Non-resonant Di-Higgs searches with the CMS experiment

Irene Dutta *for CMS collaboration*

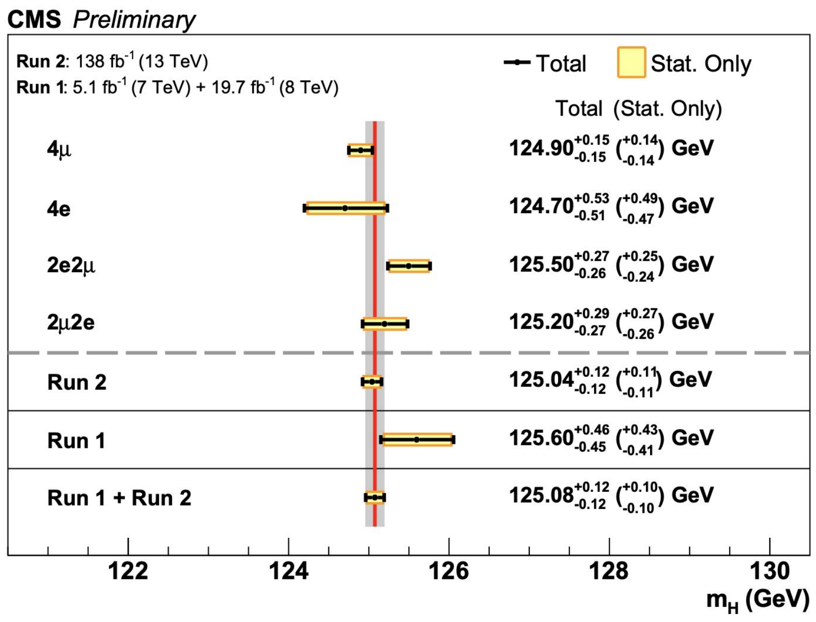
12th Edition of the Large Hadron Collider Physics

4th June, 2024

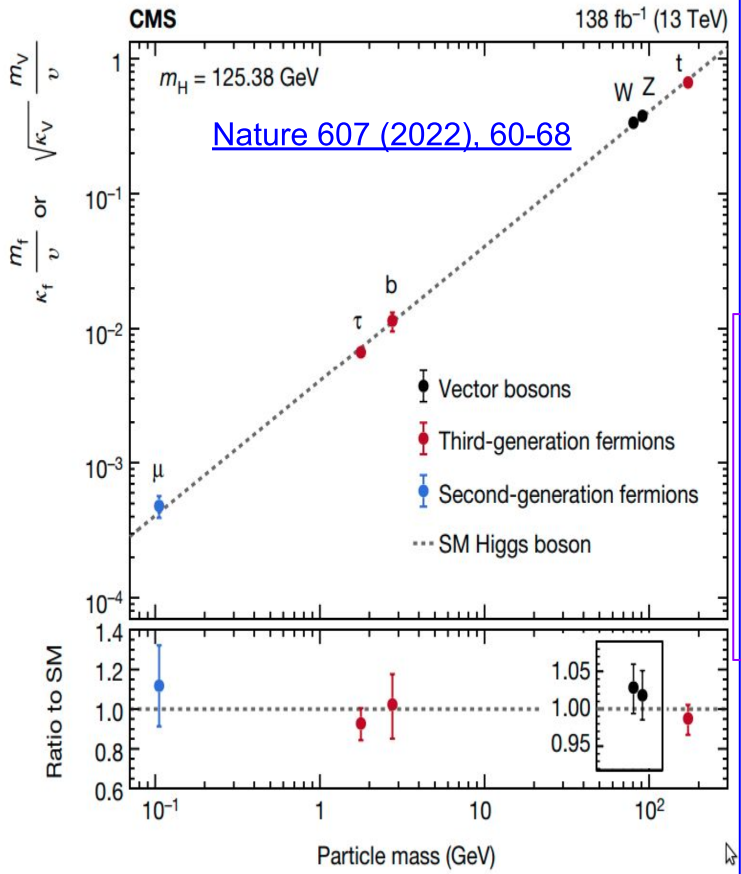
The Higgs Boson

Many of the properties of the Higgs are already precisely measured

m_H = 125.08 ± 0.12 GeV
CMS-PAS-HIG-21-019



Higgs mass measurement at 0.09% precision



Higgs couplings to the third generation fermions (t/b/τ) and to the SM bosons (W/Z/γ [effective]) are well measured

Fermilab

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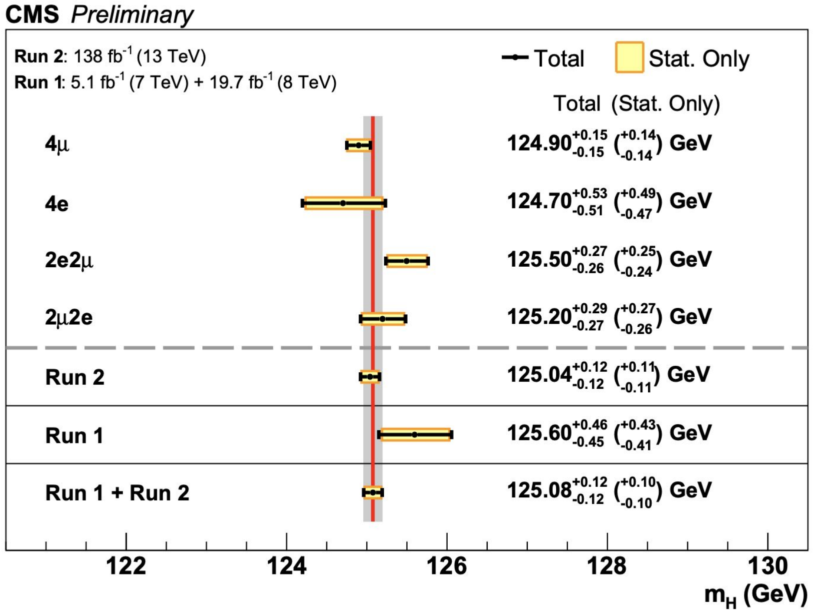
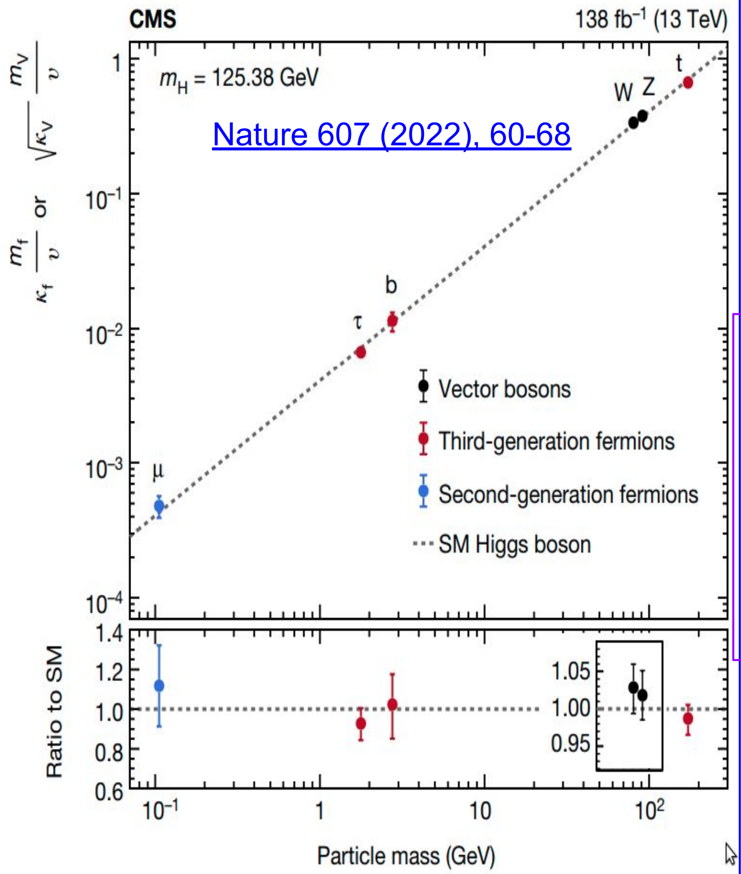


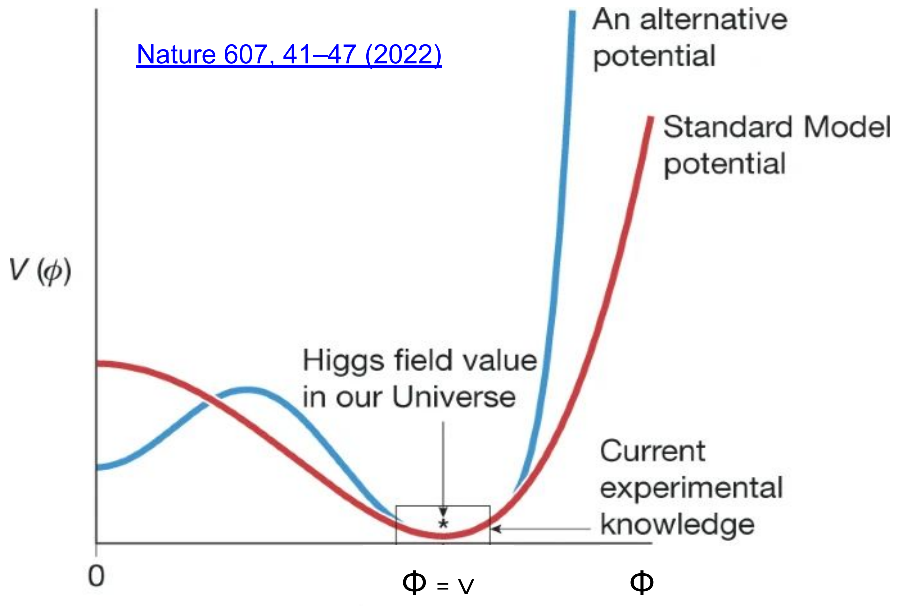


Higgs couplings to the third generation fermions (t/b/τ) and to the SM bosons (W/Z/γ [effective]) are well measured

We know very little about the Higgs potential!

