Imperial College London

Higgs boson measurements in final states with taus at CMS

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Overview

1. General introduction to SM H→ττ analyses
2. Cross section measurements in the H→ττ final state
3. Measurement of the CP properties of the H→ττ decay

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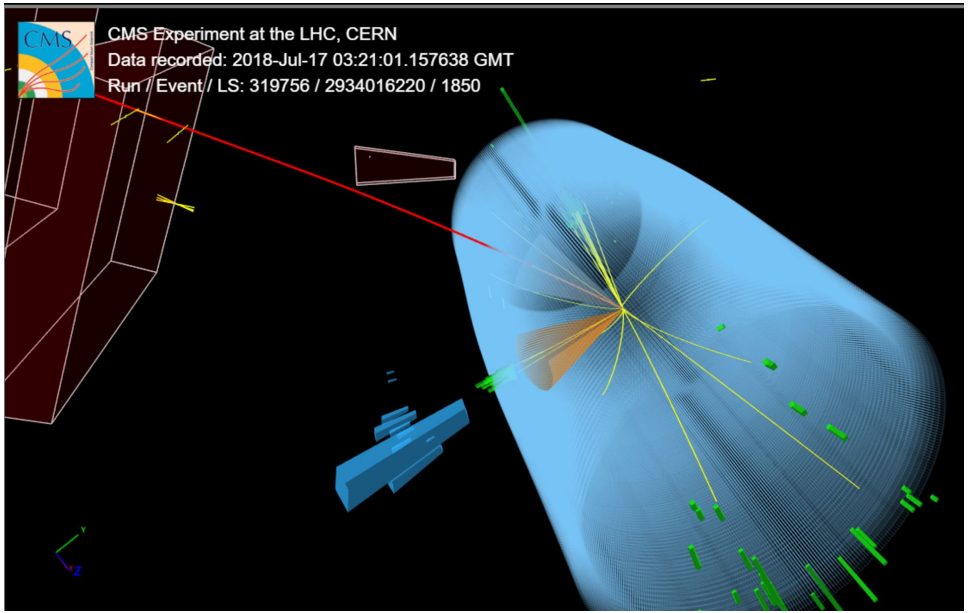
Introduction to SM H→ττ analyses

H→ττ overview

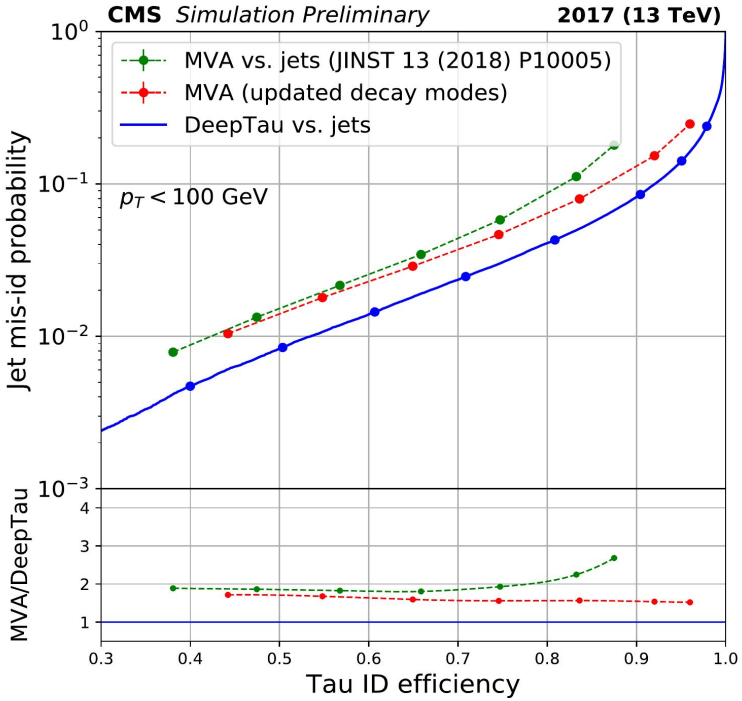
- H→ττ can probe directly the properties of the Yukawa coupling to tau leptons
- H→ττ has relatively high BR and is quite clear so can be used to probe regions of phase space with small cross sections: e.g VBF-like phase space, boosted Higgs
- But ditau final state not without challenges
- Taus are unstable and decay to leptons or hadrons plus ν's
- Because of ν's can't reconstruct Higgs system exactly



- Analyses presented today use most sensitive final states: eμ, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$

Tau identification

- Leptonically decaying tau reconstructed with standard CMS electron / muon identification
- Hadronic tau identification starts with hadron plus strips (HPS) algorithm
- HPS identifies charged hadrons and clusters together e/ɣ from π^0 decays into “strips”
- Multiclass DNN based algorithm (DeepTau) then used to reject fakes from jets, electrons, and muons
- DeepTau ID used for the first time for H→ττ analysis - gives significant improvements over older BDT-based ID!
- More detail in talk by Andrea Cardini yesterday here



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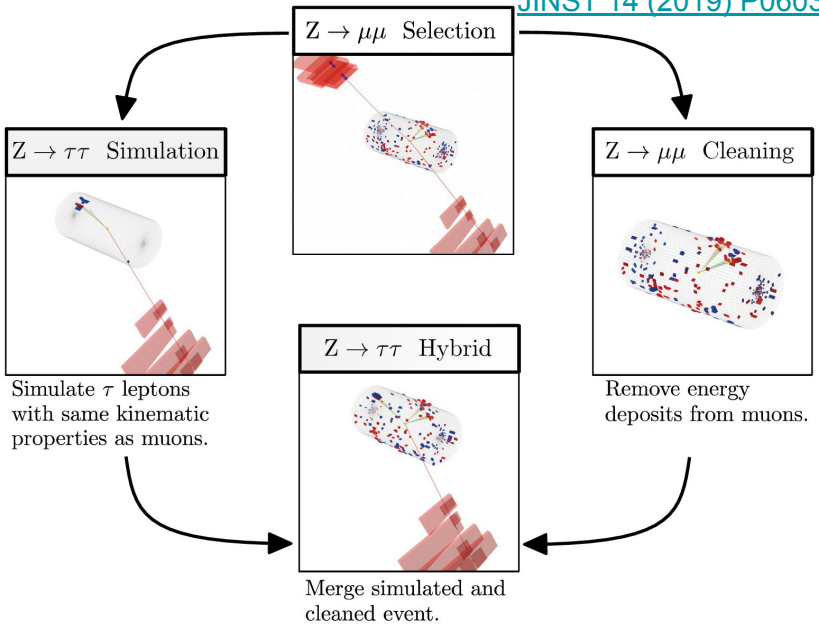
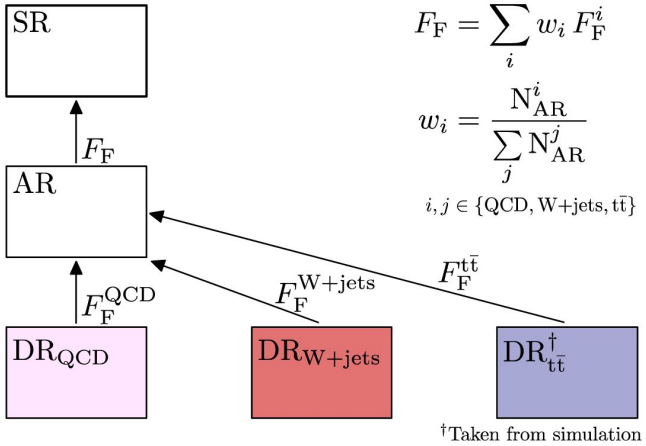
Modelling of backgrounds

- Largest irreducible background from events with 2 genuine τ leptons: mainly Z→ττ
- Estimated using semi-data-driven method: μ→τ embedding method





