Double Higgs production at CMS

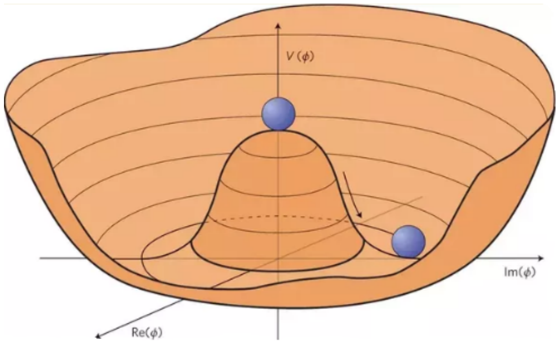
Florian Bury
On behalf of the CMS collaboration

ICHEP 2022

07/07/2022

UCLouvain
Institut de recherche
en mathématique et physique

Why do we care about HH ?



$$V(\phi^\dagger\phi) = -\mu^2(\phi^\dagger\phi) + \lambda(\phi^\dagger\phi)^2$$

EWSB $(\mu^2 = \lambda v^2)$

$$\mathcal{L}_{scalar} \ni \frac{1}{2}(\partial_\mu h \partial^\mu h) - \lambda v^2 h^2 - \lambda v h^3 - \frac{\lambda}{4}h^4 - \frac{\lambda v^4}{4}$$

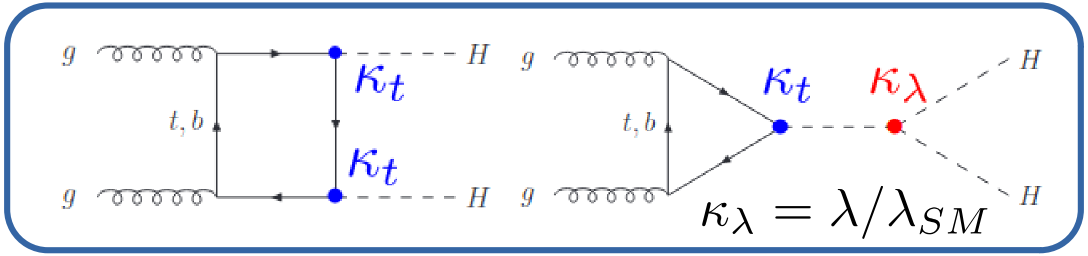
Single Higgs (2012)

$m_h = \sqrt{2\lambda v}$

Double Higgs (???)

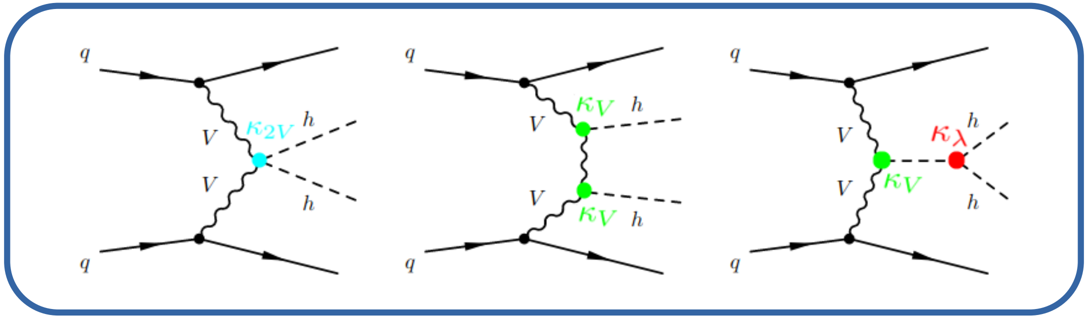
Non-resonant gluon gluon fusion (GGF)

$$\sigma^{GGF}_{HH} = 31.05 \text{ fb } \pm 3\%(\text{PDF} + \alpha_S)\ ^{+2.2\%}_{-5\%}\ (\text{scale})\ \pm 2.6\%(m_t)\ @\ 13\ TeV$$



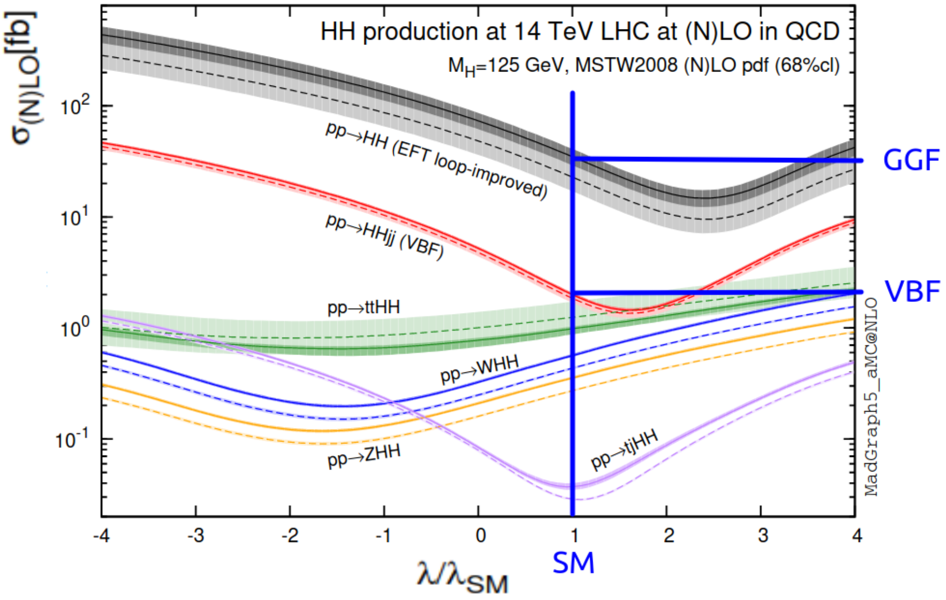
Non-resonant vector boson fusion (VBF)

$$\sigma^{VBF}_{HH} = 1.73 \text{ fb } \pm 2.1\%(\text{PDF} + \alpha_S)\ ^{+0.03\%}_{-0.04\%}\ (\text{scale})\ @\ 13\ TeV$$



Destructive interference !

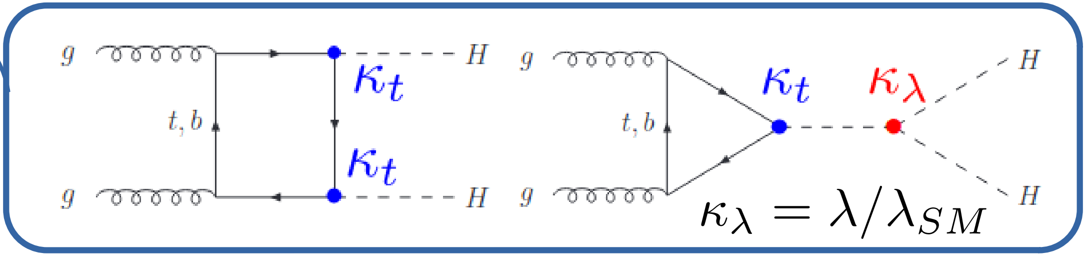
$$\sigma_{HH} \sim \frac{\sigma_H}{1000} \quad @ \; 13 \text{ TeV}$$



... not so easy to measure !

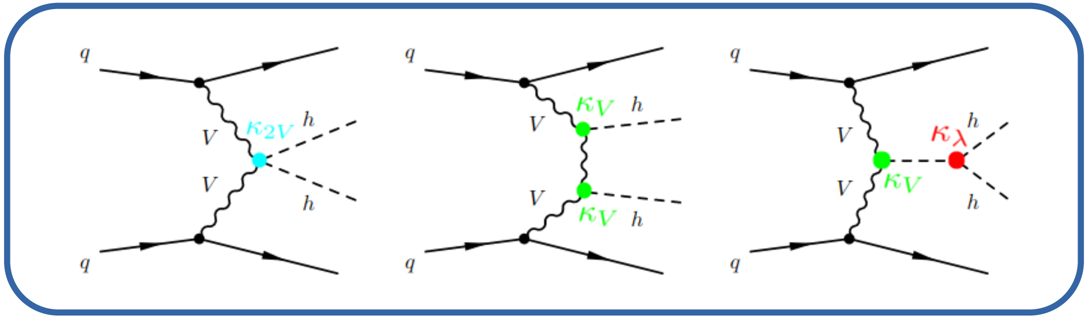
Non-resonant gluon gluon fusion

$$\sigma_{HH}^{GGF} = 31.05 \text{ fb} \; \pm 3\%(\text{PDF} + \alpha_S) \; ^{+2.2\%}_{-5\%} \; (\text{scale}) \; \pm 2.6\%(m_t) \; @ \; 13 \; TeV$$

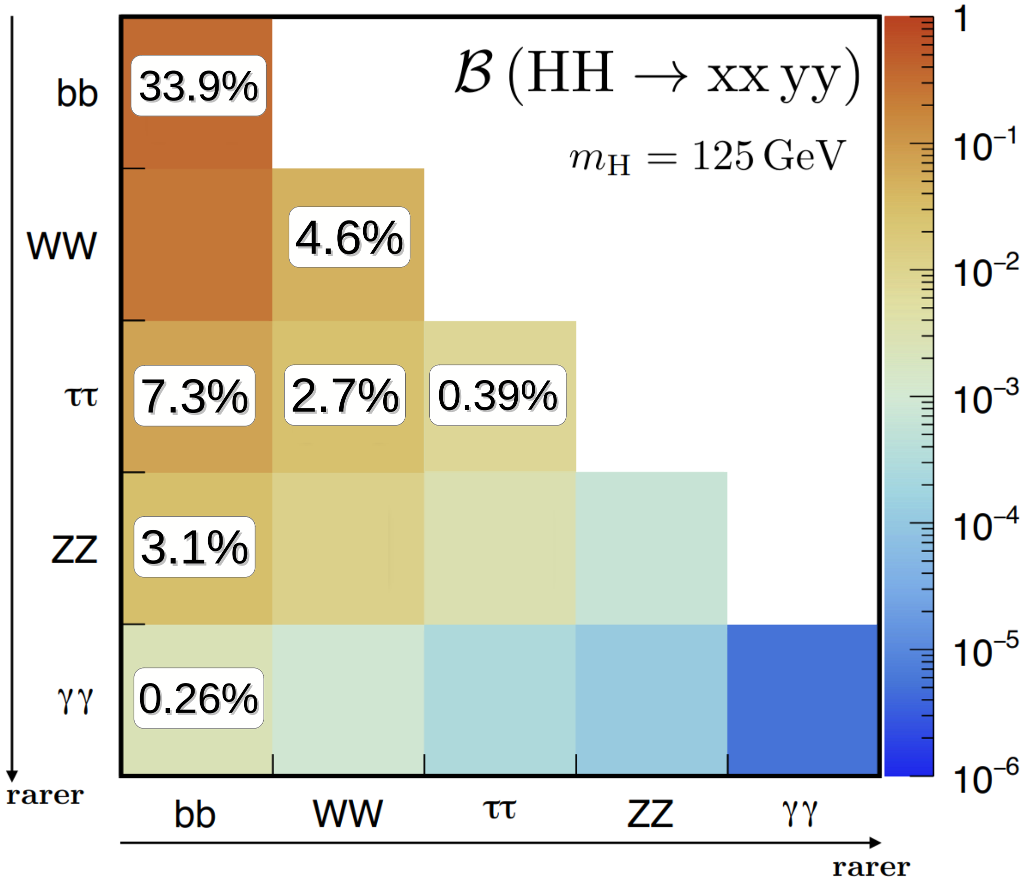


Non-resonant vector boson fusion

$$\sigma_{HH}^{VBF} = 1.73 \text{ fb} \; \pm 2.1\%(\text{PDF} + \alpha_S) \; ^{+0.03\%}_{-0.04\%} \; (\text{scale}) \; @ \; 13 \; TeV$$



HH decays : no golden channel !



bbbb (resolved) : Large BR, large backgrounds
arXiv:2202.09617

bbbb (boosted) : Merged jets topology
arXiv:2205.06667

bbττ : Sizeable BR, small backgrounds
arXiv:2206.09401

bbγγ : Small BR, very clean mass resolution
JHEP03(2021)257

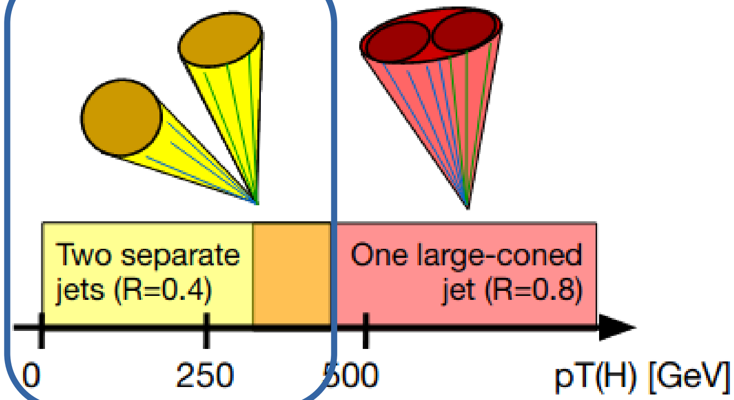
bbZZ : Medium BR, moderate backgrounds
arXiv:2206.10657

