# Recent results on Higgs boson measurements at CMS


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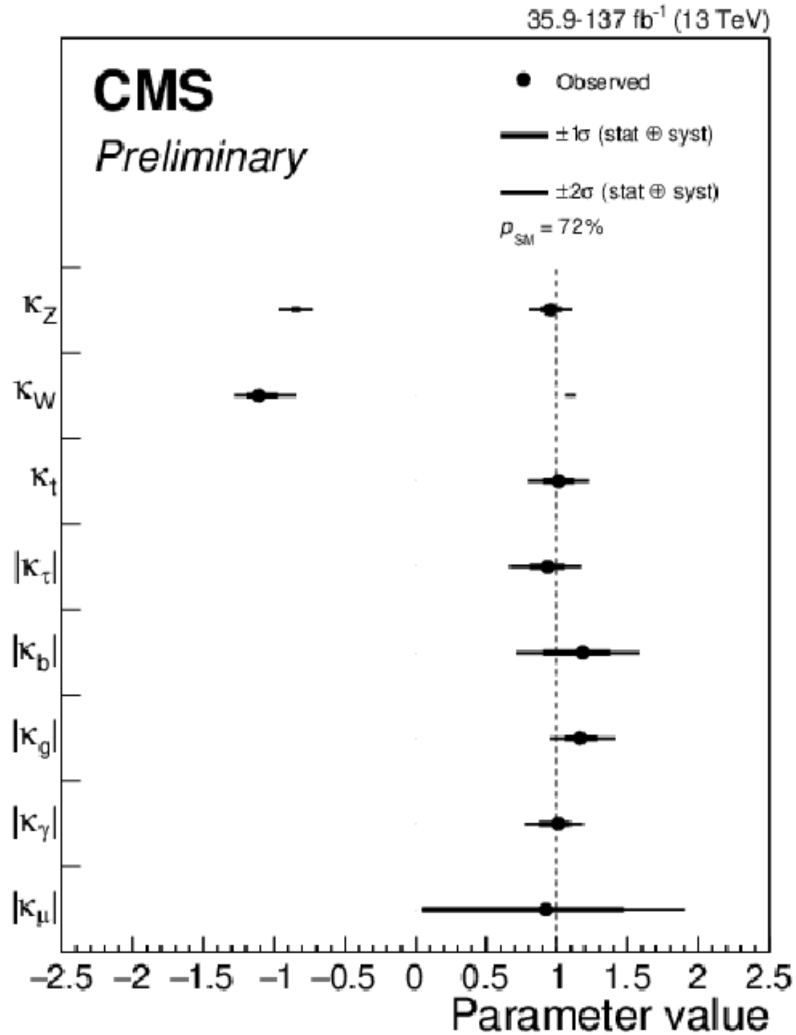
# Introduction

Since its discovery in 2012 we have made great journey in characterizing the Higgs boson

- Many of its properties are being probed, especially with the large amount of data collected at 13 TeV during LHC Run-2
- Most precise measurements of its mass, so far:

  **$m_H$ = 125.38 ± 0.14 GeV**

  (Run-1 + 2016 data)
- Couplings are being measured more precisely
- Analyses are carried out for measuring differential cross sections, probe CP-violation, anomalous couplings etc..
- This talk presents results of only a few recent measurements




CMS-PAS-HIG-19-005

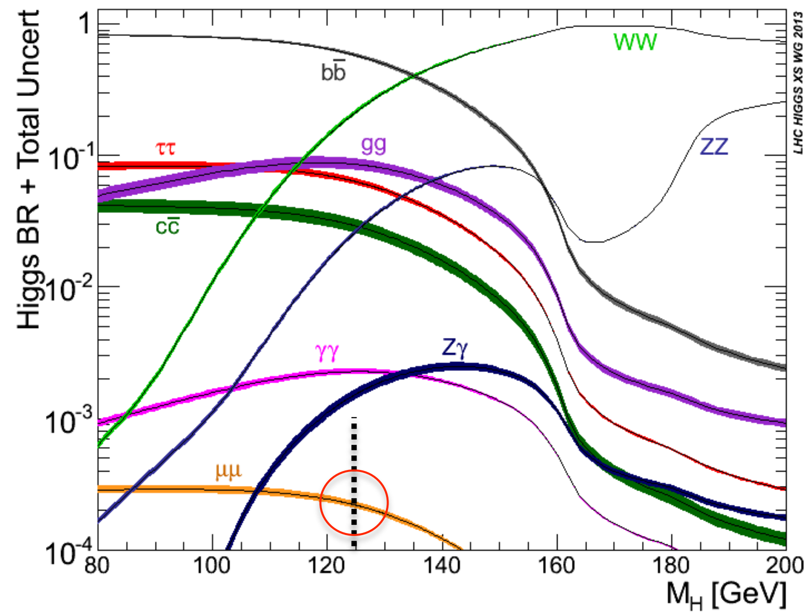
# Overview

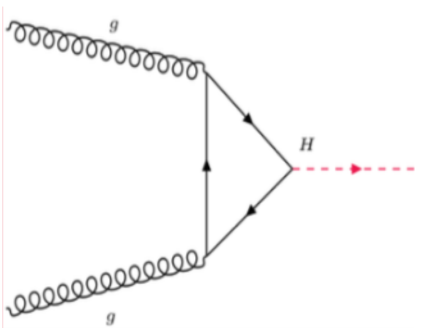
- Search for H → $\mu\mu$ decay [CMS-PAS-HIG-19-006]
- Measurement of H → $\tau\tau$ cross section and probe of CP violation [CMS-PAS-HIG-19-010, CMS-PAS-HIG-20-006]
- ttH measurements in multilepton final states [CMS-PAS-HIG-19-008]
- Measurements of properties H → $\gamma\gamma$ decay [CMS-PAS-HIG-19-015]
- Constraints on Anomalous couplings in H → $4\ell$ channel [CMS-PAS-HIG-19-009]

# H→μμ

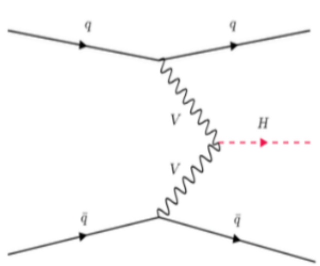
- Golden channel for probing Higgs boson coupling to 2nd generation fermion
- Challenging: Br(H→μμ) ≈ $2.18 \times 10^{-4}$
- Searches performed in four exclusive categories, targeting the production modes: ggH, VBF, VH, ttH
- Events collected using single-muon trigger
- Basic Event Selection: Two well identified and isolated, opposite charged muons with:

$$110 < m_{\mu\mu} < 150 \text{ GeV}$$

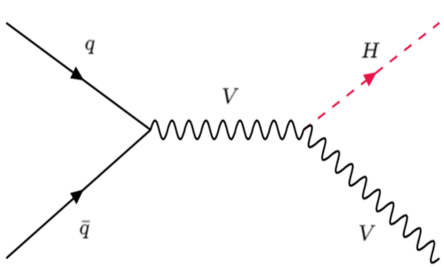


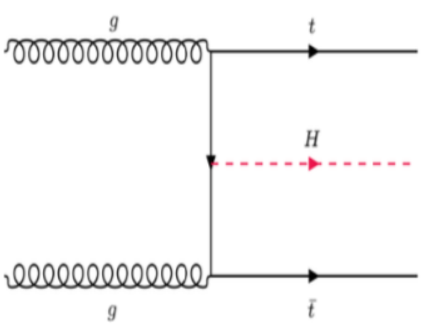
ggH



VBF



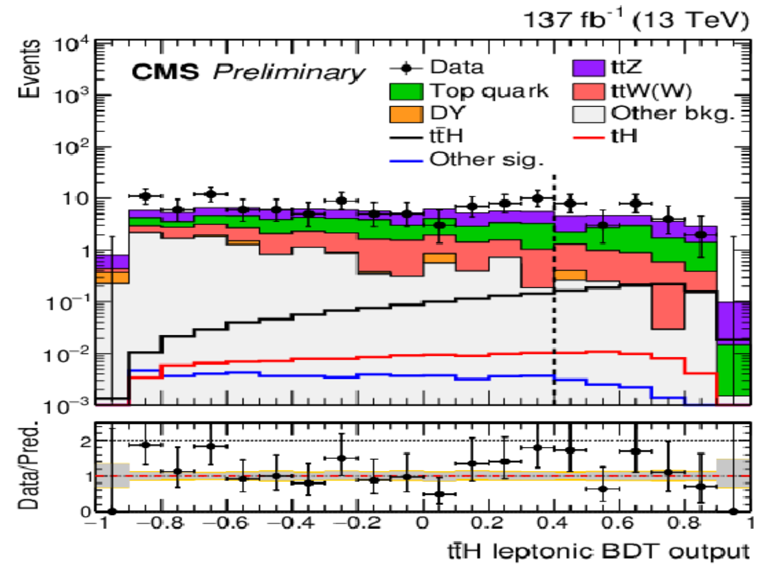
VH

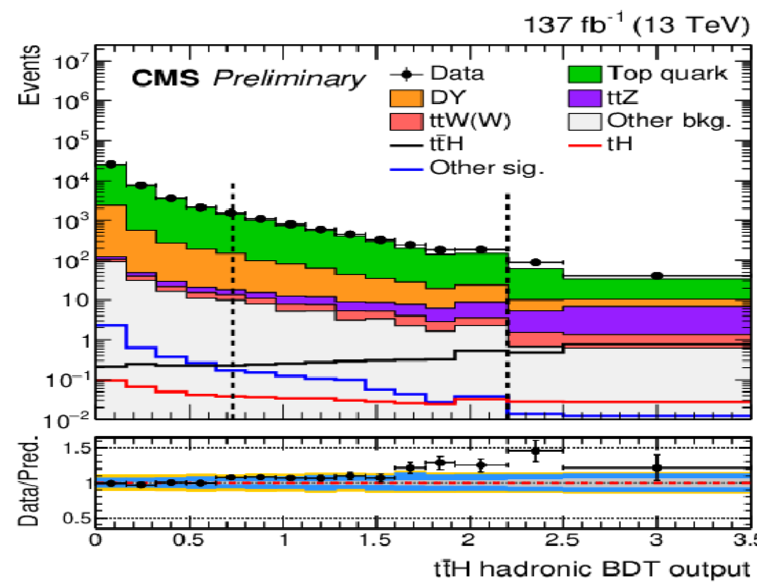


ttH

# ttH, H→μμ

- Smallest production cross section
- Event topology requires to have at least two b jets
- Events categorized based on W decay
  - Leptonic: 1 or 2 additional leptons (W→ℓν)
  - Hadronic: W→ qq', tt is major bkg
- Separate BDT trained for each categories
  - Variables sensitive to tt and μμ kinematics, but uncorrelated with $m_{\mu\mu}$ mass
- Events further splitted based on BDT output (dashed line)
  - Leptonic: 2 categories, Hadronic: 3 categories
- $m_{\mu\mu}$ distributions in each sub-categories for fitted to extract signal



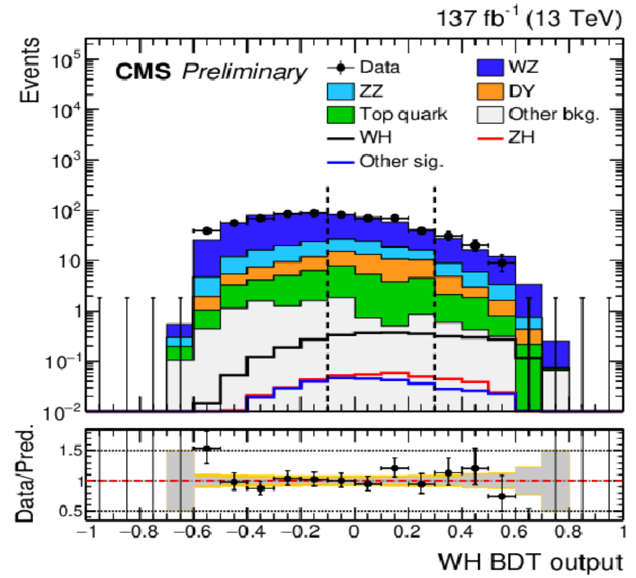
# VH, H→μμ

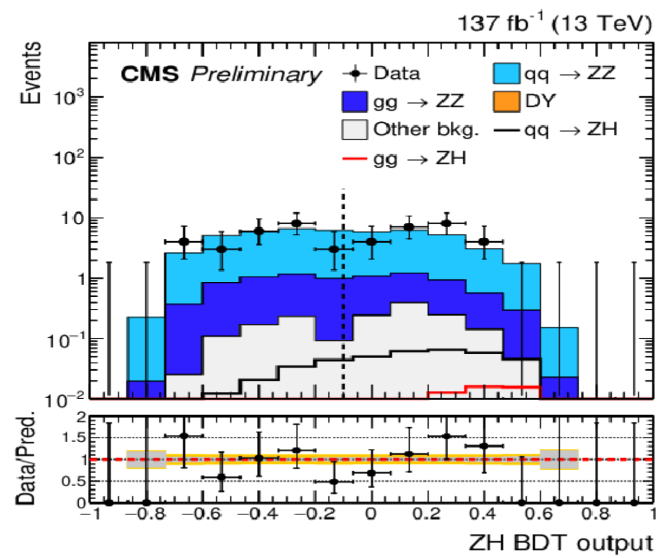
- Search for additional leptons, other than μμ pair
- Events divided into WH and ZH categories

- BDT discriminator for each categories
  - Variables exploit W/Z topology, in addition to μμ topology

- Further sub-categories based on BDT output distribution
  - WH: 3 categories
  - ZH: 2 categories

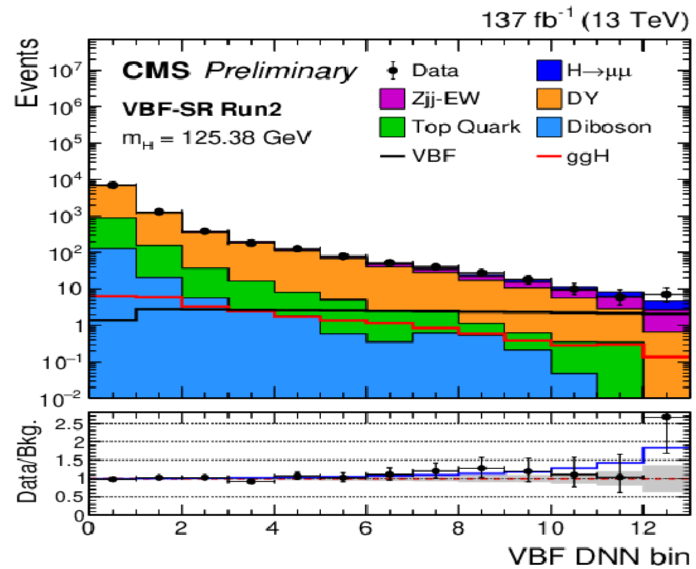
- $m_{\mu\mu}$ is fitted with Double-Crystal Ball (for signal) and modified Briet-Wigner (for background) to extract signal

