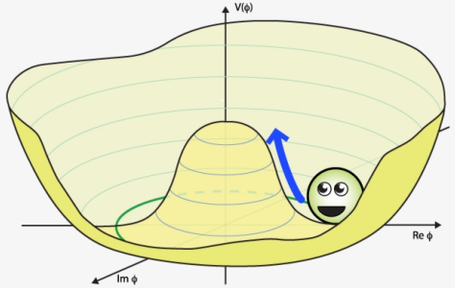
Studies of anomalous couplings and CP structure of Higgs boson in CMS experiment

Suman Chatterjee
for the CMS Collaboration

HEPHY Vienna

07/07/2022

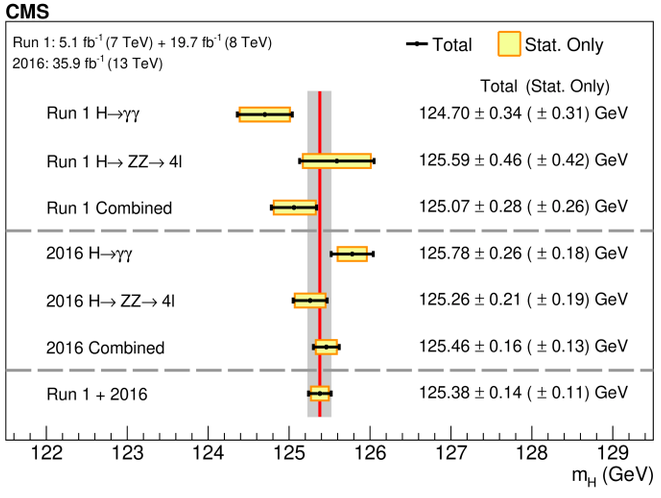


ICHEP 2022
Bologna, Italy

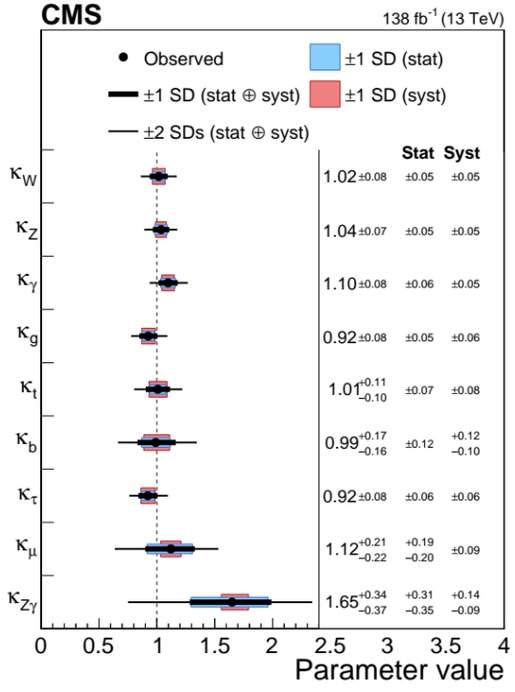
Higgs boson: where do we stand?

Newest fundamental particle discovered: Last missing piece in standard model (SM)

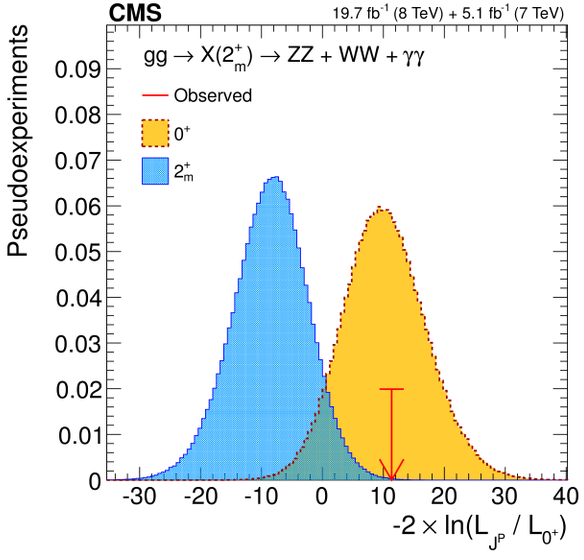
Detailed measurements of Higgs boson properties using LHC Run 1 + Run 2 data



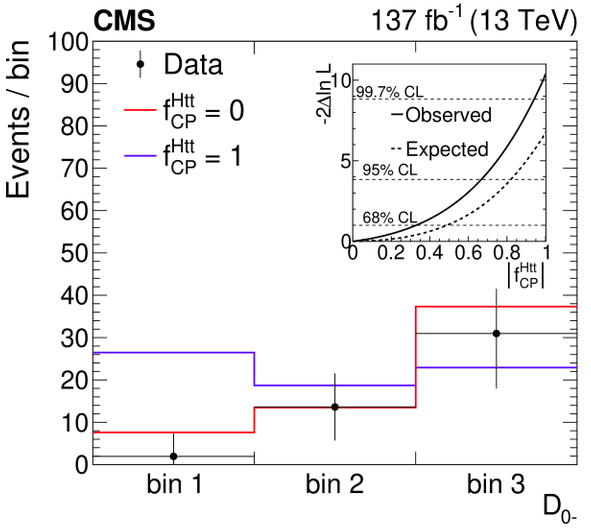
Phys. Lett. B 805 (2020) 135425



Nature 607 (2022) 60-68



Phys. Rev. D 92 (2015) 012004



Phys. Rev. Lett. 125 (2020) 061801

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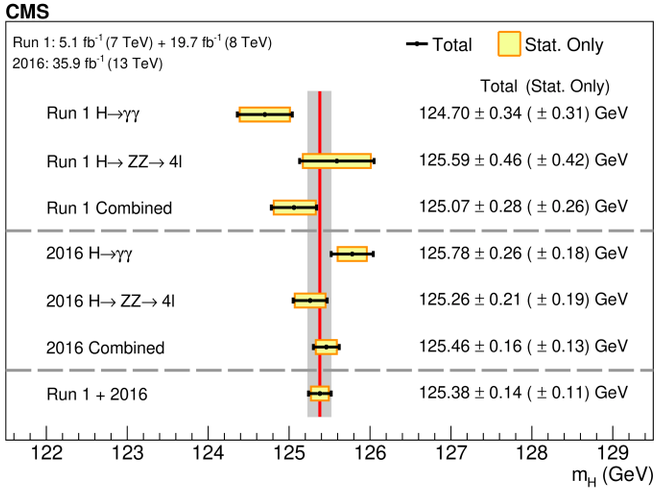

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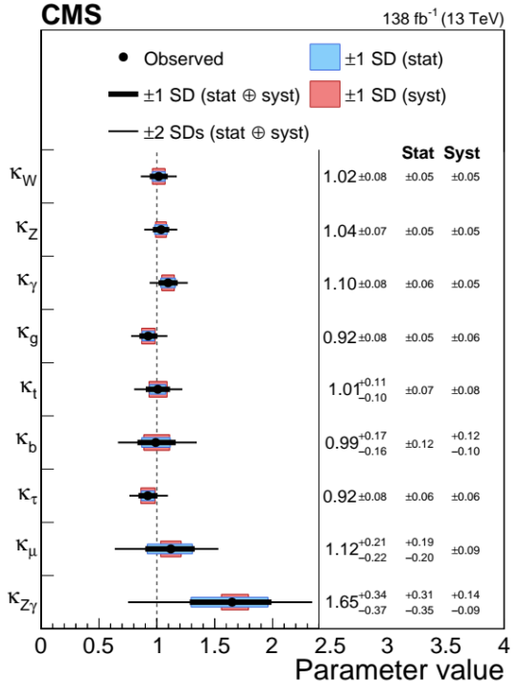

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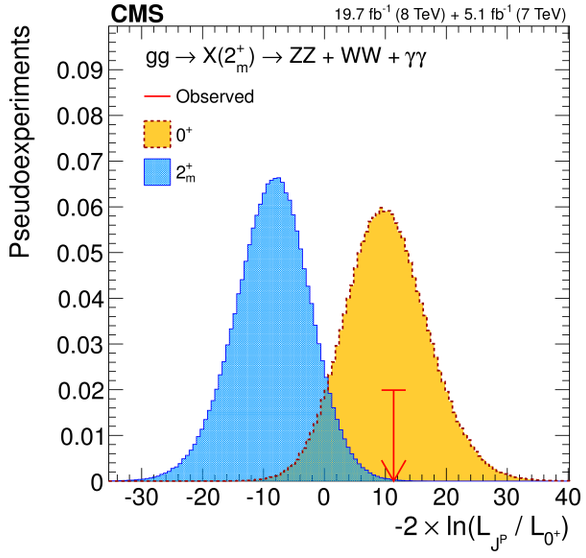

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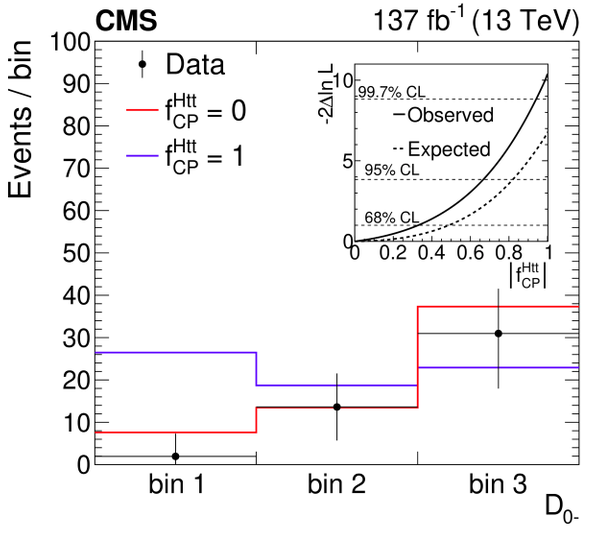

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Higgs couplings to fermions and Gauge bosons

← Precisely known in SM

← Look for deviations from SM predictions

→ If found, signature of new physics

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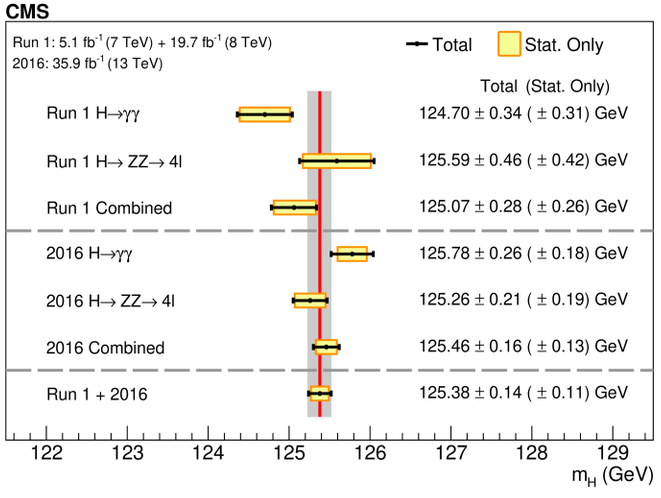

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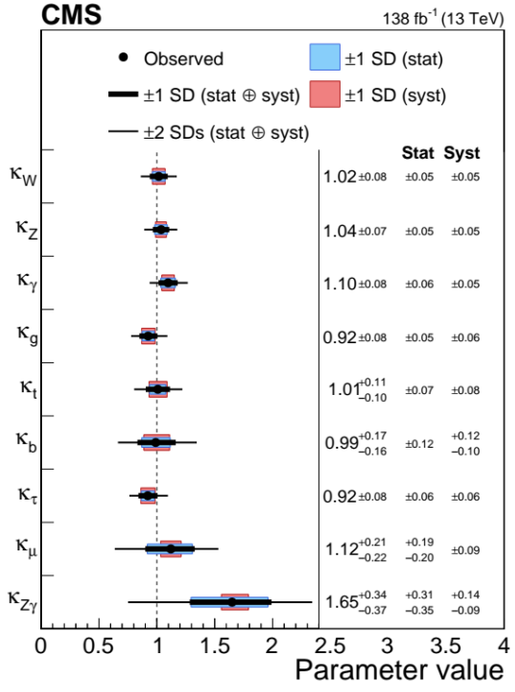

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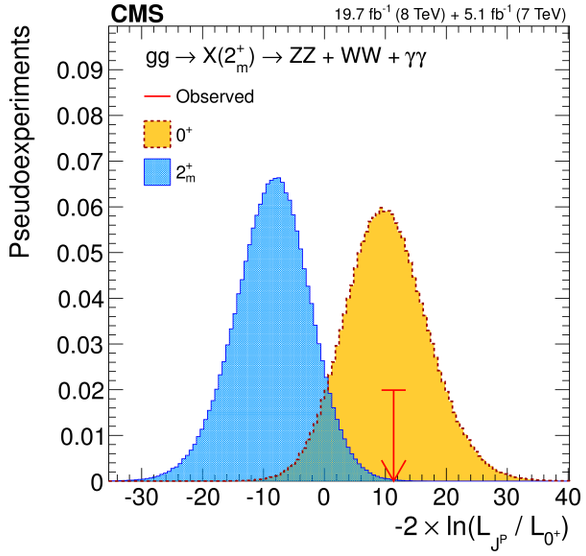

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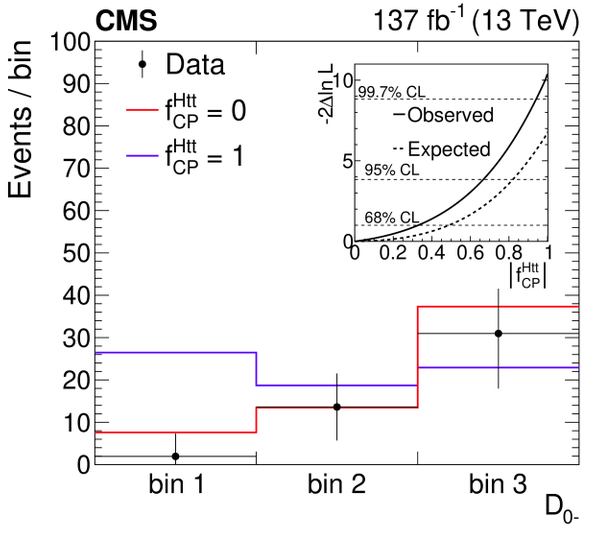

