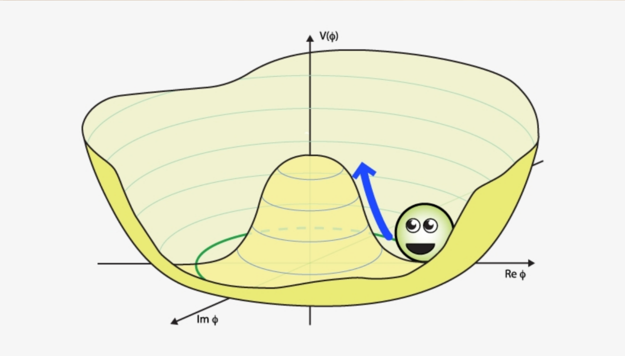
Effective field theory results from Higgs and top sector in CMS experiment

Suman Chatterjee

for the CMS Collaboration

HEPHY Vienna

13/12/2022



DAE-BRNS HEP symposium

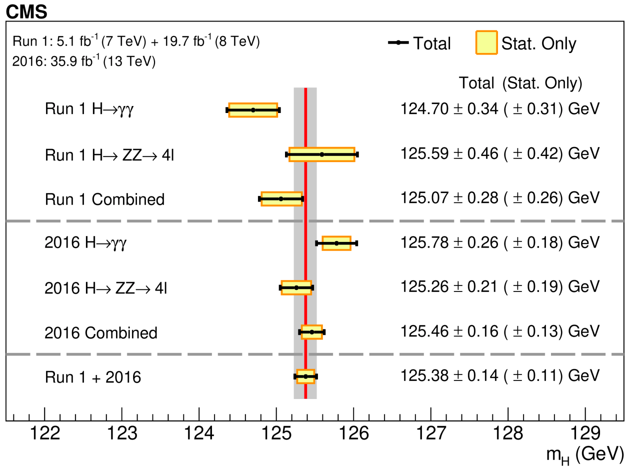
IISER Mohali, India

Higgs boson & top quark

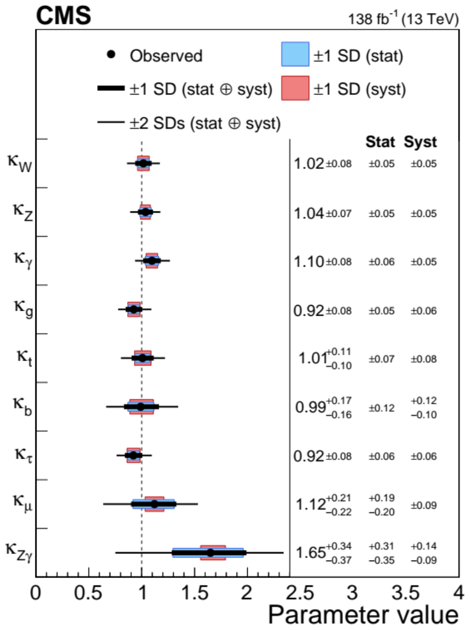
Discovered by ATLAS & CMS

Newest fundamental particle discovered

Detailed measurements using LHC Run 1 + Run 2 data



Phys. Lett. B 805 (2020) 135425



Nature 607 (2022) 60-68

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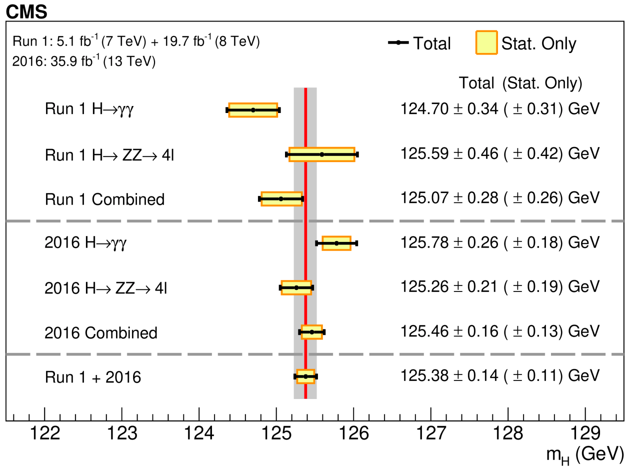

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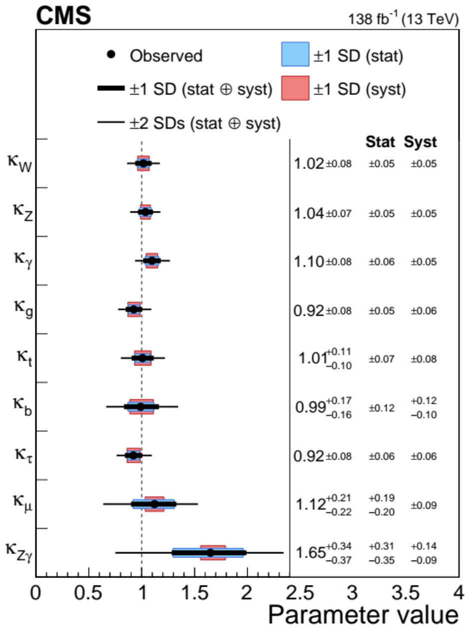

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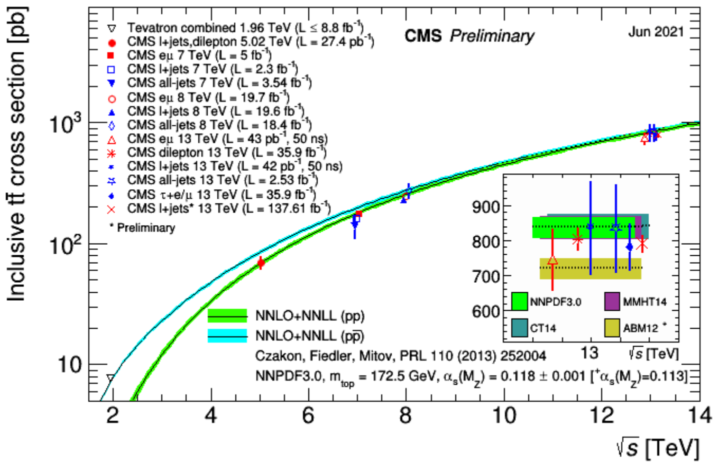
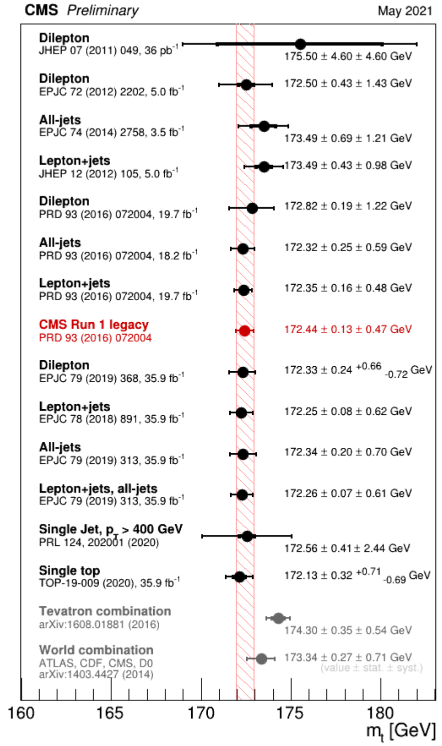


CMS Top quark summary results



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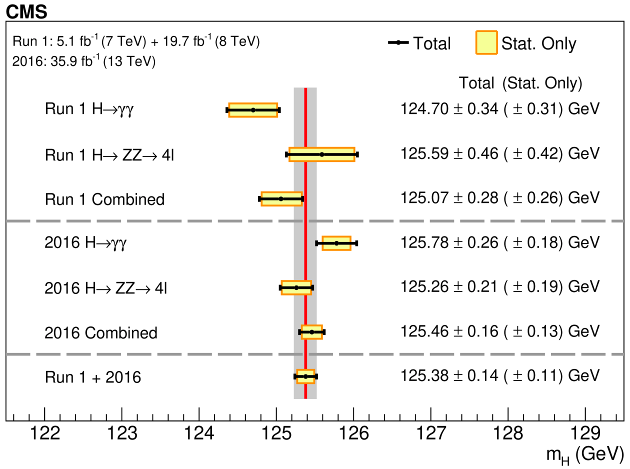

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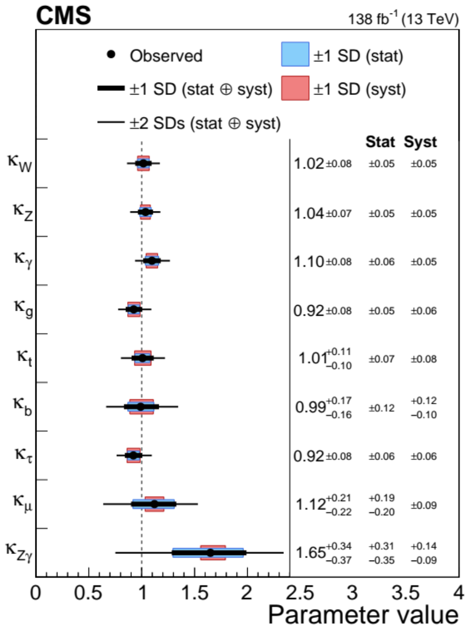

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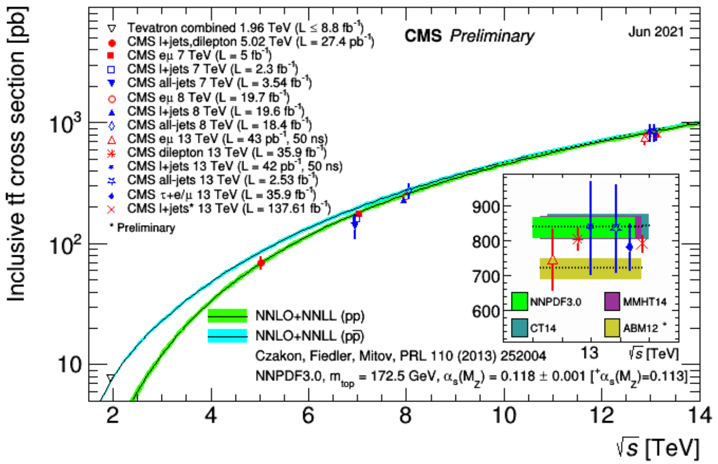

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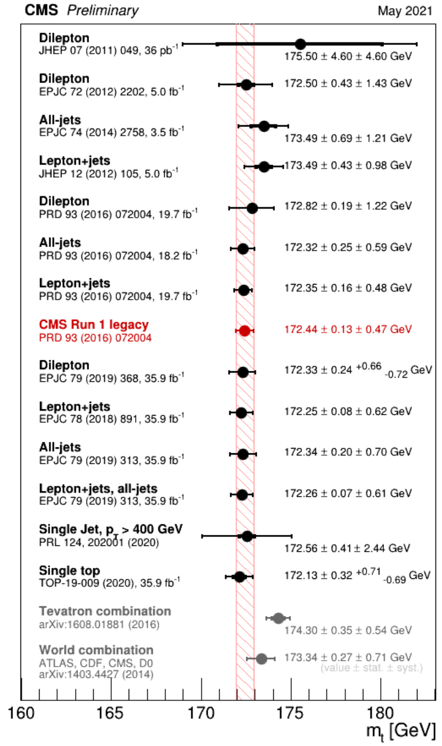


Higgs / top couplings to fermions and Gauge bosons

← Precisely known in SM

← Look for deviations from SM predictions

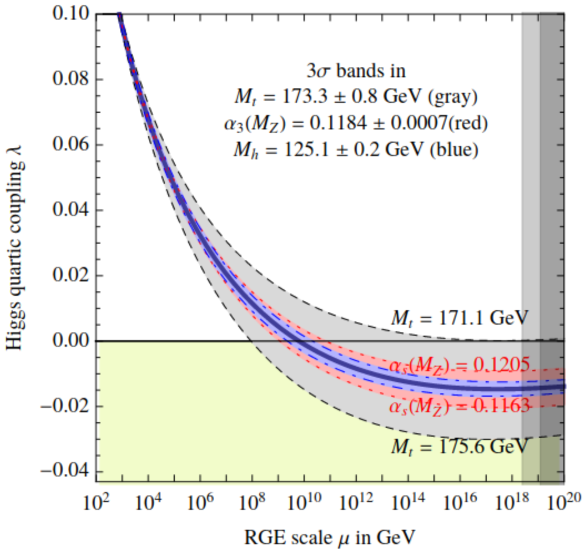
→ If found, signature of new physics

Top-Higgs connection

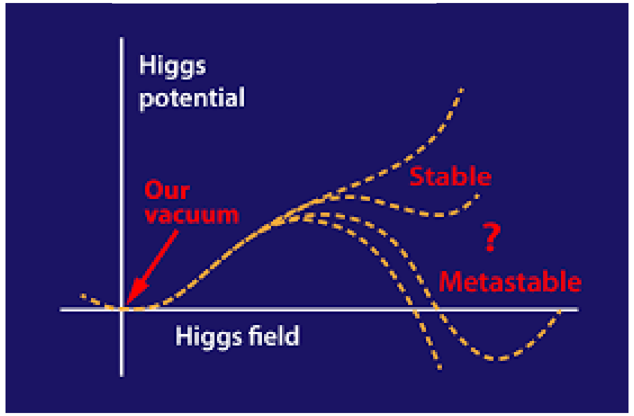
Vacuum stability influenced by top quark mass

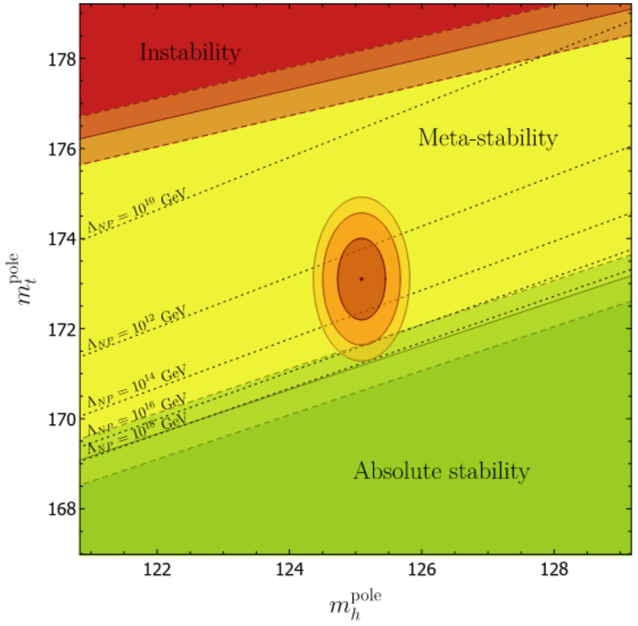
$$V(\phi) = -m^2\phi^2 + \lambda\phi^4$$

$$\mu\frac{d\lambda_i}{d\mu} = \beta_{\lambda_i}(\lambda_j)$$



Buttazzo et al. (2013)





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See Rick S. Gupta's talk for details about effective field theory (EFT)

$$V(\phi) = -m^2\phi^2 + \lambda\phi^4$$

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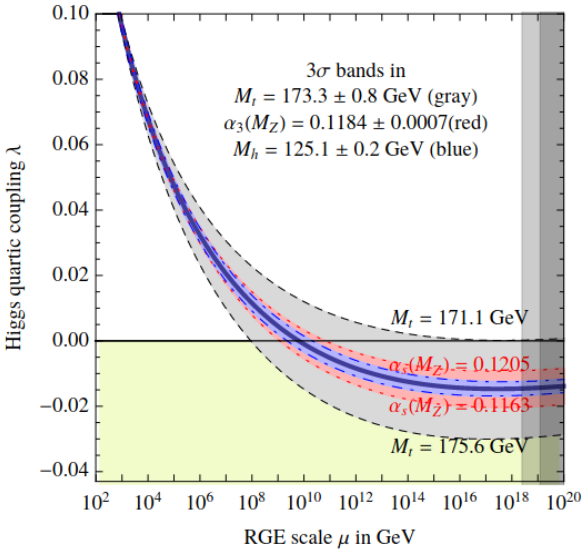
Many top & Higgs processes coupled by EFT operators



