Higgs to Tau Tau Signal Strength, Cross Section, and CPV Measurements at CMS and ATLAS

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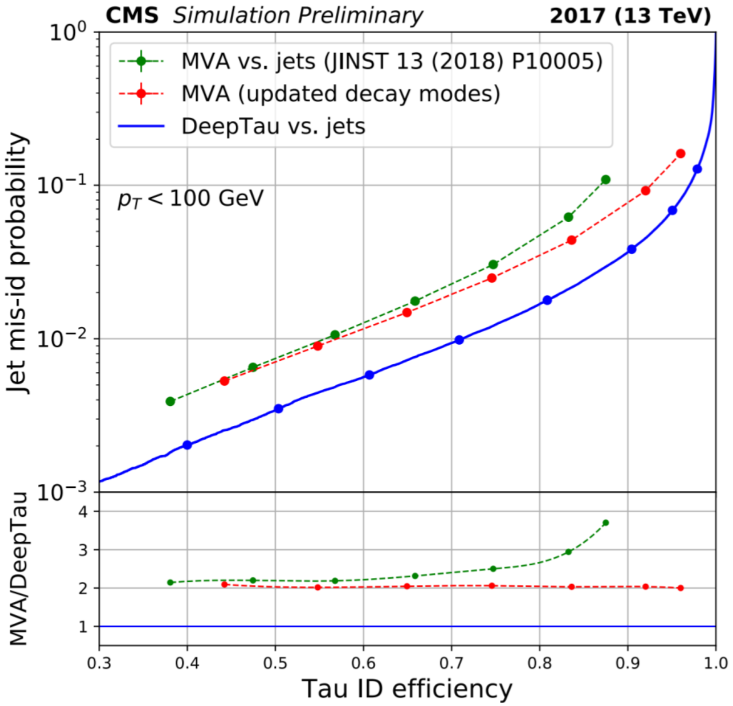
On behalf of the CMS and ATLAS Collaborations

Overview

Analysis	Years	Link to Documentation
ATLAS $H\tau\tau$ Cross Section Analysis	2015+2016	Phys. Rev. D 99 072001 (2019)
CMS $H\tau\tau$ STXS Stage 1.2 Cross Section Analysis	Run 2 (2016+2017+2018)	HIG-19-010
CMS CP Violation of $H\tau\tau$ Decay	Run 2 (2016+2017+2018)	HIG-20-006
ATLAS CP Violation of VBF Production using $H\tau\tau$	2015+2016	Phys. Lett. B 805 135426 (2020)

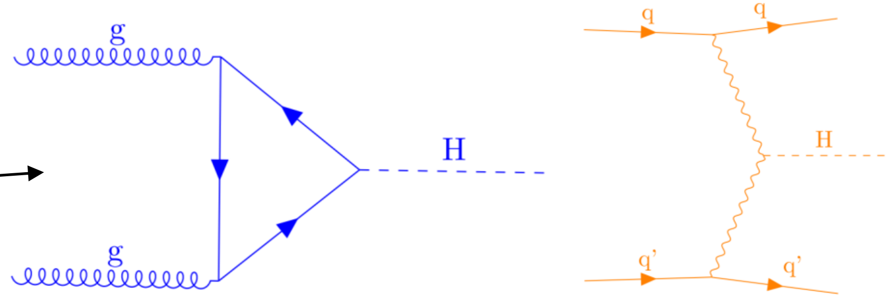
- Why look at the di-tau Higgs decay?
  - Highest branching ratio to leptons
  - Direct observation of the Yukawa coupling
  - Sensitive to VBF coupling
- CMS Run 2 Analyses now using DeepTau:
  - Convolutional neural network
  - Reduced chance of τ mis-ID

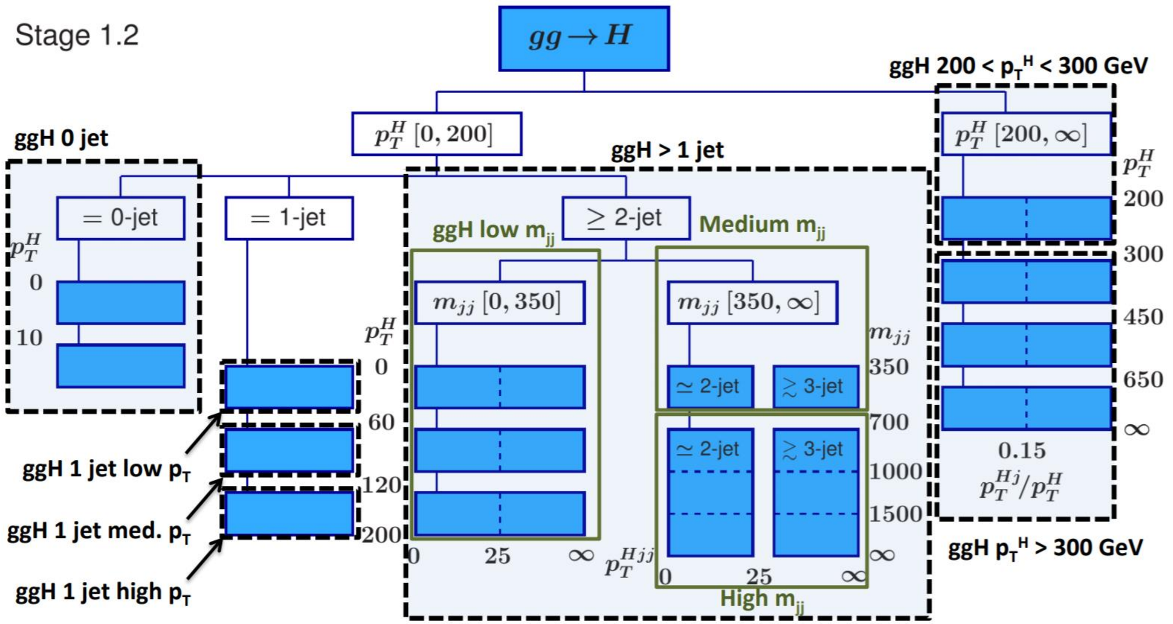


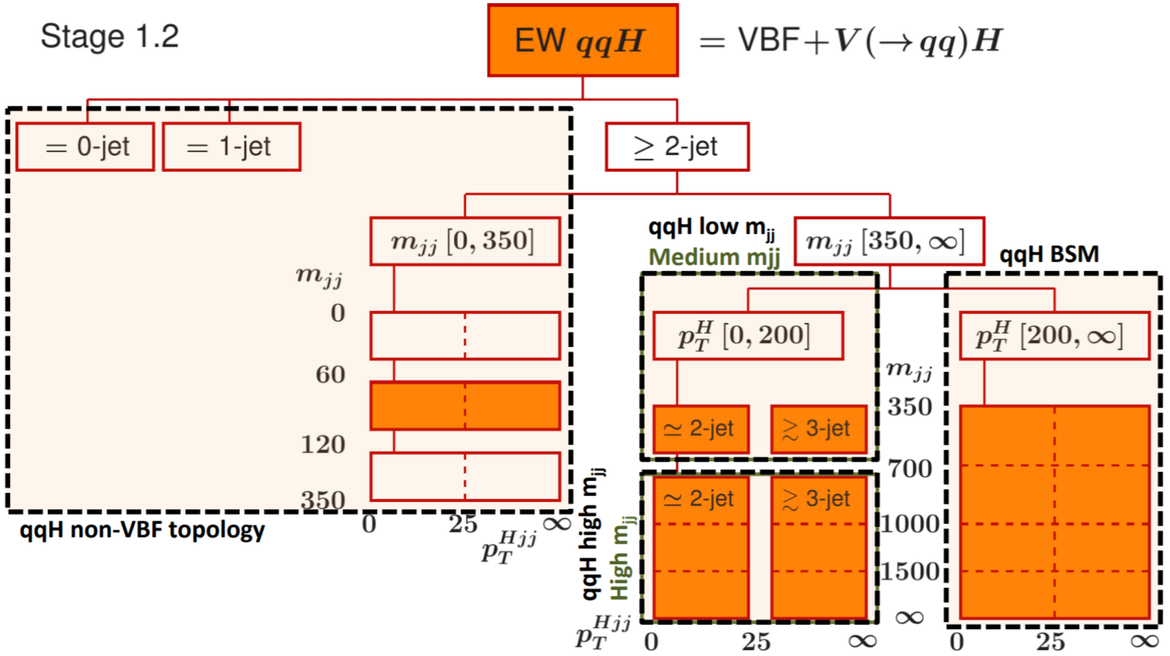
$t\bar{t}$ Jet Mis-ID chance as a function of Tau ID Efficiency, CMS-DP-2019-033

Simplified Template Cross Section Framework

- Simplified Template Cross Section (STXS) framework:
  - Sensitive fine-grained measurements
  - Reduction of theoretical uncertainties
- Inclusive: All higgs signal
- Stage 0: ggH and VBF
- Stage 1.2: below



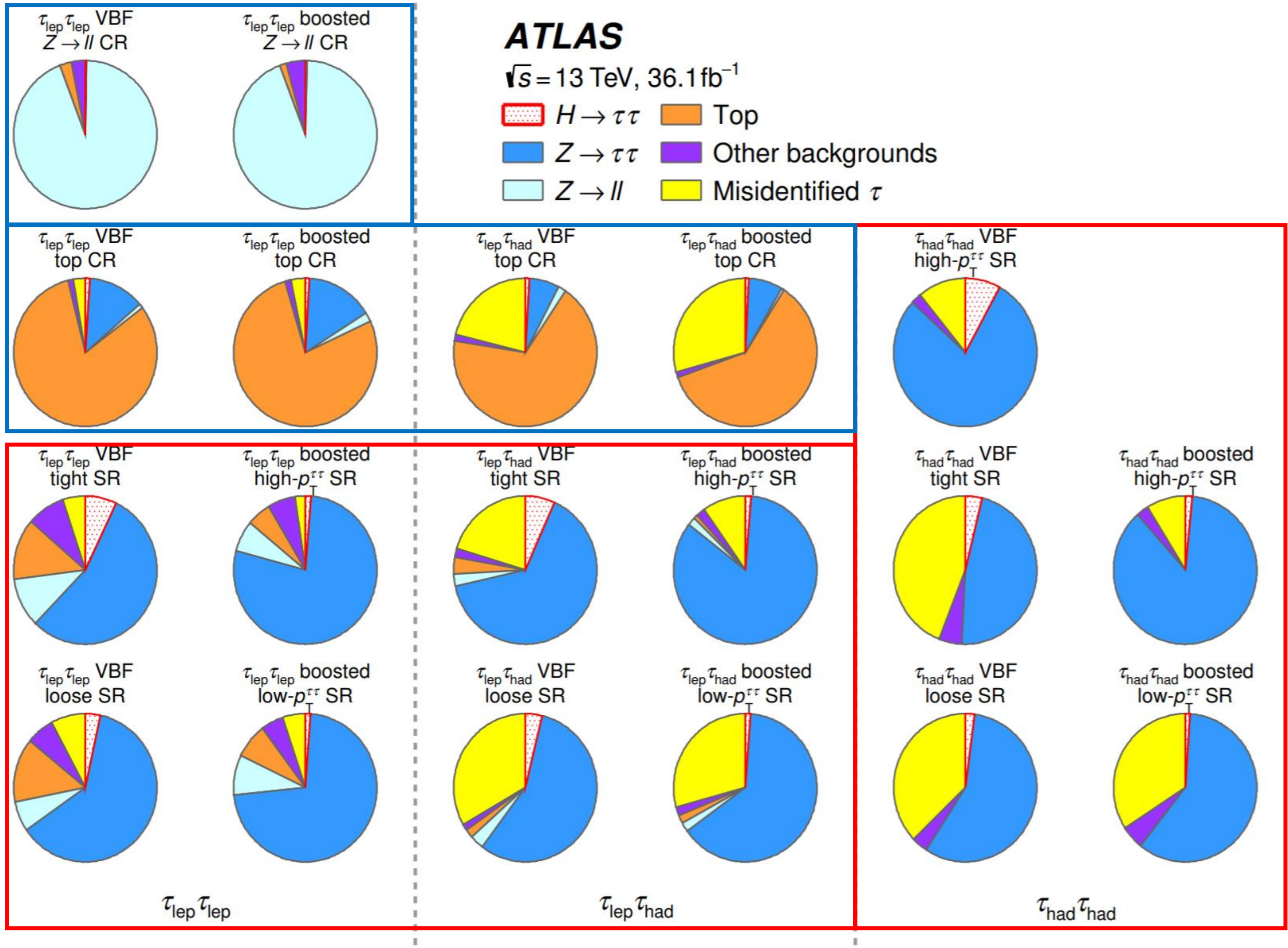




STXS ggH/VBF framework with merging of gen-level bins measured at CMS. HIG 19-010

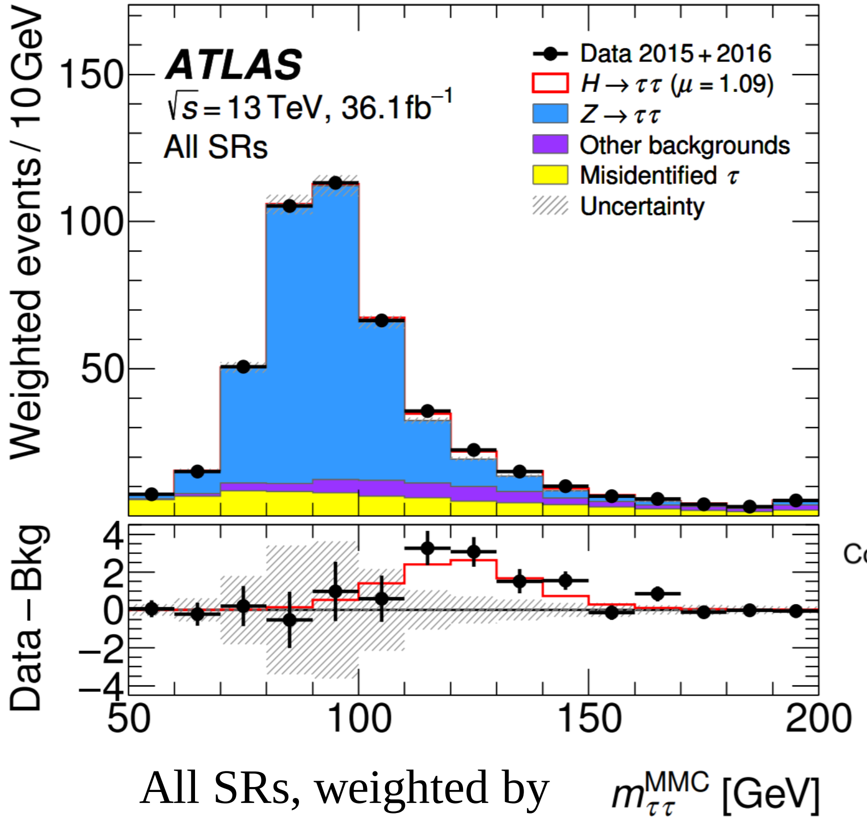
ATLAS Higgs To Taus Signal and Cross Section

