Caltech

Highlights from Higgs physics at ATLAS and CMS

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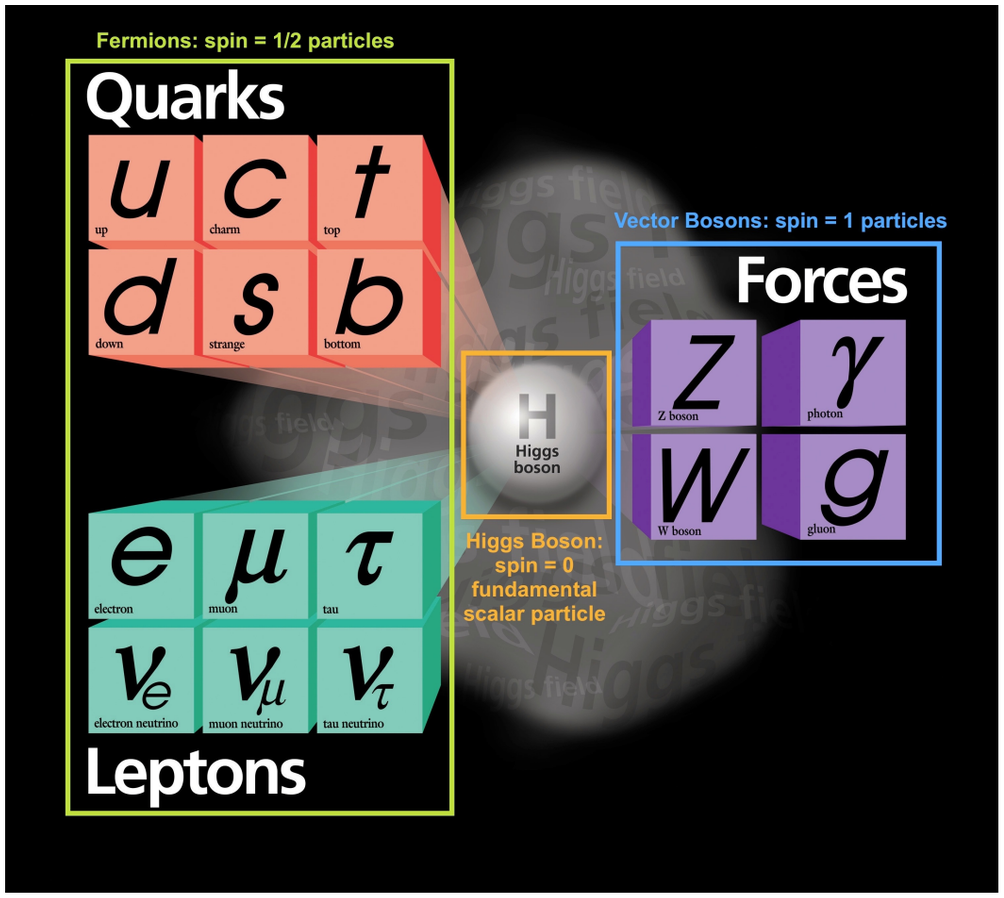
On behalf of the ATLAS and CMS Collaborations

La Thuile 2021

Les Rencontres de Physique de la Vallée d'Aost

March 11, 2021

The Standard Model Higgs Boson



- Quarks, charged leptons, W/Z bosons acquire mass through the Brout-Englert-Higgs (BEH) mechanism in the Standard Model

- Higgs boson physics is one of the most important goals of LHC physics program and the next generation collider experiments

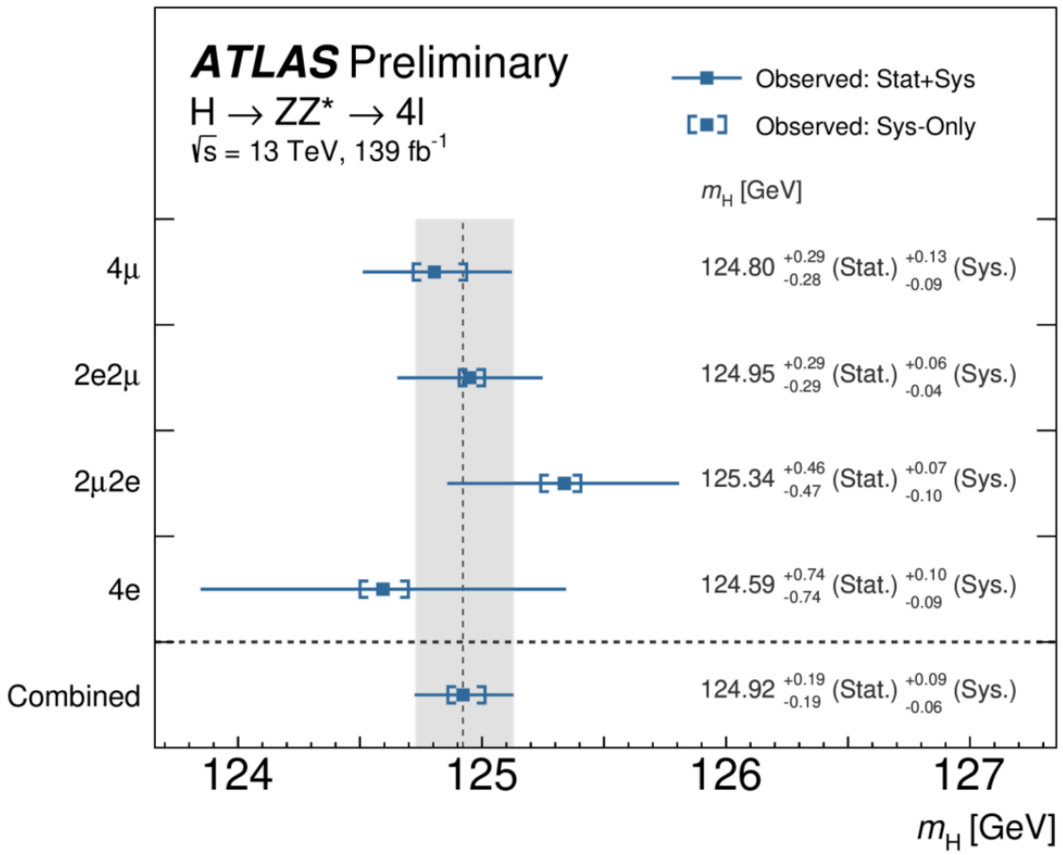
ATLAS Recent Higgs Results

CMS Recent Higgs Results

Disclaimer: this talk covers a selection of recent Run 2 ATLAS and CMS Higgs physics results

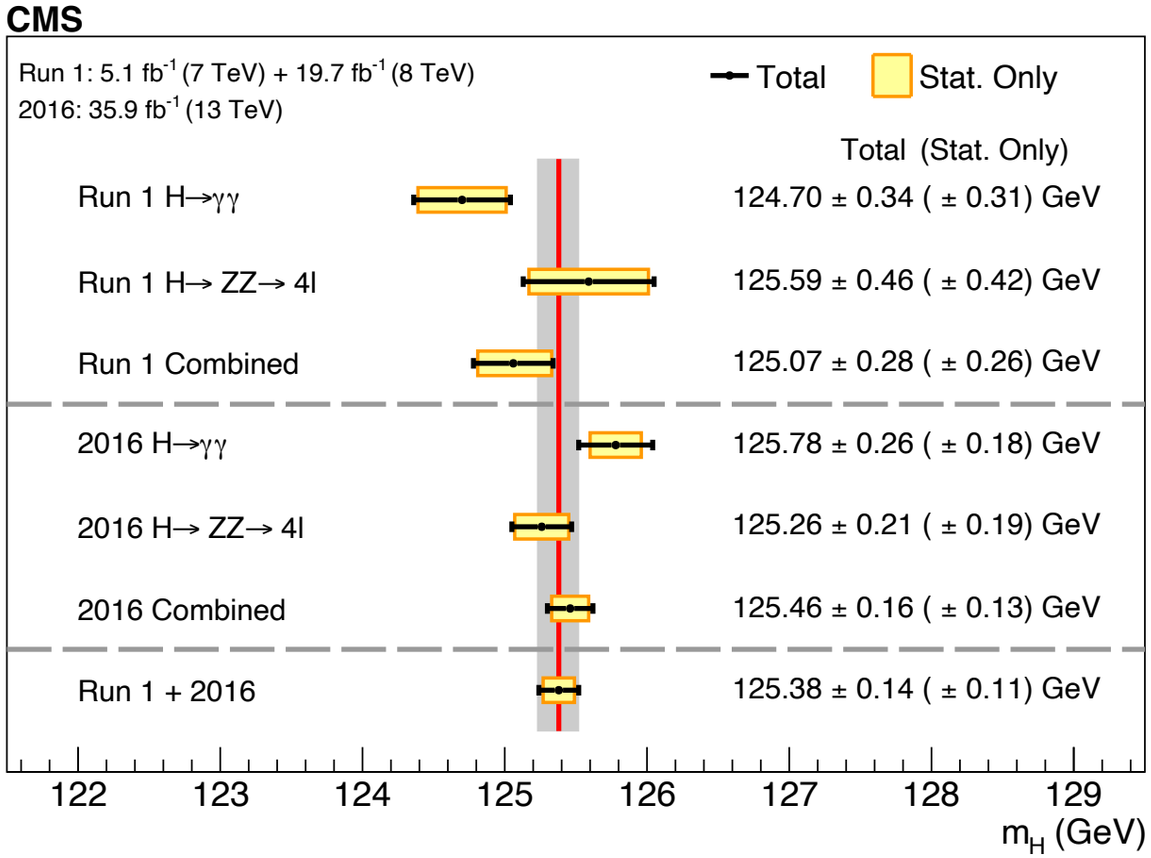
Higgs boson mass

H→ZZ*→4l



ATLAS-CONF-2020-005

H→γγ, H→ZZ*→4l



Phys. Lett. B 805 (2020) 135425

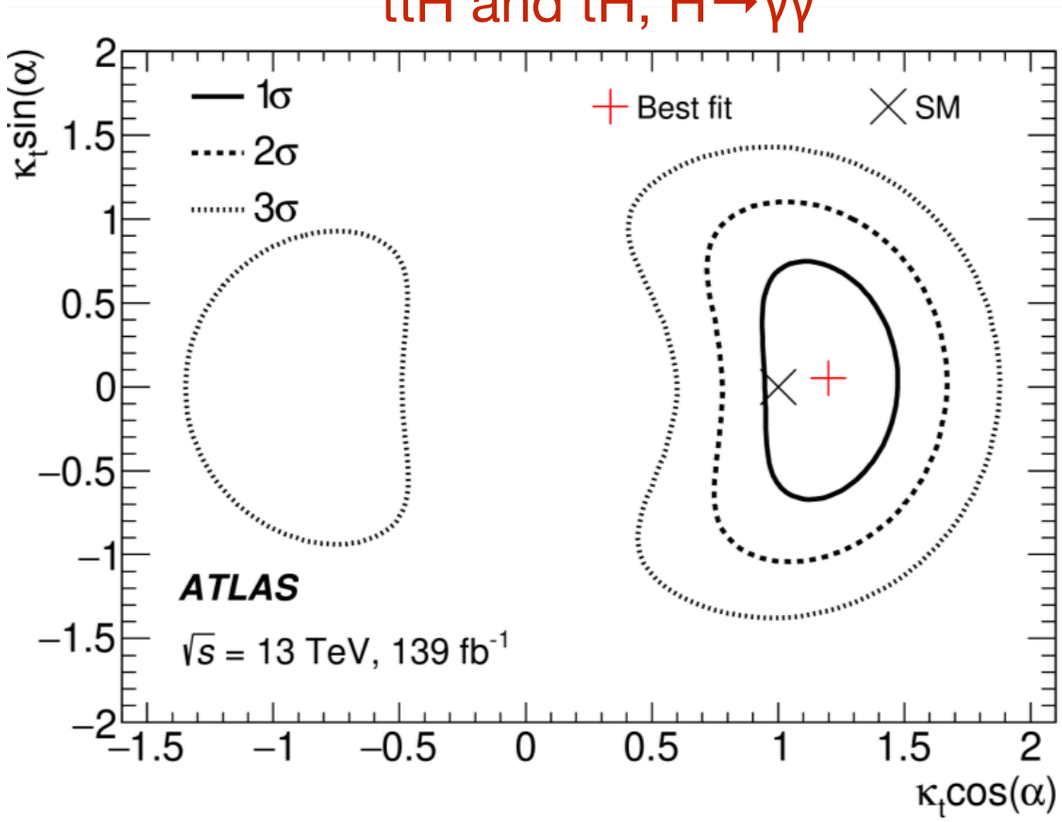
- m_H is a free parameter in the Standard Model. Once m_H is known, all Higgs boson couplings to SM particles are fixed

- Precision reaching 0.1%, still dominated by statistical uncertainty

Higgs boson CP studies

- In the SM, Higgs boson has quantum number $J^{CP} = 0^{++}$
- Run 1: spin-0 nature established, CP structure explored in Higgs-boson couplings
- Recent Run 2 results on CP structure in Higgs-fermion couplings probed in (1) H→$\tau\tau$ decay and (2) ttH production using the H→γγ decay channel; CP structure in Higgs-boson couplings probed in H→ZZ*→4l channel (backup slides)

ttH and tH, H→γγ

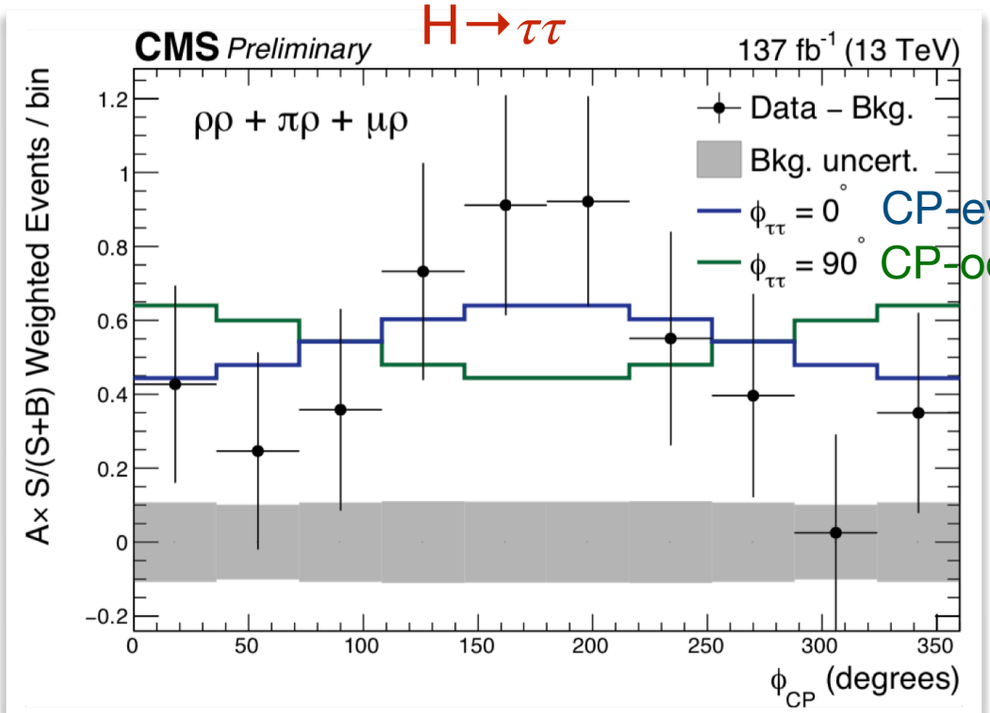


CP-mixing angle |α| < 43° @95% CL
pure CP-odd excluded at 3.9σ

ATLAS: Phys. Rev. Lett. 125 (2020) 061802

CMS: Phys. Rev. Lett. 125 (2020) 061801 (in backup slides)

H→$\tau\tau$



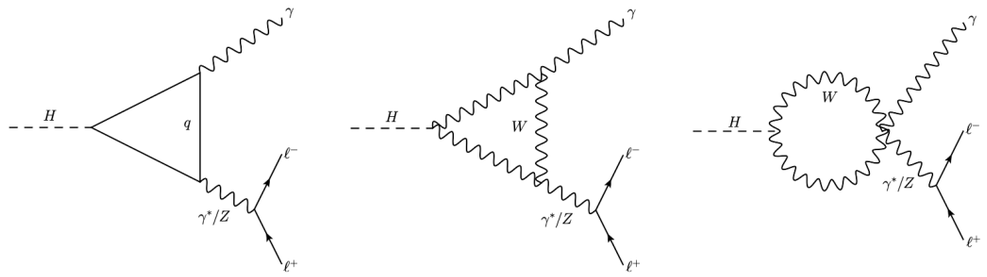
$$\tan(\phi_{\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$ CP-odd coupling / CP-even coupling

CP-mixing angle $\phi_{\tau\tau}$ = (4 ± 17)° @68% CL

CMS-PAS-HIG-20-006

Evidence for $H\to\ell\ell\gamma$

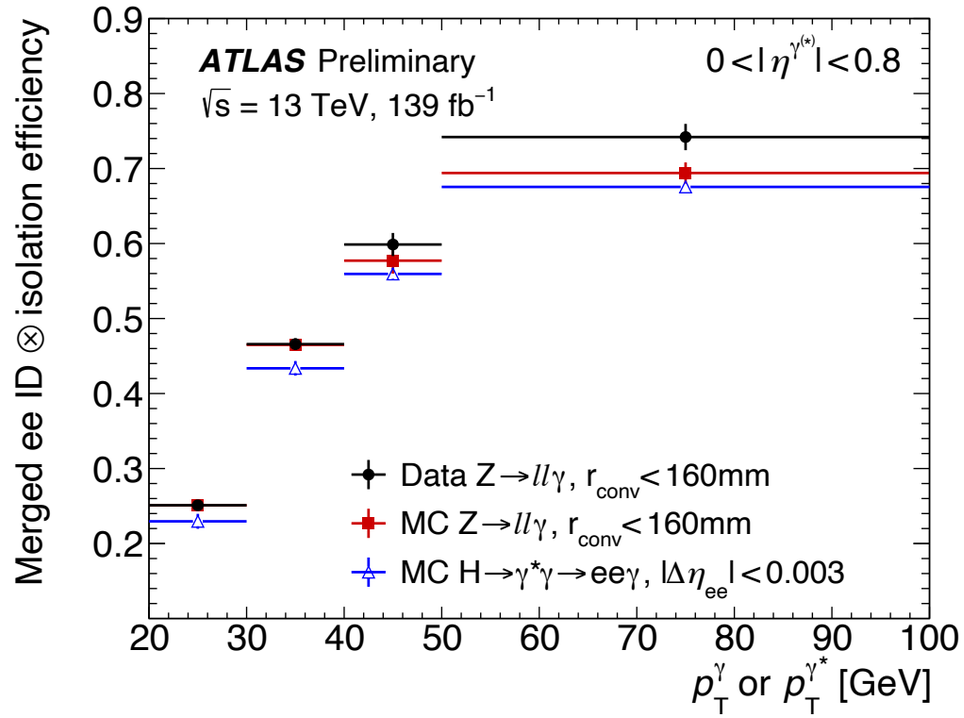
- Rare decay process $H\to\ell\ell\gamma$ ($m_{\ell\ell} < 30$ GeV) probes exotic couplings and CP-violations in the Higgs sector

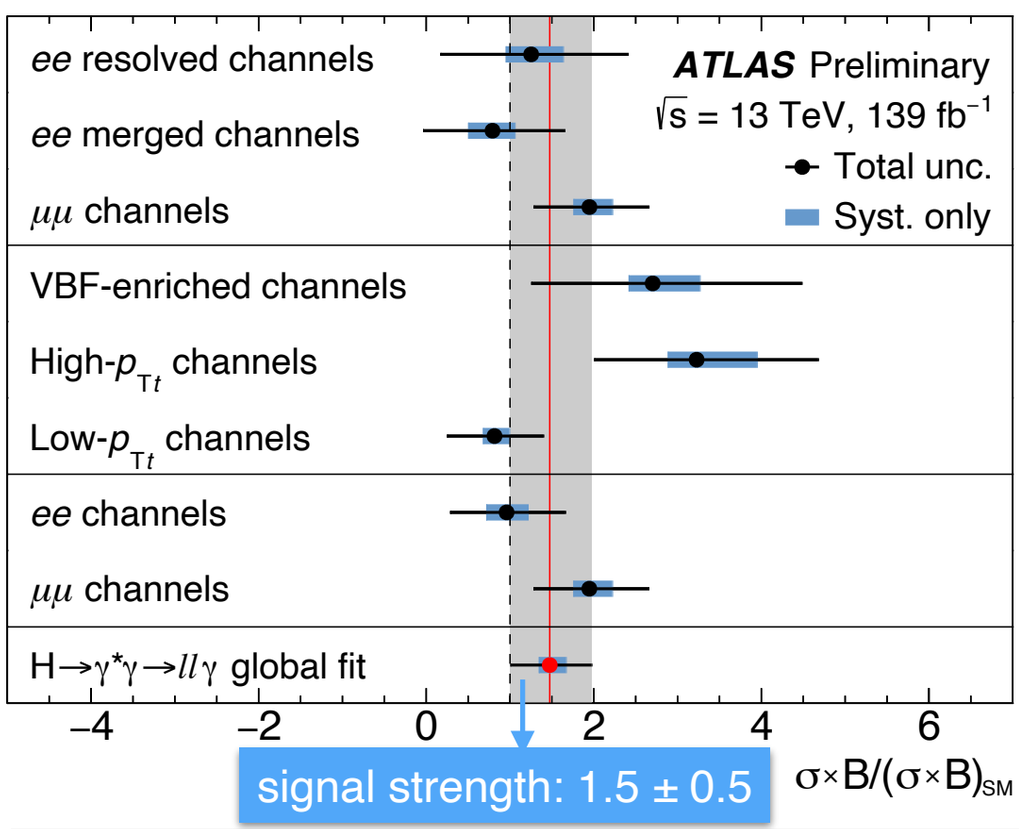


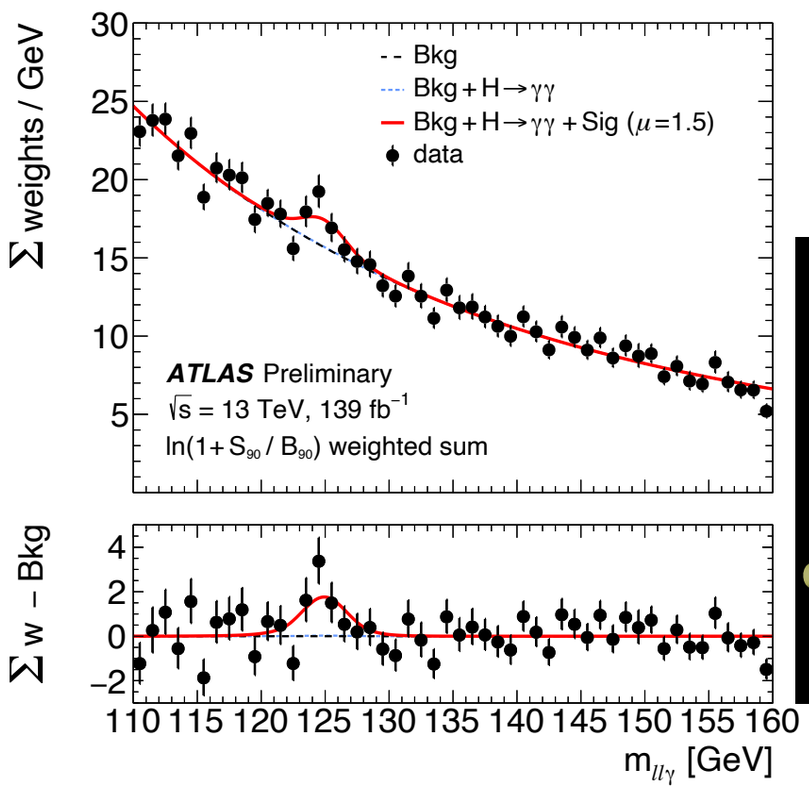
- Lepton pair is often very collimated: develop methods to reconstruct merged-ee objects

- Signal significance 3.2σ(2.1σ) obs(exp)

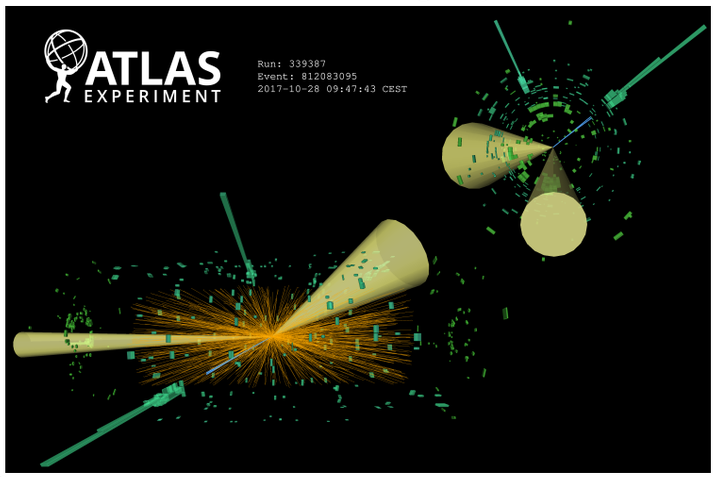
ATLAS-CONF-2021-002







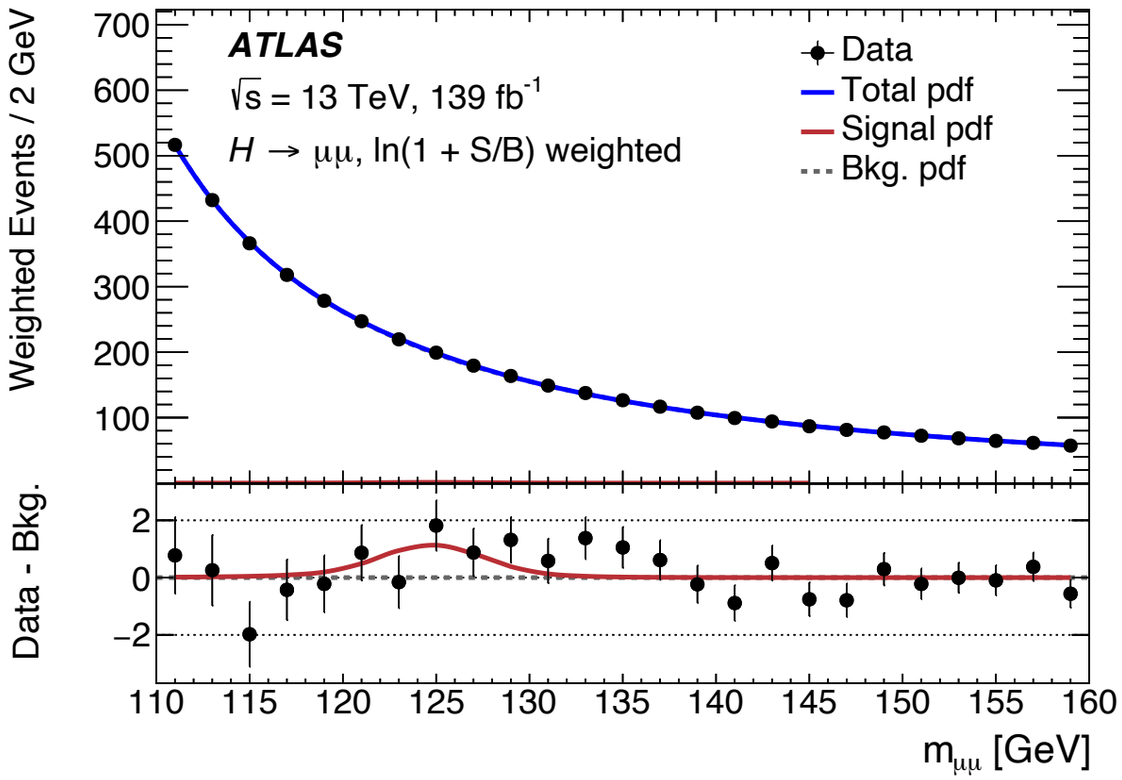
Event display of a candidate H→eeγ event from ee-merged VBF-enriched category

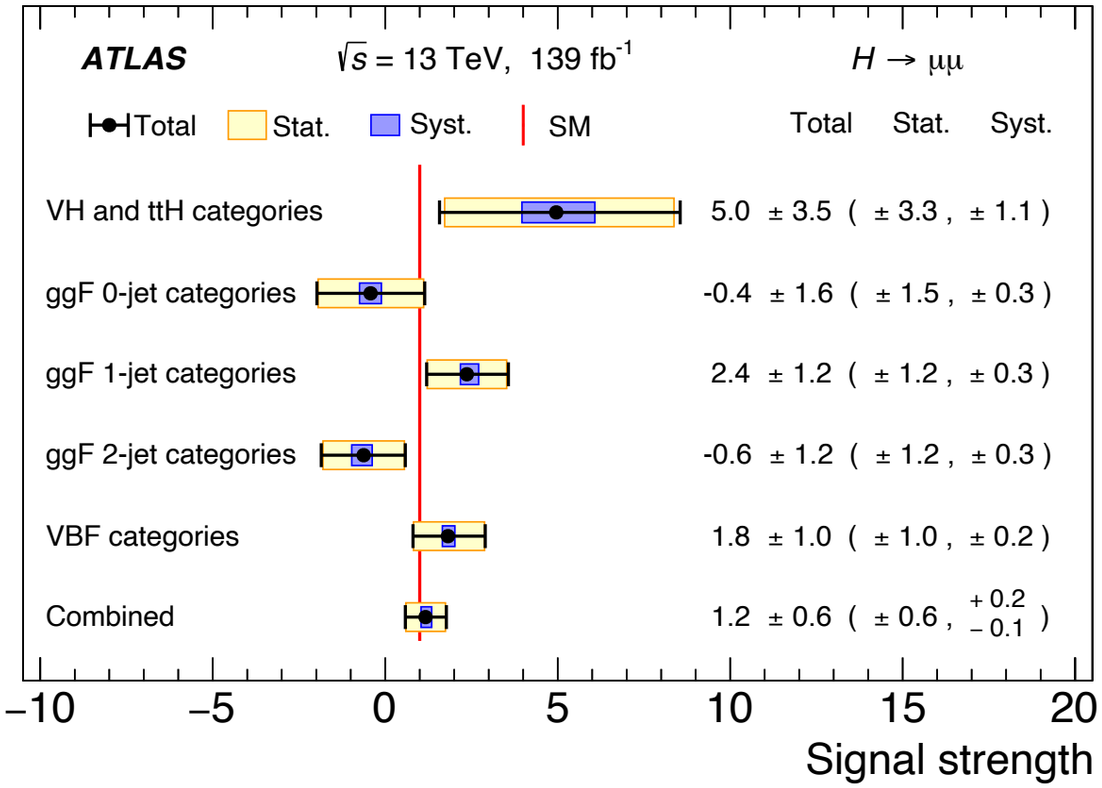


Higgs boson couplings to second generation fermions: evidence of H→μμ

Phys. Lett. B 812 (2021) 135980

- H→μμ is, to date, the most sensitive channel to study Higgs boson couplings to the 2nd generation fermions
- Studying Higgs boson to muon coupling has important implication for muon collider
- Challenge: small branching ratio BR(H→μμ): 0.02%, large background S/B: 1~2%