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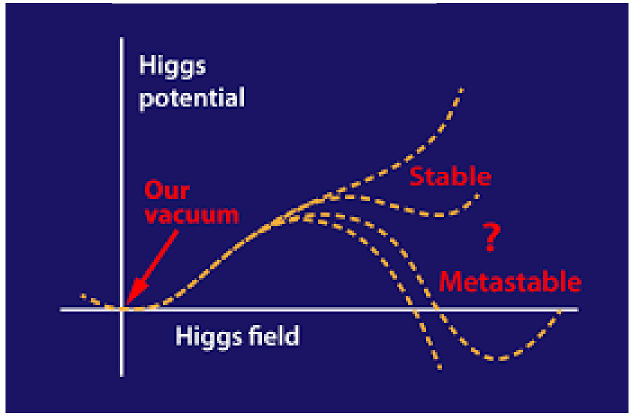
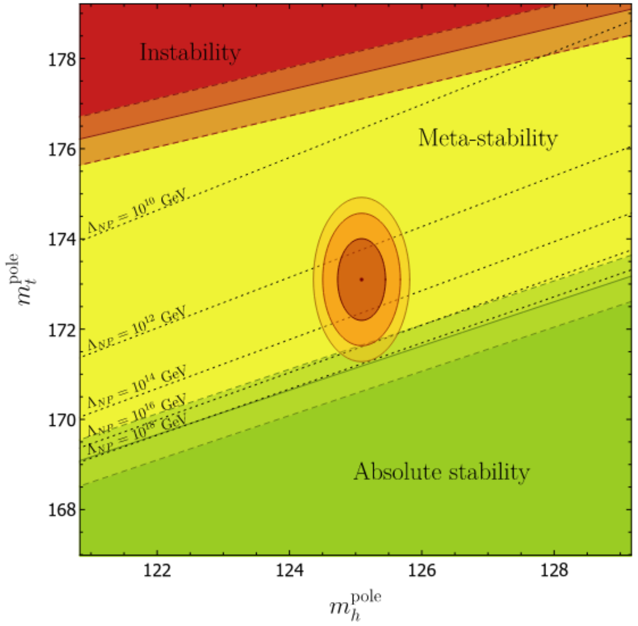
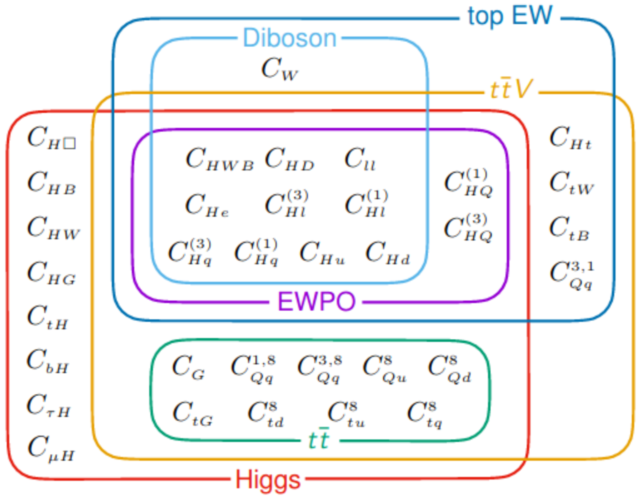






top EW

Diboson

C_W

$t\bar{t}V$

$C_{H\Box}$ C_{HB} C_{HW} C_{HG} C_{tH} C_{bH} $C_{\tau H}$ $C_{\mu H}$

C_{HWB} C_{HD} C_{ll}

C_{He} $C_{Hl}^{(3)}$ $C_{Hl}^{(1)}$

$C_{Hq}^{(3)}$ $C_{Hq}^{(1)}$ C_{Hu} C_{Hd}

EWPO

$C_{HQ}^{(1)}$ $C_{HQ}^{(3)}$

C_{Ht} C_{tW} C_{tB} $C_{Qq}^{3,1}$

C_G $C_{Qq}^{1,8}$ $C_{Qq}^{3,8}$ C_{Qu}^{8} C_{Qd}^{8}

C_{tG} C_{td}^{8} C_{tu}^{8} C_{tq}^{8}

$t\bar{t}$

Higgs

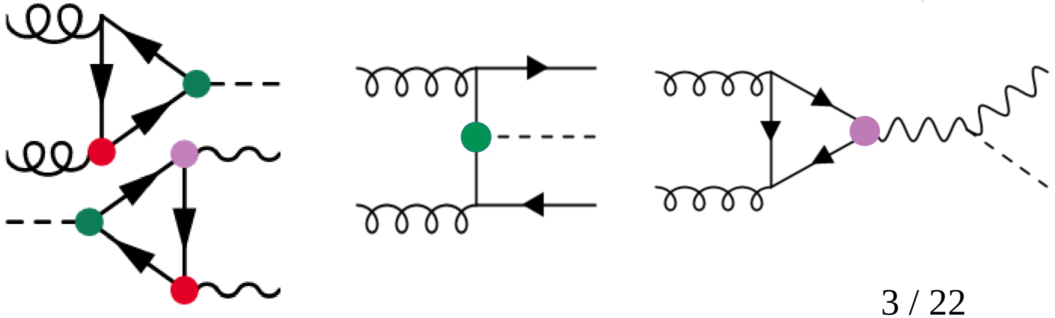
$$\mathcal{O}_{tG} = (\bar{Q}\sigma^{\mu\nu}T^a t)\tilde{H}G^a_{\mu\nu}$$

$$\mathcal{O}_{tH} = (H^\dagger H)\bar{Q}\tilde{H}t$$

$$\mathcal{O}_{HQ}^{(3)} = iH^\dagger\sigma^a\overleftrightarrow{D}_\mu H\bar{Q}\sigma^a\gamma^\mu Q$$

$$\mathcal{O}_{HQ}^{(1)} = iH^\dagger\overleftrightarrow{D}_\mu H\bar{Q}\gamma^\mu Q$$

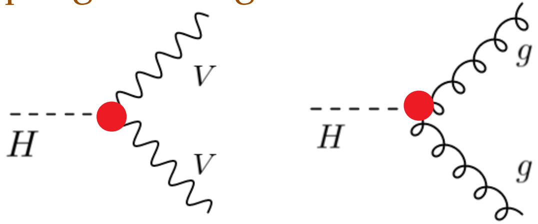
$$\mathcal{O}_{Ht} = iH^\dagger\overleftrightarrow{D}_\mu H\bar{t}\gamma^\mu t$$



+ ...

Anomalous couplings of Higgs boson

Higgs coupling to Gauge bosons

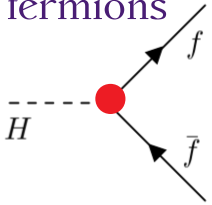


$$\mathcal{A}(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V}1}^2 \epsilon_{\mathrm{V}1}^* \epsilon_{\mathrm{V}2}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}}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

Experimentally probed by measuring cross section fractions

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

Higgs coupling to fermions

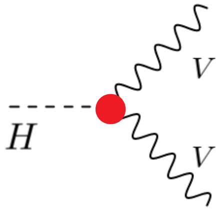


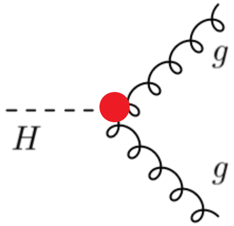
$$\mathcal{A}(\mathrm{Hff}) = -\frac{m_f}{v} \bar{\psi}_{\mathrm{f}} \left(\kappa_{\mathrm{f}} + \mathrm{i}\,\tilde{\kappa}_{\mathrm{f}} \gamma_5\right) \psi_{\mathrm{f}}$$

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

Anomalous couplings of Higgs boson

Higgs coupling to Gauge bosons





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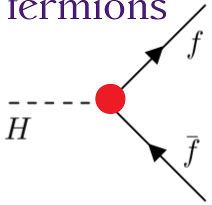

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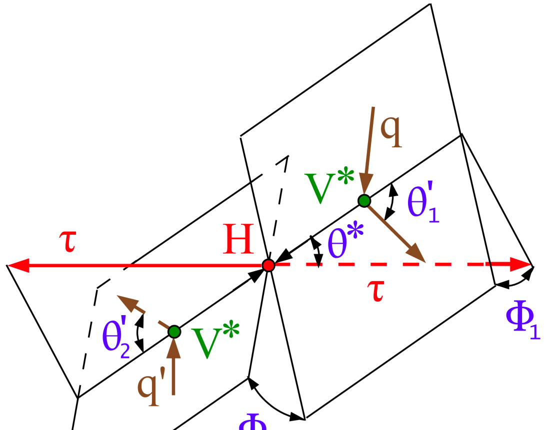


Example topology:
VBF H production + H→ ττ decay

Difficulty: Performing an optimal multi-dimensional measurement with many independent variables

Matrix element likelihood approach (MELA)

→ Construct discriminants sensitive to individual anomalous couplings

Two kinds of MELA observables:

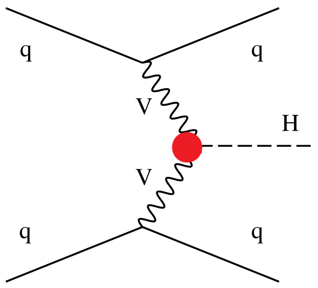
$$\mathcal{D}_{\mathrm{BSM}} = \frac{\mathcal{P}_{\mathrm{SM}}(\vec{\Omega})}{\mathcal{P}_{\mathrm{SM}}(\vec{\Omega}) + \mathcal{P}_{\mathrm{BSM}}(\vec{\Omega})} \qquad \mathcal{D}_{\mathrm{int}} = \frac{\mathcal{P}^{\mathrm{int}}_{\mathrm{SM-BSM}}(\vec{\Omega})}{\mathcal{P}_{\mathrm{SM}}(\vec{\Omega})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

Pure BSM

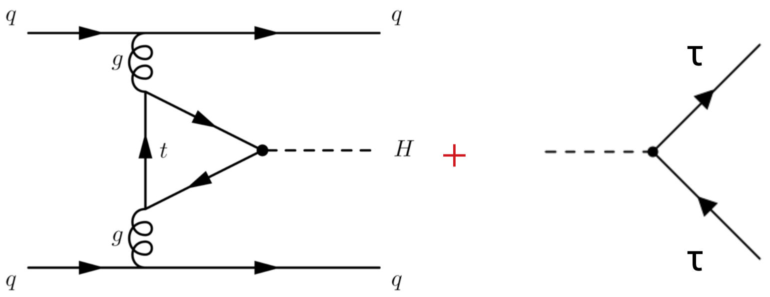
SM-BSM interference

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

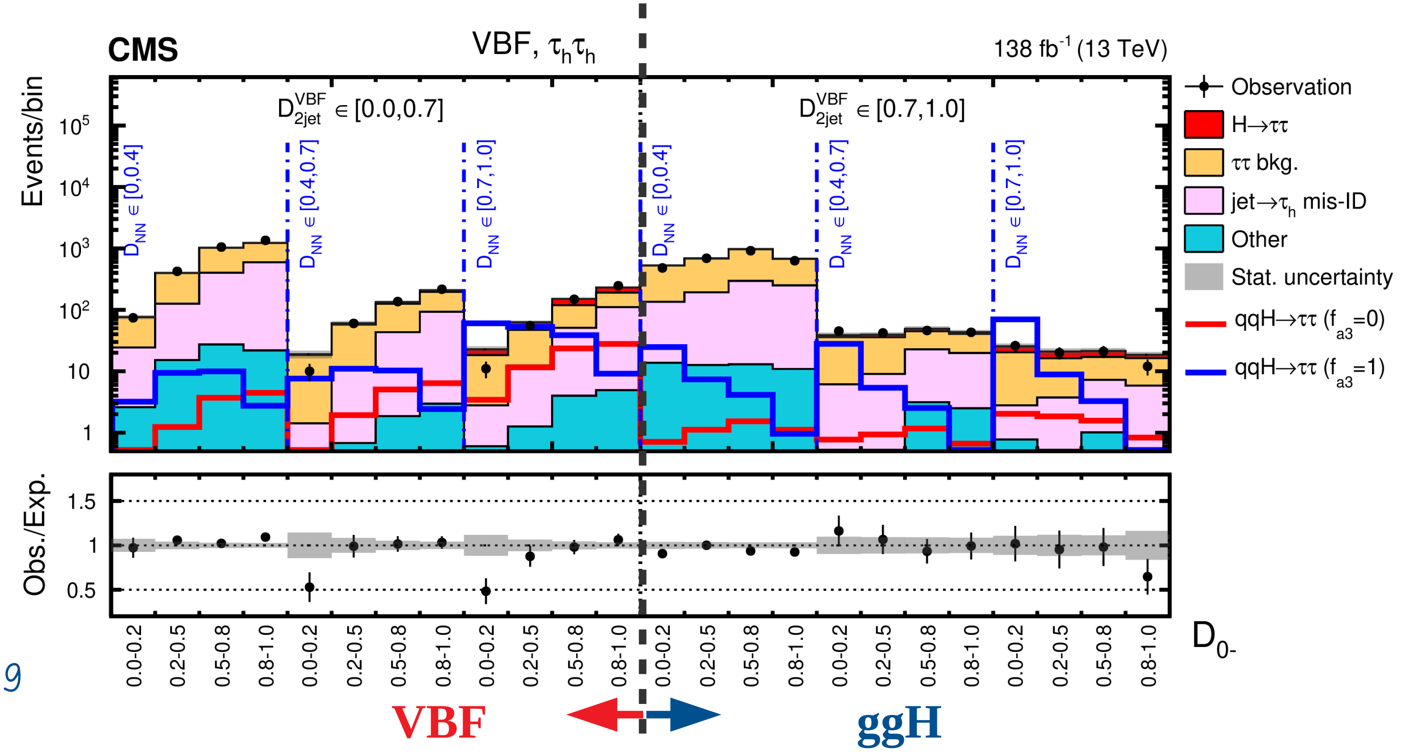
arXiv: 2205.05120



Targeted signal



Background



Final states considered:

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

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

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

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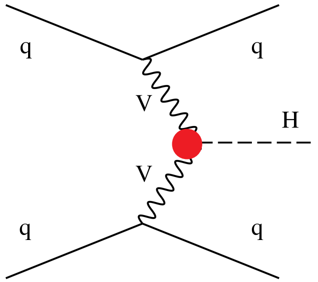

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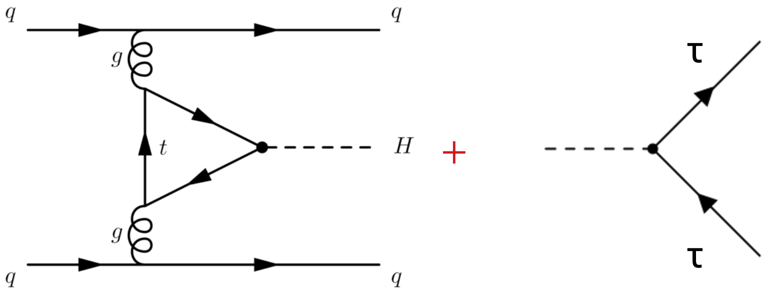

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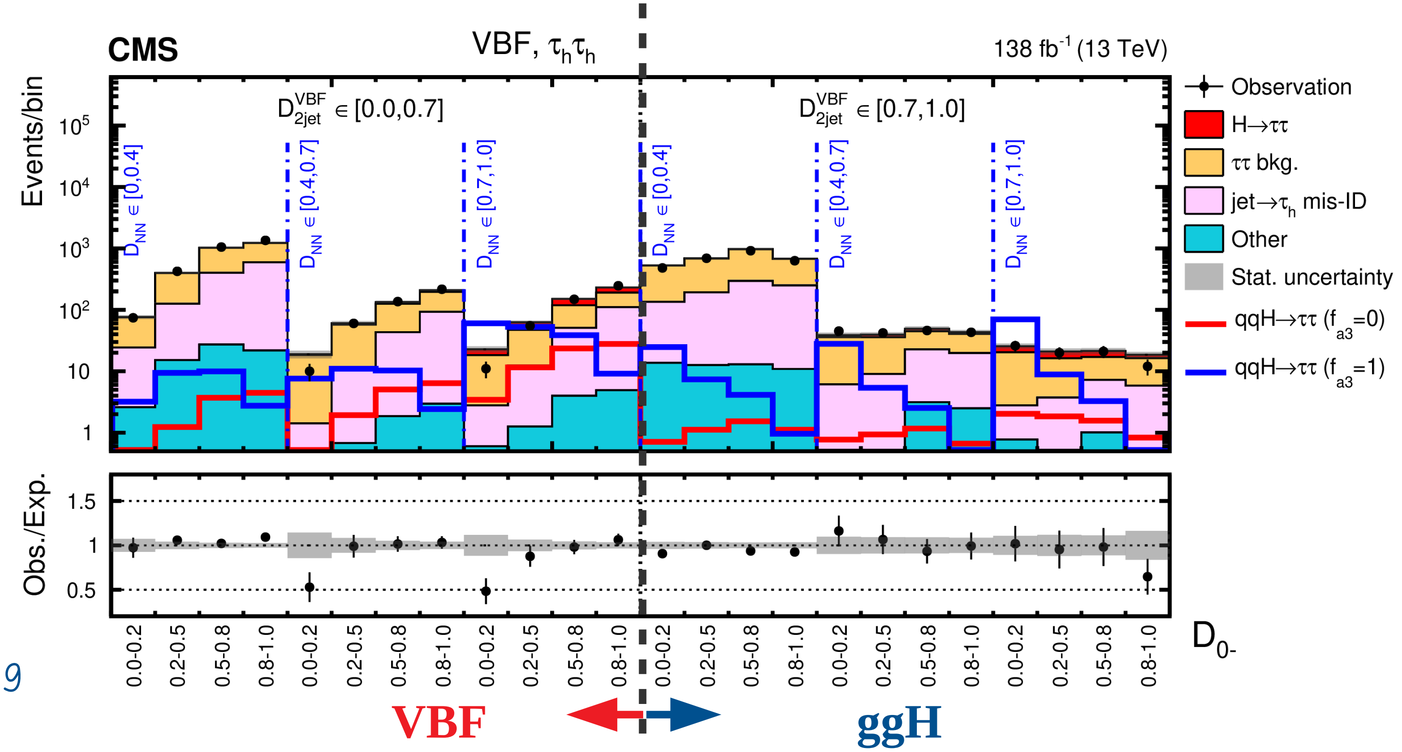

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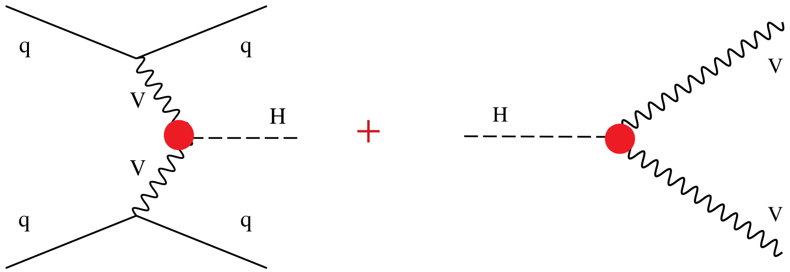
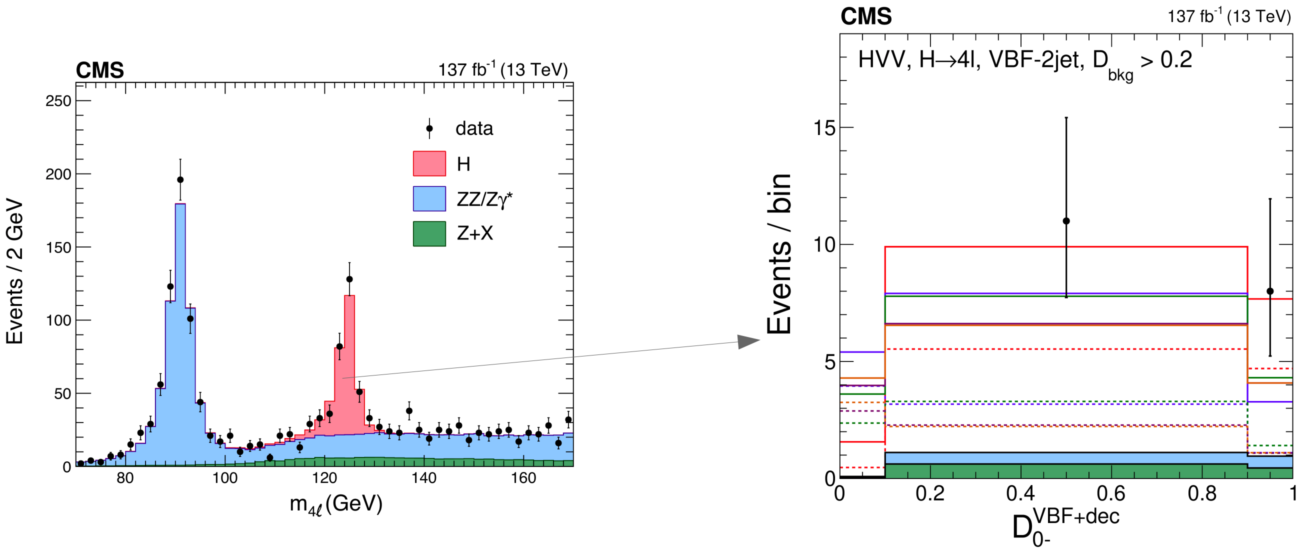
Phys. Rev. D. 104 (2021) 052004



Final states considered:

$4e + 4\mu$



Higgs to electroweak vector boson couplings

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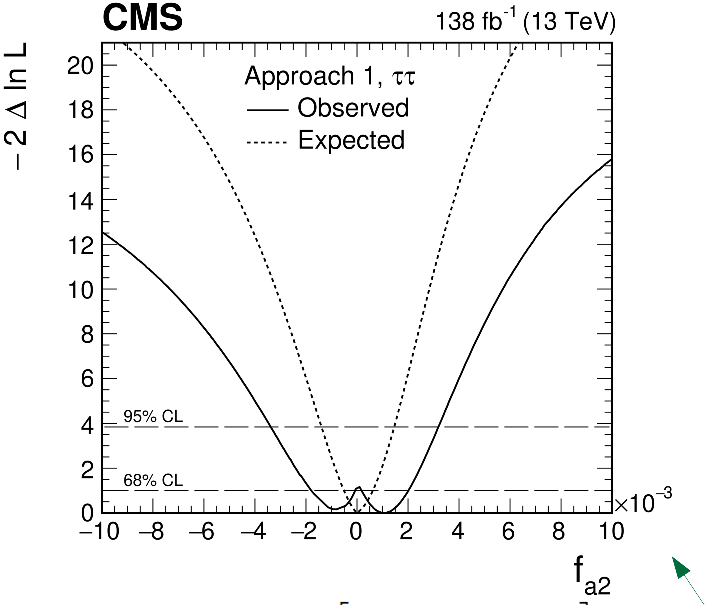

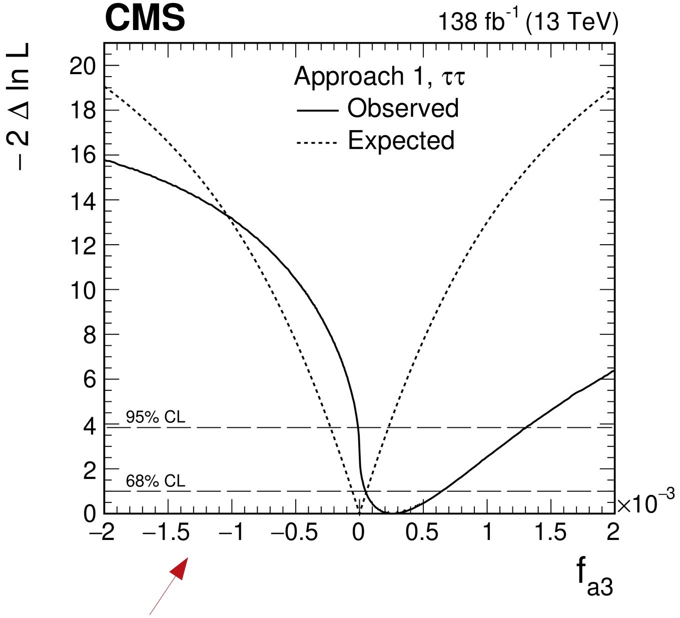

$H \rightarrow \tau\tau$ only

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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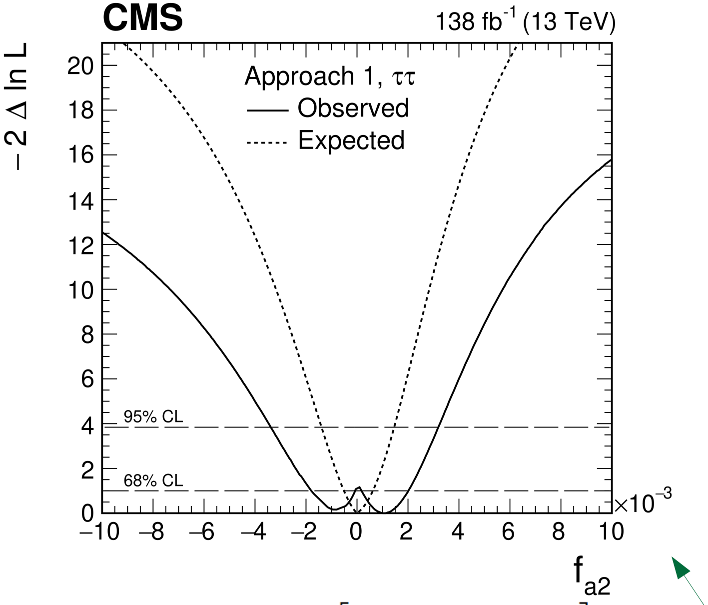

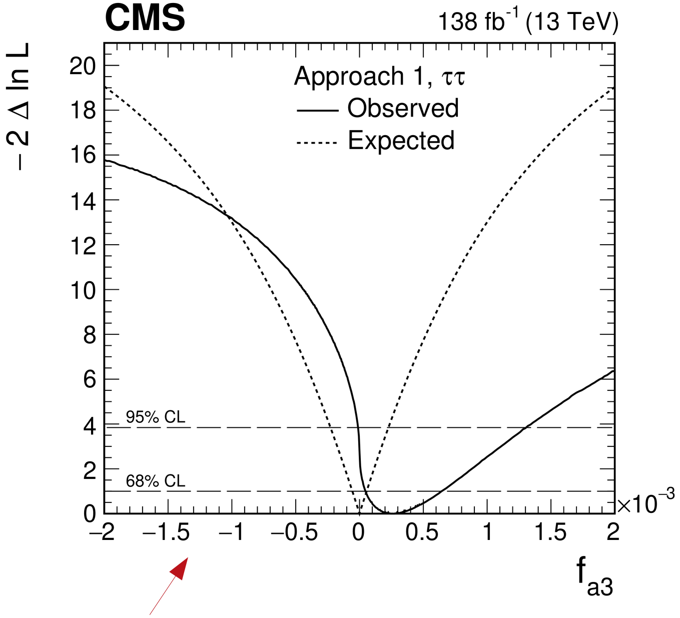

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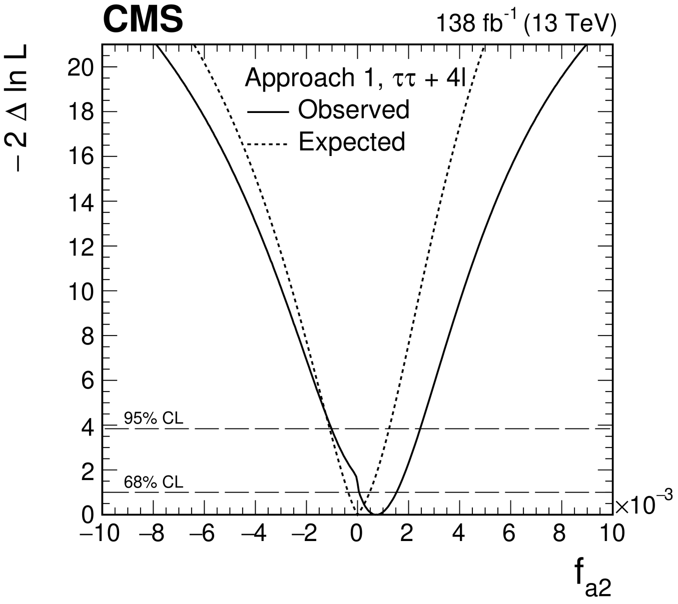

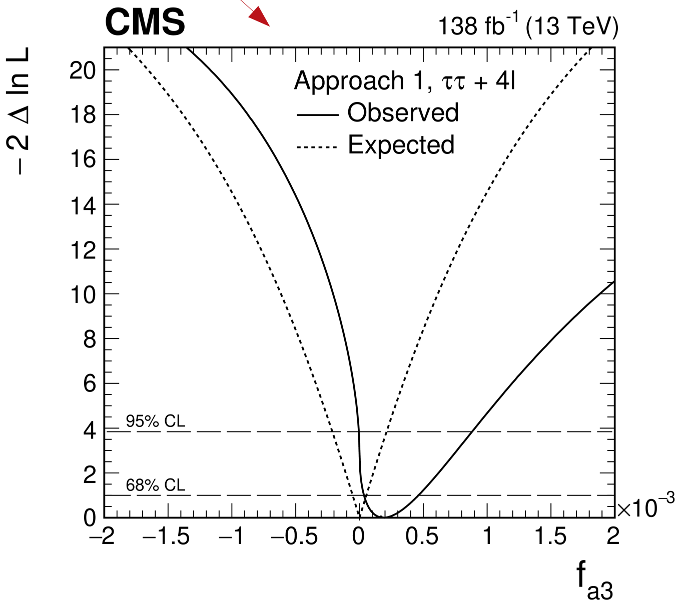

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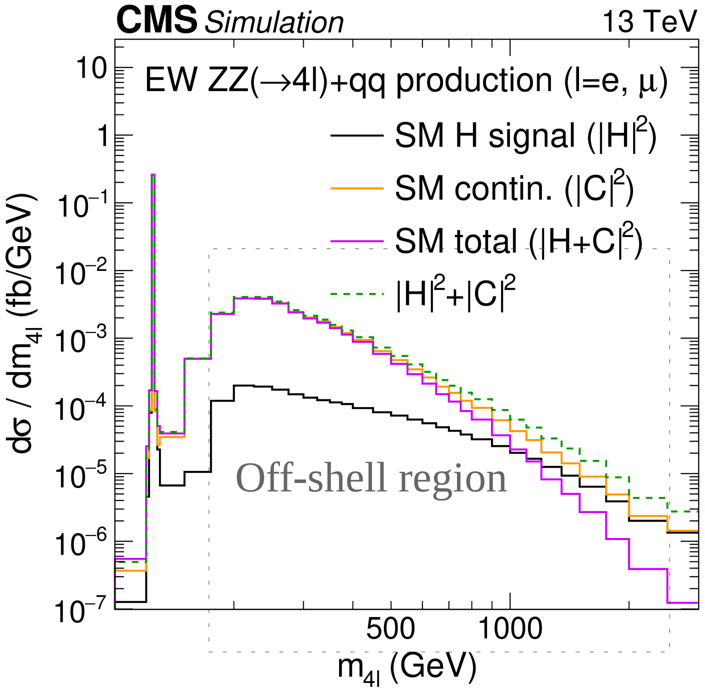
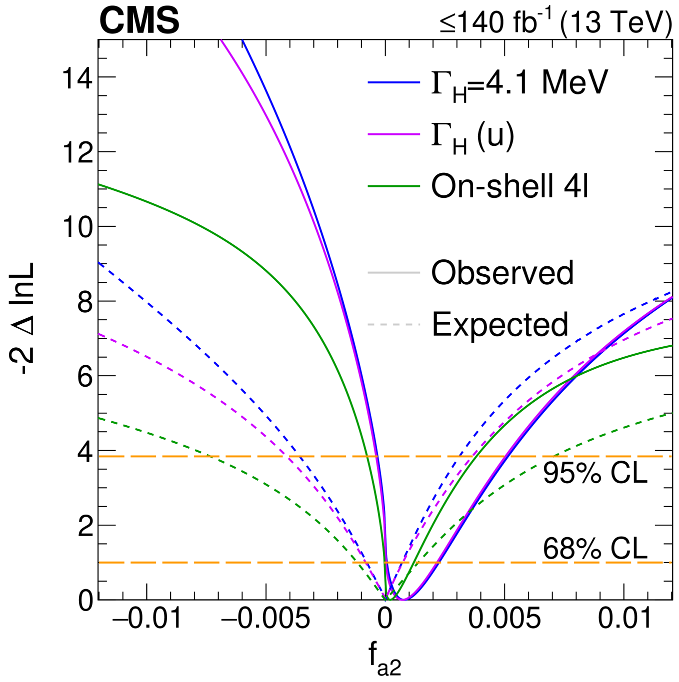
$H \to \tau\tau$ combined with $H \to ZZ^* \to 4l$

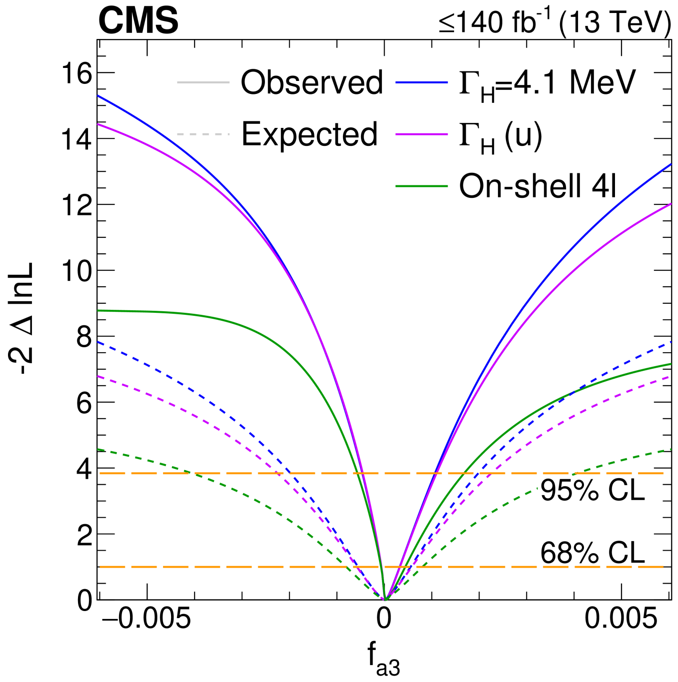
Parameter	Observed / (10^{-3})		Expected / (10^{-3})	
	68% CL	95% CL	68% CL	95% CL
f_{a3}	$0.20^{+0.26}_{-0.16}$	$[-0.01, 0.88]$	0.00 ± 0.05	$[-0.21, 0.21]$
f_{a2}	$0.7^{+0.8}_{-0.6}$	$[-1.0, 2.5]$	$0.0^{+0.5}_{-0.4}$	$[-1.1, 1.2]$

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

Nature Phys. 18 (2022) 1329





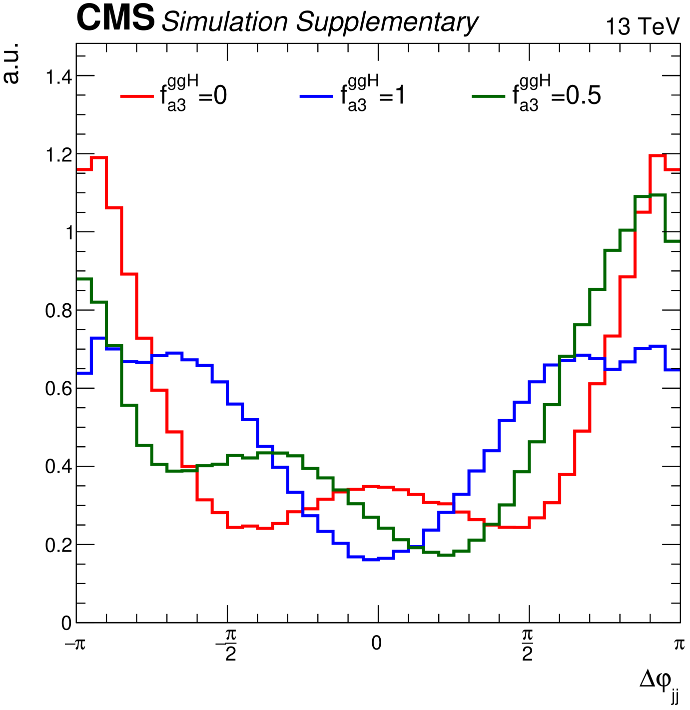


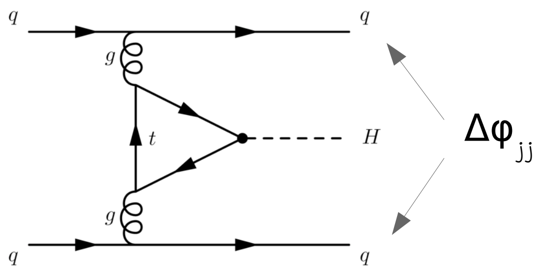
Evidence for off-shell Higgs production (>3σ)

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

Parameter	Scenario		Observed	Expected
$(\times 10^5)$		b.f.	68% | 95% CL	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	$[-6.2, 33] \mid [-46, 110]$	$[-58, 58] \mid [-225, 225]$

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

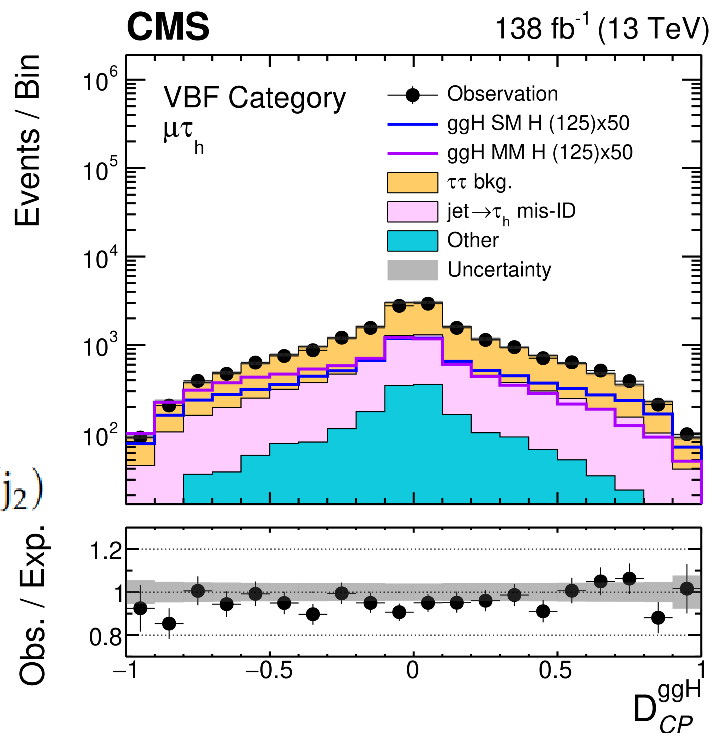




Similar sensitivity
with simple variable

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

&
MELA discriminators



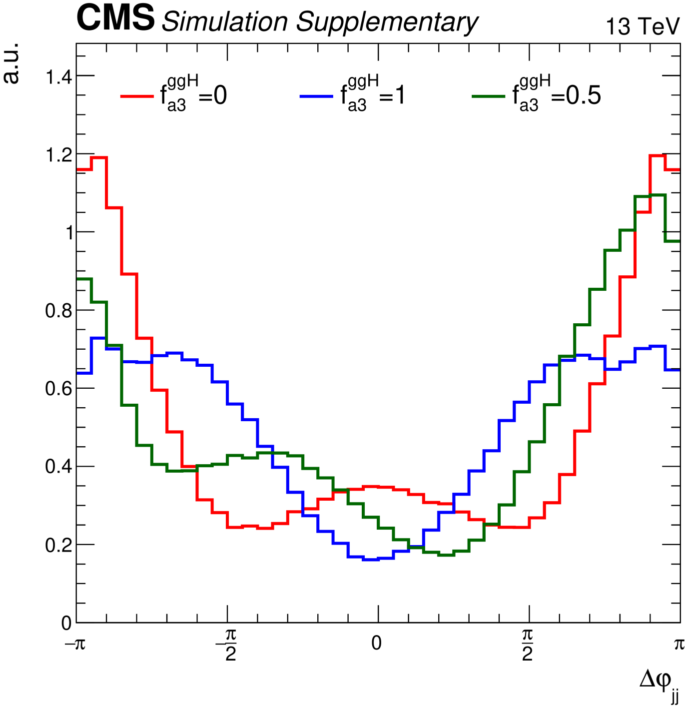
arXiv: 2205.05120

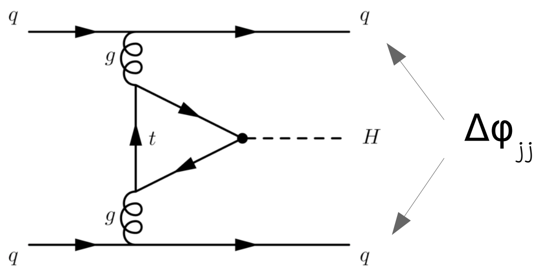
← separates interference of
CP-odd coupling with SM

