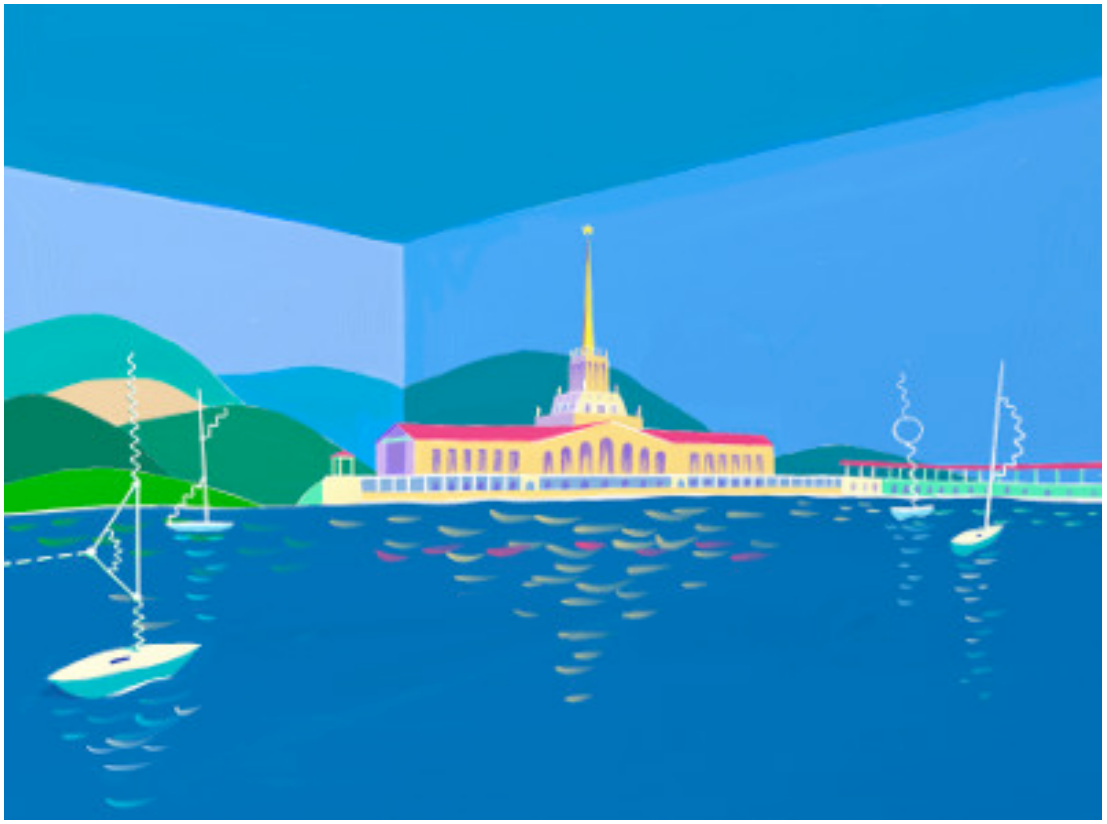
QFTHEP'2019: The XXIV International Workshop High Energy Physics and Quantum Field Theory

Higgs physics at CMS



Milos Dordevic

Vinca Institute of Nuclear Sciences,

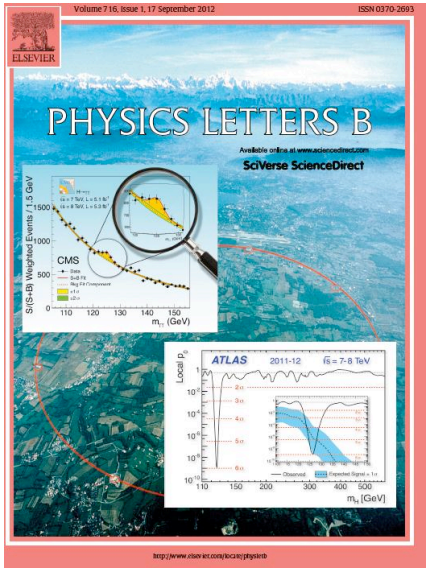
University of Belgrade

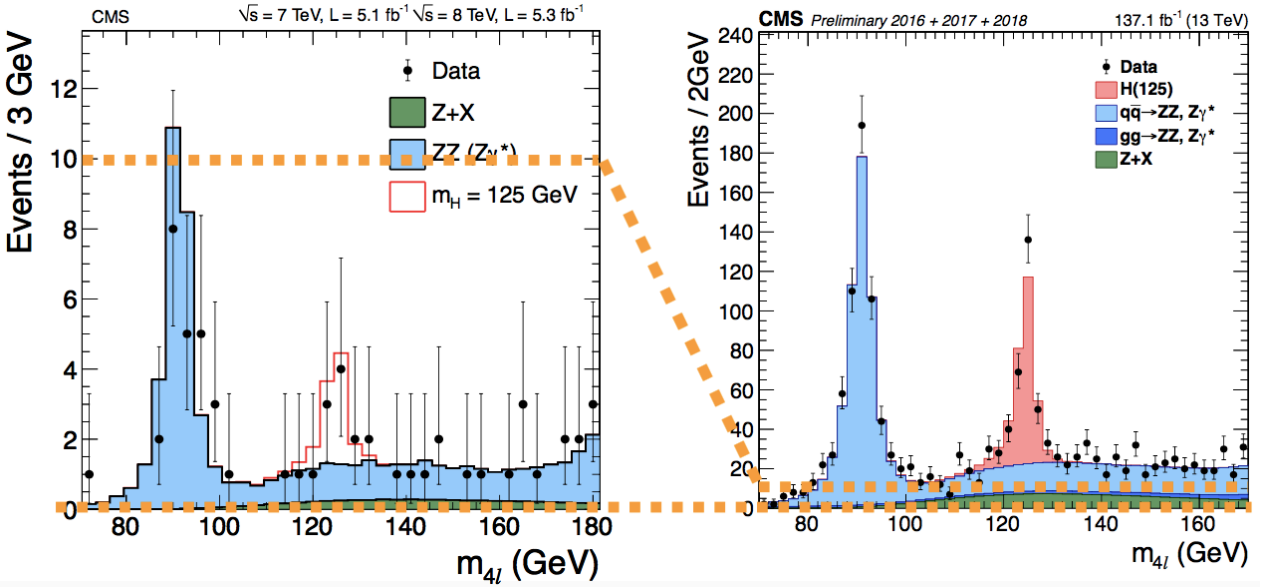
on behalf of the CMS Collaboration

22 Sep – 29 Sep 2019, Sochi, Russia

Overview of Higgs boson measurements at CMS

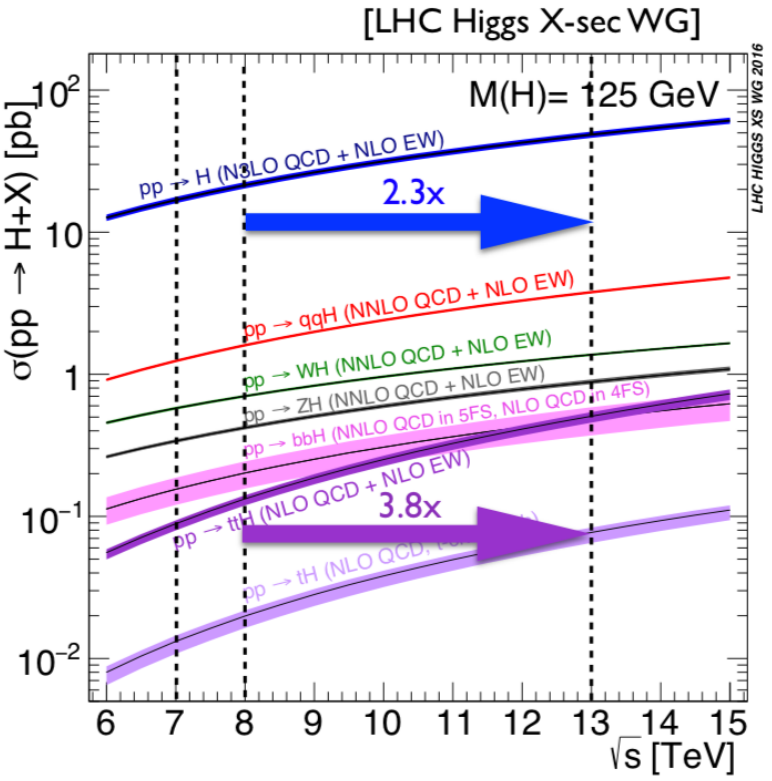
- Higgs boson discovered 7 years ago (ATLAS & CMS)
- The mass of the Higgs boson measured @~125 GeV
- Precise measurement of its properties are pursued:
  - spin-parity, width, boson and fermion couplings
- All measurements consistent with Standard Model



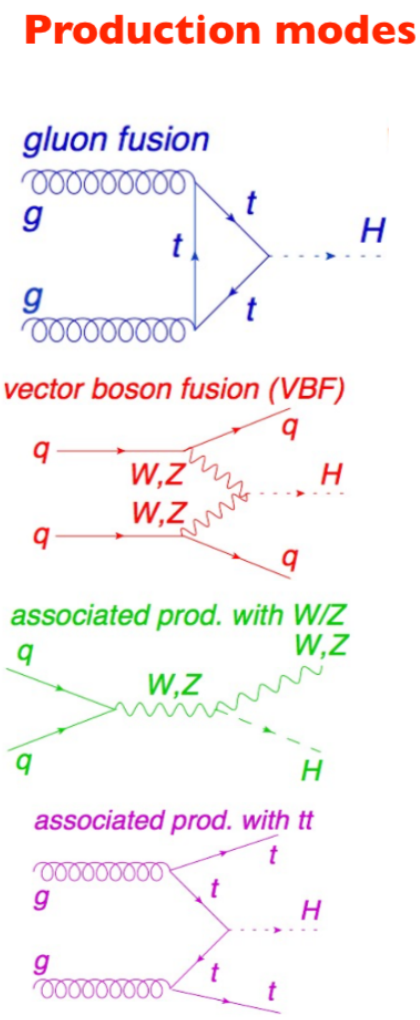


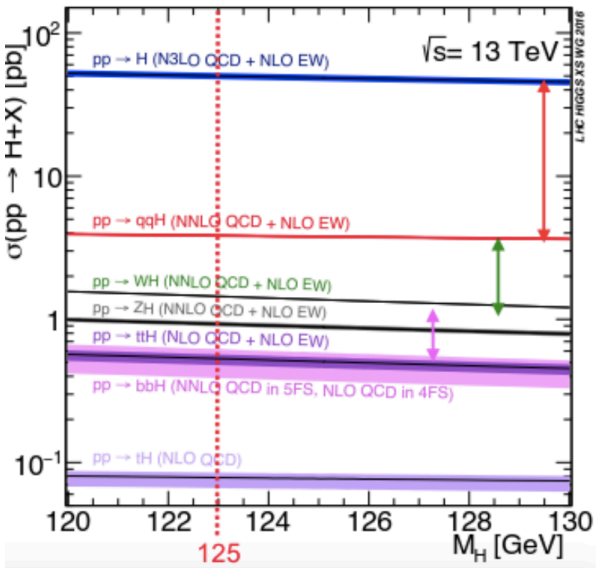
- From the discovery to precision in Run2
- Novel decay modes, anomalous coupling studies, differ. x-sec

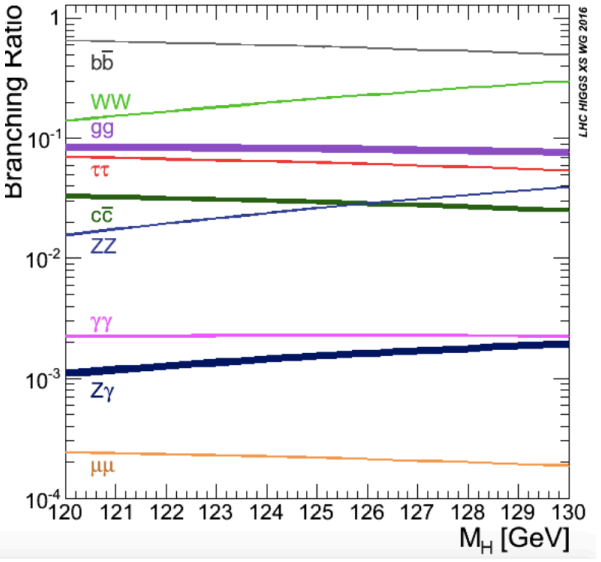
Standard Model Higgs production and decays



- Significant increase in production rate due to higher center-of-mass energy from LHC Run-1 to Run-2!



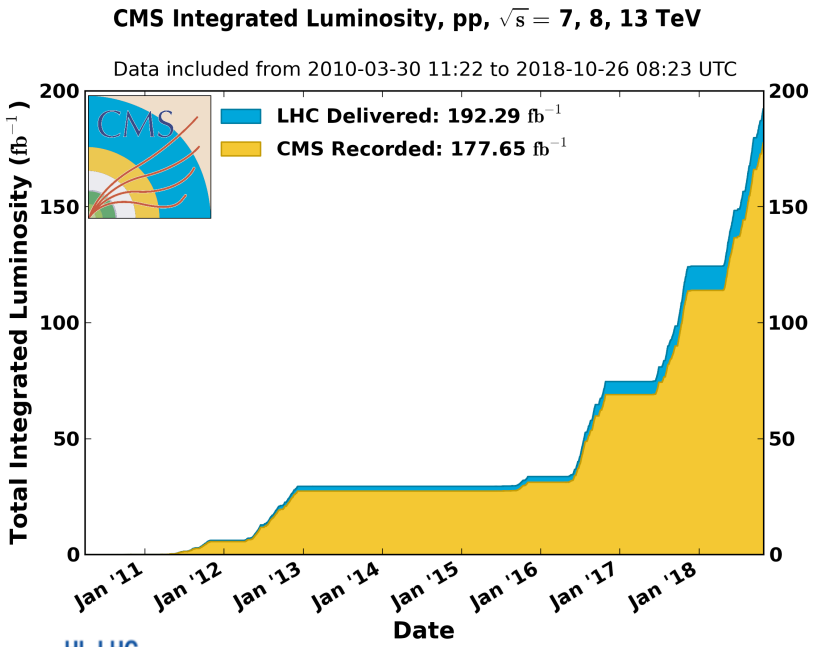


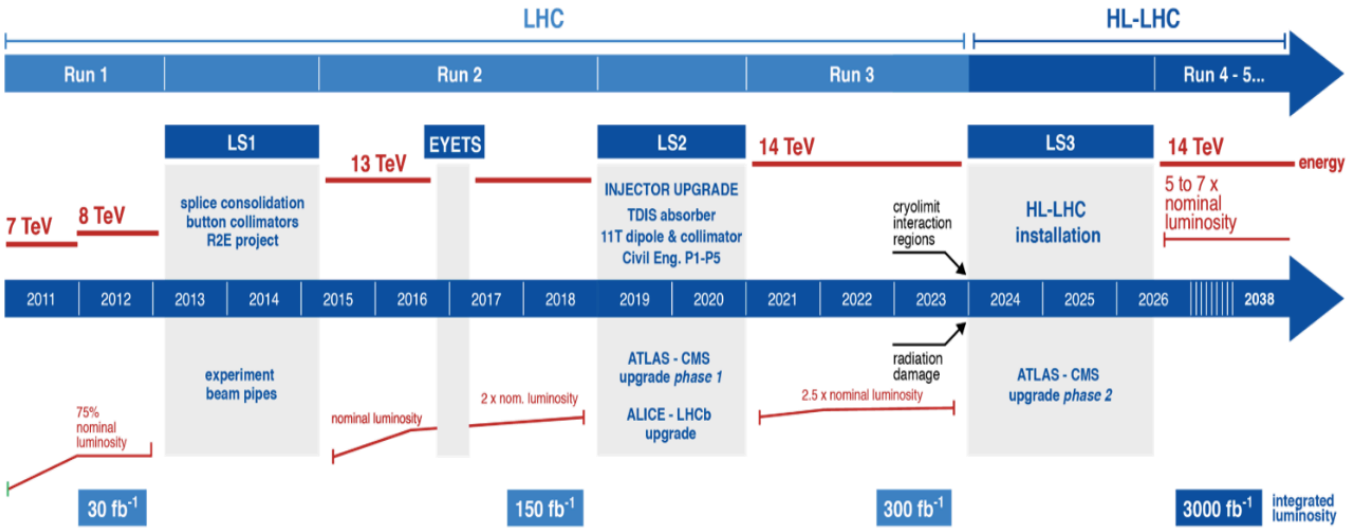


Giacinto Piacquadio - ICHEP 2018

The LHC data taking at 7, 8 and 13 TeV

- Data taking evolution presented -->
- The Run 2 gives a great opportunity to revisit Run 1 Higgs Legacy results
- From observation to precision; and from SM to BSM studies & searches



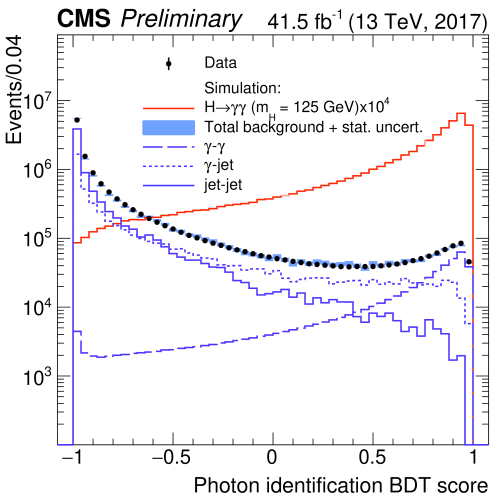


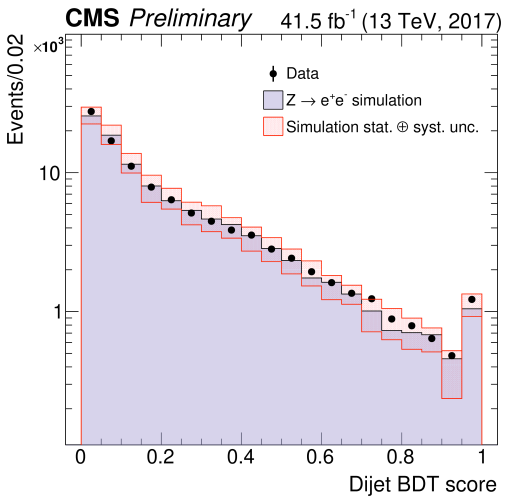
- Many analyses to be released exploiting full Run 2 dataset

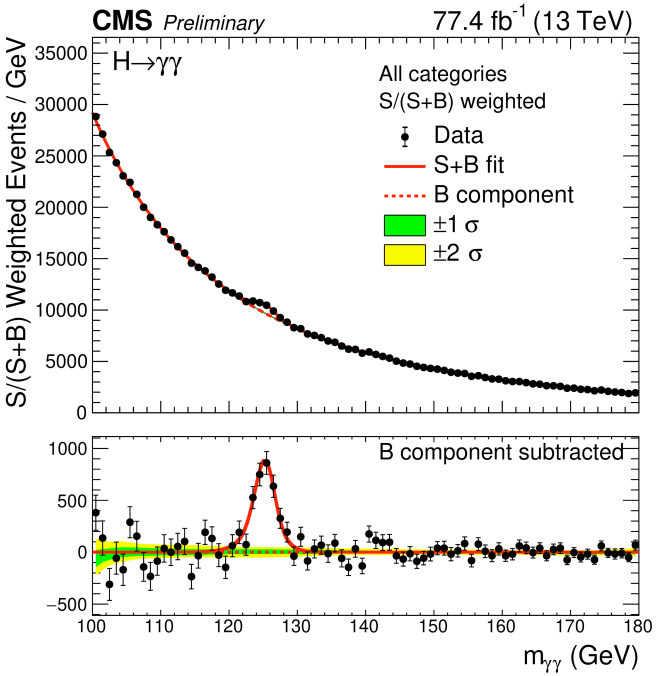
ggF and VBF Higgs to diphoton at 13 TeV

- Data collected in 2016 and 2017
- The simplified template cross section (STXS) stage framework minimize the theory dependence of the Higgs boson measurement
- ggF (VBF) with 11(5) Stage 1 bins

CMS PAS HIG-18-029







- Extensive usage of Boosted Decision Trees (BDTs): photon BDT, vertex ID BDT, vertex probability BDT, di-photon BDT and di-jet BDT (for categorizations)
- Signal plus background fit to all analysis categories, each weighted by ratio of number of S/S+B events

