Non-resonant HH production and Higgs self-coupling at CMS

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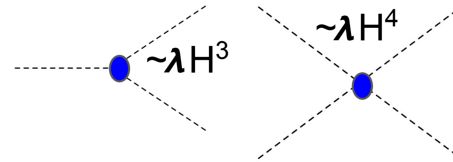
On behalf of the CMS collaboration

Introduction

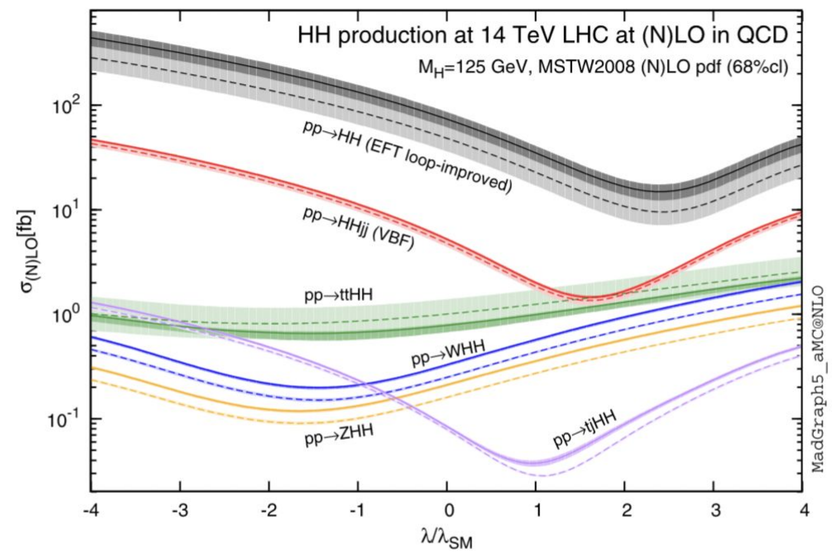
- Since Higgs boson discovery, many of its properties have been measured very precisely
- So far, the measurements agree with Standard Model predictions
- The Higgs potential $V(H) = \frac{1}{2}m_H^2 H^2 + \lambda v H^3 + \frac{1}{4}\lambda H^4$



- The Higgs self-coupling, $\boldsymbol{\lambda}$ has not been measured yet. Only upper limits have been set

$$\lambda = \frac{m_H^2}{2v^2}$$ ~0.13 (m_H, v are measured precisely)

- The coupling $\boldsymbol{\lambda}$ is difficult to measure, because the cross section for HH production, which provides sensitivity to this coupling, is very small
- $\boldsymbol{\lambda}$ can also be constrained indirect way through single Higgs production



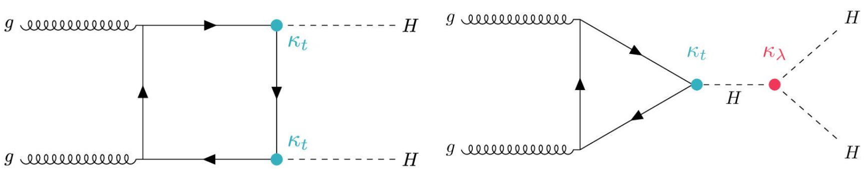
[Physics Letters B (2014) 142-149]

Introduction

❑ **HH pair can be produced in different ways:**

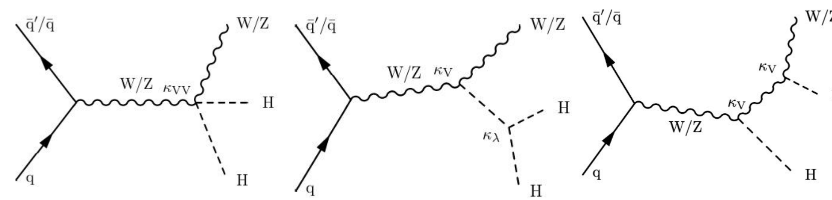
❑ GGF

$$\sigma^{GGF}_{HH}(13TeV) = 31.05 \pm 3(PDF + \alpha_S)\ ^{+6\%}_{-23\%}(scale + m_{top})\ fb$$



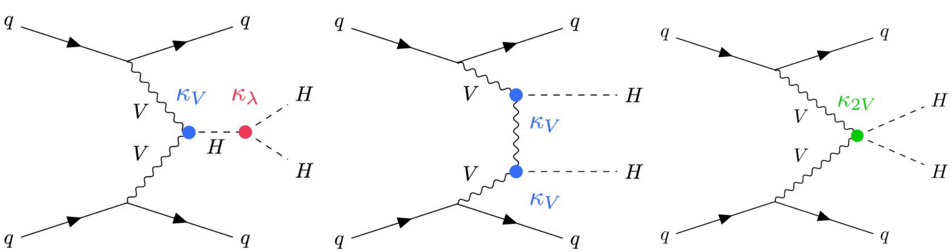
❑ VHH (New in CMS)

σ_{HH} ~ 0.86 fb



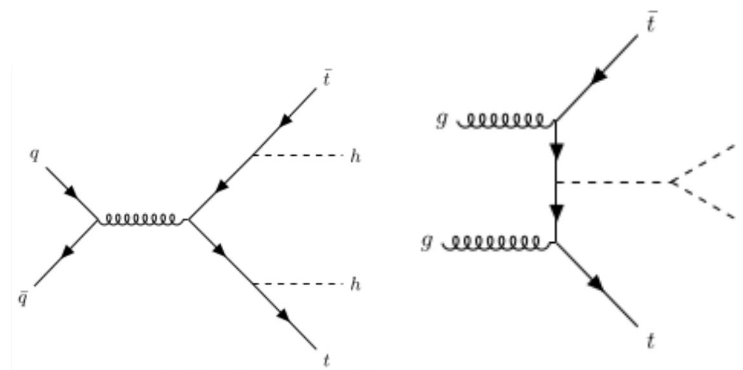
❑ VBF

$$\sigma^{VBF}_{HH}(13TeV) = 1.71 \pm 2.1\%(PDF + \alpha_S)\ ^{+0.03\%}_{-0.04\%}(scale)\ fb$$



❑ ttHH (No result today)

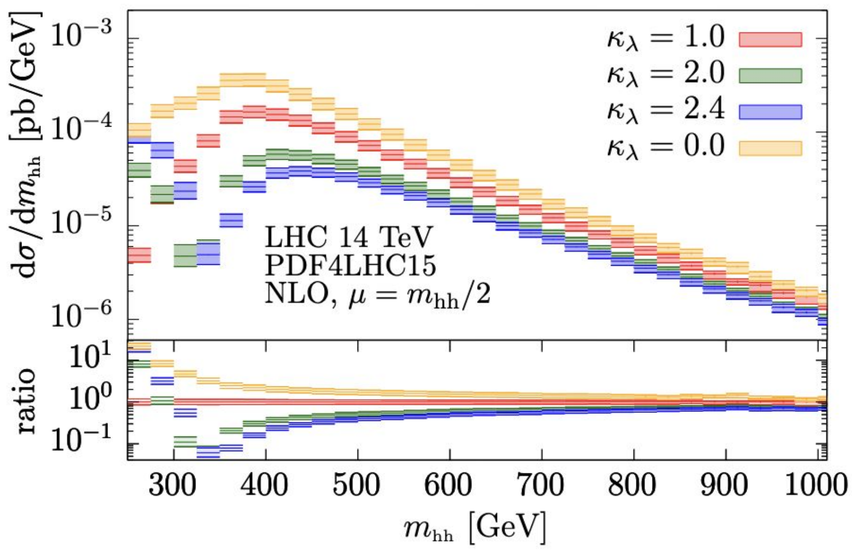
σ_{HH} ~ 0.76 fb

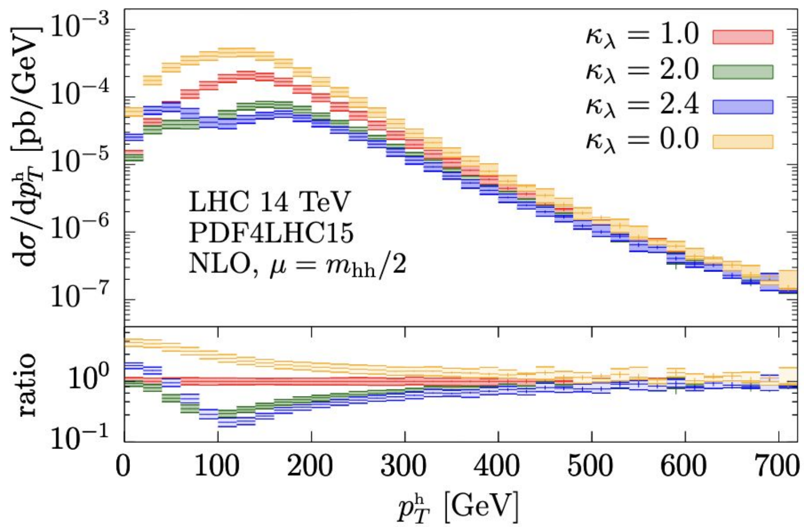


❑ Not easy to probe!!!