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Higgs couplings to fermions and Gauge bosons

← Precisely known in SM

← Look for deviations from SM predictions

→ If found, signature of new physics

Higgs boson spin-parity (J^{CP}): SM prediction = 0^{++}

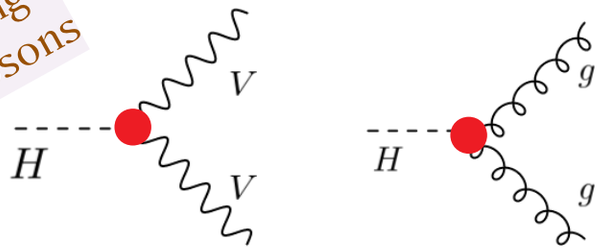
← Current measurements consistent with SM

← Still room left for a small CP-odd admixture

→ Any sign of CP-odd nature can shed light on physics beyond SM e.g., explanation of baryon asymmetry of universe

Anomalous couplings of Higgs boson

Higgs coupling to Gauge bosons



$$\mathcal{A}(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$

SM: $a_1^{WW} = a_1^{ZZ} = 2$, others 0 (@tree level)

Gauge symmetry:

$a_1^{gg} = a_1^{Z\gamma} = a_1^{\gamma\gamma} = 0$

$\kappa_1^{gg} = \kappa_2^{gg} = 0$, $\kappa_1^{\gamma\gamma} = \kappa_2^{\gamma\gamma} = 0$

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V = W,Z

a_1^{VV} ← SM-like coupling

κ_1^{VV}, κ_2^{VV}, a_2^{VV} ← CP-even anomalous coupling

a_3^{VV} ← CP-odd anomalous coupling

V = g

a_2^{gg} ← SM-like (loop-induced) + CP-even anomalous coupling

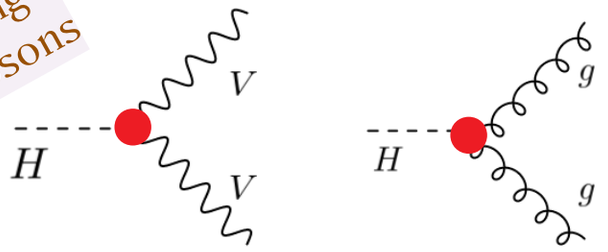
a_3^{gg} ← CP-odd anomalous coupling

Experimentally probed by measuring cross section fractions

$$f_{ai} = \frac{|a_i|^2 \sigma_i}{|a_1|^2 \sigma_1 + |a_2|^2 \sigma_2 + |a_3|^2 \sigma_3 + |\kappa_1|^2 \sigma_{\Lambda 1} + |\kappa_1^{Z\gamma}|^2 \sigma_{\Lambda 1}^{Z\gamma}} \operatorname{sgn}\left(\frac{a_i}{a_1}\right)$$

Anomalous couplings of Higgs boson

Higgs coupling to Gauge bosons



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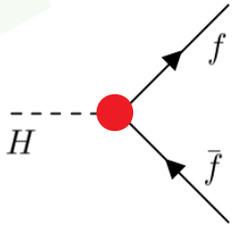
Higgs coupling to fermions

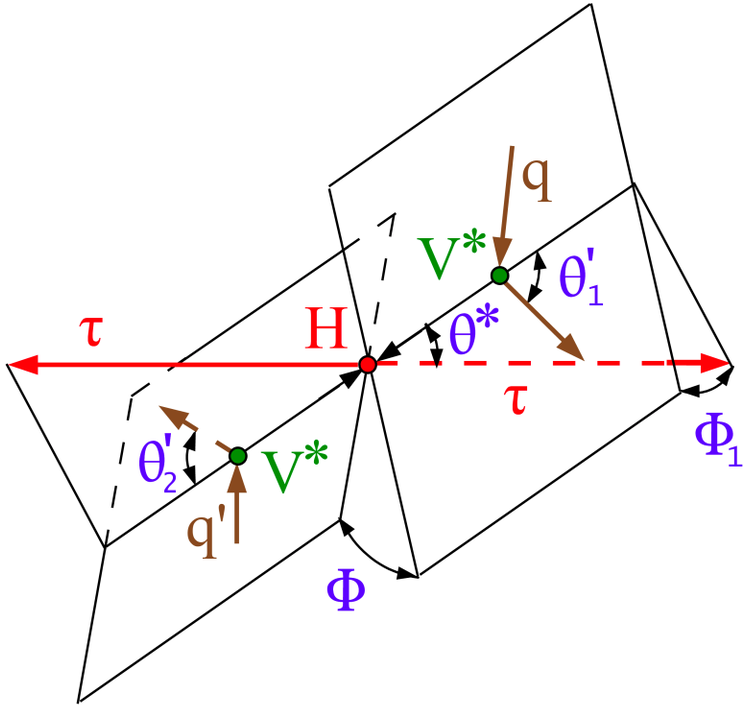


$$\mathcal{A}(\mathrm{Hff}) = -\frac{m_f}{v}\bar{\psi}_{\mathrm{f}}\left(\kappa_{\mathrm{f}} + \mathrm{i}\,\tilde{\kappa}_{\mathrm{f}}\gamma_5\right)\psi_{\mathrm{f}}$$

SM: $\kappa_f = 1$, $\tilde{\kappa}_f = 0$

Measurement observable: cross section fraction $f_{CP}^{\mathrm{Hff}} = \dfrac{|\tilde{\kappa}_{\mathrm{f}}|^2}{|\kappa_{\mathrm{f}}|^2 + |\tilde{\kappa}_{\mathrm{f}}|^2}\mathrm{sgn}\left(\dfrac{\tilde{\kappa}_{\mathrm{f}}}{\kappa_{\mathrm{f}}}\right)$ or mixing angle $\alpha^{\mathrm{Hff}} = \tan^{-1}\left(\dfrac{\tilde{\kappa}_{\mathrm{f}}}{\kappa_{\mathrm{f}}}\right)$

Curse of dimensionality: Handling a multi-dimensional problem



Example topology:

VBF H production + H→ ττ decay

Large number of variables needed to fully characterize the system

→ Difficult to perform an optimal multi-dimensional measurement with many independent variables

Solution

Matrix element likelihood approach (MELA)

→ Construct discriminants sensitive to individual anomalous couplings

Smaller number of observables, still retaining most of the discrimination power

Two kinds of MELA observables:

$$\mathcal{D}_{\text{BSM}} = \frac{\mathcal{P}_{\text{SM}}(\vec{\Omega})}{\mathcal{P}_{\text{SM}}(\vec{\Omega}) + \mathcal{P}_{\text{BSM}}(\vec{\Omega})}$$

Pure BSM

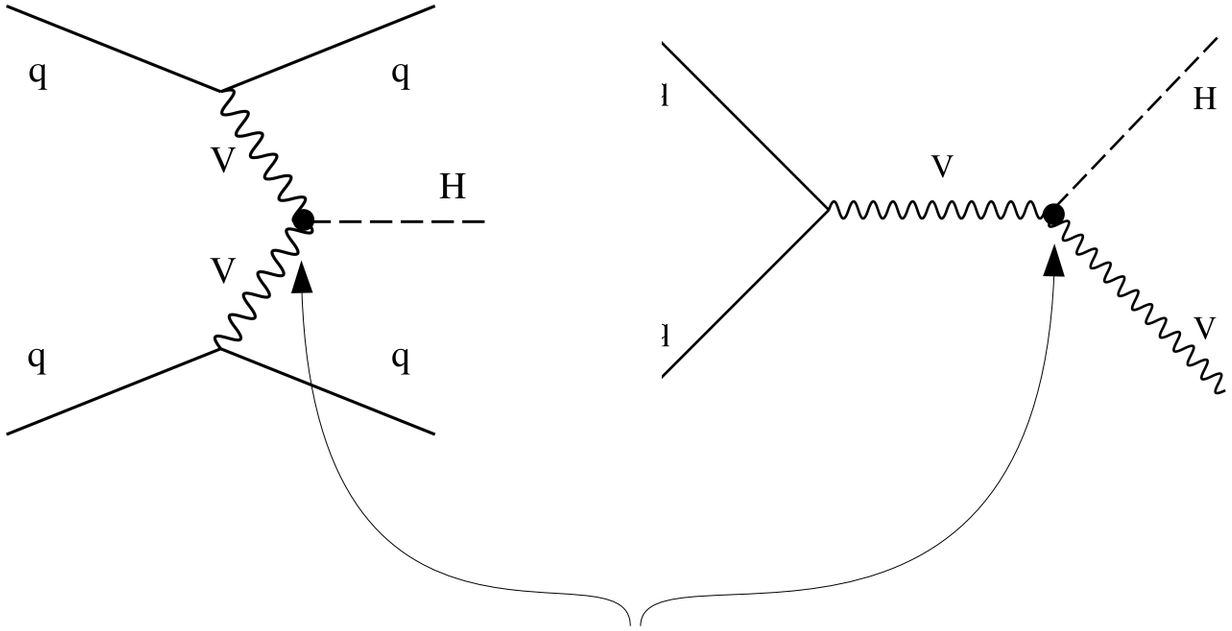
$$\mathcal{D}_{\text{int}} = \frac{\mathcal{P}^{\text{int}}_{\text{SM-BSM}}(\vec{\Omega})}{\mathcal{P}_{\text{SM}}(\vec{\Omega}) + \mathcal{P}_{\text{BSM}}(\vec{\Omega})}$$

SM-BSM interference

Anomalous couplings in H production: H→ ττ final state

arXiv: 2205.05120

Accepted for publication in PRD



Objective: To probe H-V coupling structure

Selections optimized targeting VBF topology

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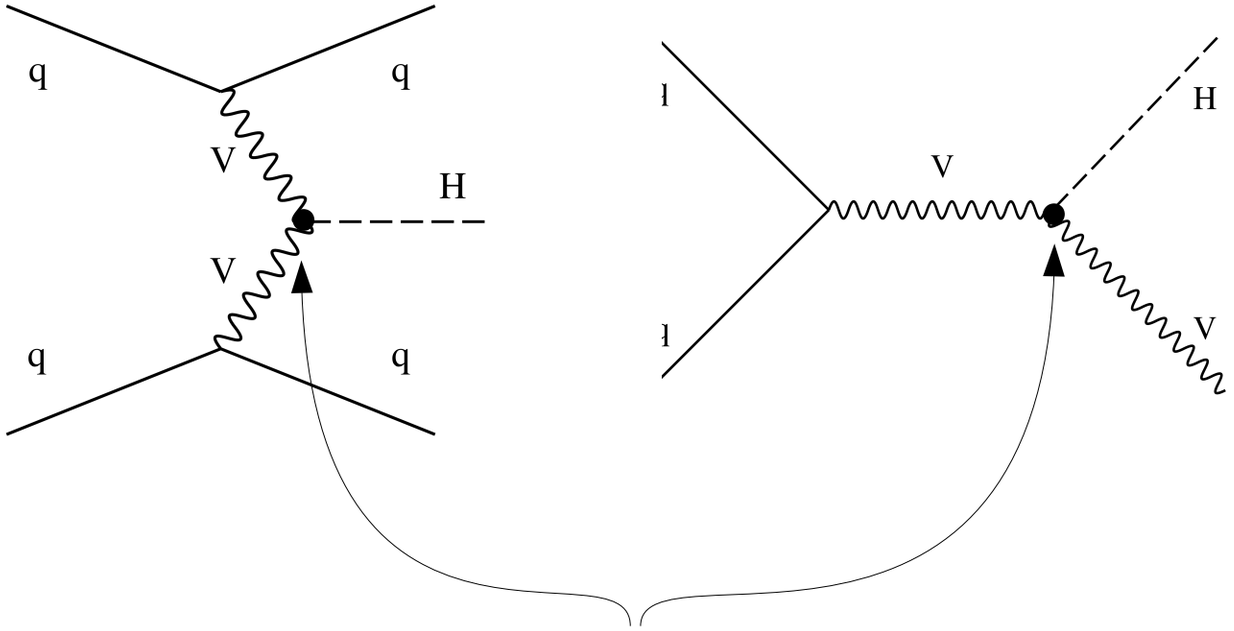

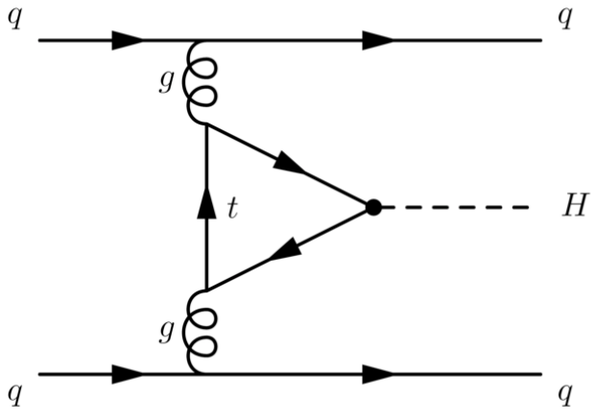

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Selections optimized targeting VBF topology

Very similar event topology from ggH + 2 jets production

→ Used to probe anomalous ggH couplings

Higgs to electroweak vector boson couplings: H→ ττ final state

arXiv: 2205.05120

Final states considered:

$e\tau_h + \mu\tau_h + \tau_h\tau_h + e\mu$

Extensive use of MVA

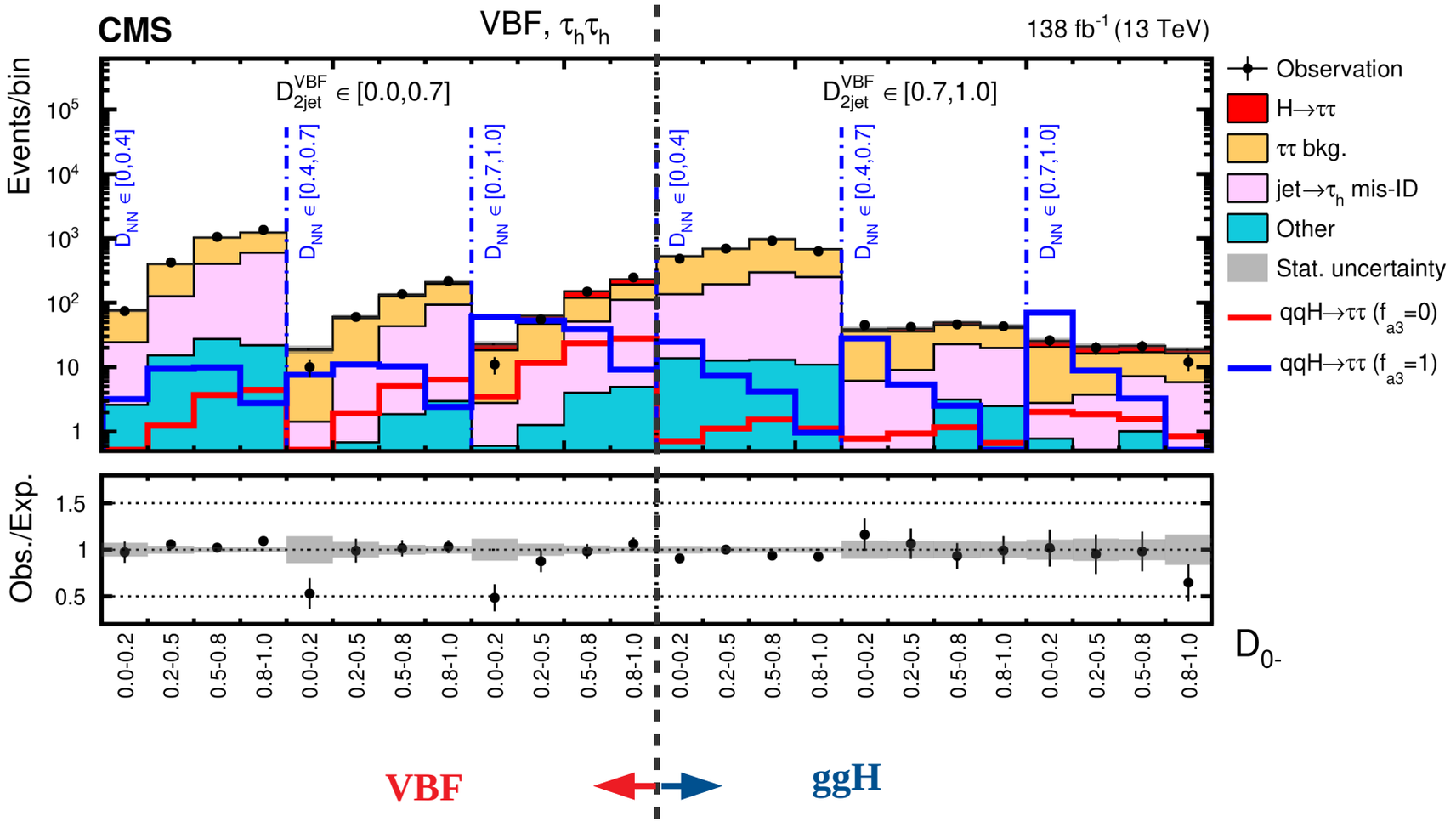
Neural network-based discrimination

D_{NN} ← separates VBF-like signal from SM background

MELA variables

D^{VBF}_{2jet} ← separates VBF from ggH

D_{0-} ← separates CP-odd anomalous coupling from SM HVV coupling



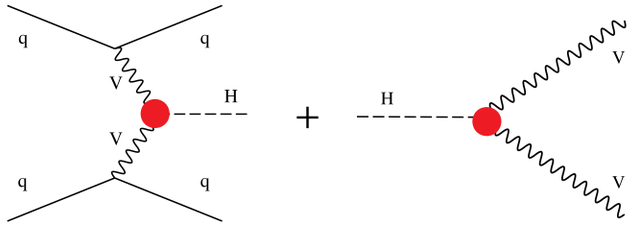
Signal extracted using multi-dimensional maximum likelihood fit

Higgs to electroweak vector boson couplings: H→ 4-l final state

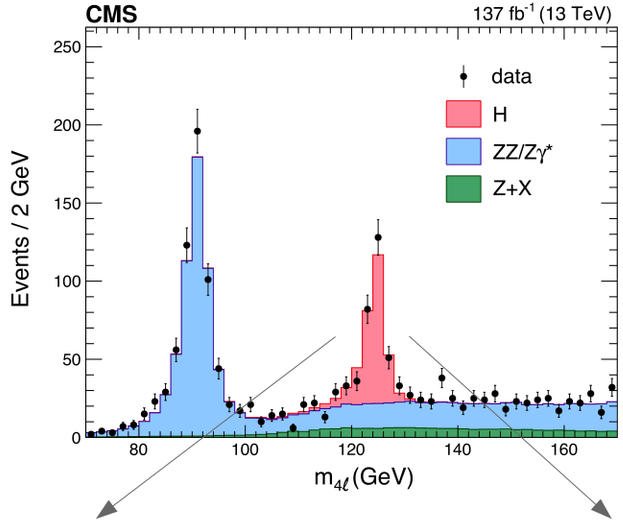
Phys. Rev. D. 104 (2021) 052004

Final states considered:

4e + 4μ



production decay

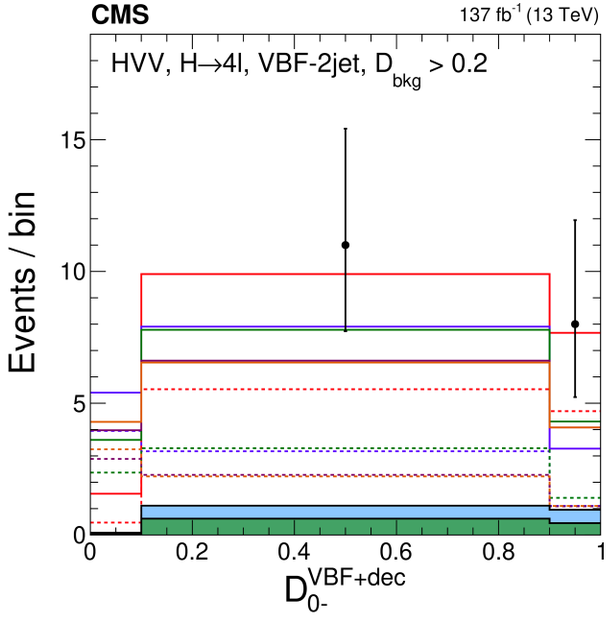


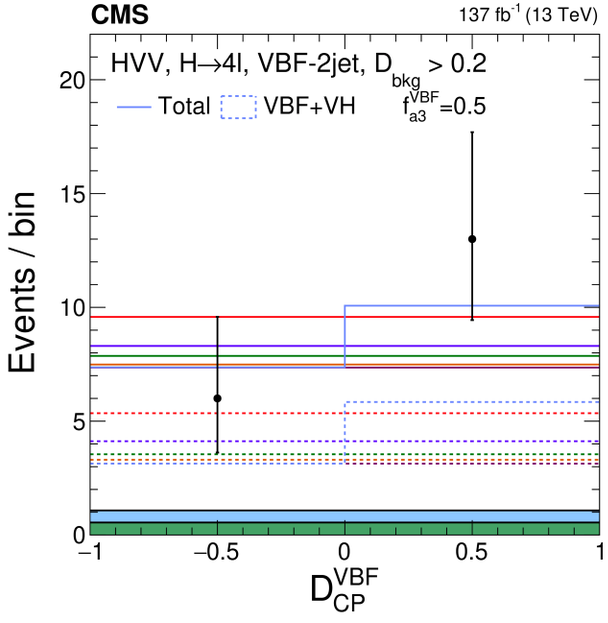
MELA variables

D_{bkg} ← separates VBF H from SM bkg

$D^{VBF+dec}_{0-}$ ← separates CP-odd anomalous coupling from SM HVV coupling (both in production & decay)

D^{VBF}_{CP} ← separates interference of CP-odd coupling with SM coupling





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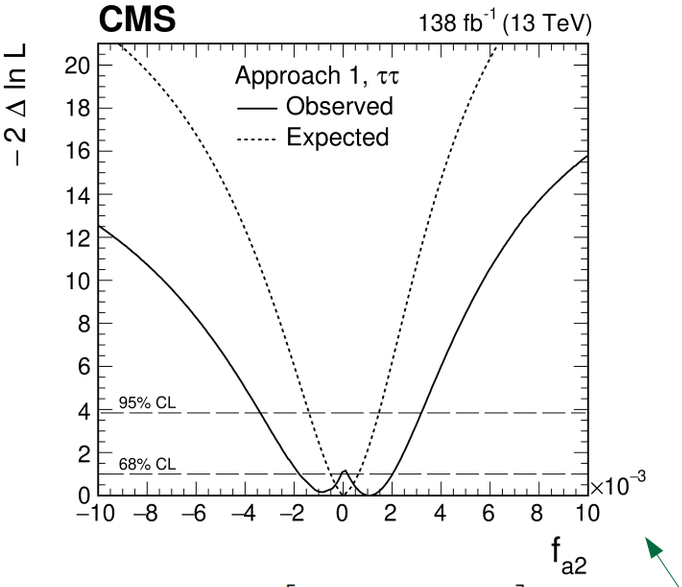

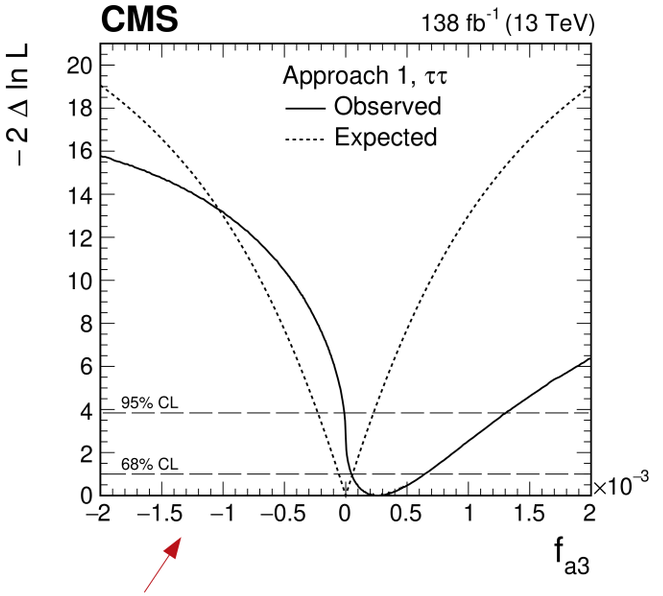

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$H \to \tau\tau$ only

Parameter	Observed/(10^{-3})		Expected/(10^{-3})	
	68% CL	95% CL	68% CL	95% CL
f_{a3}	$0.26^{+0.38}_{-0.21}$	$[-0.01, 1.30]$	0.00 ± 0.06	$[-0.23, 0.23]$
f_{a2}	$1.1^{+0.9}_{-0.9} \cup [-1.8, -0.1]$	$[-3.4, 3.2]$	$0.0^{+0.6}_{-0.5}$	$[-1.4, 1.5]$

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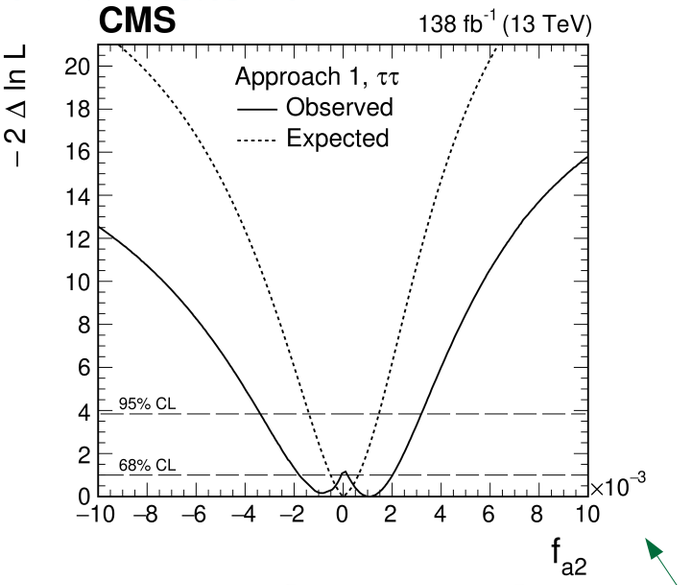

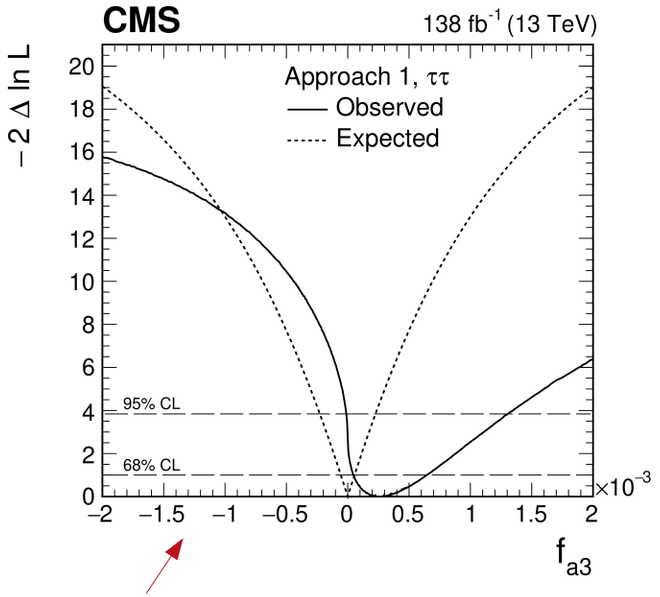

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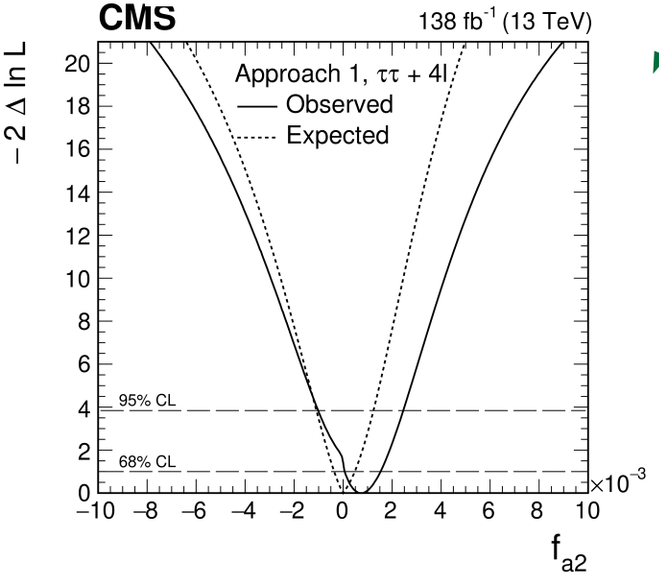