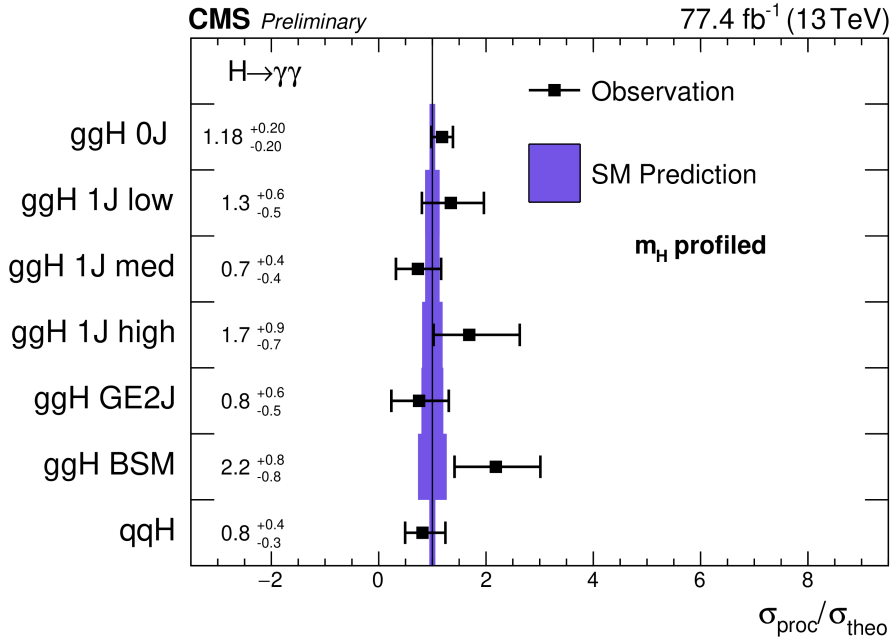
ggF and VBF Higgs to diphoton at 13 TeV

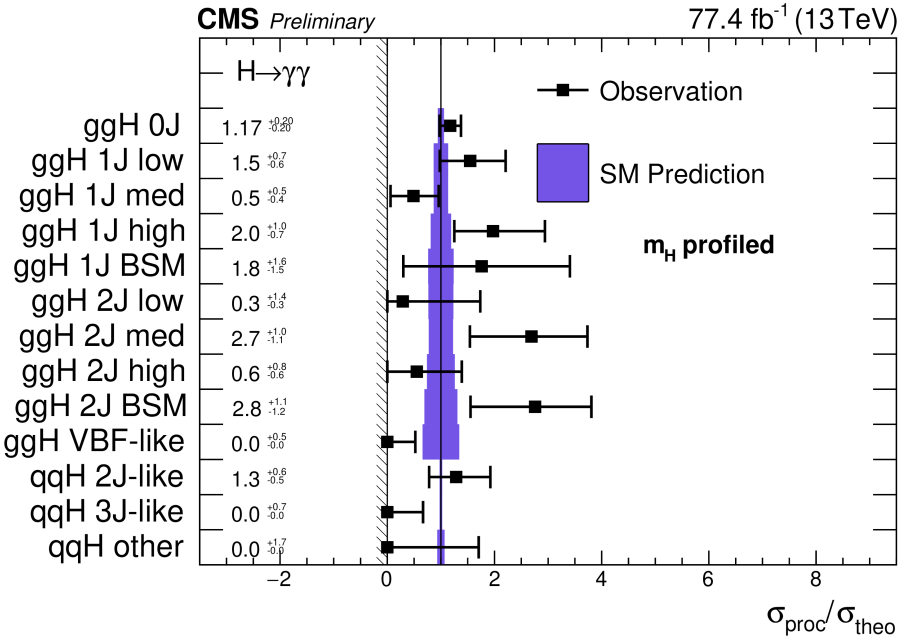
CMS PAS HIG-18-029

- Measured cross sections normalized to the corresponding SM prediction:

$$\sigma_{ggH}/\sigma^{SM}_{ggH} = 1.15^{+0.15}_{-0.15} \qquad \sigma_{qqH}/\sigma^{SM}_{qqH} = 0.8^{+0.4}_{-0.3}$$

- The results of a seven and thirteen-parameter fit in the STXS framework:

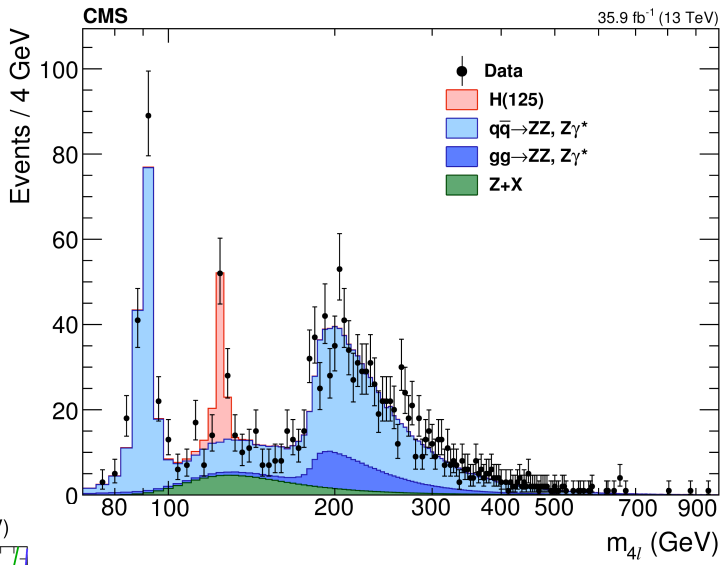


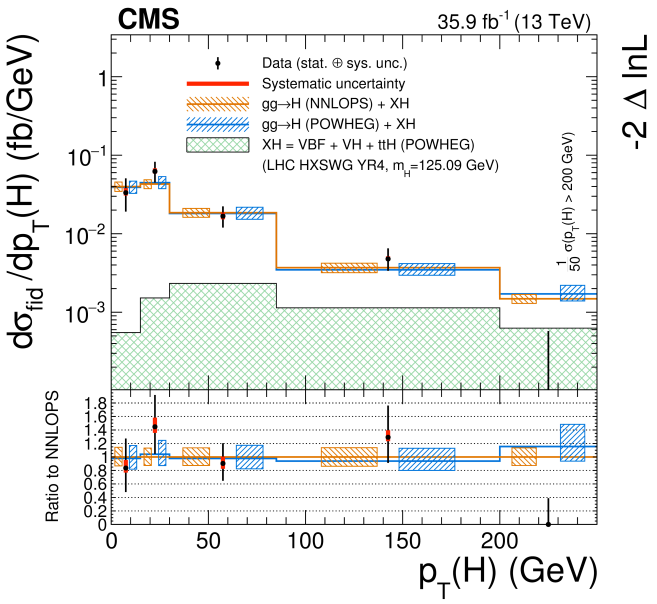


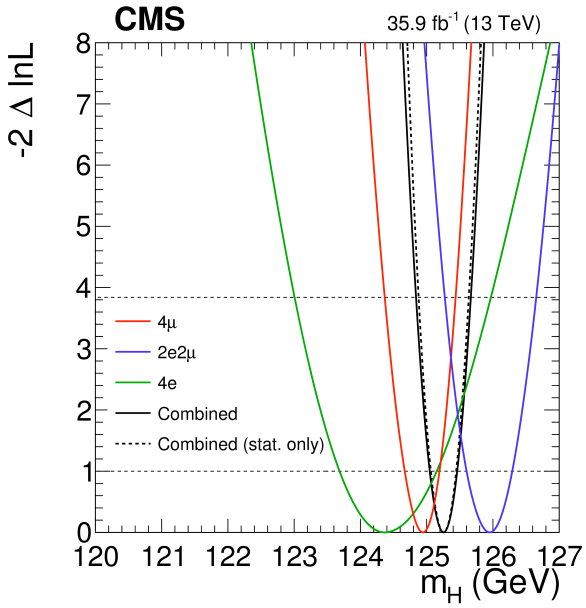
Higgs boson mass from H->ZZ->4l at 13 TeV

- The measurements of the Higgs boson properties (ZZ->4l) with the 2016 data
- Differential and fiducial cross sections, Higgs width from on-shell production
- Matrix element discriminants (D^{kin}_{bkg})

JHEP 11 (2017) 047







- Three-dimensional fit:

$$3\mathrm{D}\ \mathcal{L}(m'_{4\ell}, \mathcal{D}'_{\mathrm{mass}}, \mathcal{D}^{\mathrm{kin}}_{\mathrm{bkg}})$$

- H mass measurement:

$$m_{\mathrm{H}} = 125.26 \pm 0.21\,\mathrm{GeV}$$

±0.20 (syst.)±0.08 (stat.)

Higgs boson width from H->ZZ->4l at 13 TeV

PRD 99 (2019) 112003

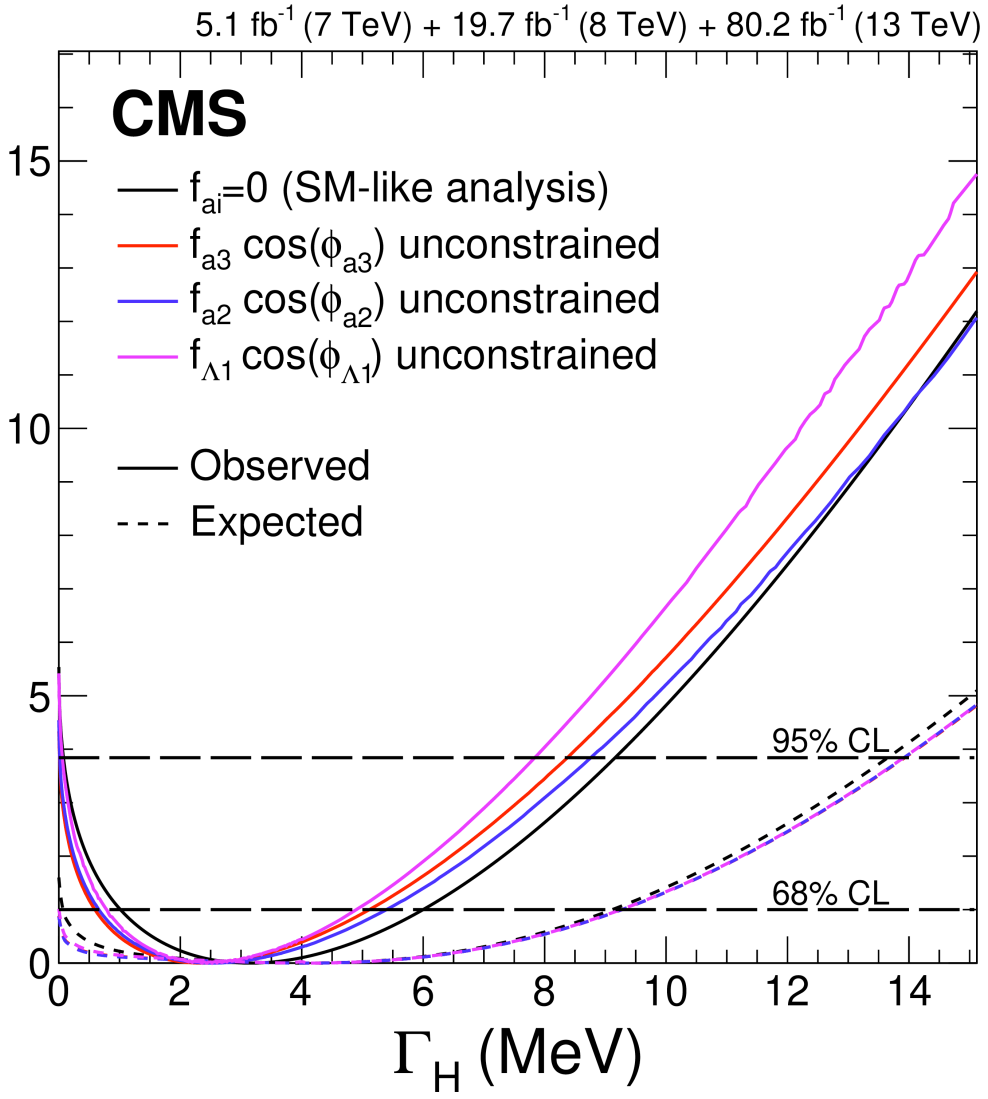
- Off-shell production method to measure the Higgs width relies on the relative off-shell to the on-shell measurement

$$\frac{\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \dfrac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}}{\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \dfrac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}}$$

- On-shell method precision is significantly worse (< 1 GeV)

Parameter	Observed	Expected
Γ_H (MeV)	$3.2^{+2.8}_{-2.2}$ [0.08, 9.16]	$4.1^{+5.0}_{-4.0}$ [0.0, 13.7]

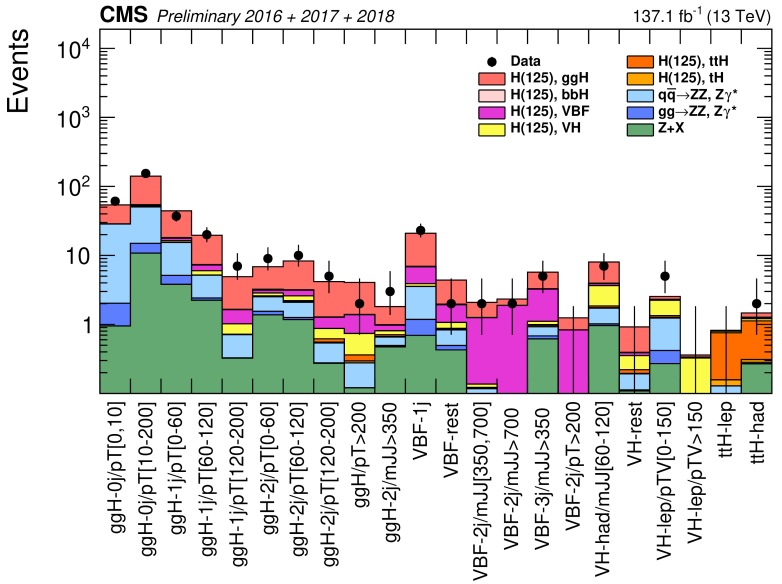
- No anomalous HVV observed

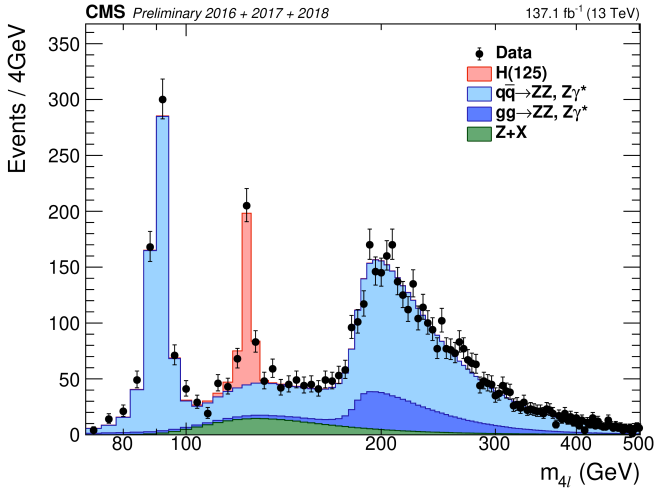


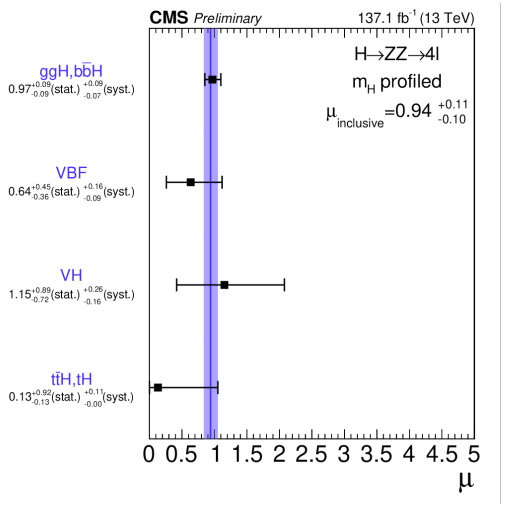
Higgs boson couplings from H->ZZ->4l at 13 TeV

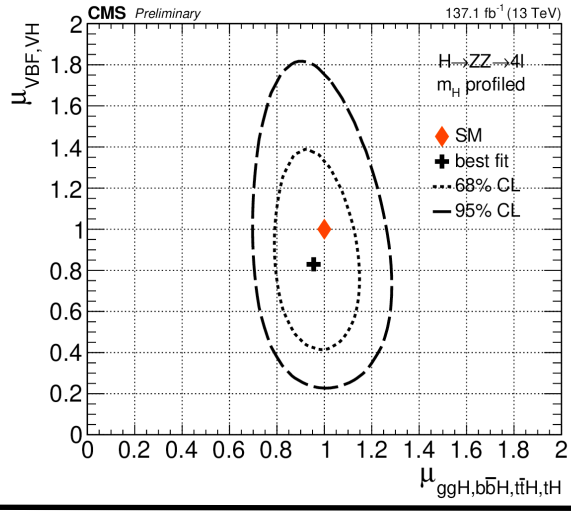
- The full LHC Run 2 dataset is utilized
- Inclusive & differential cross-section
- STSX framework approach followed
- MVA (BDT) and MEM discriminants exploiting full decay/production info
- Sig. strength modifiers and 2D L scan

CMS PAS HIG-19-001



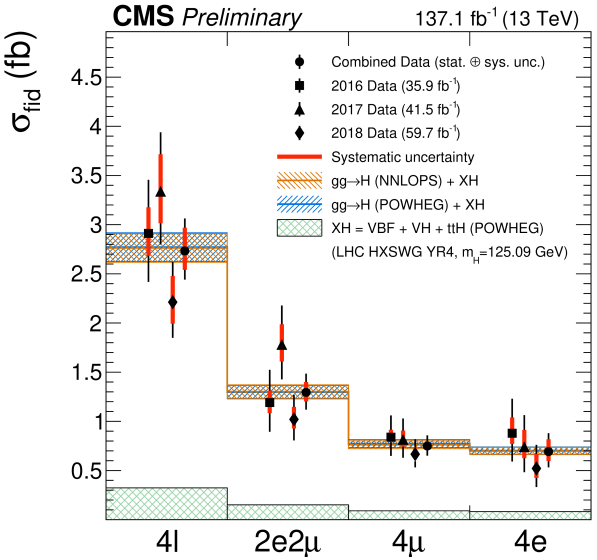


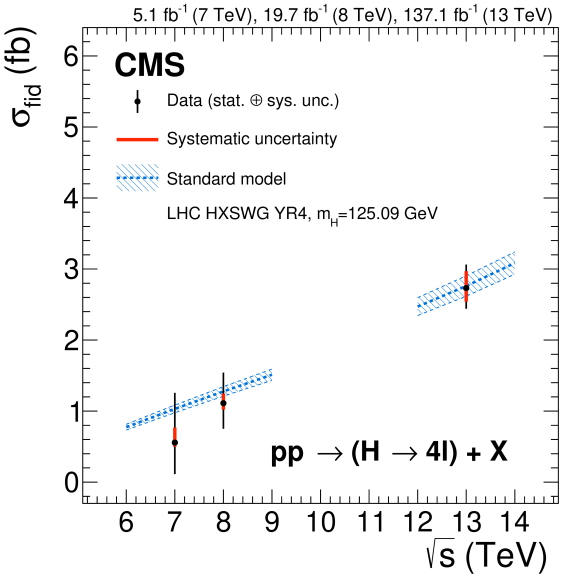


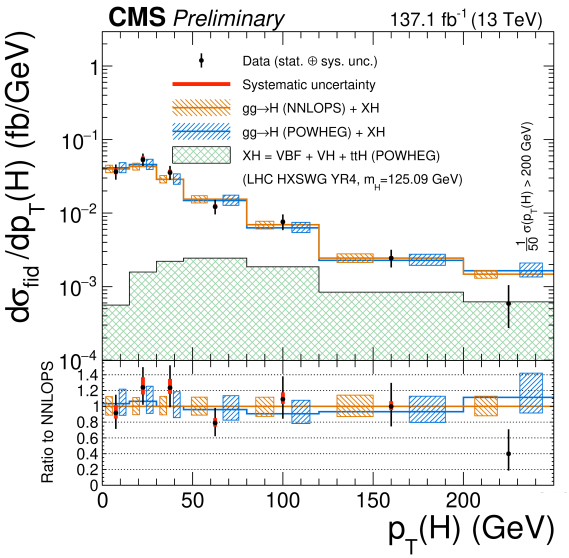


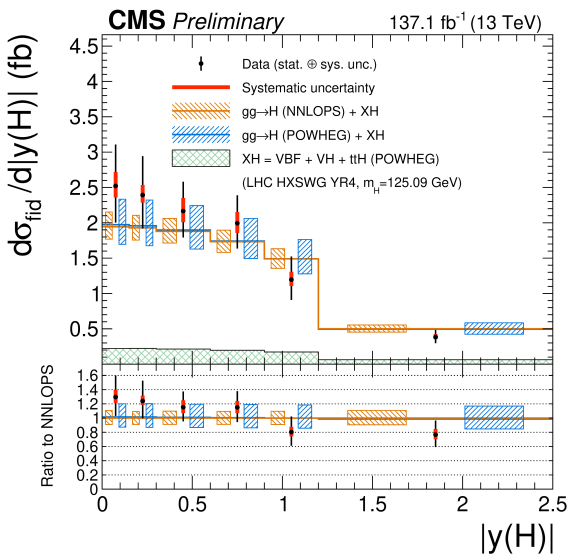
H->ZZ->4l at 13 TeV: Fiducial and differential CS