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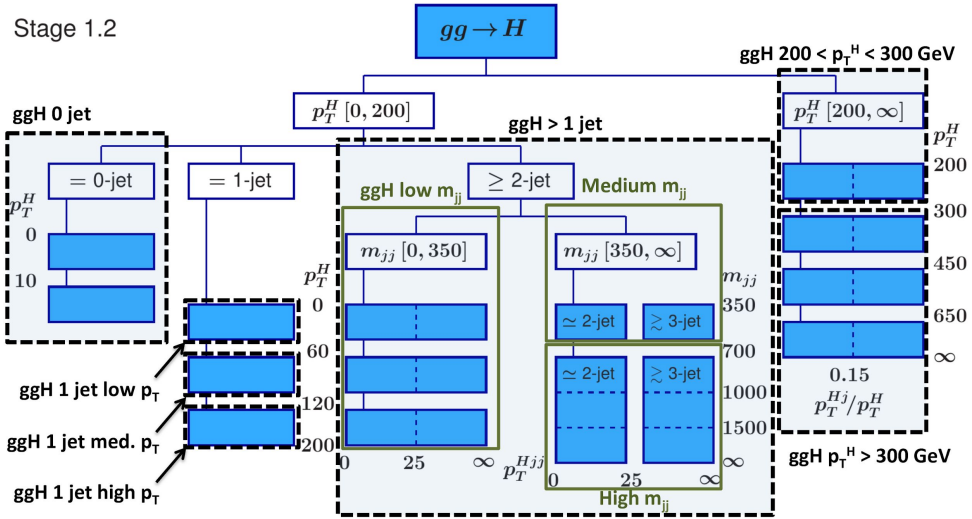
- Background with jet→τ_h fakes estimated from data driven method: fake rate method
- All other smaller background from MC
- Altogether ~ 90% of background estimated from data-driven methods

Cross section measurements in the H→ττ final state

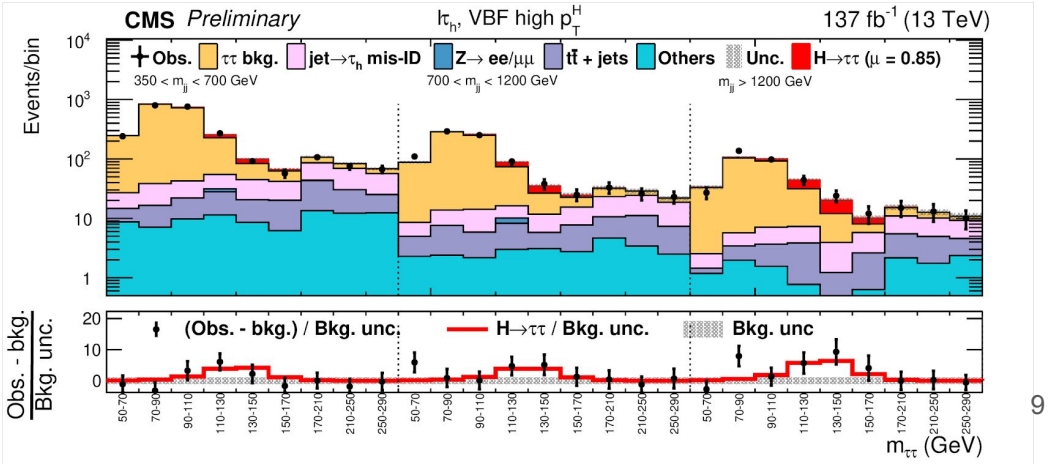
Higgs cross section measurements

- Increased data yield in Run2 open the door to precision measurements of Higgs cross sections
- Cross section of different production processes can be measured with good precision
- Measurements in simplified template cross section (STXS) framework minimises dependence on theory and allows results to be reinterpreted easily by theory community
- Latest cross section results using 137/fb of 13 TeV data presented in these slides: HIG-19-010



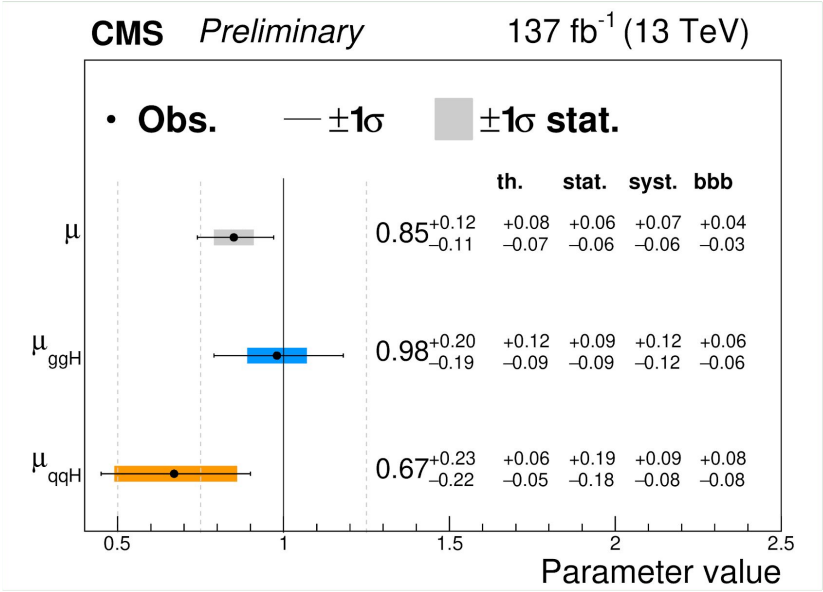
Analysis strategy

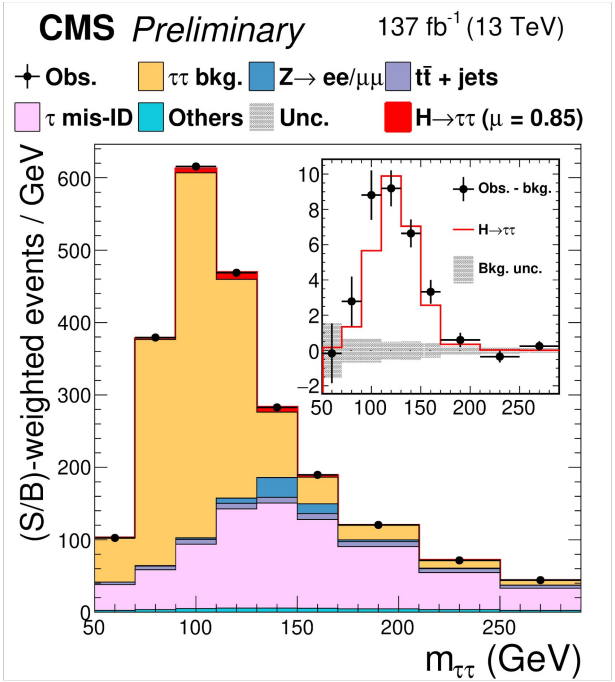
- The analysis targets the 4 most sensitive decay channels: eμ, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$
- Events are split into 3 categories to target the different production modes: 0-jet (no jets present in event), VBF (at least 2 jets + m_{jj} or $|\Delta\eta|_{jj}$ cuts), boosted (= everything else)
- Categories are then split into sub-categories to target specific STXS bins using equivalent reco. variables to match definition of GEN selections (N_{jets}, p_T^H, etc.)
- Fits of 2D discriminants to enhance sensitivity: 1 variable always ditau mass (m_{TT}), and 2nd variable either m_{jj}, p_T^H, p_T^τ