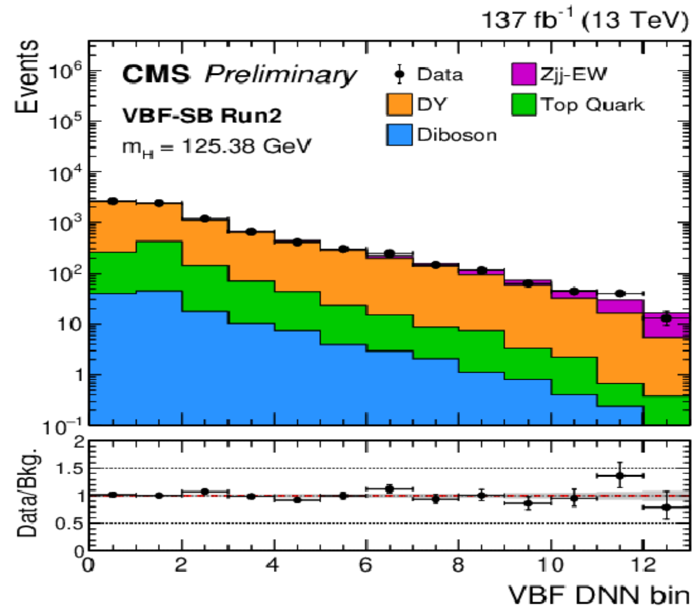


# VBF H→μμ

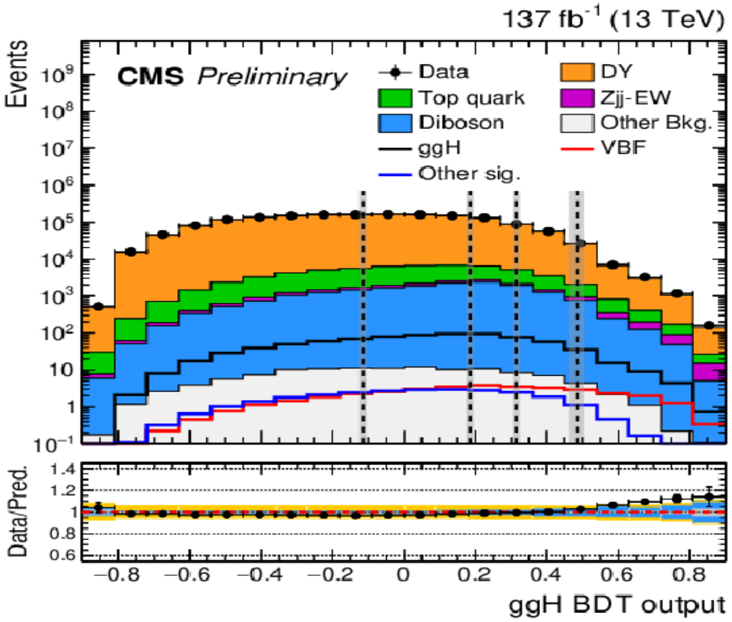
- Distinct topology of jets in VBF production process
  - Two jets in the forward direction, with large rapidity gap and large $m_{jj}$.
- Primary Backgrounds: Z+jets
  - Estimated by extrapolating from $m_{\mu\mu}$ side bands (limited by statistics)
- Deep Neural Network (DNN) for the extraction of signal
  - DNN trained on events in signal region (SR) and side-band (SB)
- Fit to the DNN output score simultaneously in SR and SB to extract signal
  - Inclusion of SB improves background normalization



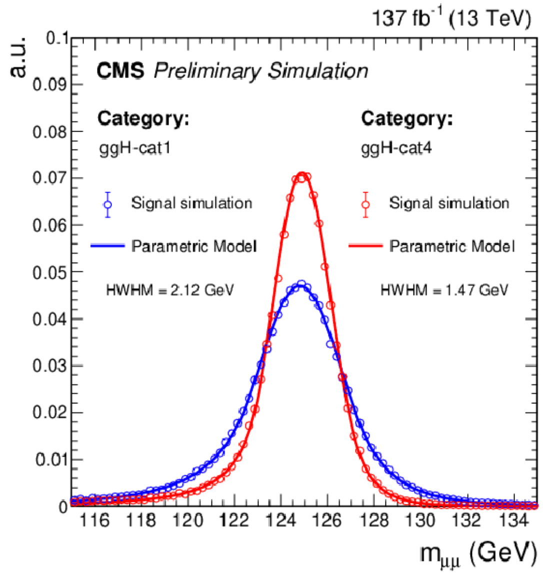
# ggH, H→μμ

- Largest fraction of inclusive events
  - Includes events rejected by all 3 previous categories
  - Dominated by events with 0/1-jets
  - Lowest purity (smallest S/B)



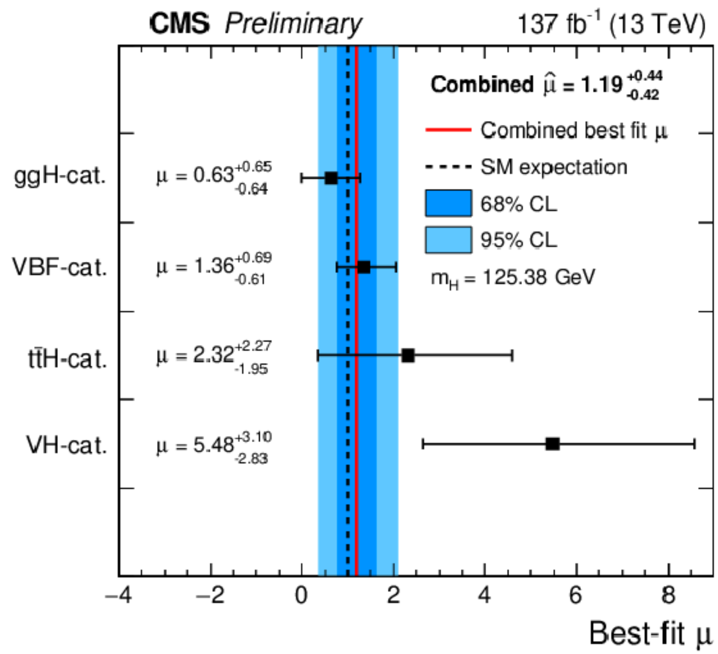

- BDT discriminator to further categorize events based on purity
  - Muon variables in training (decorrelated with $m_{\mu\mu}$)
  - Includes also jet variables, to recover H+X events

- Signal is extracted by fitting $m_{\mu\mu}$ distribution with analytical shapes
  - Signal by Double Crystall-ball function
  - Bkg (dominated by DY) by modified Breit-Wigner etc.., modulated via polynomials



# H→μμ results

CMS-PAS-HIG-19-006

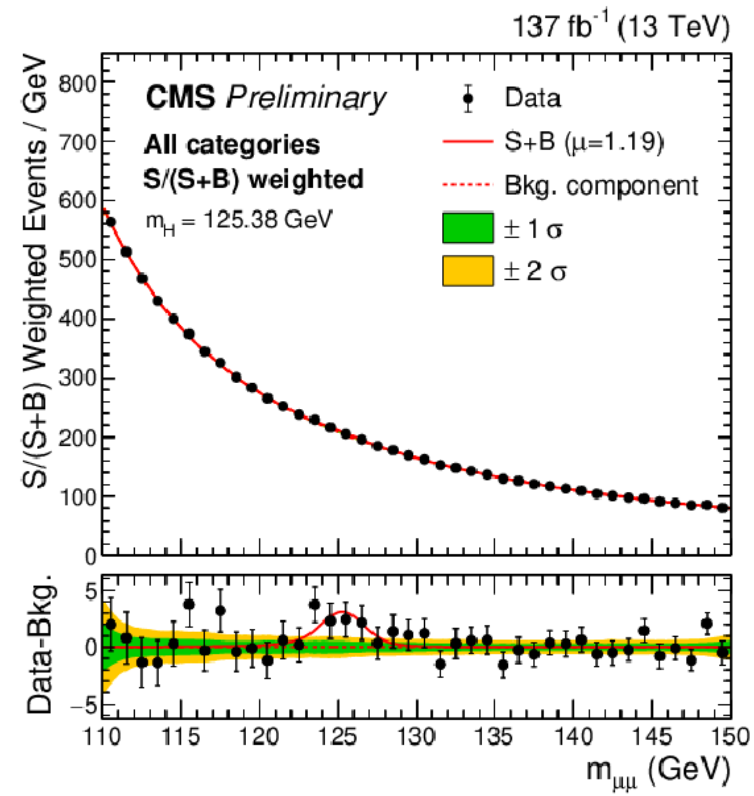



| Uncertainty source | $\Delta\mu$ | |
|---|---|---|
| Total uncertainty | +0.44 | −0.42 |
| Statistical uncertainty | +0.41 | −0.39 |
| Total systematic uncertainty | +0.17 | −0.16 |
| Size of simulated samples | +0.07 | −0.06 |
| Total experimental uncertainty | +0.12 | −0.10 |
| Total theoretical uncertainty | +0.10 | −0.11 |

Simultaneous fit to all channels

Observed signal strength $\mu = \sigma \times BR / [\sigma \times BR]_{SM}$

$$\mu = 1.19^{+0.41}_{-0.39}(stat)\,^{+0.17}_{-0.16}(syst)$$



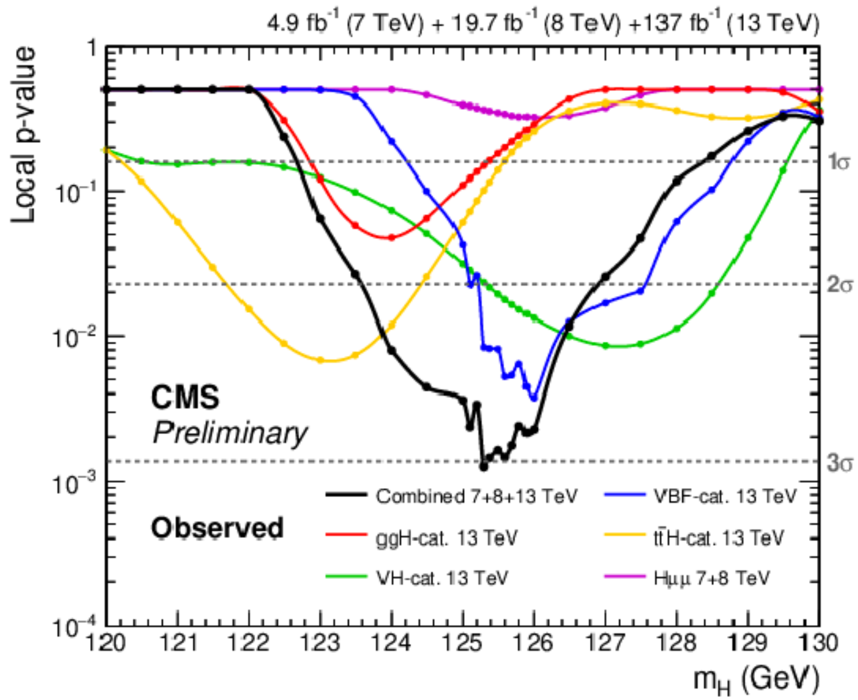

For illustration purposes only, does not represent fit results

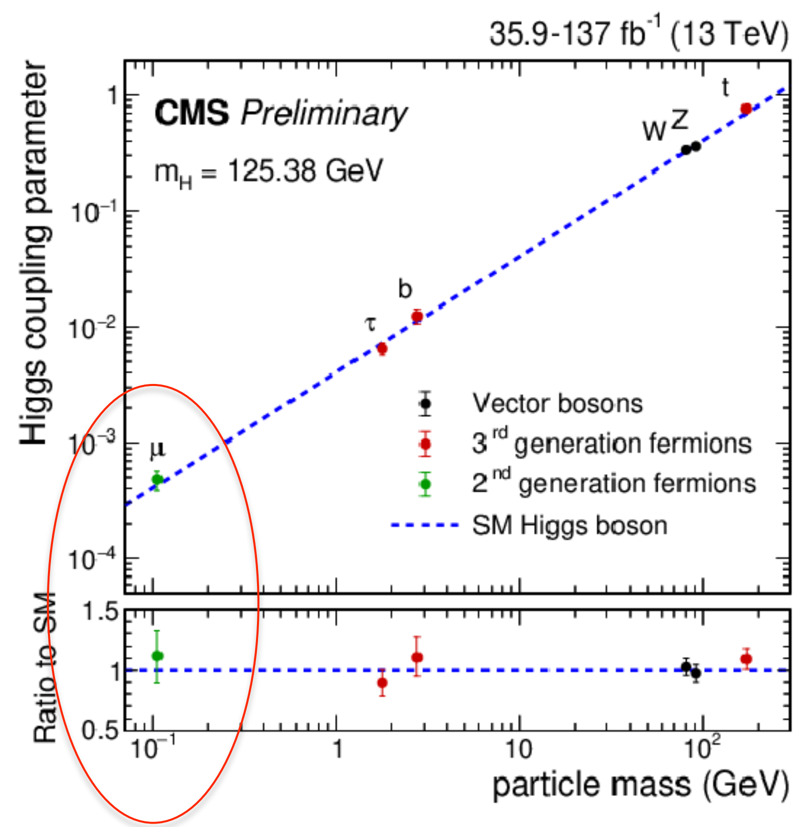
# H→μμ results

CMS-PAS-HIG-19-006

Combined with Run-1 measurement (Phys. Lett. B 744 (2015) 184)

The observed excess in data with respect to SM background corresponds to a significance of 3σ



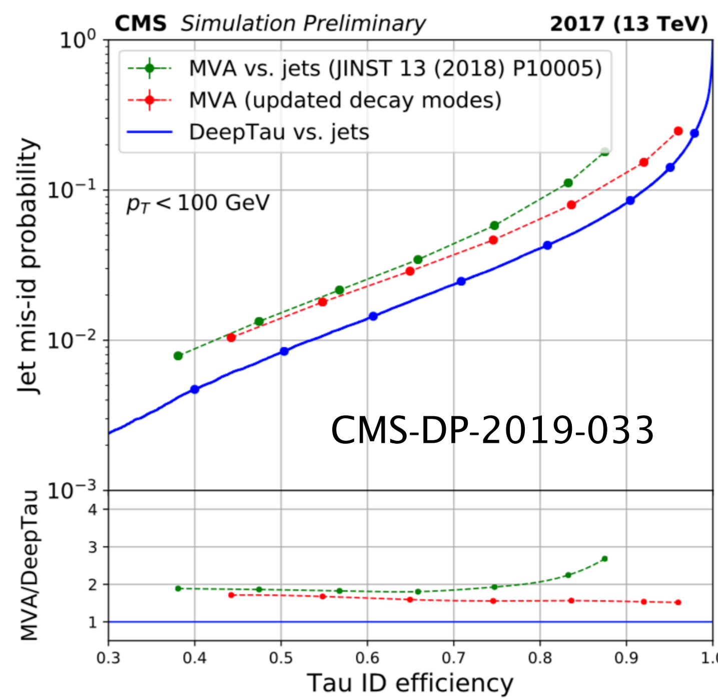

First evidence of H→μμ decay at LHC

# H→ττ

- Direct probe of Yukawa coupling to τ leptons
- Advantage:
  - Relatively larger branching fraction
  - Production topologies like VBF, boosted etc.. can be exploited
- Difficulty:
  - Identification of τ lepton decay challenging
  - τ decay includes neutrinos => Higgs system cann't be reconstructed fully
- Analysis channels based on τ decay modes: $e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$

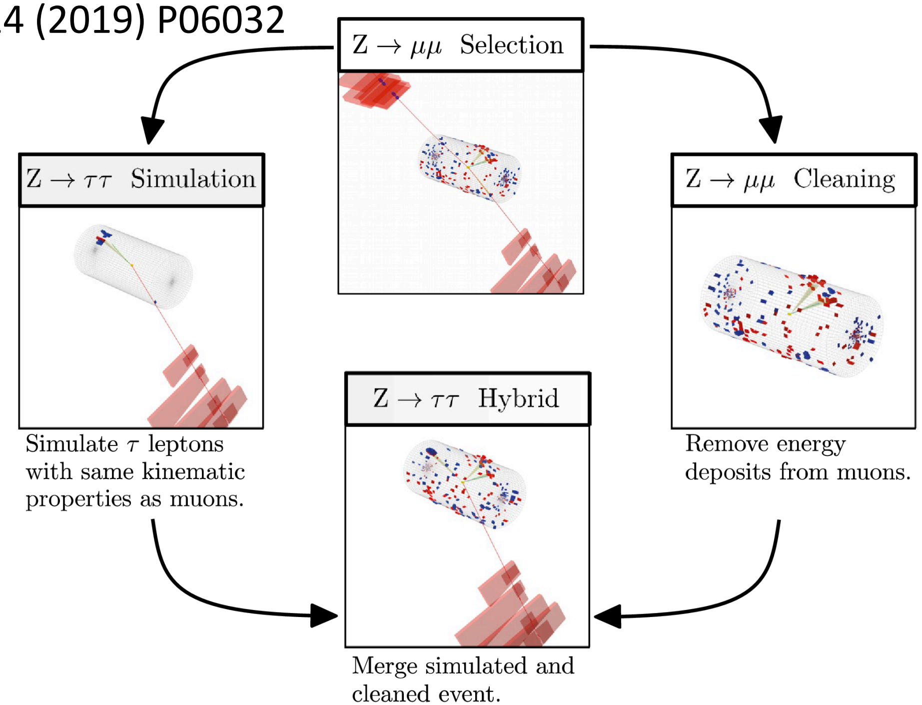
H→ττ already discovered using Run1+2016 data (PLB 779 (2018) 283)

- Hadronic decay of τ lepton ($\tau_h$) is reconstructed using hadron-plus-strips algorithm → Combines PF charged hadrons and e/γ candidates to reconstruct decay modes
- Multiclass DNN based algorithm (DeepTau) is used to reject fakes from jets, electrons, and muons
  - Significant improvement compared to previous BDT based fake discrimination

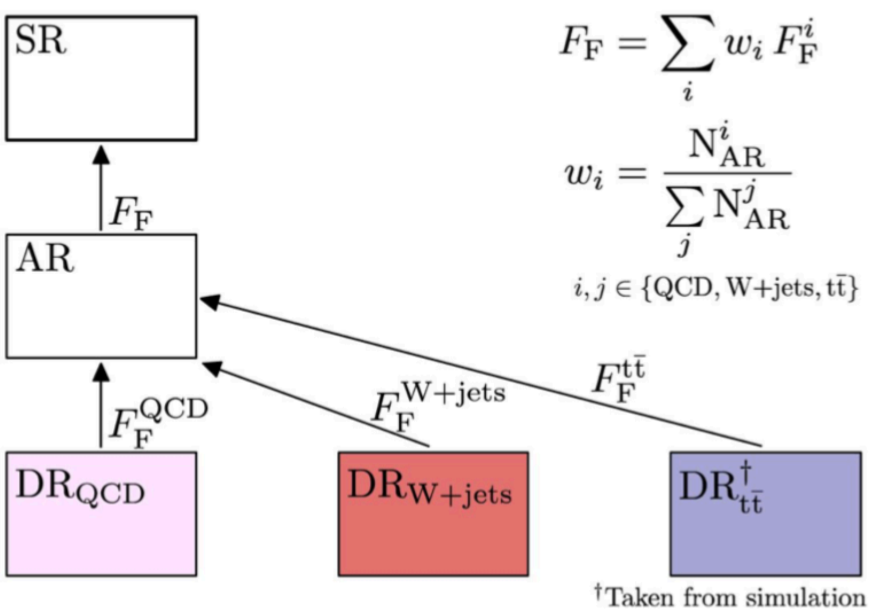


# Backgrounds

JINST 14 (2019) P06032




- Largest irreducible background: events with two genuine τ leptons (mostly Z→ττ)
- Estimated using a μ→τ embedding technique: Replace μ by a τ in Z→μμ events.

