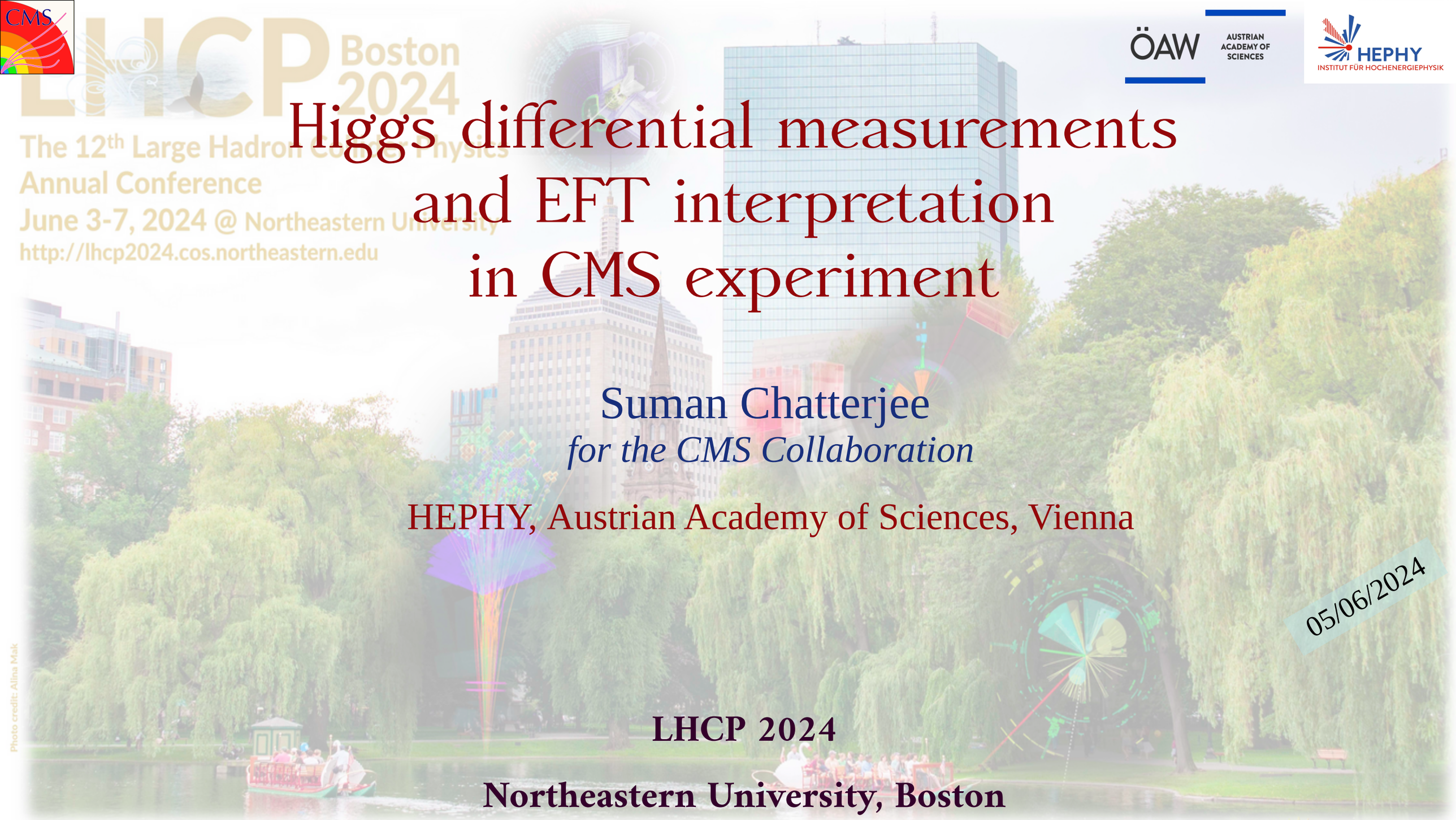


Higgs differential measurements and EFT interpretation in CMS experiment

Suman Chatterjee
for the CMS Collaboration

HEPHY, Austrian Academy of Sciences, Vienna

05/06/2024

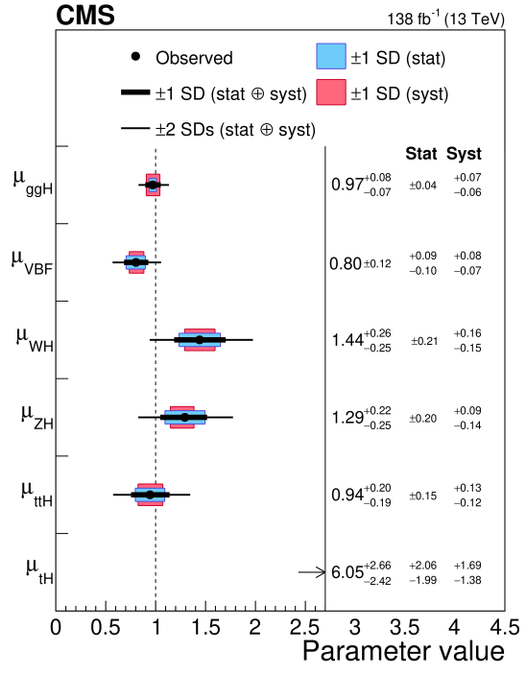
LHCP 2024

Northeastern University, Boston

Introduction

LHC Run 1: Higgs boson discovery era Run (1+)2, 3: Precision measurements of Higgs boson

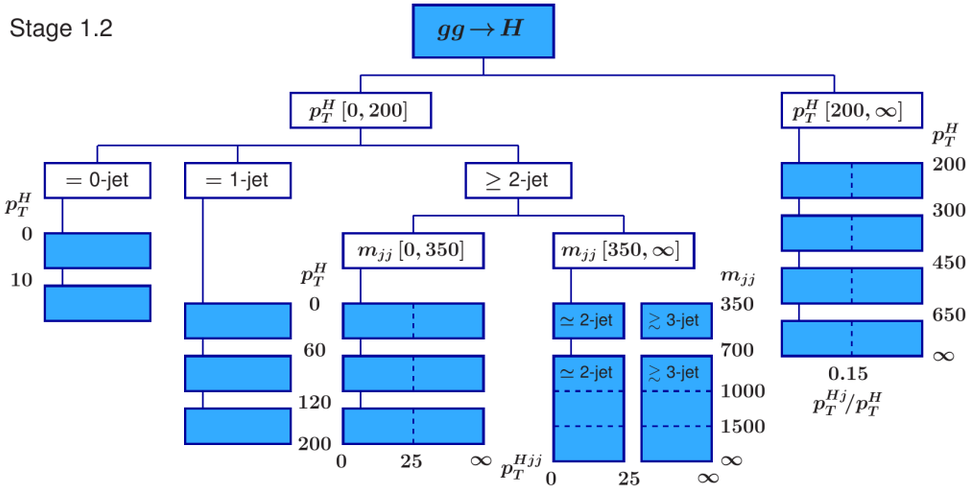
Inclusive measurements



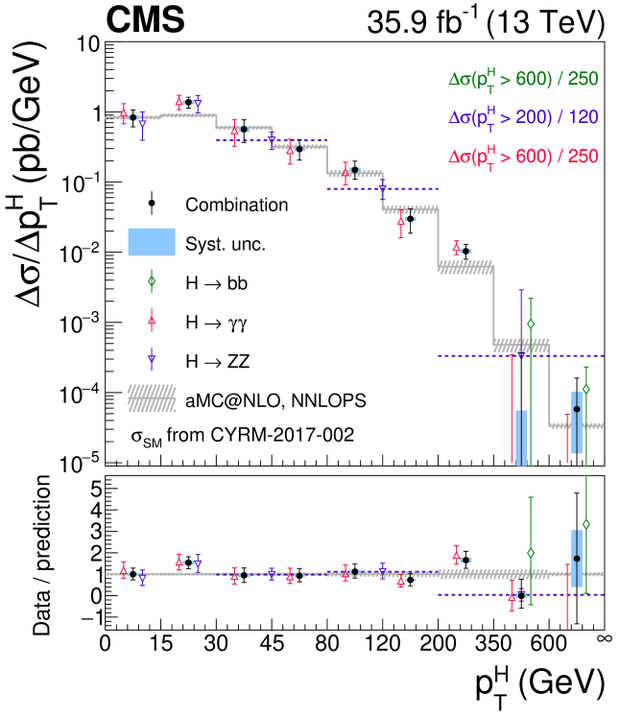
Nature 607 (2022) 7917, 60-68

Simplified template cross section (STXS)

LHCHWGFiducialAndSTXS twiki



Differential distributions (fiducial phase space)



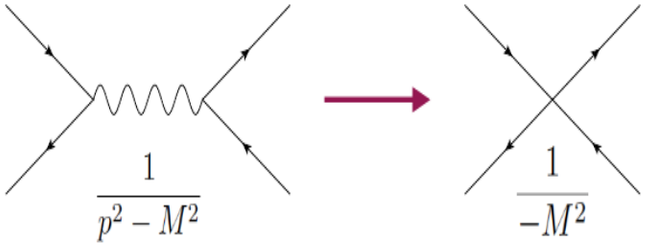
Phys.Lett.B 792 (2019) 369-396

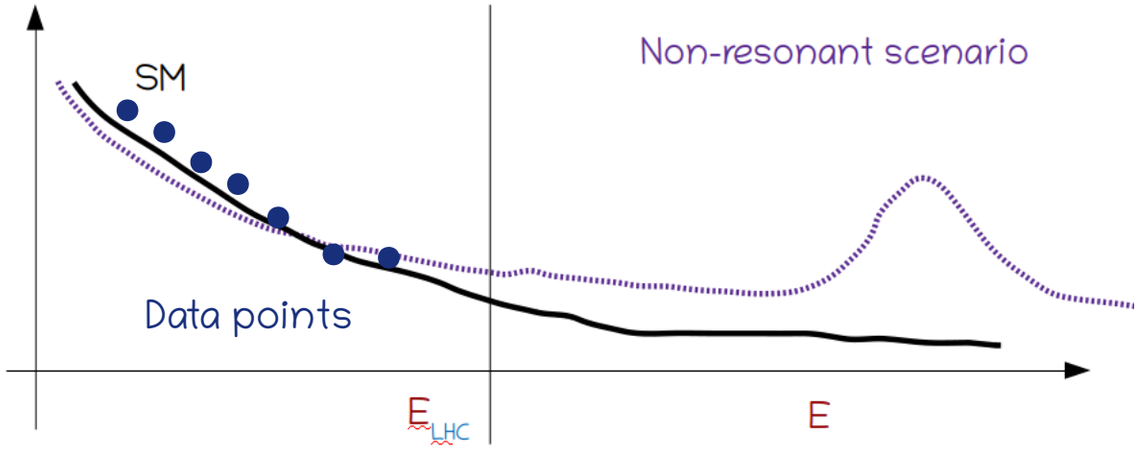
Model independence

Granular measurements improve sensitivity to new physics effects away from bulk

Effective field theory effects

Discovery through precision measurements





Interpretation in terms of effective field theory (EFT) operators

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda} \mathcal{O}_{5,i} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_{6,i} + \sum_i \frac{c_i^{(7)}}{\Lambda^3} \mathcal{O}_{7,i} + \sum_i \frac{c_i^{(8)}}{\Lambda^4} \mathcal{O}_{8,i} + \dots .$$

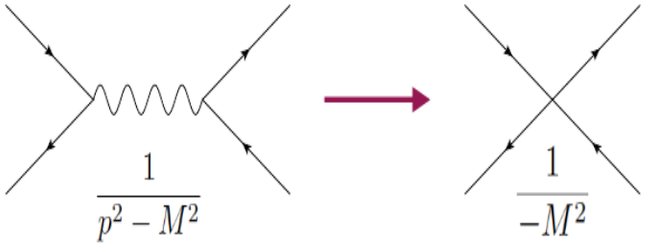
Lepton number violation

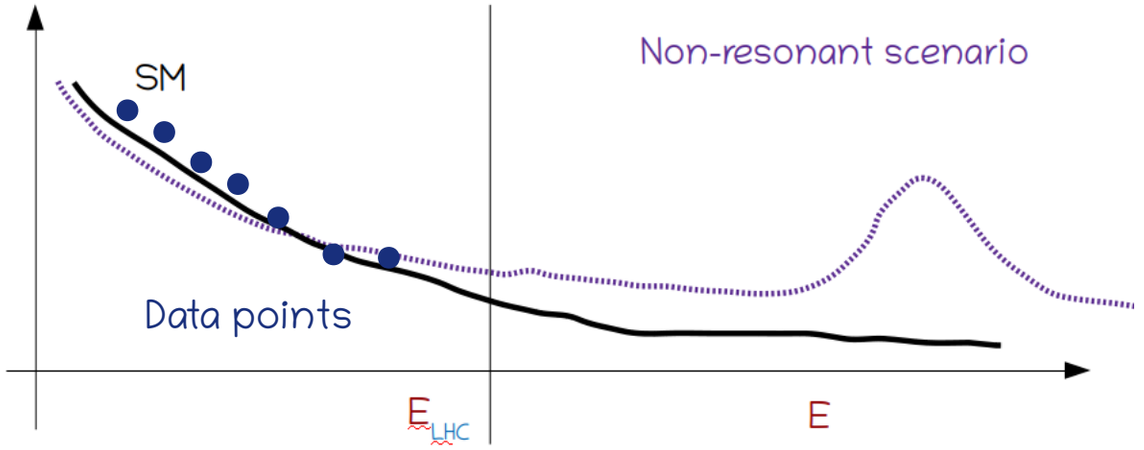
Lepton & Baryon number violation

Use measurements to probe size of dimension-6 EFT operator coefficients

Effective field theory effects

Discovery through precision measurements





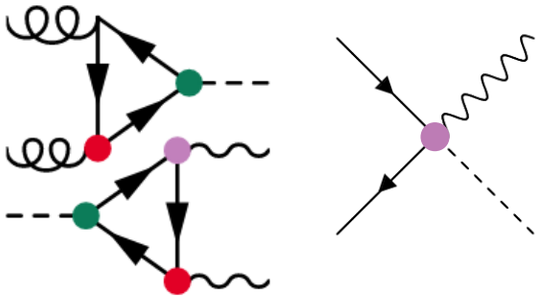
Interpretation in terms of effective field theory (EFT) operators

Requires a global approach

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda} \mathcal{O}_{5,i} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_{6,i} + \sum_i \frac{c_i^{(7)}}{\Lambda^3} \mathcal{O}_{7,i} + \sum_i \frac{c_i^{(8)}}{\Lambda^4} \mathcal{O}_{8,i} + \dots .$$

Lepton number violation

Lepton & Baryon number violation



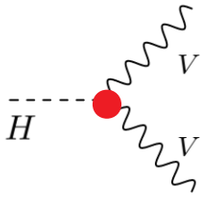
+ ...

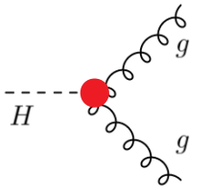
Use measurements to probe size of dimension-6 EFT operator coefficients

Anomalous couplings of Higgs boson

Higgs coupling to Gauge bosons

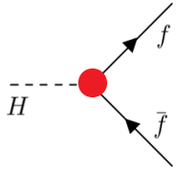
$$\mathcal{A}(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}}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





Higgs coupling to fermions

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



Constraints on anomalous couplings → bounds on EFT operator coefficients

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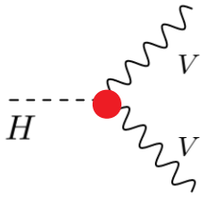

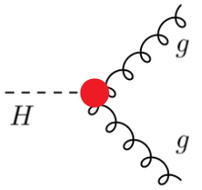

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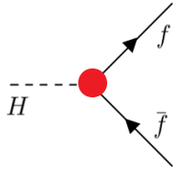

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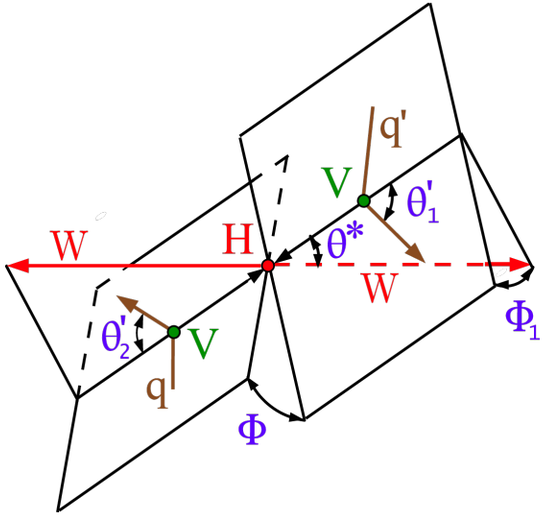

Example topology:

VBF H production + H→ WW* decay

Anomalous couplings of Higgs boson

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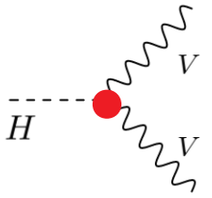

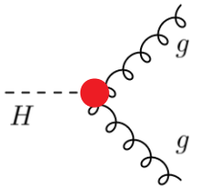

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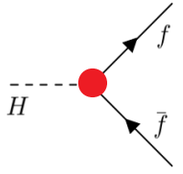
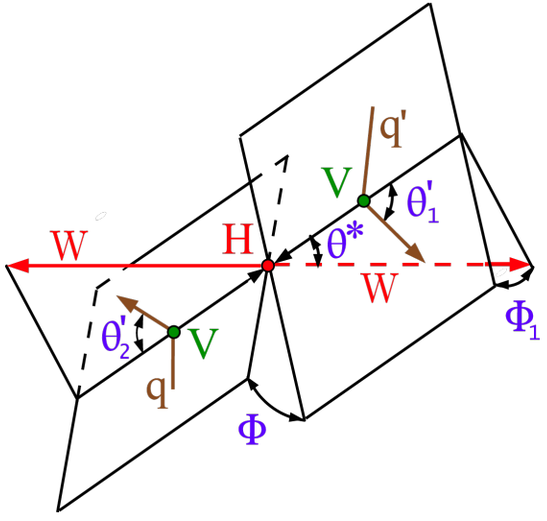


Constraints on anomalous couplings → bounds on EFT operator coefficients



Example topology:

VBF H production + H→ WW* decay

Matrix element likelihood approach (MELA)