Inclusive cross section results

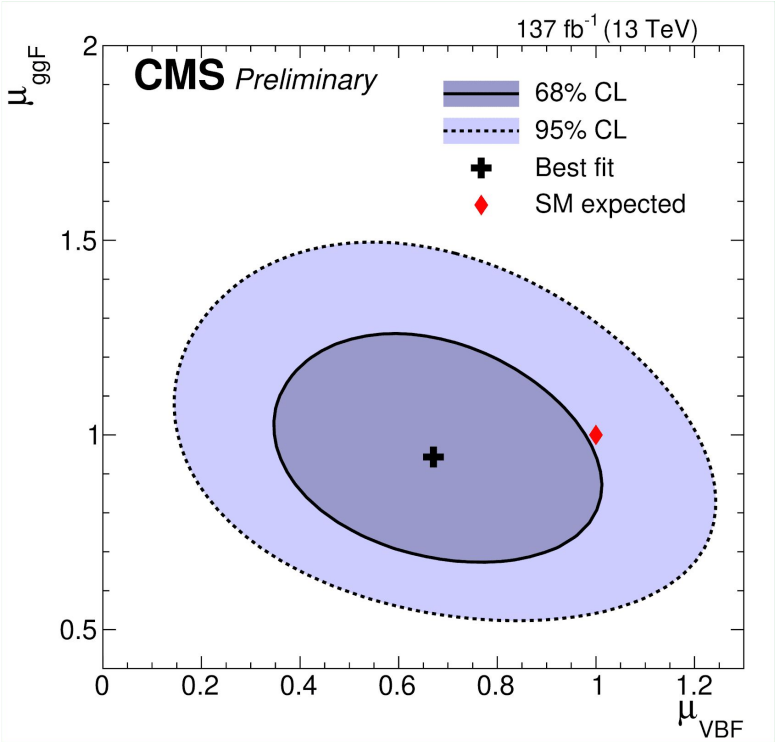
- Results extracted by simultaneous binned maximum likelihood fit
- The measured cross sections for the inclusive Higgs, ggH, and qqH relative to SM
- Right plot all categories are combined and weighted by S/B

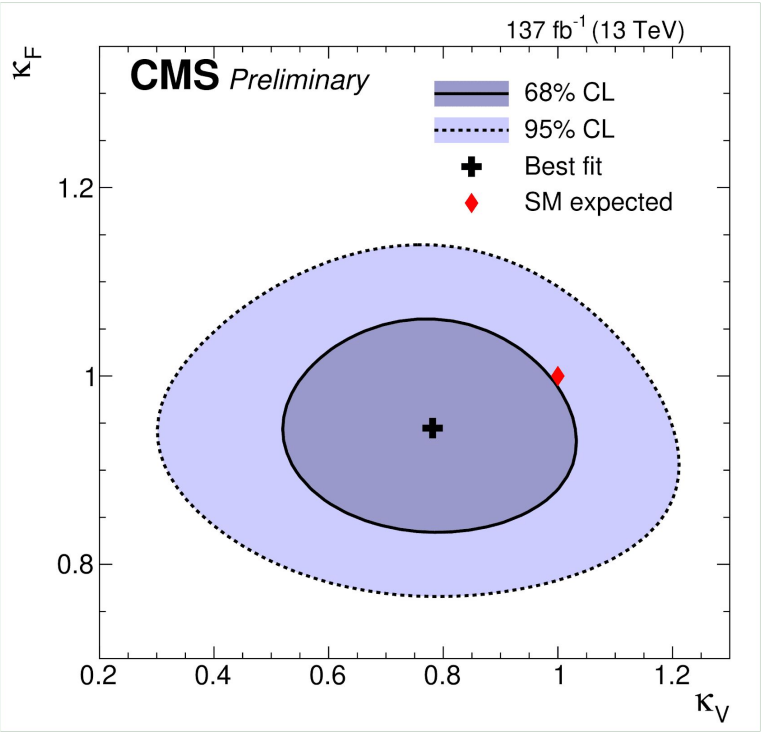




2D scans of coupling modifiers

- Results interpreted as 2D scans of ggH and VBF coupling modifiers (left) and fermionic and bosonic coupling modifiers (right)

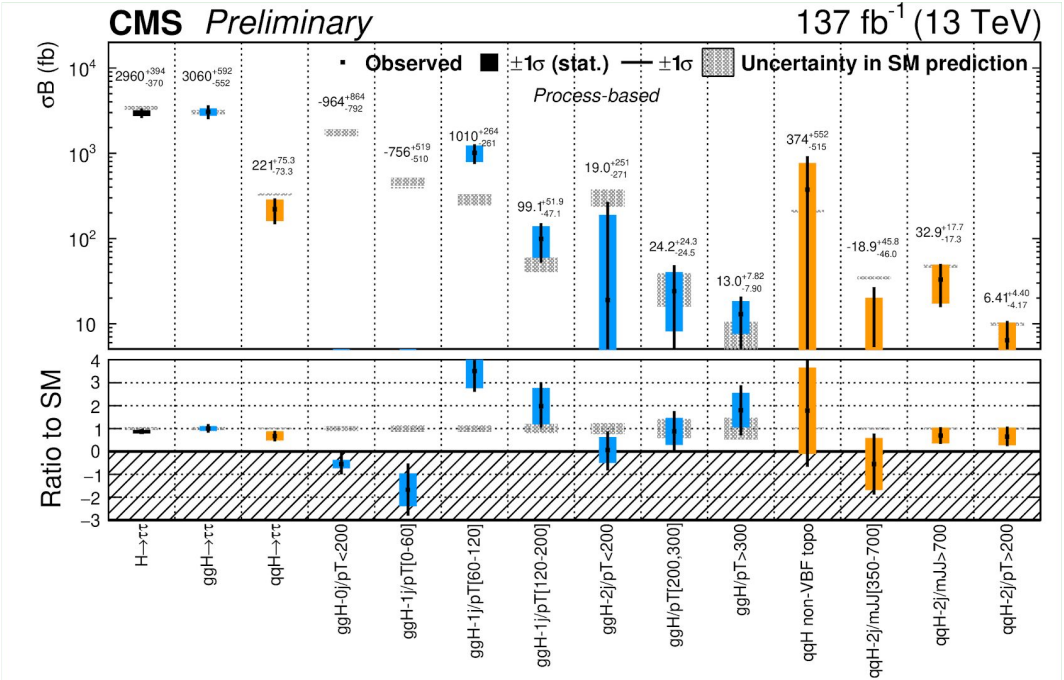


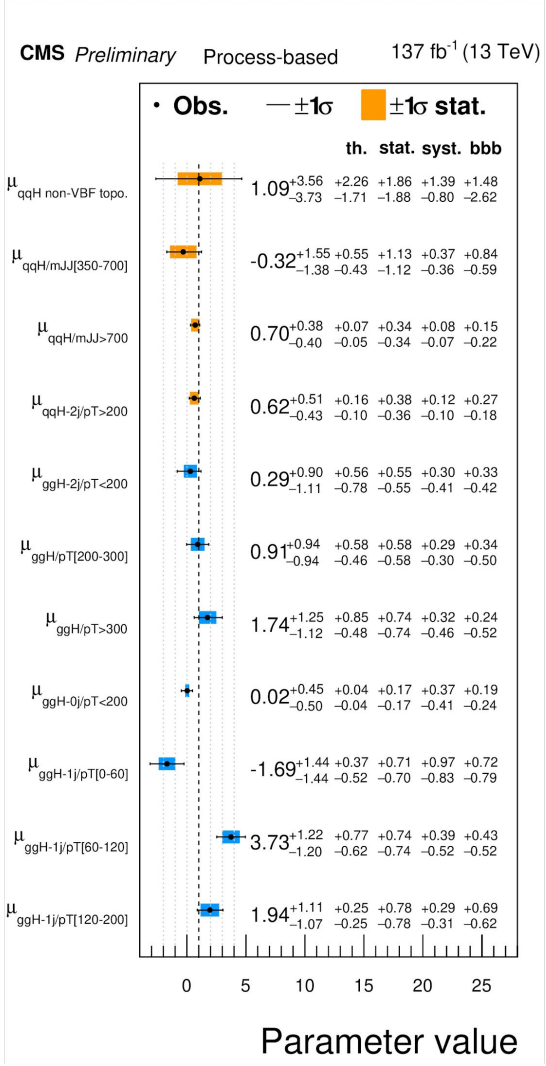


STXS results

- The Measured value of STXS signal strengths are shown
- Some STXS bins are merged: 2 different schemes