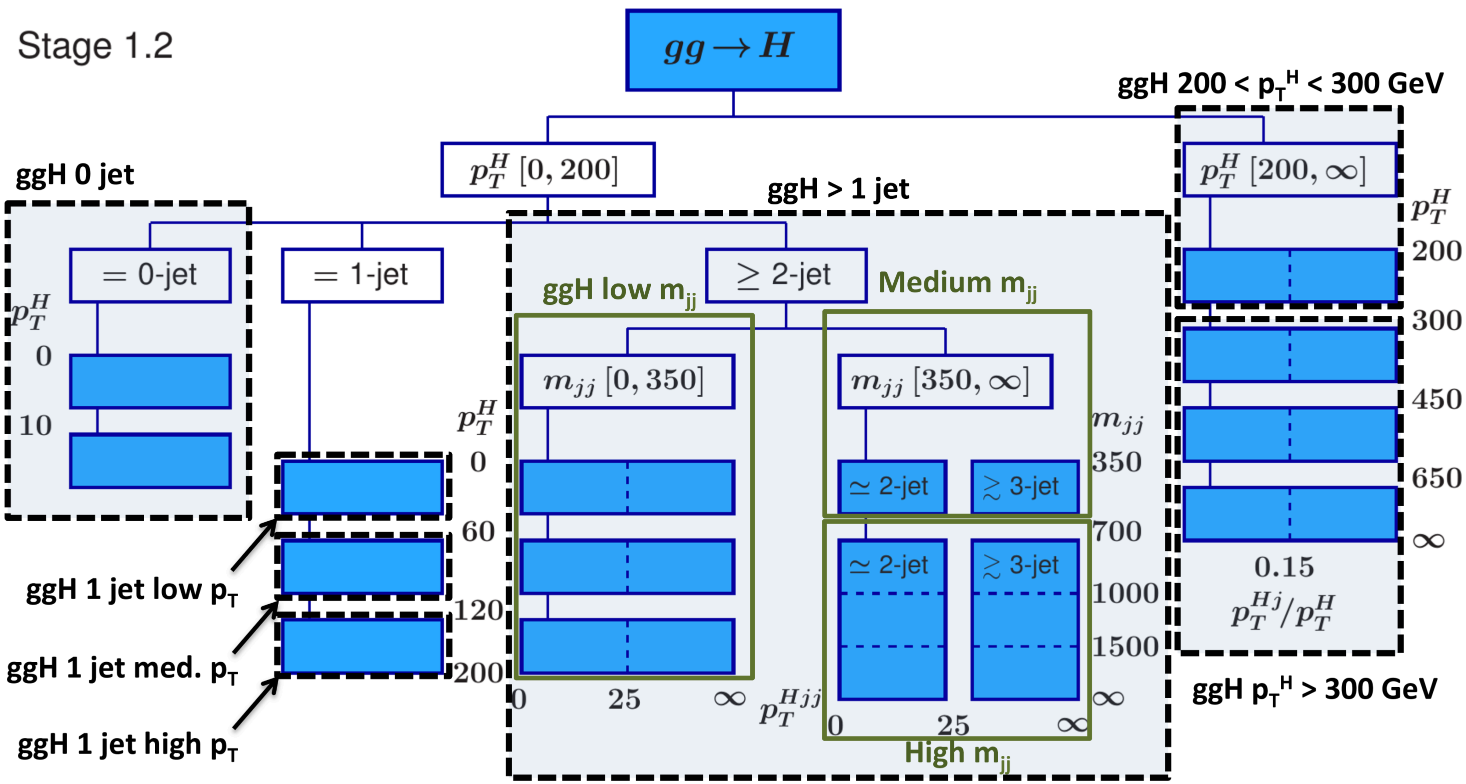



JHEP 09 (2018)007

Backgrounds with jet → $\tau_h$ fakes are estimated from data using a $\tau_h$ fake rate method.

# H→ττ cross section measurements

- Increase data allows precision measurements of Higgs cross sections
- Different production modes can be probed with better precision
- Measurements performed in simplified template cross section (STXS) framework
- Minimizes dependence on theory and allows results to be reinterpreted easily by theory community

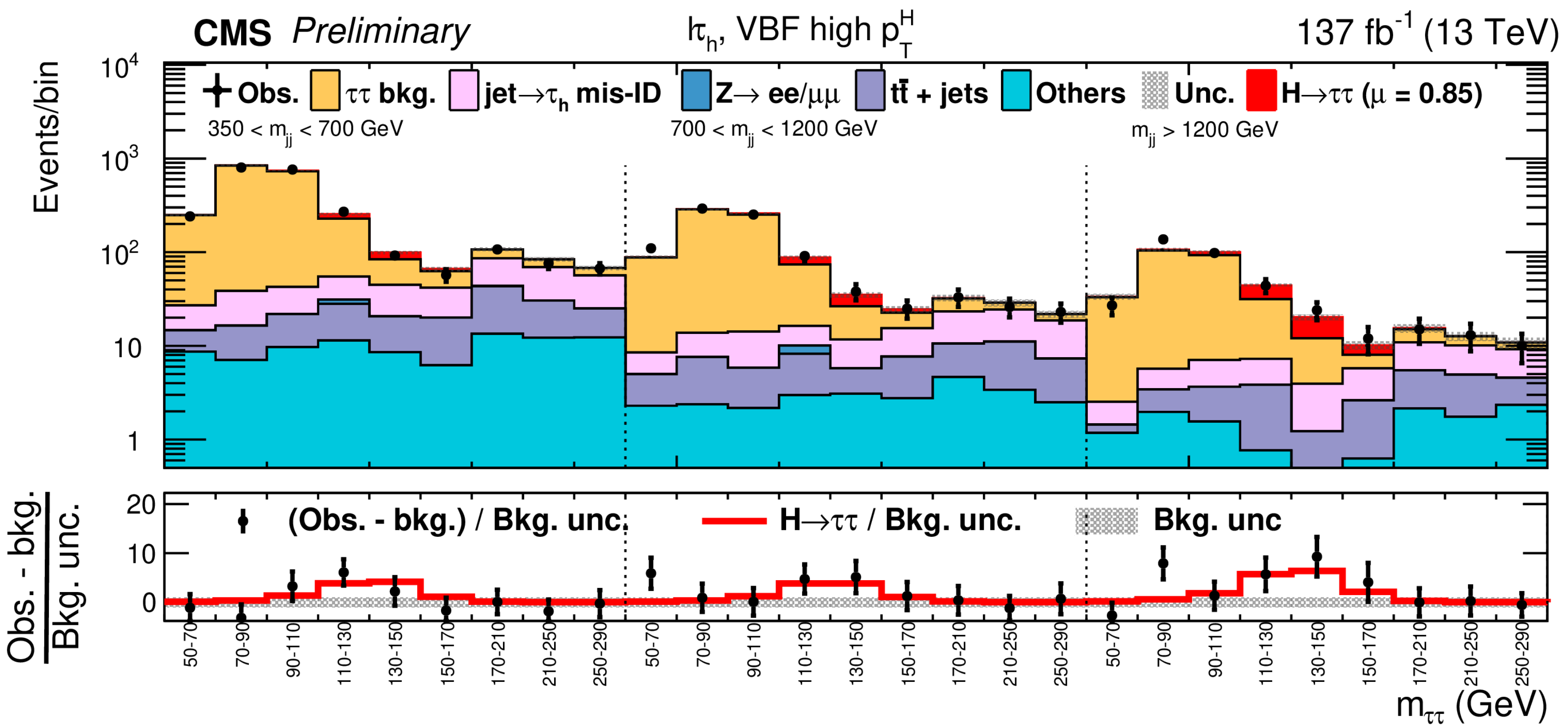




arXiv:1610.07922

# H→ττ cross section measurements

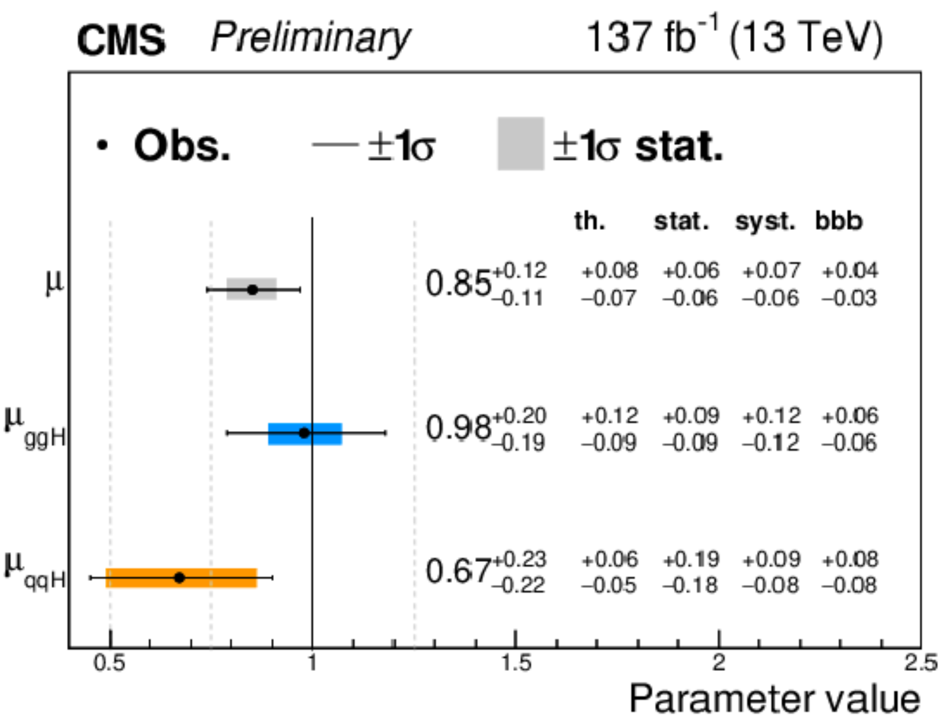
- Events split in 3 categories: 0-jet, boosted, VBF
- Further sub-categories in STXS bins
- 2D discriminants to enhance sensitivity: $m_{\tau\tau}$ vs ($m_{jj}$, $p_T^H$, $p_T^\tau$)