CP-odd cross section fraction:

= 0.08 [+ 0.35 – 0.08 @ 68% CL]

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





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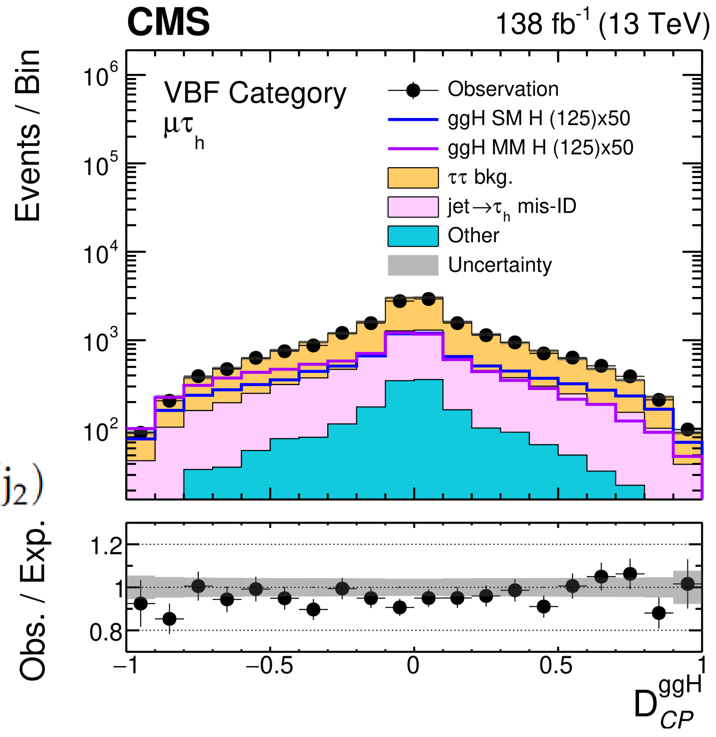
&
MELA discriminators



arXiv: 2205.05120

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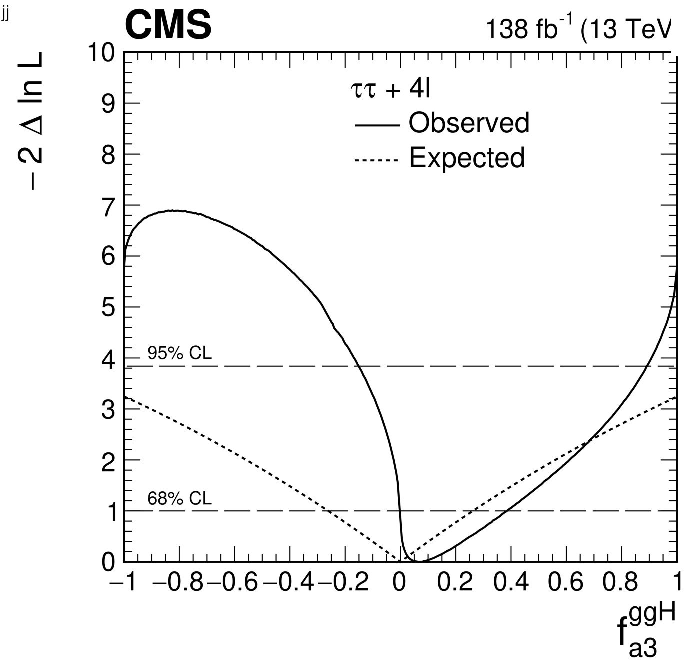


H → ττ combined
with H → ZZ* → 4l

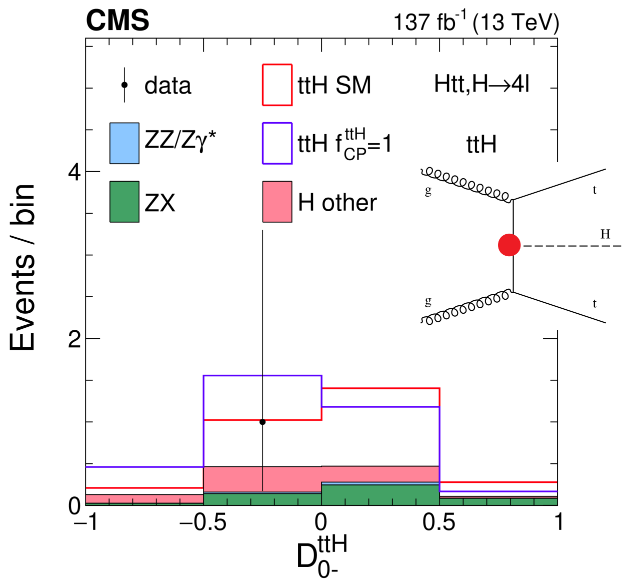
CP-odd cross section fraction:

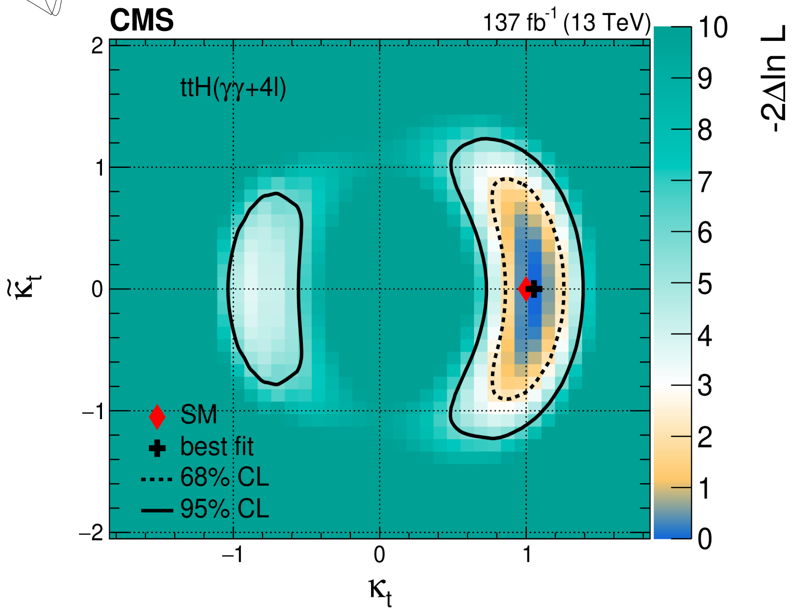
= 0.08 [+ 0.35 – 0.08 @ 68% CL]

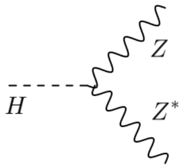
= 0.07 [+ 0.32 – 0.07 @ 68% CL]

Pure CP-odd hypothesis excluded at 2.4σ

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

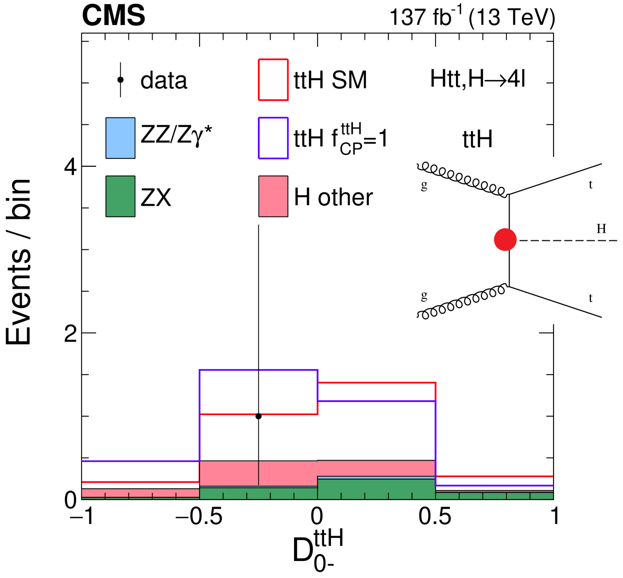


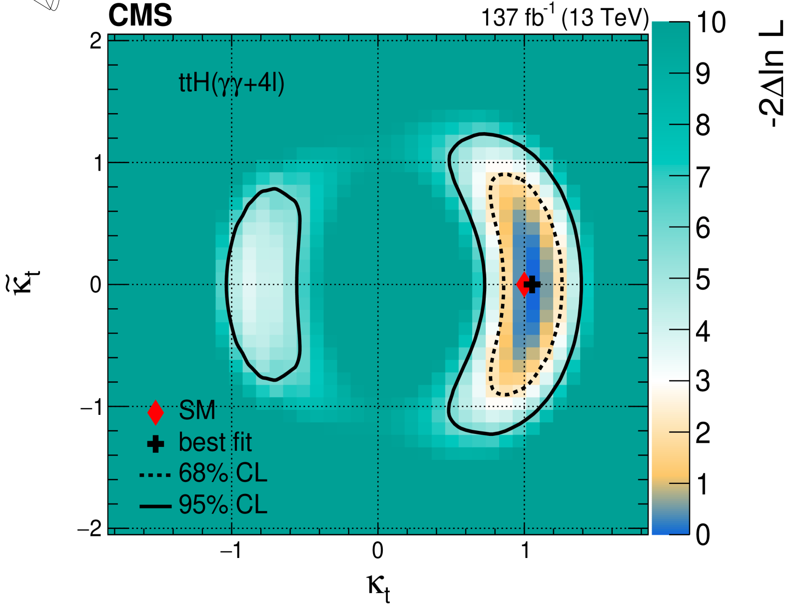


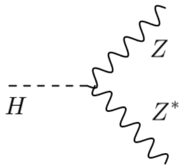


Phys. Rev. D. 104 (2021) 052004

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

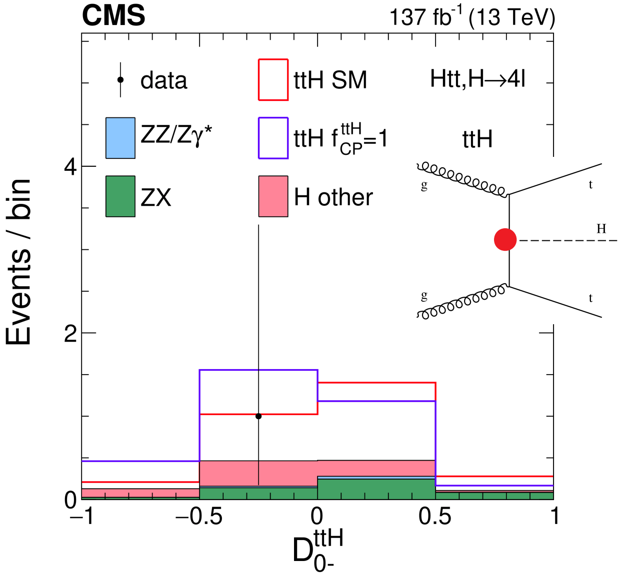


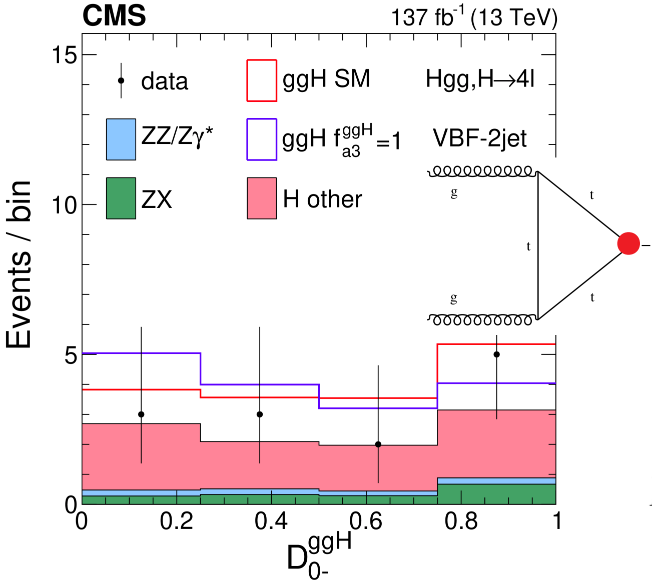




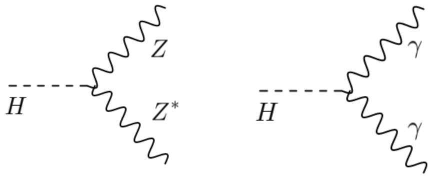
Phys. Rev. D. 104 (2021) 052004

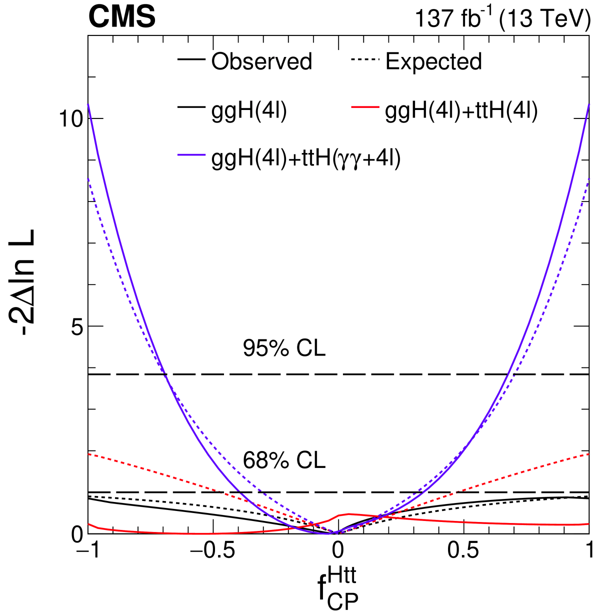
Higgs to top quark couplings: H→ 4-lepton, γγ, ττ final states