- Two Reconstruction categories:
  - VBF
  - Boosted
- VBF and boosted split into sub-categories (red)
- Adjacent control regions used to constrain backgrounds (blue)

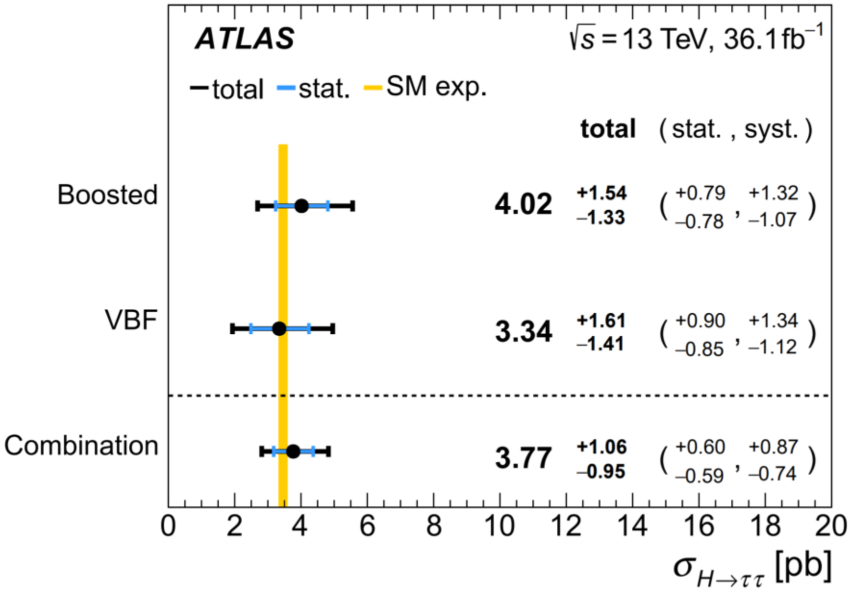


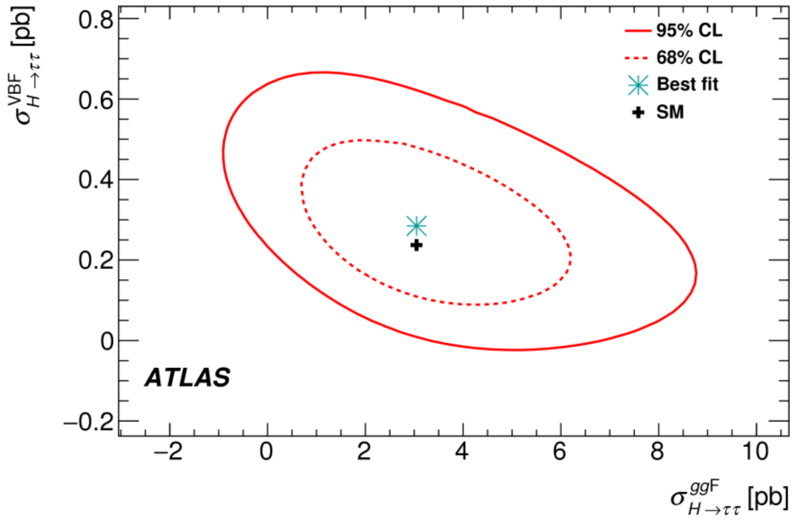
Phys. Rev. D 99 072001 (2019)

Inclusive and Stage 0
Signal Strength and Cross Section



All SRs, weighted by $\ln(1 + S/B)$





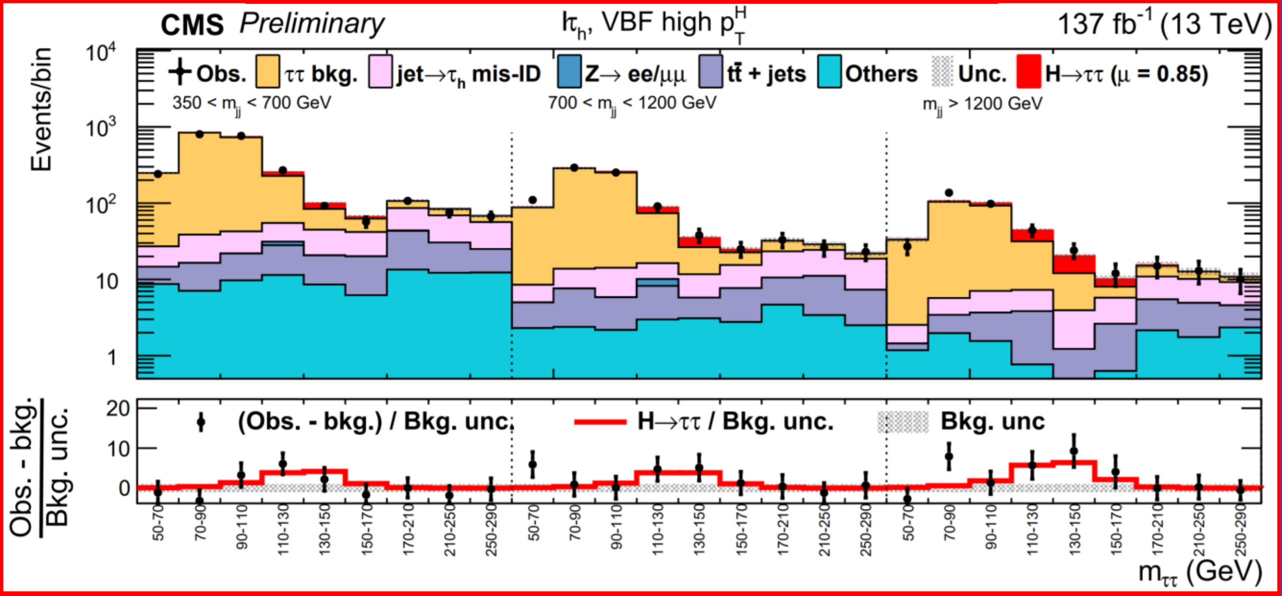
[Phys. Rev. D 99 072001 (2019)]

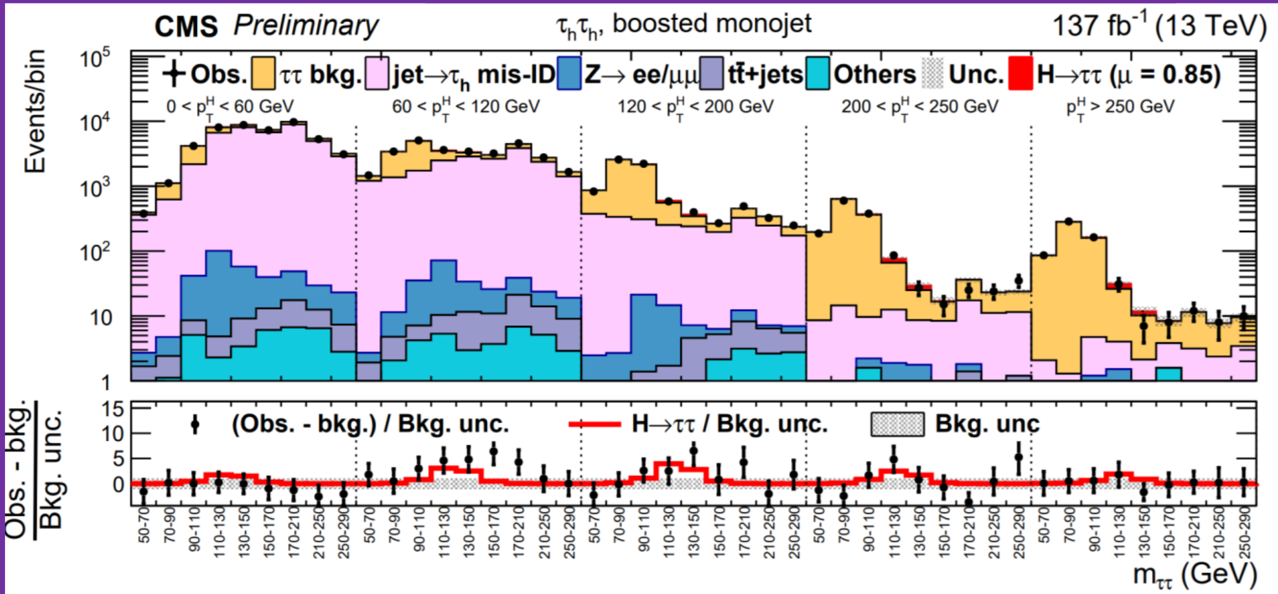
CMS STXS Measurement Strategy

- New background prediction methods (in backup)

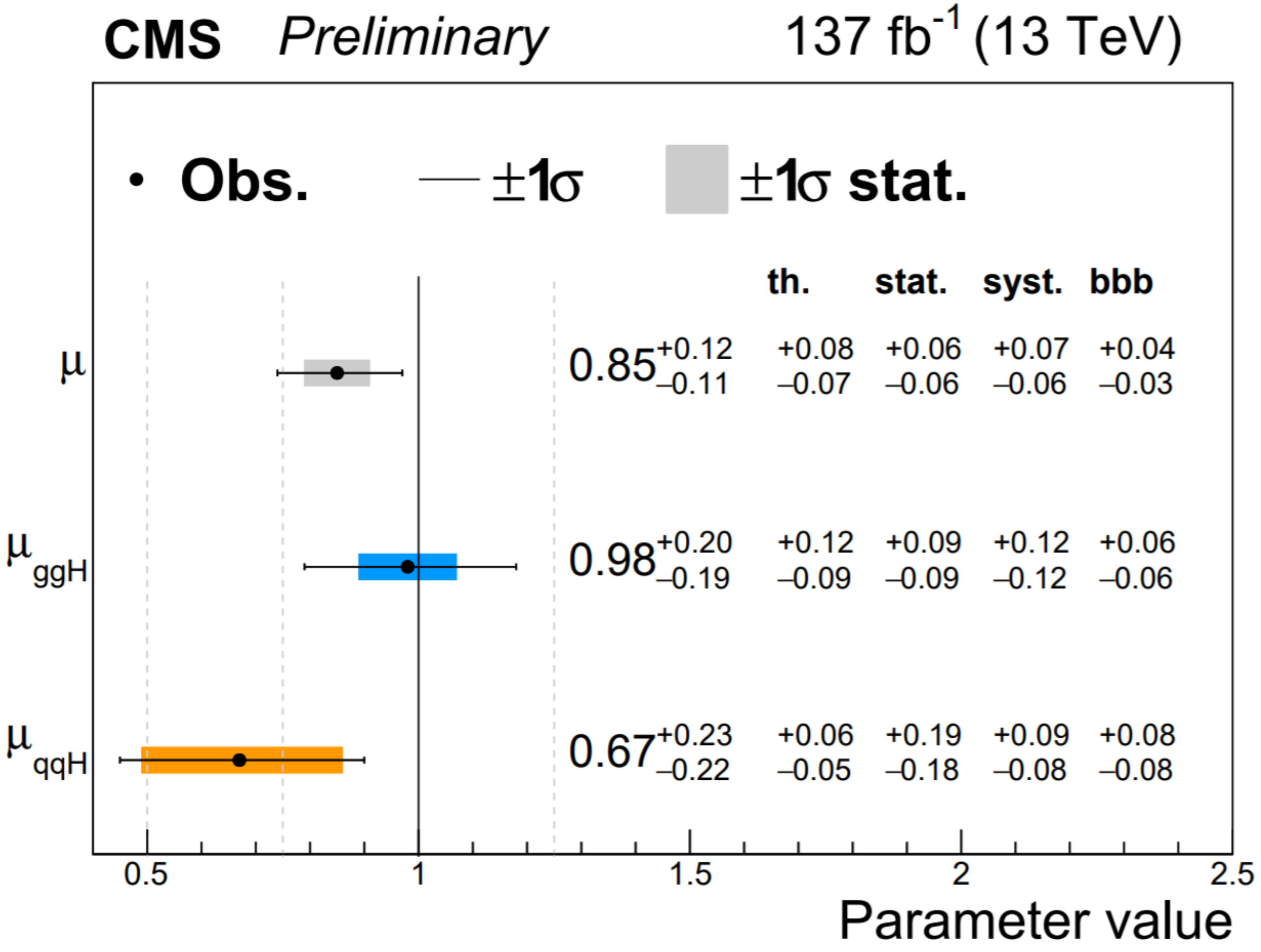
HIG-19-010

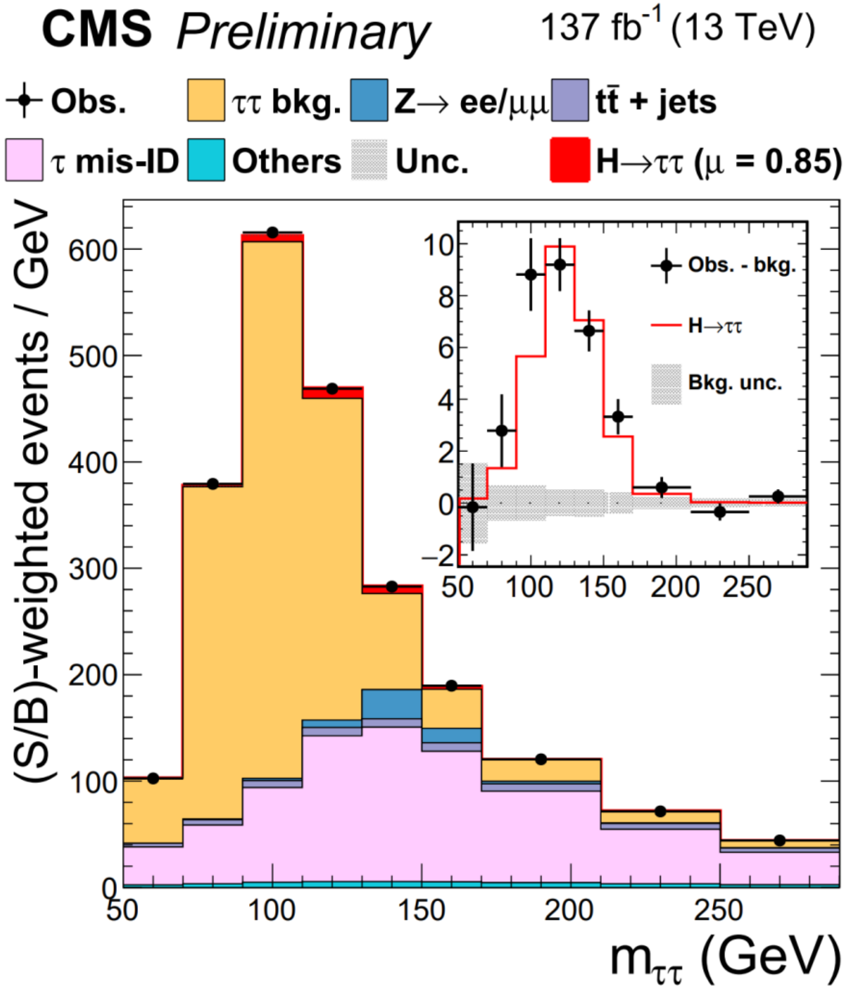
- 5 reconstruction categories:
  - VBF:
    - High Higgs Pt
    - Low Higgs Pt
    - Second variable: m_{jj}
  - 0 Jet (Not shown)
    - Second variable: p_t^{τ}
  - Boosted:
    - Monojet
    - MultiJet
    - Second variable: p_t^{H}