process-based and topology-based





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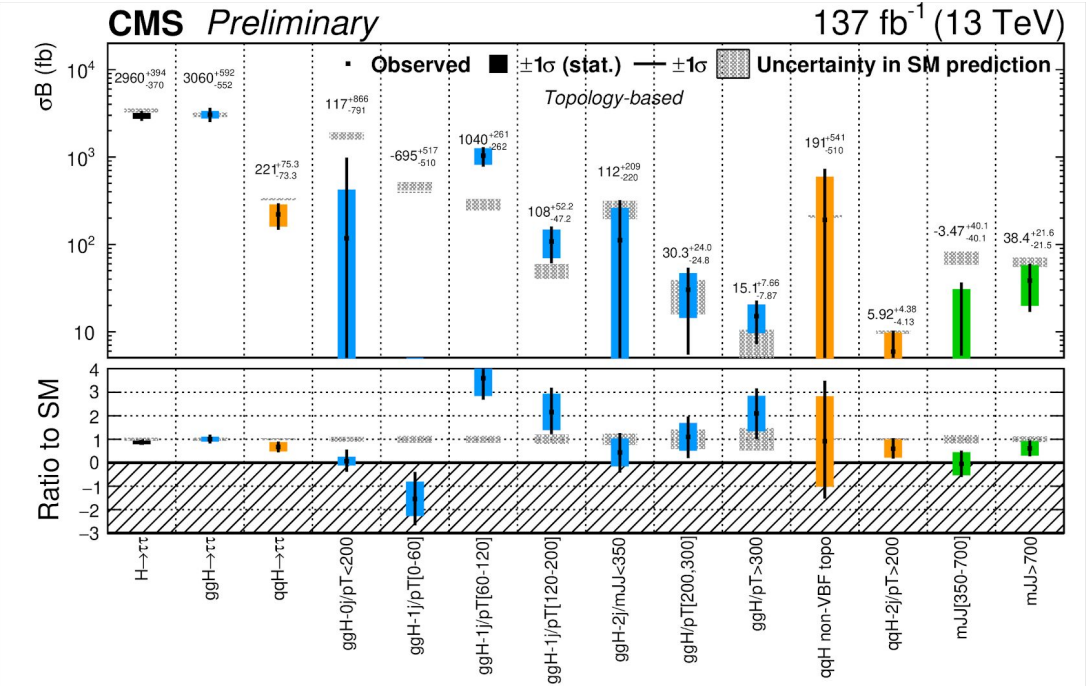
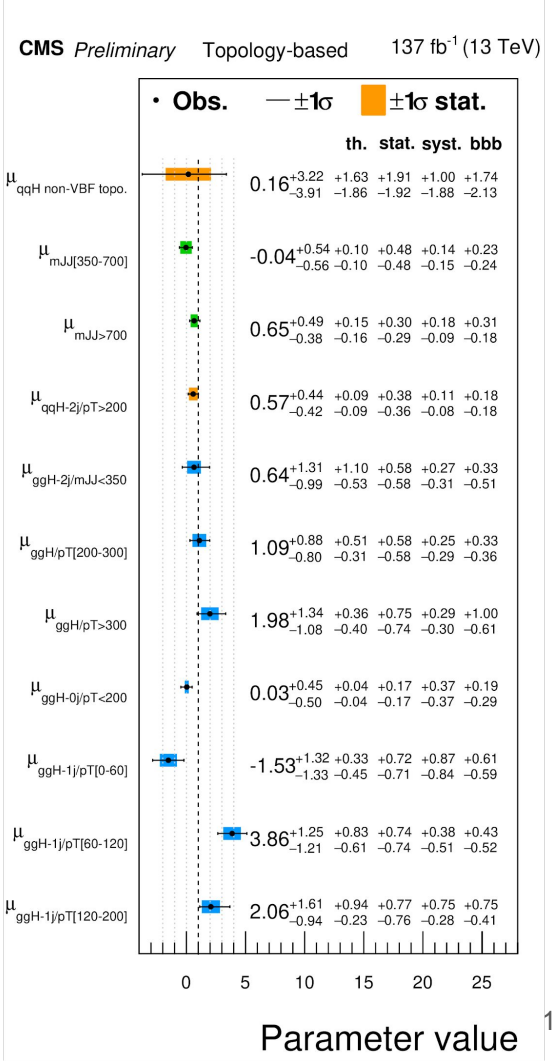




Measurement of the CP properties of the H→ττ decay

First measurement of H→ττ CP properties

- Long history of HVV CP measurement but coupling to fermions less tested
- Results by CMS (arXiv:2003.10866) and ATLAS (arXiv:2004.04545) on ttH coupling
- CP properties of coupling to tau leptons complementary to these results
- Yukawa interaction parameterised as:

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

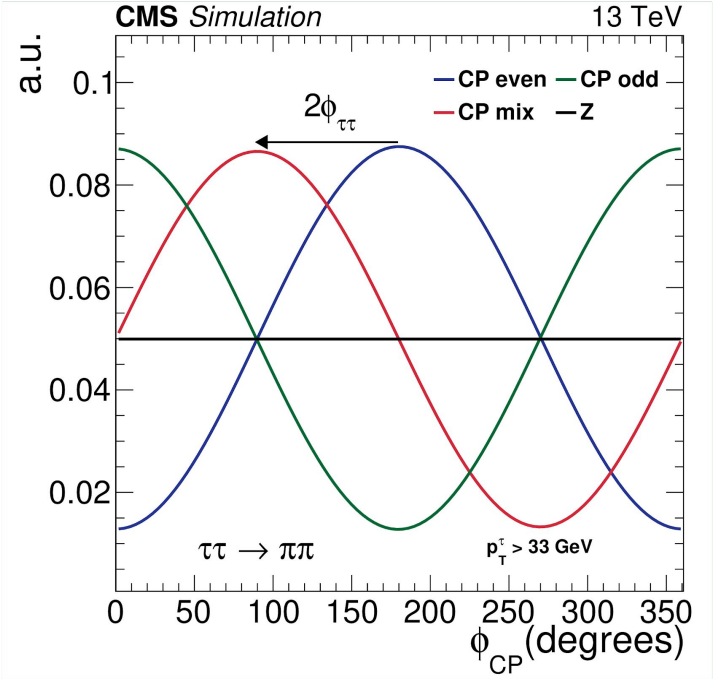
- Define parameter $\Phi_{\tau\tau}$ as:

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

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

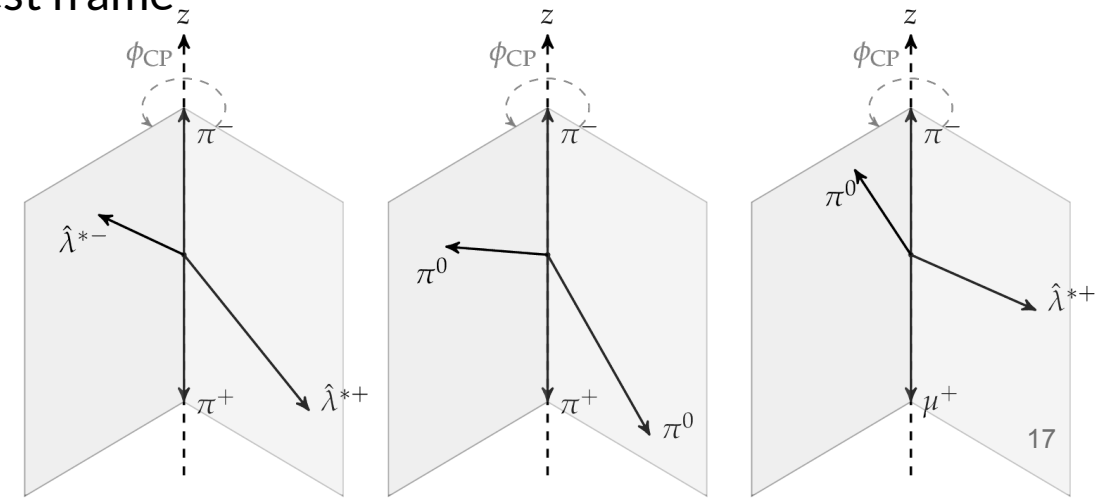
Observable sensitive to Φ_{TT}

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



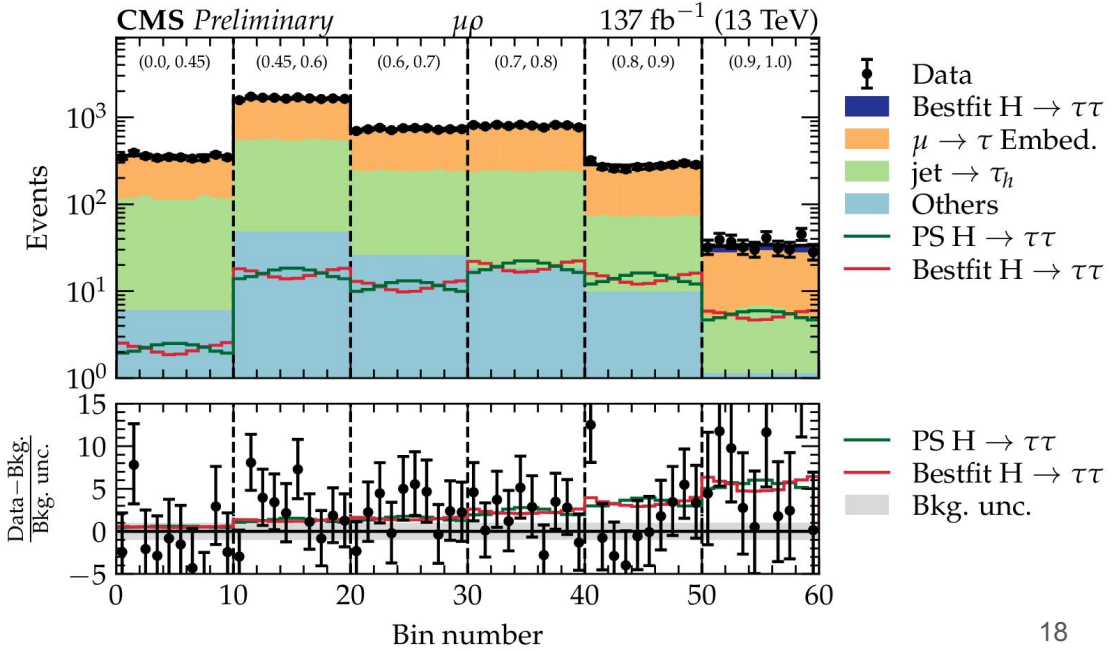
Reconstructing decay planes

- We can't reconstruct tau decay planes exactly - instead use approximations
- For events with intermediate ρ^- resonances ($\tau \to \rho^- \nu \to \pi^- \pi^0 \nu$) define plane using π^- and π^0 momenta
  - ➢ Or for $\tau \to a_1 \nu \to \rho^0 \pi \nu \to \pi^- \pi^- \pi^+ \nu$ use $\pi^- \pi^+$ pair from intermediate ρ^0
- When no ρ is present use impact parameters ($\boldsymbol{\lambda}$) and charged particle 4-vector (π^-/μ)
- All planes reconstructed in $\pi^+\pi^-$ rest frame
- Current analysis considers most Sensitive final states in $\mu\tau_h$, $\tau_h\tau_h$ channels:
  (μ,ρ,π,a_1^{1pr},a_1^{3pr})× (ρ,π,a_1^{1pr},a_1^{3pr})
- Most sensitive: $\mu\rho$, $\rho\rho$, $\pi\rho$



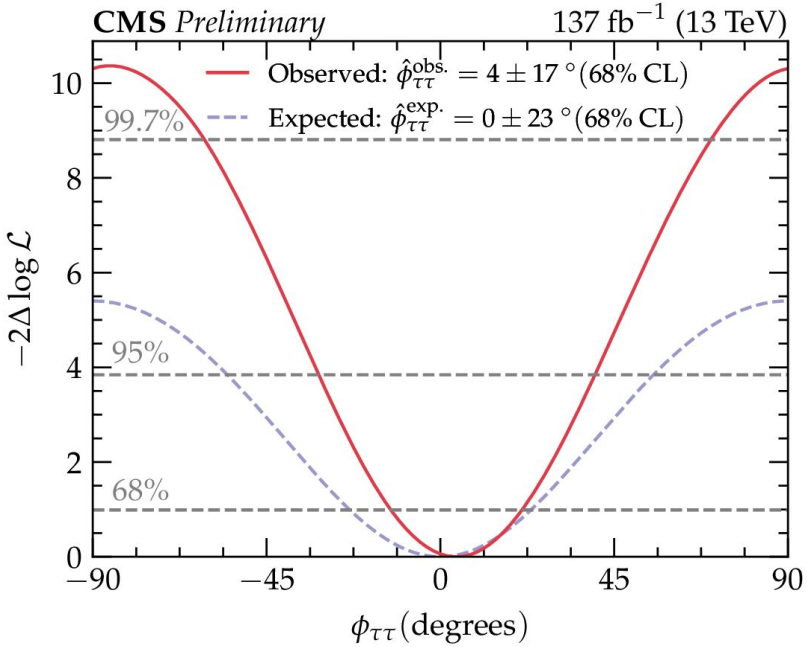
Analysis strategy

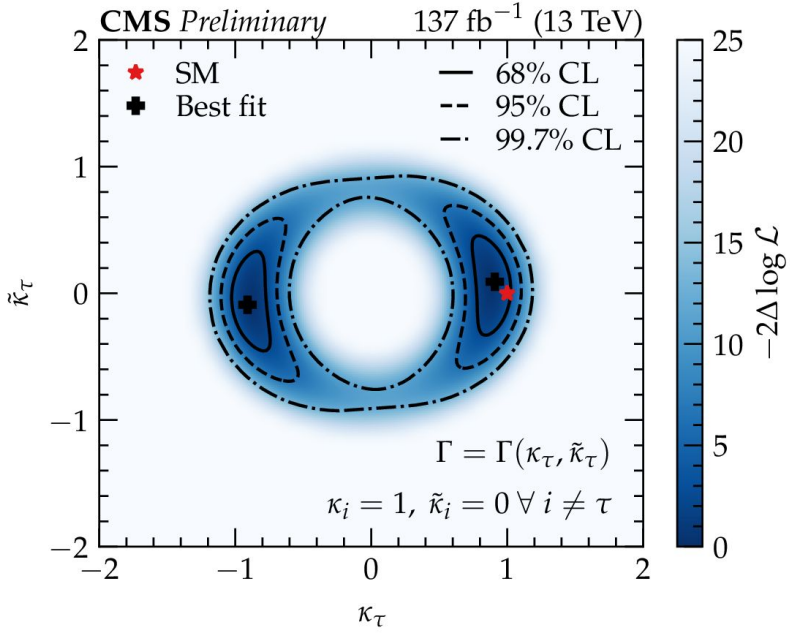
- Signal vs background differentiation using multi-class BDT (NN) for τ_h,τ_h ($\mu\tau_h$,) channels: includes kinematic variables e.g $m_{\tau\tau}$ p_T's , m_{jj}, N_{jets}, etc.
- 3 classes: genuine τ_h, fake τ_h, and Higgs (merge VBF + ggH + VH(hadronic))
- Events classified as Higgs used to extract CP information
- Fit 2D distribution of BDT/NN Score vs Φ_{CP}
- More details in HIG-20-006



H→ττ CP: results

- Simultaneous maximum likelihood fit used to extract results
- Measured value of $\Phi_{\tau\tau}$ is 4 ±17 ° [=4± 17 (stat) ± 2 (bbb) ± 1 (theo) ± 1 (syst) °]
- Assuming all other couplings = SM can be interpreted in terms of κ_τ's parameters