Introduction

- Anomalous coupling can modify the cross section of HH pair production as well as kinematic properties of HH pair



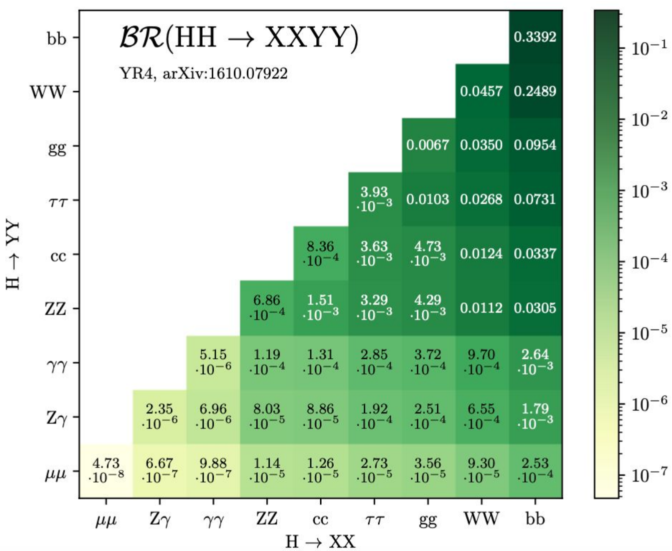


JHEP(2019)066

- Coupling modifiers κ, defined as deviation from SM value
  - $\kappa_\lambda = \lambda/\lambda_{SM}$, $\kappa_V = C_V/C_{V,SM}$, $\kappa_{2V} = C_{2V}/C_{2V,SM}$
  - Deviation from 1 indicates BSM physics

How to probe HH production

❑ Depends on decay products of Higgs boson:



H→bb highest BR,
large hadronic background
H→WW* second highest BR,
large hadronic background
H→γγ low BR,
good mass resolution
H→ZZ low BR,
clean signature in leptonic decay
H→ττ low BR,
low background

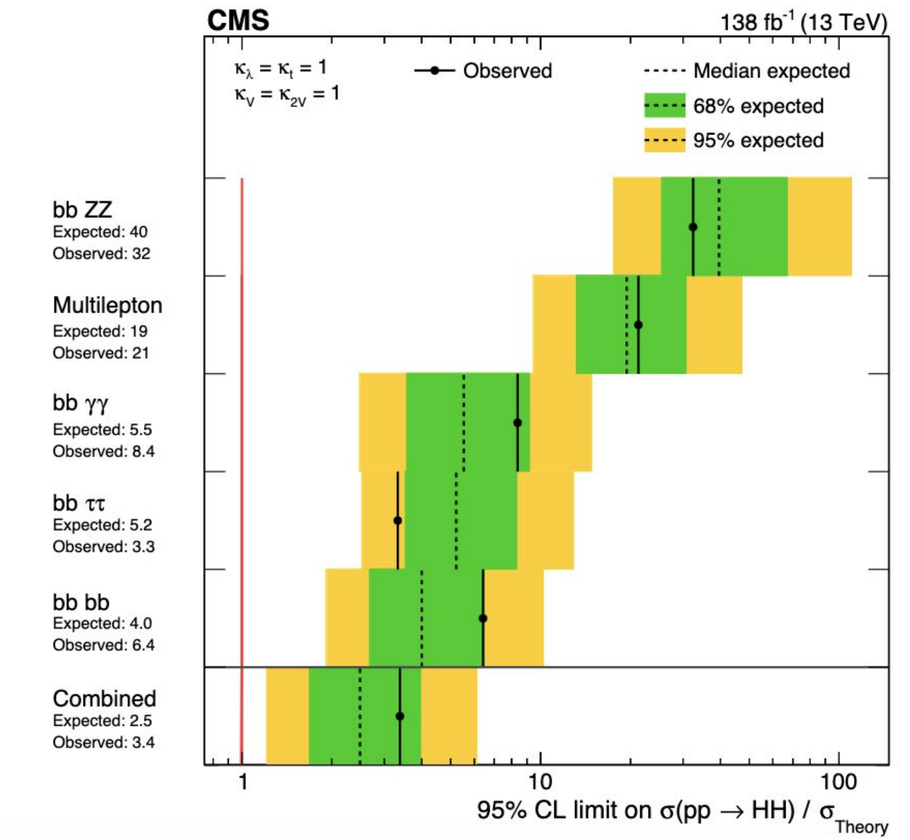
❑ **No golden channel!!!**

- ❑ **HH→bbZZ** arXiv:2206.10657 (submitted to JHEP)
- ❑ **HH→WW*WW*/WW*ττ/ττττ** arXiv:2206.10268 (submitted to JHEP)
- ❑ **HH→bbγγ** JHEP 03 (2021) 257
- ❑ **HH→bbττ** arXiv:2206.09401 (submitted to PLB)
- ❑ **HH→bbbb** Phys. Rev. Lett. 129 (2022) 081802

- ❑ HH→bbWW* CMS PAS HIG-21-005
- ❑ HH→WW*γγ CMS PAS HIG-21-014
- ❑ VHH→bbbb CMS HIG-22-006

Shown **last year**
Will be shown today

Combined limit based on previous results



Nature 607 (2022) 60-68

- **Combined upper limit on ggF+VBF production**
  $\boldsymbol{\sigma}_{HH}$ < 3.4 (2.5) $\boldsymbol{\sigma}_{HH}$(SM) based on previous result

HH→bbWW* CMS PAS HIG-21-005

Analysis Strategy

- Targeting both GGF and VBF production mode
- 2 channels, based on W decay:
  - **Double lepton**(DL): $WW^* \to l\nu l\nu$
  - **Single lepton**(SL): $WW^* \to l\nu qq$
- All channels are further splitted :
  - **Resolved**: 2 small radius jet coming from 2 b quarks
  - **Boosted**: 2 jets coming from 2 b quarks merged in a single large radius jet
- **Resolved**:
  - Jets are identified by Deep Neural network (DeepJet)
  - **1b, 2b**: 1 or 2 jets passing medium working point of Deepjet

Event Selection

Lepton:

2 (1) good lepton in DL(SL)

Veto extra lepton

Veto 81 < m_{ll} < 101 GeV in DL

Jet:

Resolved: >=2 (>=3) small radius jet in DL(SL)

Boosted: 1 large radius jet in DL, SL, >=1 small radius jet in SL

Background Estimation

QCD multijet, Fake lepton: data driven

DY: data driven in DL

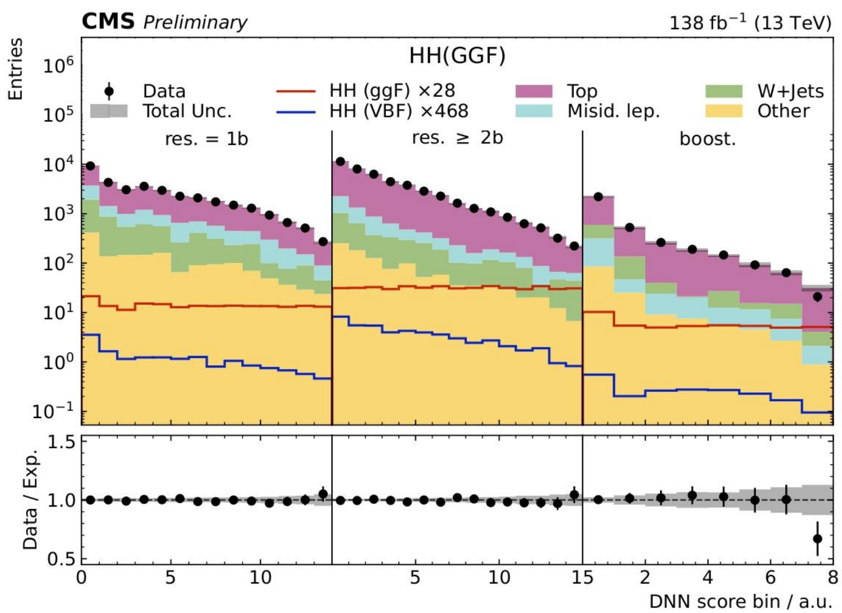
Other: Estimated from simulation

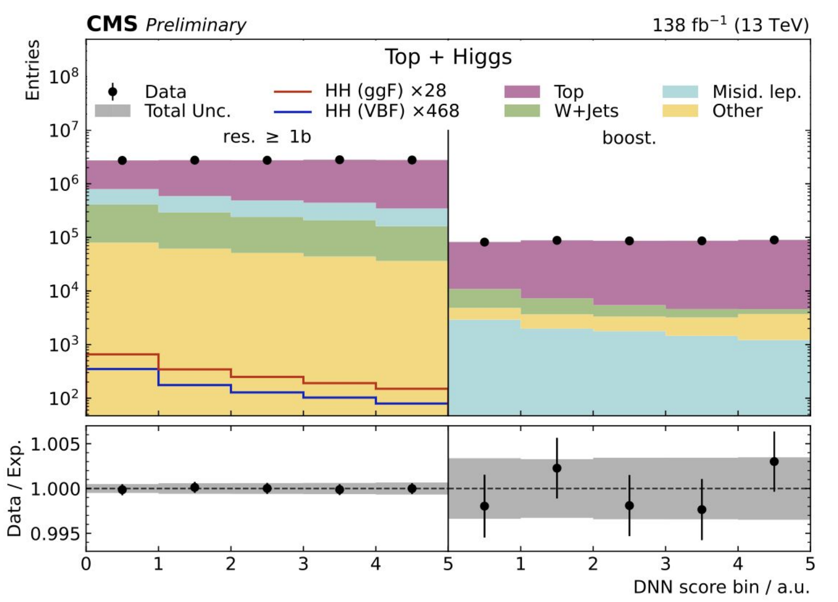
Signal Extraction

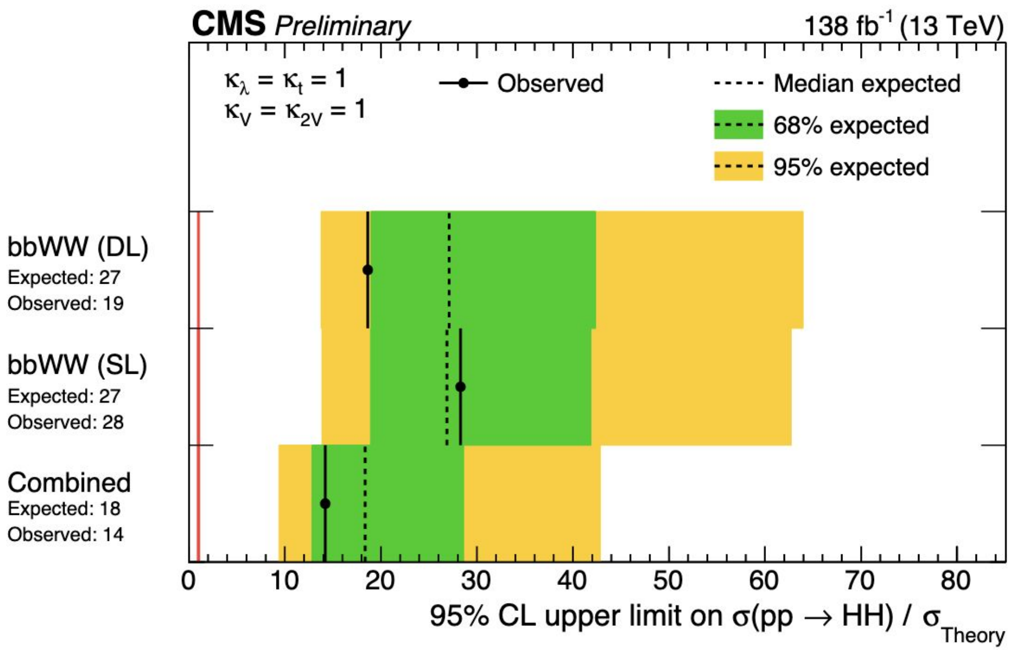
- Multi-classifier training:
  Separate GGF signal, VBF signal and other dominant backgrounds using Deep Neural Network(DNN)