Construct discriminants sensitive to individual anomalous couplings

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

(SM) signal-background & H production mode separation

Pure BSM

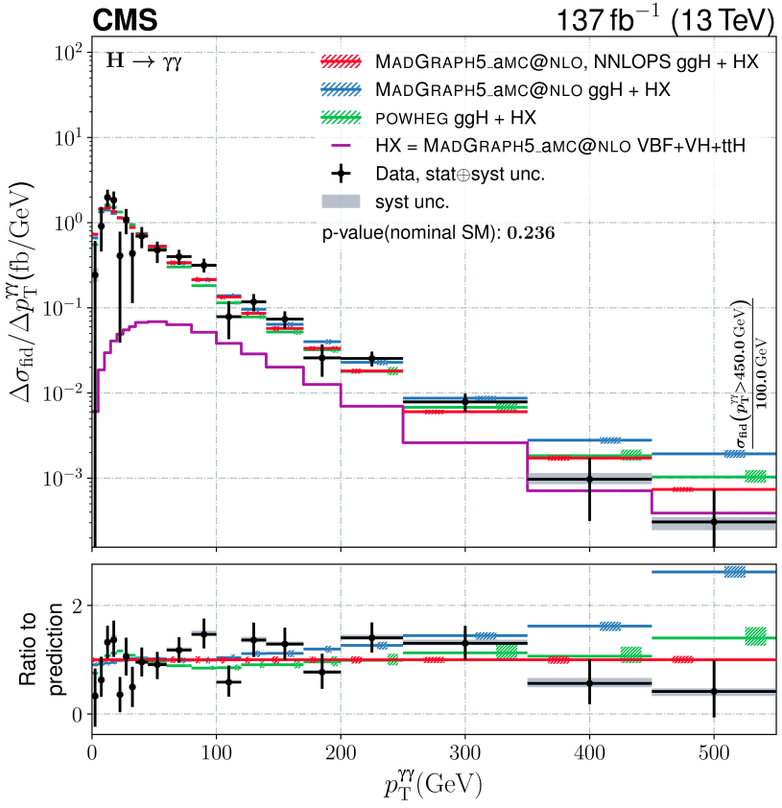
SM-BSM interference

Differential measurement: Higgs p_T in H→VV decay

Measurement of H p_T probes QCD and EWK modeling of H production → comparison between different predictions

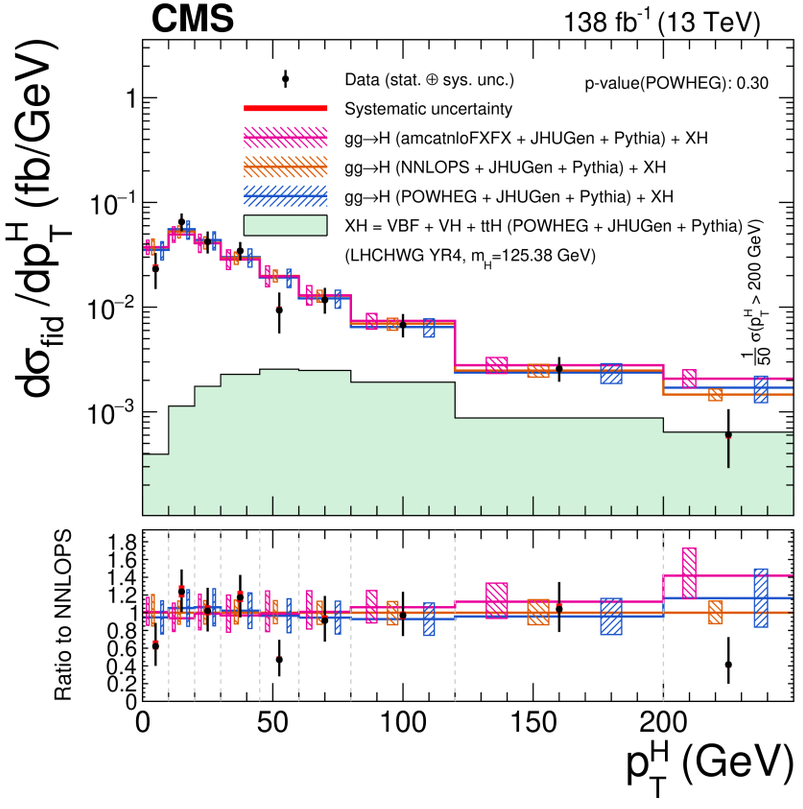
H→ γγ

JHEP 07 (2023) 091



H→ ZZ* → 4l (l= e, μ)

JHEP 08 (2023) 040



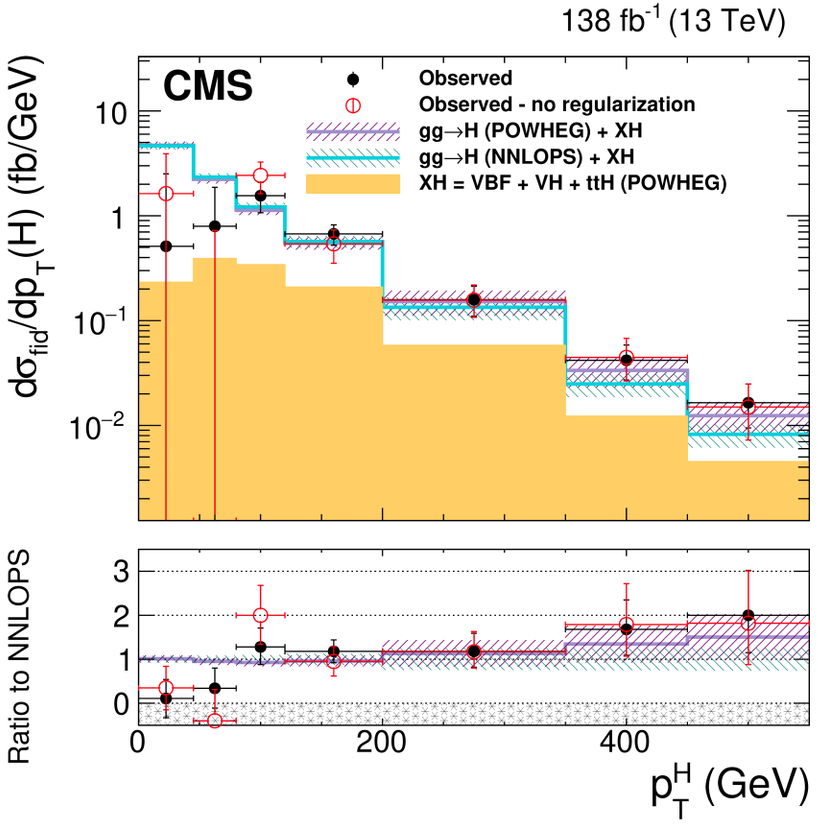
- Differential measurements also performed w.r.t. other variables: # of jets, H rapidity

Differential measurement: Higgs p_T in H→ff decay

Fermionic decay modes used to explore high-p_T region → special reconstruction technique used for boosted topology

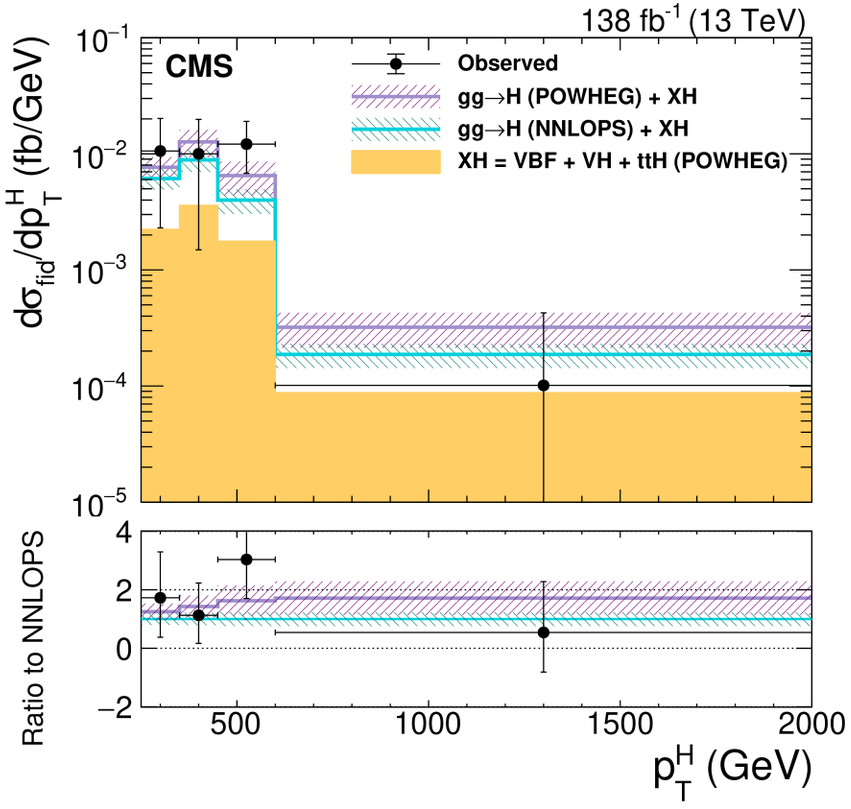
H→ ττ

Phys.Rev.Lett. 128 (2022) 8



H→ ττ (Boosted)

arXiv: 2403.20201 (Submitted to PLB)



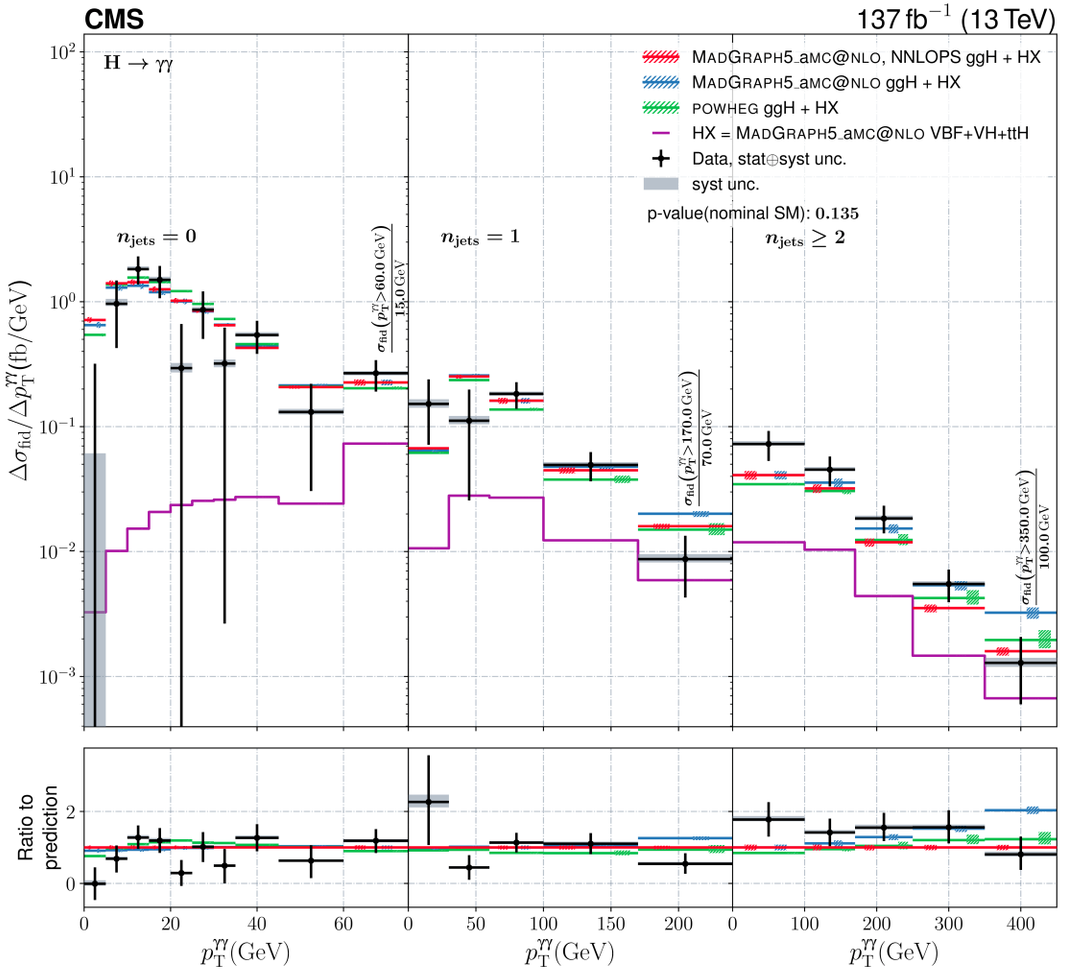
- Results for additional jet activity also reported
- High-p_T measurements are still statistics limited

Double differential measurements in H→VV decay

Measurement of H p_T in different ranges of # of number of jets, H rapidity → modeling of composition of production modes

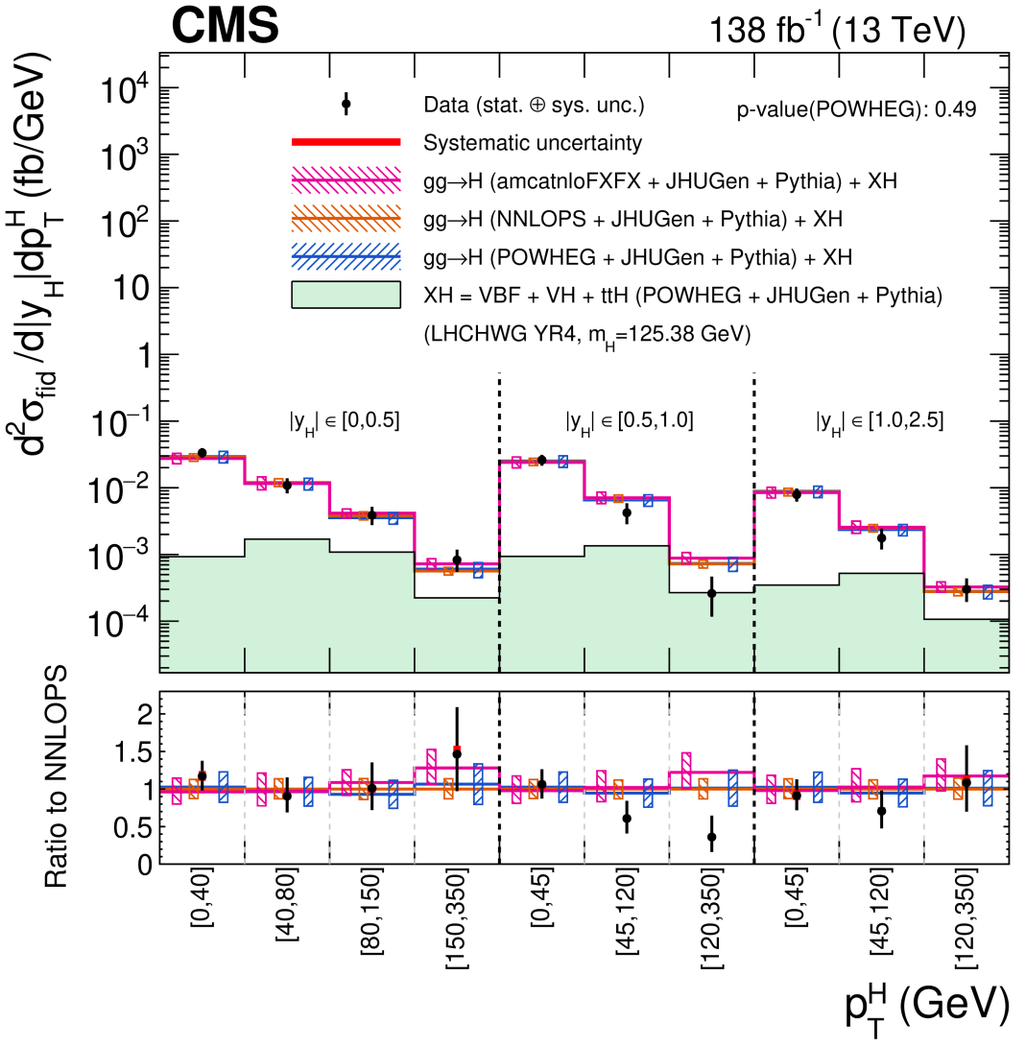
H→ γγ

JHEP 07 (2023) 091



H→ 22* → 4l (l= e, μ)

JHEP 08 (2023) 040

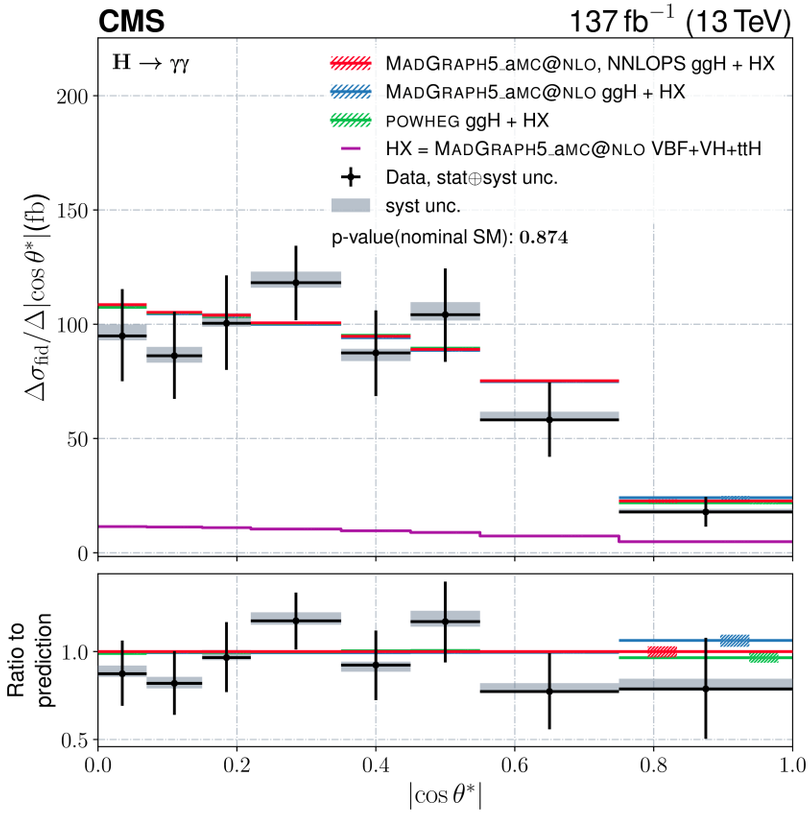


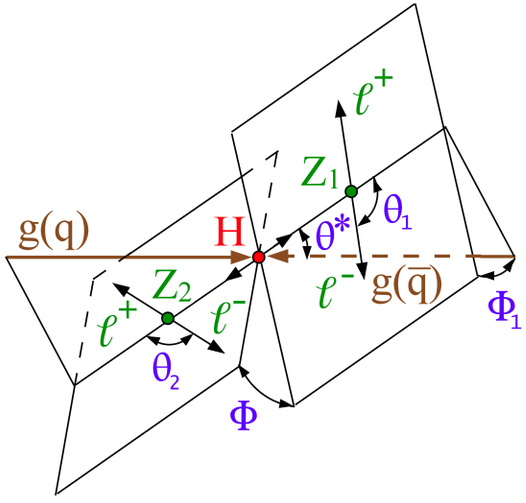
Differential measurement: Decay angles in H→VV decay