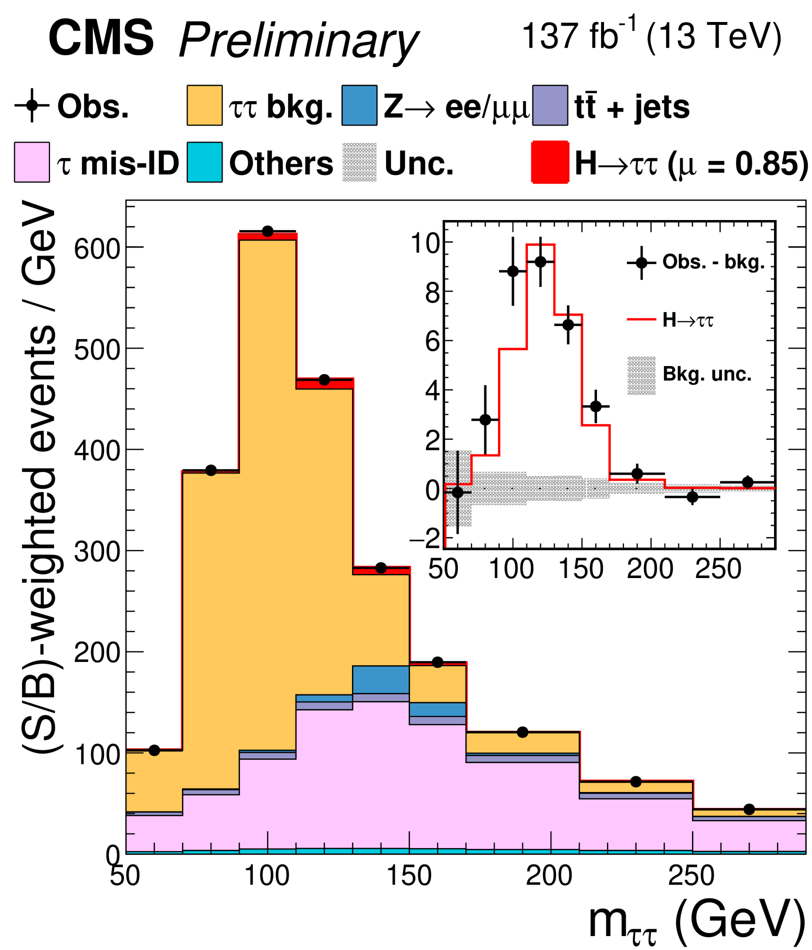
# H→ττ inclusive cross section

CMS-PAS-HIG-19-010

Results obtained using simultaneous binned maximum likelihood fit




All categories are combined and weighted by S/B



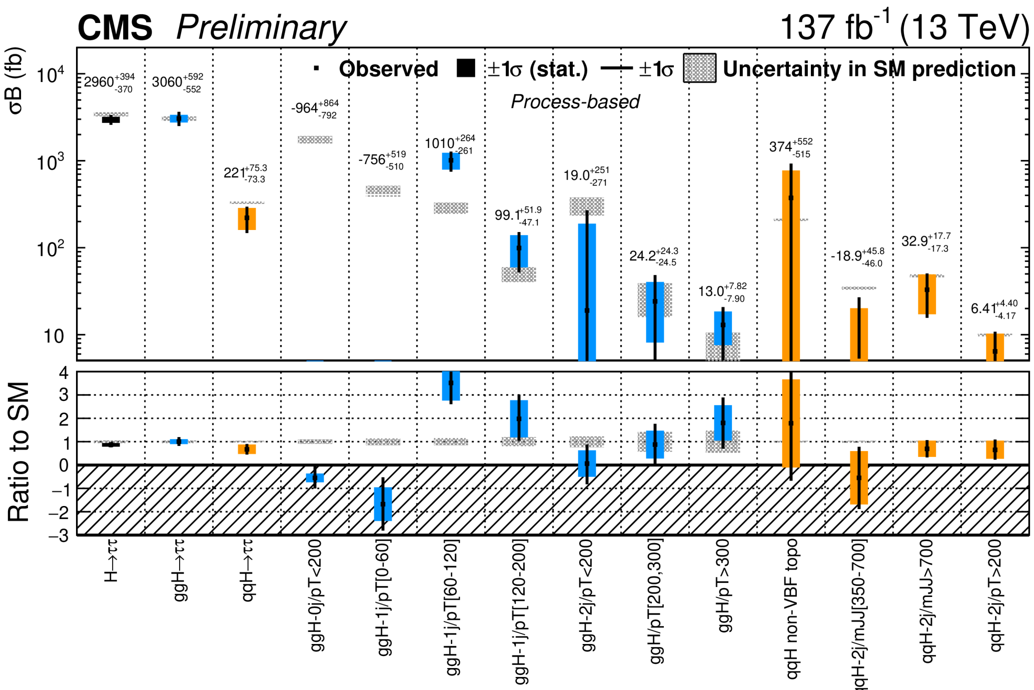
# H→ττ STXS results

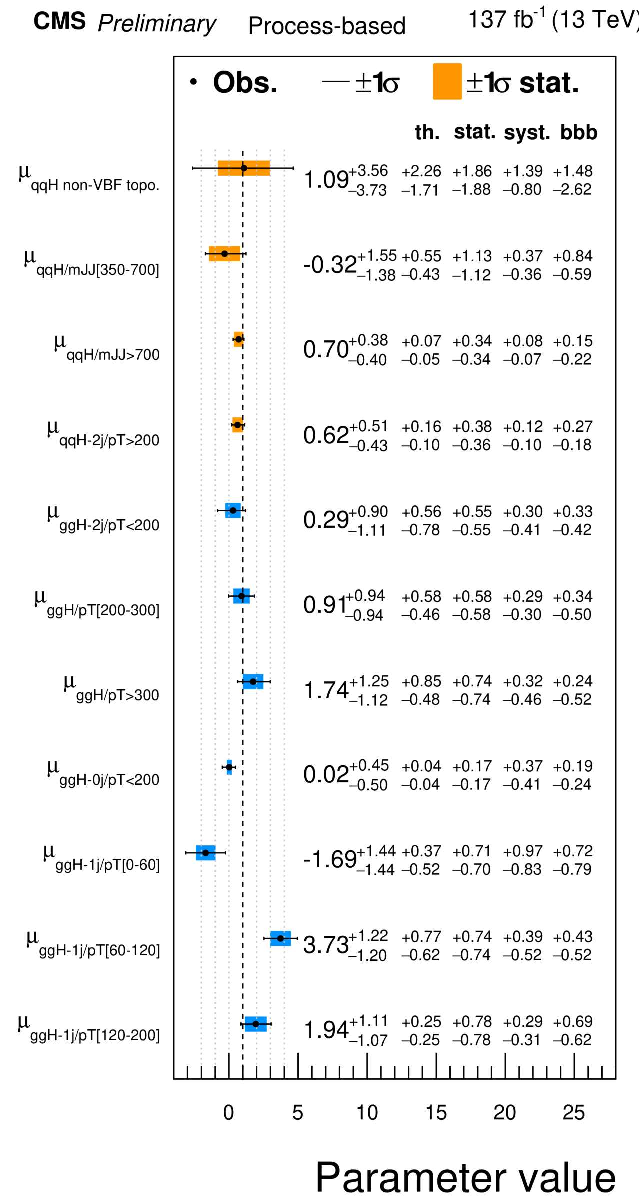
CMS-PAS-HIG-19-010

Some STXS bins are merged

2 different schemes

Process-based and topology-based



# H→ττ STXS results

CMS-PAS-HIG-19-010

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2 different schemes

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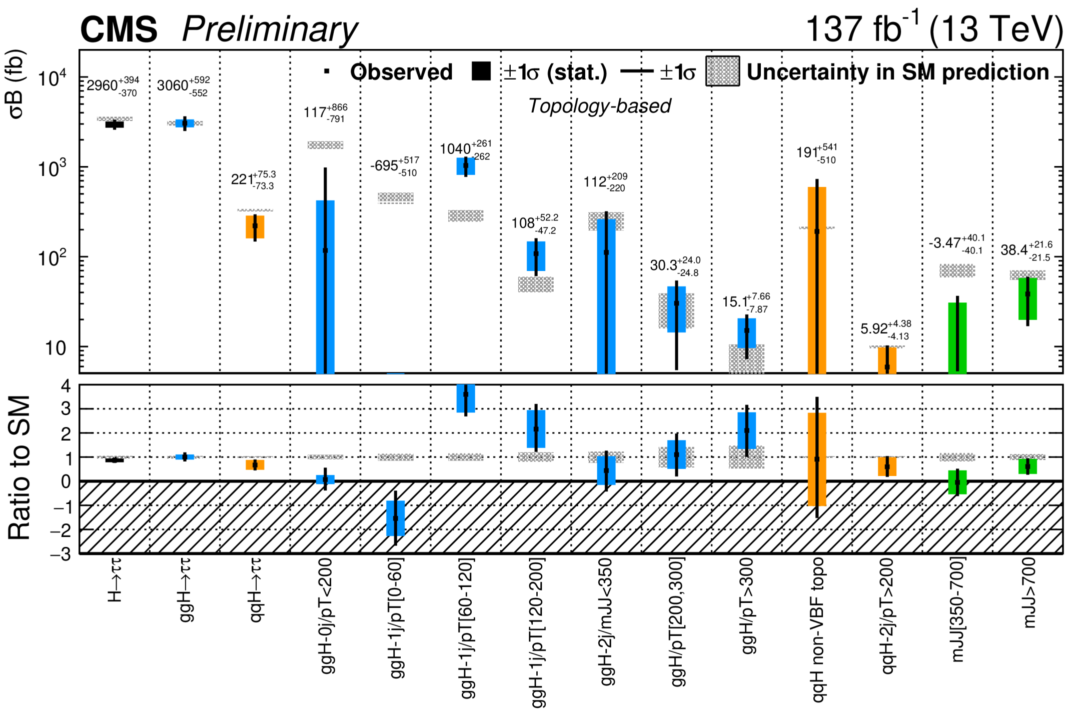
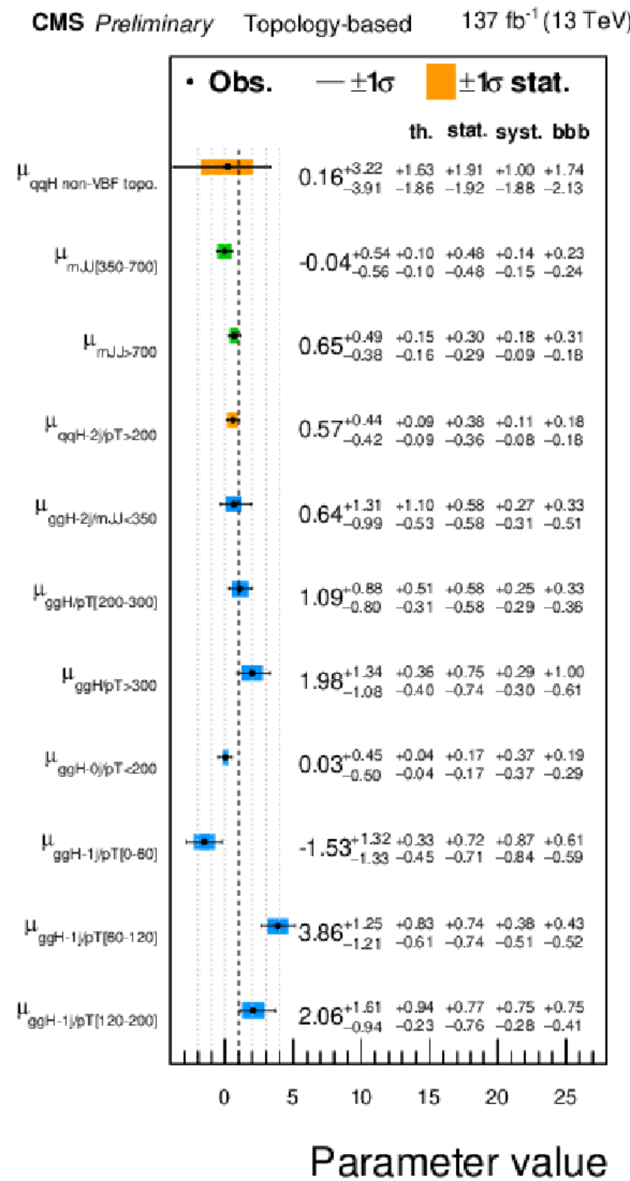


# Higgs CP in H→ττ decay

- Higgs CP in HVV couplings have been studied earlier at LHC
- It is less tested in couplings to fermions
- There have been some measurements in Higgs to top couplings (arXiv:2003.10866, arXiv:2004.04545)
- CP measurement in Higgs to tau coupling is complimentary to these results
- The interactions of Higgs boson to τ leptons can be parametrised as:

$$\mathcal{L}_Y = -\frac{m_\tau \mathrm{H}}{\mathrm{v}}(\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i \gamma_5 \tau)$$

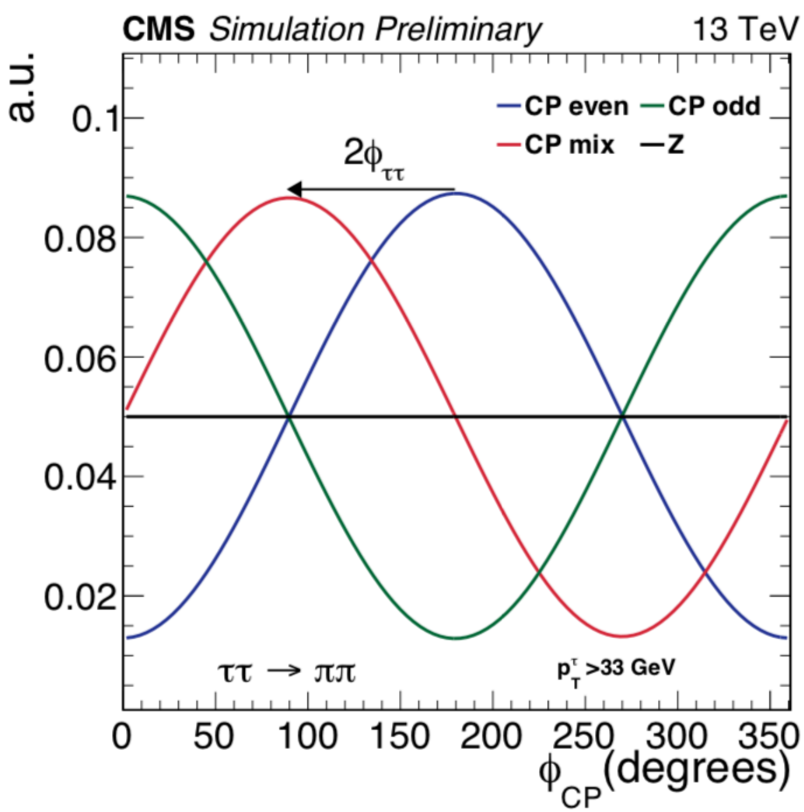
- The CP-mixing angle can be defined by

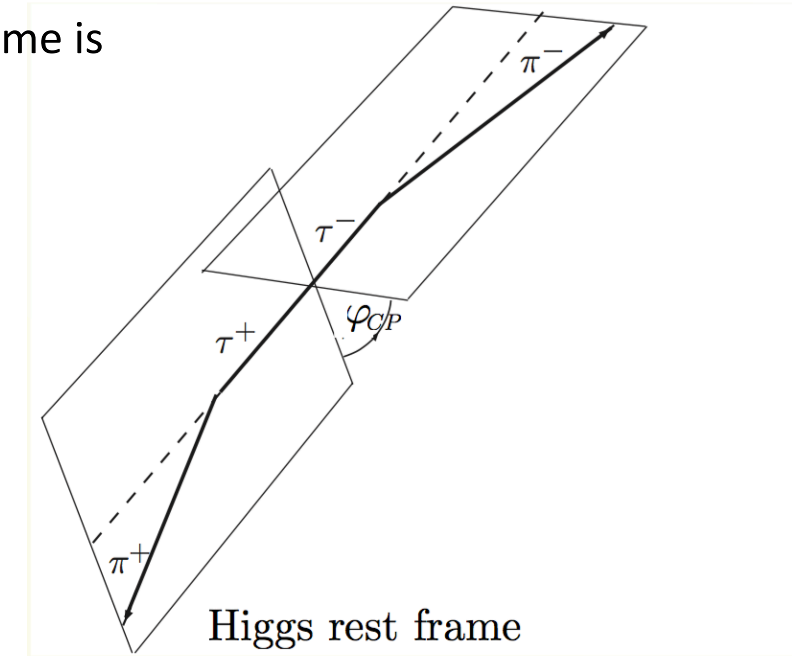
$$\tan(\phi_{\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$

- CP even: $|\phi_{\tau\tau}| = 0^o$, CP odd: $|\phi_{\tau\tau}| = 90^o$, CP mix: $0^o < |\phi_{\tau\tau}| < 90^o$

# Higgs CP observable

- Angle between tau decay planes in Higgs rest frame is sensitive to Higgs CP
- CP even: $|\phi_{\tau\tau}| = 0^o$, CP odd: $|\phi_{\tau\tau}| = 90^o$, CP mix: $0^o < |\phi_{\tau\tau}| < 90^o$




Define

$$\phi^* = \arccos(\hat{\lambda}_\perp^{*+} \cdot \hat{\lambda}_\perp^{*-})$$
$$O^* = \hat{q}^{*-} \cdot (\hat{\lambda}_\perp^{*+} \times \hat{\lambda}_\perp^{*-}),$$

Discriminates CP-odd from CP-even

Discriminates CP-inv from CP-mix

Construct

$$\phi_{\mathrm{CP}} = \begin{cases} \phi^* & \text{if } O^* \geq 0 \\ 360^\circ - \phi^* & \text{if } O^* < 0 \end{cases}$$

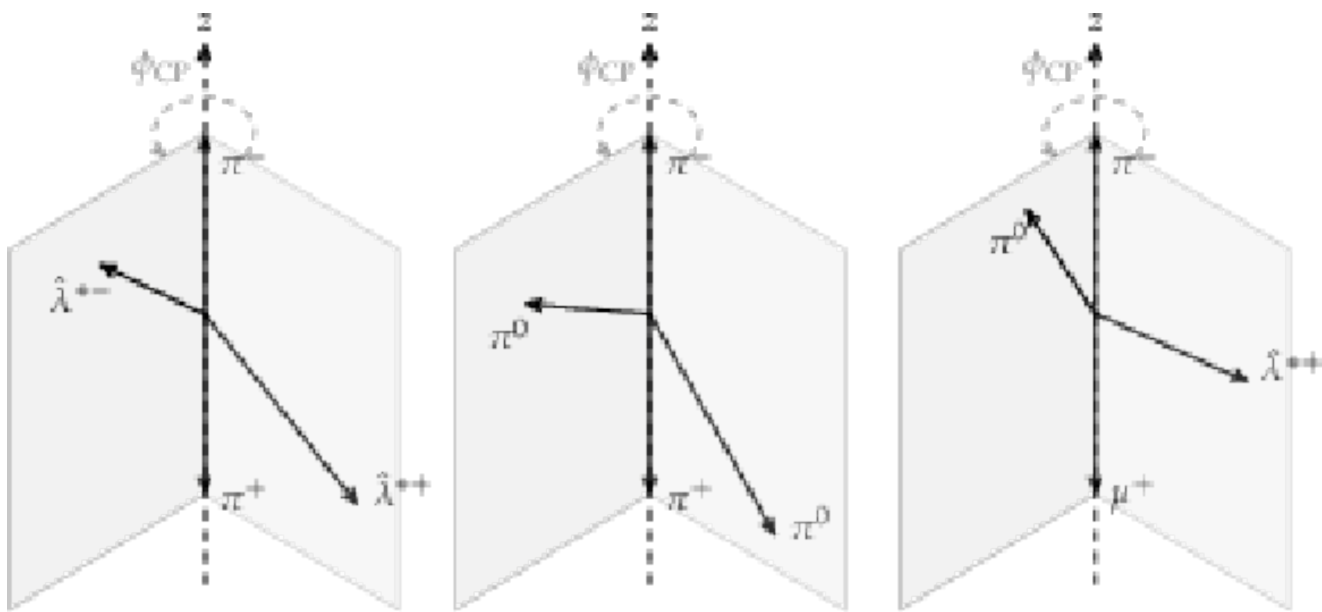


arXiv:1510.03850

# Constructing CP observable

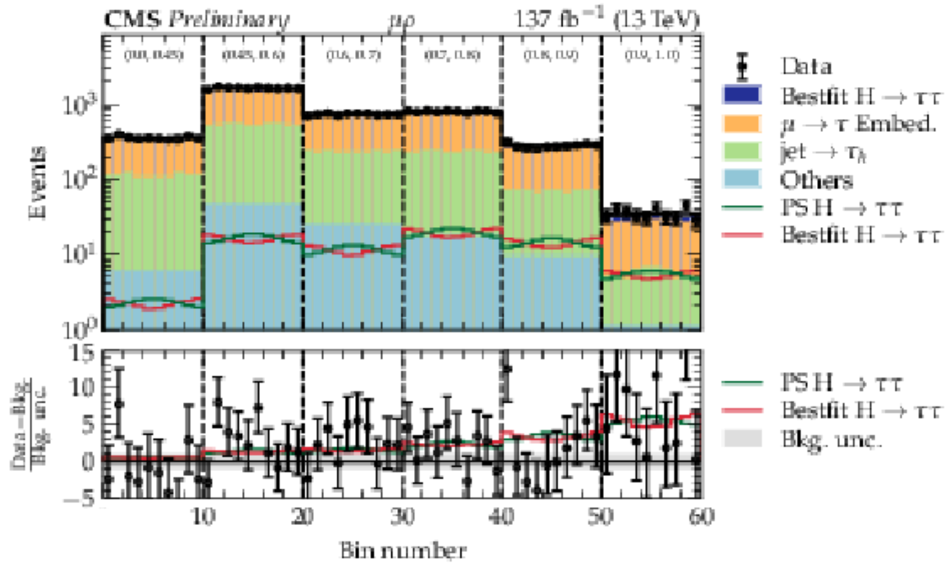
- Since Higgs rest frame can not be constructed exactly, an approximation is used
- The observable is constructed in zero-momentum-frame (ZMF) of $\pi^+\pi^-$ system
- For $\tau_h$ candidates with intermediate $\rho(a_1)$ mesons, decay plane is constructed from $\pi^\pm$ and $\pi^0$ momenta.
- When no $\rho(a_1)$ meson is present, the impact parameter and momenta of $\ell^\pm/\pi^\pm$ are used
- Considering final states in $\mu\tau_h$, $\tau_h\tau_h$: $(\mu, \rho, \pi, a_1^{1pr}, a_1^{3pr})$ X $(\mu, \rho, \pi, a_1^{1pr}, a_1^{3pr})$