Signal Strengths: Stage 0





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Signal Strengths: Stage 1.2

- Signal strengths computed for certain merging schemes of STXS bins
- Two possible merging schemes
  - Process-based
  - Topology-based
    - Plots in back-up

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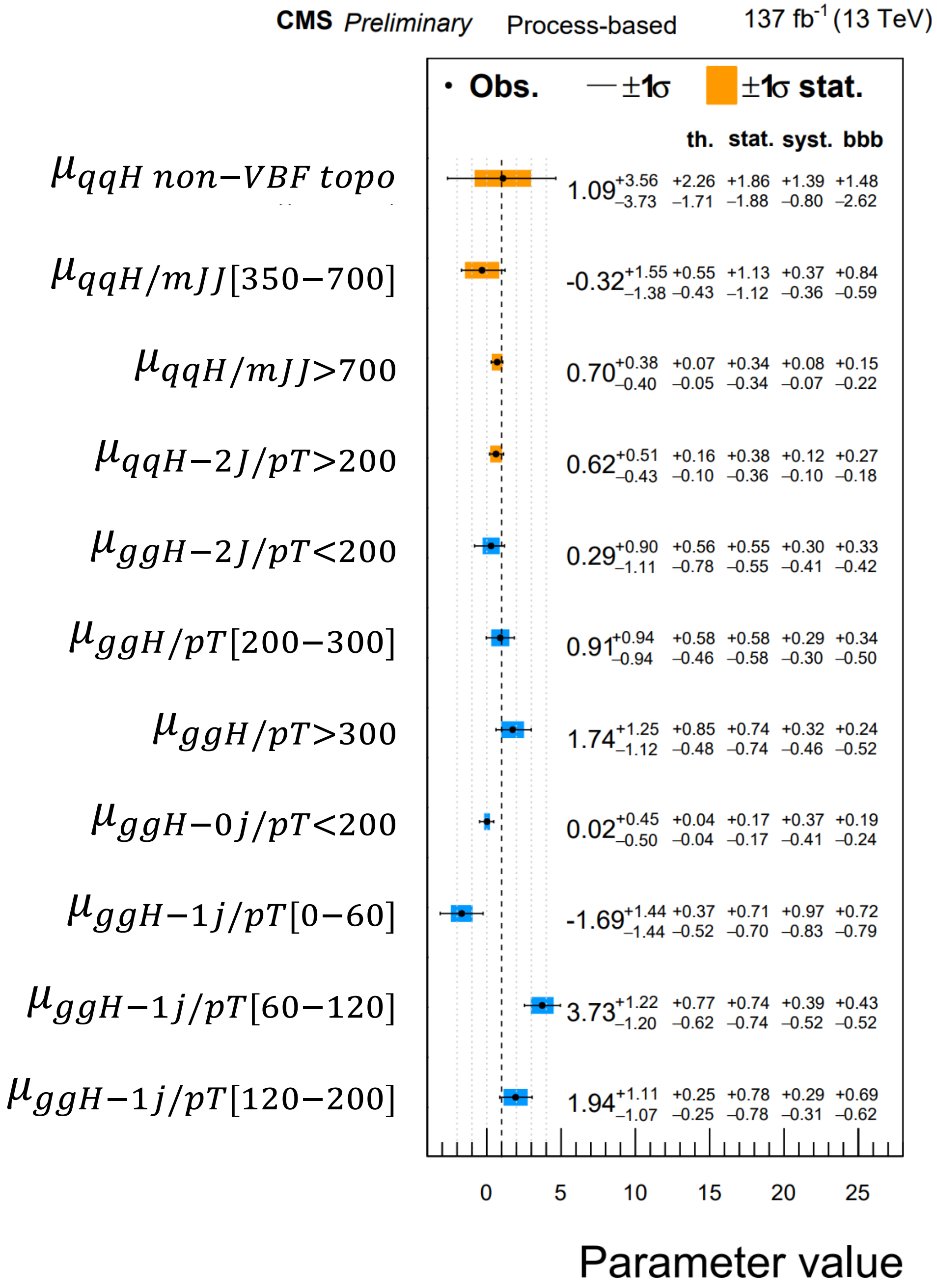
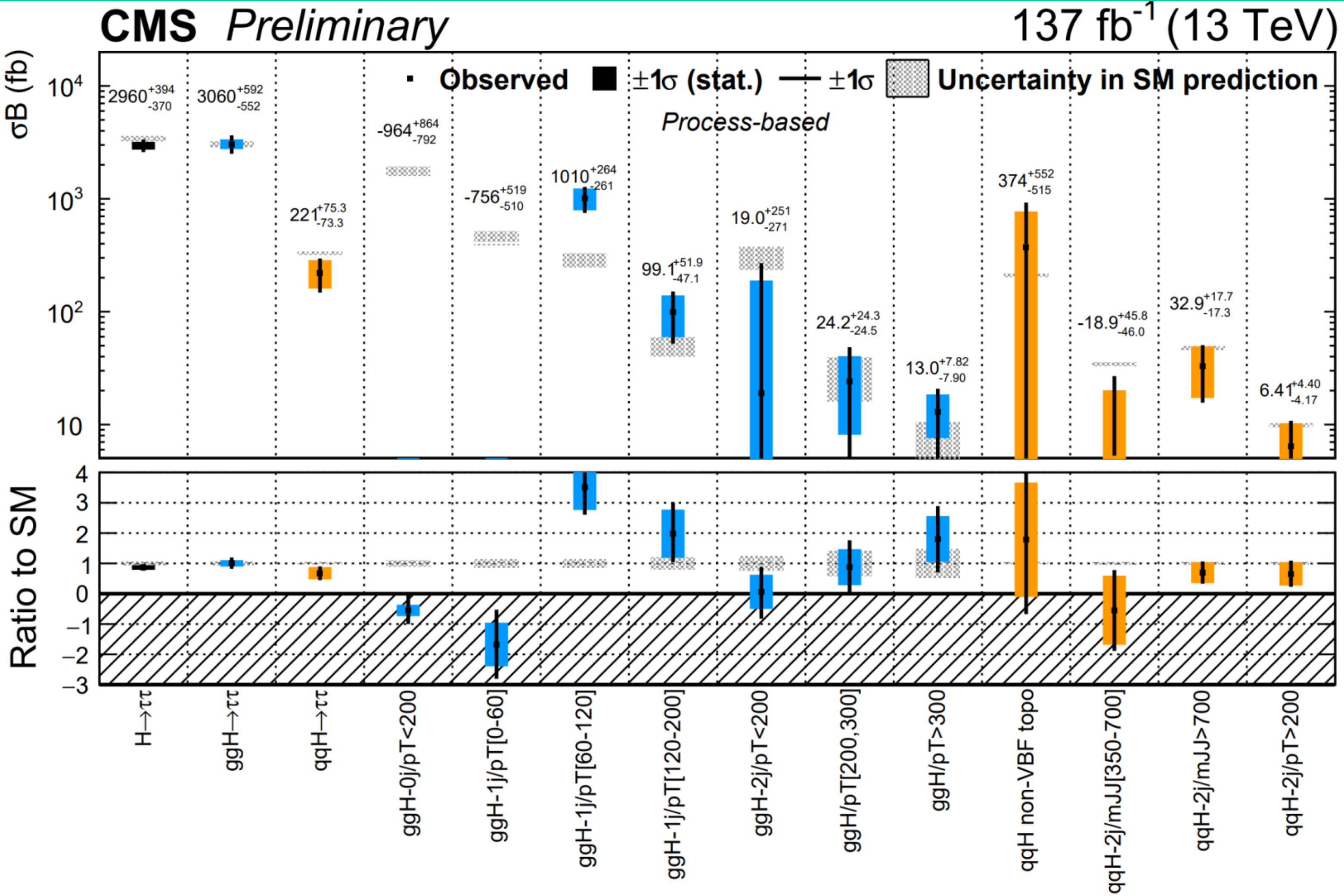


Cross Section Measurements: Stage 1.2



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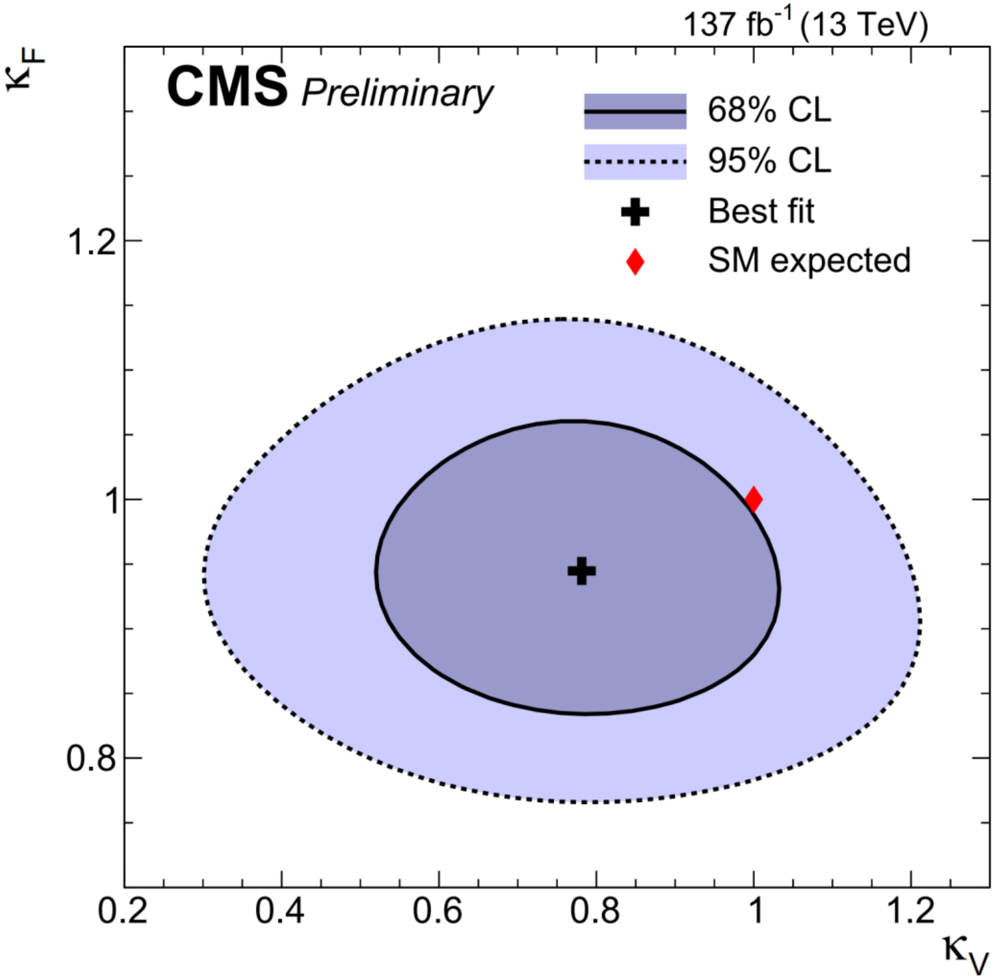
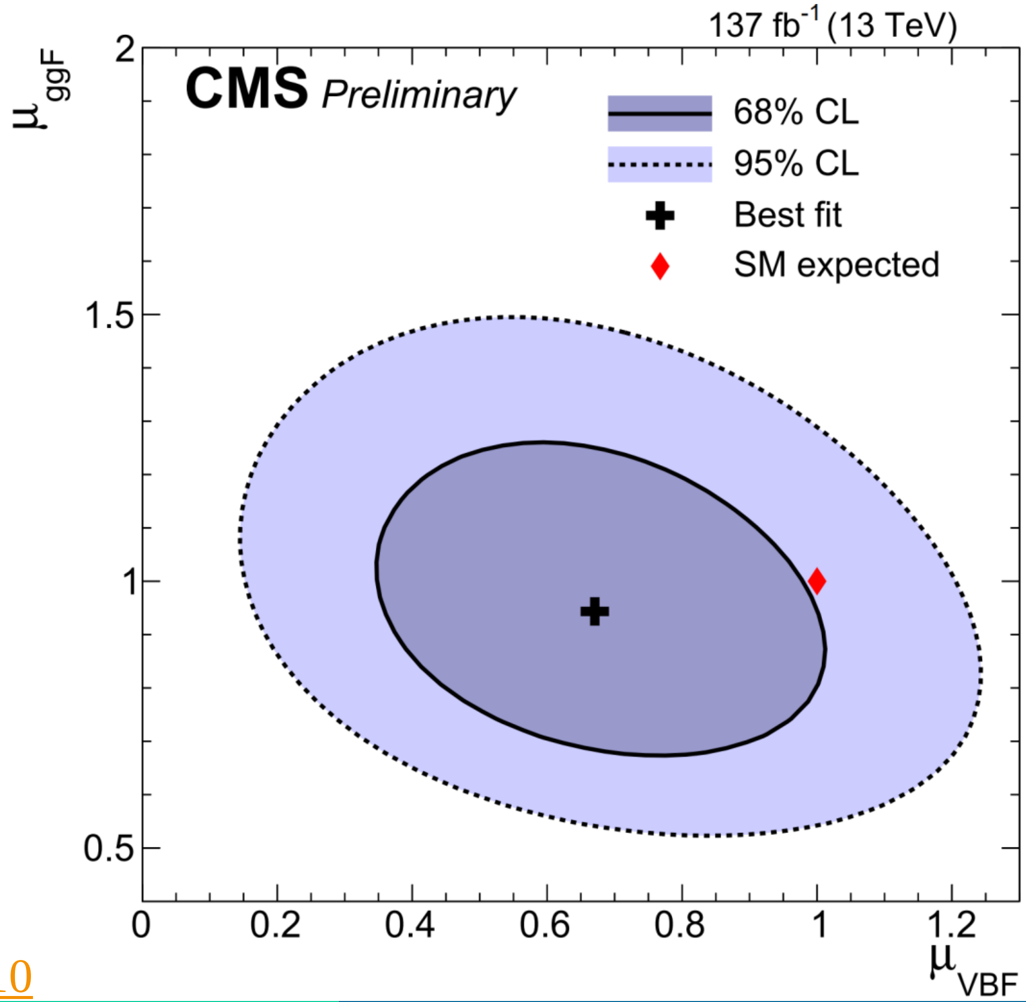
$\kappa_v \kappa_f$ and ggH vs. VBF.