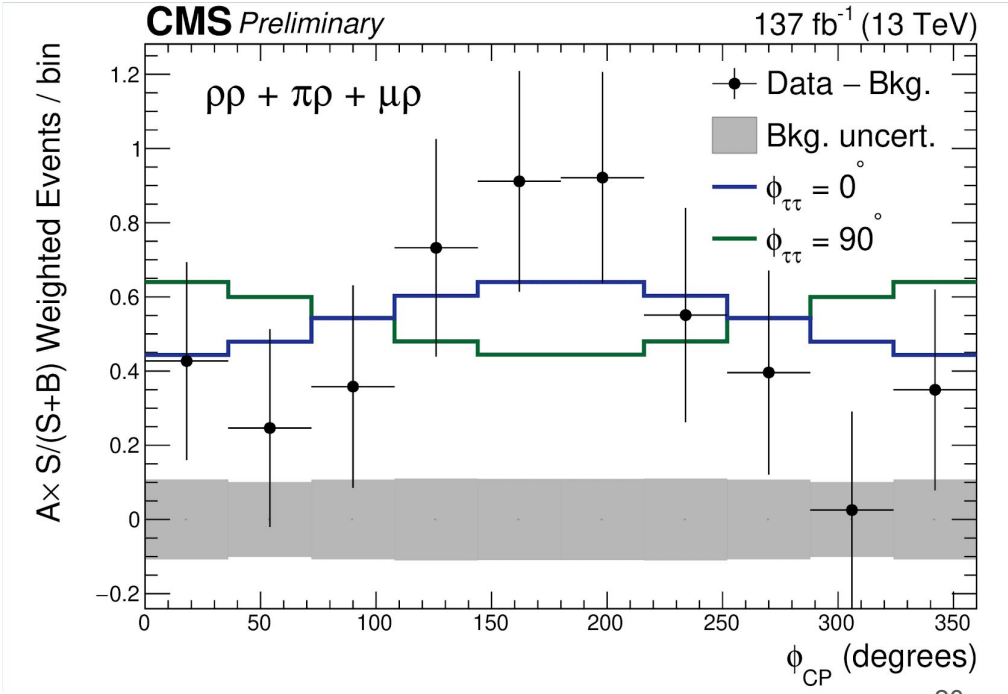


H→ττ CP: results

- To illustrate the result the 3 most sensitive channels are weighted and combined into a plot of Φ_{CP}
- Each BDT/NN score window is weighted by A S/(S+B)
- A = the "average asymmetry":

$$A = \frac{1}{N_{bins}} \sum \frac{|Exp^{\text{CP-even}} - Exp^{\text{CP-odd}}|}{Exp^{\text{CP-even}} + Exp^{\text{CP-odd}}}$$

- μρ channel is phase shifted by 180 °
- Clear preference for the CP-even Scenario: CP-odd exclusion at 3.2σ (2.3σ expected)



Conclusions

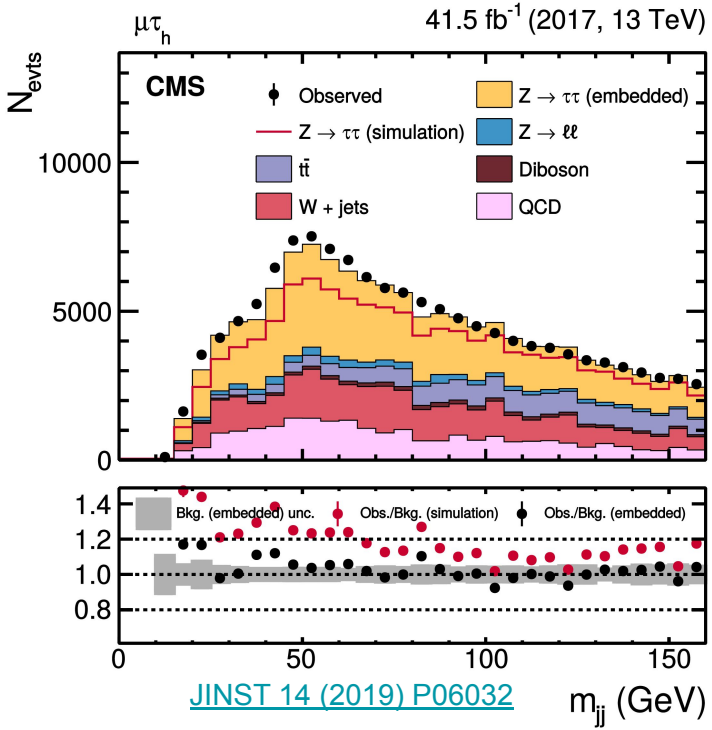
- The latest results of inclusive cross section and STXS measurement have been presented
- Inclusive cross section measured: $\mu = 0.85\ ^{+0.12}_{-0.11}$
- A measurement of the CP properties of the $H\tau\tau$ coupling has been presented for the first time
- Measured value of $\Phi_{\tau\tau}$ is $4 \pm 17^{\circ}$, CP-odd exclusion at 3.2σ

Thanks for your attention!

Backup

Comparison of embedded and MC predictions

- The prediction of the dijet invariant mass variable using embedded samples if compared to data and to MC simulation



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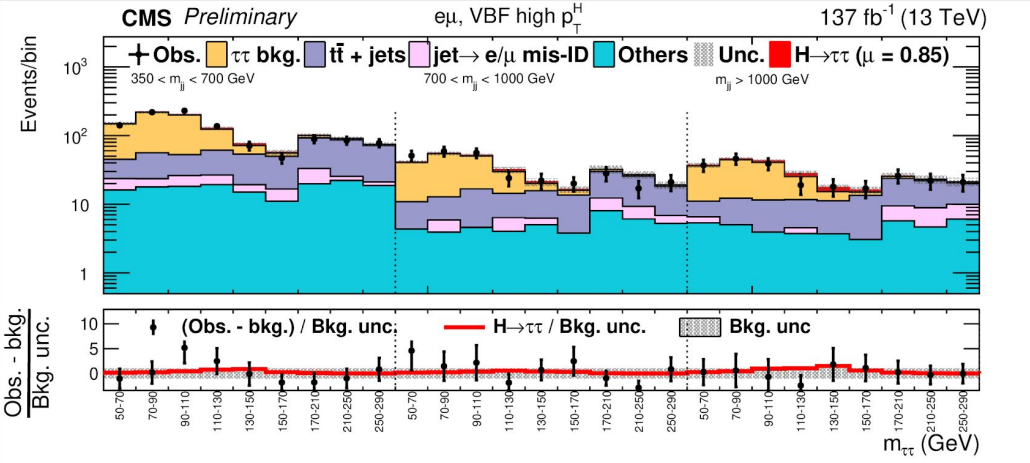
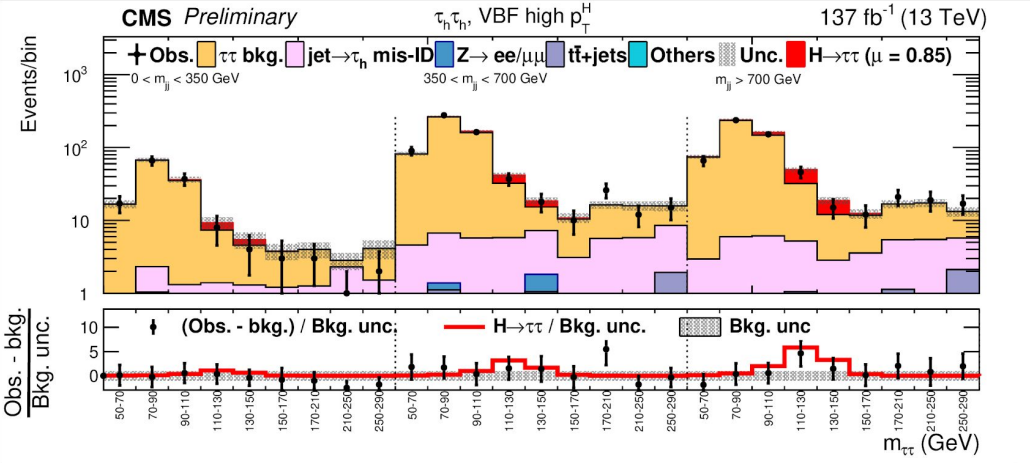
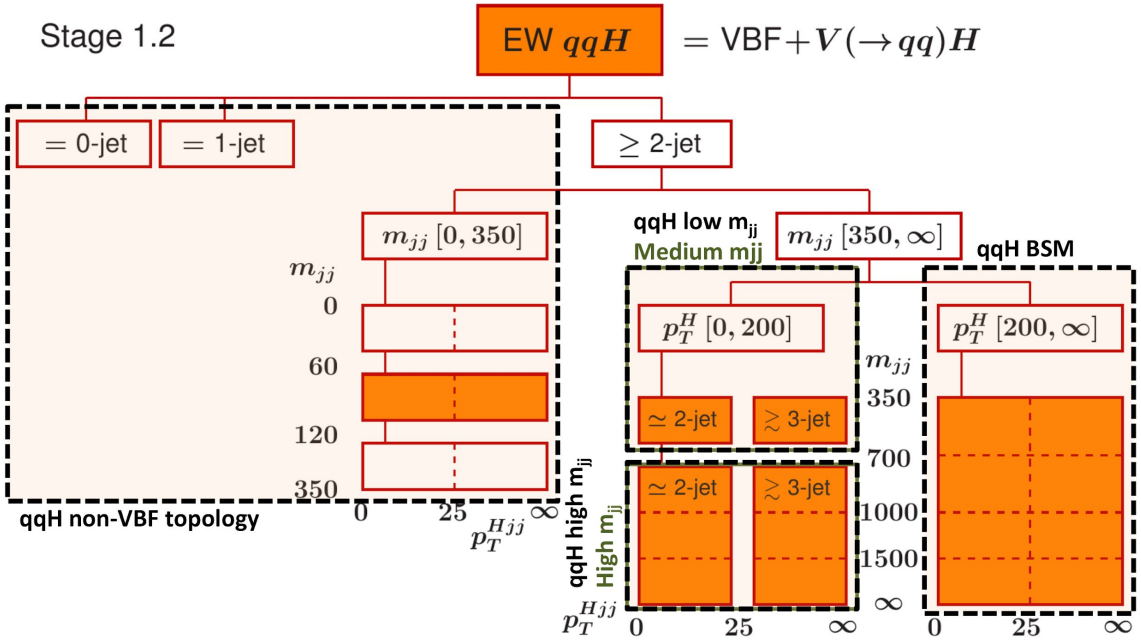
2D distributions

