. Taliercio on 07/11 (link) about a new CMS ttH multi-lepton measurement - I won't discuss today



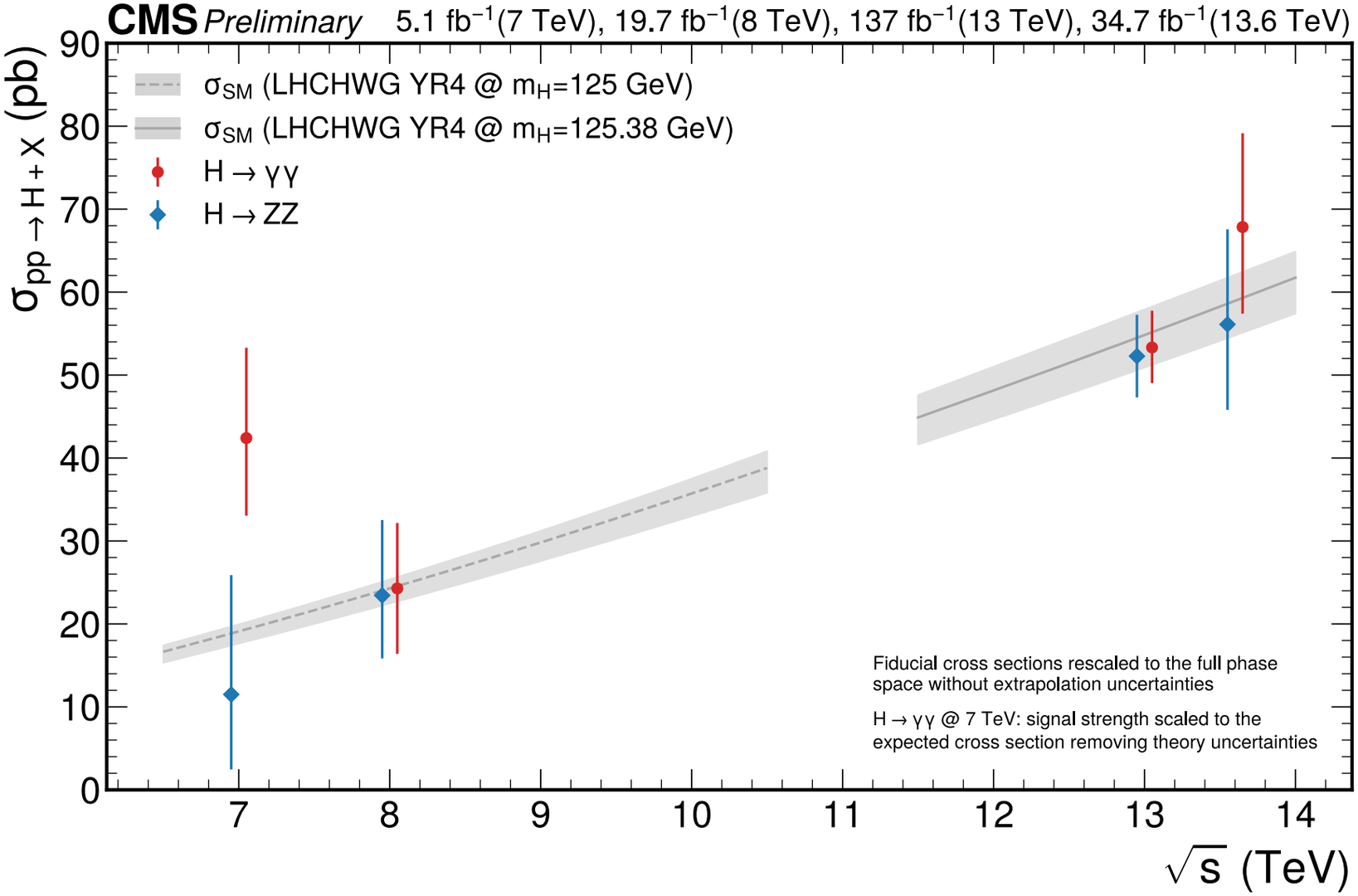
Higgs in Run-3

- Two results using Run-3 data so far: CMS-PAS-HIG-24-013 CMS-HIG-PAS-23-014

- H→γγ and H→ZZ cross-section and differential measurements using data-set collected in 2022 → 34.7/fb



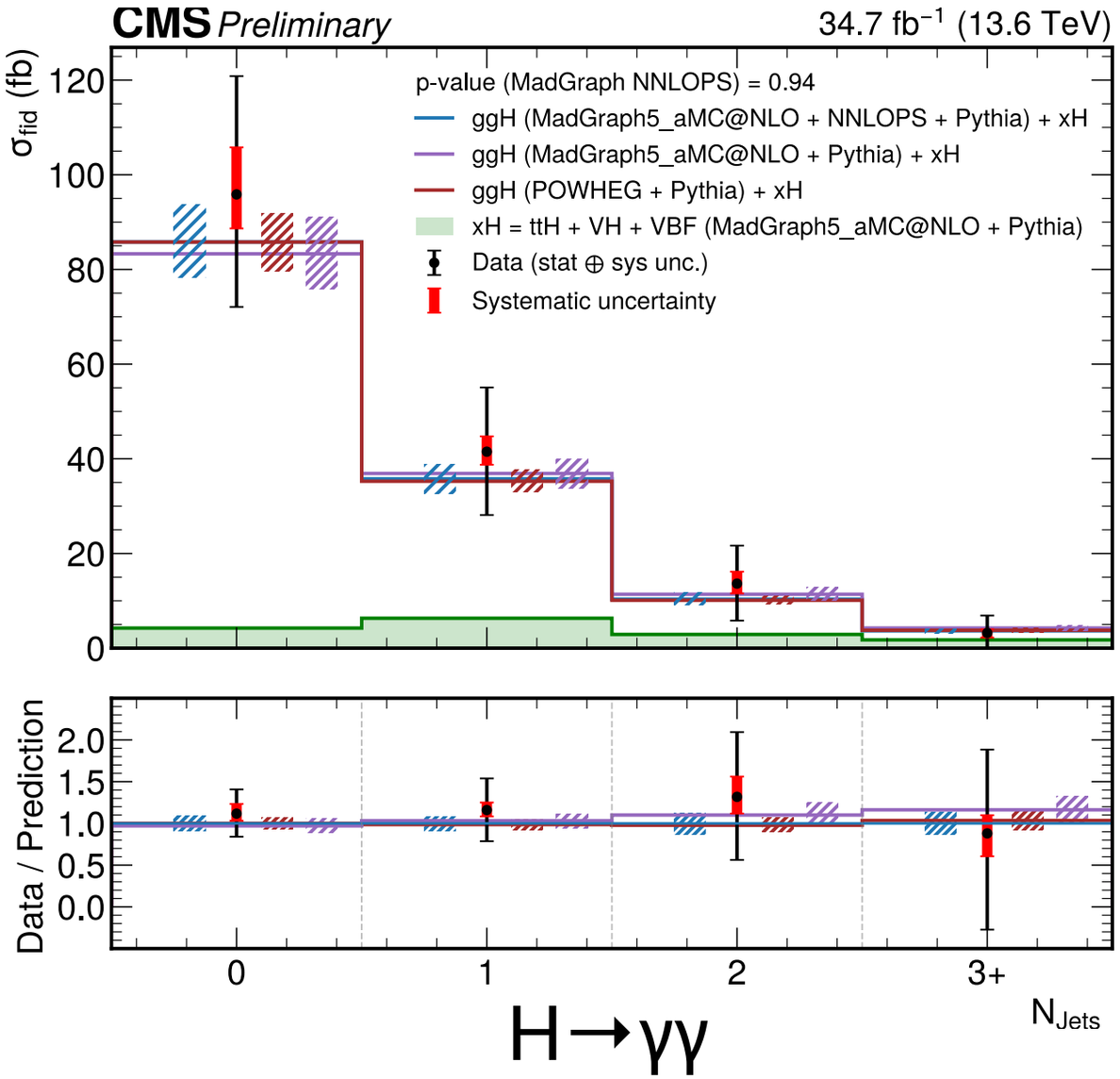
Fiducial cross-sections (rescaled to inclusive)

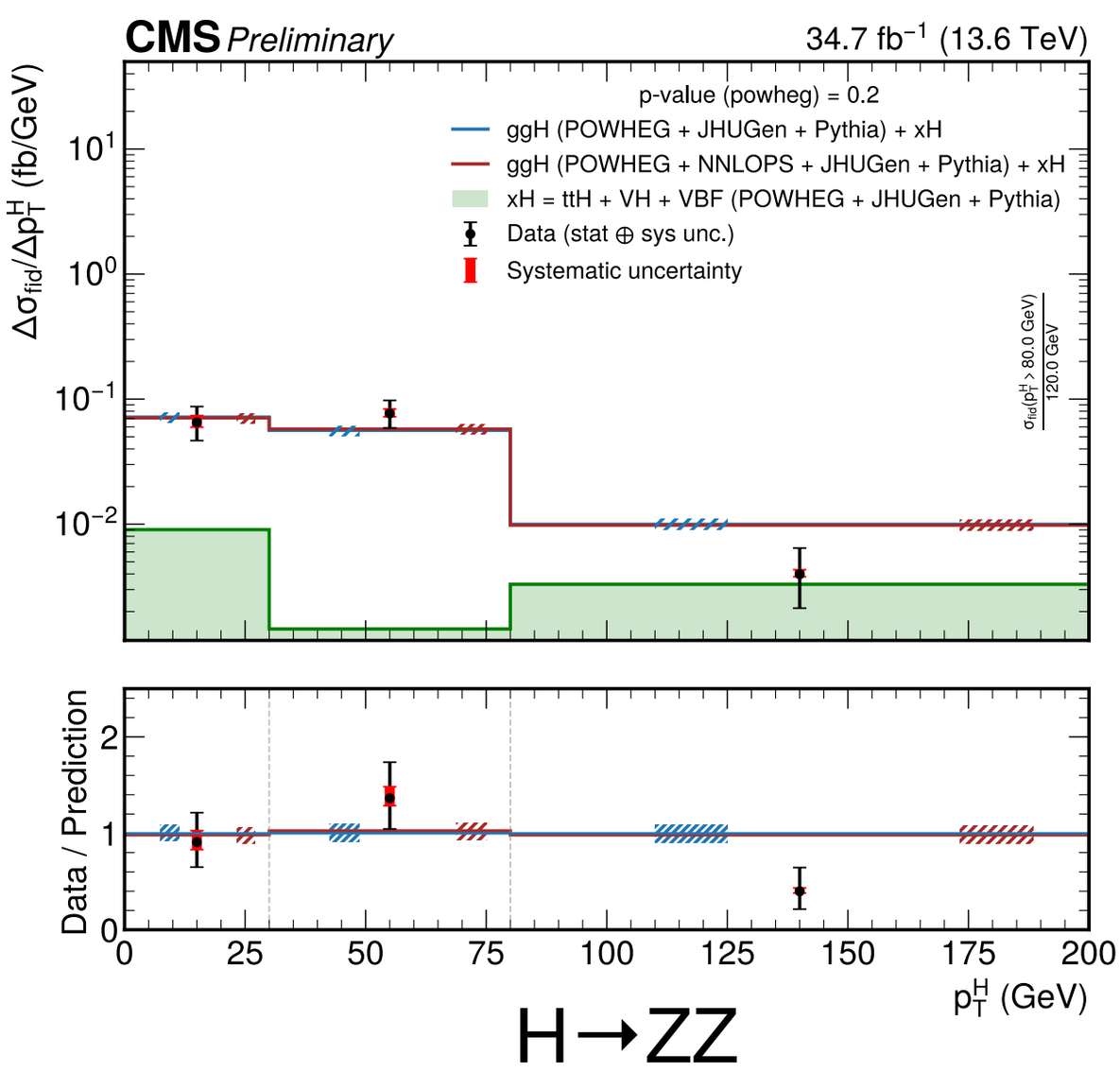


See talks by M. Bonanomi on 07/11 (link) and C. Daumann on 05/11 (link)

Higgs in Run-3

- Two results using Run-3 data so far
- Differential measurements for several variables such as Higgs p_T



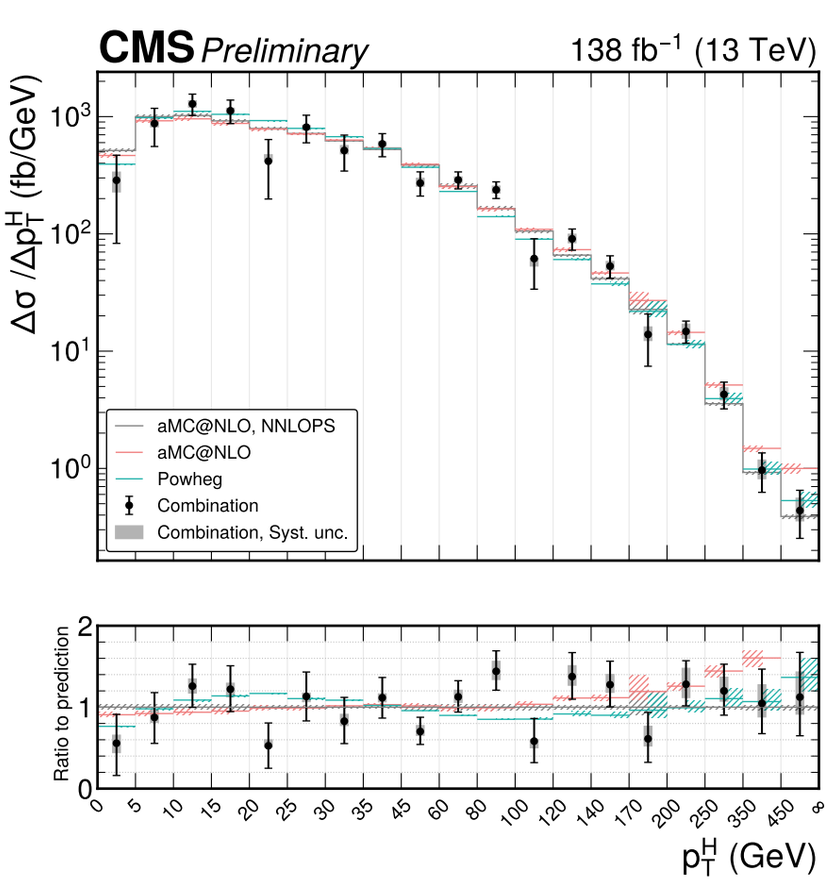


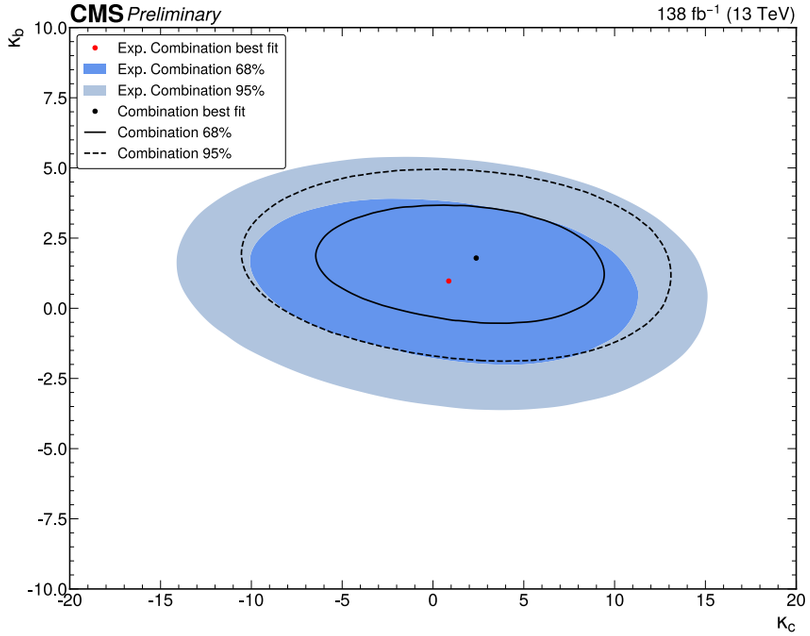
Differential measurements

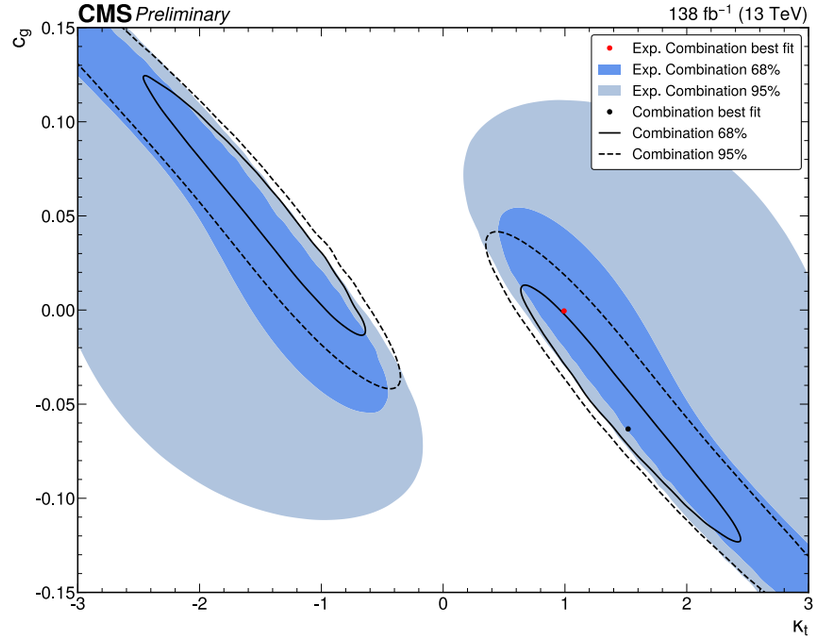
- Combination of differential measurements for γγ, ZZ, WW, and $\tau\tau$ channels: CMS-PAS-HIG-23-013

- Differential measurements for several variables

- Used to extract coupling modifiers to b and c quarks as well as set limits on several EFT coefficients







See talks by M. Bonanomi on 07/11 (link), S. Wuchterl on 06/11 (link) and M. Gallion 05/11 (link)

EFT constraints using VH→bb

- Constraints on SMEFT dimension-six operators using VH→bb events at 13 TeV: CMS-PAS-HIG-23-016

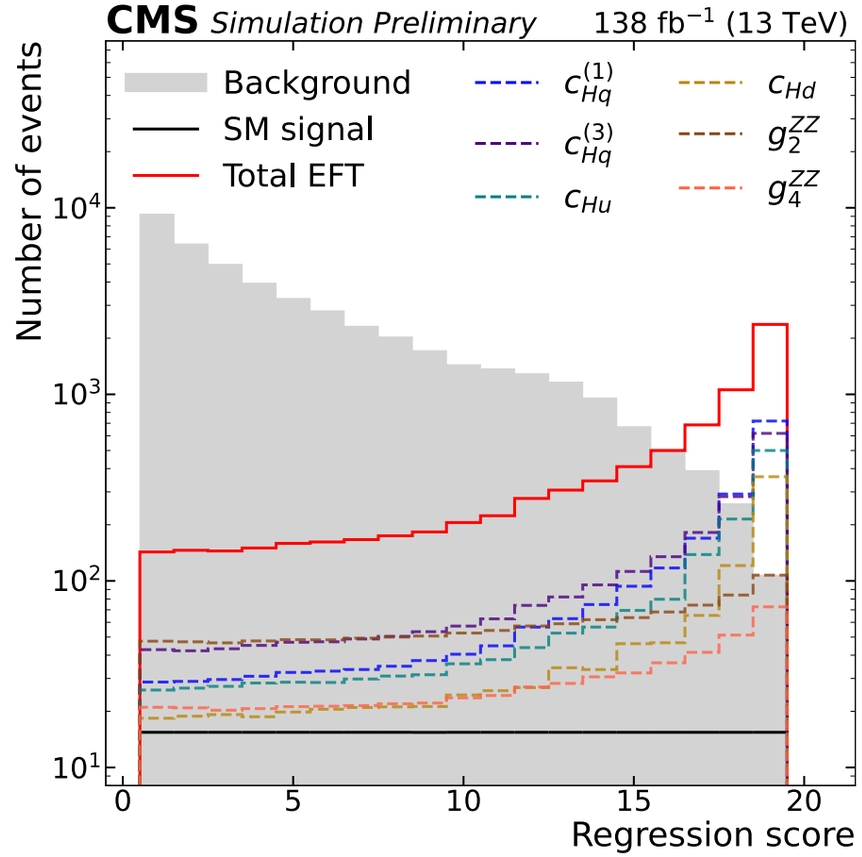
- SMEFT is a EFT with a series of higher dimensional operators which are invariant under $\mathrm{SU(3)_C \times SU(2)_L \times U(1)_Y}$

$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SM}} + \sum_{i=1}^{n_d} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)} + \ldots, \; d > 4$$

- Combining 2, 1, and 0 lepton categories targeting $Z \to ll, W \to l\nu$, and $Z \to \nu\nu$, including both resolved and boosted jet topologies

- Extraction of 6 Wilson coefficients

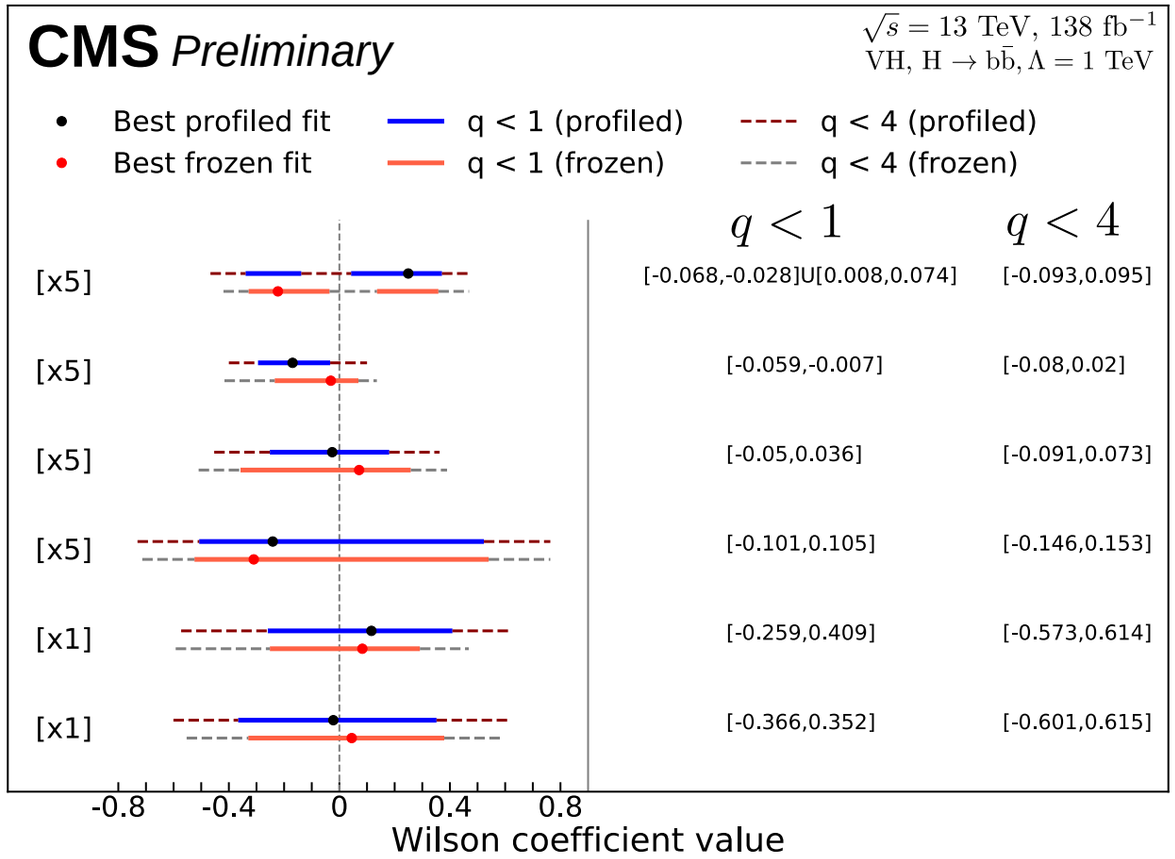
- Novel optimisation technique to ensure sensitivity to multiple Wilson coefficients

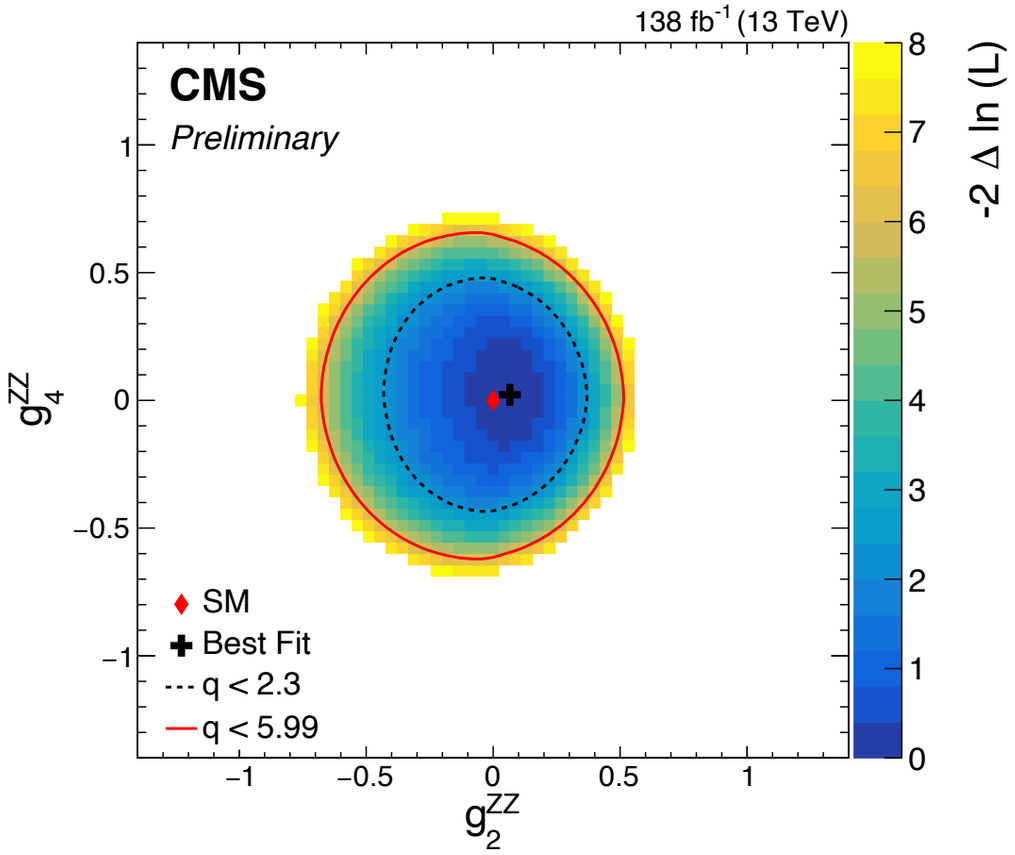


See talks by A. Nigamova on 07/11 (link), and V. Periodic on 06/11 (link)

EFT constraints using VH→bb

- Results consistent with the SM
- Measurements of the Wilson coefficients e.g in 2D planes