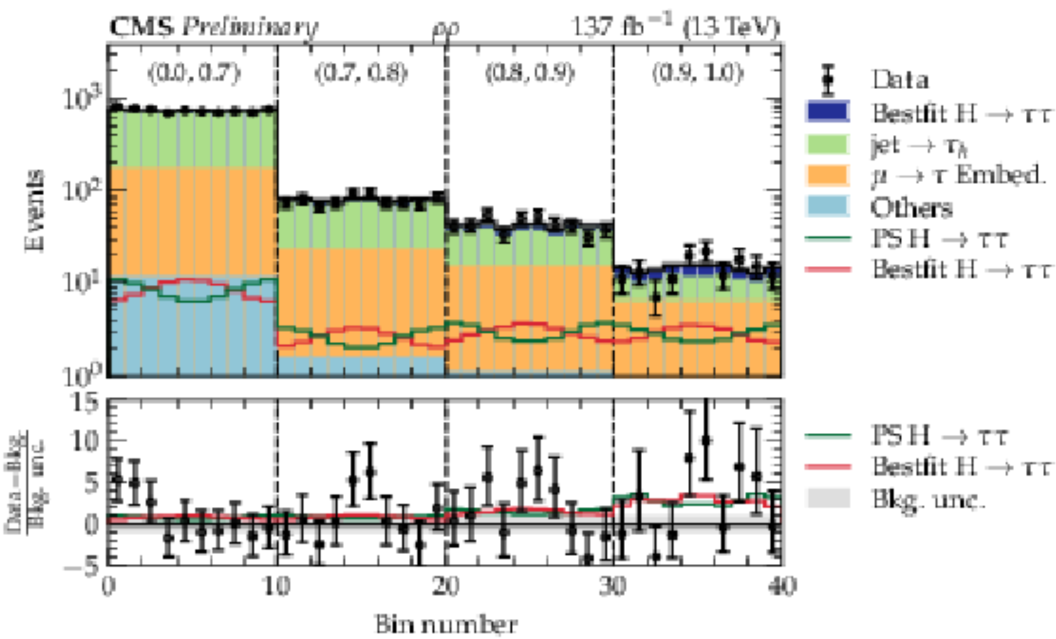
Most Sensitive:
$\mu\rho$, $\pi\rho$, $\rho\rho$



# Analysis Strategy

- Multiclass NN (BDT) for $\mu\tau_h$ ($\tau_h\tau_h$ ) channels, to separate signal from Backgrounds
  - Kinematic variables e.g, $p_T$, $m_{\tau\tau}$, $m_{jj}$, $N_{jet}$ etc.., are input to MVA
- Three output classes: genuine $\tau_h$ bkg, fake $\tau_h$ bkg, Higgs

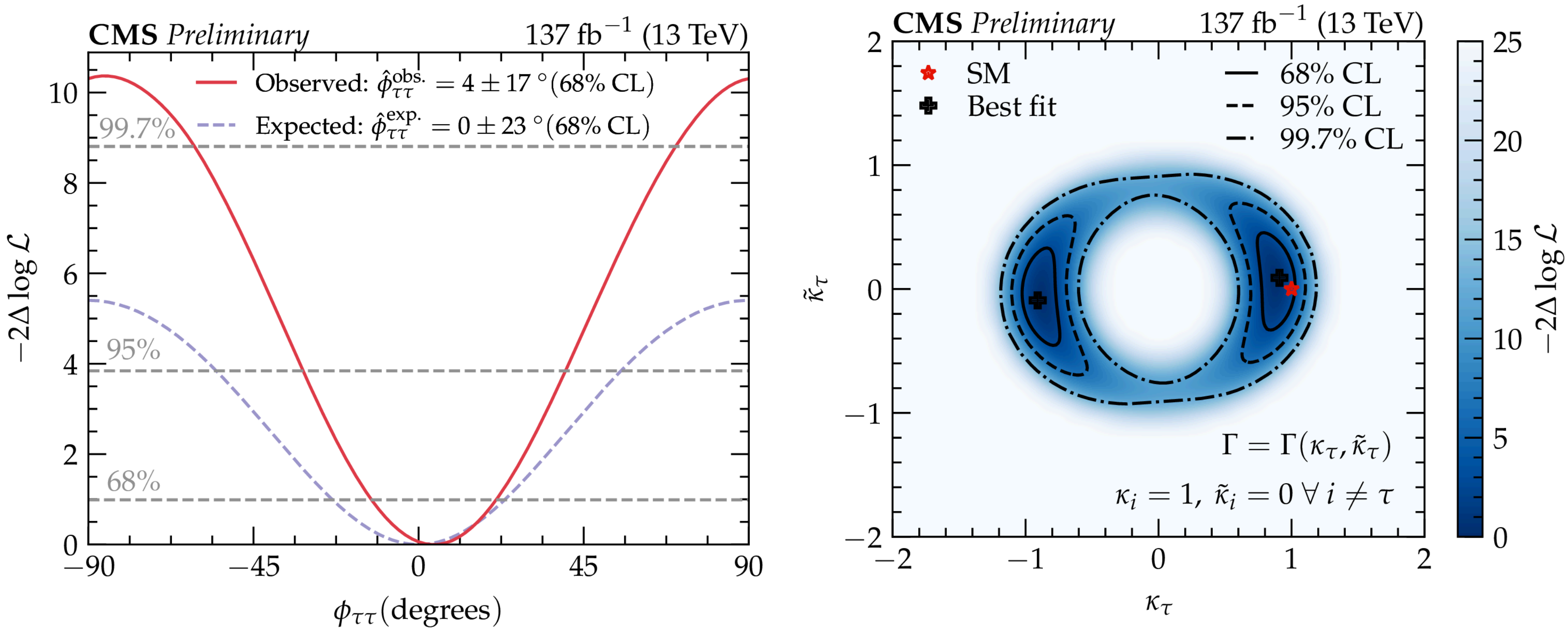



- Events falling into the Higgs category are used to extract CP information
- Fit 2D distribution of NN (BDT) score vs $\phi_{CP}$ for each channel

# CP in H→ττ : Results

- Simultaneous maximum likelihood fit to extract CP mixing parameter
- Measured value of $\phi_{\tau\tau} = 4 \pm 17^{o}$ (mostly dominated by statistical uncertainty)
- Pure CP odd exclusion: 3.2σ significance
- Interpretation in $\kappa_\tau$ framework, assuming all other couplings as SM.

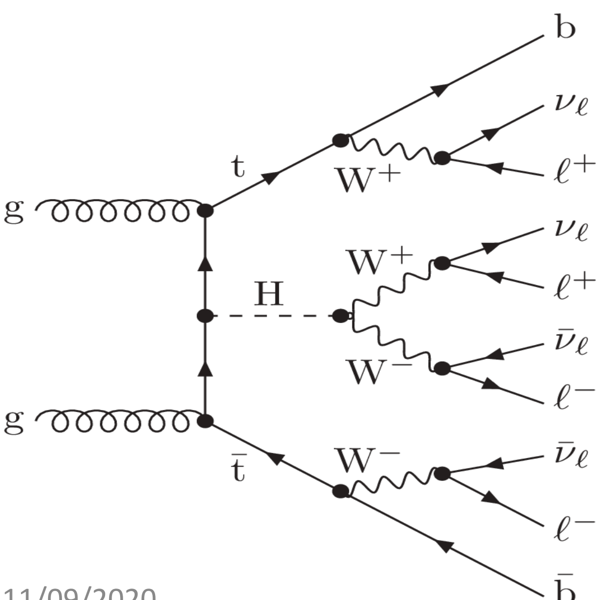


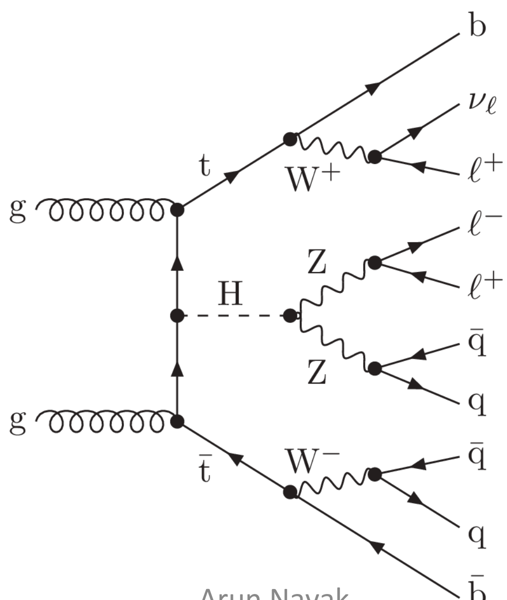

Clearly favours a CP even scenario

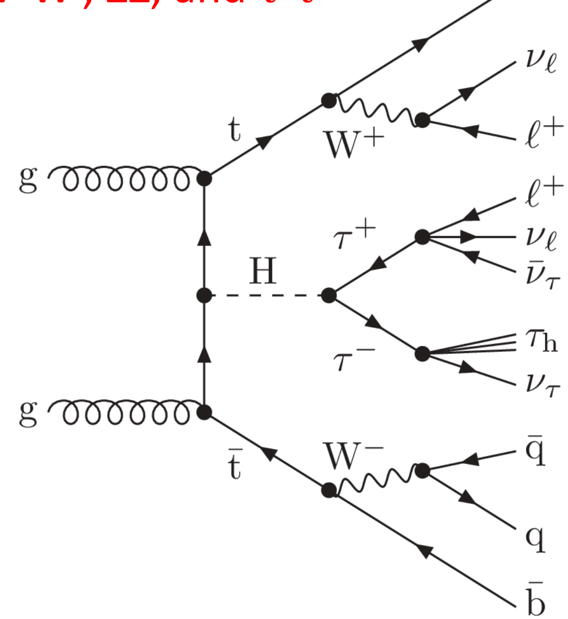
# tH & ttH in multilepton channels

## ttH:

- Direct probe of the top-Higgs interaction
  - Allows to measure the strength of Yukawa coupling, CP violation
- Challenging process at LHC:
  - Small production cross section: $\sigma \approx 0.5$ pb
  - Large tt+jets, ttW, ttZ backgrounds
  - Large combinatorics of leptons plus jets from top quark decay
- Multi-lepton final states constitute Higgs decay to $W^+W^-$, ZZ, and $\tau^+\tau^-$



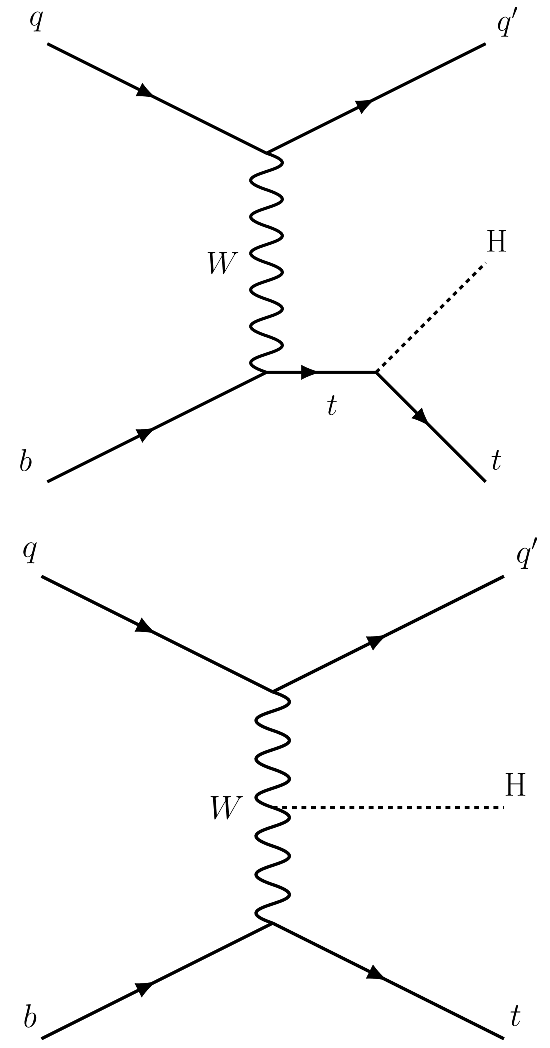



# tH & ttH in multilepton channels

tH:

- Even smaller production cross section: $\sigma \approx 74$ fb
- Sensitive to $y_t$ and $g_W$ couplings (interference between diagrams)
- $y_t/g_W = -1$ (ITC) enhances cross section by ≈10
- While ttH is not sensitive to ITC

- Multi-lepton final states constitute Higgs decay to $W^+W^-$, ZZ, and $\tau^+\tau^-$

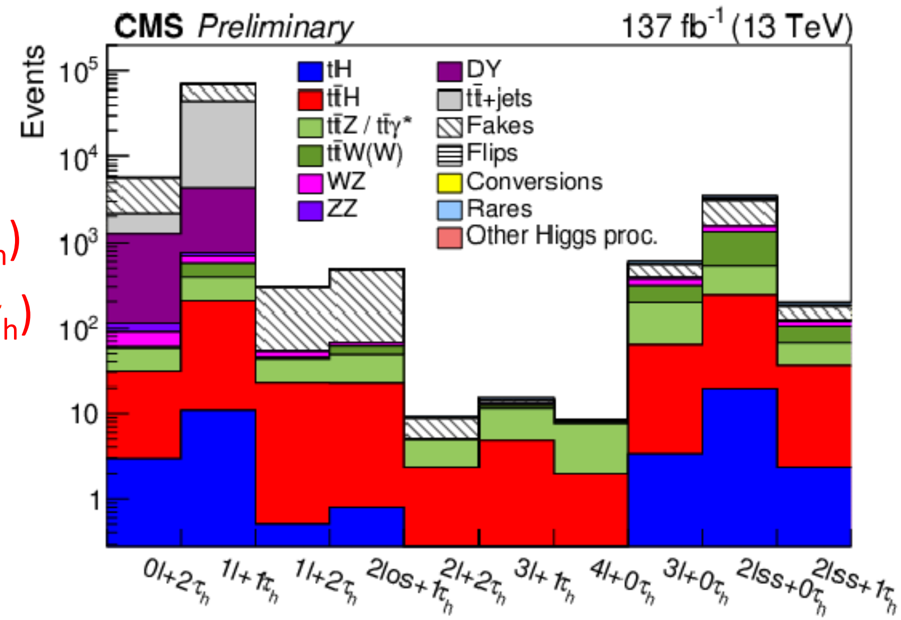


# Analysis Channels

Search performed in 10 exclusive event categories

- Four leptons ($4\ell$)
- Three leptons and zero $\tau_h$ ($3\ell$)
- Three leptons and one $\tau_h$ ($3\ell + 1\tau_h$) )
- Two same-sign leptons and zero $\tau_h$ ($2\ell ss+0\tau_h$)
- Two same-sign leptons and one $\tau_h$ ($2\ell ss + 1\tau_h$)
- Two os leptons and one $\tau_h$ ($2\ell os + 1\tau_h$)
- Two leptons and two $\tau_h$ ($2\ell + 2\tau_h$)
- One lepton and two $\tau_h$ ($1\ell + 2\tau_h$)
- One lepton and one $\tau_h$ ($1\ell + 1\tau_h$)
- Zero lepton and two $\tau_h$ ($0\ell + 2\tau_h$)

