Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

EFT interpretations in the Higgs sector with CMS

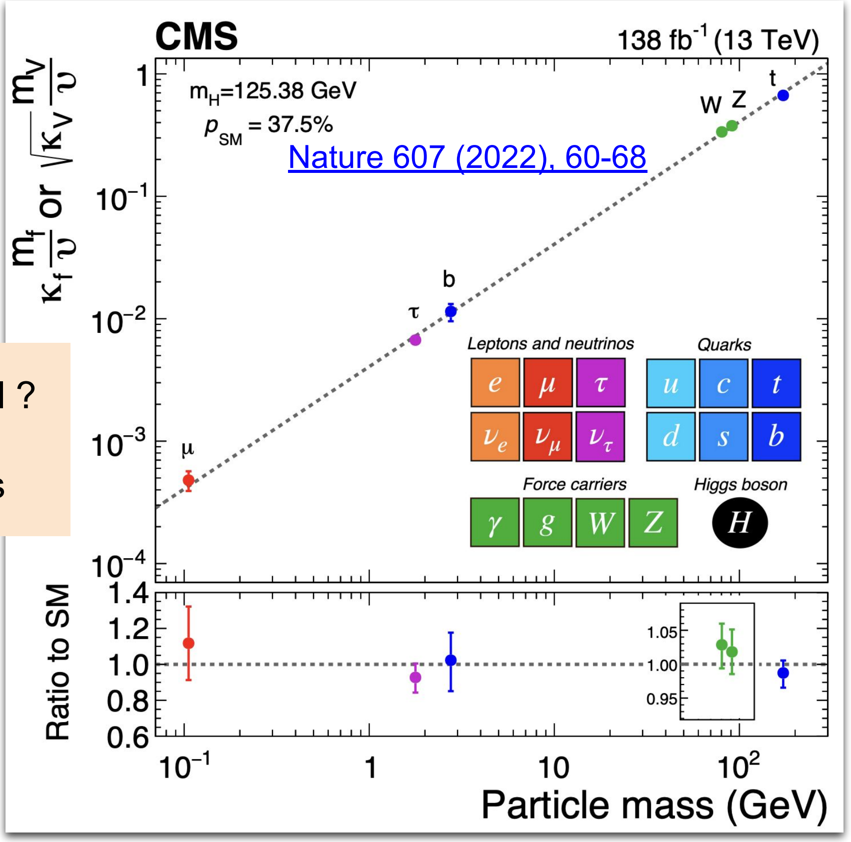
Irene Dutta *for CMS collaboration*

42nd International Conference on High Energy Physics

20th July, 2024

Why look for new physics in the Higgs sector?

Particle couplings to Higgs **not yet** measured at 1% precision



BSM at the loop level ?
→ tiny changes to predicted couplings

Look for BSM hints in H measurements

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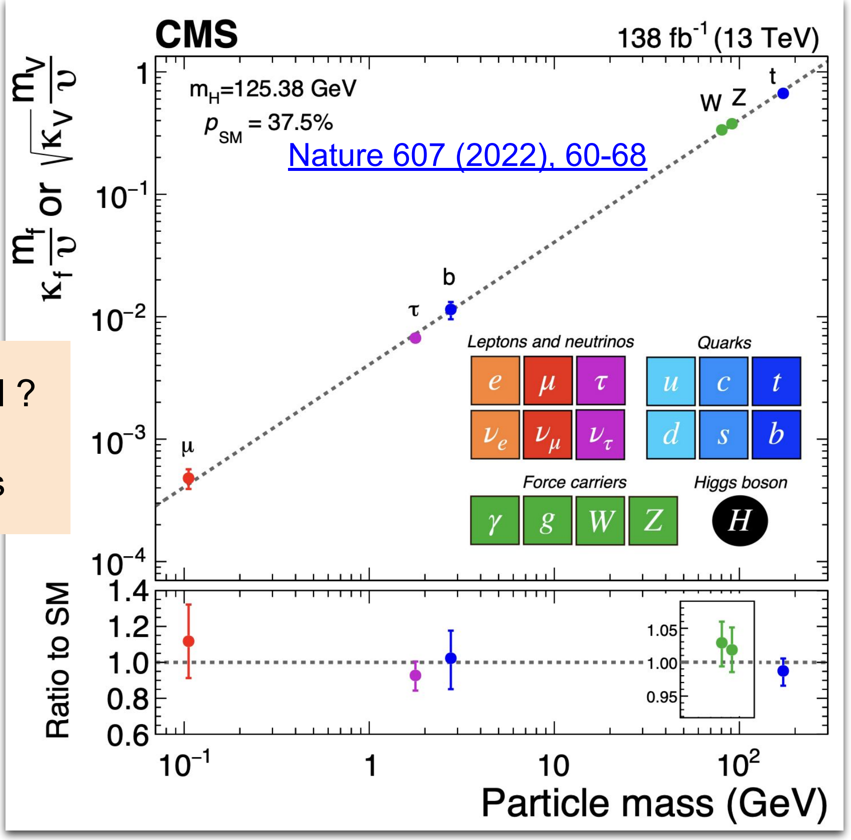
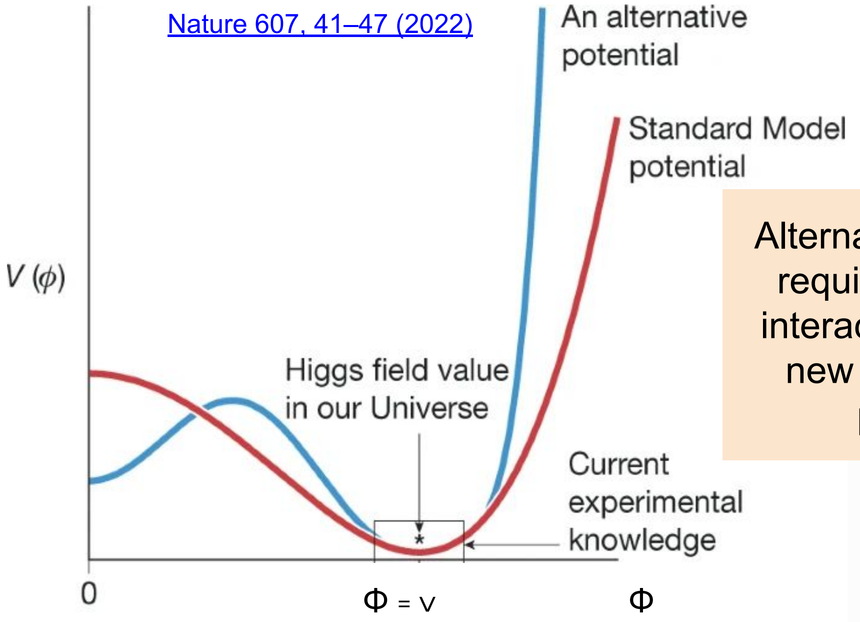


Look for BSM hints in H measurements

Our current knowledge of the Higgs potential is limited

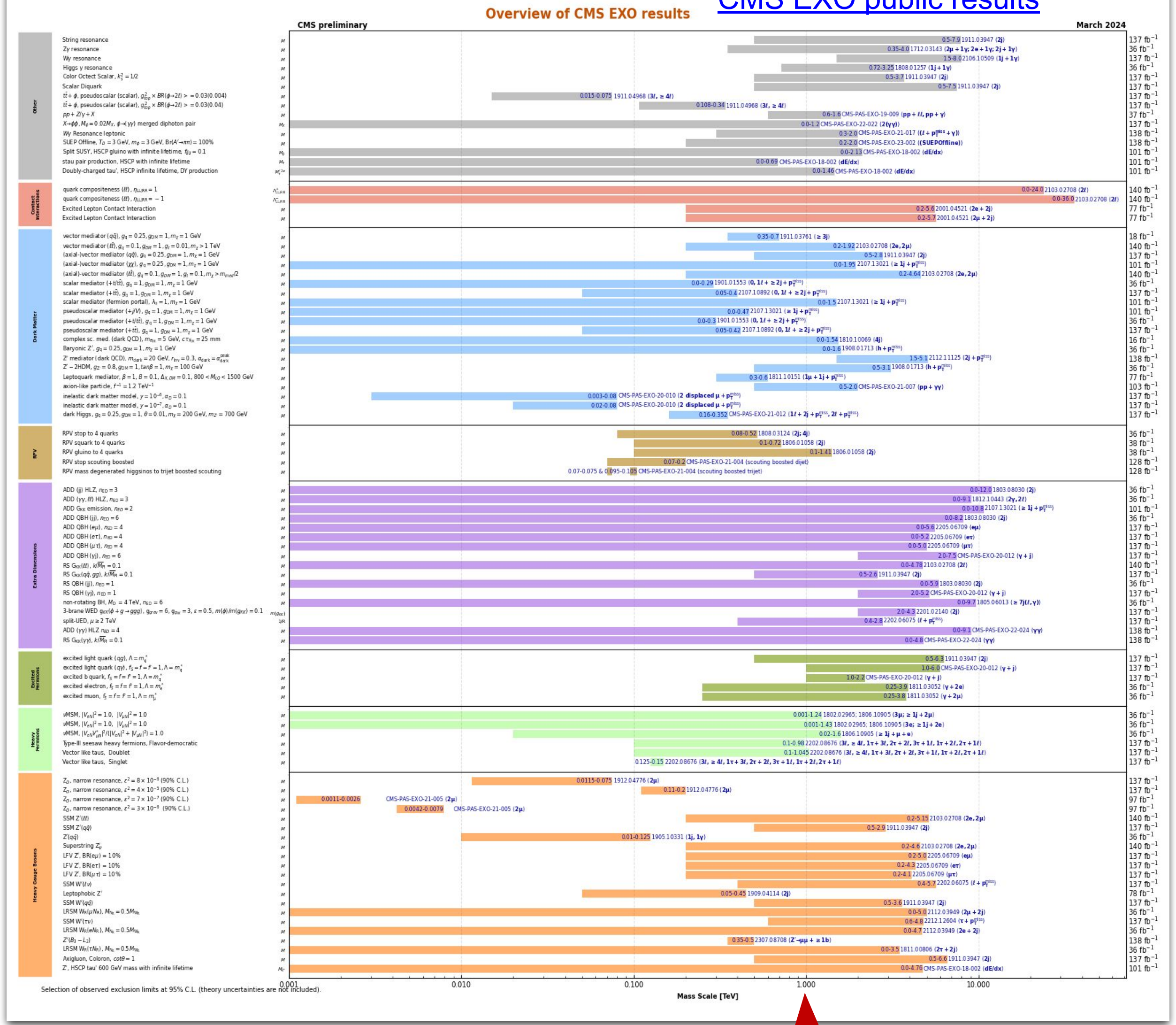


Alternative potentials require new Higgs interactions → from new **Dark Matter** particle?