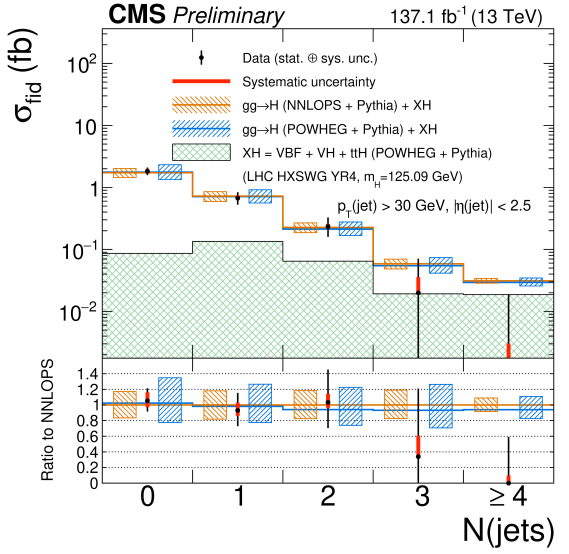
CMS PAS HIG-19-001

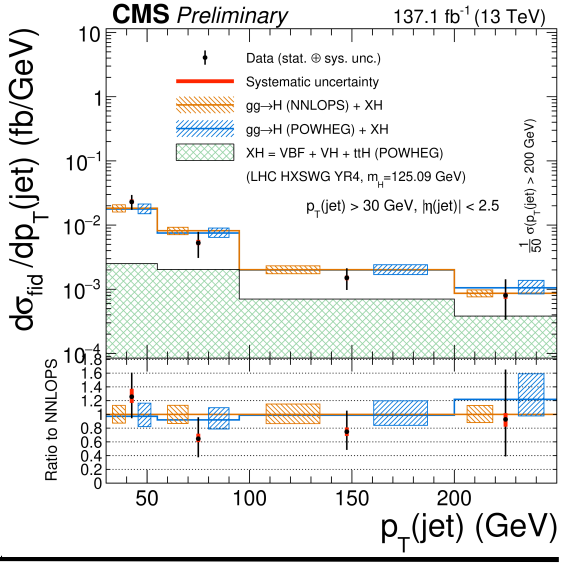










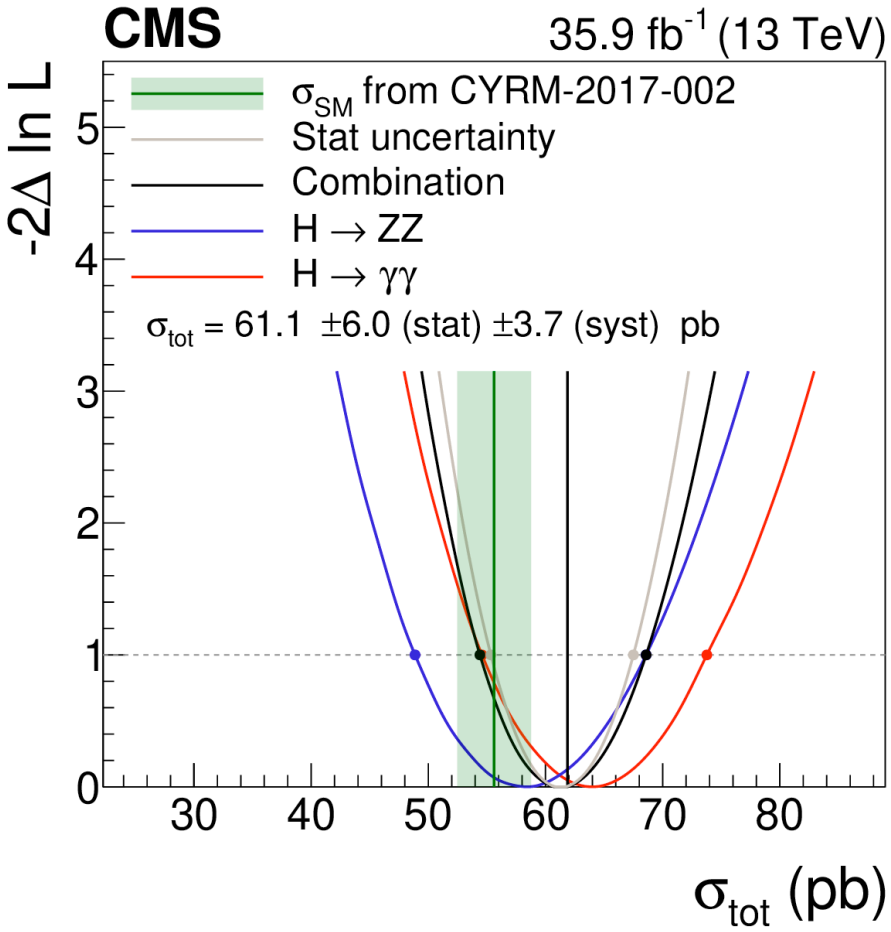


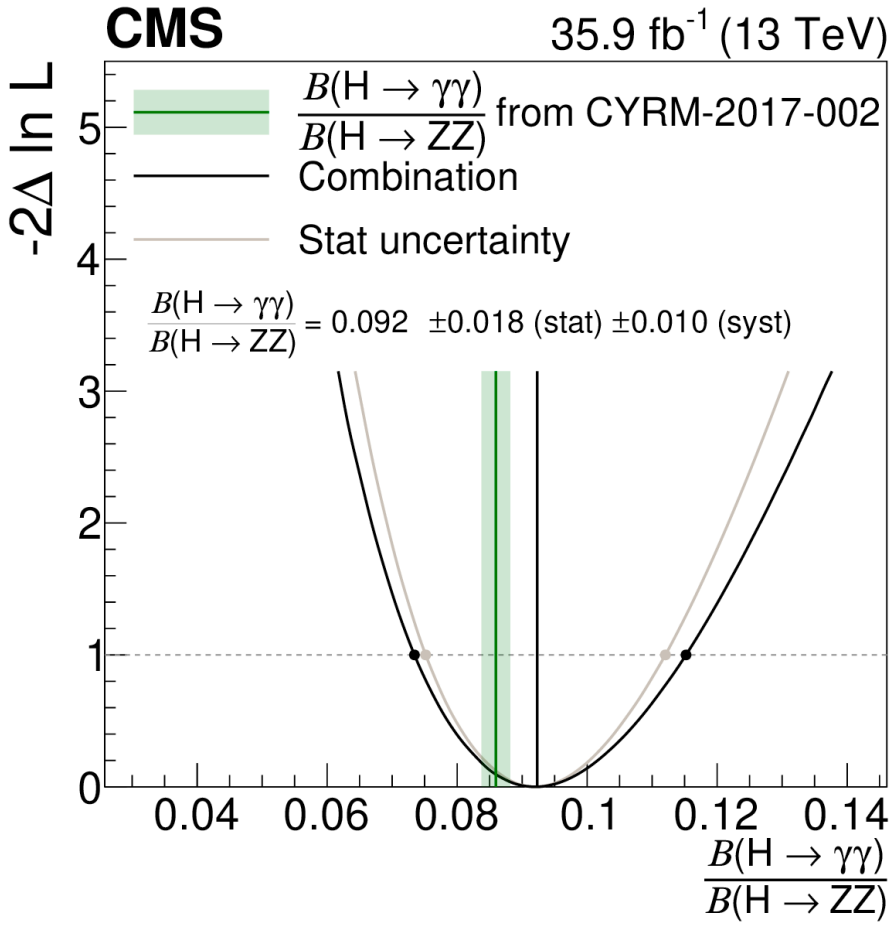
Total Higgs boson Cross Section measurement

PLB 792 (2019) 369

- Combination of H->γγ and H->ZZ->4l: $61.1 \pm 6.0\,(\text{stat}) \pm 3.7\,(\text{syst})\,\text{pb}$

SM value of $55.6 \pm 2.5\,\text{pb}$

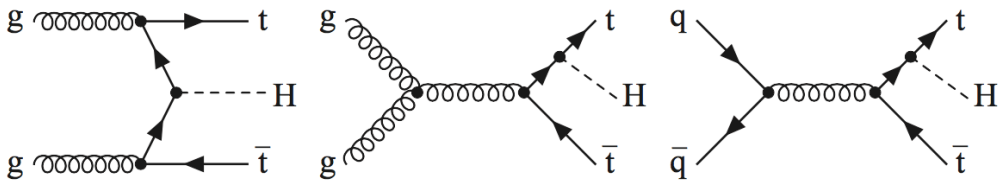


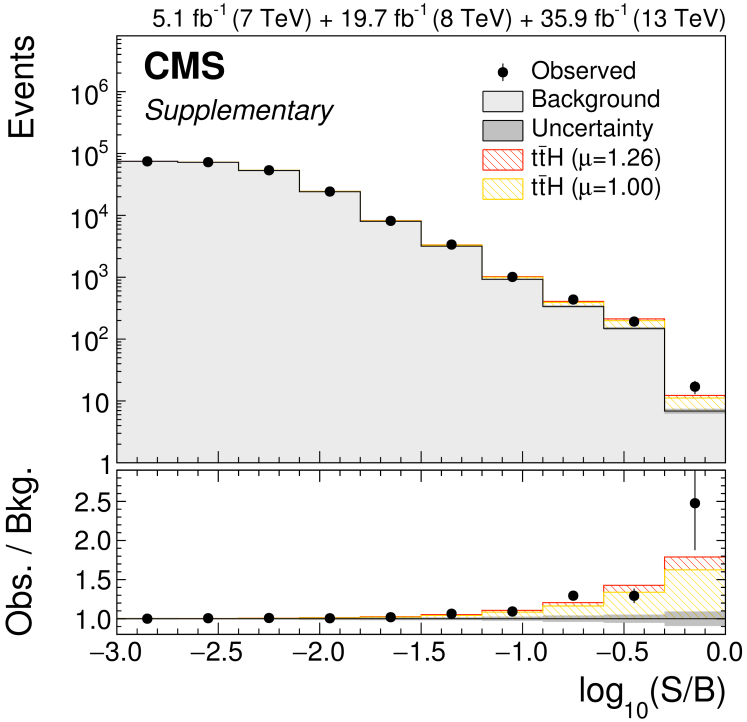


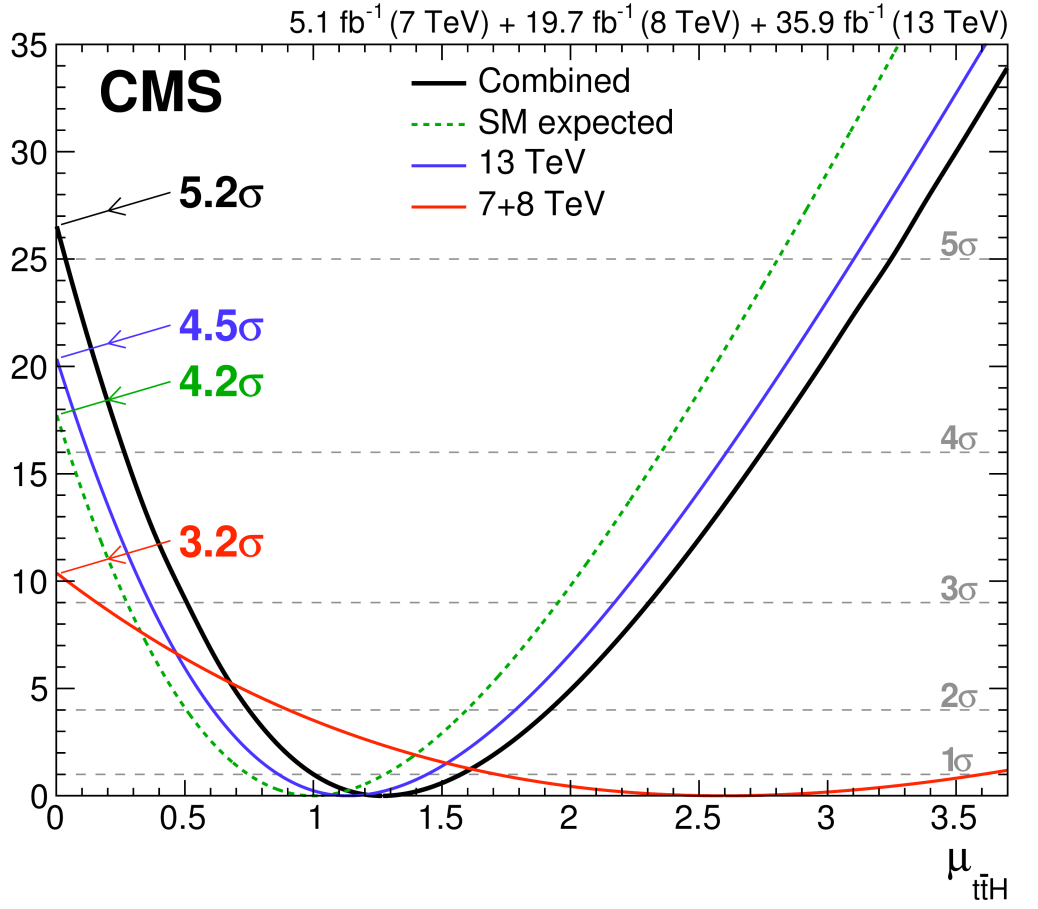
Observation of ttH production at 13 TeV

- A direct y_{top} measurement
- Constrains BSM in ggF loop
- WW, ZZ, ττ, bb, γγ channels
- Run1+2016 data combined

PRL 120 (2018) 231801





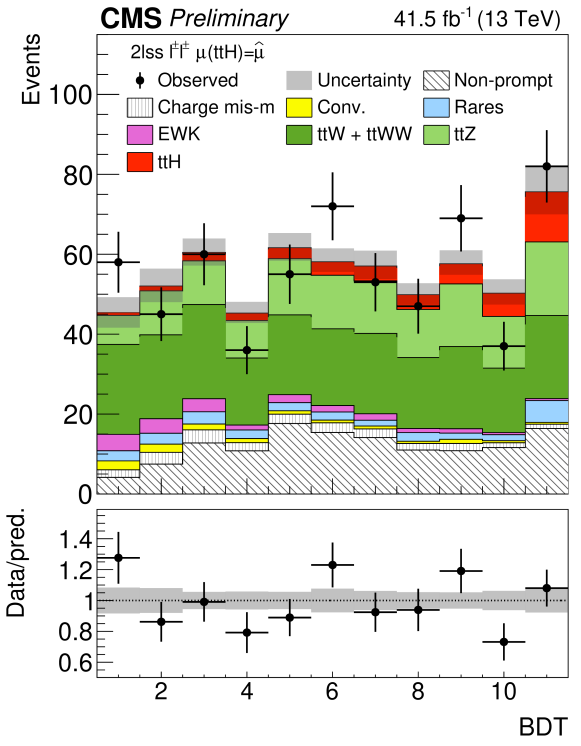


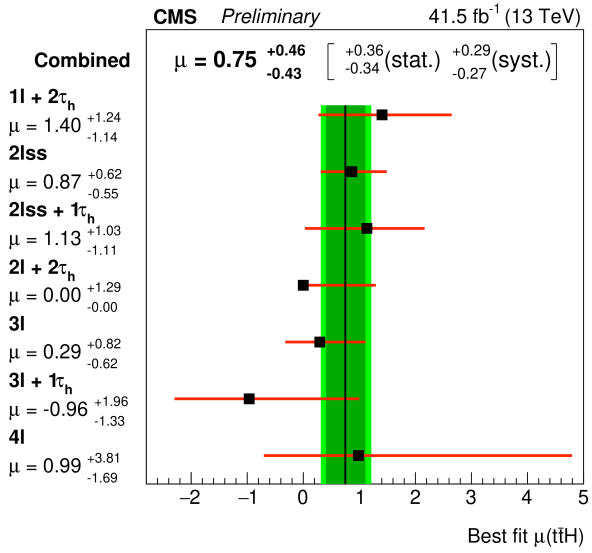
- 5.2(4.2)σ observed(expected)

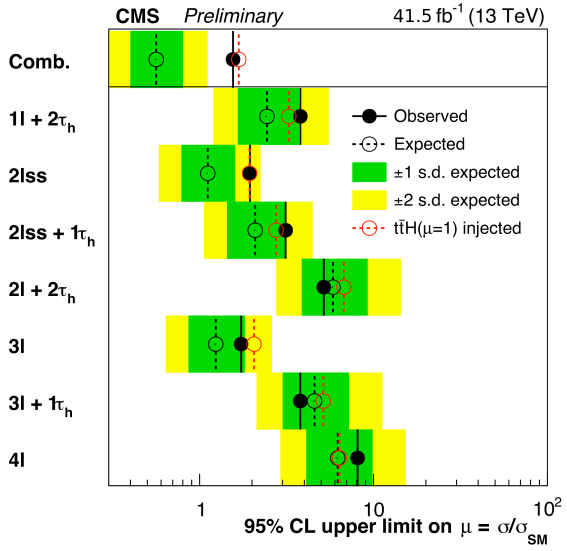
Evidence for ttH->multilepton production at 13 TeV

- Analysis of 2017 data, also combined with 2016
- H->WW, ZZ ,ττ decay modes (multilepton states)
- MVA(BDT) & matrix element (MEM) discriminant
- 2D BDT approach, recursive k-means partitioning

CMS PAS HIG-18-019





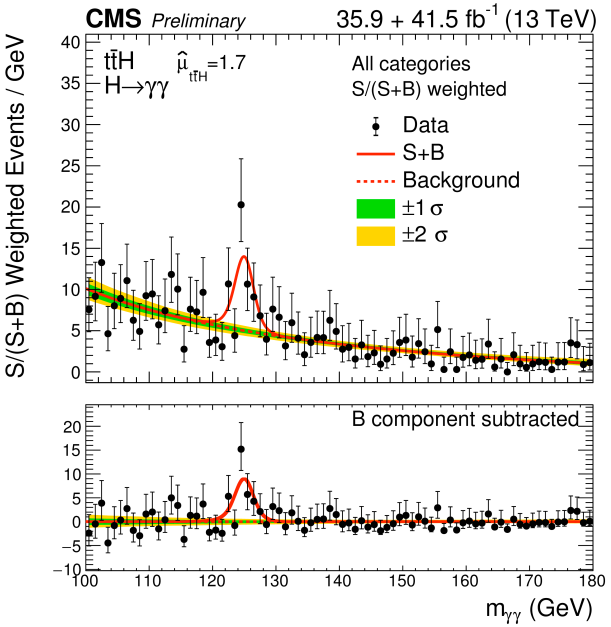


- An excess of events seen in highest bins
- Observed (expected) significance 3.2(4.0)σ

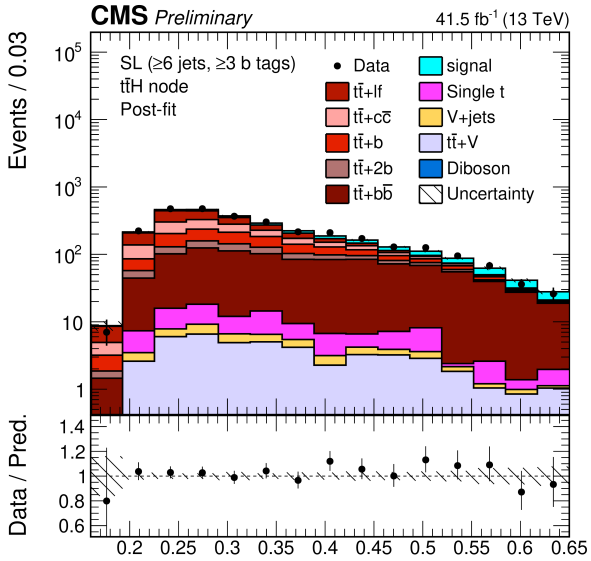
ttH(bb, γγ and ZZ->4l) production at 13 TeV