WWWW, WWττ, ττττ (Multilepton) :
Medium/small BR, multiple final states
arXiv:2206.10268

(most sensitive channels are public)

→ No golden channel

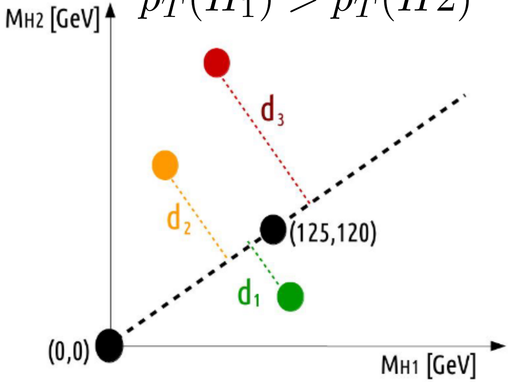
→ each channel comes with its own challenges



Jet clustering with Anti-kT (AK) algorithm

Higgs boson reconstruction

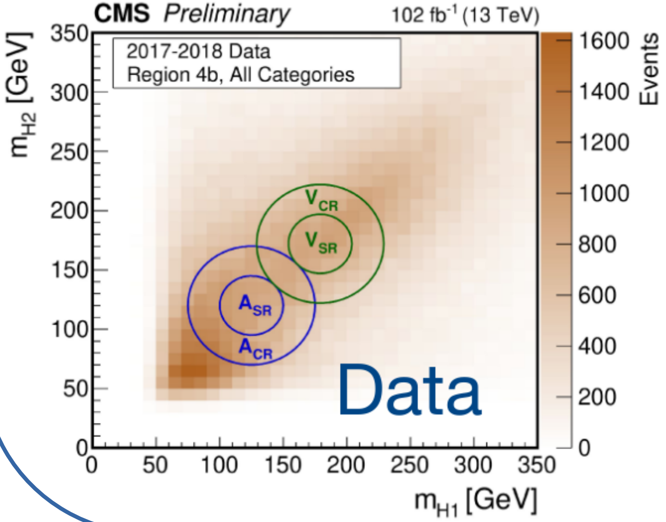
$p_T(H_1) > p_T(H2)$

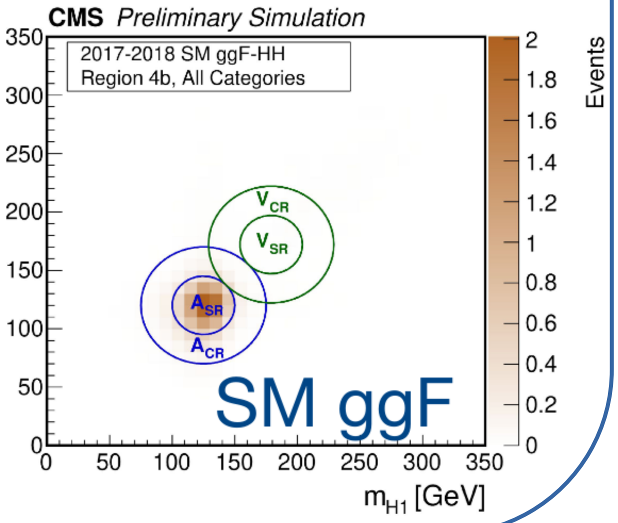


$$d = \frac{|M_{H_1} - kM_{H_2}|}{\sqrt{1+k^2}}$$

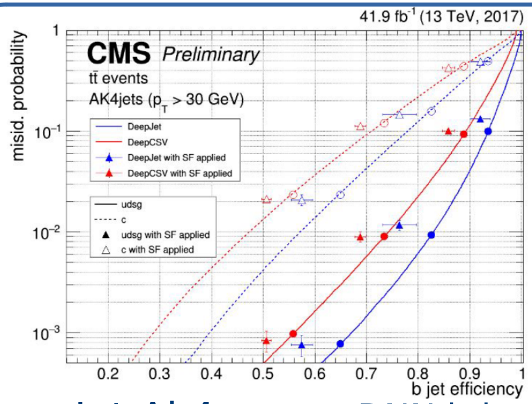
$$k = 125/120 = 1.04$$

96 % accurate for SM GGF





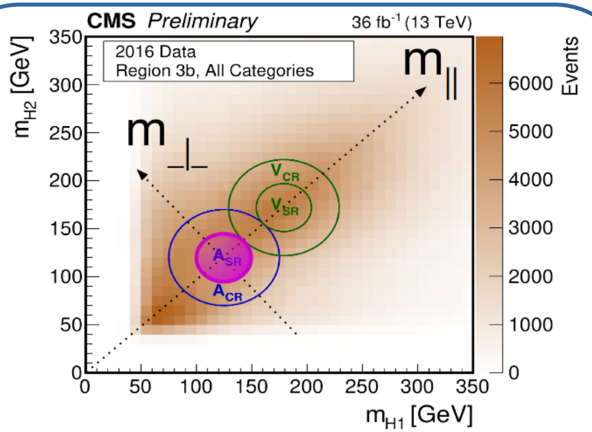
B-tagging



DeepJet Ak4
75 % b-jet eff
+
DNN b-jet
energy regression

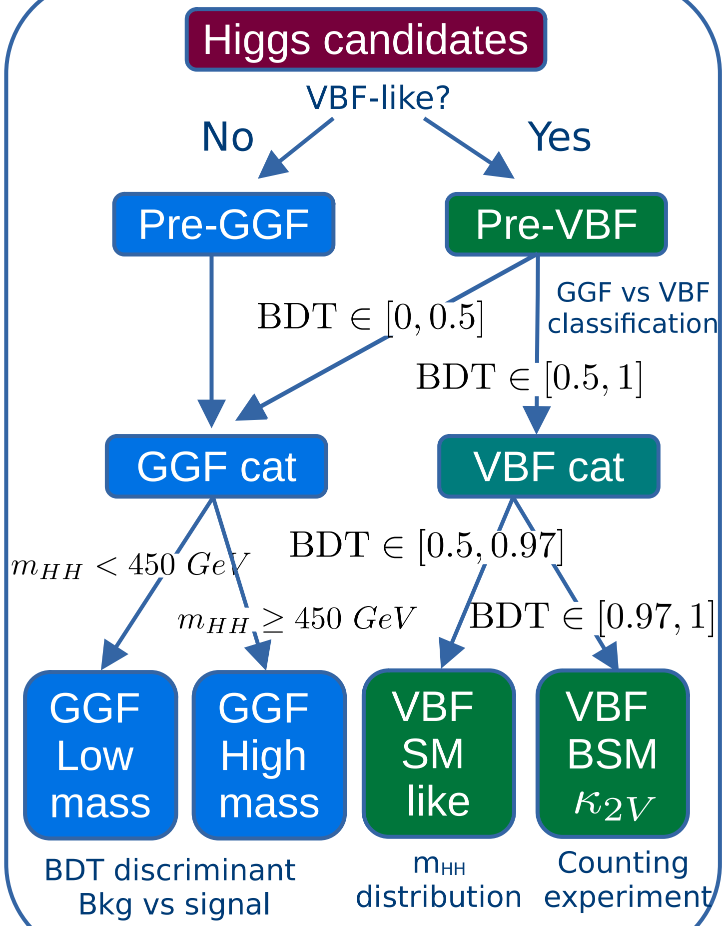
Background

QCD data-driven

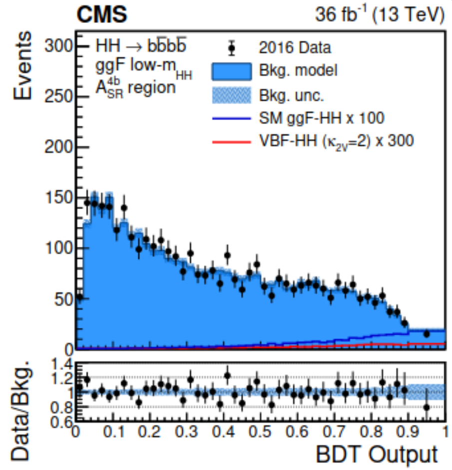


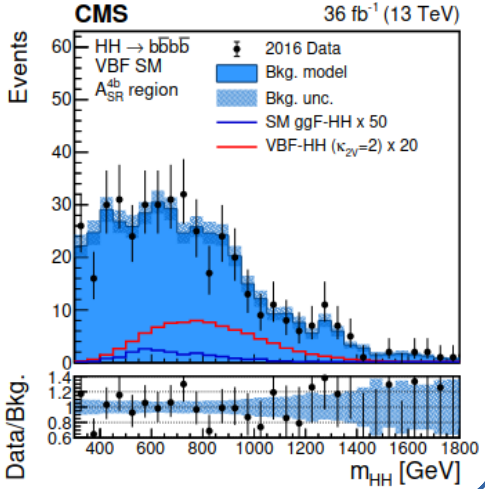
3b data → 4b QCD

Event selection



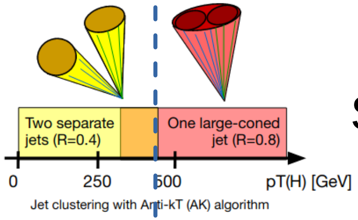
Signal region





Resolved

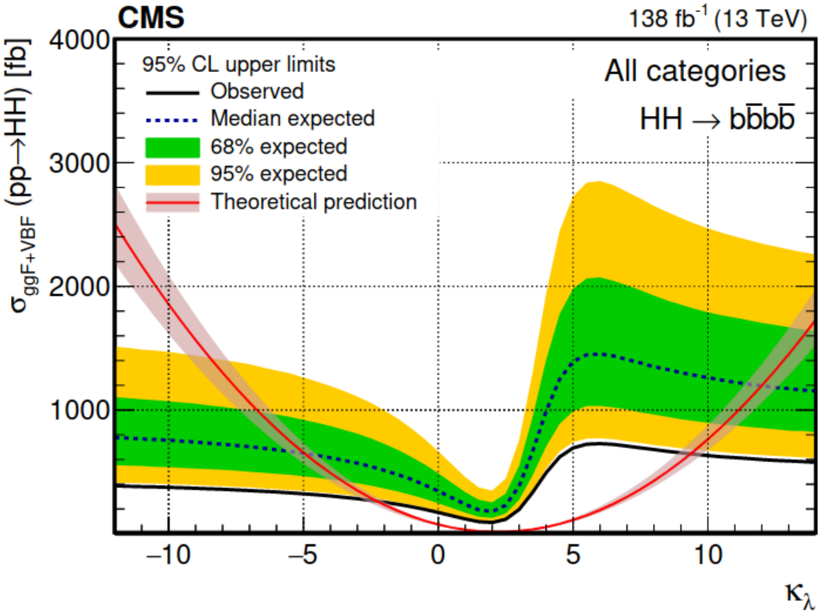
$$\sigma_{HH} < 3.9\ (7.8)\ \sigma_{HH}^{SM}$$
$$\sigma_{VBF} < 226\ (412)\ \sigma_{VBF}^{SM}$$



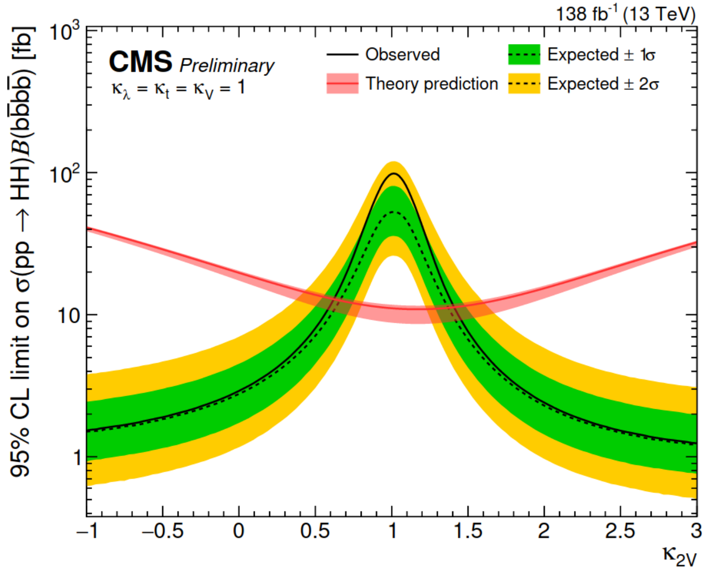
Boosted

See next talk by Valeria D'Amante

$$\sigma_{HH} < 9.9\ (5.1)\ \sigma_{HH}^{SM}$$



$$-2.3\ (-5.0) < \kappa_\lambda < 9.4\ (12.0)$$
$$-0.1\ (-0.4) < \kappa_{2V} < 2.2\ (2.5)$$



$$-9.9\ (-5.1) < \kappa_\lambda < 16.9\ (12.2)$$
$$0.62\ (0.66) < \kappa_{2V} < 1.41\ (1.37)$$