- Both close to 1σ agreement with SM





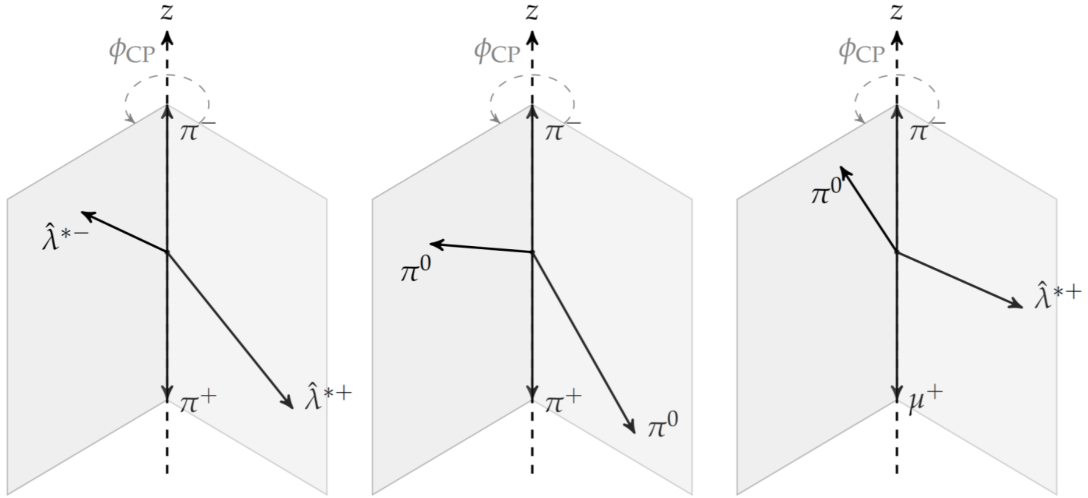
HIG-19-010

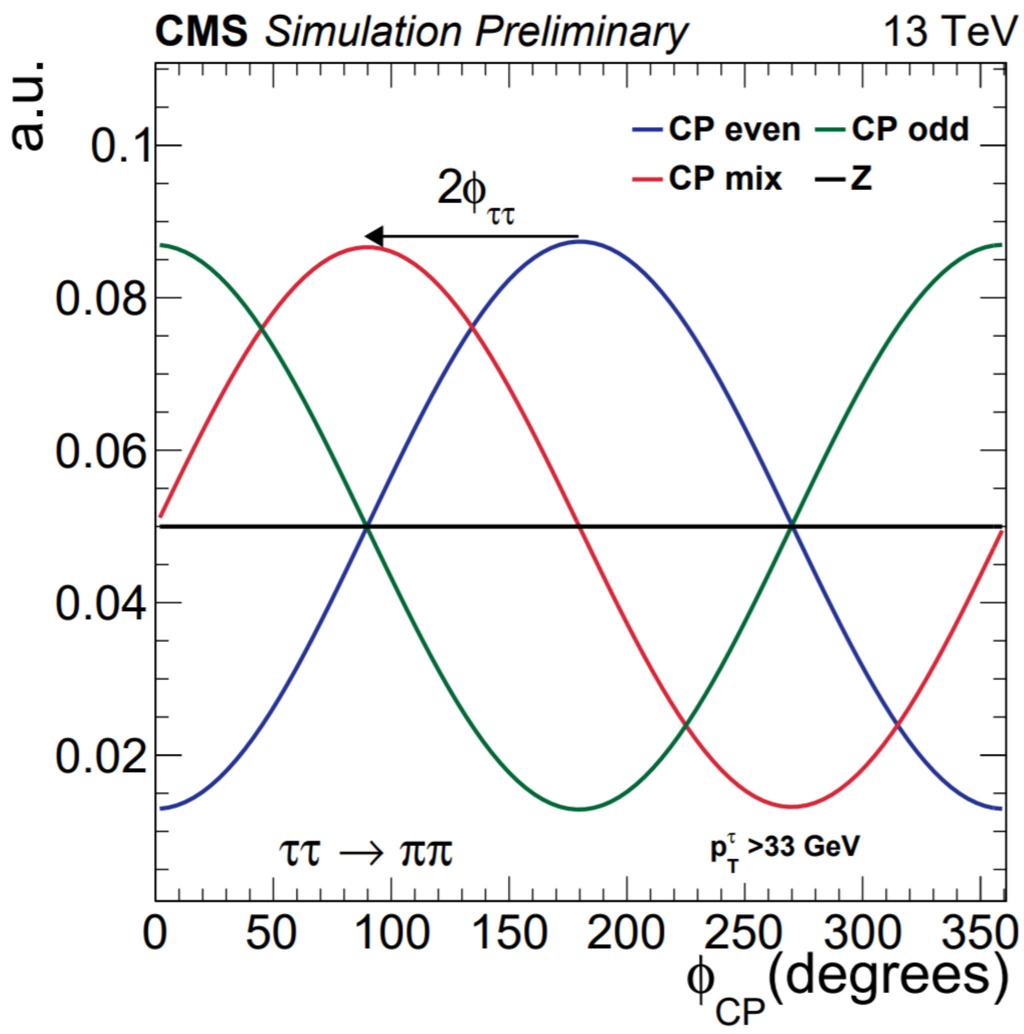
Summary of STXS Results

- Inclusive and stage 0:
  - ATLAS and CMS not statistically limited
  - CMS sees 2x increase in sensitivity over previous measurements
  - ggH and Inclusive consistent with SM within ~1σ
- STXS Stage 1.2:
  - First measurement of stage 1.2 parameters
  - Good sensitivity in merged bin schemes
  - Most bins consistent with SM within ~1σ
- κ framework measurements consistent with SM within ~1σ

CMS $H \to \tau\tau$ Decay CP Violation Strategy

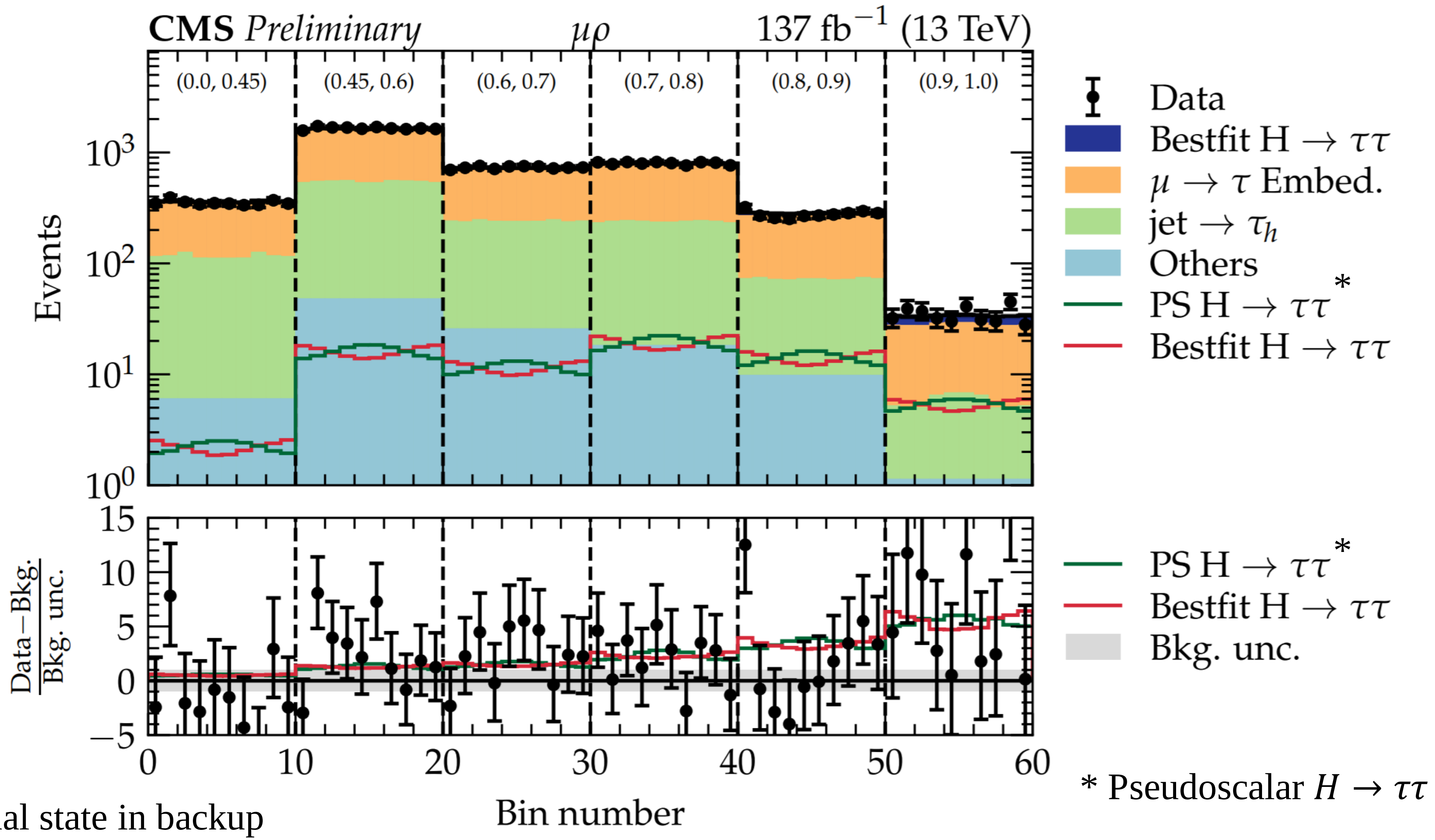
- Main strategy targets tau decay planes:
- Tau decay plane reconstruction methods:
  - Impact parameter method
  - Neutral pion method





HIG-20-006

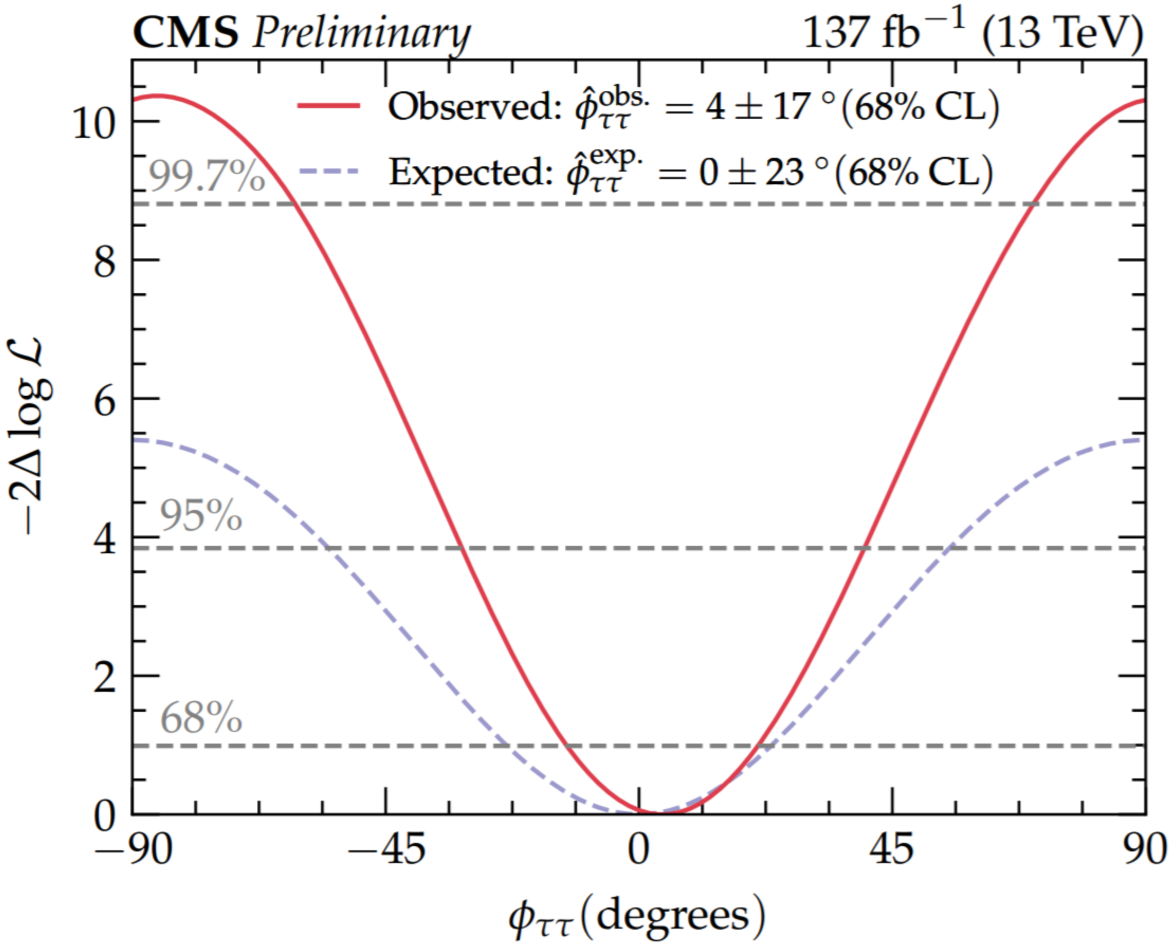
Example CP Bin Post-fits



* Pseudoscalar $H \to \tau\tau$

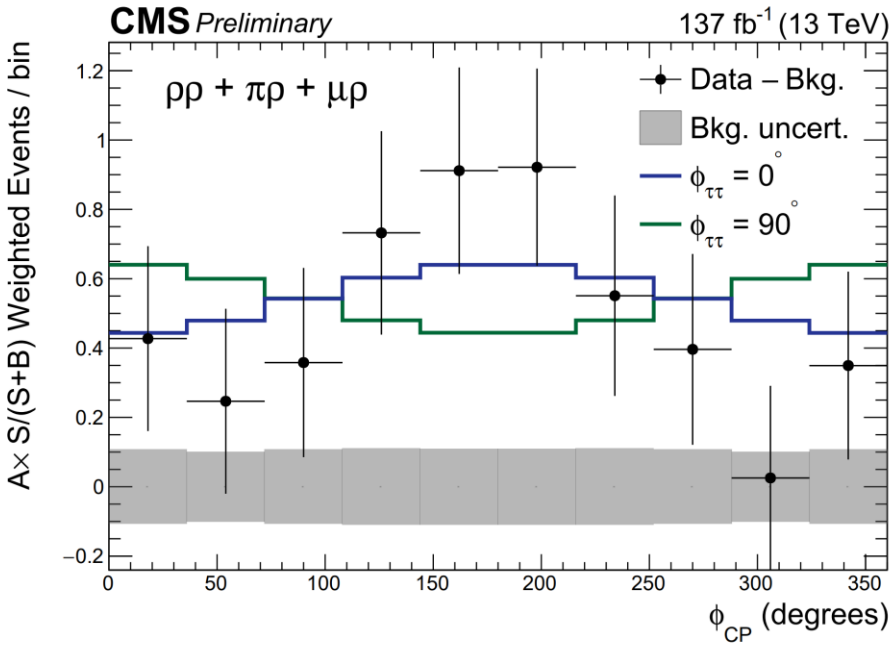
HIG-20-006, $\rho\rho$ final state in backup