CMS PAS HIG-18-030, CMS PAS HIG-18-018, CMS PAS HIG-19-001

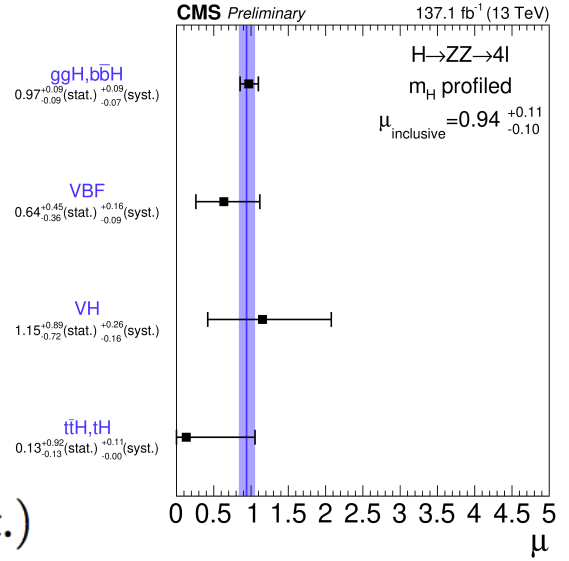
- Analyses improved and extended with 2017 data
- ttH(bb): MVA (BDTs) and matrix element (MEMs)
- Observed(expected) significance of 3.9(3.5)σ



- First evidence of ttH(bb) with improved b-tagger and the refined analysis



- ttH(γγ): 0 or 1 leptons
- The observed (expected) significance is 4.1σ(2.7σ)



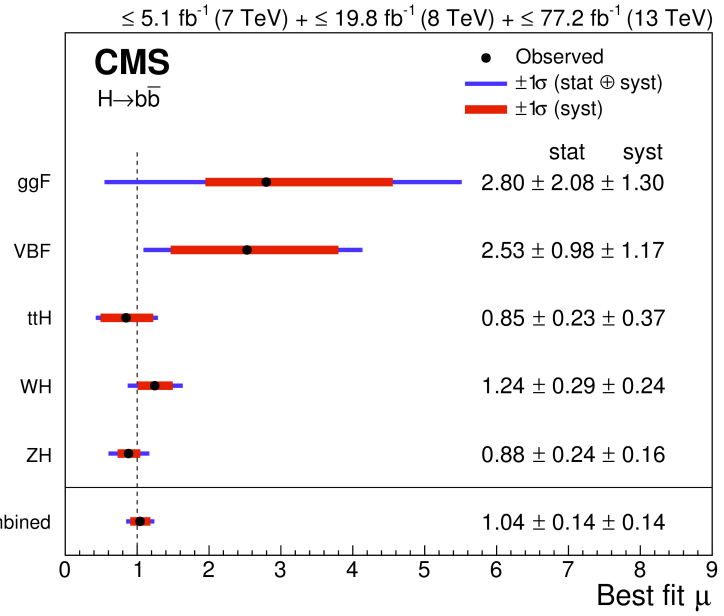
- ttH(ZZ->4l): hadronic and leptonic tag. categories

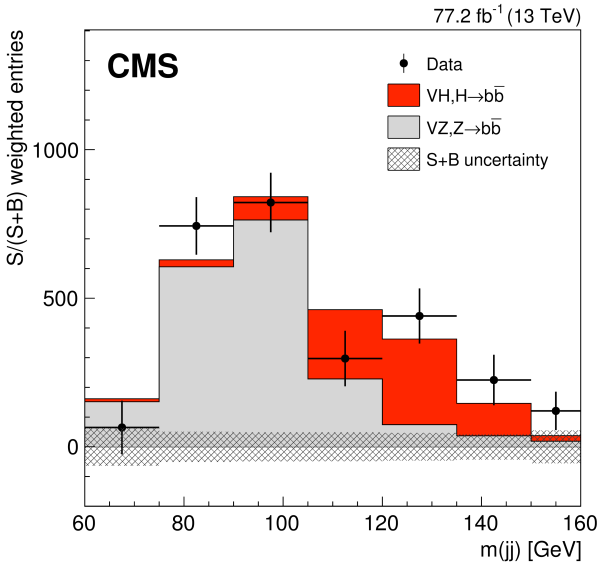
	Expected	Observed
$\mu_{t\bar{t}H,tH}$	$1.00^{+1.16}_{-0.73}(\text{stat.})^{+0.19}_{-0.04}(\text{syst.})$	$0.13^{+0.92}_{-0.13}(\text{stat.})^{+0.11}_{-0.00}(\text{syst.})$

Observation of Higgs decay to bottom quarks

- Test Yukawa coupling to down - type quark
- V(W/Z)H most sensitive production process
- Final states with 0, 1 or 2 leptons & 2 b-jets
- Backgrounds: V+jets, ttbar, single top, QCD

PRL 121 (2018) 121801



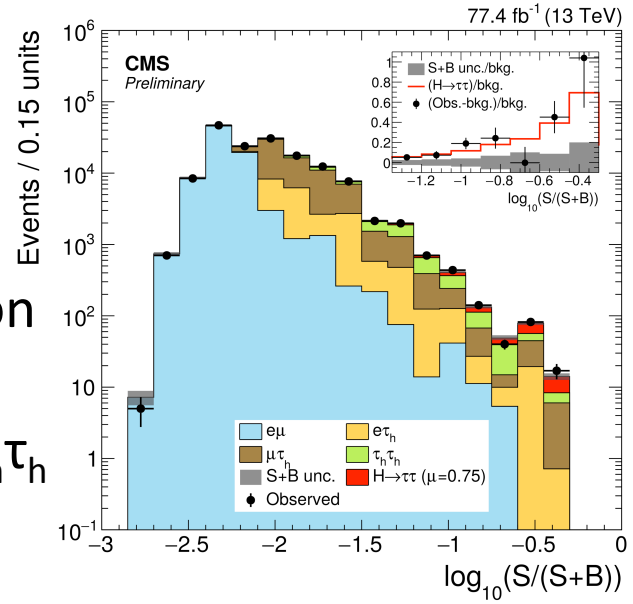


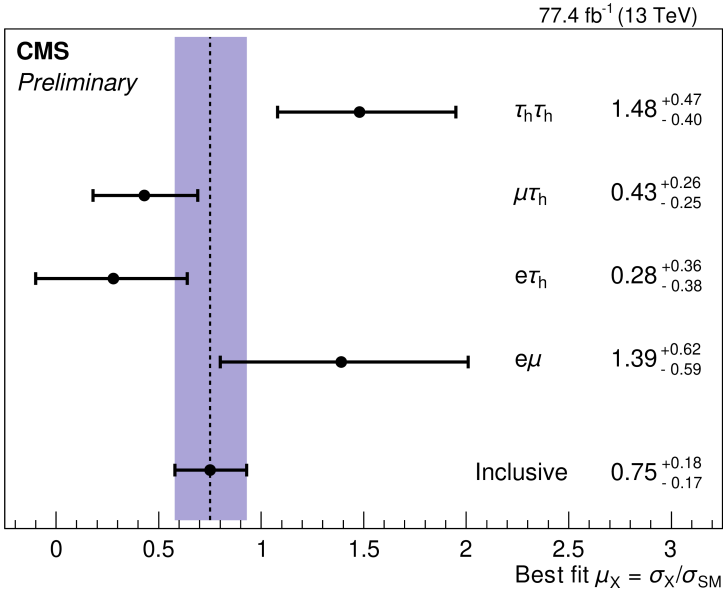
- Deep neural network discriminant for b-tagging
- m(jj) resolution is improved by DNN regression
- Combined with other VH(bb): 4.8(4.9)σ obs(exp) and H(bb) in ggF, VBF and ttH: 5.6(5.5)σ obs(exp)

Higgs boson production and decay to ττ at 13 TeV

CMS PAS HIG-18-032

- 2nd largest BR among the fermionic Higgs decays
- x-sec measurement split by prod. & decay mode
- New NN classification algo used for categorization
- Four different ττ final states -> eμ, $e\tau_h$, $\mu\tau_h$ and $\tau_h\tau_h$



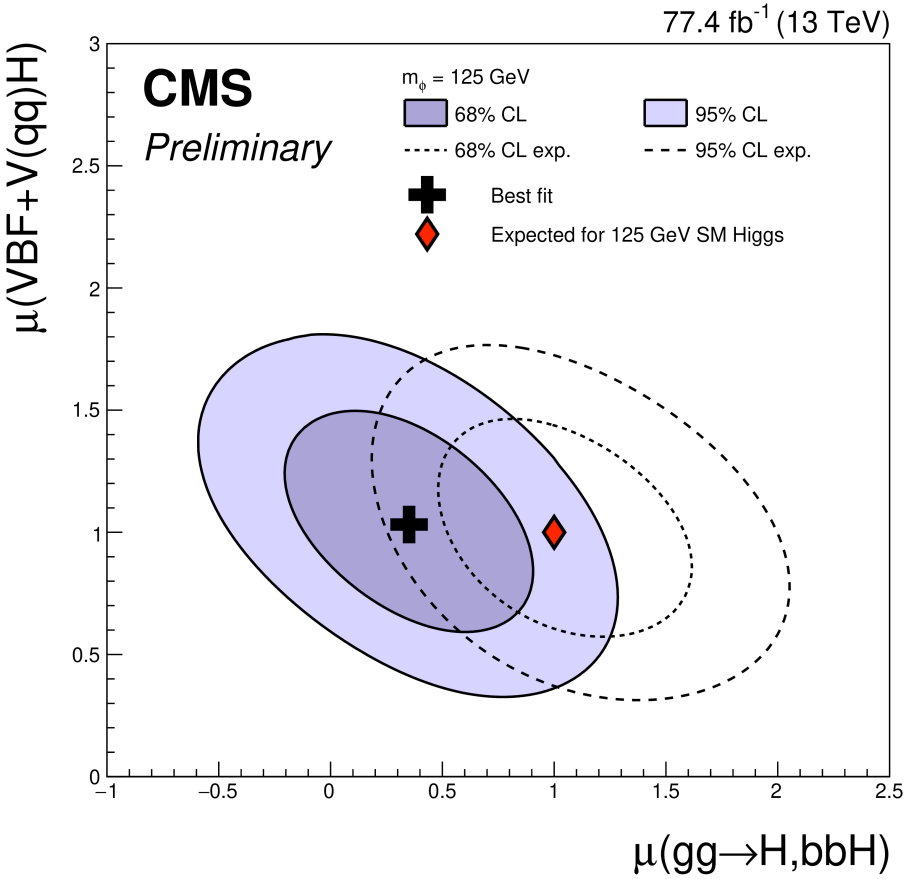


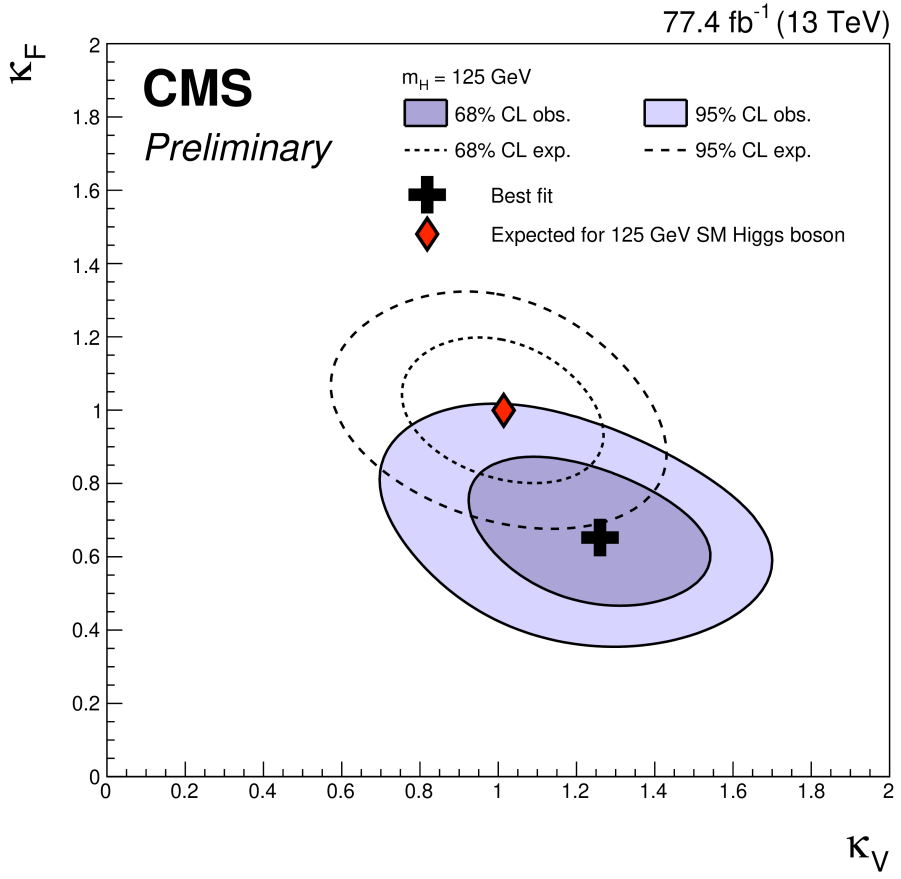
- DeepCSV b-tagging, hadron-plus-strips for τ
- The simplified template cross section (STSX)
- Backgrounds: F_F and τ embedding methods
- Observed (expected) significance: 4.7(6.6)σ

Higgs boson production and decay to ττ at 13 TeV

CMS PAS HIG-18-032

$$\sigma_{\text{incl}}\,\mathcal{B}(\text{H} \to \tau\tau) = 2.56 \pm 0.48\ (\text{stat}) \pm 0.34\ (\text{syst})\ \text{pb}$$



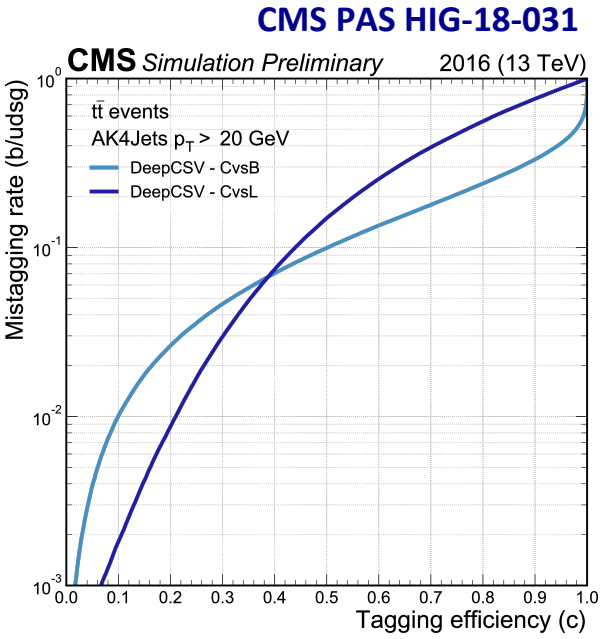


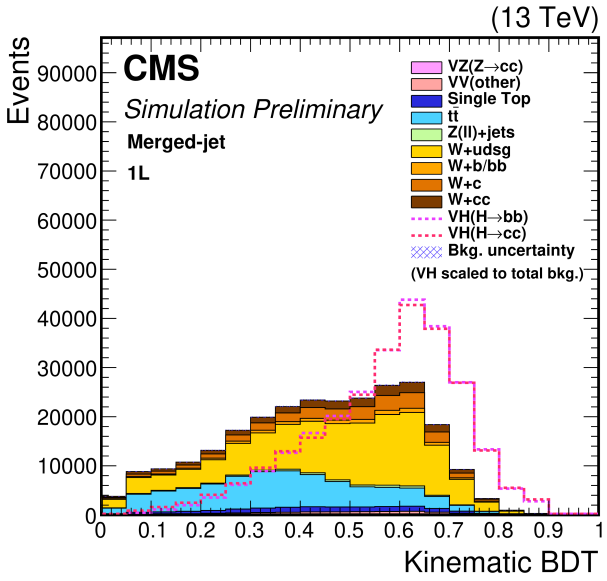
When split into σ(gg->H,bbH)xBR(H->ττ)= 1.11 ± 0.81 (stat) ± 0.78 (syst) pb

the prod. mode σ(VBF+V(qq))xBR(H->ττ)= 0.34 ± 0.08 (stat) ± 0.09 (syst) pb

Higgs boson decaying to charm quarks

- BR(H->cc) ~20 smaller than H->bb, large QCD bckg
- V(W/Z)H production, V+jet and ttbar backgrounds
- Two topologies: “resolved jet” and “merged-jet”, targeting the lower and the higher Higgs boson p_T
- Two jet collections: with radius R = 0.4 and R = 1.5



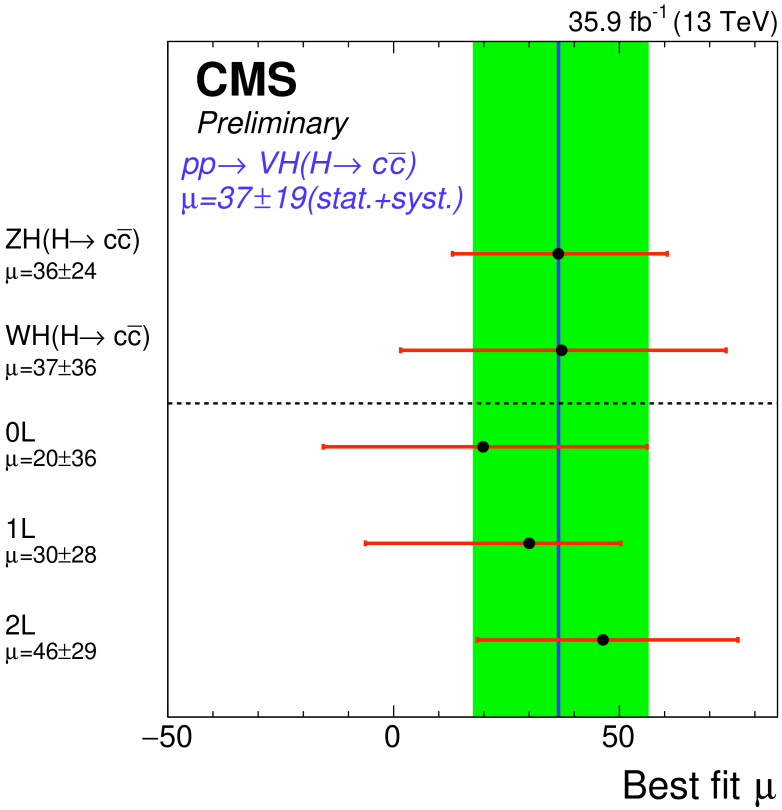


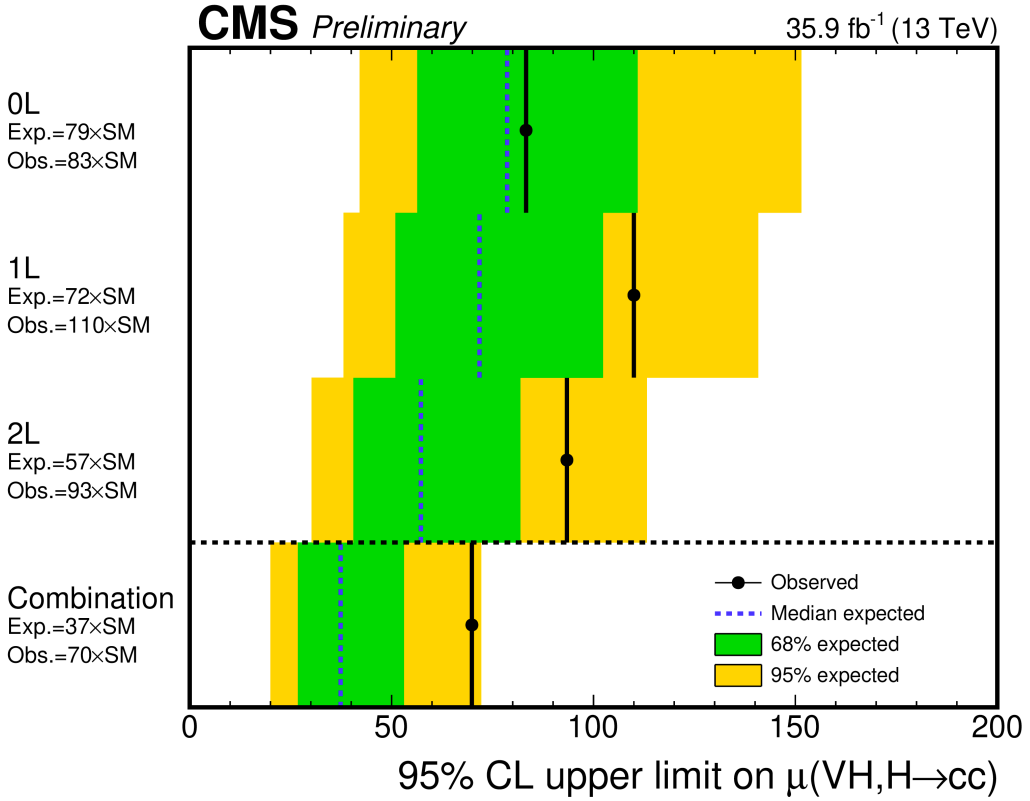
- DeepCSV c-quark tagger
- Jet substructure: Cambridge-Aachen algo, PUPPI, using modified mass drop tagger “soft drop” (SD)
- 3 channels: “0L“ (vvcc), “1L” (lvcc) and “2L” (llcc)
- Resolved: 95% of VH with p_T<200 GeV, high bckg
- Merged: 5% of VH, boosted, but low background

