Towards a measurement of the Higgs boson CP state at the gluon fusion production vertex using the di-τ final state at the CMS experiment

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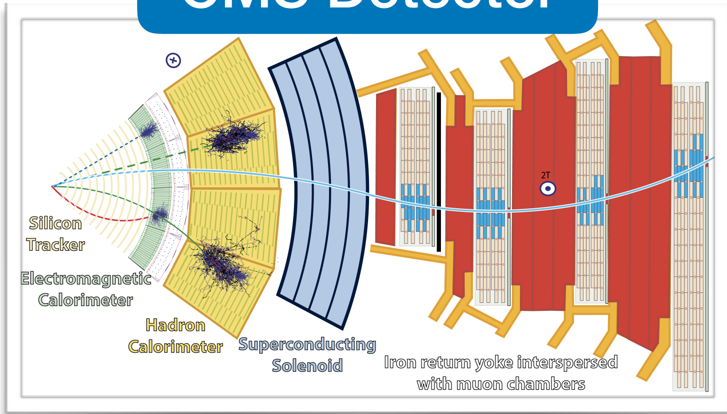
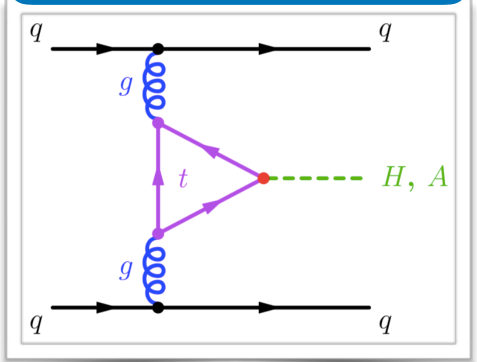
Overview

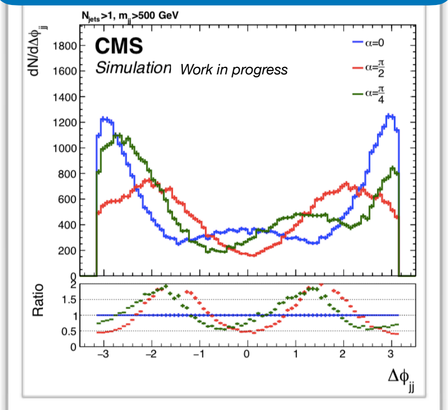
CMS Detector



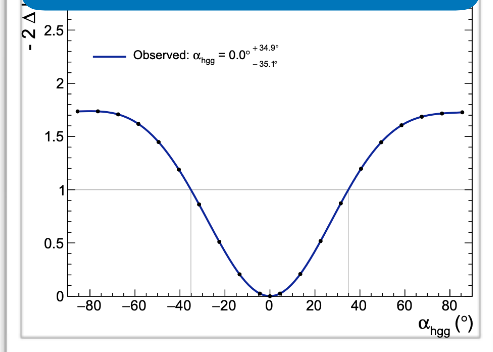
Theory



Analysis



Results



Introduction

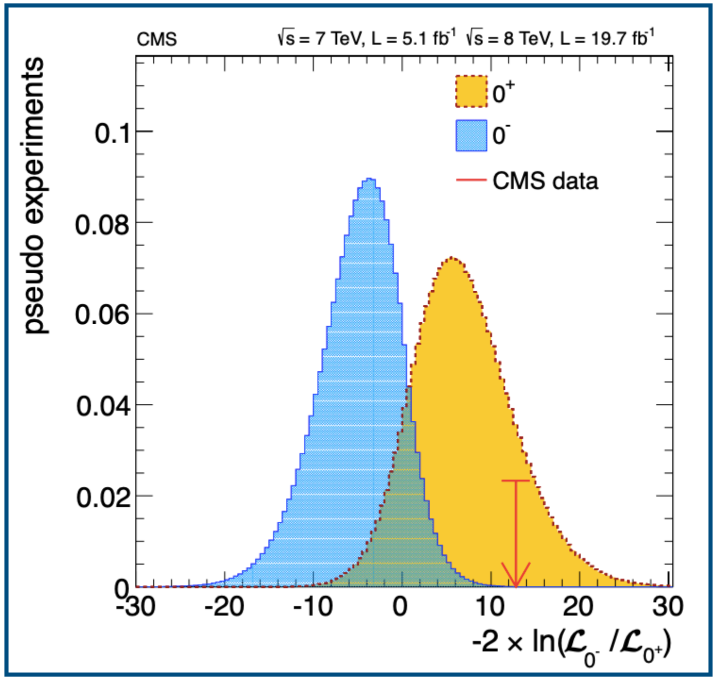
At the LHC Higgs boson CP measurement have been developing recently.

Higgs boson's CP measurement using the gluon fusion (ggH) production vertex in association with two jets.

Not yet been performed at CMS with the $H \longrightarrow \tau\tau$ final state.

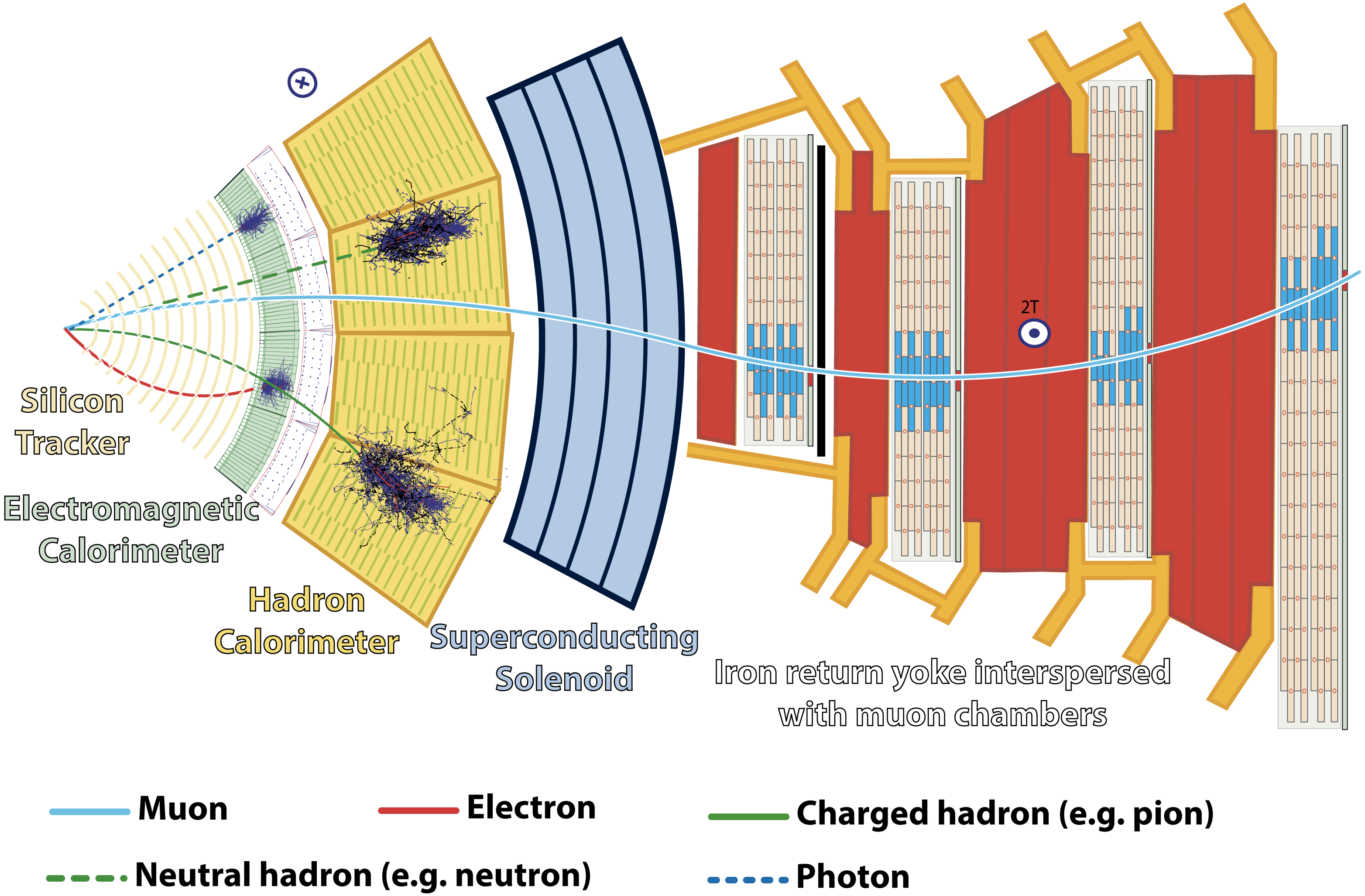
Previous measurements exclude pure pseudoscalar Higgs boson.