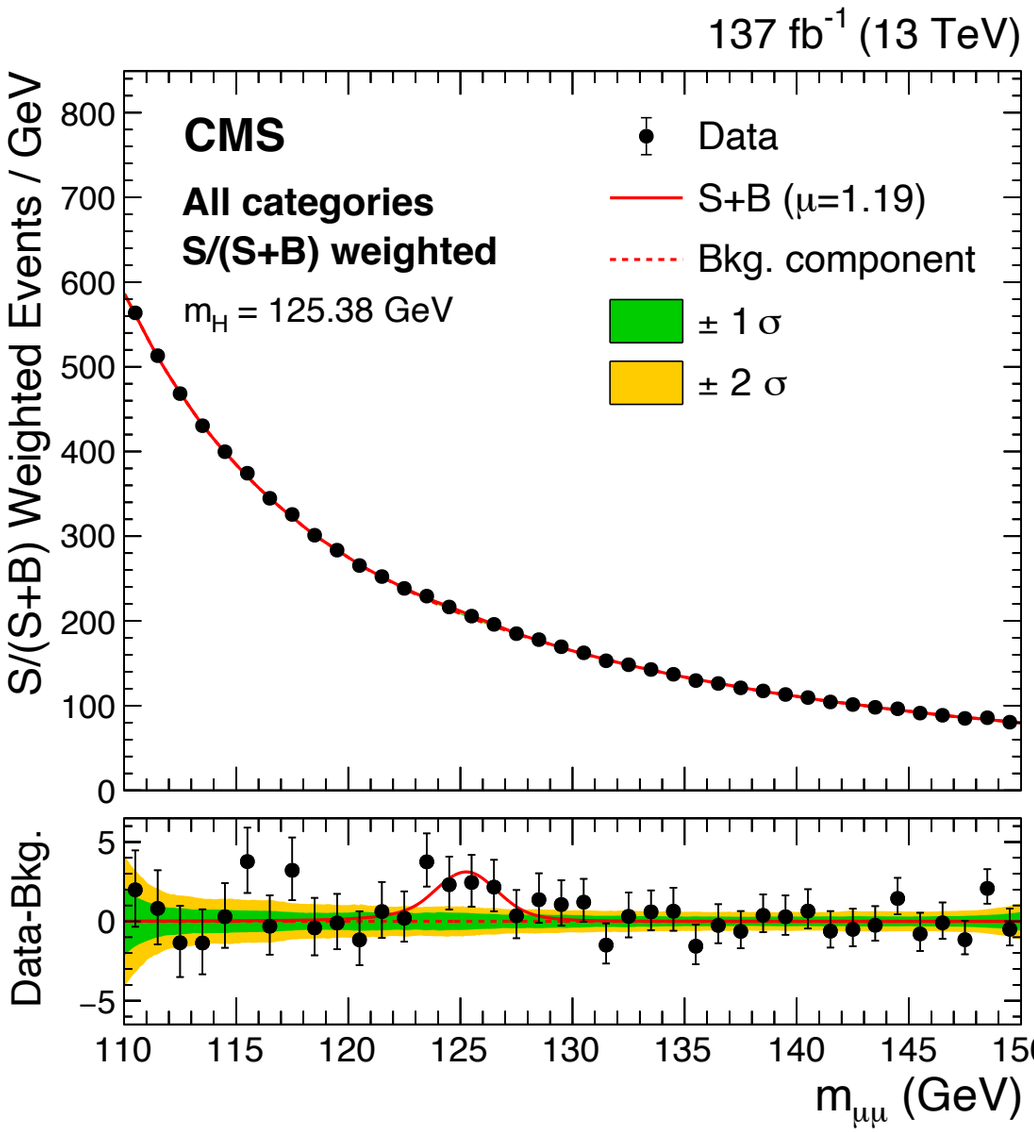


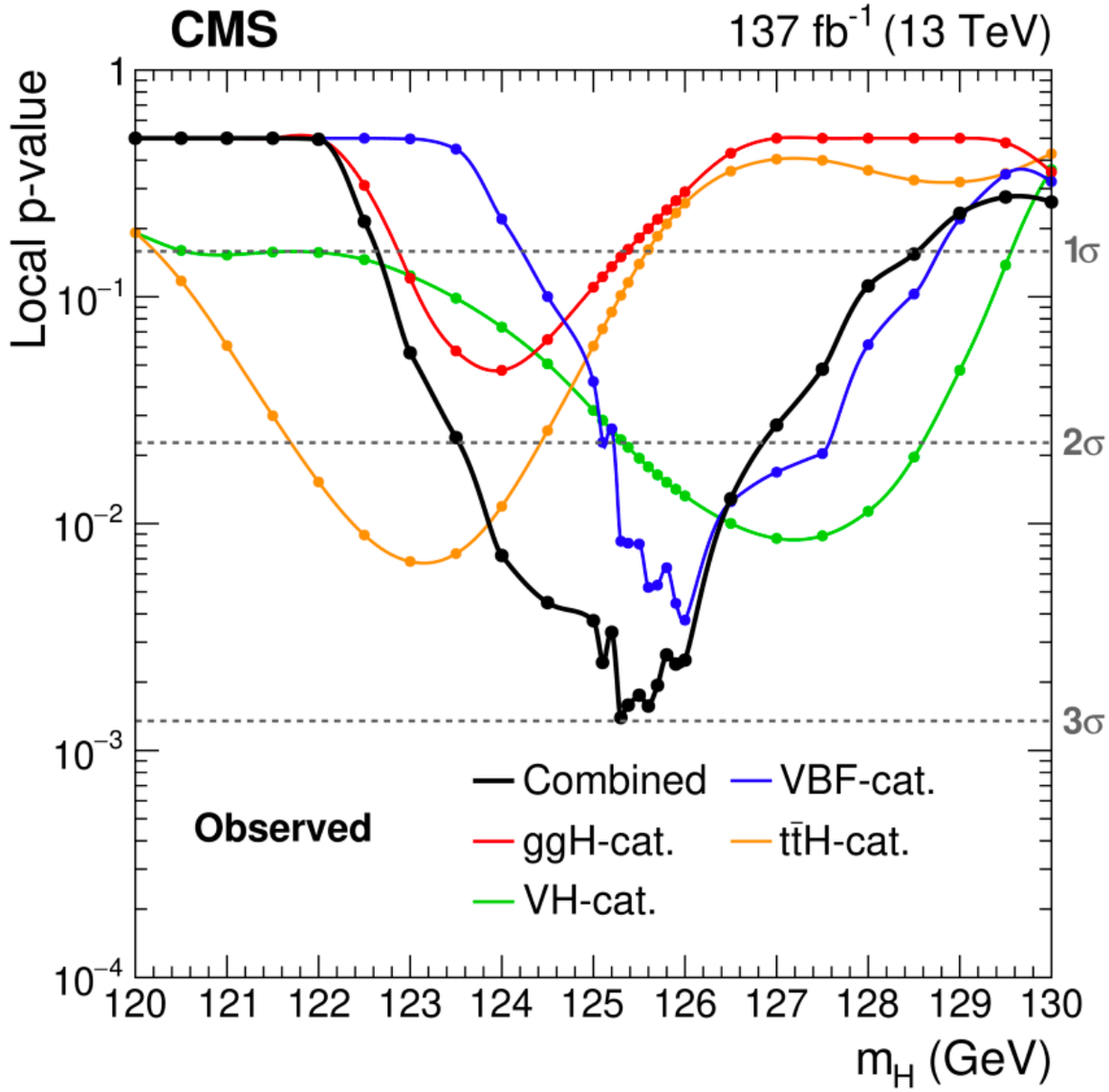


- Significance: 2.0(1.7)σ, obs(exp)
- Signal strength: $\mu = 1.2 \pm 0.58(stats.)^{+0.13}_{-0.08}(theory)^{+0.07}_{-0.03}(exp.) \pm 0.10(spurious)$
- Higgs boson coupling to muon: $\kappa_\mu = 1.12^{+0.26}_{-0.32}$ @68% CL (ATLAS-CONF-2020-027)

Higgs boson couplings to second generation fermions: evidence of H→μμ

JHEP 01 (2021) 148





- Significance: 3.0(2.4)σ, obs(exp)

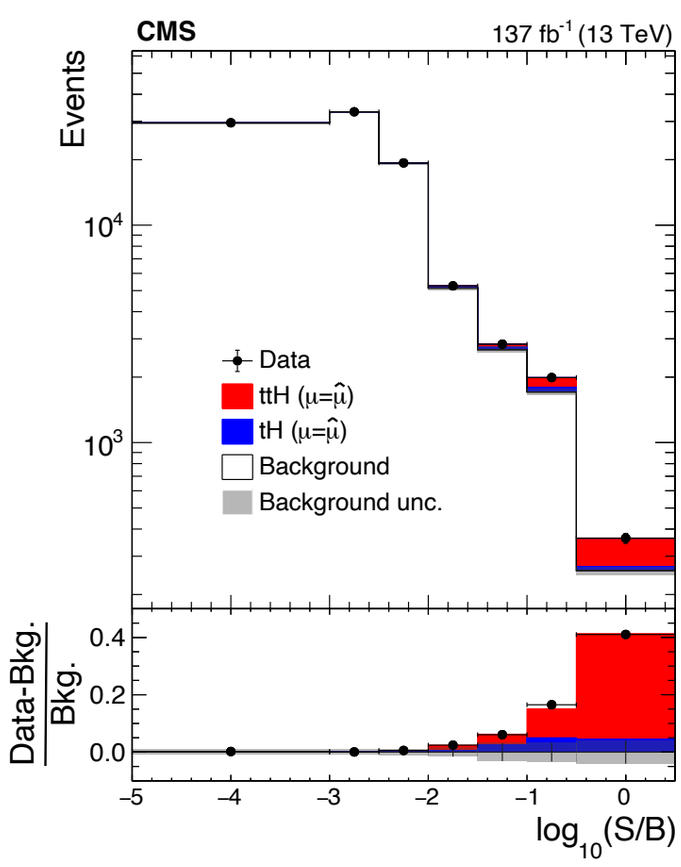
More details: YSF talk by Irene Dutta

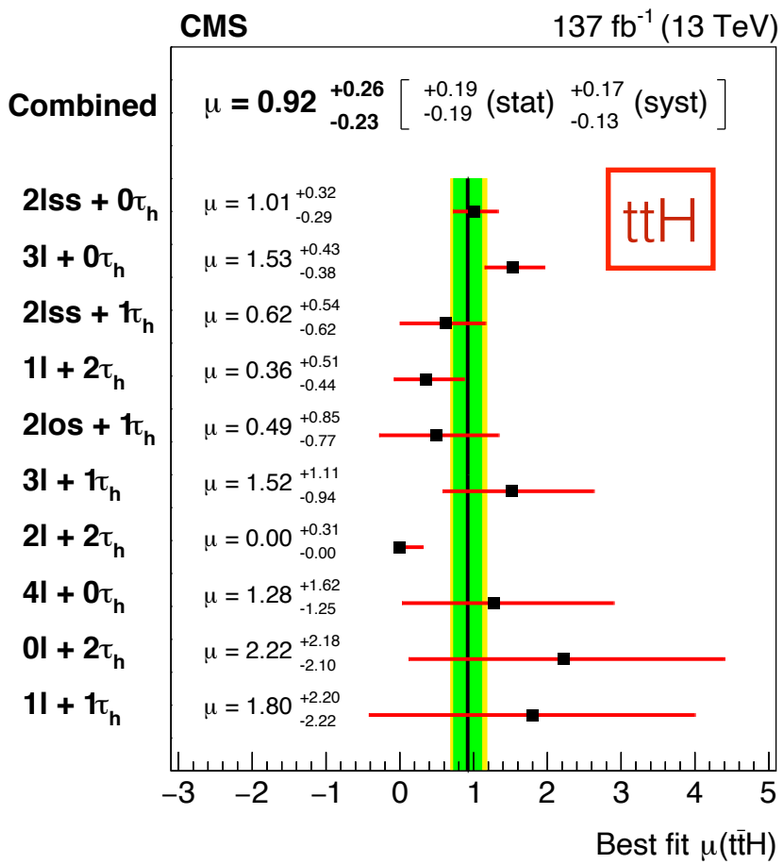
- Signal strength: $\mu = 1.19^{+0.41}_{-0.39}(stats.)^{+0.10}_{-0.11}(theory)^{+0.12}_{-0.10}(exp.)^{+0.07}_{-0.06}(MCstats.)$
- Higgs boson coupling to muon: $\kappa_\mu = 1.13^{+0.21}_{-0.22}$ @68% CL

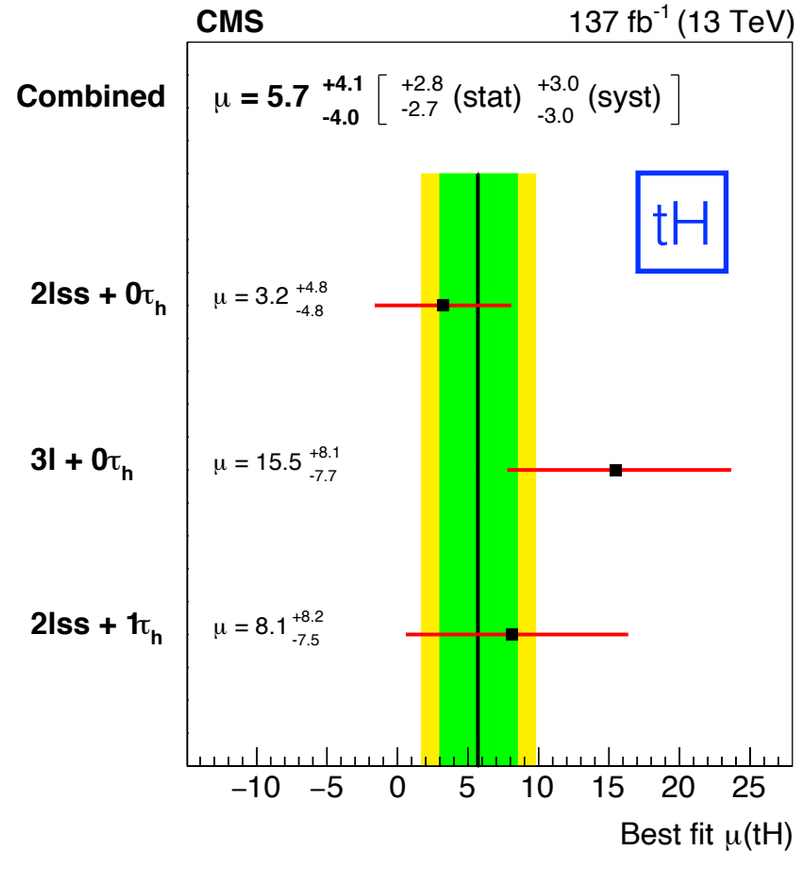
ttH and tH production: final state with electron, muon and hadronically decaying τ leptons

Eur. Phys. J. C 81 (2021) 378

- Target events in ttH and tH production modes (top quark decays either to lepton+jets or all-jet channels) and H→WW, H→ττ, or H→ZZ decays channels
- Significance ttH: 4.7(5.2)σ, tH: 1.4(0.3)σ obs(exp)
- Higgs coupling to top quark: $-0.9 < \kappa_t < -0.7 \; or \; 0.7 < \kappa_t < 1.1$ @95% CL

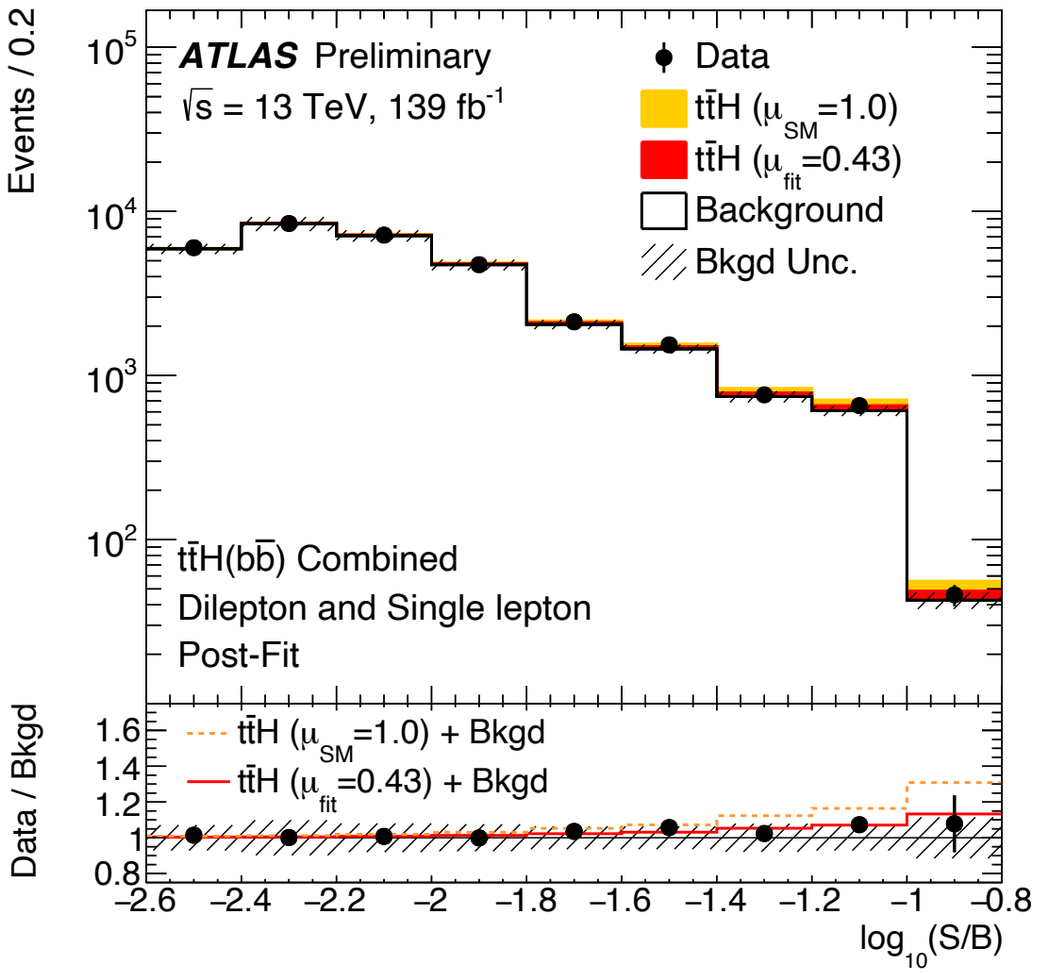


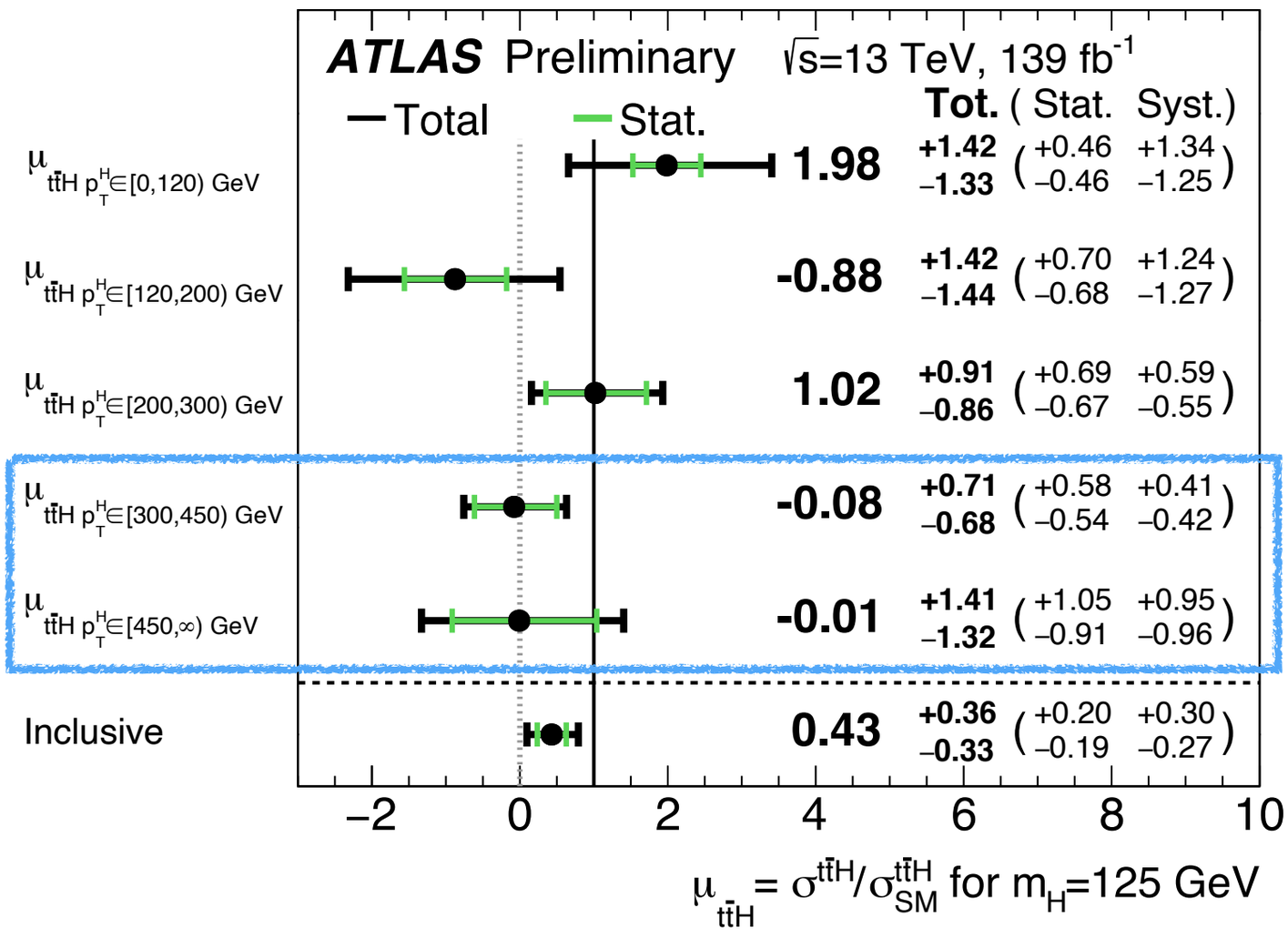




ttH production mode: ttH,H→bb channel

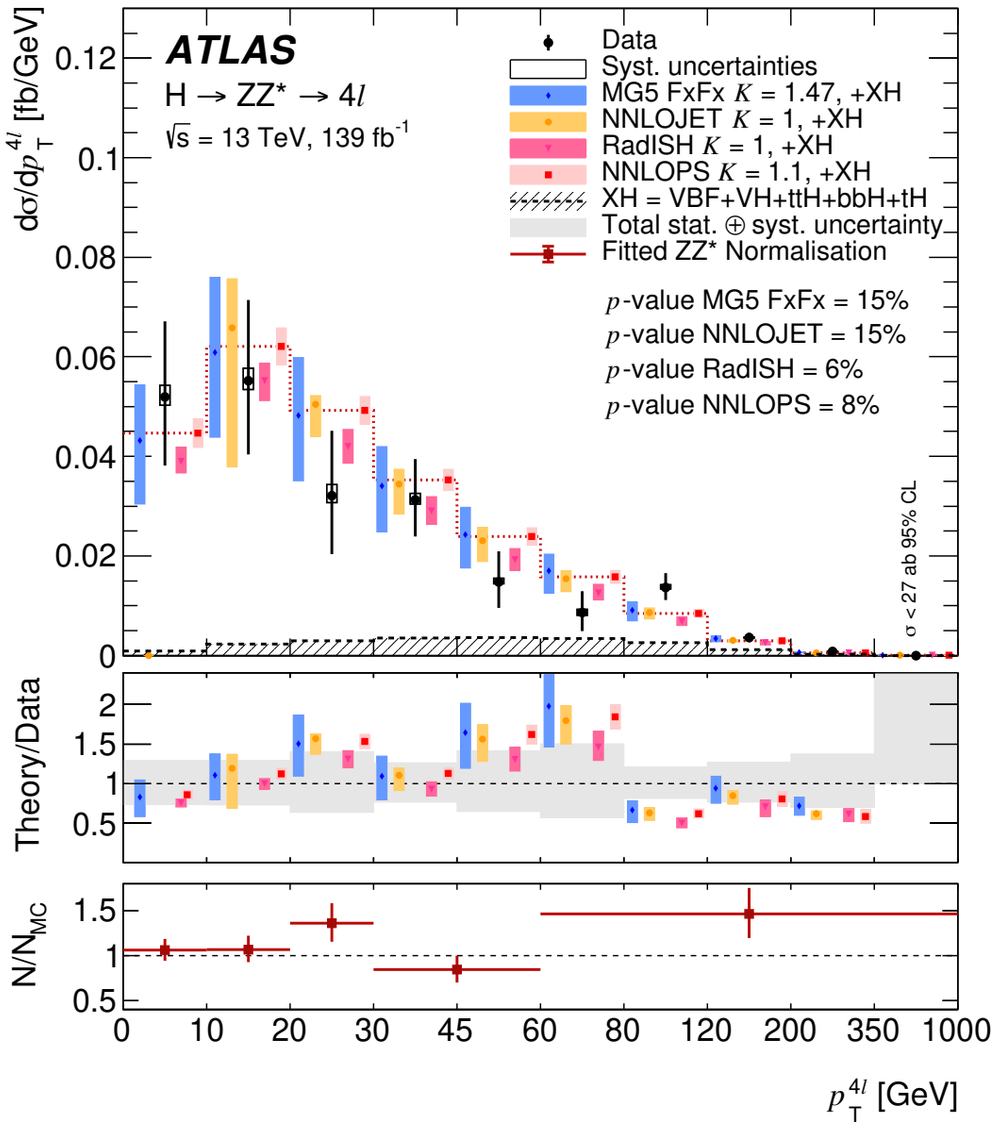
- ttH Significance: 1.3(3.0)σ, obs(exp) ATLAS-CONF-2020-058
- Simplified template cross section (STXS) measurements in five bins of pT(H), boosted selection targeting $p_T(H) > 300$ GeV





Higgs boson differential measurements

- Higgs p_T sensitive to many BSM effects: physics in the ggH loops, perturbative QCD calculations, Higgs couplings to charm and bottom quarks, …



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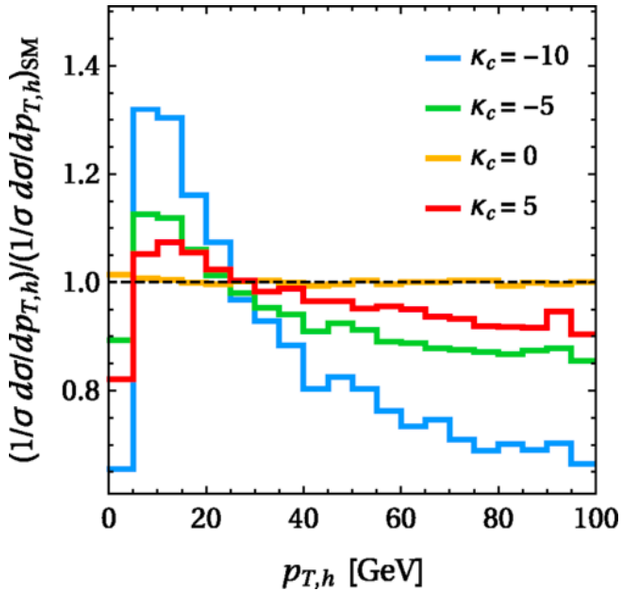
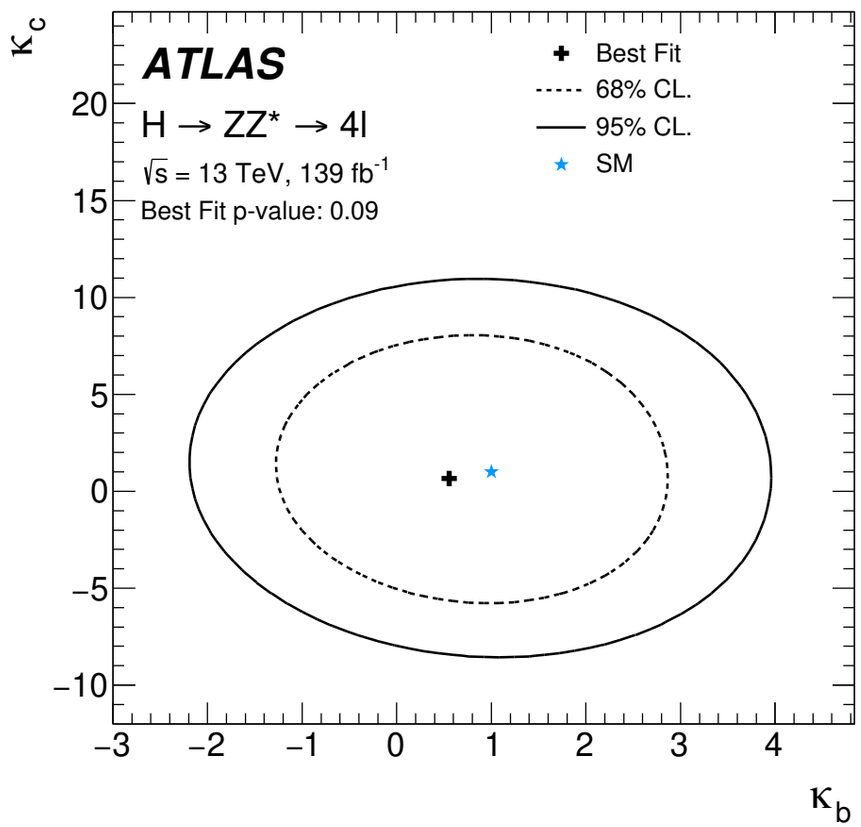