First evidence of non-zero values at 6.3 σ

Event selection

- Hadronic tau using DeepTau algorithm

$$N(\tau_h) \geq 1$$

- 2 OS leptons + 3 lepton veto
- 3 channels : τ_μ/τ_h , τ_e/τ_h , τ_h/τ_h
- 2 jets + btagging using HH-btag
- Elliptic mass cut on resonances (only GGF)

  H→ ττ (SV_{Fit} algo) and H→ bb (mass sum)

$$\frac{(m_{\tau\tau} - 129\ \text{GeV})^2}{(53\ \text{GeV})^2} + \frac{(m_{bb} - 169\ \text{GeV})^2}{(145\ \text{GeV})^2} < 1\ (\text{Resolved})$$

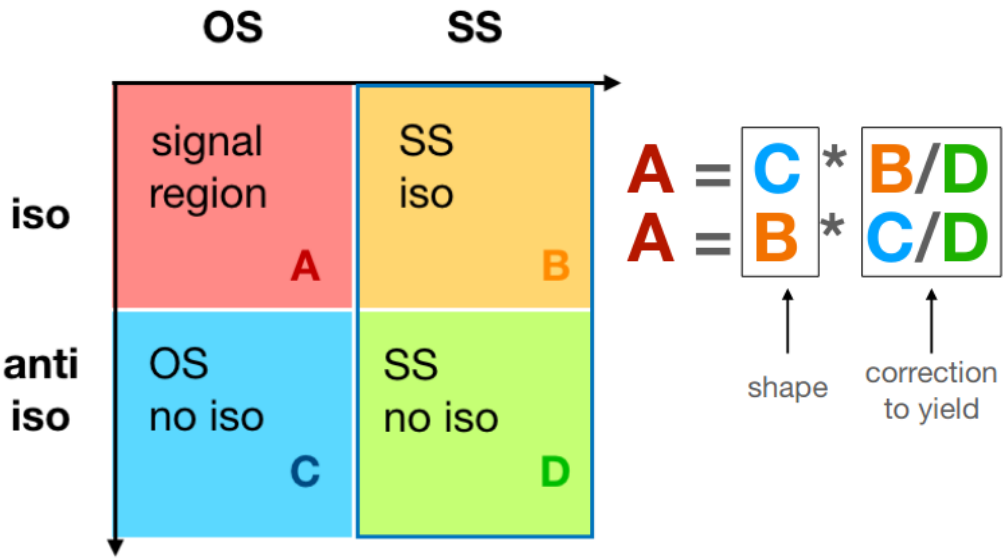
$$\frac{(m_{\tau\tau} - 128\ \text{GeV})^2}{(60\ \text{GeV})^2} + \frac{(m_{bb} - 159\ \text{GeV})^2}{(94\ \text{GeV})^2} < 1\ (\text{Boosted})$$

- DNN classification

Background estimation

- QCD multijet from datadriven ABCD method :

  → Averaged from two CR



- tt and DY : MC normalised from data CR
- Other backgrounds : pure MC

Signal extraction

Event selection

VBF selection

No — GGF cat

Yes — VBF cat

AK8 with btagged subjets
SD condition → Boosted

2-btagged AK4 jets
(medium WP) → Resolved 2b

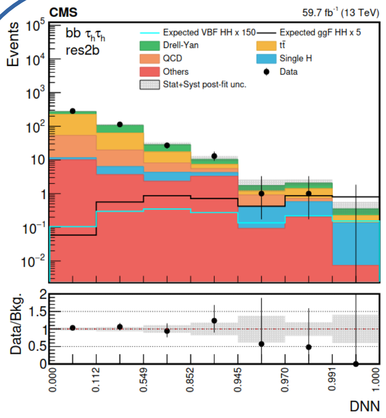
1-btagged AK4 jet
(medium WP) → Resolved 1b

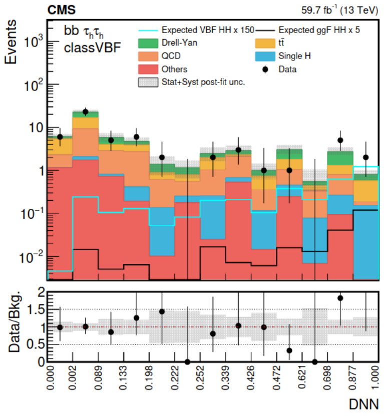
> 0 b-jet
(medium WP) → Multiclass DNN → VBF, GGF, ttH, DY, TT

+ DNN bbττ vs background

All categories are exclusive, DNN score used in fit

Signal region + results

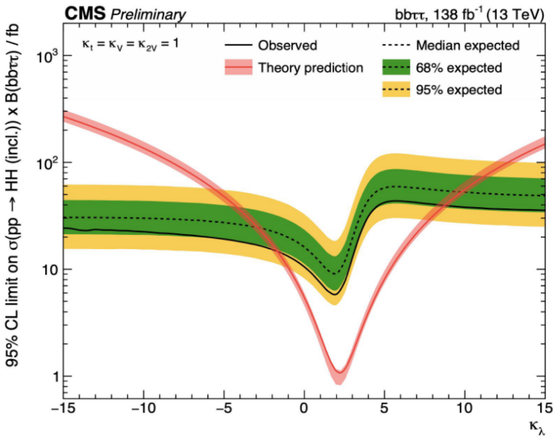


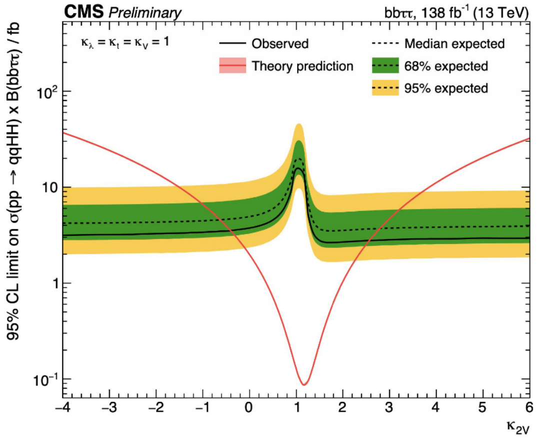


$$\sigma_{HH} < 3.3\ (5.2)\ \sigma_{HH}^{SM}$$

$$\sigma_{VBF} < 124\ (154)\ \sigma_{VBF}^{SM}$$

Most constraining HH VBF cross section measurement in CMS



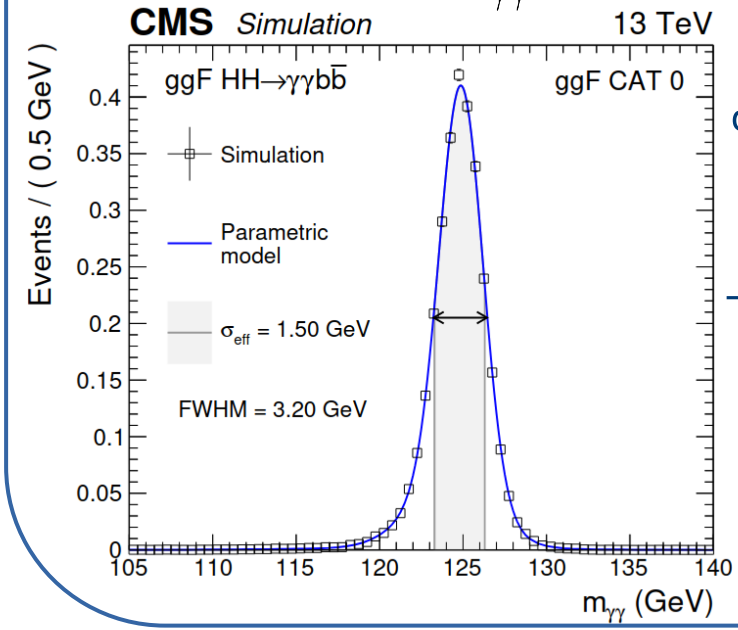


$$-1.7\ (-2.9) < \kappa_\lambda < 8.7\ (9.8) \qquad -0.4\ (-0.6) < \kappa_{2V} < 2.6\ (2.8)$$

H→ ɣɣ

- 2 photons
- Invariant mass requirements :

$$p_{T,1} > 0.33 \times m_{\gamma\gamma}$$
$$p_{T,2} > 0.25 \times m_{\gamma\gamma}$$
$$100 < m_{\gamma\gamma} < 180 \text{ GeV}$$



σ = 1.4 - 2 GeV

Excellent resolution

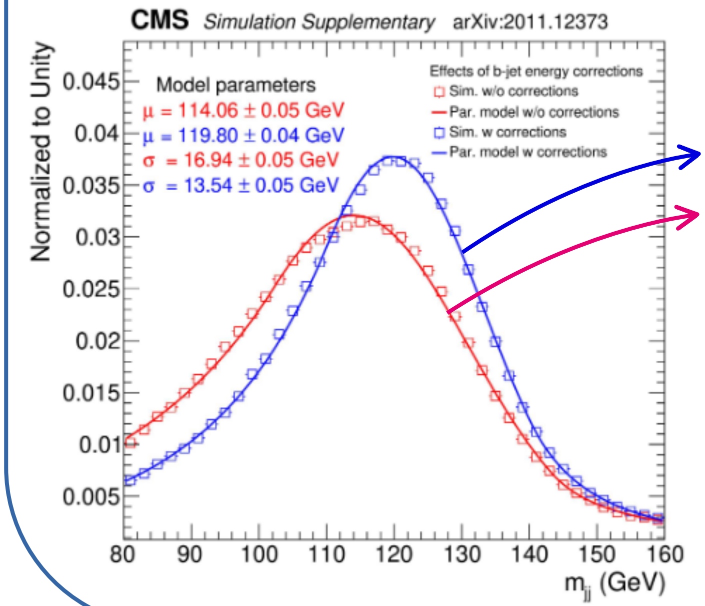
→ very important for low m_{HH} region

H→ bb

- 2 jets → b-jets (largest b-tag score)
- Invariant mass requirement :

$$70 < m_{jj} < 190 \text{ GeV}$$

- B-jet energy regression : jet + m_{jj}



After correction

Before correction

- Bias corrected ~ 5.5 GeV
- Resolution improved by 20 %

Event selection

Backgrounds

Real photons | Fake photons | Top backgrounds (ttH)

Kinematic cuts | Photon ID | Lepton/jet veto

ttH Rejection DNN ← SM HH signal + BSM mixture

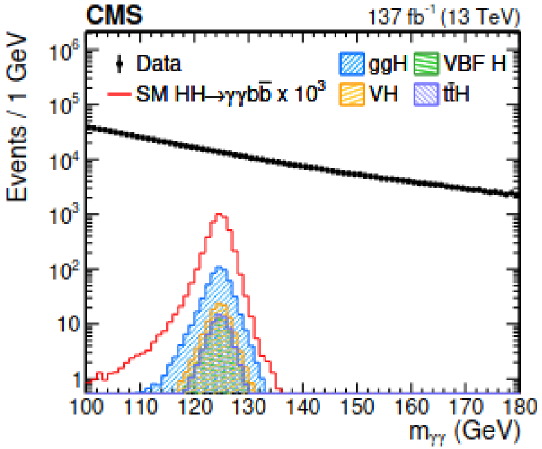
Classification BDT

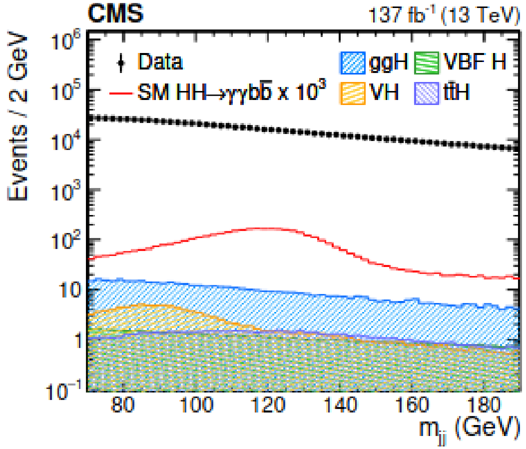
GGF: bbγγ, γ+jets, γγ+jets + $\tilde{M}_X$ → GGF Categories