CP ggH measurements with tau leptons are interesting due to tree level coupling to CP sensitive properties.

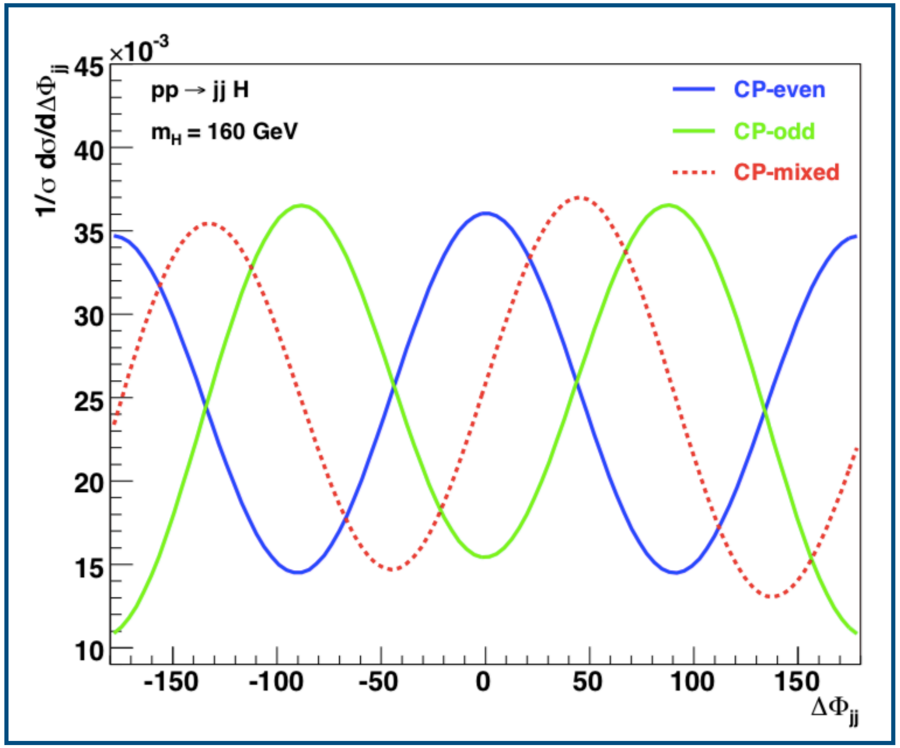


Serguei Chatrchyan, et al. Measurement of the properties of a Higgs boson in the four-lepton final state. Physical Review D, 89(9):092007, 2014.

CMS Detector



Theory



G. Klamke and D. Zeppenfeld, "Higgs plus two jet production via gluon fusion as a signal at the CERN LHC", *JHEP* **04** (2007) 052, doi:10.1088/1126-6708/2007/04/052, arXiv:hep-ph/0703202.

The Lagrangian describing the Yukawa coupling of the Higgs boson to fermions is

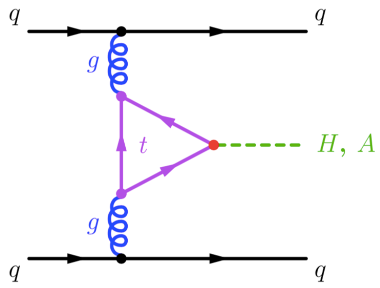
$$\mathcal{L}_Y = y_f H \bar{\psi}_f \psi_f + i\tilde{y}_f A \bar{\psi}_f \gamma_5 \psi_f$$

Reparametrise y_f into mixing angle α which is interpreted as:

- α=0° ⟶ pure scalar
- α=90° ⟶ pure pseudo-scalar
- α=45° ⟶ maximally mixing CP violating

Discriminating variable: pseudo-rapidity ordered azimuthal separation, $\Delta\phi_{jj}$, between the two (leading) jets in H+2jet events.

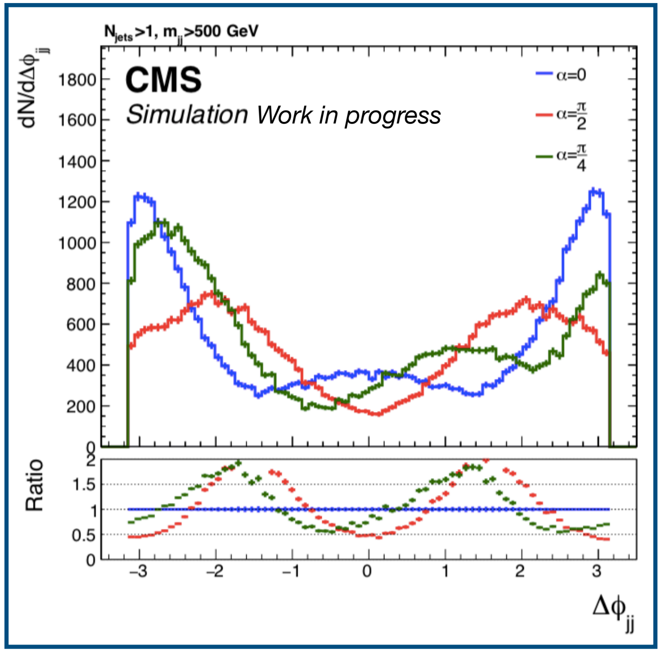
Analysis – Strategy



Working towards a **full RunII** measurement using the following four final states:

$$\tau_h\tau_h,\ \mu\tau_h,\ e\tau_h,\ e\mu$$

Especially VBF-like (high dijet mass) events show promising differentiation between different CP states.



2016 + 2017 data are (almost) complete, 2018 is being added.