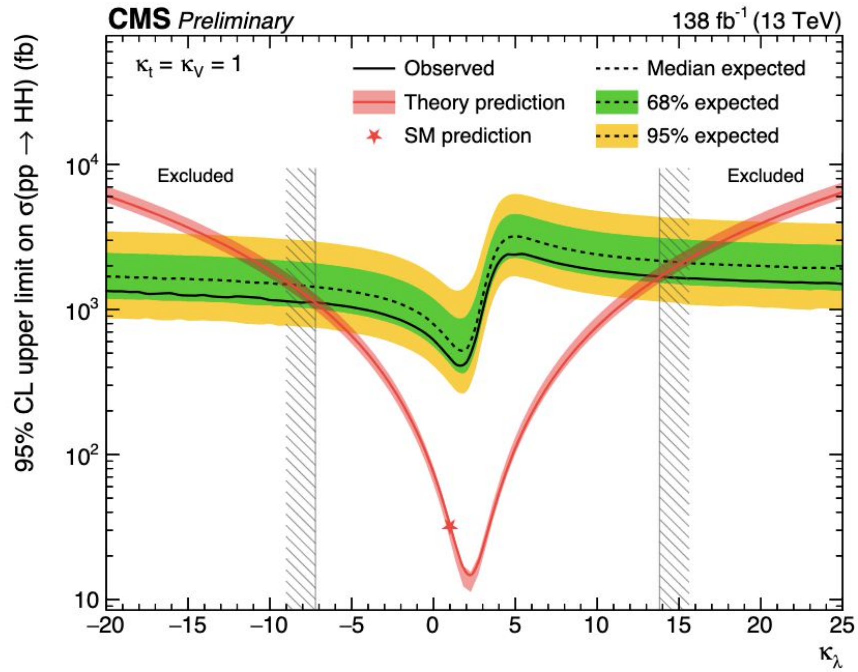
- Signal distribution is flat in signal nodes
- Total background distribution is flat in background nodes

- Use DNN score to extract signal









- Exclusion limit on HH production cross section:
  - Observed (expected): σ_{HH} < 14 (18) σ_{HH}(SM)
- Constraint on Higgs self coupling modifier:
  - Observed (expected): -7.2(-8.7) < κ_λ < 13.8(15.2)

Analysis Strategy

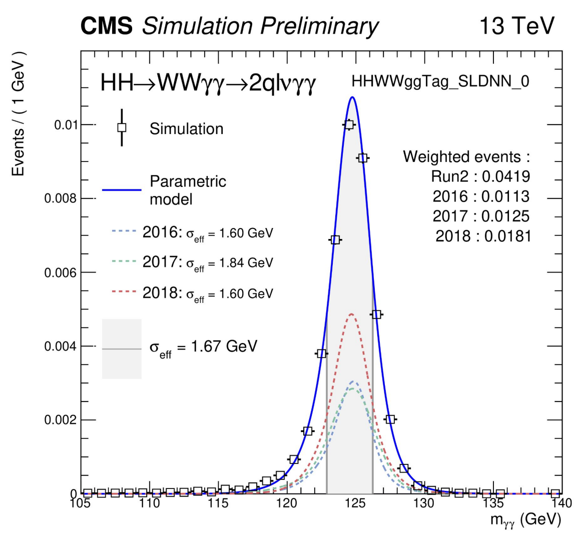
- Targeting GGF production mode
- 3 channels, based on W decay:
  - **Fully hadronic(FH):** WW*→4q
  - **Di-lepton**(DL): WW*→lνlν
  - **Single lepton(SL):** WW*→lνqq

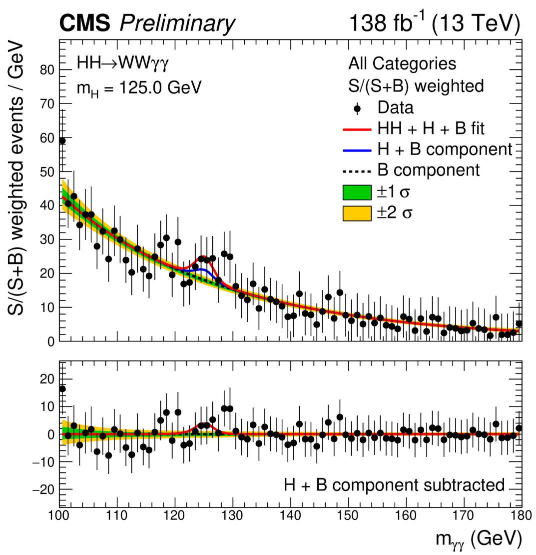
Signal and Background Modelling

- Signal: Modelled by an analytic fit of a sum of up to five Gaussians to a binned $m_{\gamma\gamma}$ distribution
- Single Higgs: Same as signal
- Continuum background: Modelled from data

Event Selection

- **Photon:**
  - 1 good di-photon candidate
  - $100 < m_{\gamma\gamma} < 180$ GeV
- Lepton:
  - 0, 1, 2 lepton in FH, SL, DL
  - Veto extra lepton
- Jet:
  - >=4 small radius jet in FH





HH→WW*$\gamma\gamma$ [CMS PAS HIG-21-014]

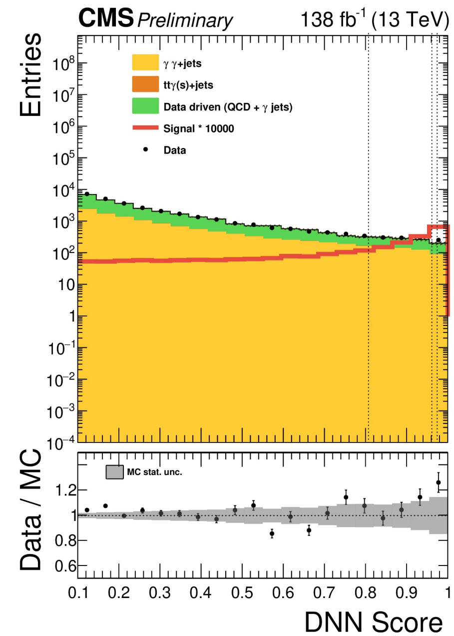
Signal Extraction

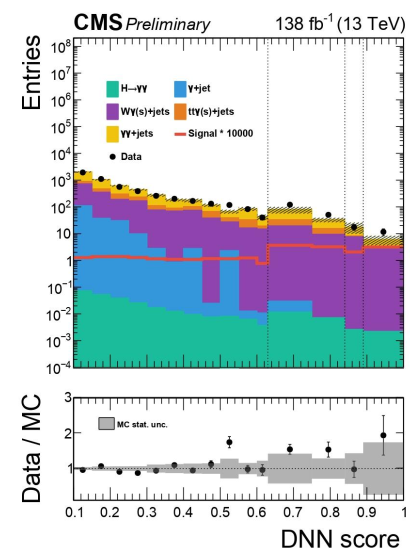
- **FH**:
  - **bb$\gamma\gamma$ rejection**: BDT classifier to separate bb$\gamma\gamma$ and WW$\gamma\gamma$
    - Signal: bb$\gamma\gamma$, Background: WW$\gamma\gamma$, $\gamma\gamma$+jets, γ+jets, QCD multijet
  - **WW$\gamma\gamma$ classifier**: BDT classifier to separate WW$\gamma\gamma$ signal and $\gamma\gamma$+jets, γ+jets, QCD multijet backgrounds

- **DL**: Cut based

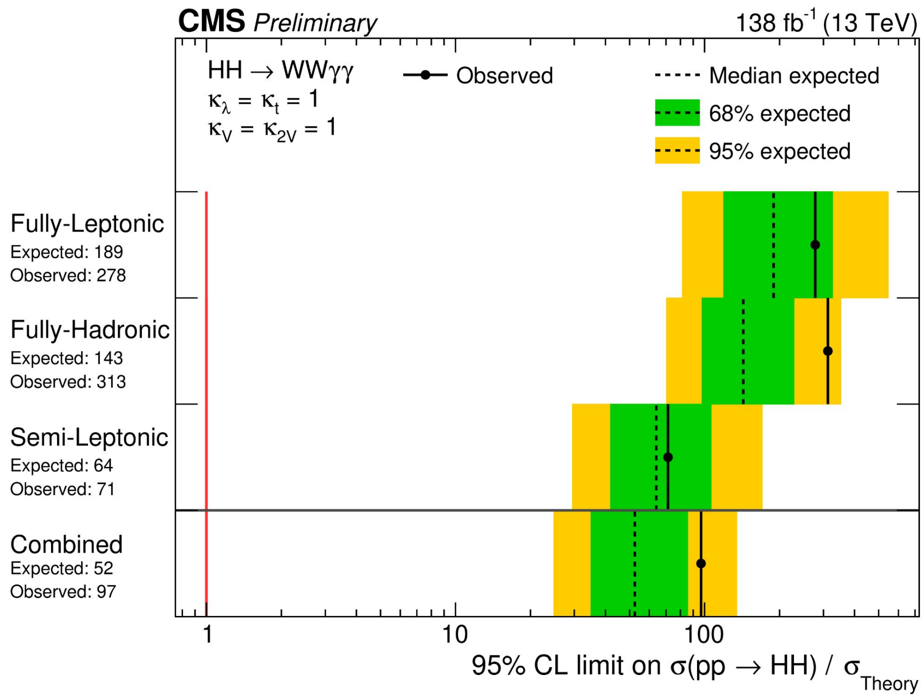
- **SL**:
  - **Multi-classifier**: Separate signal, single Higgs, and continuum background