The Higgs potential

Our current knowledge



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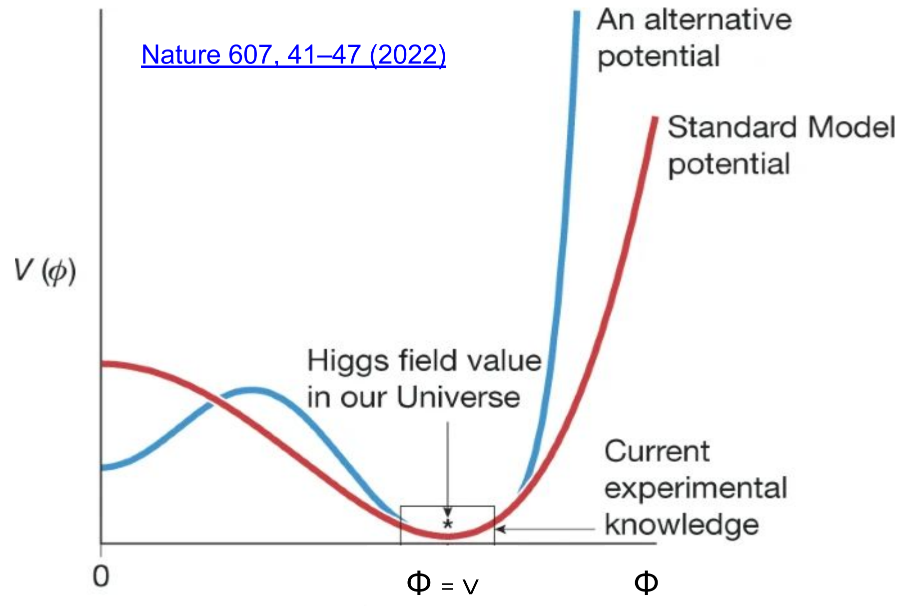

.. and why we should be expanding that knowledge

The Higgs potential

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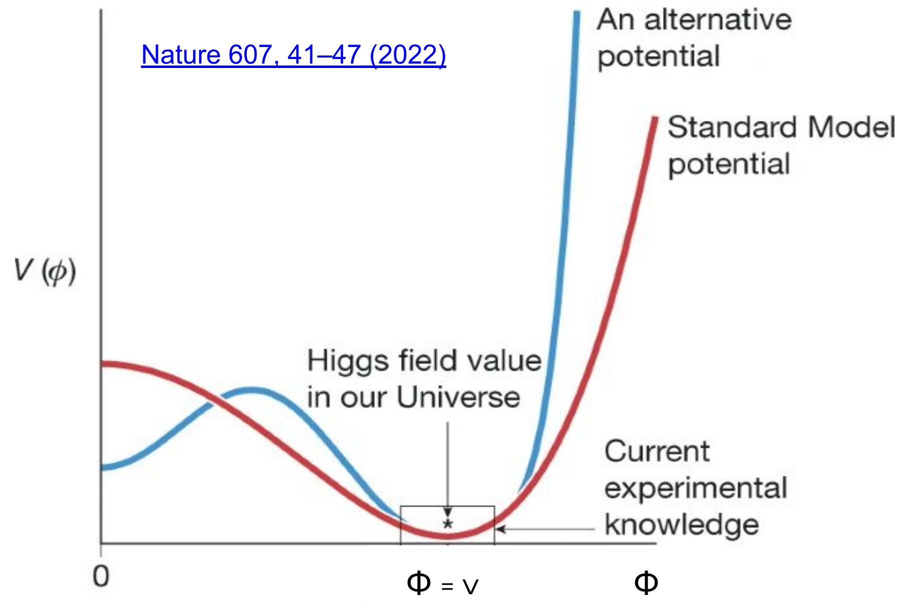

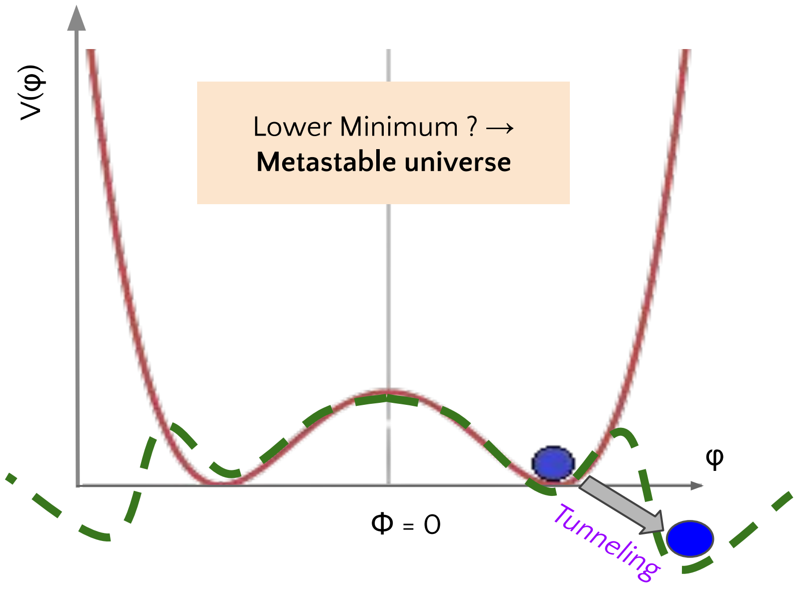

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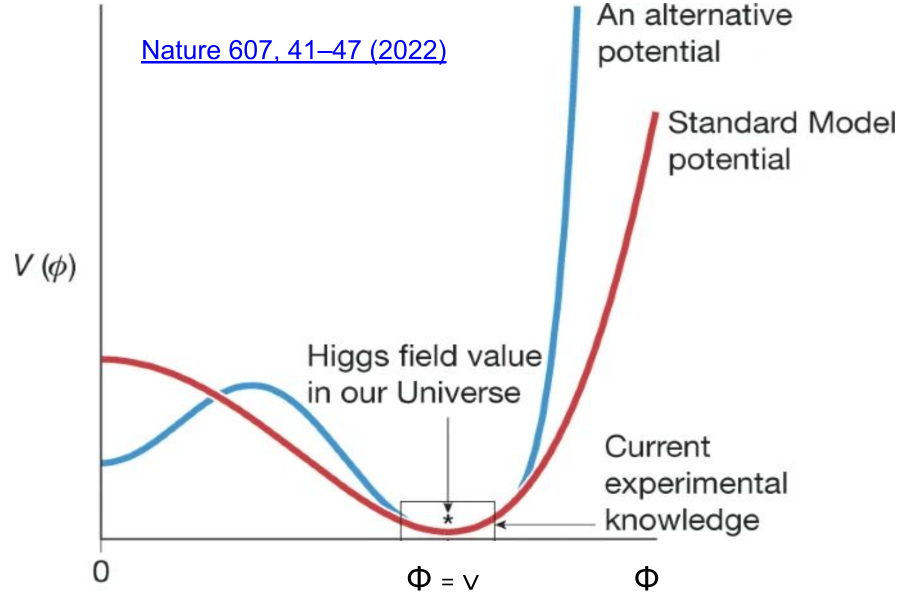

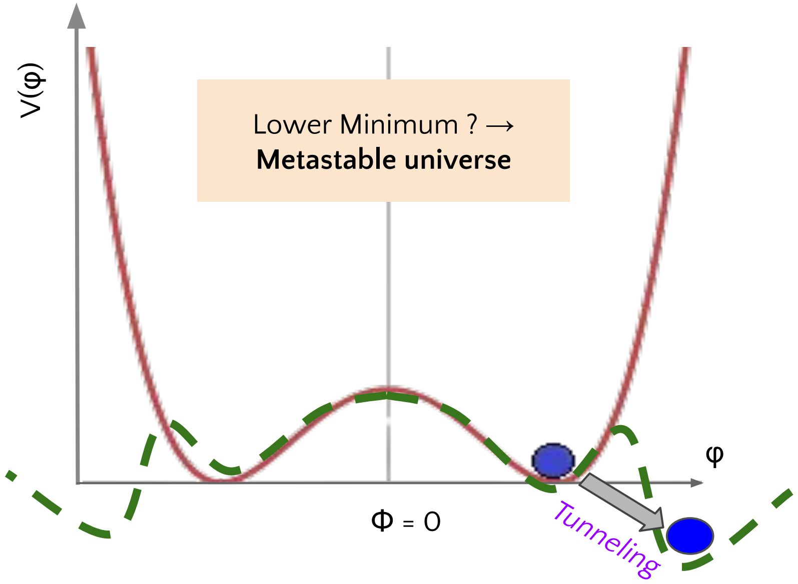

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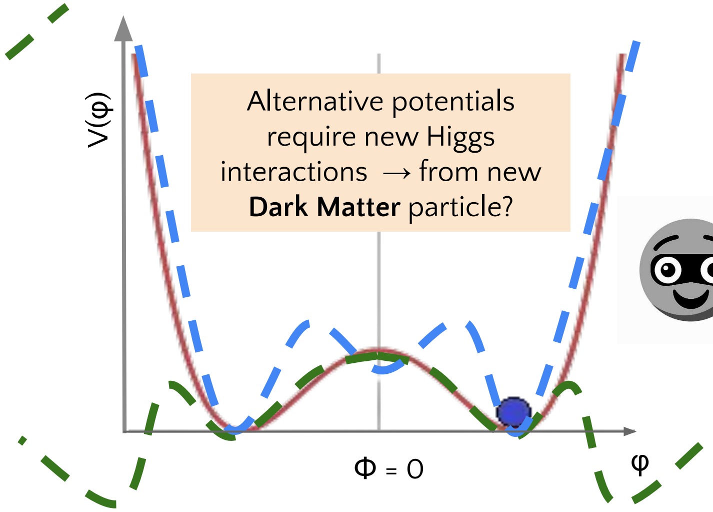

The Higgs potential

$$V(h) \sim \lambda_3 v h^3 + \tfrac{1}{4} \lambda_4 h^4$$

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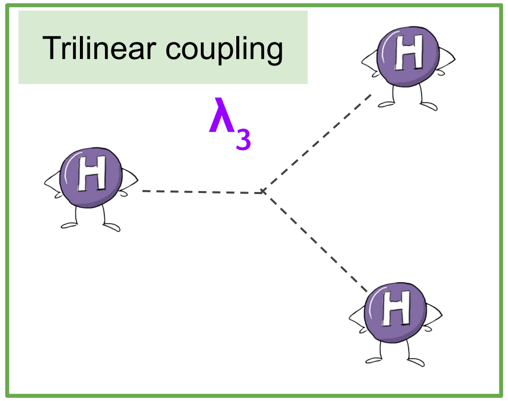

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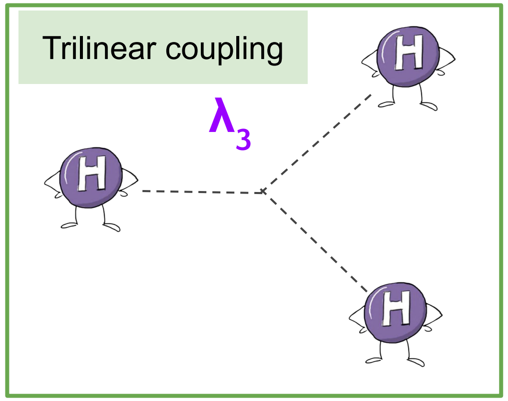