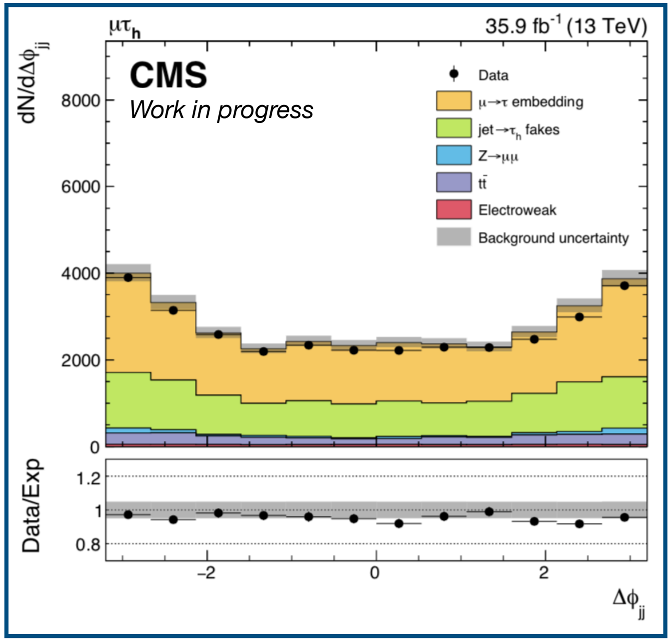
In the final fit, years will be combined separately due to non-trivial treatment of corrections and systematics.

Analysis – Background methods

Main backgrounds include: **Drell-Yan, QCD, di-boson, $t\bar{t}$, single top**

Using data-driven techniques to constrain the main backgrounds: embedding and fake factor method.

Embedding:



Covers the Drell-Yan backgrounds which include Z —> $\tau\tau$ and Z —> ll events.

Embedded samples are produced using Z —> $\mu\mu$ events in data where the muon pair is replaced with a tau pair from MC generated Z —> $\tau\tau$ events.

Majority of the event comes from data!

Check modelling by requiring a reconstructed di-τ mass of less than 100 GeV.

Analysis – Background methods

Fake-factor (FF) method:

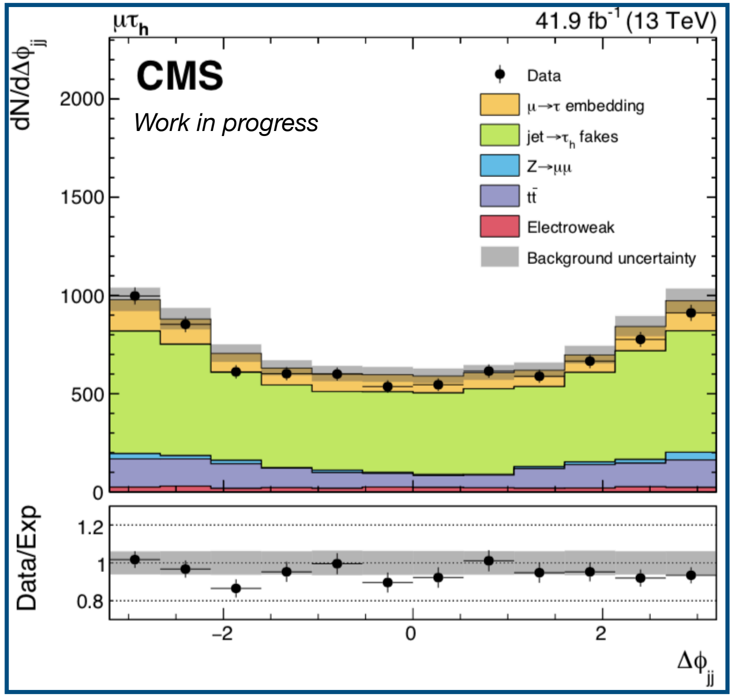
In order to model events where a jet fakes a hadronic tau: mainly QCD multijet, W+jets and some $t\bar{t}$.

Model jet $\longrightarrow \tau_h$ backgrounds from a side-band region in data, where a τ_h fails the nominal ID criteria but satisfies a looser ID one.

Calculate FF (for each process) in jet $\longrightarrow \tau_h$ enriched region as

$$\frac{N\,(\mathrm{tight})}{N\,(\mathrm{very\ loose}\ \&\&\ !\mathrm{tight})}$$

and scale the events in the side-band region by that ratio.



Check data/MC agreement of FF backgrounds in a jet $\longrightarrow \tau_h$ enriched region (di-τ mass > 150 GeV)

Other backgrounds: Diboson, $t\bar{t}$, single-top processes estimated from MC, in addition to VBF and VH production, treated as backgrounds in this analysis.

Analysis – Categorisation

Sensitivity to CP mixing angle comes from high dijet mass events.

However, still fit all other categories (0-jet, 1-jet and 2-jet events with dijet mass < 300 GeV) to contrain backgrounds and systematics.

Category	Definition (*)
0-jet	N_{jets} == 0
boosted	!(0-jet) **AND** !($N_{jets} \geq 2$ **AND** $m_{jj} > 300$ GeV)
dijet loose-m_{jj}	$N_{jets} \geq 2$ **AND** $300 > m_{jj} > 500$ GeV **AND** $pT_{\tau\tau} < 150$ GeV
dijet loose-m_{jj} boosted	$N_{jets} \geq 2$ **AND** $300 > m_{jj} > 500$ GeV **AND** $pT_{\tau\tau} > 150$ GeV
dijet tight-m_{jj}	$N_{jets} \geq 2$ **AND** $m_{jj} > 500$ GeV **AND** $pT_{\tau\tau} < 150$ GeV
dijet tight-m_{jj} boosted	$N_{jets} \geq 2$ **AND** $m_{jj} > 500$ GeV **AND** $pT_{\tau\tau} > 150$ GeV