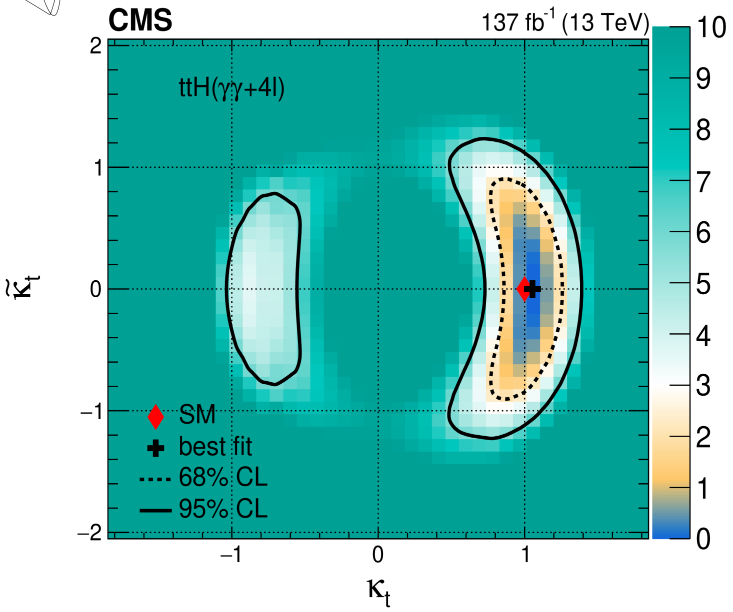


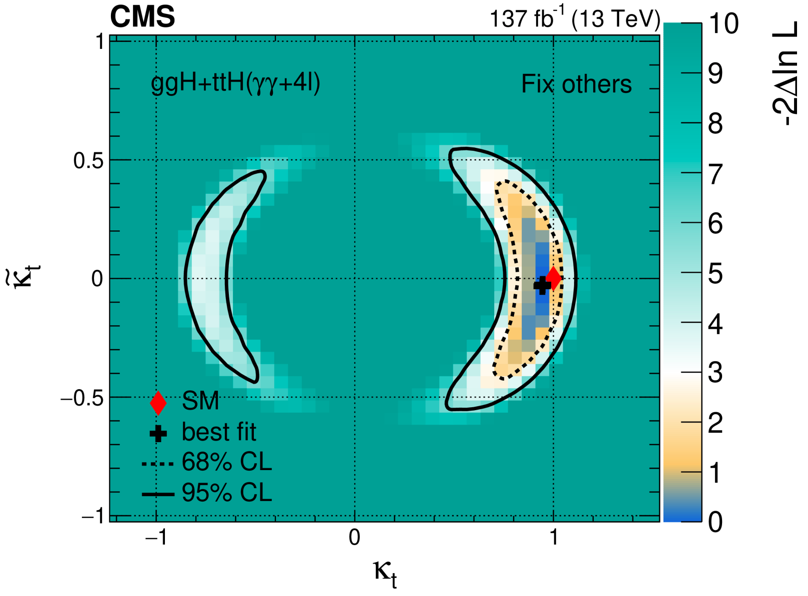


ttH & ggH categories combined to enhance sensitivity



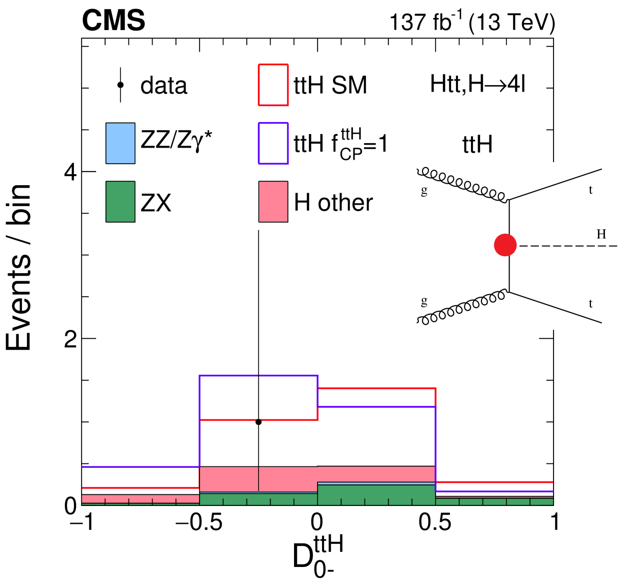


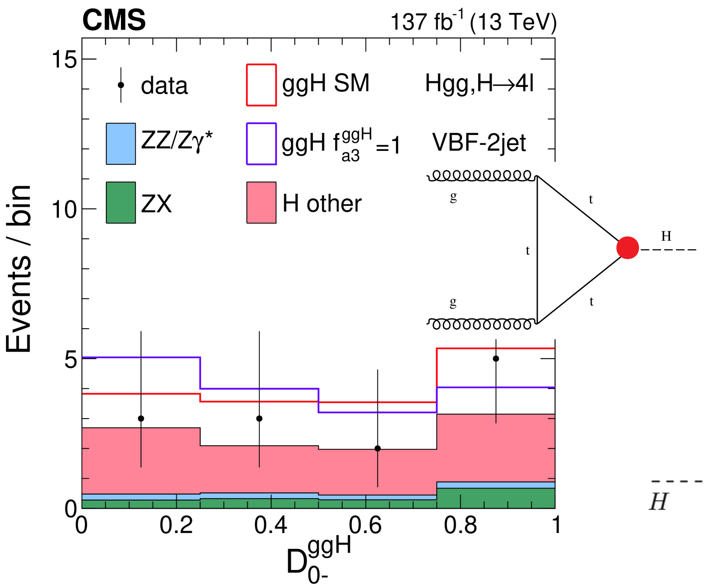




Phys. Rev. D. 104 (2021) 052004

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





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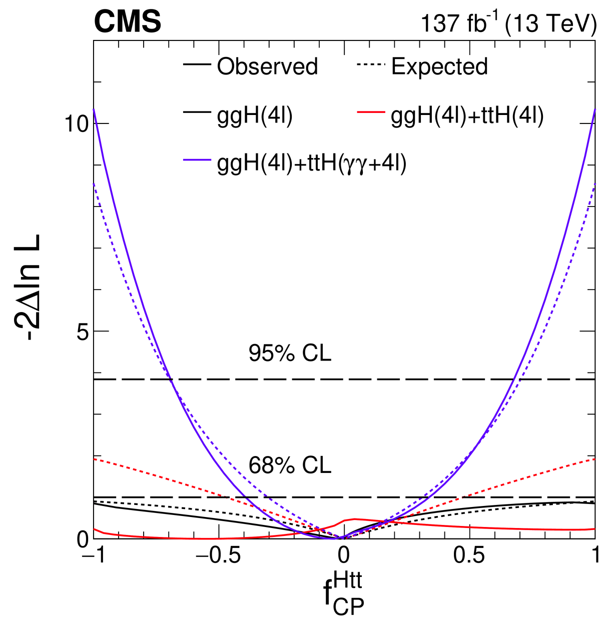
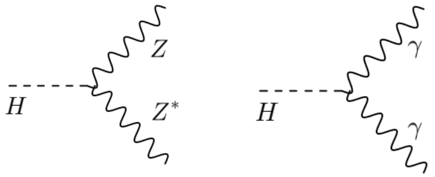
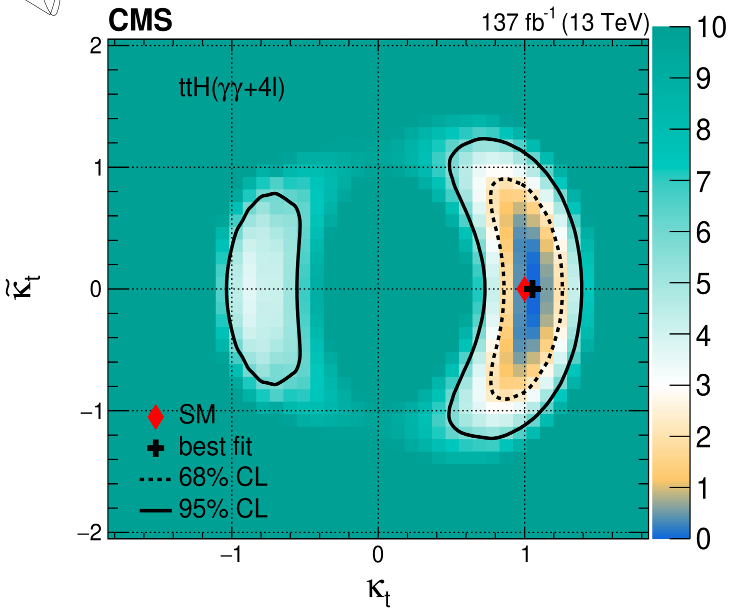
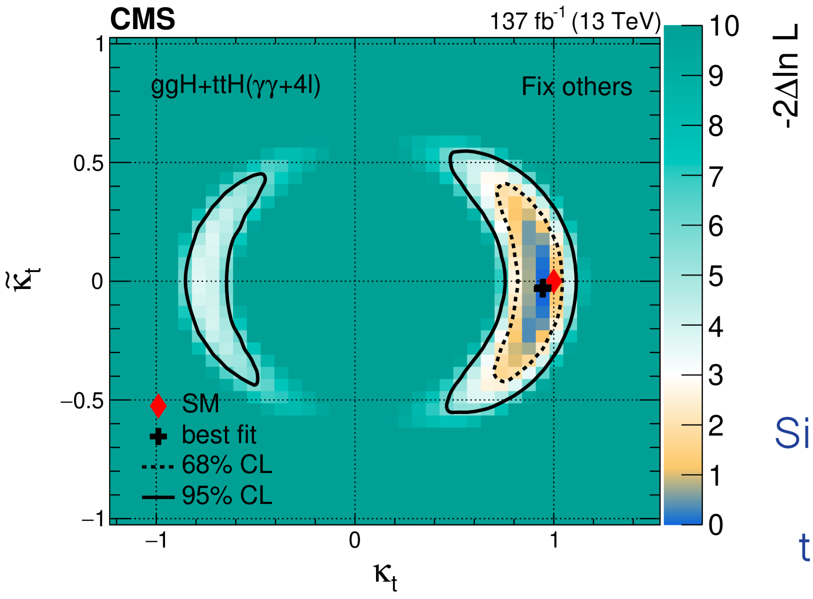
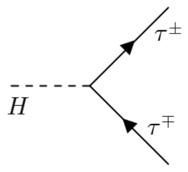
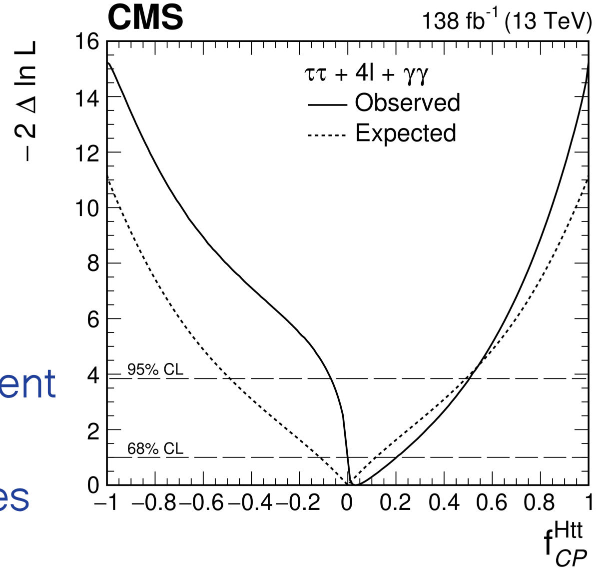












Significant improvement after combining three H decay modes

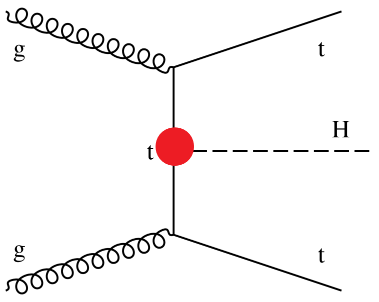
Phys. Rev. D. 104 (2021) 052004

arXiv: 2205.05120

CP nature of Higgs to top quark coupling: Multilepton final states

arXiv: 2208.02686 (accepted in JHEP)

Final states considered:
2 same-sign leptons + 0 τ_h
2 same-sign leptons + 1 τ_h
3 leptons + 0 τ_h

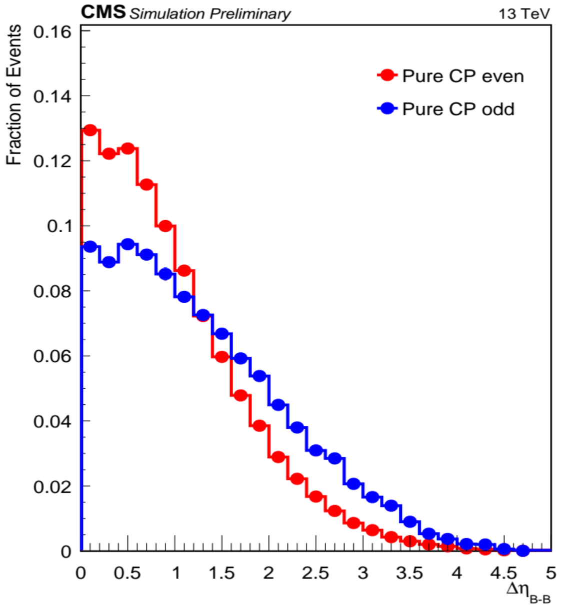


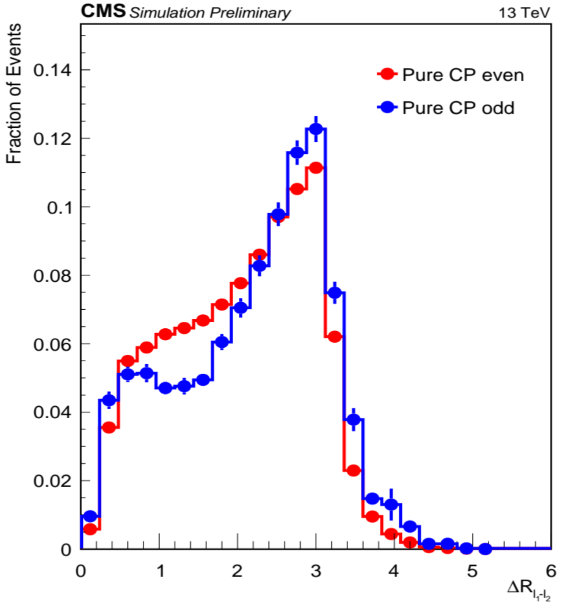
$$\mathcal{L}_{t\bar{t}H} = \frac{-y_t}{2}\bar{\psi}_t(\kappa_t + i\gamma_5\widetilde{\kappa_t})\psi_t H$$

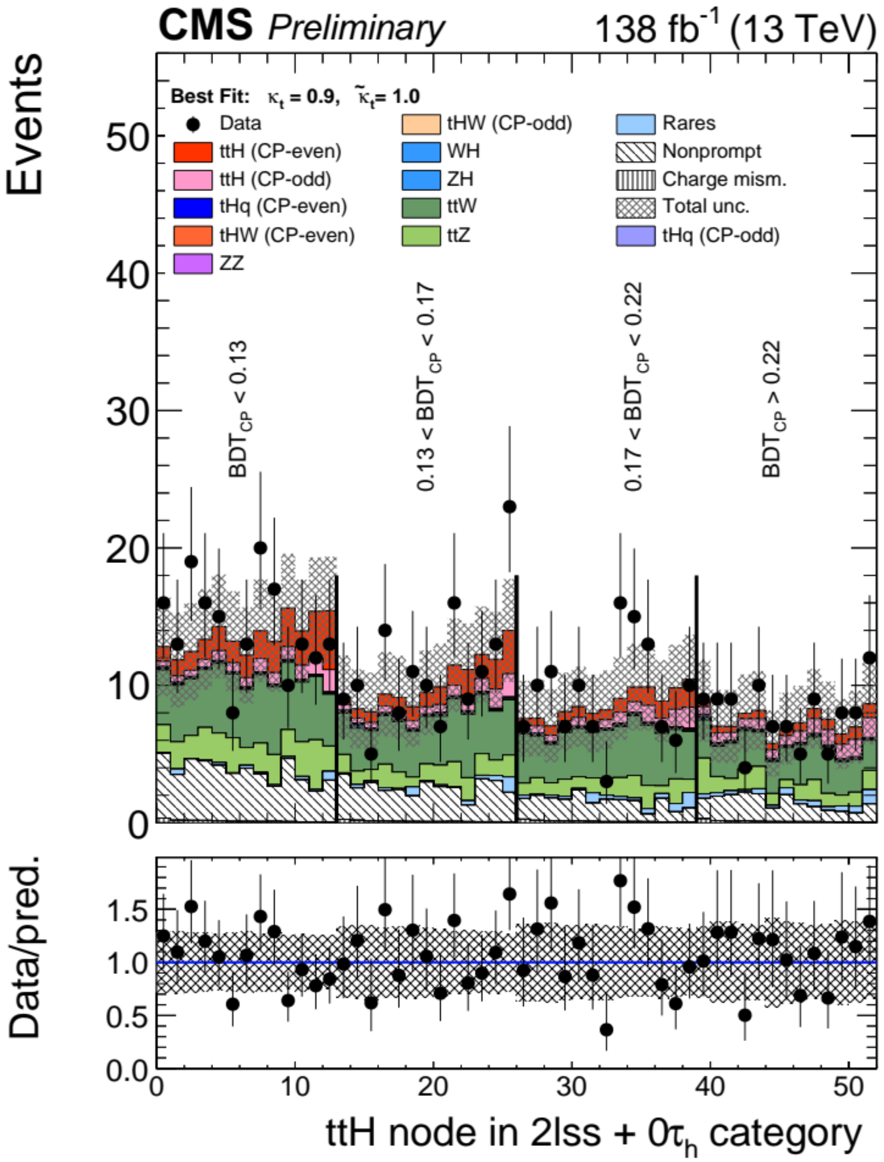
Signal-background separation:

Multi-class neural network → {
- ttH
- tHq
- Others

CP separation in ttH category: BDT using CP-sensitive variables



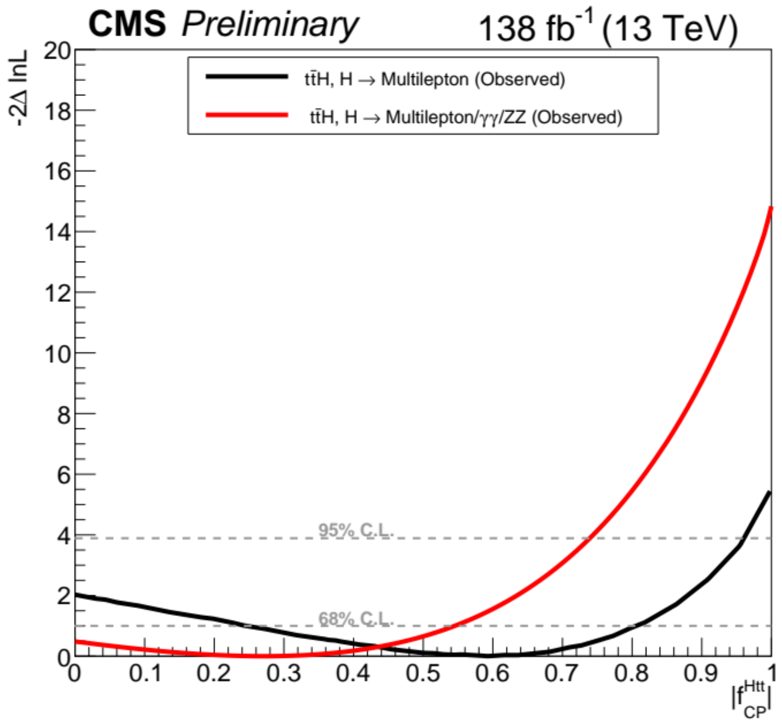


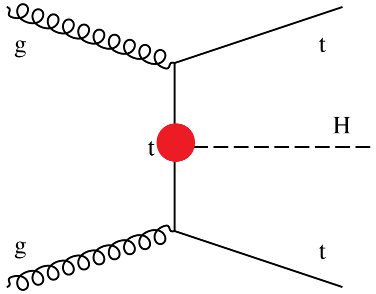


ttH score of NN →

CP nature of Higgs to top quark coupling: Multilepton final states

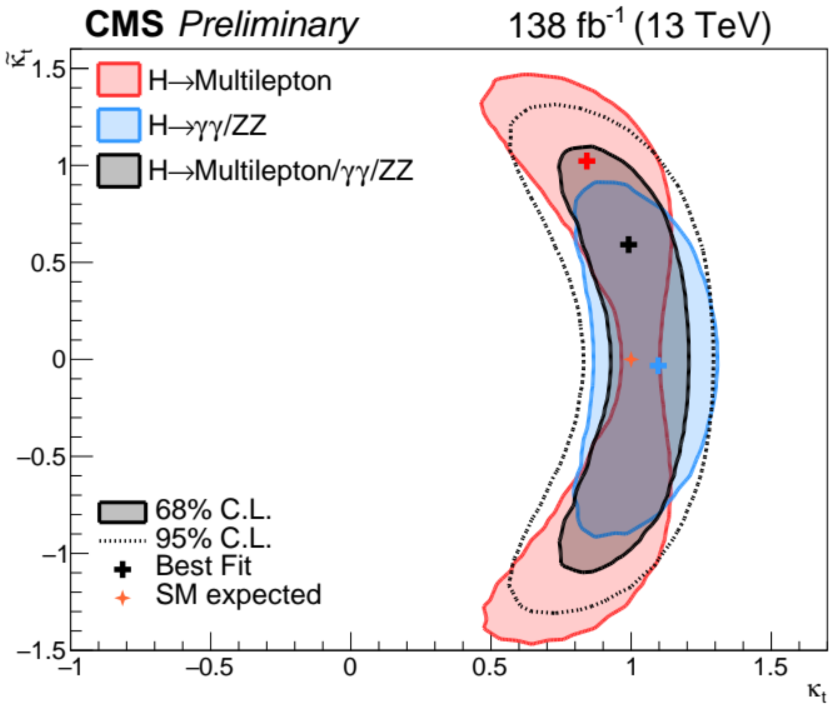
arXiv: 2208.02686 (accepted in JHEP)





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

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



Results from ttH (→ ττ) combined with ttH (→ γγ) & ttH (→ ZZ* → 4l)