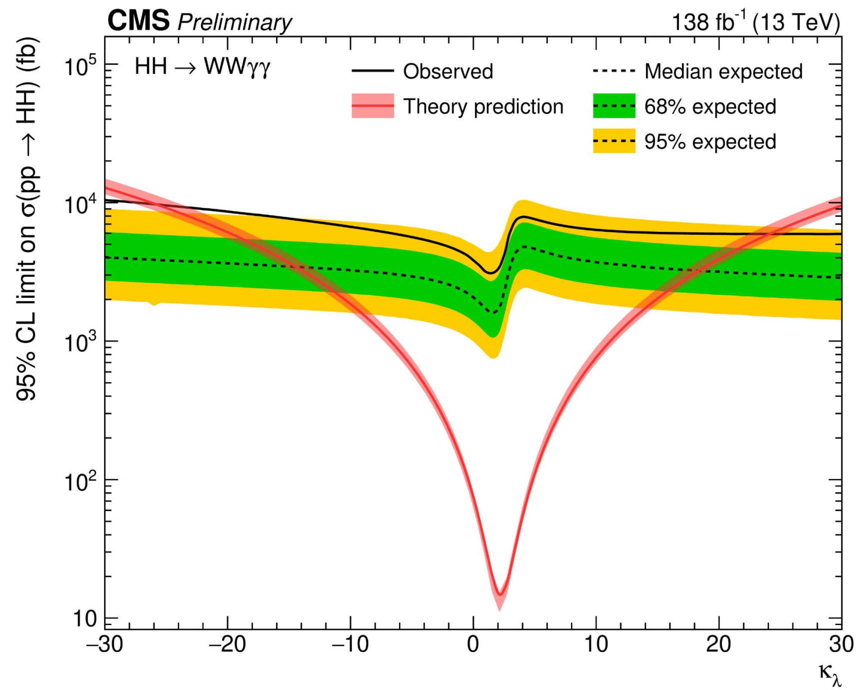
- 4 categories are defined for each classifier output to maximize signal sensitivity
- Combined fit of $m_{\gamma\gamma}$ is performed in all classifier categories to extract signal





HH→WW*γγ [CMS PAS HIG-21-014]





- Exclusion limit on HH production cross section:
  - Observed (expected): σ_{HH} < 52 (97) σ_{HH}(SM)
- Constraint on Higgs self coupling modifier:
  - Observed (expected): -25.8 (-14.4) < k_{λ} < 24.1 (18.3)

VHH→4b CMS HIG-22-006

Analysis Strategy

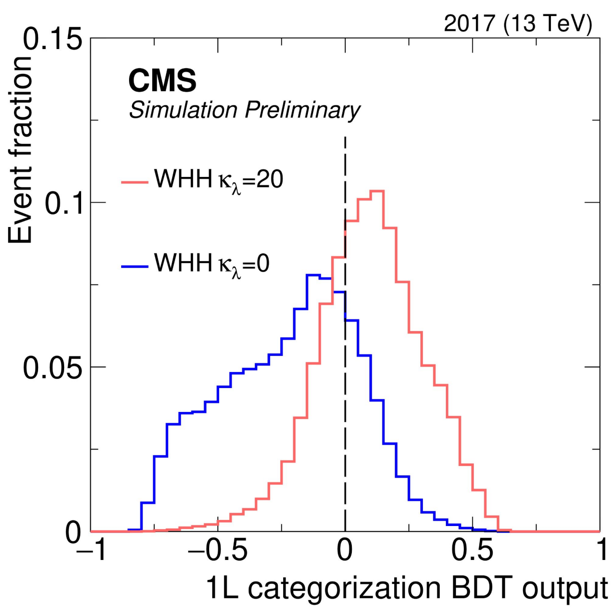
- 4 channels, based on W/Z decay:
  - **SL**(W→lν), **MET**(Z→$\nu\nu$), **DL**(Z→ll), **FH**(W/Z→qq)
- BDT training to separate κ_λ and κ_{VV} coupling enriched regions
- **Resolved** (All channels):
  - Jets are identified by Deep Neural network (DeepJet) training
  - **3b, 4b**: 3 or 4 jets passing medium working point of Deepjet
- **Boosted (Single lepton, MET):**
  - Jets are identified by **ParticleNet** **training**
  - Low, High purity: Classified based on **ParticleNet score**

Event Selection

Jet:
>=2 large radius jet (boosted) or
>=3 small radius jet (resolved)
Lepton:
1 (SL) , 2 (DL) good lepton
MET:
Missing transverse energy >150 (resolved),
250 (boosted) GeV

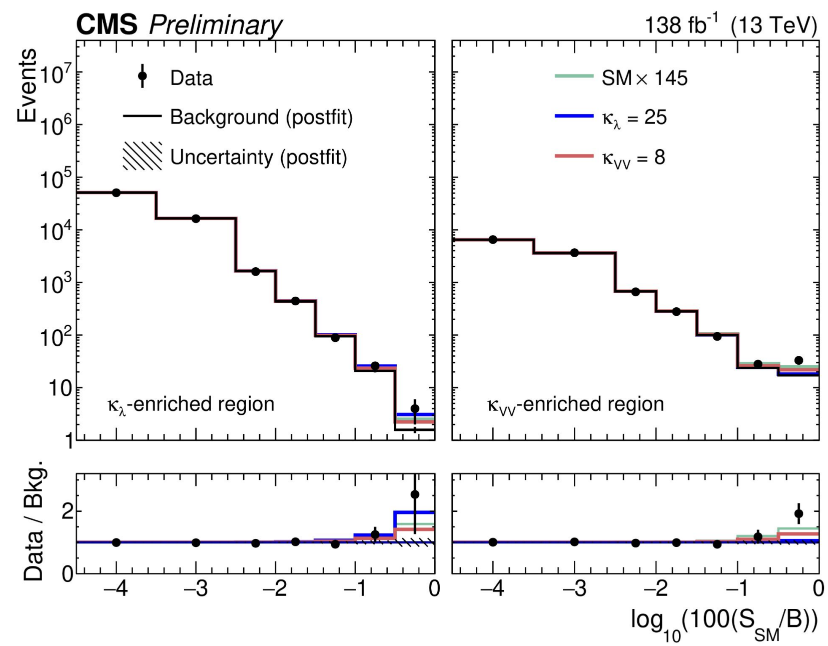
Background Estimation

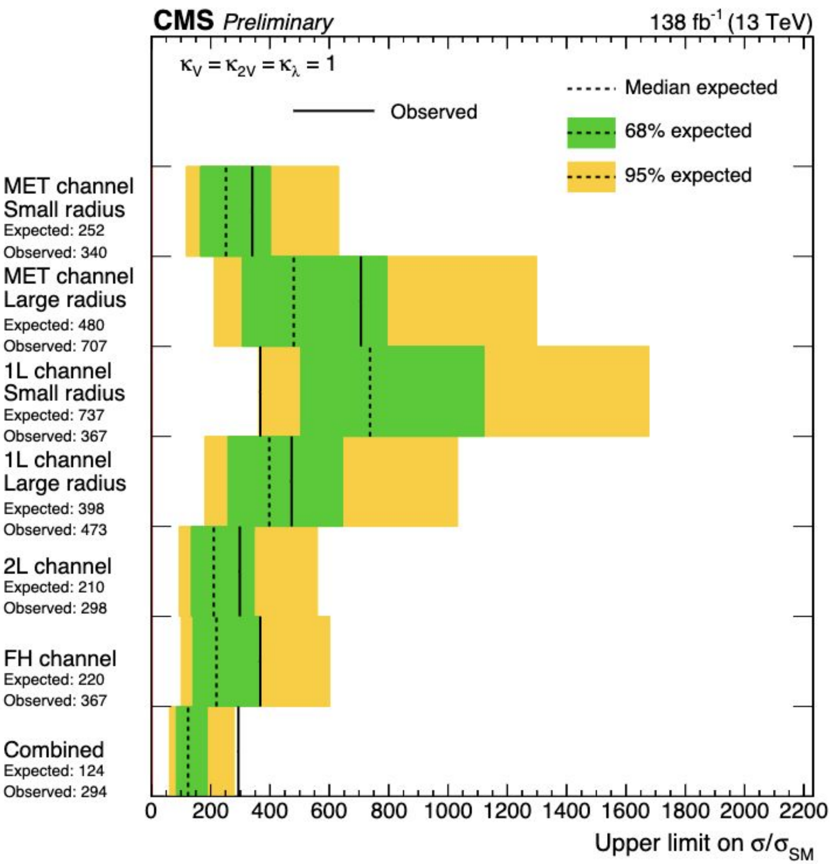
- BDT reweighting:
  - Used in statistics depleted region
  - Train between nominal region and other region with some cuts inverted
- QCD multijet in FH:
  - Data driven
- Other: From simulation

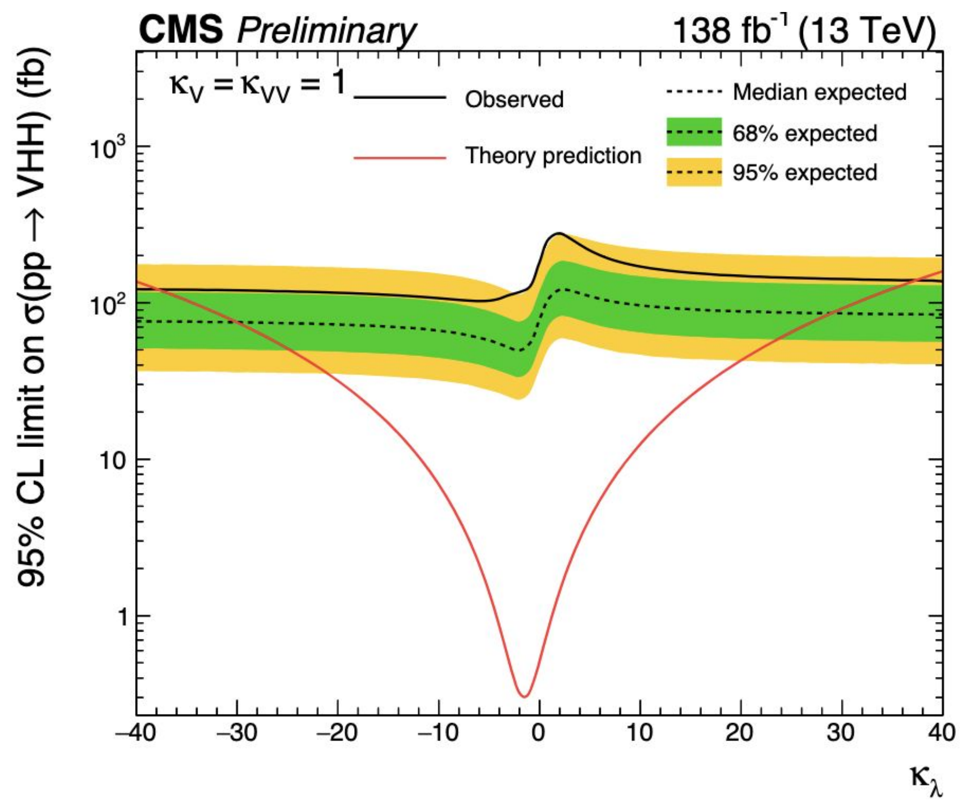


Signal Extraction

- BDT or Neural network training to separate signal and background
- Separate training for each κ_λ and κ_{VV} enhanced regions
- Use classifier output to extract signal