Look for BSM hints in HH measurements

New Physics is likely heavy (> 1 TeV)

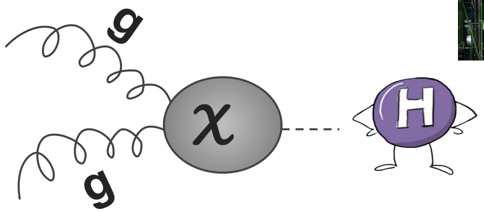
CMS EXO public results

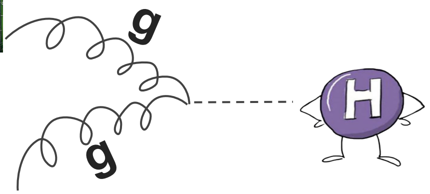


1 TeV

Reasonable to assume SM is a low energy approximation of a more complex model

The EFT approach



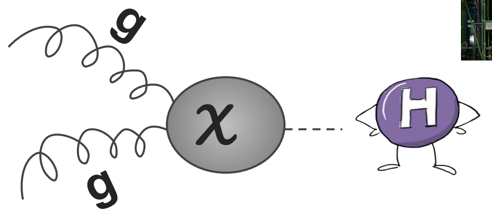


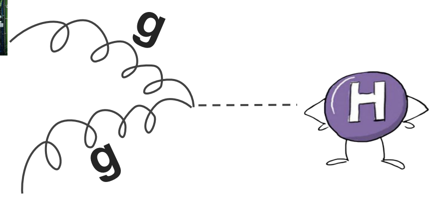
What we see at a lower energy scale

Assume new physics at some high energy scale Λ

An effective anomalous coupling (point-like interaction)

The EFT approach





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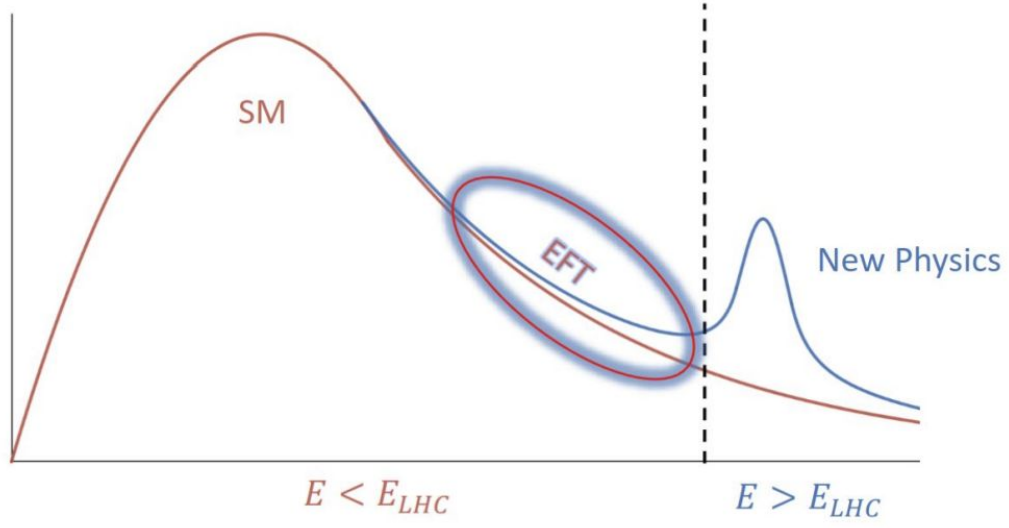
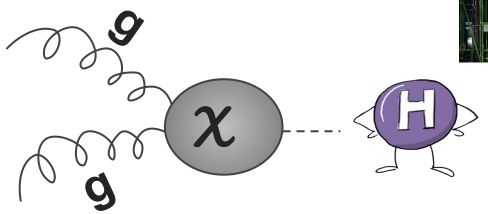


Look for deviations in kinematic distributions

The EFT approach



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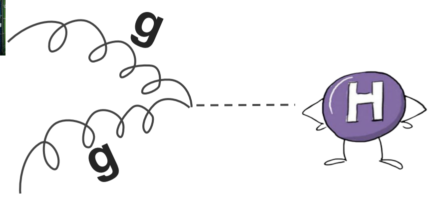

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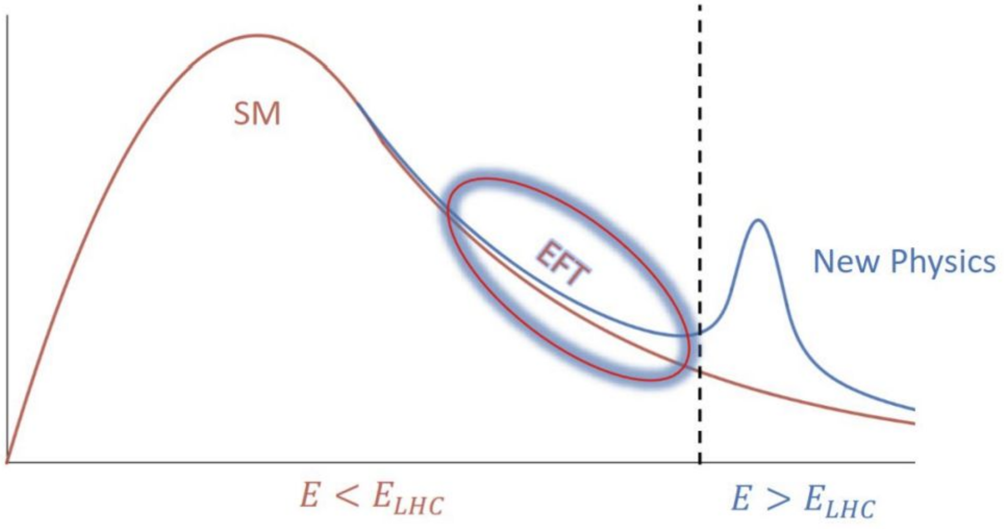
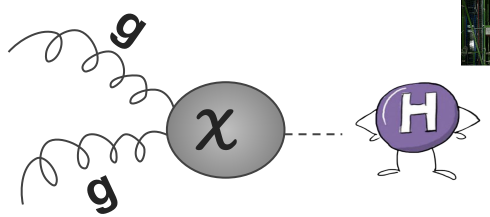


Look for deviations in kinematic distributions

Discovery through precision measurements!

The EFT approach



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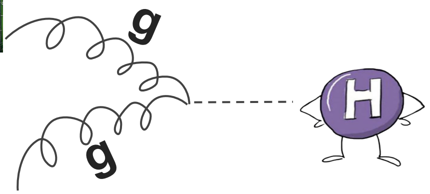

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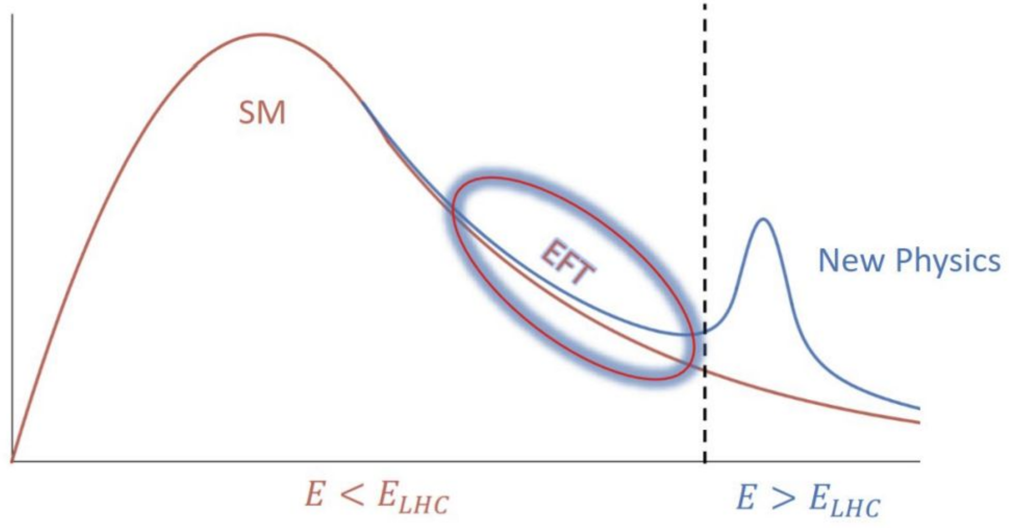

Look for deviations in kinematic distributions

Discovery through precision measurements!

Scope of this talk : SMEFT and HEFT interpretations in Higgs

See D.Moran talk for anomalous Higgs boson couplings
and B. Camaiani talk for STXS and differential measurements

SMEFT : SM Effective Field Theory

SM with series of higher dimensional operators which are invariant under SU(3) x SU(2) x U(1) symmetry

Higgs field : SU(2) doublet

New physics scale Λ >> SM

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

Lepton number violation

Lepton & Baryon number violation

Probe EFT Wilson coefficients c_i of dimension-6 operators

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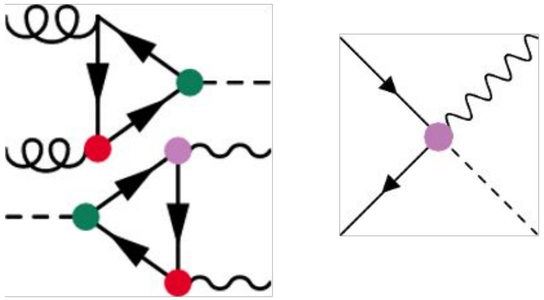


+ ...

One operator can affect many processes ..
Many operators can affect one process ..

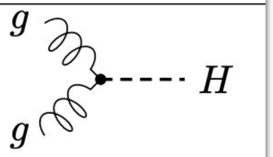
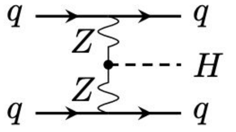
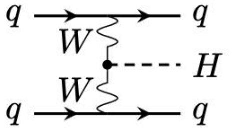
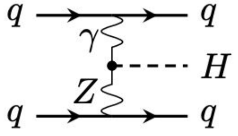
Needs a global EFT data analysis approach

[CMS-PAS-HIG-23-013](CMS-PAS-HIG-23-013)

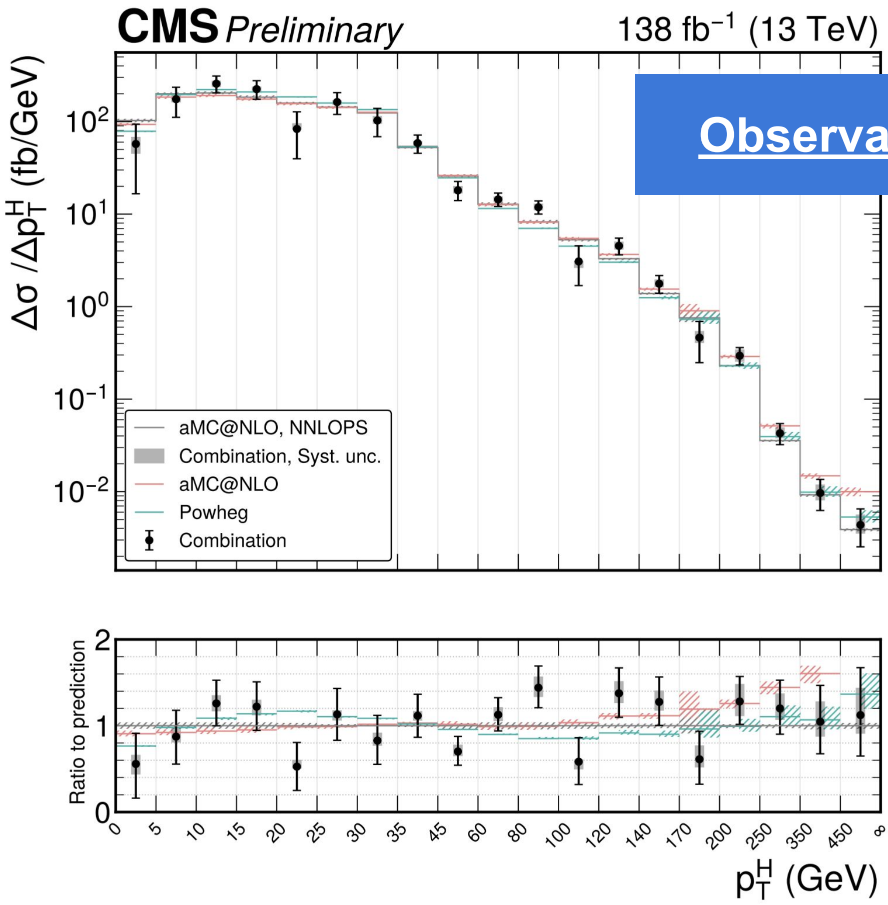
EFT search in combination of H→X decays

Combination of analyses : JHEP07(2023) 091, JHEP08(2023) 040, JHEP03(2021) 003, Phys. Rev. Lett. 128, 081805, arXiv:2403.20201