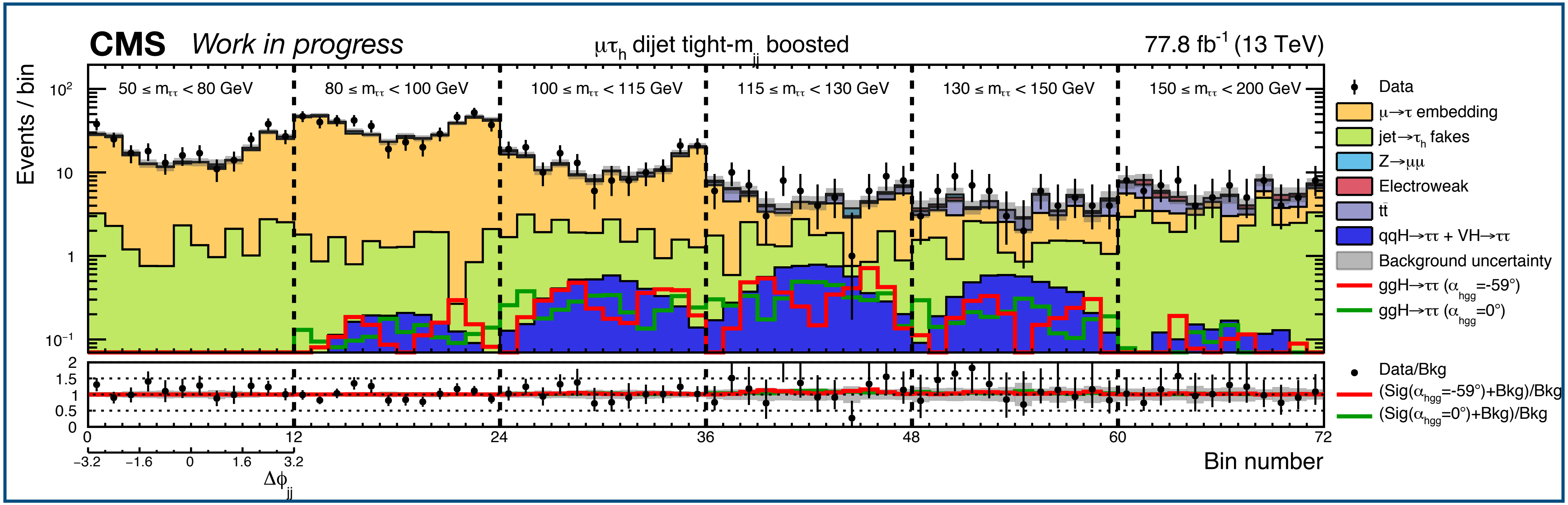
* additional b-jet veto is applied for the semi-leptonic and fully leptonic channels to further reject $t\bar{t}$ contamination

Analysis – Categorisation

Sensitivity to CP mixing angle comes from high dijet mass events

Fit all other categories (0-jet, 1-jet and 2-jet events with dijet mass < 300 GeV) to contrain backgrounds and systematics.

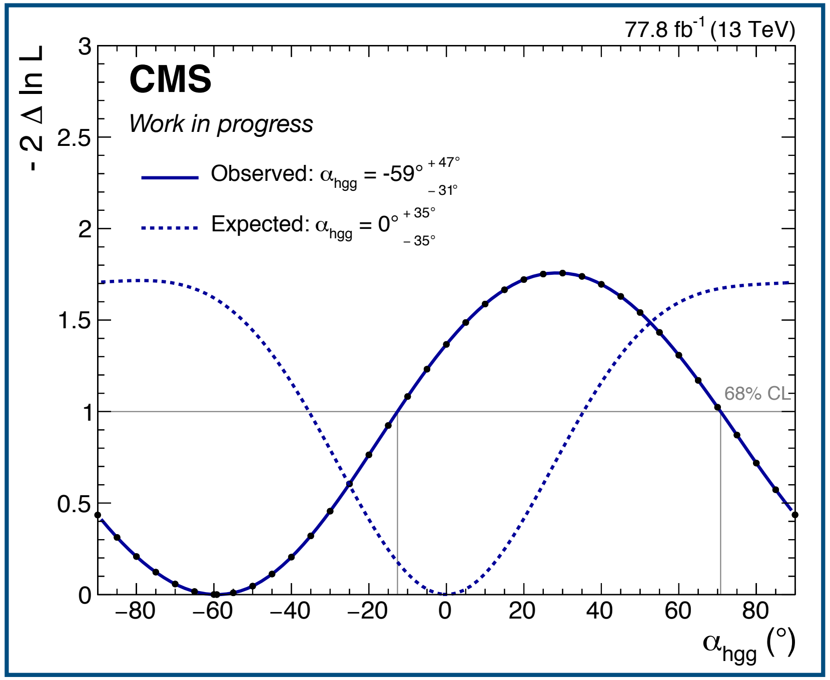
Dijet plots for Δϕ in windows of di-τ mass for increased S/B. Here showing postfit.



Results

The expected and observed sensitivities using **2016 + 2017** data is shown in the scan over alpha below.

The expected measured value is $\alpha = 0^{+35}_{-35}$ (degrees), whereas the observed mixing angle is -59^{+47}_{-31} (degrees), which is very consistent with the SM expectation.



Conclusion and Plans

An overview of the current state of the analysis measuring the CP state of the Higgs boson at the gluon fusion production vertex has been presented.

Advanced techniques have been employed to improve the modelling of backgrounds.

Future plans include completing this measurement with the full RunII dataset.

Additionally, a combination will be performed with other final states such as H —> ZZ, which will bring the best result.

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Thank you!

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Backup

Theory

The Lagrangian describing the Yukawa coupling of the Higgs boson to fermions is

$$\mathcal{L}_Y = y_f H \bar{\psi}_f \psi_f + i\tilde{y}_f A \bar{\psi}_f \gamma_5 \psi_f$$

Under the assumption that the loop in ggH production is dominated by the top quark to write an effectve Lagrangian for

$$\mathcal{L}_{\text{eff}} = \frac{y_t}{y_t^{SM}} \cdot \frac{\alpha_s}{12\pi\nu} \cdot H G^a_{\mu\nu} G^{a\ \mu\nu} + \frac{\bar{y}_t}{y_t^{SM}} \cdot \frac{\alpha_s}{16\pi\nu} \cdot A G^a_{\mu\nu} G^a_{\rho\sigma} \epsilon^{\mu\nu\rho\sigma}$$

The tensor structure of the gluon vertex then is

$$T^{\mu\nu} = a_2 \left(q_1 \cdot q_2 g^{\mu\nu} - q_1^\nu q_2^\mu \right) + a_3 \epsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma}$$

In this way the CP mixing angle can be extracted as the ratio of the scalar form factors

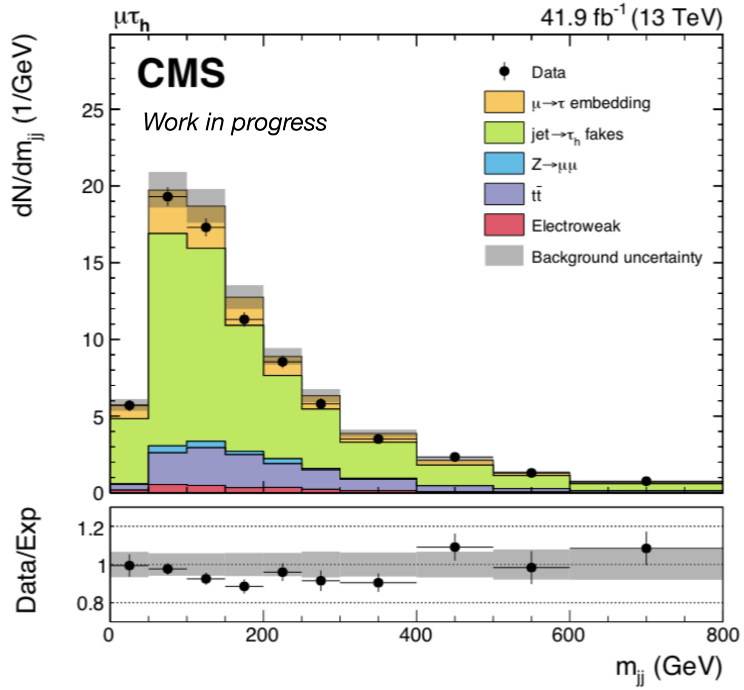
$$a_2 = a \cos\alpha \qquad\qquad a_3 = a \sin\alpha$$

Analysis – Background methods

Fake-factor (FF) method:

$$\frac{N\,(\text{tight})}{N\,(\text{very loose}\ \&\&\ !\text{tight})}$$

Apply the average FF (covering all processes) as event weight to obtain data template, repeat procedure for MC events with genuine τ_h candidates and subtract MC from data.