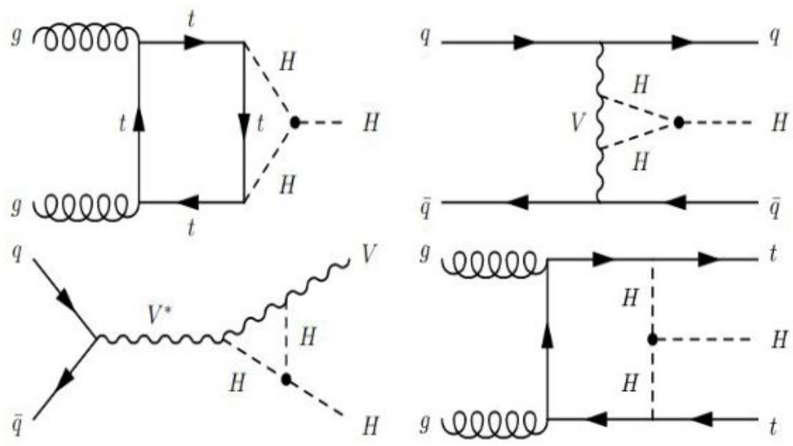




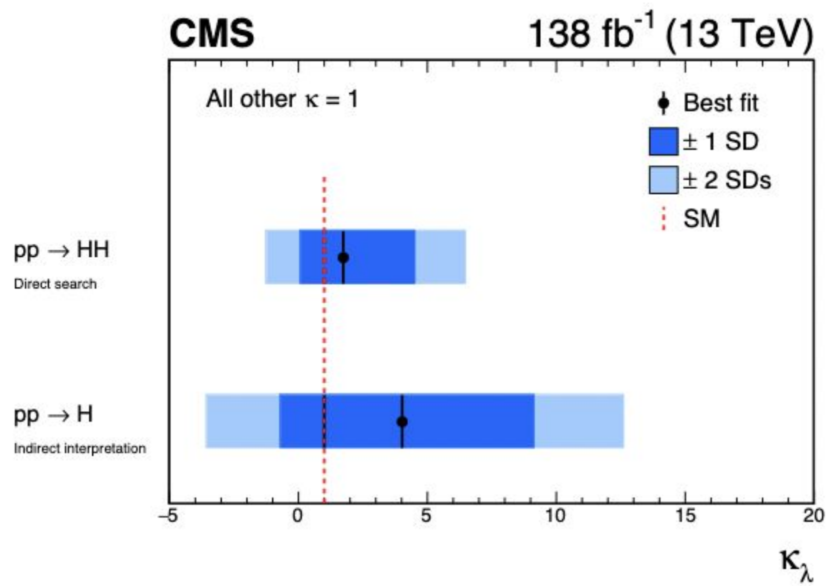
- ❑ Exclusion limit on HH production cross section:
  - ❑ Observed (expected): σ_{HH} < 294 (124) σ_{HH}(SM)
- ❑ Constraint on Higgs self coupling modifier:
  - ❑ Observed (expected): −37.7(-30.1) < k_λ < 37.2 (28.9)

Constraint on Higgs self-coupling through single Higgs production

- Higgs self-coupling can be constrained through single Higgs production at NLO corrections



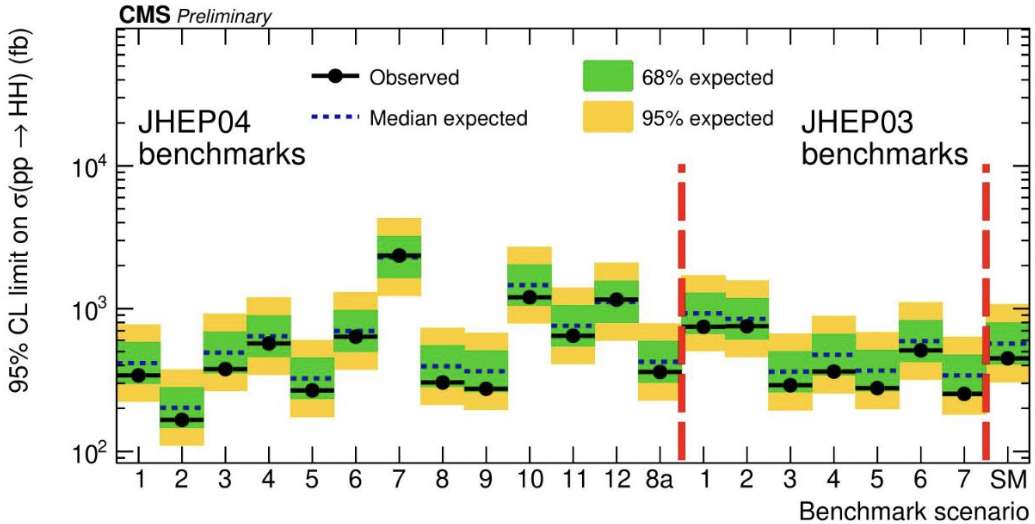
NLO diagrams contributing to Higgs self-coupling



Nature 607 (2022) 60-68

Summary

- ❑ Search for non-resonant HH production has been probed in different final states using the full LHC Run2
- ❑ Three new channels (HH→bbWW*, HH→WW*$\gamma\gamma$, VHH→bbbb) have been added since last year
- ❑ Many BSM studies have been done (More in back up)

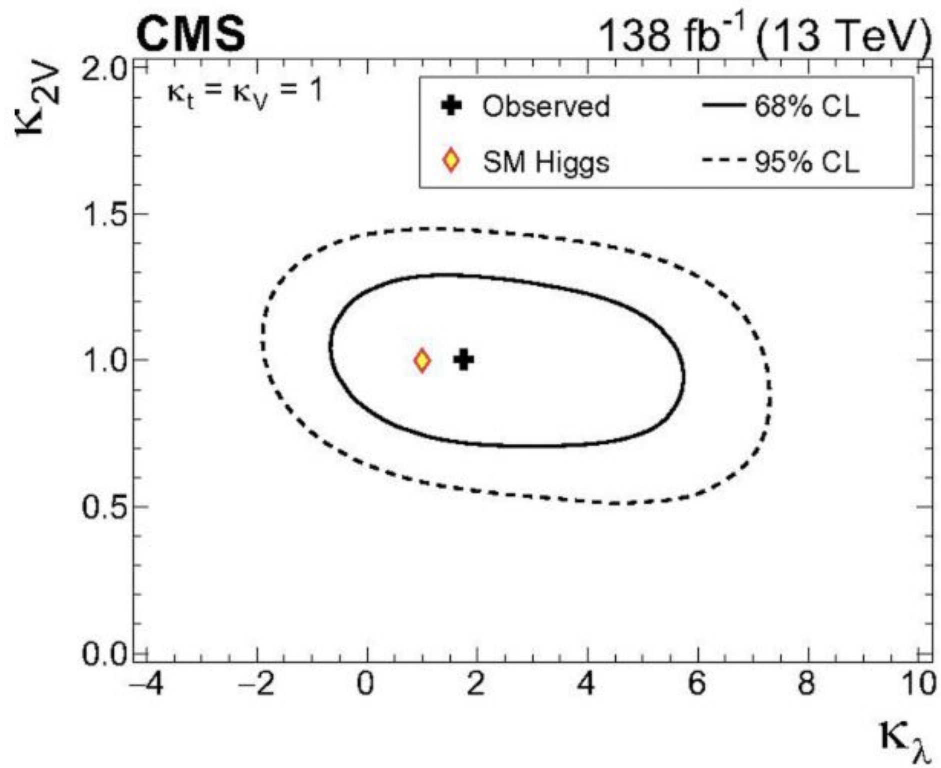


- ❑ Looking forward to seeing many interesting results with Run3 and full combination

Stay tuned!!!

Back up

Constraint on κ_λ vs κ_{2V}



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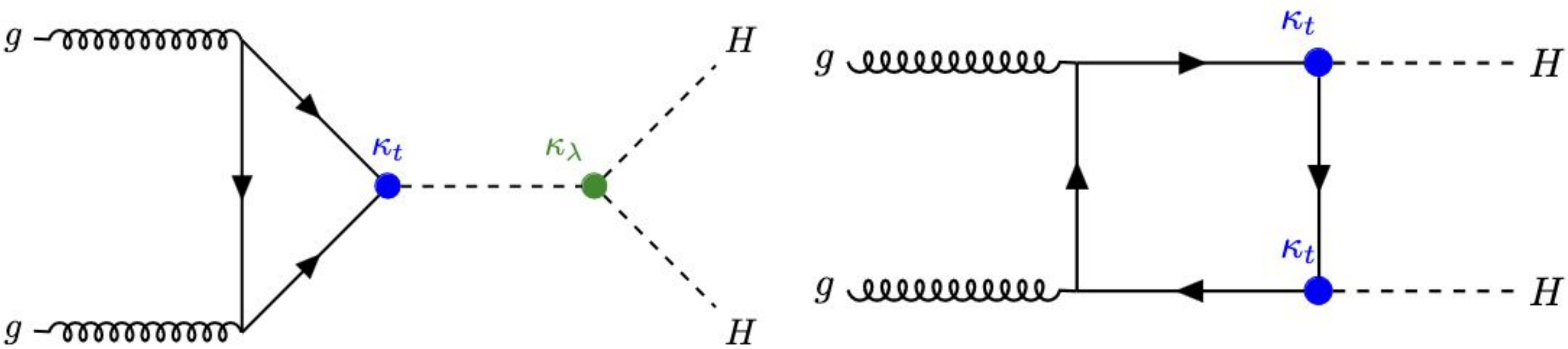
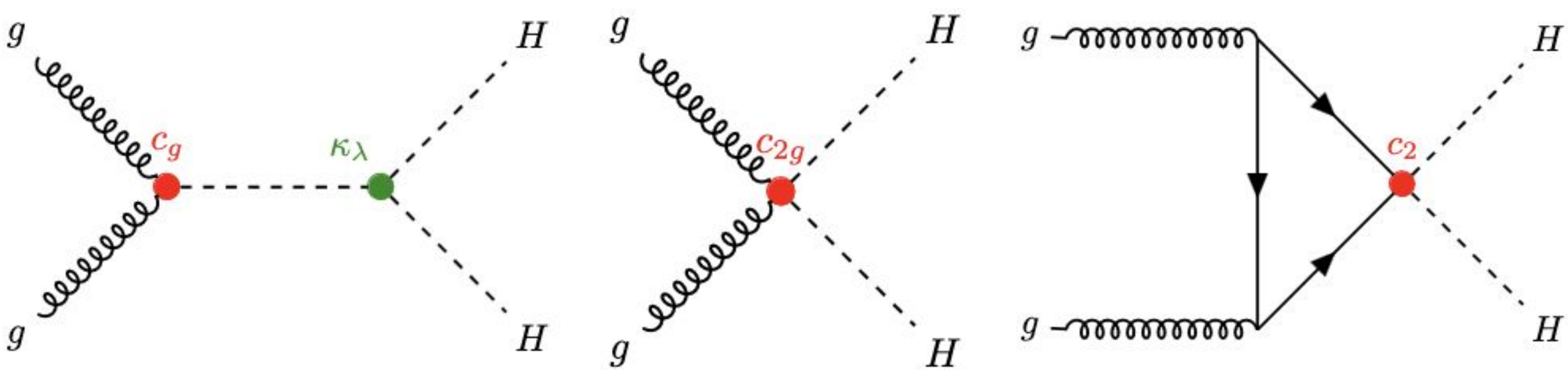
BSM