- Examples of 2D distributions that are fitted to extract results in the eμ and $\tau_h\tau_h$ and channels





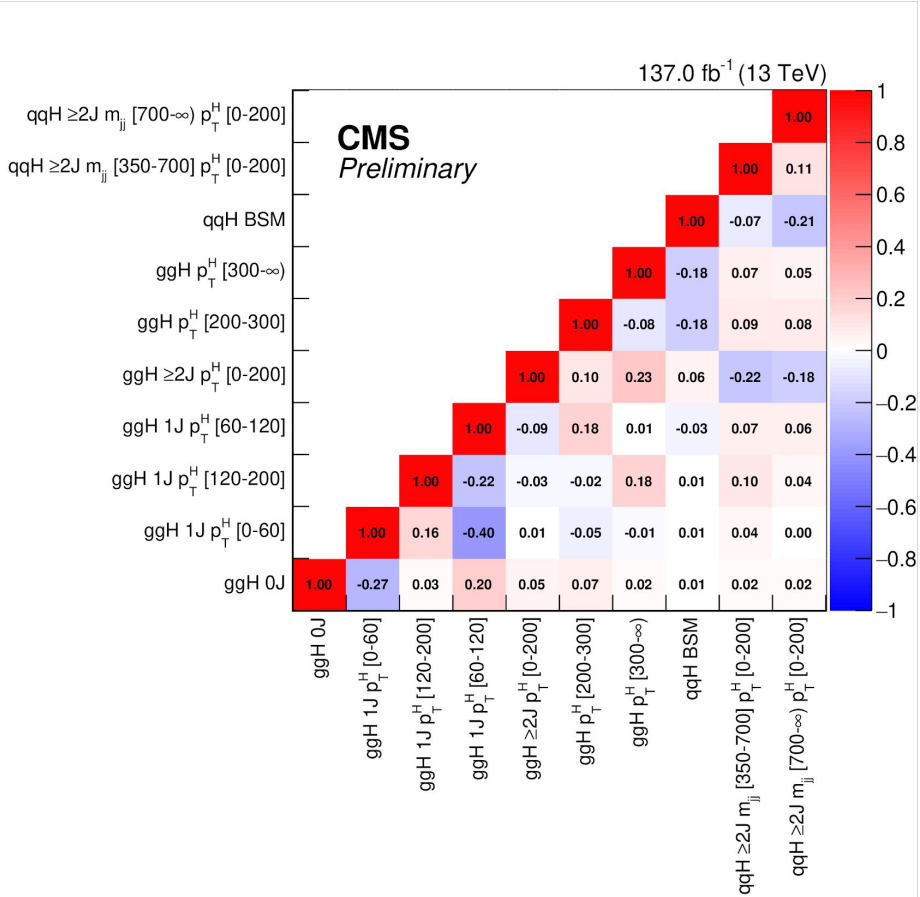
Stage 1.2 STXS category definition for qqH



STXS merging schemes

- Merging is performed to reduce number of bins with large uncertainties and/or large correlations between bins/processes
- Process based:
  - ggH and qqH process treated separately
  - Some neighbouring bins in STXS qqH and ggH categories merged
- Topology based:
  - ggH and qqH tied together for VBF-like topology bins
  - Some STXS bins also merged for non VBF-like bins but keeping ggH and qqH seperate

Correlations between STXS bins

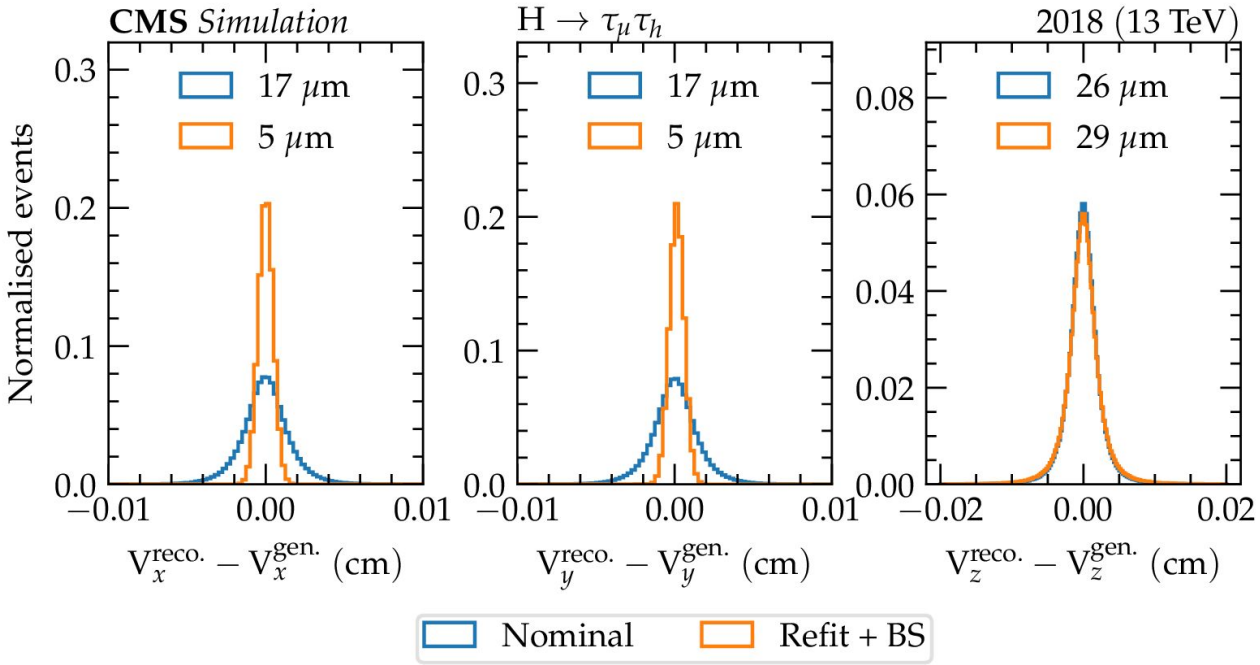


Reconstructing decay modes and IPs

- Dedicated BDT discriminator to reconstruct τ_h decay mode
- More details in poster talk by Mohammad Hassan Hassanshahi tomorrow (here)
- Gives significant improvements over HPS decay mode application
- IP reconstruction improved in 2 ways:
  - ➢ Use of refitted PV excluding tau tracks and using constraint from LHC luminous region "beam spot constraint" (more details here)
  - ➢ Minimize distance between track and PV numerically in 3D taking into account helical track geometry
- Reconstruction of IP also estimate an uncertainty used to define a significance: SIP = σIP/|IP|
- Cut of SIP>1.5 used to reject poorly reconstructed events