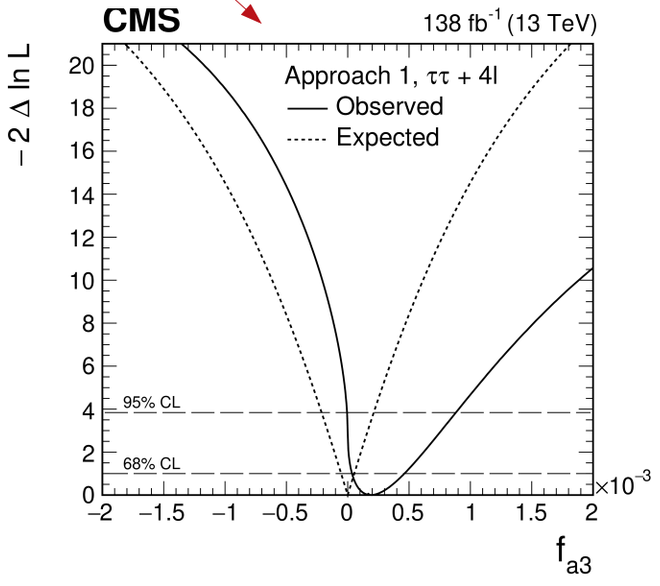

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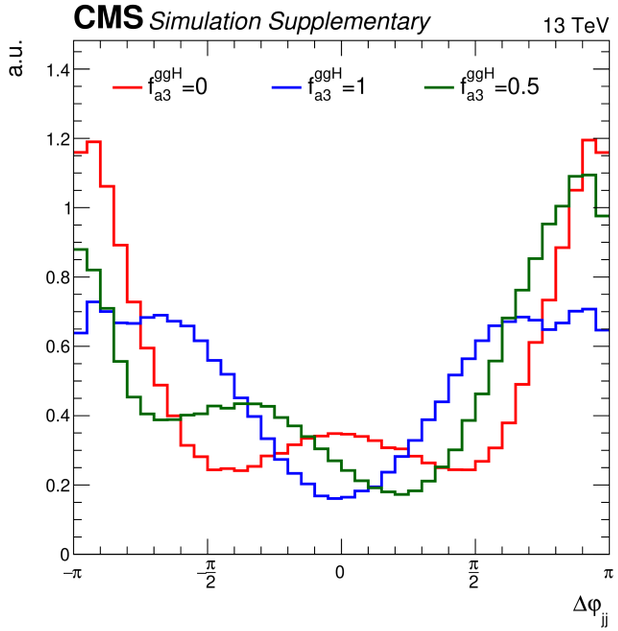
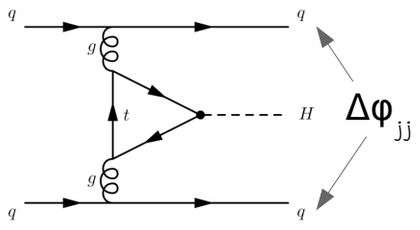
H → ττ combined with H → ZZ* → 4l

Parameter	Observed / (10^{-3})		Expected / (10^{-3})	
	68% CL	95% CL	68% CL	95% CL
f_{a3}	$0.20^{+0.26}_{-0.16}$	$[-0.01, 0.88]$	0.00 ± 0.05	$[-0.21, 0.21]$
f_{a2}	$0.7^{+0.8}_{-0.6}$	$[-1.0, 2.5]$	$0.0^{+0.5}_{-0.4}$	$[-1.1, 1.2]$

Higgs to gluon couplings: H→ ττ, 4-lepton final states



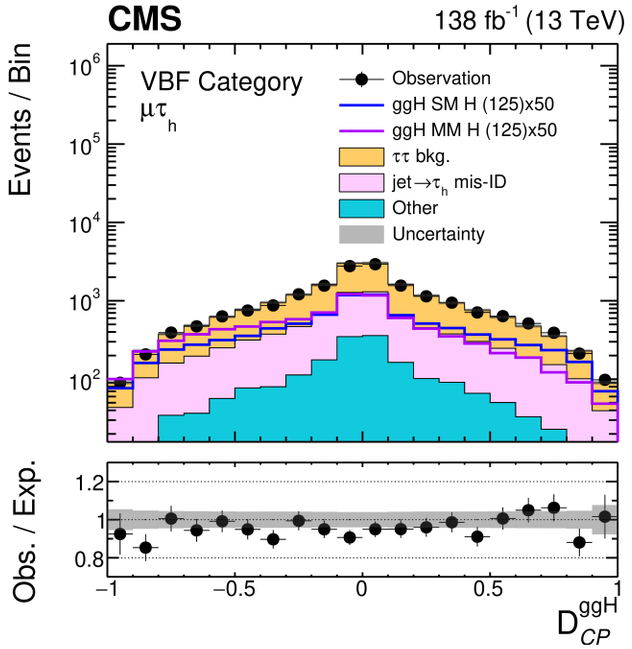


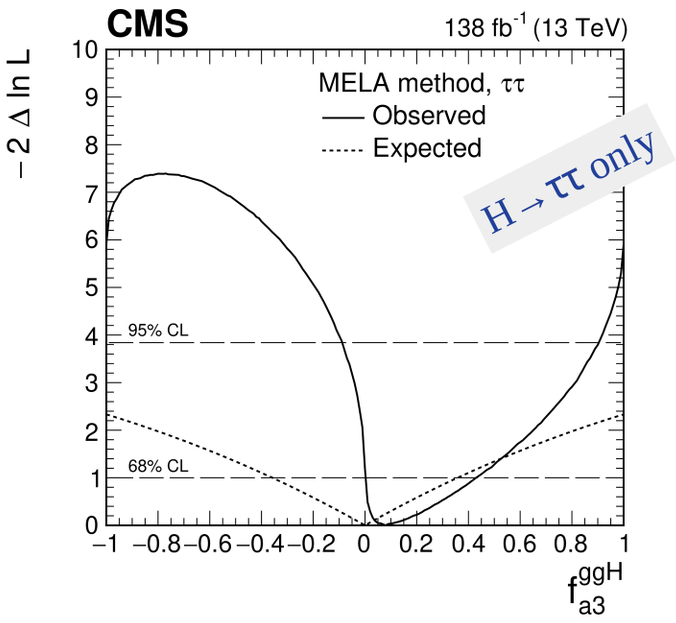
Similar sensitivity
with simple variable

$\Delta\phi_{jj} = \phi(j_1) - \phi(j_2)$, with $\eta(j_1) < \eta(j_2)$

&

MELA discriminators





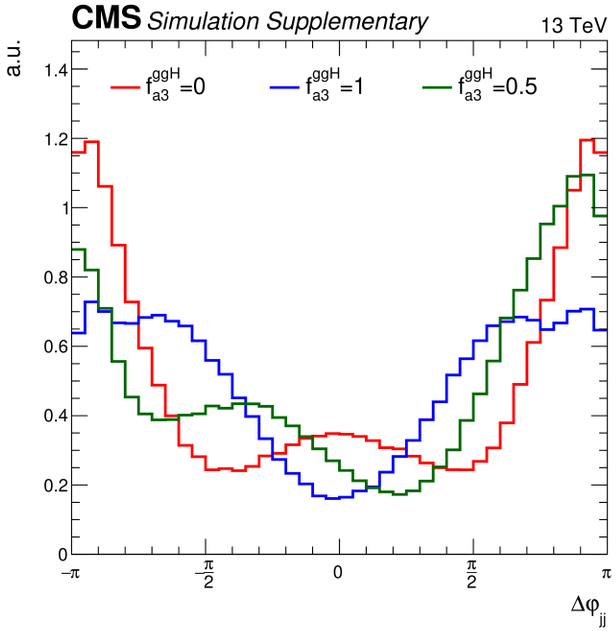
arXiv: 2205.05120

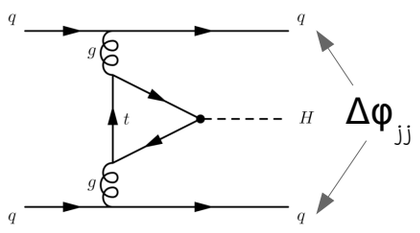
D_{CP}^{ggH} ← separates interference of
CP-odd coupling with SM coupling

CP-odd cross section fraction:

= 0.08 [+ 0.35 – 0.08 @ 68% CL]

Higgs to gluon couplings: H→ ττ, 4-lepton final states



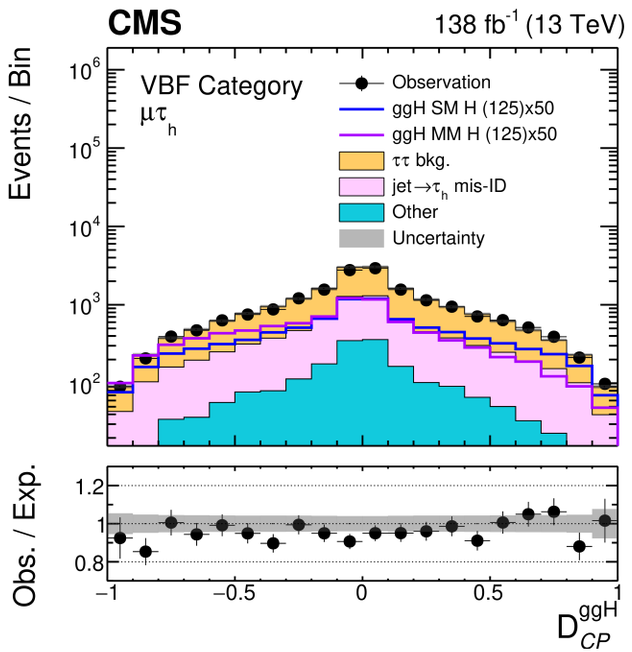


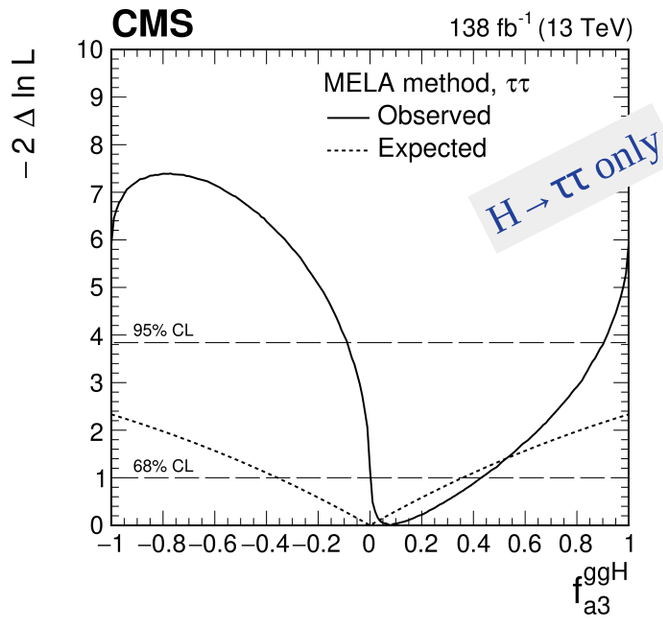
Similar sensitivity with simple variable

$\Delta\phi_{jj} = \phi(j_1) - \phi(j_2)$, with $\eta(j_1) < \eta(j_2)$

&

MELA discriminators





arXiv: 2205.05120

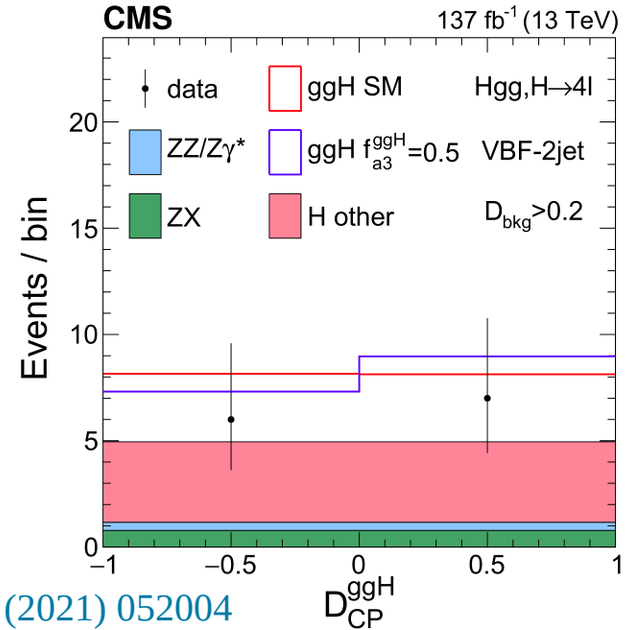
D^{ggH}_{CP} ← separates interference of CP-odd coupling with SM coupling

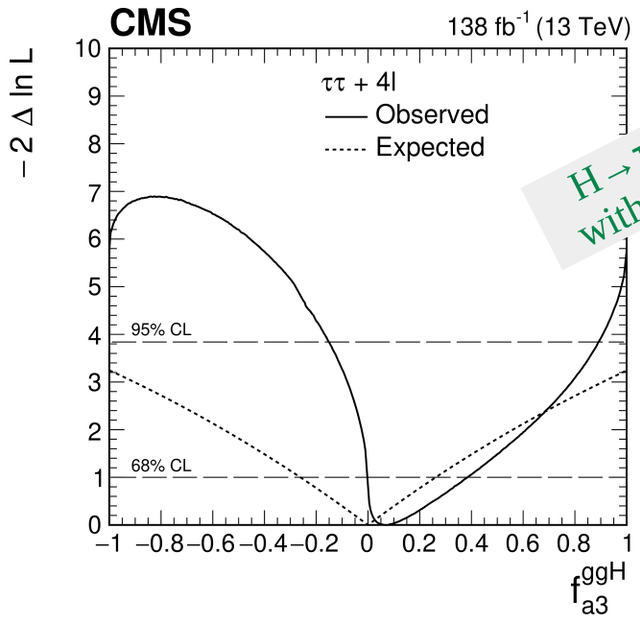
CP-odd cross section fraction:

= 0.08 [+ 0.35 – 0.08 @ 68% CL]

= 0.07 [+ 0.32 – 0.07 @ 68% CL]

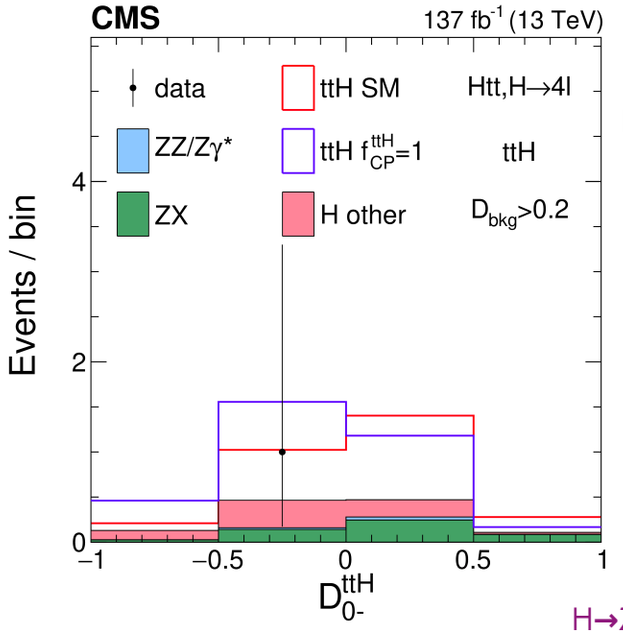
Pure CP-odd hypothesis excluded at 2.4σ





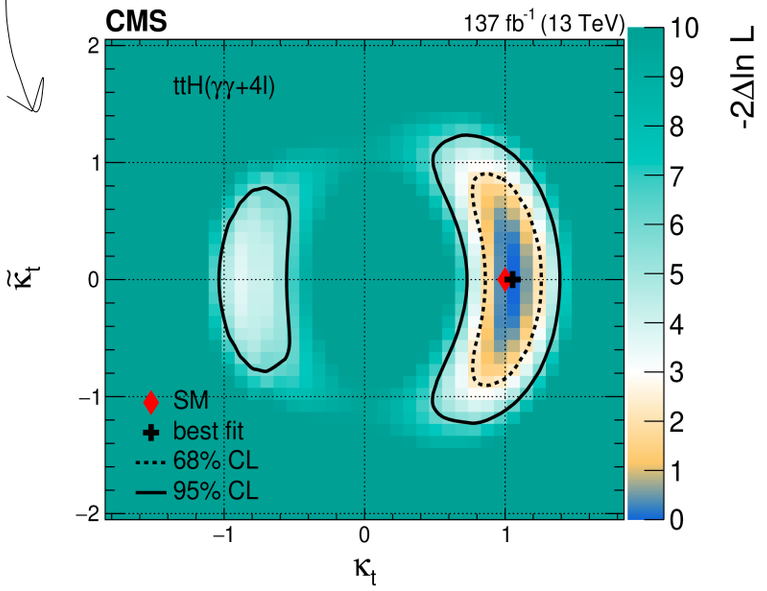
Phys. Rev. D. 104 (2021) 052004

Higgs to top quark couplings: H→ 4-lepton, γγ, ττ final states



H→ZZ*→ 4l

H→ZZ*→ 4l + H→γγ



Phys. Rev. D. 104 (2021) 052004

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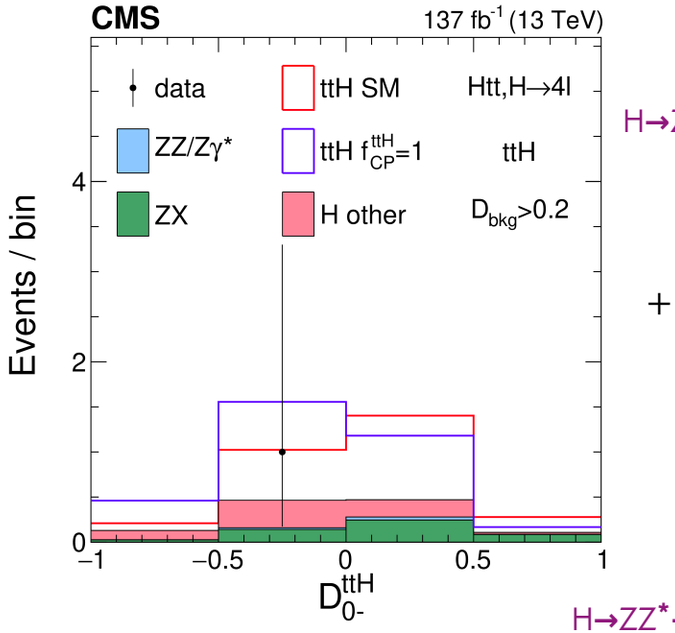
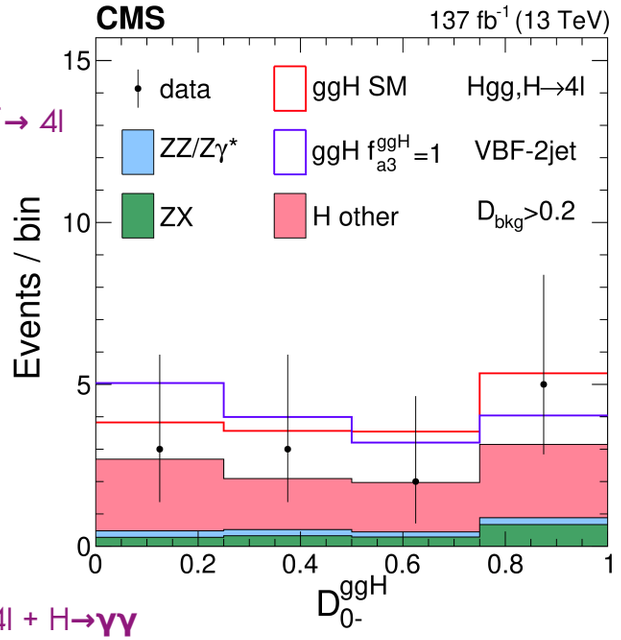
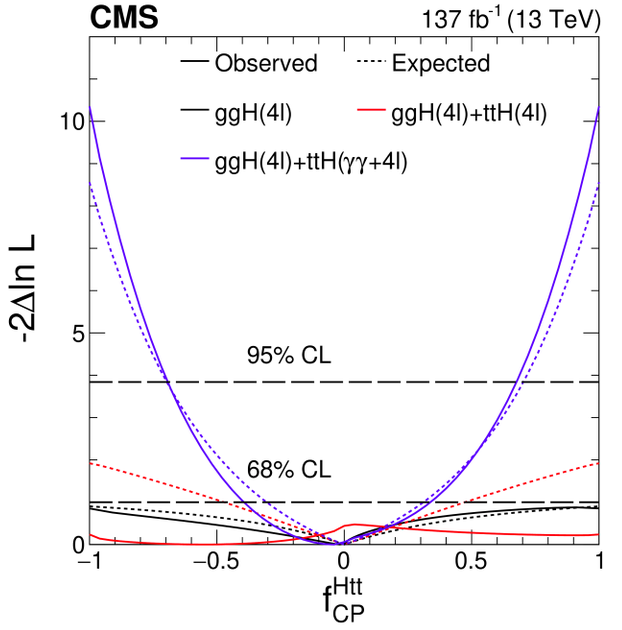


H→ZZ*→ 4l

+



ttH & ggH categories
combined
to enhance sensitivity



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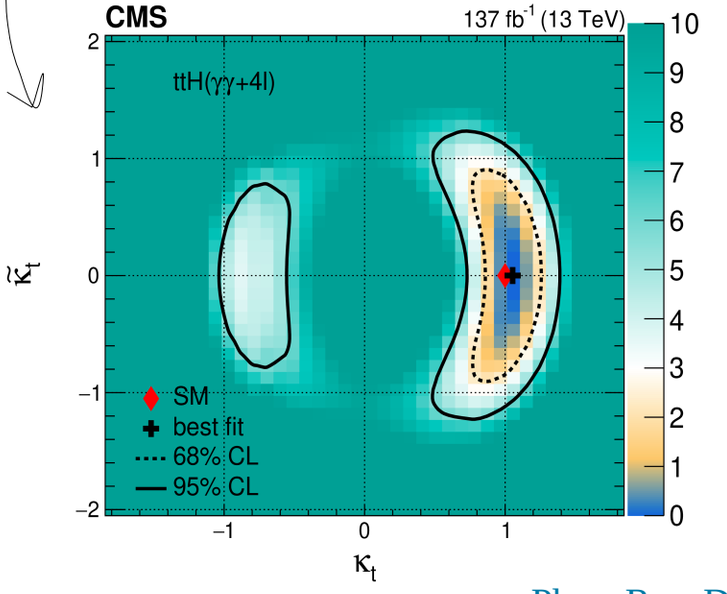
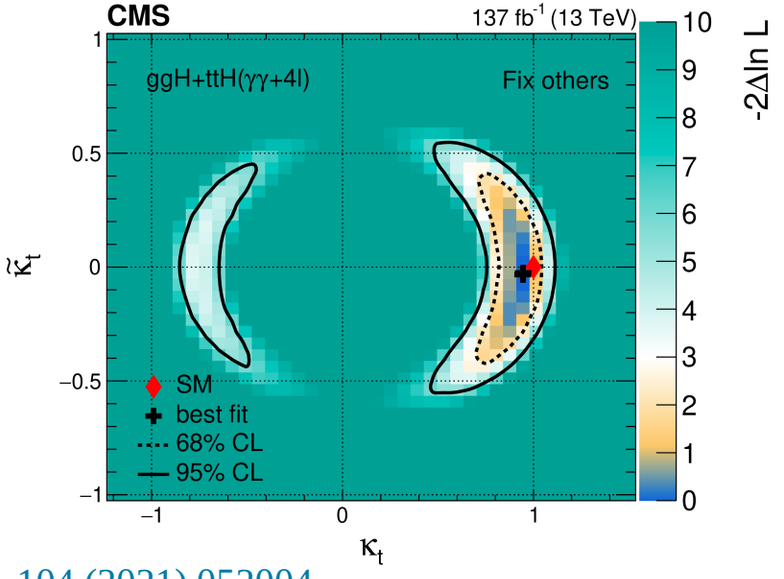
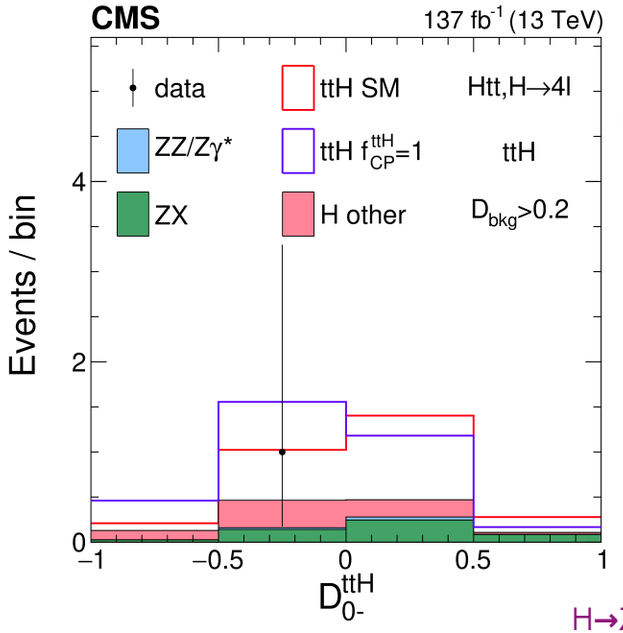