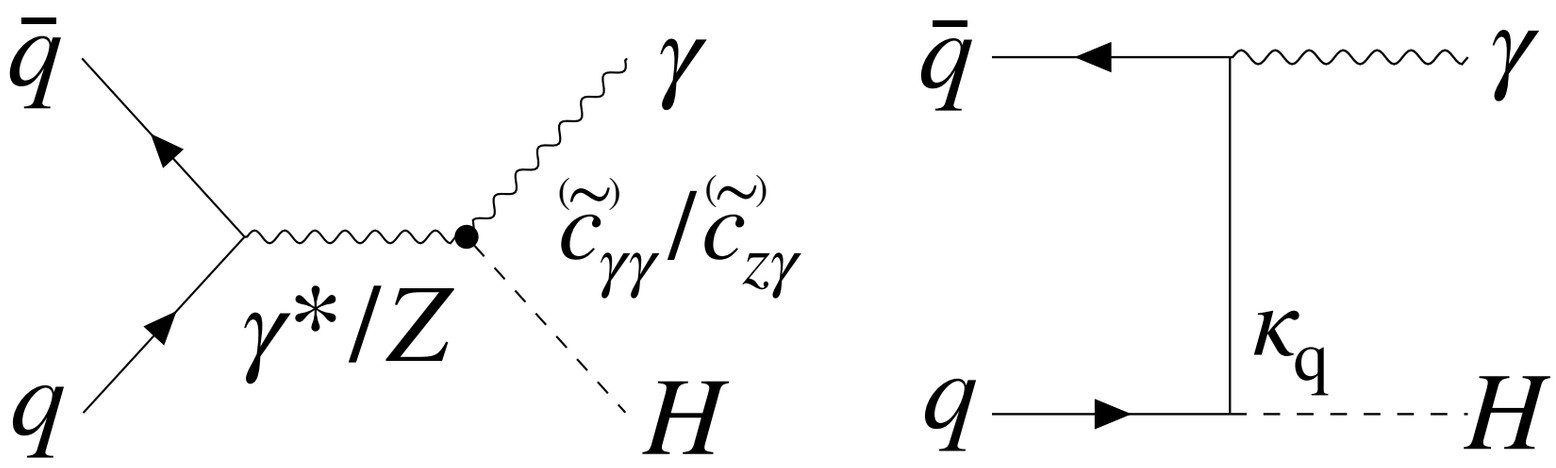




Search for H+γ production

- Search for H+γ production using the H→bb and H→ZZ channels: CMS-PAS-HIG-23-011

- H+γ process is sensitive to light quark couplings as well as anomalous couplings that do not appear in the SM

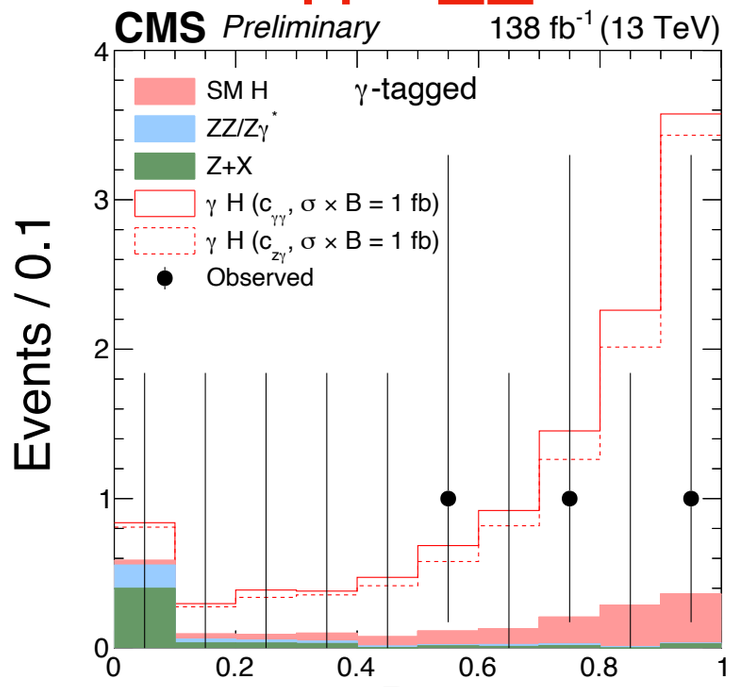


M_{PNet} = mass regressed by Particle Net algorithm

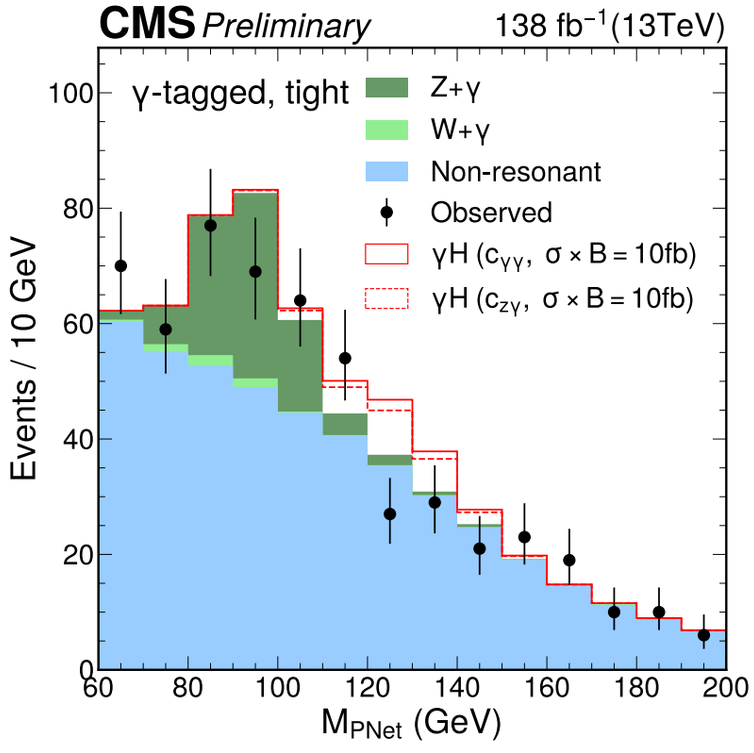
D_{bkg} is Matrix element observable = $\dfrac{\mathscr{P}_{sig}}{\mathscr{P}_{sig} + \mathscr{P}_{bkg}}$

See talks by S. Wuchterl on 06/11 (link), and V. Periodic on 06/11 (link)

H→ZZ



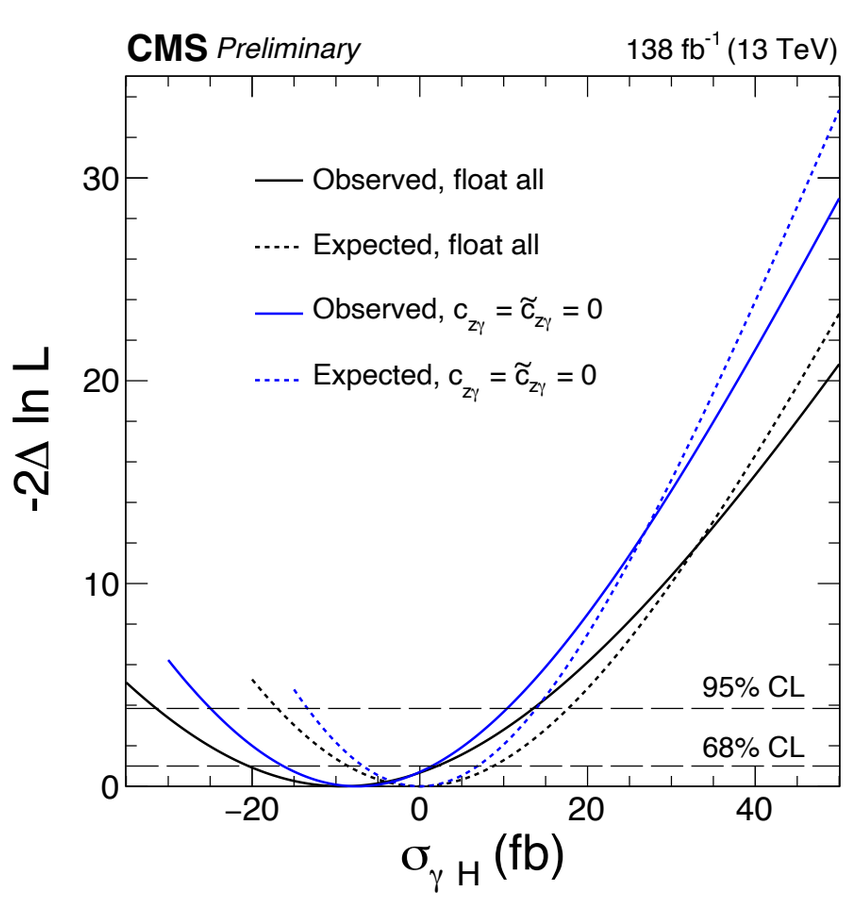
H→bb

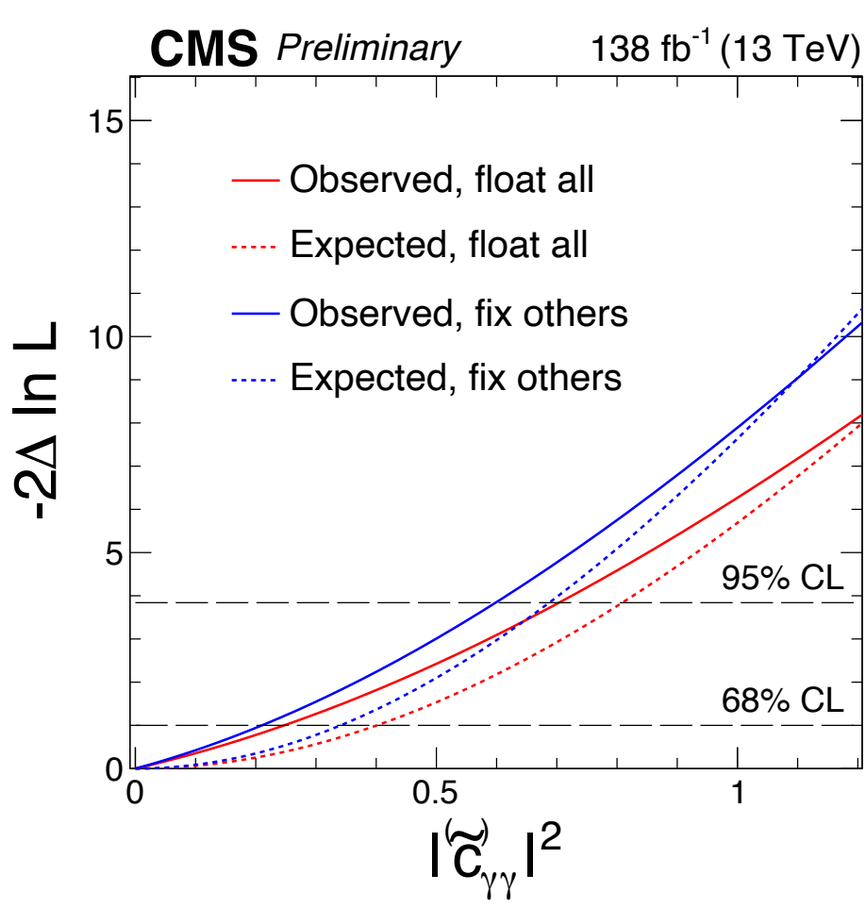


Search for H+γ production

- Cross-section constrained to be < 15.7/fb at 95% CL

- Results are also interpreted as limits on various anomalous couplings and light quark couplings

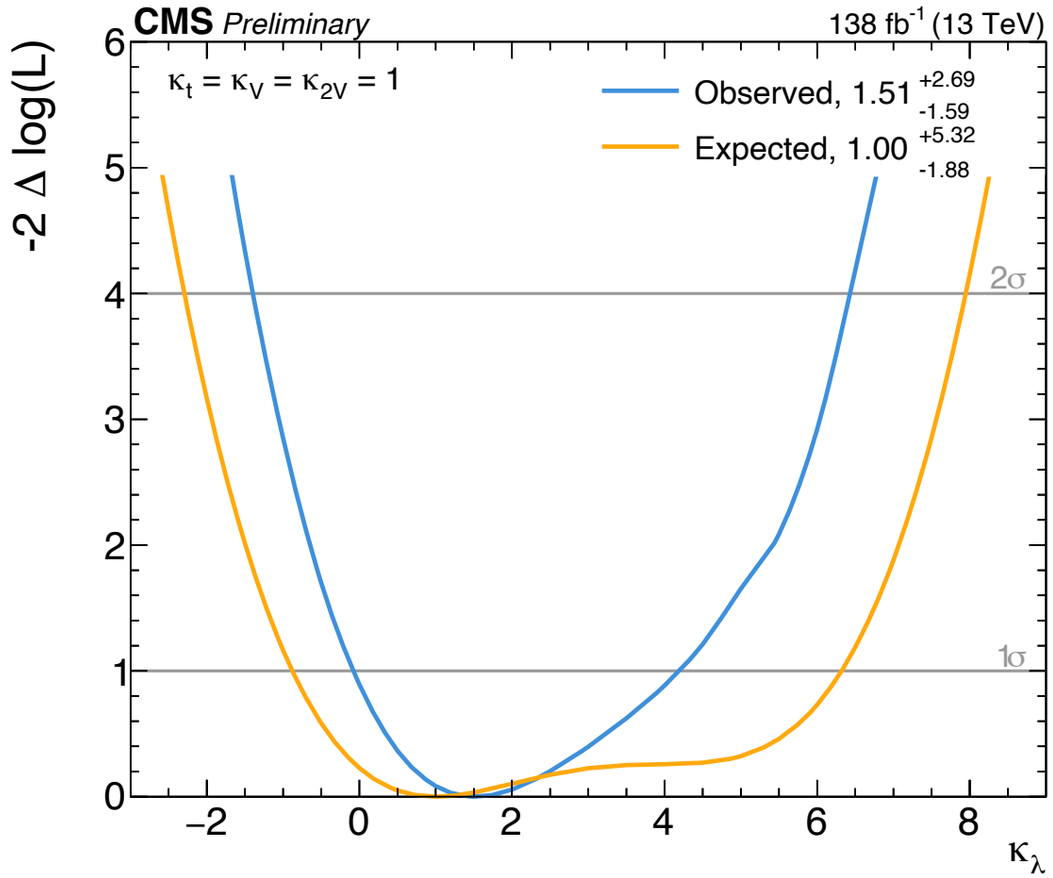


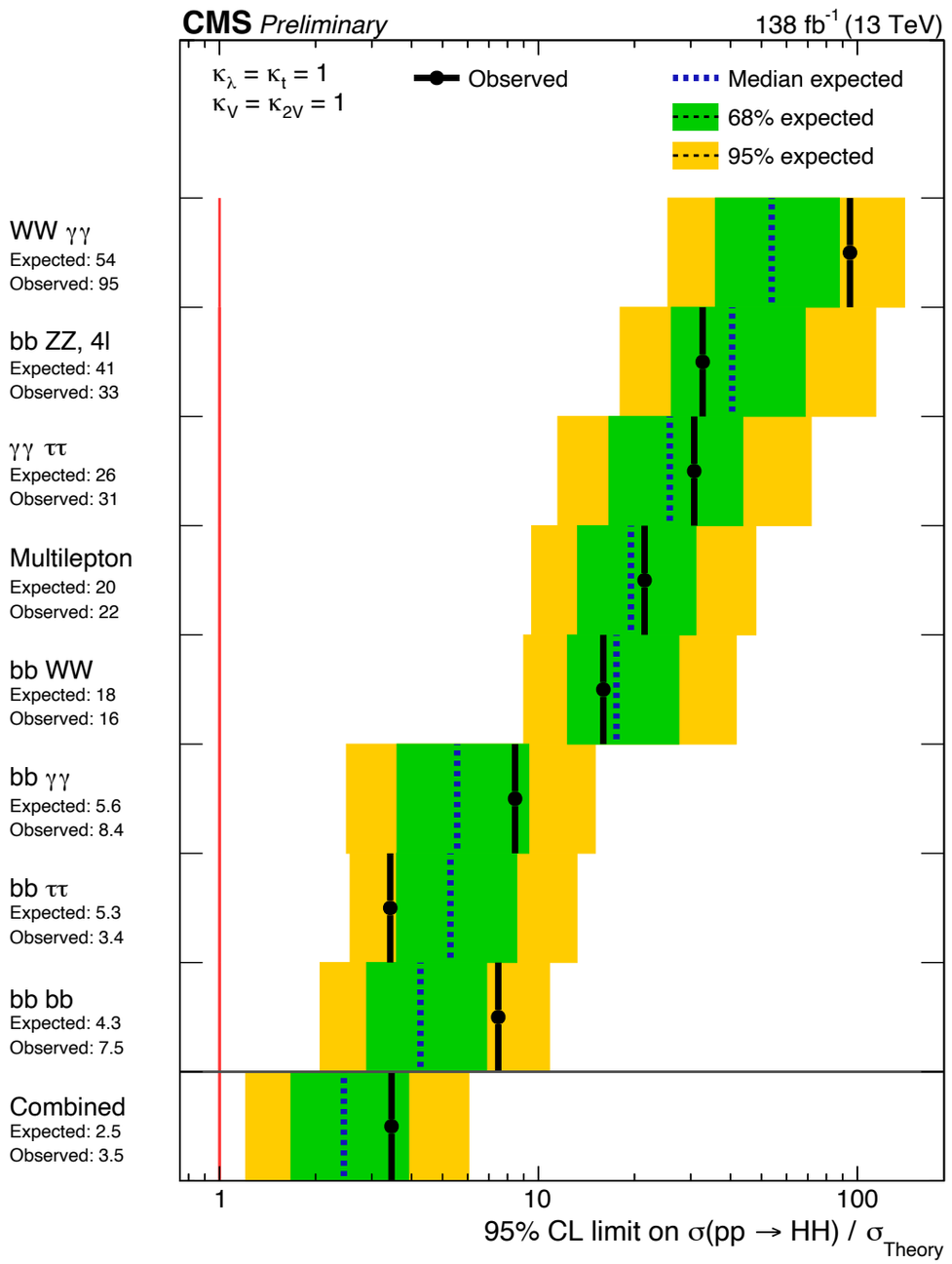


di-Higgs non-resonant

NEW!

- New combination of CMS di-Higgs channels: CMS-PAS-HIG-20-011
- Update adds additional channels: bbWW, WWγγ, and ττγγ, and additional VHH production mode for 4b channel
- Obs. (Exp.) limit on ggHH cross-section of 3.5 (2.5) times SM
- 95% CL limit on κ_λ is set between –1.39 and 7.02 (expected –1.02 and 7.19)



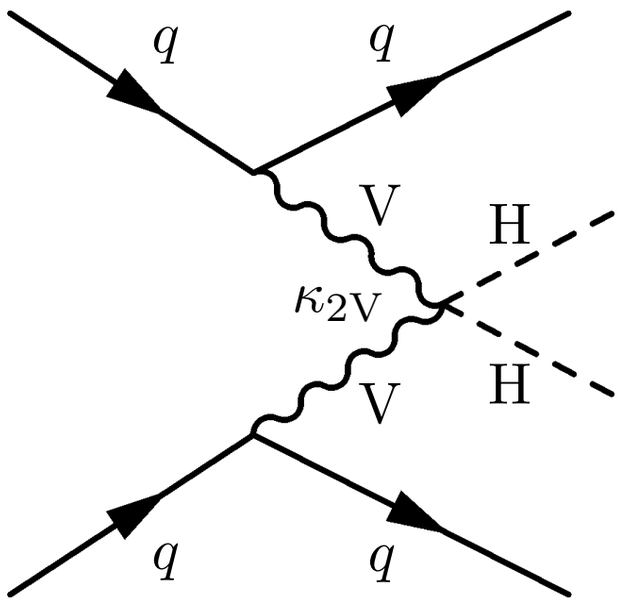


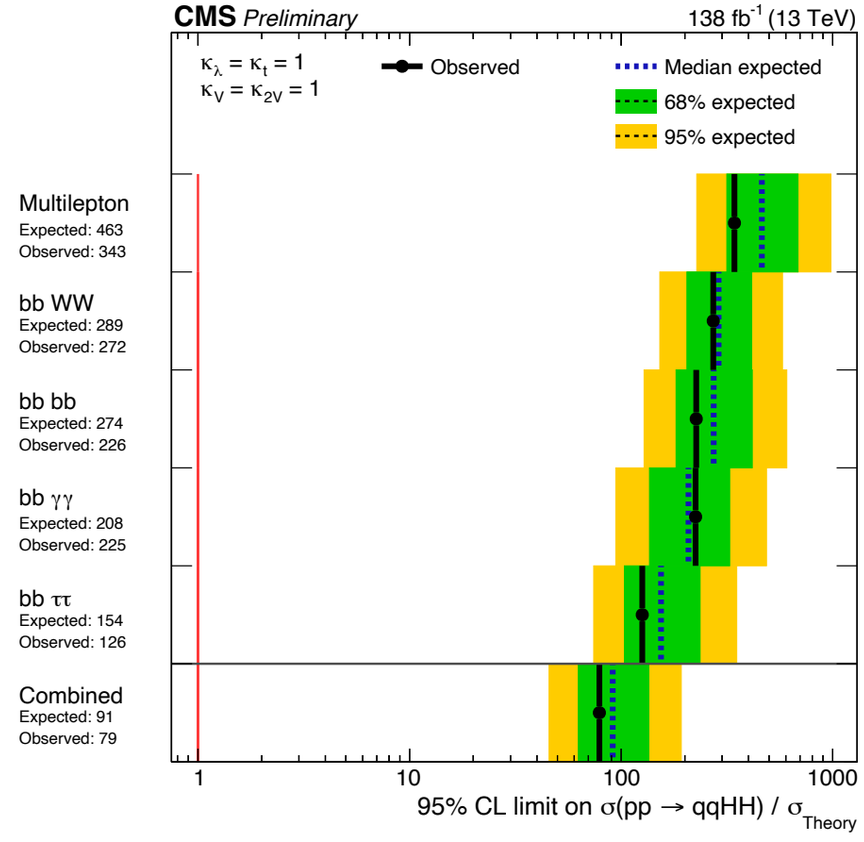
See talks by R. Gerosa on 07/11 (link) and J. Motta on 05/11 (link)

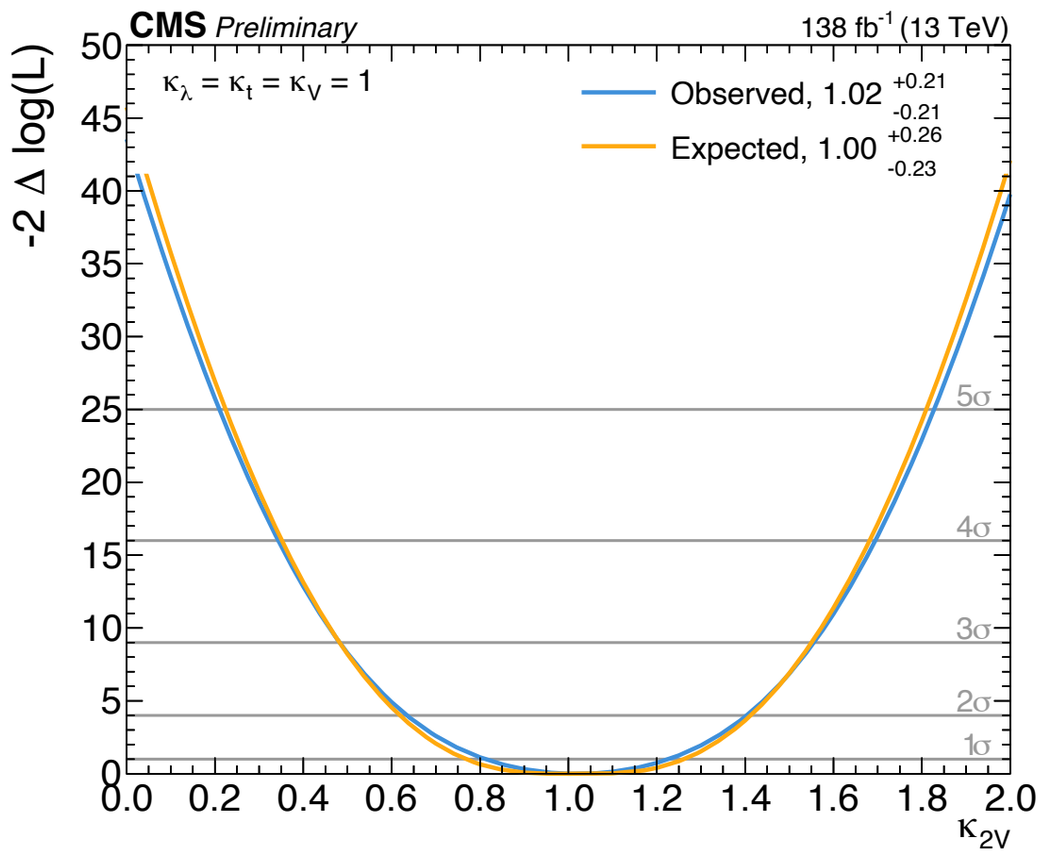
di-Higgs non-resonant

NEW!

- Sensitivity to κ_{2V} from VBF and VHH categories
- Obs. (Exp.) limit on cross-section of 79 (91) times the SM
- 95% CL limit on κ_{2V} is set between 0.62 and 1.42 (expected 0.69 and 1.35) excluded by > 5σ!



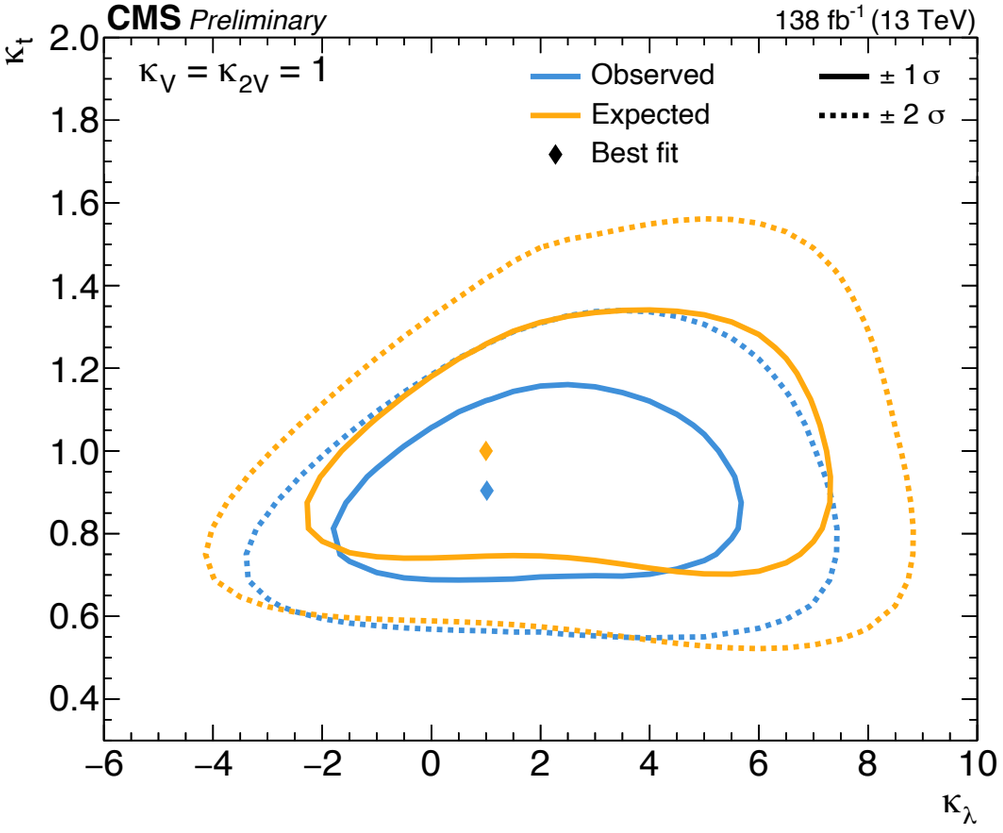


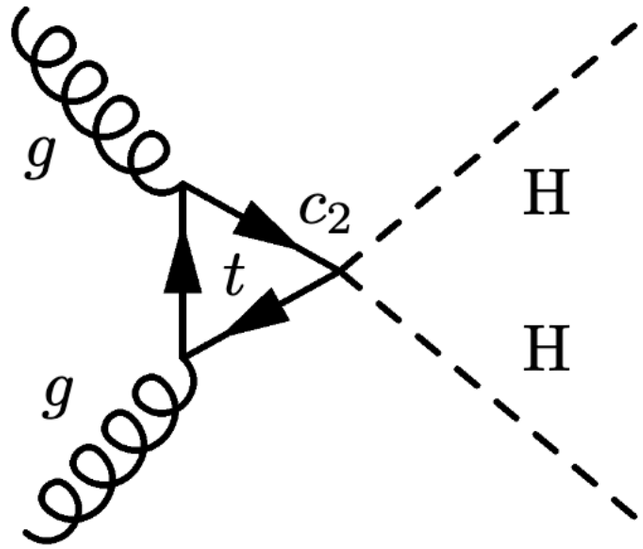


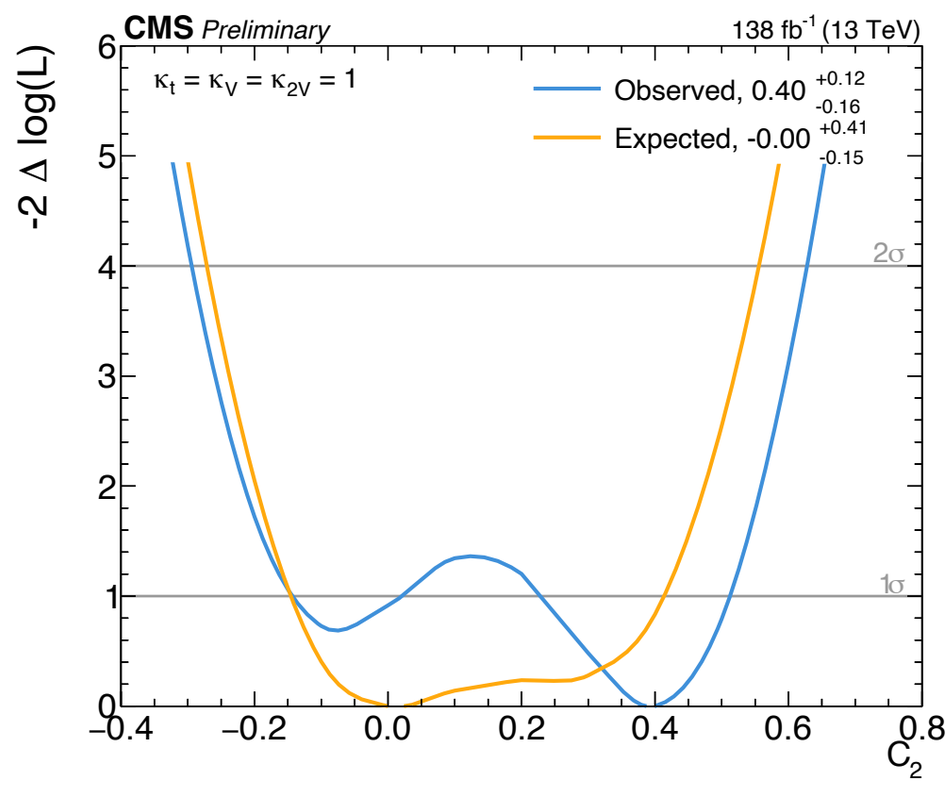
di-Higgs non-resonant

NEW!