Signal processes : H → γγ, H → ZZ, H → WW, H → ττ, H → ττ (boosted)

Class	Operator	Wilson coefficient	Example process
$\mathcal{L}_6^{(4)} - X^2H^2$	$H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}$	c_{HG}	
	$H^\dagger H \tilde{G}^a_{\mu\nu} G^{a\mu\nu}$	$\tilde{c}_{HG}$	
	$H^\dagger H B_{\mu\nu} B^{\mu\nu}$	c_{HB}	
	$H^\dagger H \tilde{B}_{\mu\nu} B^{\mu\nu}$	$\tilde{c}_{HB}$	
	$H^\dagger H W^i_{\mu\nu} W^{i\mu\nu}$	c_{HW}	
	$H^\dagger H \tilde{W}^i_{\mu\nu} W^{i\mu\nu}$	$\tilde{c}_{HW}$	
	$H^\dagger \sigma^i H W^i_{\mu\nu} B^{i\mu\nu}$	c_{HWB}	
	$H^\dagger \sigma^i H \tilde{W}^i_{\mu\nu} B^{i\mu\nu}$	$\tilde{c}_{HWB}$	

Fit pairs of CP-even, CP-odd WCs while setting all other WC = 0 (SM)

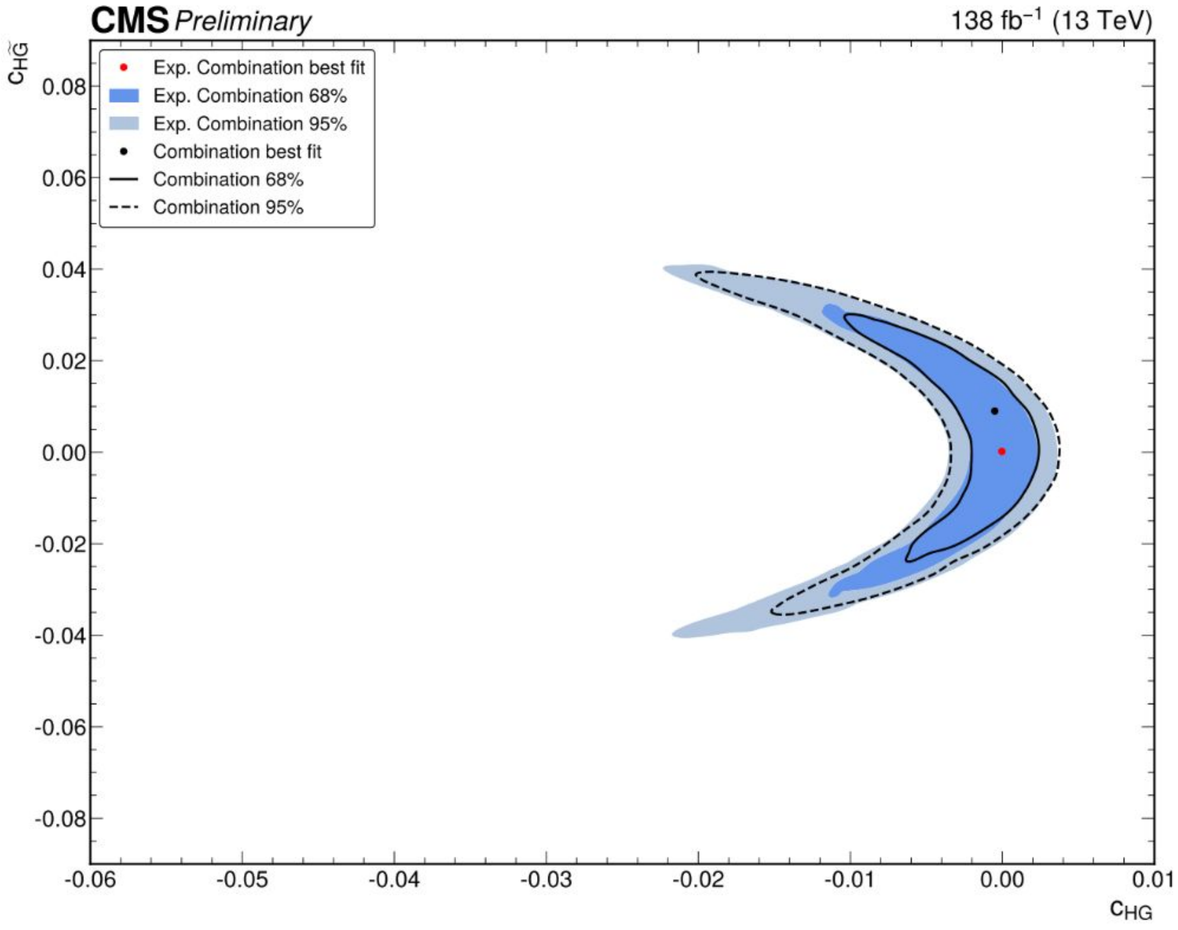


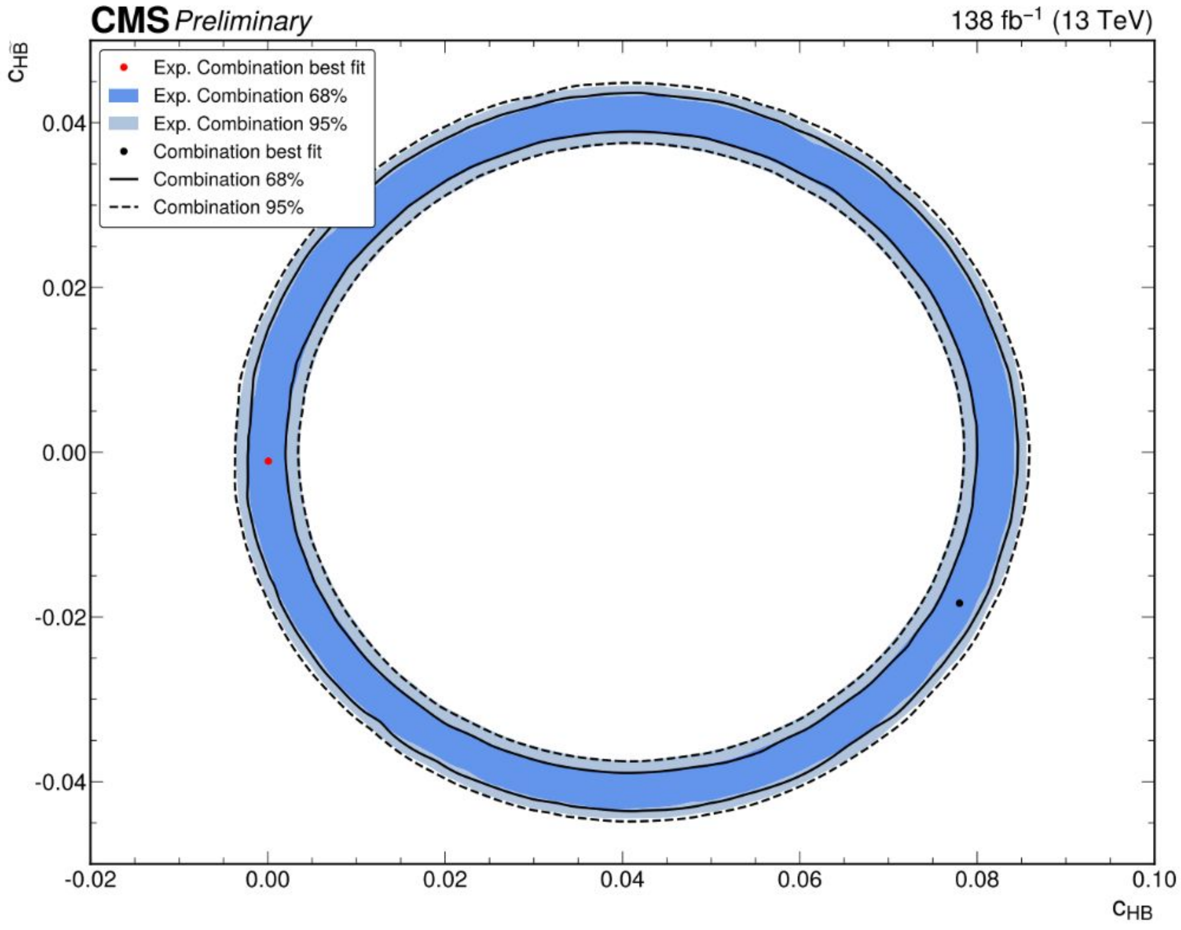
Observable - p_T^H

NEW!