CP Mixing Angle Results



HIG-20-006

- First measurement of CP Violation at the $H \rightarrow \tau\tau$ vertex
- Higgs to taus decays consistent with SM, CP even case preferred over CP odd case with 3.2σ
- Measurement is still statistics limited
- No strong dependence on the overall Higgs signal strength



VBF CP Violation Strategy

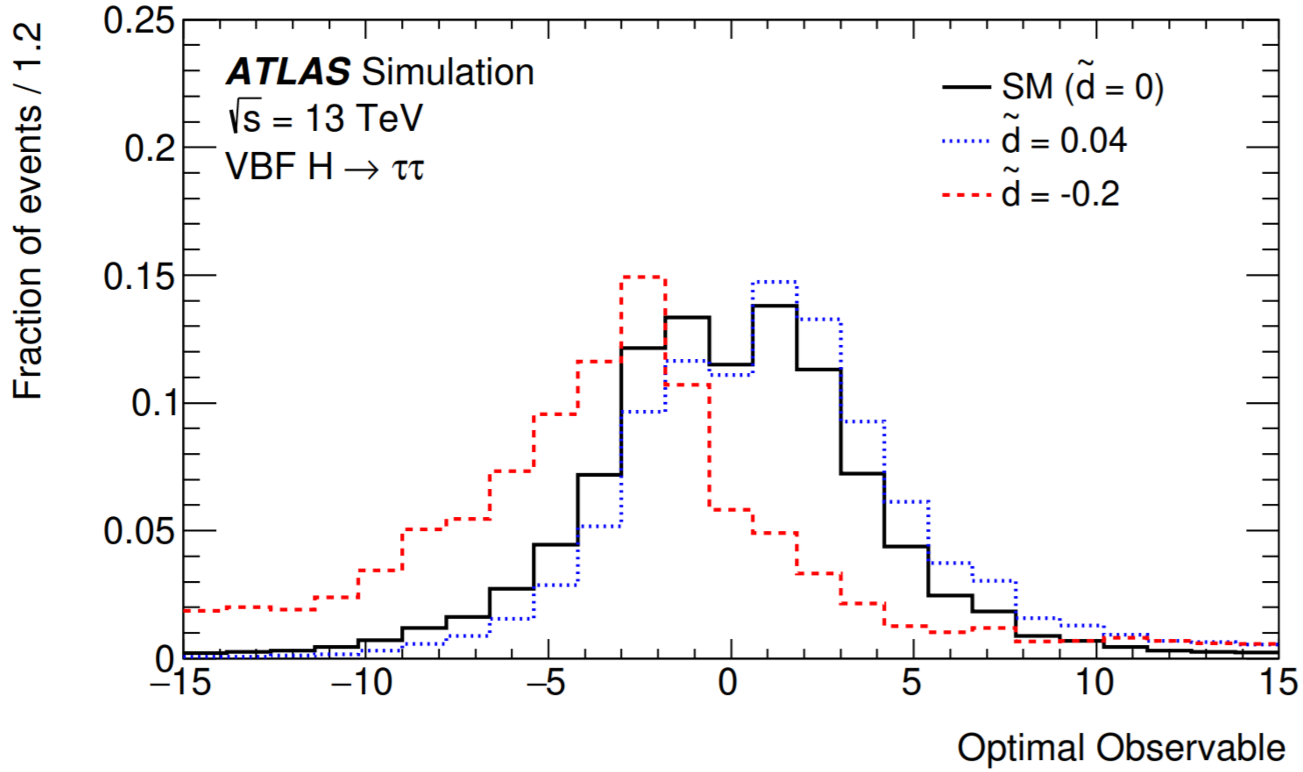
- Measures HVV vertex CP violation
  - Categorized by single parameter: $\tilde{d}$
- Optimal Observable:

$$\frac{2Re(\mathcal{M}_{SM}^{*}\mathcal{M}_{CP-odd})}{|\mathcal{M}_{SM}|^2}$$

  - From Matrix element:

$$|\mathcal{M}_{SM}|^2 + \tilde{d}\cdot 2Re(\mathcal{M}_{SM}^{*}\mathcal{M}_{CP-odd}) + \tilde{d}^2|\mathcal{M}_{CP-odd}|^2$$

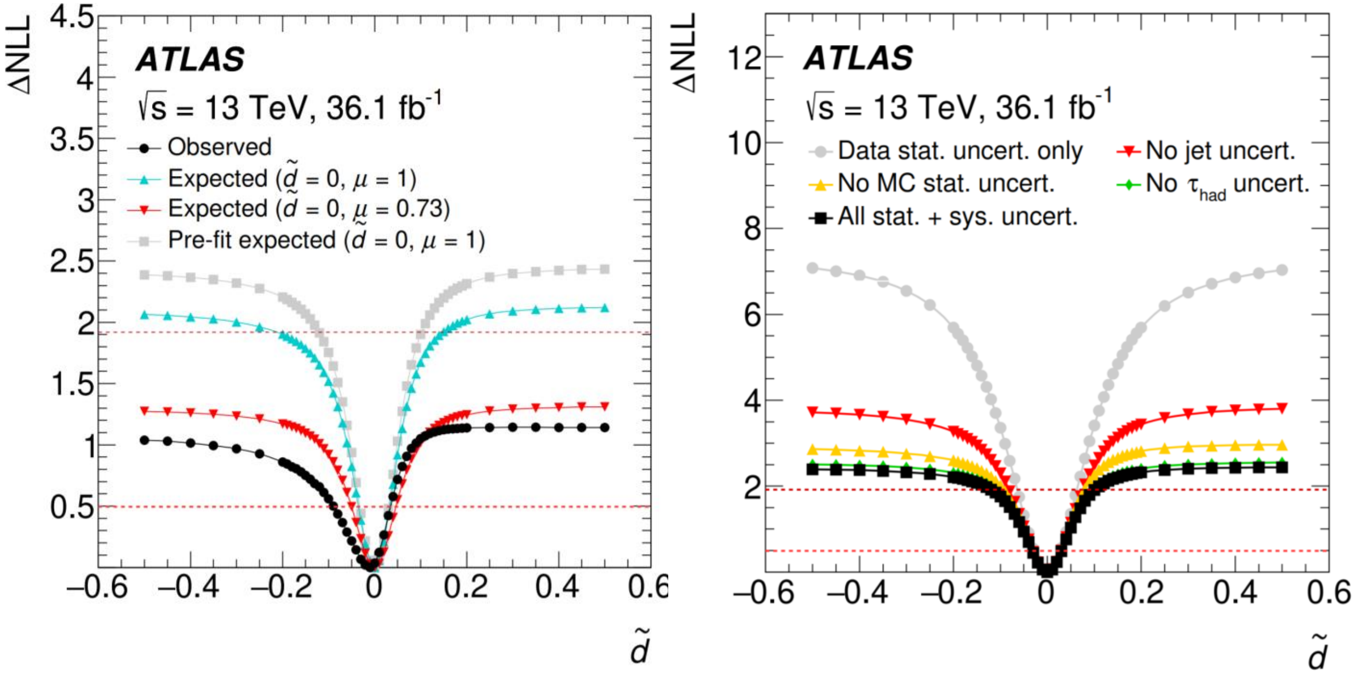
  - Calculated based on jet and higgs four momenta
- $\tilde{d}$ determined in a shape fit to data.
- Similar CMS analysis
  - Slides in backup

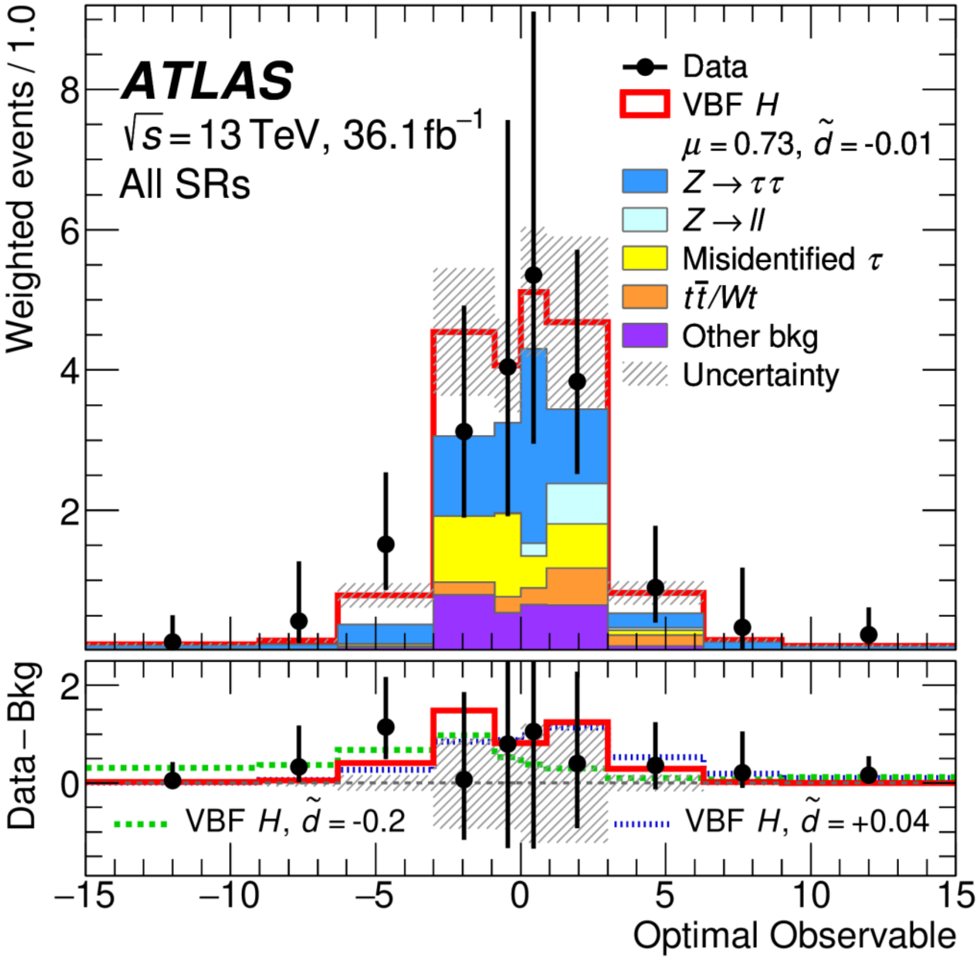


Phys. Lett. B 805 135426 (2020)

VBF CP Violation Results

- BDT used to separate VBF Signal
- $\tilde{d} = -0.013^{+0.048}_{-0.077}$, consistent with SM expectation





Phys. Lett. B 805 135426 (2020), right taken from auxiliary public figures here

All SRs, weighted by $\ln(1 + S/B)$

Summary

- New standards of sensitivity to different areas of Higgs to Taus physics
  - CMS/ATLAS Inclusive/Stage 0 cross section measurements not limited by statistics
  - First STXS Stage 1.2 cross section measurements
  - First CP Measurement of Higgs to taus vertex, evidence of preference against CP odd case.
  - Measurement of CP violation in HVV vertex performed in VBF $H \rightarrow \tau\tau$
- In all cases, there is good agreement with SM expectations.