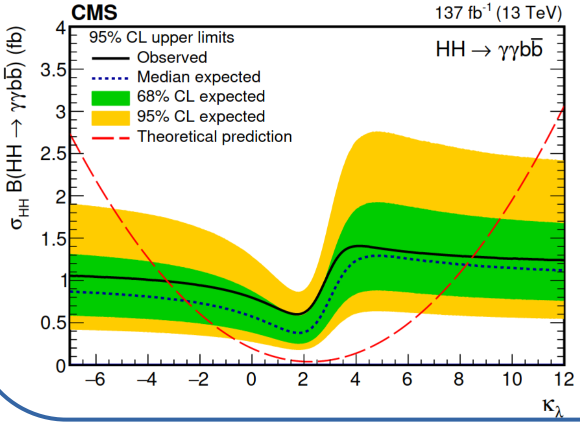
VBF: GGF, VBF, γ(γ)+jets + $\tilde{M}_X$ → VBF Categories

Signal extraction and results

$m_{\gamma\gamma} \times m_{jj}$ 2D likelihood fit







$$\sigma_{HH} < 7.7\ (5.2)\ \sigma_{HH}^{SM}$$

$$\sigma_{VBF} < 225\ (208)\ \sigma_{VBF}^{SM}$$

$$-3.3\ (-2.5) < \kappa_\lambda < 8.5\ (8.2)$$

$$-1.3\ (-0.9) < \kappa_{2V} < 3.5\ (3.1)$$

Event selection

- 2 pairs of OS SF isolated leptons
- ZZ candidates :

$$40 \text{ GeV} < m_{Z_1} < 120 \text{ GeV}$$
$$12 \text{ GeV} < m_{Z_2} < 120 \text{ GeV}$$

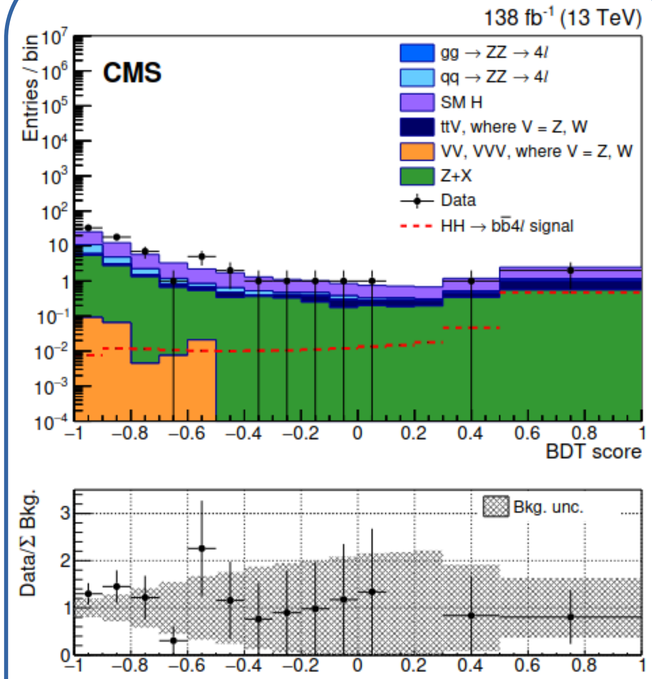
- 2 jets → b-jets (highest b-tag score)
- 3 categories: 4e, 4μ, 2e2μ
- 4l invariant mass

$$115 \text{ GeV} < m(4l) < 135 \text{ GeV}$$

Backgrounds

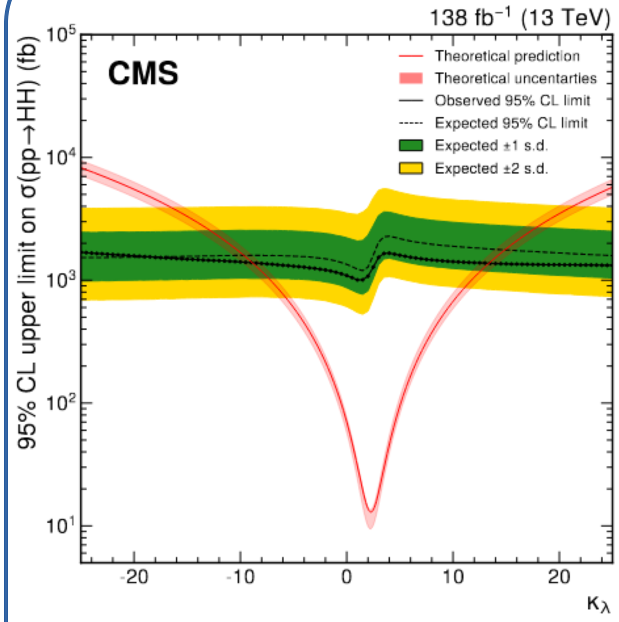
- Irreducible :
  - Single Higgs
  - qq→ZZ*, gg → ZZ*
  - ttW, ttZ
- Reducible : Z+X (fake leptons)
  → data-driven approach :
  fake factor e, μ in control regions

Signal extraction



BDT for each category and data taking year

Results



$$\sigma_{HH} < 32.4 \ (39.6) \ \sigma_{HH}^{SM}$$

$$-8.8 \ (-9.8) < \kappa_\lambda < 13.4 \ (15.0)$$

HH→Multilepton (WWWW, WWττ, ττττ)

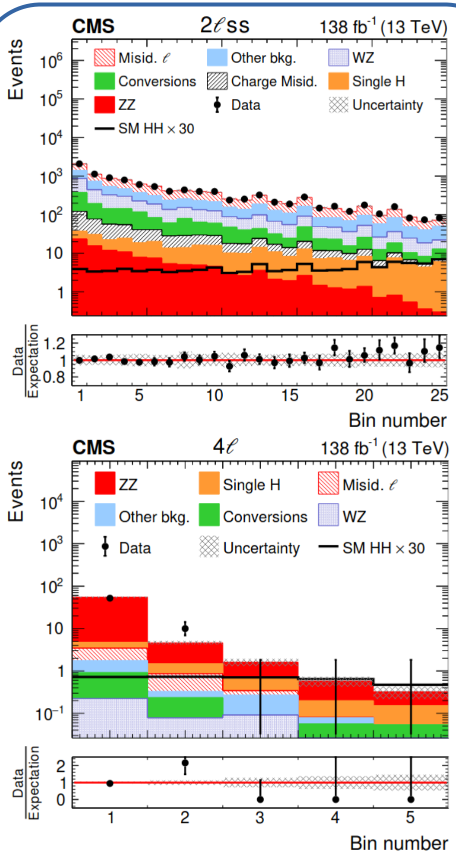
Event selection

- 7 categories based on l/τ
  → 2lss, 3l, 4l, 3l+1τ_h, 2l+2τ_h,
  1l+3τ_h, 0l+4τ_h
- AK4/AK8 jets (hadronic W decay)
  → 2lss and 3l categories
- B-jet veto
- M_{ll} cuts
  - Remove meson decays
  - Overlap with bbZZ
  - Reduce DY background

Backgrounds

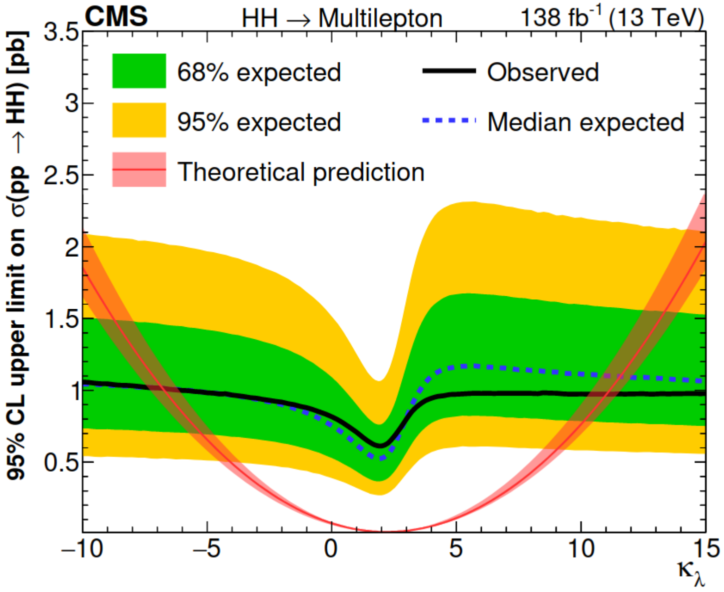
- l/τ_h fakes : data-driven
  with fake factor method in CR
- Electron charge flip measurement :
  data-driven using similar method
- Other backgrounds : simulation

Signal extraction



BDT for each category (combined for all years)

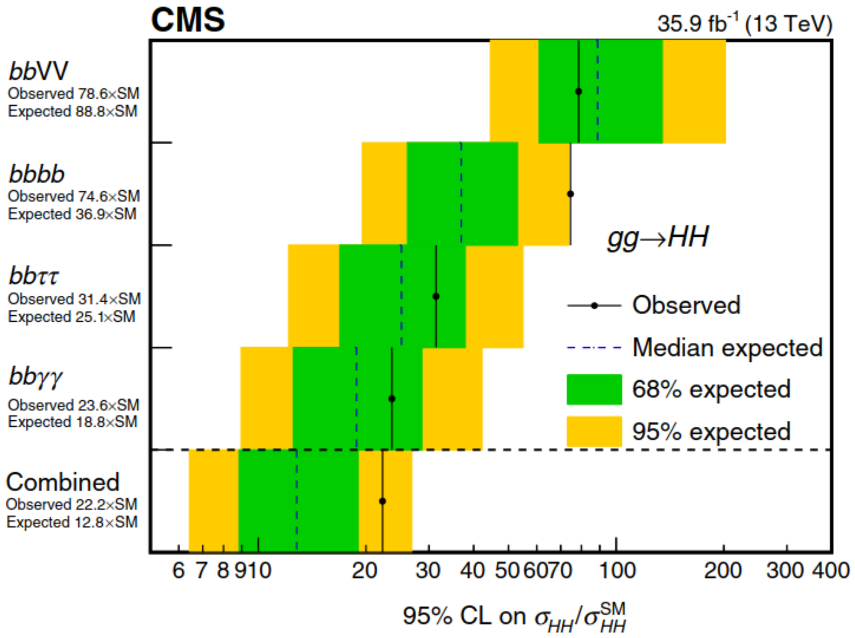
Results



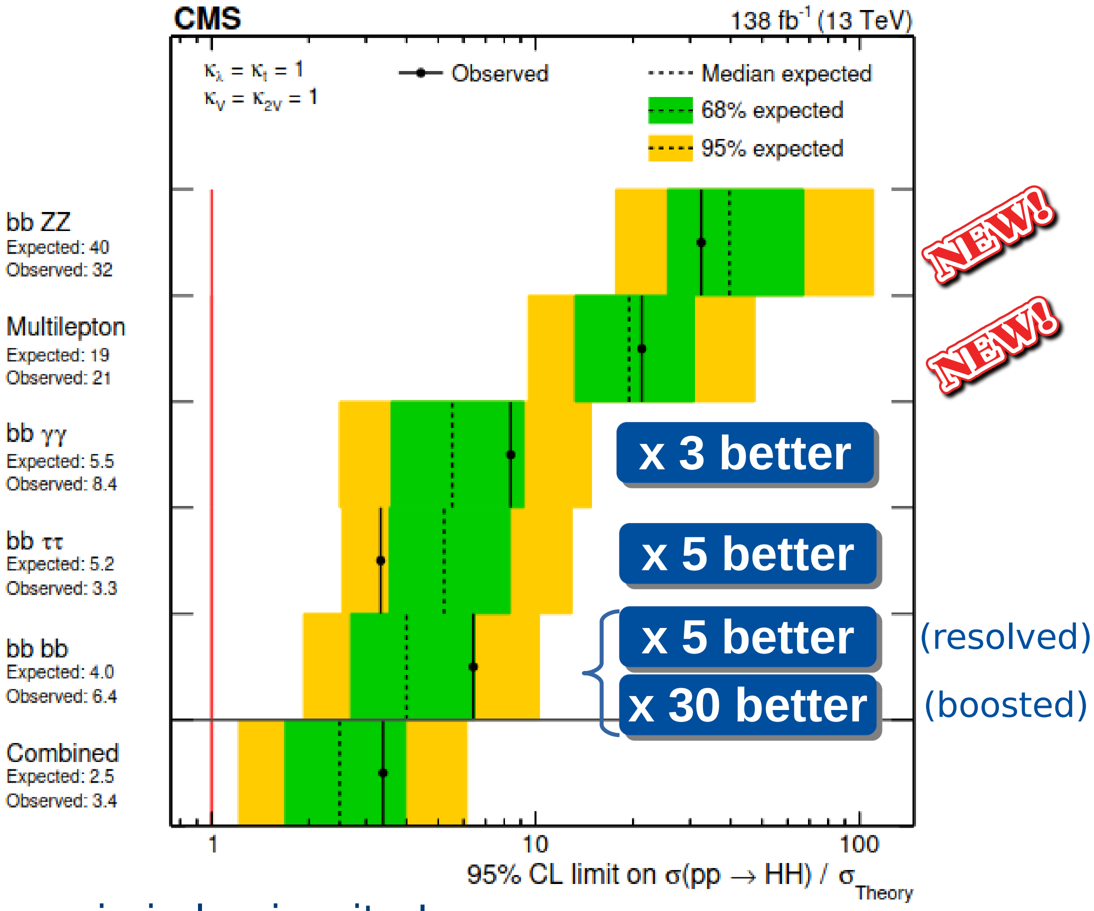
$$\sigma_{HH} < 21.3\ (19.4)\ \sigma_{HH}^{SM}$$

$$-6.9\ (-6.9) < \kappa_\lambda < 11.1\ (11.7)$$

2016 HH combination



Run-2 HH combination



2016 combination results :