Higgs boson decaying to charm quarks

CMS PAS HIG-18-031

- Signal extracted using binned likelihood fit in 2 categories, then combined





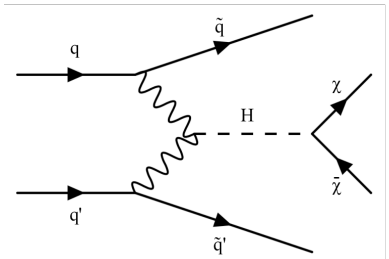
	Resolved-jet (inclusive)				Merged-jet (inclusive)			
	0L	1L	2L	All channels	0L	1L	2L	All channels
expected UL	84	79	59	38	81	88	90	49
observed UL	66	120	116	75	74	120	76	71

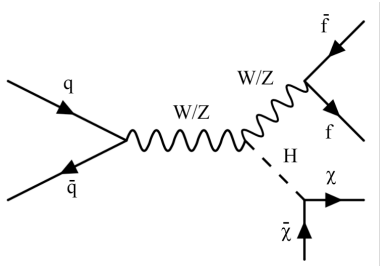
	95% CL exclusion limit					
	resolved-jet ($p_T(V) < 300$ GeV)	merged-jet ($p_T(V) \geq 300$ GeV)	combination			
			0L	1L	2L	All channels
expected	45^{+18}_{-13}	73^{+34}_{-22}	79^{+32}_{-22}	72^{+31}_{-21}	57^{+25}_{-17}	37^{+16}_{-11}
observed	86	75	83	110	93	70

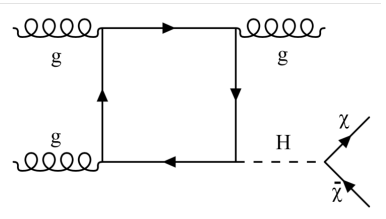
VBH Higgs to invisible decays at 13 TeV

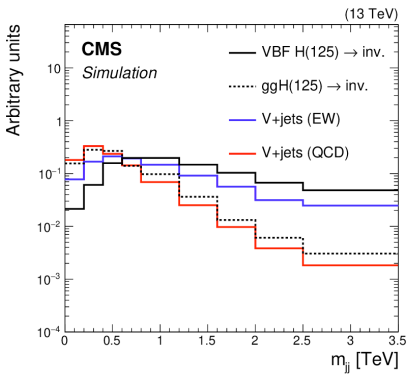
- Invisible Higgs decay only via ZZ->4ν in SM
- Sensitive to the BSM: Higgs as portal to DM
- VBF Higgs: large m_{jj} & $|\Delta\eta_{jj}|$ and small $|\Delta\phi_{jj}|$
- Main backgr.: V + jets

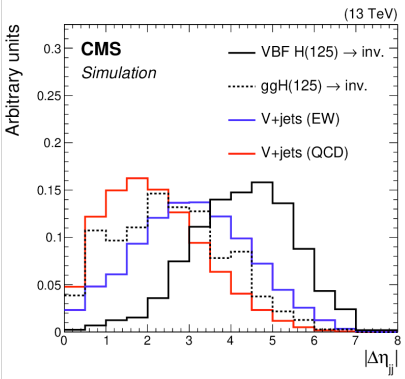
Phys. Lett. B 793 (2019) 520

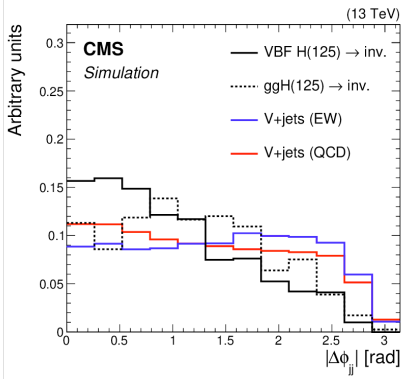


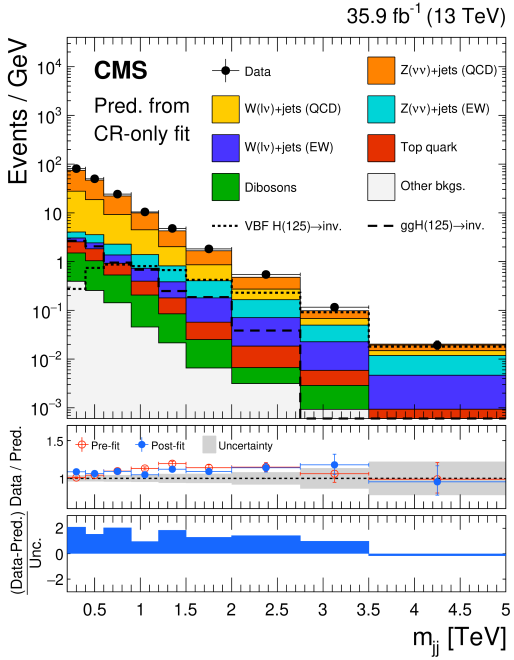






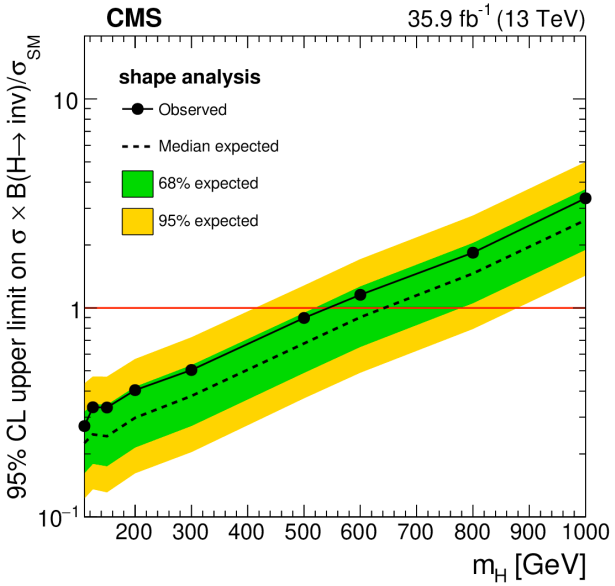


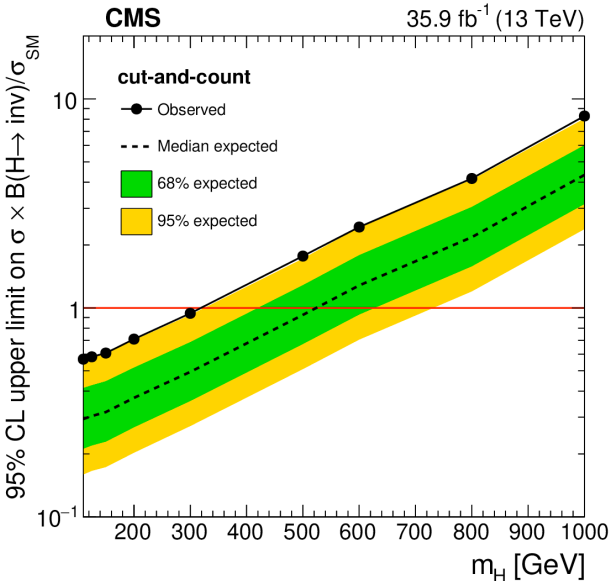




- Distinctive VBF kin. features: fitting the m_{jj} shape
- Additionally, cut-and-count analysis is performed
- Slight excess (4 - 10%), inconsistent with the VBF

VBH Higgs to invisible decays at 13 TeV





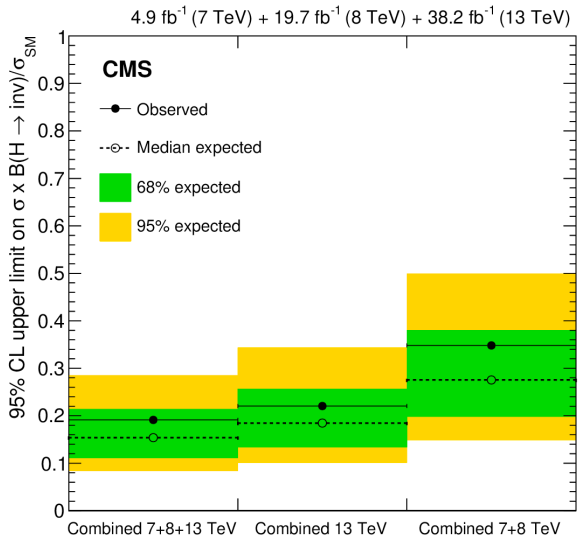
Phys. Lett. B 793 (2019) 520

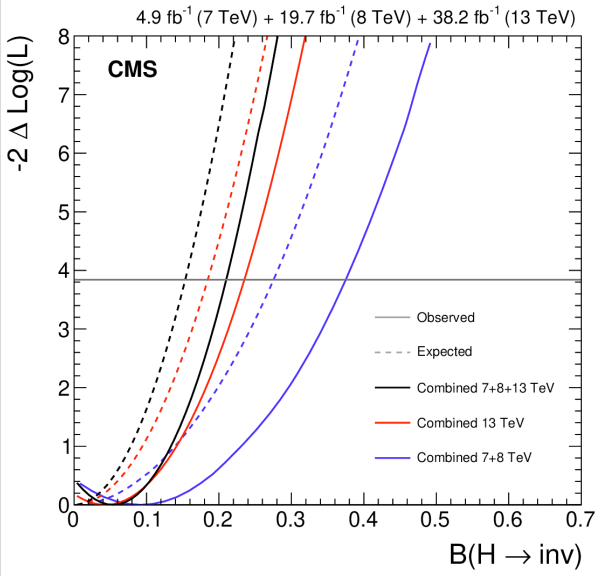
Expected and observed 95% CL upper limits on (σ/σ_{SM}) x BR(H -> inv) for the SM - like Higgs boson as f-ion of (m_H)

Shape analysis (left) and cut and a count approach (right)

Observed and expected 95% CL upper limits on the (σ/σ_{SM}) x BR (H -> inv) for the 7+8 or 13 TeV data as well as the combination

The profile likelihood ratios as the function of the *BR*(H -> inv)

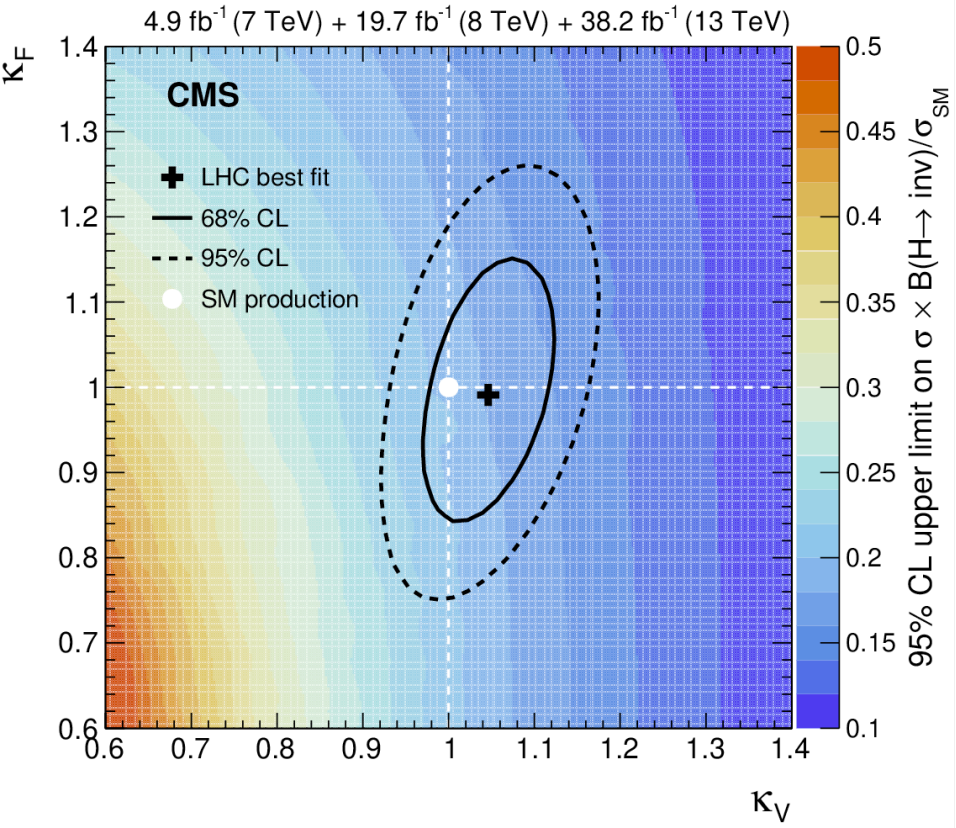


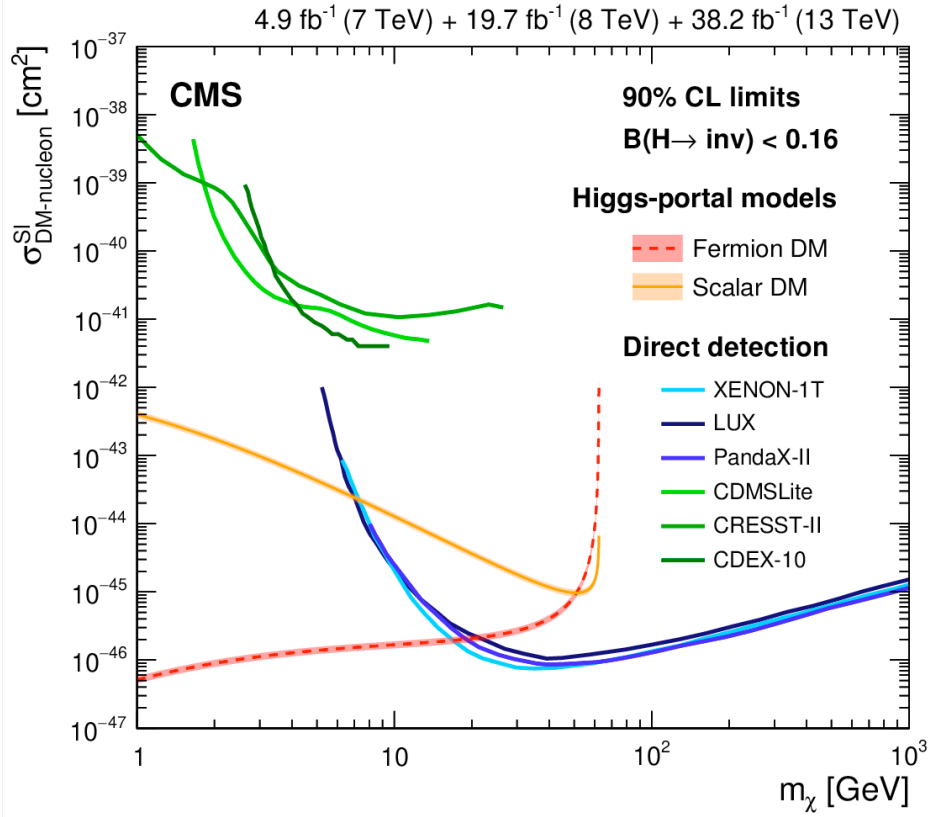


VBH Higgs to invisible decays at 13 TeV

Phys. Lett. B 793 (2019) 520

- Interpretation in the context of Higgs - portal models of DM interaction



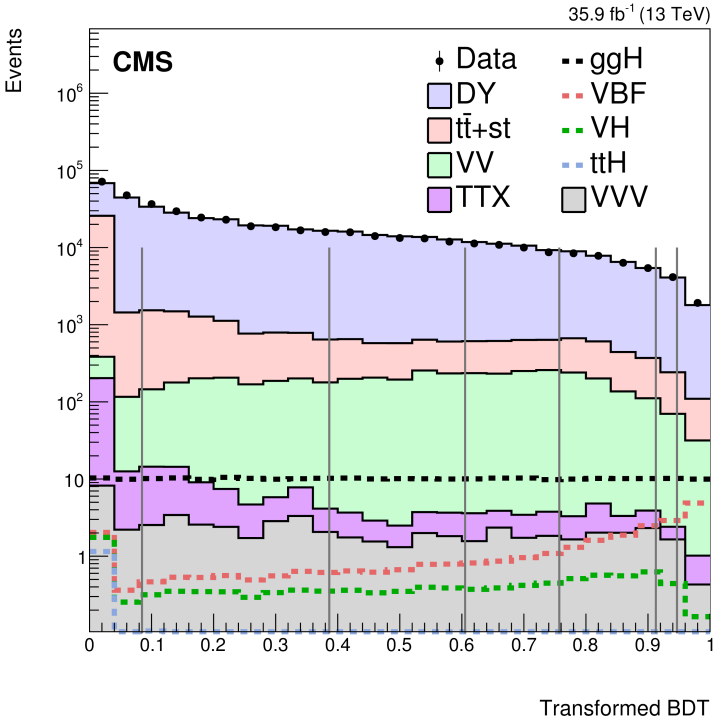


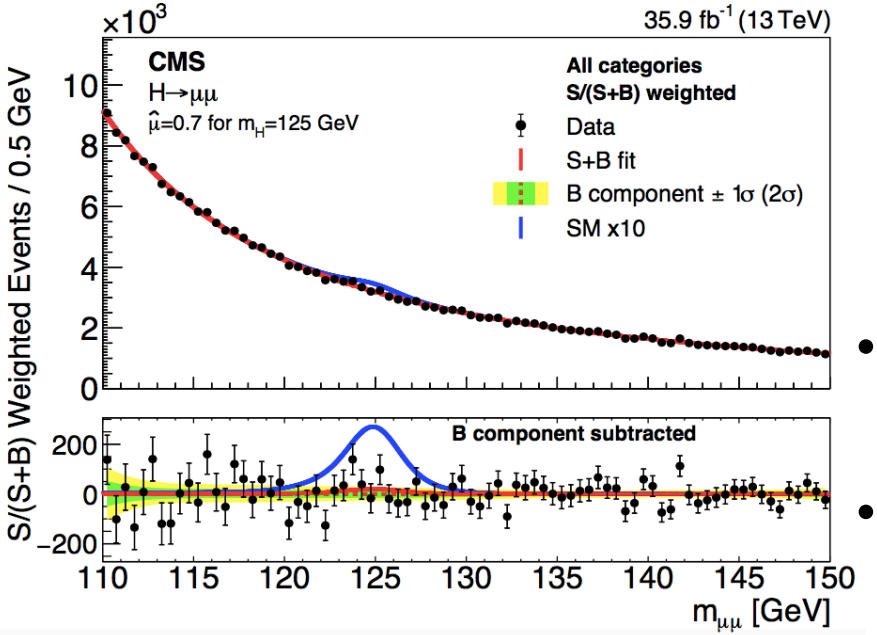
- Most stringent limits for m_χ smaller than 18(7) GeV (fermion(scalar) DM cand.)