Phys. Rev. Lett. 118 (2017) 121801

constraint from p_T(H) shape

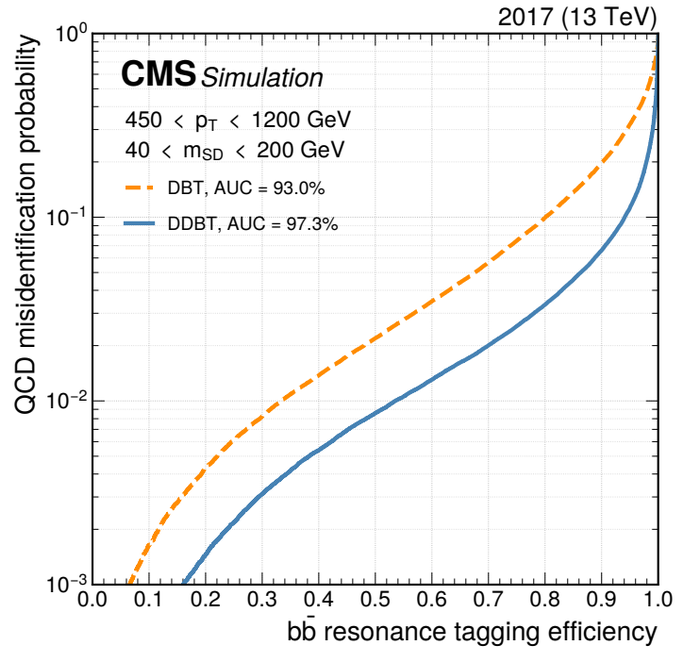


Higgs boson differential measurements

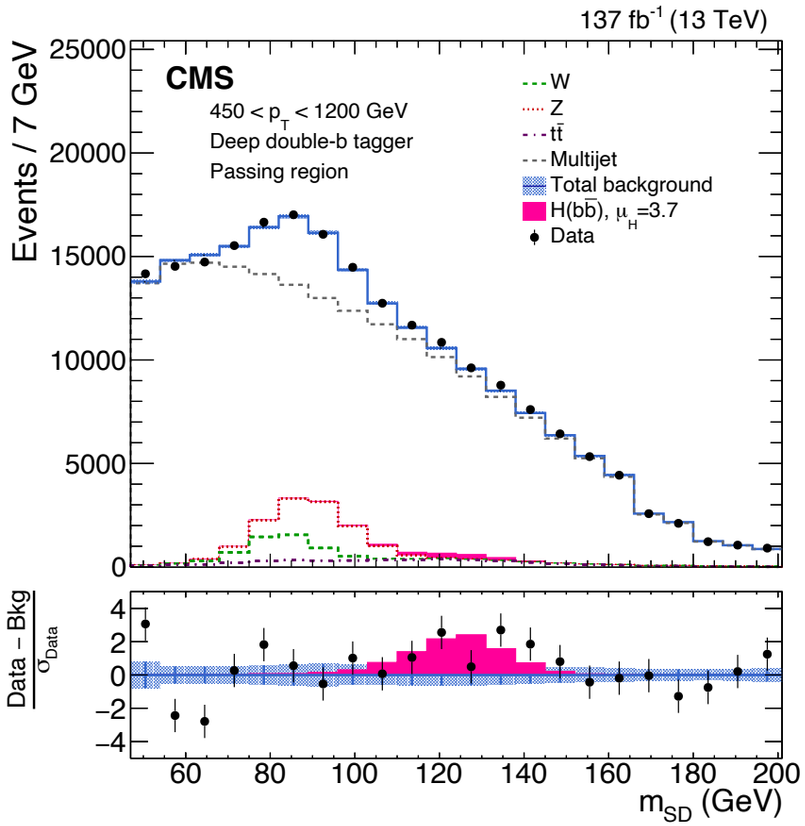
JHEP 12 (2020) 085

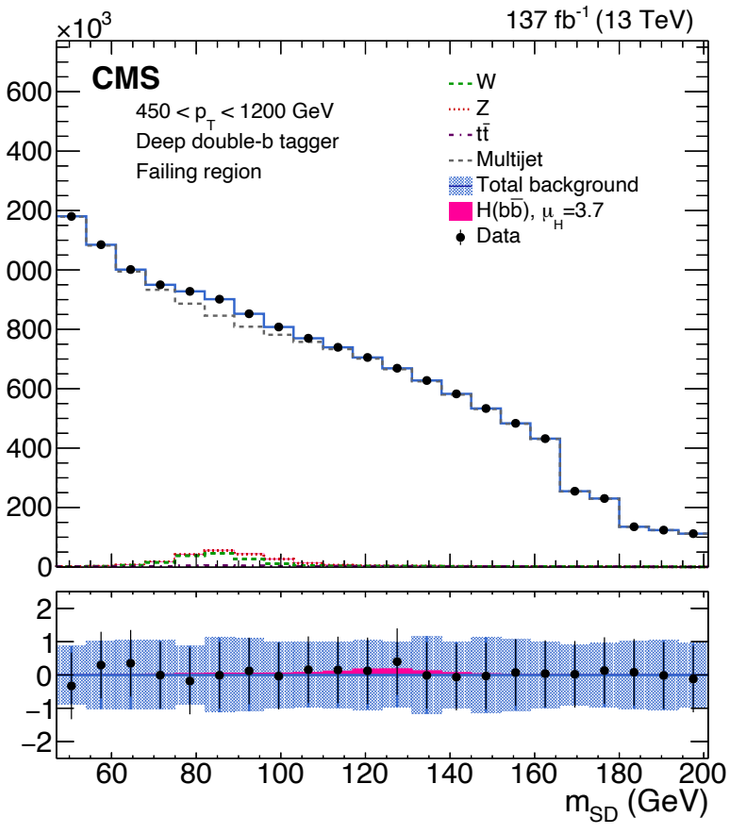
Boosted Higgs as a tool to access very high-p_T regime, sensitive to BSM physics

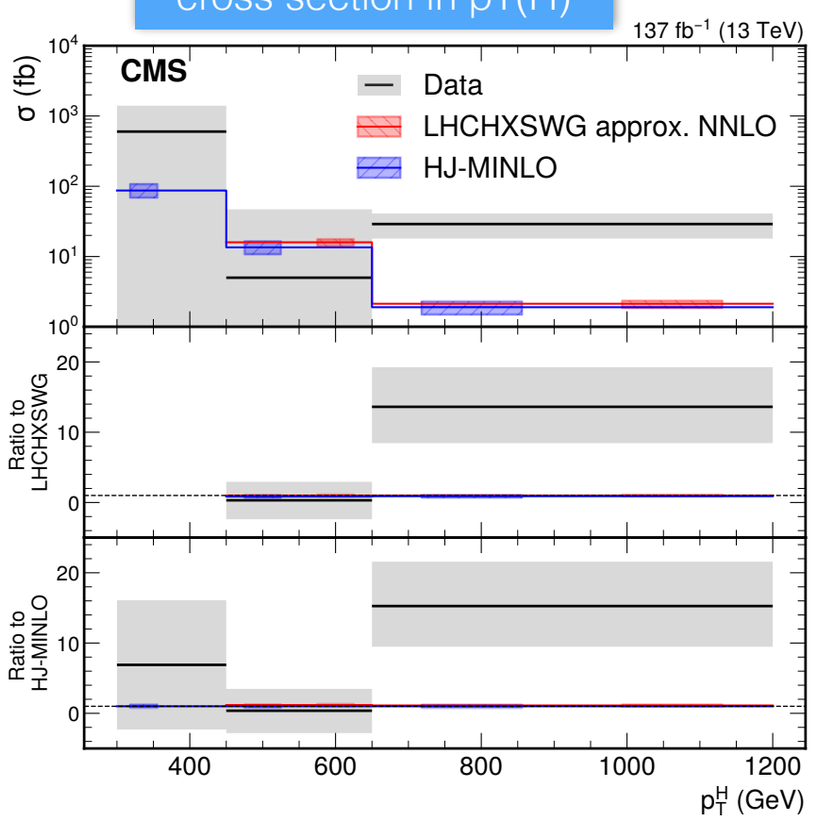
- tagging the Higgs with machine-learning methods based on signature of two b quarks inside a fat jet
- DDBT improves bb tagging efficiency by a factor of 1.6 at same QCD misidentification rate



Unfolded differential cross section in pT(H)



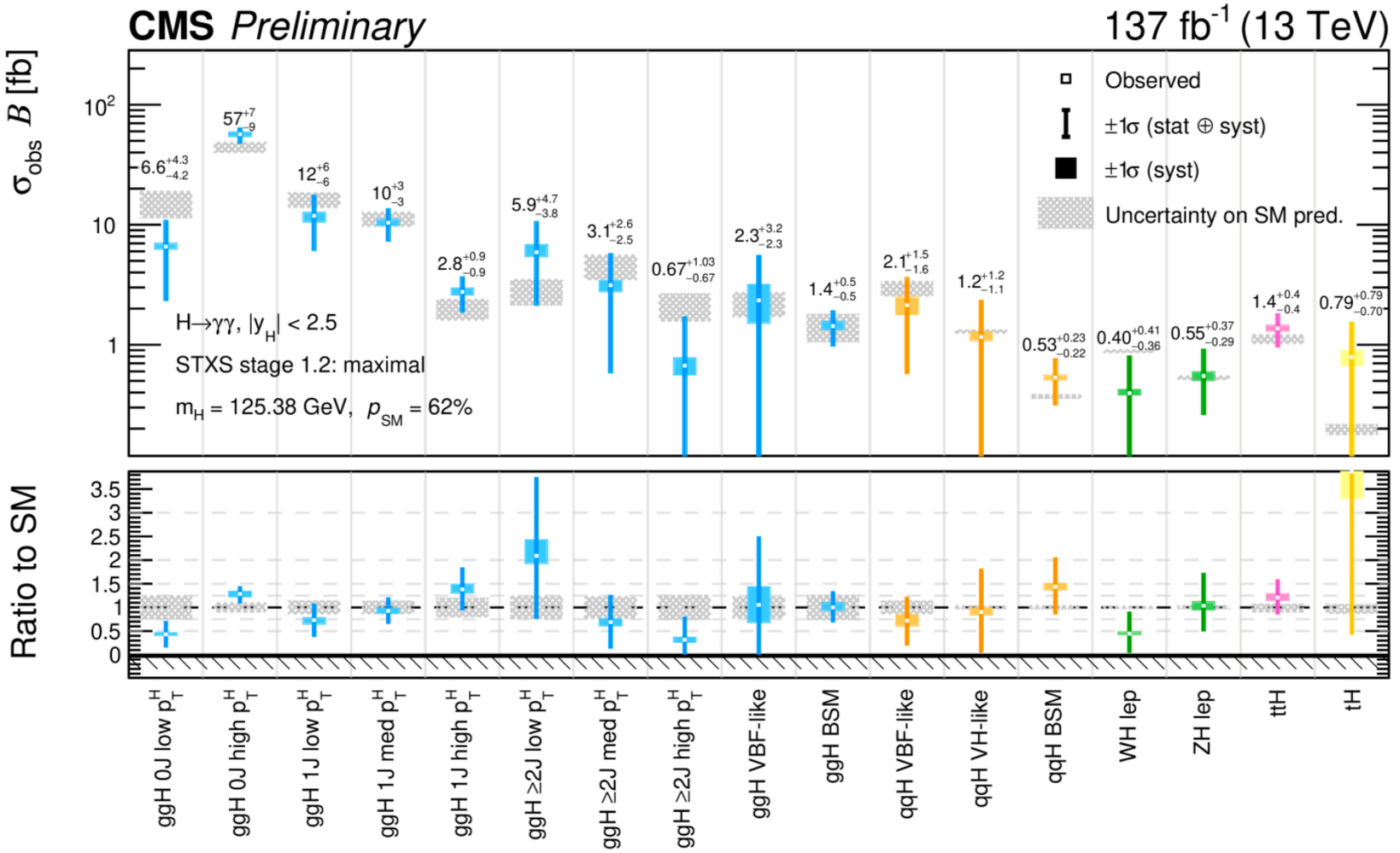


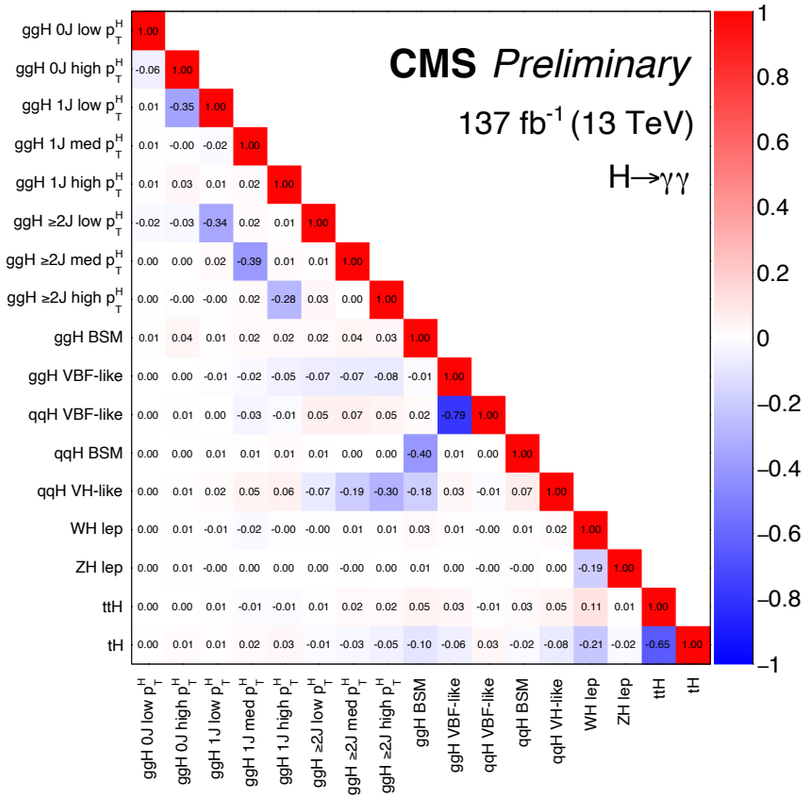


Simplified template cross section measurements — H→$\gamma\gamma$ decay channel

CMS-PAS-HIG-19-015

- Extract production mode cross section in exclusive phase space (STXS bins)
- Simultaneously maximize the sensitivity of measurements and minimize their theory dependence
- Significant progress from ATLAS and CMS across accessible Higgs decays



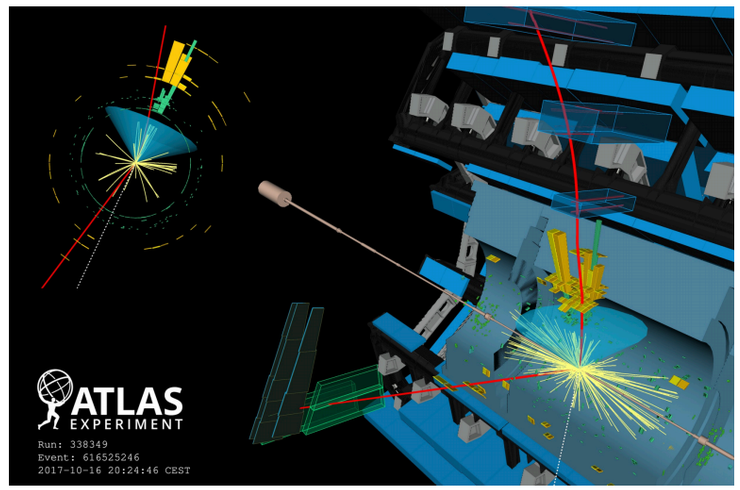


Simplified template cross section measurements — VH→bb decay channel

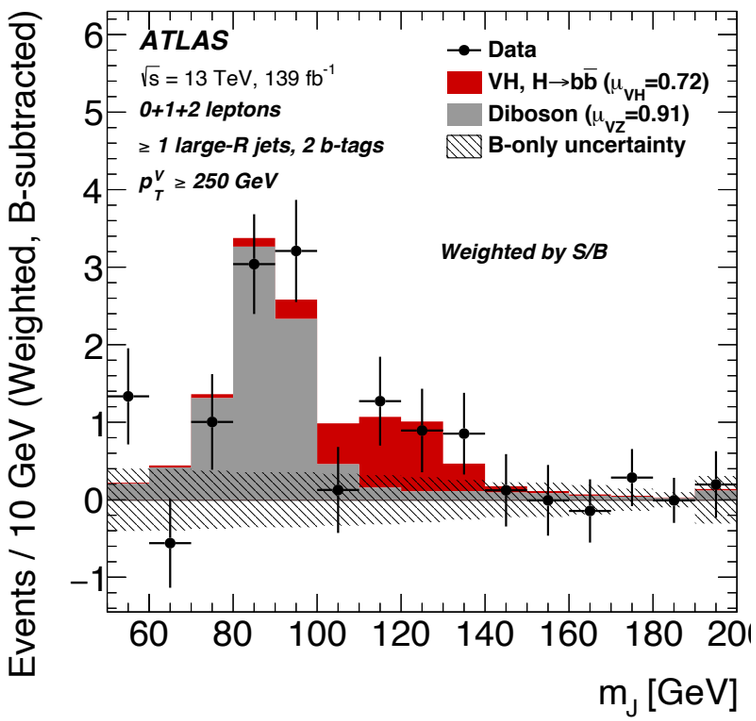
Boosted analysis: Phys. Lett. B 816 (2021) 136204
small-R jets analysis: Eur. Phys. J. C 81 (2021) 178

Complementary analyses using small-R jets and boosted Higgs physics objects:

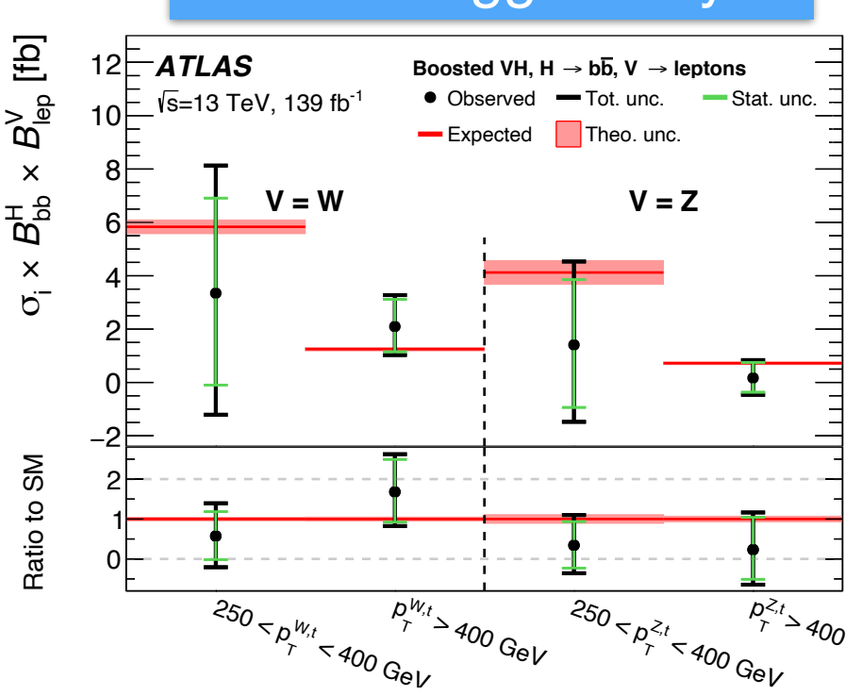
- Strong evidence 4.0σ for WH and observation 5.3σ of ZH from small-R jets analysis
- Boosted Higgs analysis: 2.1σ of VH



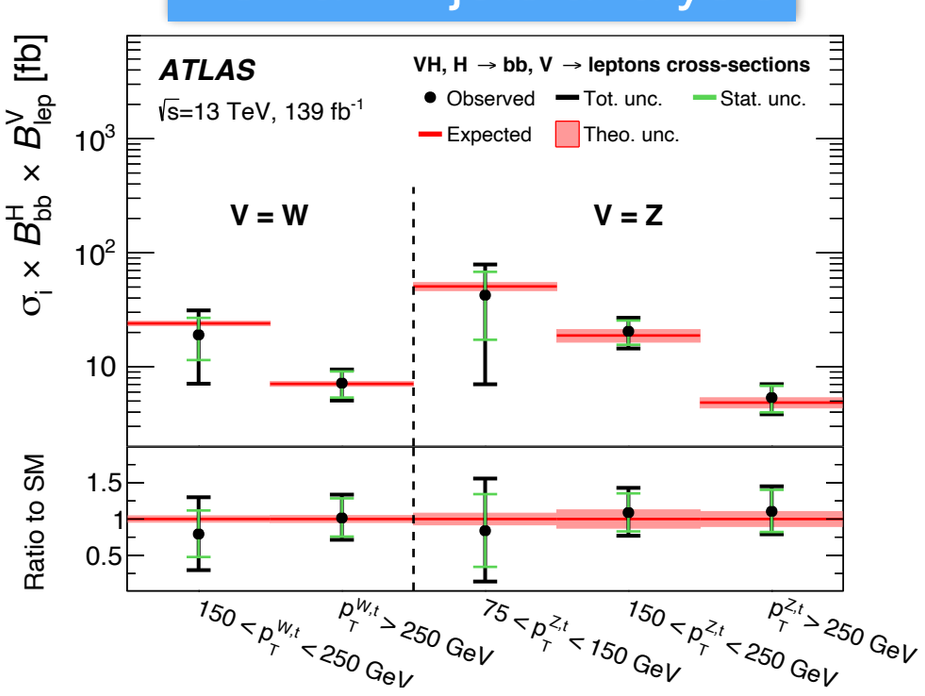
boosted Higgs analysis



boosted Higgs analysis



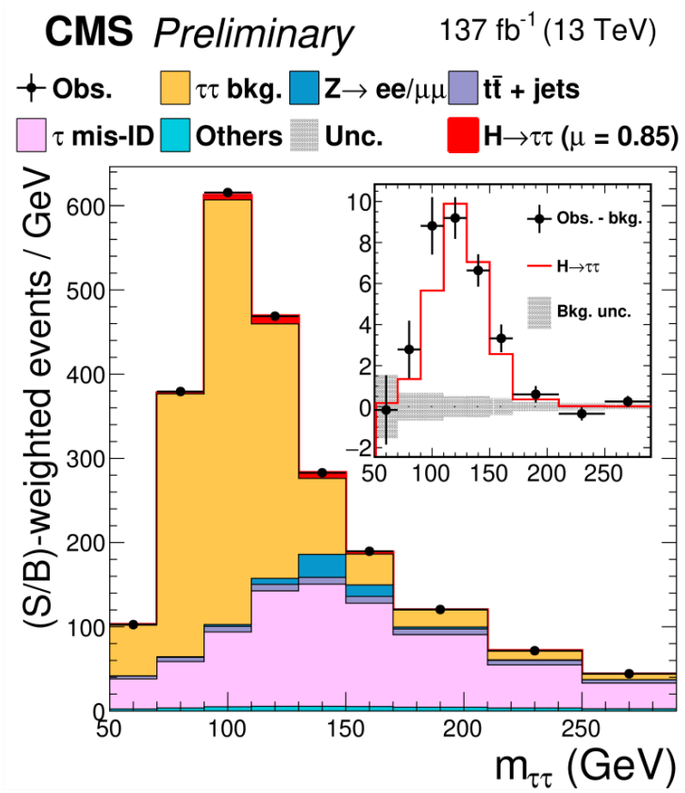
small-R jets analysis

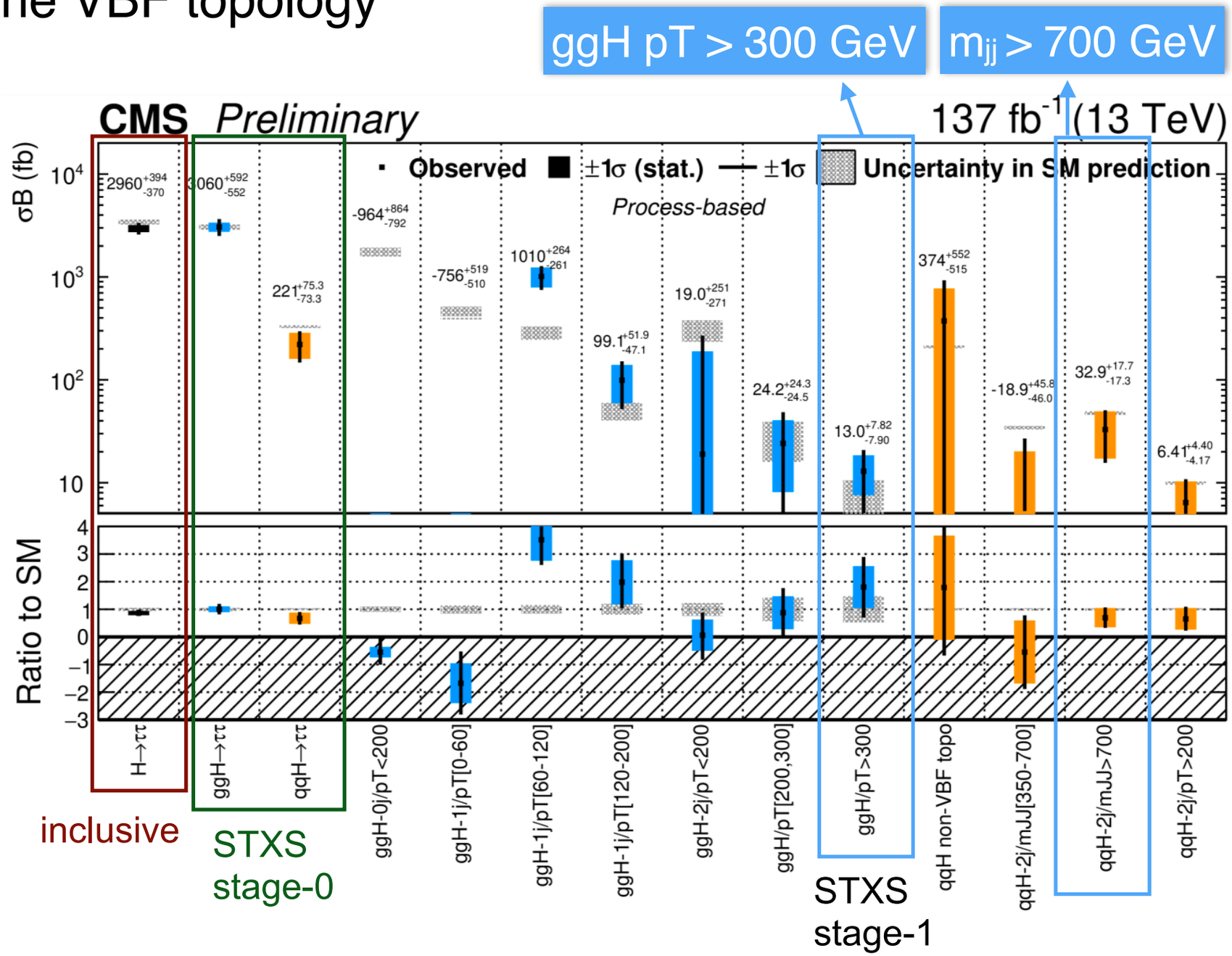


Simplified template cross section measurements — H→$\tau\tau$ decay channel

CMS-PAS-HIG-19-010

- Sensitive to the gluon fusion process with relatively high Higgs boson p_T and sensitive to the VBF topology



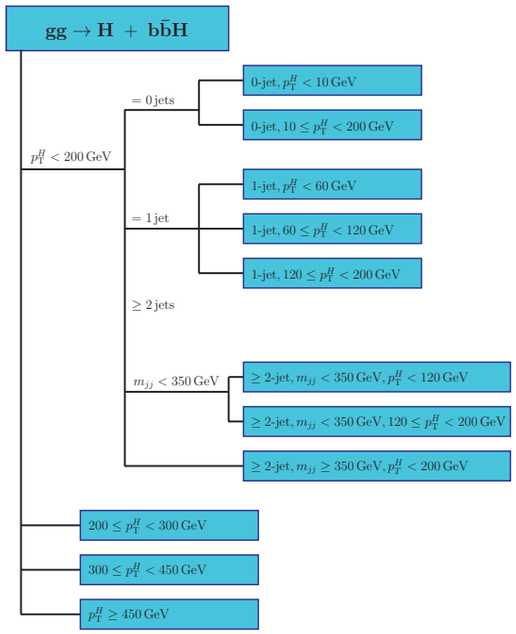


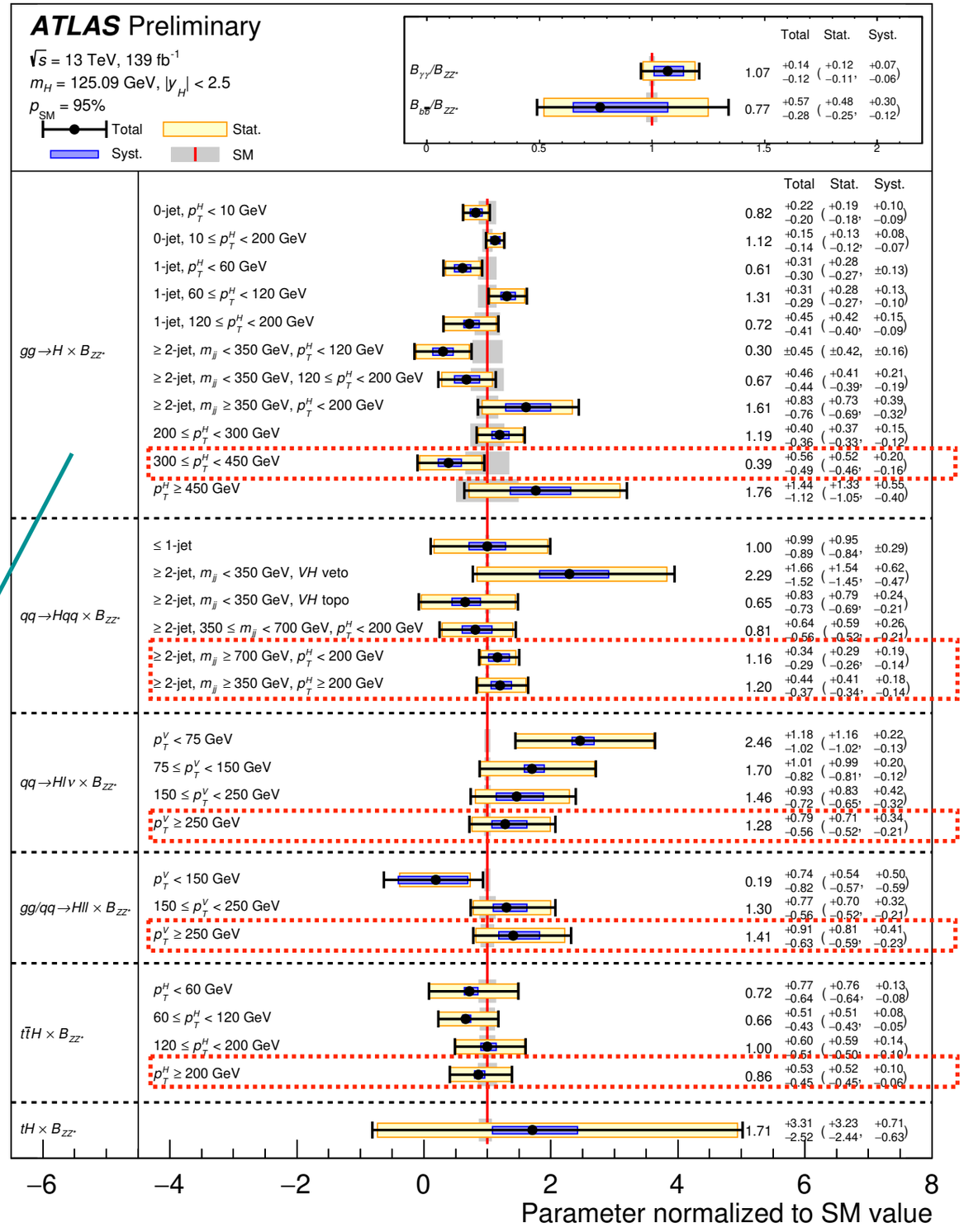
Simplified template cross section measurements — combination

p-value 95%

ATLAS-CONF-2020-027

- Combination of STXS measurements in H→$\gamma\gamma$, H→ZZ*→4l and VH,H→bb
- Overall good compatibility with SM
- Measurements interpreted using EFT framework and BSM models: ATLAS-CONF-2020-053
- Statistical precision, in particular in most BSM-sensitive regions is still limited: more data will help!