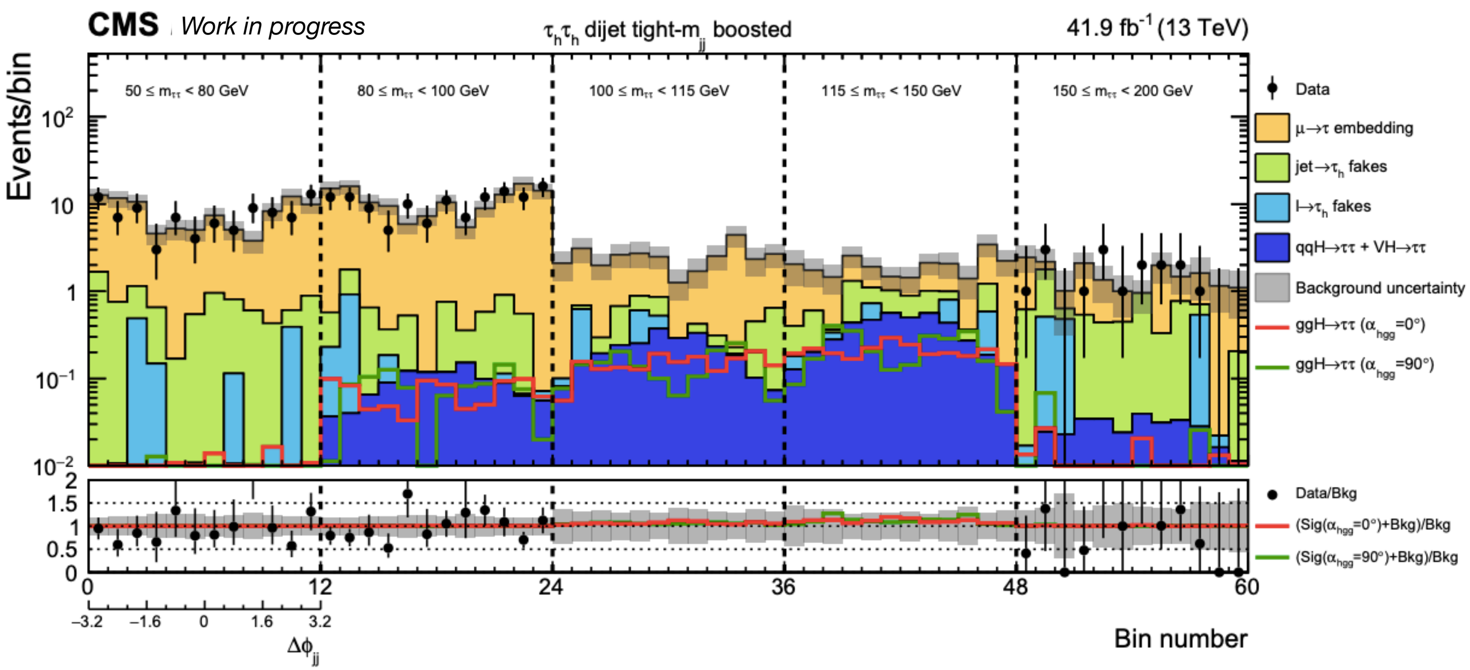
Channel	Process	SR selection	DR selection
	QCD	$q_{\tau_l}\cdot q_{\tau_h} <0$, $m_T <50$GeV, $I^l_{rel} < 0.15(0.1)$ [1]	$q_{\tau_l}\cdot q_{\tau_h} >0$, $m_T <50$ GeV, $0.05(0.02) < I^l_{rel} < 0.15$ [2]
$e\tau_h(\tau_\mu\tau_h)$	W+jets	$m_T <50$ GeV	$m_T >70$ GeV, $N_{bjets}=0$
	$t\bar{t}$	-	MC
$\tau_h\tau_h$	QCD	$q_{\tau_l}\cdot q_{\tau_h} <0$	$q_{\tau_l}\cdot q_{\tau_h} >0$

[1] 0.15 for 2017 and $\mu\tau$ in 2016, 0.1 for $e\tau$ in 2016
[2] 0.05 for 2016/$\mu\tau$ in 2017, 0.02 for $e\tau$ in 2017

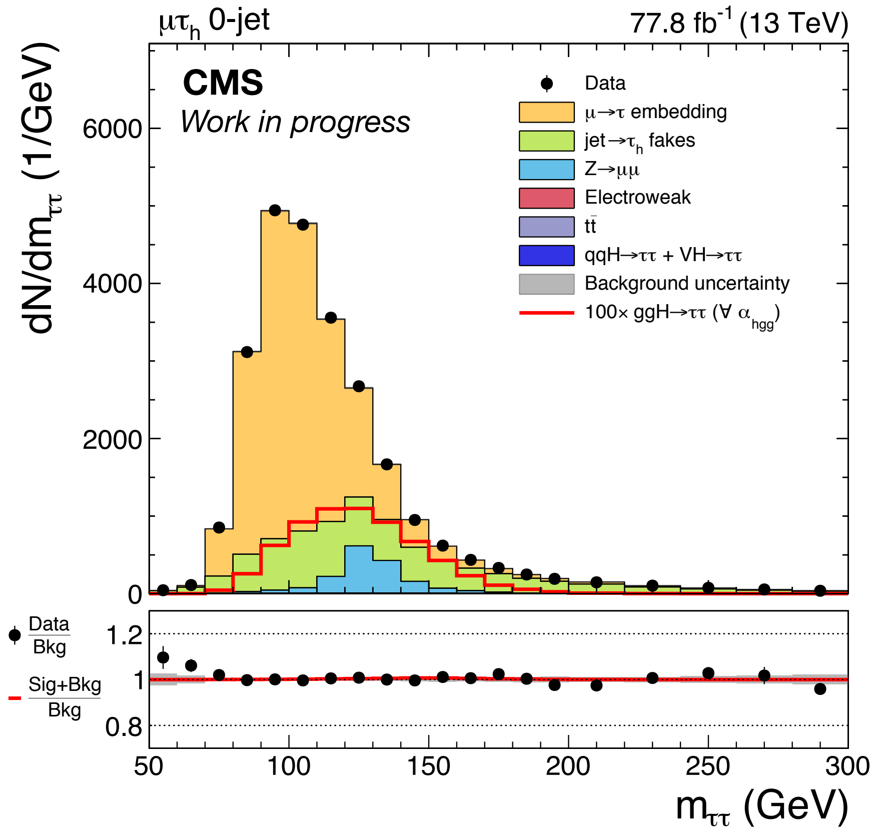
Analysis – Categorisation

Cut-based: Sensitivity to CP mixing angle comes from high dijet mass events, however, still fit all other categories (0-jet, 1-jet and 2-jet events with dijet mass < 300 GeV) to contrain backgrounds and systematics.