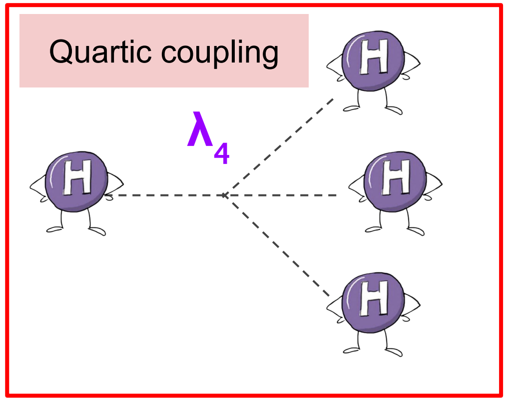

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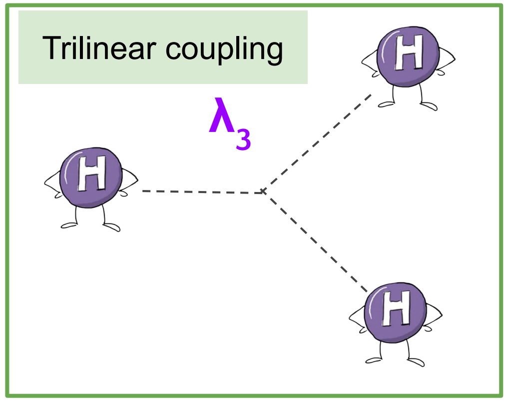

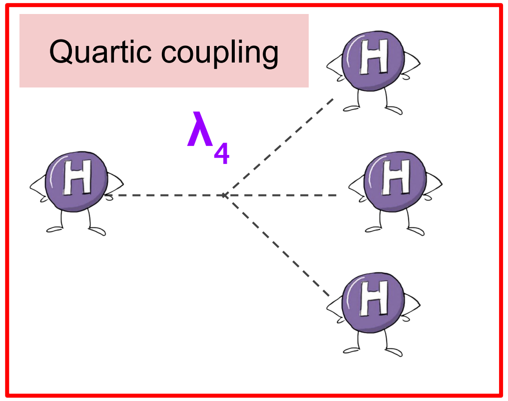

$\lambda_3 = \lambda_4$ in SM

$\lambda = m_h^2/2v^2 \sim 0.13$

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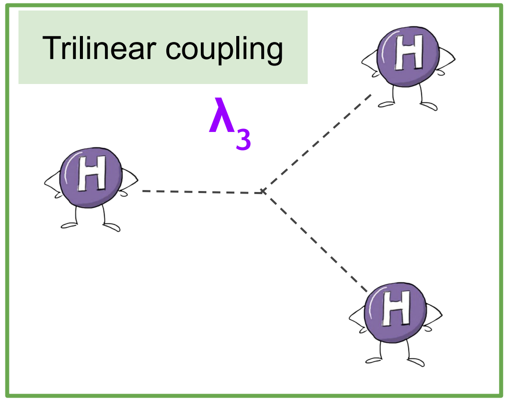
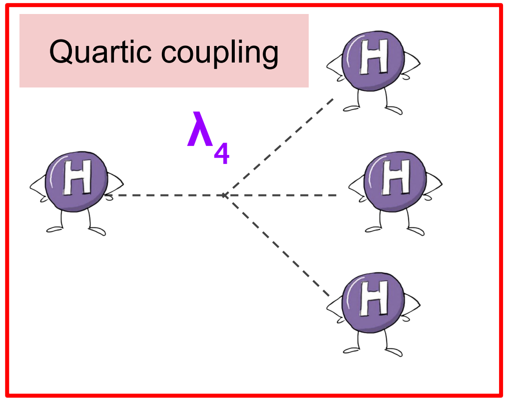
1 in 10^{12} (trillion) pp collisions





Expect observation in HL-LHC

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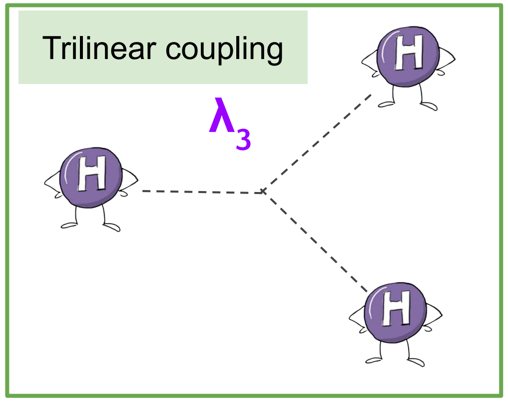

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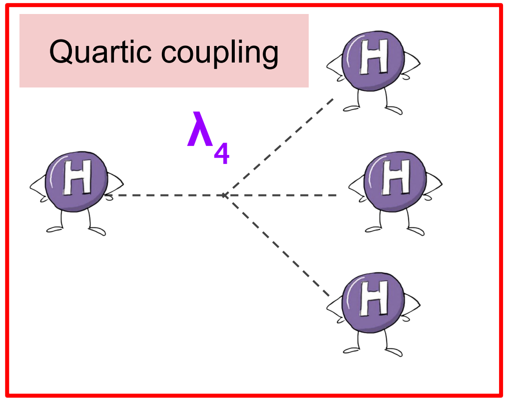

Out of reach at current colliders

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Fermilab

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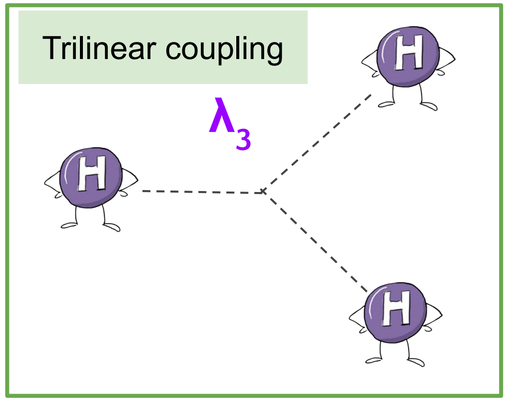

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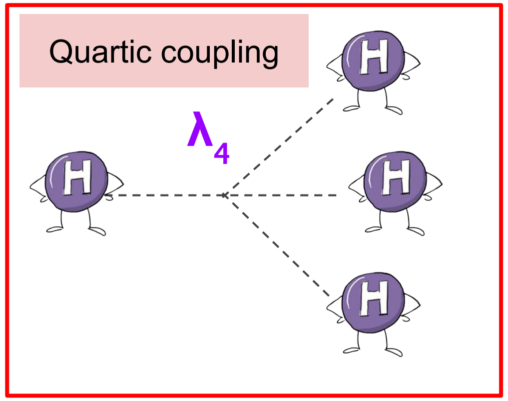

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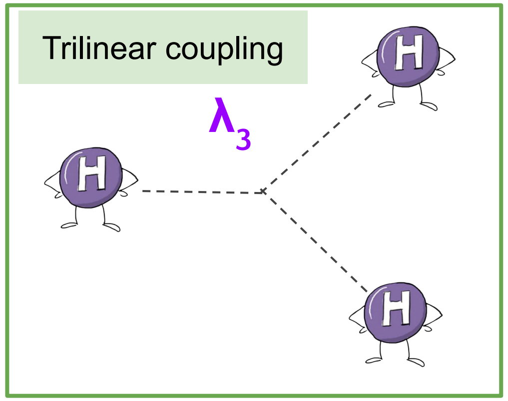

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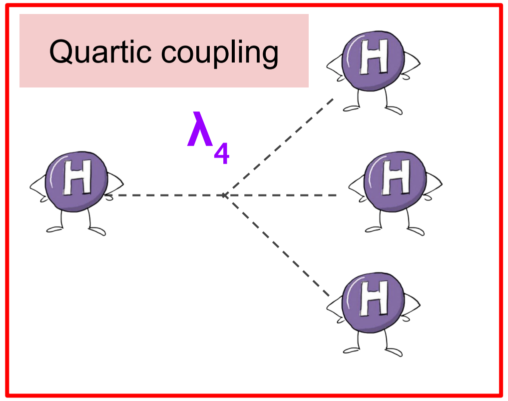

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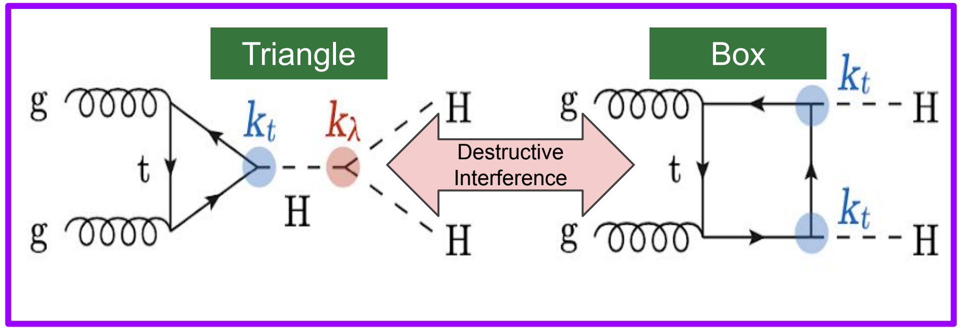
Kappa framework $\kappa_c = c^{obs}/c^{SM}$ for any coupling c

Test *accuracy* and *deviation* of SM

For e.g., $\kappa_\lambda = \lambda_3^{obs}/\lambda_3^{SM} = 1$ in SM

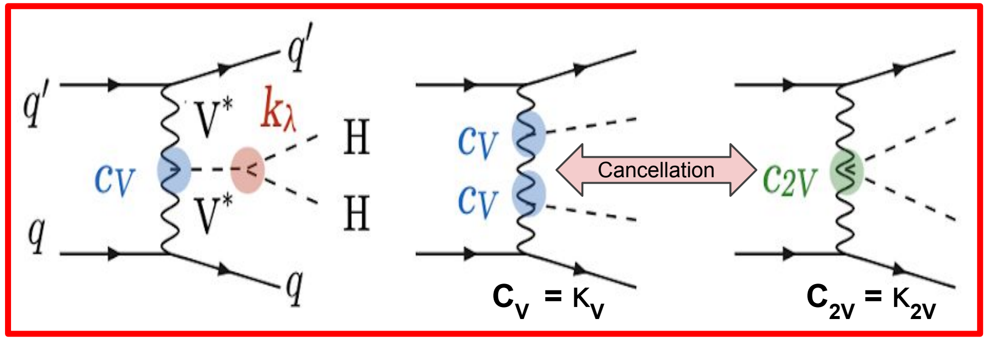
HH production at LHC

gluon-gluon Fusion (ggF) - 31.05 fb @ 13 TeV



Dominant production mechanism

Vector Boson Fusion (VBF) - 1.73 fb @ 13 TeV

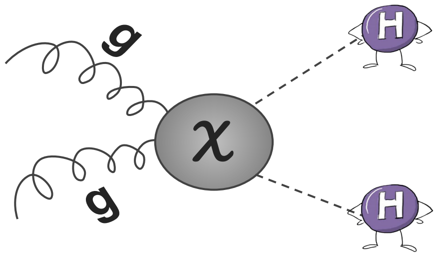


Unique handle to study qqHH (κ_{2V}) coupling

4600 Higgs Boson pairs ($\sigma \times \mathcal{L}$) produced in pp collisions between 2016 - 2018

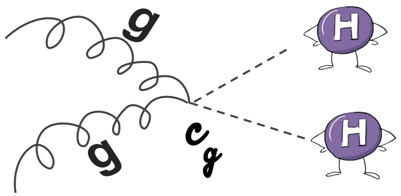
Challenging to find experimentally

Additional non SM like couplings in HH

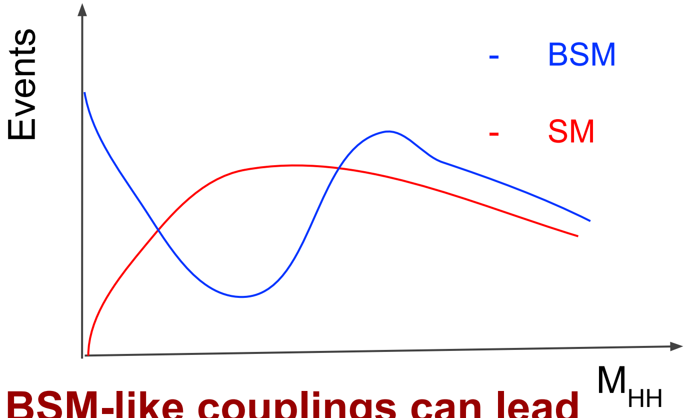


Assume new physics at some high energy scale Λ

What we see at a lower energy scale



An effective anomalous coupling (point-like interaction)