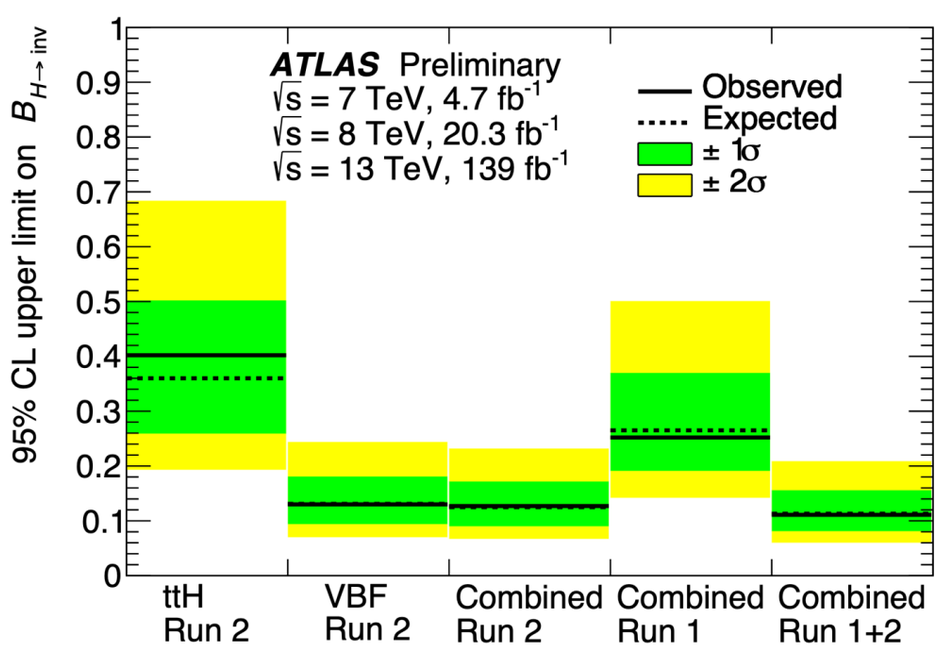


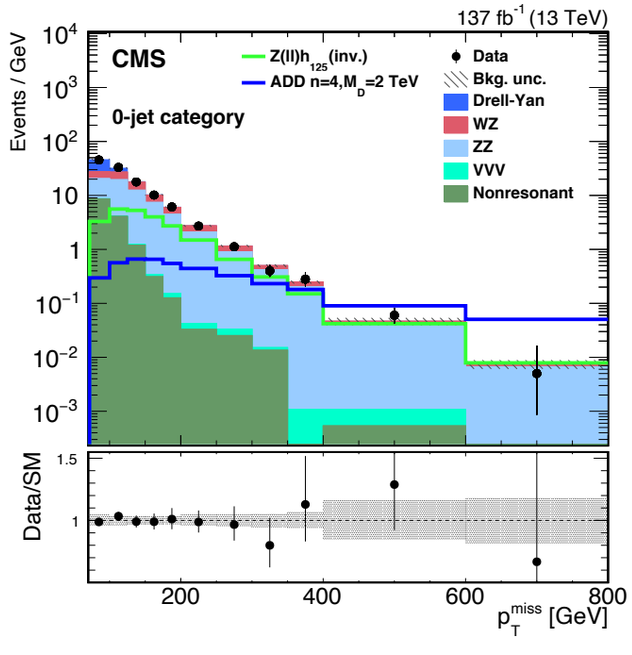
BSM Higgs: H→invisible

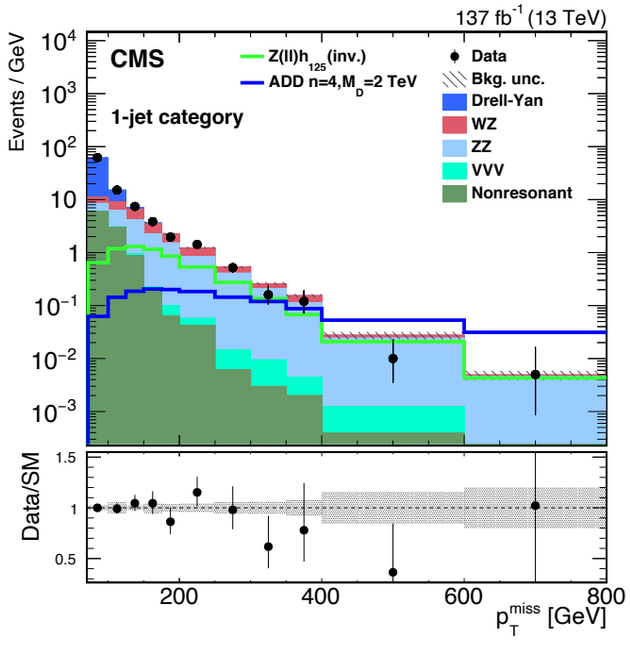
A broad program in BSM Higgs searches: additional Higgses, invisible decays, lepton-flavour-violating decay and 2HDM+scalar models with h→aa, Charged Higgses,…

- Searches for invisible Higgs decays: Higgs portal to dark matter and invisible particles in BSM models
- SM prediction: BR(H→invisible) = 1×10^{-3} from H→ZZ*→4ν decays

ATLAS H→invisible Run 1, 2 combination:
ATLAS-CONF-2020-052
CMS Z(ll)H,H→invisible full Run 2 result:
Eur. Phys. J. C 81 (2021) 13



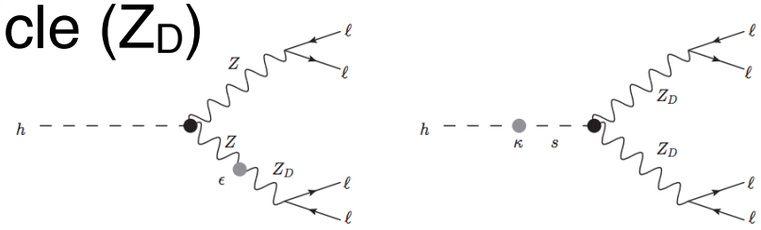




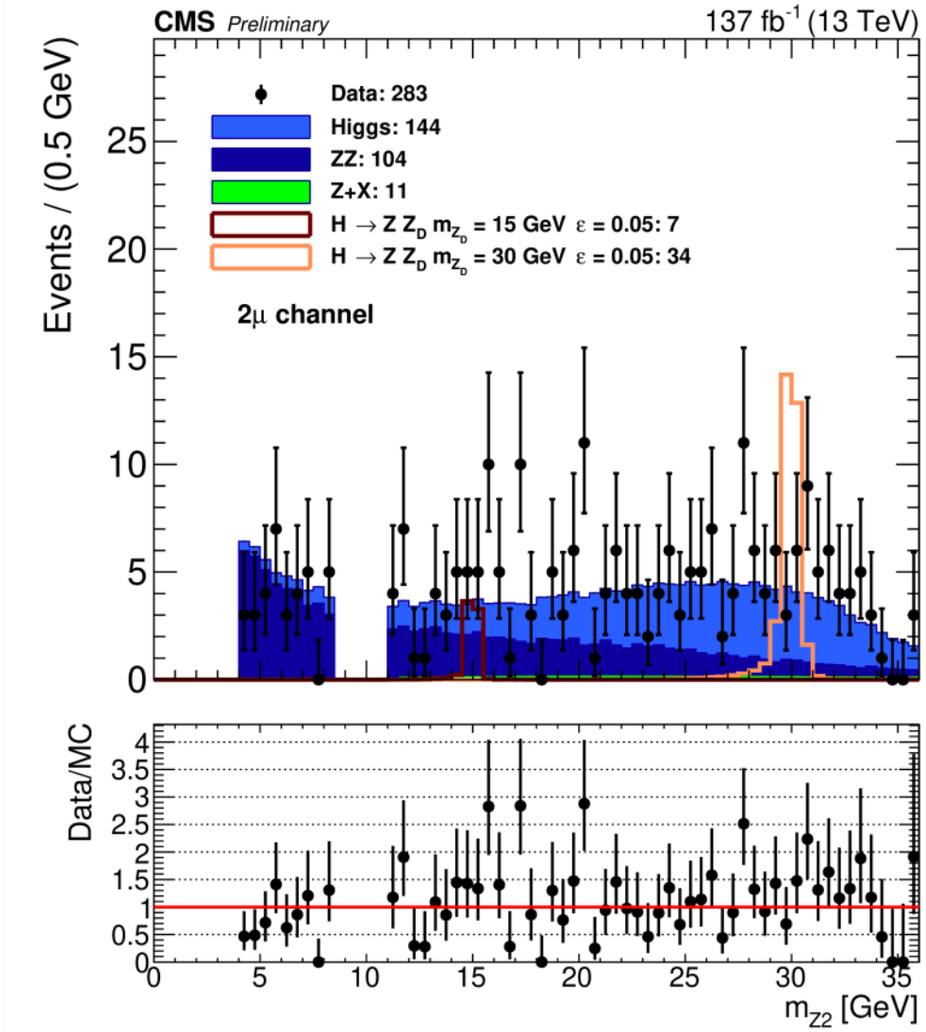
- Observed upper limit from combination of VBF and ttH,H→invisible: BR(H→invisible) < 11% @95% CL
- Observed upper limit from Z(ll)H,H→invisible: BR(H→invisible) < 29% @95% CL

Recent BSM Higgs search results

- Search for dark photon and axion-like particle (Z_D)

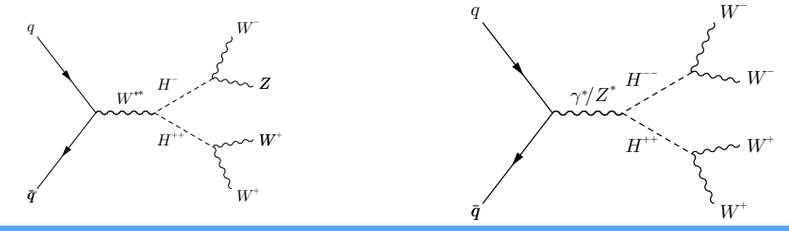


Search for $H \to ZZ_D, Z_DZ_D$ in four lepton channel

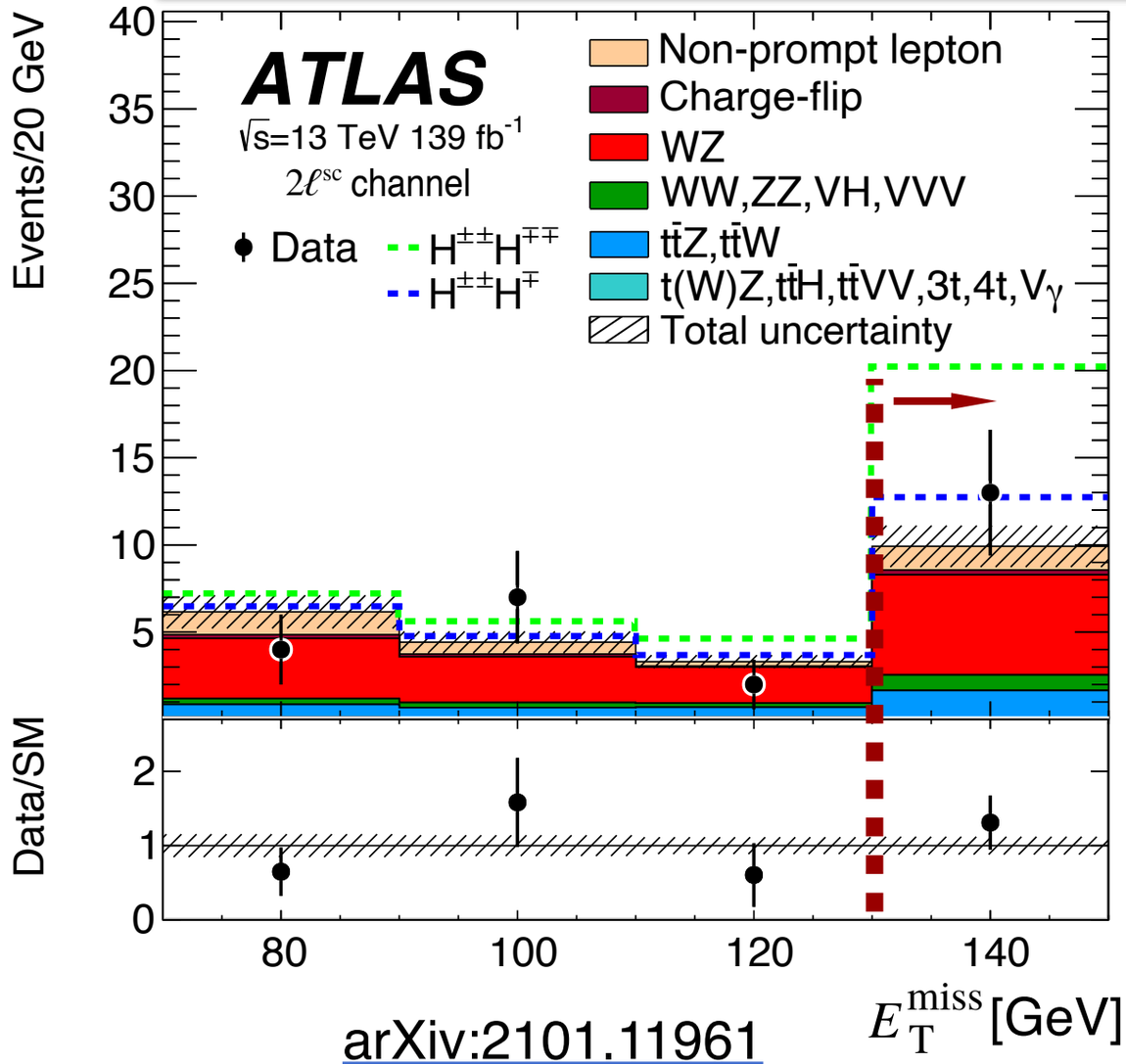


CMS-PAS-HIG-19-007

- Search for (double) charged Higgs



m($H^{\pm\pm}$) excluded up to 350 and 230 GeV at 95% CL for the pair and associated production modes



arXiv:2101.11961

Higgs boson self-coupling: HH searches

- Higgs self-coupling probes the nature of the Higgs potential:

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4$$

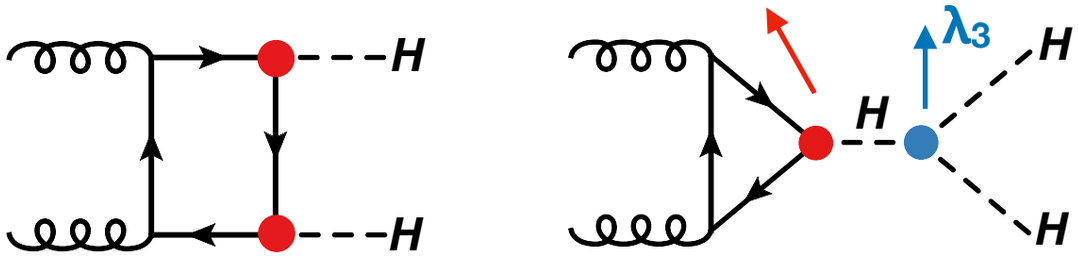
- *λ_3 : Trilinear Higgs self-coupling strength*
- λ_3 can be probed via HH production: extremely challenging to measure at LHC, accessible at HL-LHC

	λ_3/λ_{SM} 95%CL	$\sigma_{HH}/\sigma_{SM\ HH}$
ATLAS 2015+16 data	[-5.0, 12.0]	< 6.9
CMS 2016 data	[-11.8, 18.8]	< 22.2

more in backup slides

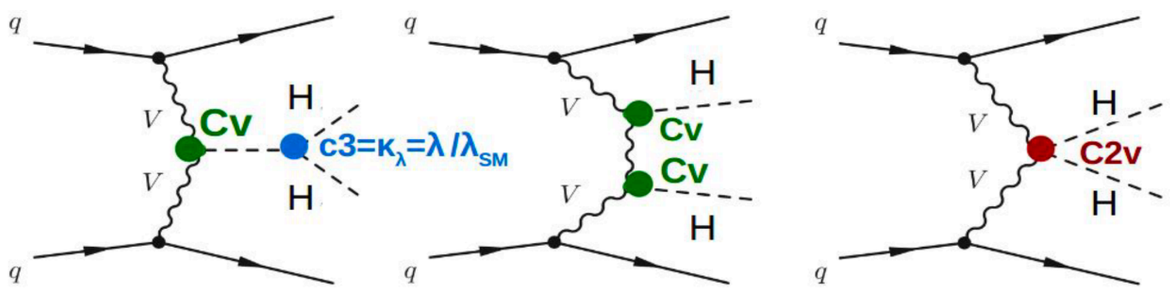
- main production mode ggF ~31.05 fb @13 TeV NNLO$_{FTapprox}$

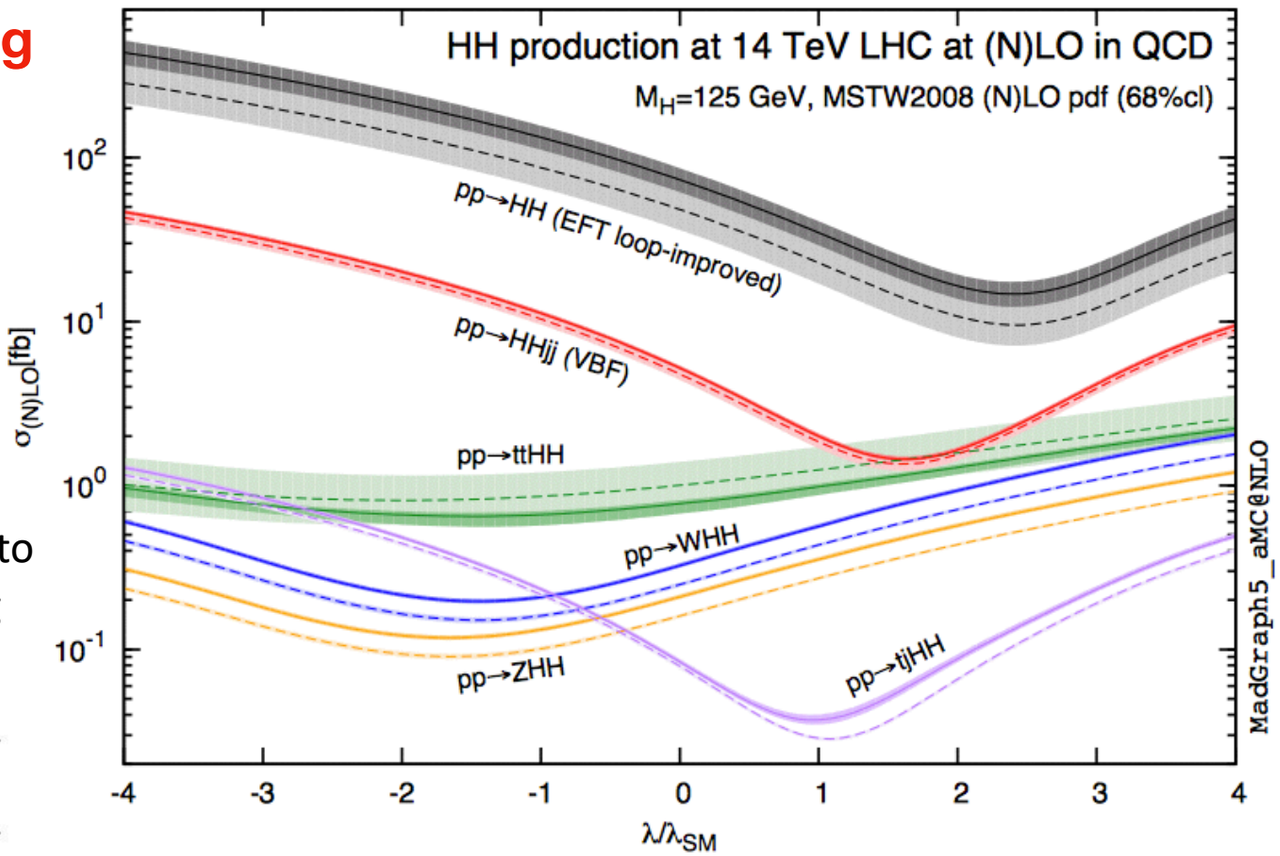
y_t Top Yukawa coupling



- sub-leading VBF ~1.73 fb @13 TeV N^{3}LO QCD

VBF channel offers access to the HHVV quartic coupling





R.Frederix et al: Phys.Lett. B732 (2014) 142-149

Recent Higgs boson self-coupling results using full Run 2 data

- New HH decay channels and significantly improved analysis strategies
- Explore VBF production mode and HHVV coupling

CMS HH→bbγγ (JHEP 03 (2021) 257):

- $-3.3 < \kappa_\lambda < 8.5$ obs @95% CL
- $\sigma(HH)/\sigma(HH_{SM}) < 7.7$ (5.2) obs(exp) @95% CL

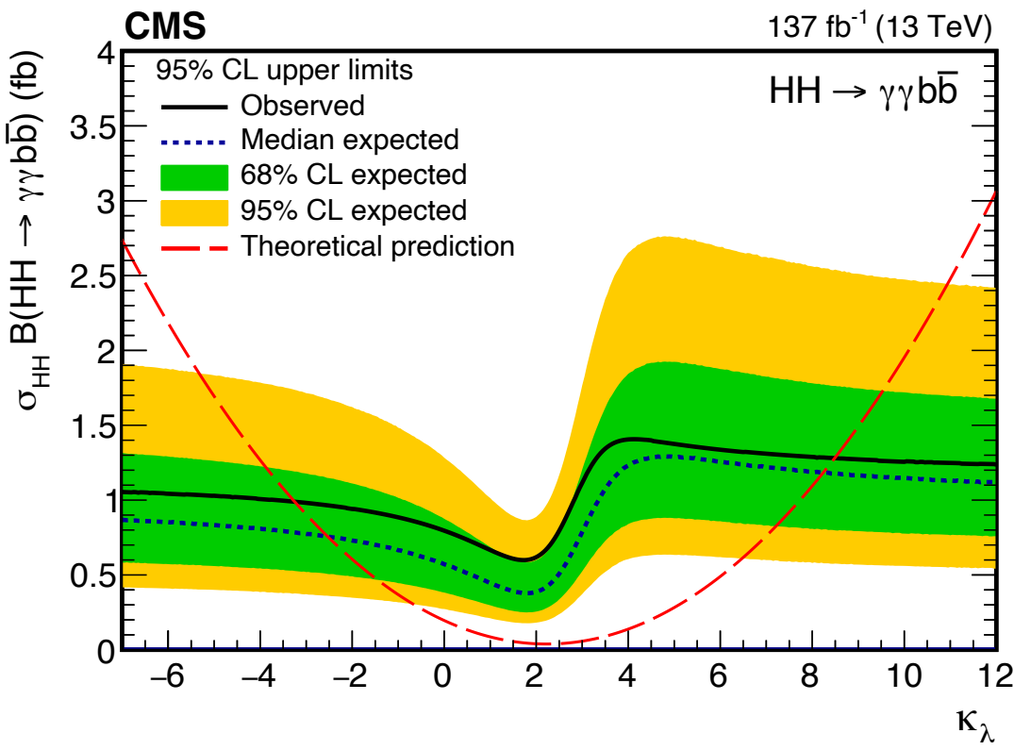
CMS HH→bbZZ*→bb4l (CMS-PAS-HIG-20-004):

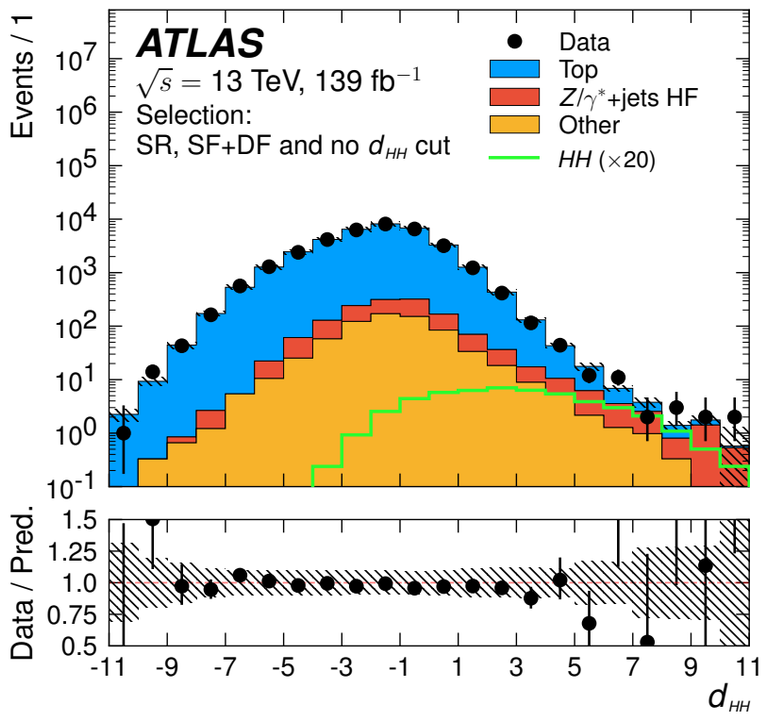
- $-9 < \kappa_\lambda < 14$ obs @95% CL
- $\sigma(HH)/\sigma(HH_{SM}) < 30$ (37) obs(exp) @95% CL

ATLAS HH→bblvlv (Phys. Lett. B 801 (2020) 135145):

- $\sigma(HH)/\sigma(HH_{SM}) < 40$ (29) obs(exp) @95% CL

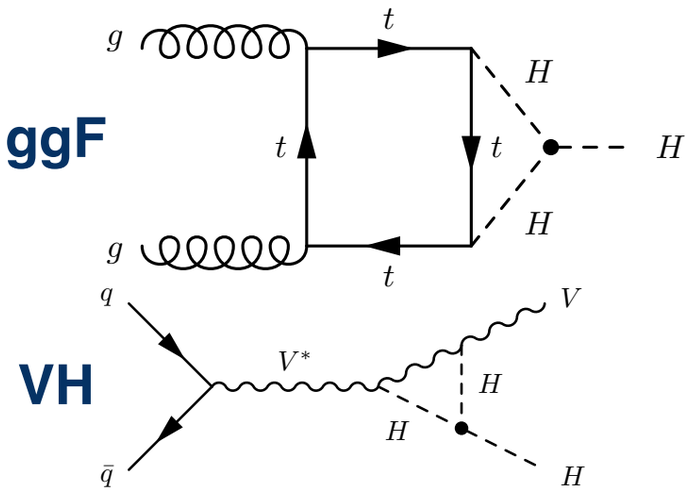
ATLAS search for resonant HH production in boosted bb pair and boosted ττ pair (JHEP 11 (2020) 163) (backup slides)

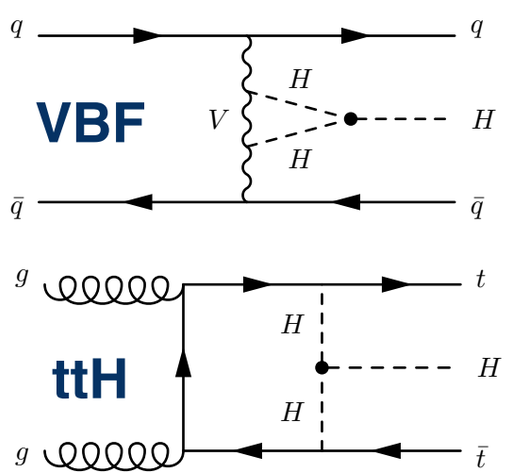




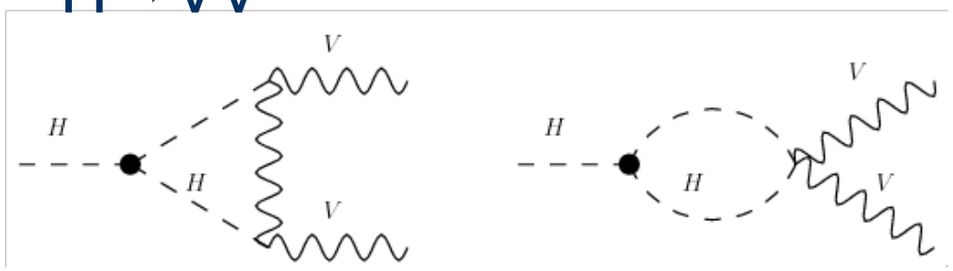
Higgs boson self-coupling: H and HH combination

- Single Higgs boson production & decay rates, kinematics, are sensitive to Higgs self-coupling through EW corrections => indirectly constrain κ_λ, assuming no other BSM effects



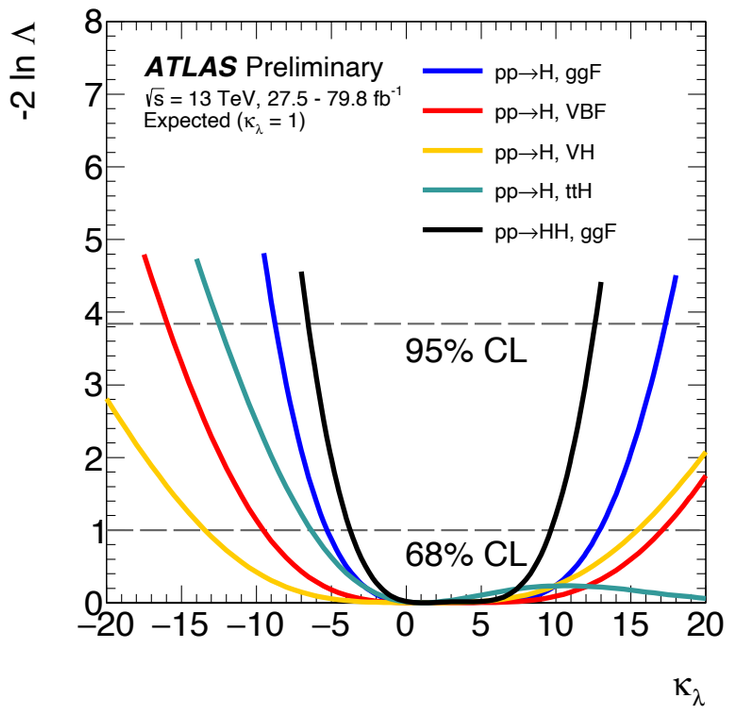


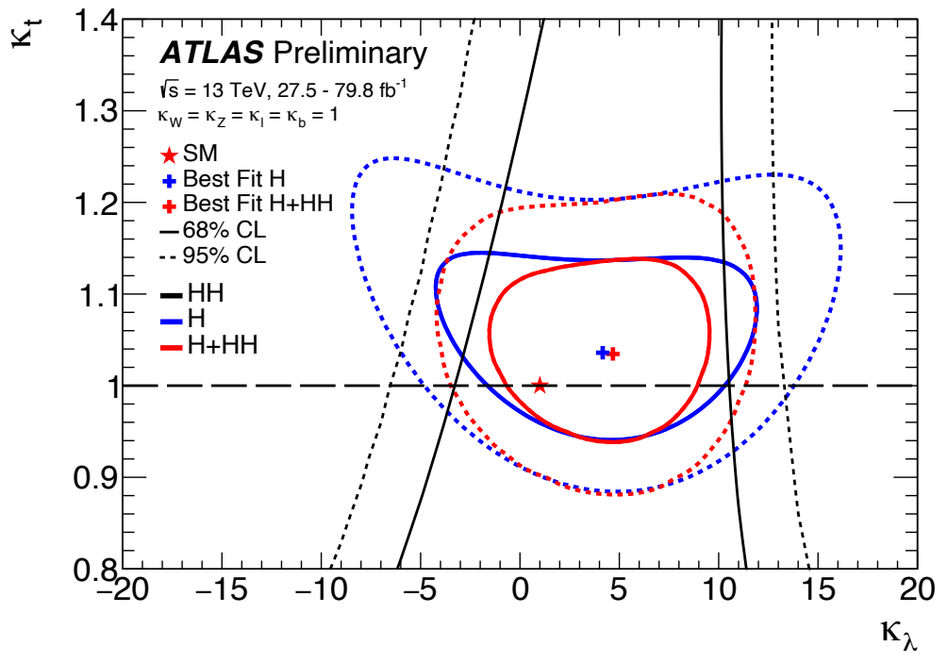
H→VV



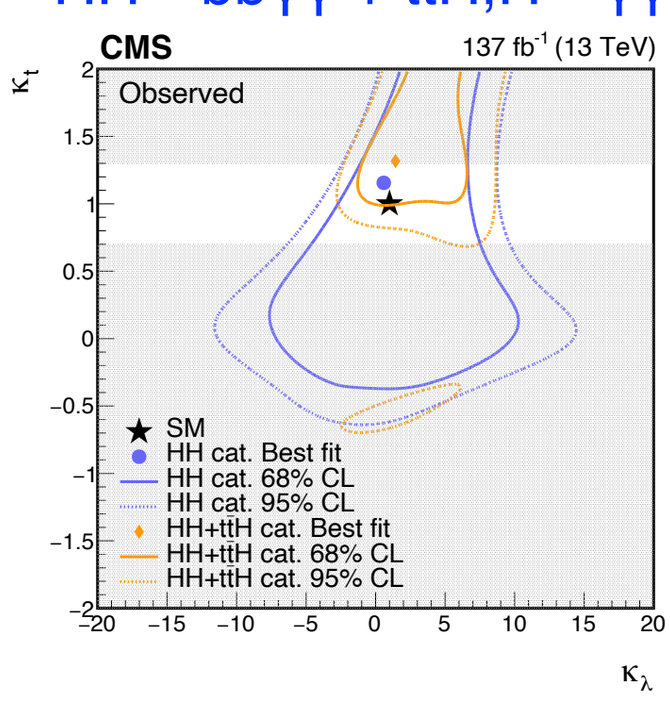
G. Degrassi et. al., JHEP 12 (2016) 080
F. Maltoni et. al., EPJC 77 (2017) 887