  $\ell$ = e or $\mu$, charge consistent with final state




- ❑ Jets and b-jets multiplicity according to ttH final state
- ❑ 2lss + $0\tau_h$, 2lss + $1\tau_h$ and 3l + $0\tau_h$ channels enlarged to accept tH events
  - Allowing events with one light (forward) jet and one b tag

# Background discrimination

- Major irreducible backgrounds: ttW, ttZ
- tt+jets, DY also irreducible in some channels

MVA discriminators to separate signals from backgrounds

- Kinematic, angular, and object identification variables of jets and leptons are used as input to MVA

2lss + $0\tau_h$, 2lss + $1\tau_h$ and 3l + $0\tau_h$ channels:

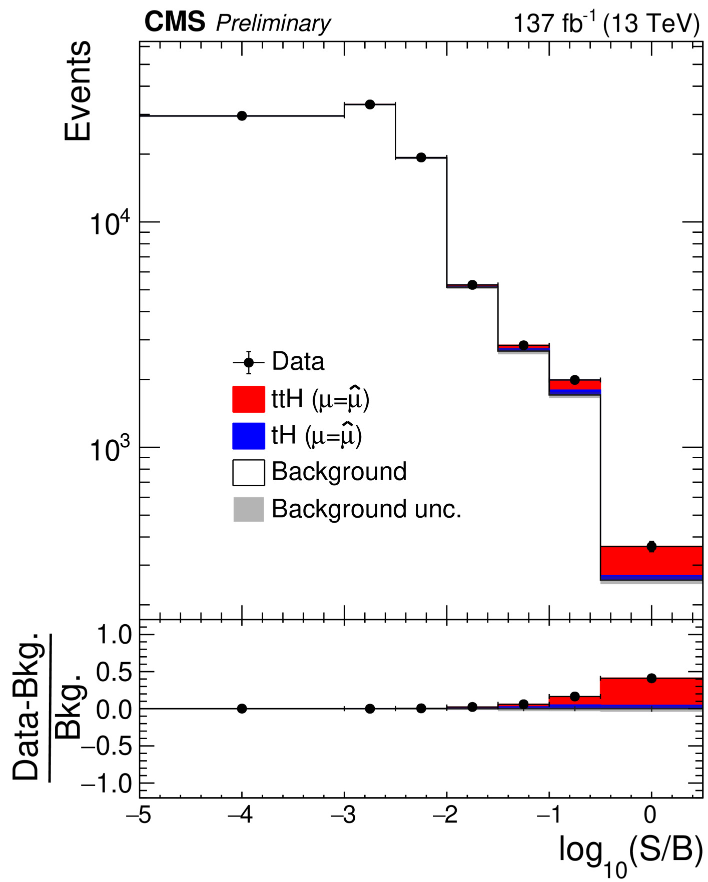
- Multiclass DNN to classify ttH, tH, and backgrounds
- Events categorized based on DNN score and event topology

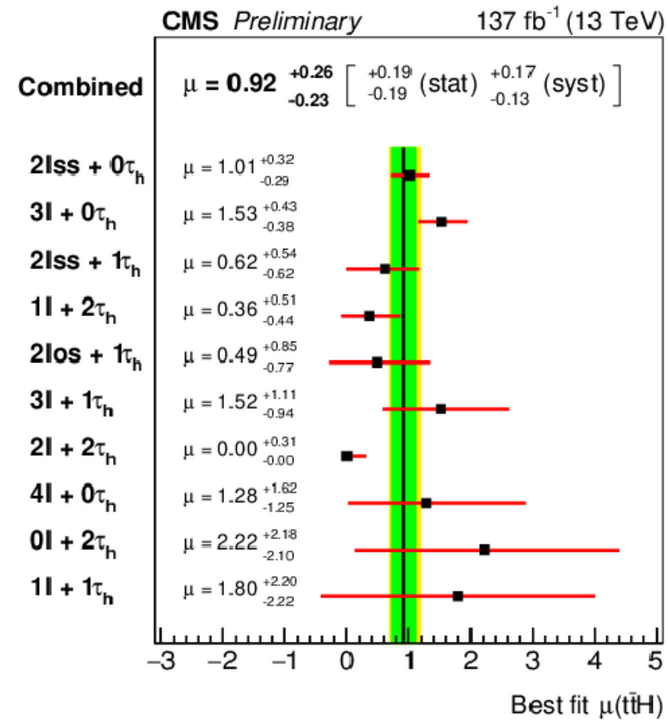
Other channels:

- No sensitivity to tH process
- BDT used to separate ttH signal from backgrounds
- Event categories based on BDT score

# ttH & tH multilepton: Results

CMS-PAS-HIG-19-008




| Process | Signal strength |
|---|---|
| $t\bar{t}H$ | $0.92^{+0.26}_{-0.23}$ |
| $tH$ | $5.7^{+4.1}_{-4.0}$ |
| $t\bar{t}Z$ | $1.03 \pm 0.14$ |
| $t\bar{t}W$ | $1.43 \pm 0.21$ |

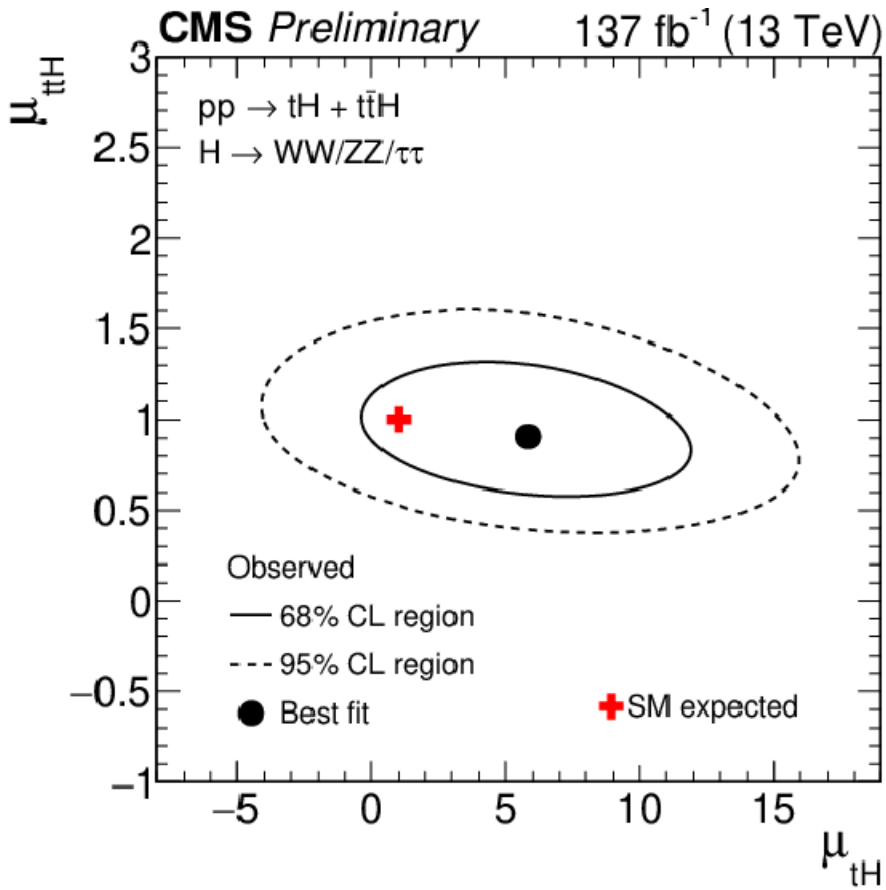
Observed significance for ttH production: 4.7 σ

Observed significance for tH production: 1.4 σ

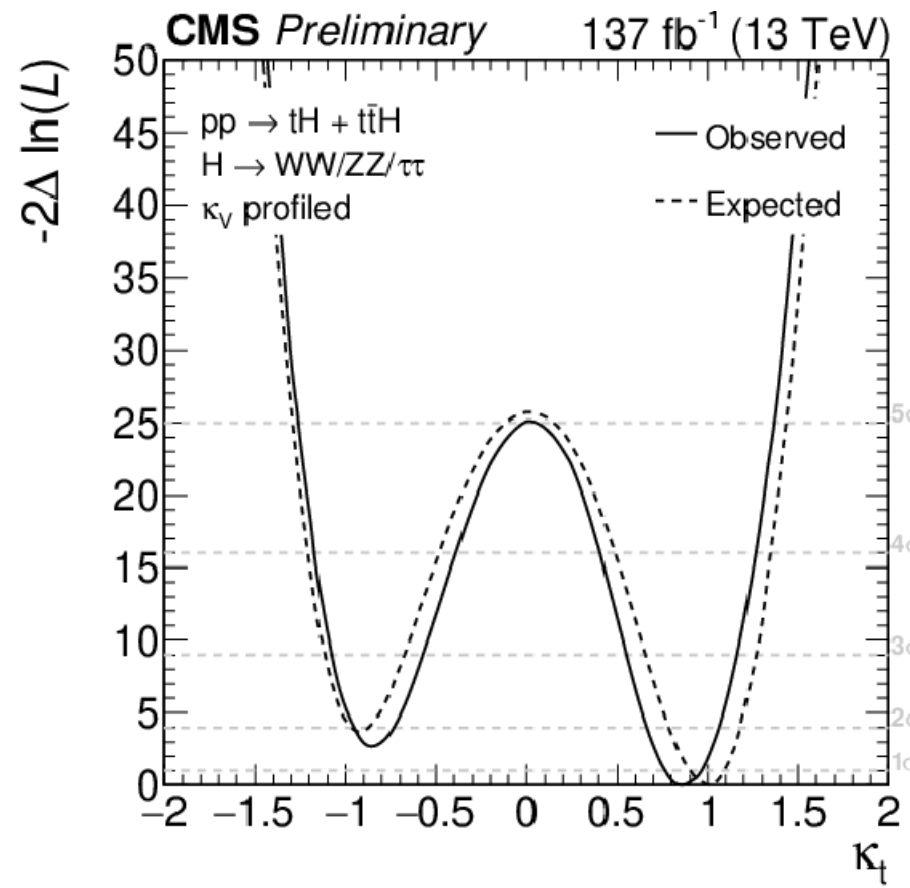
# ttH & tH multilepton: Results

CMS-PAS-HIG-19-008

Two-dimensional contour of the likelihood function




Interpretation in κ framework (in terms of $\kappa_t$ and $\kappa_V$)

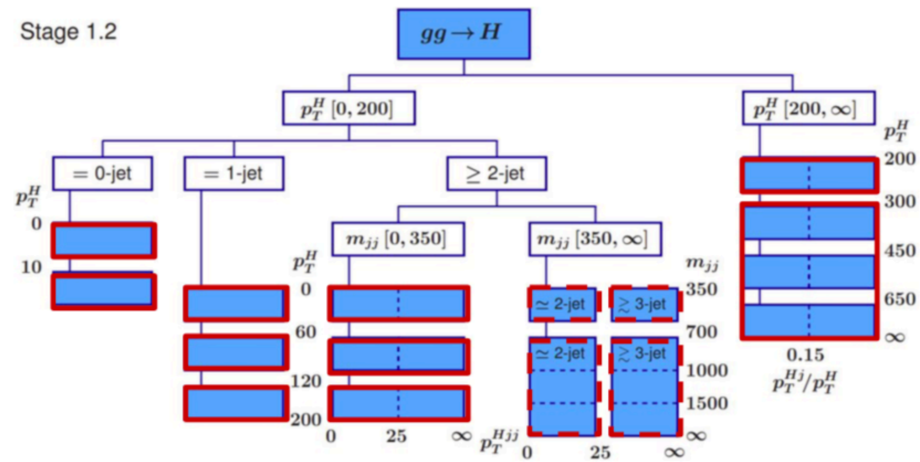


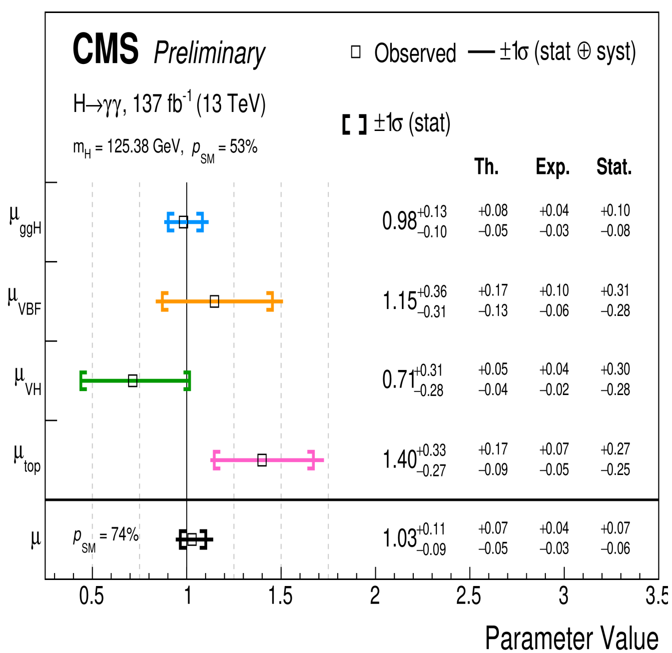

Best fit consistent with the SM expectation

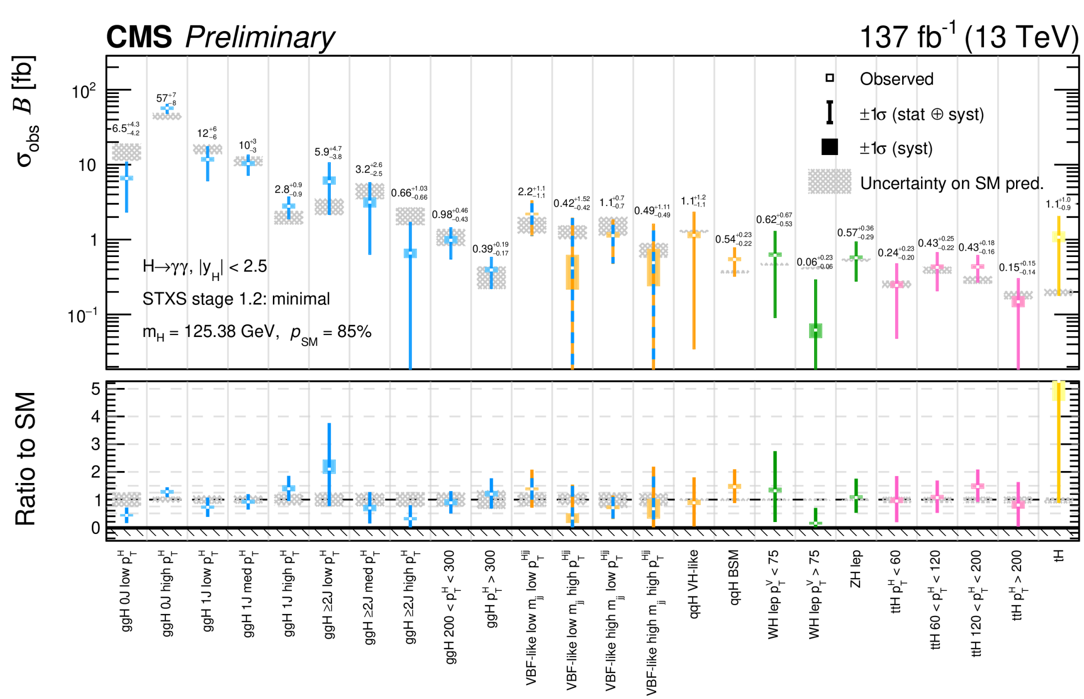
# H→γγ measurements

Recent results on H →γγ cross section measurements using full Run-2 data

- Individual production mode signal strengths
- Measurements in STXS framework
- More details in CMS-PAS-HIG-19-015