- We also provide 2D scans of parameters and interpretation in “Higgs Effective Field Theory” (HEFT) framework [*,**] (C_2 coefficient)







* **Phys. Lett. B 722, 330 (2013)**

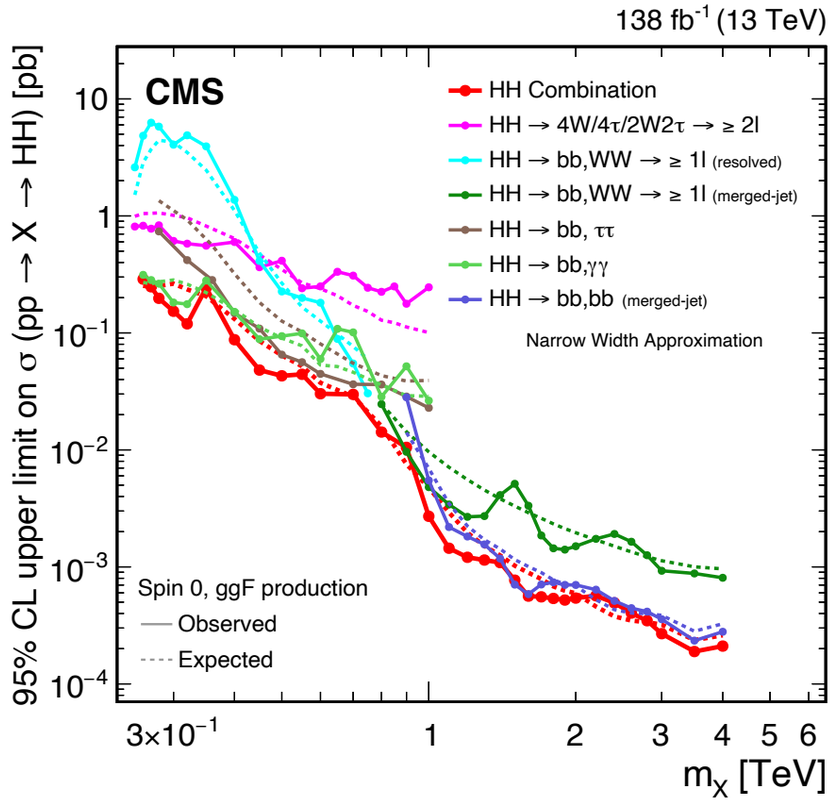
** **Nucl. Phys. B880, 552 (2014)**

di-Higgs resonant

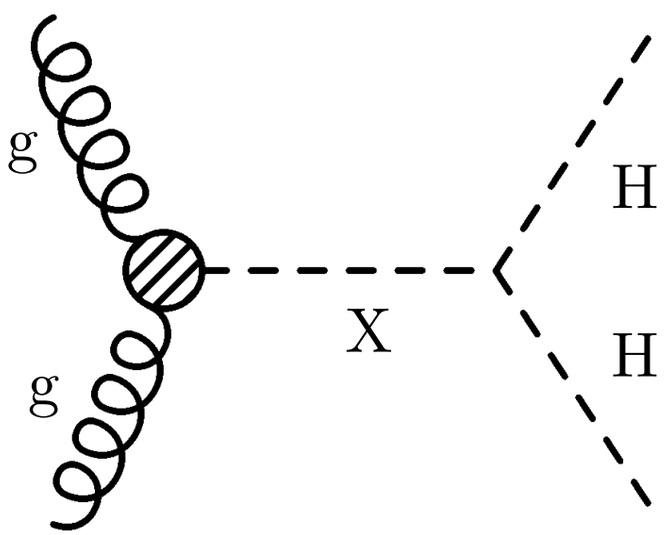
- di-Higgs spectrum can also be enhanced by additional resonant contributions

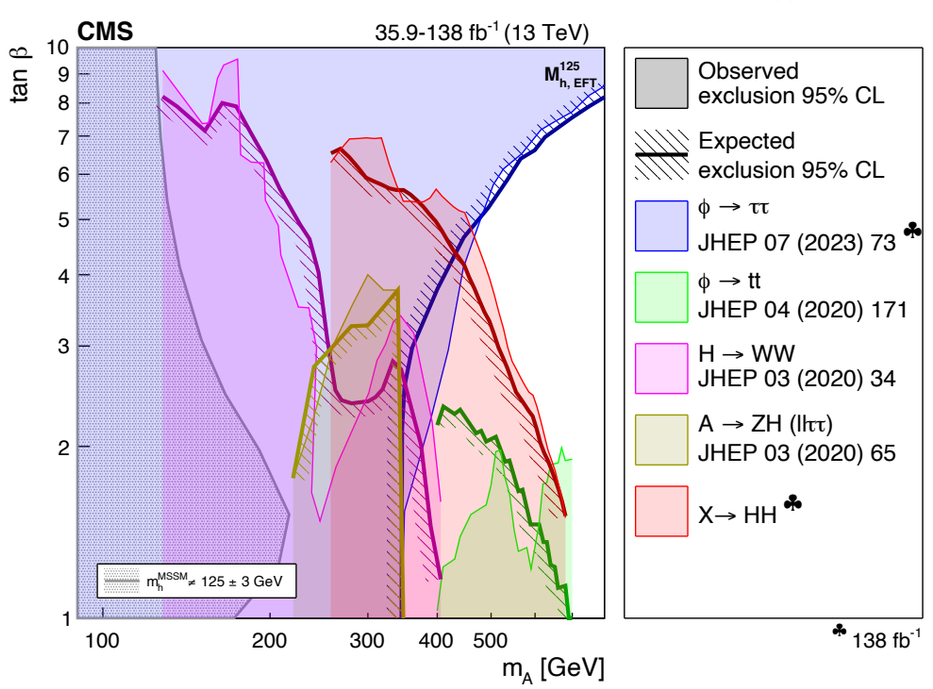
- Several channels can be used to search for this process, strength of each depends on mass range → combine results to achieve best sensitivity

- CMS-B2G-23-002



- Results interpreted in several BSM scenarios e.g MSSM





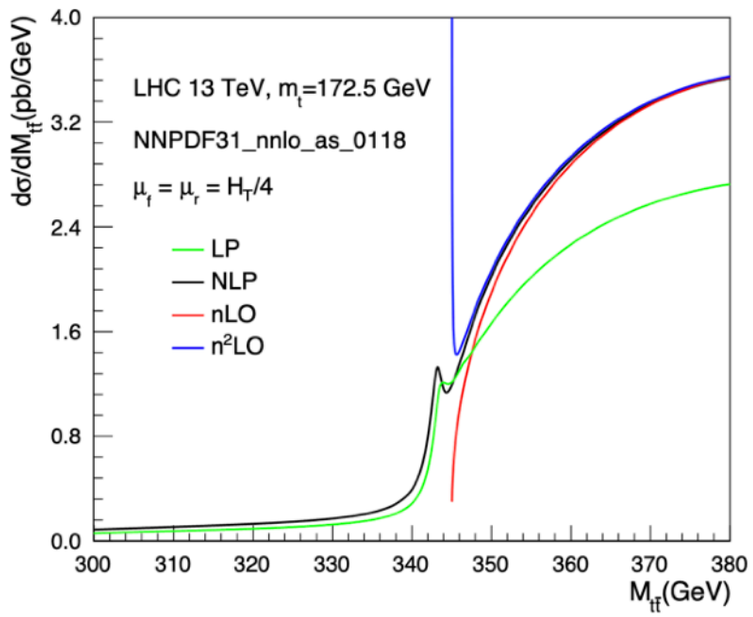
See talks by S. Laurila on 08/11 (link) and D. Zuolo on 05/11 (link)

Search for H/A→$t\bar{t}$

- Search for gg→H/A→$t\bar{t}$ using 13 TeV data: CMS-PAS-HIG-22-013

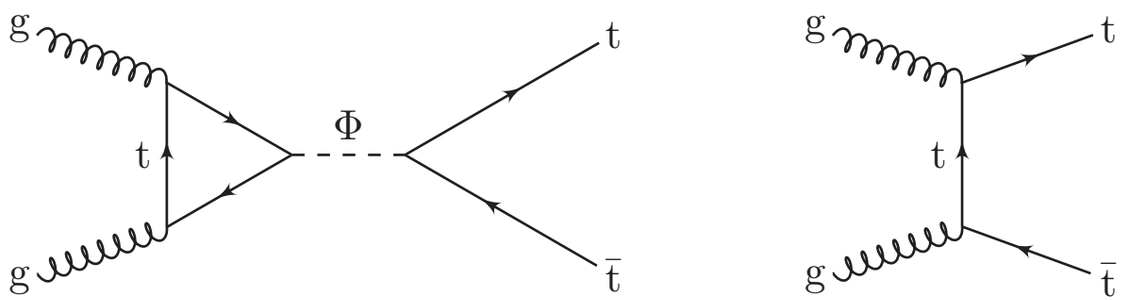
- Complicated analysis due to interference between signal and SM background, and non-perturbative QCD effects at low mass inc. tt bound states

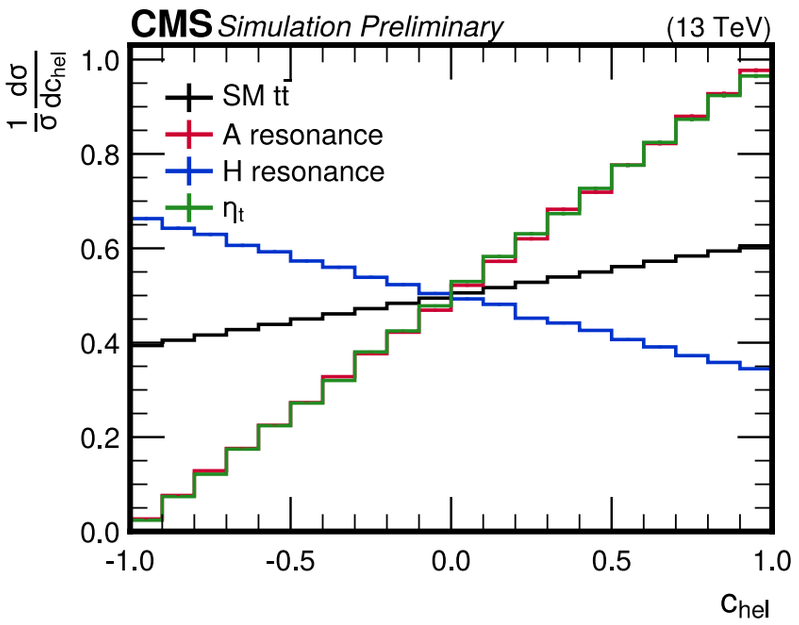
- Combination of leptonic and semi-leptonic channels



Ju et al. JHEP 06 (2020) 158

- Spin sensitive observables (c_{hel}, c_{han}, $\cos\theta^*$) differentiate A and H from each other and the background, used in fitting along with reconstructed mass, m_{tt}

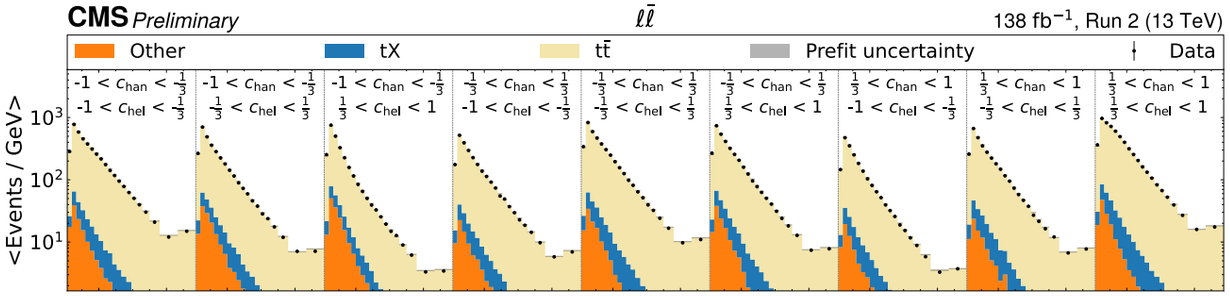


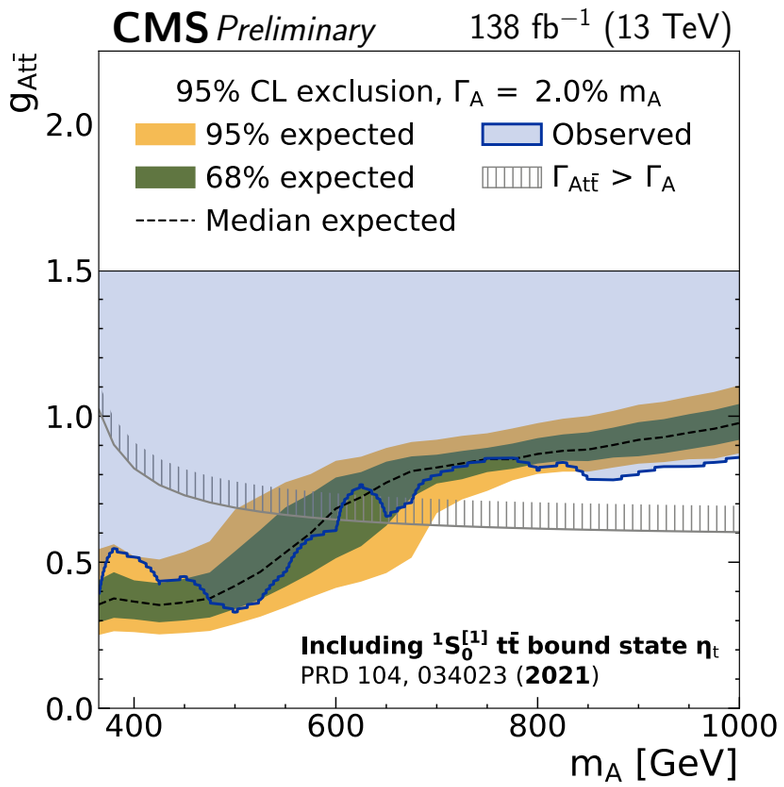


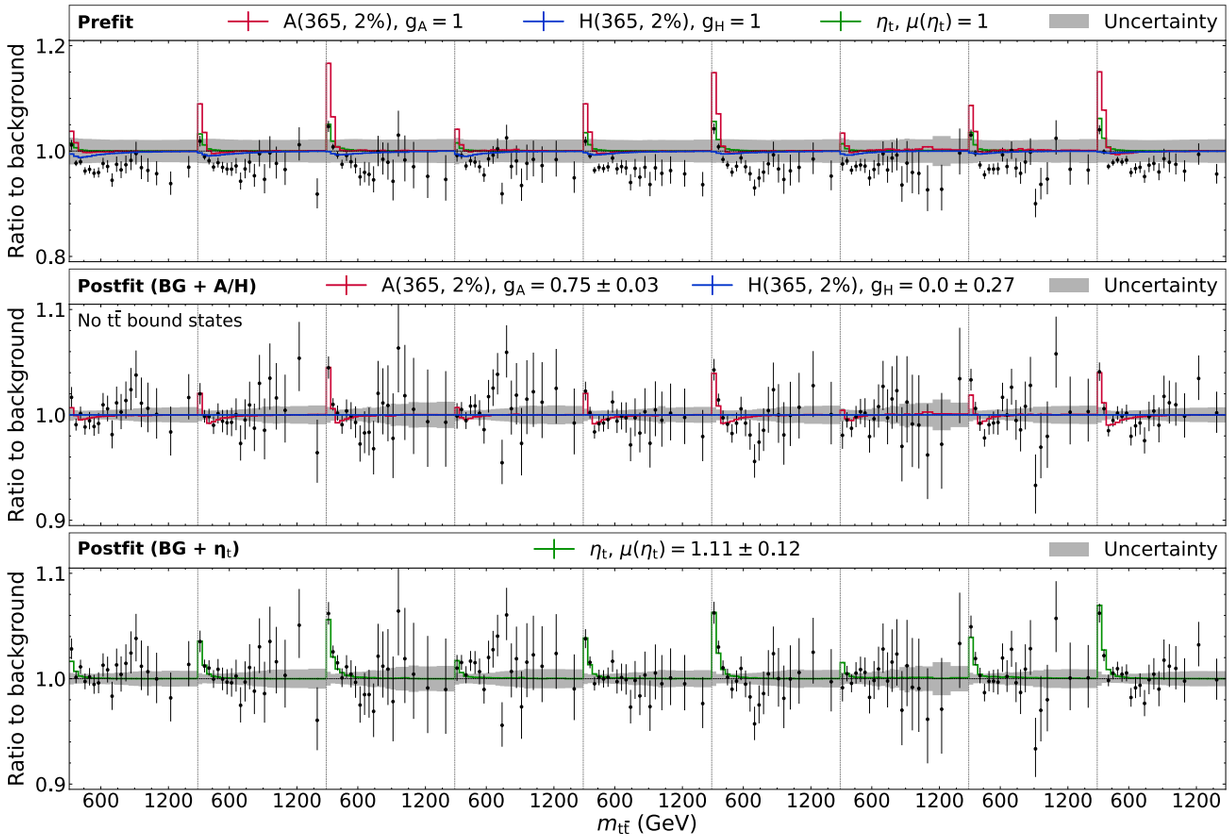
See talks by D. Duda on 08/11 (link) and P. Mastrapasqua on 05/11 (link)

Search for H/A→$t\bar{t}$

- Perturbative $t\bar{t}$ modelled using NLO MC (POWHEG) with reweighing to NNLO in QCD and NLO in EW
- Toy model to account for $t\bar{t}$ bound state $1S_0^{[1]}$ "η_t" (Fuks et al. Phys.Rev.D 104 (2021) 3)
- Deviations from perturbative-only predictions at low m_{tt} (>> 5 sigma)
- Equally well described by η_t model or A resonance
- η_t cross-section measured to be 7.1 pb with 11% uncertainty
  - Quite good agreement with theory prediction of 6.43 pb (Fuks et al.)
- Limits on A/H set in scenarios w/o η_t in background model

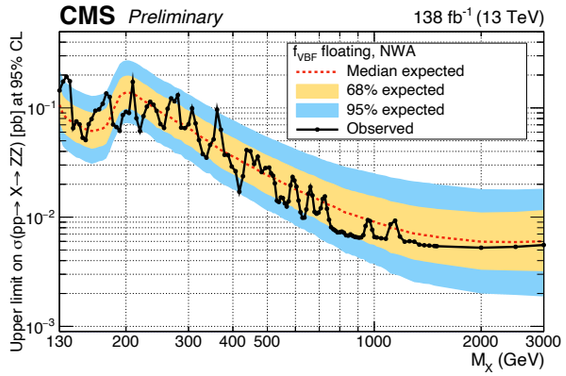


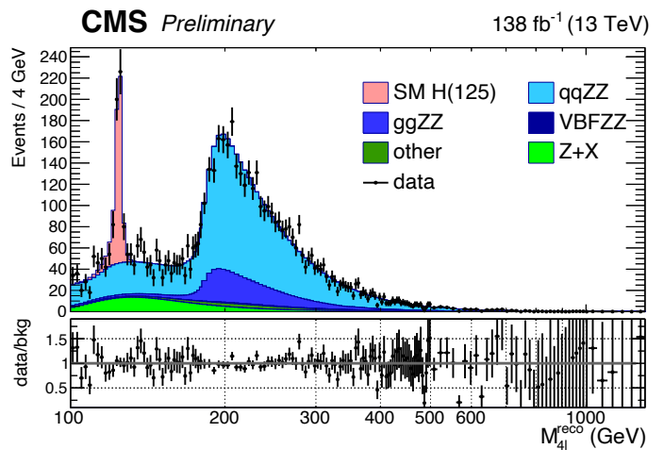




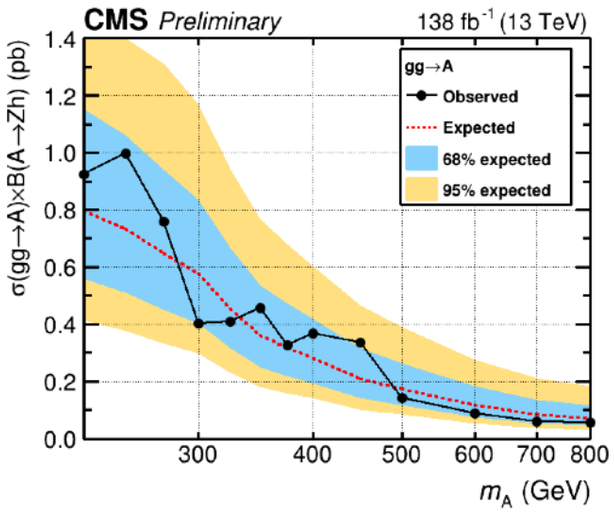
Other searches for H and A bosons

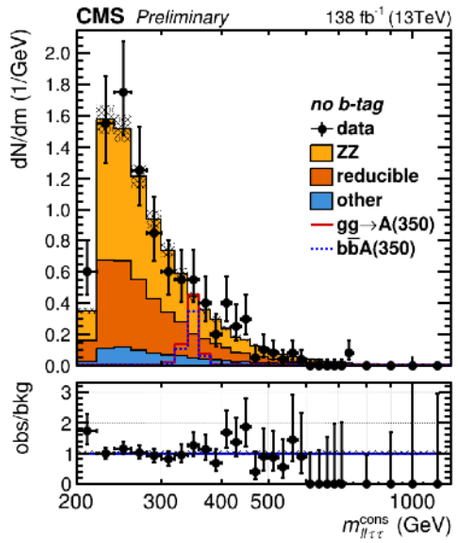
- Search for heavy H→ZZ at 13 TeV using the 4l final state: CMS-PAS-HIG-24-002 →
  - ggH and VBF production, several width hypotheses



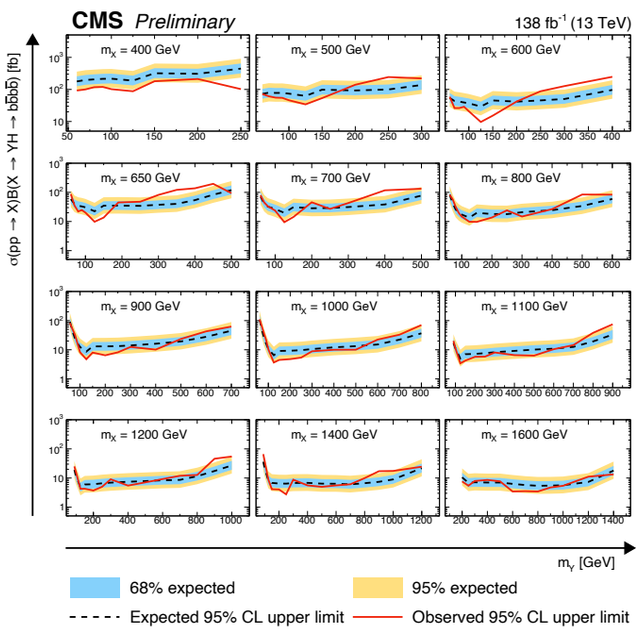


- Search for A→Zh125, h125→ττ: CMS-PAS-HIG-22-004 →
  - ggH or bbH production





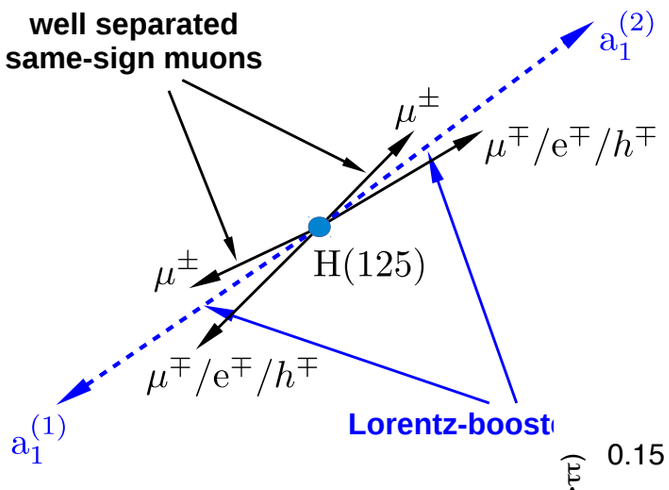
- Search for X→Yh125→ 4b: CMS-PAS-HIG-20-012 →
  - Largest excess 4.1σ (2.5σ) local (global) at m_X = 700, m_Y=400 GeV



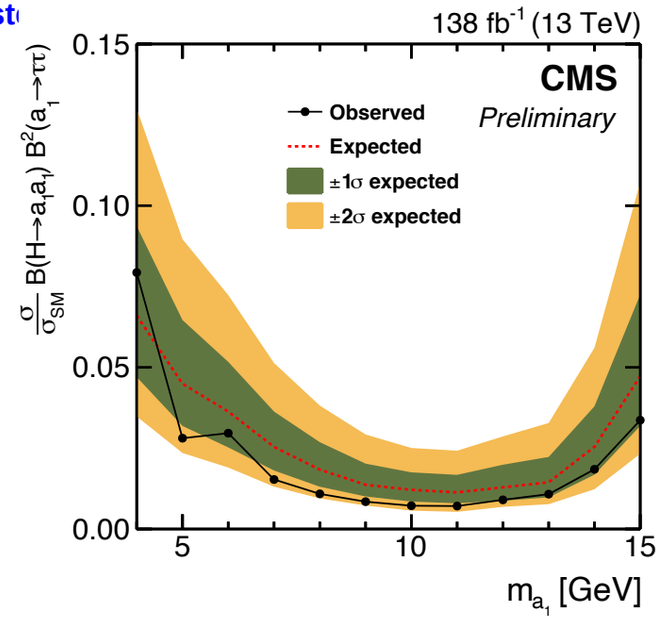
See talks by D. Duda on 08/11 (link), P. Mastrapasqua on 05/11 (link), S. Laurila on 08/11 (link) and D. Zuolo on 05/11 (link)