BSM-like couplings can lead to non-standard kinematics

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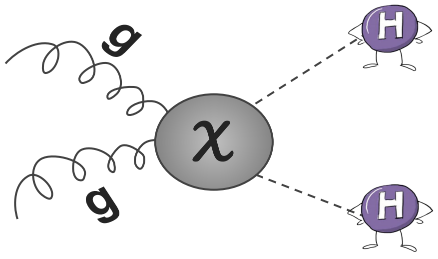

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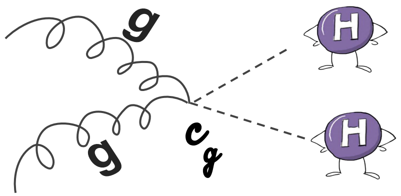

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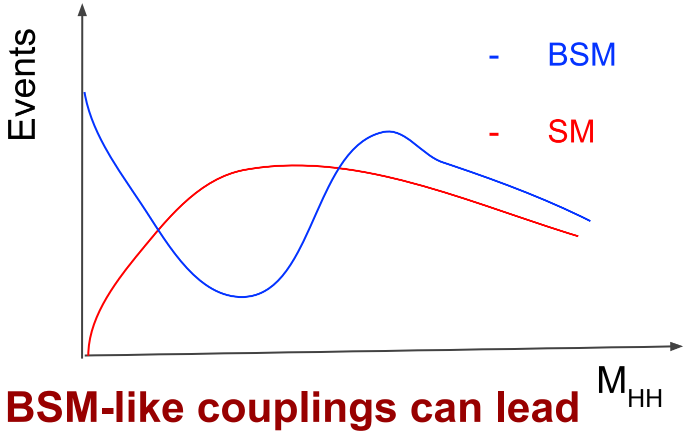
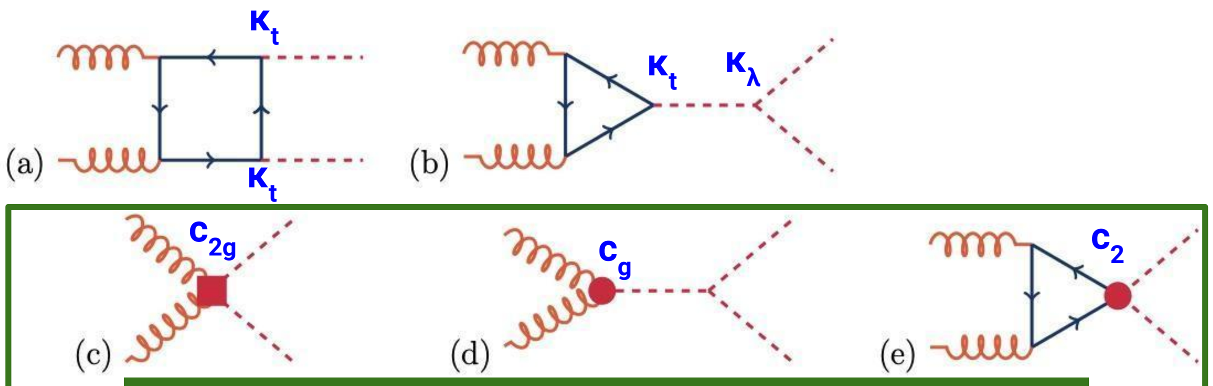


BSM-like couplings can lead to non-standard kinematics

Study with Higgs Effective Field Theory (HEFT)



Non-SM modifications to ggHH

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

HH decays

Use all events in our data

Increasing statistics

HH branching ratios

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

○ Public result by CMS

Decreasing background complexity

Also see plenary tomorrow
DiHiggs production at LHC (SM) Alison

● ggF ● VBF ☆ New since LHCP 2023

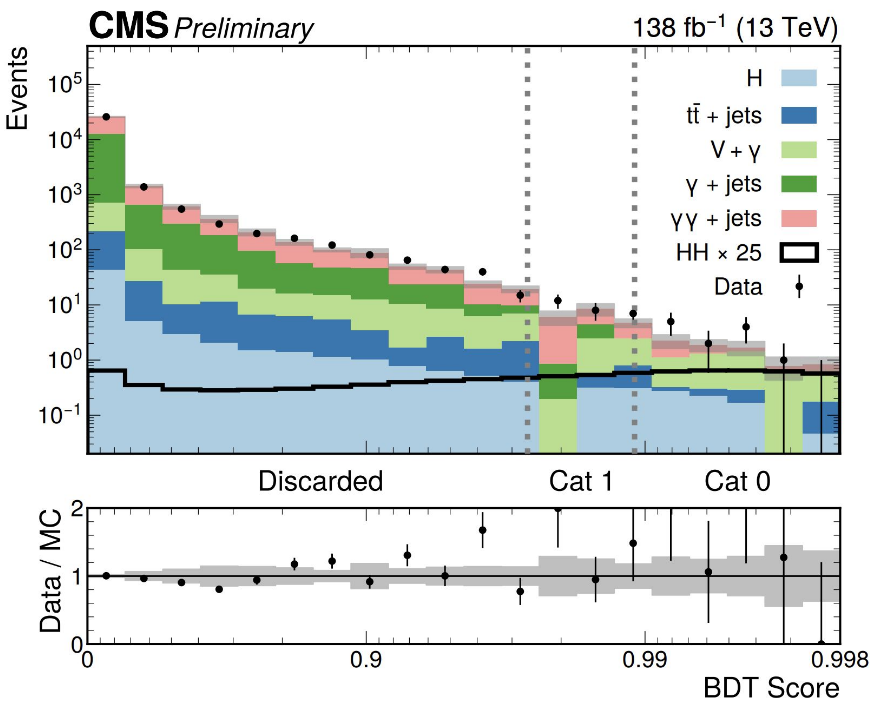
HH → ττγγ (all τ final states)	ggF ☆	CMS-PAS-HIG-22-012
H + HH combination	☆	CMS-PAS-HIG-23-006
HH → γγbb	ggF, VBF	JHEP03 (2021) 257
HH → 4b, boosted	ggF, VBF	Phys. Rev. Lett. 131, 041803
HH → 4b, resolved	ggF, VBF	Phys. Rev. Lett. 129, 081802
VHH → 4b		CMS-HIG-22-006
HH → ττbb (boosted and resolved)	ggF, VBF	Phys. Lett. B 842 (2023) 137531
HH → WWWW, WWττ, ττττ (multilepton)	ggF, VBF	JHEP 07 (2023) 095
HH → bbZZ(4l)	ggF, VBF	JHEP 06 (2023) 130
HH → bbWW (single lepton and dilepton final state)	ggF, VBF	CMS-HIG-21-005
HH → WWγγ (all WW final states)	ggF	CMS-PAS-HIG-21-014