κ_t : [0.96, 1.16] at 68% CL

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

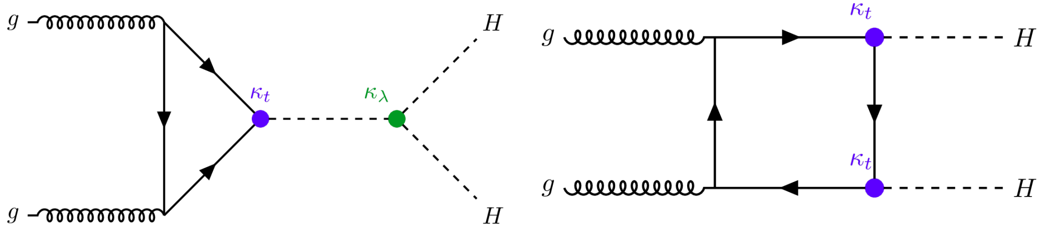
CP-odd fraction

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

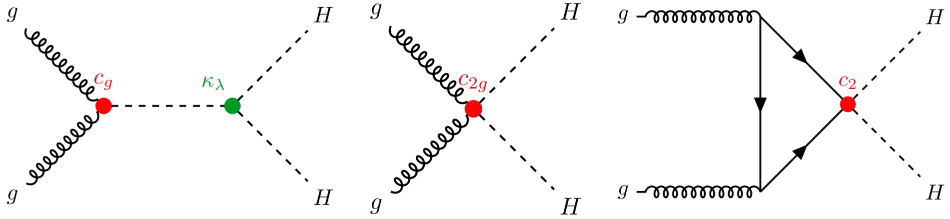
Pure CP-odd hypothesis excluded at 3.7σ

HH → WWγγ

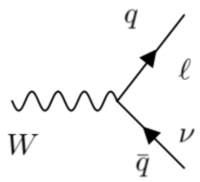
CMS-PAS-HIG-21-014



(a) SM-like processes



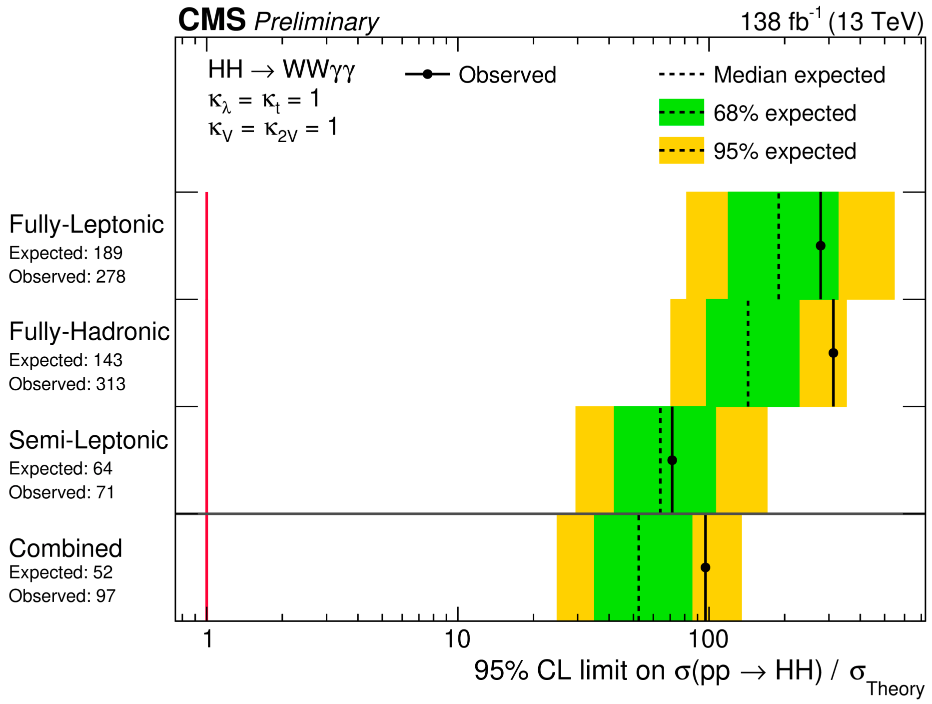
(b) Pure BSM processes



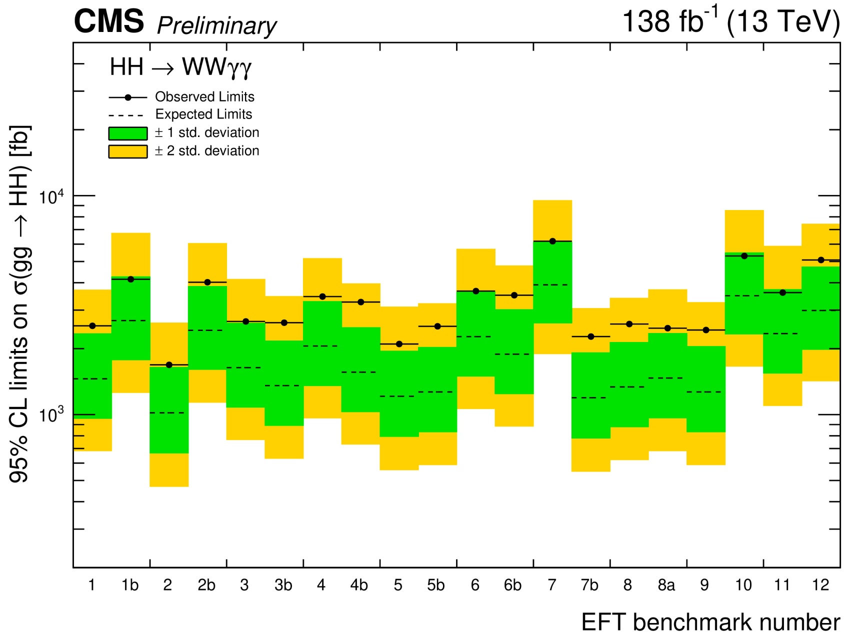
More on di-Higgs measurements in talk by S. Mukherjee

Signal extraction using DNN (in semi-leptonic & hadronic channels)
Kinematic cuts (in fully leptonic final state)

Upper limit on σ(HH) interpreted using EFT benchmark scenarios

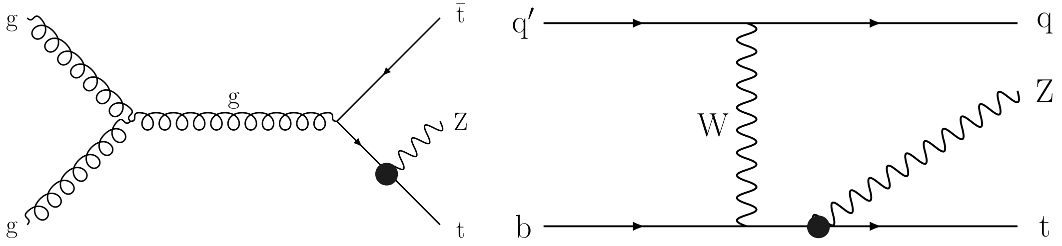


Benchmark	κ_λ	κ_t	c_2	c_g	c_{2g}
SM	1.0	1.0	0.0	0.0	0.0
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	-0.8	0.6
3	1.0	1.0	-1.5	0.0	-0.8
4	-3.5	1.5	-3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	-1
6	2.4	1.0	0.0	0.2	-0.2
7	5.0	1.0	0.0	0.2	-0.2
8	15.0	1.0	0.0	-1	1
9	1.0	1.0	1.0	-0.6	0.6
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	1	-1
12	15.0	1.0	1.0	0.0	0.0



EFT analysis for ttZ in multilepton final states

JHEP 12 (2021) 083



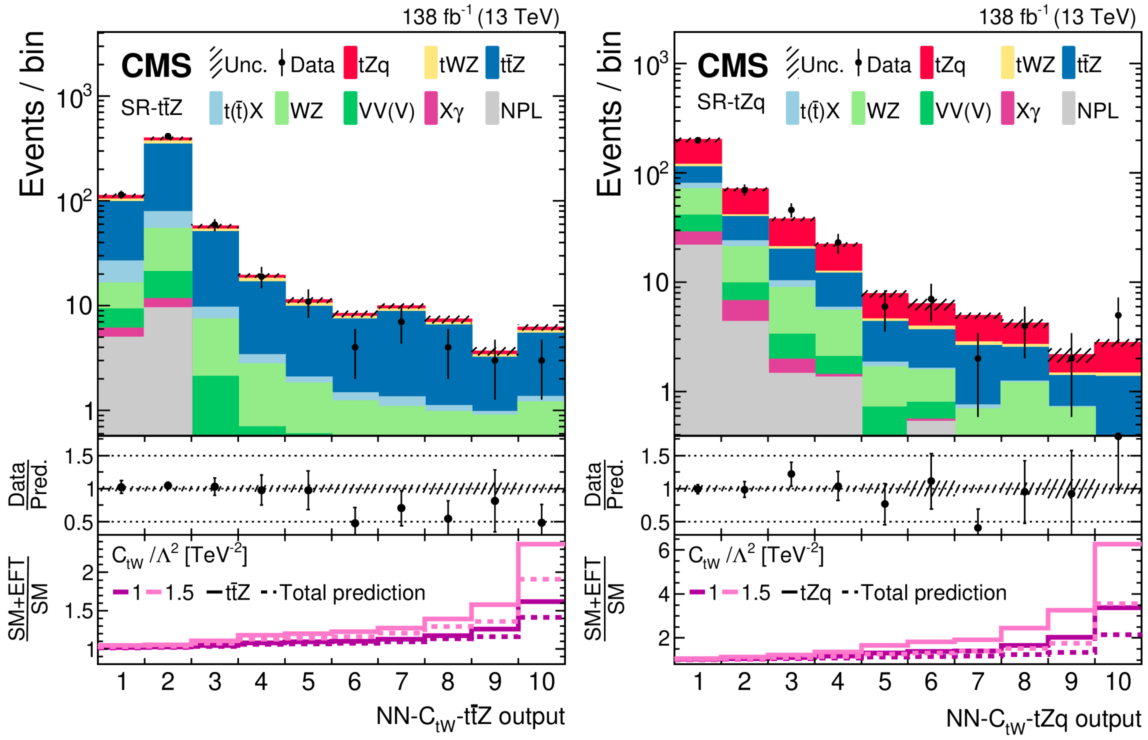
SMEFT operators considered:

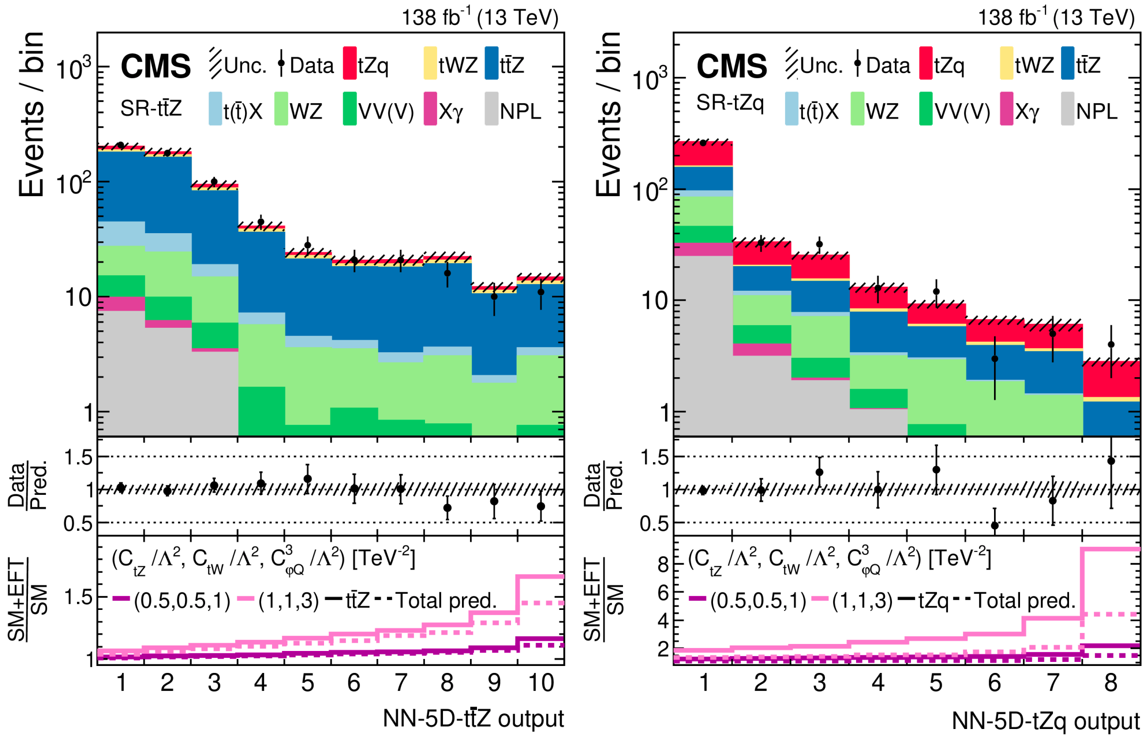
Dipole $\mathcal{O}_{tZ}$ $\mathcal{O}_{tW}$

Current $\mathcal{O}^{(3)}_{HQ}$ $\mathcal{O}^{-}_{HQ}$ $\mathcal{O}_{Ht}$

Two sets of neural networks used:

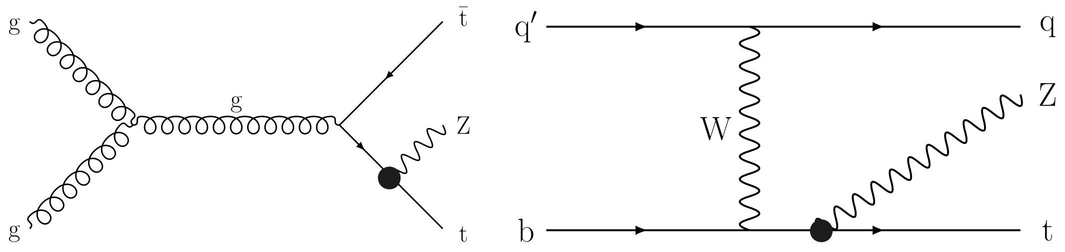
1. Distinguishing ttZ, tZq, & SM background
2. Separating EFT effects in ttZ & tZq





EFT analysis for ttZ in multilepton final states

JHEP 12 (2021) 083



SMEFT operators considered:

Dipole $\mathcal{O}_{tZ}\ \mathcal{O}_{tW}$

Current $\mathcal{O}^{(3)}_{HQ}\ \mathcal{O}^{-}_{HQ}\ \mathcal{O}_{Ht}$

Two sets of neural networks used:

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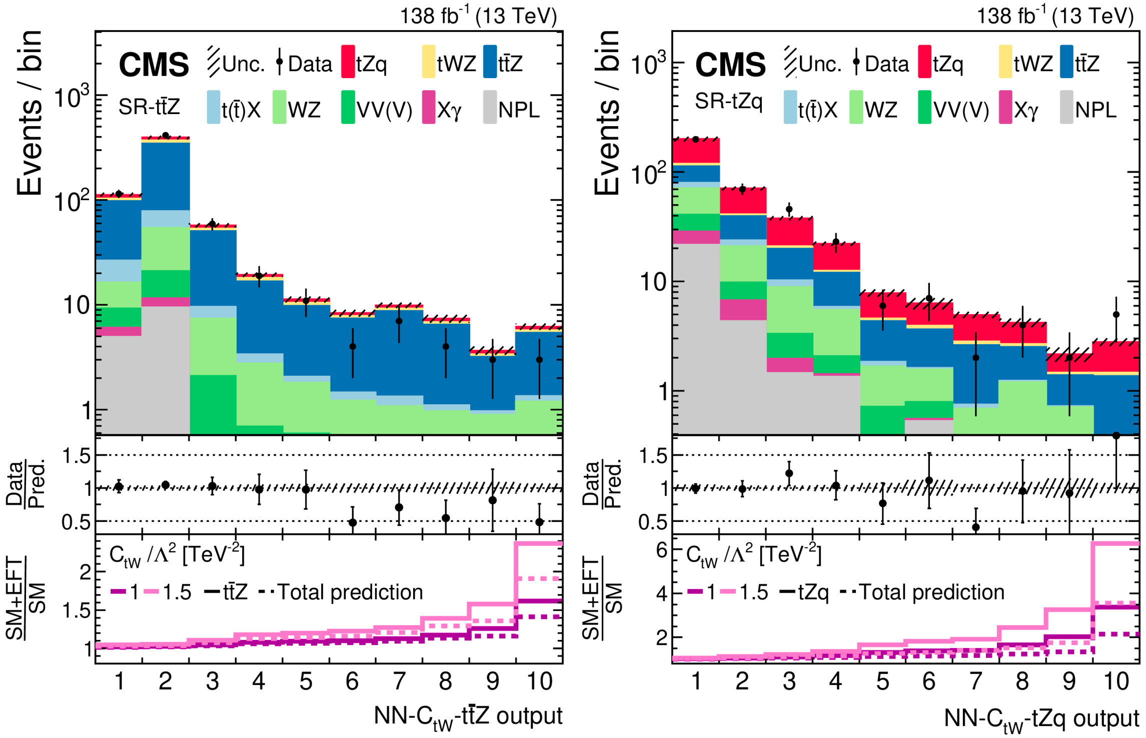
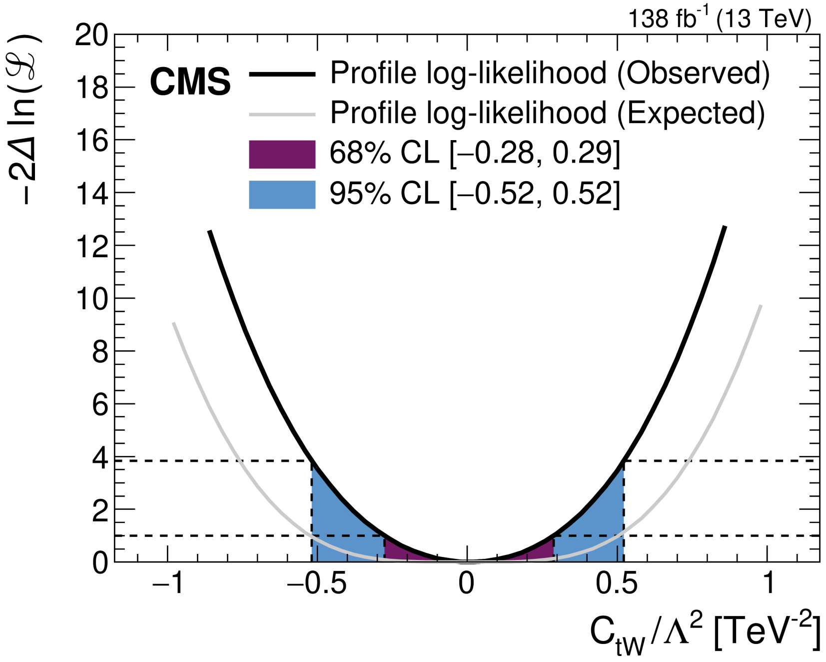
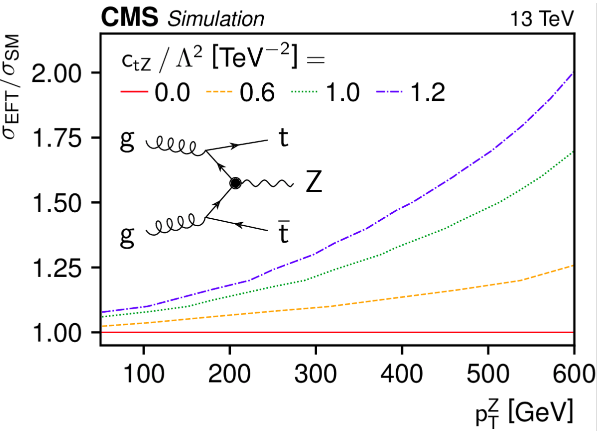
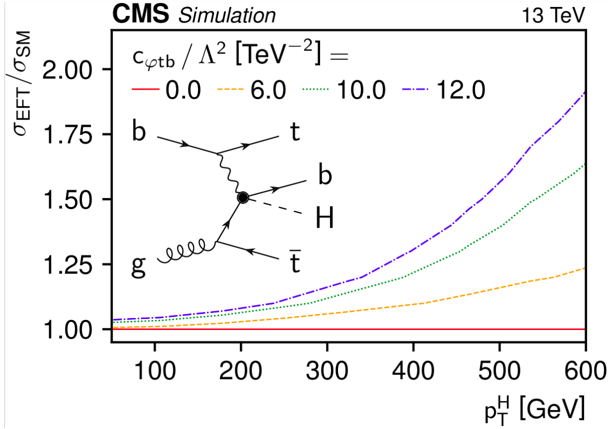