Phys. Rev. D. 104 (2021) 052004

Higgs to top quark couplings: H→ 4-lepton, γγ, ττ final states



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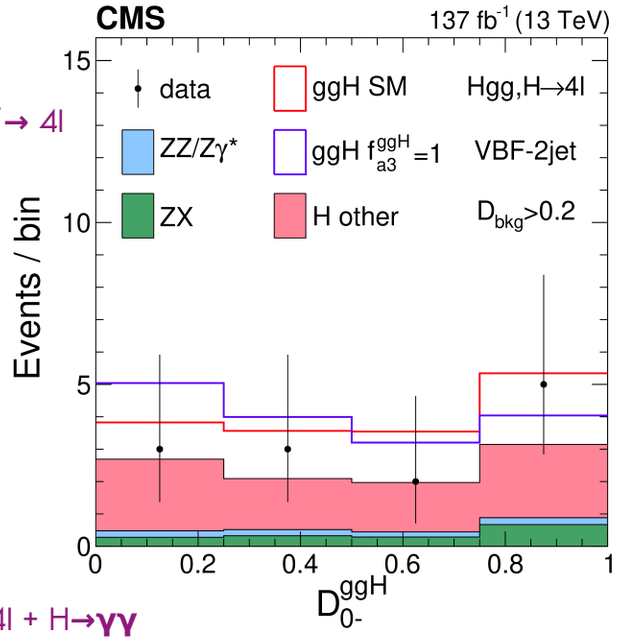
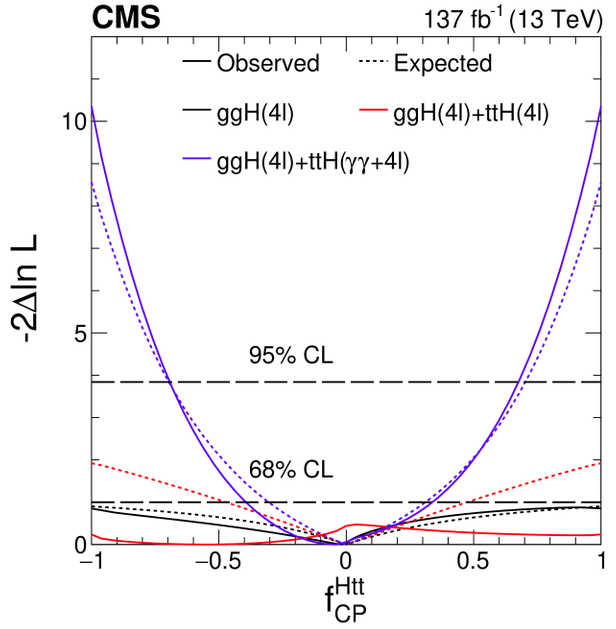
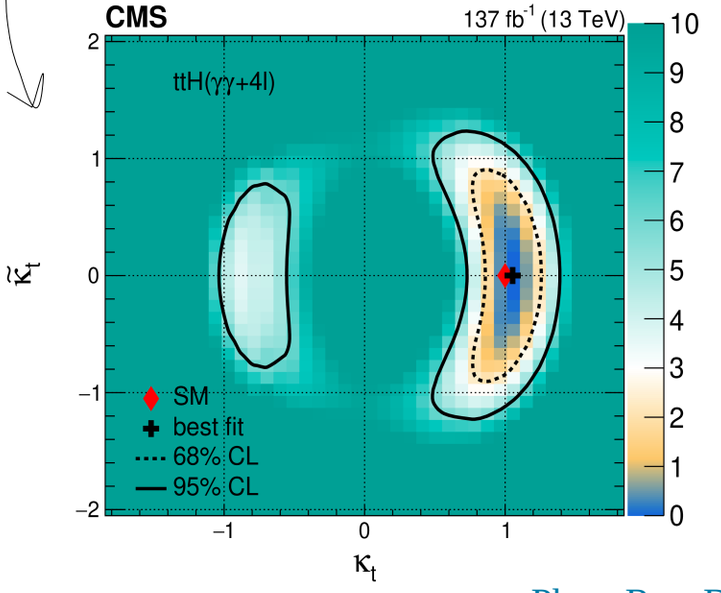
+

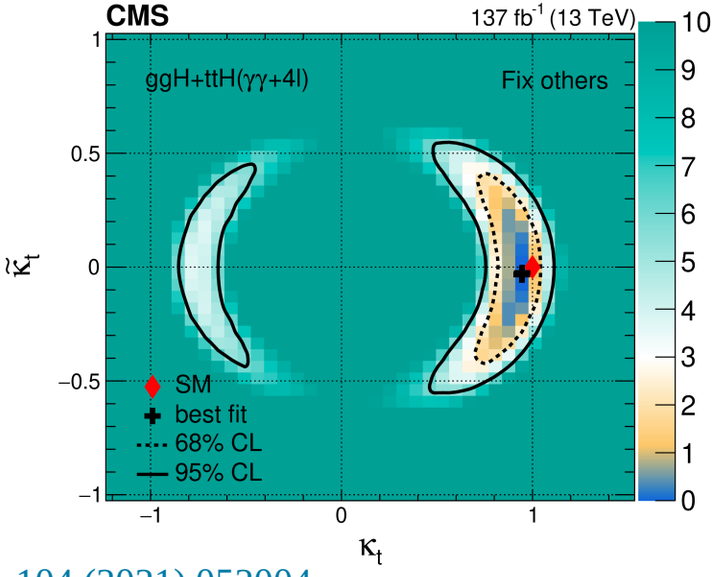


ttH & ggH categories combined to enhance sensitivity



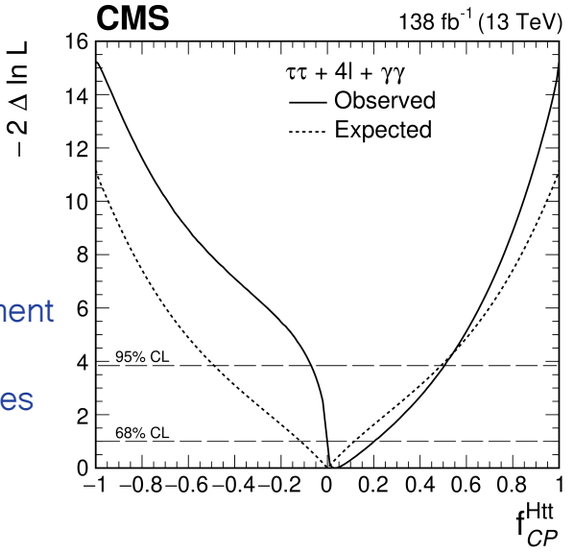
H→ZZ*→ 4l + H→γγ





-2Δln L

Significant improvement after combining three H decay modes

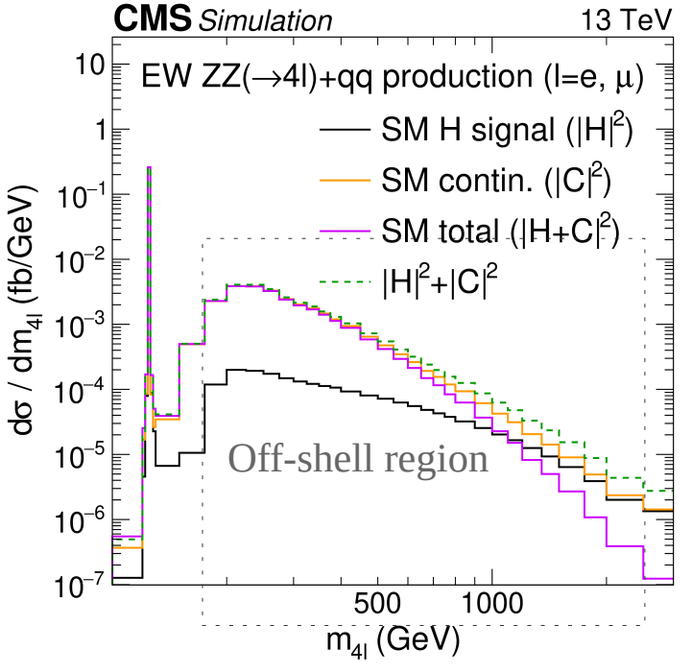


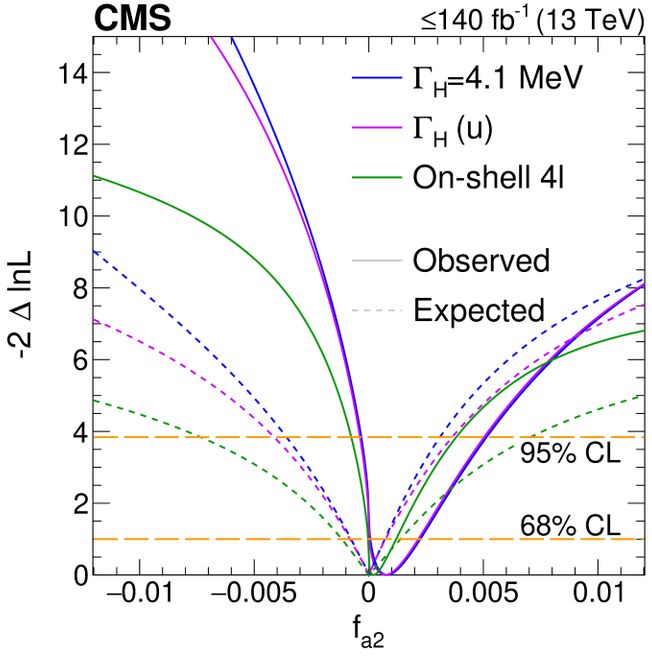
Phys. Rev. D. 104 (2021) 052004

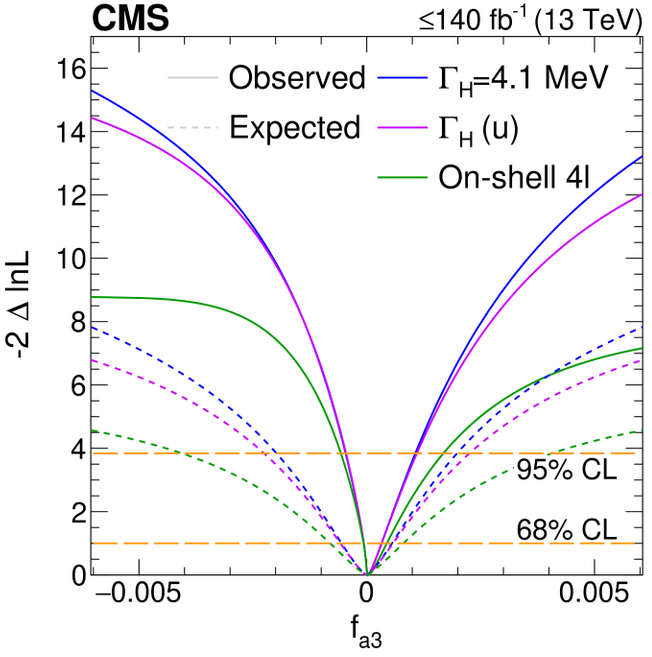
arXiv: 2205.05120

Higgs to electroweak vector boson couplings with off-shell H: H→ ZZ* → 4-lepton / 2-lepton + 2-ν final state

arXiv: 2202.06923
Submitted to Nature Physics







Evidence for off-shell Higgs production (>3σ)

Parameter ($\times 10^5$)	Scenario	b.f.	Observed 68% | 95% CL	Expected 68% | 95% CL
f_{a2}	$\Gamma_H = \Gamma_H^{SM}$	79	$[6.6, 225] \mid [-32, 514]$	$[-78, 70] \mid [-359, 311]$
	Γ_H unconst.	72	$[2.7, 216] \mid [-38, 503]$	$[-82, 73] \mid [-413, 364]$
f_{a3}	$\Gamma_H = \Gamma_H^{SM}$	2.2	$[-6.4, 32] \mid [-46, 107]$	$[-55, 55] \mid [-198, 198]$
	Γ_H unconst.	2.4	$[-6.2, 33] \mid [-46, 110]$	$[-58, 58] \mid [-225, 225]$

Roughly 10% gain in sensitivity @95% CL by adding off-shell region

CP nature of Higgs to top quark coupling: H→ WW*, ττ → Multilepton final states

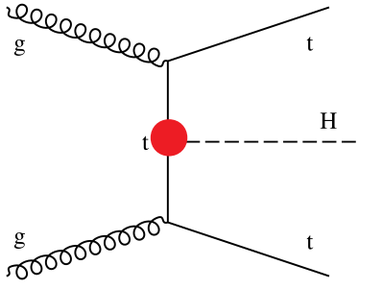
CMS-PAS-HIG-21-006

Final states considered:

2 same-sign leptons + 0 τ_h

2 same-sign leptons + 1 τ_h

3 leptons + 0 τ_h



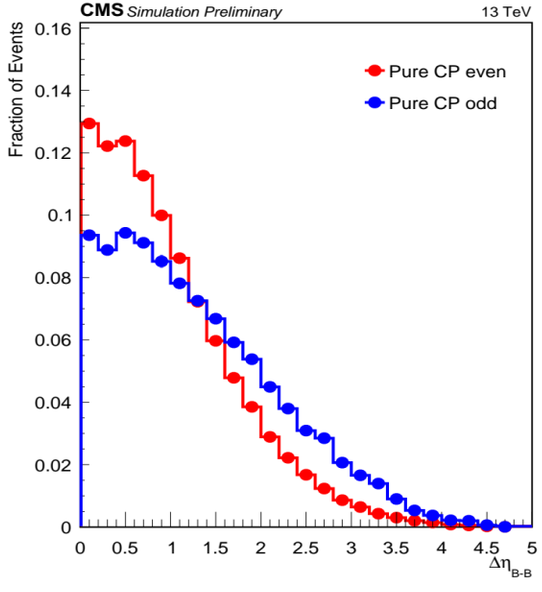
Signal-background separation:

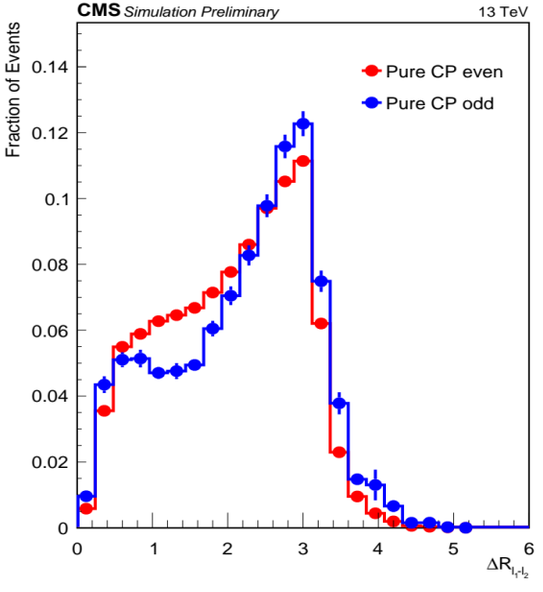
Multi-class neural network → { ttH, tHq, other, ttW (only for 2 same-sign lepton + 0 τ_h) }