- What’s the outlook for Higgs to Taus physics going forward?
  - A complete set of full Run 2 Analyses.
  - Differential analyses
  - More exclusive production modes and charge parity analyses

References

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2. "*Handbook of LHC Higgs cross sections: 4. deciphering the nature of the Higgs sector*", LHC Higgs Cross Section Working Group, doi:10.2172/1345634,10.23731/CYRM-2017-002, arXiv:1610.07922.
3. "*Measurement of Higgs boson production in the decay channel with a pair of τ leptons*", CMS Collaboration, 2020, CMS-PAS-HIG-19-010, https://cds.cern.ch/record/2725590
4. "*Cross-section measurements of the Higgs boson decaying into a pair of τ-leptons in proton-proton collisions at $\sqrt{s}=13\ TeV$*", ATLAS Collaboration, Apr. 2019, arXiv:1811.08856, https://arxiv.org/abs/1811.08856

   and

   "*Cross-section measurements of the Higgs boson decaying into a pair of τ-leptons in proton-proton collisions at $\sqrt{s}=13\ TeV$ with the ATLAS detector*", ATLAS Collaboration, Apr. 2019, Phys. Rev. D 99 072001, https://journals.aps.org/prd/abstract/10.1103/PhysRevD.99.072001
5. "*Observation of the SM scalar boson decaying to a pair of τ leptons with the CMS experiment at the LHC*", CMS Collaboration, 2017, HIG-16-043, http://cds.cern.ch/record/2264522
6. "*Analysis of the CP structure of the Yukawa coupling between the Higgs boson and τ leptons in proton-proton collisions at $\sqrt{s}=13\ TeV$*", CMS Collaboration, 2020, CMS-PAS-HIG-20-006, http://cds.cern.ch/record/2725571
7. "Constraints on anomalous HVV couplings in the production of Higgs bosons decaying to tau lepton pairs", CMS Collaboration, 2018, CMS-PAS-HIG-17-034, http://cds.cern.ch/record/2648943
8. "*Test of CP invariance in vector-boson fusion production of the Higgs boson in the $H\rightarrow\tau\tau$ channel in proton–proton collisions at $\sqrt{s}=13\ TeV$ with the ATLAS detector*", ATLAS Collaboration, Jun. 2020, arXiv:2002.05315, https://arxiv.org/abs/2002.05315

   and

   "Test of CP invariance in vector-boson fusion production of the Higgs boson in the $H\rightarrow\tau\tau$ channel in proton–proton collisions at $\sqrt{s}=13\ TeV$ with the ATLAS detector", ATLAS Collaboration, Jun 2020, Phys. Lett. B 805 135426, https://www.sciencedirect.com/science/article/pii/S0370269320302306?via=ihub

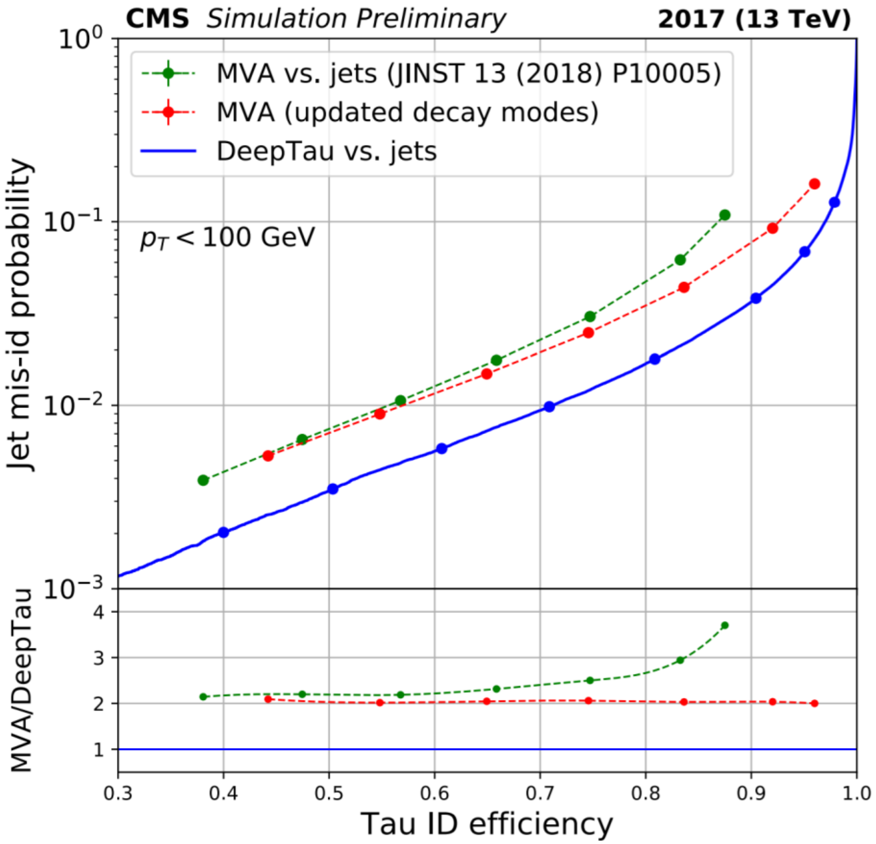
   and

   http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2018-14/
9. "*Performance of reconstruction and identification of tau leptons in their decays to hadrons and tau neutrino in LHC Run-2*", CMS Collaboration, 2016, TAU-16-002, https://cds.cern.ch/record/2196972
10. "*Measurement of the tau lepton reconstruction and identification performance in the ATLAS experiment using pp collisions at $\sqrt{s}=13\ TeV$*", ATLAS Collaboration, May 2017, ATLAS-CONF-2017-029, https://cds.cern.ch/record/2261772
11. "*Reconstruction, Energy Calibration, and Identification of Hadronically Decaying Tau Leptons in the ATLAS Experiment for Run-2 of the LHC*", ATLAS Collaboration, Nov. 2015, ATL-PHYS-PUB-2015-045, https://cds.cern.ch/record/2064383
12. "*Identification of hadronic tau lepton decays using neural networks in the ATLAS experiment*", ATLAS Collaboration, Aug. 2019, ATL-PHYS-PUB-2019-033, https://cds.cern.ch/record/2688062
13. "*An embedding technique to determine genuine $\tau\tau$ backgrounds from CMS data*", CMS Collaboration, 2018, TAU-18-001, http://cds.cern.ch/record/2646208

Backup

Tau Reconstruction at CMS

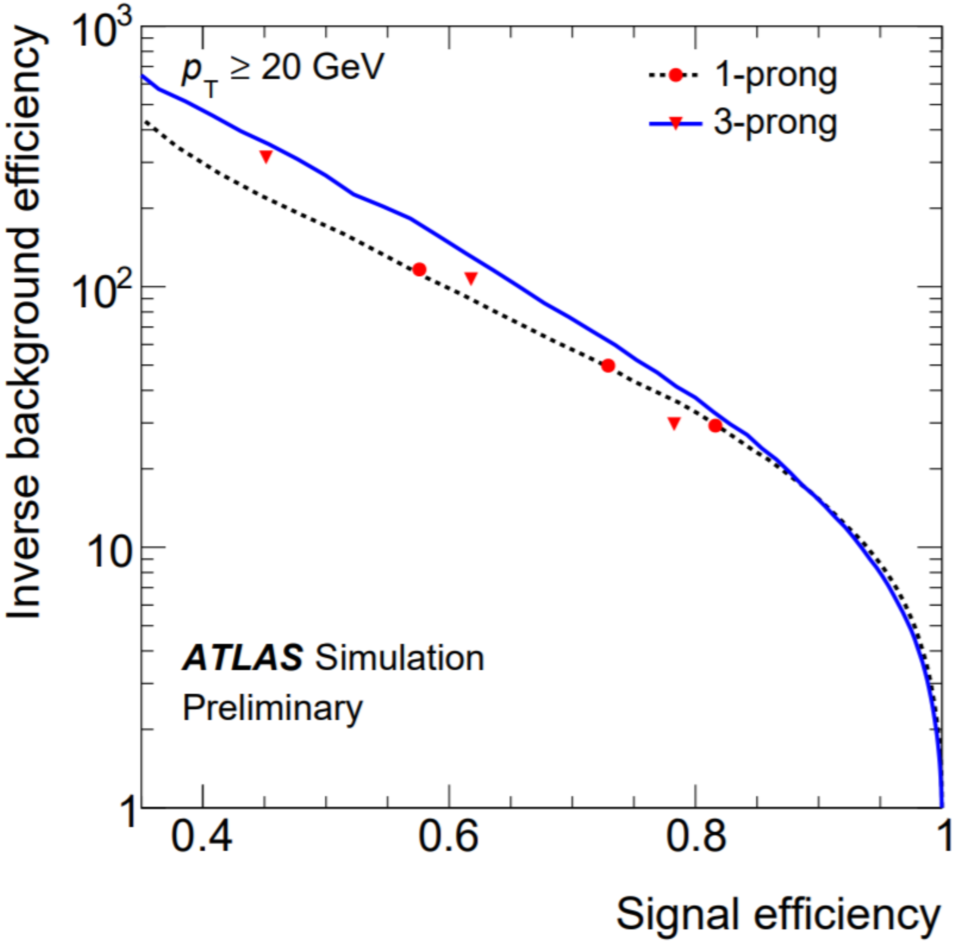
- Leptonic final states, i.e. electronic and muonic final states, are reconstructed via the CMS standard Particle Flow algorithm
- Hadronic taus are reconstructed via the Hadrons-Plus-Strips (HPS) algorithm.
  - Hadronic jets form the "seed" of the reconstructed tau
  - Dynamic η-ϕ strips
- New: DeepTau algorithm for ID and Jet Discrimination
  - Convolutional Neural Network
  - ~1/2($t\bar{t}$)-2/3(W+Jets) the chance of misidentifying hadronic jets as a tau compared to previous methods.



$t\bar{t}$ Jet Mis-ID chance as a function of Tau ID Efficiency, taken from CMS-DP-2019-033

Tau Reconstruction at ATLAS

- Hadronic taus are seeded by reconstructed jets
- Tau vertex is then chosen within $\Delta R < 0.2$ cone
  - η/ϕ is calculated with this vertex/cone
  - Energy and pt are reconstructed via MVA techniques
- To reject hadronic background, a boosted decision tree (BDT) offers efficiency working points
  - A tau ID based on neural networks has been developed for future work



Taken from ATL-PHYS-PUB-2015-045

ATLAS XS Categorization Requirements

Signal Region Definitions

Signal Region		Inclusive	$\tau_{lep}\tau_{lep}$	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$
VBF	High-$p_T^{\tau\tau}$	$p_T^{j_2} > 30$ GeV $\|\Delta\eta_{jj}\| > 3$ $m_{jj} > 400$ GeV $\eta_{j_1} \cdot \eta_{j_2} < 0$ Central leptons	—		$p_T^{\tau\tau} > 140$ GeV $\Delta R_{\tau\tau} < 1.5$
	Tight		$m_{jj} > 800$ GeV	$m_{jj} > 500$ GeV $p_T^{\tau\tau} > 100$ GeV	Not VBF high-$p_T^{\tau\tau}$ $m_{jj} > (1550 - 250 \cdot \|\Delta\eta_{jj}\|)$ GeV
	Loose		Not VBF tight		Not VBF high-$p_T^{\tau\tau}$ and not VBF tight
Boosted	High-$p_T^{\tau\tau}$	Not VBF $p_T^{\tau\tau} > 100$ GeV	$p_T^{\tau\tau} > 140$ GeV $\Delta R_{\tau\tau} < 1.5$		
	Low-$p_T^{\tau\tau}$		Not boosted high-$p_T^{\tau\tau}$		

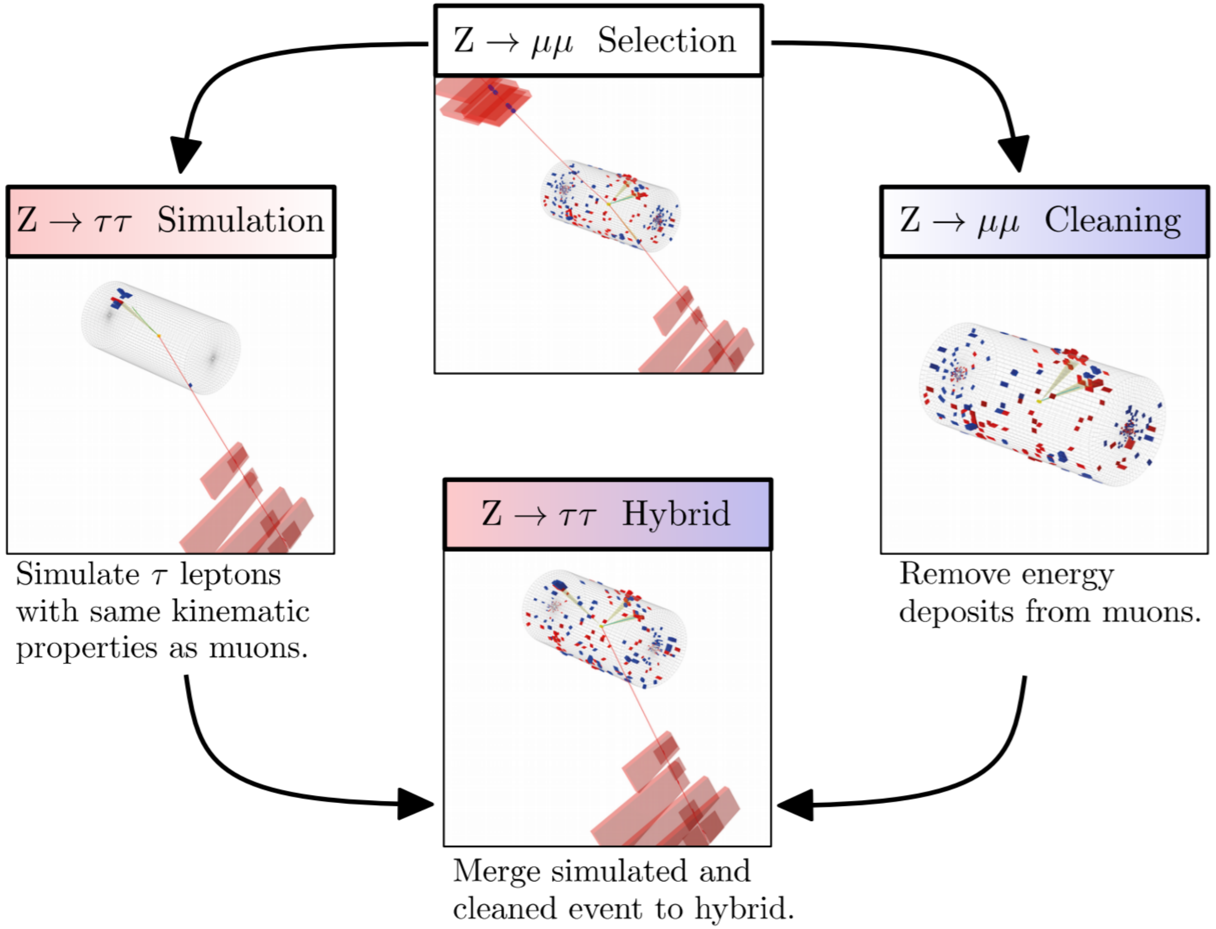
Control Region Definitions

Region	Selection
$\tau_{lep}\tau_{lep}$ VBF $Z \to \ell\ell$ CR	$\tau_{lep}\tau_{lep}$ VBF incl. selection, $80 < m_{\ell\ell} < 100$ GeV, SF
$\tau_{lep}\tau_{lep}$ boosted $Z \to \ell\ell$ CR	$\tau_{lep}\tau_{lep}$ boosted incl. selection, $80 < m_{\ell\ell} < 100$ GeV, SF
$\tau_{lep}\tau_{lep}$ VBF top CR	$\tau_{lep}\tau_{lep}$ VBF incl. selection, inverted b-jet veto
$\tau_{lep}\tau_{lep}$ boosted top CR	$\tau_{lep}\tau_{lep}$ boosted incl. selection, inverted b-jet veto
$\tau_{lep}\tau_{had}$ VBF top CR	$\tau_{lep}\tau_{had}$ VBF incl. selection, inverted b-jet veto, $m_T > 40$ GeV
$\tau_{lep}\tau_{had}$ boosted top CR	$\tau_{lep}\tau_{had}$ boosted incl. selection, inverted b-jet veto, $m_T > 40$ GeV

arXiv:1811.08856

CMS Embedding Technique

- Used for the prediction of genuine tau backgrounds in CMS analyses



HIG-19-010

CMS Fake Factor Technique

- Used for the prediction of Mis-ID'd τ_{had} due to hadronic jets
  1. Measure ratio of anti-isolated taus to isolated ones in determination regions as a function of the hadronic tau pt
     1. W+Jets
     2. QCD
     3. $t\bar{t}$
  2. Corrections in terms of the other object pt
  3. Correction for differences between measurement and signal region
  4. Measure fractions of Mis-ID'd τ_{had} in the isolated signal region with MC
  5. Apply to anti-isolated signal region, and subtract any genuine contributions
- Used for the precision across a large number of kinematic variables