Measurement of angular variables in H rest frame → probing new physics effects in decay

H→ γγ

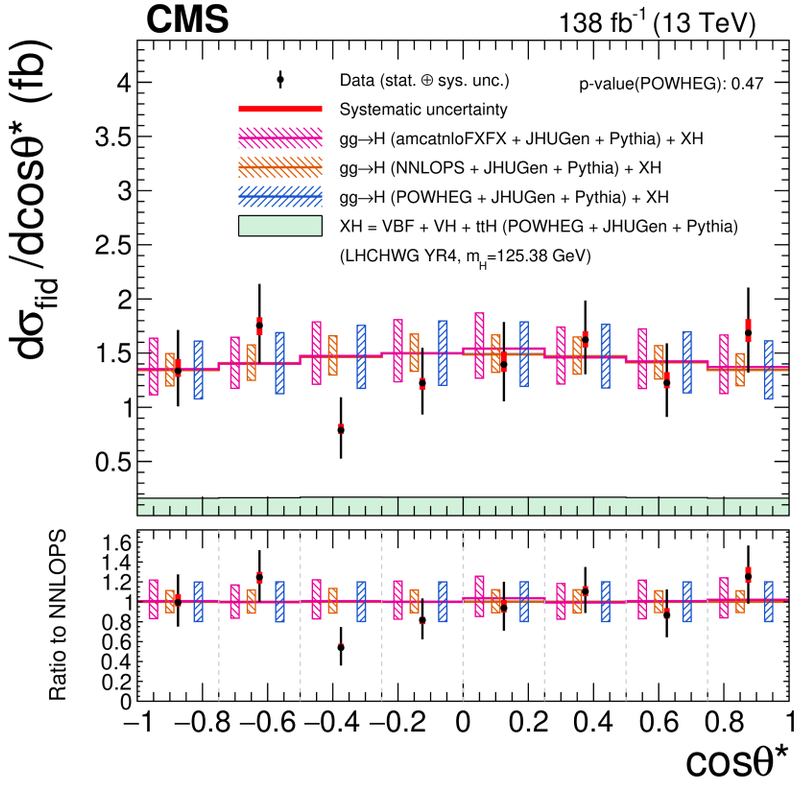
JHEP 07 (2023) 091





H→ ZZ* → 4l (l= e, μ)

JHEP 08 (2023) 040



Polar angle in Collins-Soper frame of diphoton system

- Differential measurements also performed w.r.t. event shape variables, final state object kinematics, MELA discriminants (for ZZ*)

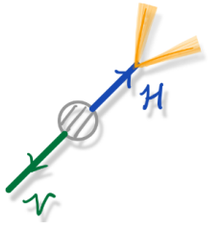
STXS measurements for VH(bb)

- Targeting leptonic V decays of V: $Z \to ll/\nu\nu$, $W \to l\nu$

Phys. Rev. D 109 (2024) 092011

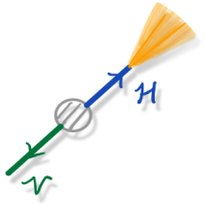
Resolved category

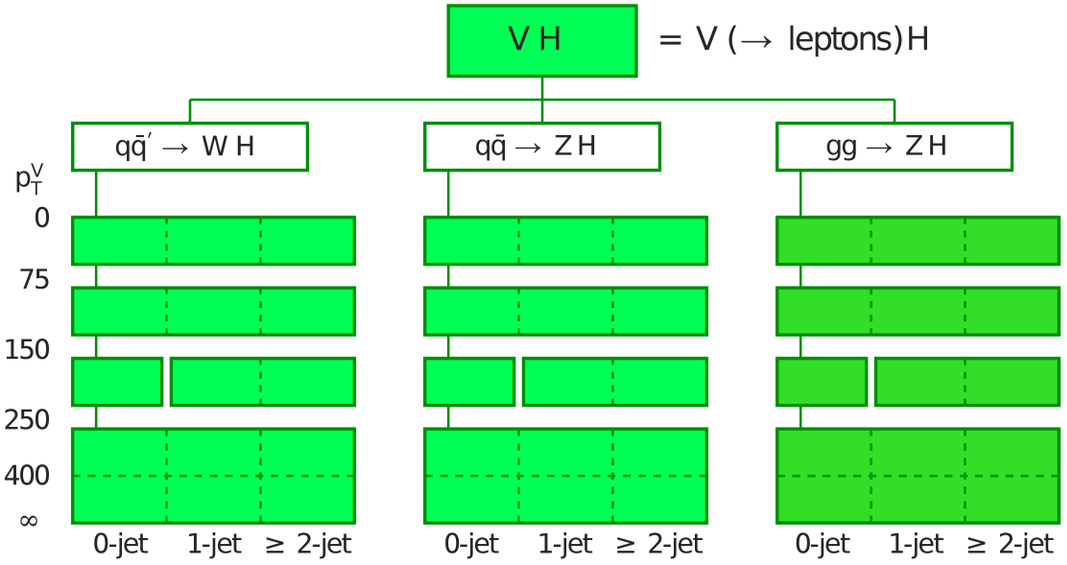
- 2 b-tagged AK4 jets [DeepJet]
- Signal extraction using DNN

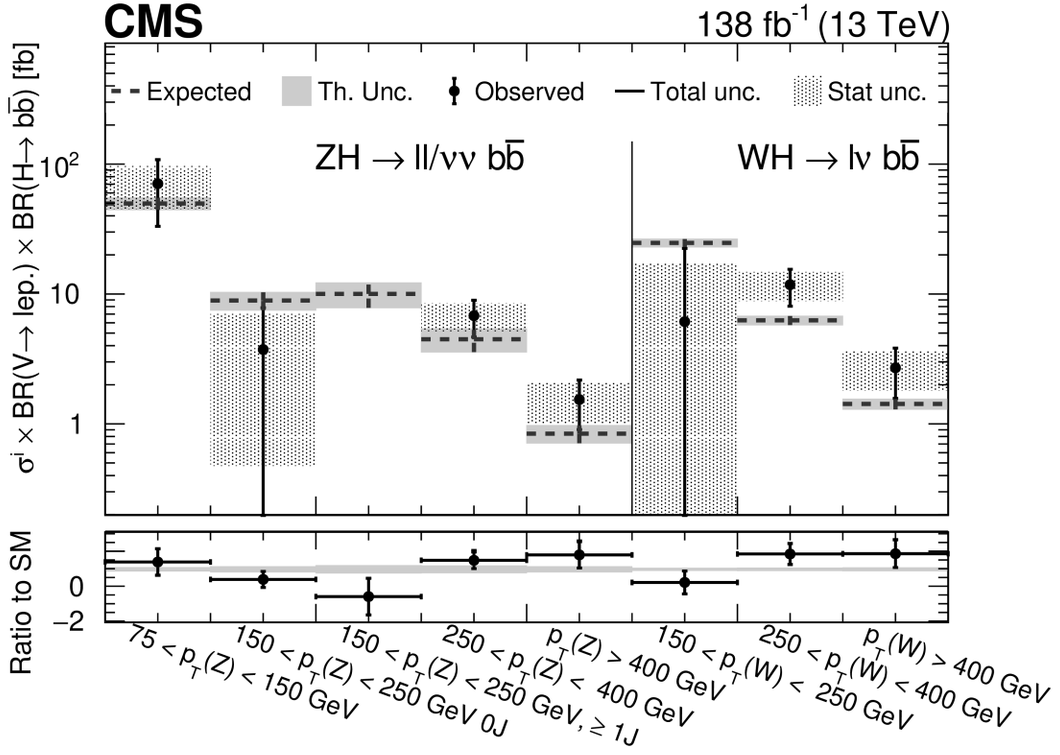


Boosted category

- 1 bb-tagged AK8 jets [DeepAK8]
- Signal extraction with BDT

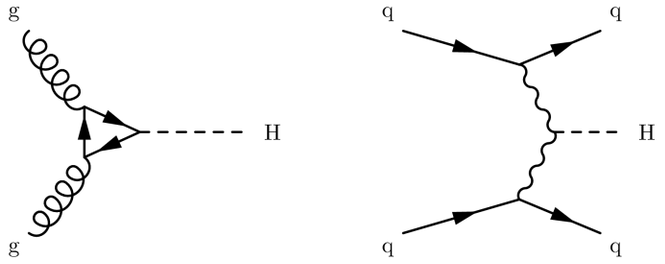


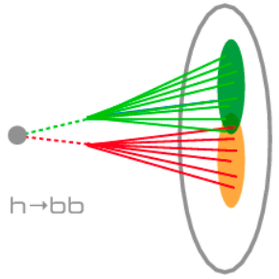




Largest deviation from SM: ~ 2σ in medium p_T ([150, 250] GeV) & 1-jet bin in ZH

Boosted H→bb production via vector boson and gluon fusion

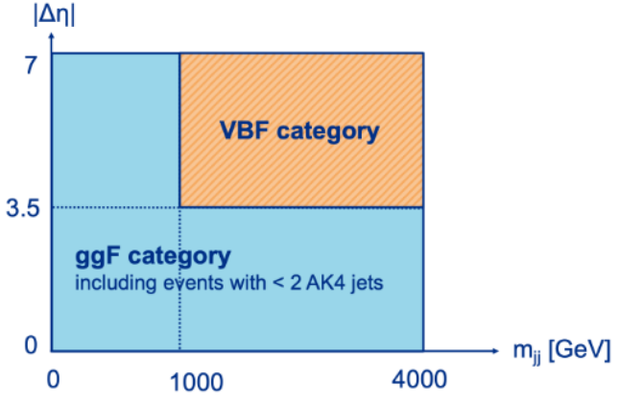




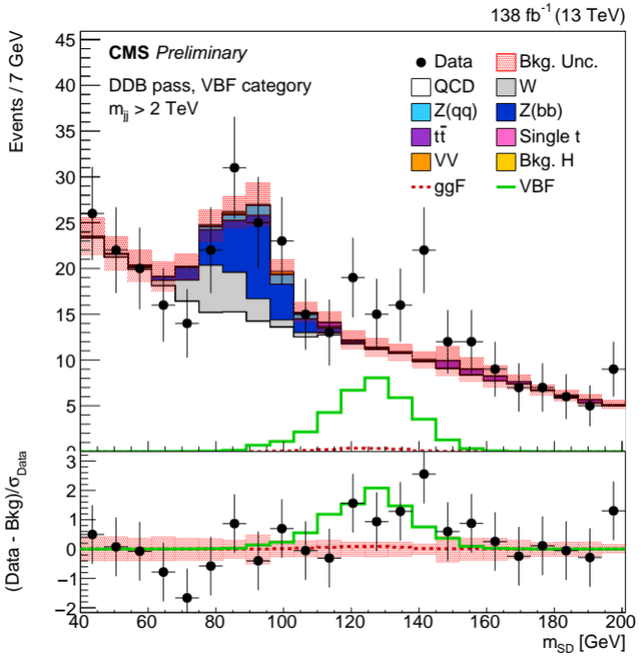
H → bb identification with AK8 jet:

- Double b tagging CMS-DP-2022-041
- N_2 Moult, Necib, Thaler (2016)

AK4 jets used to separate VBF and ggF productions

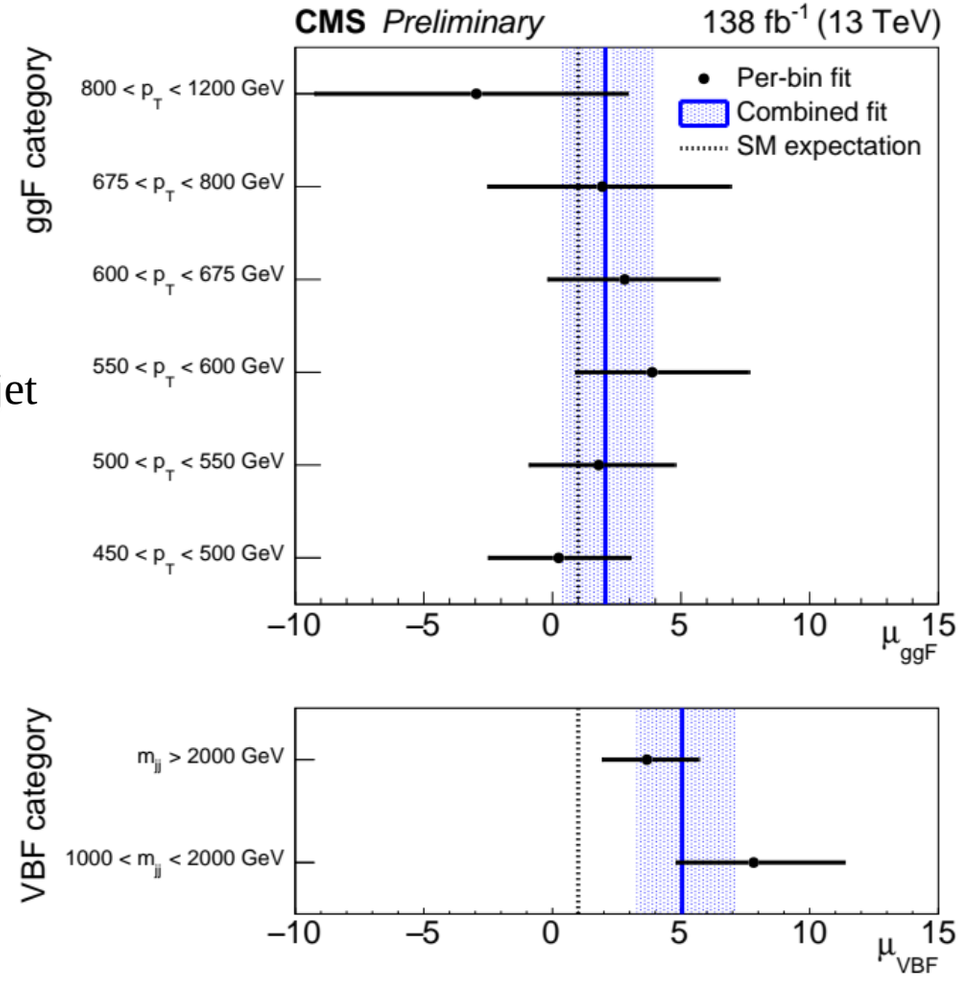


Signal extraction using soft-drop mass of H jet

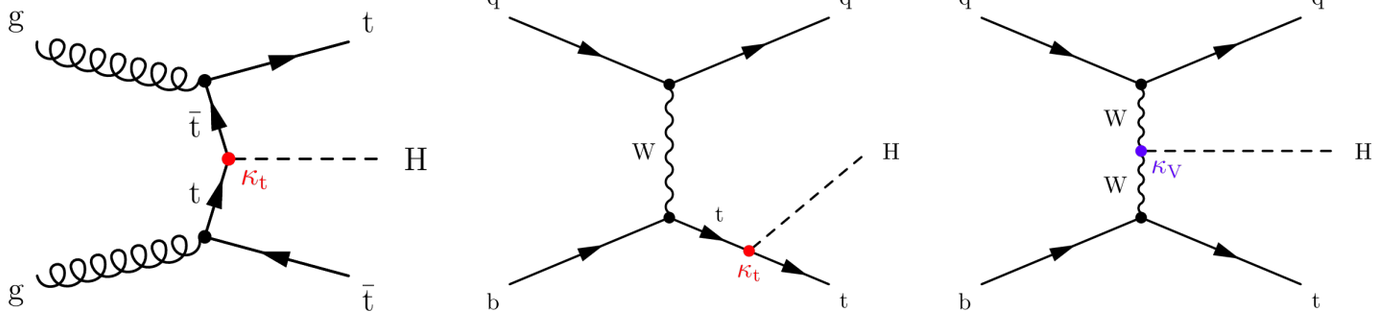


CMS-PAS-HIG-21-020

Results reported in reconstruction-level bins



STXS measurements for ttH/tH(bb)