EFT search in combination of H→X decays

2D scans of Wilson Coefficients





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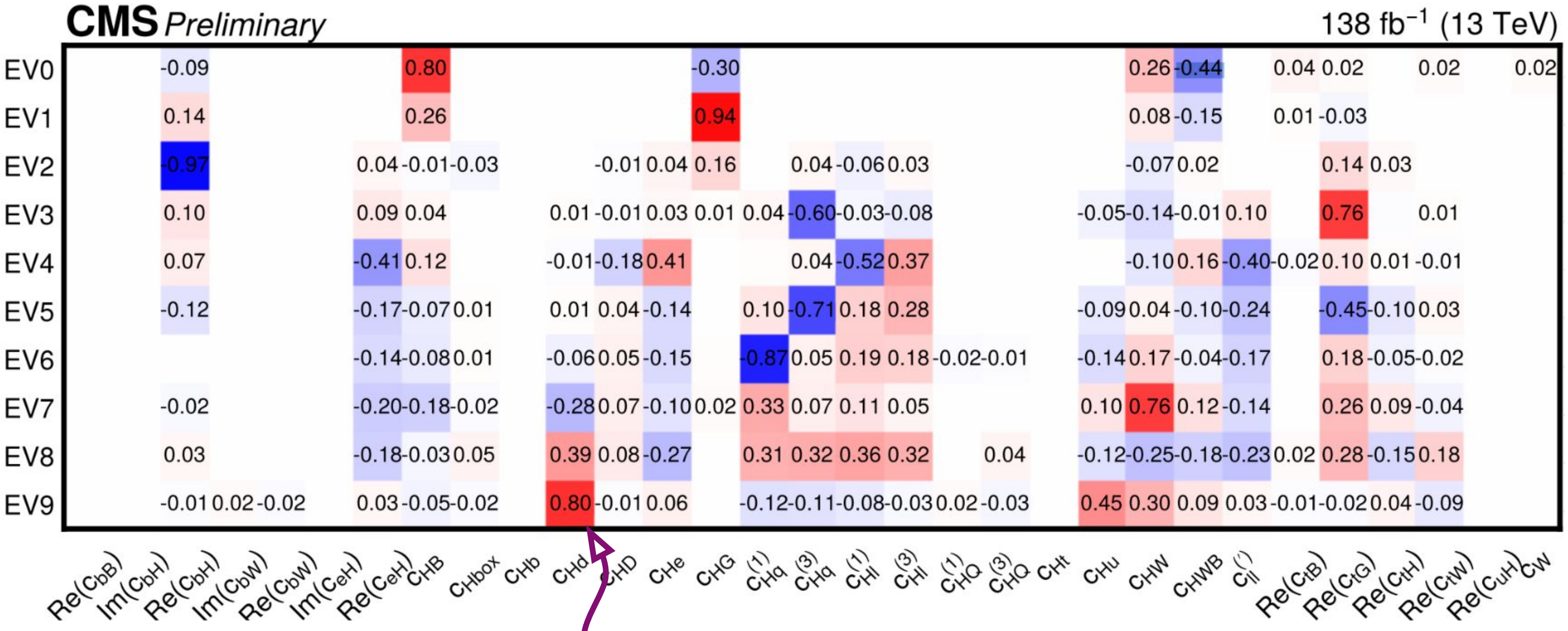
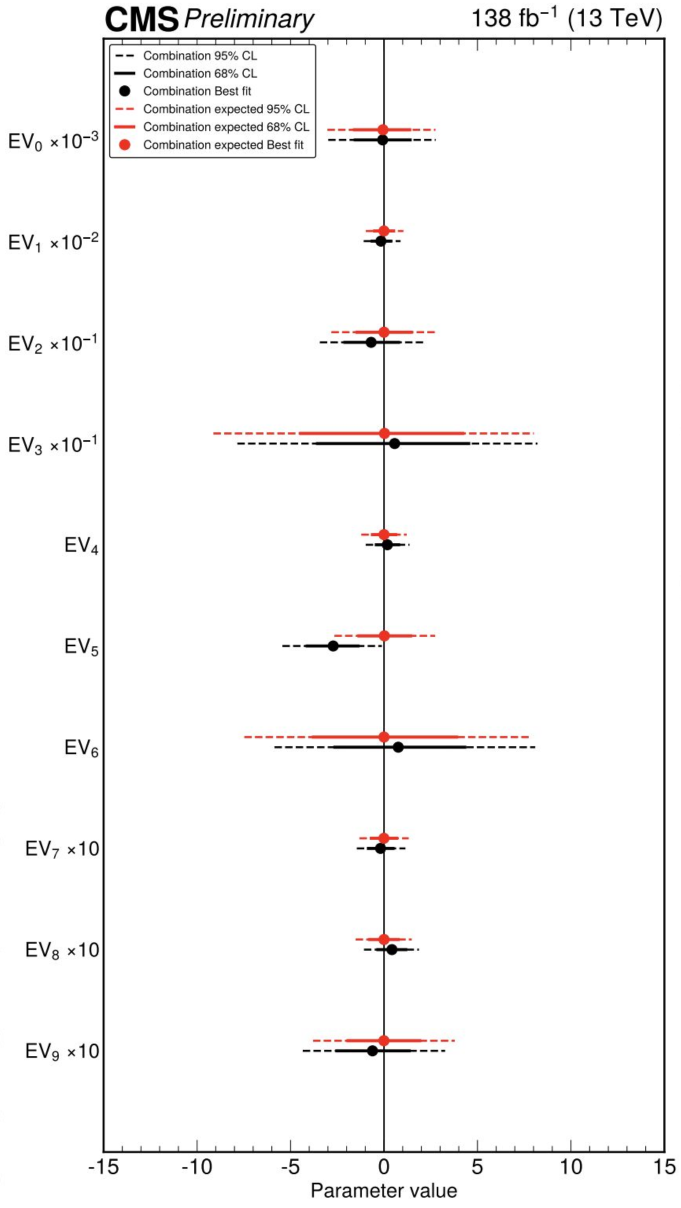
NEW!

EFT search in combination of H→X decays

Define linear combinations of WCs to simultaneously constrain 10 directions in the parameter space



Absolute value signifies importance of WC in linear combination



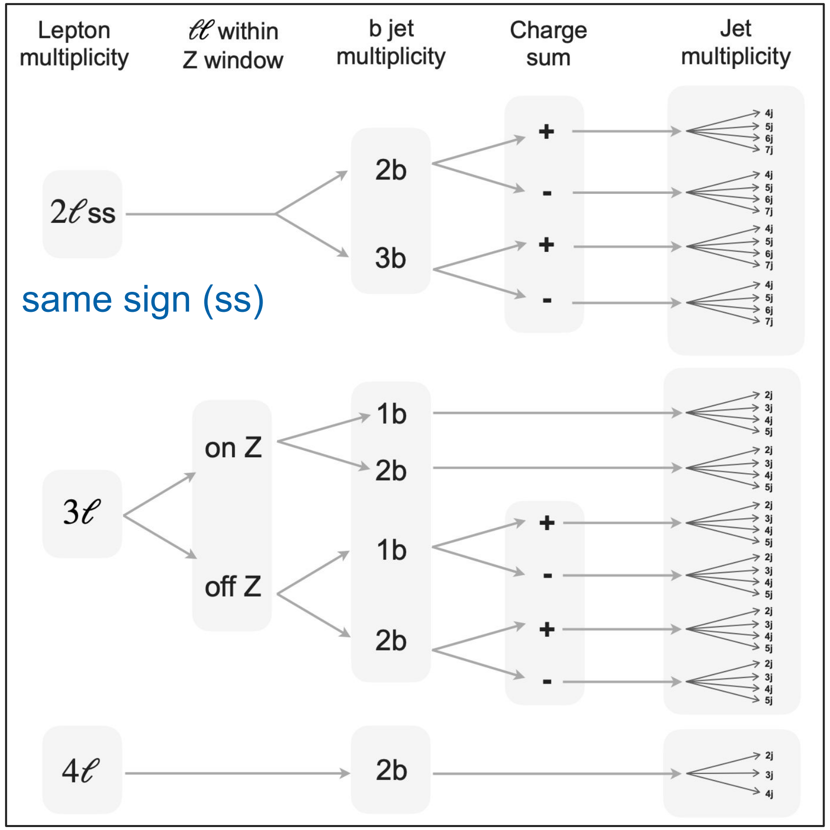
See more details in plenary CMS Highlights talk by [M. Pierini]

EFT search in t($\bar{t}$)X

Global approach : 26 dimension six operators fitted simultaneously

JHEP 12 (2023) 068

Signal processes: $tt\ell\nu$, $tt\ell\ell$, ttH, tZq, tHq, tttt



43 categories based on multiplicity of charged leptons + jets

EFT search in $t(\bar{t})X$

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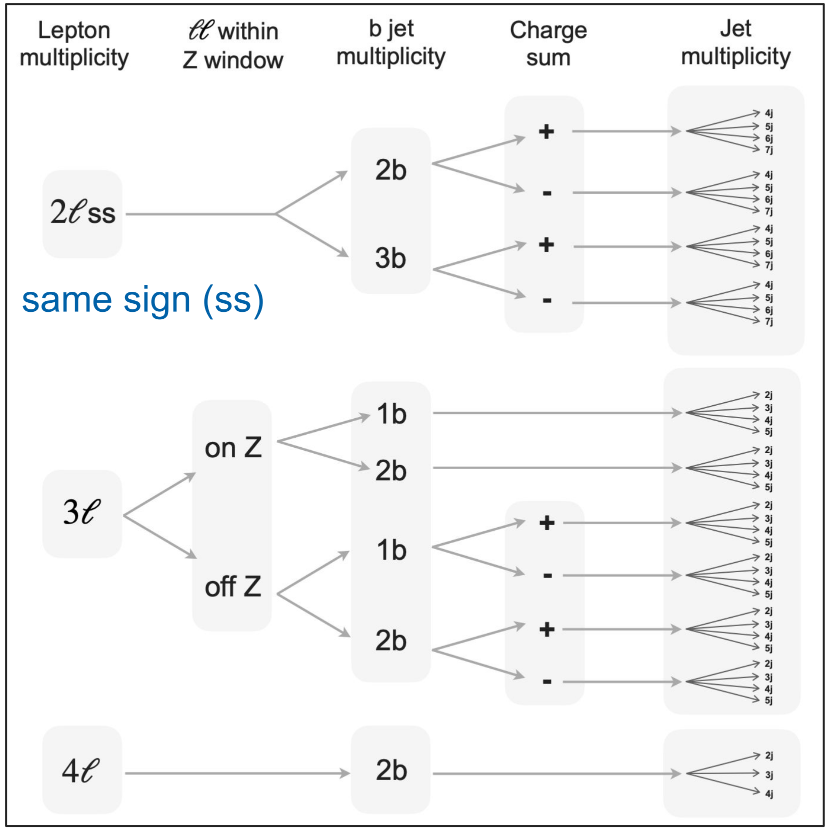
JHEP 12 (2023) 068