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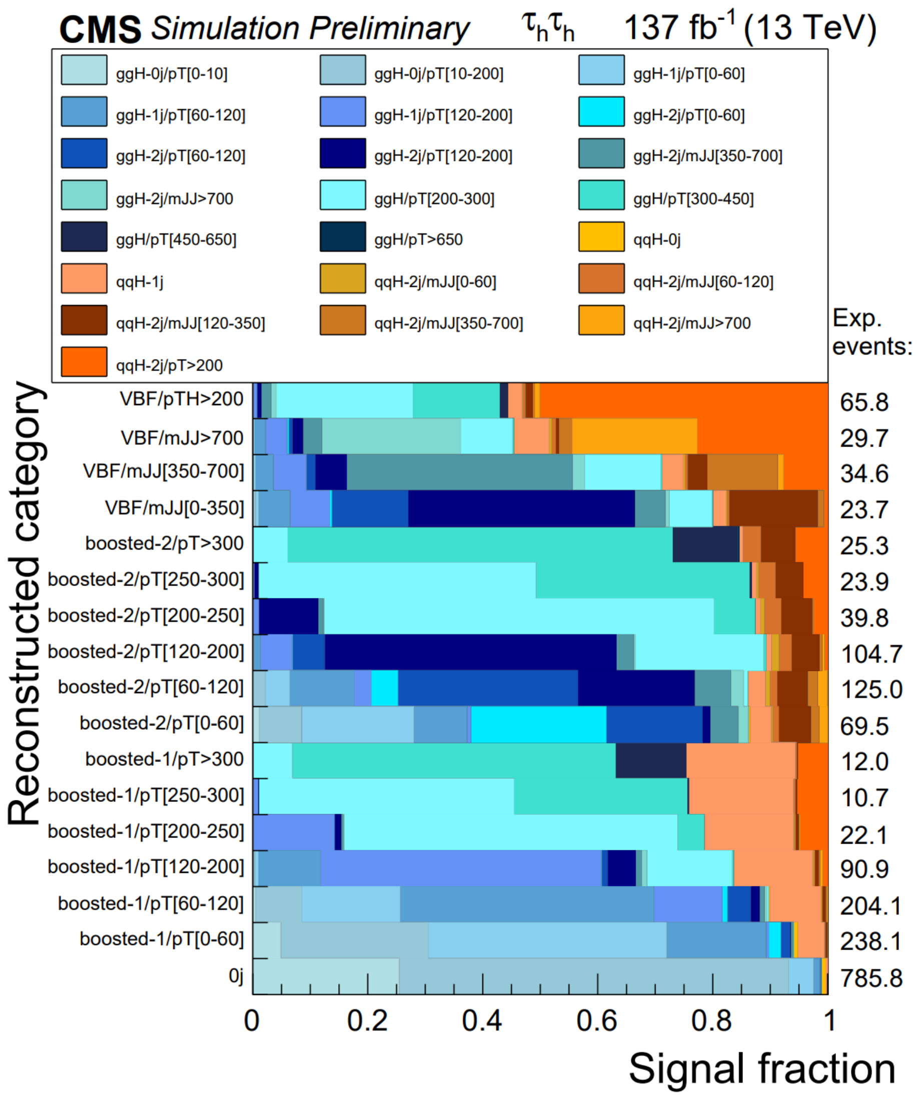
CMS STXS Category Purity



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Topology Scheme Signal Strengths

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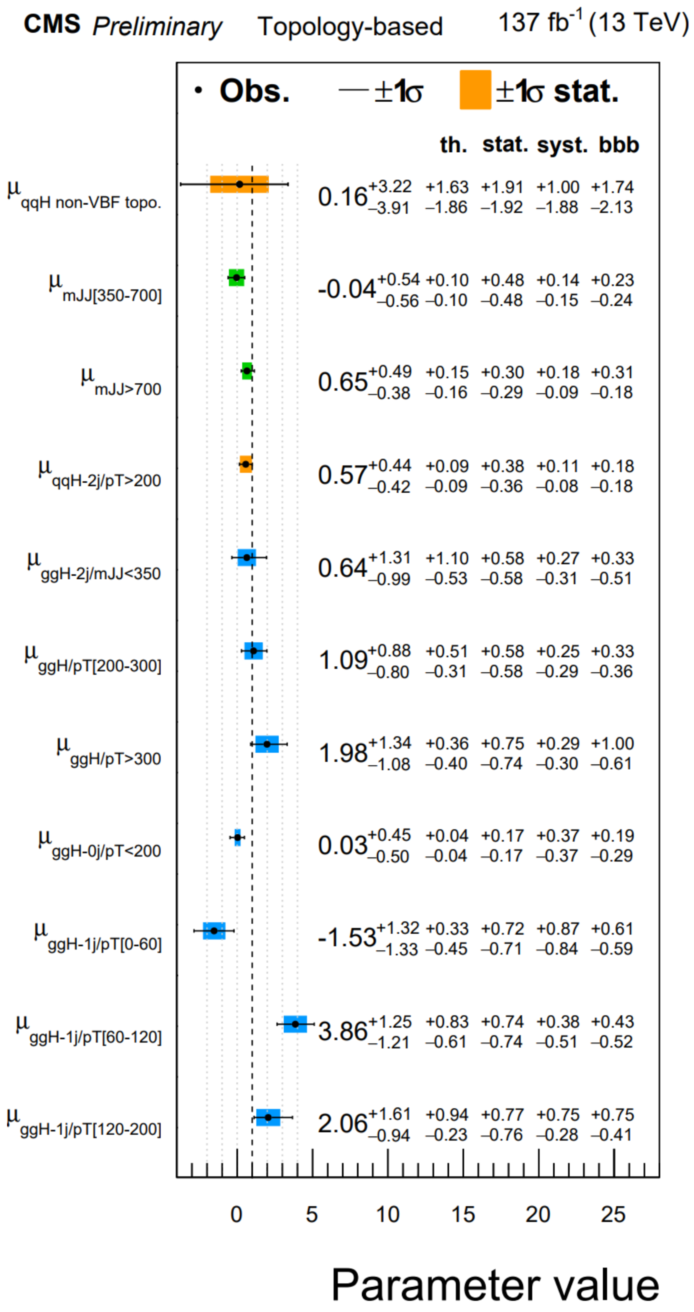
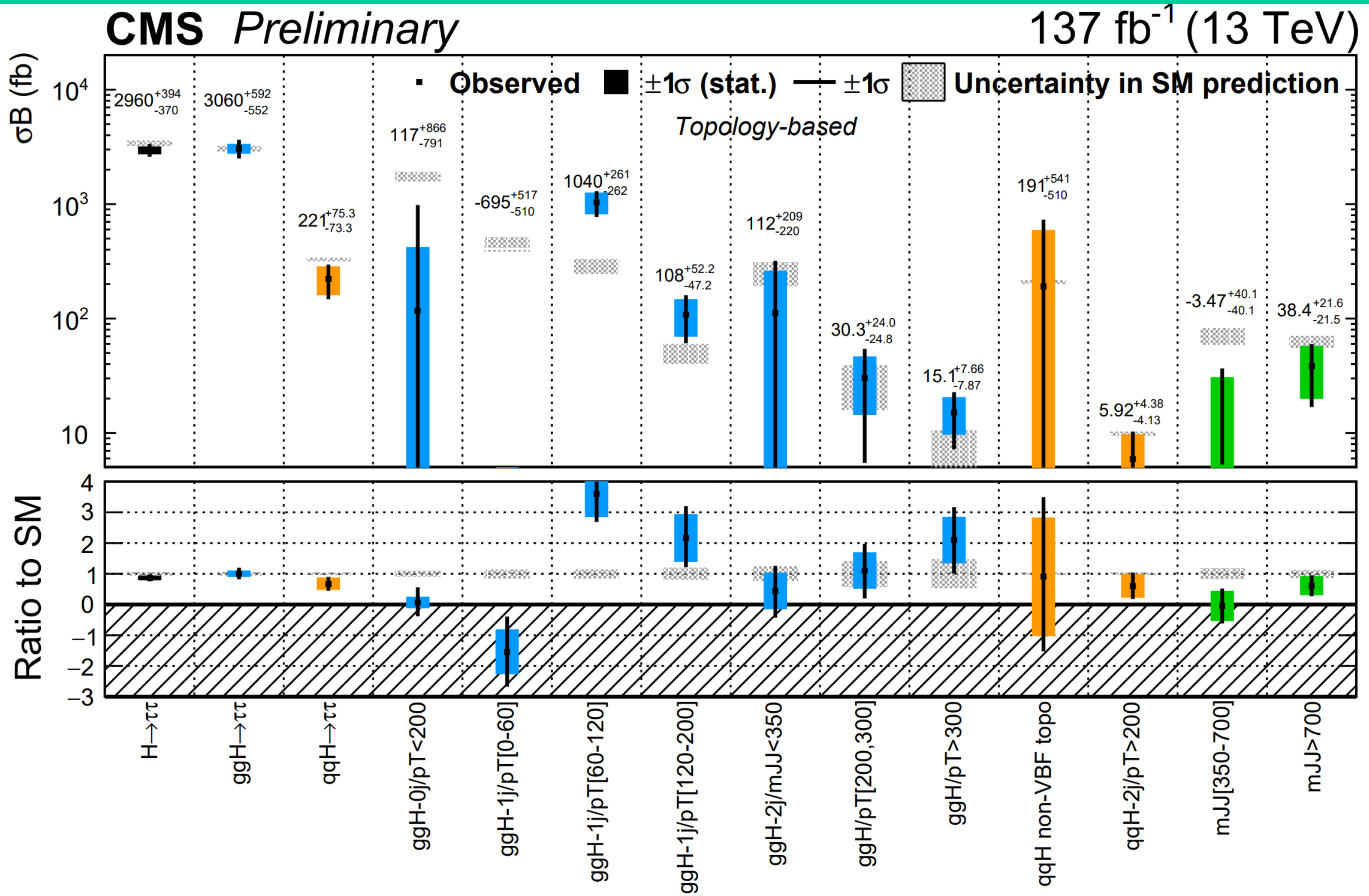


Topology Based Cross Sections



HIG-19-010

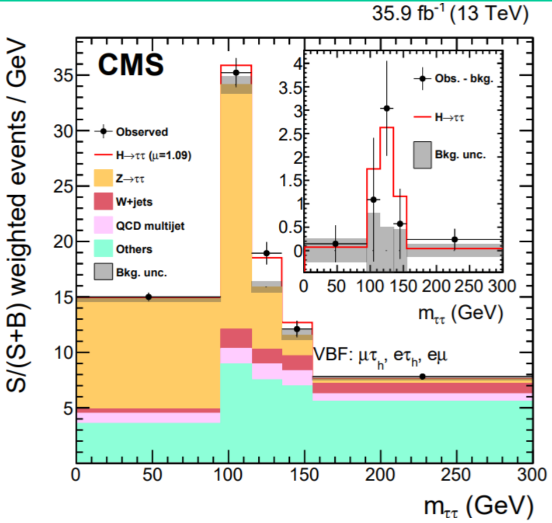
Comparison Between Old and New CMS Results

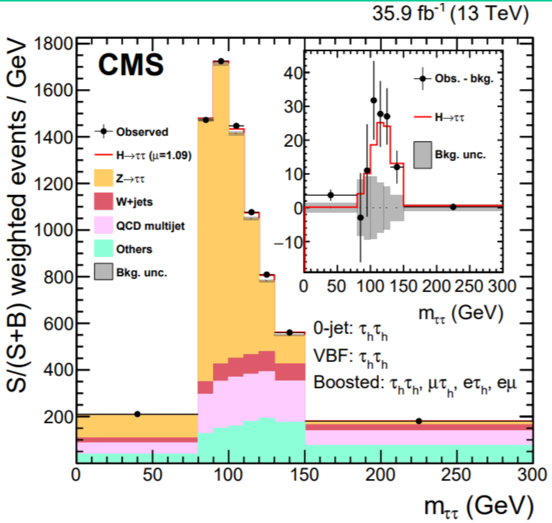
HIG-16-043

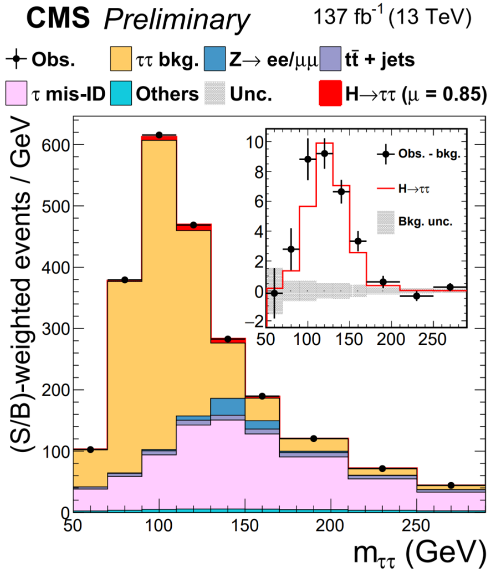
- 3 categories
  - 0 jet
  - VBF
  - Boosted
- $\mu = 1.06 \pm 0.25$

HIG-19-010

- 5 categories
  - 0 jet
  - VBF High Higgs Pt
  - VBF Low Higgs Pt
  - Boosted High Higgs Pt
  - Boosted Low Higgs Pt
- $\mu = 0.85^{+0.12}_{-0.11}$