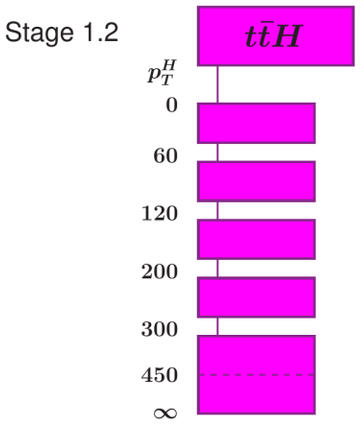


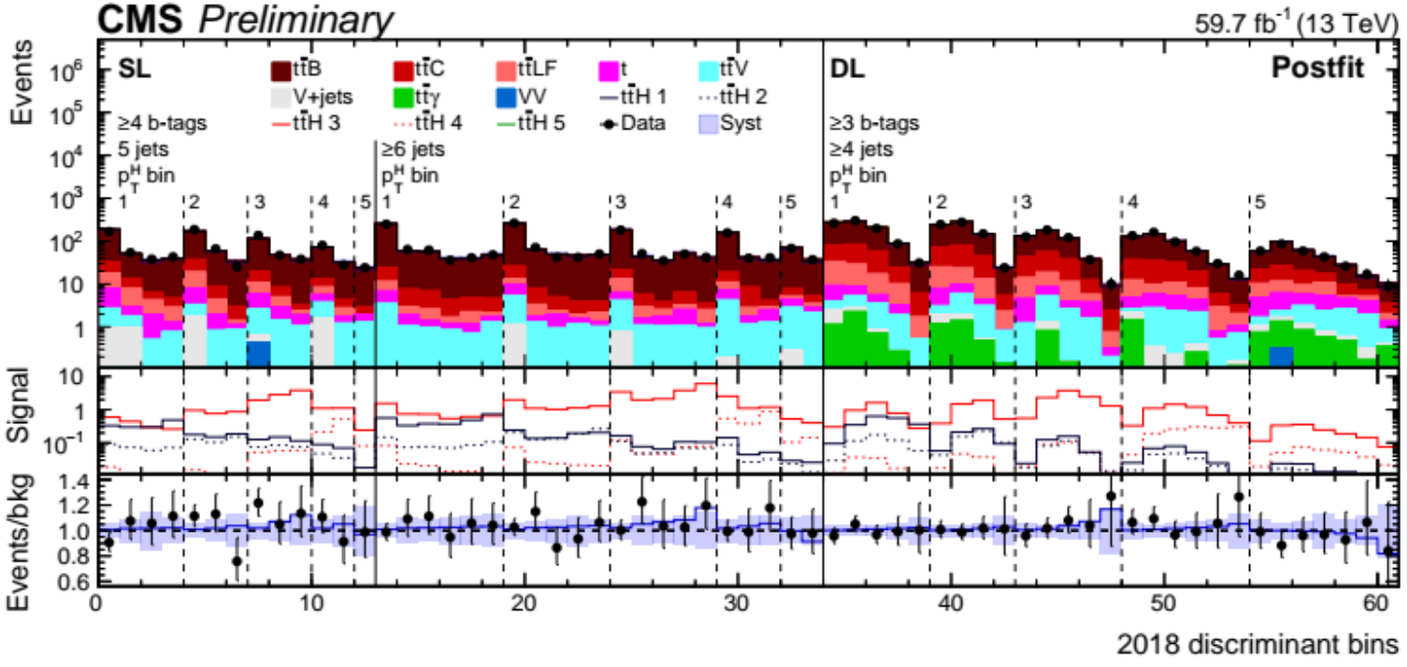
CMS-PAS-HIG-19-011

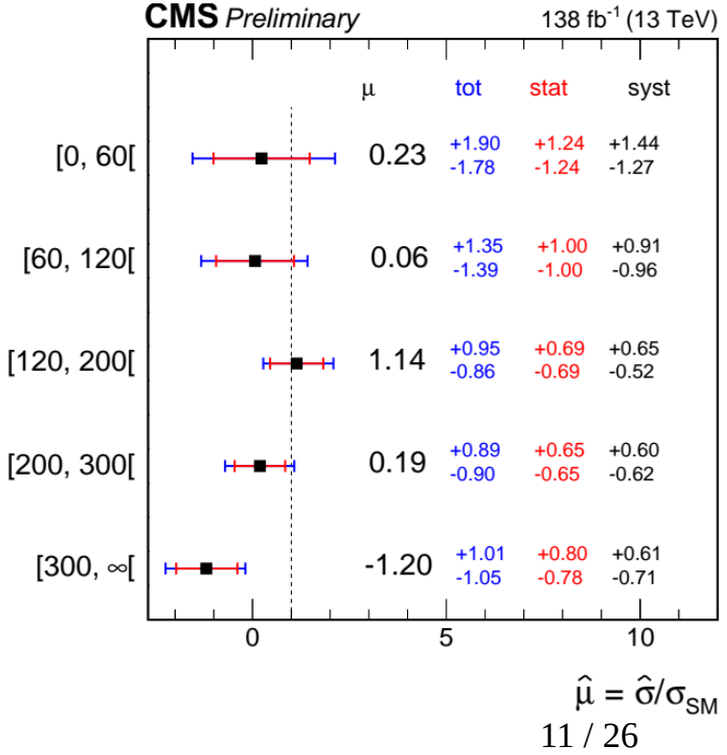
Assigning events to STXS H p_T bins:

- artificial neural networks (ANNs) [leptonic channels]
- kinematic reconstruction [hadronic channel]

Signal extraction with (combinations of) ANN scores







See M. Marchegiani's talk for details

Anomalous Higgs to top coupling

CP structure of t-H coupling is probed using ttH & tH measurements *(H-V coupling fixed to SM prediction)*

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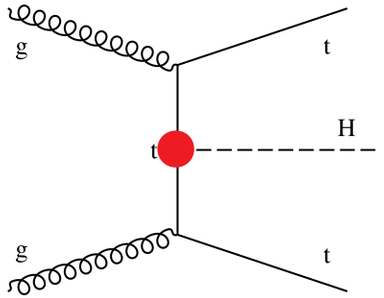

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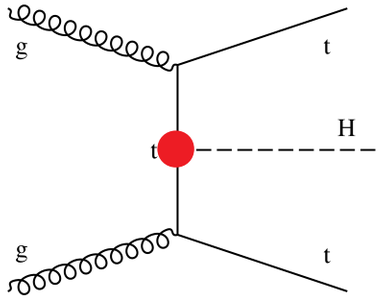
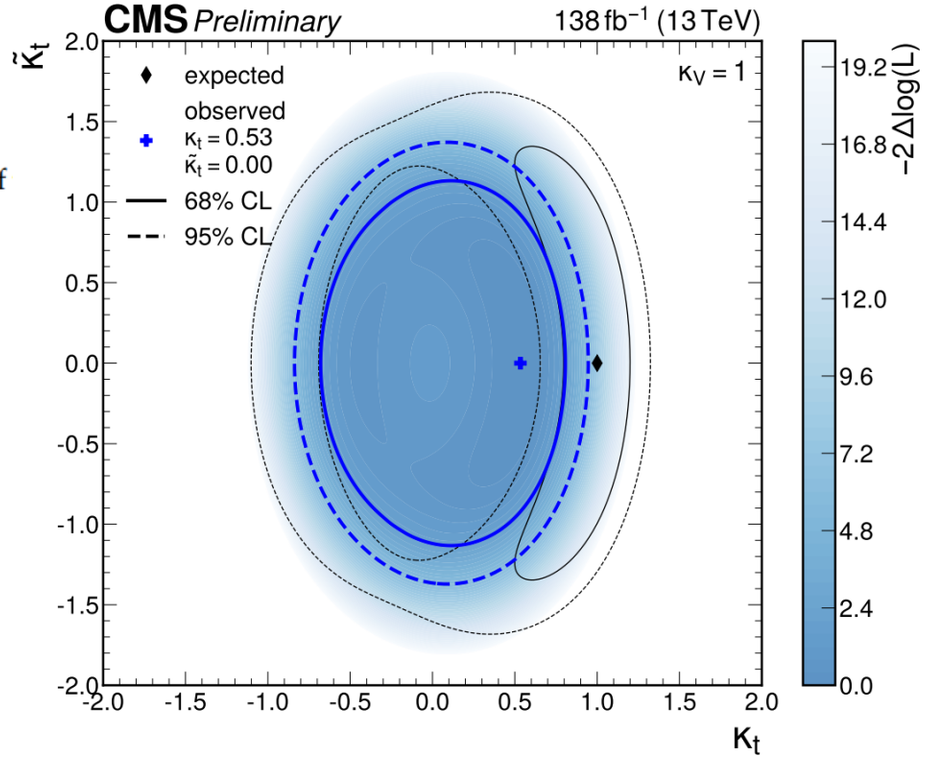


$H \to b\bar{b}$

CMS-PAS=HIG-19-011



Compatibility with SM: ~2σ

Anomalous Higgs to top coupling

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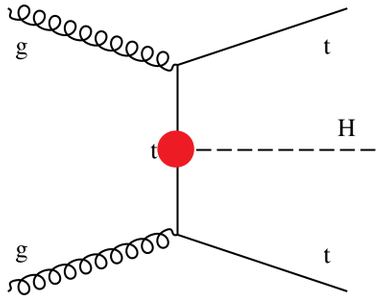

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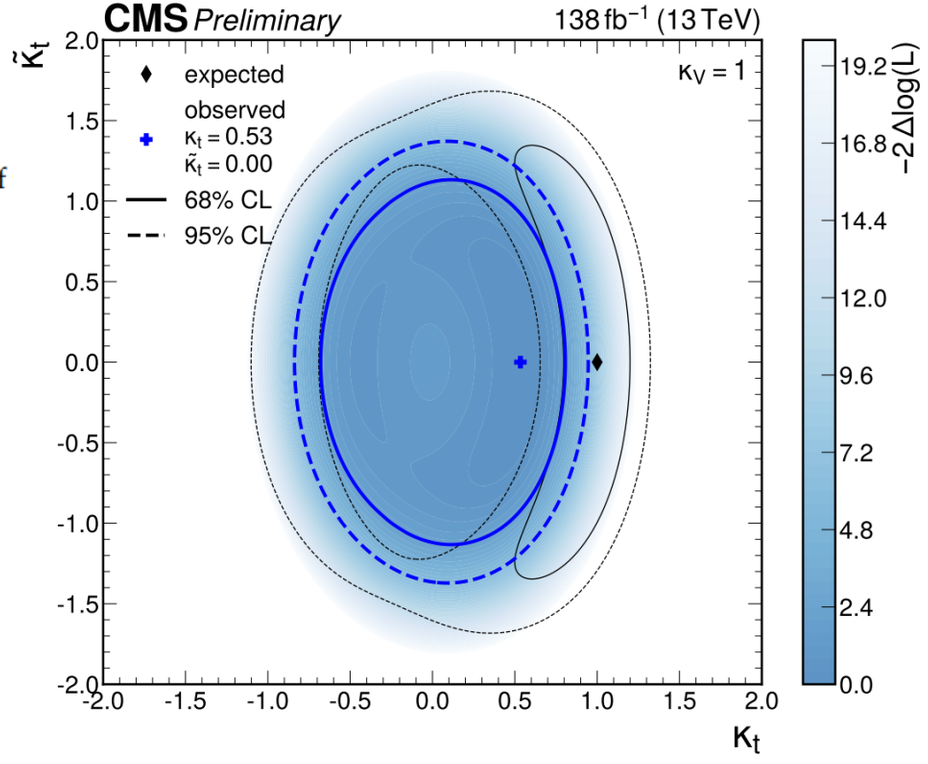
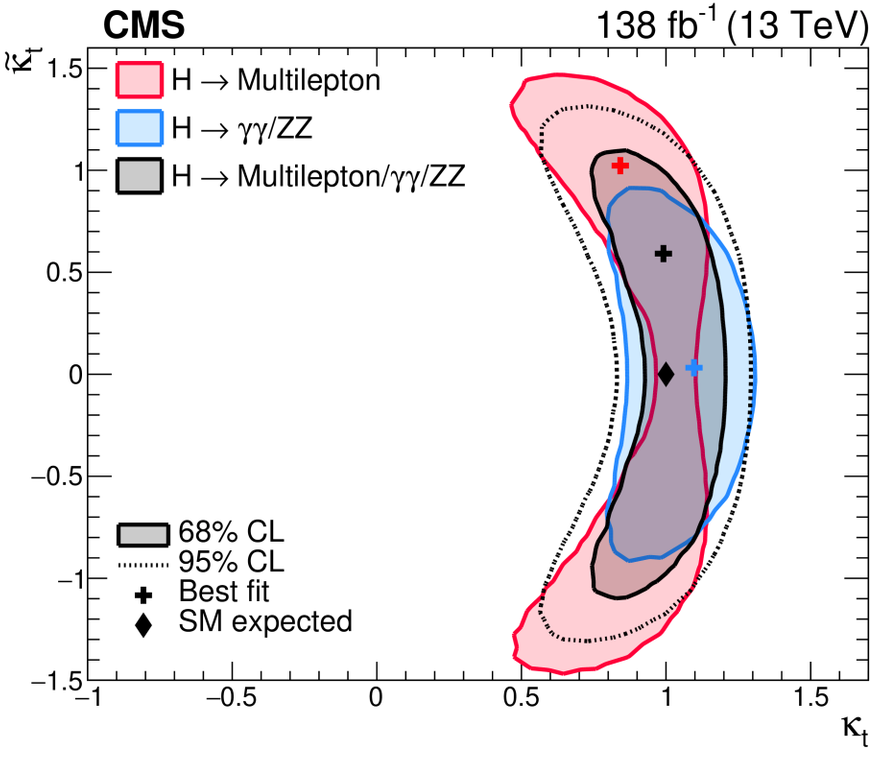
CMS-PAS-HIG-19-011



Compatibility with SM: ~2σ

$H \to ZZ^* / \gamma\gamma$ / Multilepton ($WW^* / \tau\tau$)

JHEP 07 (2023) 092



Pure CP-odd hypothesis excluded at 3.7σ

EFT analysis in ttH production: H→bb (boosted)

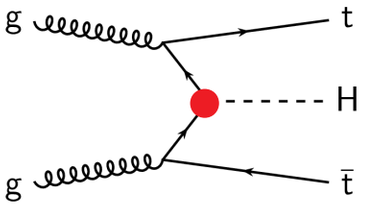
Phys.Rev.D 108 (2023) 032008

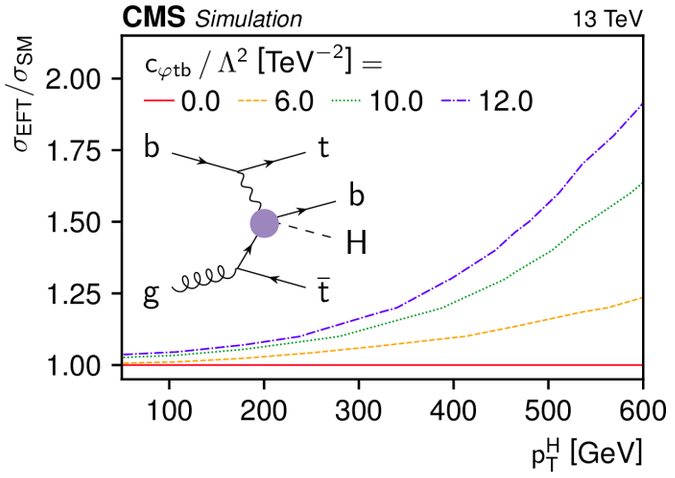
SMEFT operators at work

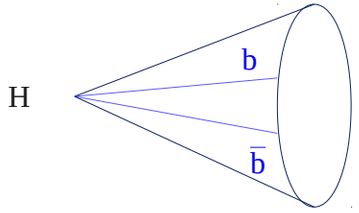
Dipole $\mathcal{O}_{tW}$

Current $\mathcal{O}^{(3)}_{\varphi Q}$ $\mathcal{O}^{-}_{\varphi Q}$ $\mathcal{O}_{\varphi t}$ $\mathcal{O}_{\varphi tb}$

Yukawa $\mathcal{O}_{t\varphi}$







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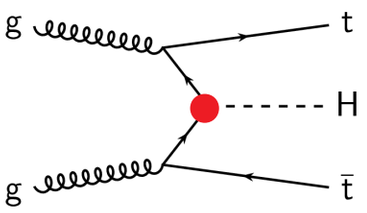

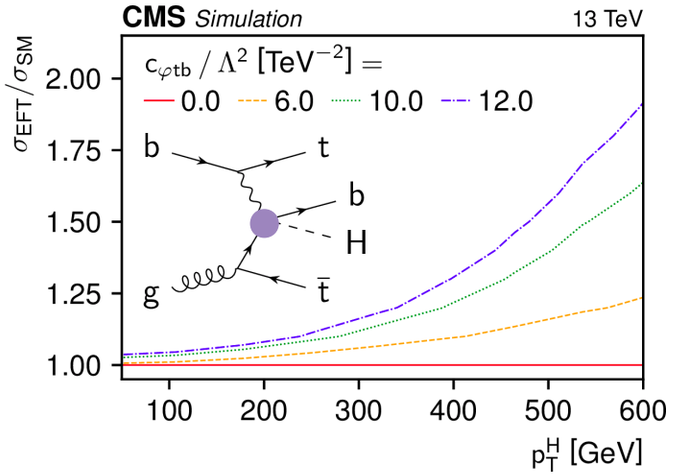

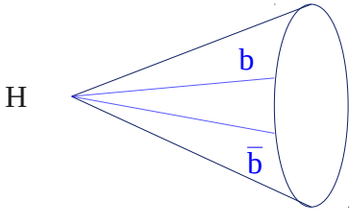

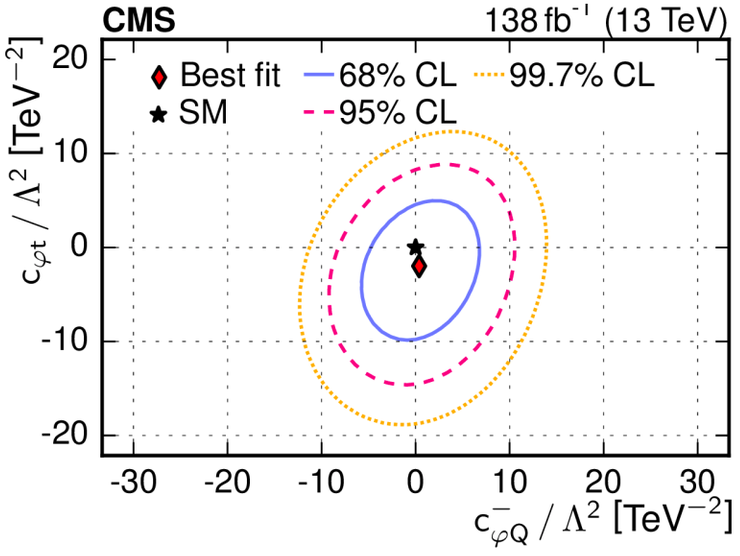

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Phys.Rev.D 108 (2023) 032008