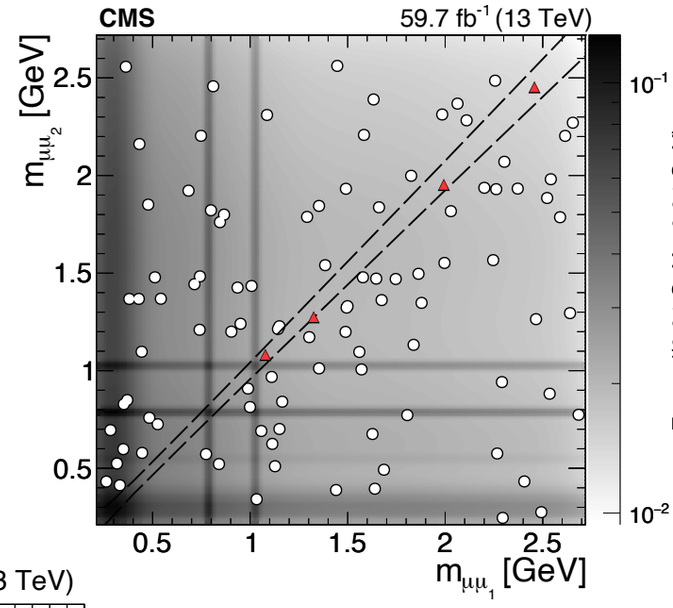
BSM Higgs boson decays: H→aa

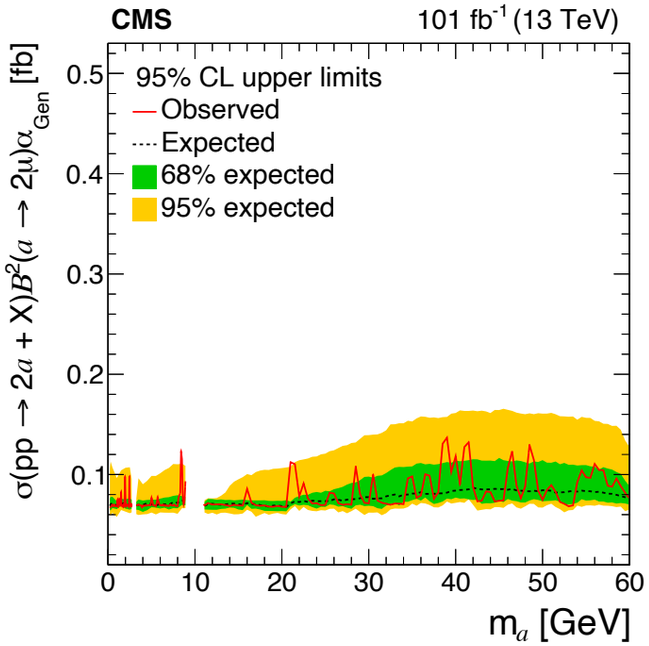
- Searches for Higgs boson decays into pseudo scalars H→aa
- 4τ / 2τ2μ channels with $4<m_a<15$ GeV (CMS-PAS-SUS-24-002) [left]
- 4μ channel with $0.21<m_a<60$ GeV (CMS-HIG-21-004) [right]



4τ





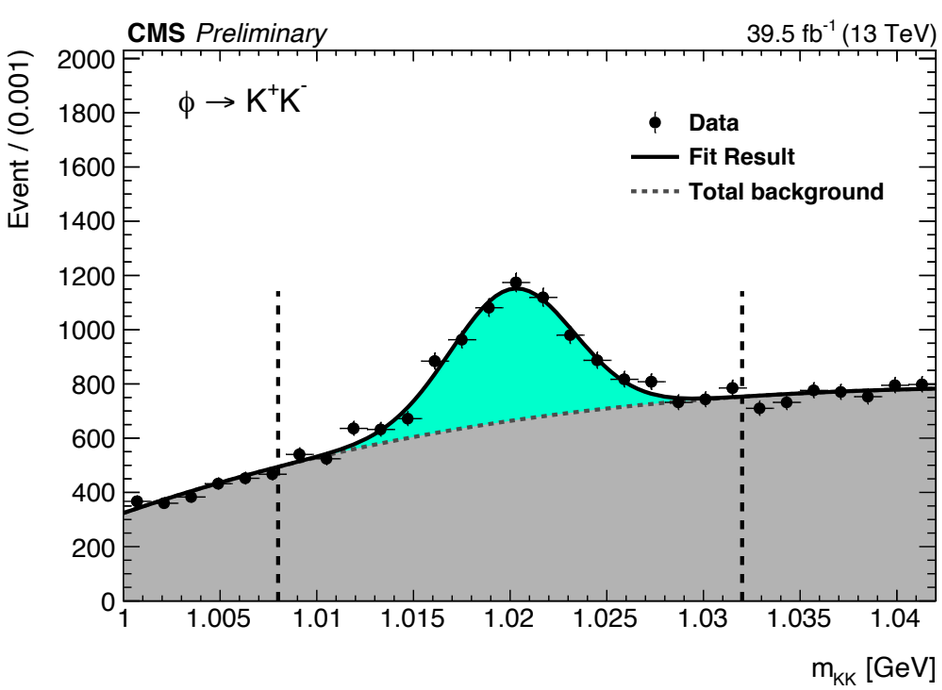


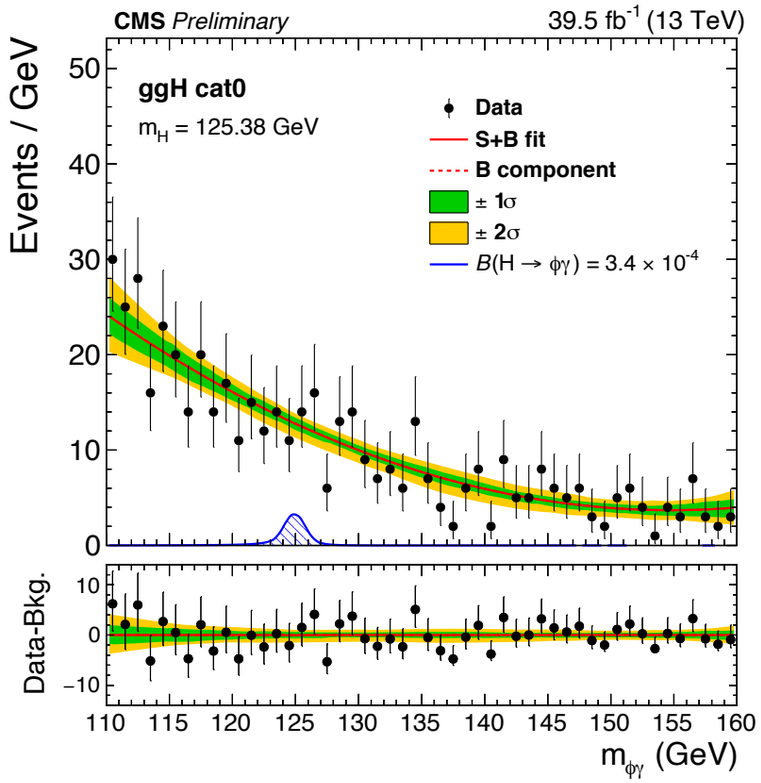
4μ

See talks by P. Pani on 08/11 (link) and A. Vijay on 05/11 (link)

Rare Higgs boson decays

- Search for rare decay of H into $\rho^0(770)$, $\phi(1020)$, or $K^{*0}(892)$ meson + γ: CMS-PAS-HIG-23-005
- Final states with $\rho^0 \to \pi^\pm \pi^\mp$ / $\phi \to K^\pm K^\mp$ / $K^{*0} \to K^\pm \pi^\mp$
- Sensitive to light quark Yukawa couplings
- Upper limits on branching fractions at 95% CL of 2.74×10^{-4}, 2.97×10^{-4}, and 1.71×10^{-4}, respectively
  - 22 times the SM expectation for $\rho^0(770)$ and 129 times the SM expectation for $\phi(1020)$





See talks by G. Gregorio on 07/11 (link), and A. Vijay on 05/11 (link)

Higgs mass measurement

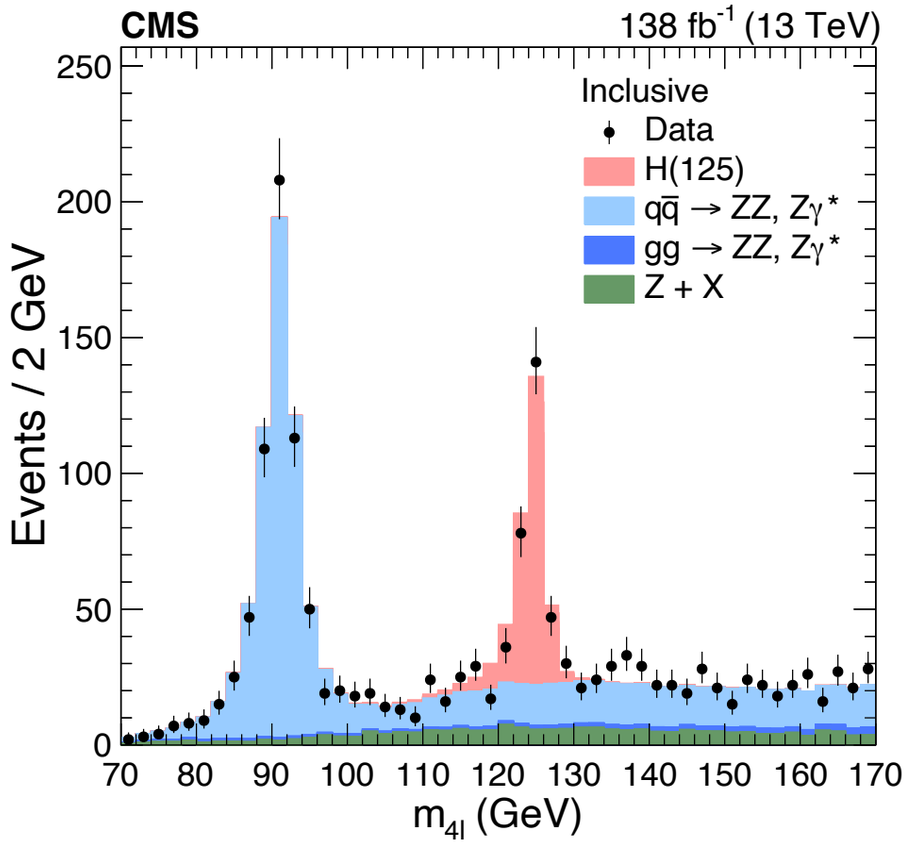
- Measurement of Higgs mass using H→ZZ, combining 4μ, 4e, and 2e2μ channels:
  CMS-HIG-21-019

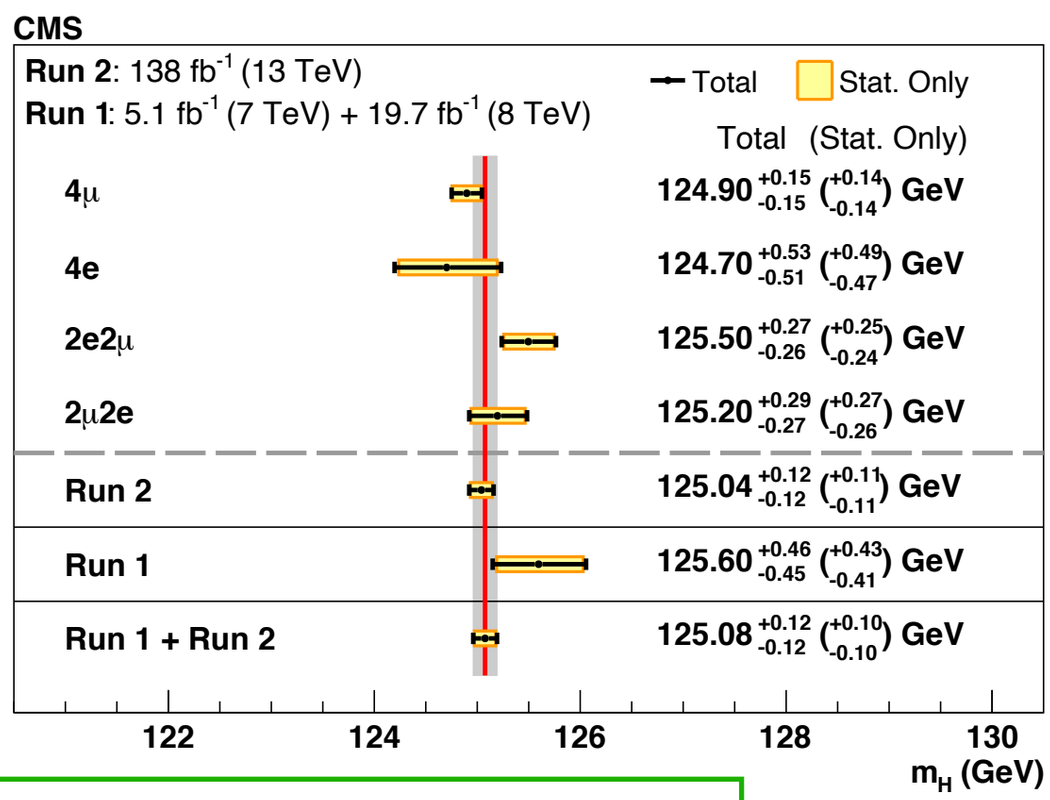
- Improvements to muon track reconstruction, reduction in leptons momentum scale uncertainties, and improved categorisation

- Plus increase in data from 36/fb→138/fb

- Statistics dominated [0.14 GeV (stat) vs 0.05 GeV (syst)], largest systematic due to lepton momentum scale and resolution

- **Most sensitive measurement to date by a single channel (H→4μ)!**



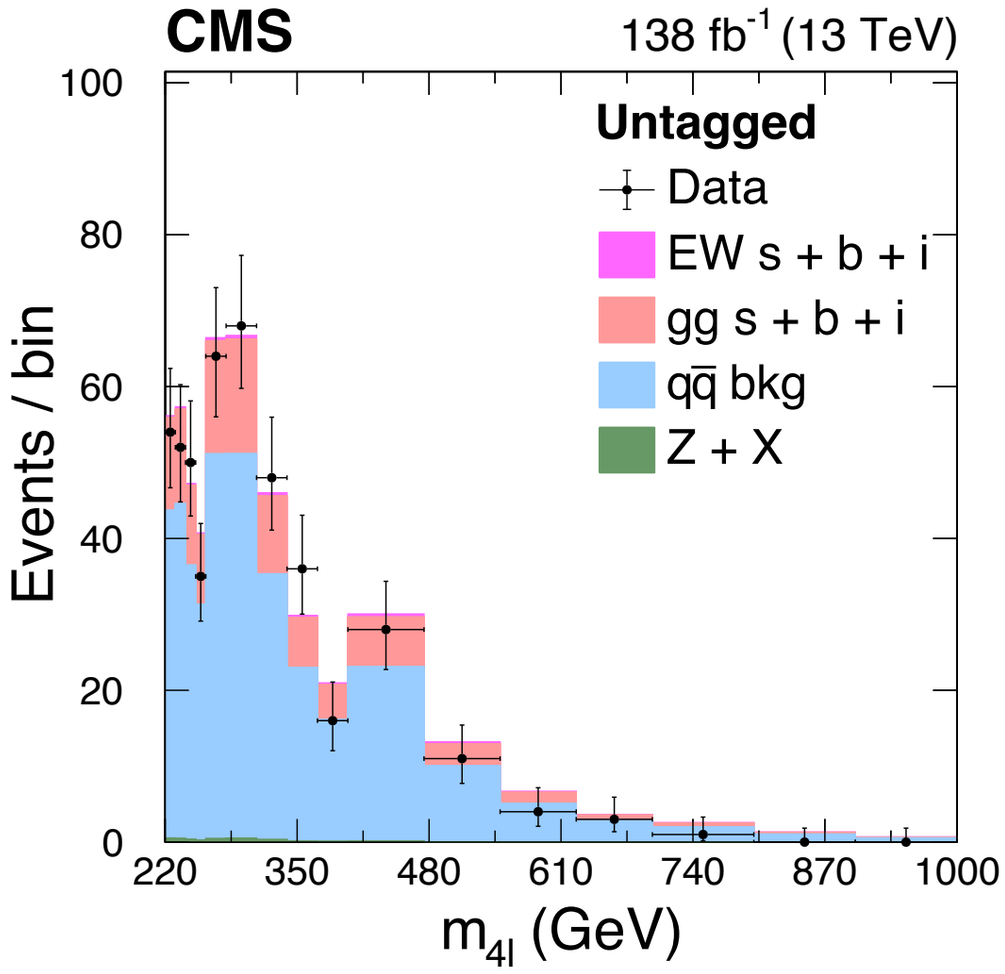


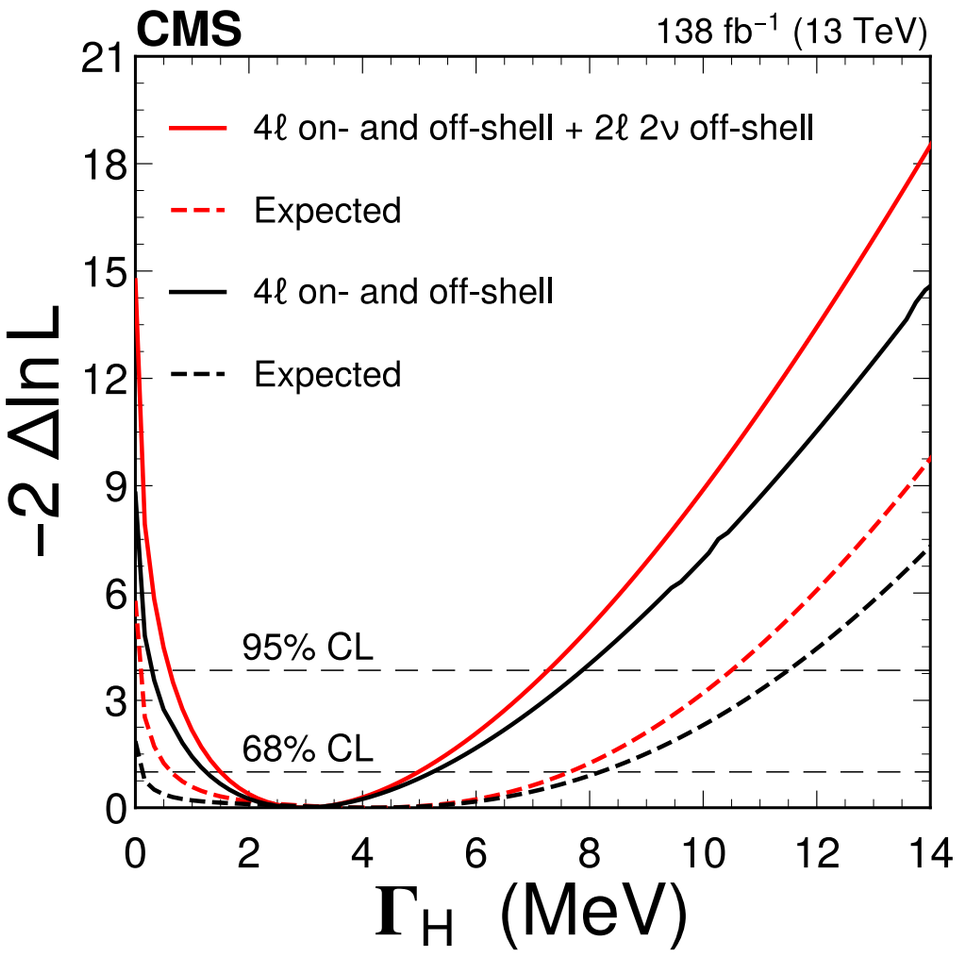
See talks by P. Bokan on 07/11 (link), and R. Gargiulo on 05/11 (link)

Higgs width measurement

- Update of Higgs width measurement using off-shell events: CMS-HIG-21-019
- Compare off-shell vs on-shell measurements to extract the width
  - General idea: $\sigma^{\text{on-shell}} \propto \mu^{\text{on-shell}}$, $\sigma^{\text{off-shell}} \propto \mu^{\text{on-shell}} \Gamma_H$
  - But interference effects with ZZ continuum as well
- Update of result this year to include full Run-2 for 4l channel (138/fb vs 78/fb)
- **Measured value** $3.0^{+2.0}_{-1.5}$ **MeV (**4.1 ± 3.5 **MeV expected)**

See talks by P. Bokan on 07/11 (link), and R. Gargiulo on 05/11 (link)





Summary

- Lots of new interesting Higgs results from CMS in the last year
- We have seen first measurements using Run-3 data @ 13.6 TeV and we expect many more results to following in the near future
- In addition, we continue to exploit the Run-2 13 TeV data
- Several new measurements and searches have been conducted
- Stay tuned for more Higgs results in the future!

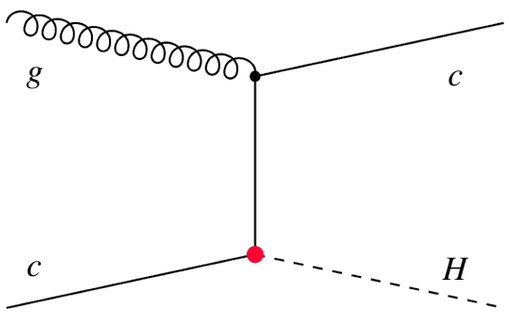
Backup

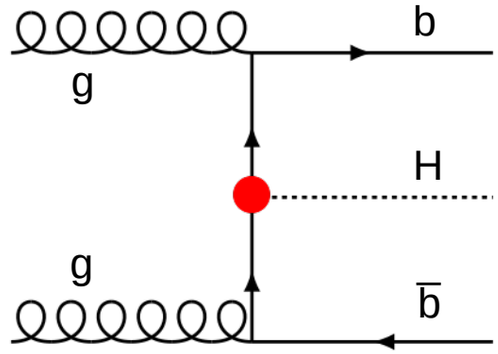
Constraints on y_b and y_c from production

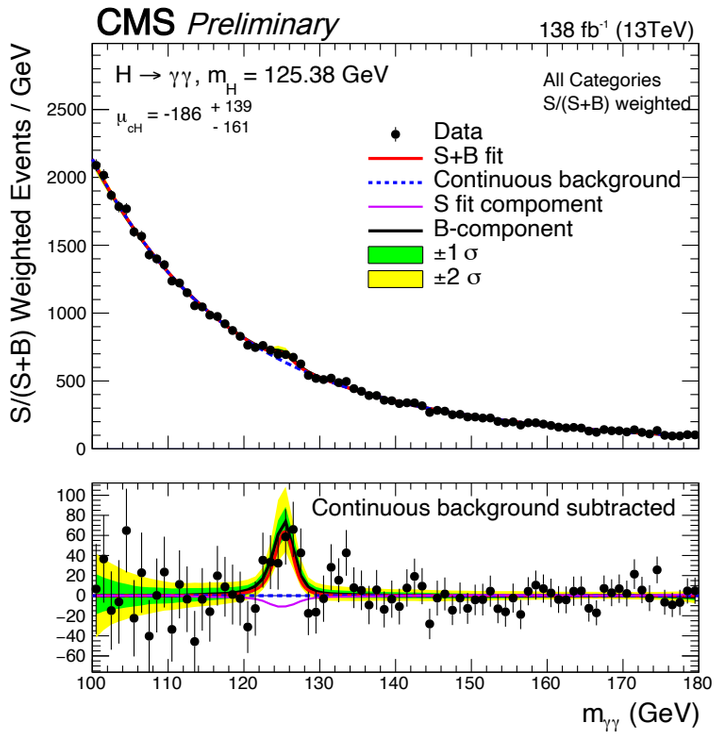
- Measurements of b and c Yukawa couplings using associated production with b-jets (CMS-HIG-23-003) and c-jets (CMS-PAS-HIG-23-010)

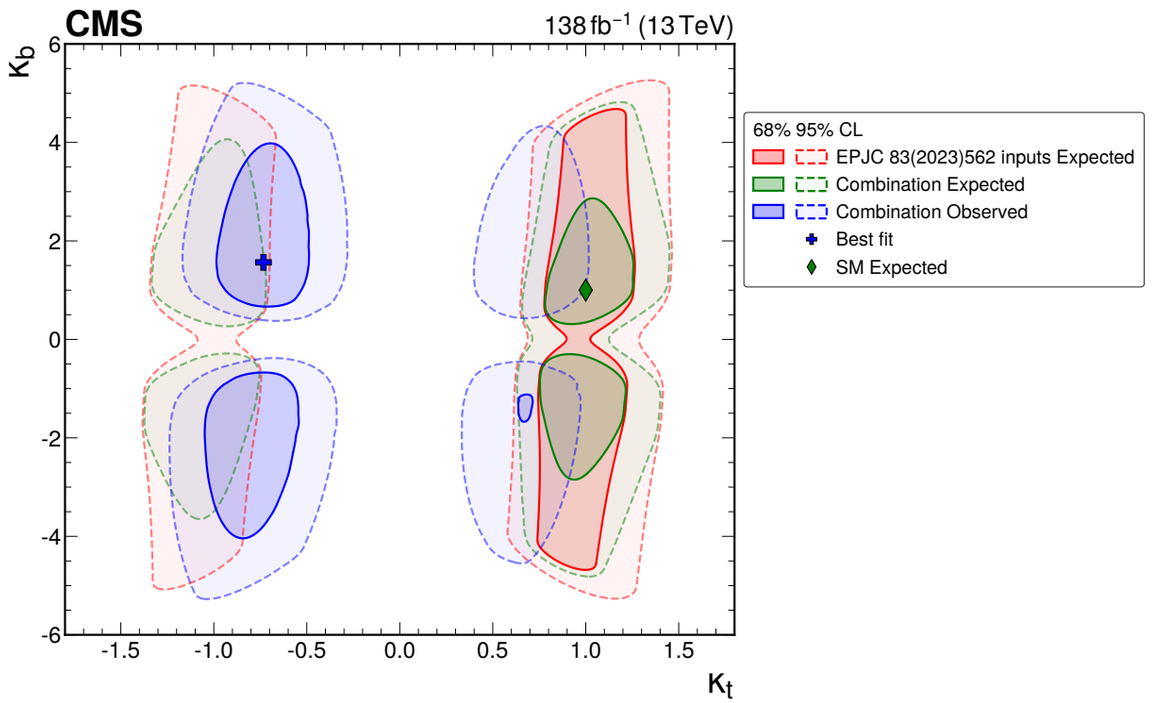
- Charm coupling measured using H+c events where H→γγ and c quark produced c-tagged jet: obs. (exp.) limit κ_c <38.1 (72.5)

- Bottom coupling measured using H+b-jet(s) events where H→ $\tau\tau$/WW: obs. (exp.) limit κ_b < 3.7 (6.1)