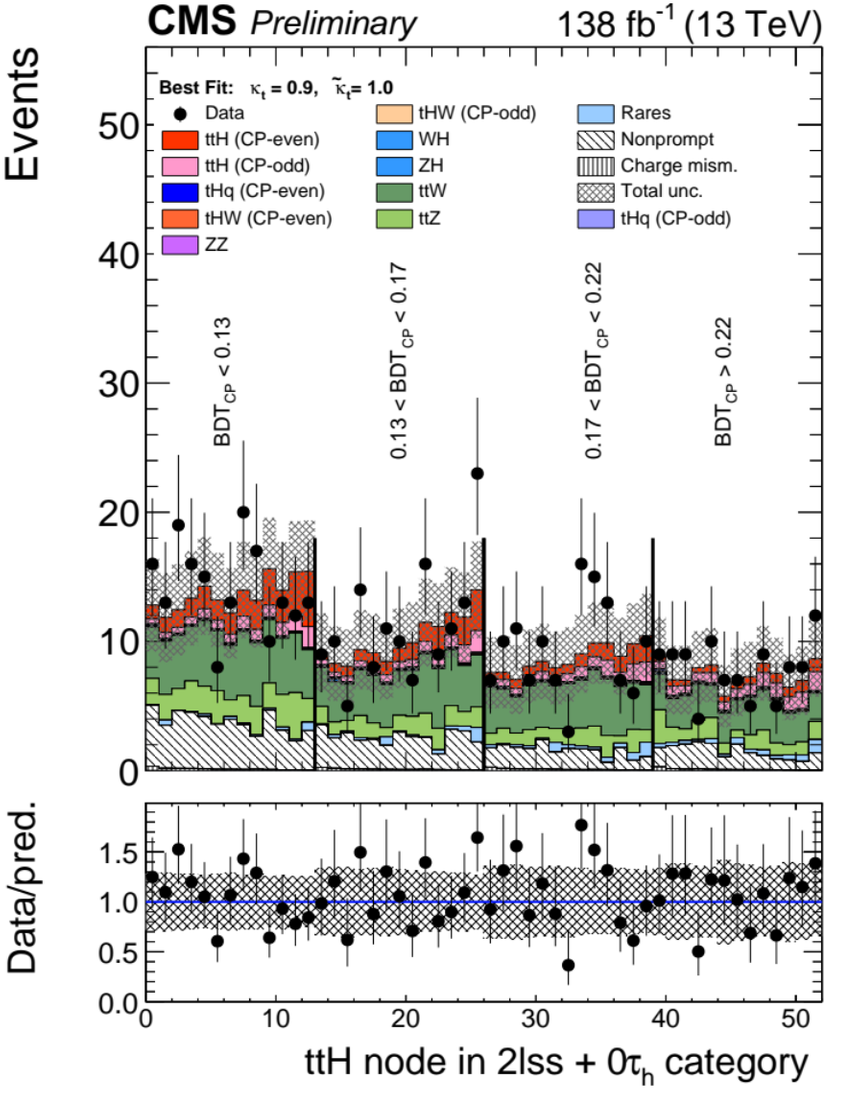
$$\mathcal{L}_{t\bar{t}H} = \frac{-y_t}{2}\bar{\psi}_t(\kappa_t + i\gamma_5\tilde{\kappa}_t)\psi_t H$$

CP separation in ttH category:

BDT using CP-sensitive variables



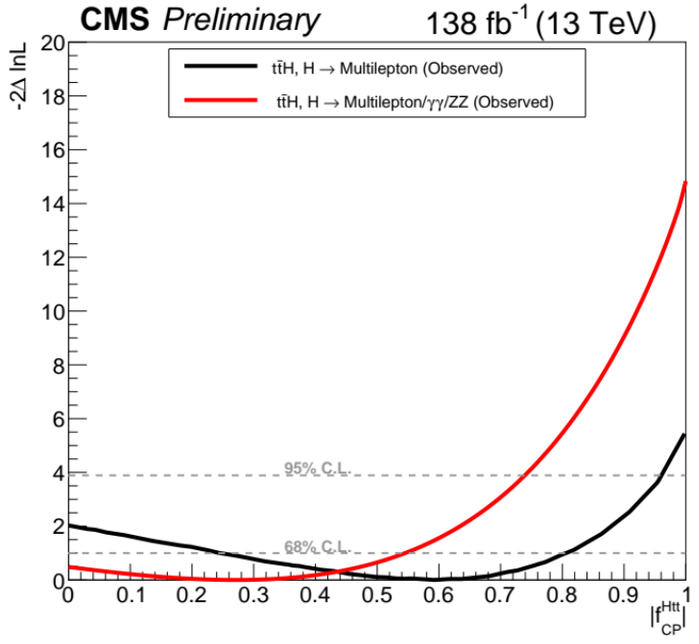


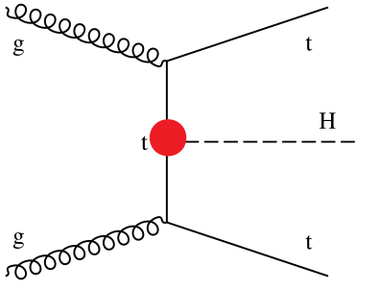


ttH score of NN →

CP nature of Higgs to top quark coupling

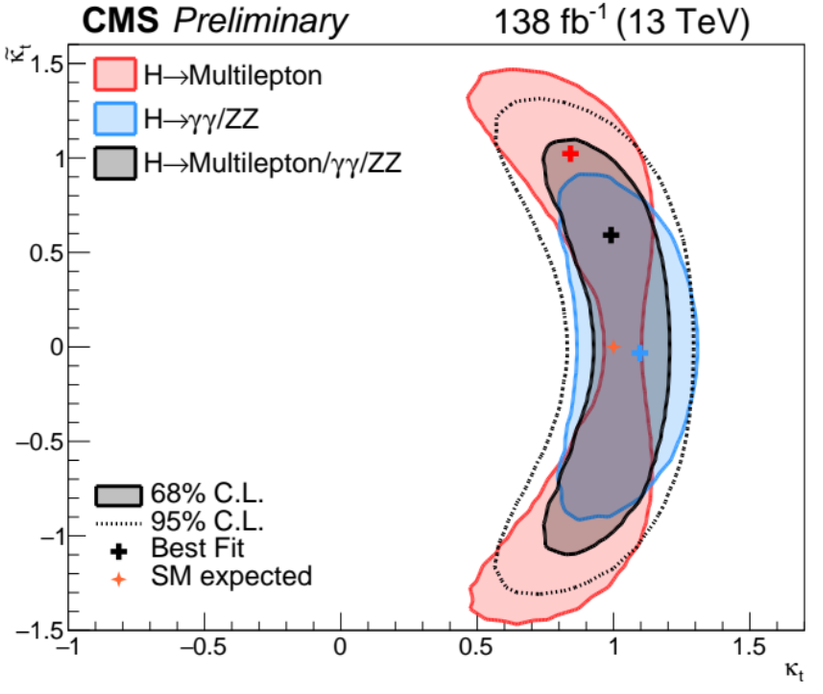
CMS-PAS-HIG-21-006





$$\mathcal{L}_{t\bar{t}H} = \frac{-y_t}{2}\bar{\psi}_t(\kappa_t + i\gamma_5\tilde{\kappa}_t)\psi_t H$$

$$|\tilde{\kappa}_t|^2 / (|\kappa_t|^2 + |\tilde{\kappa}_t|^2)$$



Results from ttH ($\rightarrow \tau\tau$) combined with ttH ($\rightarrow \gamma\gamma$) & ttH ($\rightarrow ZZ^* \rightarrow 4l$)

κ_t : [0.96, 1.16] at 68% CL

$\tilde{\kappa}_t$: [-0.86, 0.85] at 68% CL

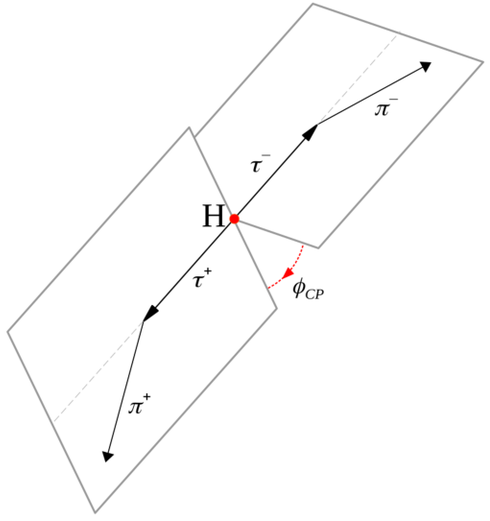
CP-odd fraction

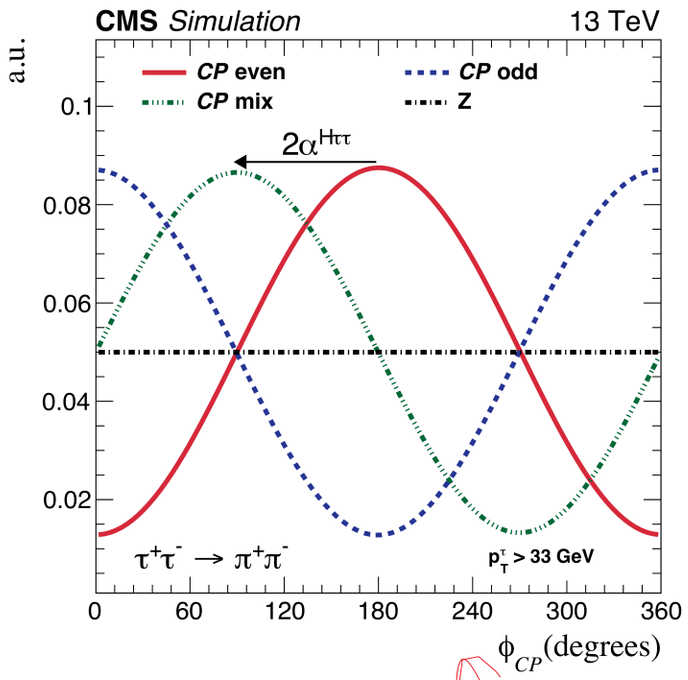
= 0.28 ([-0.55, +0.55] at 68% CL)

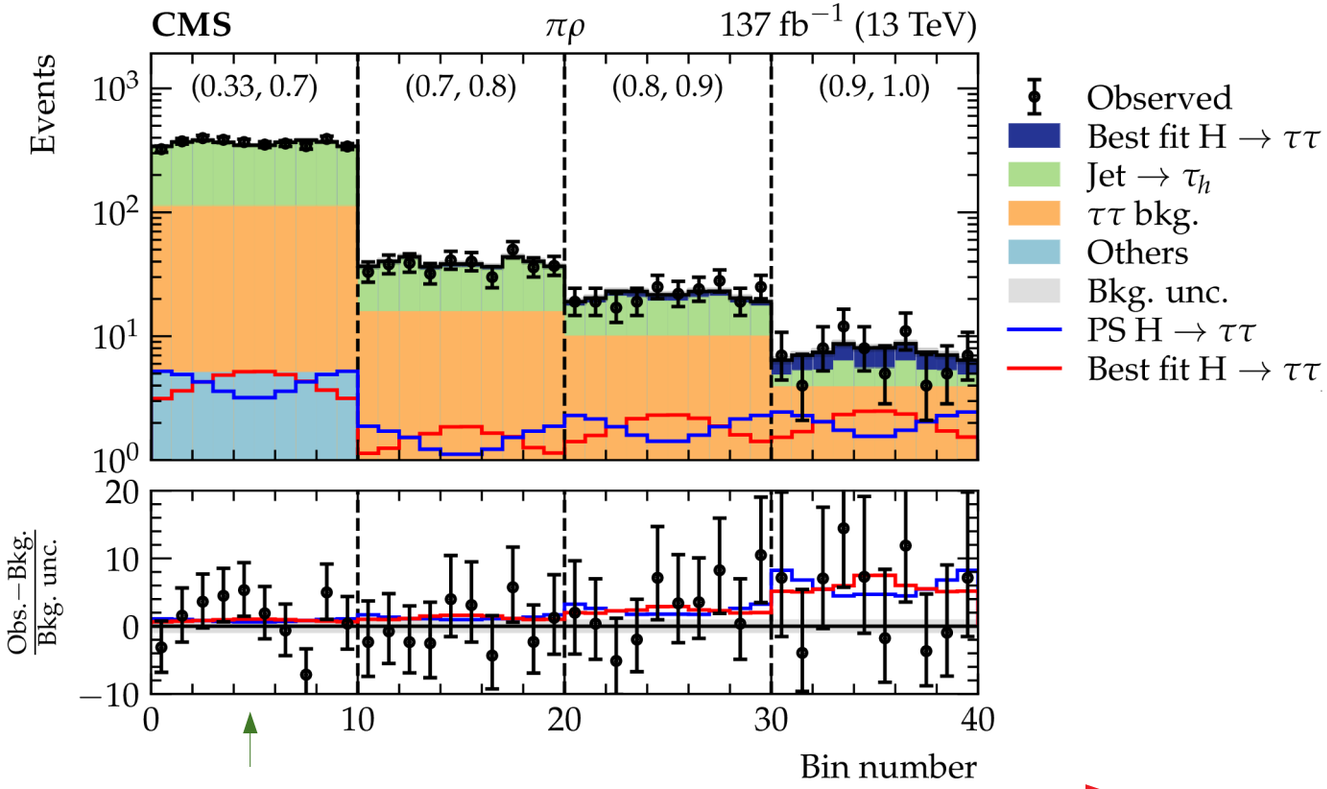
Pure CP-odd hypothesis excluded at 3.7σ

Search for CP violation in H→ ττ decay

JHEP 06 (2022) 012







Bins in ϕ_{CP}: [0, 2Π]

Neural network score

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

$$\tan(\alpha^{H\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$

$$\frac{d\Gamma}{d\phi_{CP}}(H \to \tau^+\tau^-) \sim 1 - b(E^+)b(E^-)\frac{\pi^2}{16}\cos(\phi_{CP} - 2\alpha^{H\tau\tau})$$

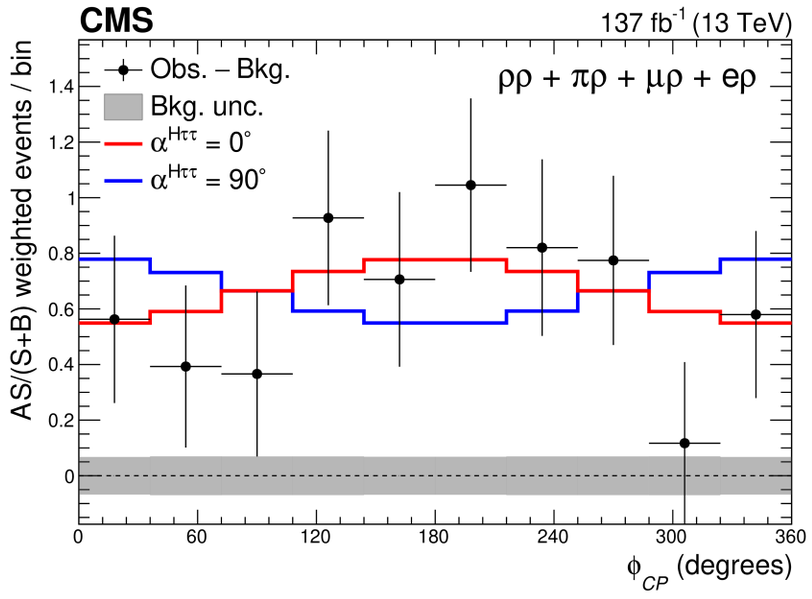
Final states considered:

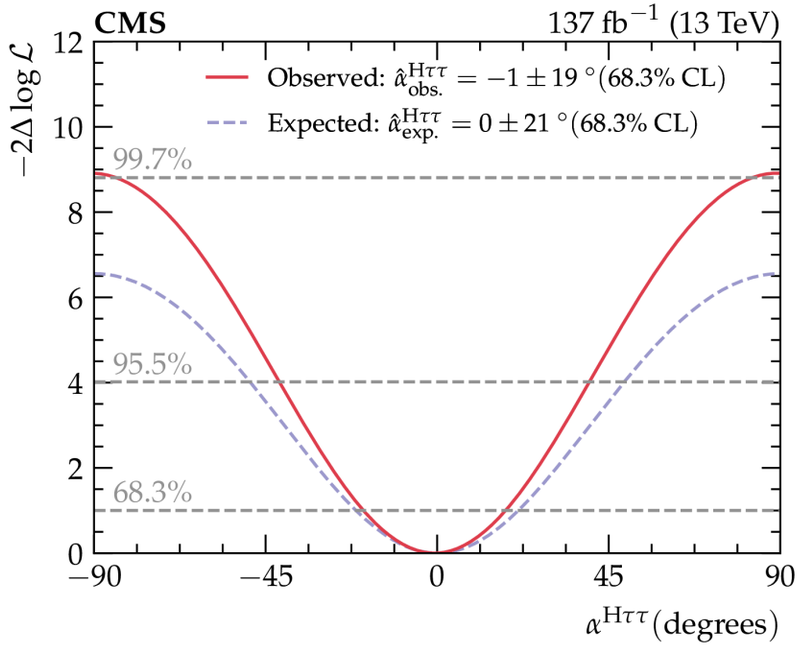
$e\tau_h + \mu\tau_h + \tau_h\tau_h$

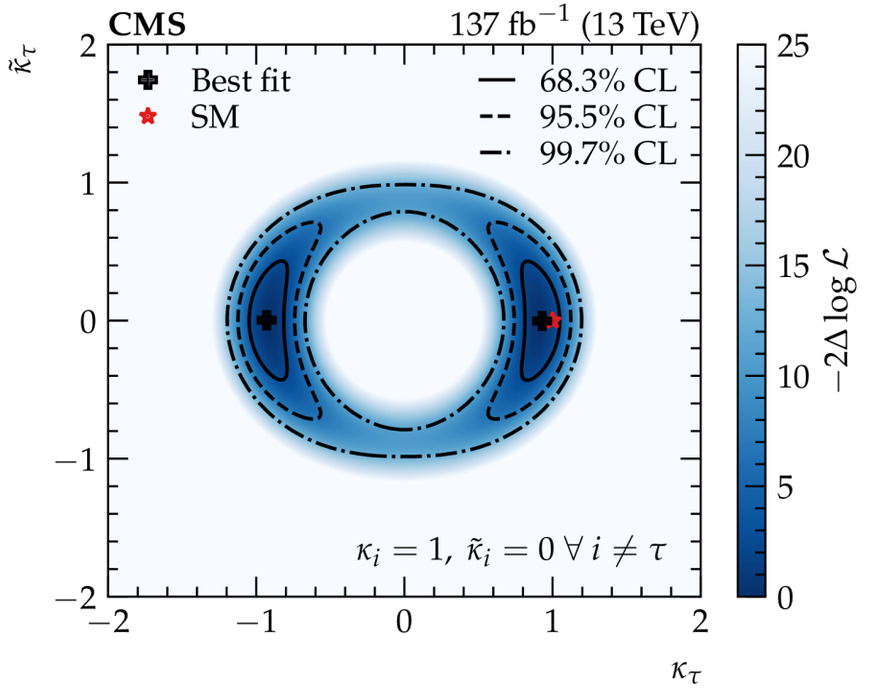
- Signal to background separation using neural network
- > 90% of background contribution estimated using data

Search for CP violation in H→ ττ decay

JHEP 06 (2022) 012







$$\alpha^{H\tau\tau} = -1 \pm 19\,(\text{stat}) \pm 1\,(\text{syst}) \pm 2\,(\text{bin-by-bin}) \pm 1\,(\text{theo})^{\circ}$$

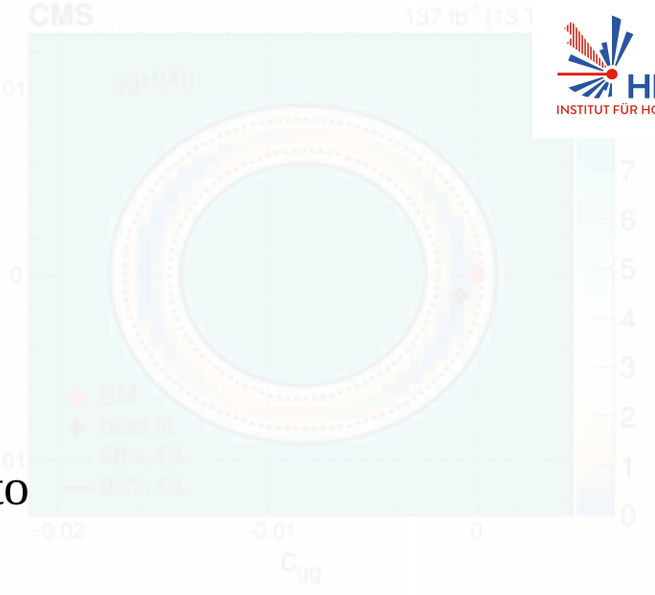
Only sensitive to relative sign between κ_τ and $\tilde{\kappa}_\tau$

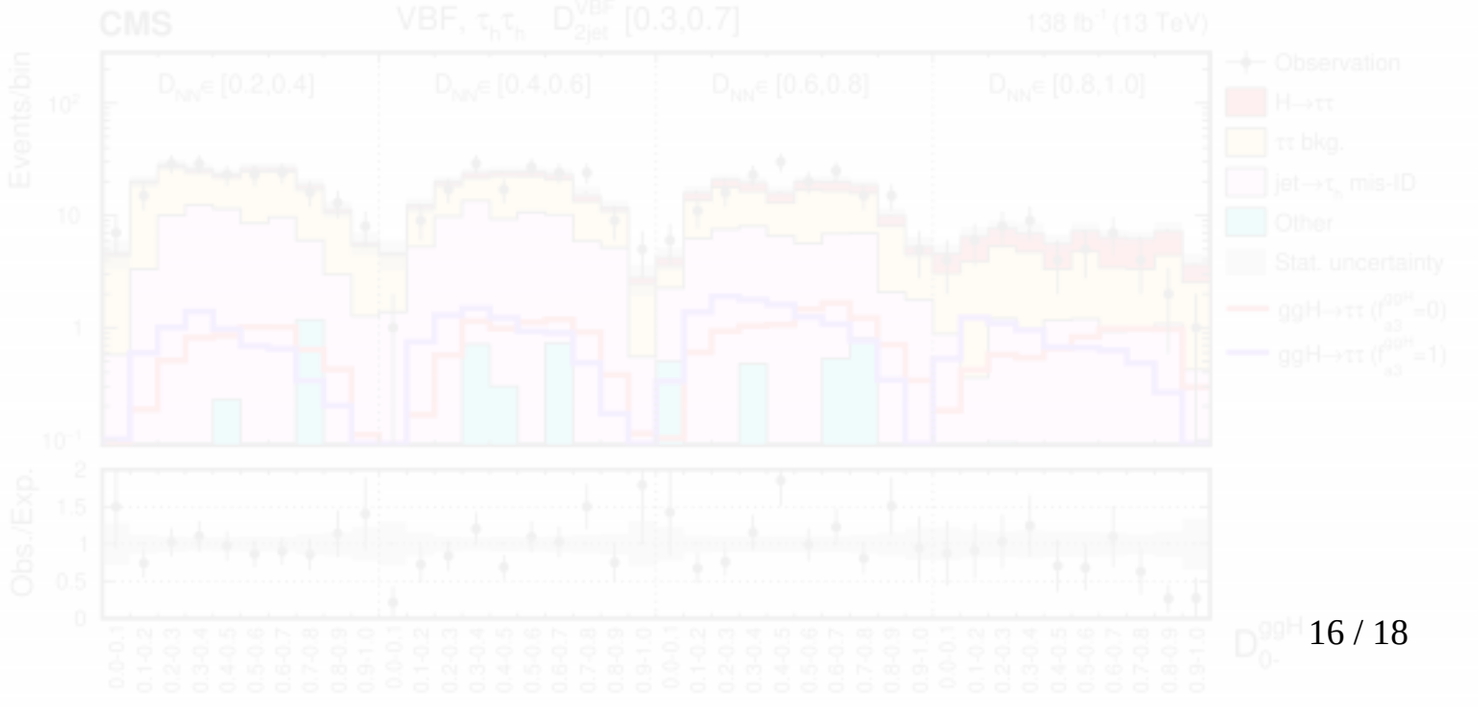
Pure CP-odd hypothesis excluded at 3σ

Summary & Outlook

- Precision measurement of Higgs boson properties ongoing
- Probing Higgs boson couplings test possible new physics scenarios
- Presented recent CMS results on search for anomalous coupling of Higgs boson to
  - $W^{\pm}$ and Z bosons, gluon
  - Top quark, τ lepton
  - Including possible source of CP violation

Full list of public results from CMS on Higgs boson measurement: Link





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More Run-2 results to appear

Looking forward to Run-3

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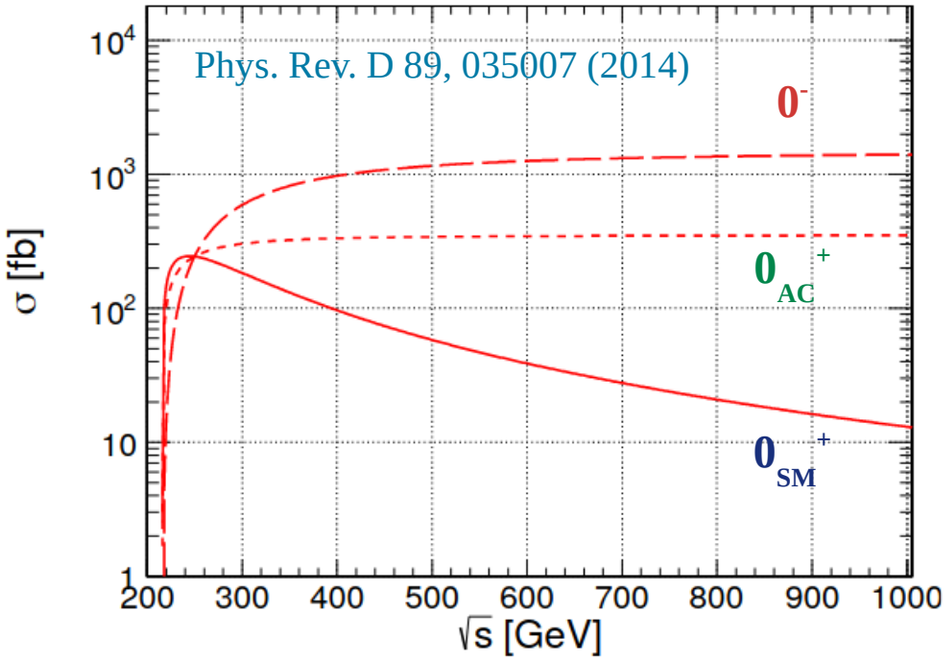
Looking forward to Run-3

Extra Material

Higgs to vector boson couplings: Need for high energy



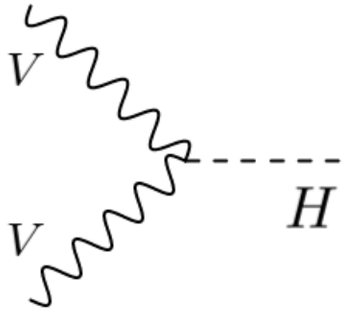
Anomalous couplings contribute at higher order / loop in cross section

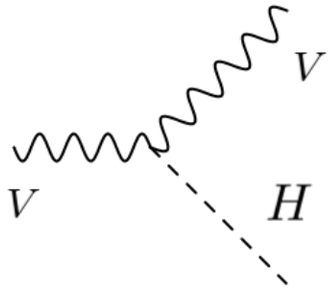
→ Suppression of effects

← Experimentally challenging

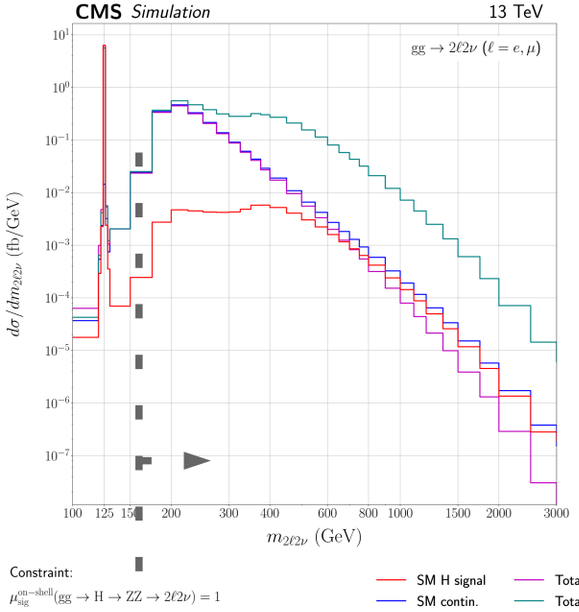
BSM contribution increases with energy → sensitivity enhancement

Use VBF & VH production modes with high energy transfer





Use off-shell region



CMS-PAS-HIG-21-013