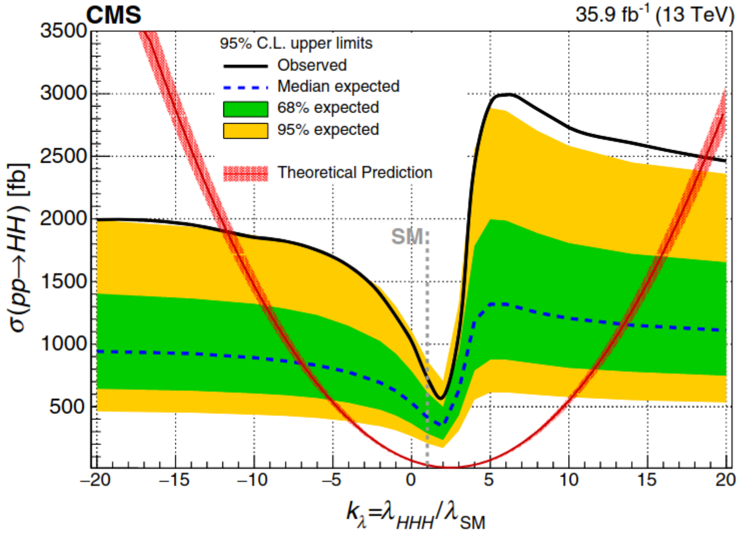
$$\sigma_{HH} < 22.2\ (12.8)\ \sigma_{HH}^{SM}$$

Run-2 current combination results :

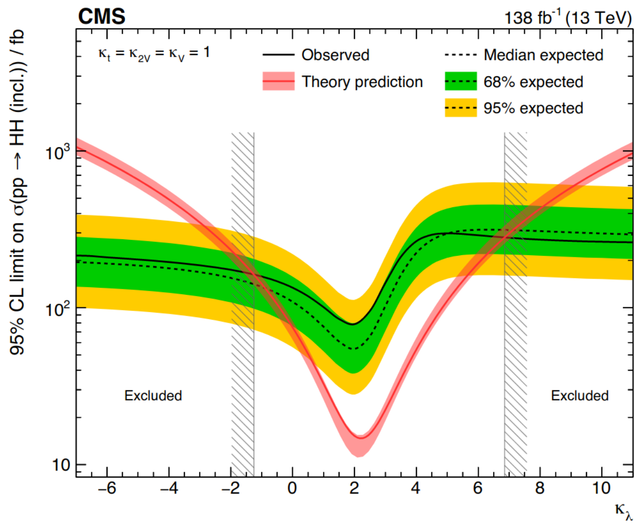
$$\sigma_{HH} < 3.4\ (2.5)\ \sigma_{HH}^{SM}$$

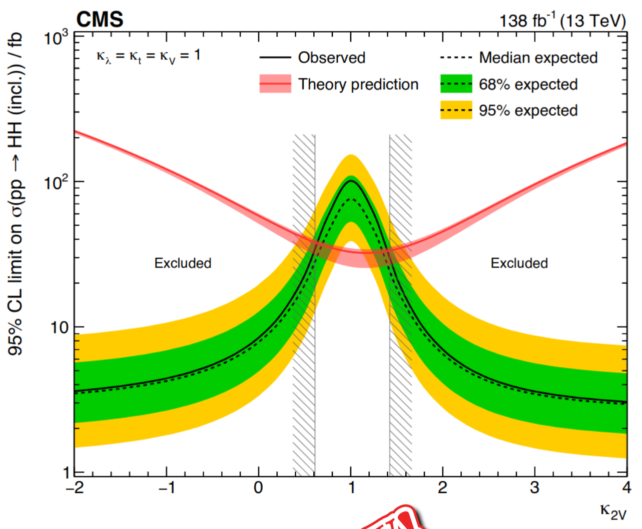
… not only from the gain in luminosity !

2016 HH combination



Run-2 HH combination





NEW!

2016 combination results :

$$-11.8\ (-7.1) < \kappa_\lambda < 18.8\ (13.6)$$

Run-2 current combination results :

$$-1.24 < \kappa_\lambda < 6.49$$

$$0.67 < \kappa_{2V} < 1.38$$

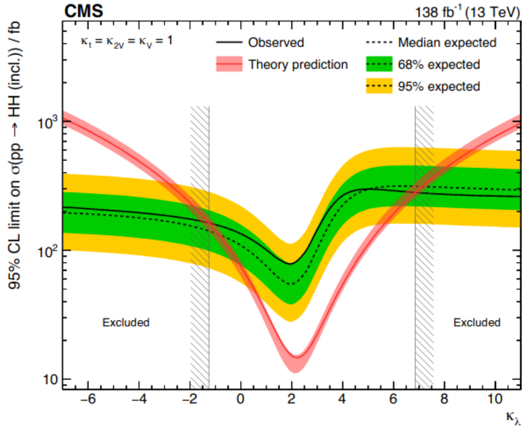
$$\kappa_{2V} = 0 \text{ excluded at } 6.6\ \sigma$$

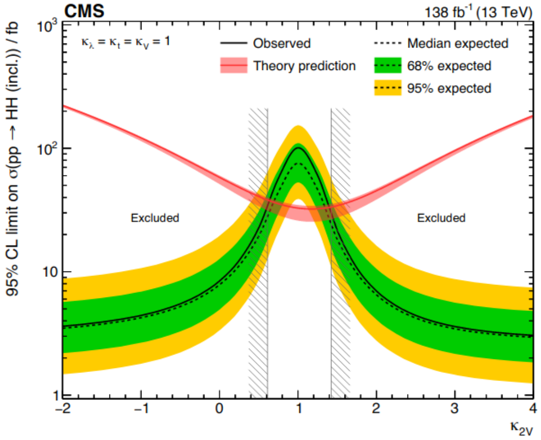
… not only from the gain in luminosity !

Summary

- Non-resonant Higgs pair production mechanism :
  - Probe Higgs self-coupling → Scalar potential shape
  - Measure predicted couplings and search for new physics
- Latest CMS combined Run-2 results :
  - Inclusive HH cross section :
  - Trilinear couplings :
  - VVHH coupling :
  - … and many more (couplings, EFT interpretation, resonant)
- Run-2 exceeded expectations thanks to :
  - Better reconstruction of boosted topologies
  - Additional final states considered
  - More performant b-tagging
  - Inclusion of VBF measurements
- Run-3 : closing in on σ_{HH}^{SM} ? → stay tuned !

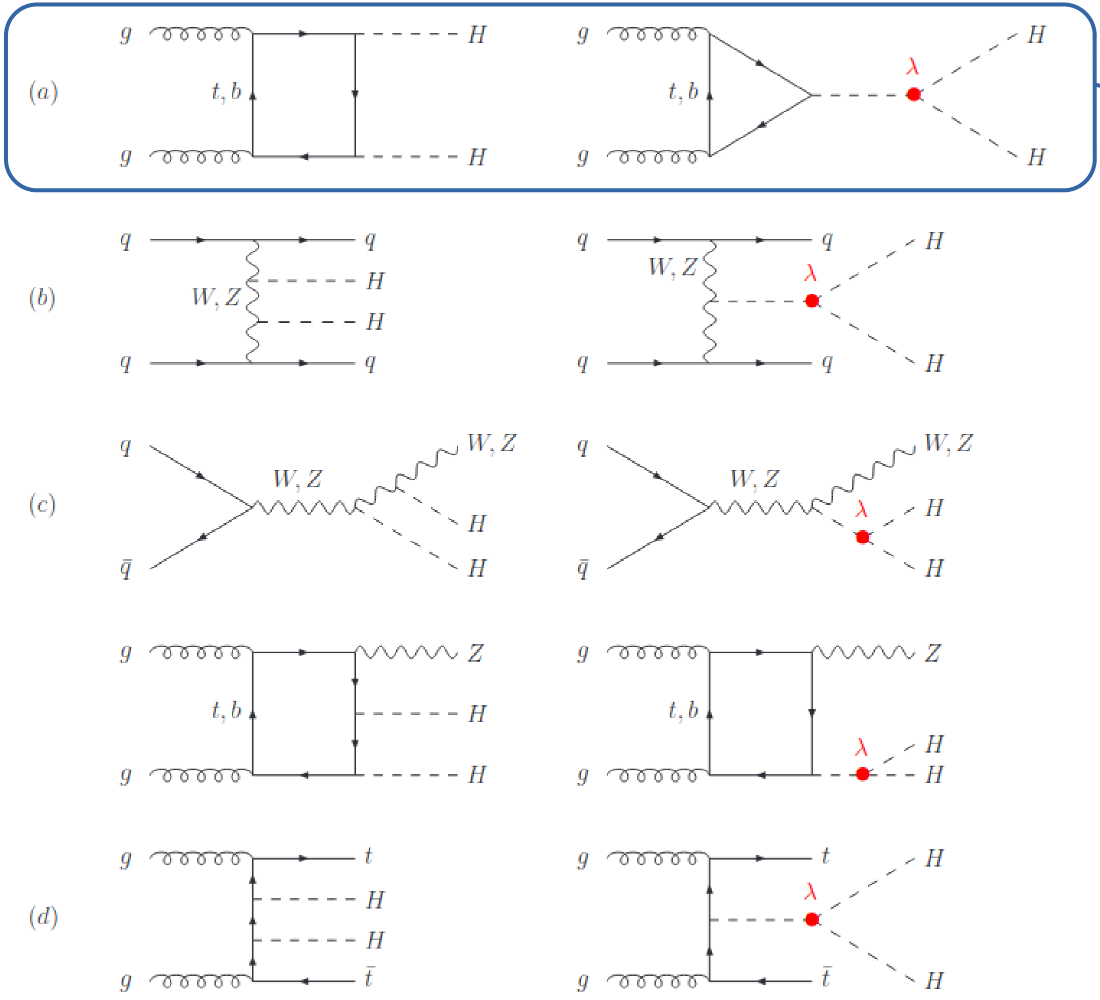
$$\sigma_{HH} < 3.4\ (2.5)\ \sigma_{HH}^{SM}$$
$$-1.24 < \kappa_\lambda < 6.49 \text{ @ } 95\ \%\ \text{CL}$$
$$0.67 < \kappa_{2V} < 1.38 \text{ @ } 95\ \%\ \text{CL}$$