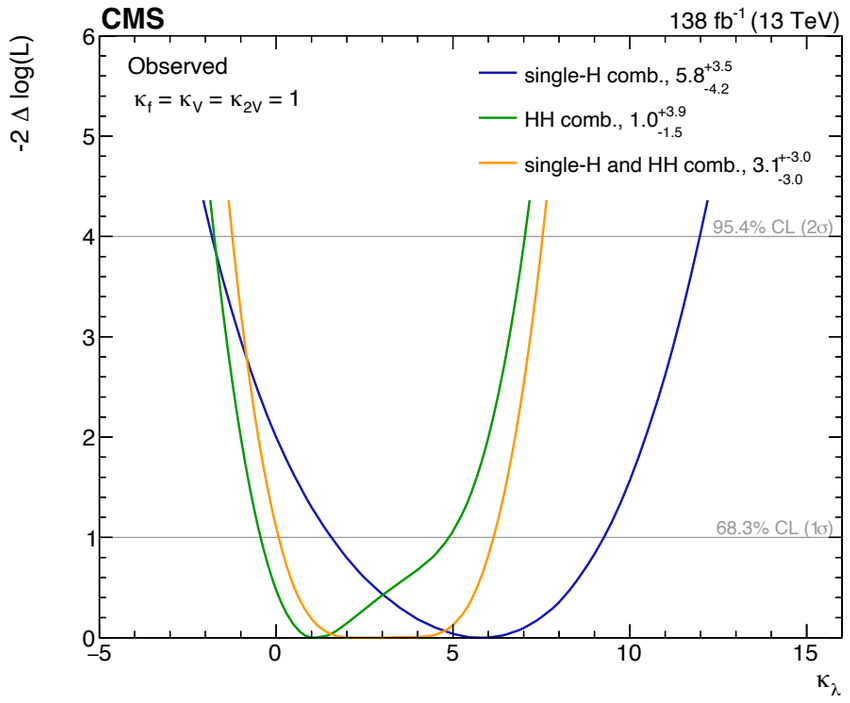


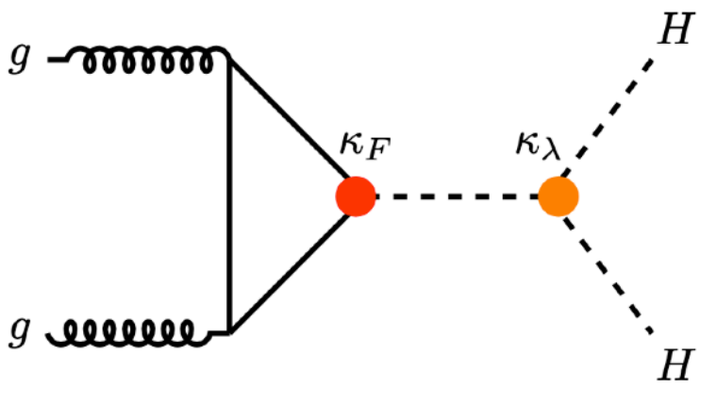


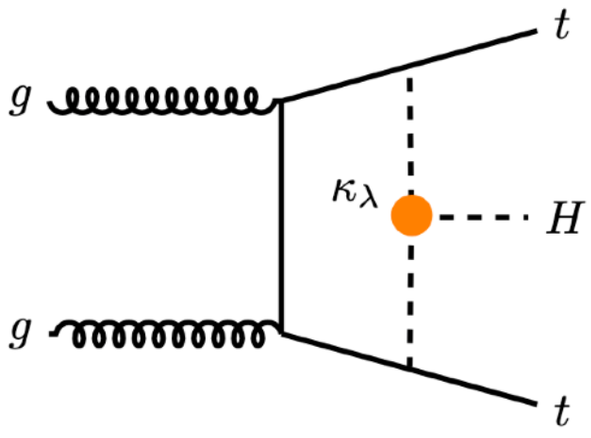
Higgs self-coupling

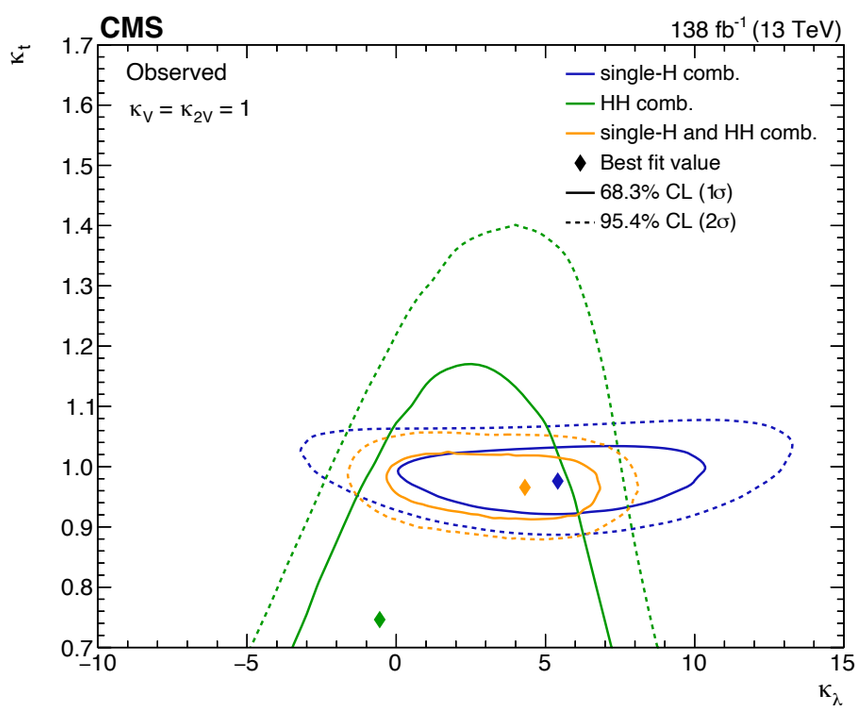
- Constraints on trilinear Higgs coupling, λ, from non-resonant double-Higgs searches and precision measurements of single-Higgs production

- Latest CMS results include a combination of double- and single-H: CMS-HIG-23-006





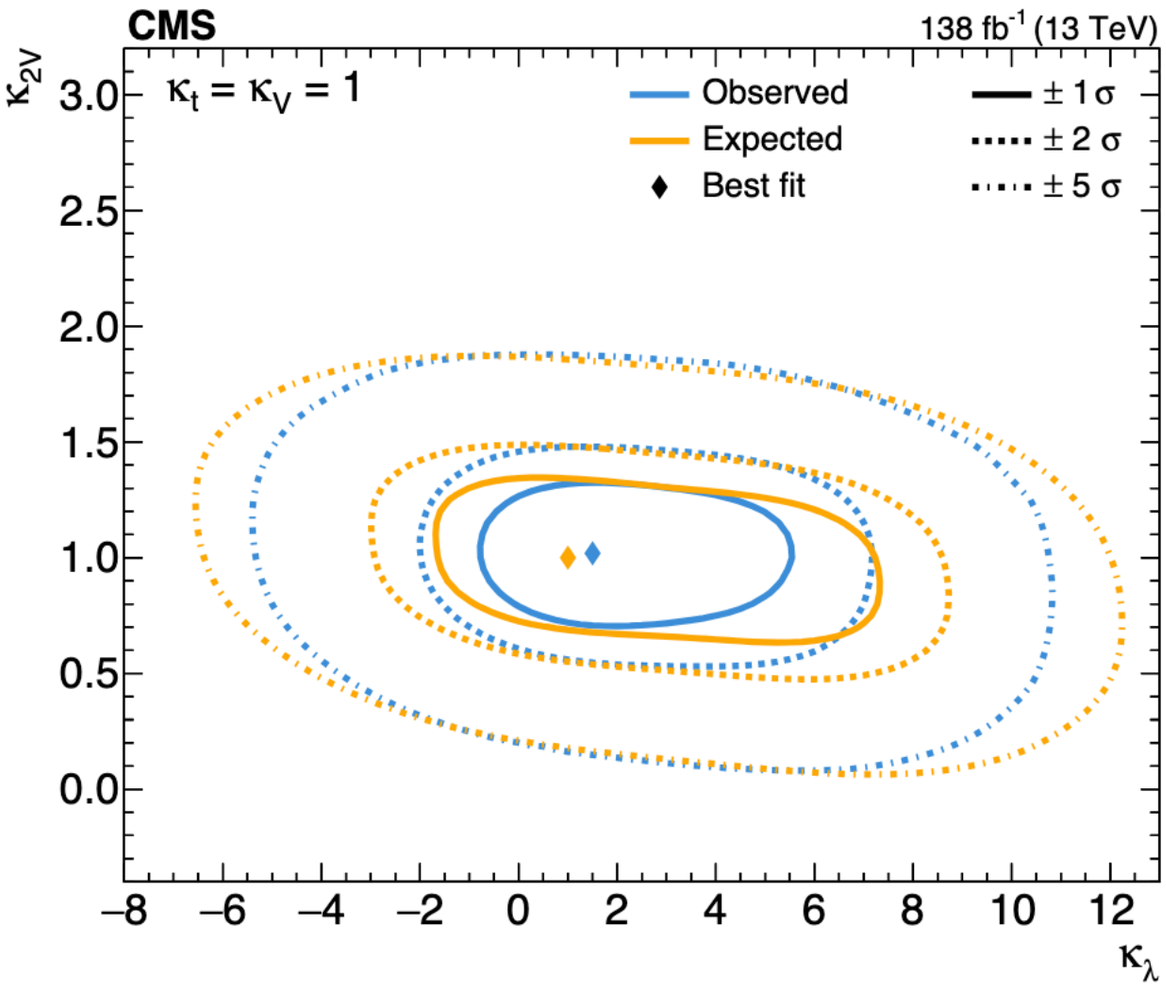


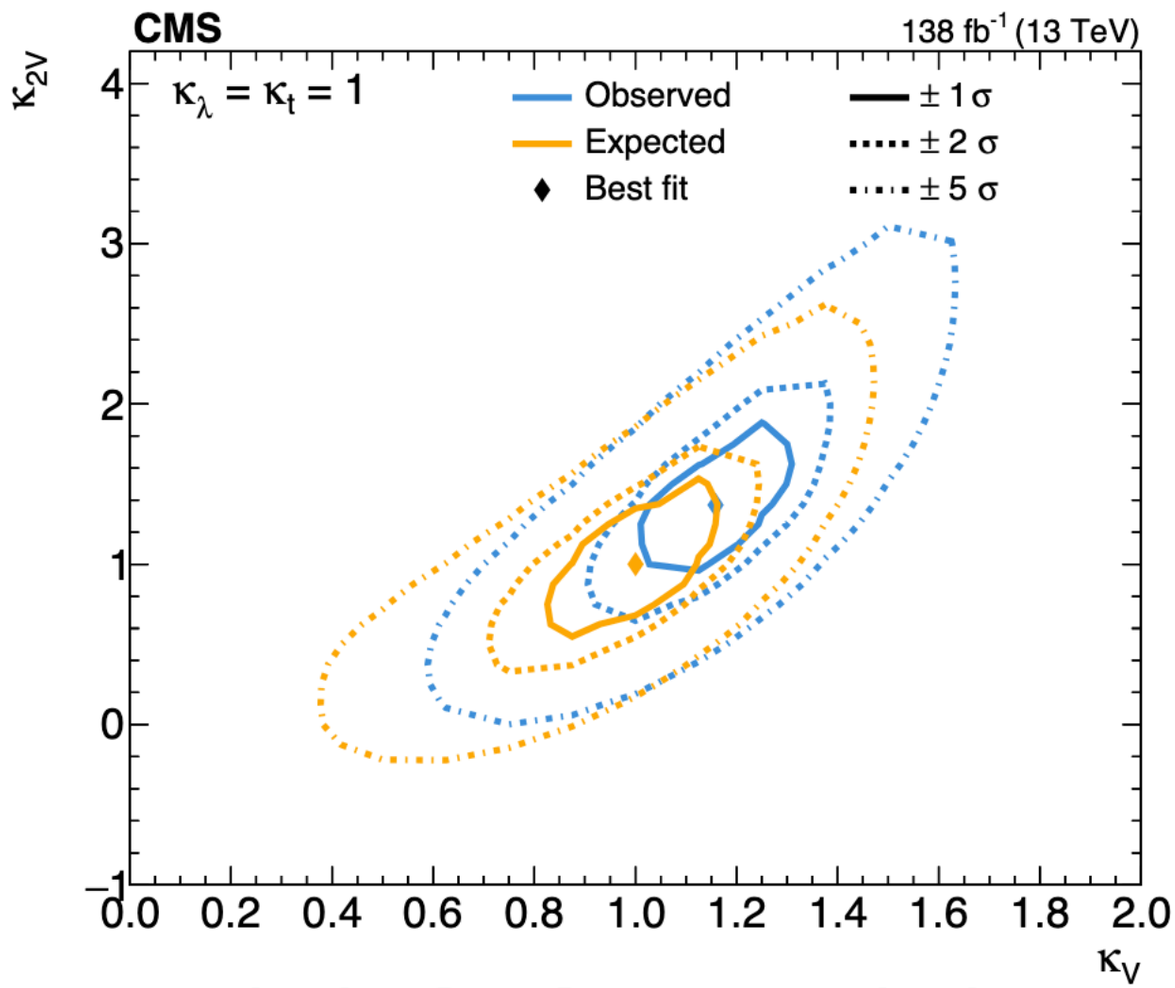


di-Higgs non-resonant

NEW!

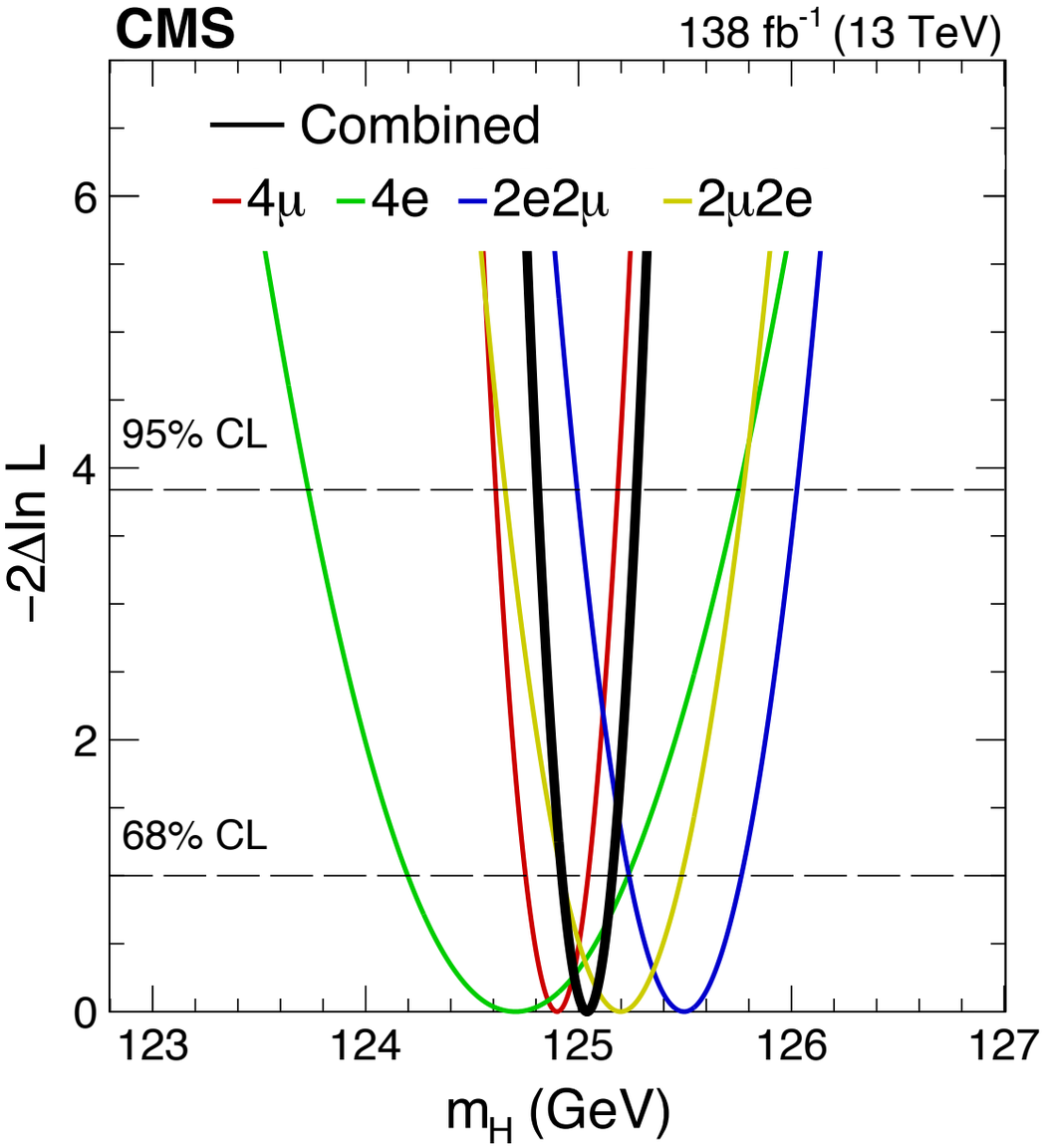
- Additional 2D scans

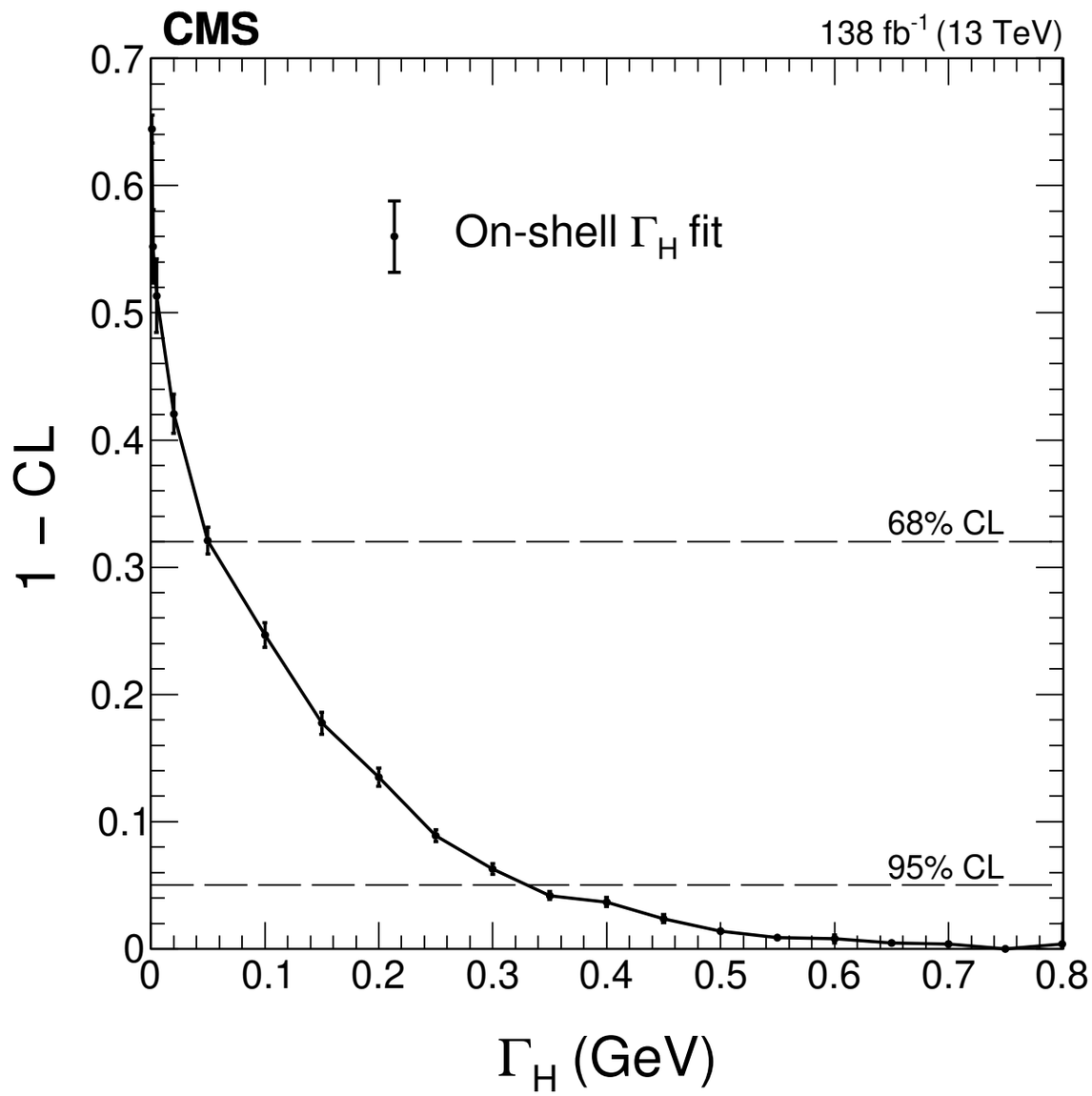




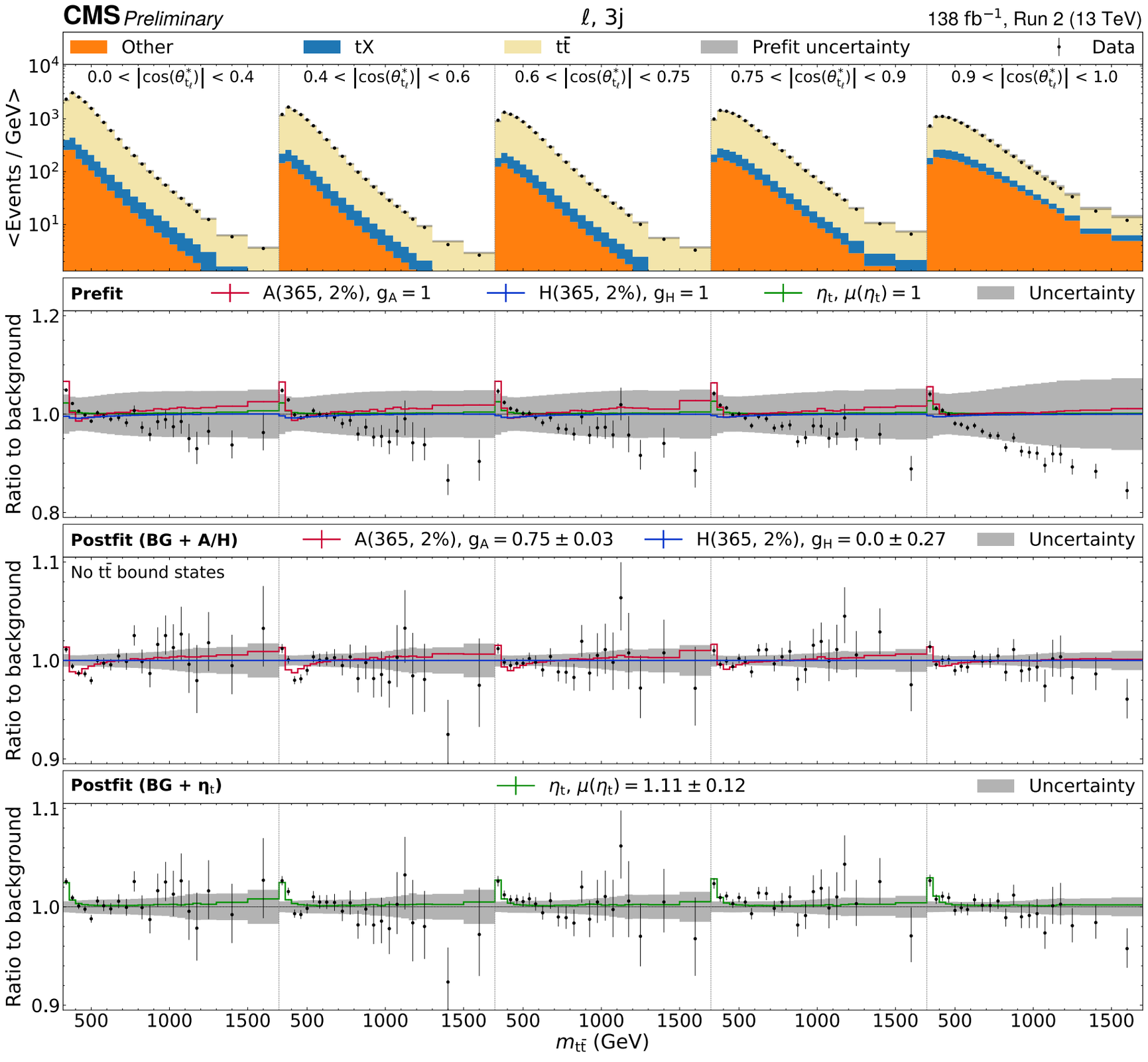
Higgs mass/ width

- Left: Mass measurements by channel
- Right: direct measurement of width using on-shell events