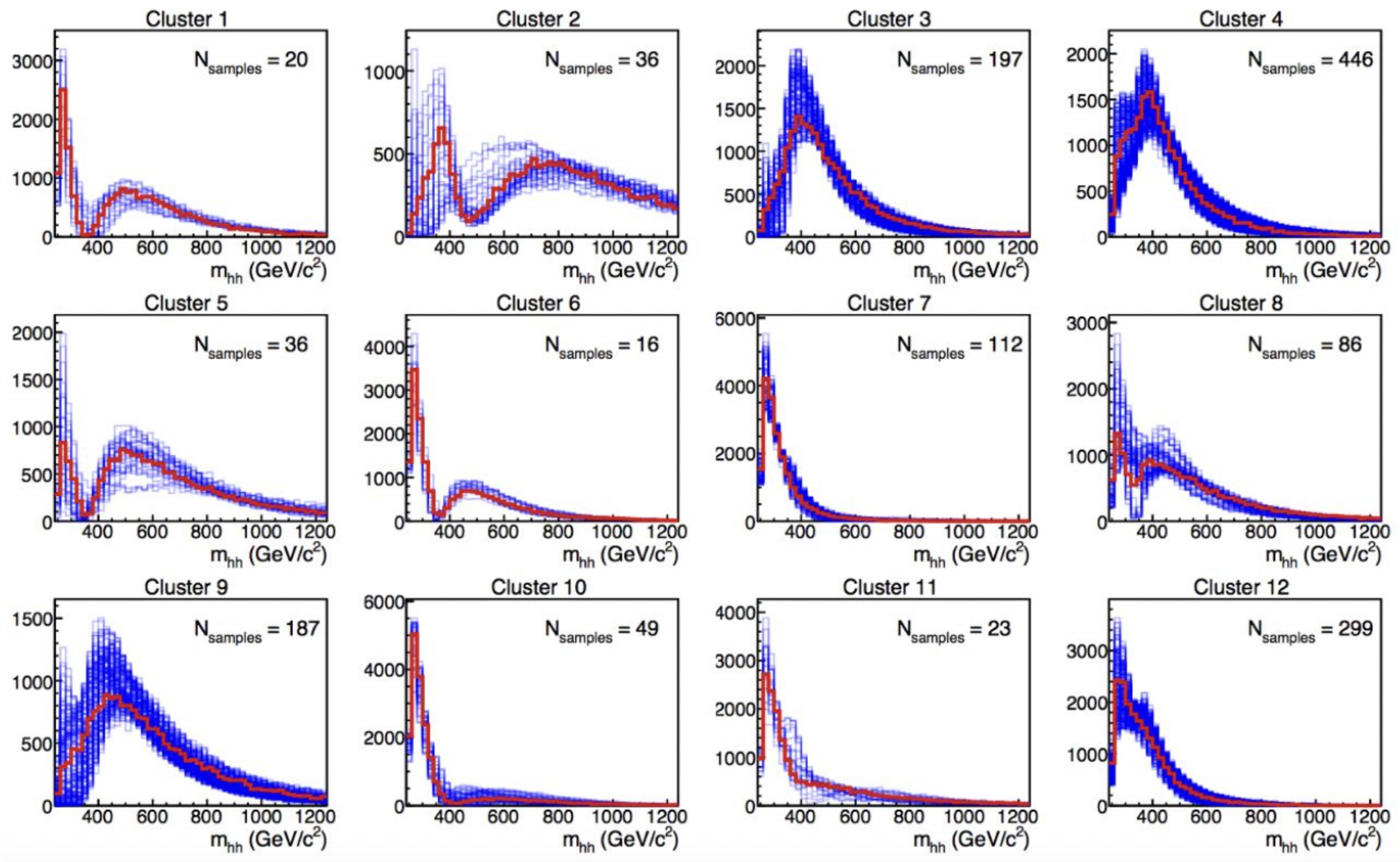


(a) SM-like processes

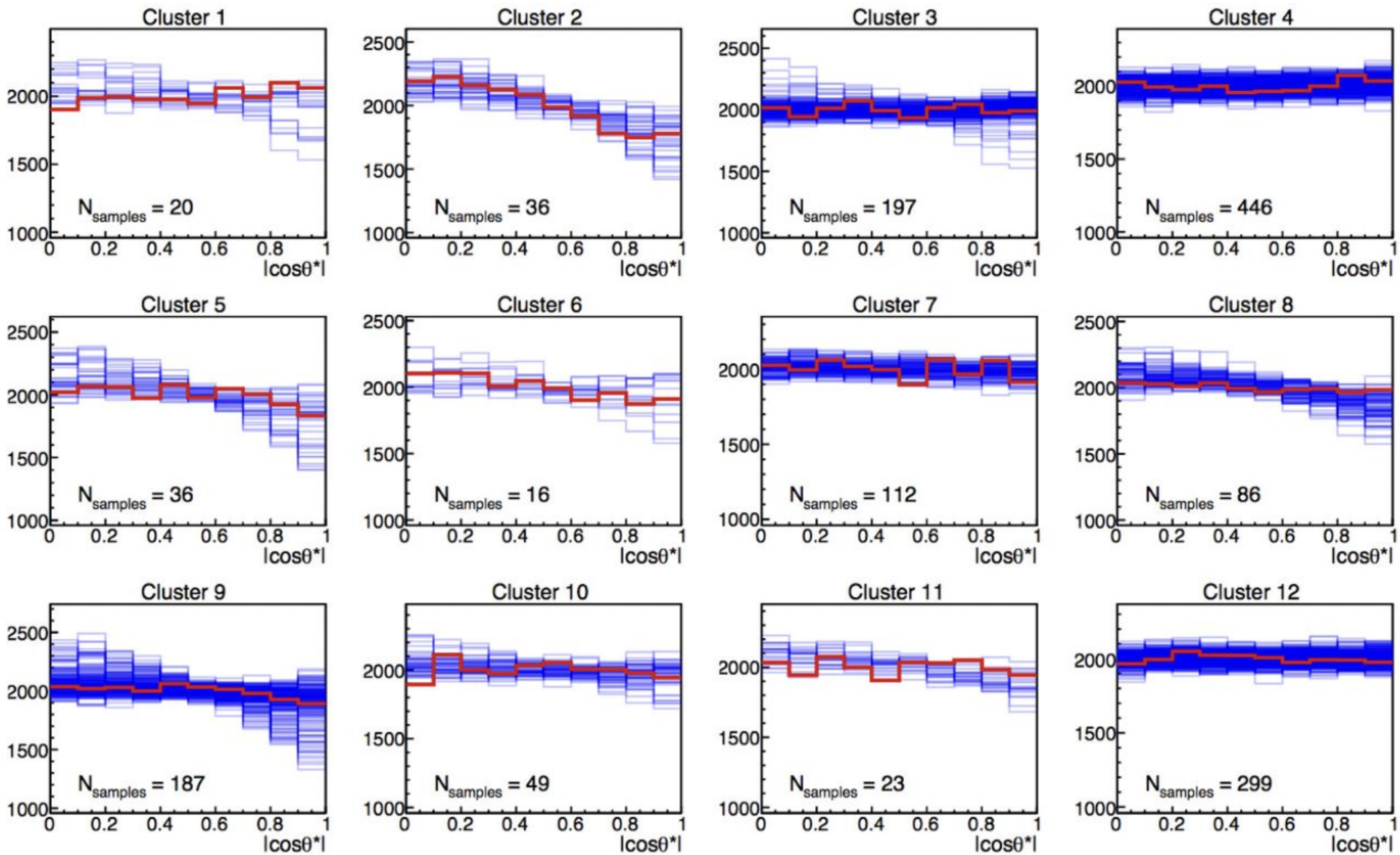


(b) Pure BSM processes

EFT benchmarks arXiv:1507.02245



EFT benchmarks arXiv:1507.02245



JHEP04

	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

JHEP03

	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.)