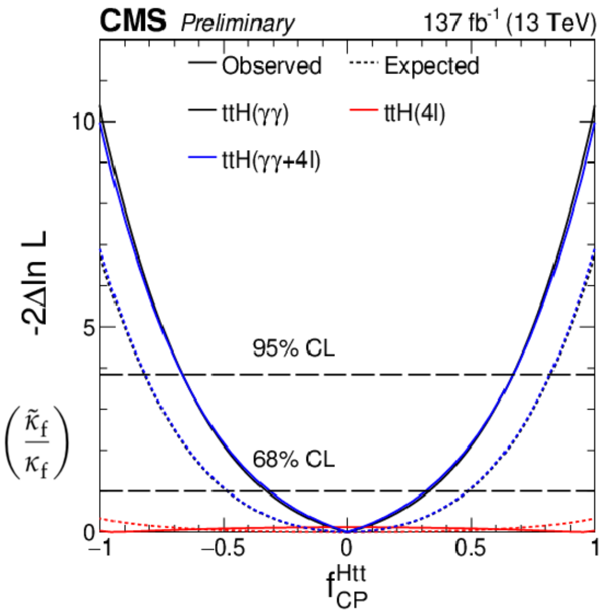


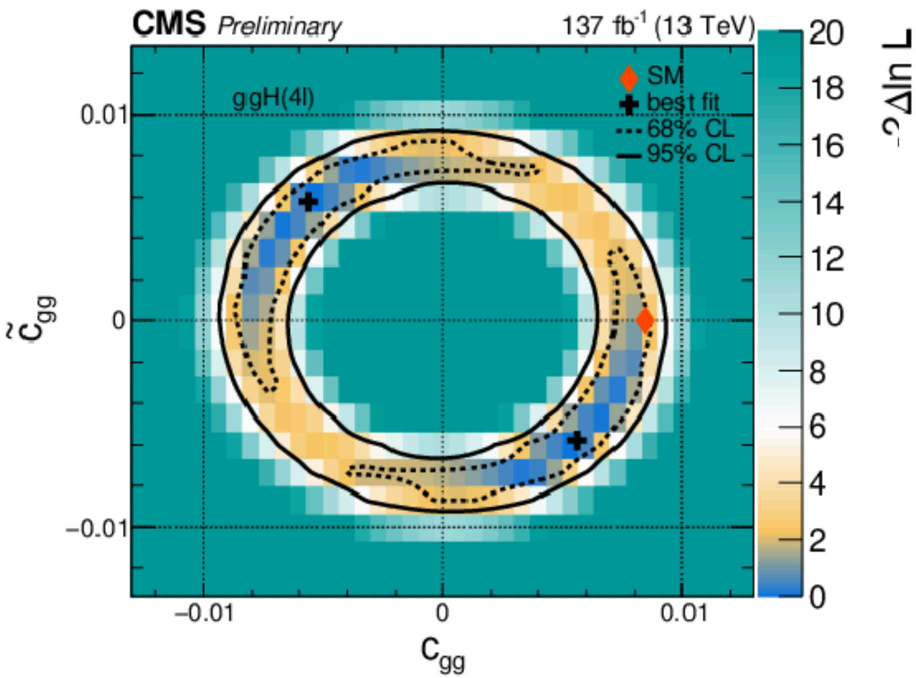
# Constraints on anomalous couplings in H→4ℓ channel

- CMS studied CP-violation and anomalous couplings of the Higgs boson to vector bosons and fermions, in H→ 4l channel
- Results are interpreted in the EFT framework (arXiv:1610.07922, arXiv:2002.09888)
- More details in CMS-PAS-HIG-19-009

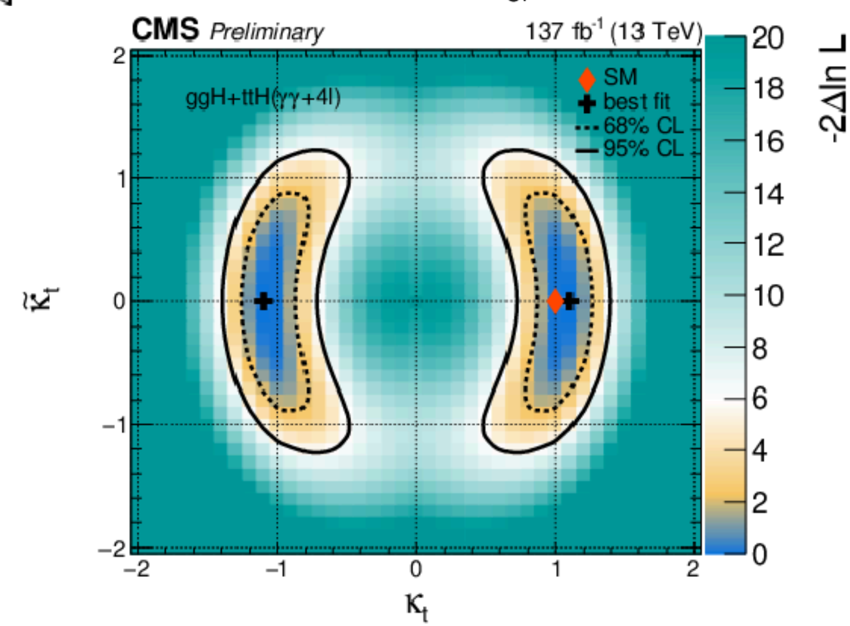



$$f_{CP}^{Hff} = \frac{|\tilde{\kappa}_f|^2}{|\kappa_f|^2 + |\tilde{\kappa}_f|^2}\,\mathrm{sign}\left(\frac{\tilde{\kappa}_f}{\kappa_f}\right)$$

$$\frac{h}{v}\,\tilde{c}_{gg}\,\frac{g_s^2}{4}\,G^a_{\mu\nu}\tilde{G}^a_{\mu\nu}$$

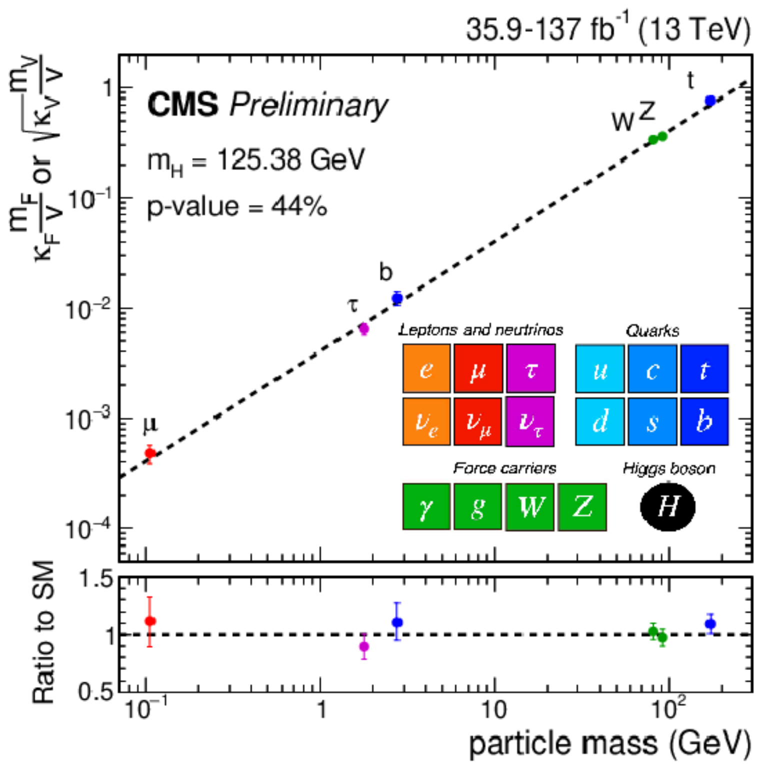



$$\frac{h}{v}\,c_{gg}\,\frac{g_s^2}{4}\,G^a_{\mu\nu}G^a_{\mu\nu}$$



# Summary

- With accumulation of more data we are slowly moving towards precision studies of the Higgs boson
- Discussed a few recent measurements by CMS, with full LHC run-2 data.
  - First evidence of H→μμ decay
  - CP measurements in H→ττ
  - ttH and tH measurements in multileptons
  - STXS measurements in H→γγ and anomalous couplings in H→4ℓ
- Looking forward to more precision measurements in future
  - Hoping for something unexpected…



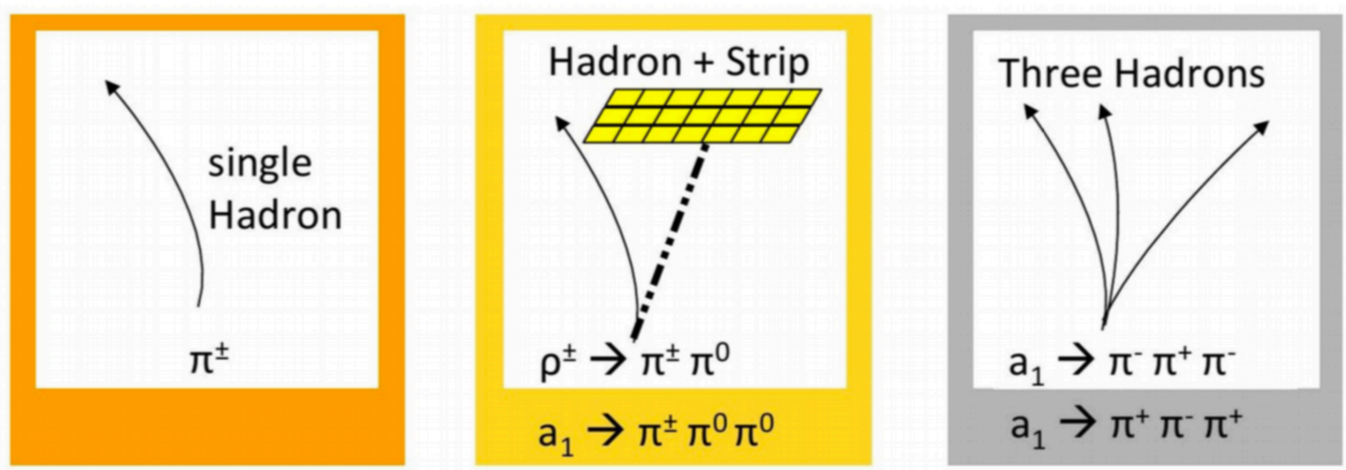

Thank you for your attention

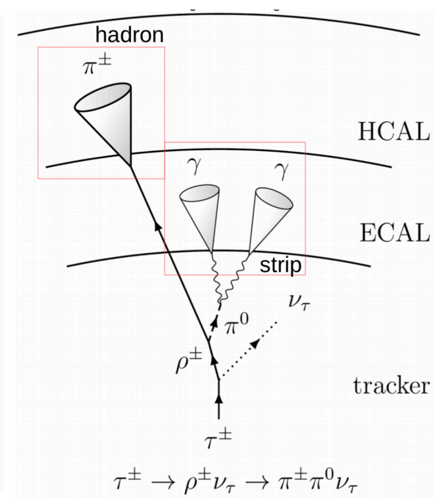
backup

# $\tau_h$ identification

- Hadronic τ decay is reconstructed using the so called "hadron-plus-strip" (HPS) algorithm
  - It reconstructs individual decay modes, combining charged hadrons and PF e/γ candidates.
- Fakes arising from jets, electrons, and muons are suppressed using a DNN-based (DeepTau) discriminator

| Decay mode | Resonance | $\mathcal{B}$ (%) | |
|---|---|---|---|
| Leptonic decays | | 35.2 | |
| $\tau^- \to e^- \bar{\nu}_e \nu_\tau$ | | | 17.8 |
| $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$ | | | 17.4 |
| Hadronic decays | | 64.8 | |
| $\tau^- \to h^- \nu_\tau$ | | | 11.5 |
| $\tau^- \to h^- \pi^0 \nu_\tau$ | $\rho(770)$ | | 25.9 |
| $\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$ | $a_1(1260)$ | | 9.5 |
| $\tau^- \to h^- h^+ h^- \nu_\tau$ | $a_1(1260)$ | | 9.8 |
| $\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$ | | | 4.8 |
| Other | | | 3.3 |



# CP in H→ττ : Results

Visual Interpretation:

- Three most sensitive channels are weighted and combined into a single $\Phi_{CP}$ distribution
- Each NN/BDT score bin is weighted by A × S/(S+B)

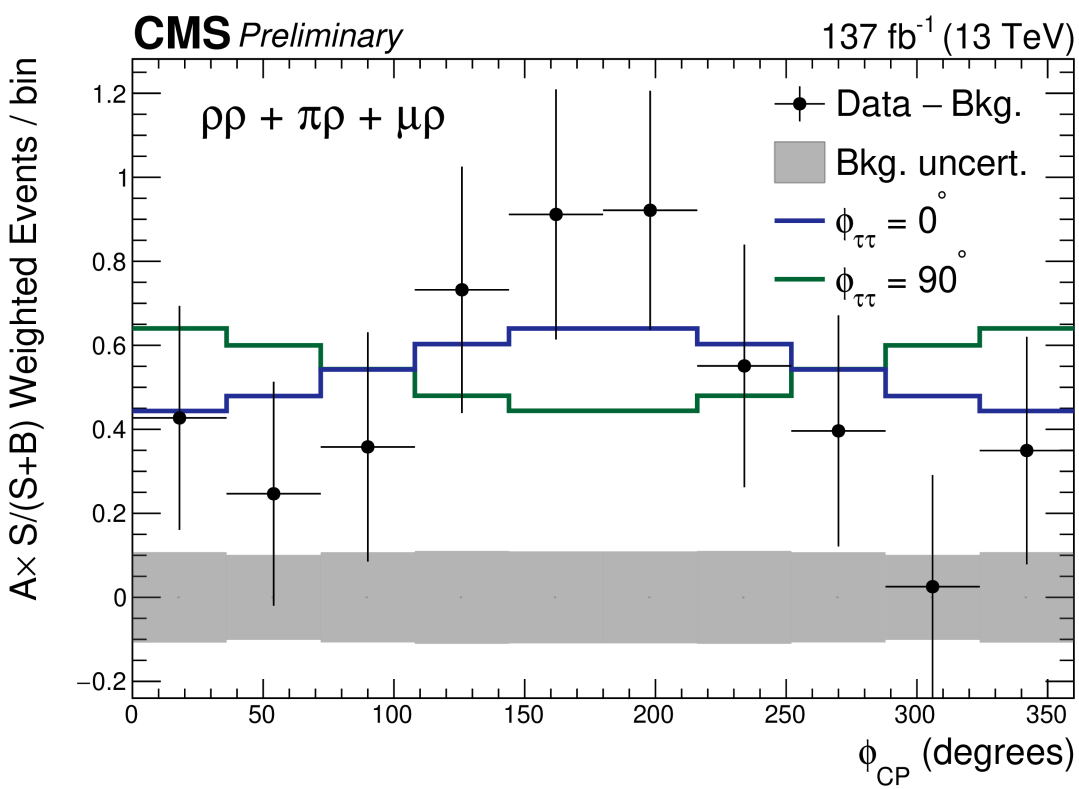
A = the average asymmetry

$$A = \frac{1}{N_{bins}} \sum \frac{|CPeven - CPodd|}{CPeven + CPodd}$$

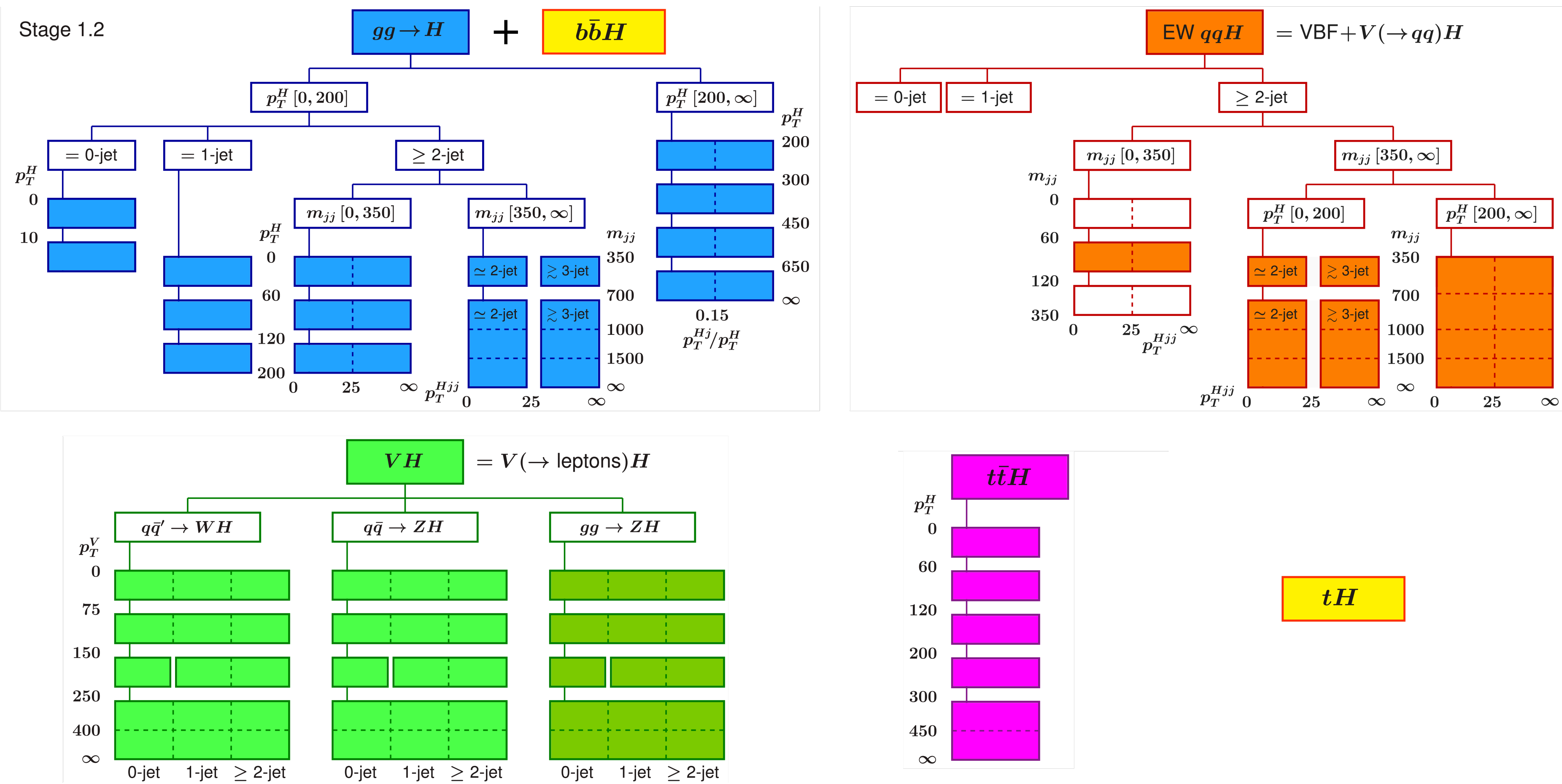
Data clearly favours the CP-even scenario