Signal processes: ttℓν, ttℓℓ, ttH, tZq, tHq, tttt

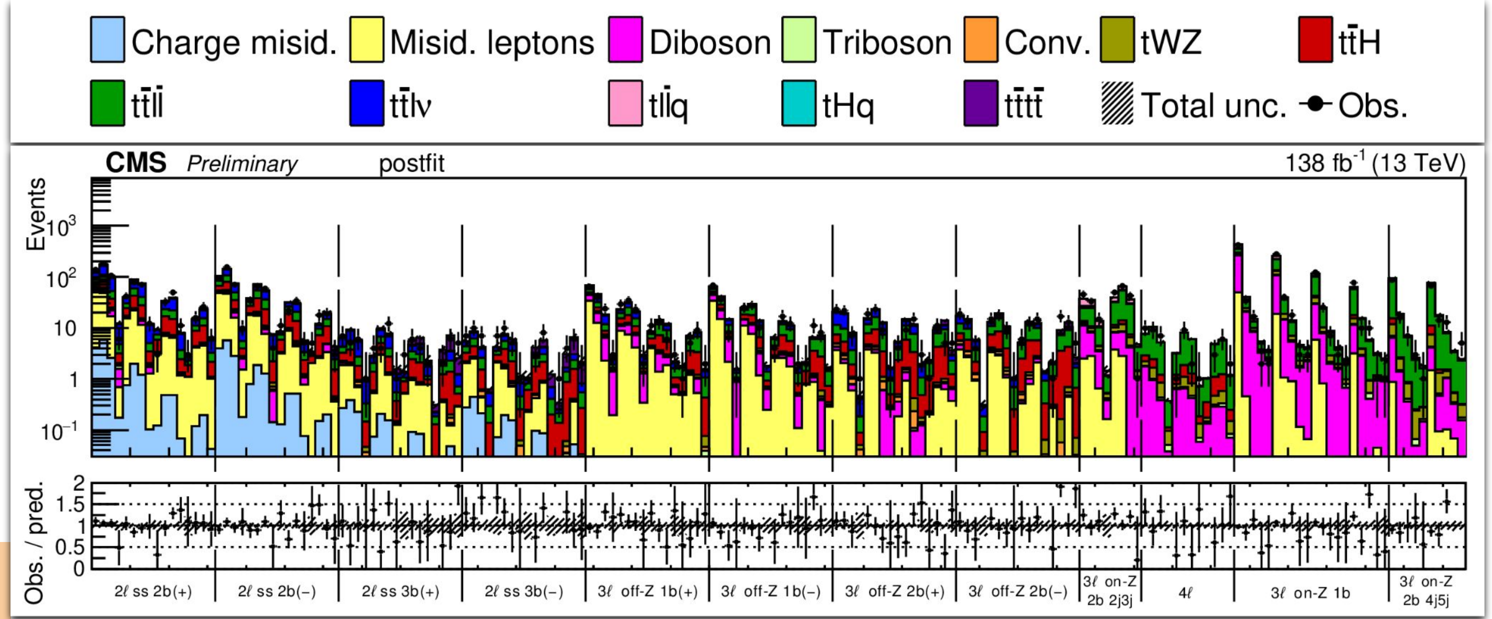


43 categories based on multiplicity of charged leptons + jets

Further binning of each category with

- p_T of most energetic pair of leptons and jets, OR
- p_T of Z boson candidate

178 total analysis bins → binned maximum likelihood fit



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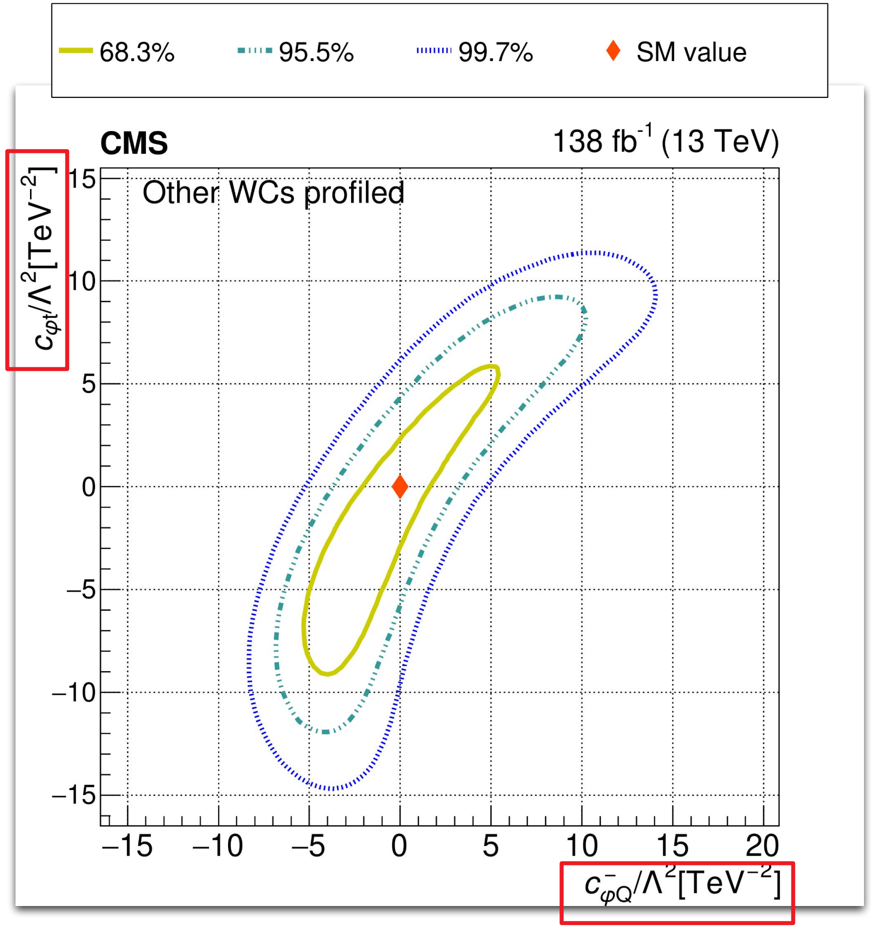
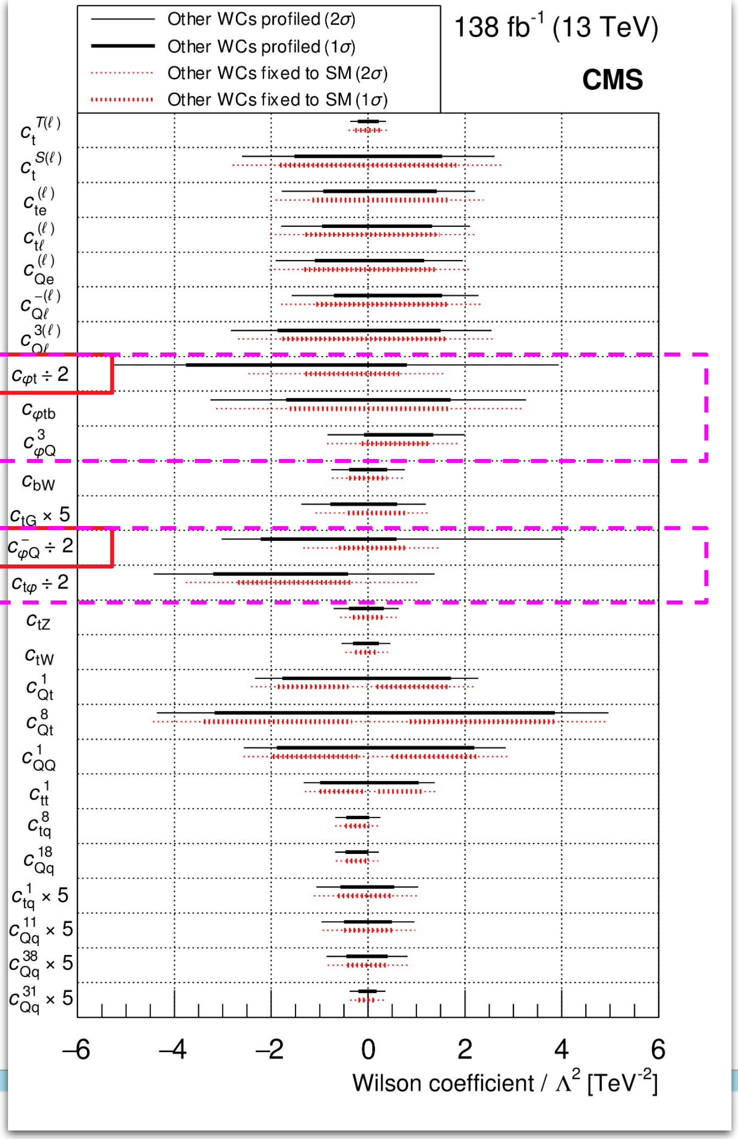
EFT search in $t(\bar{t})X$

JHEP 12 (2023) 068

Improving previous constraints from JHEP 03 (2021) 095 by factors of 2 to 6





Operators involving Higgs

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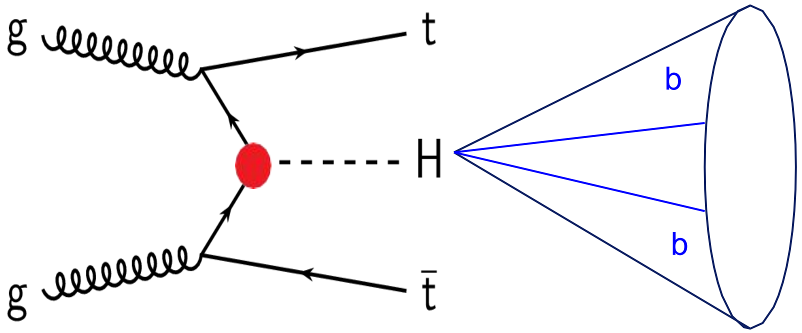
EFT search in semi-leptonic ttH with boosted H→bb

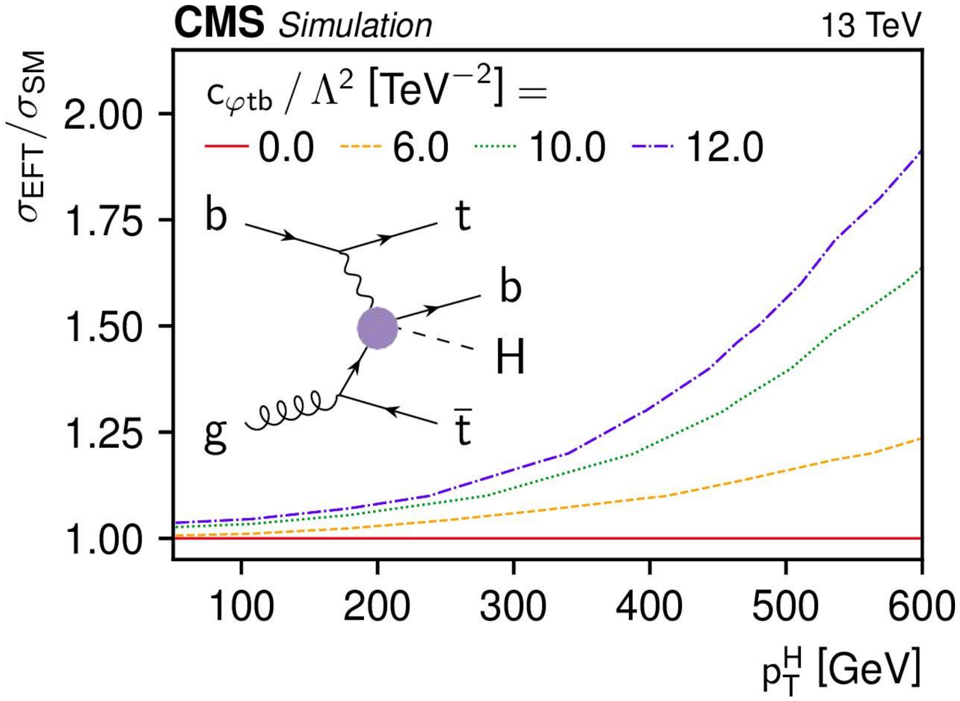
Phys.Rev.D 108 (2023) 032008

Global approach : 8 dimension six operators fitted simultaneously



SMEFT operators at work

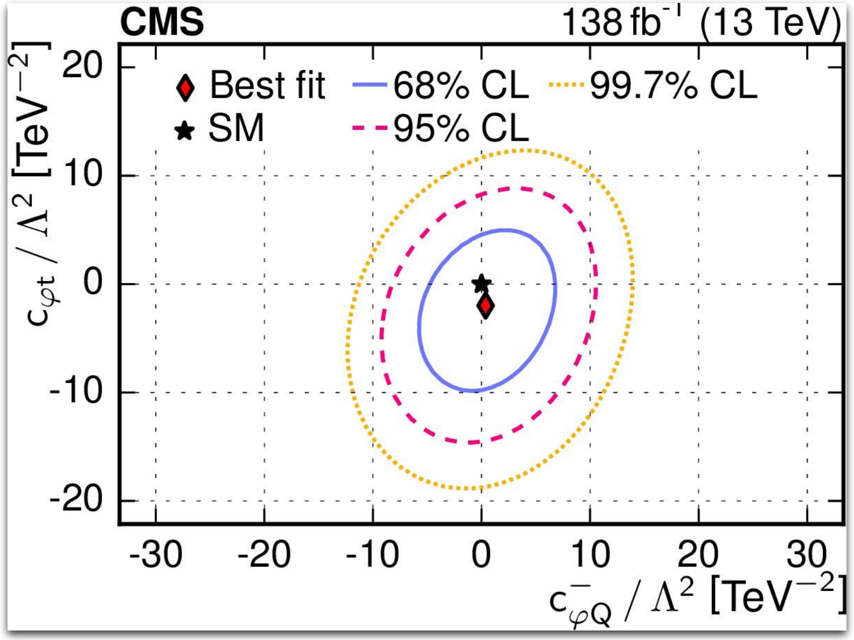
Dipole	$\mathcal{O}_{tW}$
Current	$\mathcal{O}^{(3)}_{\varphi Q}$ $\mathcal{O}^{-}_{\varphi Q}$ $\mathcal{O}_{\varphi t}$ $\mathcal{O}_{\varphi tb}$
Yukawa	$\mathcal{O}_{t\varphi}$