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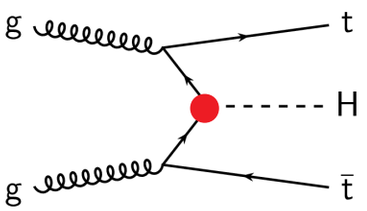
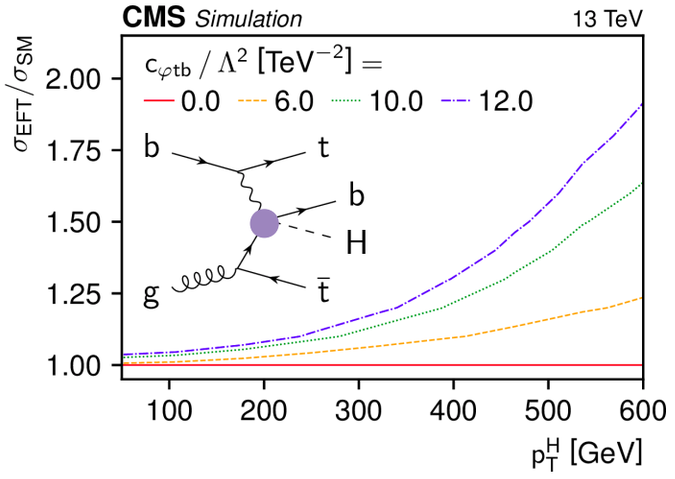
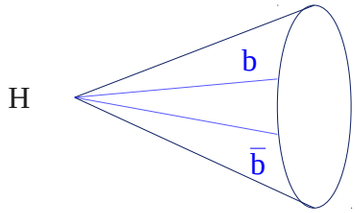
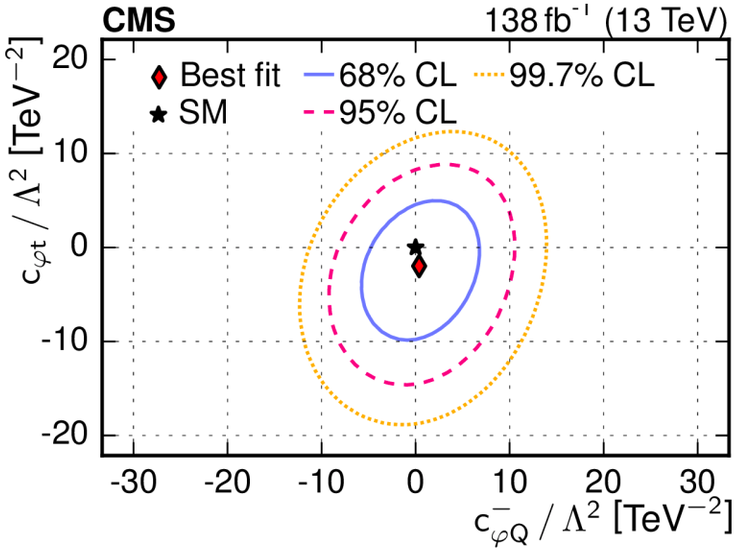
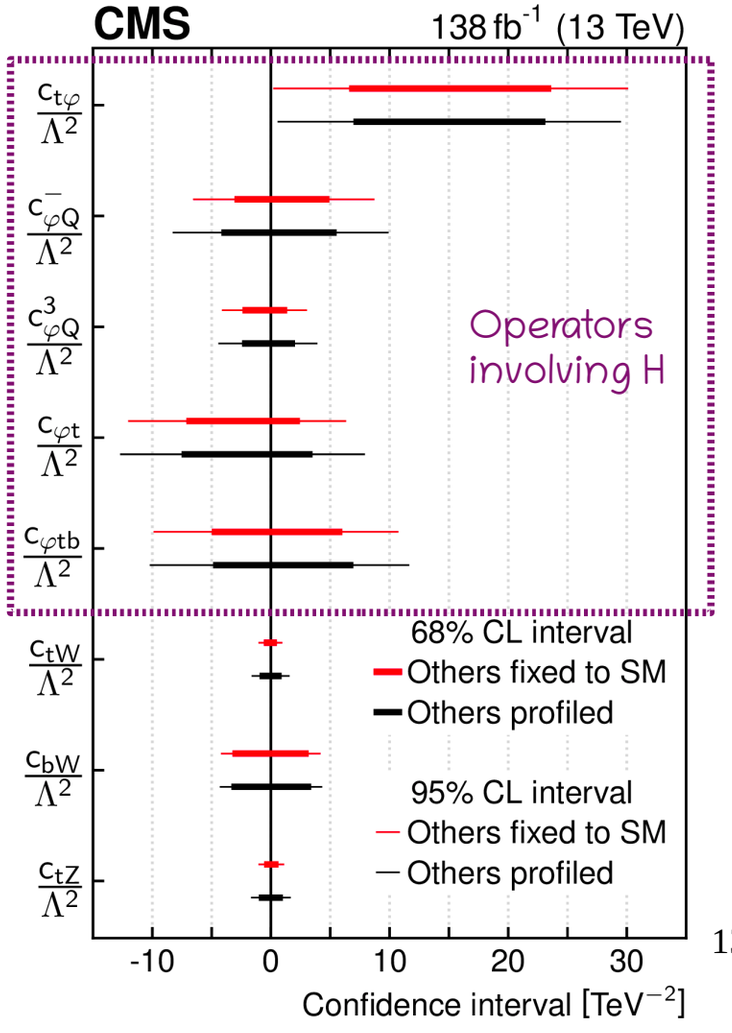








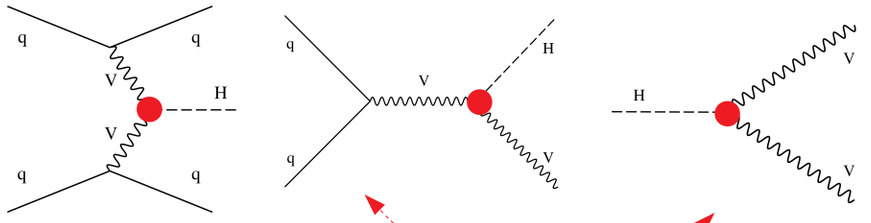


Smaller statistics compared to other measurements

[JHEP 03 (2020) 056, JHEP 03 (2021) 095, JHEP 12 (2021) 083, JHEP 05 (2022) 091]

← Still competitive in sensitivity

Anomalous H-V couplings with H→WW* decay mode



Effects in both production & decay

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

arXiv: 2403.00657
(accepted in EPJC)

Decay mode: H→ WW* → e μ ν_e ν_μ

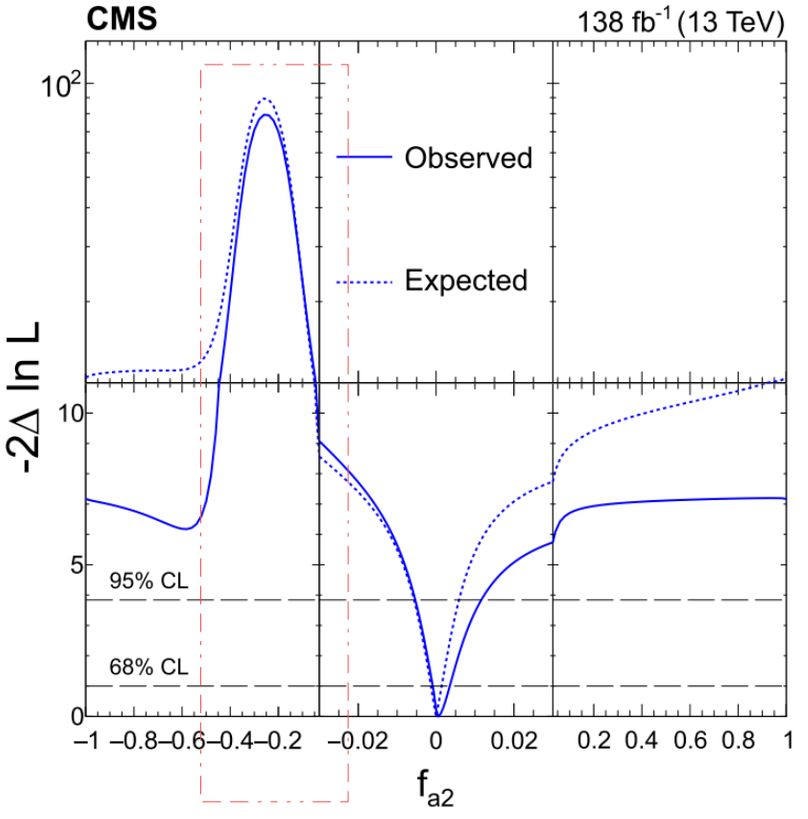
Extensive use of MELA variables:
To separate production modes & EFT effects (interference and pure-BSM)

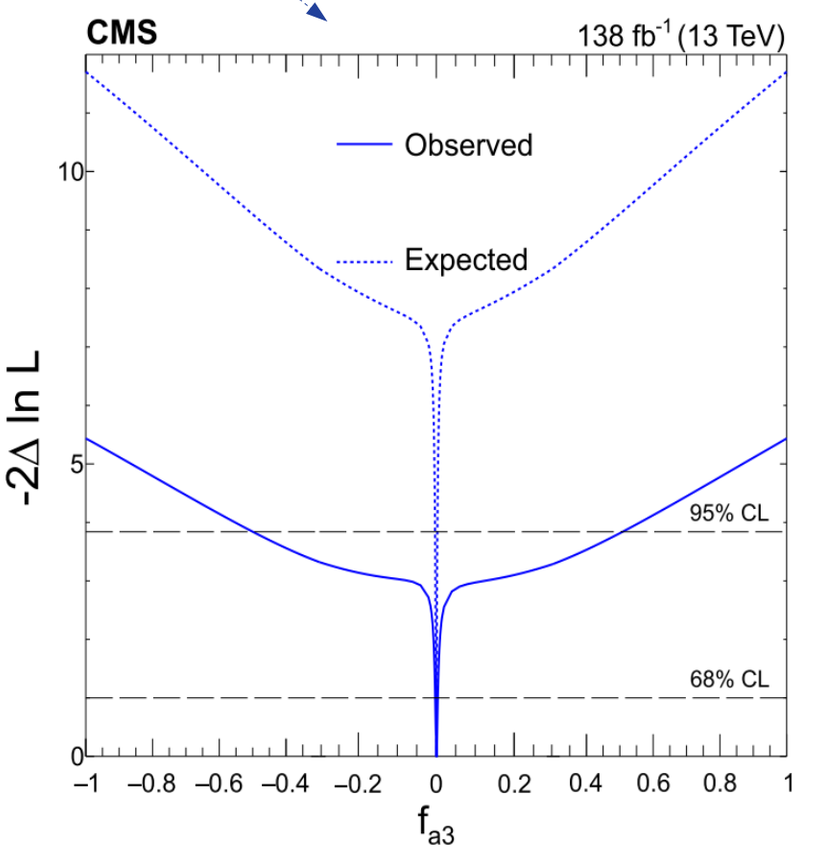
Approach 1:

Equal ZZ & WW couplings $a_i^{WW}=a_i^{ZZ}$

Observable:

$$f_{ai} = \frac{|a_i|^2\sigma_i}{\sum_j |a_j|^2\sigma_j}\,\mathrm{sign}\left(\frac{a_i}{a_1}\right)$$

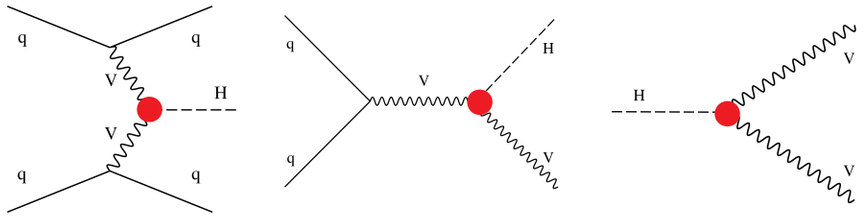




Interference effects are significant for a_2 (also for Λ_1)

Modification in VBF & VH production (w/ high q^2)
→ enhances sensitivity at low f_{ai}

Anomalous H-V couplings with H→WW* decay mode



arXiv: 2403.00657
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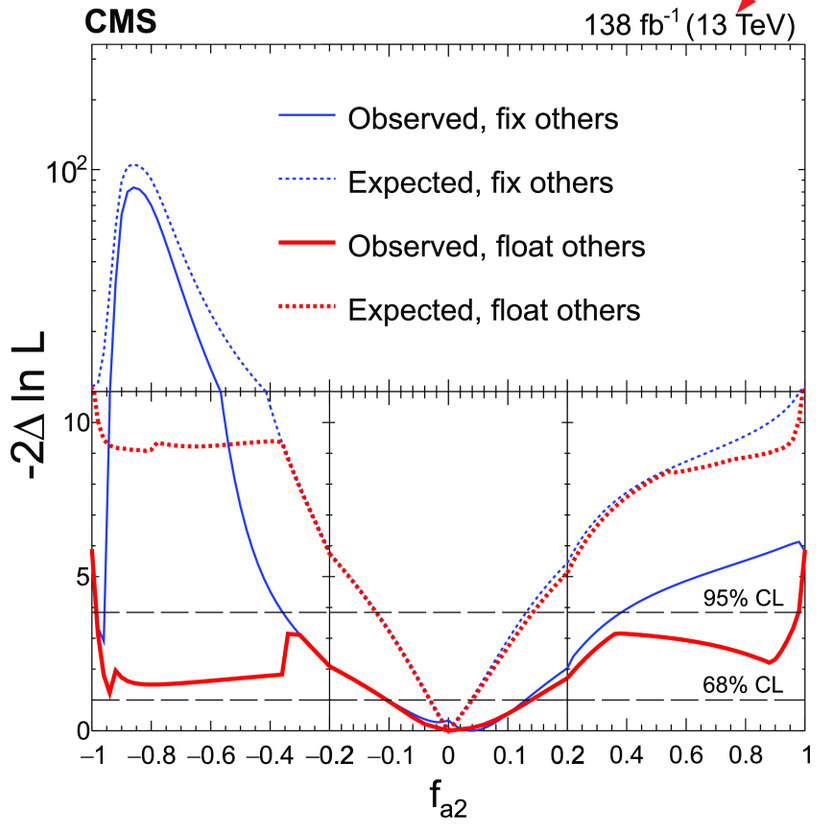
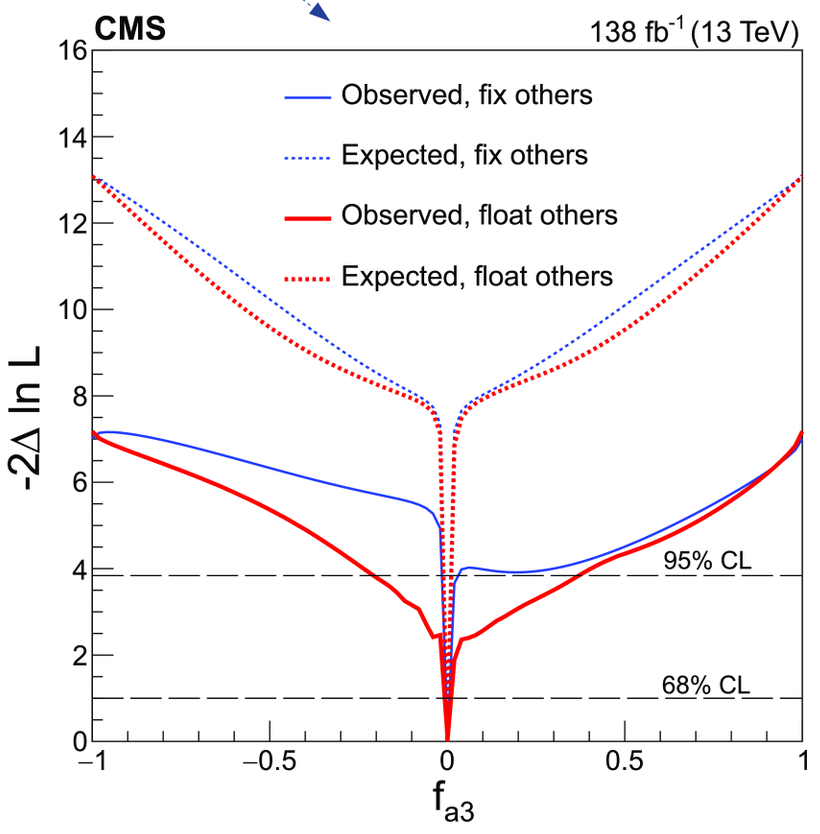
Approach 2:

Use SU(2)xU(1) symmetry

$$a_1^{\mathrm{WW}} = a_1^{\mathrm{ZZ}},$$
$$a_2^{\mathrm{WW}} = c_{\mathrm{w}}^2 a_2^{\mathrm{ZZ}},$$
$$a_3^{\mathrm{WW}} = c_{\mathrm{w}}^2 a_3^{\mathrm{ZZ}},$$
$$\frac{\kappa_1^{\mathrm{WW}}}{(\Lambda_1^{\mathrm{WW}})^2} = \frac{1}{c_{\mathrm{w}}^2 - s_{\mathrm{w}}^2} \left(\frac{\kappa_1^{\mathrm{ZZ}}}{(\Lambda_1^{\mathrm{ZZ}})^2} - 2 s_{\mathrm{w}}^2 \frac{a_2^{\mathrm{ZZ}}}{m_{\mathrm{Z}}^2} \right)$$
$$\frac{\kappa_2^{\mathrm{Z}\gamma}}{(\Lambda_1^{\mathrm{Z}\gamma})^2} = \frac{2 s_{\mathrm{w}} c_{\mathrm{w}}}{c_{\mathrm{w}}^2 - s_{\mathrm{w}}^2} \left(\frac{\kappa_1^{\mathrm{ZZ}}}{(\Lambda_1^{\mathrm{ZZ}})^2} - \frac{a_2^{\mathrm{ZZ}}}{m_{\mathrm{Z}}^2} \right),$$



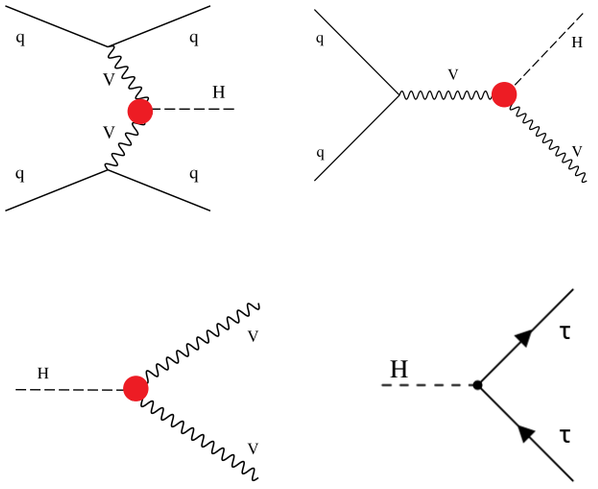


Compatibility with SM: p-value ~ 91% (while floating all anomalous couplings together)

Constraints translated to SMEFT operator coefficients (including CP-odd operators) in Higgs & Warsaw bases