HH → ττγγ

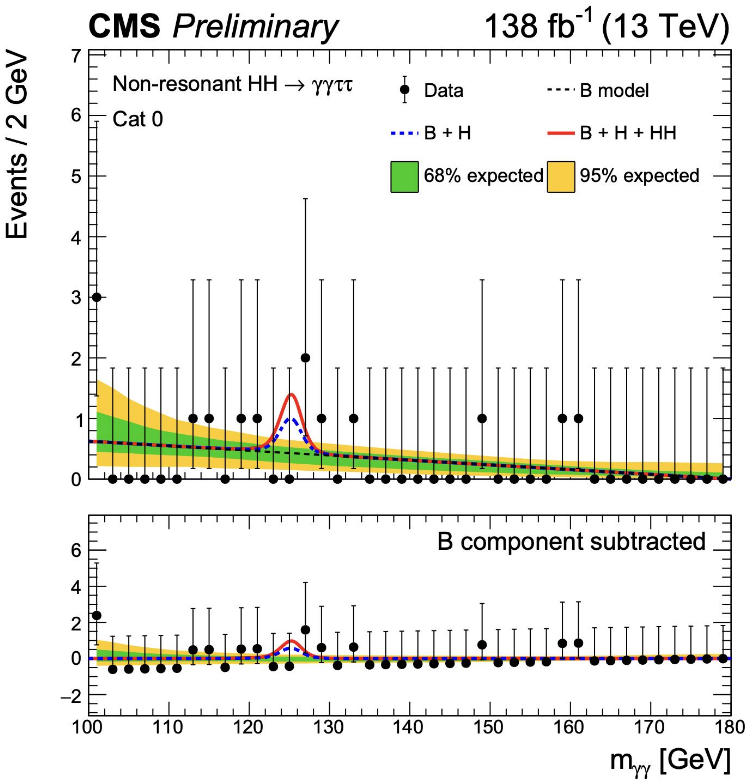
CMS-PAS-HIG-22-012

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

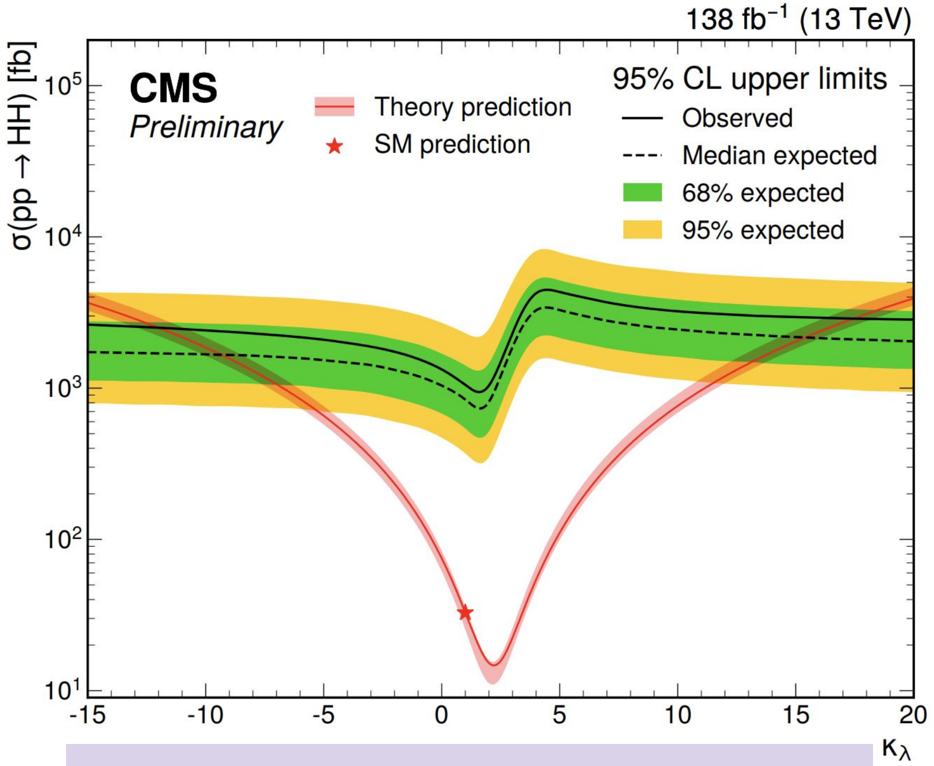
- Background modelling: Analytic functions determined by fitting the $m_{\gamma\gamma}$ spectrum
- Signal (and single Higgs): double Crystal Ball fitted on simulation

Fermilab

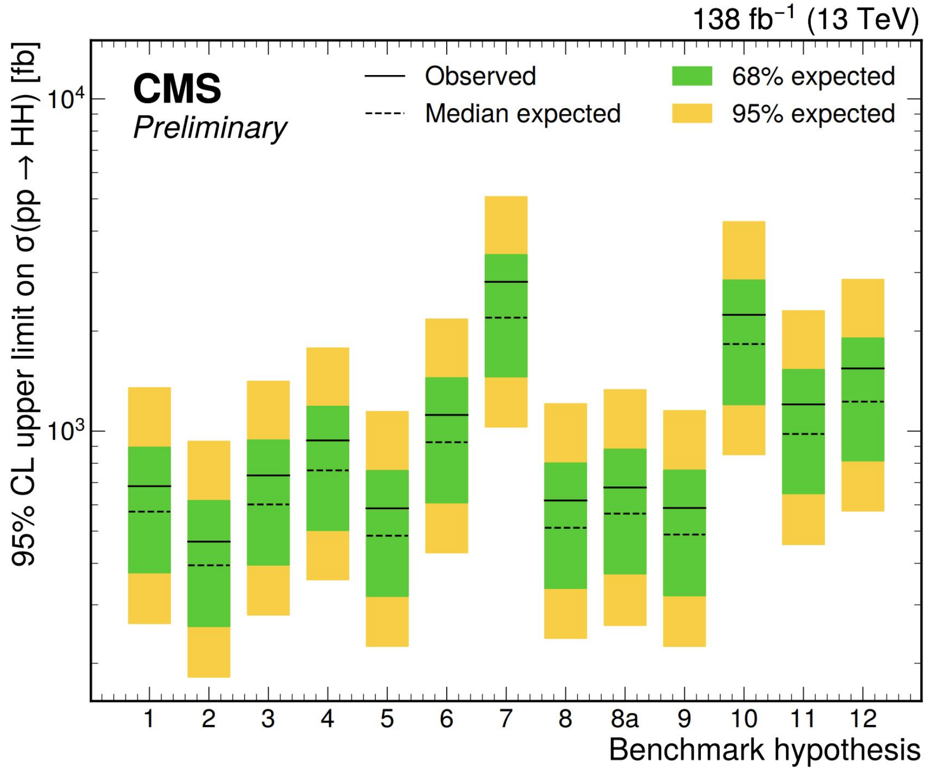
HH → ττγγ

CMS-PAS-HIG-22-012

95% CL Upper limit on σ_{HH} - 33 (26) x SM Obs (Exp)



-13 **(-11)** < κ_λ < 18 **(16)** Obs **(Exp)**



HEFT benchmark limits

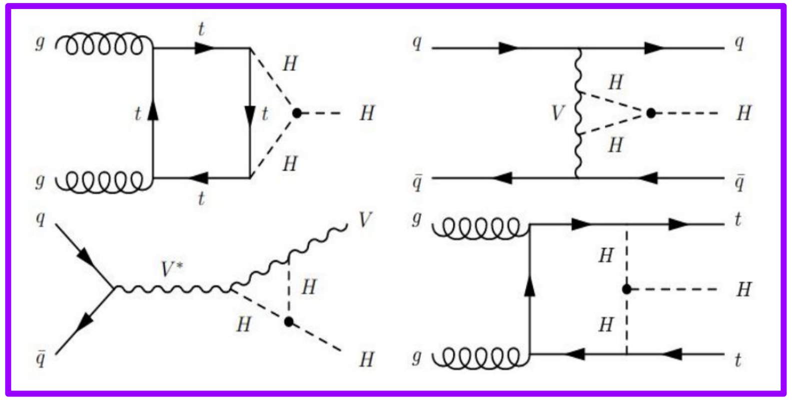
.. Also includes results on resonant X → HH and X → HY production
See plenary from Monday, S. Hirose

H + HH combination

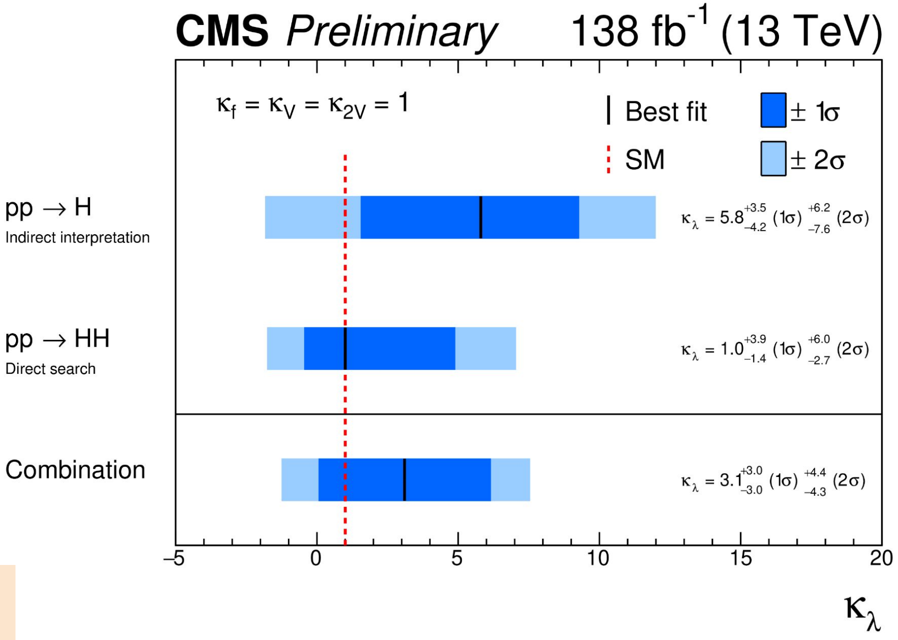
CMS-PAS-HIG-23-006

Combine all available single H and HH analyses from CMS

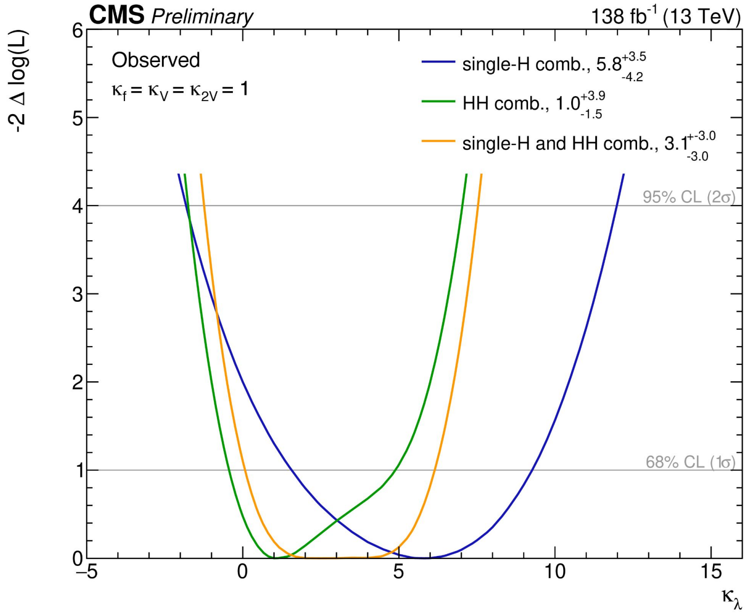
Indirect κ_λ access through NLO contributions to single Higgs production and decay



$\sigma_H > \sigma_{HH} \Rightarrow$ sensitivity to smaller variations



Best fit values of κ_λ



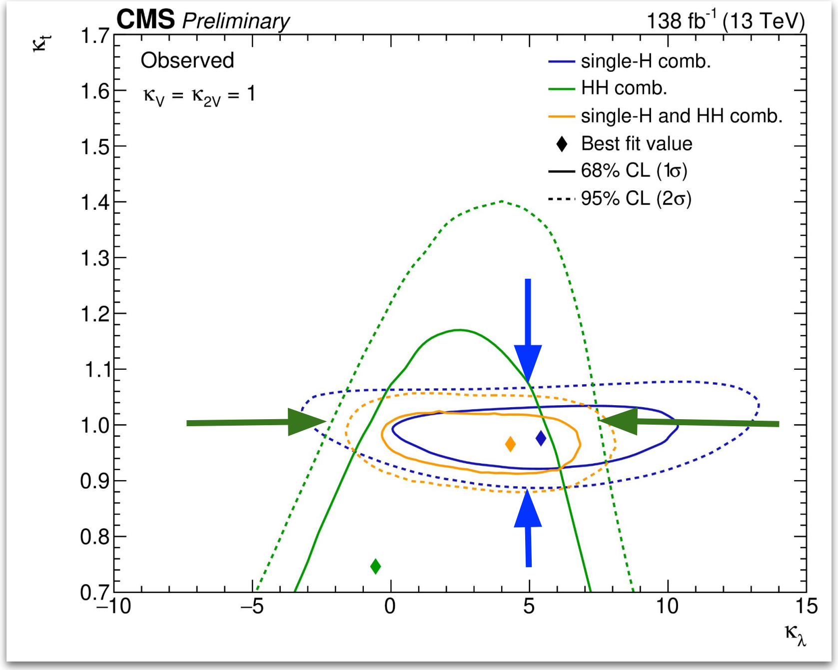
1D likelihood scan of κ_λ with other couplings fixed to 1