HH→bbγγ + ttH,H→γγ





ATLAS-CONF-2019-049

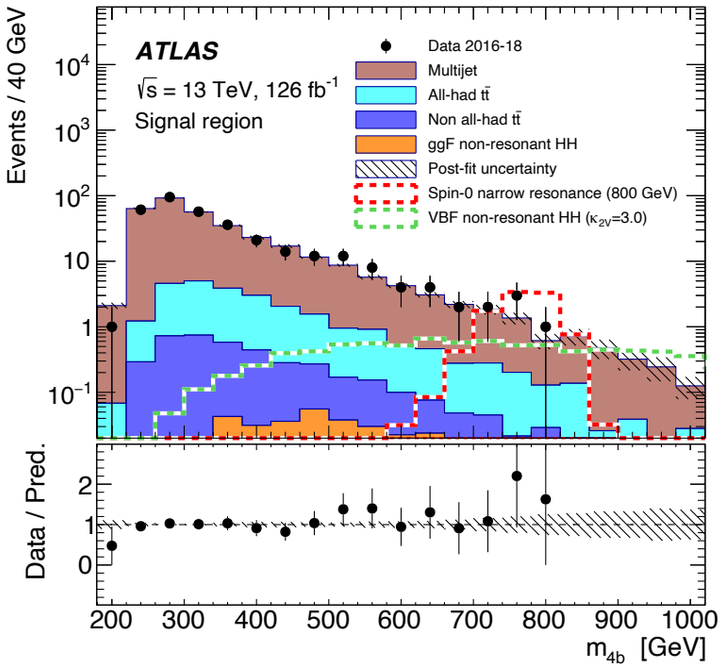


JHEP 03 (2021) 257

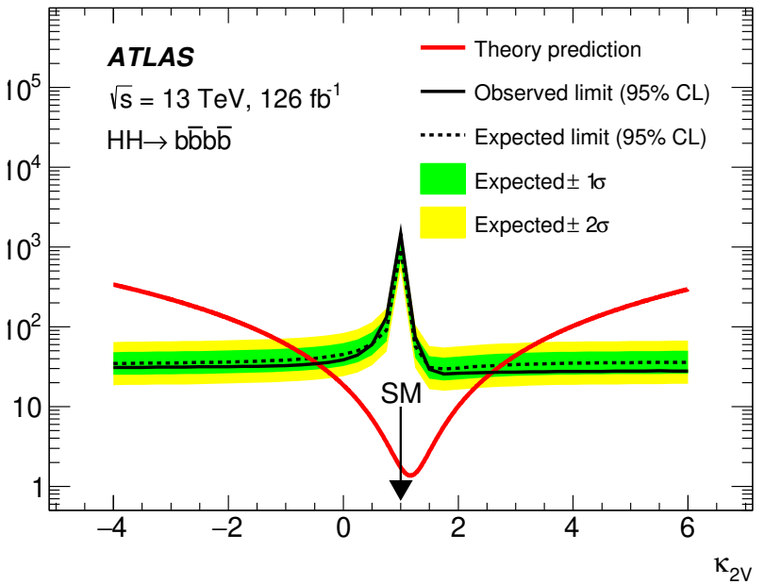
Probe HHVV coupling

- ATLAS VBFHH→bbbb Run 2 data:
  - four b-jets, two VBF jets with m_{jj}>1 TeV and $|\Delta\eta_{jj}| > 5.0$
  - $-0.43 < \kappa_{2V} < 2.56$ @95% CL

- final discriminant m_{4b}



JHEP 07 (2020) 108 [Erratum]



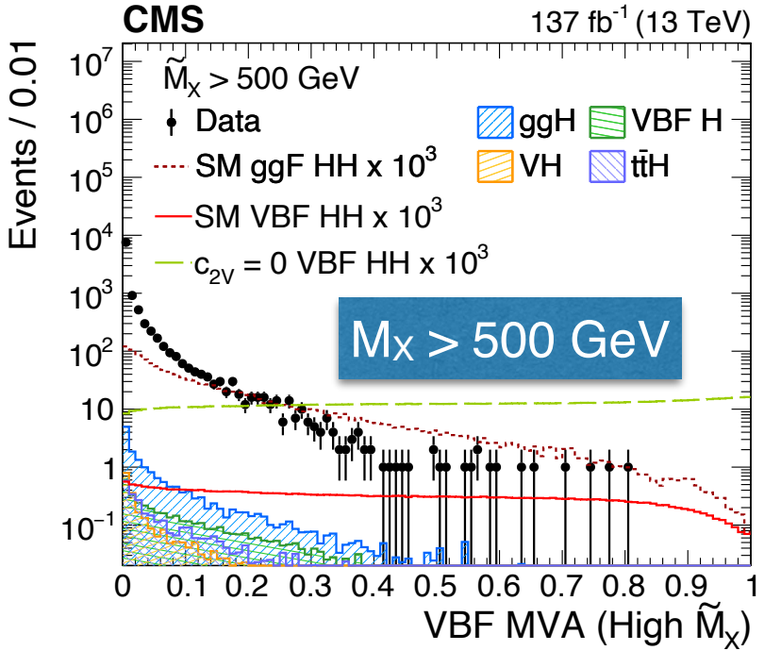
- CMS VBFHH→bbγγ Run 2 data:
  - two VBF categories:

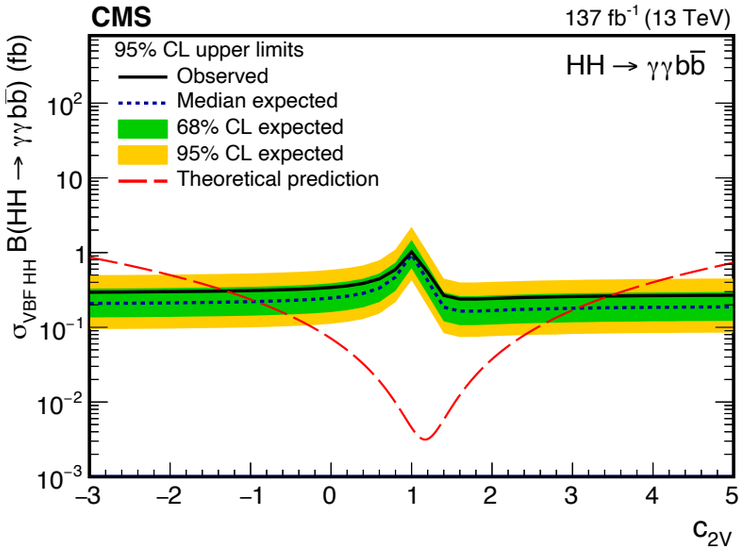
$$\tilde{M}_X = m_{\gamma\gamma jj} - (m_{jj} - m_H) - (m_{\gamma\gamma} - m_H)$$

Category	MVA	$\tilde{M}_X$ (GeV)
VBF CAT 0	0.52-1.00	>500
VBF CAT 1	0.86-1.00	250-500

  - $-1.3 < \kappa_{2V} < 3.5$ @95% CL

arXiv:2011.12373



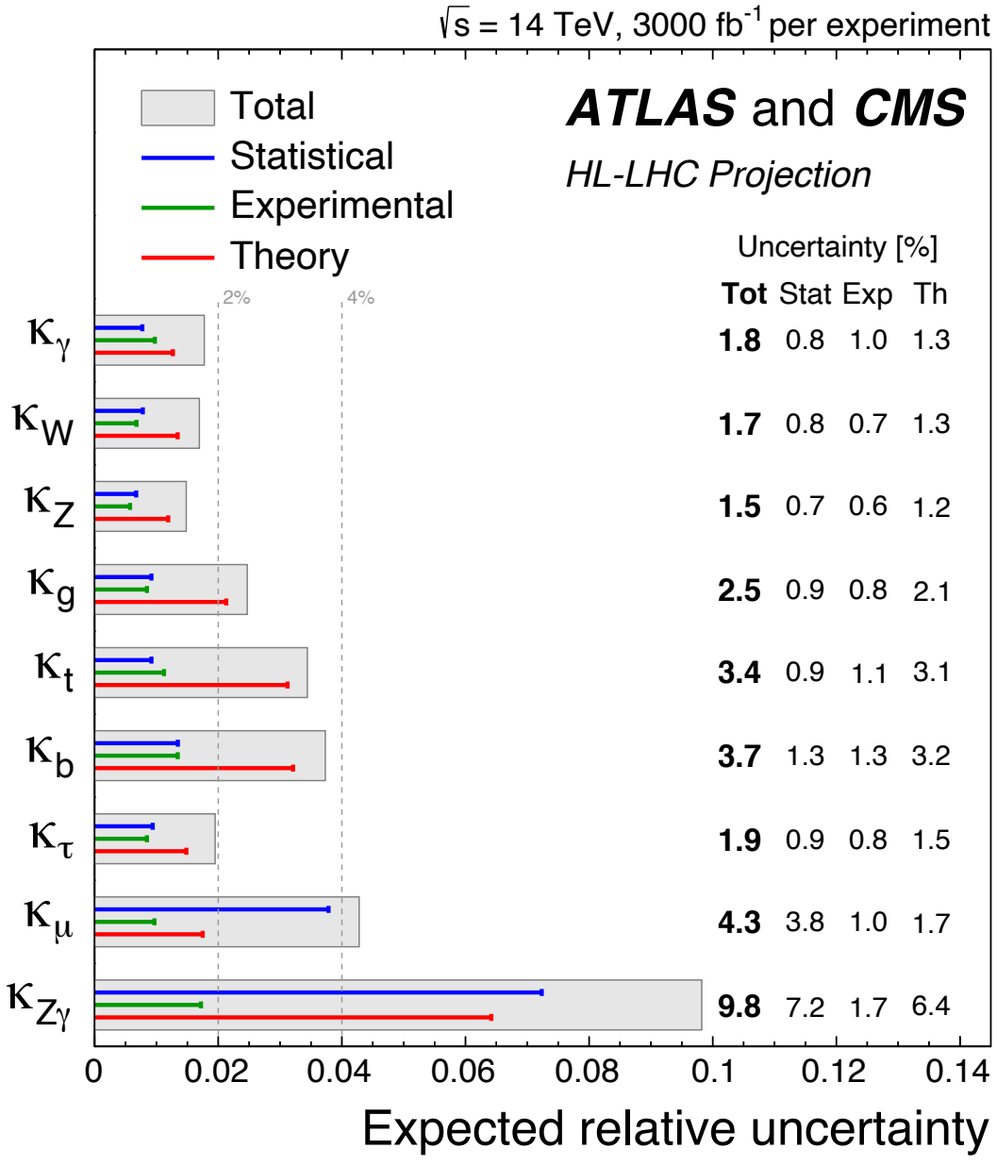


Conclusions

- Measurements of Higgs boson properties so far in agreement with SM, hints for new physics could be currently covered by uncertainties
  - Major productions and decays now reaching ~10% level precision, improved sensitivity to rare process e.g. evidence of H→μμ and H→$\ell\ell\gamma$
  - Significant progress in fiducial/differential and STXS measurements
  - Higgs boson coupling CP-structure studied in both Higgs-fermion and Higgs-boson couplings, no sign of CP-mixing so far
- Good progress in HH searches with new channels and improvements in analysis techniques: upper limit on σ(HH) getting close to 5 × SM
- A broad program to search for BSM physics in the Higgs sector

Stay tuned for new Run 2 Higgs physics results!

Projection for HL-LHC
arXiv:1902.00134

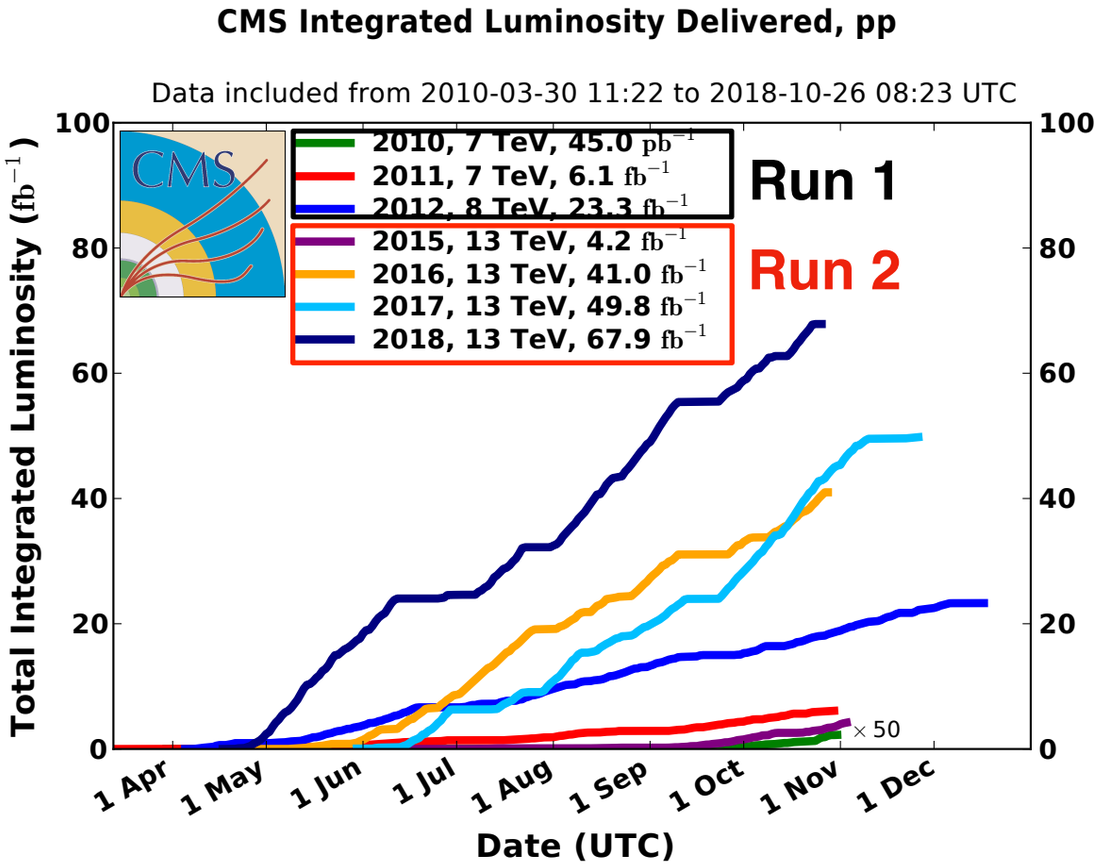


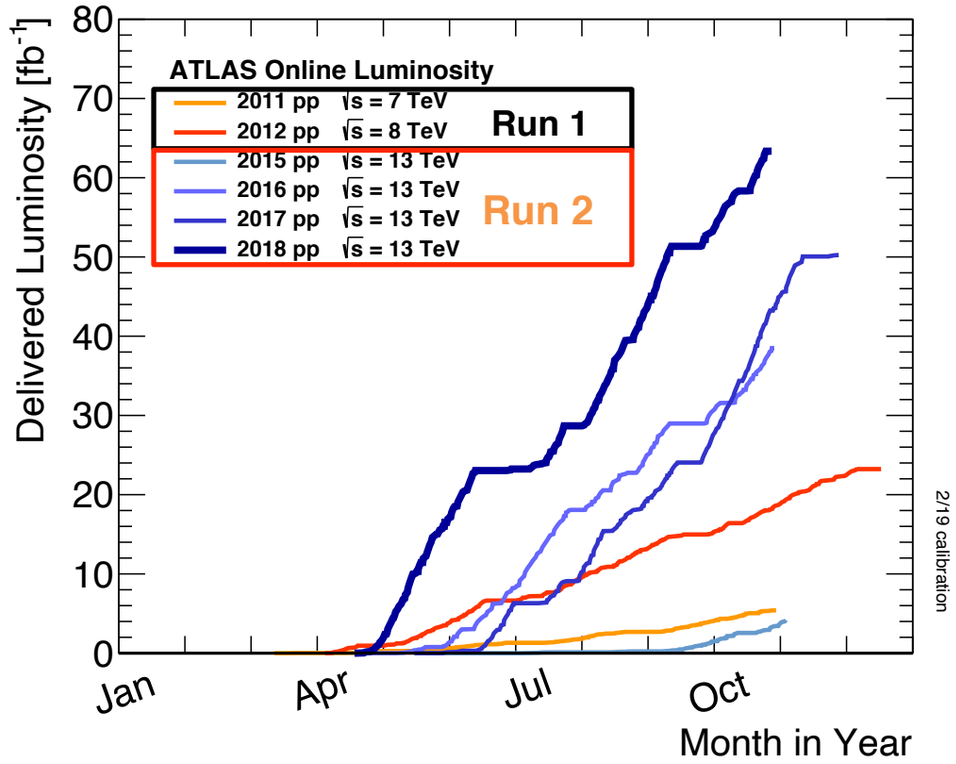
Current dataset only 5% of expected LHC total dataset

Thank you!

Backup slides

LHC, ATLAS and CMS: excellent performance

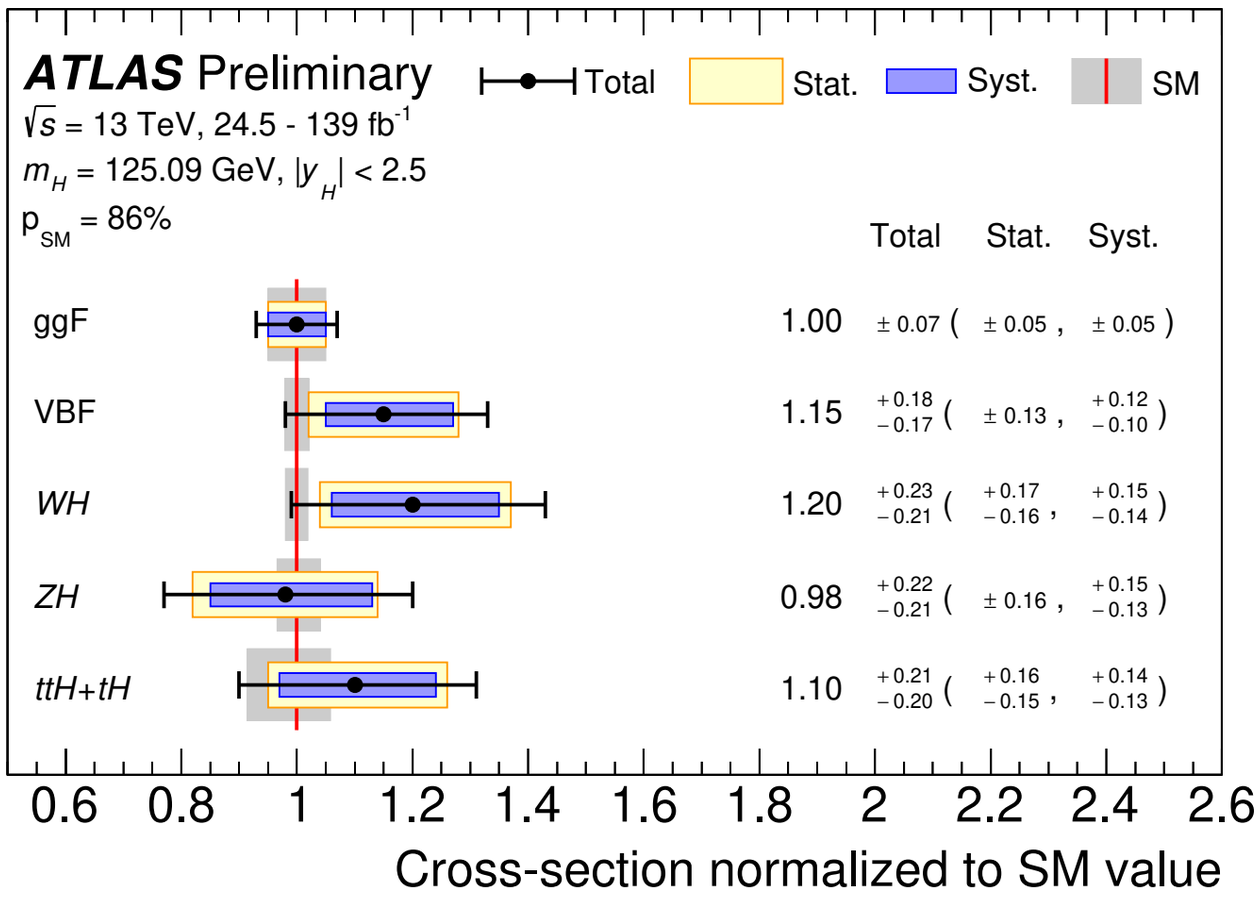




- **139 fb^{-1} and 137 fb^{-1}** of **13 TeV** proton-proton collision data collected for physics by ATLAS and CMS detectors
- Thanks to the excellent LHC performance and smooth operation of ATLAS and CMS detectors

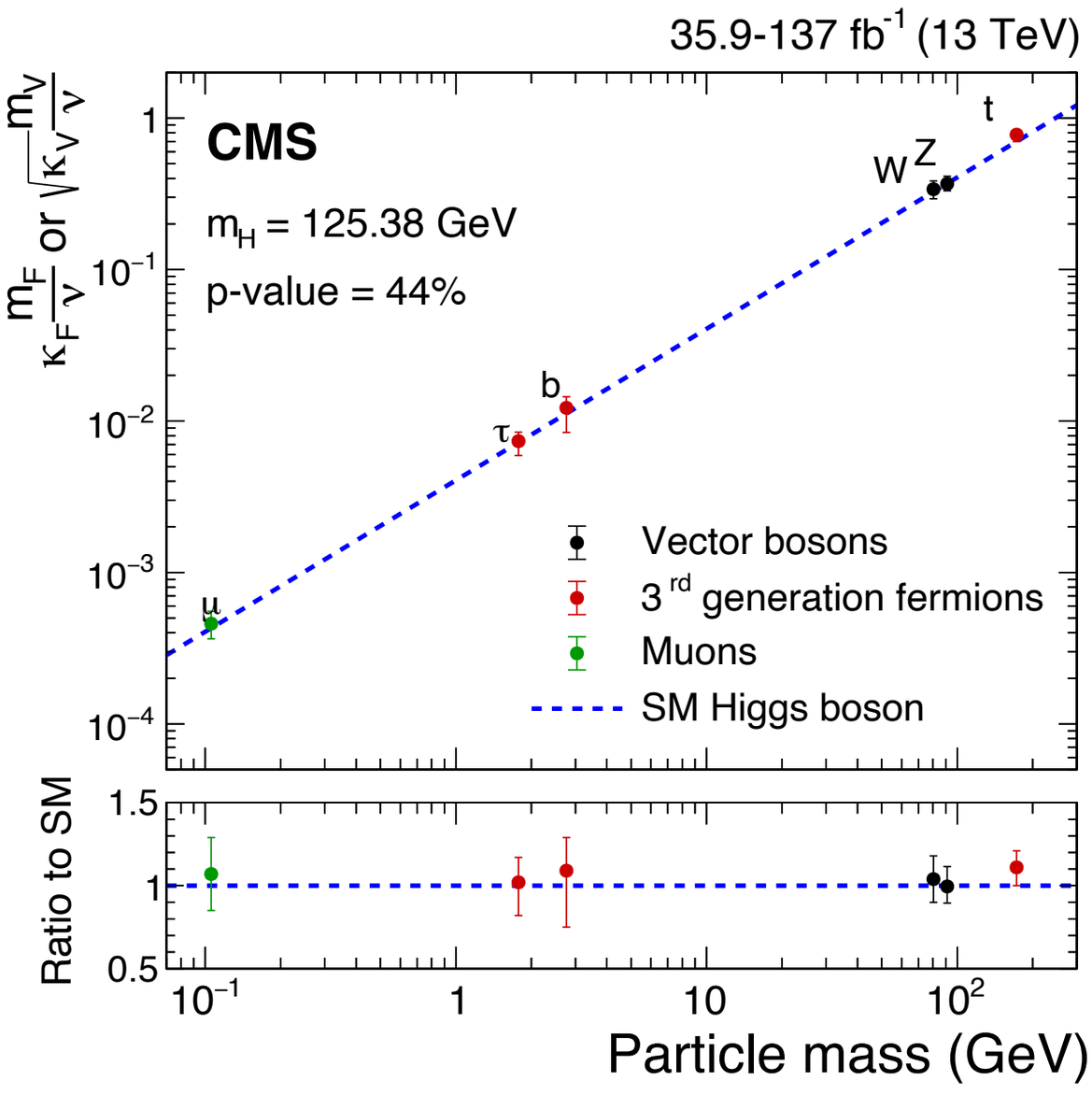
Higgs production and decay rates, couplings to SM particles

- Measurements so far consistent with SM prediction



Production mode cross-sections (assuming SM BRs)