CP-odd exclusion at 3.2σ

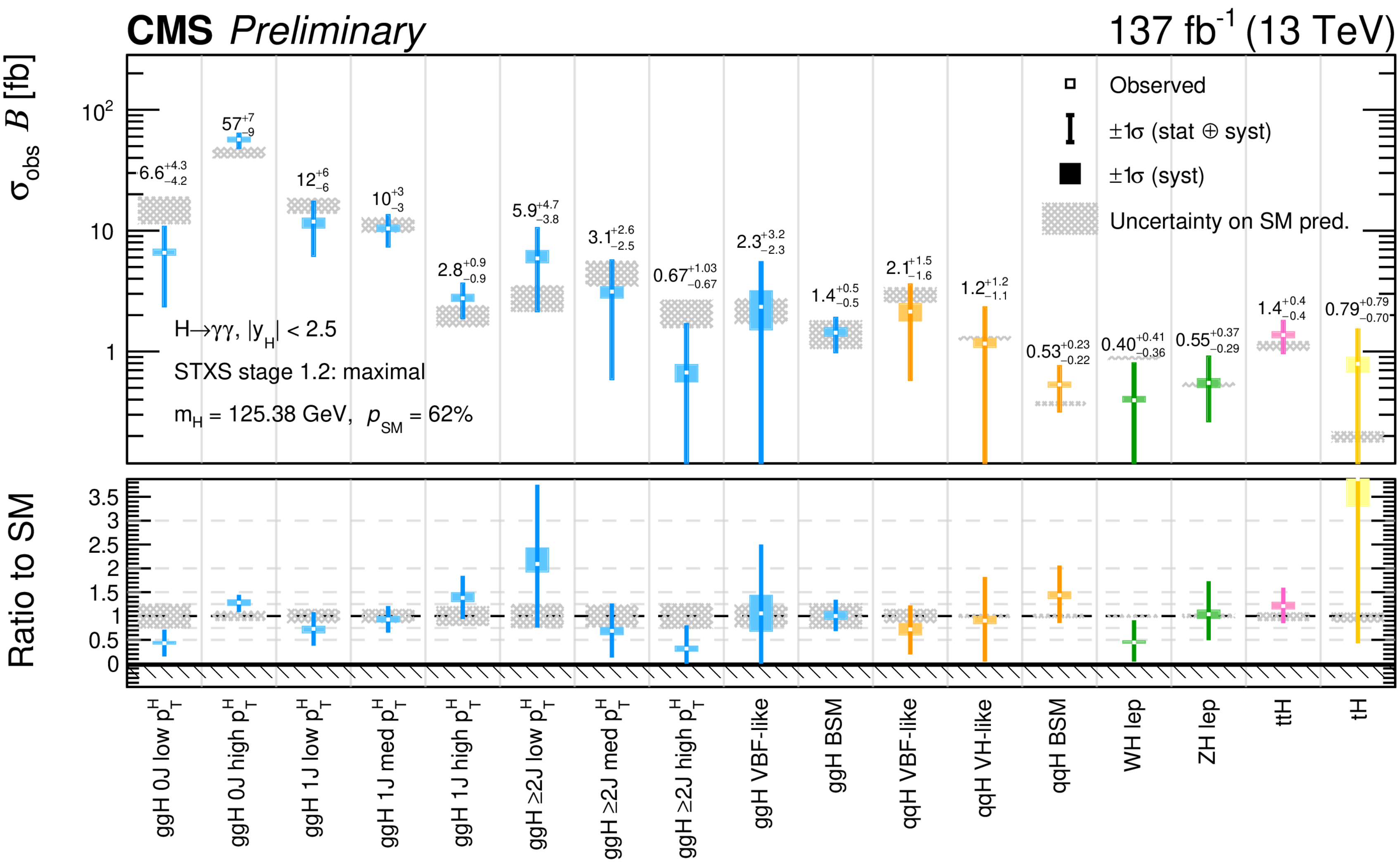
(2.3σ expected)



# STXS bins

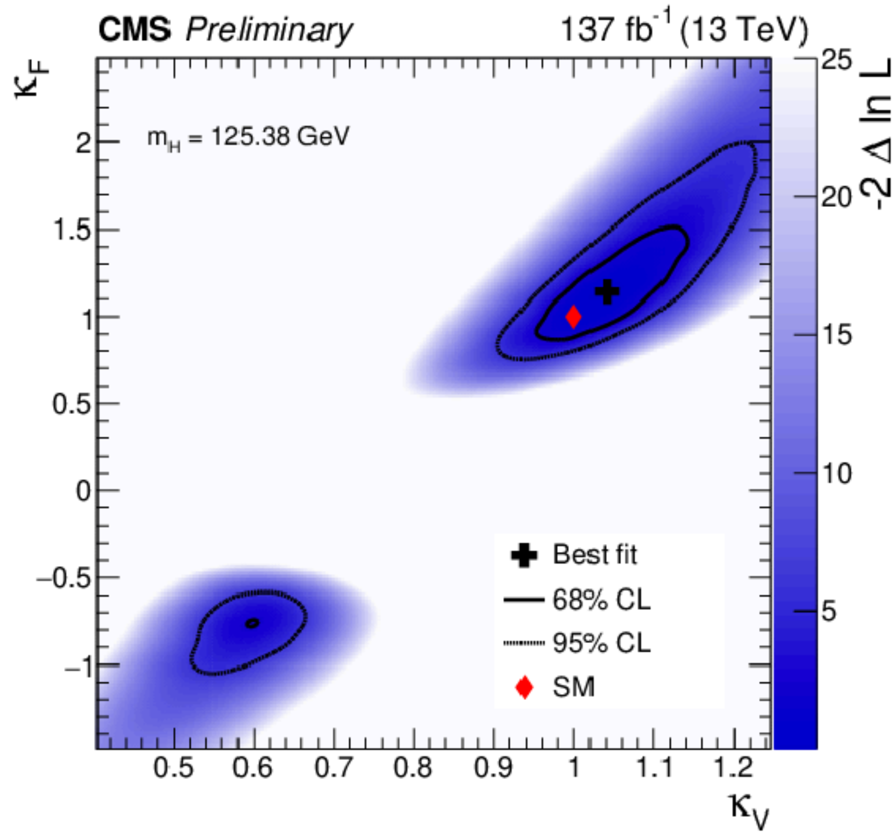

Stage 1.2
$gg \to H$
+
$b\bar{b}H$
$p_T^H$ [0, 200]
$p_T^H$ [200, ∞]
= 0-jet
= 1-jet
≥ 2-jet
$m_{jj}$ [0, 350]
$m_{jj}$ [350, ∞]
≃ 2-jet
≳ 3-jet
$p_T^H$
0 10
0 60 120 200
200 300 450 650 ∞
0.15
$p_T^{Hj}/p_T^H$
$m_{jj}$
350 700 1000 1500 ∞
$p_T^{Hjj}$
0 25 ∞
EW $qqH$
= VBF + $V(\to qq)H$
$p_T^H$ [0, 200]
$p_T^H$ [200, ∞]
0 60 120 350
$VH$
= $V(\to$ leptons$)H$
$q\bar{q}' \to WH$
$q\bar{q} \to ZH$
$gg \to ZH$
$p_T^V$
0 75 150 250 400 ∞
0-jet
1-jet
≥ 2-jet
$t\bar{t}H$
0 60 120 200 300 450 ∞
$tH$

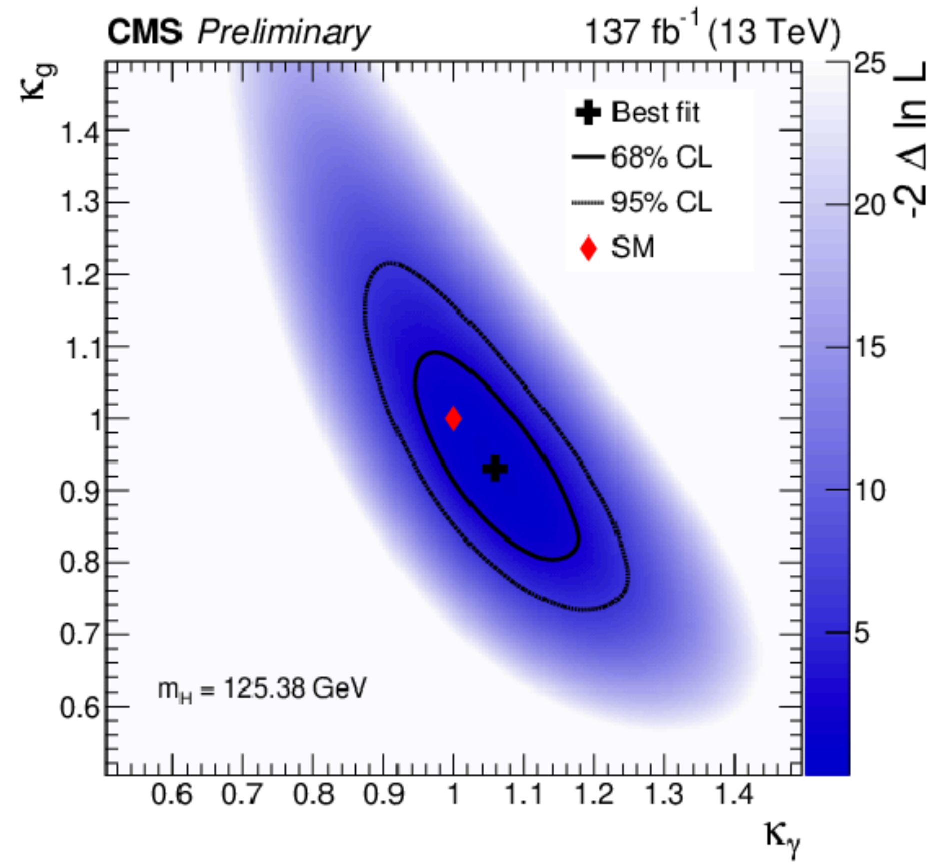
# H→γγ measurements



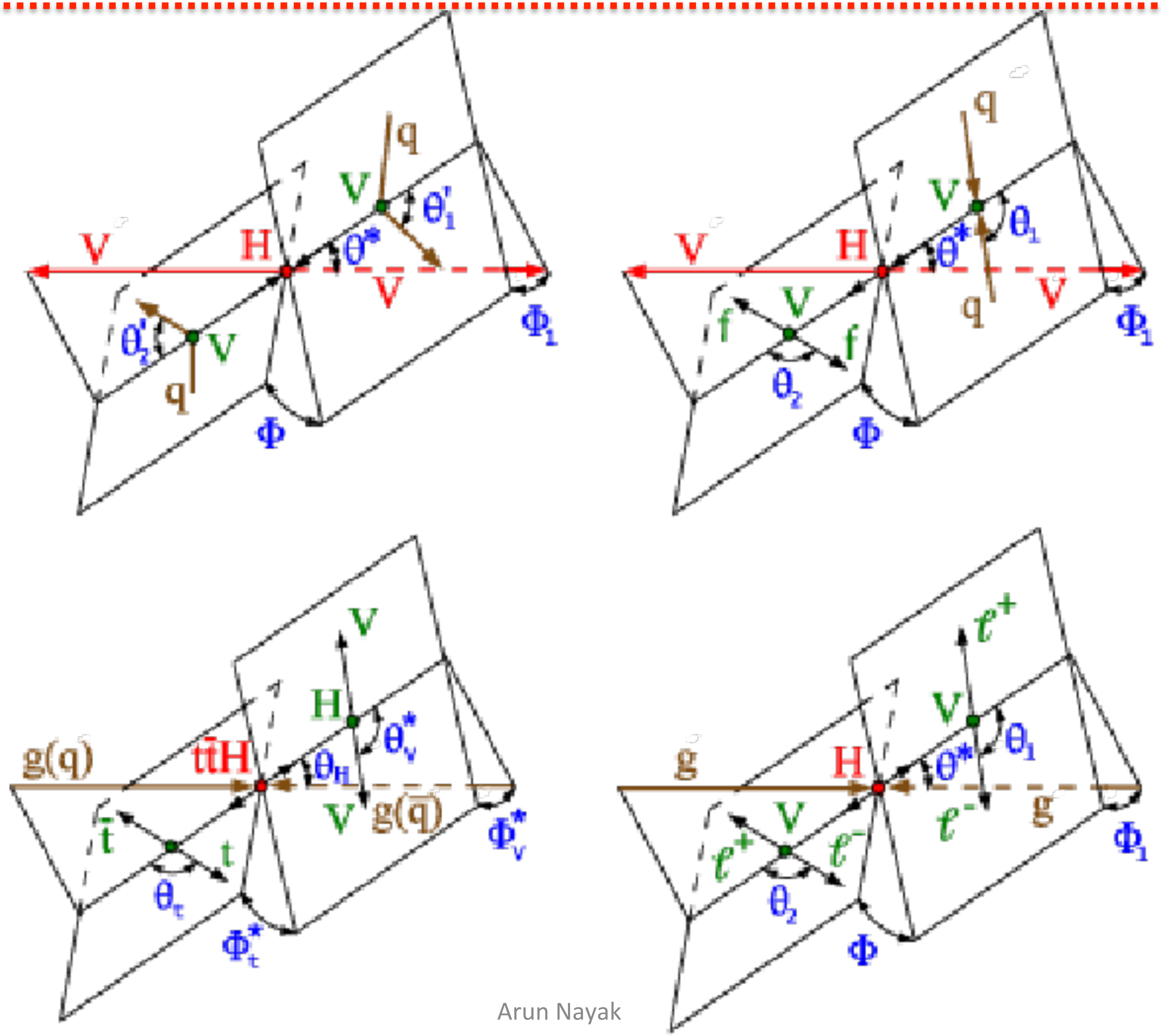
# H→γγ measurements

CMS-PAS-HIG-19-015



# production and decay topologies of H→4l



# Constraints on anomalous couplings in H→4ℓ channel

- Results in the EFT framework
- More details in CMS-PAS-HIG-19-009

constraints on the CP-sensitive parameter in the H boson couplings to gluons

| Parameter | Observed | Expected |
|---|---|---|
| $f_{a3}^{ggH}$ | $-0.53^{+0.51}_{-0.47}$ $[-1, 1]$ | $0 \pm 1$ $[-1, 1]$ |

constraints on the Htt, Hgg, Hff, and HVV coupling parameters in the Higgs basis of the EFT formalism

| 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 | |
| $t\bar{t}H$ | $\kappa_t$ | $1.06^{+0.14}_{-0.18}$ | $1.00^{+0.15}_{-0.23}$ | | 1 | | |
| | $\tilde{\kappa}_t$ | $0.00^{+0.76}_{-0.72}$ | $0.00^{+0.80}_{-0.80}$ | | 0.000 | 1 | |
| $t\bar{t}H + ggH$ | $\kappa_f$ | $0.76^{+0.23}_{-0.21}$ | $1.00^{+0.26}_{-0.39}$ | | 1 | | |
| | $\tilde{\kappa}_f$ | $-0.21^{+0.28}_{-0.12}$ | $0.00 \pm 0.37$ | | +0.745 | 1 | |
| $VBF + VH + H \to 4\ell$ | $\delta c_z$ | $-0.25^{+0.27}_{-0.07}$ | $0.00^{+0.10}_{-0.28}$ | 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 |