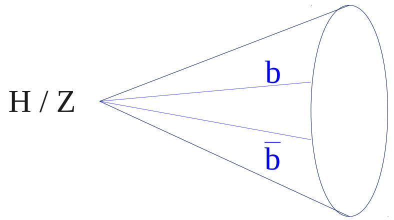
EFT analysis for ttZ & ttH in boosted phase space

arXiv: 2208.12837 (submitted to PRD)





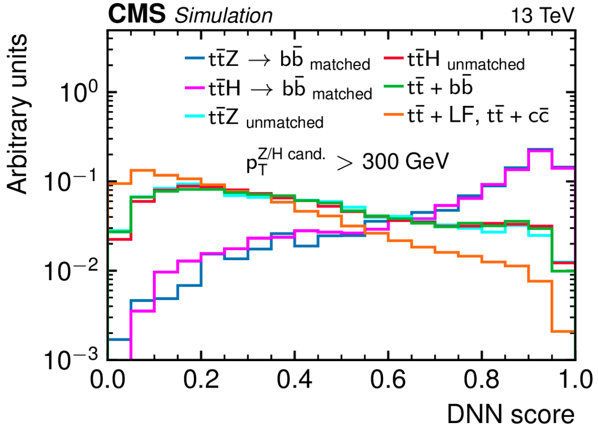
SMEFT operators considered:



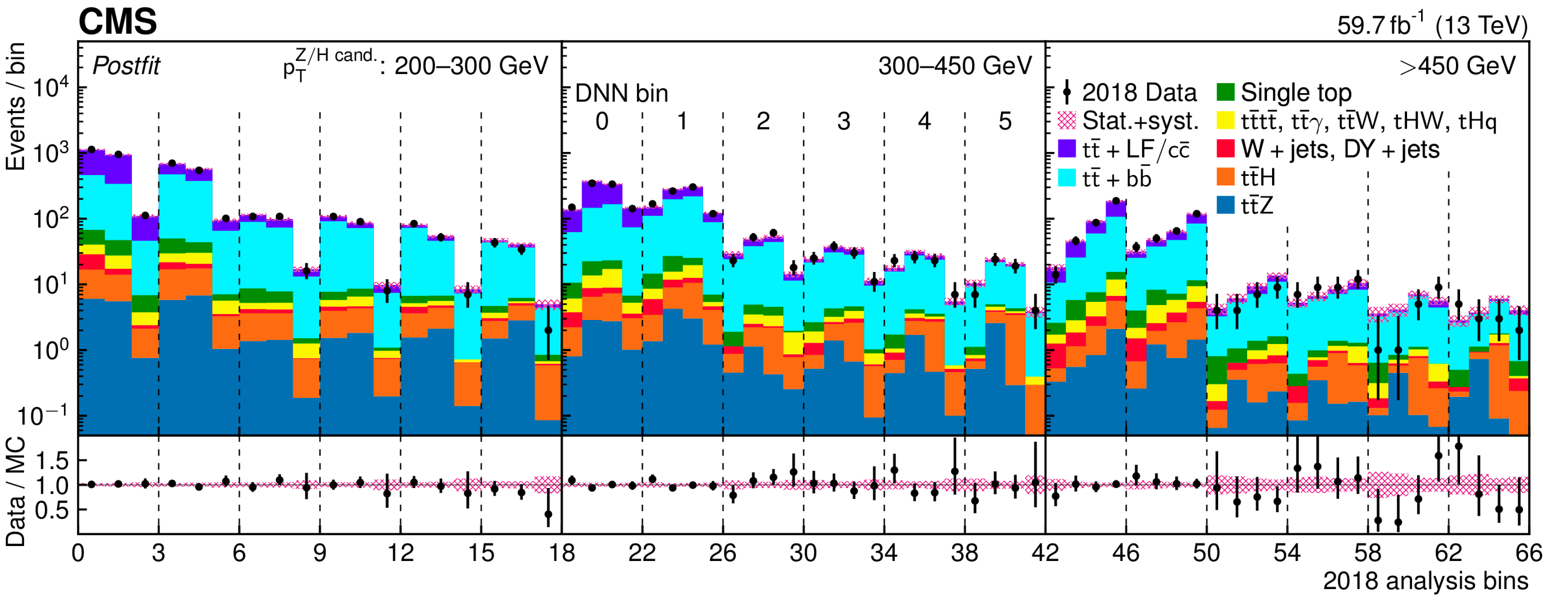
Dipole $\mathcal{O}_{tW}$

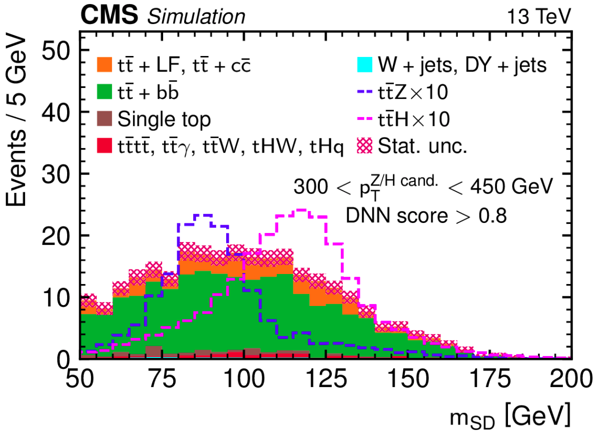
Current $\mathcal{O}^{(3)}_{HQ}$ $\mathcal{O}^{-}_{HQ}$ $\mathcal{O}_{Ht}$ $\mathcal{O}_{Htb}$

Yukawa $\mathcal{O}_{tH}$



DNN separating ttH + ttZ events from SM bkg

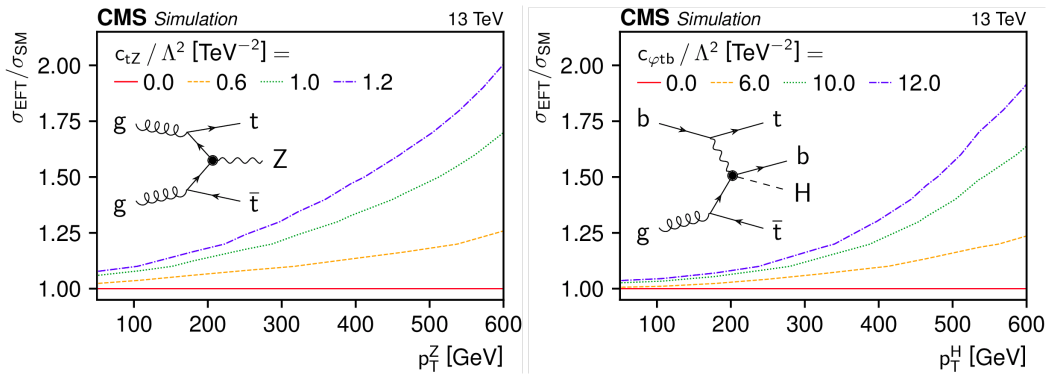




Jet soft-drop mass distinguishing ttH & ttZ

EFT analysis for ttZ & ttH in boosted phase space

arXiv: 2208.12837 (submitted to PRD)

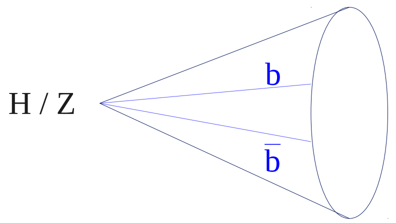


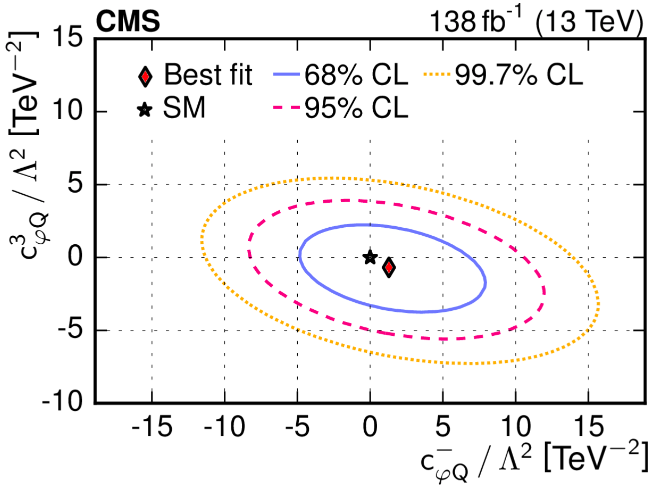
SMEFT operators considered:

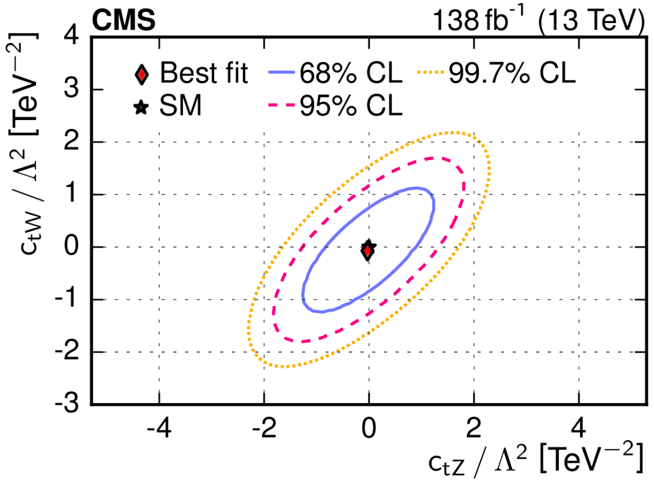
Dipole $\mathcal{O}_{tW}$

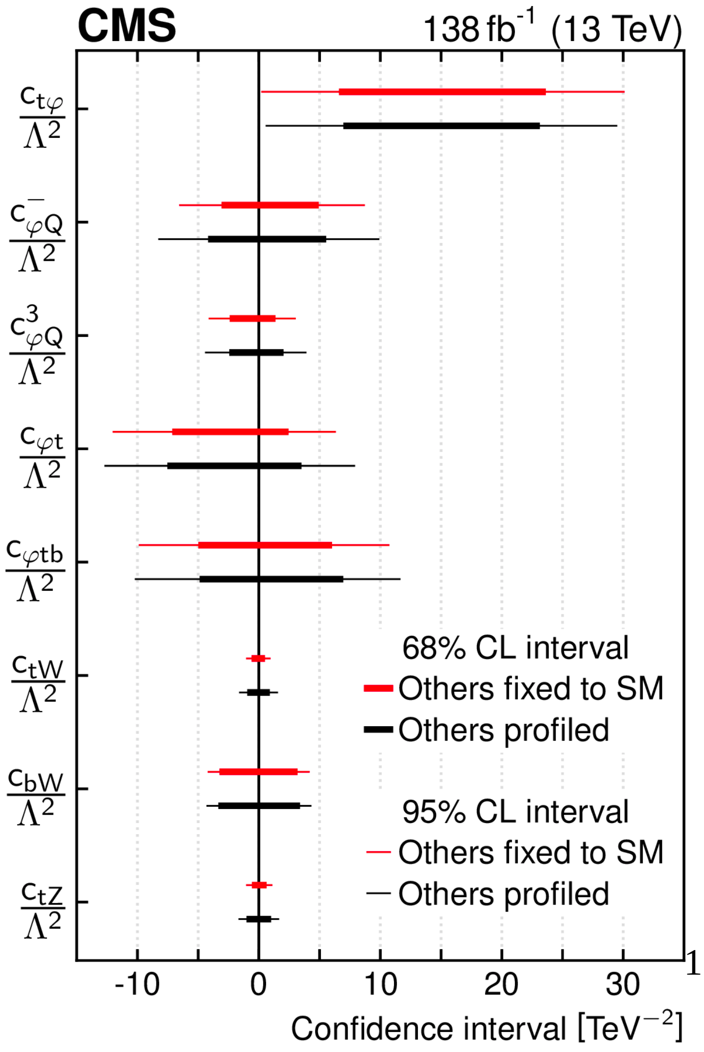
Current $\mathcal{O}_{HQ}^{(3)}$ $\mathcal{O}_{HQ}^{-}$ $\mathcal{O}_{Ht}$ $\mathcal{O}_{Htb}$

Yukawa $\mathcal{O}_{tH}$









Smaller statistics compared to ones used in existing results
[JHEP 03 (2020) 056, JHEP 03 (2021) 095, JHEP 12 (2021) 083, JHEP 05 (2022) 091]

← Still competitive in sensitivity

Summary & Outlook

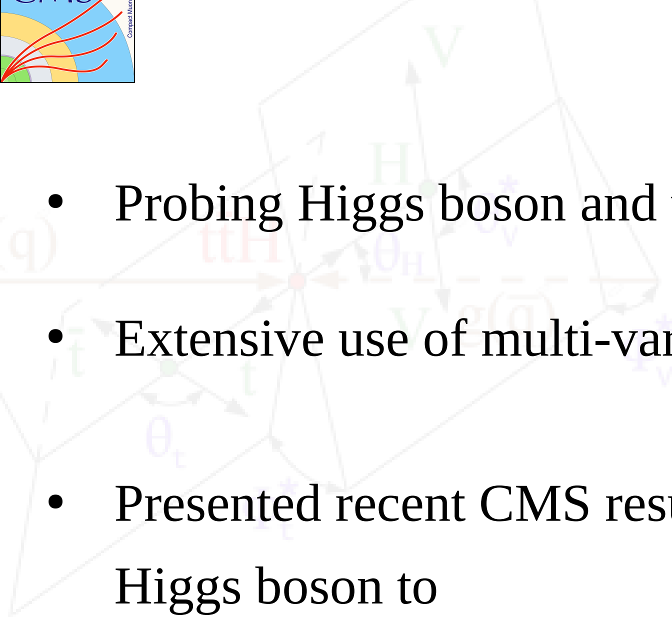
- Probing Higgs boson and top quark couplings test possible new physics scenarios

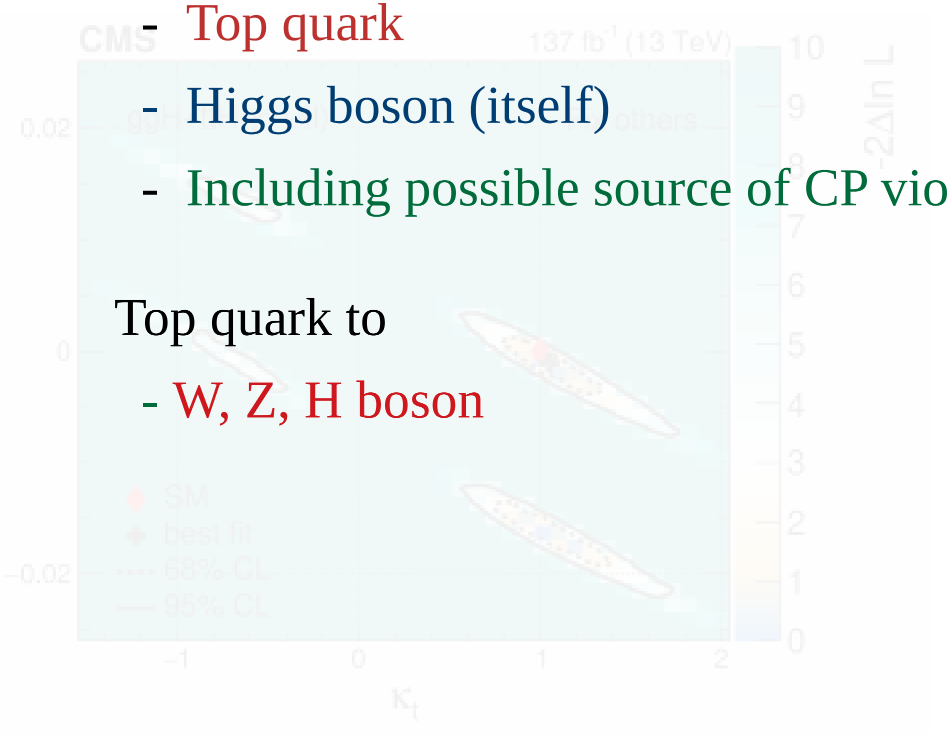
- Extensive use of multi-variate analysis to probe possibility of new physics coupling to top & Higgs

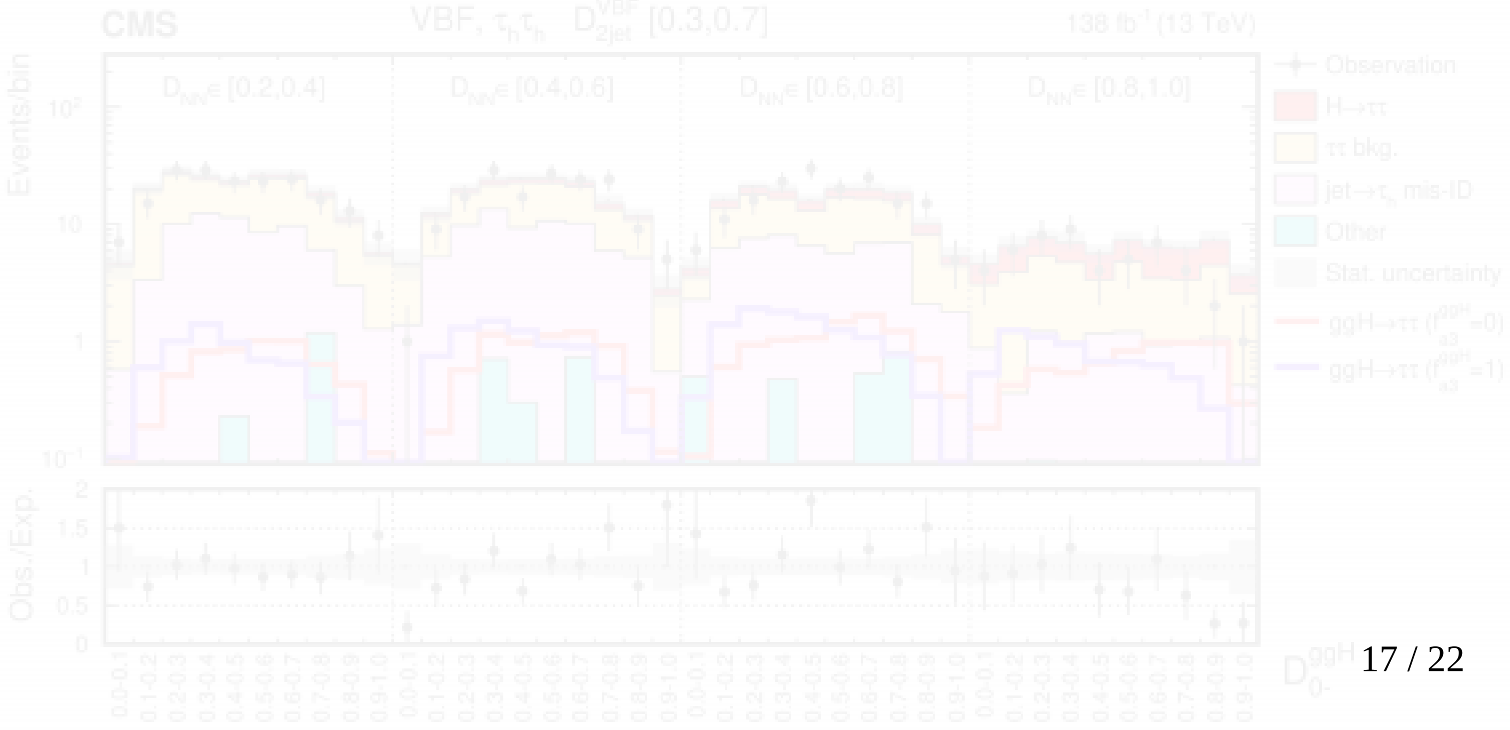
- Presented recent CMS results on search for anomalous coupling of