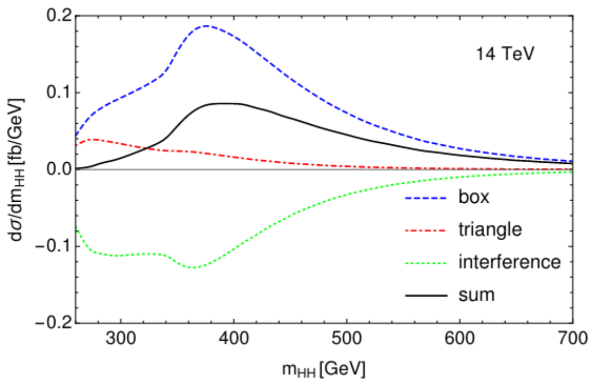


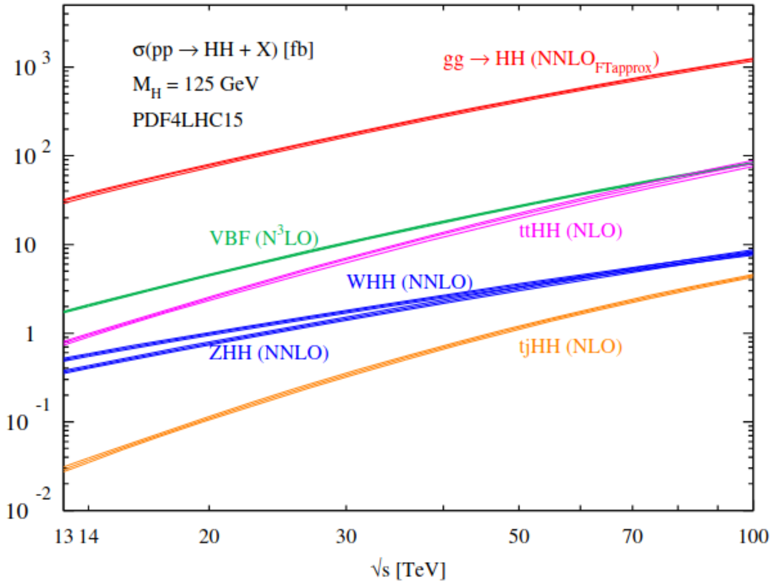


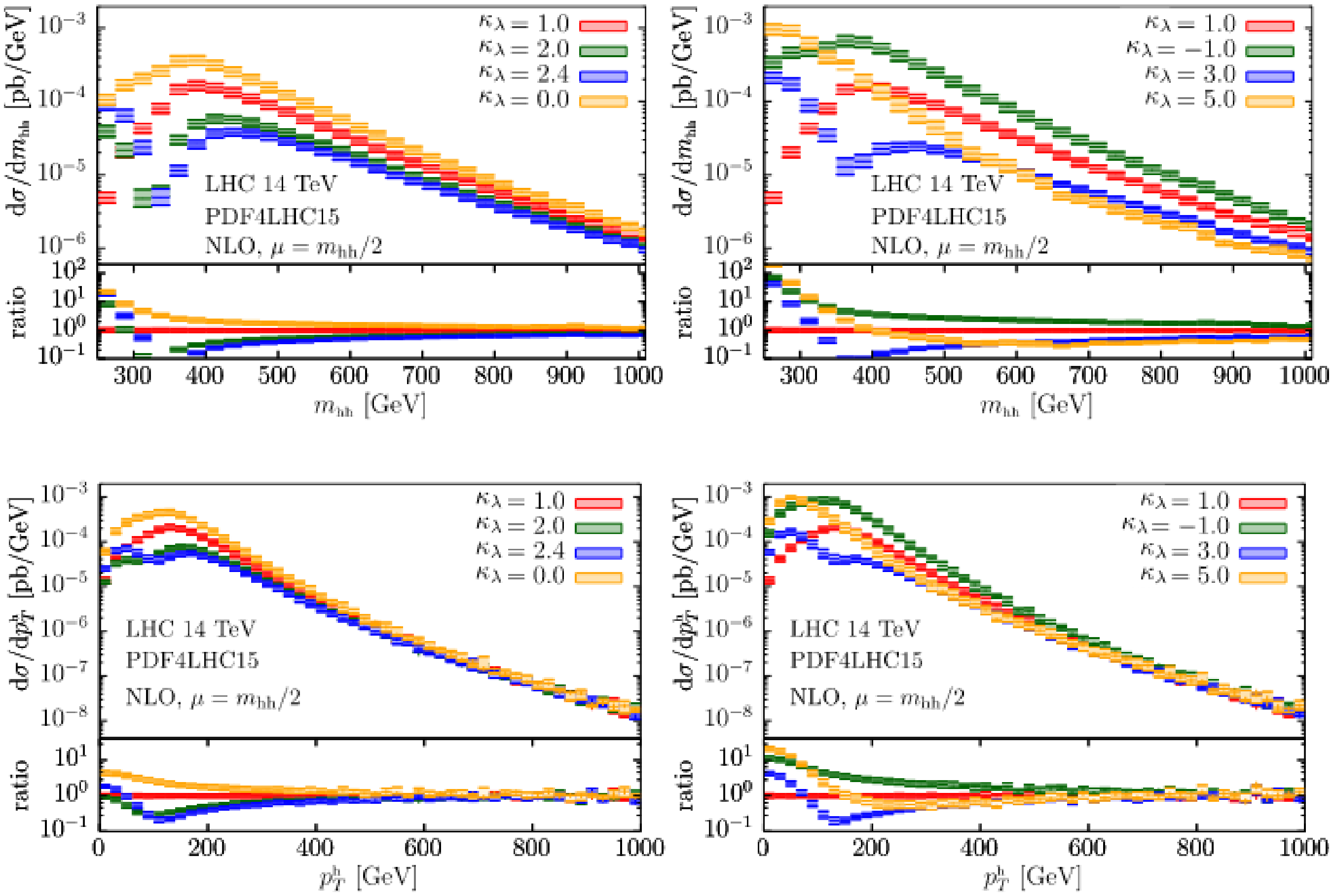
Back-up

HH production mechanism

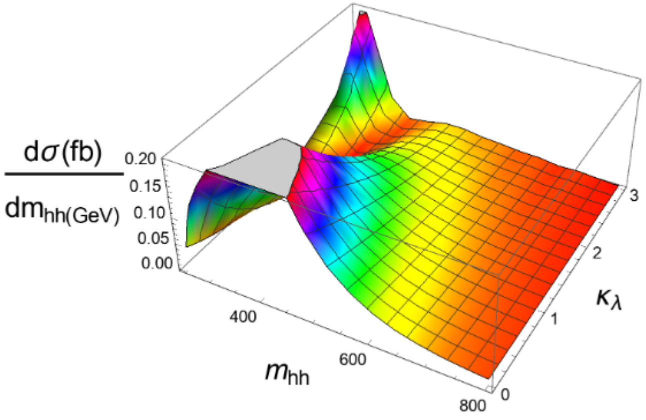








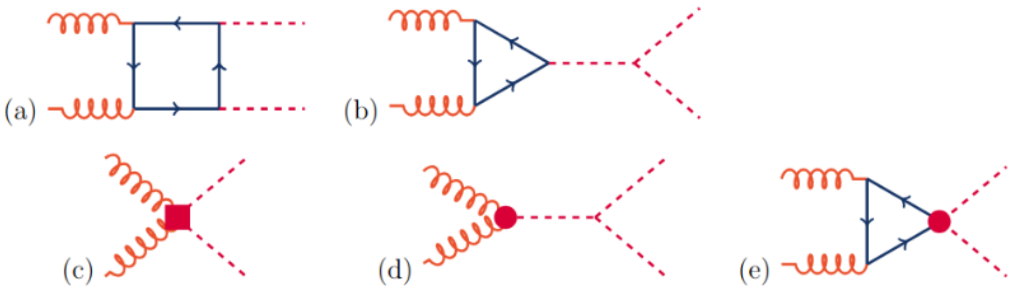
$\kappa_\lambda = 1.0$
$\kappa_\lambda = 2.0$
$\kappa_\lambda = 2.4$
$\kappa_\lambda = 0.0$
$\kappa_\lambda = -1.0$
$\kappa_\lambda = 3.0$
$\kappa_\lambda = 5.0$
LHC 14 TeV
PDF4LHC15
NLO, $\mu = m_{hh}/2$
$d\sigma/dm_{hh}$ [pb/GeV]
$d\sigma/dp_T^h$ [pb/GeV]
ratio
m_{hh} [GeV]
p_T^h [GeV]



$\frac{d\sigma(fb)}{dm_{hh(GeV)}}$
m_{hh}
κ_λ

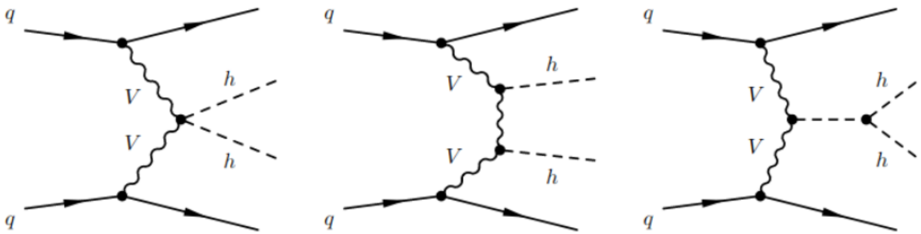
GGF

$$
\begin{aligned}
\mathcal{L}_h = &\frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{2}m_H^2 h^2 - \kappa_\lambda \frac{m_H^2}{2v} h^3 \\
&- m_t \left(v + \kappa_t \frac{h}{v} + c_2 \frac{H^2}{v^2} \right) \left(\bar{t}_L t_R + h.c. \right) \\
&+ \frac{\alpha_s}{12\pi} \left(c_g \frac{h}{v} - c_{2g} \frac{h^2}{2v^2} G^a_{\mu\nu} G^{a,\mu\nu} \right),
\end{aligned}
$$



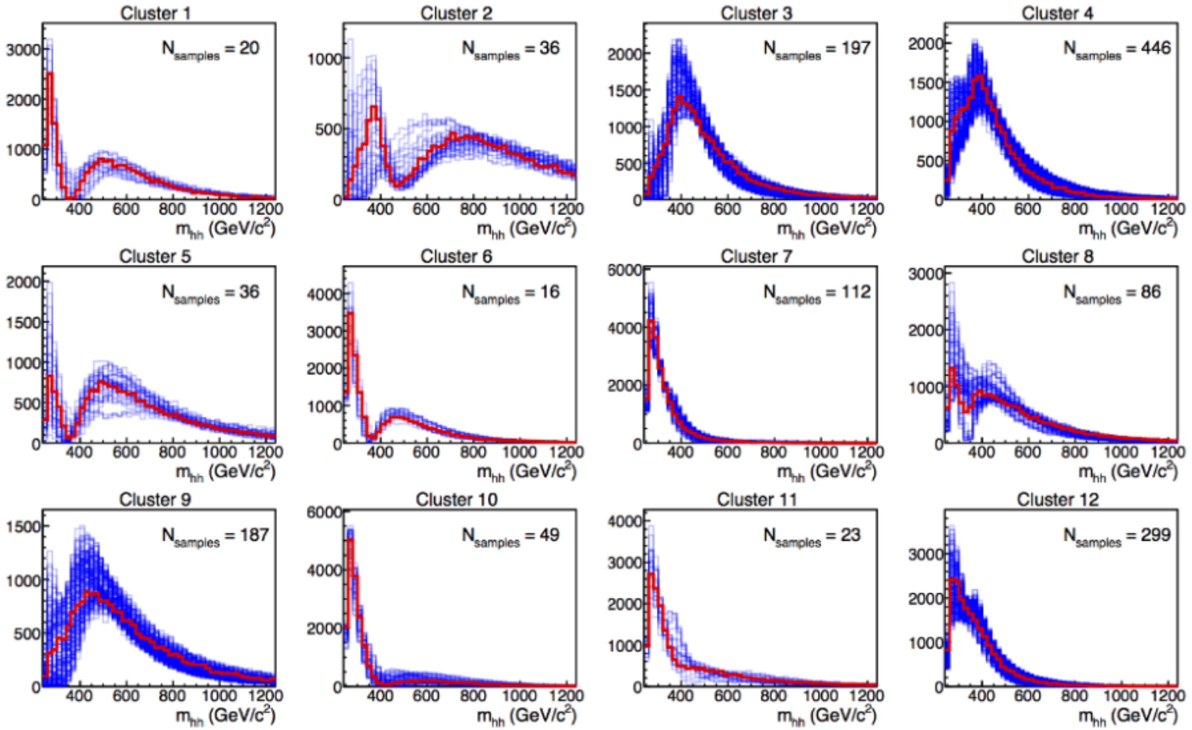
VBF

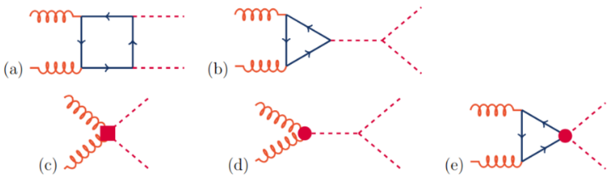
$$
\mathcal{L}_{VBF} = \frac{v^2}{4} Tr \left(D_\mu \Sigma^\dagger D^\mu \Sigma \right) \left[1 + 2c_V \frac{h}{v} + c_{2V} \frac{h^2}{v^2} + \ldots \right]
$$