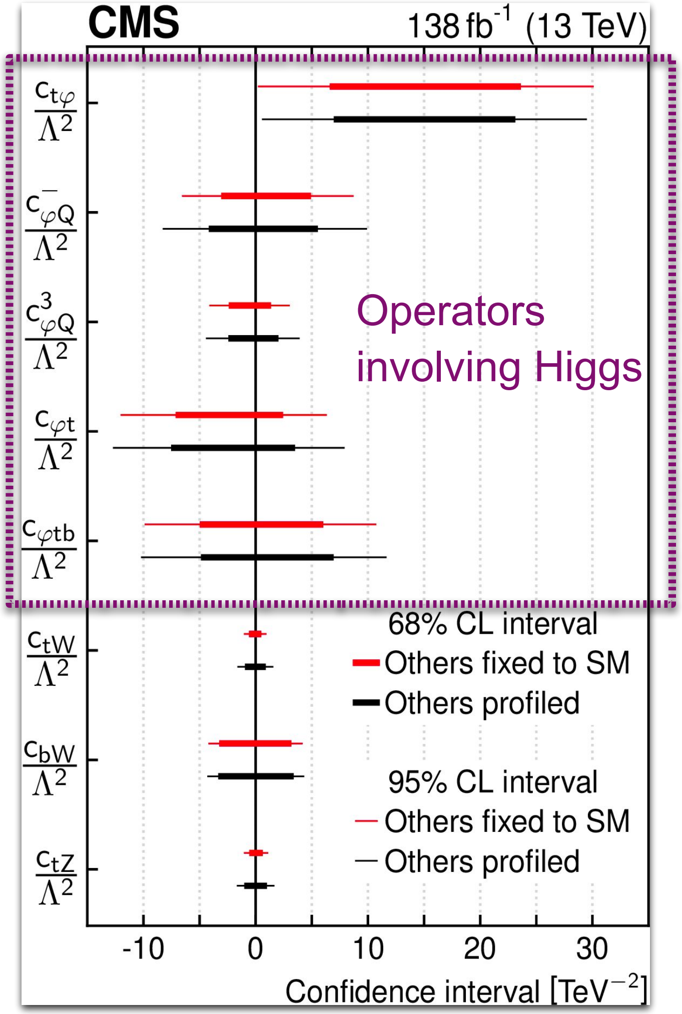


Higher sensitivity to coupling deviations in boosted regime

EFT search in semi-leptonic ttH with boosted H→bb

Phys.Rev.D 108 (2023) 032008





Smaller statistics compared to other measurements

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

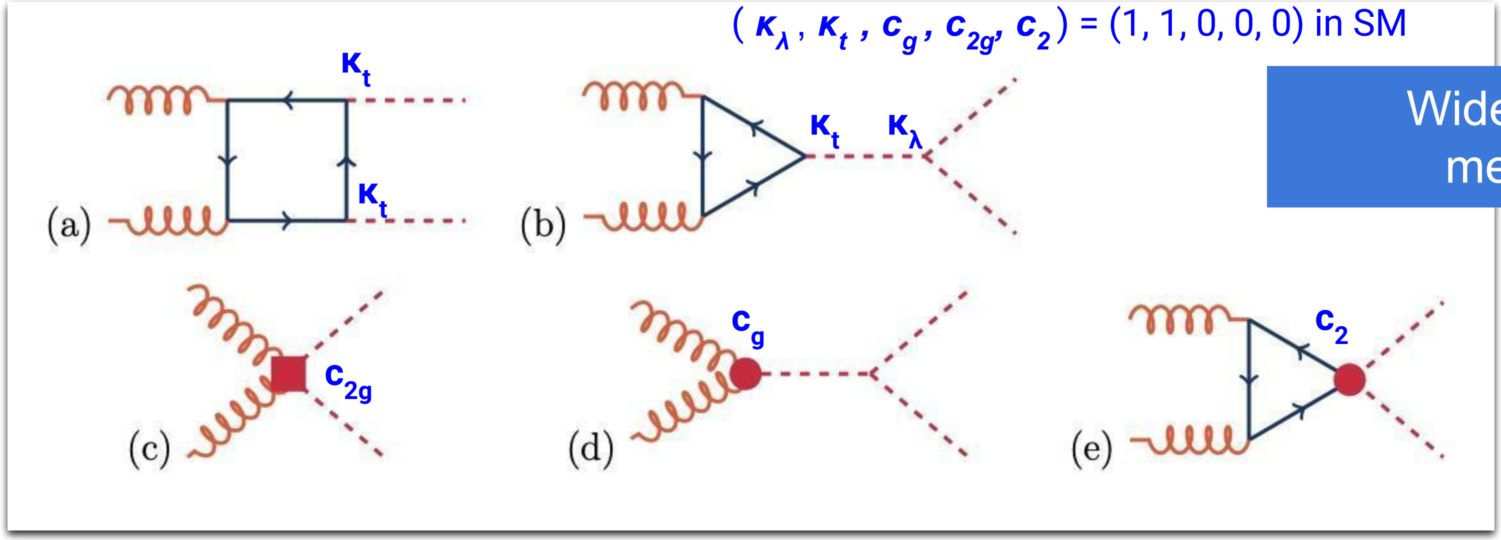
Still competitive in sensitivity

HEFT : Higgs Effective Field Theory

Chiral perturbation theory, no power counting unlike SMEFT

Higgs field : EW singlet

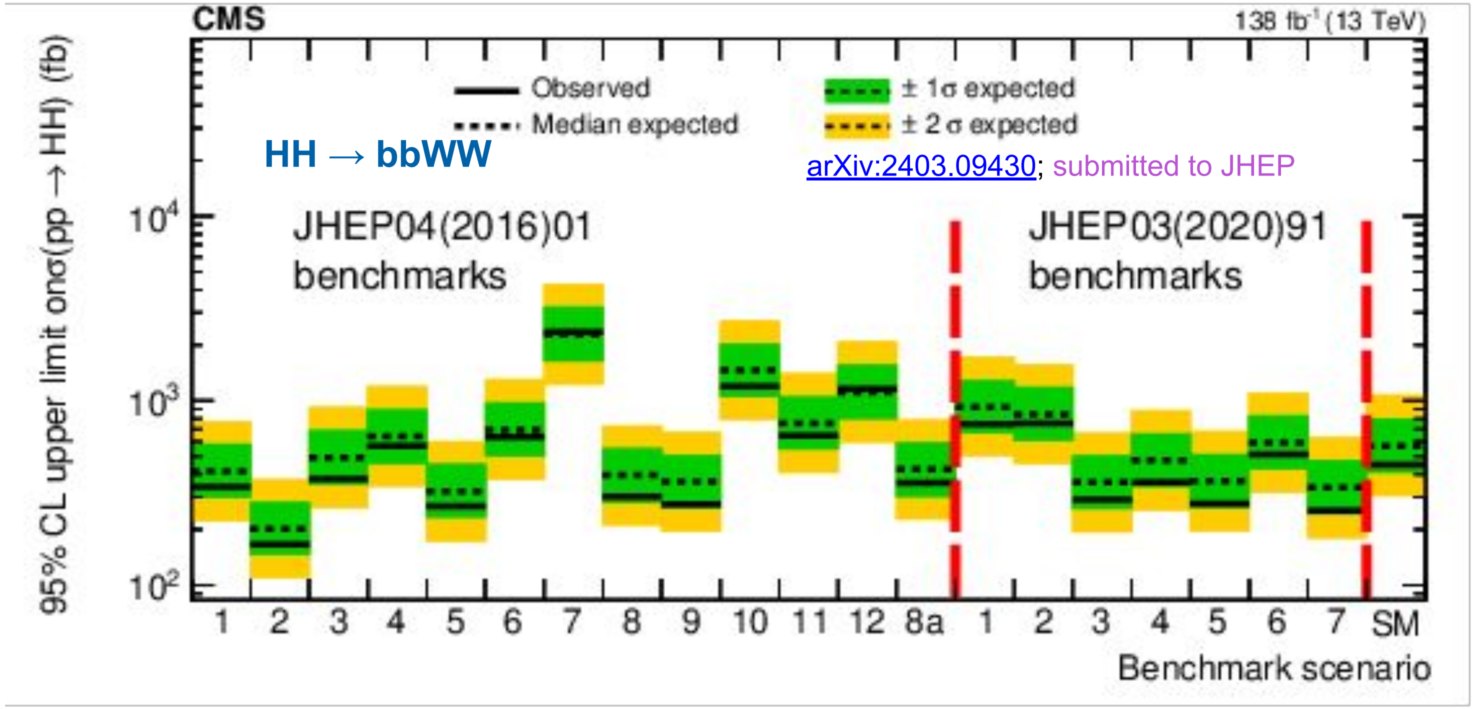
$$\Delta\mathcal{L}_{HEFT} = -m_t(\kappa_t \frac{h}{\nu} + c_2 \frac{h^2}{\nu^2})\bar{t}t - \kappa_\lambda \frac{m_h^2}{2\nu} h^3 + \frac{\alpha_s}{8\pi}(c_g \frac{h}{\nu} + c_{2g} \frac{h^2}{\nu^2}) G^a_{\mu\nu} G^{\mu\nu,a}$$