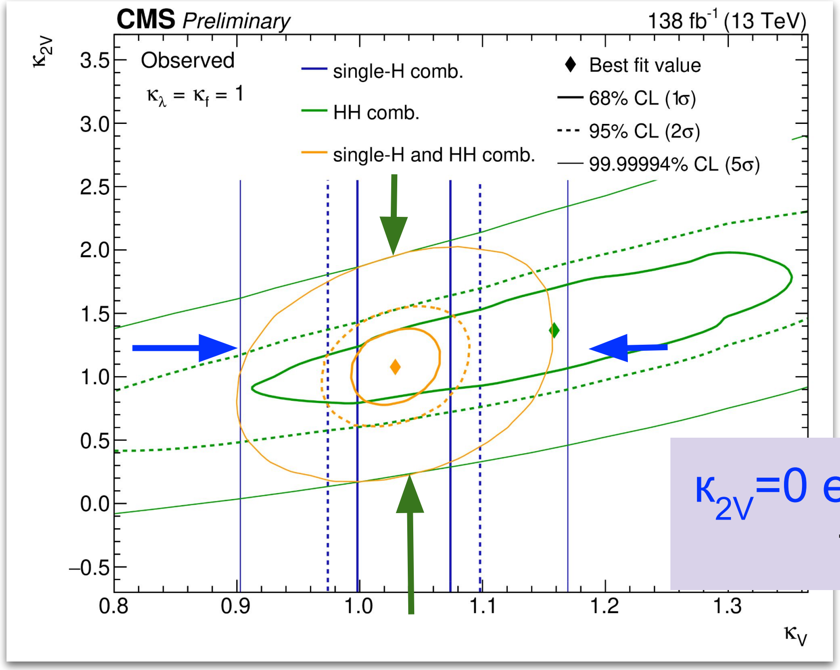
Fermilab

H + HH combination

CMS-PAS-HIG-23-006

Constrain parameter phase-space in 2D





κ_{2V}=0 excluded at >5σ for **all** $\boldsymbol{\kappa_V}$

Constrain with single Higgs

Constrain with HH

Non-resonant HH Run 2 combination

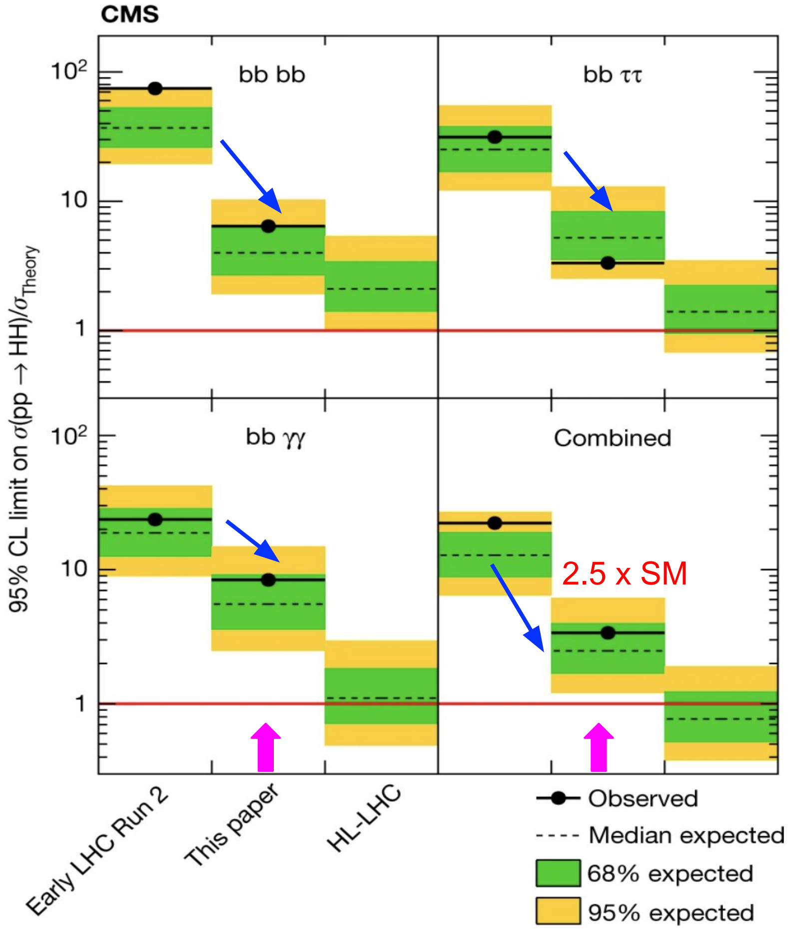
[Nature 607 (2022), 60-68]

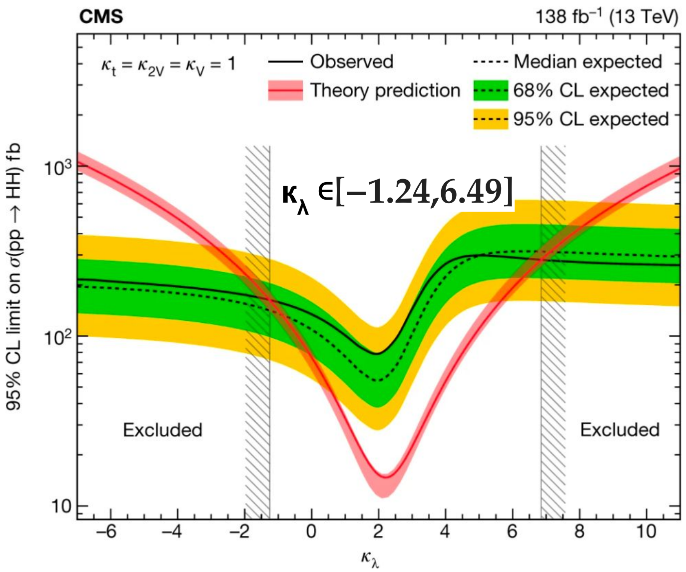
Increased luminosity
+
Complex analysis methods