  Higgs boson to
  - $W^{\pm}$ and Z bosons, gluon
  - Top quark
  - Higgs boson (itself)
  - Including possible source of CP violation

  Top quark to
  - W, Z, H boson







Summary & Outlook

- Probing Higgs boson and top quark couplings test possible new physics scenarios

- Extensive use of multi-variate analysis to probe possibility of new physics coupling to top & Higgs

- Presented recent CMS results on search for anomalous coupling of

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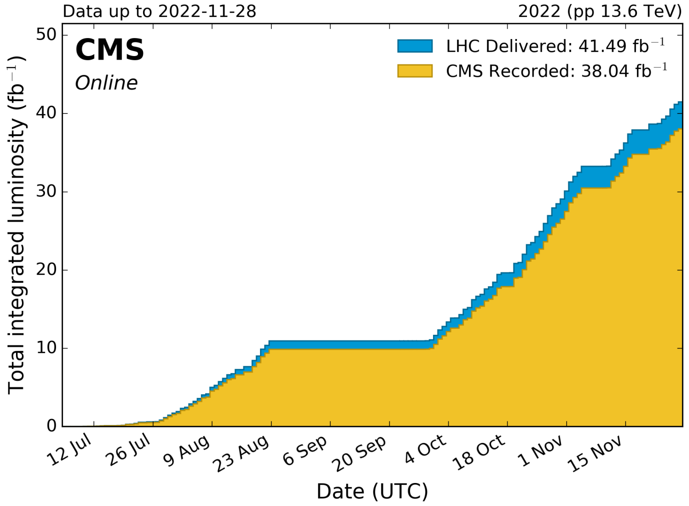
  - $W^{\pm}$ and Z bosons, gluon
  - Top quark
  - Higgs boson (itself)
  - Including possible source of CP violation

  Top quark to
  - W, Z, H boson



Looking forward to new data from Run-3

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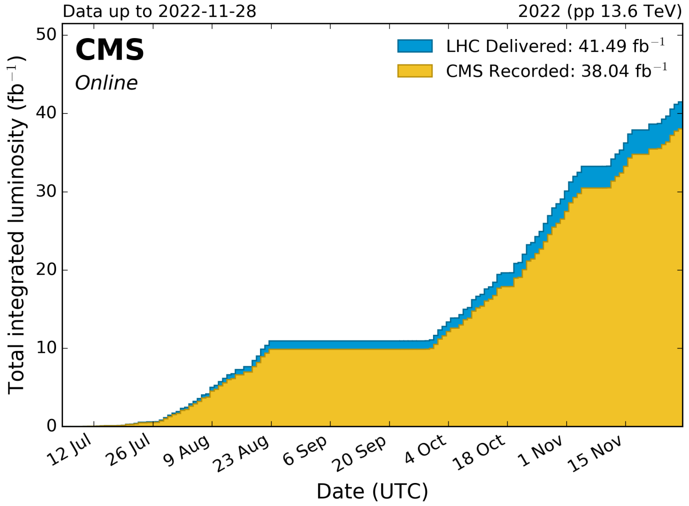
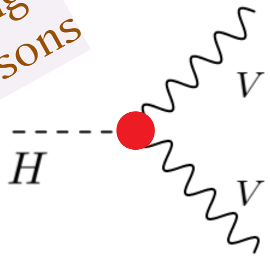


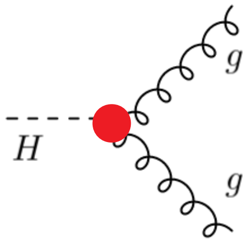
Looking forward to new data from Run-3

Extra Material

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:

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

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

$\kappa_1^{ZZ} = \kappa_2^{ZZ}$, $\kappa_1^{Z\gamma} = 0$

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

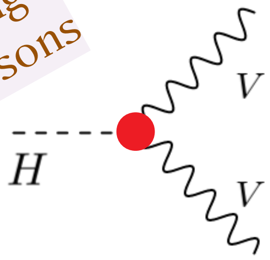
a_3^{gg} ← CP-odd anomalous coupling

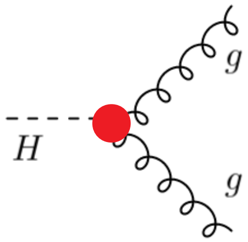
Experimentally probed by measuring cross section fractions

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

Anomalous couplings of Higgs boson

Higgs coupling to Gauge bosons





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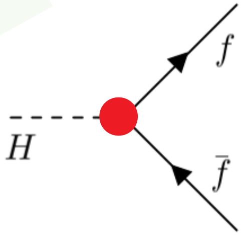
Higgs coupling to fermions



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

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

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

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

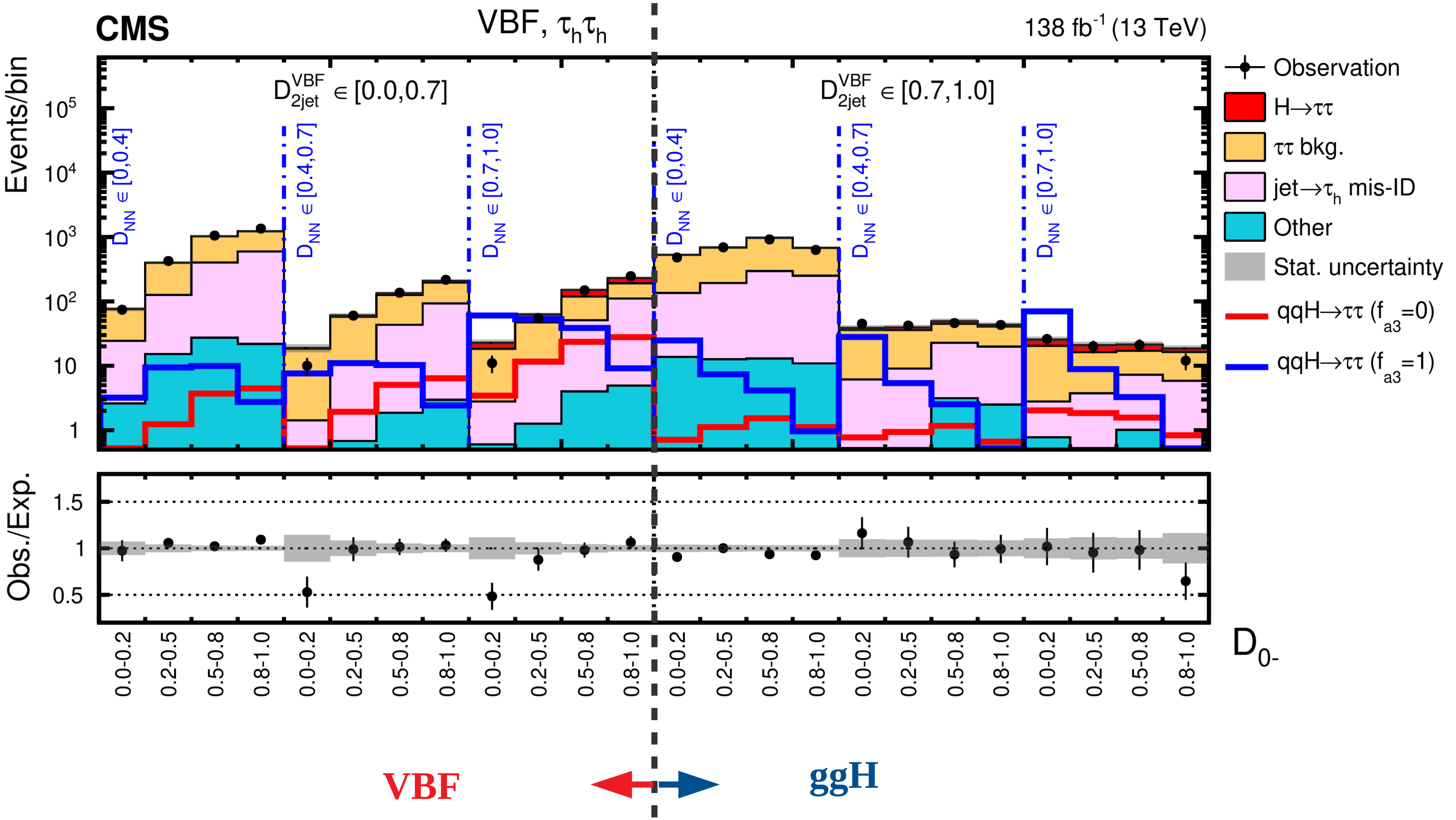
Neural network-based discrimination

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

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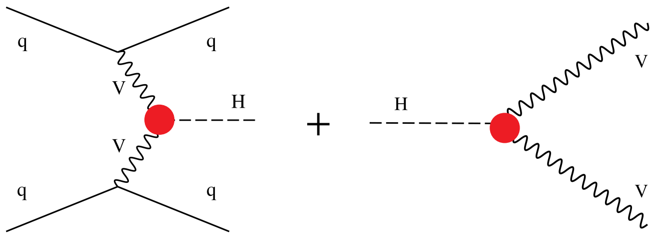
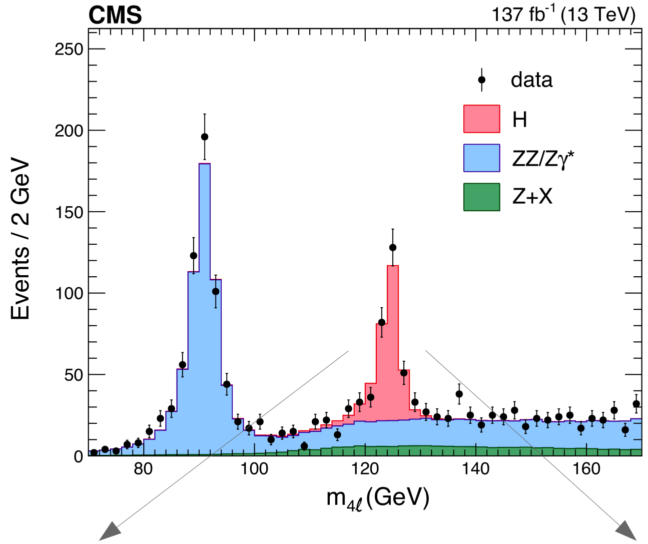
Final states considered:

4e + 4μ



production

decay

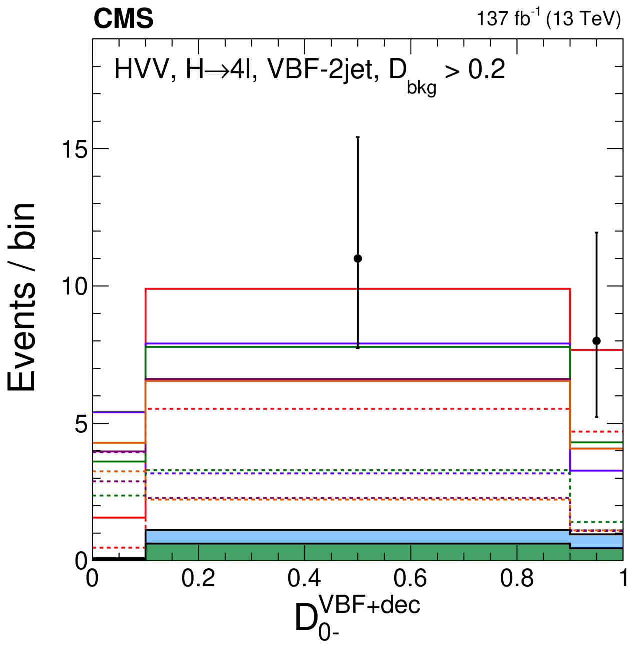


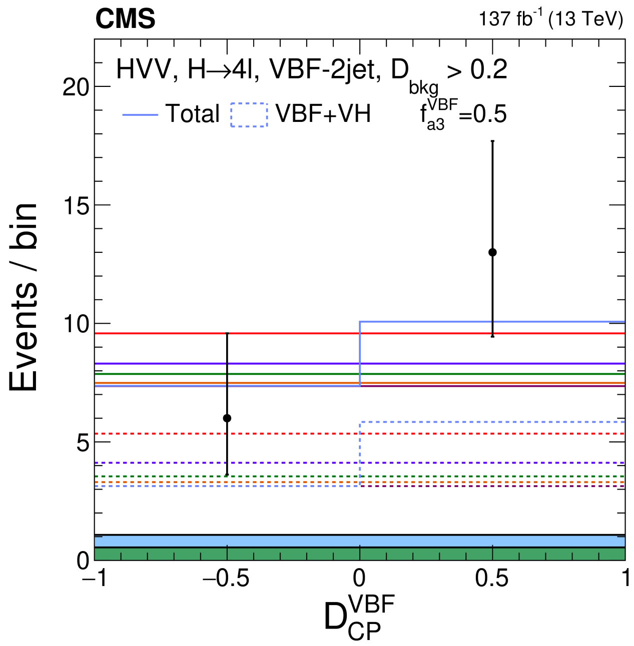
MELA variables

D_{bkg} ← separates VBF H from SM bkg

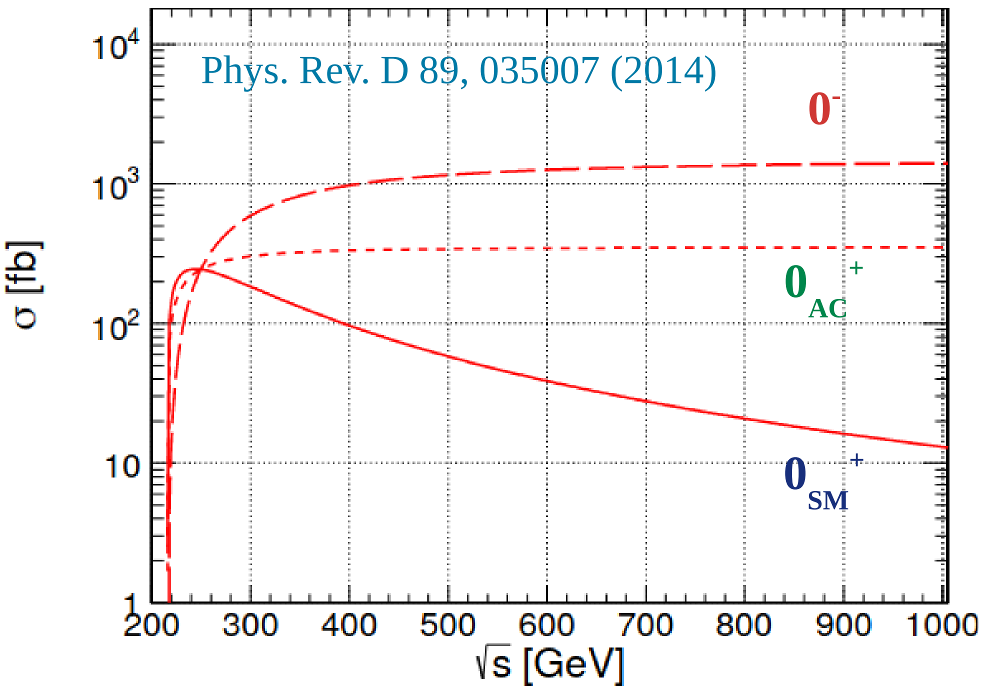
$D^{VBF+dec}_{0-}$ ← separates CP-odd anomalous coupling from SM HVV coupling (both in production & decay)

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





Higgs to vector boson couplings: Need for high energy


Phys. Rev. D 89, 035007 (2014)

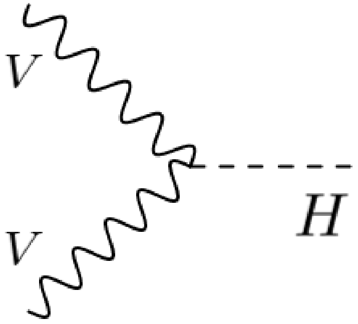
Anomalous couplings contribute at higher order / loop in cross section

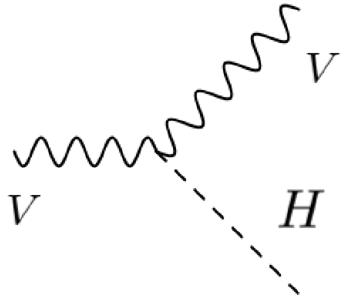
→ Suppression of effects

← Experimentally challenging

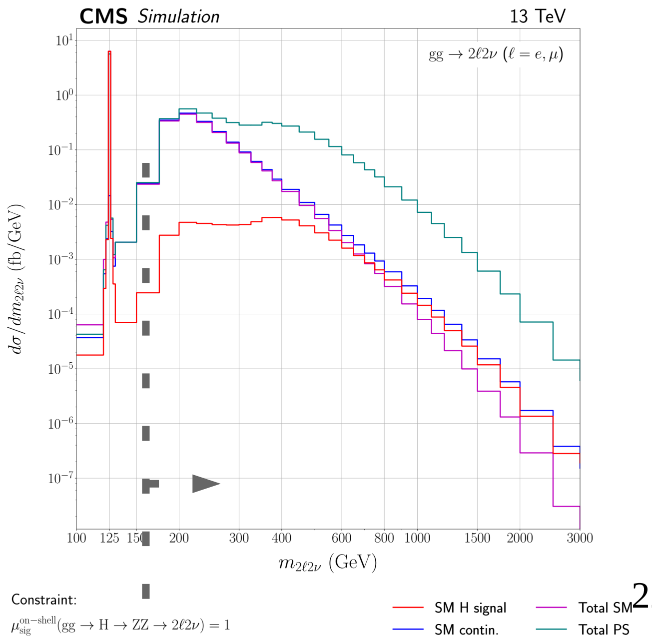
BSM contribution increases with energy → sensitivity enhancement

Use VBF & VH production modes with high energy transfer





Use off-shell region



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