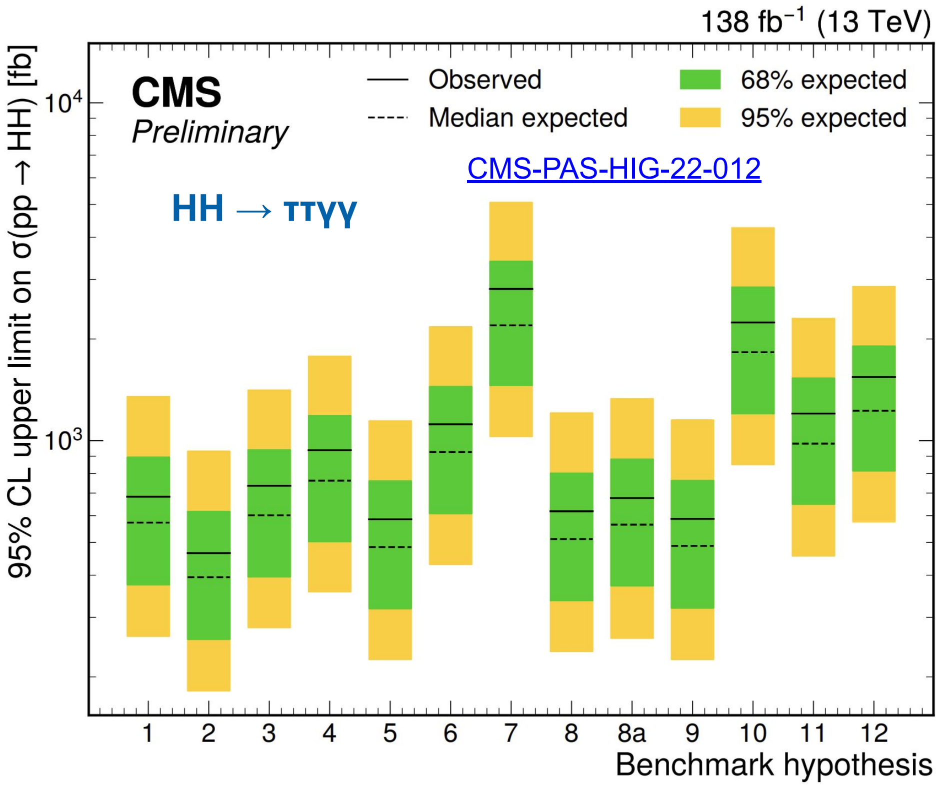


Widely used in HH measurements

HEFT benchmark limits

** New since ICHEP 2022

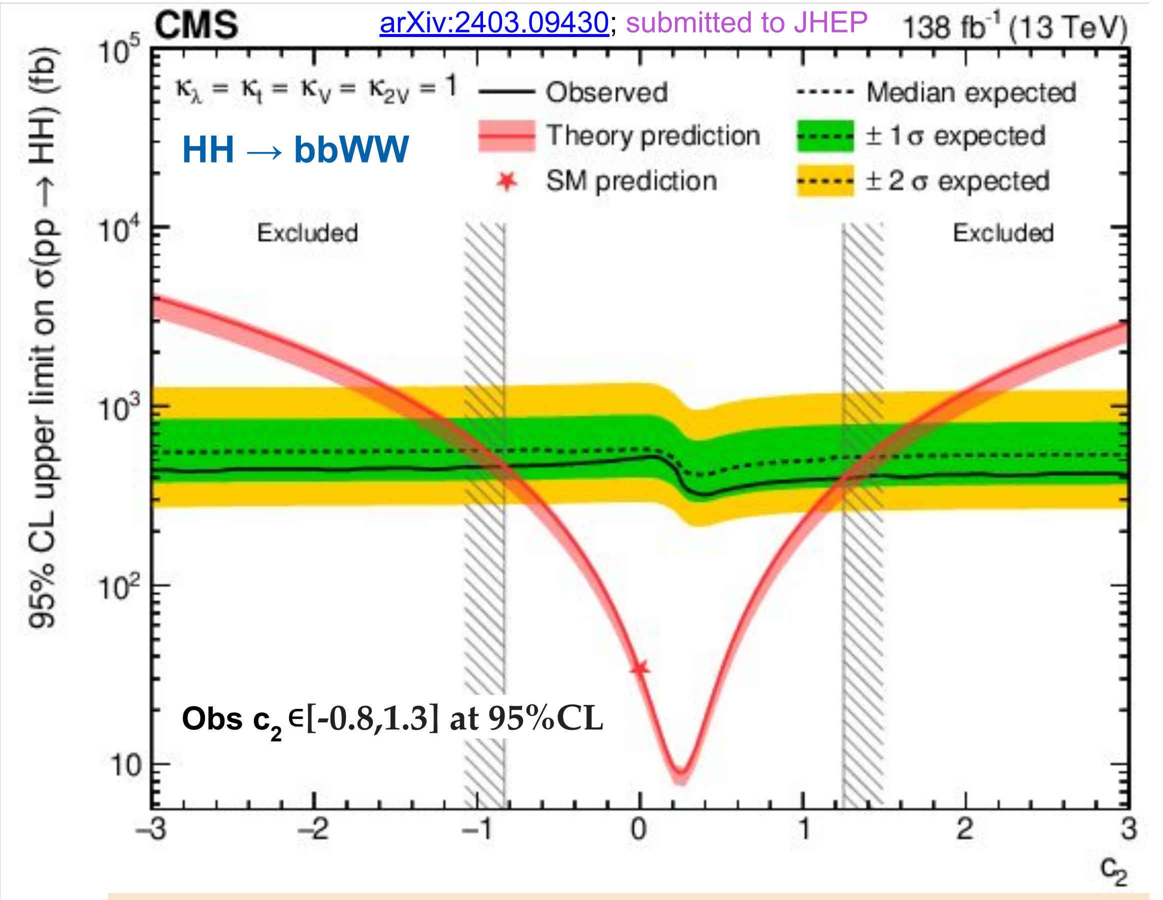




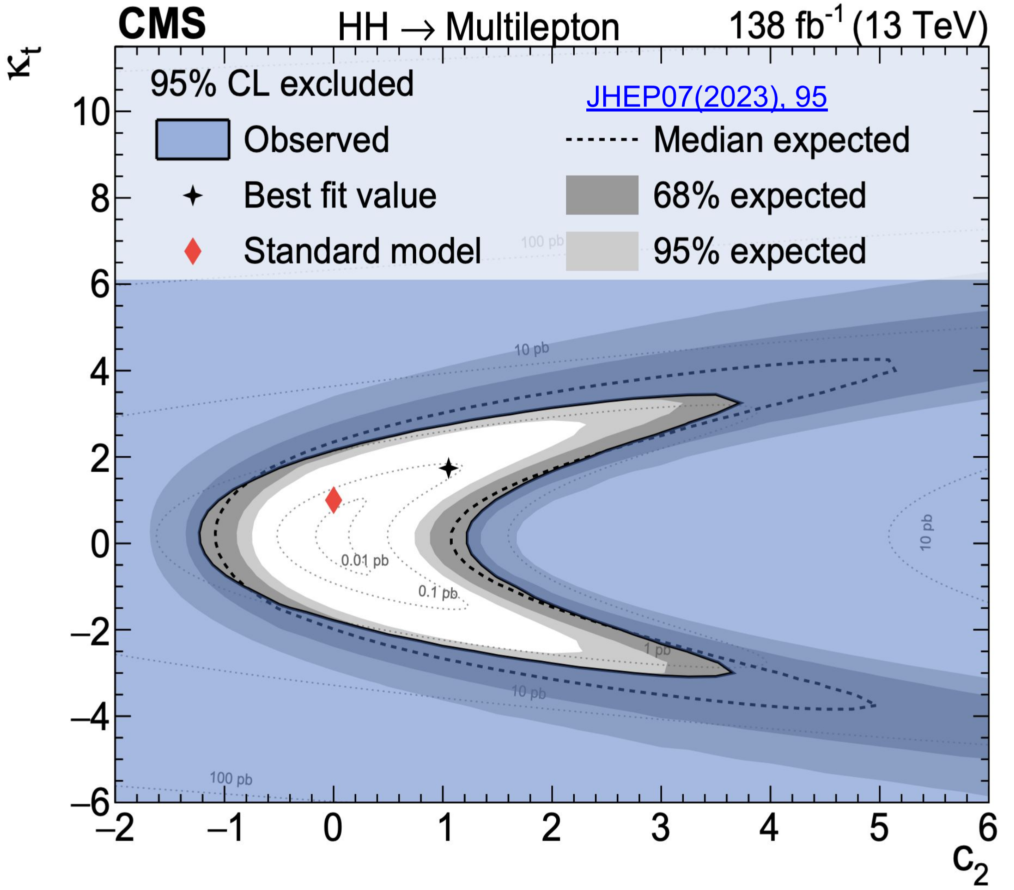
Explore HEFT sensitivity with 20 coupling configurations
JHEP04(2016)126, JHEP03(2020)091

Scans of HEFT parameters

** New since ICHEP 2022



Cross section upper limits as a function of c_2



2D likelihood scan of c_2 vs κ_t

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Summary

- EFT is a powerful tool to test precision of SM and search for new physics
- CMS is actively pursuing a global approach to EFT analyses which include Higgs, top .. etc
- Looking forward to exciting times in Run 3 and beyond!

New physics can lurk
in unexpected places

... Thank you !

Backup

EFT search in $t(\bar{t})X$

JHEP 12 (2023) 068

Grouping of WCs	WCs	Lead categories
Two heavy quarks with two leptons	$c_{Q\ell}^{3(\ell)}$, $c_{Q\ell}^{-(\ell)}$, $c_{Qe}^{(\ell)}$, $c_{t\ell}^{(\ell)}$, $c_{te}^{(\ell)}$, $c_{t}^{S(\ell)}$, $c_{t}^{T(\ell)}$	3ℓ off-Z
Four heavy quarks	c_{QQ}^{1}, c_{Qt}^{1}, c_{Qt}^{8}, c_{tt}^{1}	$2\ell ss$
Two heavy quarks with two light "$t\bar{t}l\nu$-like"	c_{Qq}^{11}, c_{Qq}^{18}, c_{tq}^{1}, c_{tq}^{8}	$2\ell ss$
Two heavy quarks with two light "$tl\bar{l}q$-like"	c_{Qq}^{31}, c_{Qq}^{38}	3ℓ on-Z
Two heavy quarks with with bosons "$t\bar{t}l\bar{l}$-like"	c_{tZ}, $c_{\varphi t}$, $c_{\varphi Q}^{-}$	3ℓ on-Z and $2\ell ss$
Two heavy quarks with with bosons "tXq-like"	$c_{\varphi Q}^{3}$, $c_{\varphi tb}$, c_{bW}	3ℓ on-Z
Two heavy quarks with with bosons with significant impacts on many processes	c_{tG}, $c_{t\varphi}$, c_{tW}	3ℓ and $2\ell ss$

Summary of categories that provide leading contributions to the sensitivity for subsets of the WCs.