GGF

$$R_{HH} = \sigma_{LO}/\sigma_{LO}^{SM} = A_1\kappa_t^4 + A_2 c_2 + (A_3\kappa_t^2 + A_4 c_g^2)\kappa_\lambda^2 + A_5 c_{2g}^2 + (A_6 c_2 + A_7\kappa_t\kappa_\lambda)\kappa_t^2$$
$$+ (A_8\kappa_t\kappa_\lambda + A_9 c_g\kappa_\lambda)c_2 + A_{10}c_2 c_{2g} + (A_{11}c_g\kappa_\lambda + A_{12}c_{2g})\kappa_t^2$$
$$+ (A_{13}\kappa_\lambda c_g + A_{14}c_{2g})\kappa_t\kappa_\lambda + A_{15}c_g c_{2g}\kappa_\lambda$$





HH inference

HH inference tool :

- Documentation : https://cms-hh.web.cern.ch/tools/inference/
- Wrapper around combine commands with a task scheduler law
- Useful manipulation scripts
- Physics model containing
  - BR scaling with the couplings
  - Single Higgs scaling with the couplings
  - NNLO scaling + theory systematics
  - Interpolation for a given set of coupling points and their associated shapes (see below)
  - ...

$$A = \kappa_t \kappa_\lambda \triangle + \kappa_t^2 \square$$

$$\sigma(\kappa_t, \kappa_\lambda) \sim |A|^2 = \kappa_t^2 \kappa_\lambda^2 |\triangle|^2 + \kappa_t^4 |\square|^2 + \kappa_t^3 \kappa_\lambda |\triangle^* \square + \triangle \square^*|$$
$$= \boldsymbol{c}(\kappa_t, \kappa_\lambda)^T . \boldsymbol{v},$$

with

$$\boldsymbol{c}(\kappa_t, \kappa_\lambda) = (\kappa_t^2 \kappa_\lambda^2, \kappa_t^4, \kappa_t^3 \kappa_\lambda)$$

If 3 points are known, then $\boldsymbol{v} = \boldsymbol{C}^{-1} \boldsymbol{\sigma}$ is fully determined

The limits can be established for any value of the couplings via

$$\sigma(\kappa_t, \kappa_\lambda) = \boldsymbol{c}(\kappa_t, \kappa_\lambda)^T \boldsymbol{C}^{-1} \boldsymbol{\sigma}$$

Note :

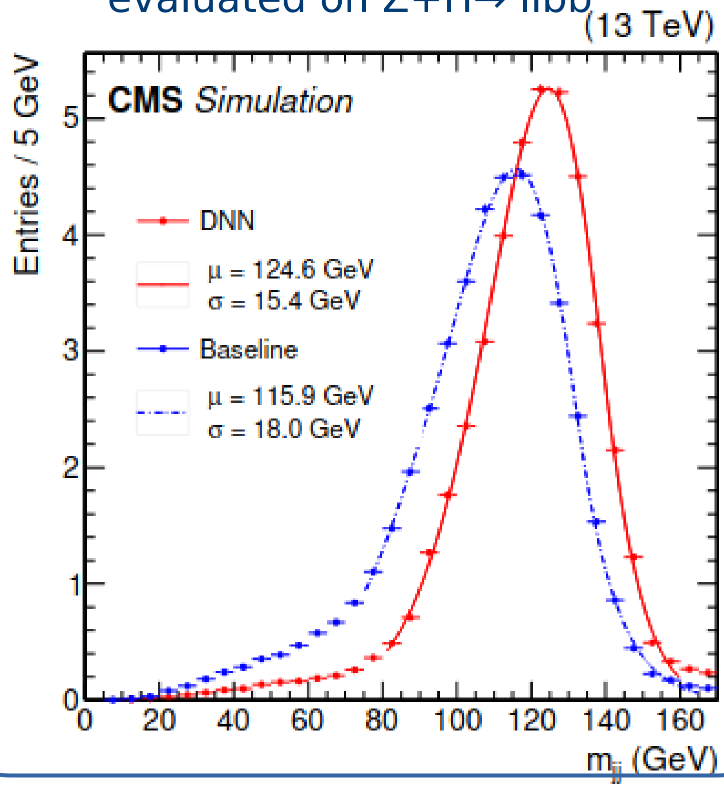
- Also works at NLO (still scale with the power of the couplings)
- Also works for differential measurement (→ histograms)
- Can also be applied to more couplings (3 couplings → 6 points)
- Caveat : points used in interpolation must be representative enough

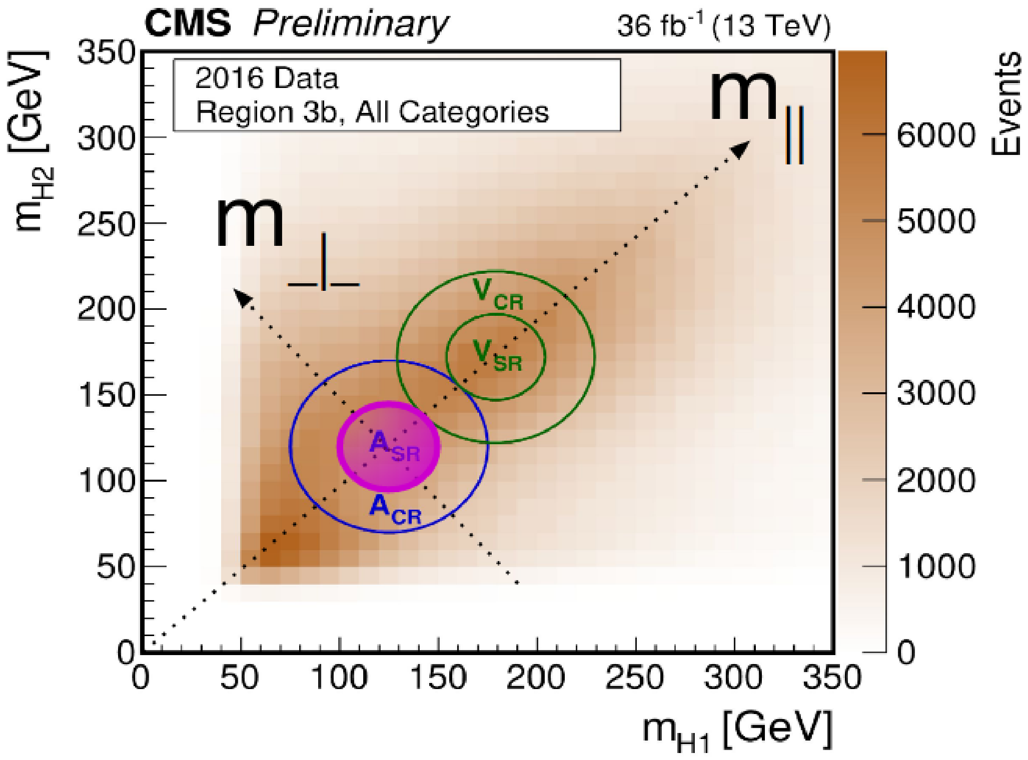
HH→bbbb (resolved)

Triggers :
- 2016 :
  - 4 jets with pT > 45 GeV
  - 2 jets with pT > 30 GeV
    + 2 jets with pT > 90 GeV
- 2017(2018) :
  - 4 jets with
    pT > 40,45,60,75 GeV
  - HT > 300 (330) GeV

Offline :
- Jets :
  - |η| < 2.4 (2.5)
  - pT > 30 (40) GeV
  - Pileup ID when pT < 50 GeV
- DeepJet
  - Medium WP : 75 % b-jet efficiency
    1(10) % mistag for gluons (charm)
  - Tight WP : 58 % b-jet efficiency
    0.1(2) % mistag for gluons (charm)

B-jet energy regression arXiv:1912.06046
DNN trained on tt events,
evaluated on Z+H→ llbb





Application :

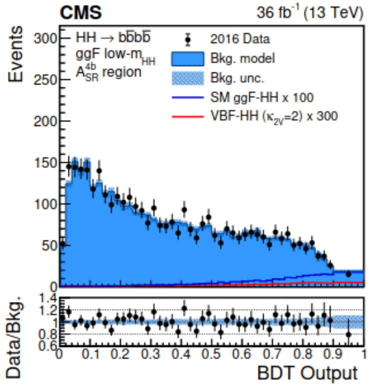
- SR (4b) QCD estimation using SR (3b) data
$$A_{SR}^{3b} \rightarrow A_{SR}^{4b}$$
- Scaling the number of events using the TF in the CR
$$\mathrm{TF} = A_{CR}^{4b}/A_{CR}^{3b}$$
TF dependence in the mass plane parameterised by
$$m_{||}$$
- BDT-reweighting used to model differences between 3b and 4b regions,
→ trained on CR, applied on SR
→ For each GGF and VBF categories

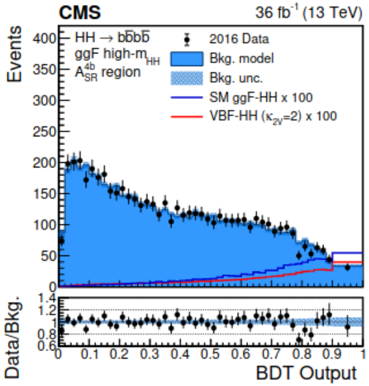
Validation :

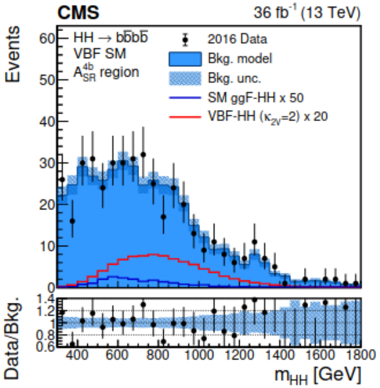
- Depleted signal region V
- Same method applied
→ Found good agreement between estimation and
$$V_{SR}^{4b}$$

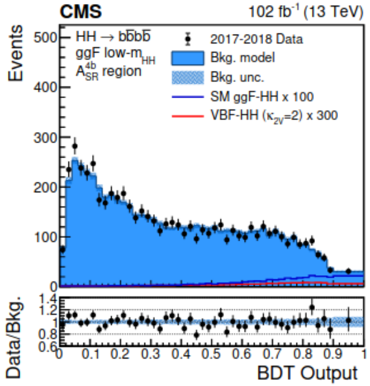
HH→bbbb (resolved)