Anomalous H-V couplings in H→ 4-lepton and ττ final states

Phys.Rev.D 108 (2023) 3, 032013



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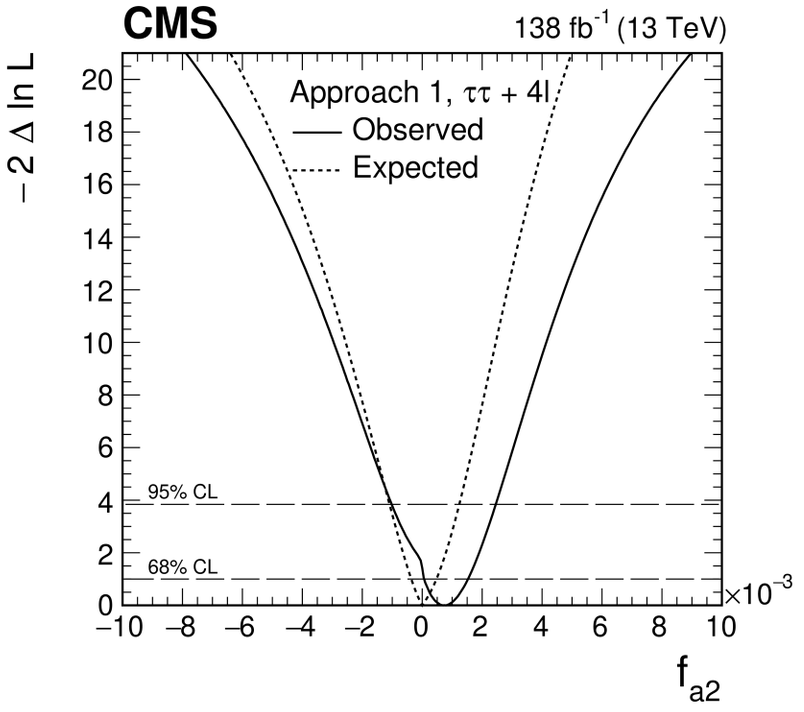
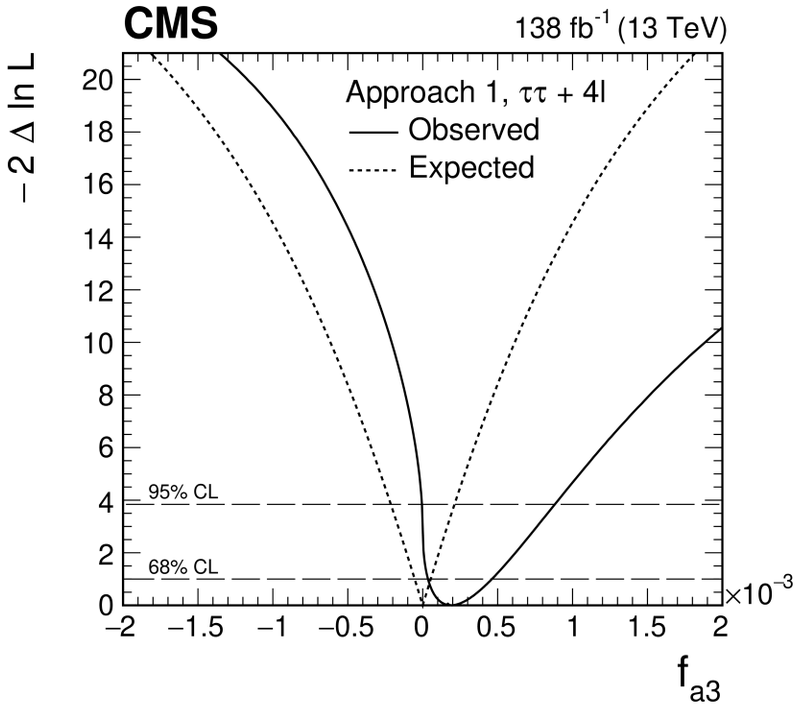




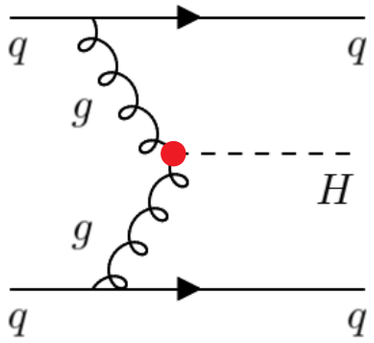
Approach 1:

Equal ZZ & WW couplings $a_i^{WW}=a_i^{ZZ}$

Strong constraints on CP-even and -odd anomalous Higgs to electroweak vector boson couplings

Anomalous Higgs to gluon couplings

Higgs-to-gluon coupling in production is probed in H+2 jets events



$$f_{a3}^{ggH} = \frac{|a_3^{gg}|^2}{|a_2^{gg}|^2 + |a_3^{gg}|^2} \operatorname{sgn}\left(\frac{a_3^{gg}}{a_2^{gg}}\right)$$

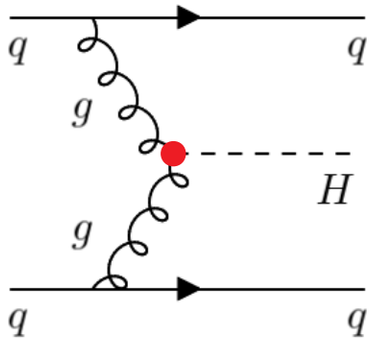
CP-odd cross section fraction

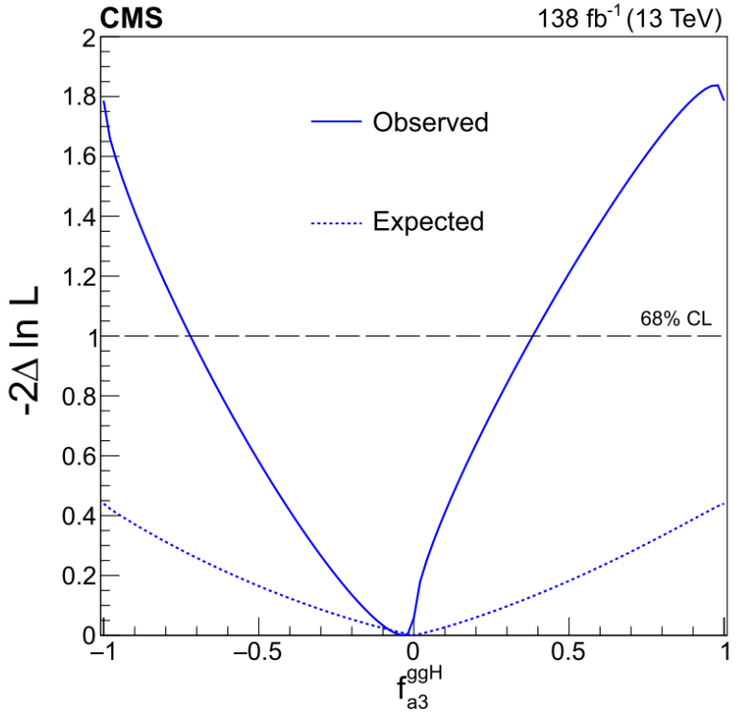
Anomalous Higgs to gluon couplings

Higgs-to-gluon coupling in production is probed in H+2 jets events

H→ WW*

arXiv: 2403.00657 (accepted in EPJC)





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CP-odd cross section fraction = -0.034 [+ 0.38 – 0.72 @ 68% CL]

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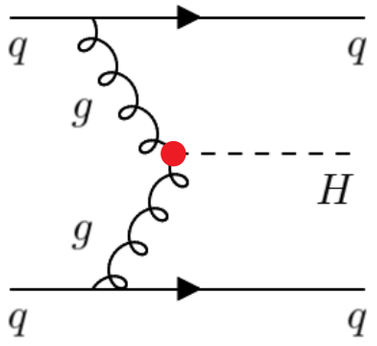

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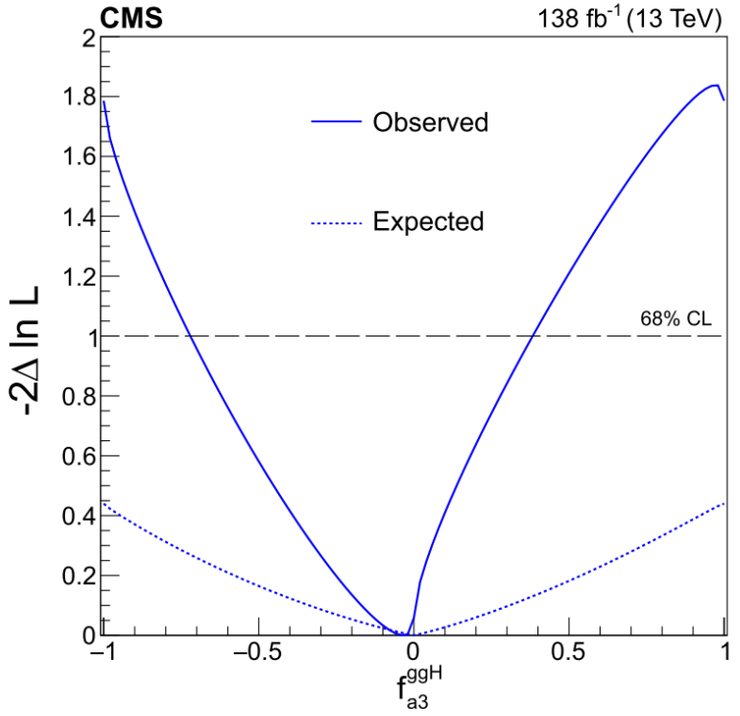
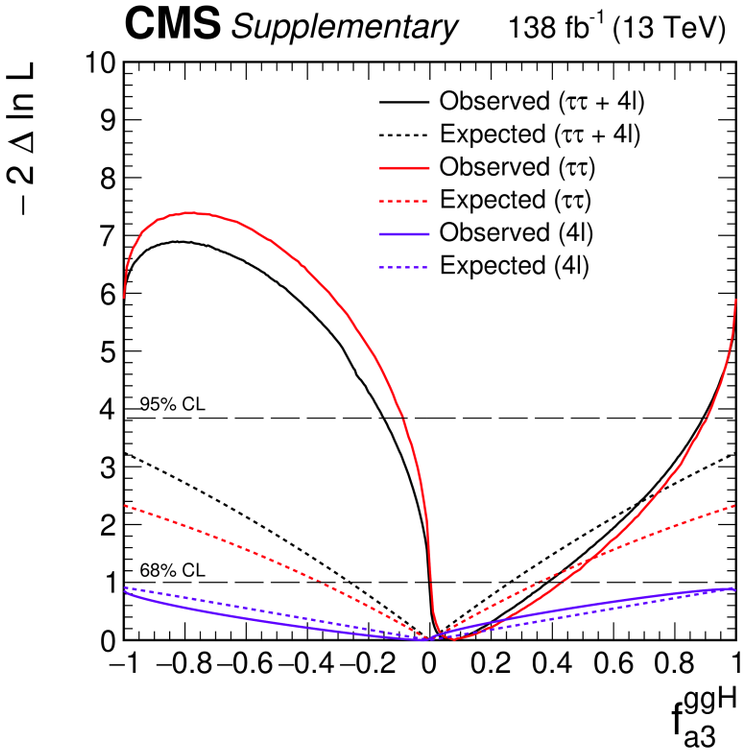
arXiv: 2403.00657 (accepted in EPJC)



CP-odd cross section fraction = -0.034 [+ 0.38 – 0.72 @ 68% CL]

H→ ττ + H→ ZZ*→ 4l

Phys.Rev.D 108 (2023) 3, 032013



= 0.07 [+ 0.32 – 0.07 @ 68% CL]

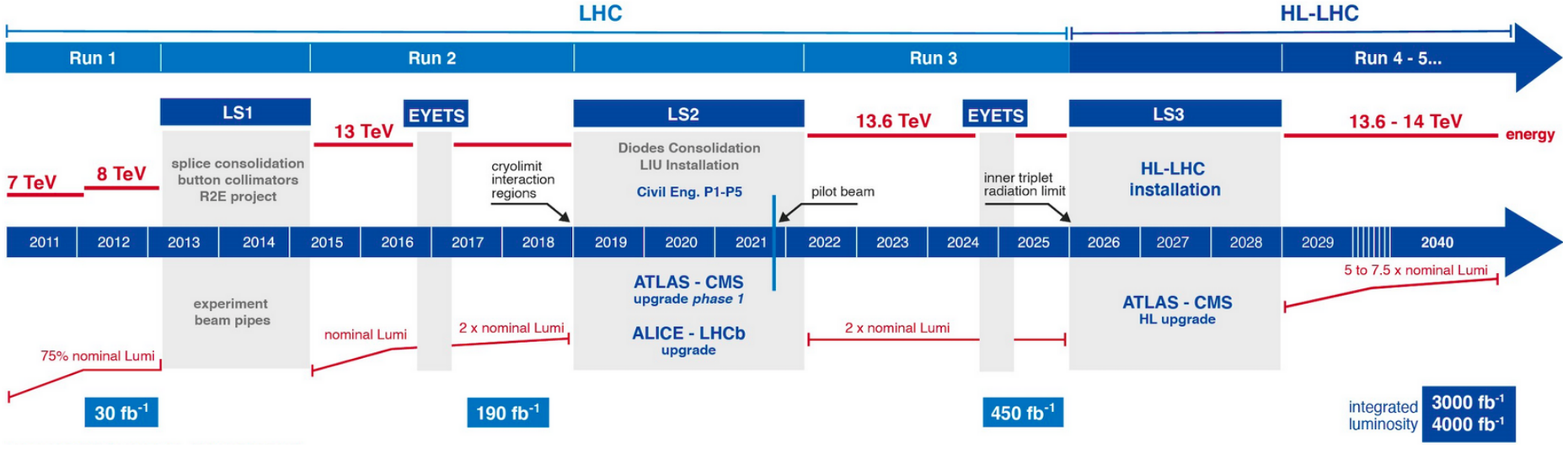
Summary & Outlook

- Experiments performing more granular measurements with larger data set
- Probing Higgs boson couplings and EFT operator effects to test possible new physics scenarios
- A subset of results presented here, new interesting ones on the way *(e.g., combination of measurements)*

Not covered in this talk:

EFT effects in di-Higgs production (see I. Dutta's talk)
EFT effects in H-τ coupling
(see C. R. Alvarez's talk & L.Kang's talk)

Looking forward to new results from Run-3 & beyond



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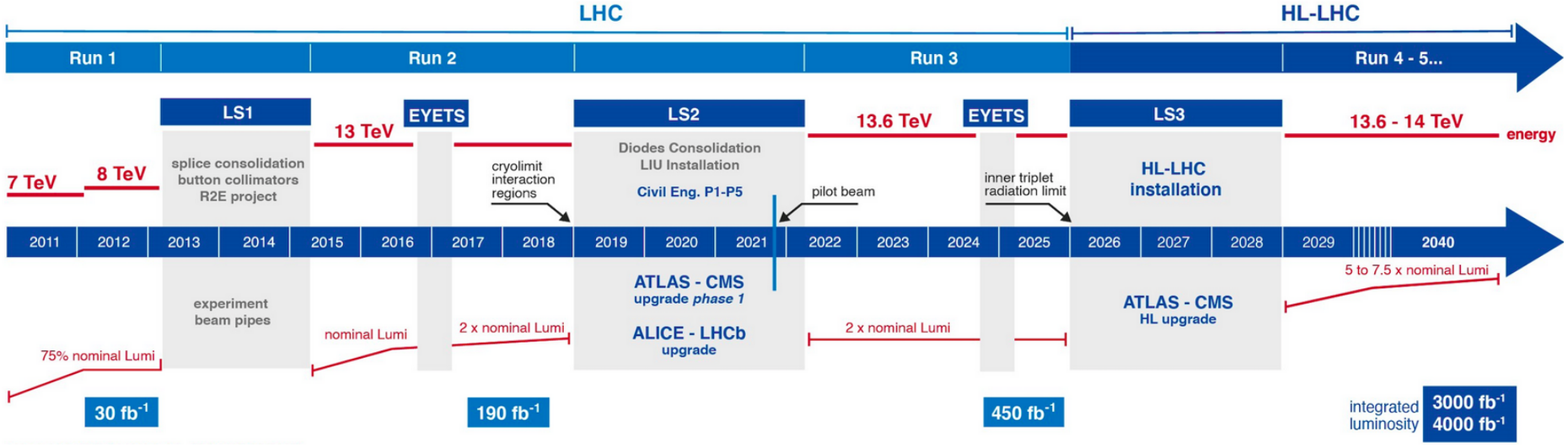
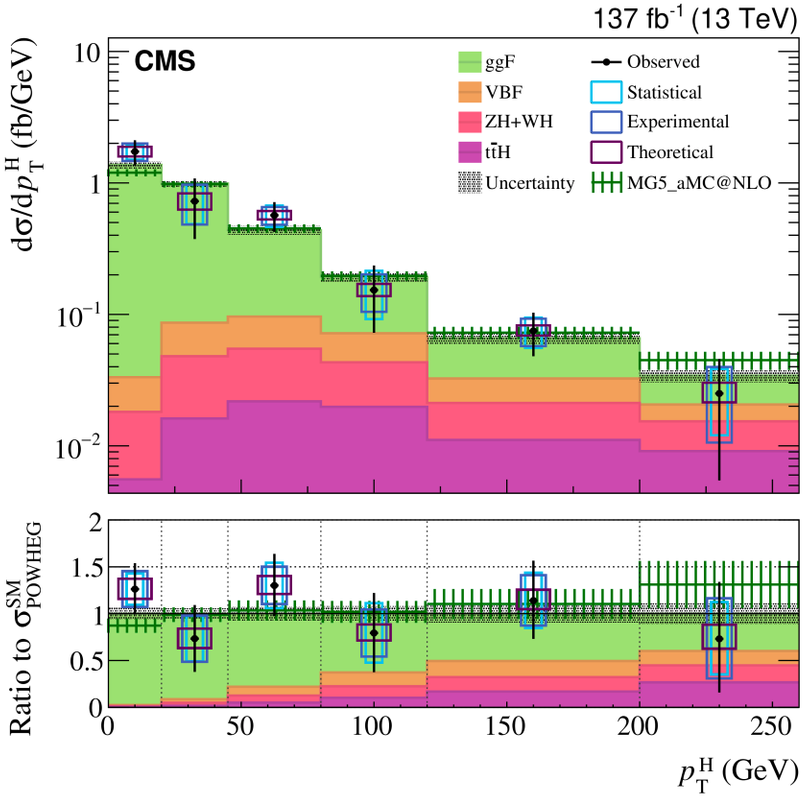


Extra Material

Differential measurement: Higgs p_T

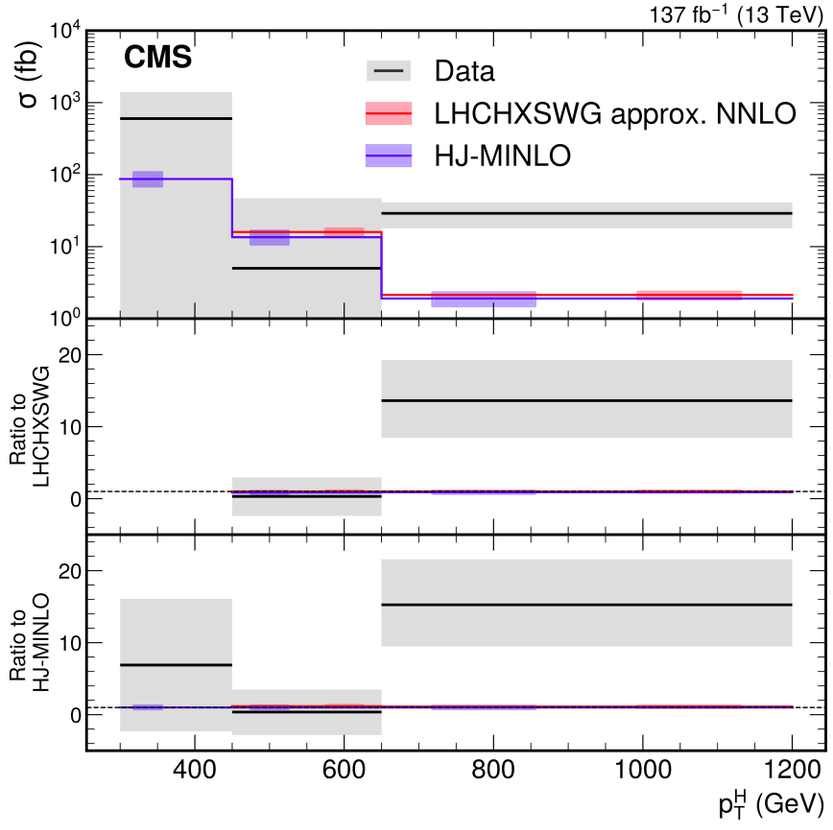
$H \to WW^* \to e\,\mu\,\nu_e\,\nu_\mu$

JHEP 03 (2021) 003



$H \to b\bar{b}$ (Boosted)