Unroll dijet plots for $\Delta\phi$ in windows of di-τ mass for increased S/B. Here showing prefit.

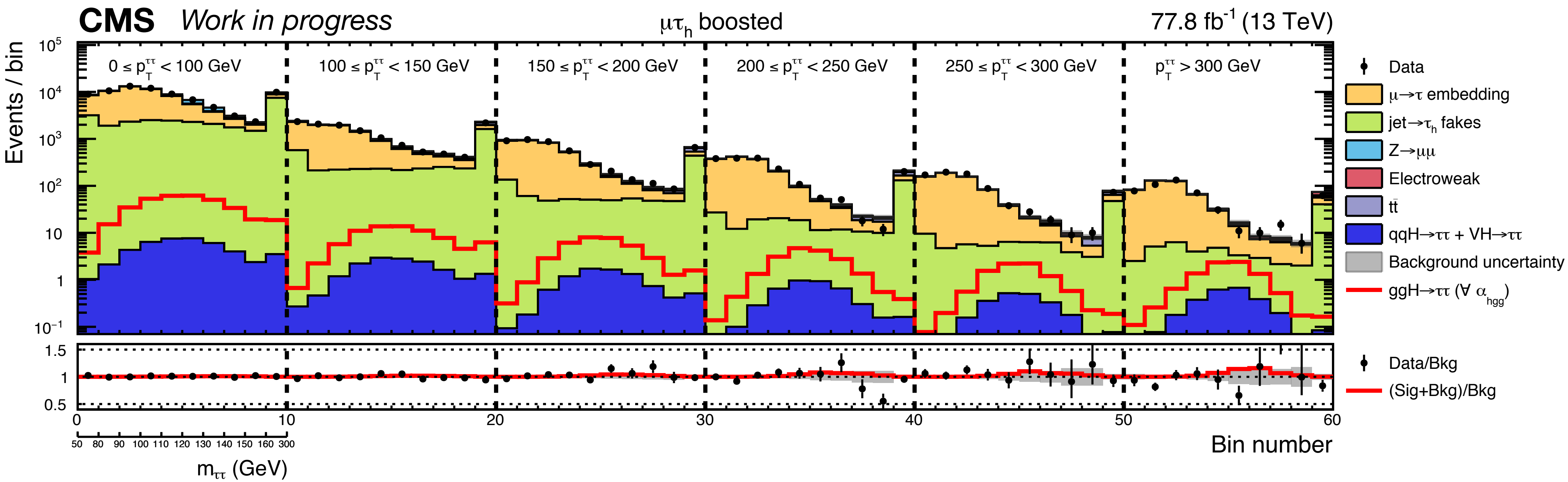


0-jet – $\mu\tau$

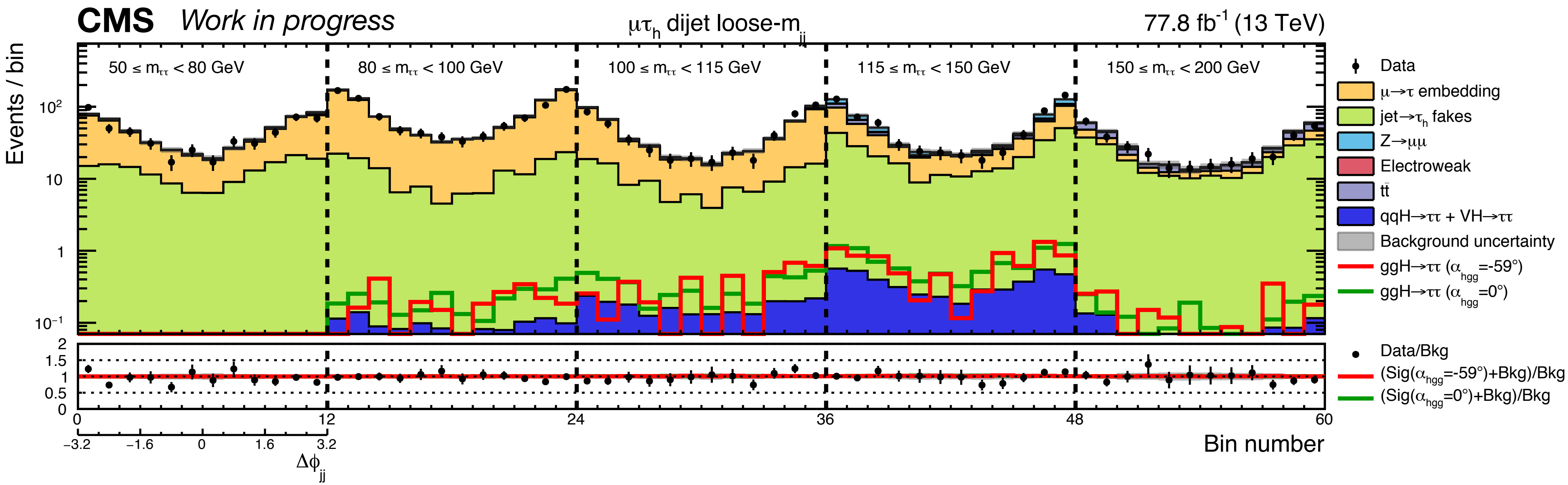


$\mu\tau_h$ 0-jet
77.8 fb^{-1} (13 TeV)
CMS
Work in progress
Data
$\mu\to\tau$ embedding
jet$\to\tau_h$ fakes
$Z\to\mu\mu$
Electroweak
$t\bar{t}$
$qqH\to\tau\tau$ + $VH\to\tau\tau$
Background uncertainty
100× $ggH\to\tau\tau$ ($\forall\ \alpha_{hgg}$)
$dN/dm_{\tau\tau}$ (1/GeV)
0
2000
4000
6000
Data / Bkg
Sig+Bkg / Bkg
1.2
1
0.8
50
100
150
200
250
300
$m_{\tau\tau}$ (GeV)