Higgs boson decaying to two muons at 13 TeV

- Small expected BR of 2.17 x 10^{-4} for H->μμ
- Primary production mechanisms: VBF, ggH
- BDT to suppress backgrounds: DY, st, ttbar
- Iterative procedure to optimize categories

PRL 122 (2019) 021801



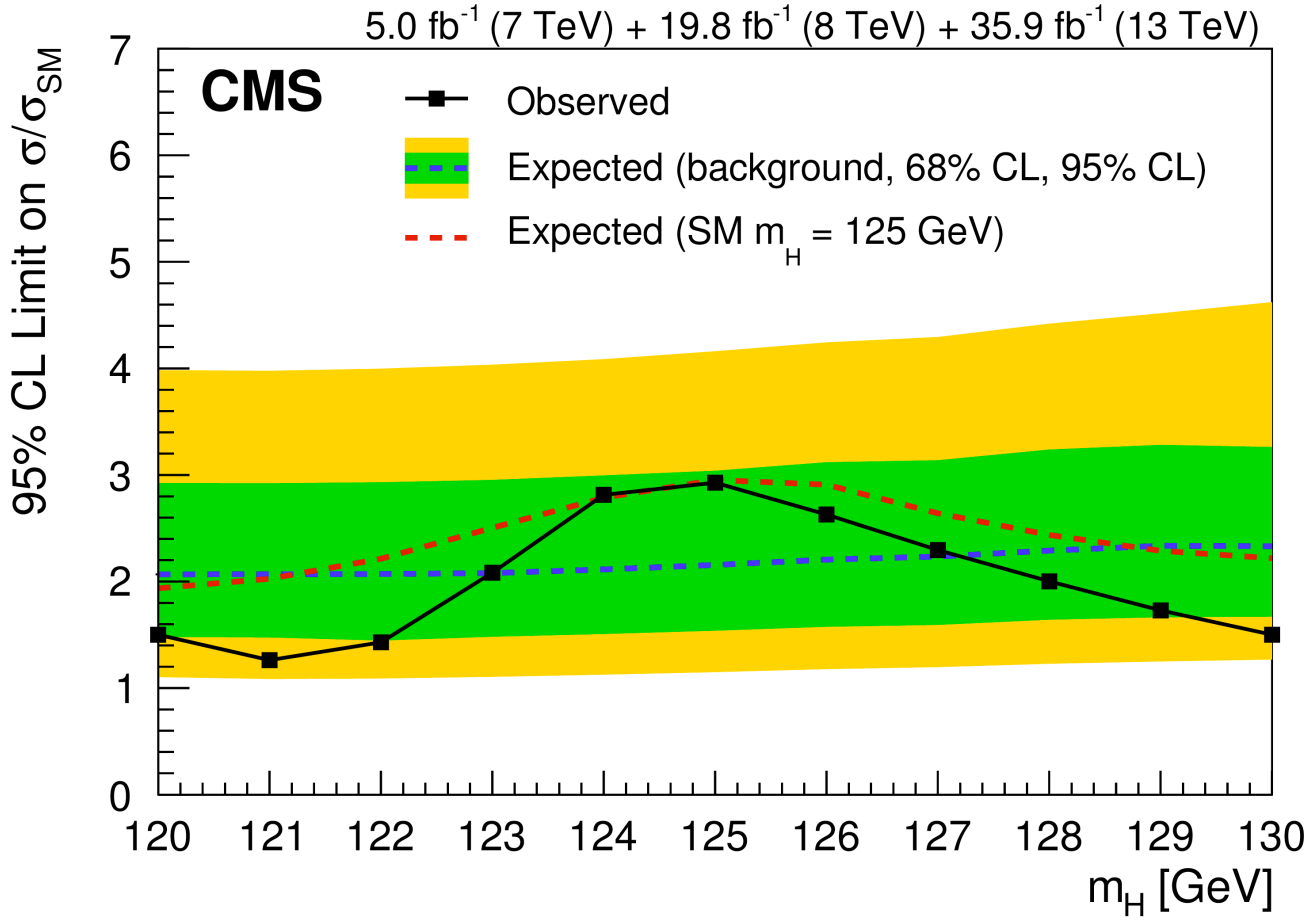


- The total of 15 event categories utilized
- Max. likelihood S+B fit to di-muon mass

Higgs boson decaying to two muons at 13 TeV

PRL 122 (2019) 021801

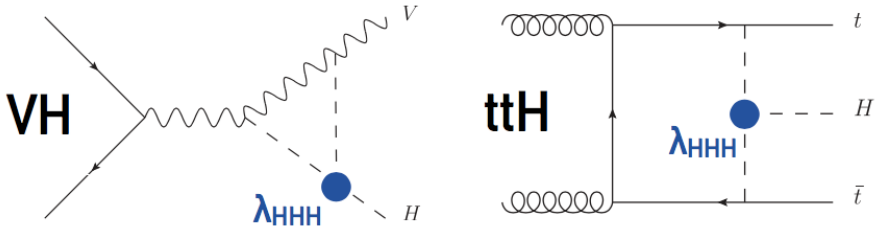
- 2016 data: obs.(exp.) 3.0(2.5)σ -> combined with 7 and 8 TeV: 2.9(2.2)σ



- Observed upper limit on the Higgs boson BR to muon pair ---> 6.4×10^{-4}

Higgs boson pair production at 13 TeV

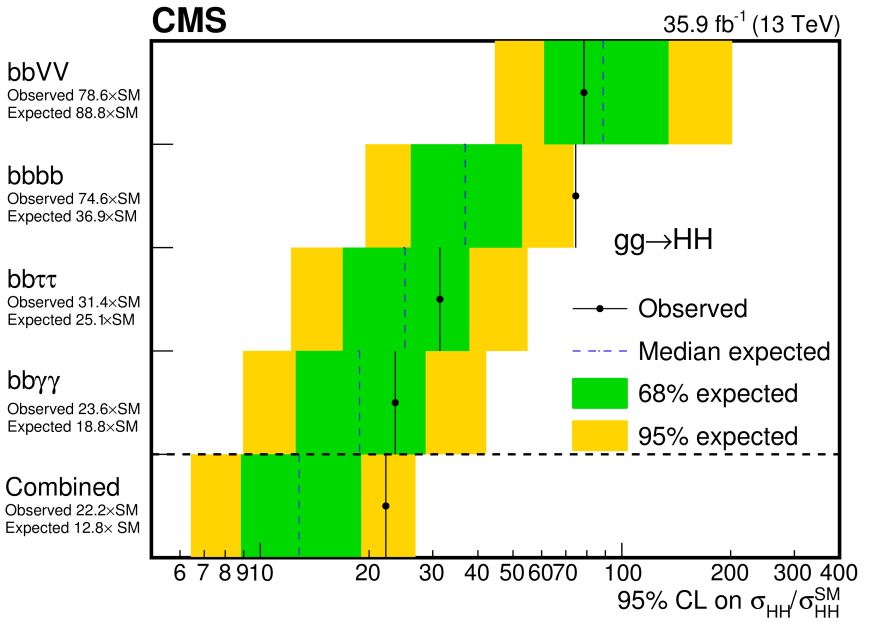
- Higgs self-coupling: independent SM test, access to shape of H scalar field potential

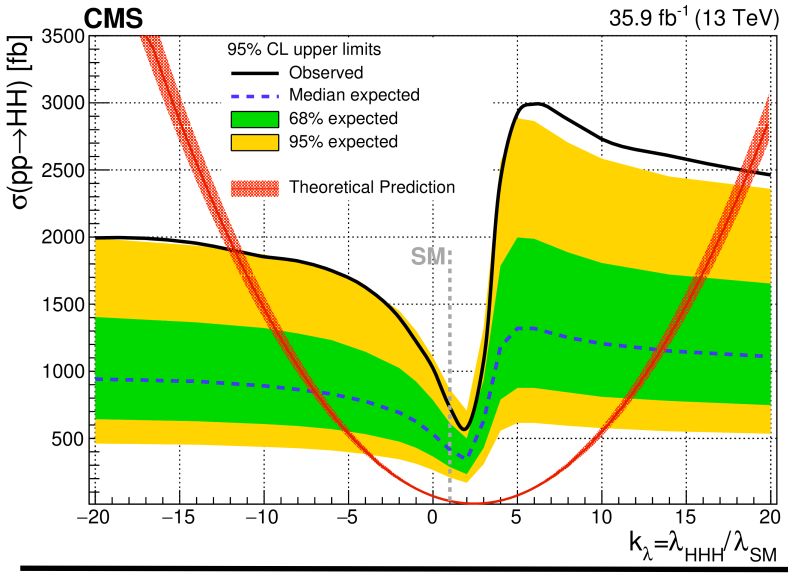


- Higgs trilinear couplings by measuring HH

- Heavy BSM resonances can decay to a HH

PRL 122 (2019) 121803



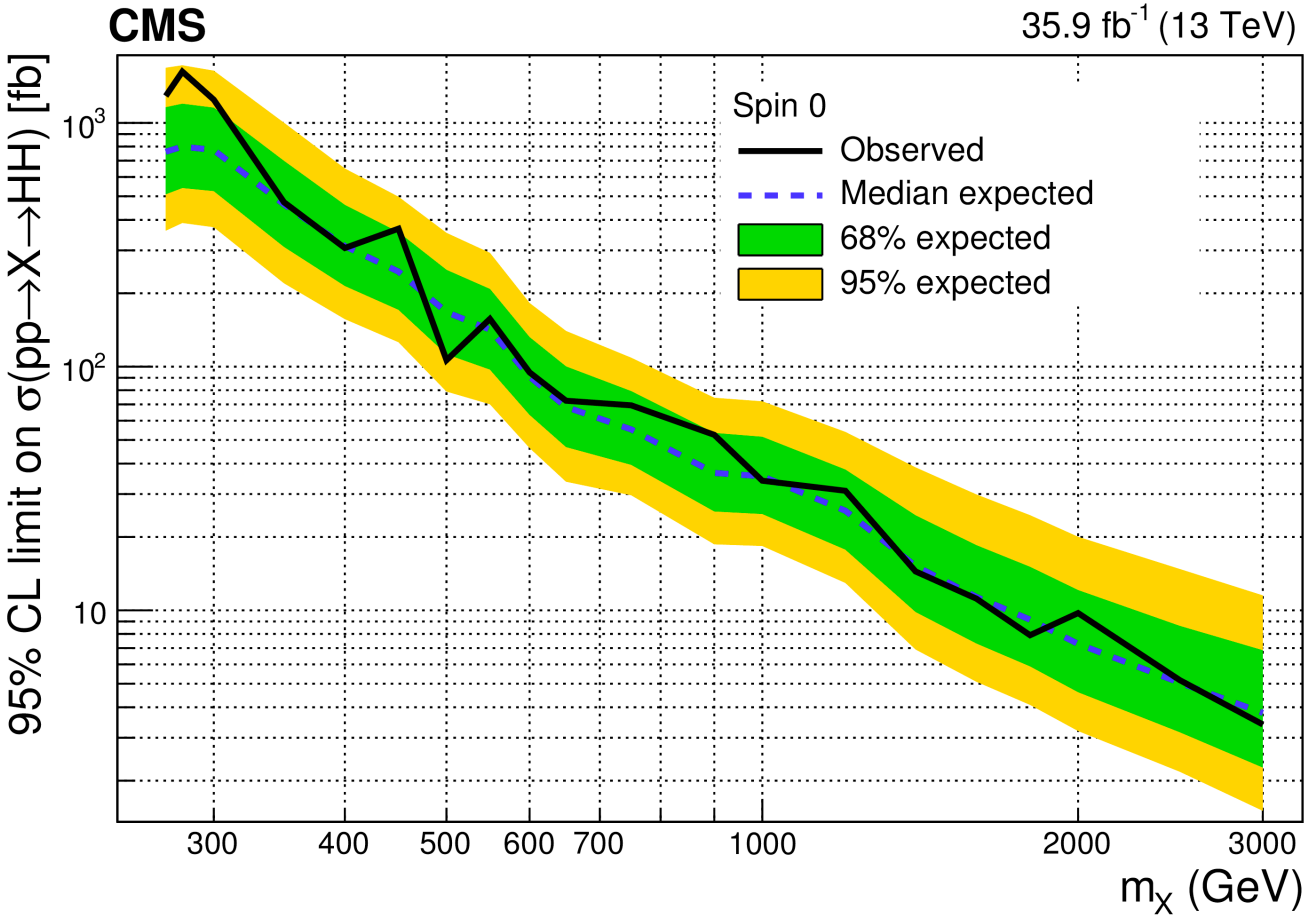


- Non-resonant Higgs boson pair production
- EFT: five couplings -> $y_{t,}$ λ_{HHH}, c_2, c_{2g} and c_g, with $k_\lambda = \lambda_{HHH} / \lambda_{SM}$ and $k_t = y_t / y_{SM}$ defined
- Resonant: either a CP-even spin-0 (radion) or spin-2 (graviton), width << detector res.
- bbγγ, bbττ, bbbb & bbVV analyses (V=W/Z)

Higgs boson pair production at 13 TeV

PRL 122 (2019) 121803

- Non-resonant obs.(exp.) limits at 95% CL -> 22.2(12.8) x SM

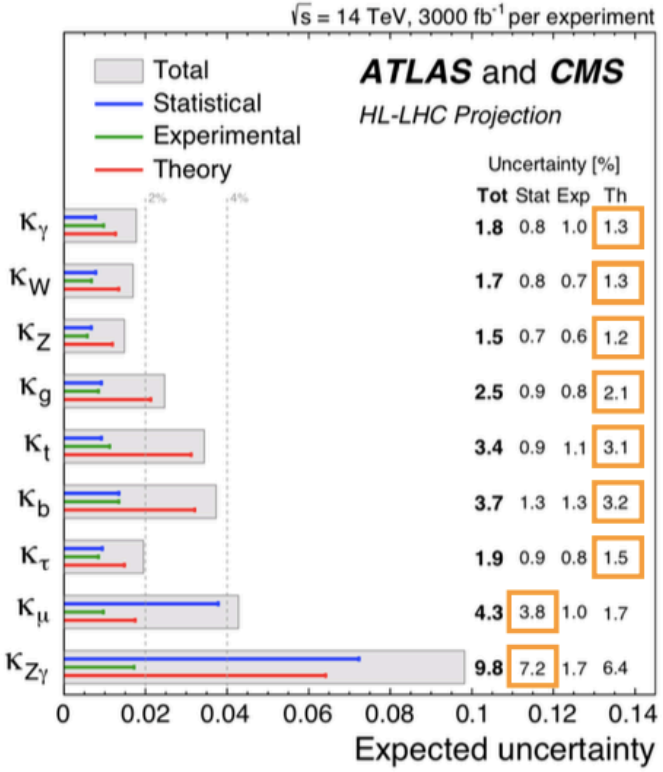


- Resonant production: upper exclusion limits at 95% CL in 250 to 3000 GeV

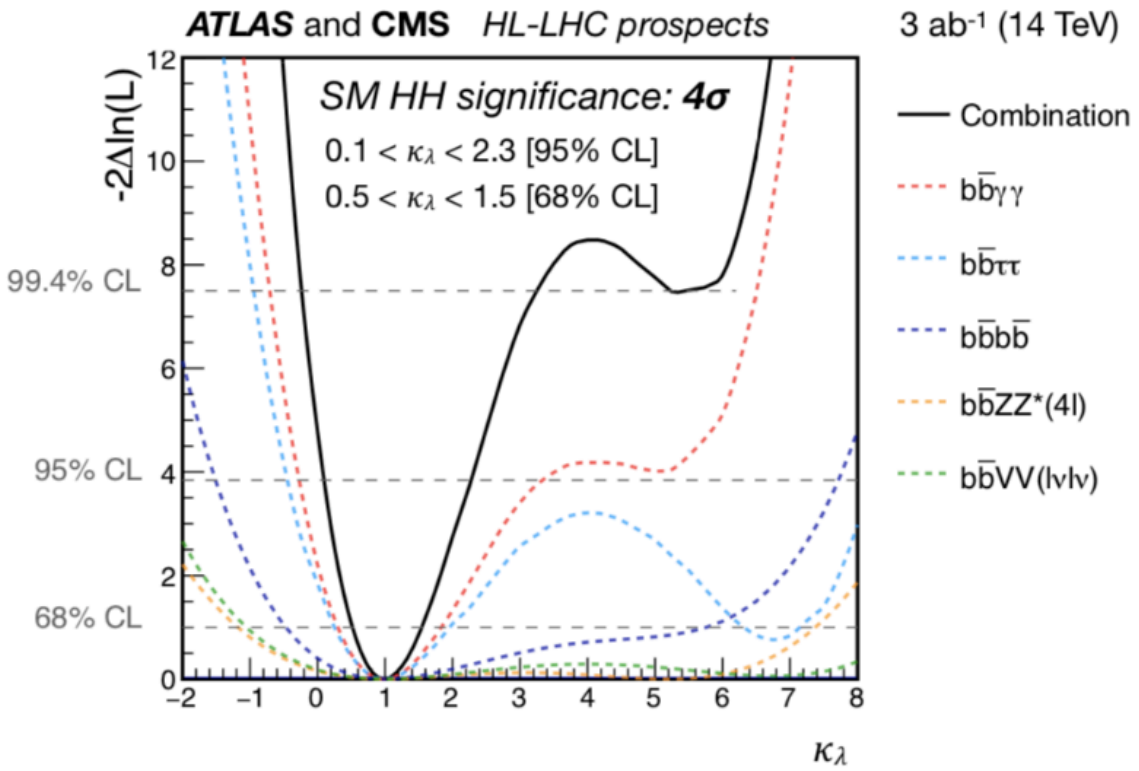
Higgs couplings at HL-LHC

arXiv:1902.00134

- Extrapolation studies for Higgs coupling combination at 3000 fb^{-1} (HL-LHC)
- Up to 200 pp collisions per bunch crossing -> extensive detector upgrades



Higgs couplings to other particles



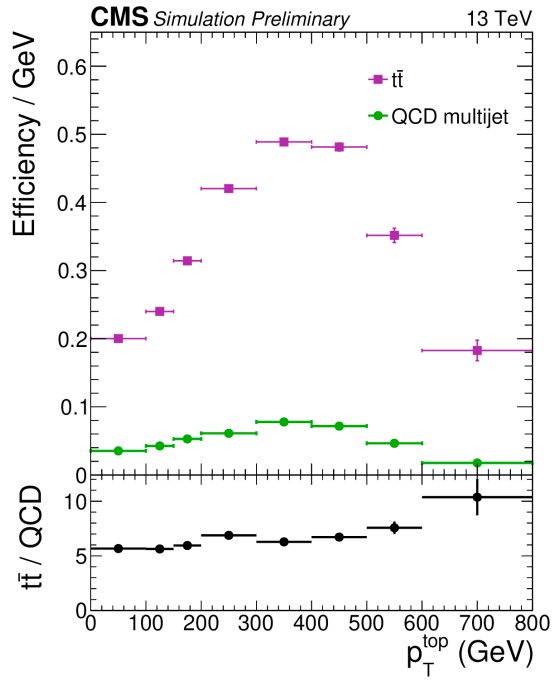
Higgs boson self couplings

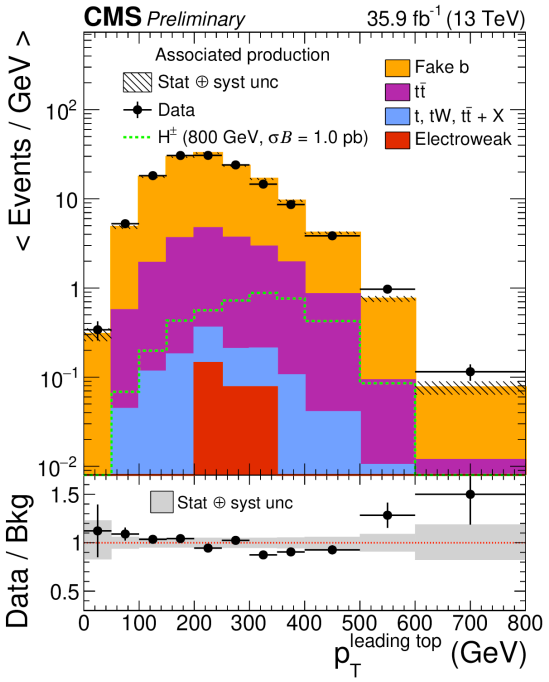
Summary and Outlook

- Higgs boson observation in 2012 major event in high-energy physics
- Characterization of the Higgs properties to explore the EWSB in SM
- Mass, spin-parity, width measurements from high precision decays
- Higgs observation in γγ, ZZ, WW, bb, ττ and tt+H production modes
  - Yukawa couplings to fermions confirmed at an O(20%) precision
- Inclusive and differential CS and new approaches (STXS etc.) applied
- Rare processes being studied: H->μμ, H->cc, Higgs self-couplings etc.
- HL-LHC: improving measurement precision of Higgs boson couplings