JHEP 12 (2020) 085



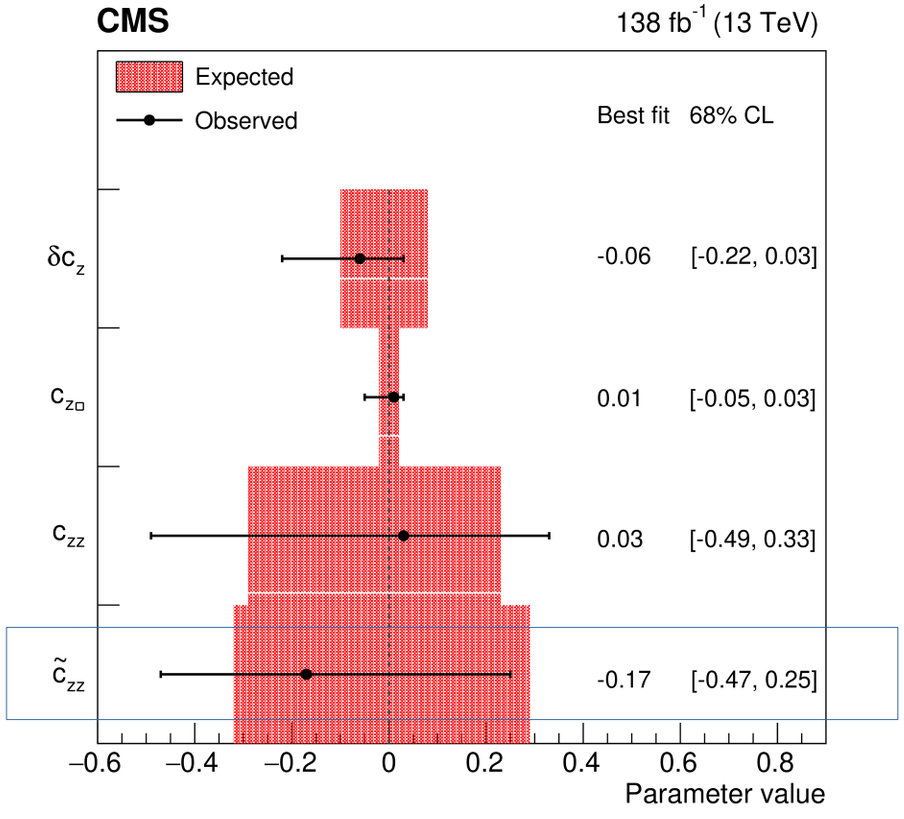
- Differential measurements also performed w.r.t. other variables: # of jets (in all cases), H rapidity (for $H \to \gamma\gamma$ & $H \to$ 4l)

Anomalous H-V couplings with H→WW* decay mode

arXiv: 2403.00657
(accepted in EPJC)

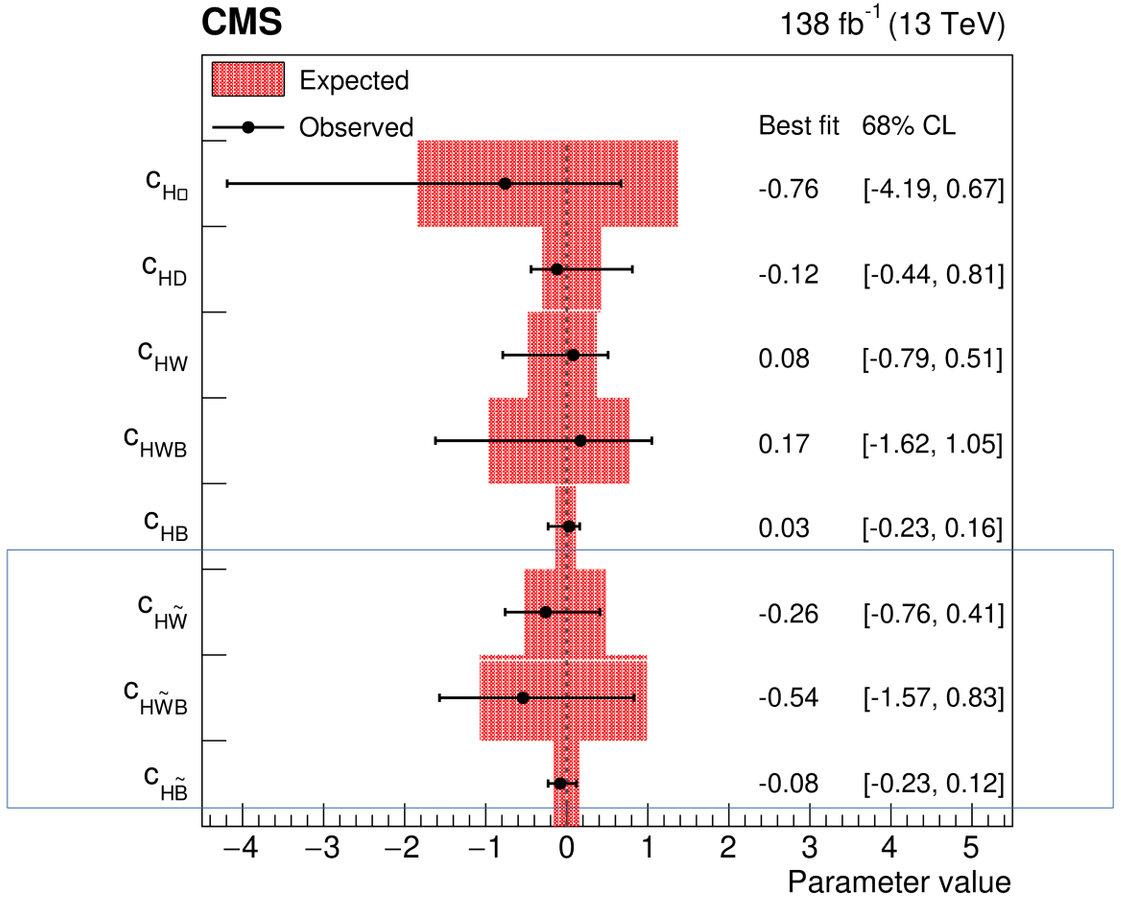
Constraints translated to SMEFT operator coefficients

Higgs basis



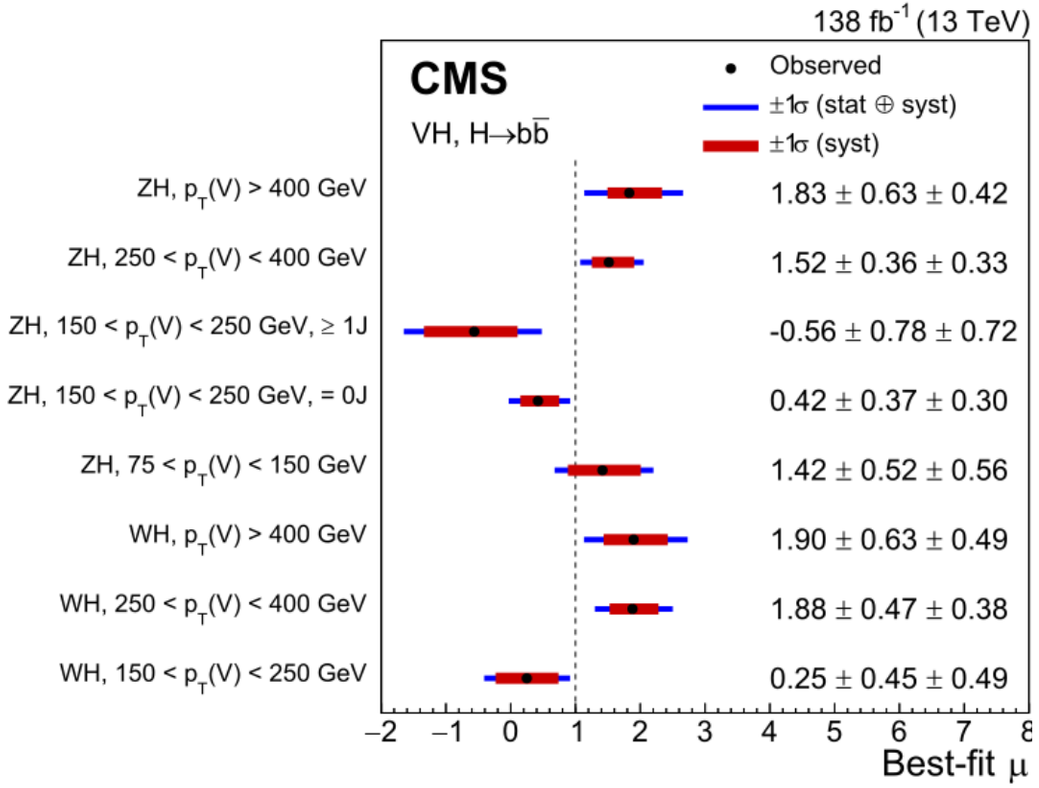
CP-odd

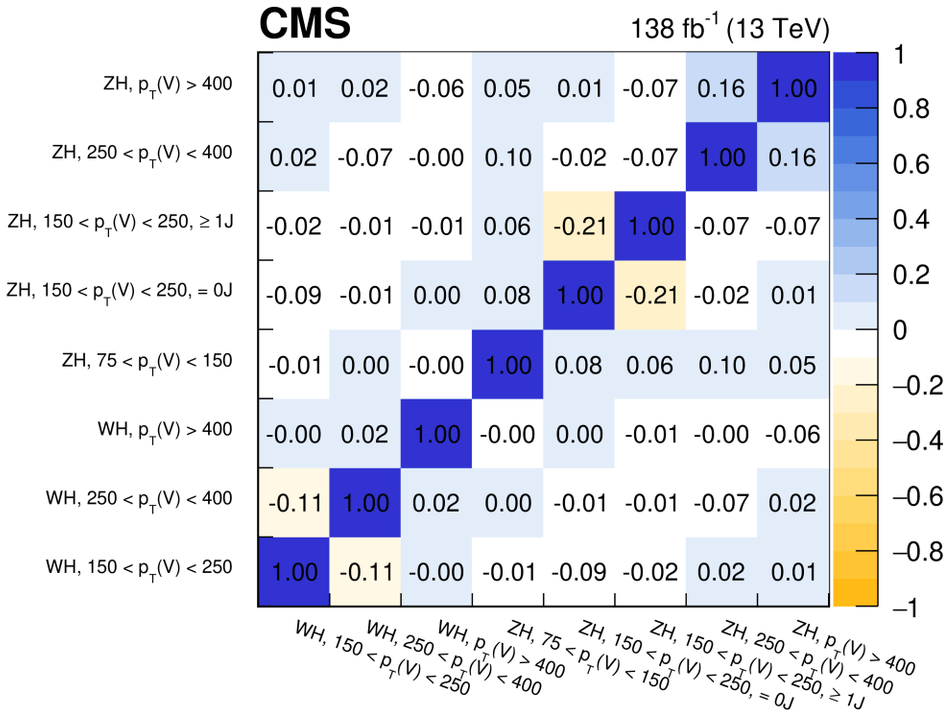
Warsaw basis

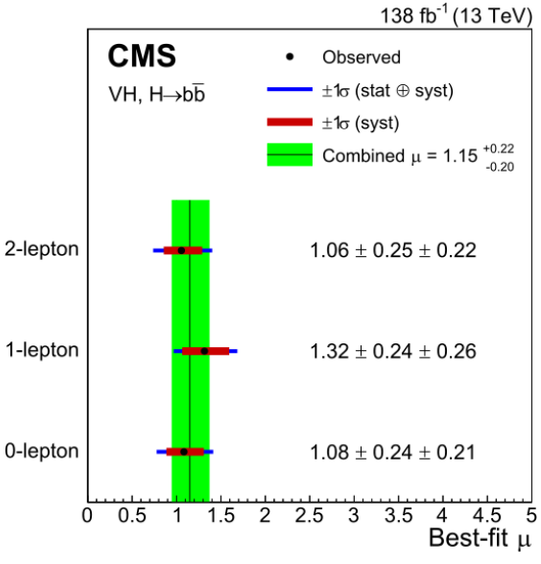


VHbb STXS

arXiv: 2312.07562
(accepted in PRD)