HIG-19-010, HIG-16-043

Comparison between ATLAS and CMS Cut Based Analysis Styles

Similarities

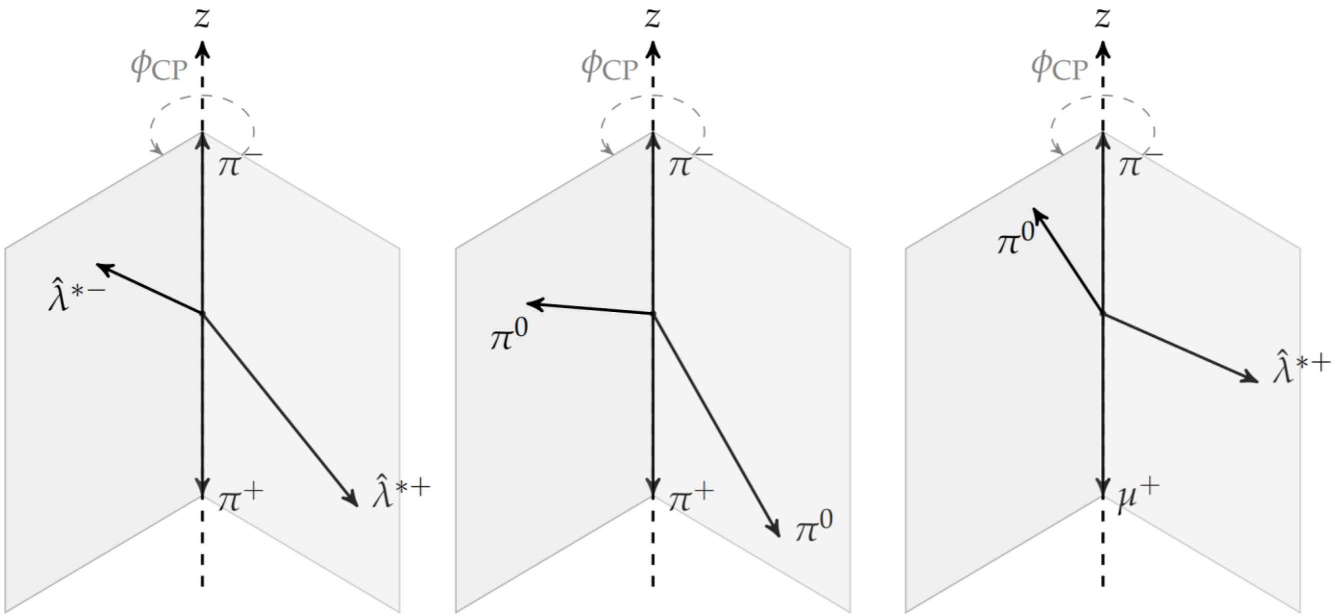
- VBF Category(ies)
  - 2 jets + quality cuts
- Boosted Category(ies):
  - Not the other categories
- Use of “fake-factor” method in semi-leptonic channel:
  - However, details differ somewhat,

Differences

- ATLAS-Only: Control Regions
- CMS-Only: Use of zero jet category
- Exact definitions and of categories:
  - CMS:
    - VBF High and Low Higgs Pt
    - Boosted Mono- and Multi- Jet
  - ATLAS:
    - VBF Tight and Loose (and High di-tau Higgs Pt)
    - Boosted High and Low di-Tau Pt
- CMS-Only: Use of second variable/dimension in categories
- Prediction of $Z \rightarrow \tau\tau$ region:
  - ATLAS: MC with validation regions
  - CMS: “Embedding” Technique
- ATLAS: Other mis-ID tau methods
  - Isolation inverted templates in fully leptonic channel
  - Same sign method for hadronic taus.

Impact Parameter and π^0 Method in CP Violation

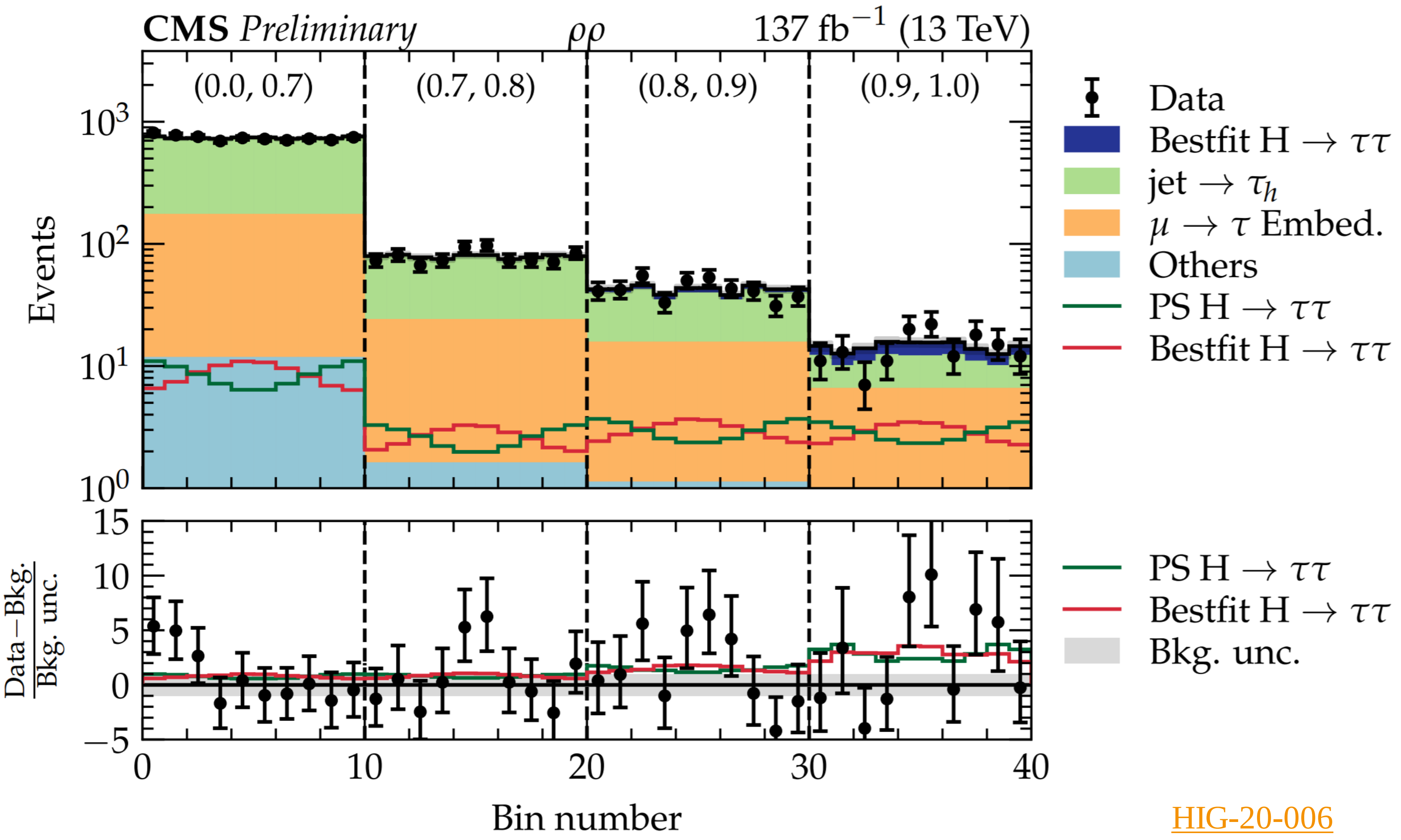
- Impact parameter method,
  - Works via definition of vector to point of closest approach
  - This, and the reconstructed charged π vector define a (boosted) plane.
  - Used for single $\pi^{\pm}$ and μ decays
- π^0 method,
  - Uses vector of neutral pion and vector of charged track to construct planes that are then boosted
  - Used for any applicable decay mode
    - Including three pronged a decay, where a neutral rho is recreated, and the opposite sign pion is treated as the "π^0"



Impact parameter method used for both taus (left), π^0 method used for both taus (center), and the mixed case (right)

HIG-20-006

Rho Rho CP Analysis Final State



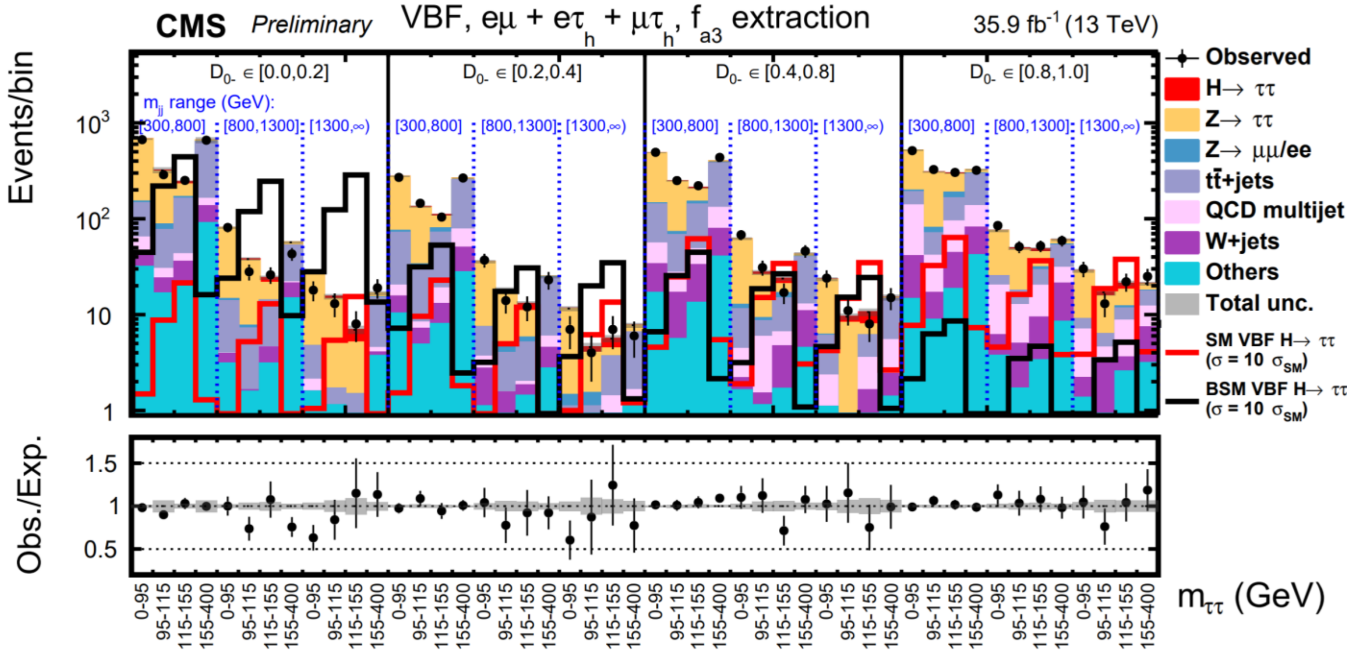
HIG-20-006

CMS VBF CP Violation Strategy

- CP Violation characterized by:

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_2|^2\sigma_3}, \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right)$$

- Matrix Element Likelihood Approach, "MELA"
  - Calculated based on event and decay angles
- Categorized similarly to CMS observation effort



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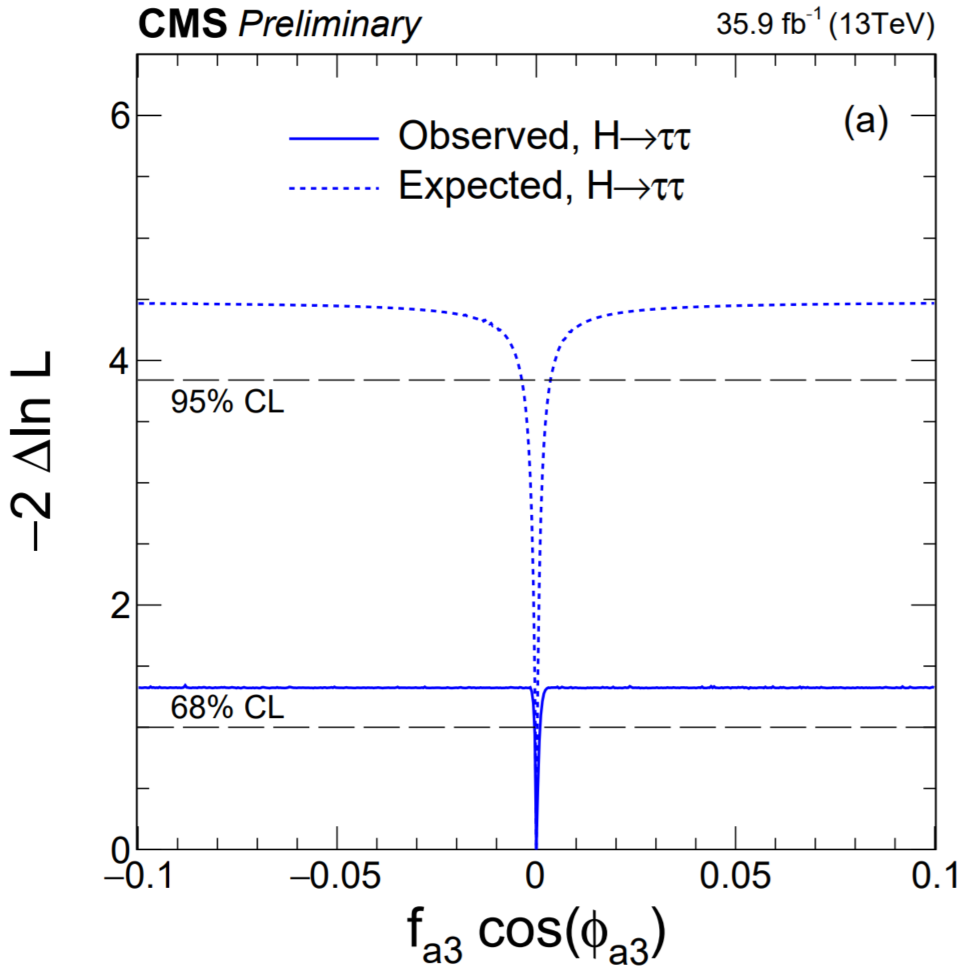
CMS VBF CP Violation Results

- $f_{a3}\cos(\phi_{a3}) = (0.0^{+0.93}_{-0.43}) \times 10^{-3}$ consistent with SM expectation



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