WC/Λ^2 [TeV^{-2}]	2σ Interval (others profiled)	2σ Interval (others fixed to SM)
$c_{t}^{T(\ell)}$	[-0.37, 0.37]	[-0.40, 0.40]
$c_{t}^{S(\ell)}$	[-2.60, 2.59]	[-2.80, 2.80]
$c_{te}^{(\ell)}$	[-1.76, 2.20]	[-1.90, 2.39]
$c_{t\ell}^{(\ell)}$	[-1.78, 2.10]	[-2.01, 2.20]
$c_{Qe}^{(\ell)}$	[-1.89, 1.94]	[-2.04, 2.12]
$c_{Q\ell}^{-(\ell)}$	[-1.56, 2.27]	[-1.80, 2.33]
$c_{Q\ell}^{3(\ell)}$	[-2.81, 2.54]	[-2.68, 2.58]
$c_{\varphi t}$	[-10.76, 7.91]	[-4.95, 3.19]
$c_{\varphi tb}$	[-3.23, 3.23]	[-3.15, 3.19]
$c_{\varphi Q}^{3}$	[-0.81, 2.01]	[-0.84, 1.91]
c_{bW}	[-0.75, 0.76]	[-0.75, 0.75]
c_{tG}	[-0.27, 0.24]	[-0.22, 0.25]
$c_{\varphi Q}^{-}$	[-6.09, 8.20]	[-2.66, 2.95]
$c_{t\varphi}$	[-8.98, 2.85]	[-7.68, 2.15]
c_{tZ}	[-0.70, 0.63]	[-0.58, 0.59]
c_{tW}	[-0.54, 0.45]	[-0.47, 0.41]
c_{Qt}^{1}	[-2.71, 2.66]	[-2.75, 2.62]
c_{Qt}^{8}	[-5.15, 5.74]	[-5.24, 5.66]
c_{QQ}^{1}	[-3.03, 3.28]	[-3.04, 3.28]
c_{tt}^{1}	[-1.56, 1.60]	[-1.54, 1.63]
c_{tq}^{8}	[-0.67, 0.25]	[-0.68, 0.24]
c_{Qq}^{18}	[-0.68, 0.21]	[-0.67, 0.21]
c_{tq}^{1}	[-0.21, 0.21]	[-0.22, 0.20]
c_{Qq}^{11}	[-0.19, 0.19]	[-0.19, 0.19]
c_{Qq}^{38}	[-0.17, 0.16]	[-0.17, 0.16]
c_{Qq}^{31}	[-0.08, 0.07]	[-0.08, 0.07]

EFT search in semi-leptonic ttH with boosted H→bb

Phys.Rev.D 108 (2023) 032008

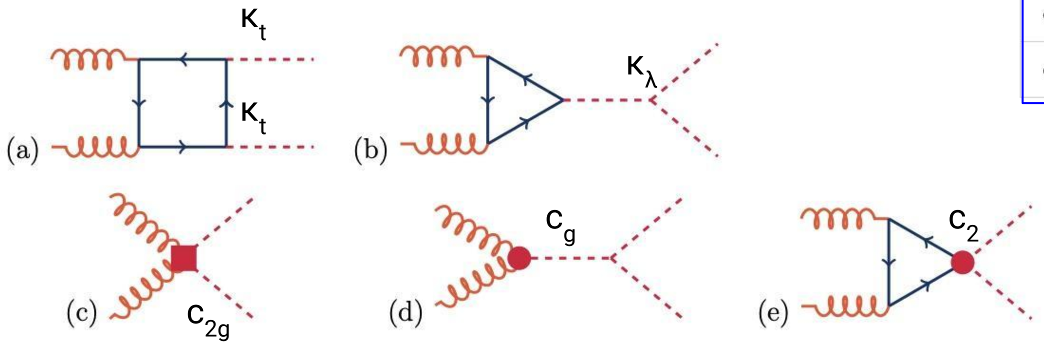
Operator	Definition	WC
‡$O_{u\varphi}^{(ij)}$	$\bar{q}_i u_j \tilde{\varphi}\,(\varphi^\dagger \varphi)$	$c_{t\varphi} + i\cancel{c^{I}_{t\varphi}}$
$O_{\varphi q}^{(ij)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{q}_i \gamma^\mu q_j)$	$c^{-}_{\varphi Q} + c^{3}_{\varphi Q}$
$O_{\varphi q}^{3(ij)}$	$(\varphi^\dagger i\overleftrightarrow{D}^{I}_\mu \varphi)(\bar{q}_i \gamma^\mu \tau^I q_j)$	$c^{3}_{\varphi Q}$
$O_{\varphi u}^{(ij)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{u}_i \gamma^\mu u_j)$	$c_{\varphi t}$
‡$O_{\varphi ud}^{(ij)}$	$(\tilde{\varphi}^\dagger i D_\mu \varphi)(\bar{u}_i \gamma^\mu d_j)$	$c_{\varphi tb} + i\cancel{c^{I}_{\varphi tb}}$
‡$O_{uW}^{(ij)}$	$(\bar{q}_i \sigma^{\mu\nu} \tau^I u_j)\, \tilde{\varphi} W^{I}_{\mu\nu}$	$c_{tW} + i\cancel{c^{I}_{tW}}$
‡$O_{dW}^{(ij)}$	$(\bar{q}_i \sigma^{\mu\nu} \tau^I d_j)\, \varphi W^{I}_{\mu\nu}$	$c_{bW} + i\cancel{c^{I}_{bW}}$
‡$O_{uB}^{(ij)}$	$(\bar{q}_i \sigma^{\mu\nu} u_j)\, \tilde{\varphi} B_{\mu\nu}$	$\frac{c_W}{s_W}(c_{tW} + i\cancel{c^{I}_{tW}}) - \frac{1}{s_W}(c_{tZ} + i\cancel{c^{I}_{tZ}})$

Ignore imaginary terms which are CP violating

Simultaneous fit of 8 WCs

WC/Λ^2	95% CL interval [TeV^{-2}] (Others profiled)	(Others fixed to SM)
$c_{t\varphi}/\Lambda^2$	[0.56, 30]	[0.20, 30]
$c^{-}_{\varphi Q}/\Lambda^2$	[−8.3, 9.9]	[−6.6, 8.7]
$c^{3}_{\varphi Q}/\Lambda^2$	[−4.4, 3.9]	[−4.1, 3.0]
$c_{\varphi t}/\Lambda^2$	[−13, 7.9]	[−12, 6.3]
$c_{\varphi tb}/\Lambda^2$	[−10, 12]	[−9.9, 11]
c_{tW}/Λ^2	[−1.6, 1.6]	[−1.0, 0.96]
c_{bW}/Λ^2	[−4.3, 4.3]	[−4.2, 4.2]
c_{tZ}/Λ^2	[−1.7, 1.7]	[−1.0, 1.1]

HEFT Interpretation benchmarks



12+1 benchmarks of JHEP04(2016)126

	1	2	3	4	5	6	7	8	9	10	11	12	8a
kl	7.5	1.0	1.0	-3.5	1.0	2.4	5.0	15.0	1.0	10.0	2.4	15.0	1.0
kt	1.0	1.0	1.0	1.5	1.0	1.0	1.0	1.0	1.0	1.5	1.0	1.0	1.0
c2	-1.0	0.5	-1.5	-3.0	0.0	0.0	0.0	0.0	1.0	-1.0	0.0	1.0	0.5
cg	0.0	-0.8	0.0	0.0	0.8	0.2	0.2	-1.0	-0.6	0.0	1.0	0.0	0.8/3
c2g	0.0	0.6	-0.8	0.0	-1.0	-0.2	-0.2	1.0	0.6	0.0	-1.0	0.0	0.0

7 benchmarks of JHEP03(2020)091

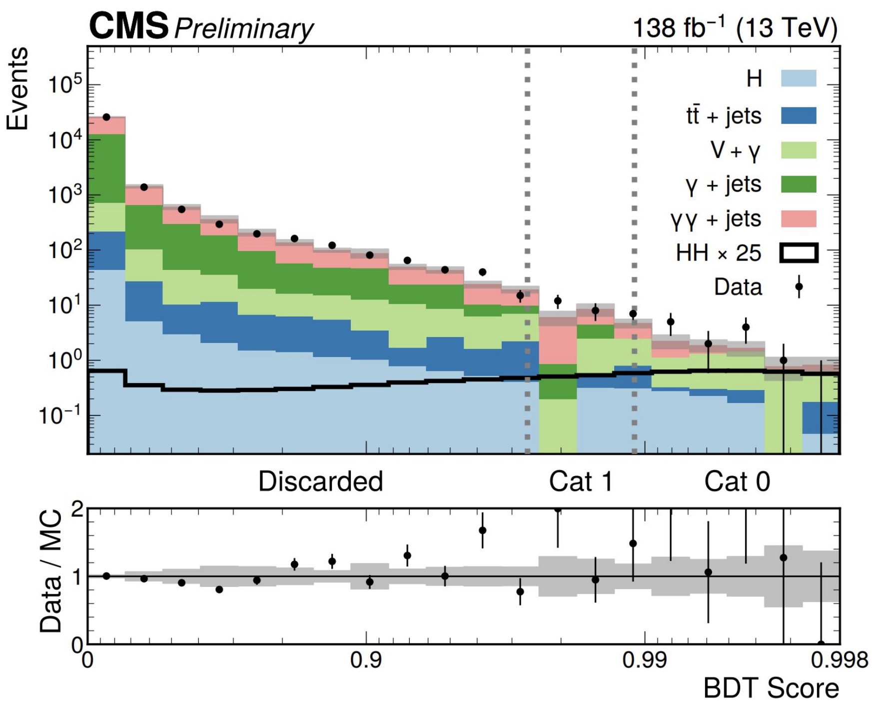
	1	2	3	4	5	6	7
kl	3.94	6.84	2.21	2.79	3.95	5.68	-0.10
kt	0.94	0.61	1.05	0.61	1.17	0.83	0.94
c2	-1./3.	1./3.	-1./3.	1./3.	-1./3.	1./3.	1.
cg	0.5*1.5	0.0*1.5	0.5*1.5	-0.5*1.5	1./6.*1.5	-0.5*1.5	1./6.*1.5
c2g	1./3.*(-3.)	-1./3.*(-3.)	0.5 *(-3.)	1./6.*(-3.)	-0.5 *(-3.)	1./3.*(-3.)	-1./6.*(-3.)

$HH \to \tau\tau\gamma\gamma$

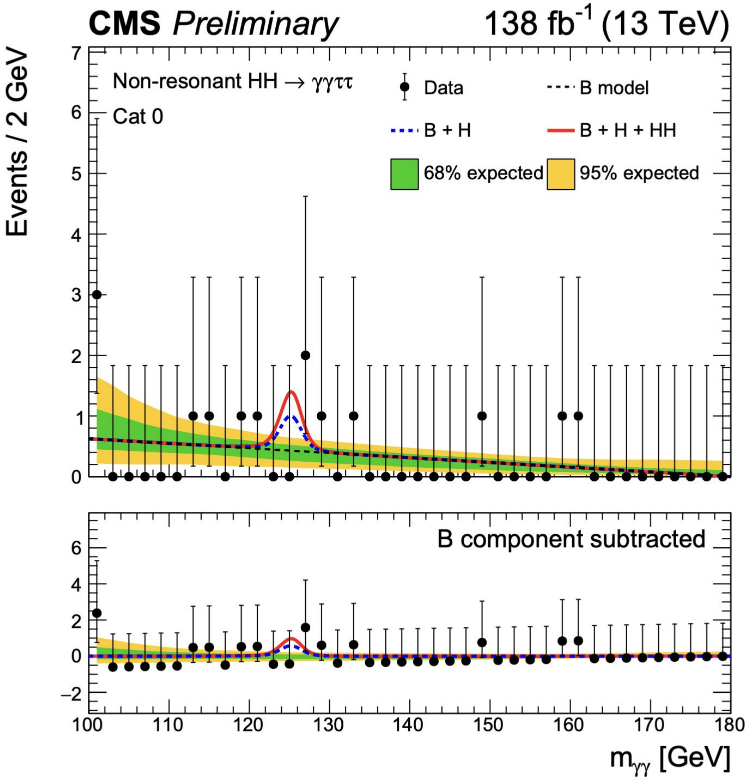
CMS-PAS-HIG-22-012

Tiny BR (0.028% of HH) but clean final state - first analysis!

Search in hadronic + leptonic τ final states



BDT to define signal enriched categories



Bump hunt in $m_{\gamma\gamma}$ spectrum

- Background modelling: Analytic functions determined by fitting the $m_{\gamma\gamma}$ spectrum
- Signal (and single Higgs): double Crystal Ball fitted on simulation

Older HEFT results from CMS

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