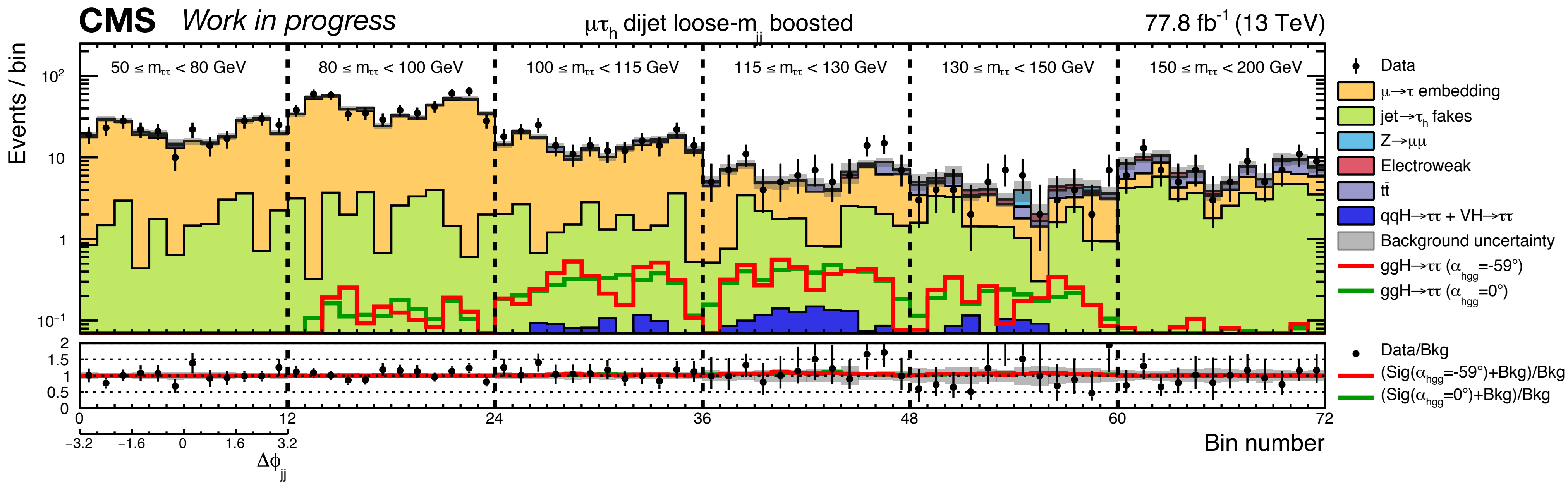
boosted – $\mu\tau$



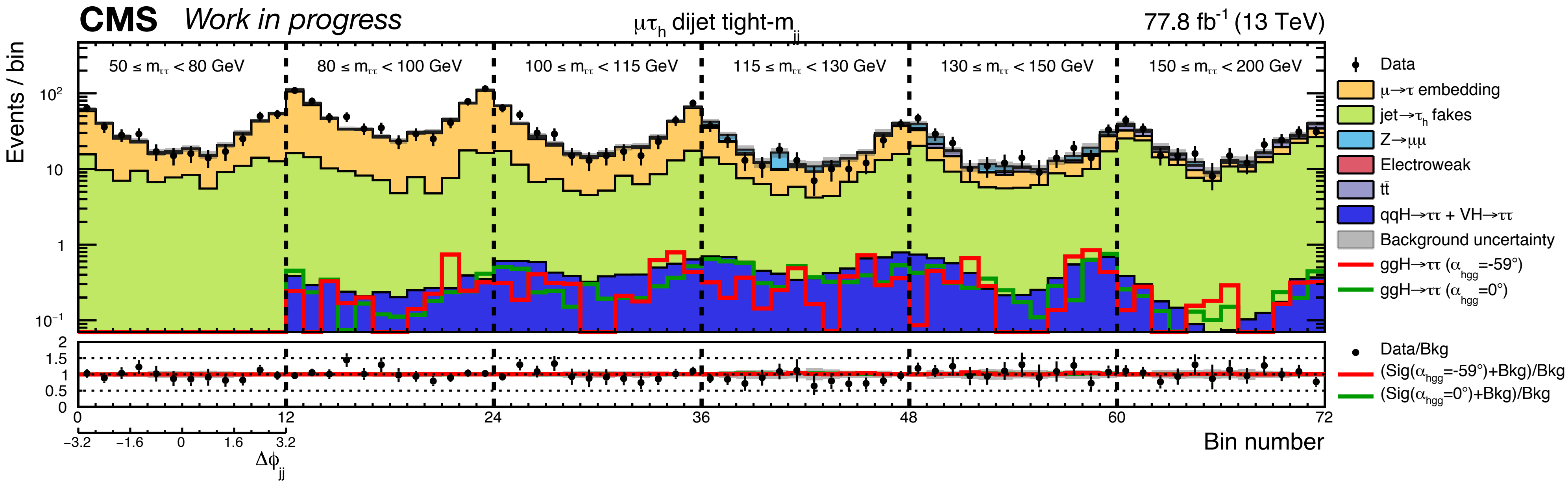
dijet loose-mjj – $\mu\tau$



dijet loose-mjj boosted – $\mu\tau$



dijet tight-mjj – $\mu\tau$

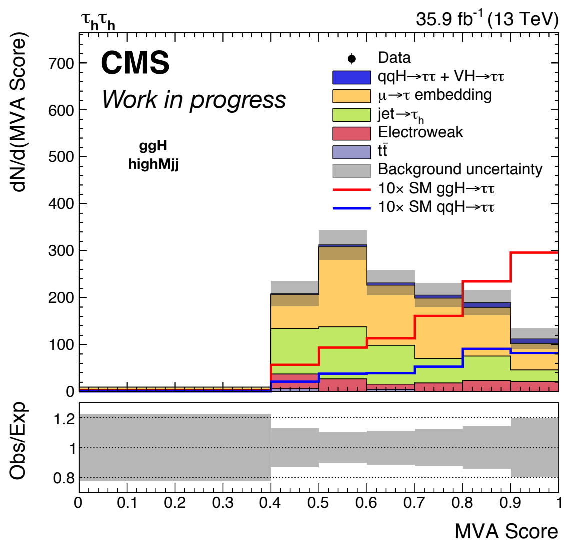


Analysis – Categorisation

MVA-based: Sensitivity to CP mixing angle comes from high mjj events, mix VBF and ggH events in training for optimisation towards VBF-like events.

Results in output score for each process that is trained —> select highest score as predicted class by MVA.

Fit 2D unrolled plots of MVA score and $\Delta\phi_{jj}$. Here showing ggH-enriched category.