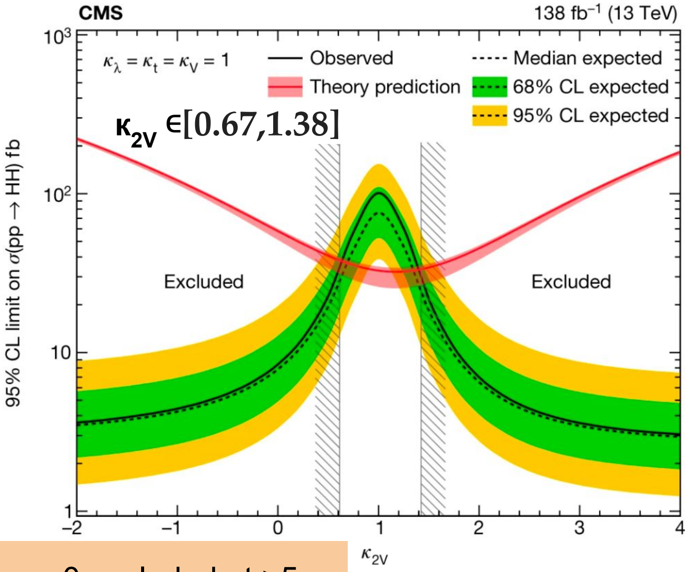
↓

Big improvement from early Run 2 result

All in *<5 % of the total data* to be collected from the LHC + HL-HLC







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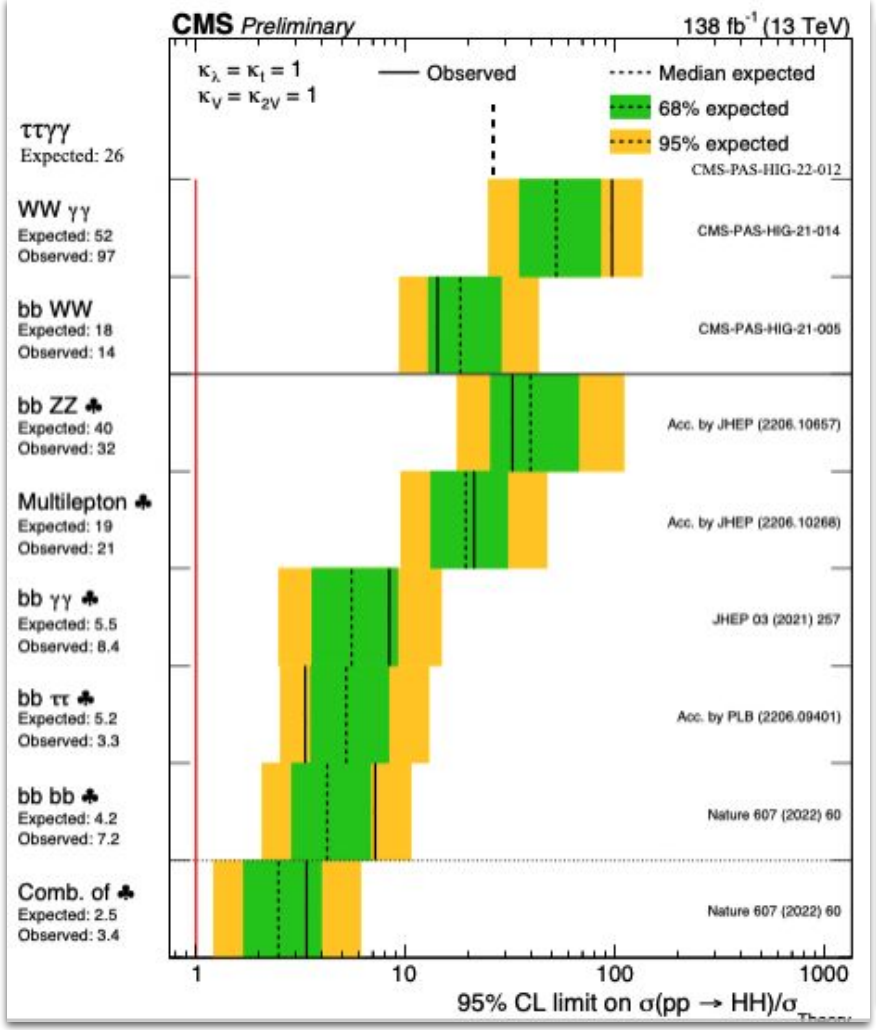
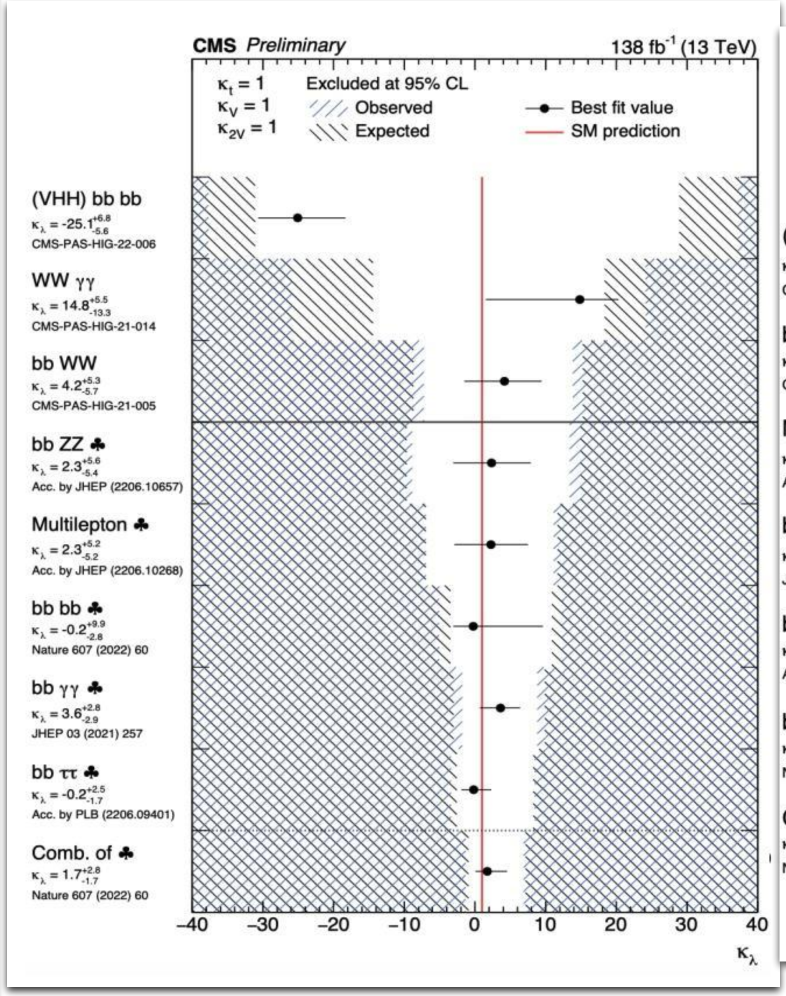
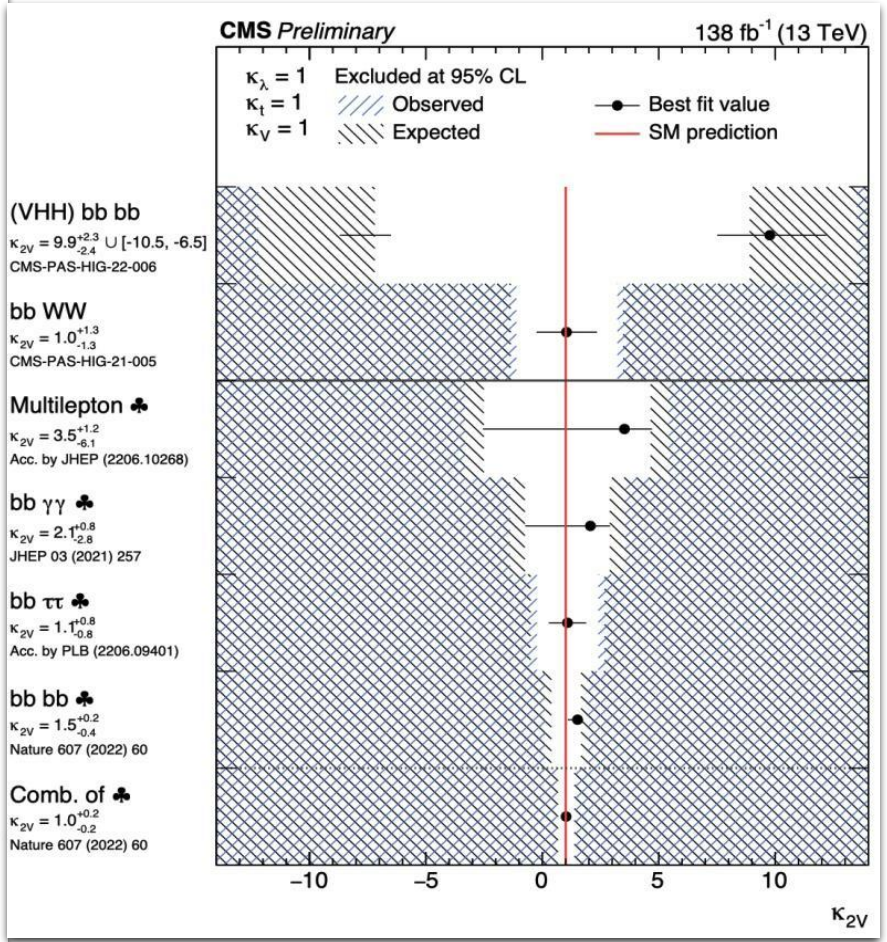
Summary of results from HH analyses

CMS Summary results for HIggs



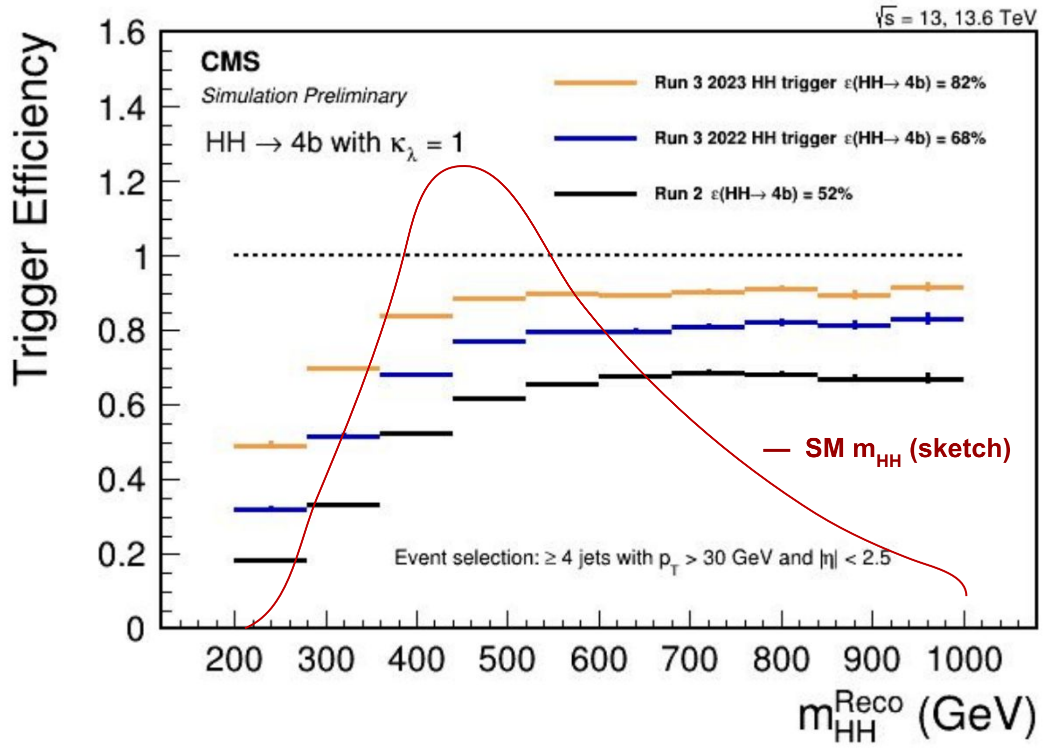


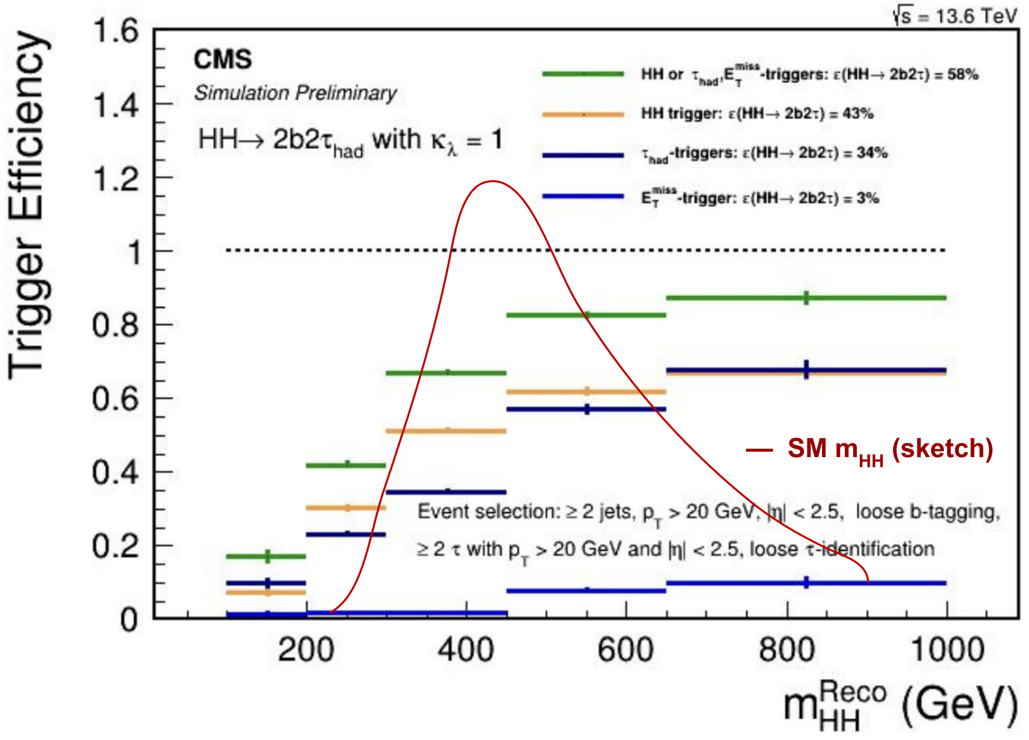


CERN-CMS-DP-2023-050
CMS DP -2020/002
Phys. Rev. D 101, 056019
JINST 17 (2022) P07023

Run 3 improvements

New online triggering strategies for Run 3 based on **ParticleNet for b-tagging** and **DeepTau for τ tagging** show great improvements over Run 2 baseline