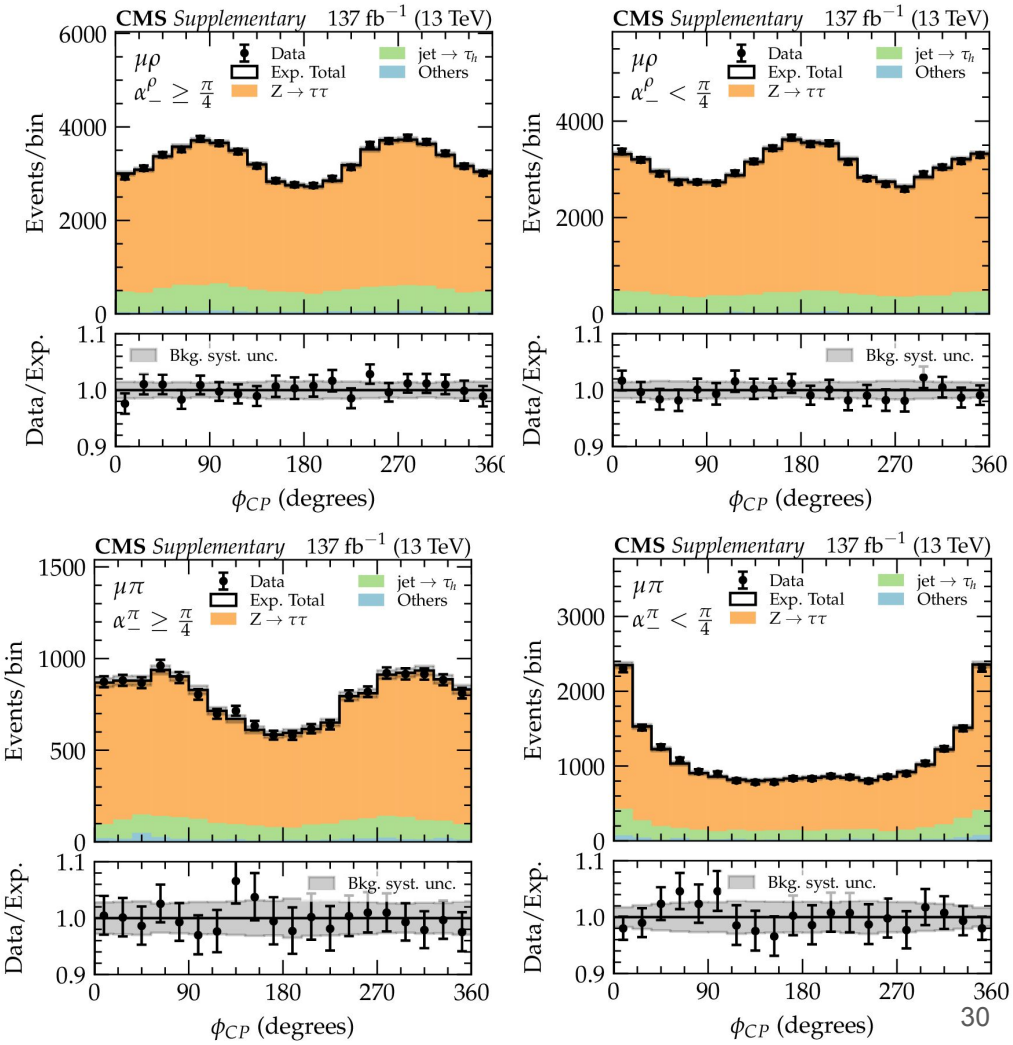
PV resolution comparisons

- The resolution of vertex definition used for the CP analysis is compared to the nominal CMS definition
- Vertex is refit excluding tau tracks and with use of beam-spot constraint



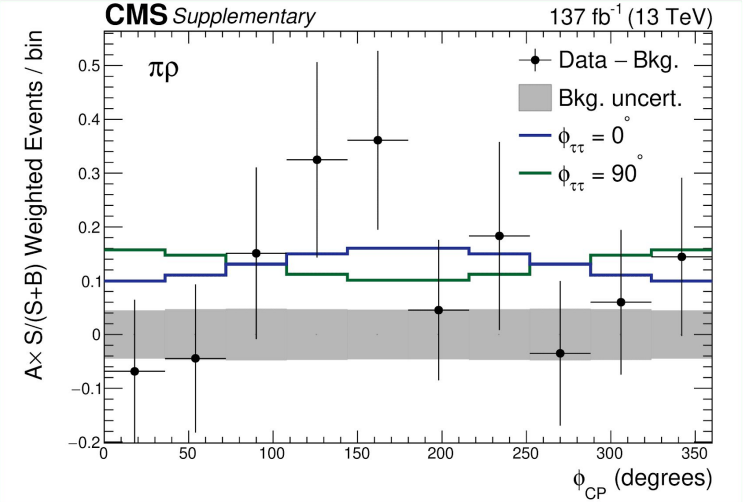
Validation with Z→ττ

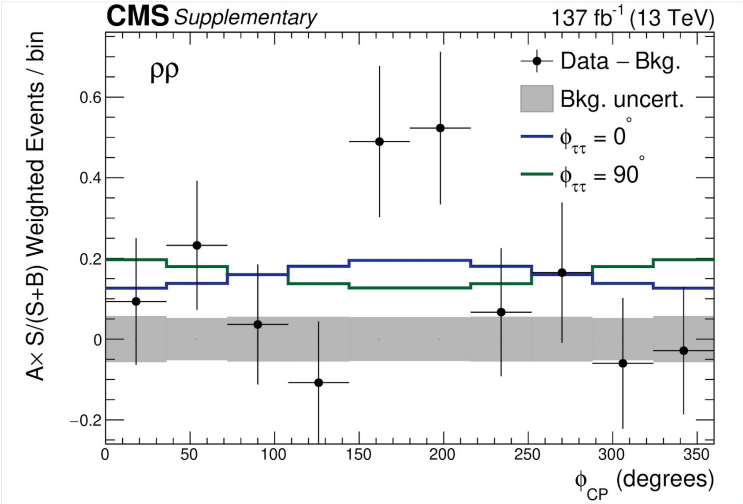
- Z→ττ has ~ flat distribution of Φ_{CP}
- But we can split into two sinusoidal contributions using α_- variable
- Definition in paper by [Stefan Berge et al.]

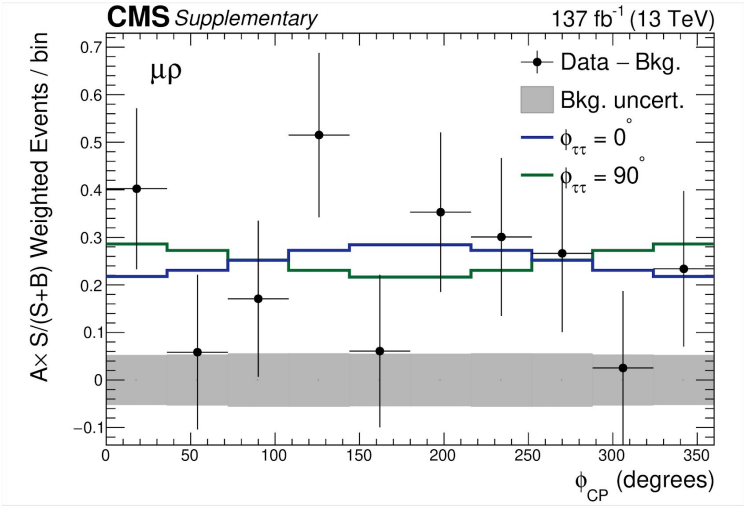


Φ_{CP} by channel

- Weighted Φ_{CP} plots are shown individually for the 3 most sensitive channels







Fitted distributions for CP Extraction

- The 2D fitted distributions for 3 /4 of the most sensitive channels are shown