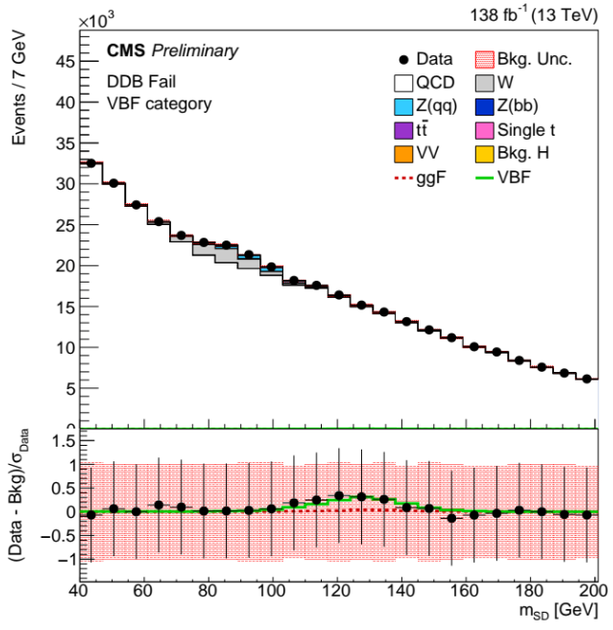


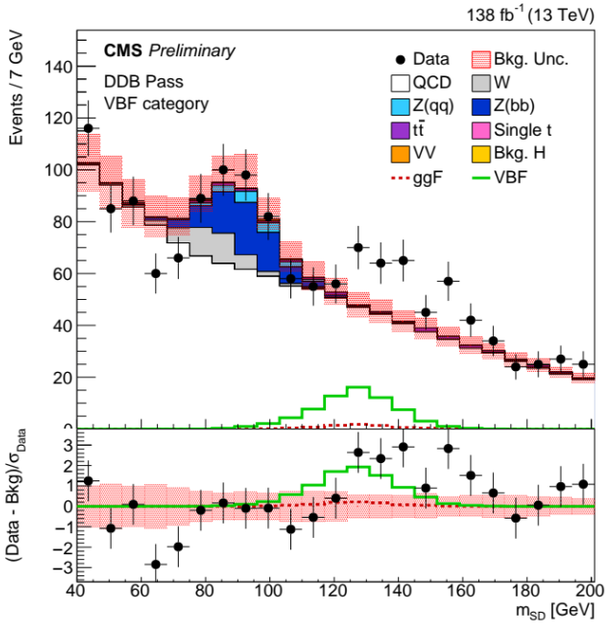


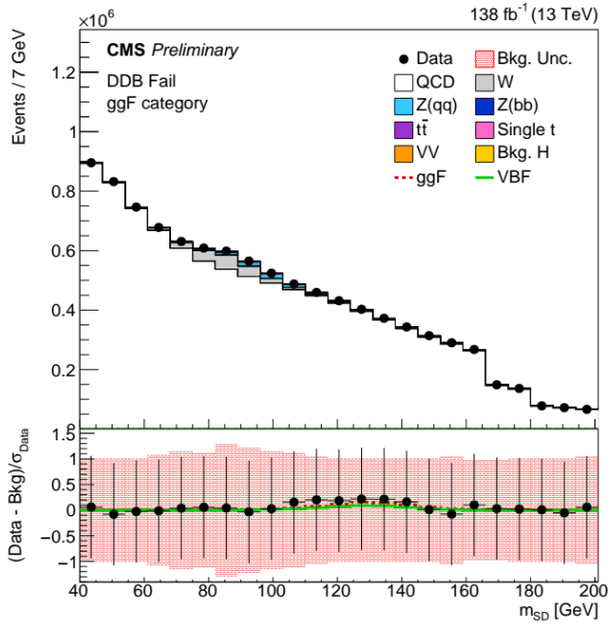


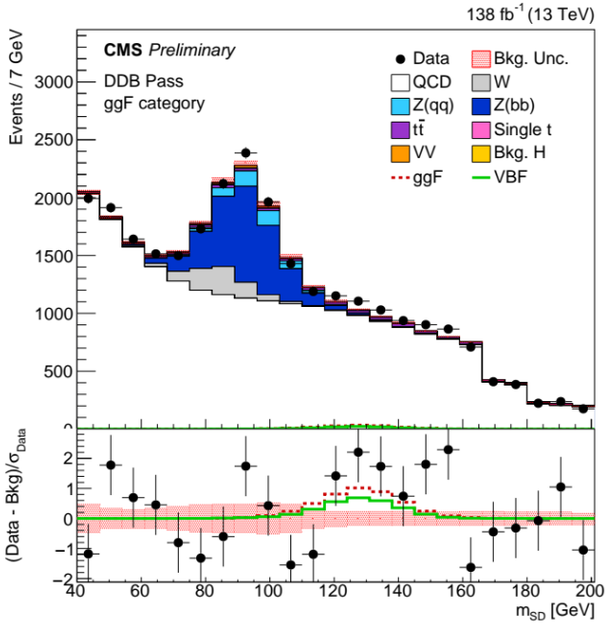
VBF + ggF Hbb

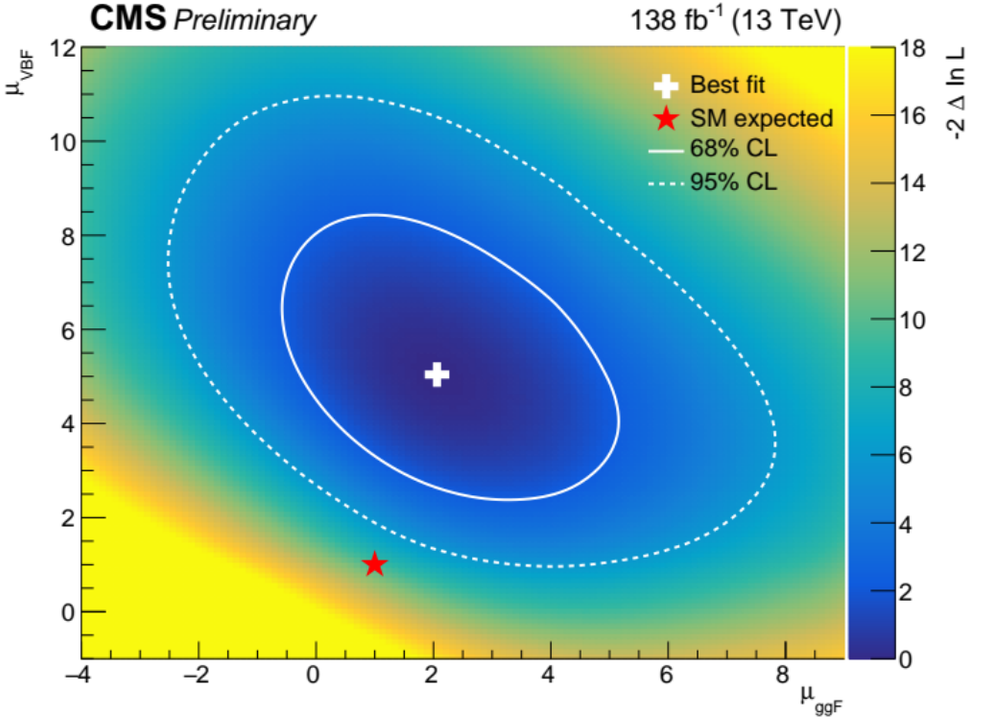
CMS-PAS-HIG-21-020





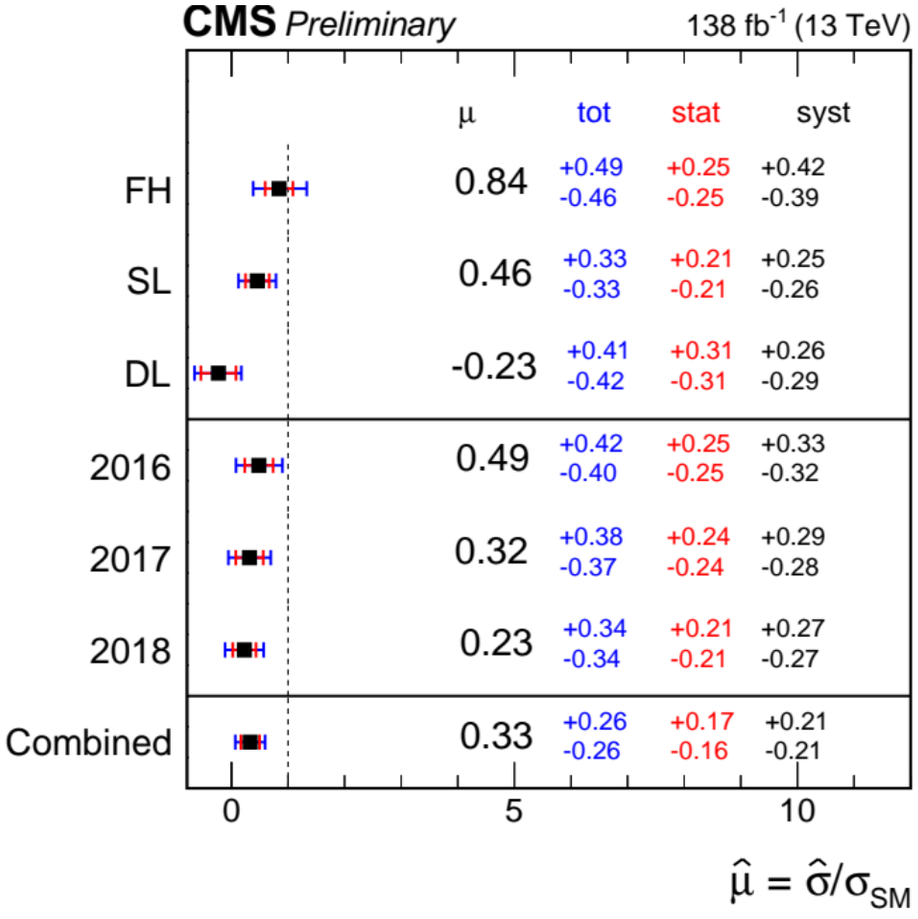


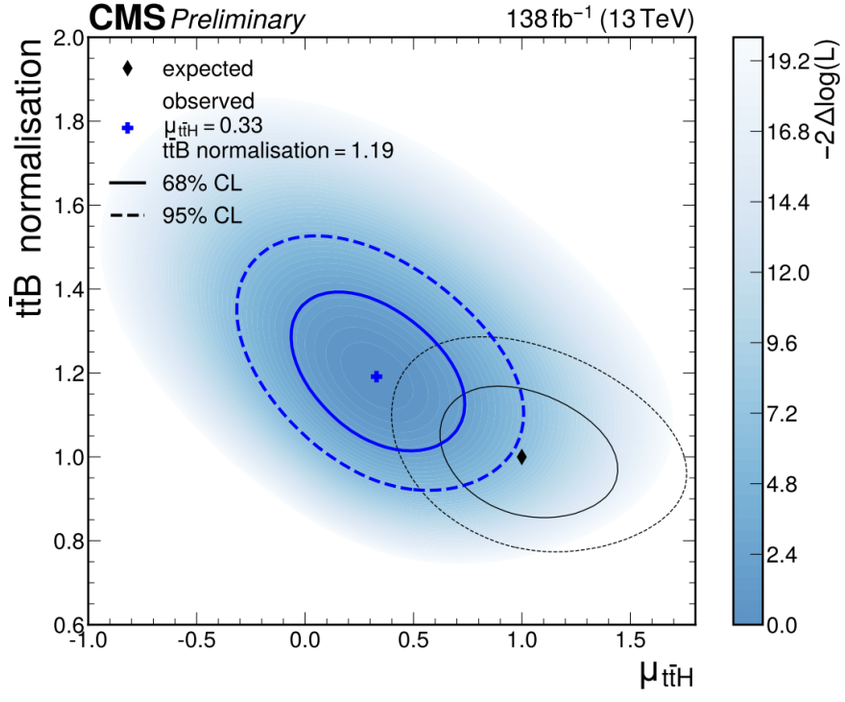


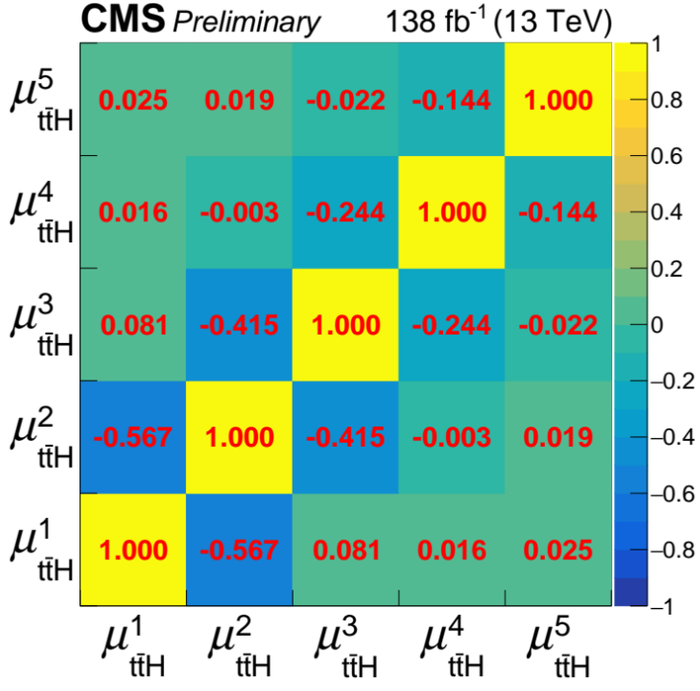


ttH/tH Hbb

CMS-PAS-HIG-19-011





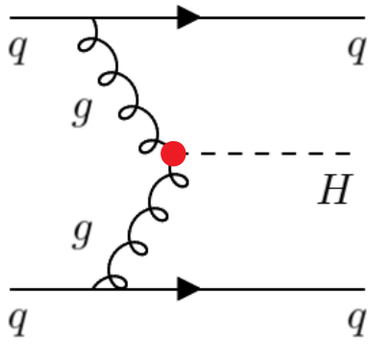


Anomalous Higgs to gluon couplings

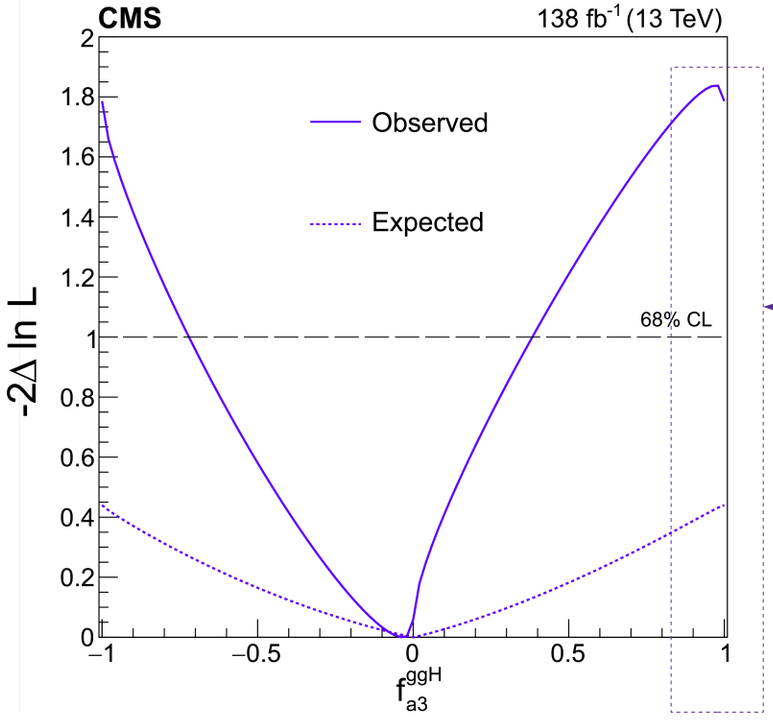
Higgs-to-gluon coupling is probed in H+2jets events

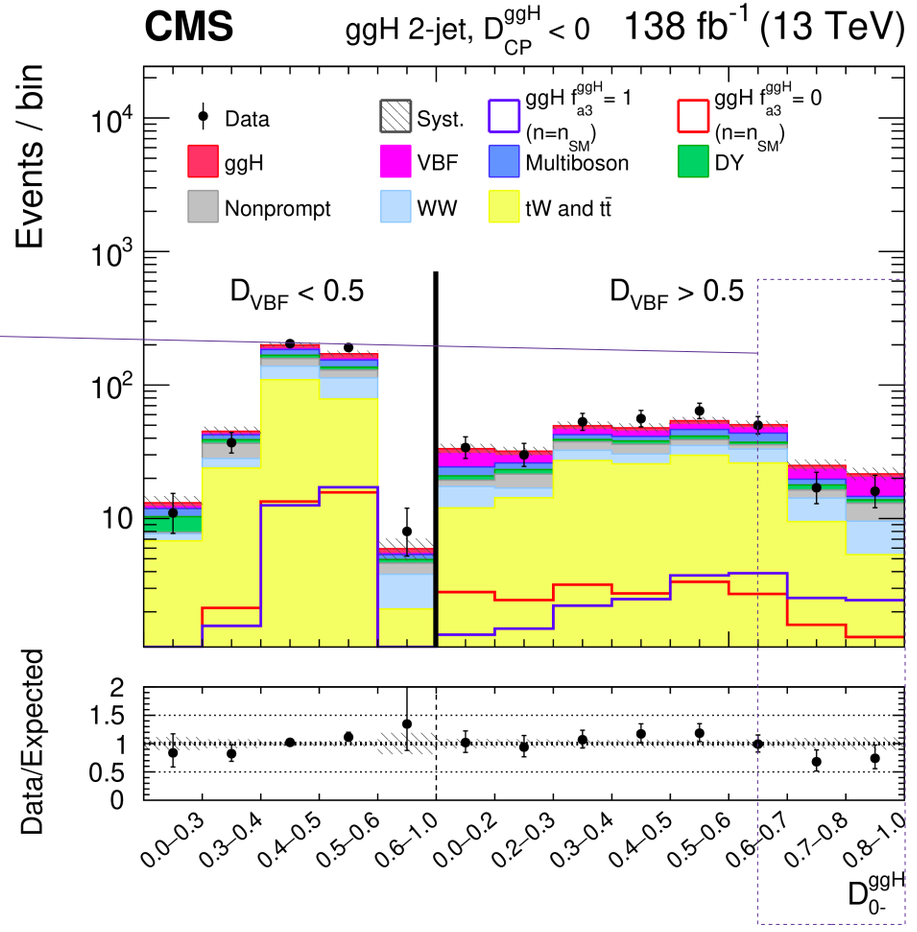
H→ WW*

arXiv: 2403.00657 (accepted in EPJC)



$$f_{a3}^{ggH} = \frac{|a_3^{gg}|^2}{|a_2^{gg}|^2 + |a_3^{gg}|^2} \operatorname{sgn}\left(\frac{a_3^{gg}}{a_2^{gg}}\right)$$





CP-odd cross section fraction: = -0.034 [+ 0.38 – 0.72 @ 68% CL]

Measurements for ttH/tH(bb)

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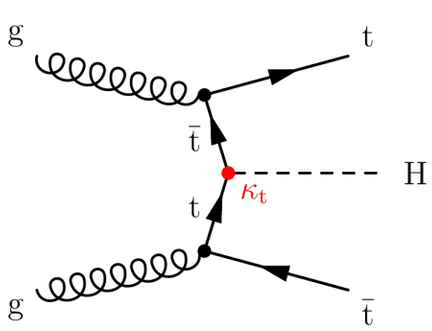
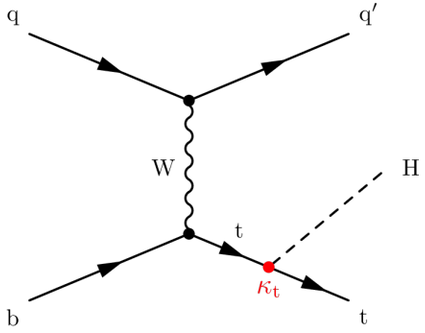
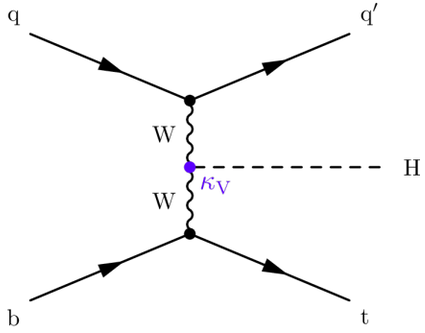






ttH(→bb): 4b + 0/1/2 leptons + jets

tH(→bb)W: 3b + 0/1/2 leptons + jets

tH(→bb)q: 3b + 0/1 leptons + jets (1 forward)

Signal regions defined using # of jets, # of b-tagged jets

↓

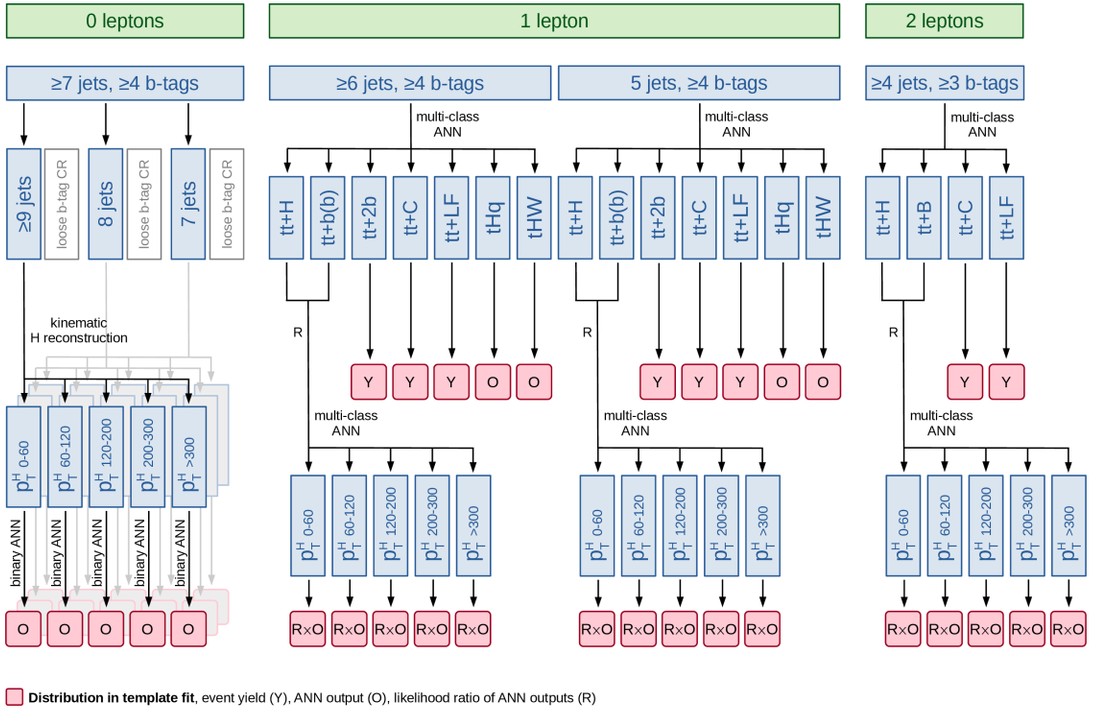
Artifical neural networks (ANNs) used to separate signal & backgrounds

↓

Assigning events to STXS H p_T bins: ANN or kinematic reconstruction

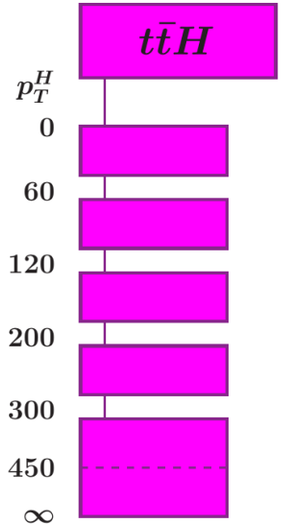
↓

Signal extraction with (combination of) ANN scores



Distribution in template fit, event yield (Y), ANN output (O), likelihood ratio of ANN outputs (R)

Stage 1.2



See M. Marchegiani's talk