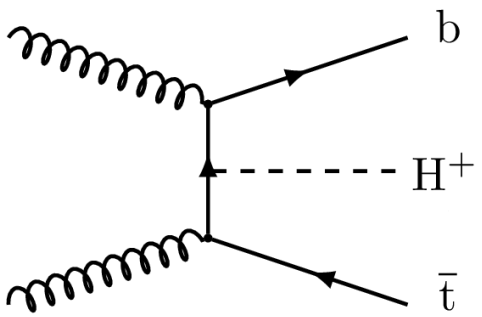
BACKUP

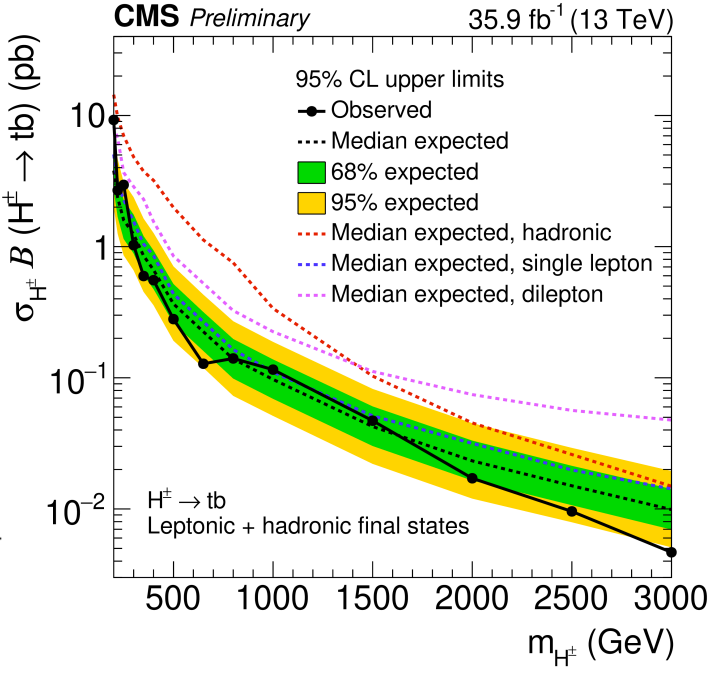
Charged Higgs to top and bottom at 13 TeV

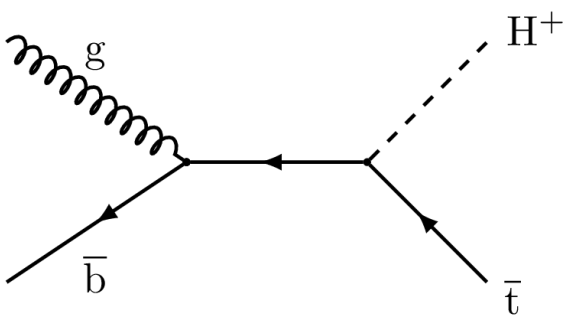


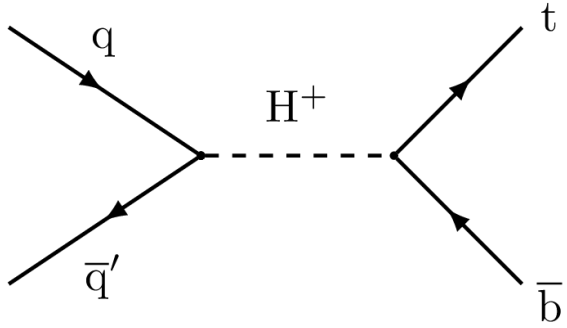


CMS PAS HIG-18-015



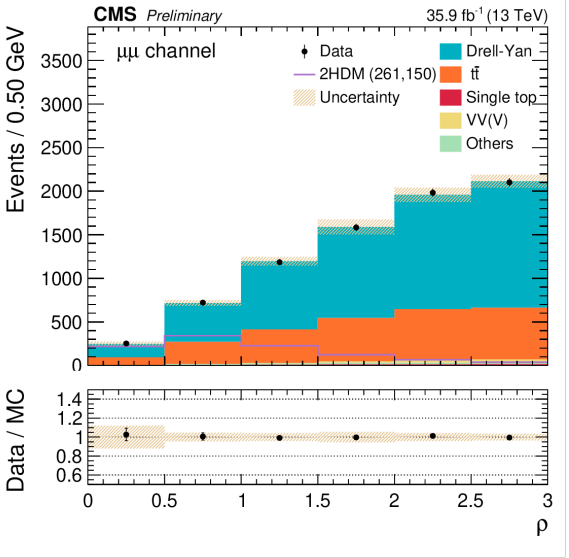


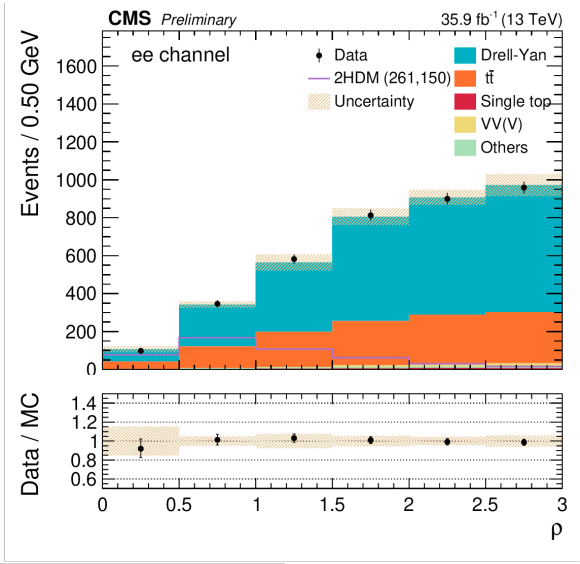


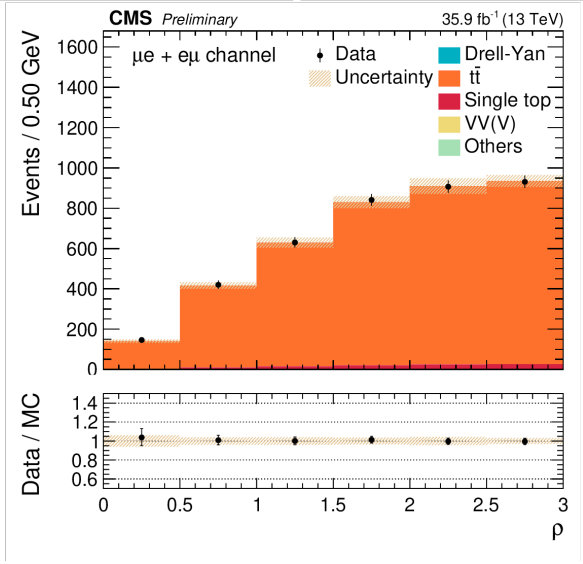


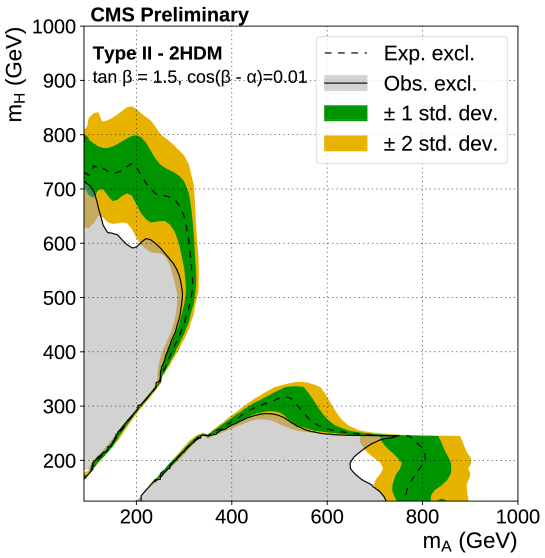
Search for 2HDM neutral H->ZA->llbb at 13 TeV

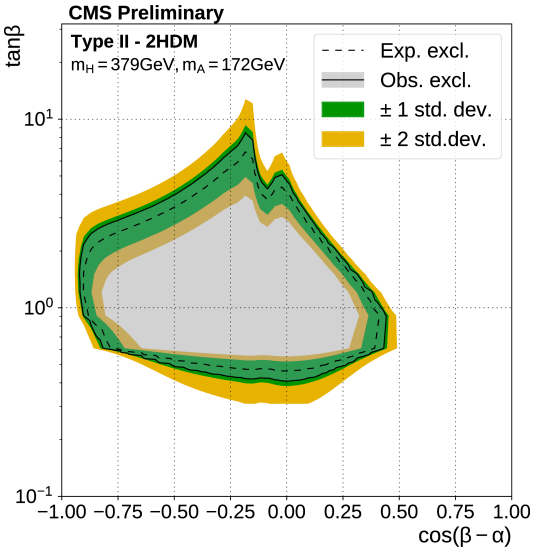
CMS PAS HIG-18-015





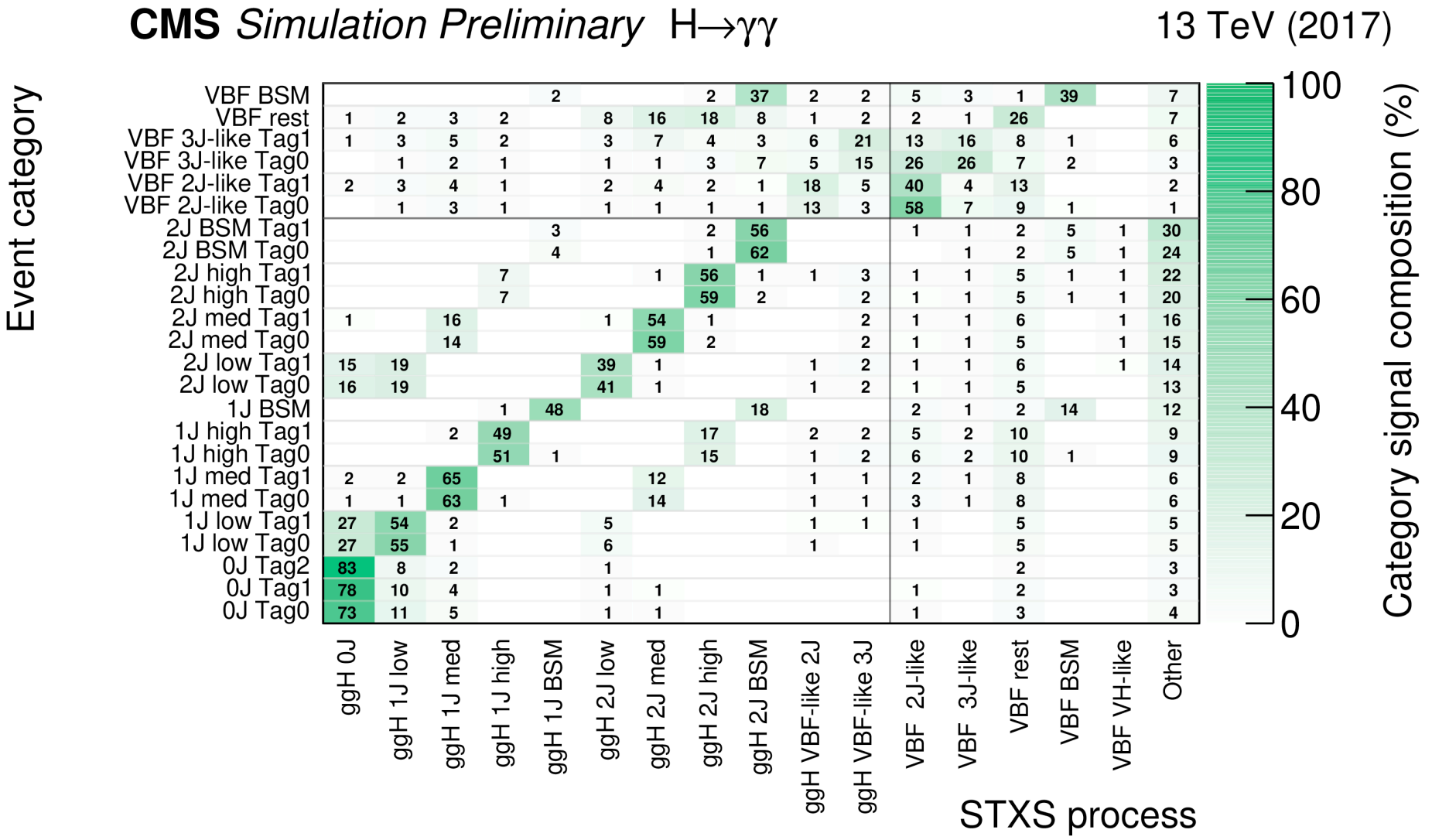






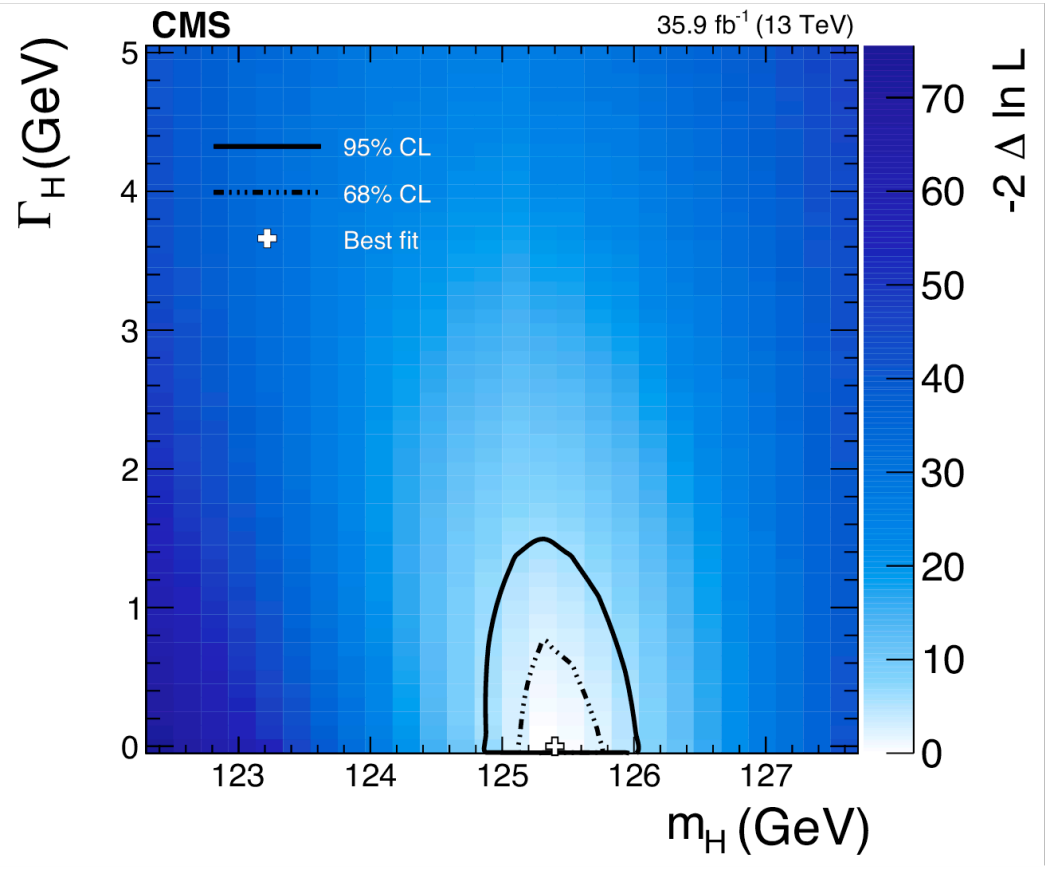
ggF and VBF Higgs to diphoton at 13 TeV

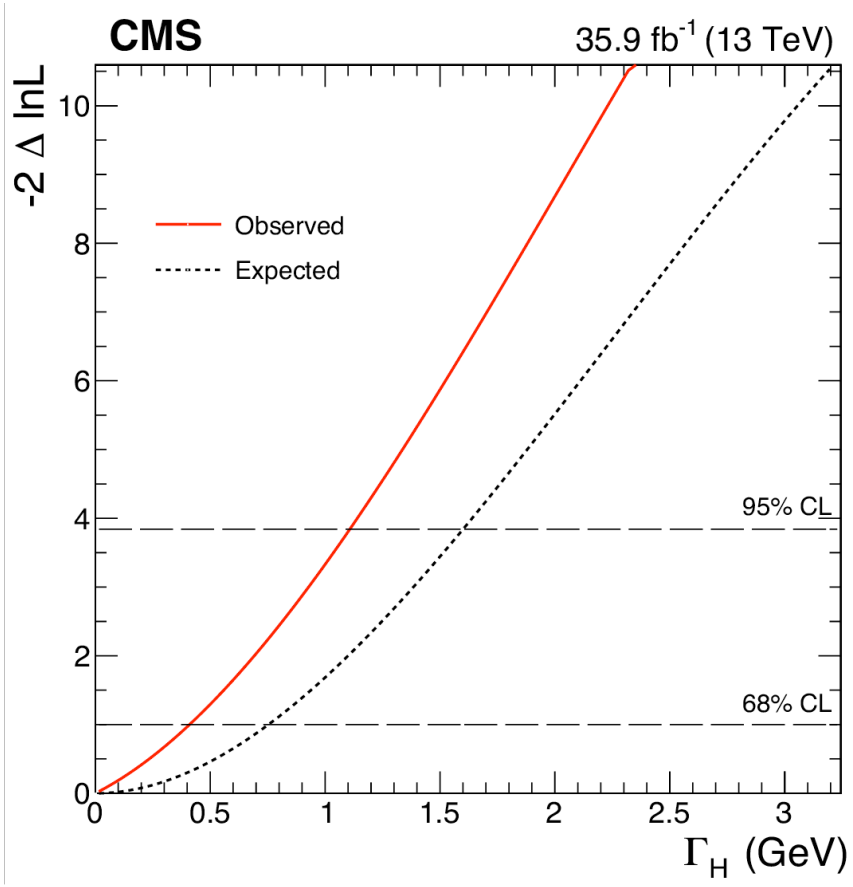
CMS PAS HIG-18-029



Higgs boson mass from H->ZZ->4l at 13 TeV

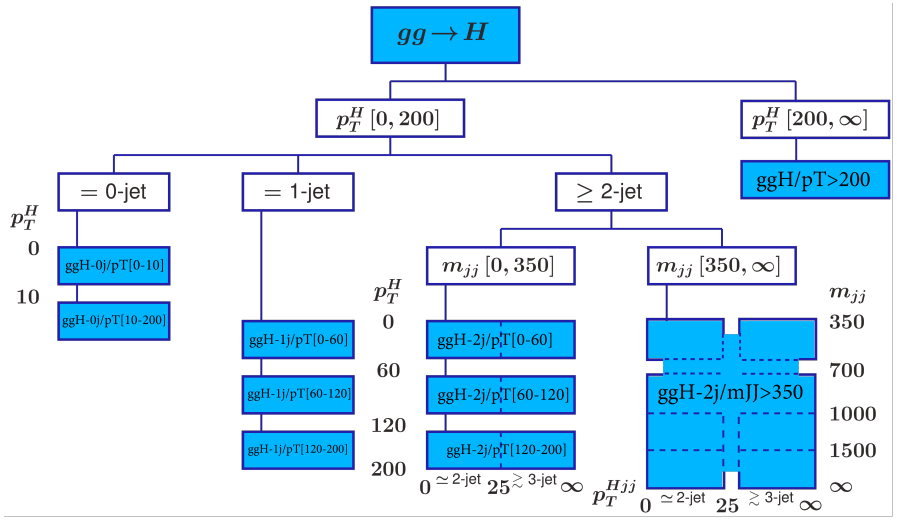
JHEP 11 (2017) 047

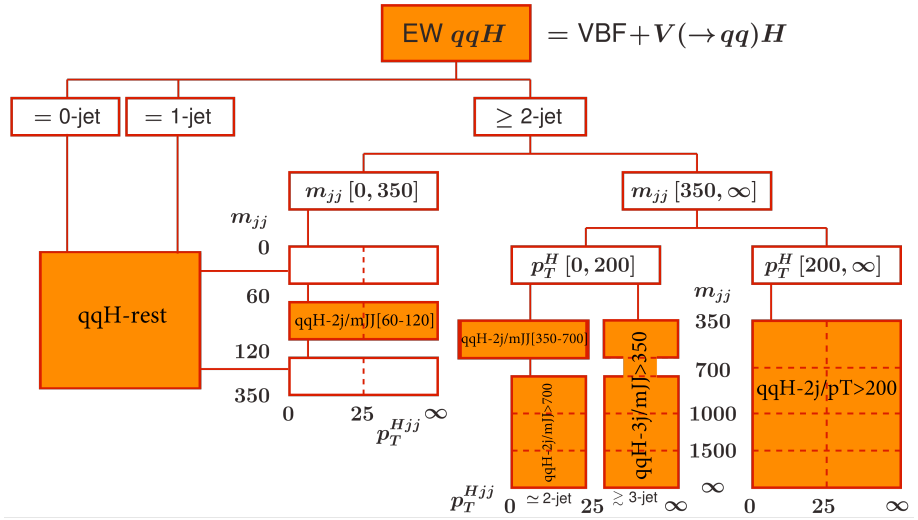




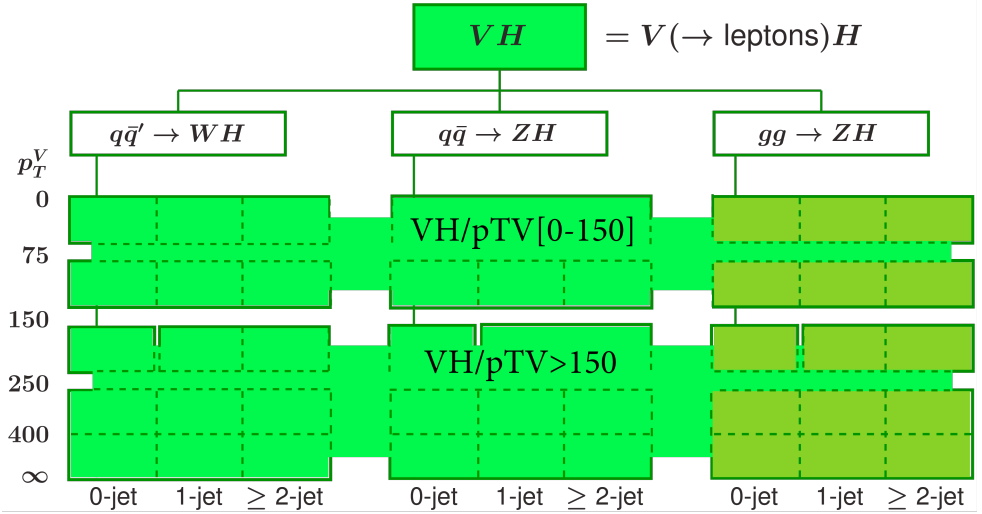
Higgs boson couplings from H->ZZ->4l at 13 TeV