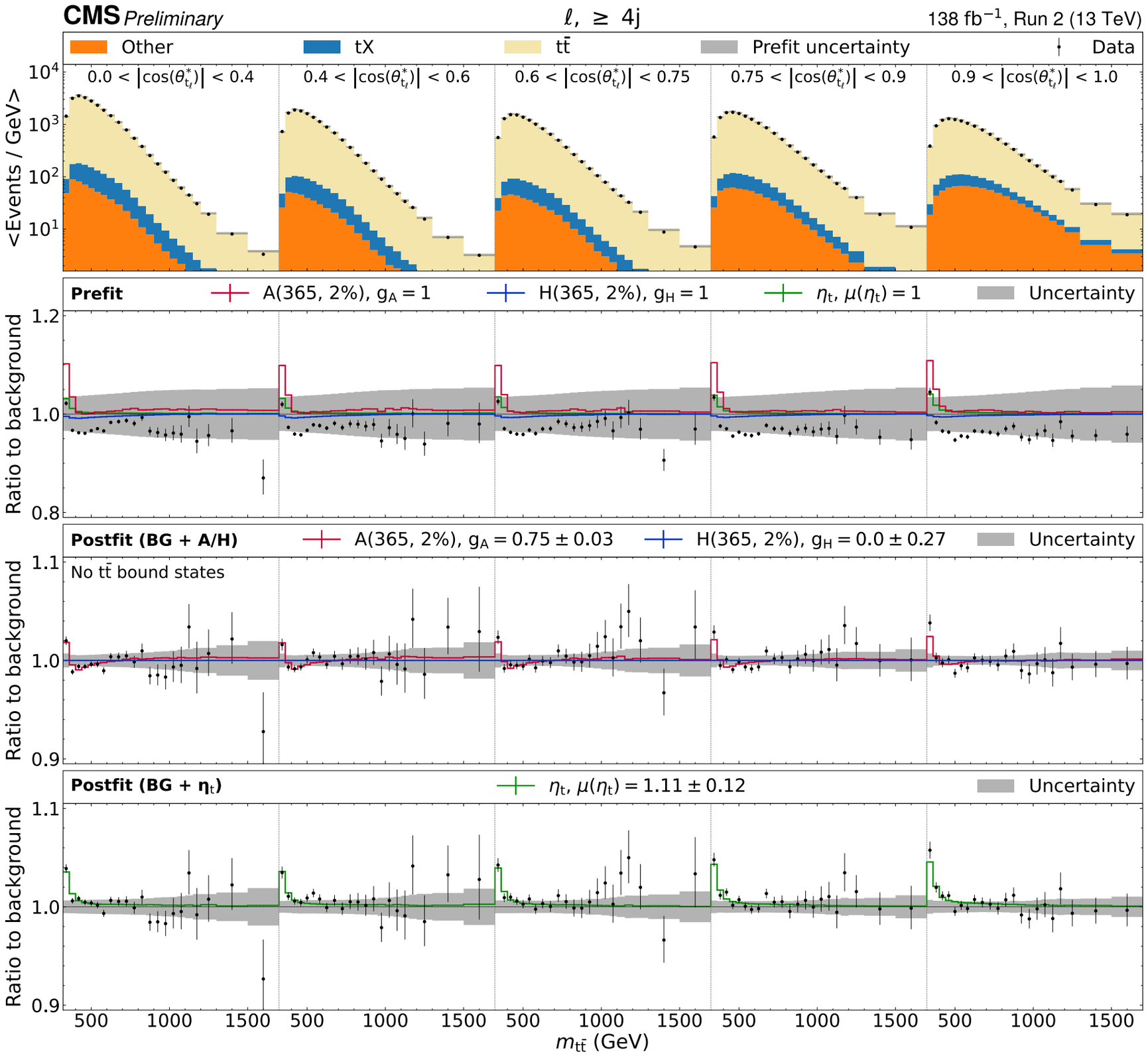




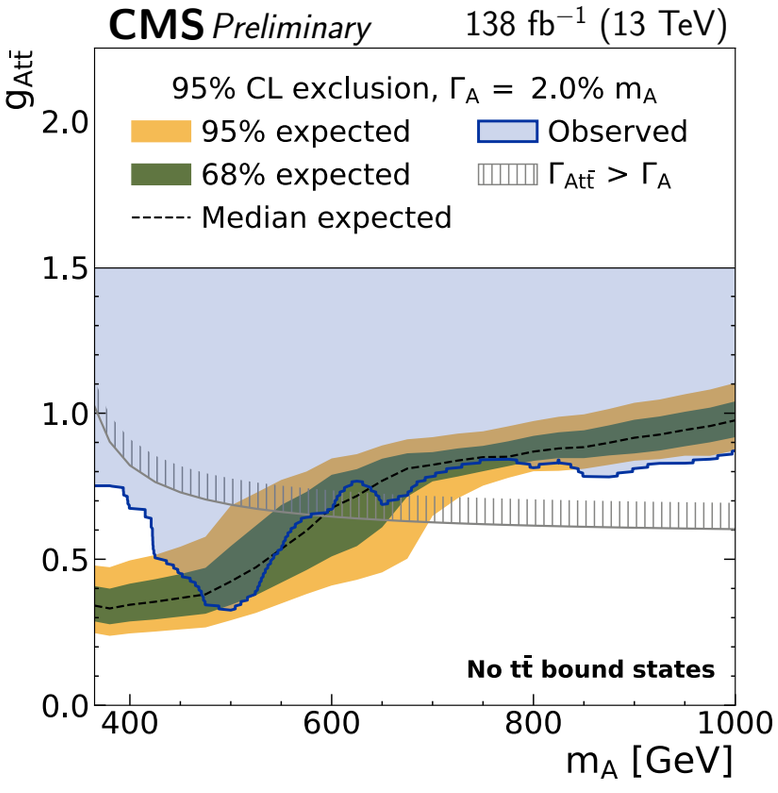
H/A→$t\bar{t}$: semi-leptonic channels

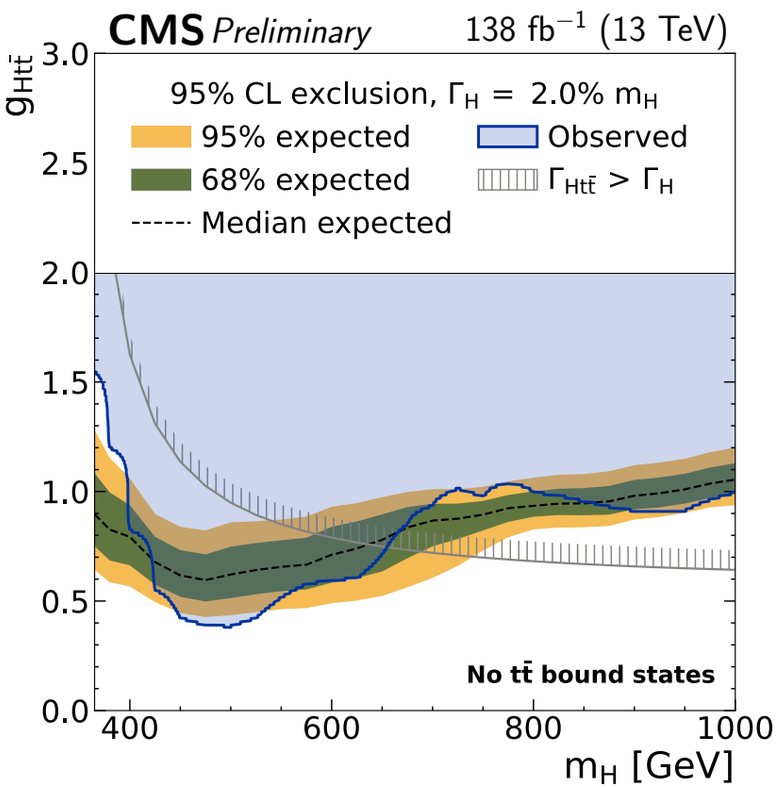


H/A→$t\bar{t}$: semi-leptonic channels

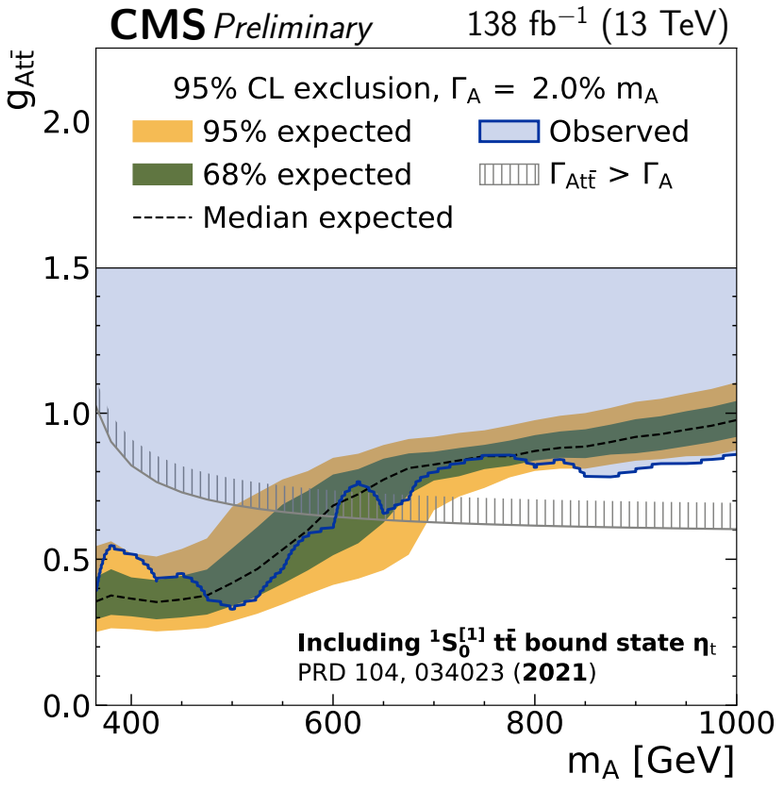


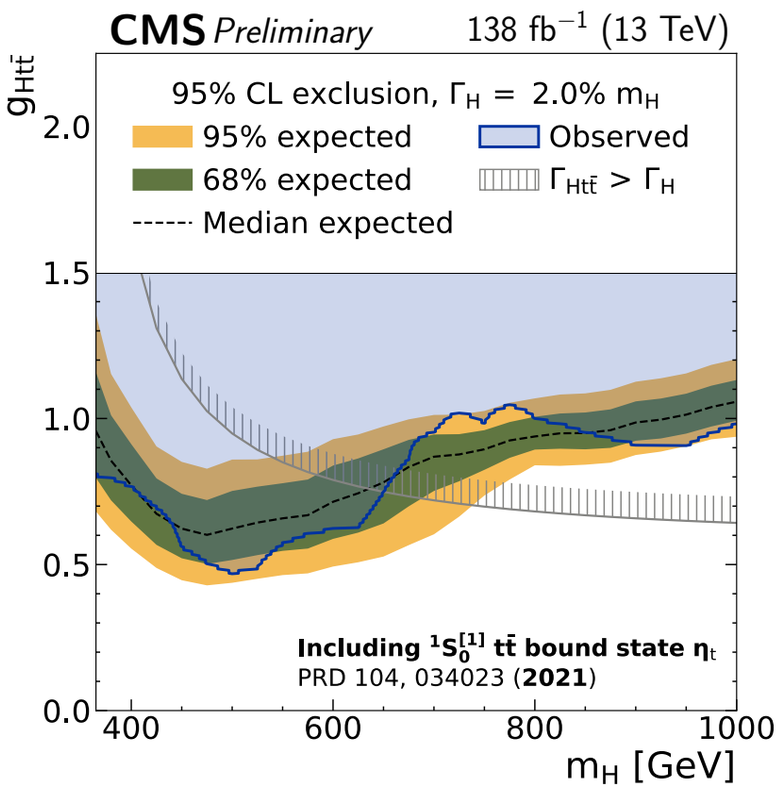
H/A→$t\bar{t}$ limits w/o η_t





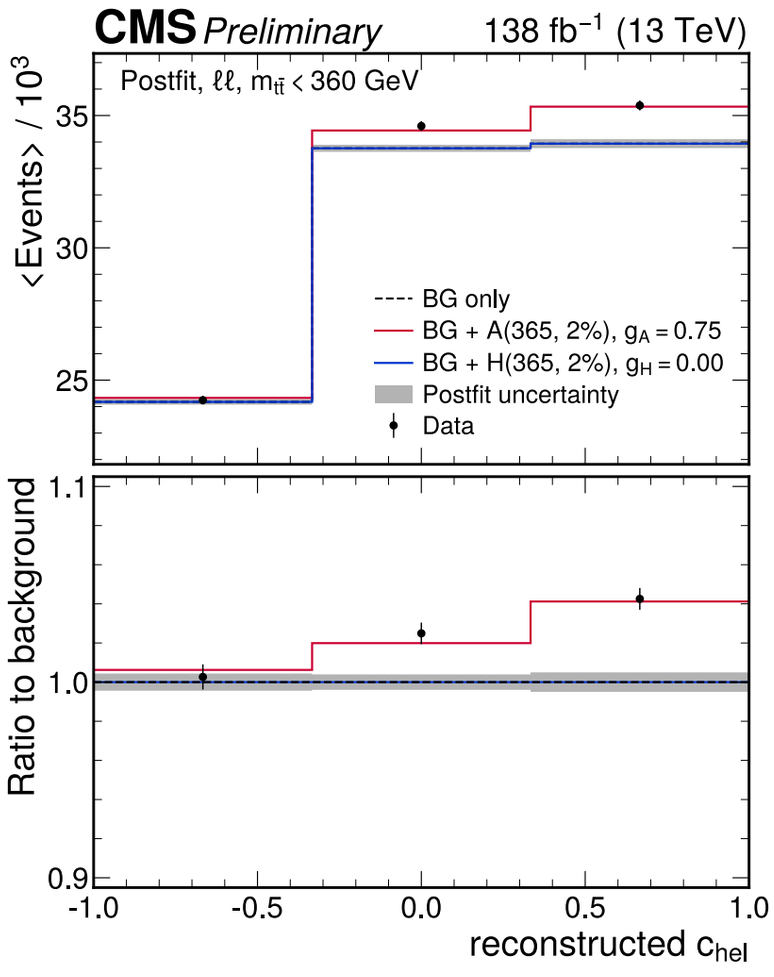
No η_t

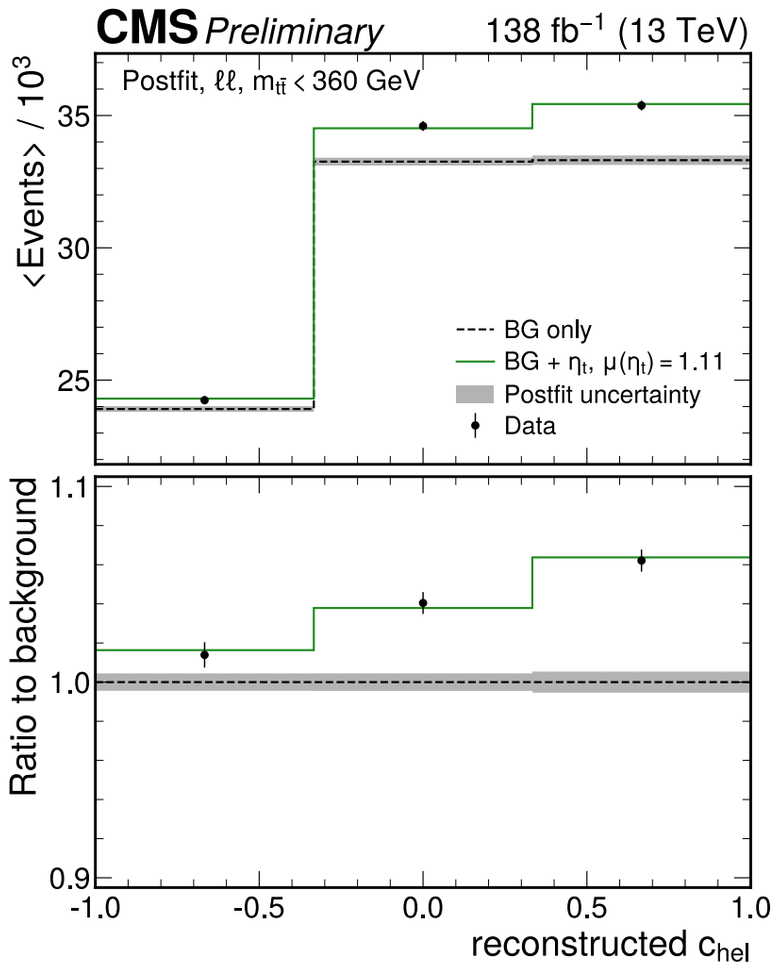




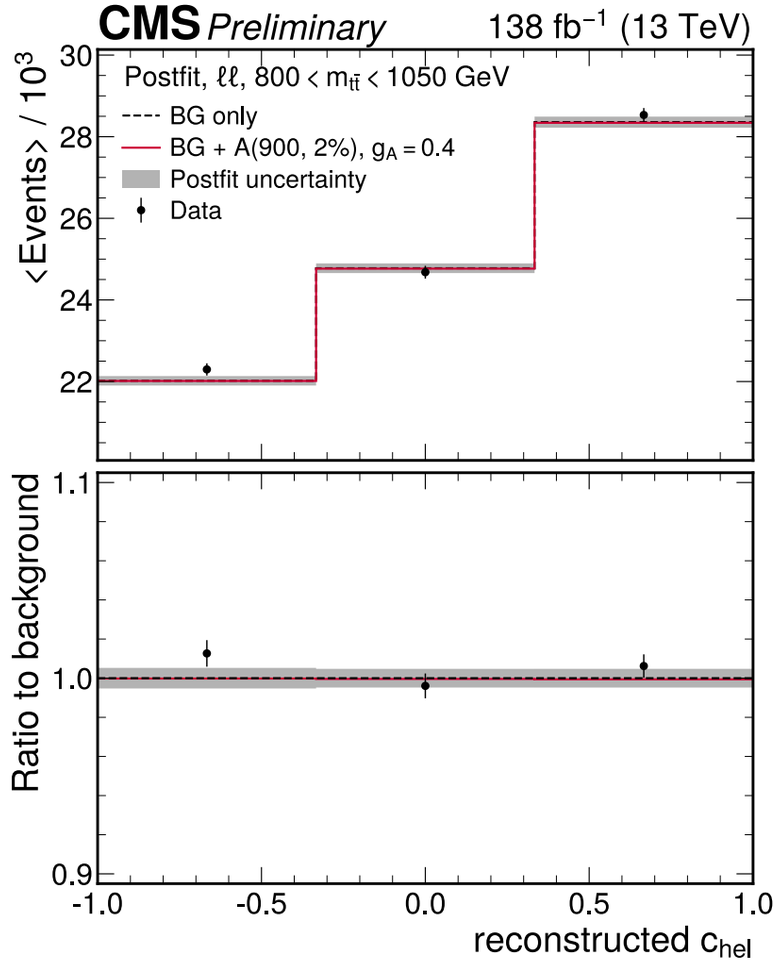
Inc. η_t

H/A→$t\bar{t}$ spin sensitive observable





Low mass < 360 GeV

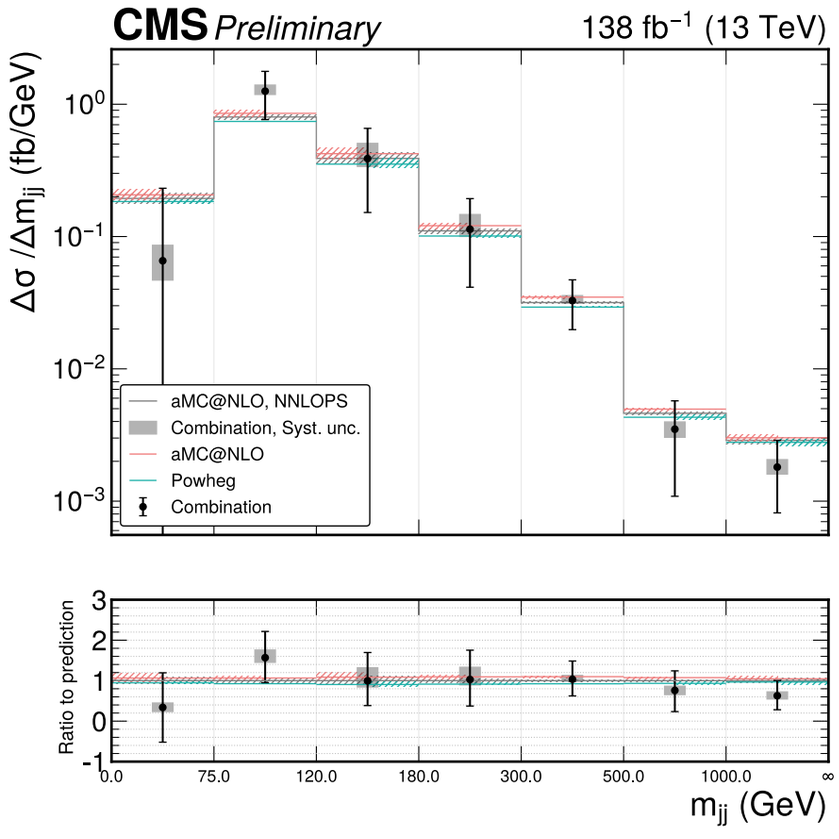


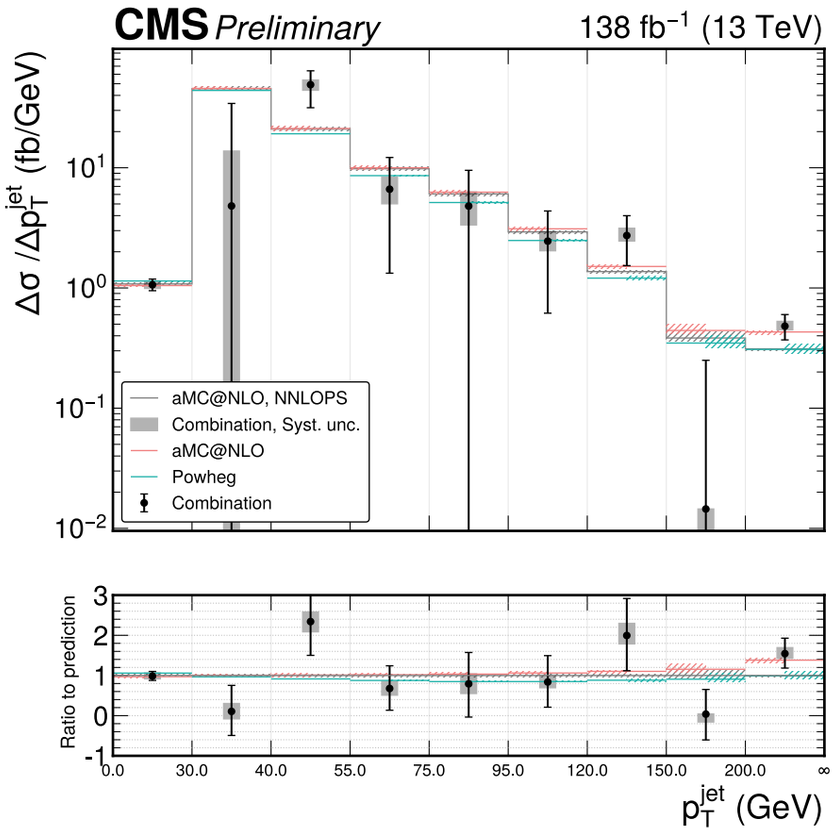
High mass 800–1050 GeV

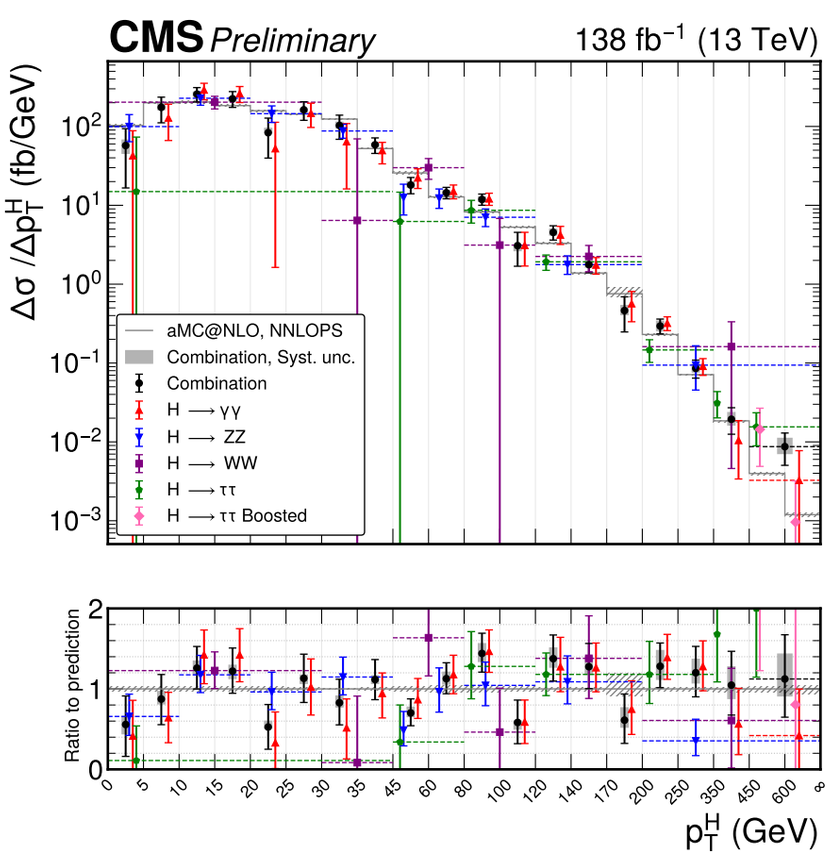
Differential measurements

- Combination of differential measurements for γγ, ZZ, WW, and $\tau\tau$ channels: CMS-PAS-HIG-23-013

- Other examples of measured variables and p_T measurements comparing each channel

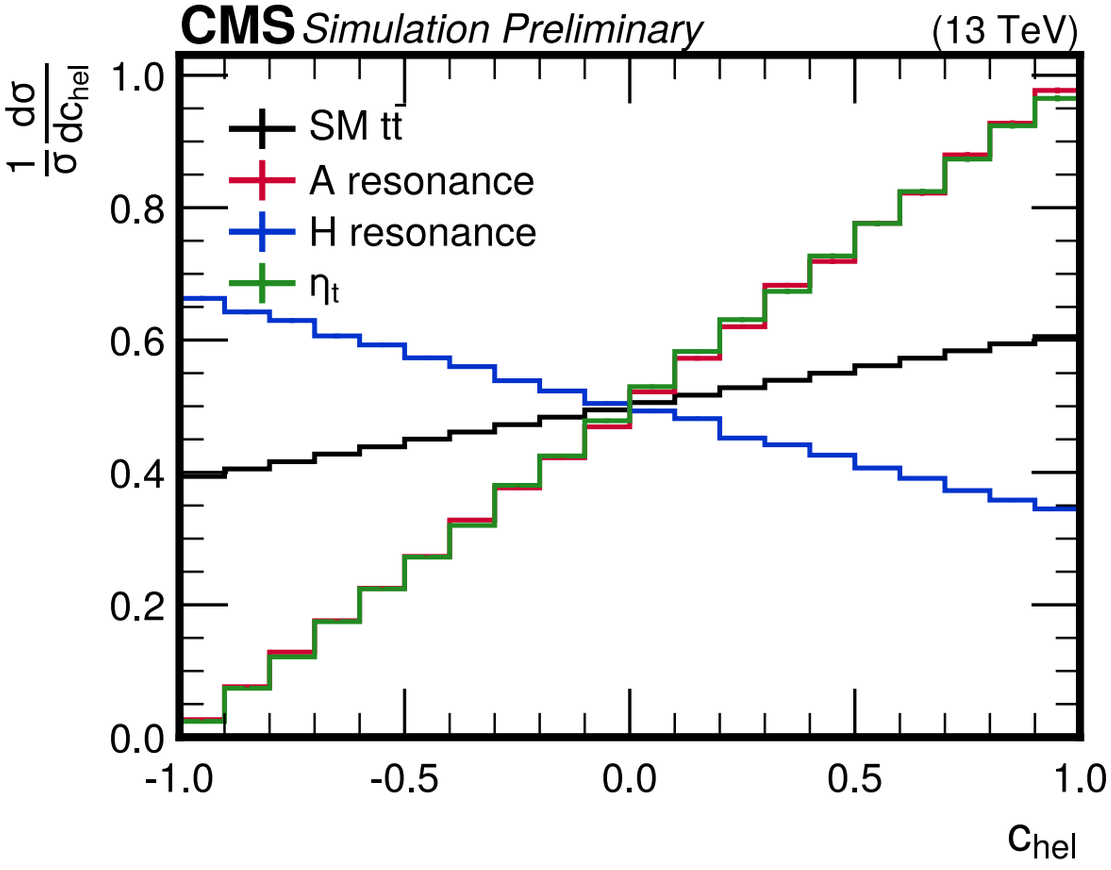


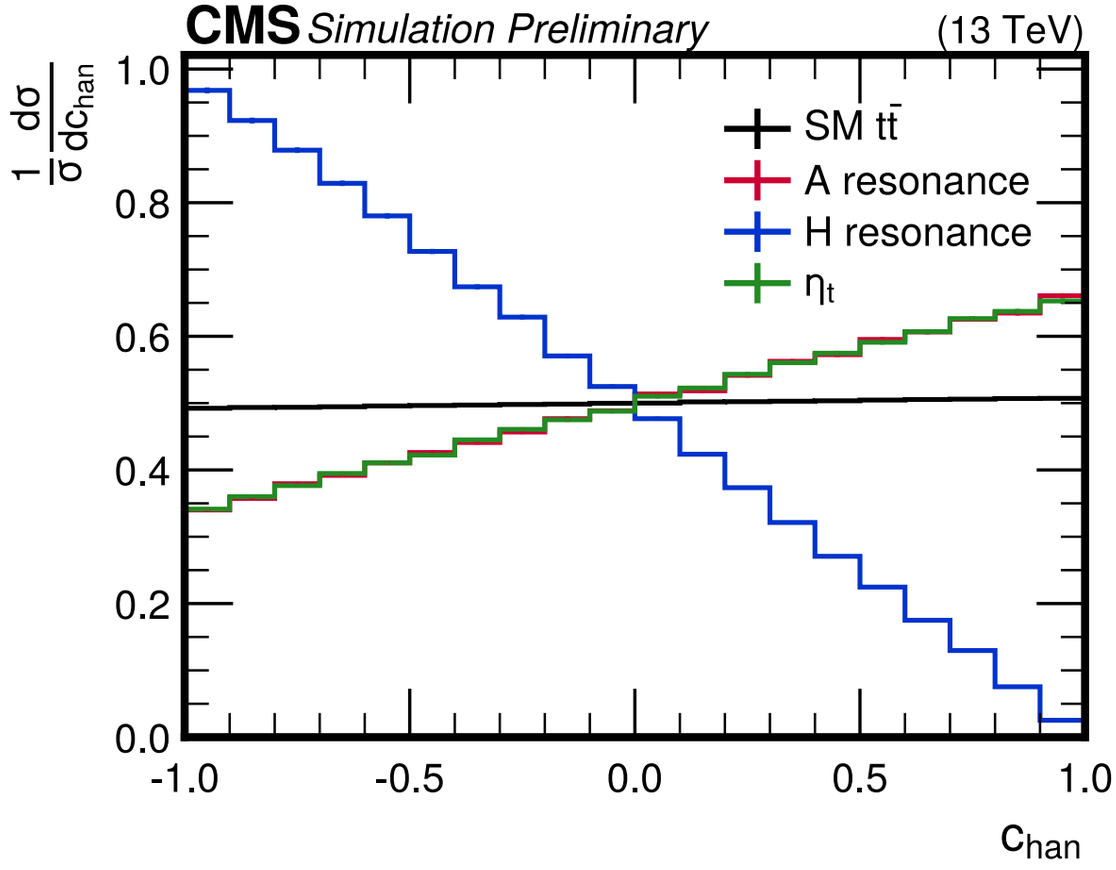




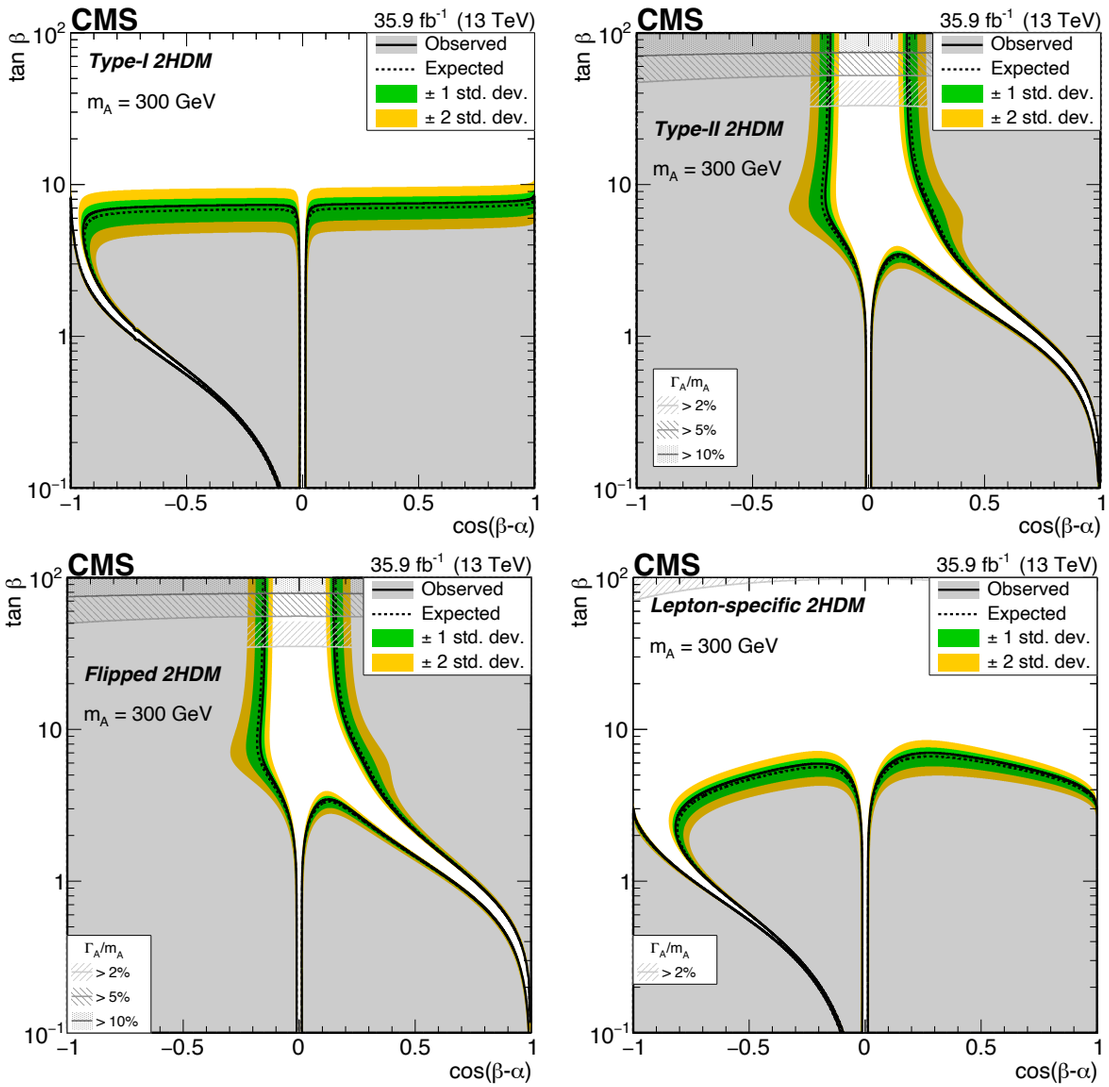
H/A→$t\bar{t}$: spin correlation observables