ATLAS-CONF-2020-027



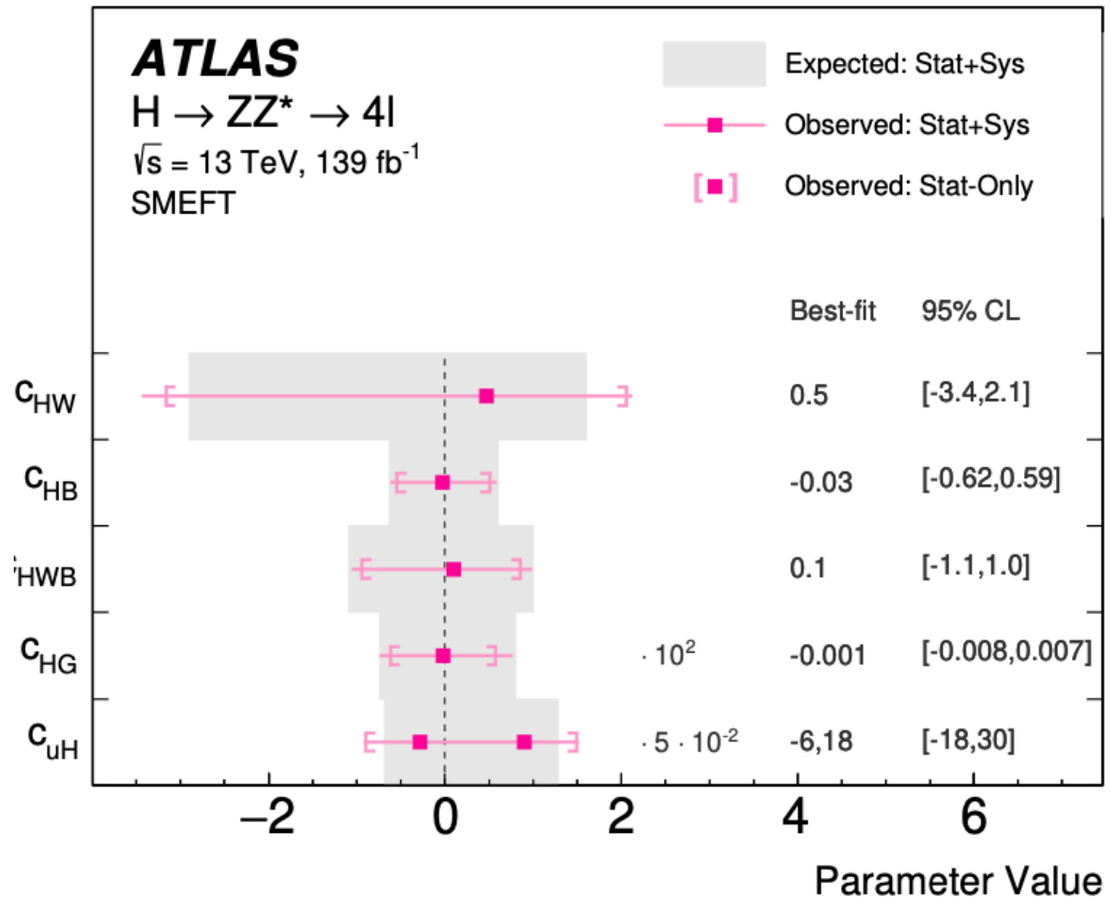
Phys. Lett. B 812 (2021) 135980

Higgs boson anomalous couplings and EFT studies in H→ZZ*→4l decay channel

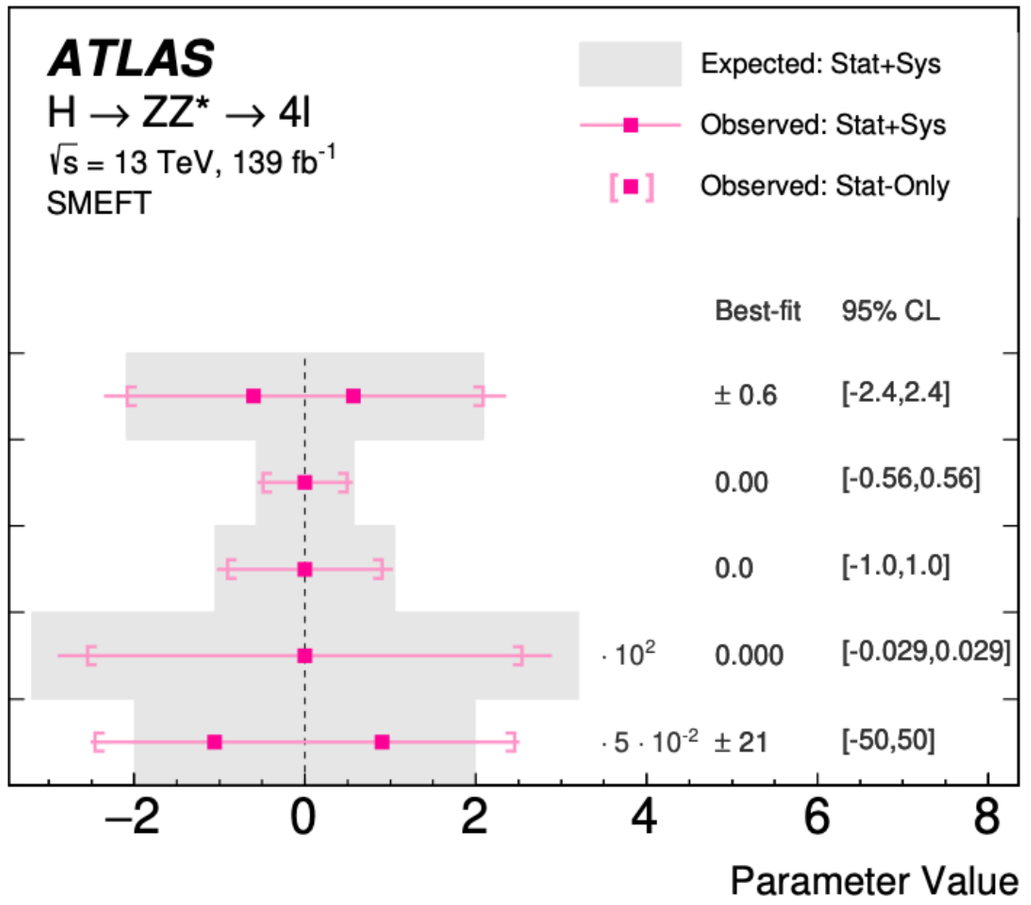
Eur. Phys. J. C 80 (2020) 957

ATLAS full Run 2 H→ZZ*→4l analysis constrain on SMEFT Wilson coefficients

CP-even couplings

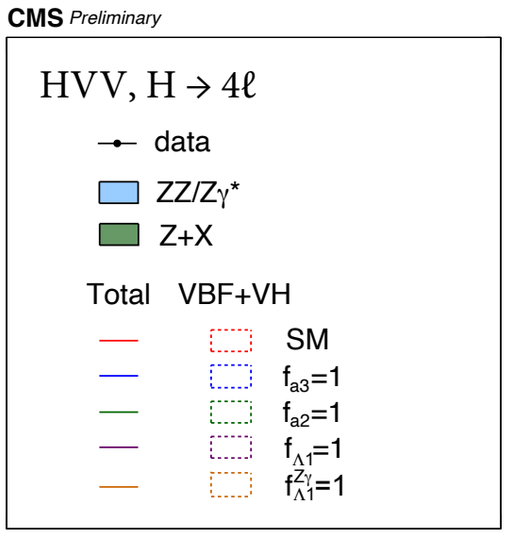


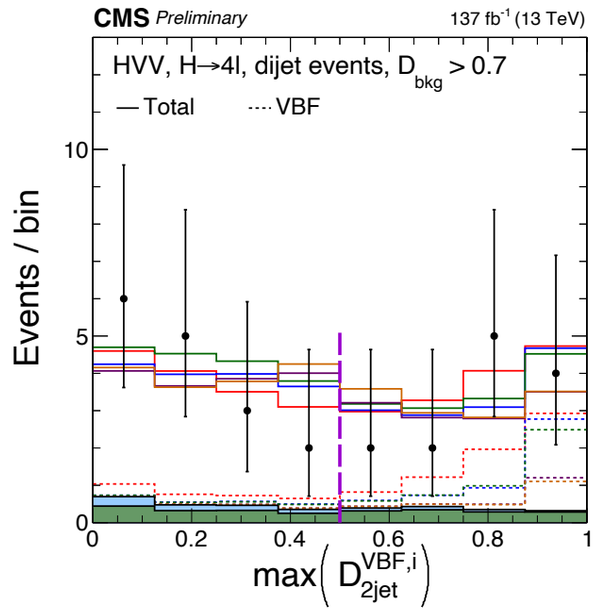
CP-odd BSM couplings

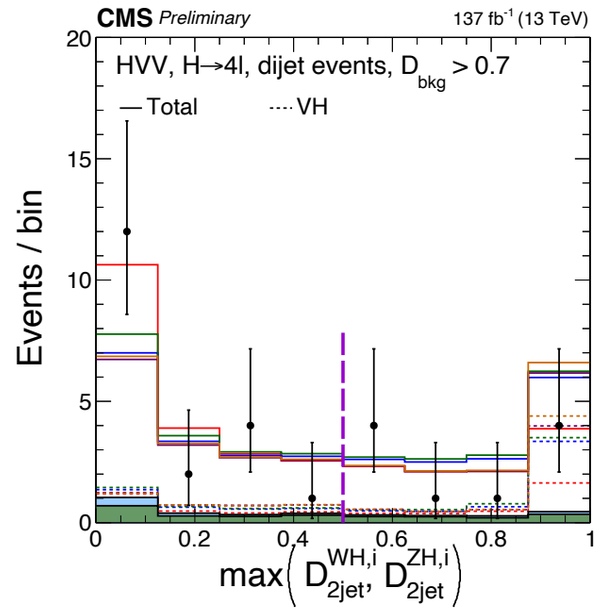


Higgs boson anomalous couplings and EFT studies in H→ZZ*→4l decay channel

CMS full Run 2 results: HIG-19-009-pas





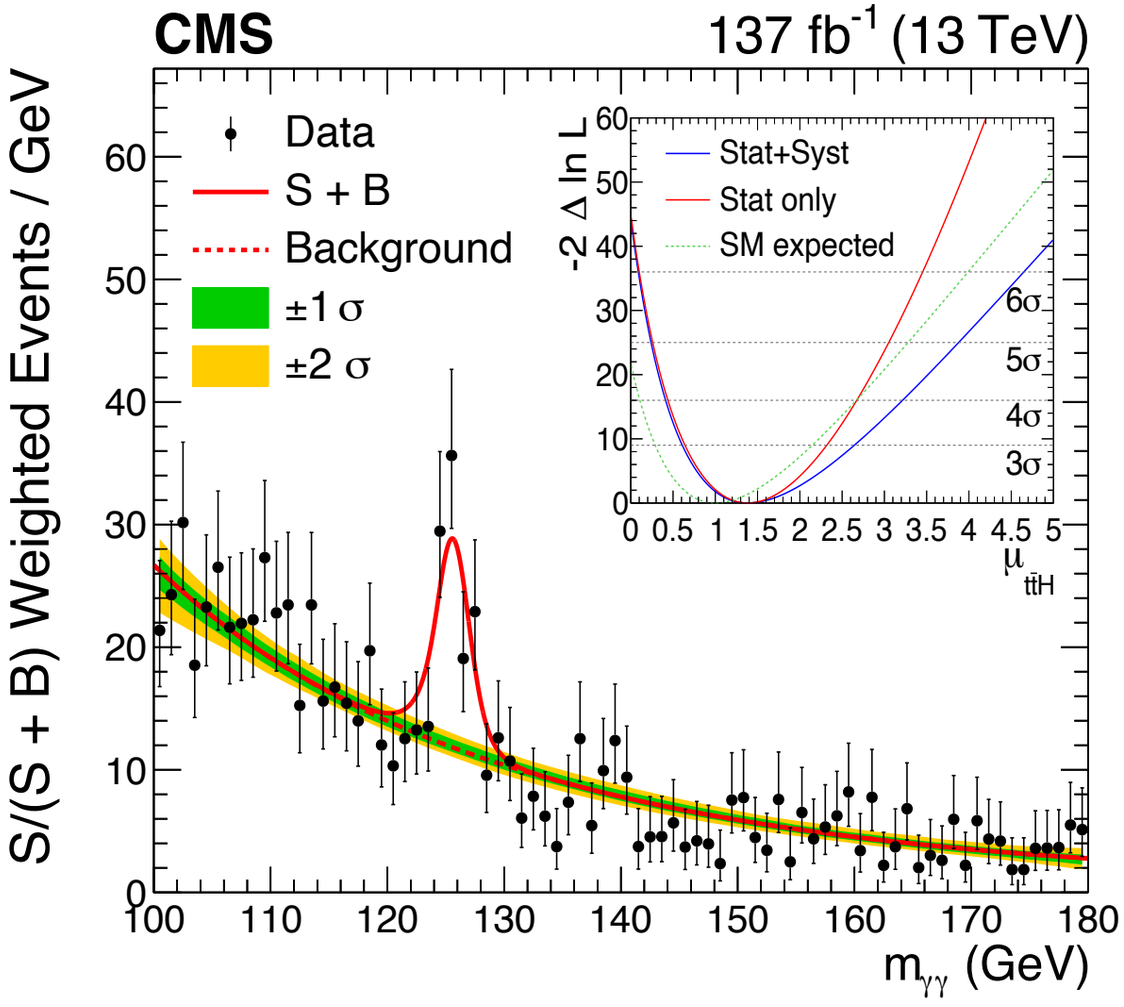


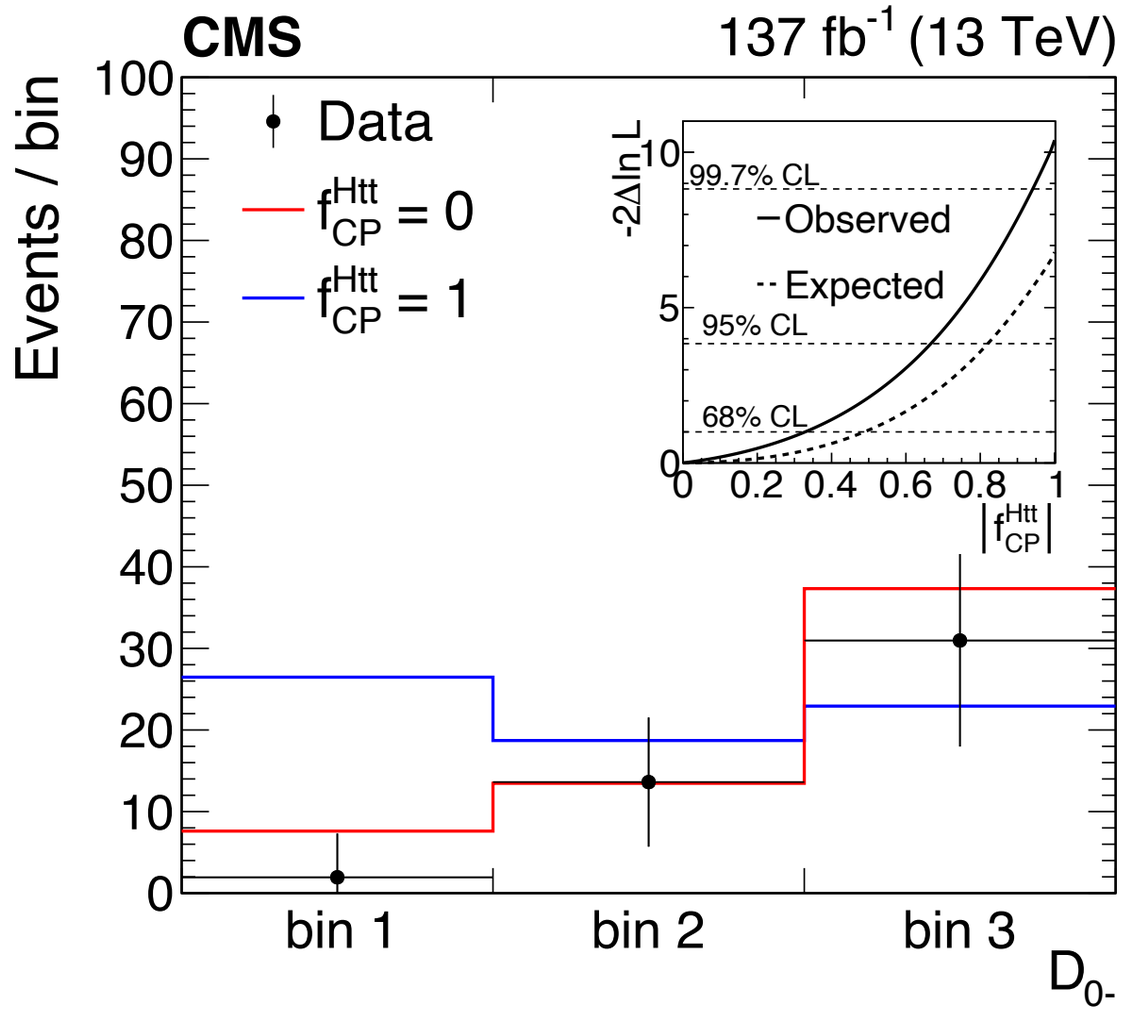
Channels	Coupling	Observed	Expected	Observed correlation			
ggH	c_{gg}	$0.0056^{+0.0025}_{-0.0039}$	$0.0084^{+0.0007}_{-0.0084}$		1		
	$\tilde{c}_{gg}$	$-0.0058^{+0.0037}_{-0.0024}$	$0.0000^{+0.0085}_{-0.0085}$		+0.980	1	
$t\bar{t}H$	κ_t	$1.06^{+0.14}_{-0.18}$	$1.00^{+0.15}_{-0.23}$		1		
	$\tilde{\kappa}_t$	$0.00^{+0.76}_{-0.72}$	$0.00^{+0.80}_{-0.80}$		0.000	1	
$t\bar{t}H + ggH$	κ_f	$0.76^{+0.23}_{-0.21}$	$1.00^{+0.26}_{-0.39}$		1		
	$\tilde{\kappa}_f$	$-0.21^{+0.28}_{-0.12}$	0.00 ± 0.37		+0.745	1	
VBF + VH + H → 4ℓ	δc_z	$-0.25^{+0.27}_{-0.07}$	$0.00^{+0.10}_{-0.28}$	1			
	c_{zz}	$0.03^{+0.10}_{-0.10}$	$0.00^{+0.22}_{-0.16}$	+0.144	1		
	$c_{z\Box}$	$-0.03^{+0.04}_{-0.04}$	$0.00^{+0.06}_{-0.09}$	−0.186	−0.847	1	
	$\tilde{c}_{zz}$	$-0.11^{+0.30}_{-0.31}$	$0.00^{+0.63}_{-0.63}$	+0.077	−0.016	+0.009	1

Higgs boson CP studies in ttH, H→γγ channel

CMS: $|f_{CP}^{Htt}| < 0.67$ @95 % CL, pure CP-odd excluded at 3.2σ

Phys. Rev. Lett. 125, 061801 (2020)





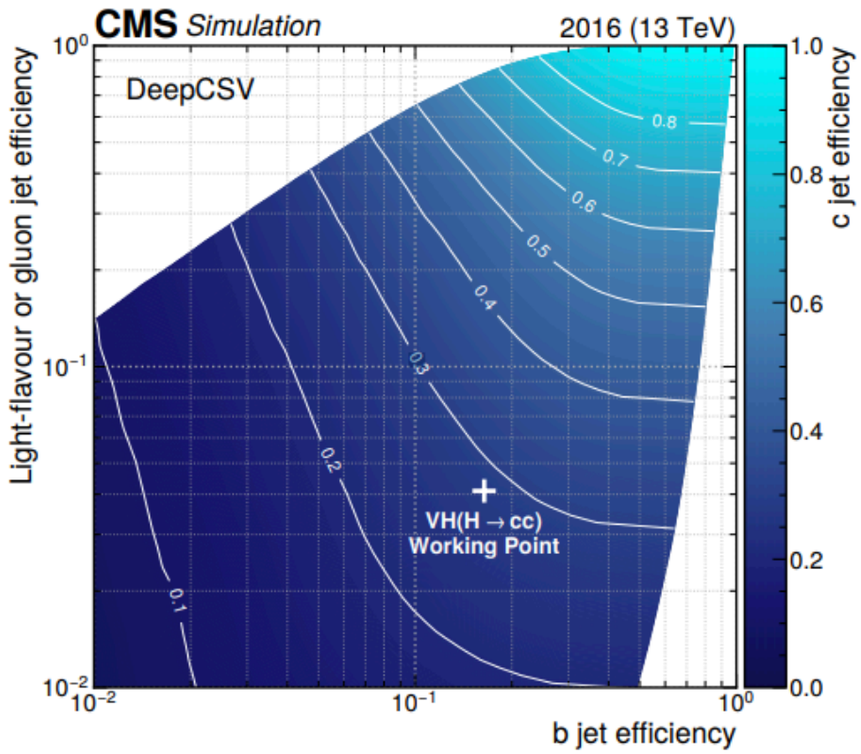
Higgs boson couplings to second generation fermions: H→cc

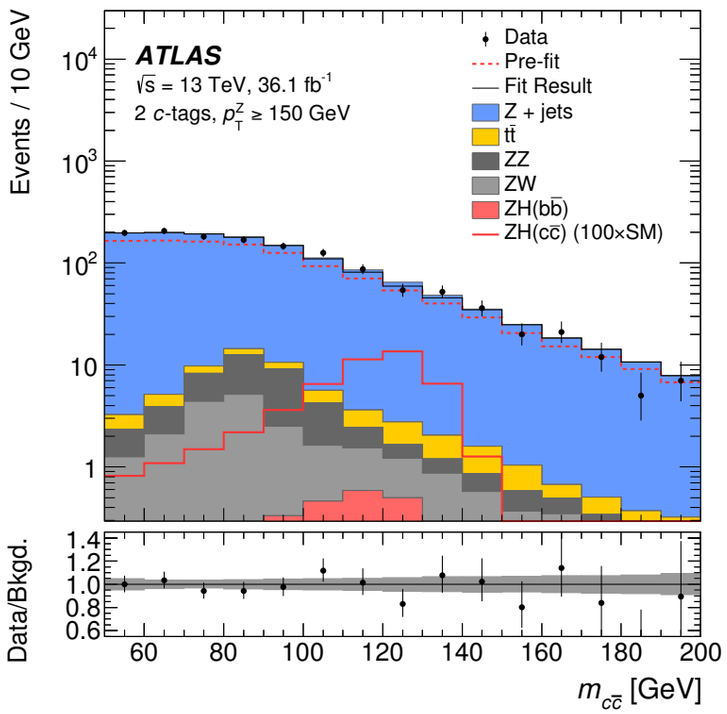
- Charm tagging is critical
- CMS results using 2016 data (JHEP 03 (2020) 131):
  - observed (expected) 95% CL upper limit on cross section

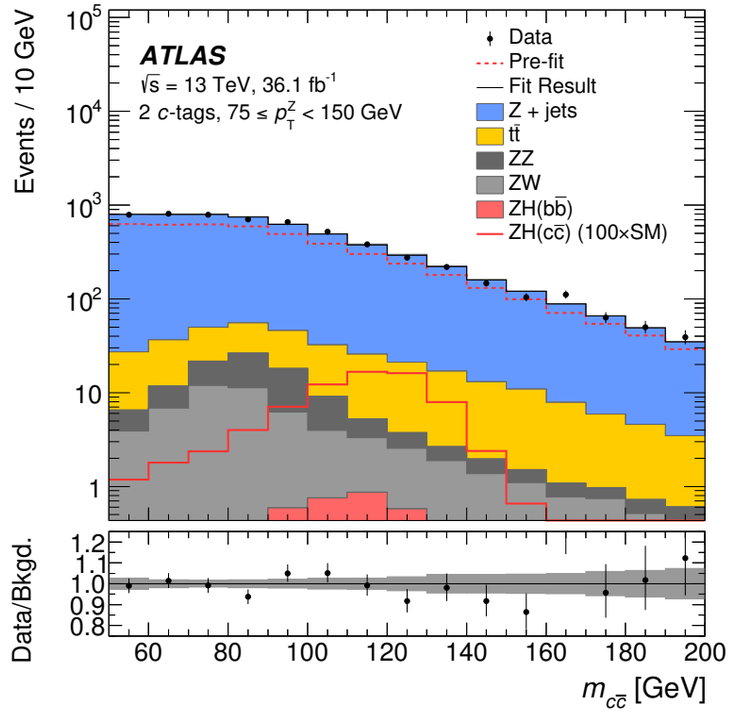
    VH(cc): 70(37) × SM
- ATLAS results using 2015+16 data (Phys. Rev. Lett. 120 (2018) 211802)
  - observed (expected) 95% CL upper limit on cross section

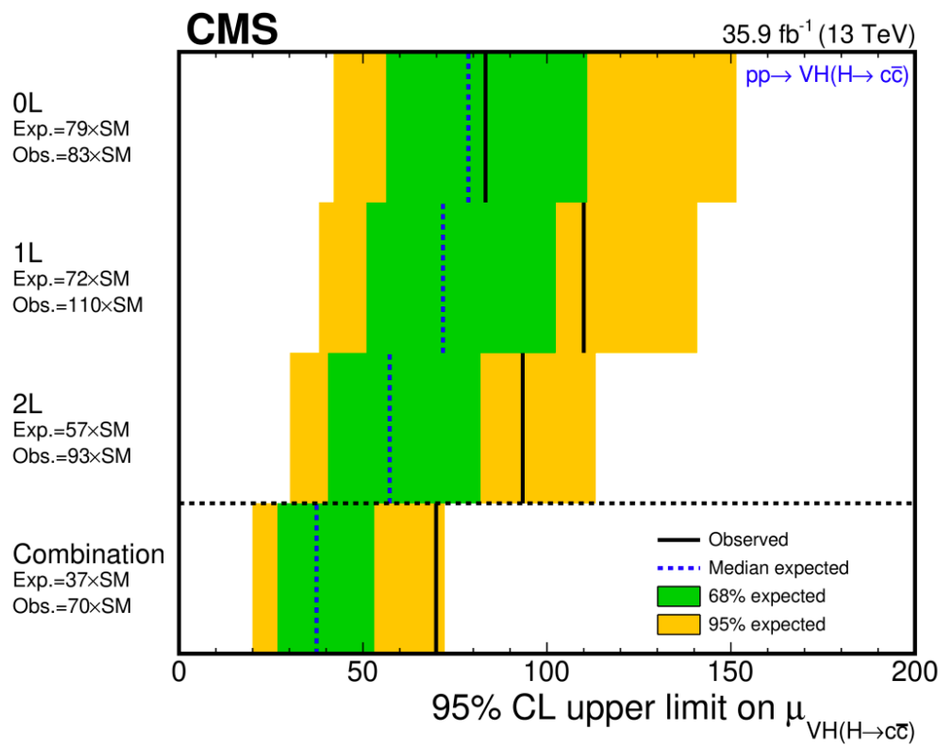
    ZH(cc): 104(150) × SM

resolved jets pT > 20 GeV







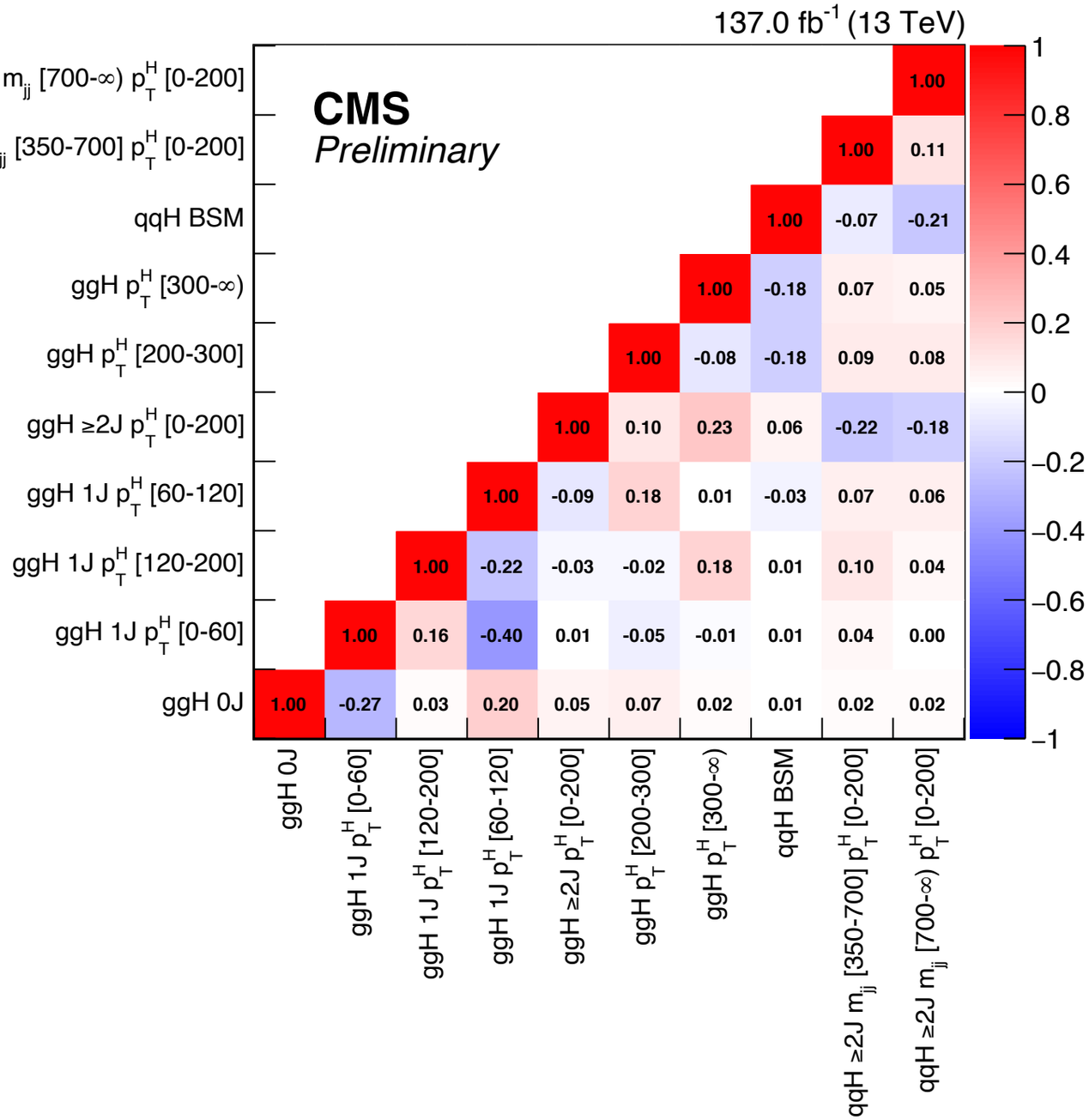


Simplified template cross section measurements — H→$\tau\tau$ decay channel

CMS-PAS-HIG-19-010

Channel	Trigger requirement	Minimal lepton selection		
		p_T (GeV)	η	Isolation
$\tau_h\tau_h$	τ_h[35] & τ_h[35] (2016) τ_h[40] & τ_h[40] (2017, 2018)	$p_T^{\tau_h} > 40$	$\lvert\eta^{\tau_h}\rvert < 2.1$	DNN τ_h ID
$\mu\tau_h$	μ[22] (2016) μ[19] & τ_h[21] (2016) μ[24] (2017, 2018) μ[20] & τ_h[27] (2017, 2018)	$p_T^{\mu} > 20$ $p_T^{\tau_h} > 30$	$\lvert\eta^{\mu}\rvert < 2.1$ $\lvert\eta^{\tau_h}\rvert < 2.3$	$I^{\mu} < 0.15$ DNN τ_h ID
eτ_h	e[25] (2016) e[27] (2017) e[32] (2018) e[24] & τ_h[30] (2017, 2018)	$p_T^{e} > 25$ $p_T^{\tau_h} > 30$	$\lvert\eta^{e}\rvert < 2.1$ $\lvert\eta^{\tau_h}\rvert < 2.3$	$I^{e} < 0.15$ DNN τ_h ID
eμ	e[12] & μ[23] (all years) e[23] & μ[8] (all years)	$\min(p_T^{e}, p_T^{\mu}) > 15$ $\max(p_T^{e}, p_T^{\mu}) > 24$	$\lvert\eta^{e}\rvert < 2.4$ $\lvert\eta^{\mu}\rvert < 2.4$	$I^{e} < 0.15$ $I^{\mu} < 0.15$

Final state	Category	Selection	Observables
$\ell\tau_h$, eμ	0-jet	0 jet	$m_{\tau\tau}$, τ_h p_T ($\ell\tau_h$) $m_{\tau\tau}$ (eμ)
	VBF low p_T^H	$\geq$ 2 jets, $m_{jj} > 350$ GeV, $p_T^H < 200$ GeV	$m_{\tau\tau}$, m_{jj}
	VBF high p_T^H	$\geq$ 2 jets, $m_{jj} > 350$ GeV, $p_T^H > 200$ GeV	$m_{\tau\tau}$, m_{jj}
	Boosted 1 jet	1 jet	$m_{\tau\tau}$, p_T^H
	Boosted $\geq$ 2 jets	Not in VBF, $\geq$ 2 jets	$m_{\tau\tau}$, p_T^H
$\tau_h\tau_h$	0-jet	0 jet	$m_{\tau\tau}$
	VBF low p_T^H	$\geq$ 2 jets, $\Delta\eta_{jj} > 2.5$(2.0 for 2016), $100 < p_T^H < 200$ GeV	$m_{\tau\tau}$, m_{jj}
	VBF high p_T^H	$\geq$ 2 jets, $\Delta\eta_{jj} > 2.5$(2.0 for 2016), $p_T^H > 200$ GeV	$m_{\tau\tau}$, m_{jj}
	Boosted 1 jet	1 jet	$m_{\tau\tau}$, p_T^H
	Boosted $\geq$ 2 jets	Not in VBF, $\geq$ 2 jets	$m_{\tau\tau}$, p_T^H