CMS PAS HIG-19-001



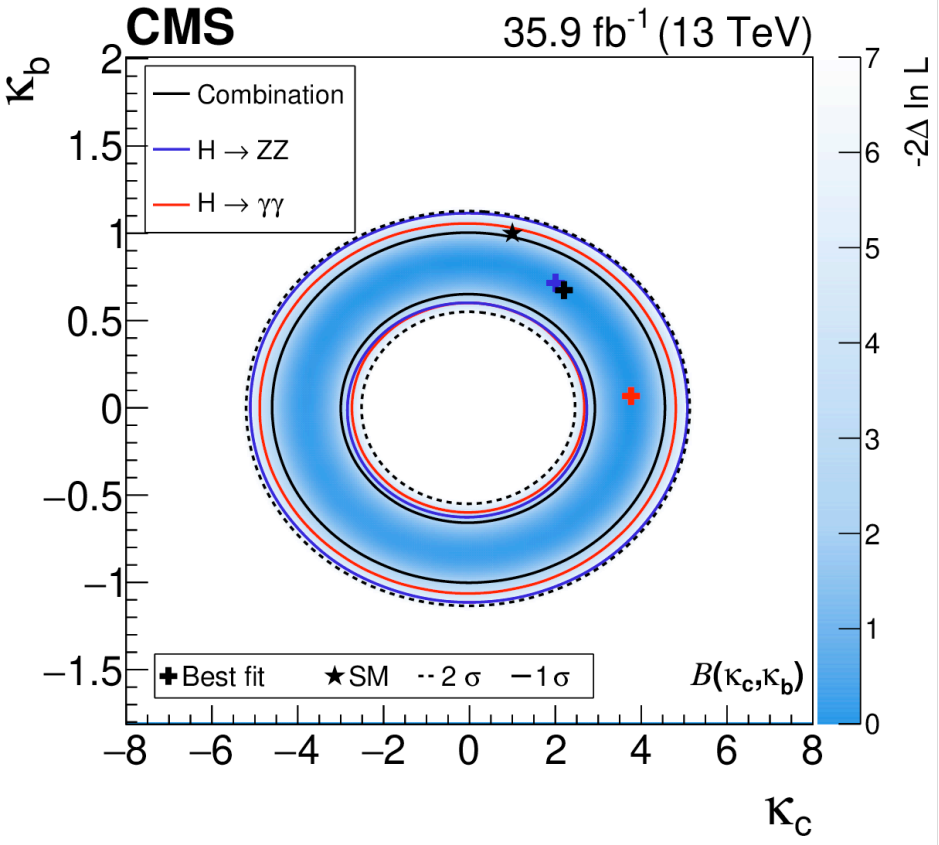


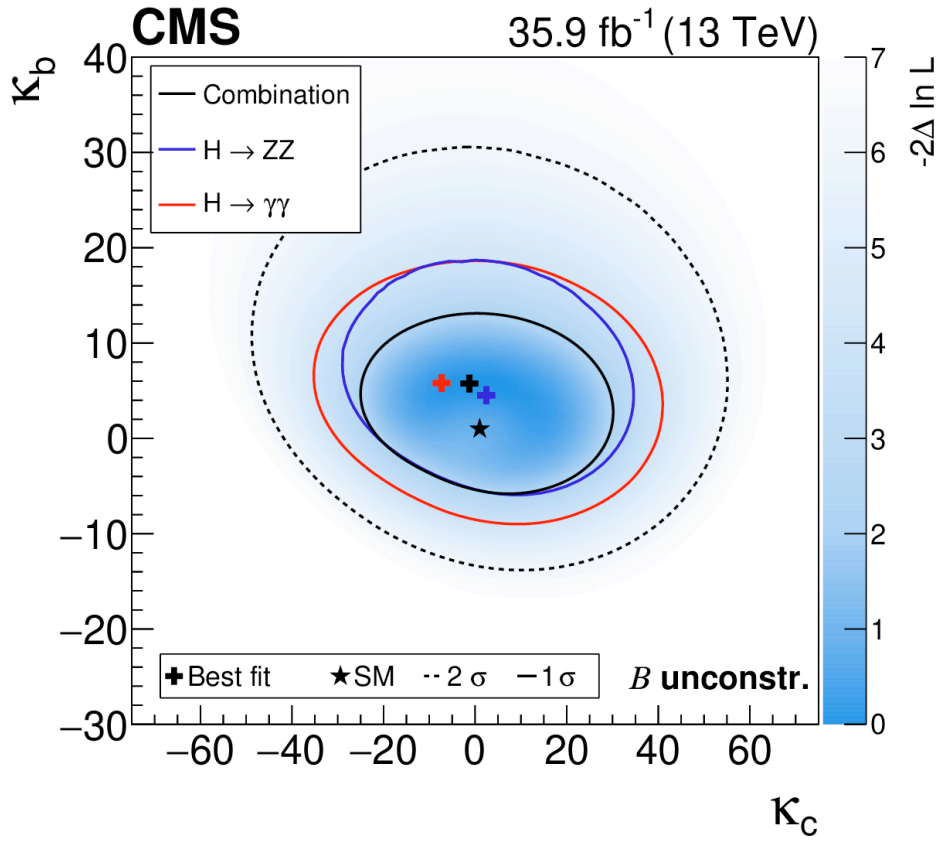
Binning of various production modes in STXS stage approach



Total Higgs boson Cross Section measurement

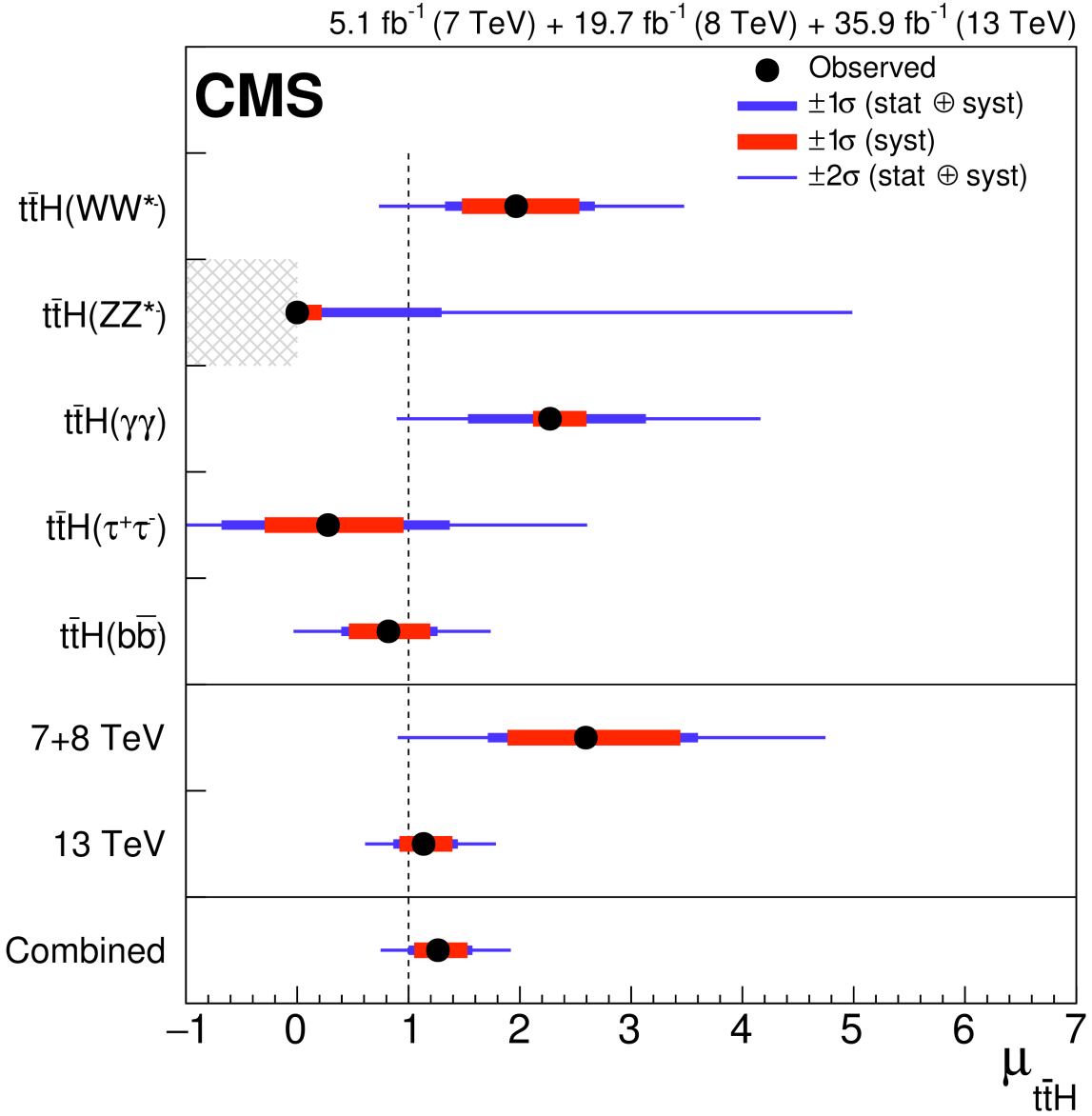
PLB 792 (2019) 369





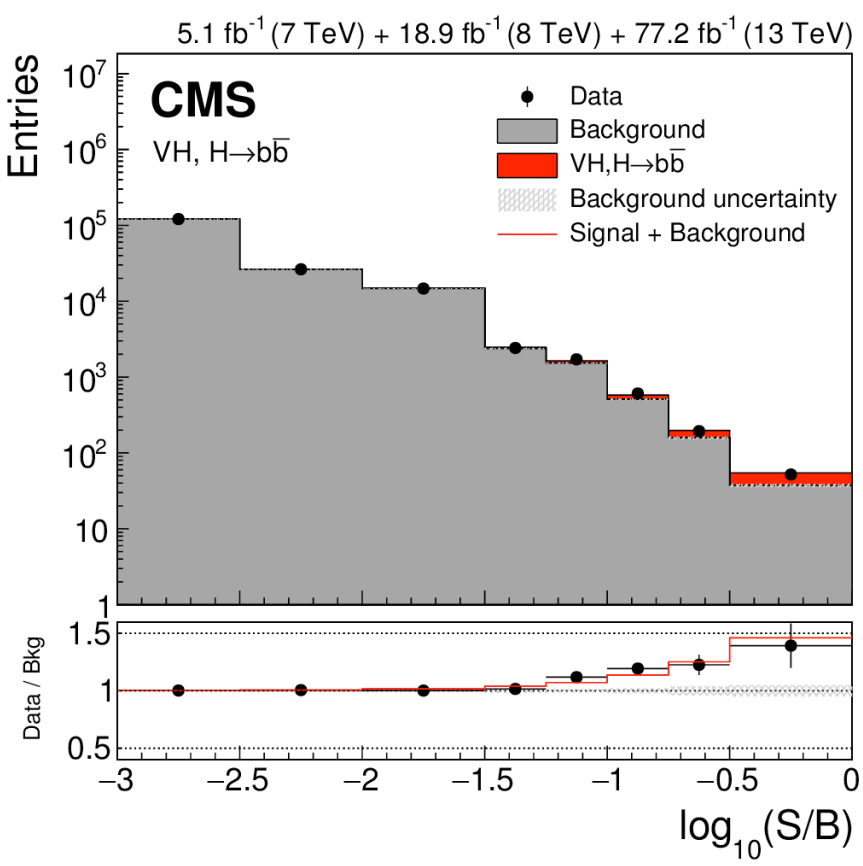
Observation of ttH production at 13 TeV

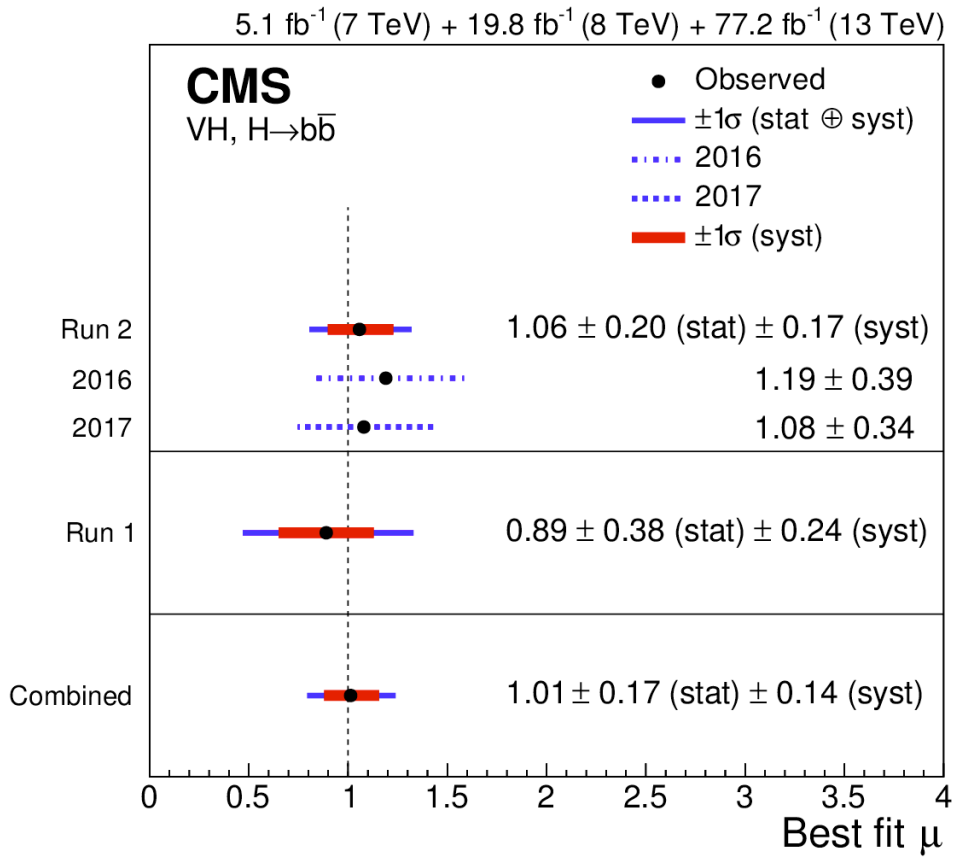
PRL 120 (2018) 231801



Observation of Higgs decay to bottom quarks

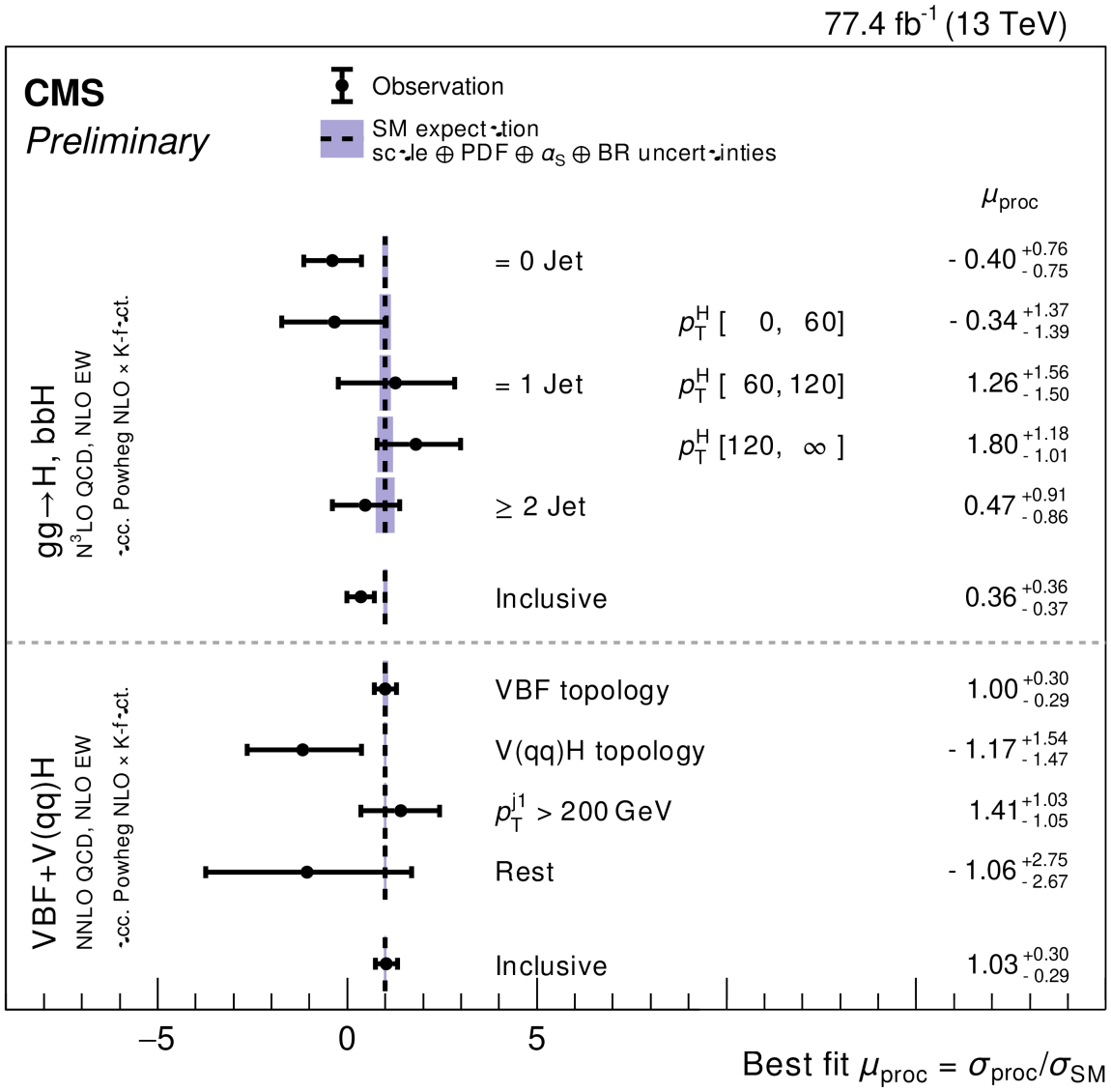
PRL 121 (2018) 121801





Higgs boson production and decay to ττ at 13 TeV

CMS PAS HIG-18-032



Higgs boson decaying to charm quarks

CMS PAS HIG-18-031