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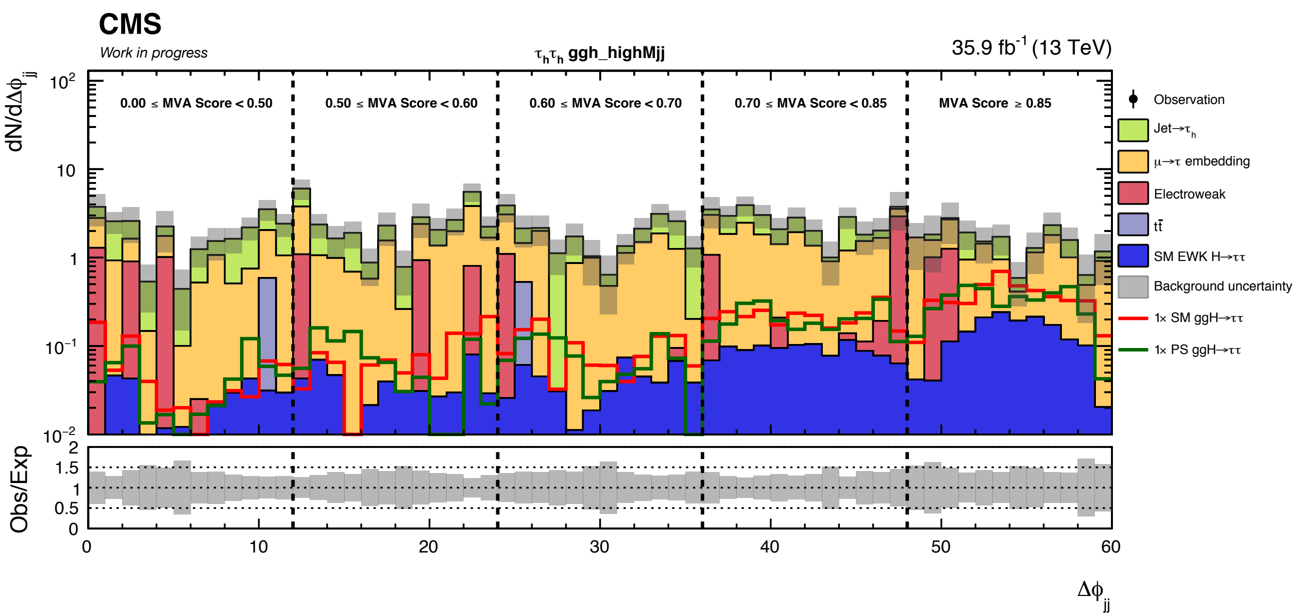
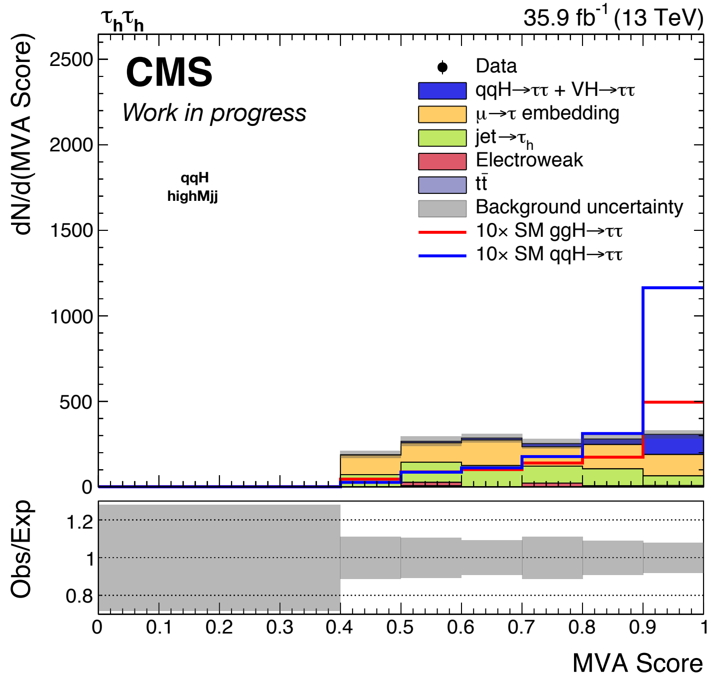
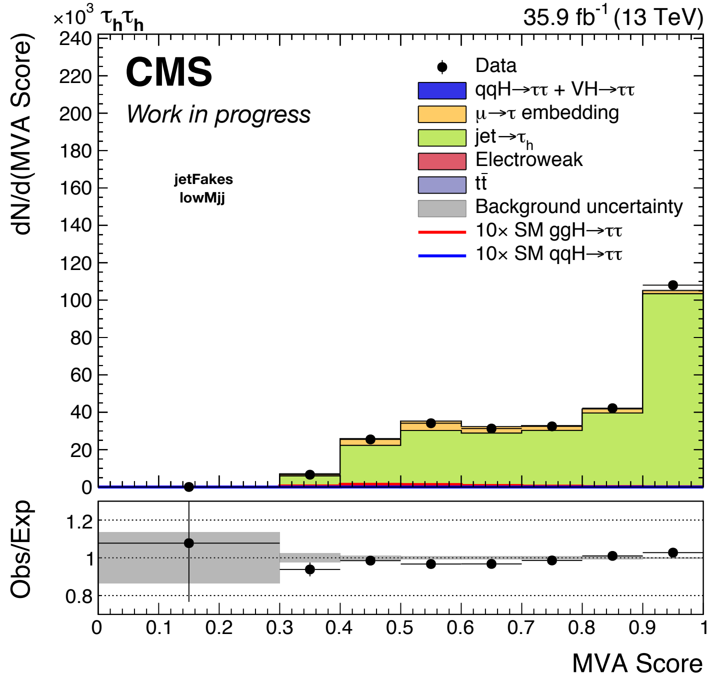


MVA-based



ττ (h subscripts)
35.9 fb-1 (13 TeV)
CMS
Work in progress
qqH
highMjj
Data
qqH→ττ + VH→ττ
μ→τ embedding
jet→τh
Electroweak
tt̄
Background uncertainty
10× SM ggH→ττ
10× SM qqH→ττ
dN/d(MVA Score)
Obs/Exp
MVA Score
0
500
1000
1500
2000
2500
0.8
1
1.2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

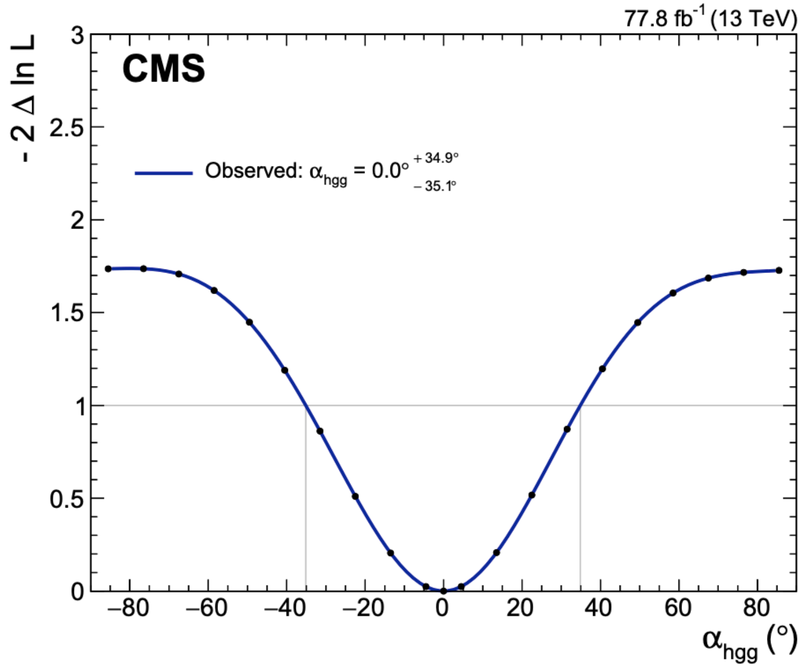


×10³
ττ (h subscripts)
35.9 fb-1 (13 TeV)
CMS
Work in progress
jetFakes
lowMjj
Data
qqH→ττ + VH→ττ
μ→τ embedding
jet→τh
Electroweak
tt̄
Background uncertainty
10× SM ggH→ττ
10× SM qqH→ττ
dN/d(MVA Score)
Obs/Exp
MVA Score
0
20
40
60
80
100
120
140
160
180
200
220
240
0.8
1
1.2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Expected sensitivity

The expected sensitivity using 2016 + 2017 (Asimov) data is shown in the scan over alpha below.

The expected measured value is α **= 0 ± 35**°.



Plans – CP with decays

Future plans include studying the CP state of the Higgs boson at the decay side with full RunII data.

CP in decays analysis exploits angular correlations between decay planes and/or impact parameters of tau decay products to infer on the CP mixing angle.