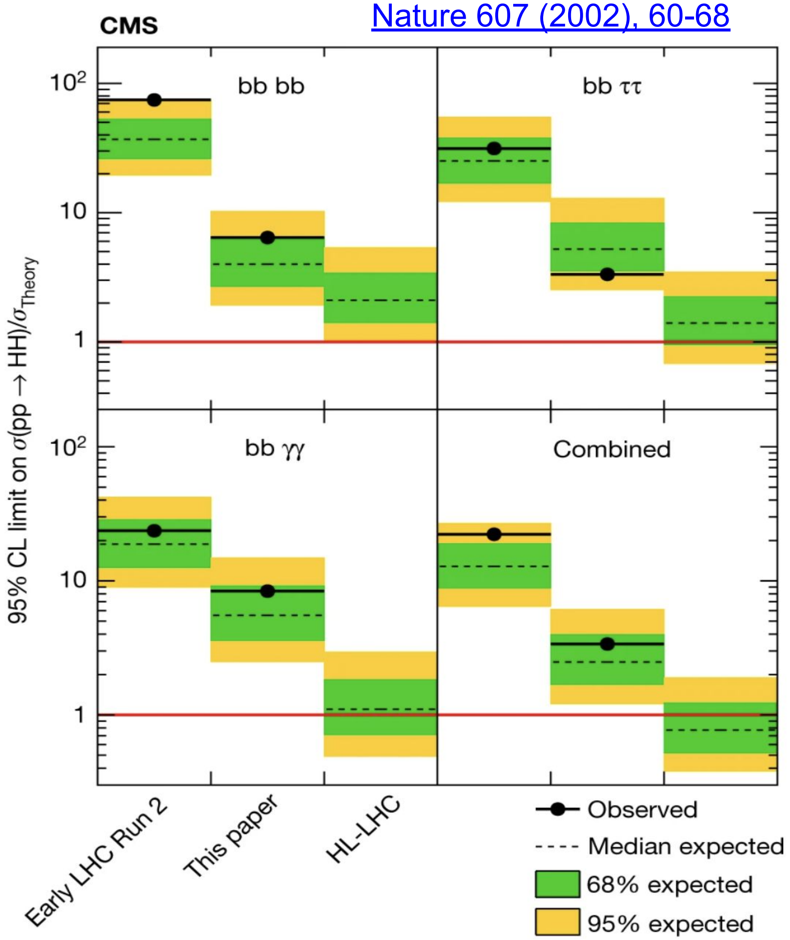
Expect improvements to all HH searches with decays to **bb** or **ττ**

Run3 and HL-LHC projections

Data-taking period	Lumi (fb^{-1})	HH projection	Reference
Run 2	137	2.5 x SM (CMS)	Nature, 607, 60-68 (2022)
Run 2 + Run 3	137 +150 = 300	1 x SM (ATLAS + CMS)	Luminosity based scaling (back-of envelope)
HL-LHC (with upgraded detectors)	3000	4σ (ATLAS +CMS)	CERN-LPCC-2018-04 (based on fast simulations)

The many new developments *(triggers, machine learning based taggers, new decay channels, novel detectors ..)* have the **potential to observe HH at 5σ at HL-LHC**

Nature 607 (2002), 60-68



Fermilab

Summary

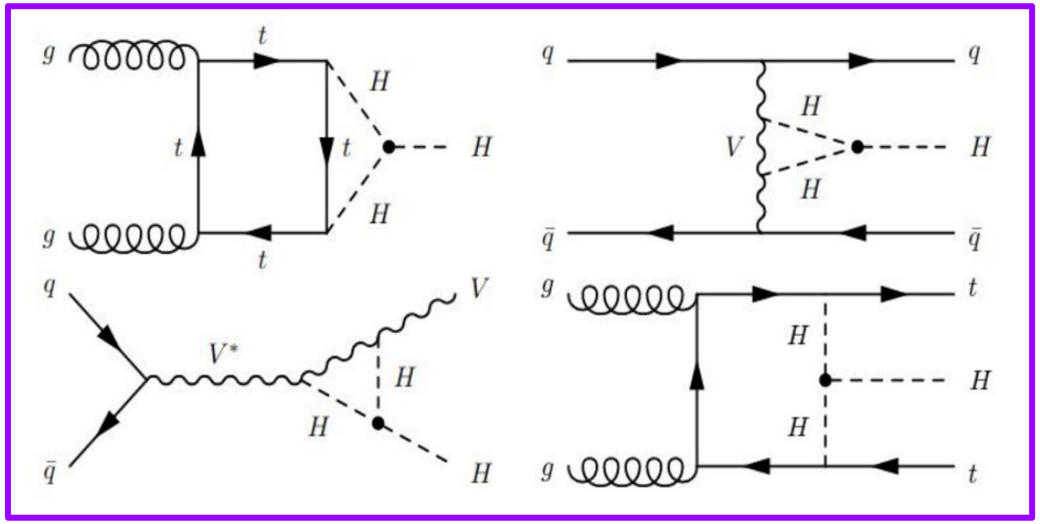
- The HH process is crucial for understanding the shape of the Higgs potential
- Great results from Run 2
  - complex analysis techniques
  - new HH decay channels
  - H+HH combination
- Run 3 will bring new opportunities → improved triggering strategy
- The novel detector technology, ML techniques, triggering strategies … etc have the capacity to push to 5σ observation at HL-LHC

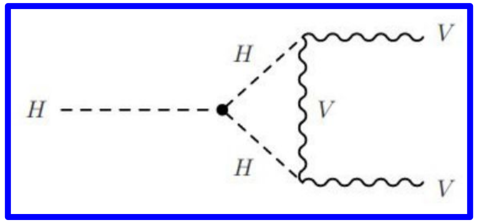
Backup

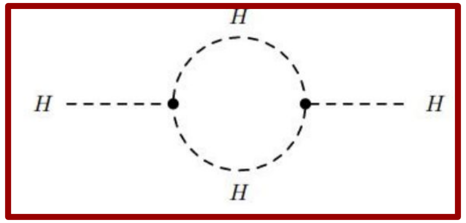
Accessing κ_λ in single Higgs

LHCHWG-2022-002

κ_λ also be accessed through indirect NLO contributions to single Higgs production and decay







$\sigma_H > \sigma_{HH} \Rightarrow$ sensitivity to smaller variations

Allows constraining HH couplings independent of other H couplings

H + HH combination

Combine all available single H and HH analyses from CMS

Analysis	Int. luminosity (fb^{-1})	Max. granularity	References
$H \to ZZ \to 4l$	138	STXS 1.2	[35]
$ggH(b\bar{b})$	138	Inclusive	[36]
$VH \to b\bar{b}$	77	Inclusive	[37, 38]
$t\bar{t}H(b\bar{b})$	36	Inclusive	[39]
$t\bar{t}H$ multilepton	138	Inclusive	[40]
$H \to \mu\mu$	138	Inclusive	[41]
$H \to \gamma\gamma$	138	STXS 1.2	[42, 43]
$H \to \tau\tau$	138	STXS 1.2	[44]
$H \to WW$	138	STXS 1.2	[45]

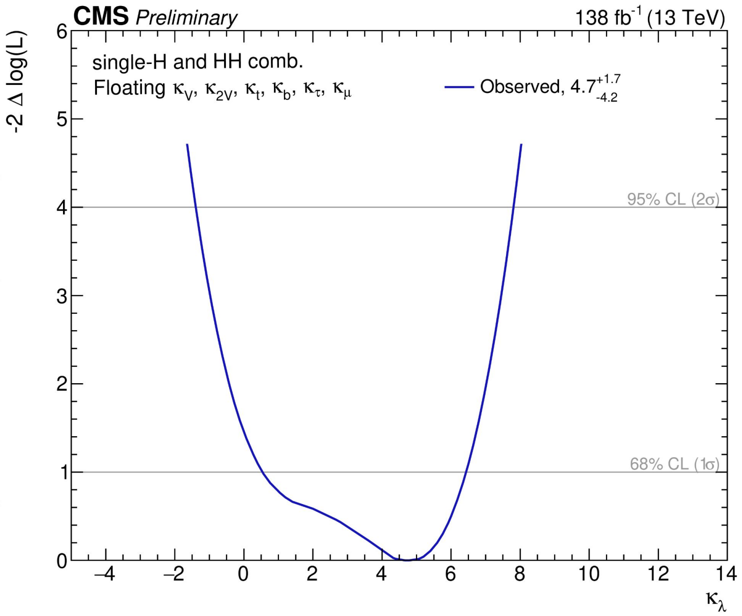
Analysis	Int. luminosity (fb^{-1})	Targeted production modes	References
$HH \to \gamma\gamma b\bar{b}$	138	ggHH and qqHH	[43]
$HH \to \tau\tau b\bar{b}$	138	ggHH and qqHH	[46]
$HH \to 4b$	138	ggHH and qqHH	[47, 48]
HH (leptons)	138	ggHH	[49]
$HH \to WWb\bar{b}$	138	ggHH and qqHH	[50]
$VHH \to b\bar{b}b\bar{b}$	138	VHH	[51]

H + HH combination

CMS-PAS-HIG-23-006

Combine all available single H and HH analyses from CMS

	Best fit $\pm 1\sigma$		95% CL interval	
Hypothesis	Expected	Observed	Expected	Observed
Other couplings fixed to SM	$1.0^{+4.6}_{-1.7}$	$3.1^{+3.0}_{-3.0}$	$[-2.0, +7.7]$	$[-1.2, +7.5]$
Floating ($\kappa_V, \kappa_{2V}, \kappa_f$)	$1.0^{+4.7}_{-1.8}$	$4.5^{+1.8}_{-4.7}$	$[-2.2, +7.8]$	$[-1.7, +7.7]$
Floating ($\kappa_V, \kappa_t, \kappa_b, \kappa_\tau$)	$1.0^{+4.8}_{-1.8}$	$4.7^{+1.7}_{-4.1}$	$[-2.3, +7.7]$	$[-1.4, +7.8]$
Floating ($\kappa_V, \kappa_{2V}, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu$)	$1.0^{+4.8}_{-1.8}$	$4.7^{+1.7}_{-4.2}$	$[-2.3, +7.8]$	$[-1.4, +7.8]$



1D likelihood scan of κ_λ with other couplings floating

Run 3 triggers

CERN-CMS-DP-2023-050

$$\varepsilon = \frac{N_{\text{events}}(\text{pass trigger and event selection})}{N_{\text{events}}(\text{pass event selection})}$$

Trigger	Requirement	Rates at HLT at 2x10^34 cm-2s-1
2023 HH trigger	HT > 280 GeV, 4 jets with pT > 30 GeV, PNet@AK4(mean 2 highest b-tag score) > 0.55	180 Hz
2022 HH trigger	4 jets pT > 70, 50, 40, 35 GeV, HT > 340 GeV PNet@AK4(mean 2 highest b-tag score) > 0.65	60 Hz
2018 triple b-tag [2,3]	HT > 340 GeV, 4 jets pT > 75, 60, 45, 40 GeV, 3 b-tags with DeepCSV > 0.24	8 Hz
Run 3 tau-triggers [4]	Double medium DeepTau taus with pT > 35 GeV |η| < 2.1 Double medium DeepTau taus with pT > 30 GeV |η| < 2.1 , PFJet 60 GeV Single loose DeepTau on hadronic tau with pT > 180 GeV |η| < 2.1	50 Hz 20 Hz 17 Hz
Run 3 MET-trigger [5]	Missing transverse energy (MET) (no muon) > 120 GeV, HT (no muon) > 120 GeV	42 Hz