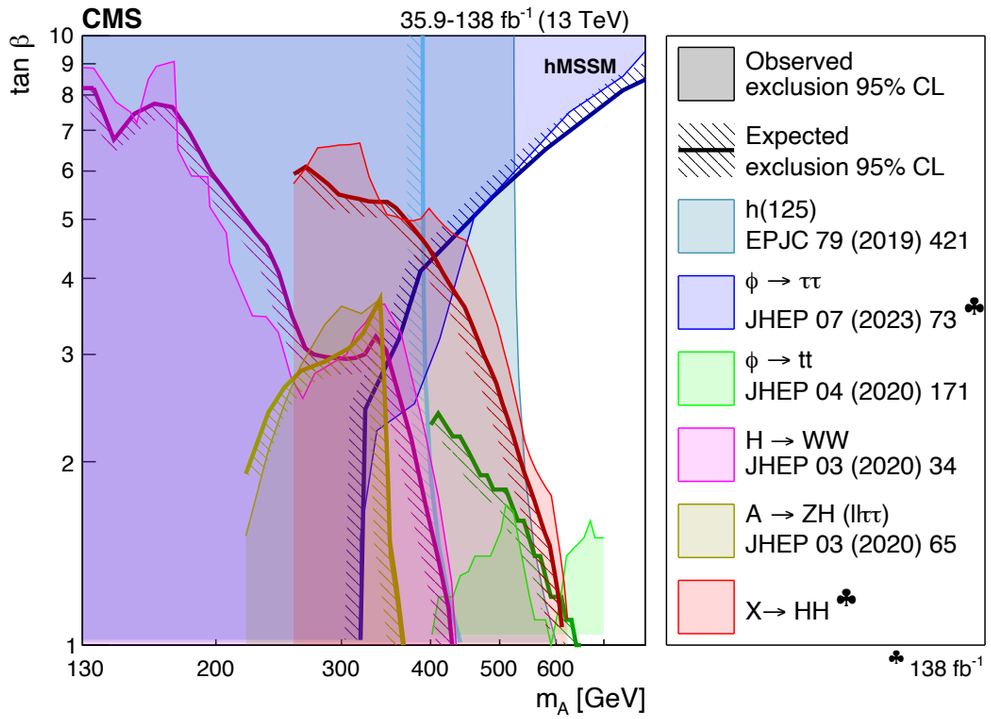
- θ^* scattering angle of leptonic top quark
- c_{hel} and c_{han}: spin correlation observables
  - Linear combinations of entries in spin density matrix
  - c_{hel}: distinguishes mostly SM vs. A (pseudoscalar). $c_{hel} = \hat{l}_t^+ \cdot \hat{l}_t^-$ (units vectors in helicity frames)
  - c_{han}: distinguishes mostly SM vs. H (scalar). Flips sign component parallel to top quark direction for either $\hat{l}_t^+$ or $\hat{l}_t^-$ then take scalar product



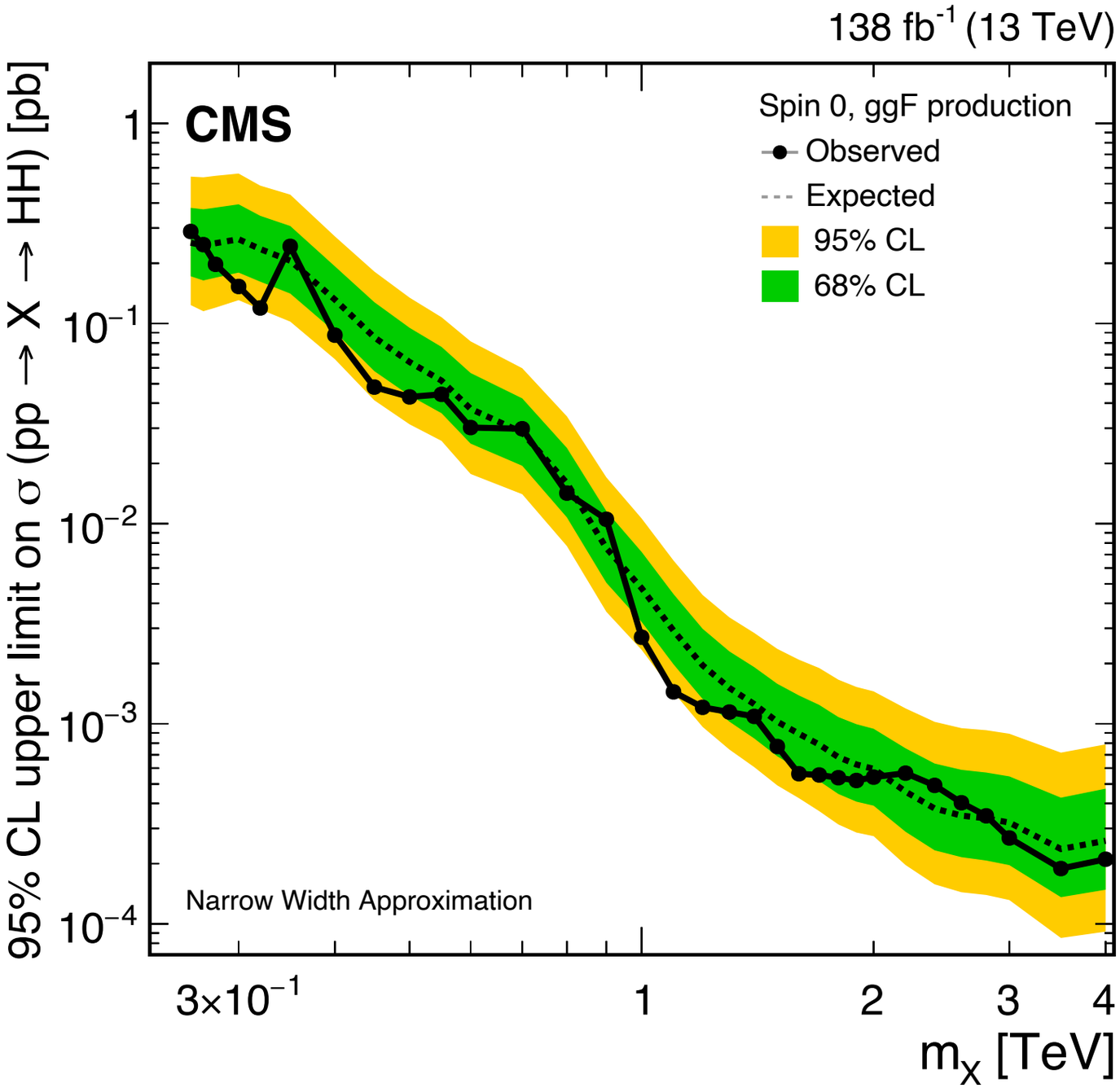


di-Higgs resonant - more interpretations

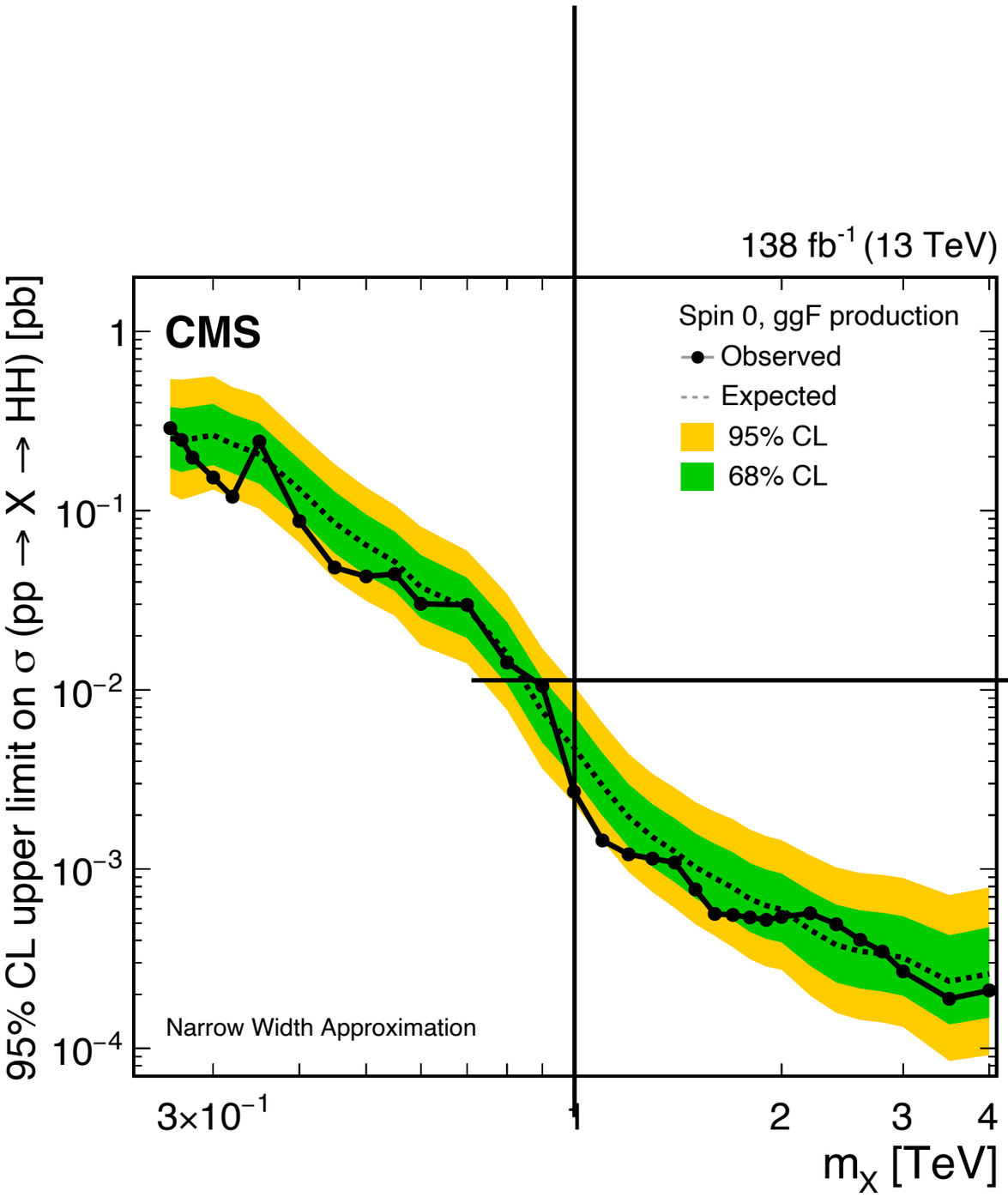


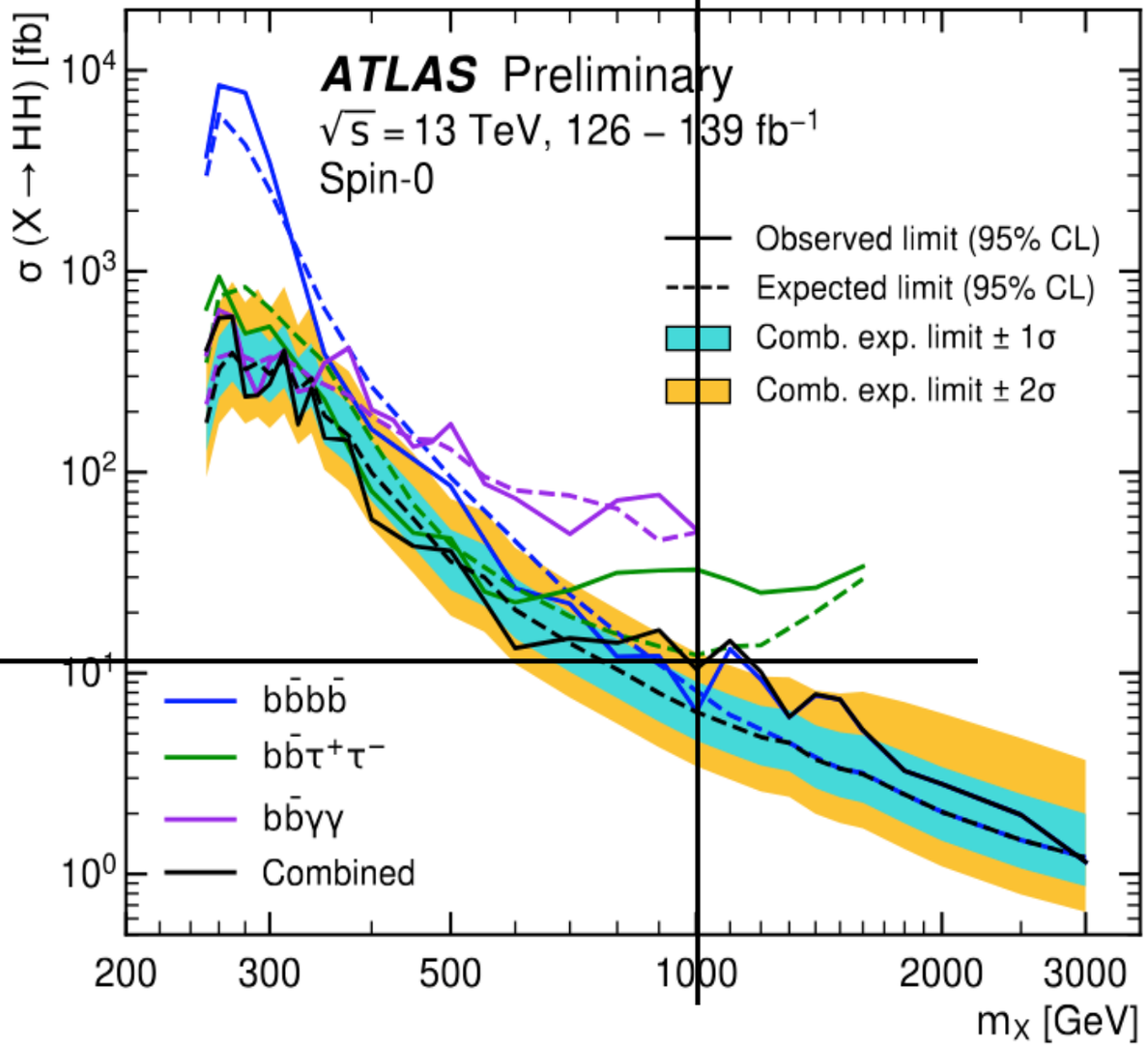


di-Higgs resonant - limits with confidence regions

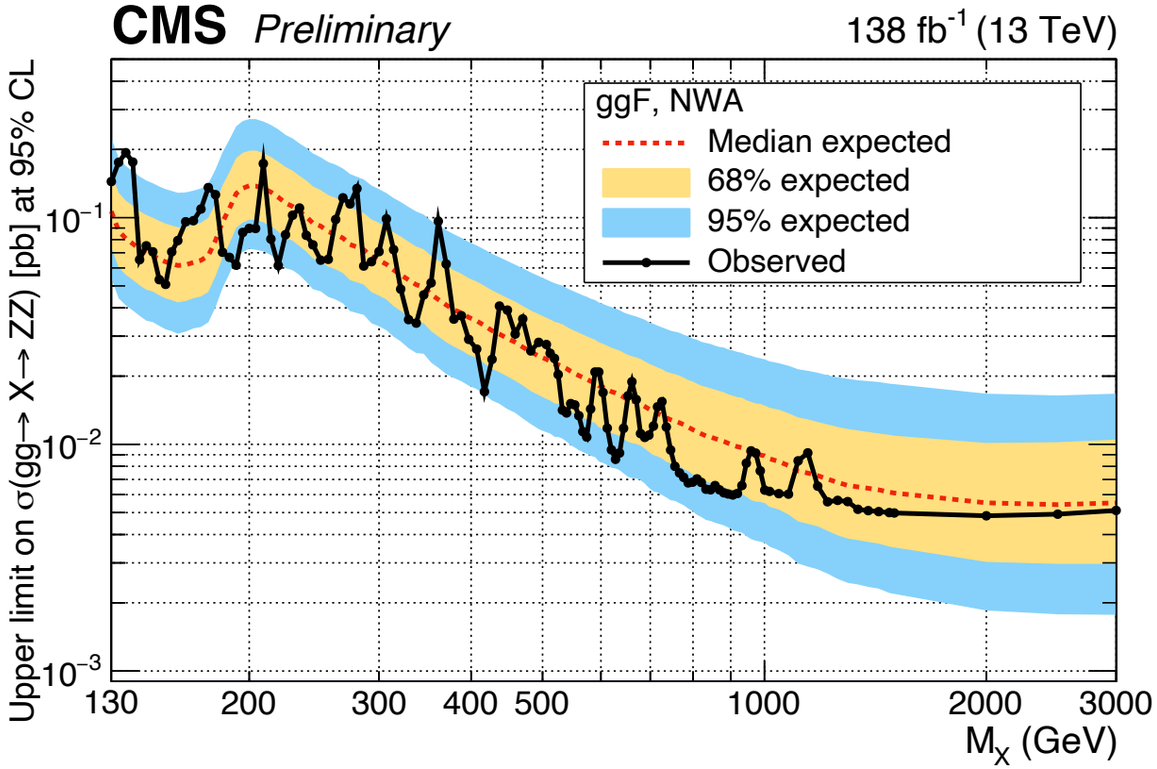


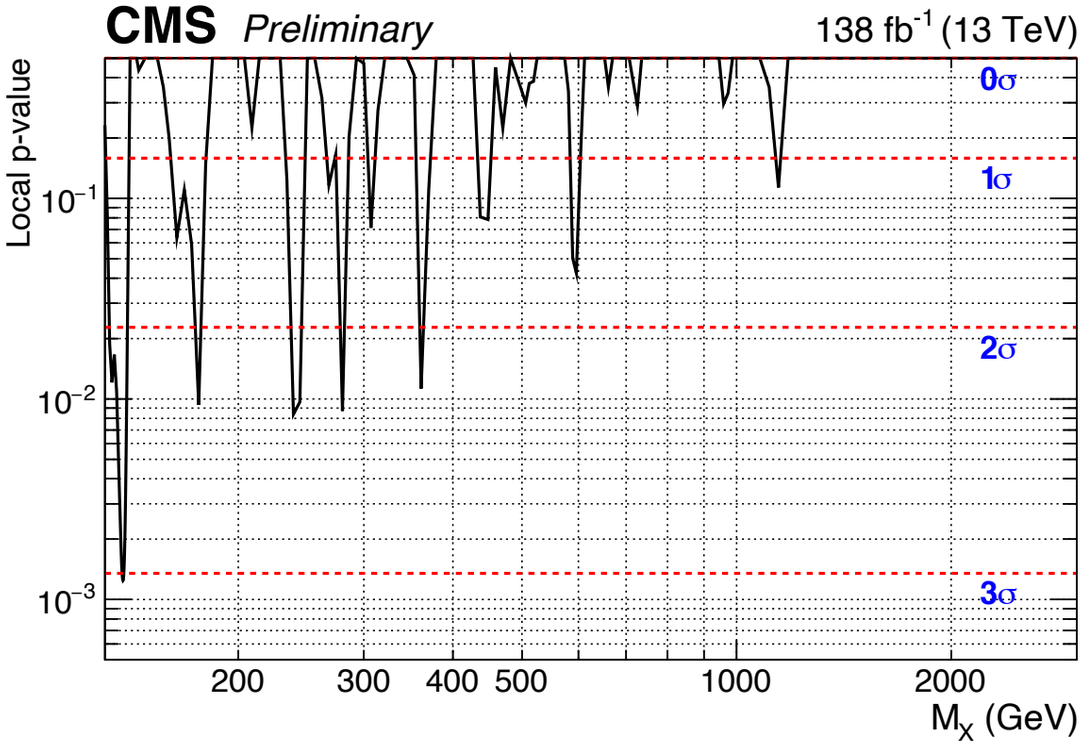
di-Higgs resonant - comparison to ATLAS excess

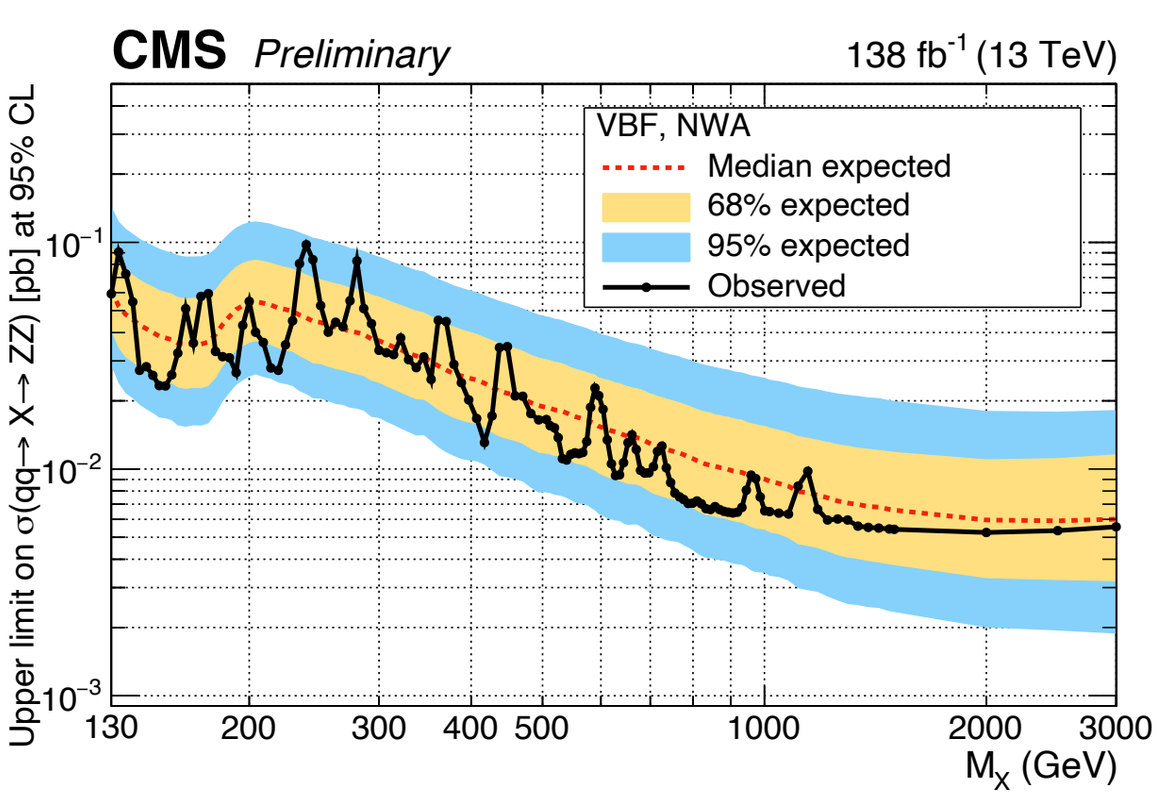




Heavy H→ZZ

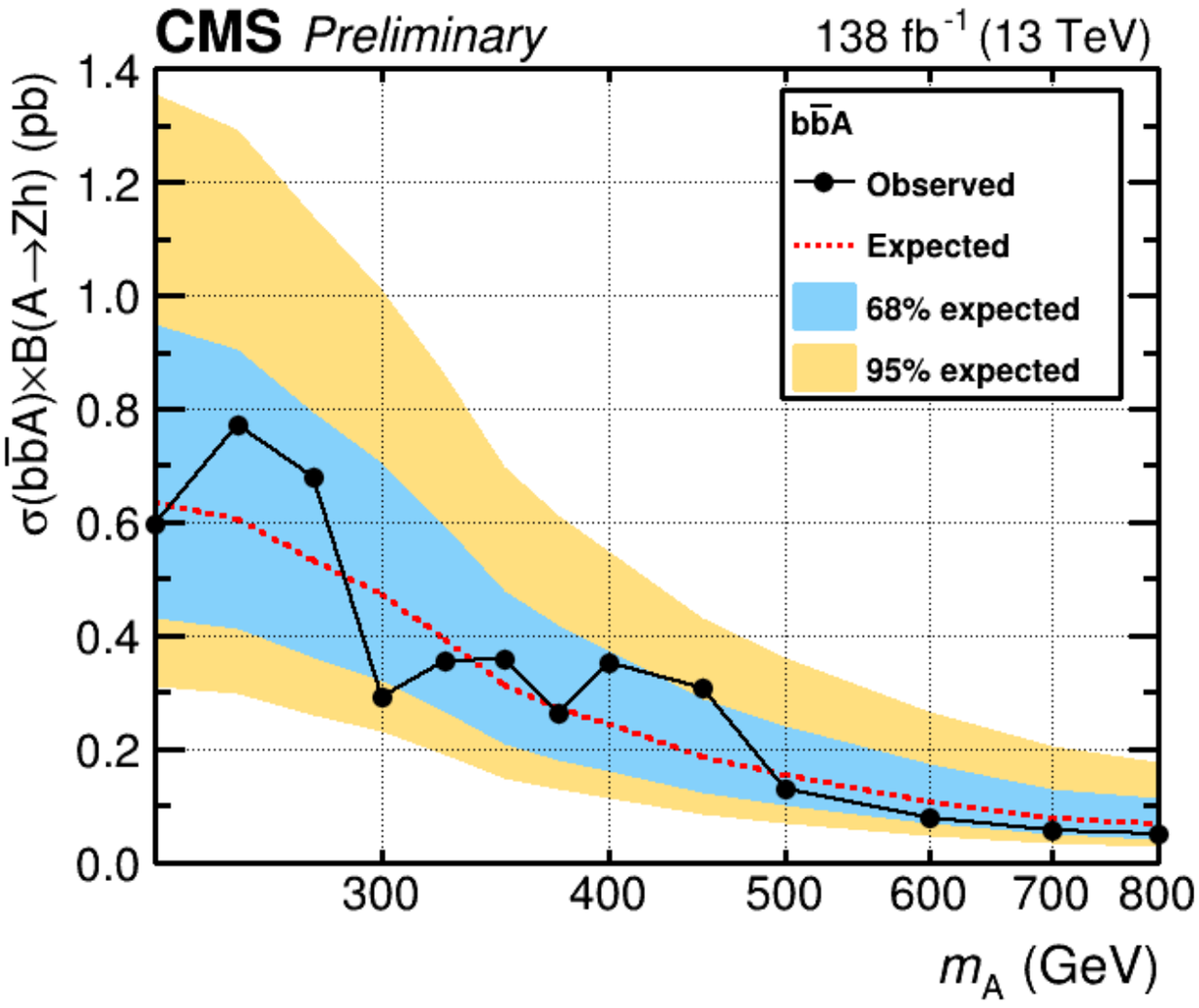

CMS Preliminary
138 fb-1 (13 TeV)
ggF, NWA
Median expected
68% expected
95% expected
Observed
Upper limit on σ(gg→ X→ ZZ) [pb] at 95% CL
10−1
10−2
10−3
130
200
300
400
500
1000
2000
3000
MX (GeV)