Object selection

- Small radius jet:
  - p_T > 25 GeV, $|\eta|$ < 2.4
  - Medium working point of DeepJet score
- Large radius jet:
  - p_T > 200 GeV, $|\eta|$ < 2.4, τ_2 / τ_1 < 0.75
  - p_T of subjet > 20 GeV
  - 30 < m_{SD} < 210
- m_{ll} > 12 GeV

Event category in SL channel:

Categories	Sub-Categories		
HH(GGF)	Resolved 1b	Resolved 2b	Boosted
HH(VBF)	Resolved 1b	Resolved 2b	Boosted
Top + Higgs	Resolved		Boosted
WJets + Other	Inclusive		

Event category in DL channel:

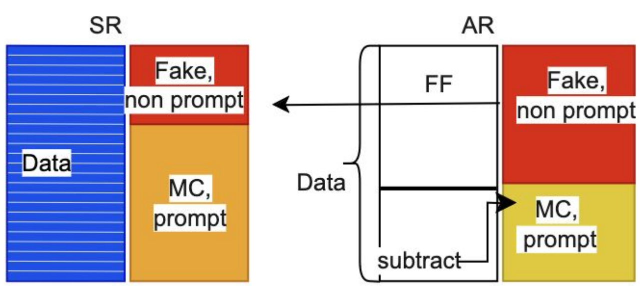
Categories	Sub-Categories		
HH(GGF)	Resolved 1b	Resolved 2b	Boosted
HH(VBF)	Resolved 1b	Resolved 2b	Boosted
Top + Other	Resolved		Boosted
DY + Multi-boson	Inclusive		

HH→bbWW* CMS PAS HIG-21-005

QCD multijet, Fake lepton estimation:

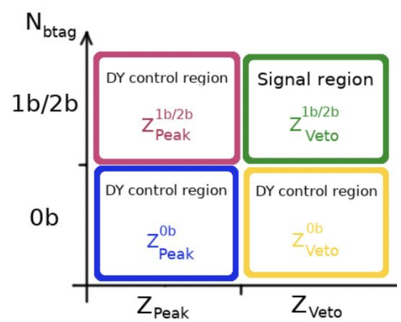
- ❑ SR → Signal region
- ❑ AR → Similar to signal region but lepton fails the tight selection
- ❑ Prompt → lepton matched with generator level lepton coming from W, Z, τ or Higgs
- ❑ FF → fake factor which is the probability to pass the fake to tight cut

$$w = (-1)^{n+1} \prod_{i=1}^{n} \frac{f_i}{1-f_i},$$



DY estimation:

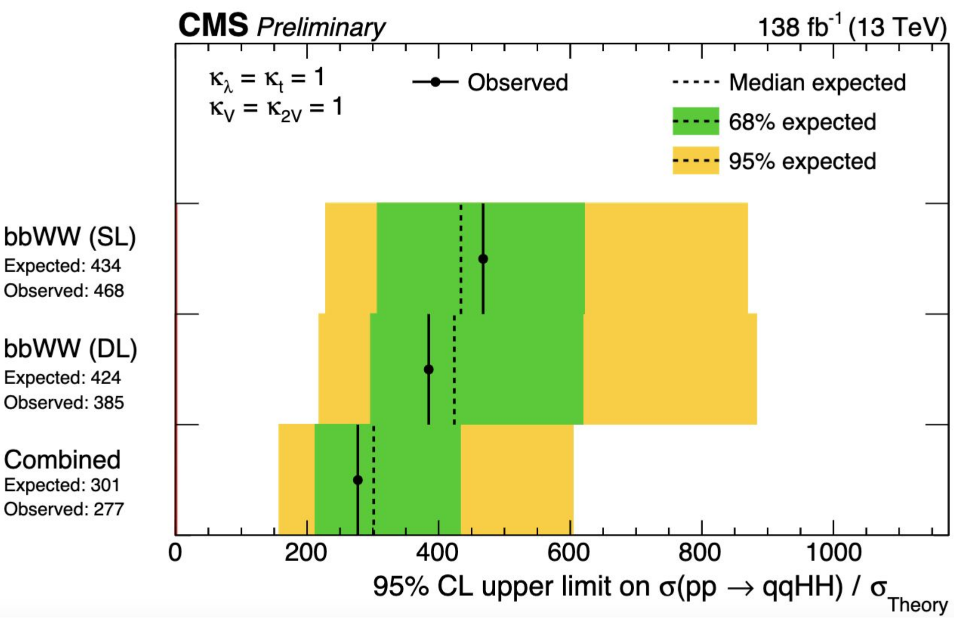
- ❑ Calculate transfer weight from 0-bjet →1/2-bjet region in Z-peak region
- ❑ Weights are binned in HT (P_T sum of AK4 jets) for resolved and softdrop mass of leading AK8 jet for boosted category.
- ❑ Apply transfer weight in Z-veto region
- ❑ Non DY backgrounds are subtracted from data in both Z-peak and Z-veto region.

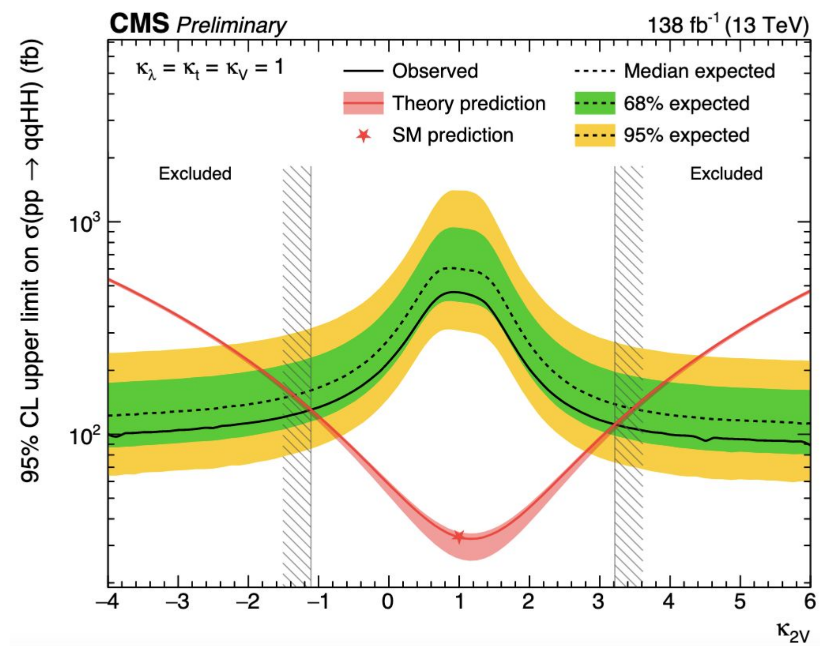


$$N\left(Z^{1b/2b}_{Veto}\right) = N\left(Z^{0b}_{Veto}\right) \frac{N\left(Z^{1b/2b}_{Peak}\right)}{N\left(Z^{0b}_{Peak}\right)}$$

Z_{veto} = | $M_{ll} - M_Z$ | > 10 GeV
Z_{peak} = | $M_{ll} - M_Z$ | ≤ 10 GeV
0b/1b/2b = N(Ak4 bjets)

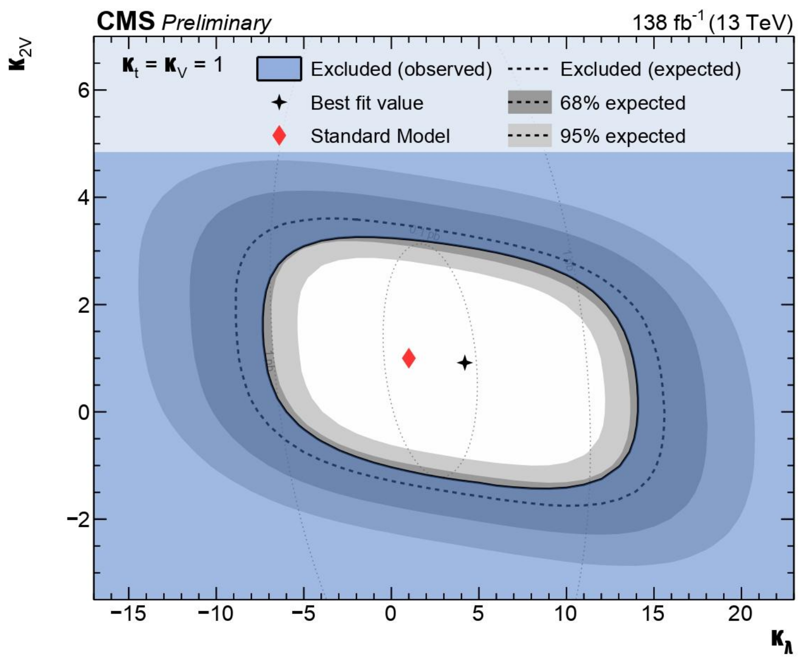
HH→bbWW* CMS PAS HIG-21-005





- Exclusion limit on HH production cross section in VBF production:
  - Observed (expected): $\boldsymbol{\sigma}_{HH}$ < 277 (301) $\boldsymbol{\sigma}_{HH}$(SM)
- Constraint on $\boldsymbol{\kappa}_{2V}$:
  - Observed (expected): −1.1(-1.4) < $\boldsymbol{\kappa}_{2V}$< 3.2 (3.5)