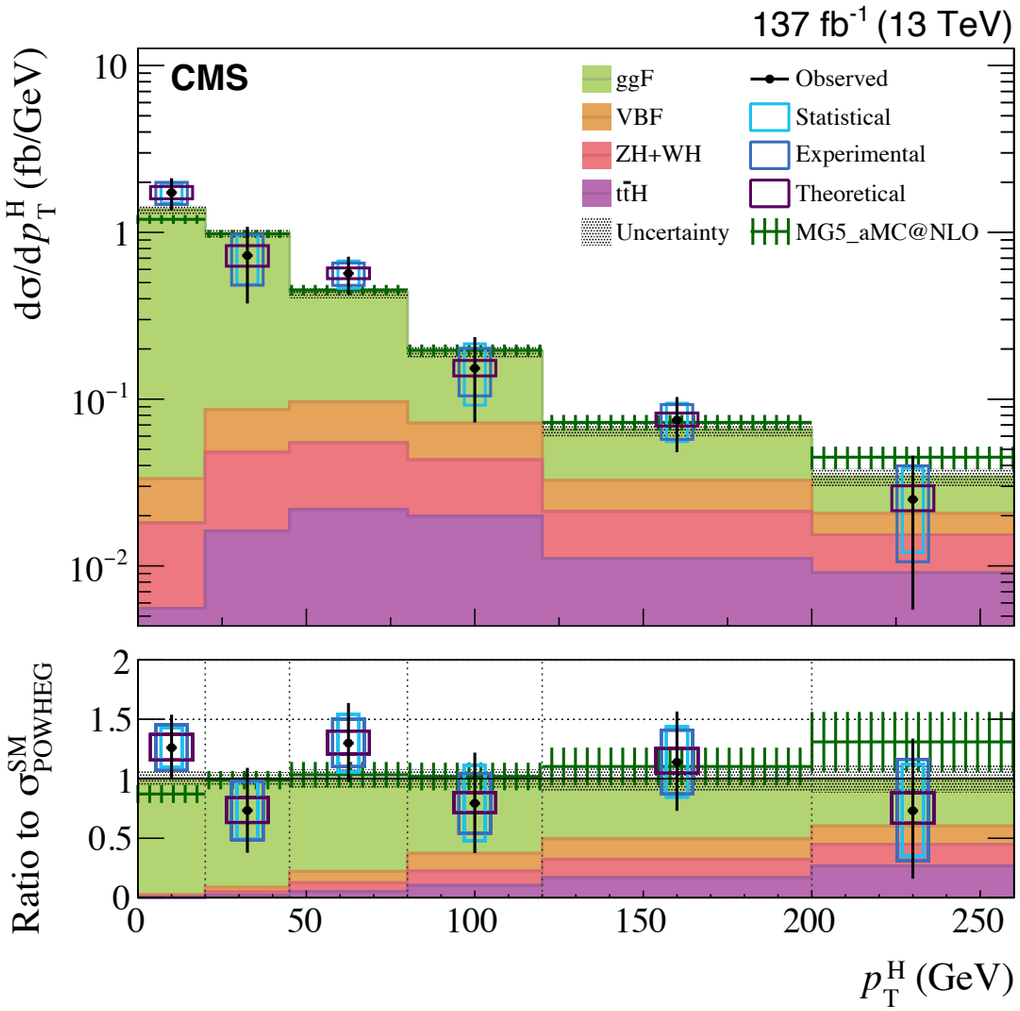


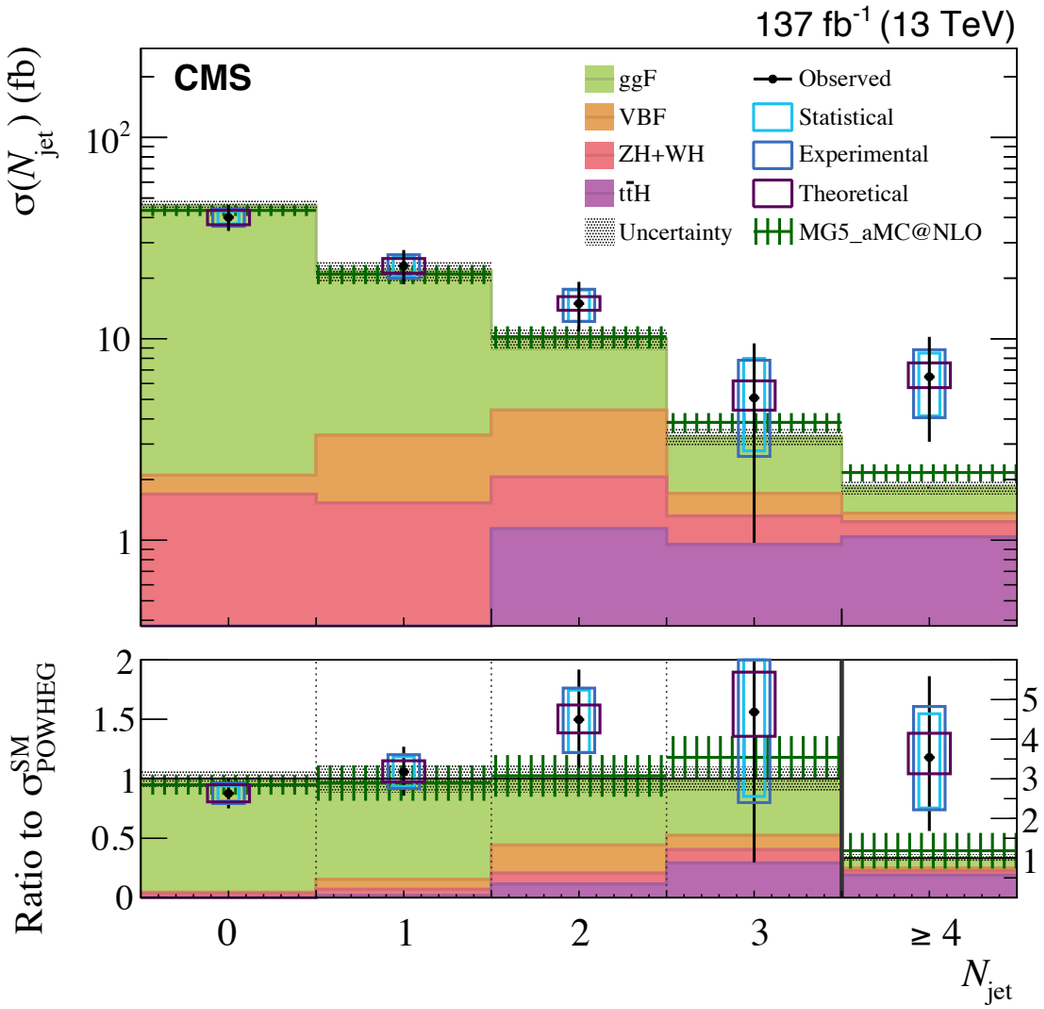
Higgs boson differential measurements

JHEP 03 (2021) 003

Measurements in WW→μevv decay channel using full Run 2 data

- large branching ratio makes this channel competitive with H→γγ and H→ZZ*→4l channels

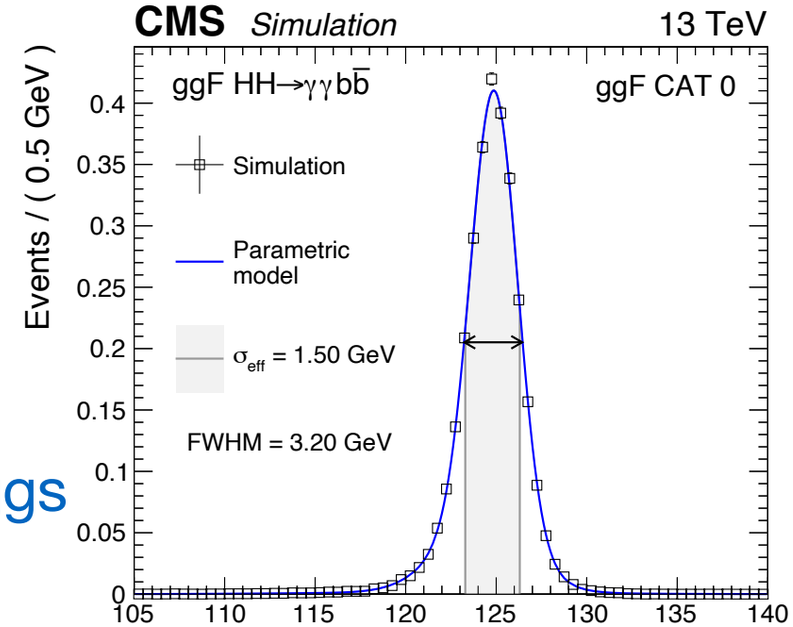




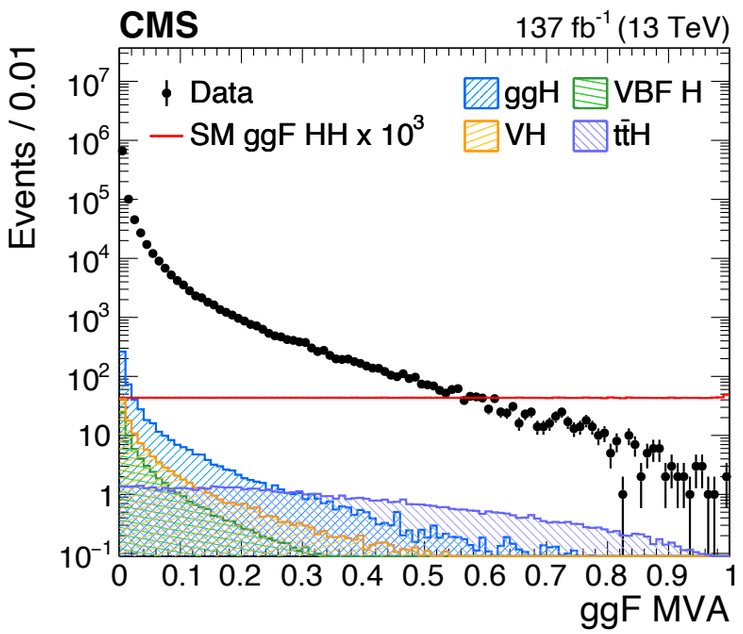
HH→bbγγ search full Run 2 data

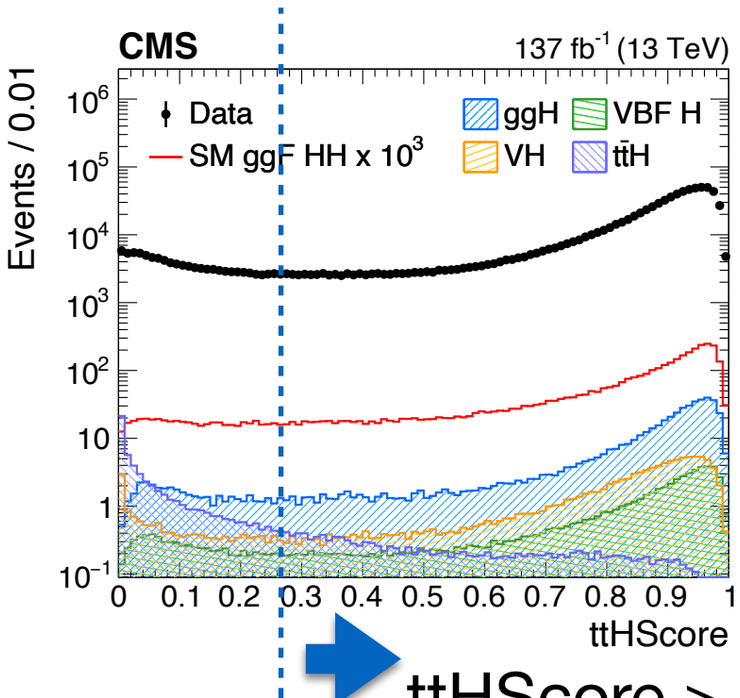
JHEP 03 (2021) 257

- Currently the most sensitive channel for HH search:
  - good resolution of $m_{\gamma\gamma}$
  - relatively low background rates
- Analysis strategy:
  - dedicated ttH classifier to reject ttH backgrounds
  - HH categories based on MVA classifier and mass of Higgs boson pair system: 12 ggF and 2 VBF categories

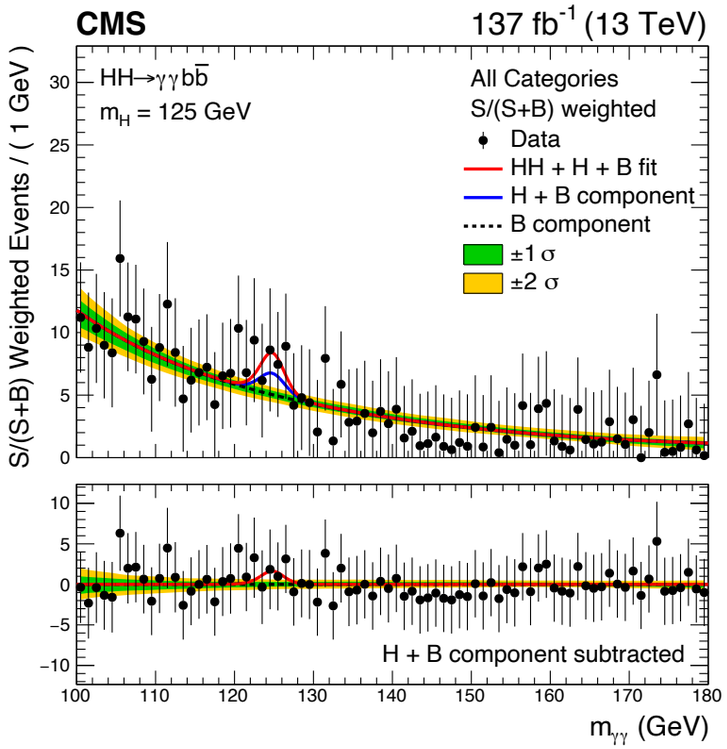


- ttH categories to constraint the top-Higgs coupling



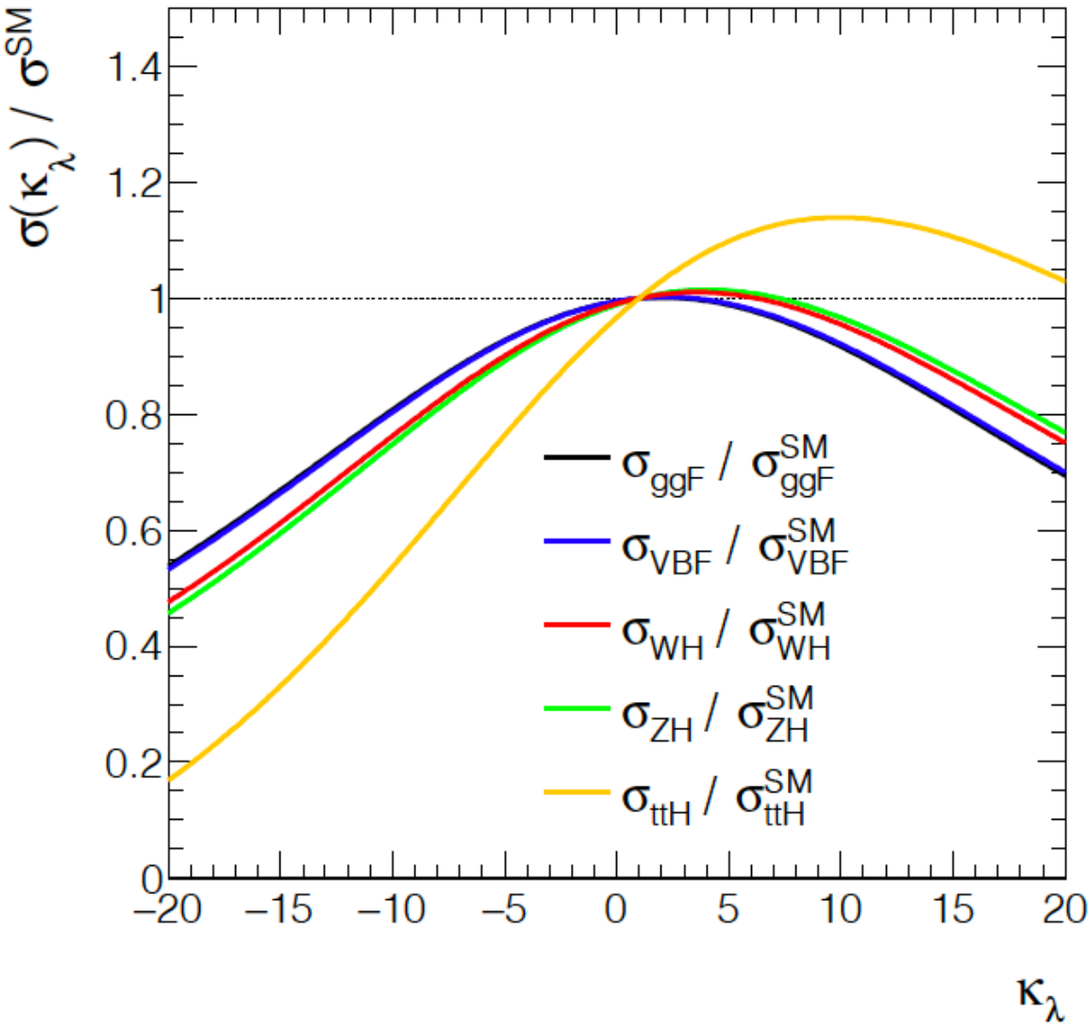


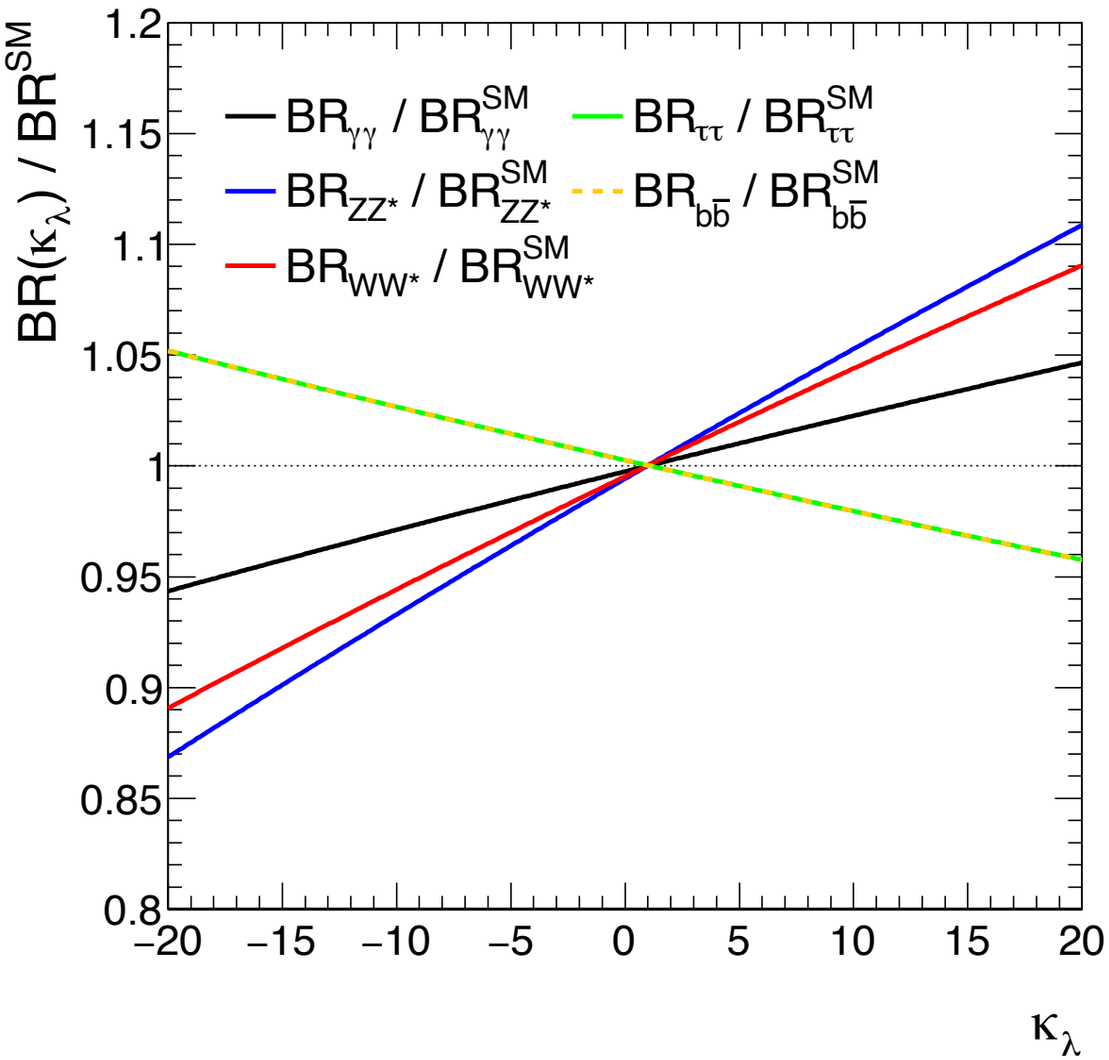
ttHScore > 0.26



Higgs boson self-coupling: constraint from single Higgs

Single Higgs boson production & decay rates, kinematics, are sensitive to the Higgs self-coupling λ_3 through EW corrections => can be used to indirectly constrain $\kappa_\lambda = \lambda_3/\lambda_3^{SM}$, assuming no other BSM effects





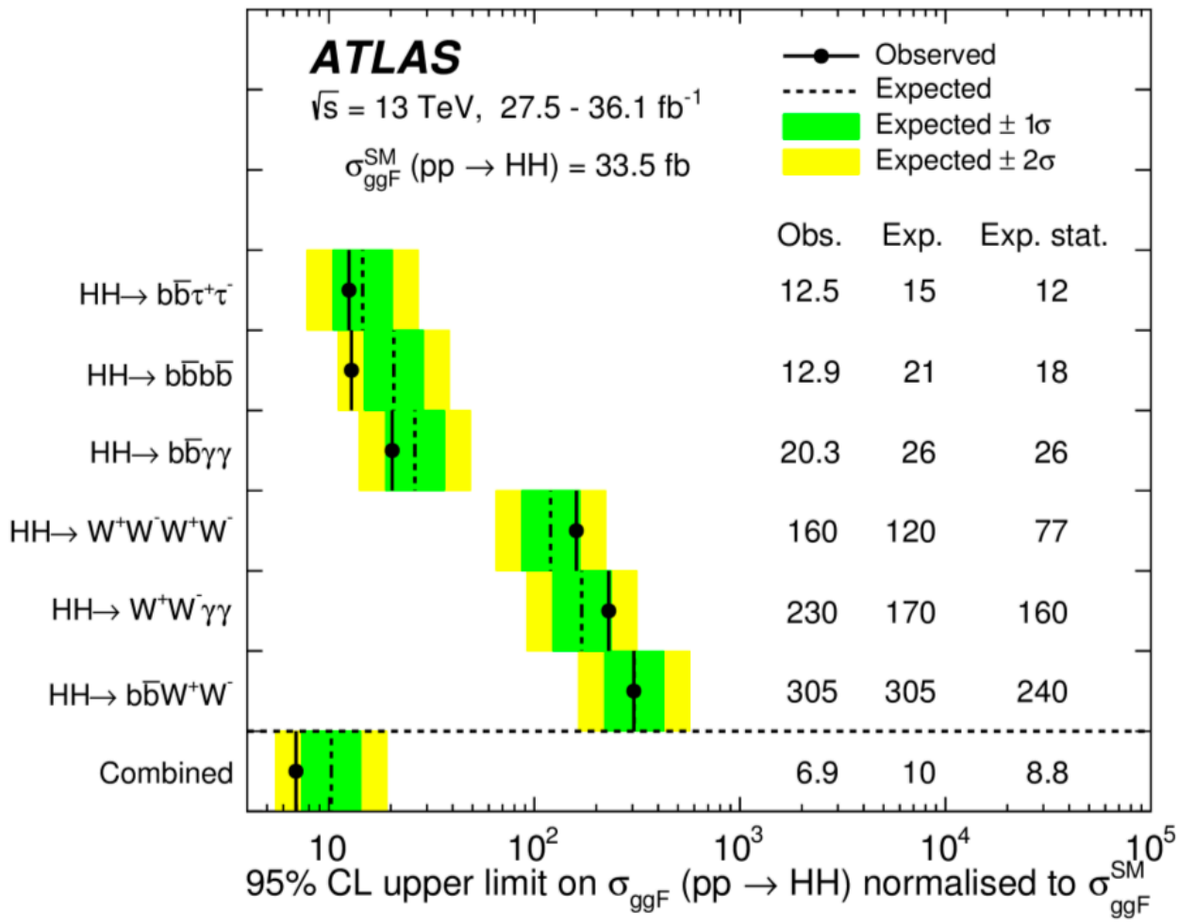
G. Degrassi et. al., JHEP 12 (2016) 080
F. Maltoni et. al., EPJC 77 (2017) 887

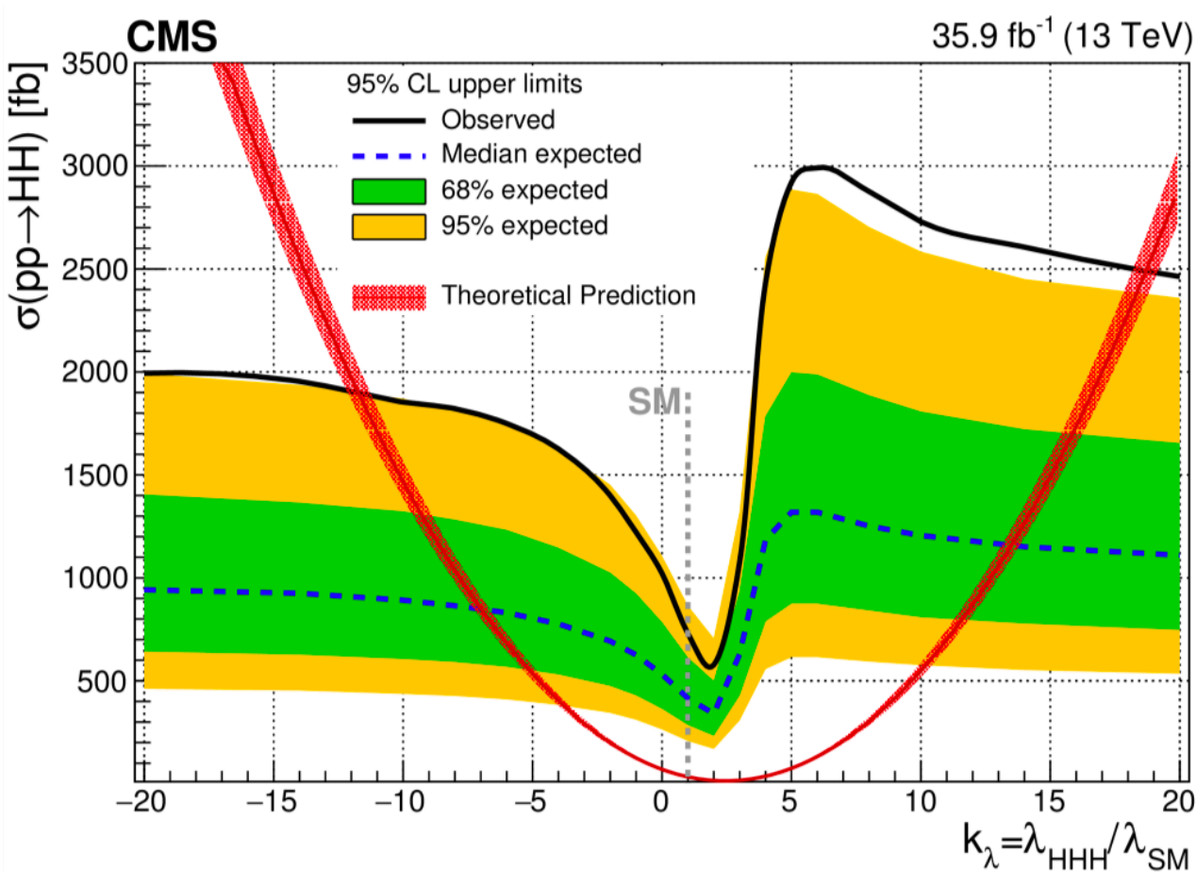
HH searches combination

$$\kappa_\lambda = \lambda_3/\lambda_3^{SM}$$

Upper limit $\sigma_{HH}/\sigma_{SM\ HH}$:
ATLAS < 6.9, CMS < 22.2 at 95% CL

k_λ: ATLAS [-5.0, 12.0],
CMS [-11.8, 18.8] at 95% CL





Phys. Lett. B 800 (2020) 135103

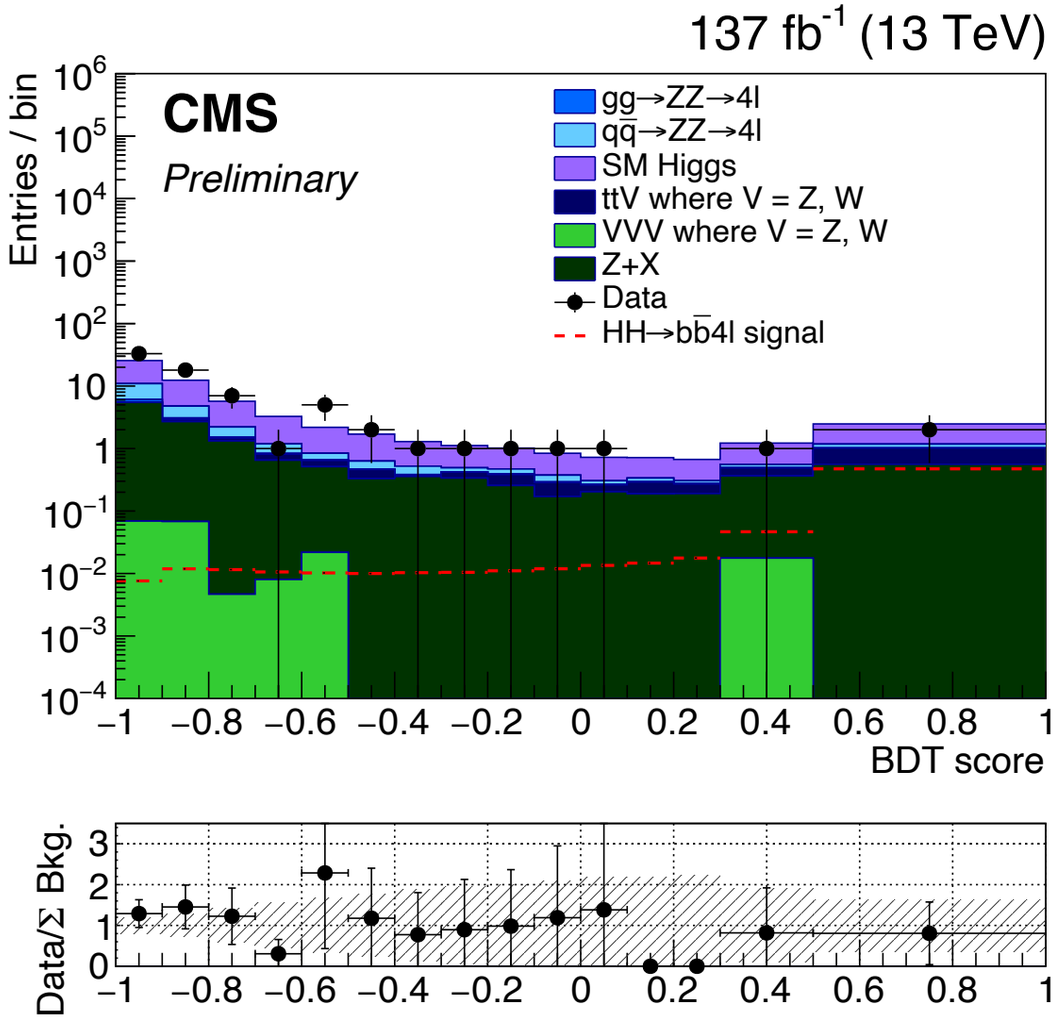
Phys. Rev. Lett. 122 (2019) 121803

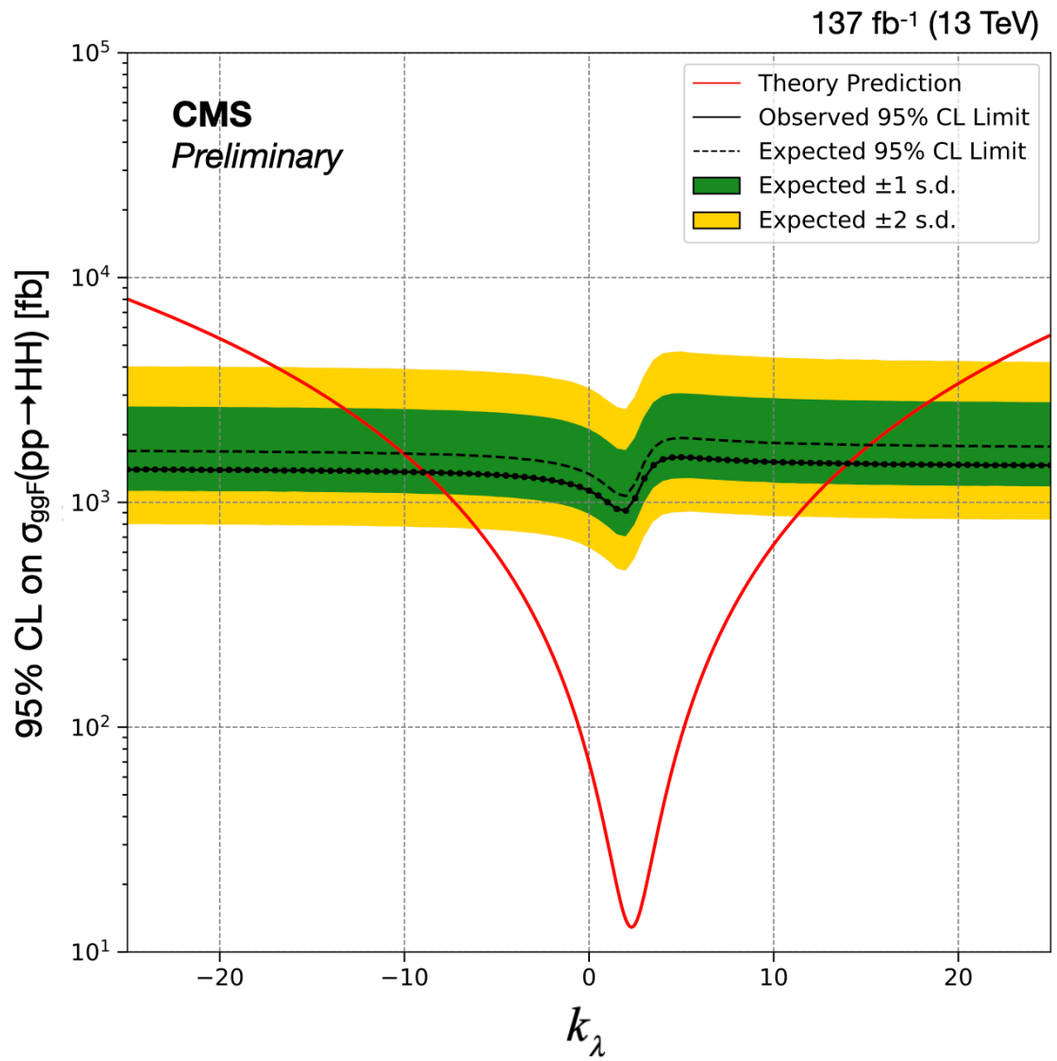
Recent Higgs boson self-coupling results using full Run 2 data