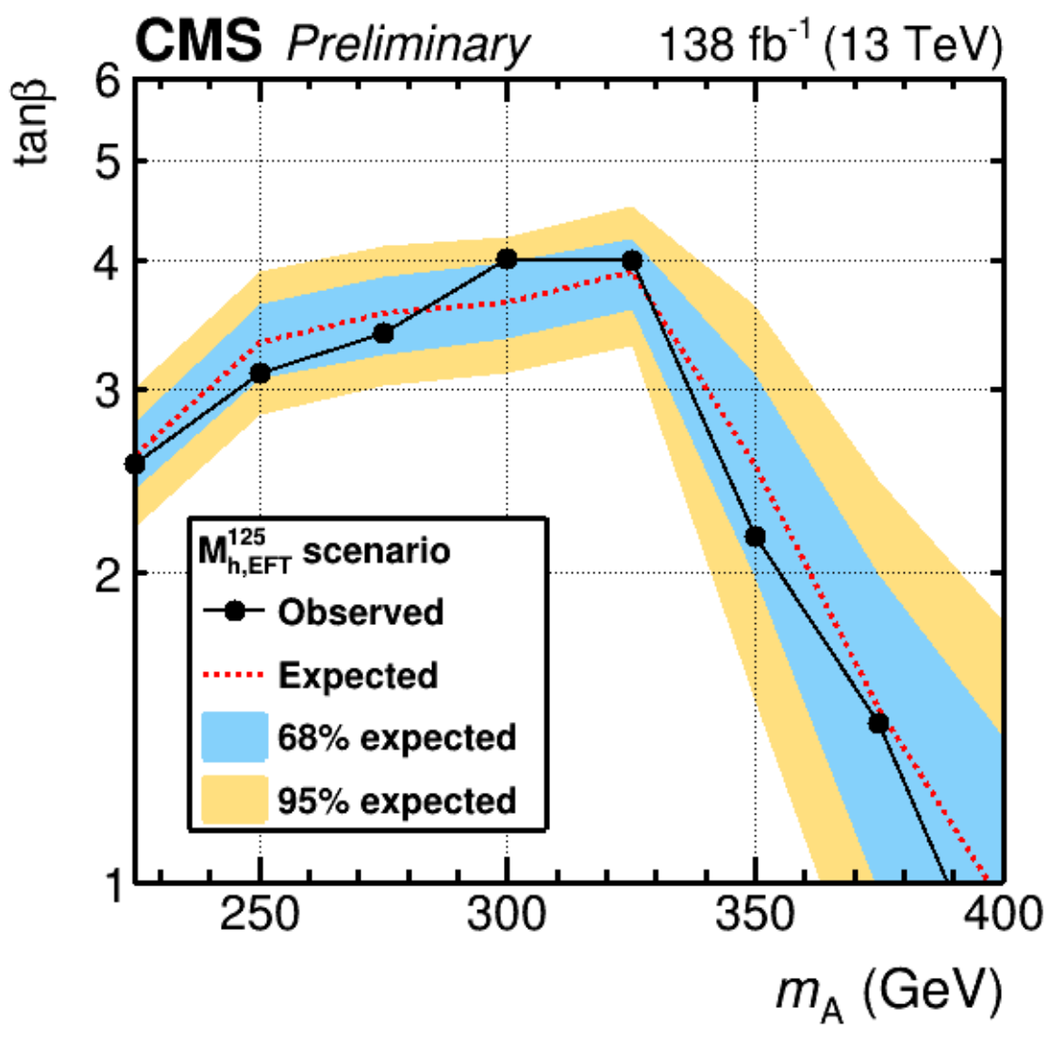

CMS Preliminary
138 fb-1 (13 TeV)
Local p-value
10−1
10−2
10−3
0σ
1σ
2σ
3σ
200
300
400
500
1000
2000
MX (GeV)


CMS Preliminary
138 fb-1 (13 TeV)
VBF, NWA
Median expected
68% expected
95% expected
Observed
Upper limit on σ(qq→ X→ ZZ) [pb] at 95% CL
10−1
10−2
10−3
130
200
300
400
500
1000
2000
3000
MX (GeV)

$A \rightarrow Zh_{125}$

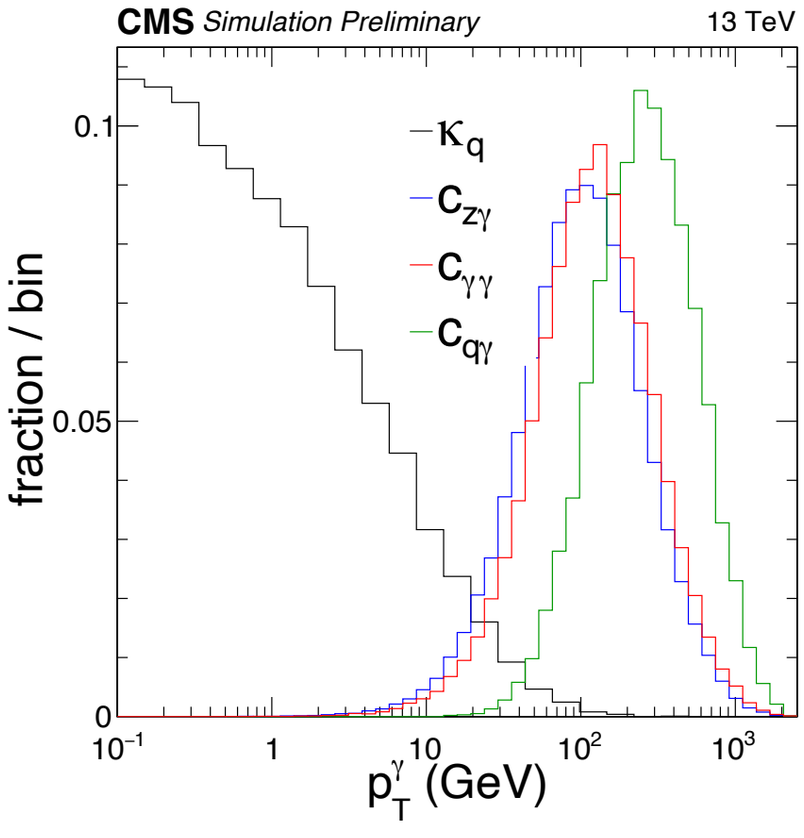
- bbH limits (left) and MSSM interpretation (right)

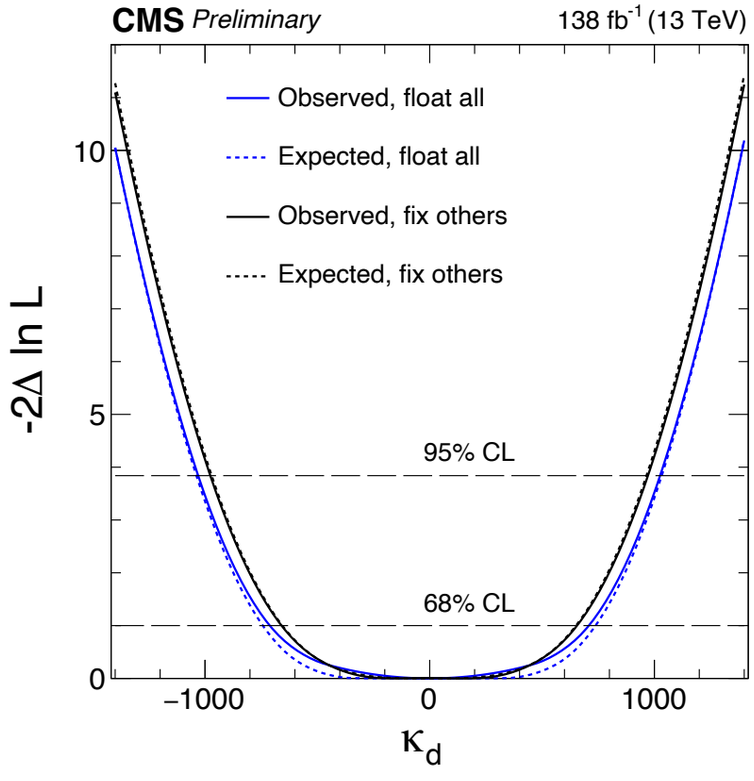


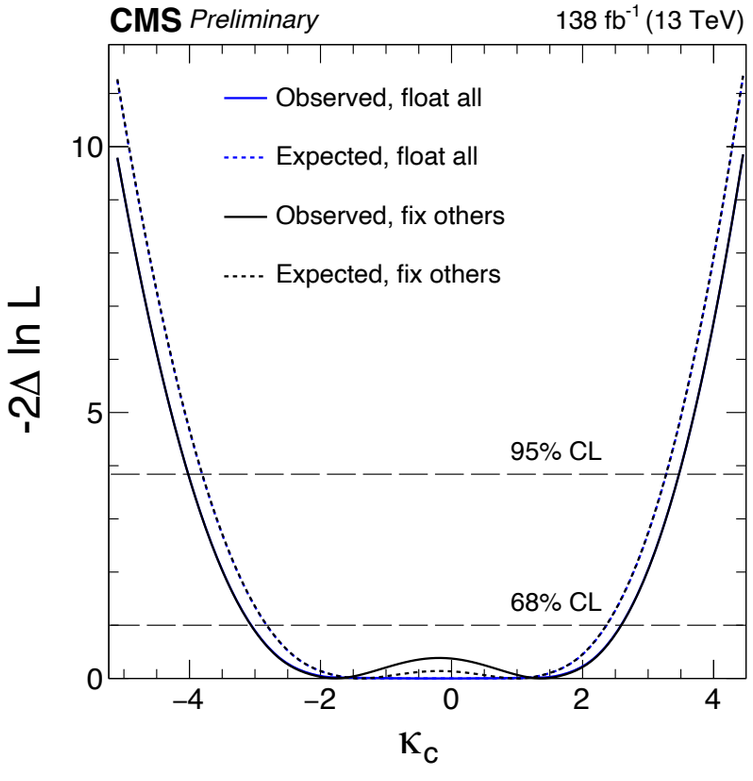


Search for H+γ production

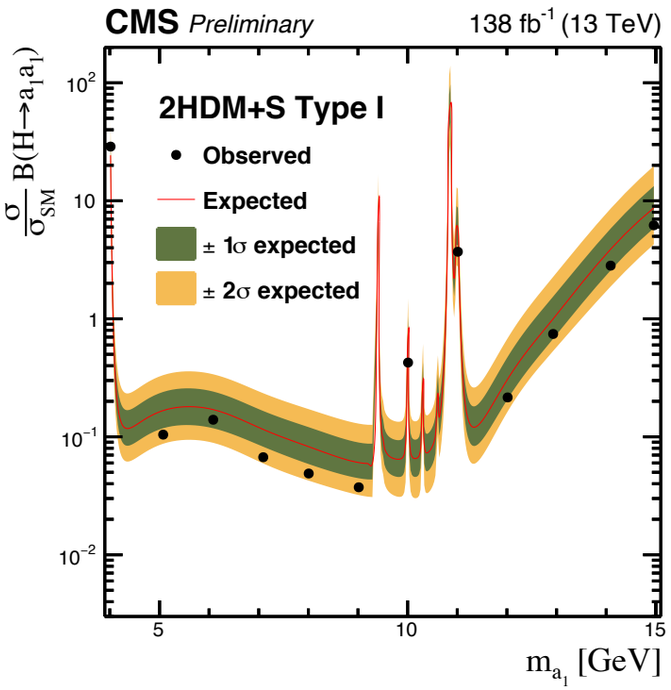
- Left: Photon p_T distribution for different scenarios
- Centre and right: examples of constraints on light-quark couplings

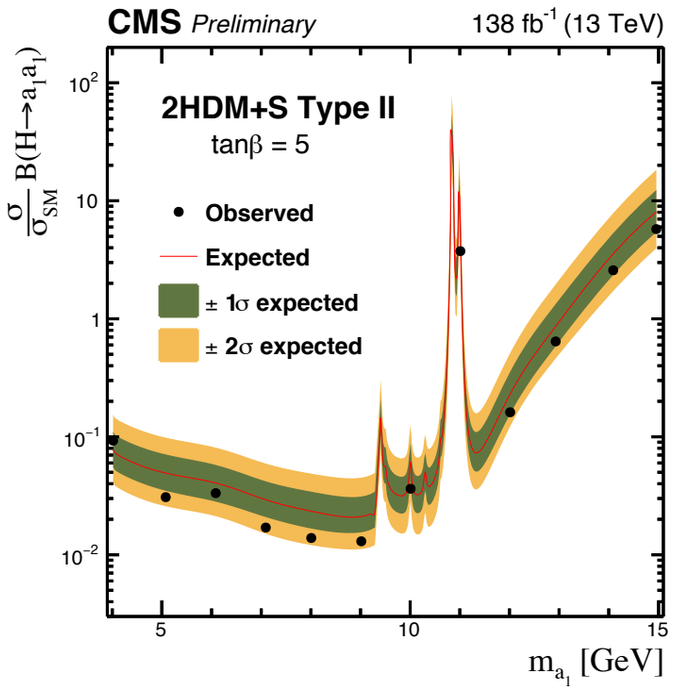


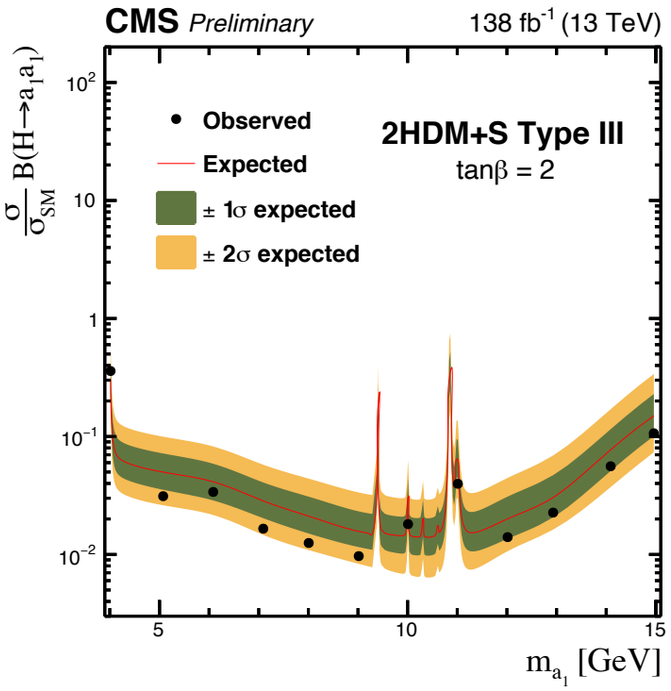


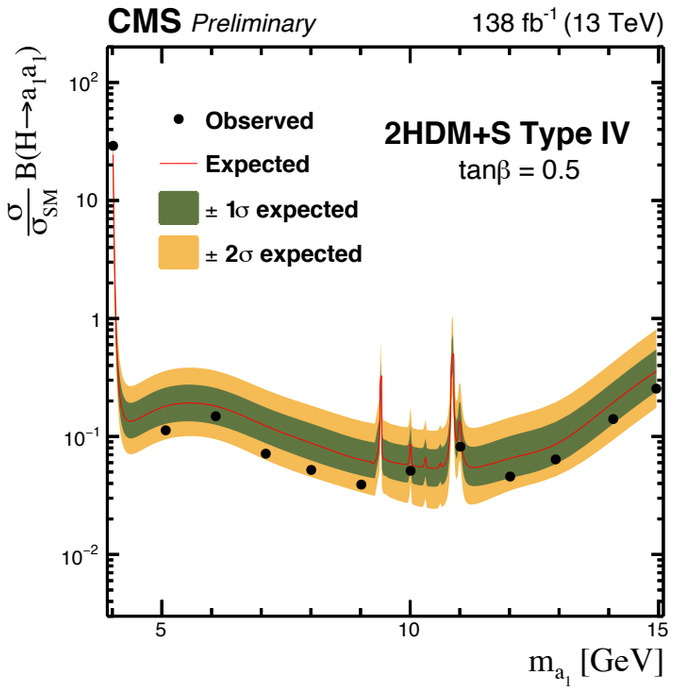


H→aa→ 4τ / 2τ2μ interpretations

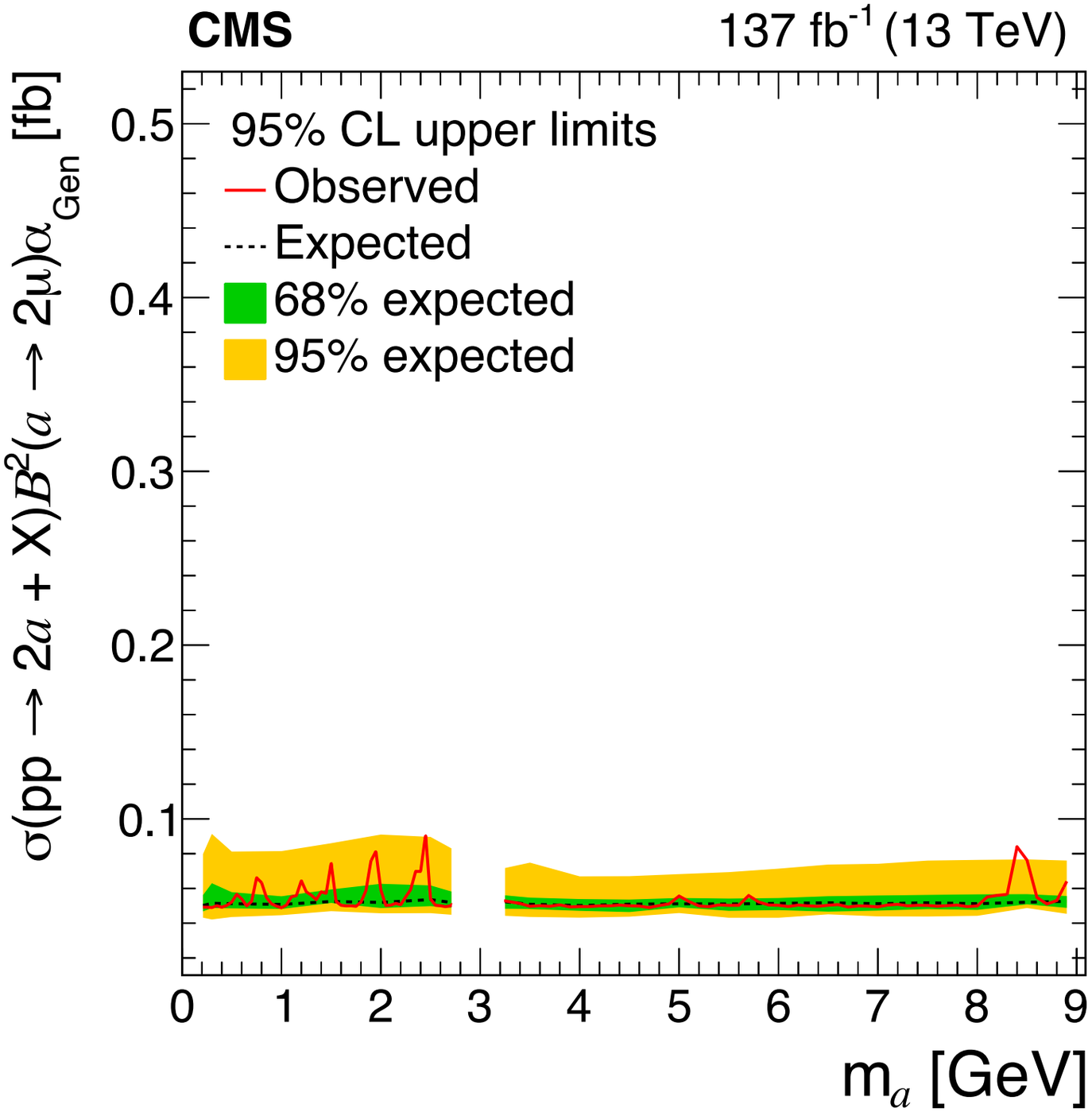




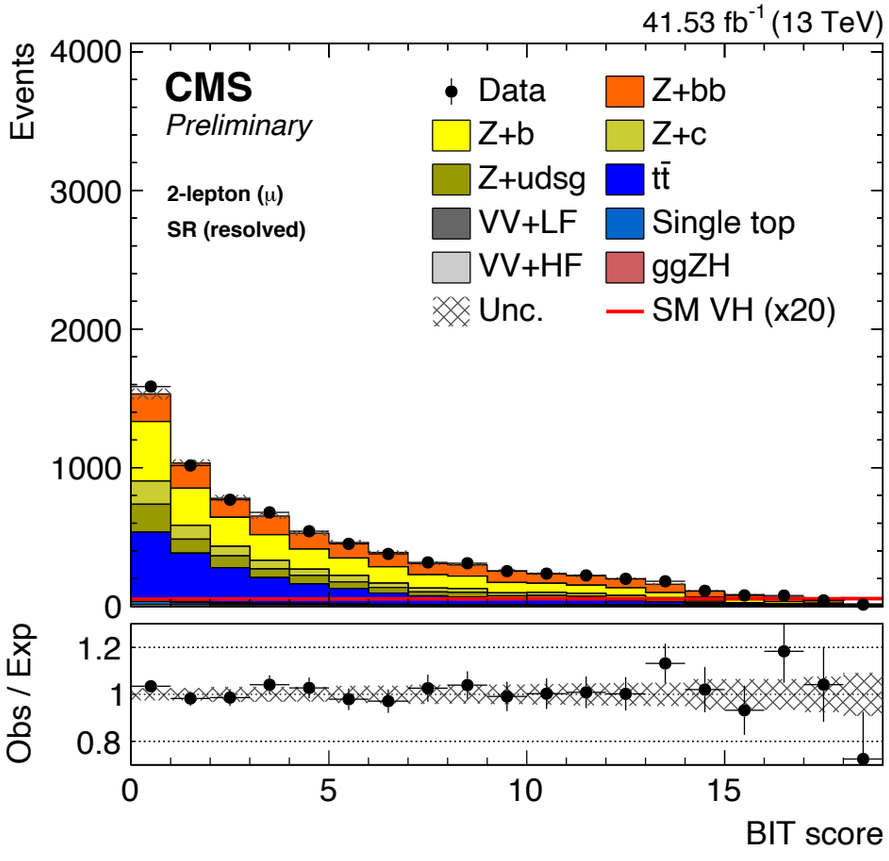


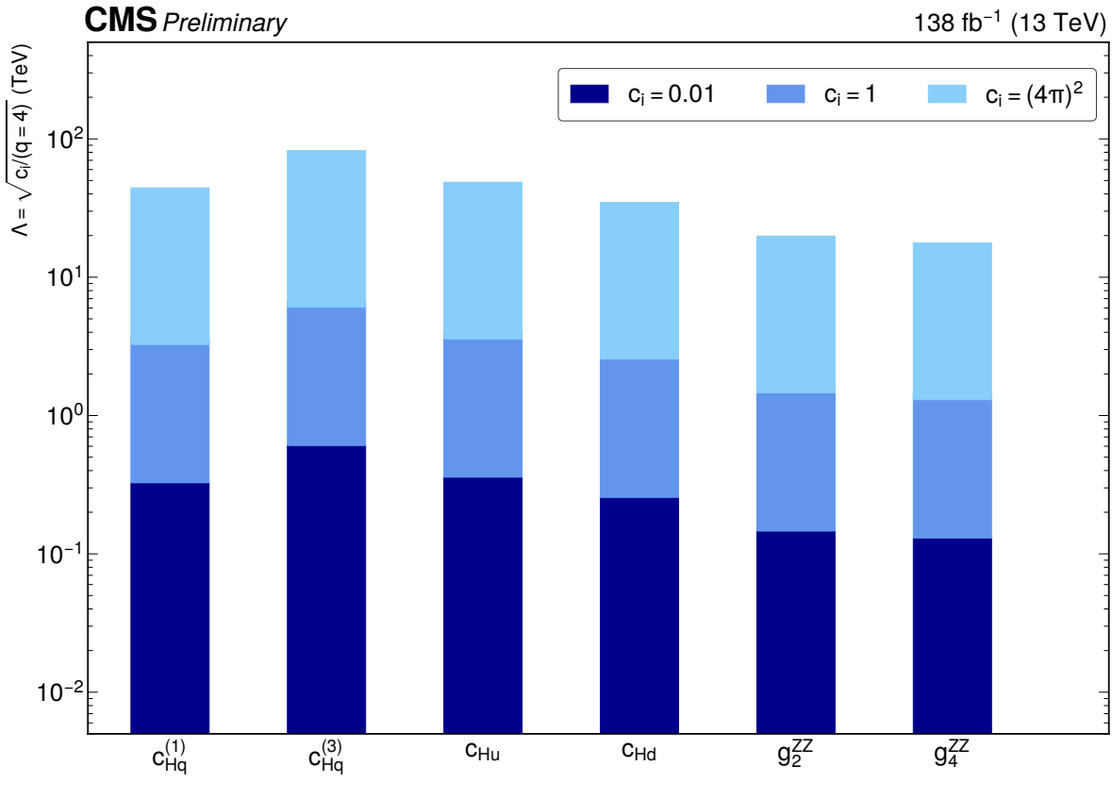


H→aa→ 4μ limits combining with 2016



EFT constraints using VH→bb





$X \rightarrow Y h_{125} \rightarrow$ 4b limits