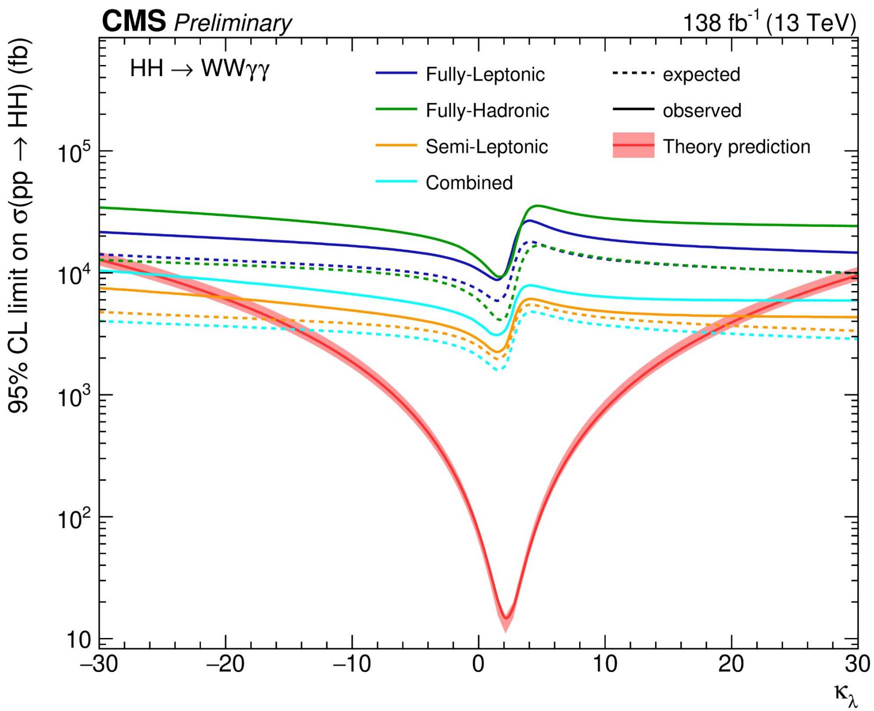
HH→bbWW* CMS PAS HIG-21-005

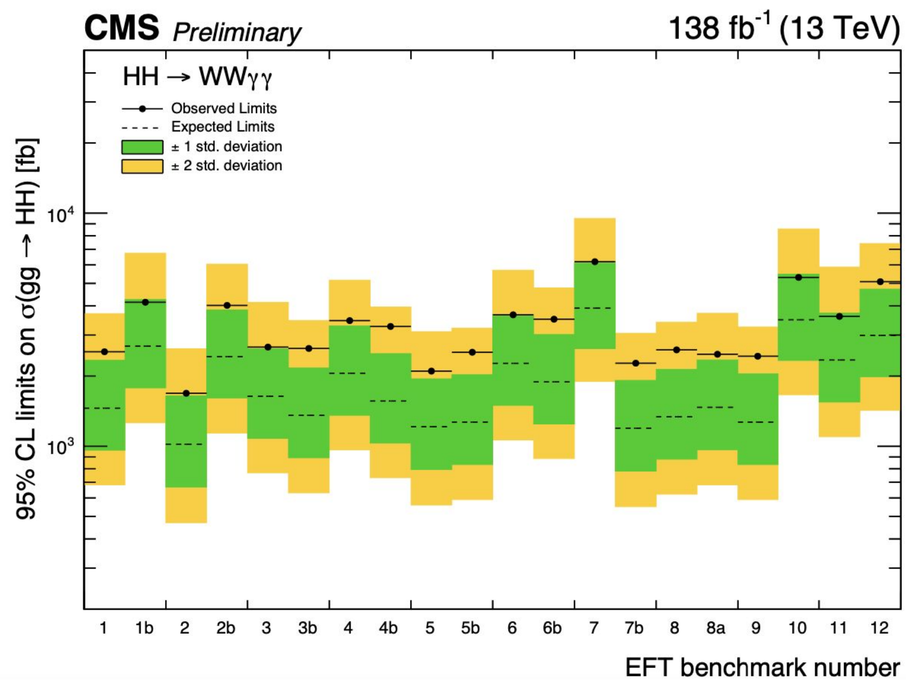


Object selection:

- ❑ p_T > 35 (25) GeV leading (sub-leading) photon
- ❑ $|\eta|$ < 2.5
- ❑ $p_T/m_{\gamma\gamma}$ > 1/3 (1/4) for leading(sub-leading) photon in Fully Hadronic and Di-lepton channel
- ❑ Jet p_T > 25GeV, $|\eta|$ < 2.4
- ❑ No jet with medium working point of btag score in Di-leptonic channel

HH→WW*γγ CMS PAS HIG-21-014





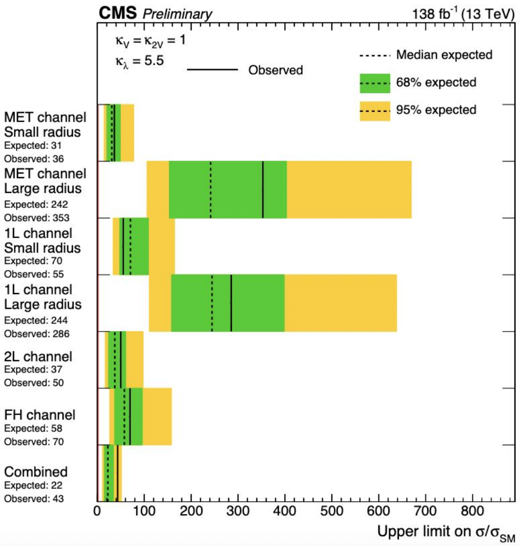
Object Selection

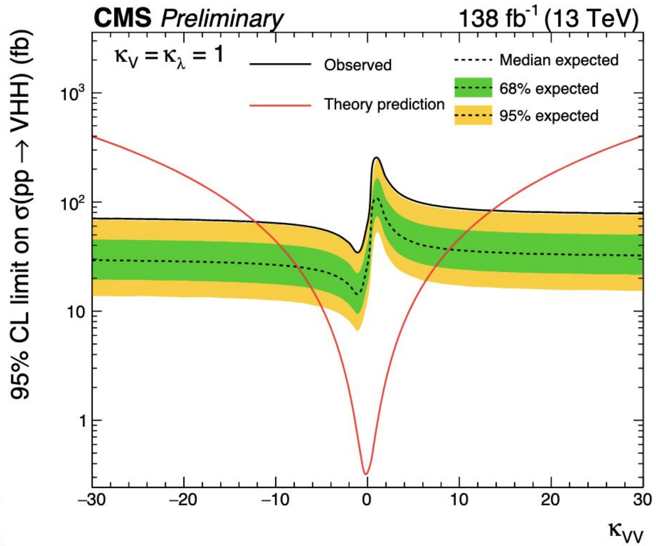
Channel	Vector boson decay products selection	Vector boson reconstruction and selection	Jet selection
MET small-radius		$\vec{p}_{\mathrm{T}}^{\mathrm{Z}} = \vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ $p_{\mathrm{T}}^{\mathrm{Z}} > 150\,\mathrm{GeV}$	$\geq$4 small-radius jets with $p_{\mathrm{T}} > 35\,\mathrm{GeV}$
MET large-radius		$\vec{p}_{\mathrm{T}}^{\mathrm{Z}} = \vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ $p_{\mathrm{T}}^{\mathrm{Z}} > 250\,\mathrm{GeV}$	$\geq$2 large-radius jets with $p_{\mathrm{T}} > 200\,\mathrm{GeV}$
1L	$p_{\mathrm{T}}^{\mathrm{e}} > 32(28)\,\mathrm{GeV}$ 2018/2017 (2016) OR $p_{\mathrm{T}}^{\mu} > 25\,\mathrm{GeV}$ $\Delta\phi(\vec{p}_{\mathrm{T}}^{\ell}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}) < 2.0$	$\vec{p}_{\mathrm{T}}^{\mathrm{W}} = \vec{p}_{\mathrm{T}}^{\ell} + \vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ $p_{\mathrm{T}}^{\mathrm{W}} > 125\,\mathrm{GeV}$	$\geq$3 small-radius jets with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ and $\geq$4 small-radius jets with $p_{\mathrm{T}} > 15\,\mathrm{GeV}$ OR $\geq$2 large-radius jets with $p_{\mathrm{T}} > 200\,\mathrm{GeV}$
2L	$p_{\mathrm{T}}^{\mu_1} > 20\,\mathrm{GeV}$ $p_{\mathrm{T}}^{\mu_2} > 20\,\mathrm{GeV}$ $p_{\mathrm{T}}^{\mathrm{e}_1} > 25\,\mathrm{GeV}$ $p_{\mathrm{T}}^{\mathrm{e}_2} > 20\,\mathrm{GeV}$	$\vec{p}^{\,\mathrm{Z}} = \vec{p}^{\,\ell_1} + \vec{p}^{\,\ell_2}$ $p_{\mathrm{T}}^{\mathrm{Z}} > 50\,\mathrm{GeV}$	$\geq$4 small-radius jets with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$
FH	$p_{\mathrm{T}}^{\mathrm{J}_i} > 20\,\mathrm{GeV}$	$\vec{p}^{\,\mathrm{V}} = \vec{p}^{\,\mathrm{J}_1} + \vec{p}^{\,\mathrm{J}_2}$ $65 < m_{\mathrm{V}} < 105\,\mathrm{GeV}$	$\geq$4 small-radius jets with $p_{\mathrm{T}} > 40\,\mathrm{GeV}$ and $\geq$6 small-radius jets with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$

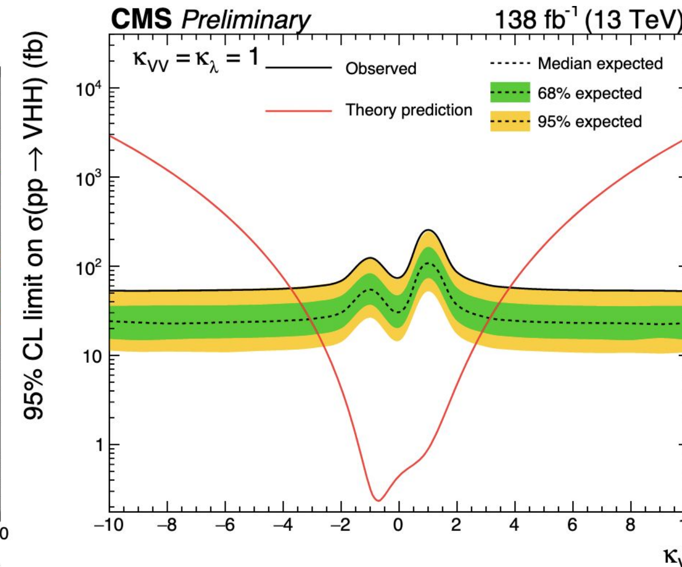
Event Categories

	MET small-radius	MET large-radius	1L small-radius	1L large-radius	2L	FH
Coupling enrichment	$\kappa_\lambda, \kappa_{VV}$	κ_{VV}	$\kappa_\lambda, \kappa_{VV}$	κ_{VV}	$\kappa_\lambda, \kappa_{VV}$	$\kappa_\lambda, \kappa_{VV}$
N_b	$N_b \geq 3$	—	$N_b \geq 3$	—	$N_b = 3$ $N_b = 4$	$N_b = 4$
$D_{b\bar{b},1} \times D_{b\bar{b},2}$	—	HP, LP	—	HP, LP	—	—
SR, CR	SR+CR	SR+CR	SR+CR	SR+CR	SR, CR	SR
SB	$\kappa_\lambda + \kappa_{VV}$	HP, LP	$\kappa_\lambda + \kappa_{VV}$	HP, LP	$N_b = 3$ $N_b = 4$	—
$t\bar{t}$ CR	—	—	—	—	One	—
Year split	Per year	Per year	Per year	Per year	Combined	Per year
Total regions	9	12	9	12	11	6

VHH→4b CMS HIG-22-006







- Constraint on $\boldsymbol{\kappa_{VV}}$:
  - Observed (expected): −12.2(-7.2) < $\boldsymbol{\kappa_{VV}}$ < 13.5 (8.9)
- Constraint on $\boldsymbol{\kappa_V}$:
  - Observed (expected): −3.7(-3.1) < k_λ < 3.8 (3.1)