HH→ZZ*→4l:

- $-9(-10.5) < \kappa_\lambda < 14(15.5)$ obs (exp) @95% CL
- $\sigma(HH)/\sigma(HH_{SM}) < 30\ (37)$ obs (exp) @95% CL

CMS-PAS-HIG-20-004

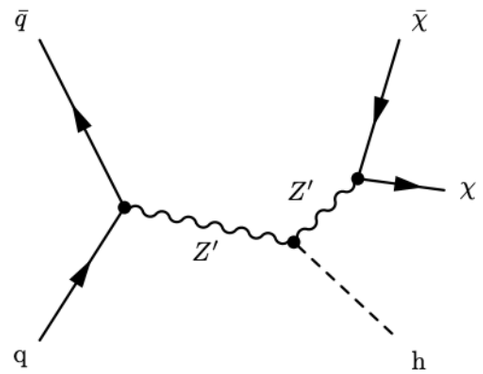




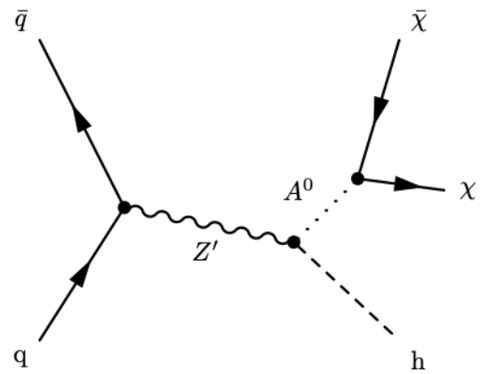
Search for dark matter in H(γγ)+MET events

- ATLAS-CONF-2020-054 full Run 2 data

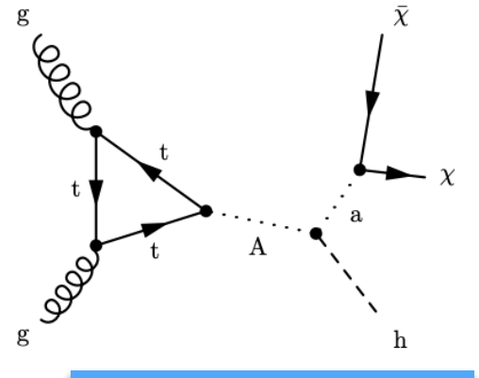
- Representative diagram of the production of dark matter (χ) in association with



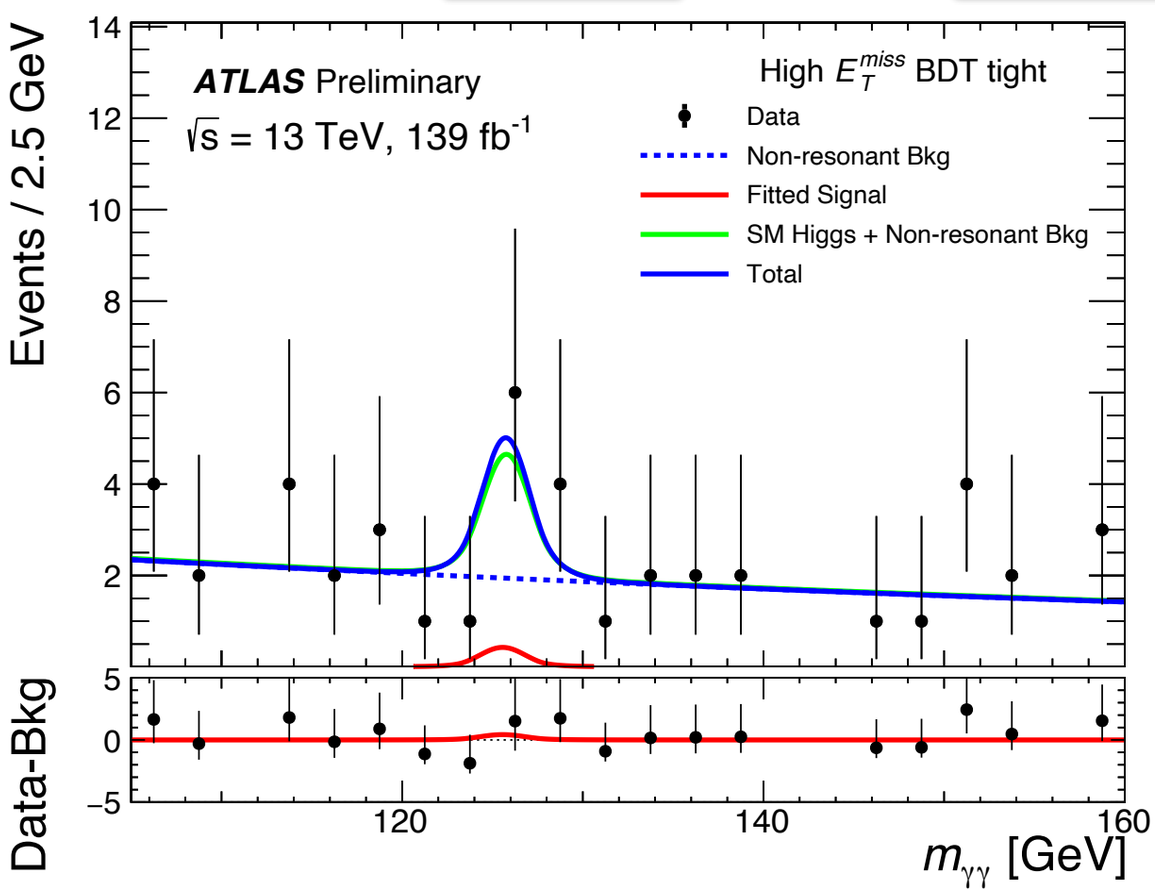
Z'_B model

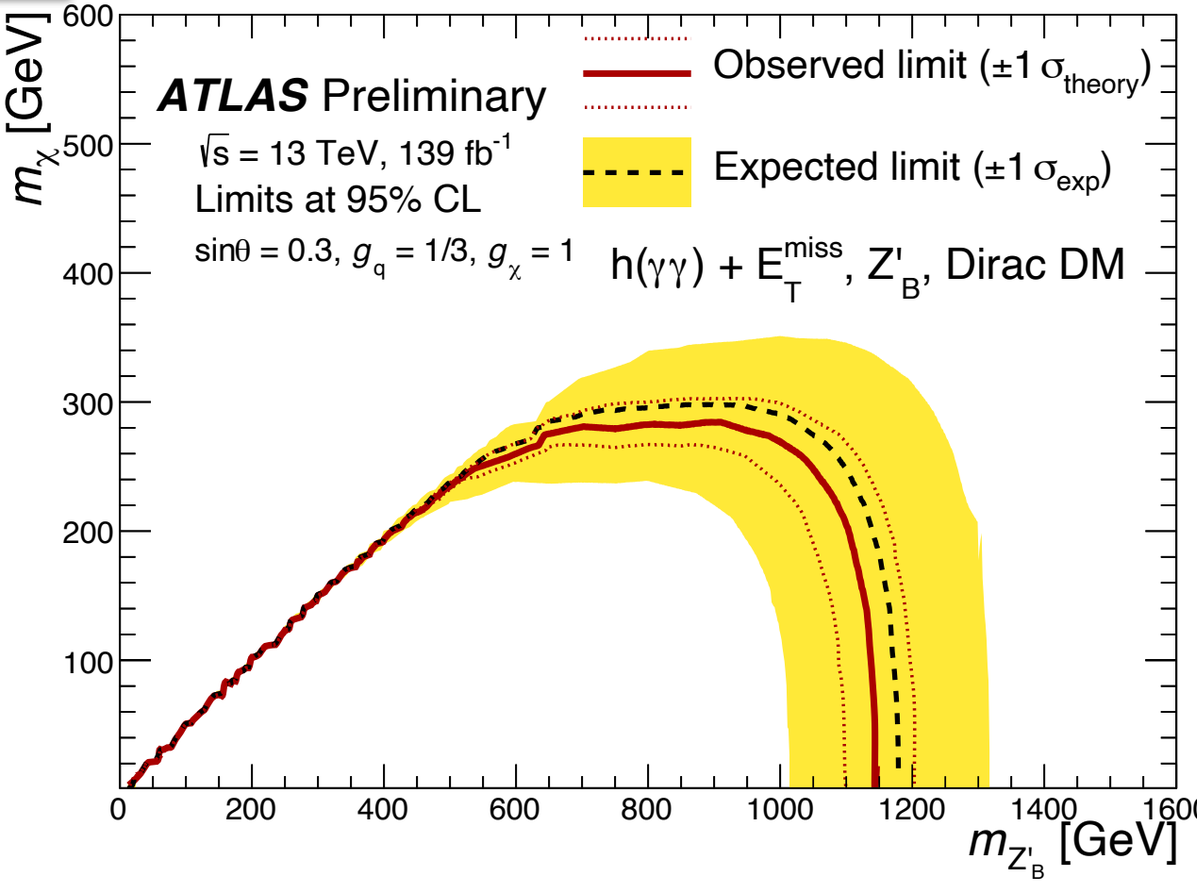


Z'- 2HDM model



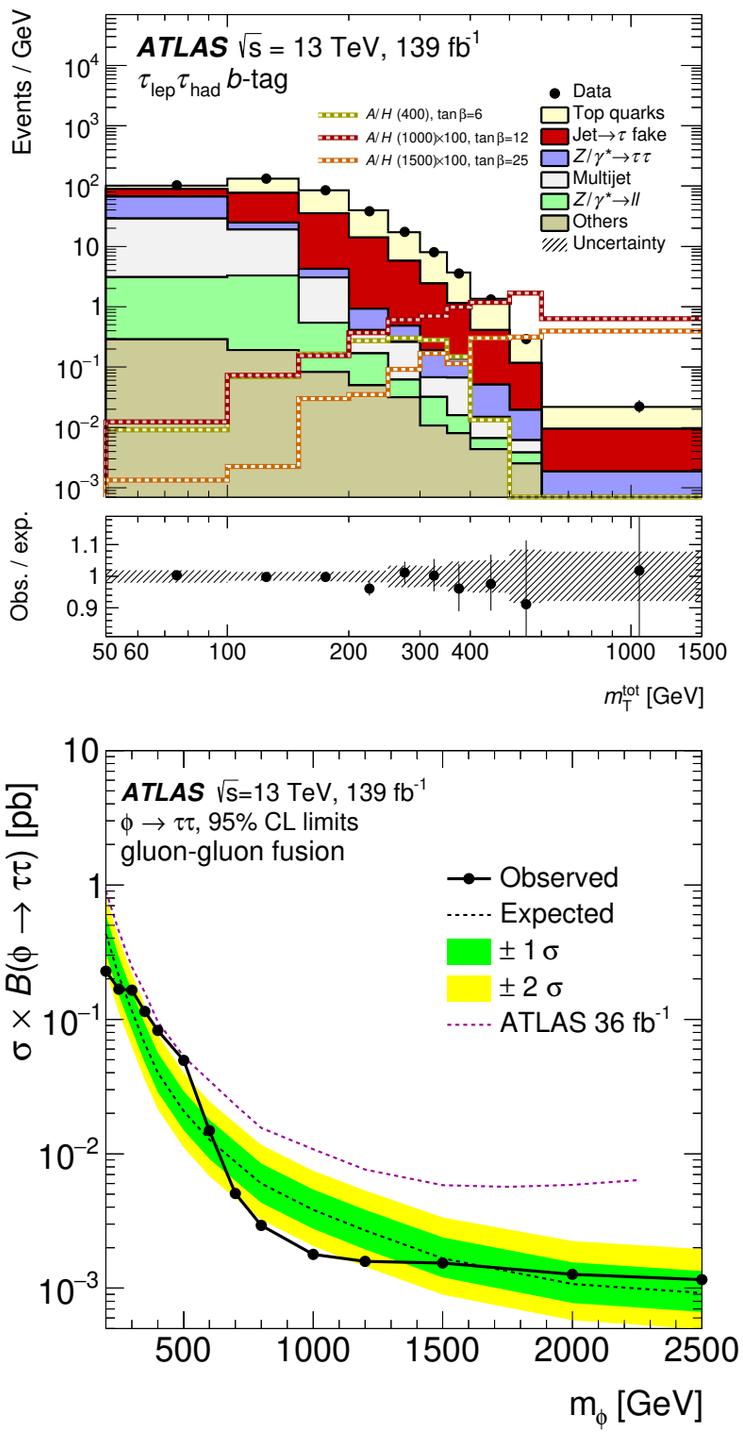
2HDM + a model

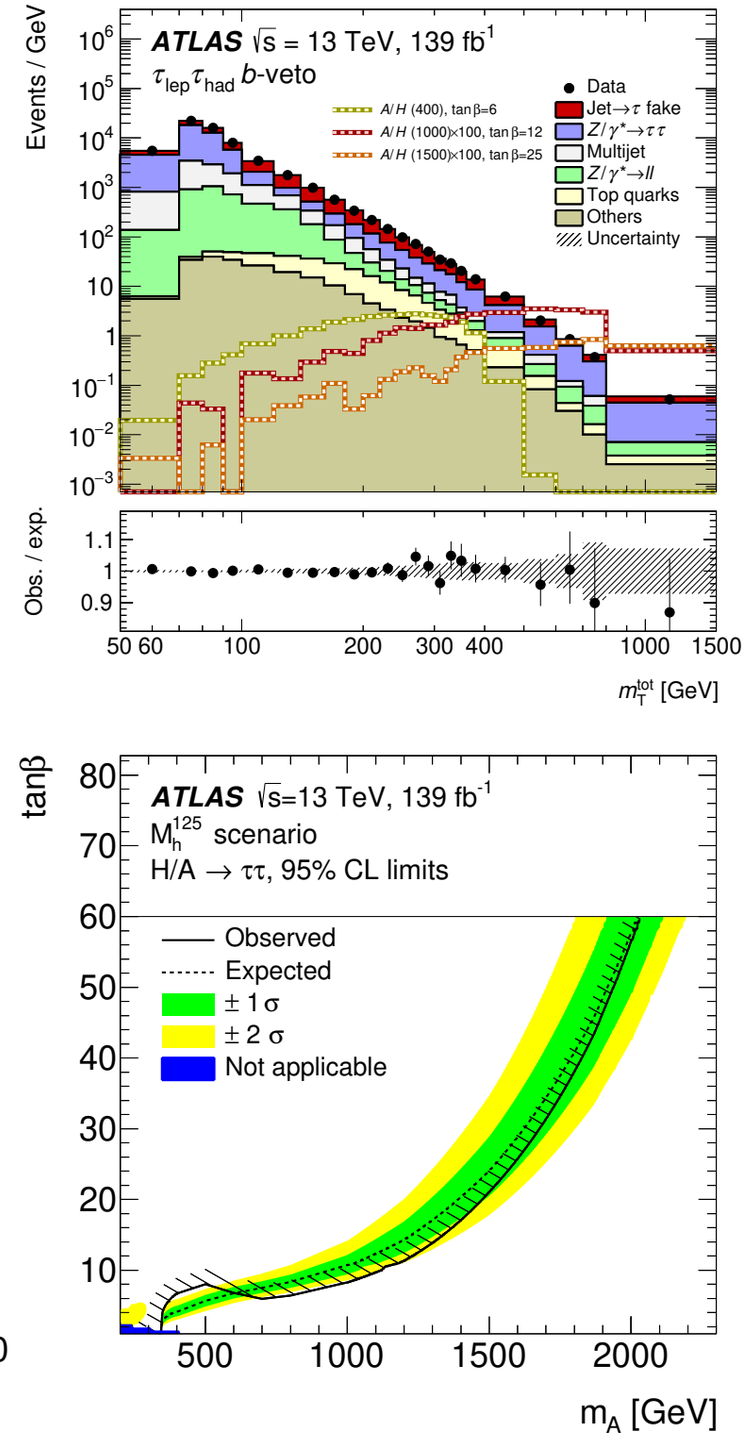




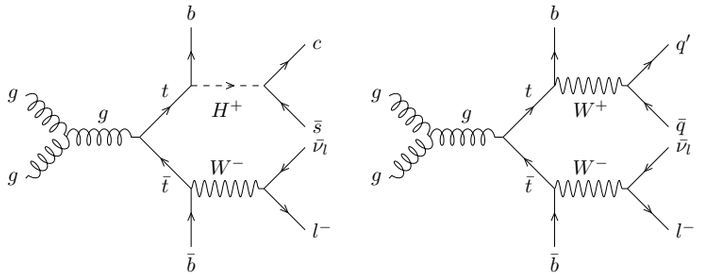
Search for BSM A/H→ττ

- Phys. Rev. Lett. 125 (2020) 051801 full Run 2 data

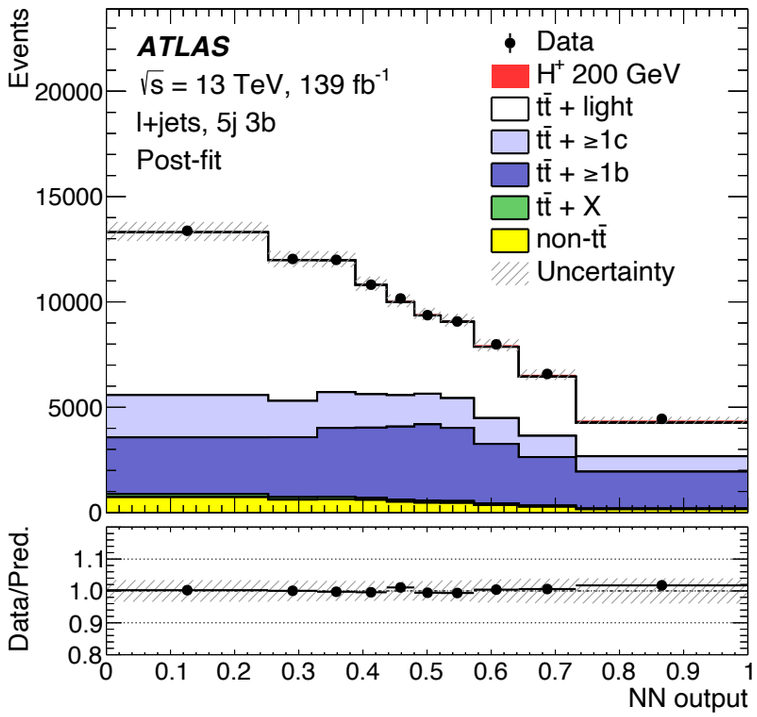


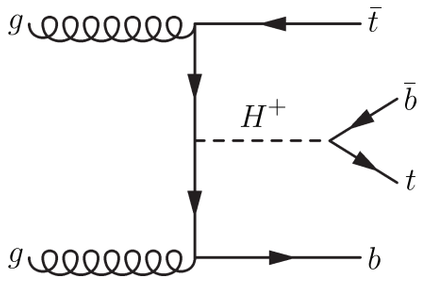


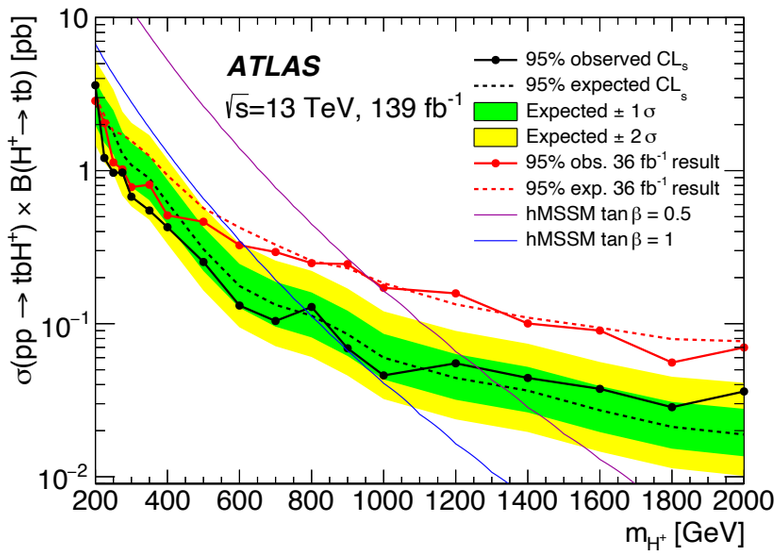
Search for Charged Higgs



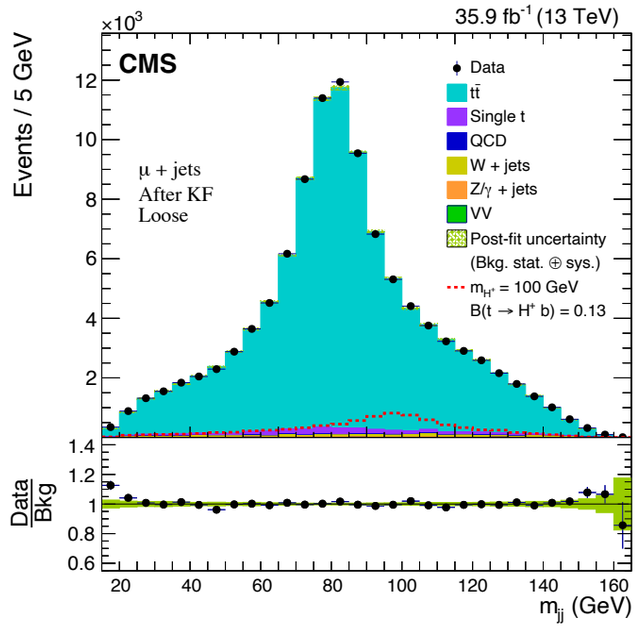
Search for production of a heavy charged Higgs boson in association with a top quark and a bottom quark, pp→tbH⁺→tbtb: HDBS-2018-51

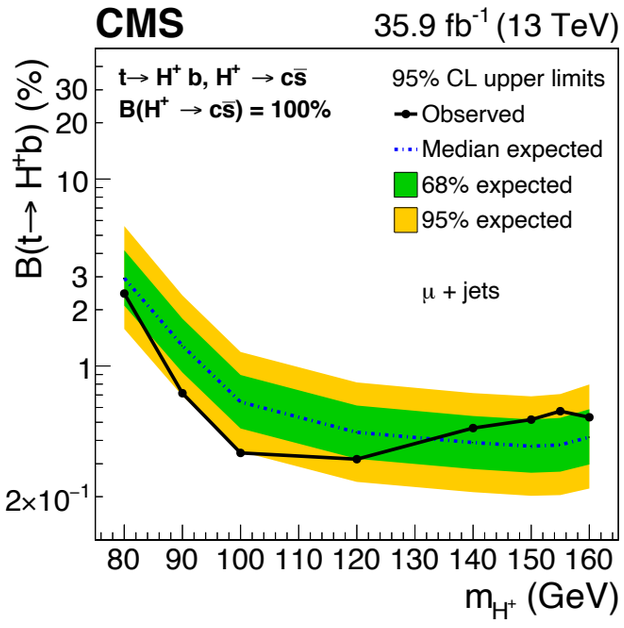






Search for a light charged Higgs boson in the H±→cs channel Phys. Rev. D 102 (2020) 072001





HH resonant searches

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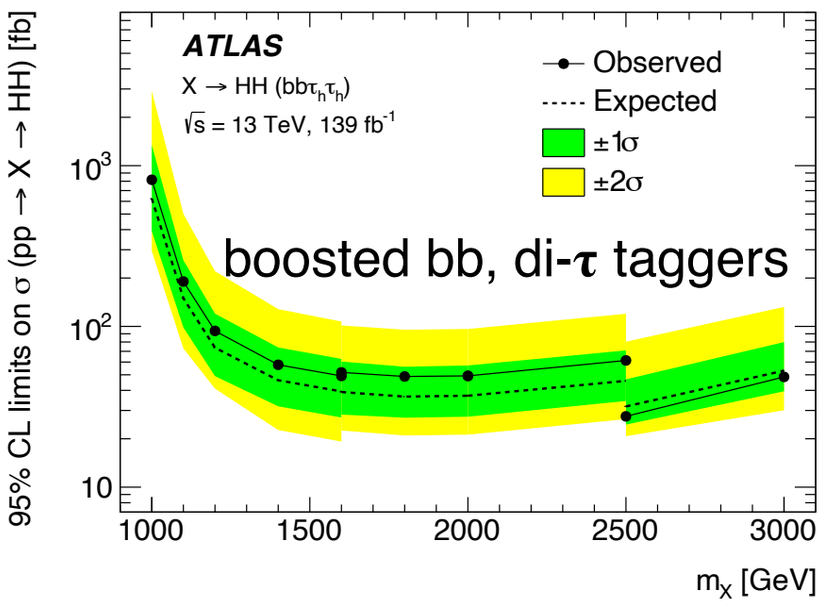
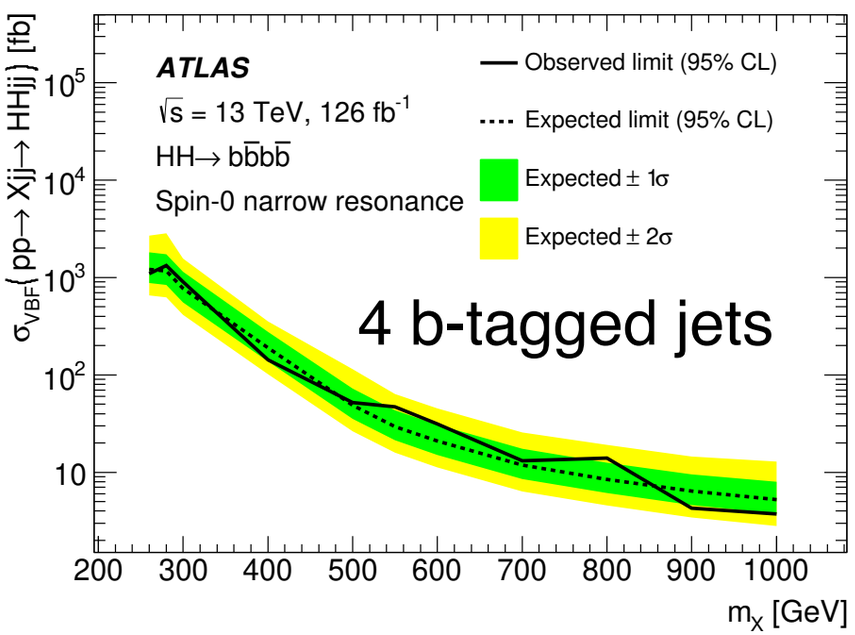
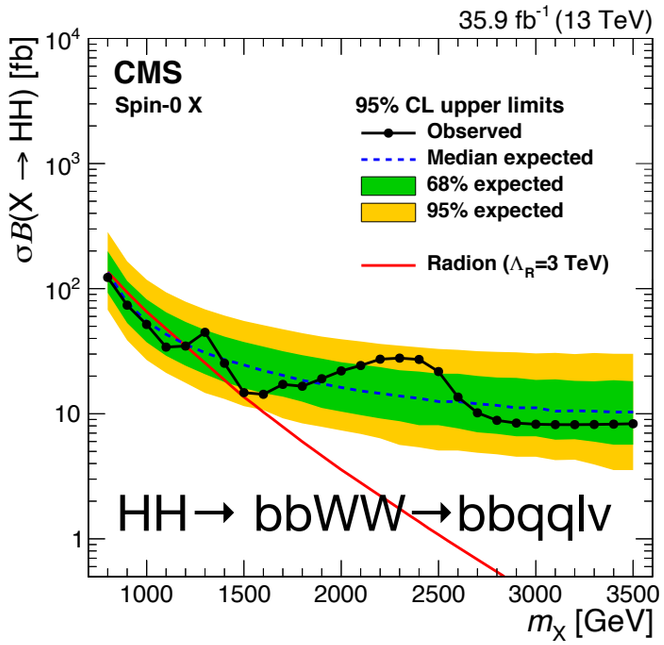


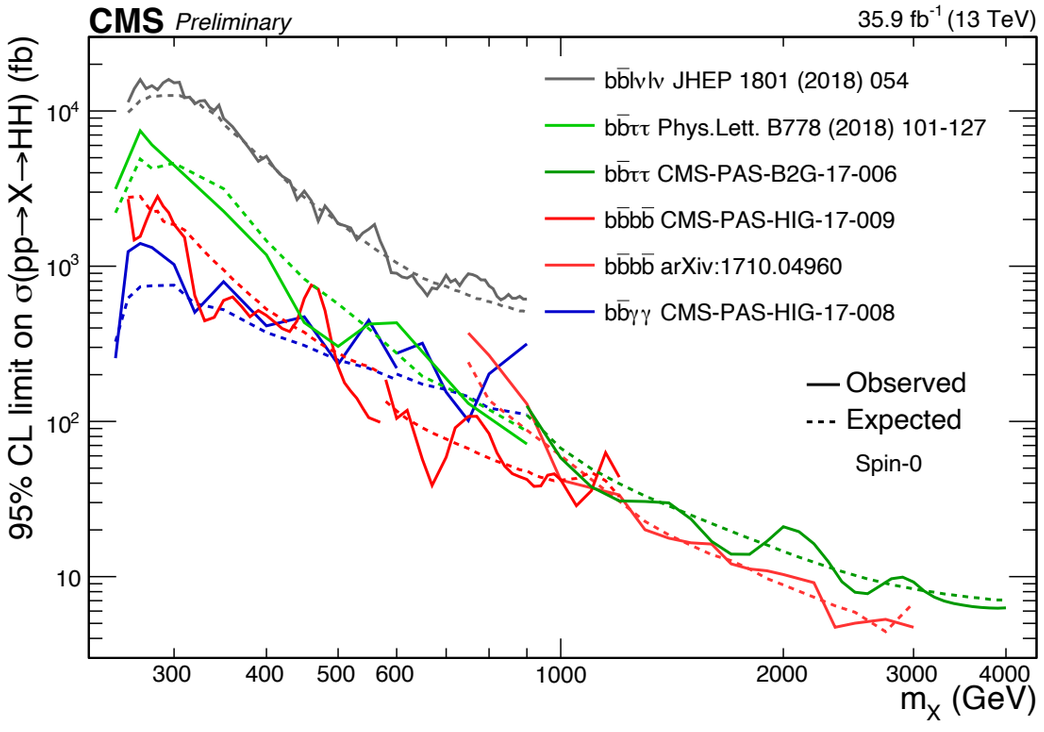
JHEP 07 (2020) 108



JHEP 03 (2021) 257



identify final state quarks as substructure within boosted jets



No significant excess observed:

- both ggF and VBF production modes being searched
- Lower mass range below 1 TeV: limit σ(X→HH) O(0.1 ~ 10 pb)
- bbbb and bb$\tau\tau$ more sensitive in higher mass range 1~4 TeV, limit σ(X→HH) O(10 fb)