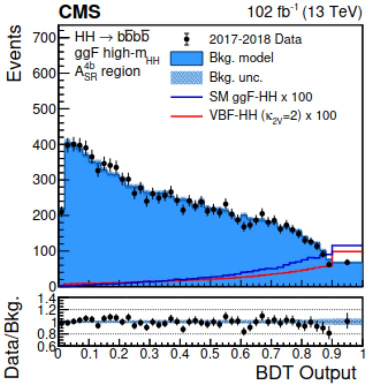
arXiv:2202.09617

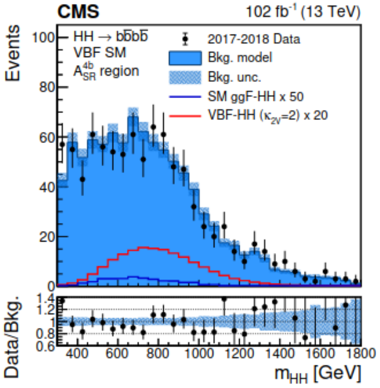


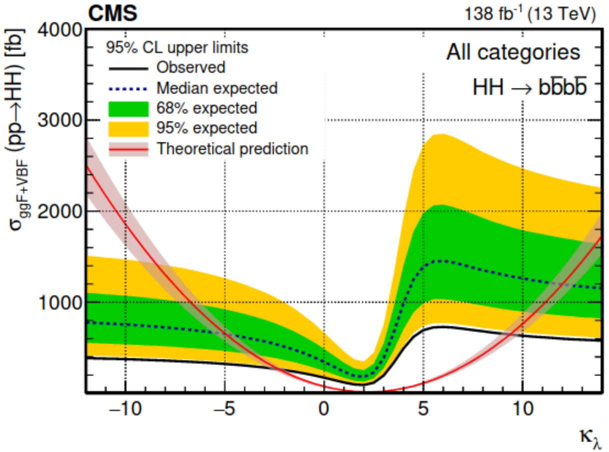


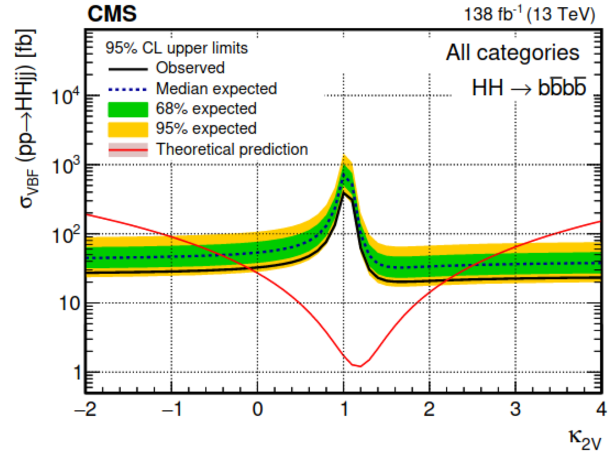








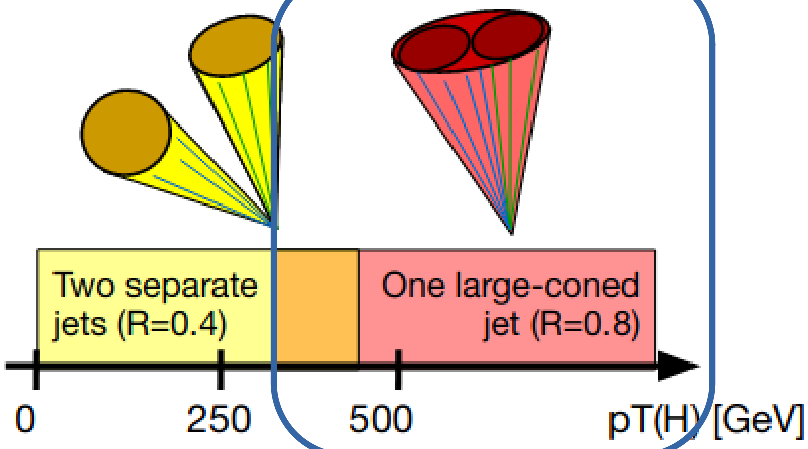




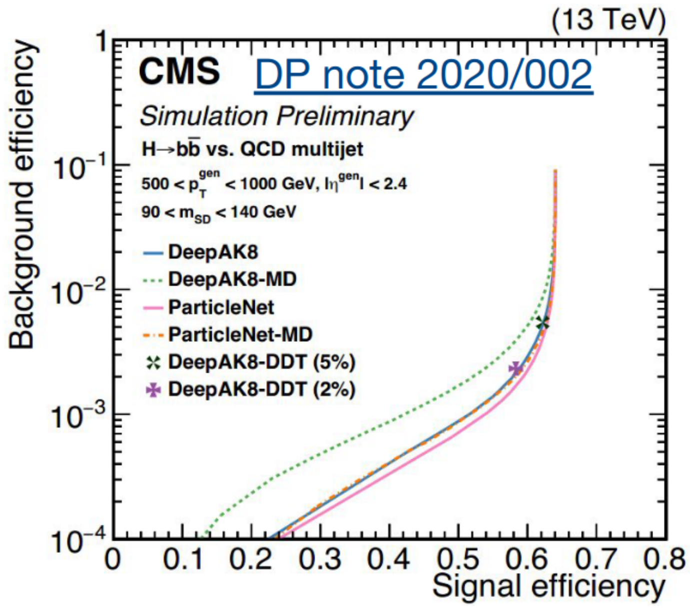
Trigger strategy

Several single-jet + HT triggers :

- Requirements :
  HT, jet pT,
  trimmed mass & double b-tagging
- Fully efficient for jet pT > 500 GeV



B-tagging



AK8 jet tagger : ParticleNet

- Graph neural network
- Mass-decorrelated
- 0.1 % bkg eff at 50 % signal eff

+ jet mass regression

Discriminant score : D_{bb}

Event selection

Preselection

> 2 AK8 jets with pT>300 GeV (central)

HH selection

pT, ΔΦ & Δη requirements

$D_{bb} > 0.9 \quad 50 < m_{reg} < 200 \quad \text{GeV}$

VBF-like?

No → **GGF cat**

$D_{bb}^{j_1} > D_{bb}^{j_2}$
$D_{bb}^{j_1} > 0.8$
$m_{reg}^{j2} > 50$ GeV

BDT GGF vs QCD +tt

GGF Cat 1 | **GGF Cat 2** | **GGF Cat 3**

BDT + j2 Dbb based categories

j2 reg variable in fit

Yes → **VBF cat**

VBF selection : Two forward jets

$m_{jj} = 500$ GeV
$\Delta\eta_{jj} > 4$

D_{bb} classification

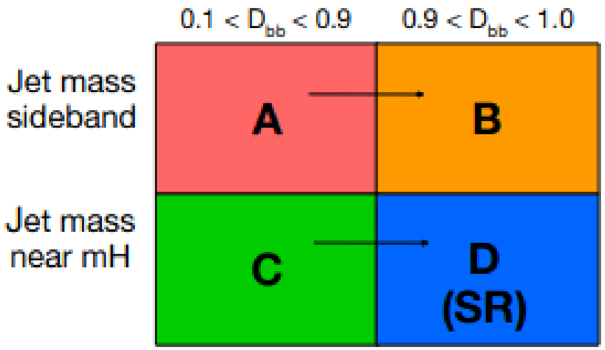
VBF HP | **VBF MP** | **VBF LP**

High, medium, low purity categories

mHH variable in fit

Background estimation

QCD multijet



Alphabet (ABCD) Method

Model D = C x TF

TF computed from A and B

VBF categories

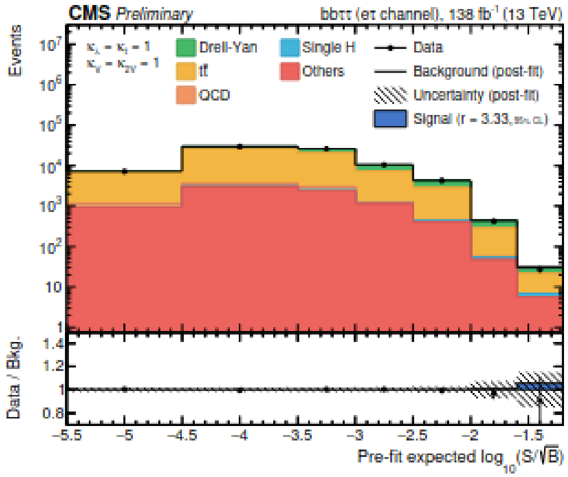
GGF categories

- Parametric alphabet method
- Regions defined by BDT score and j2 Dbb score
- TF parameterized as j2 mreg

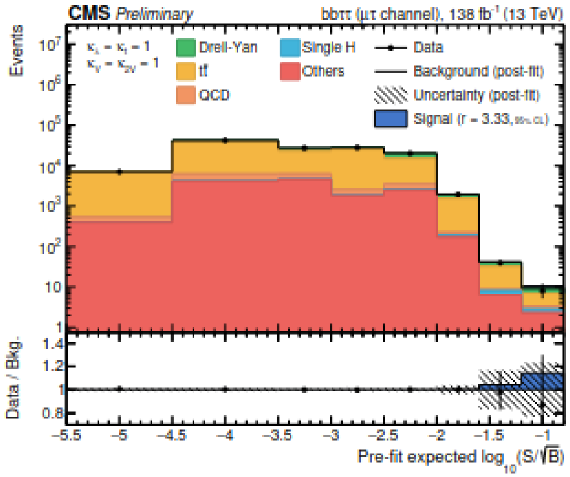
tt + minor backgrounds : MC + corrections

Table 1: Summary of selections applied to the $\tau\tau$ pair. Trigger thresholds in parentheses refer to the 2017–2018 data-taking period.

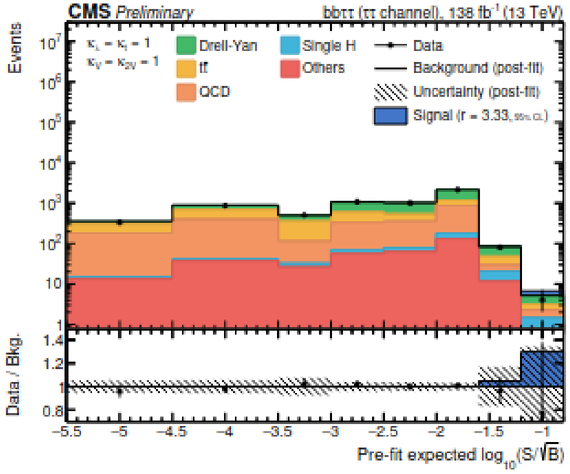
Online p_{T} trigger thresholds	single-e: $p_{\mathrm{T}} > 25(32)$ GeV, cross-e: $p_{\mathrm{T}} > 24$ GeV single-μ: $p_{\mathrm{T}} > 22(24)$ GeV, cross-μ: $p_{\mathrm{T}} > 19(20)$ GeV di-tau: $p_{\mathrm{T}} > 35$ GeV, di-tau VBF: $p_{\mathrm{T}} > 20$ GeV
Offline p_{T} thresholds	1 GeV (electrons and muons), 5 GeV (taus)
η thresholds	electrons and muons: $\lvert\eta\rvert < 2.1$ tau: $\lvert\eta\rvert < 2.1$ (2.3) for di-tau and cross (single) triggers
Lepton ID and Isolation	Tight electron MVA ID+Iso, Tight muon ID and Iso
τ_{h} isolation ($\tau_{\mathrm{e}}\tau_{\mathrm{h}}$, $\tau_{\mu}\tau_{\mathrm{h}}$ channels)	Medium DeepTauVsJet Tight DeepTauVsMu Very-loose DeepTauVsEle
τ_{h} isolation ($\tau_{\mathrm{h}}\tau_{\mathrm{h}}$ channel)	Medium DeepTauVsJet Very-loose DeepTauVsMu Very-very-loose DeepTauVsEle
Distance to PV	$\lvert d_{xy}\rvert < 0.045$ cm (electrons and muons only) $\lvert d_z\rvert < 0.2$ cm
Pair selections	opposite sign, $\Delta R > 0.5$



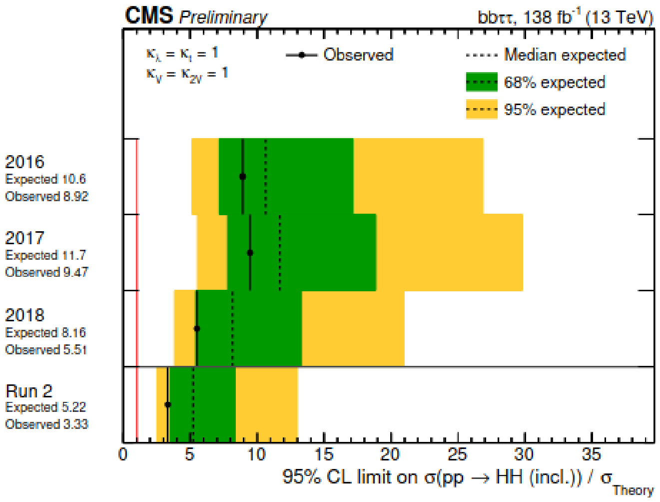
CMS Preliminary
bbττ (eτ channel), 138 fb-1 (13 TeV)
Drell-Yan
Single H
Data
tt
Others
Background (post-fit)
QCD
Uncertainty (post-fit)
Signal (r = 3.33, 95% CL)
Events
Data / Bkg.
Pre-fit expected log10(S/√B)



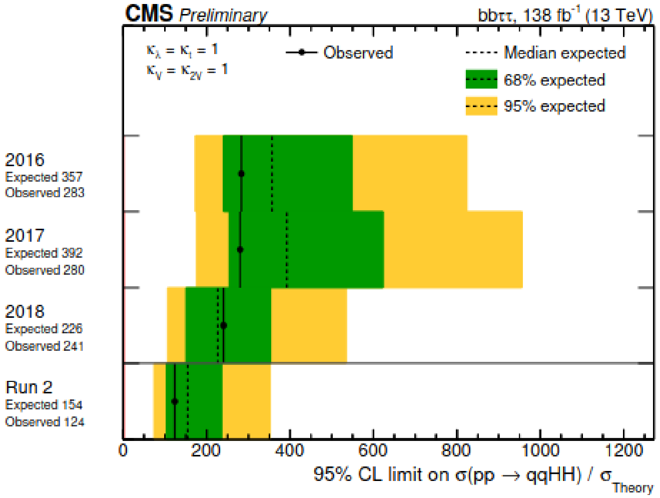
CMS Preliminary
bbττ (μτ channel), 138 fb-1 (13 TeV)
Drell-Yan
Single H
Data
tt
Others
Background (post-fit)
QCD
Uncertainty (post-fit)
Signal (r = 3.33, 95% CL)
Events
Data / Bkg.
Pre-fit expected log10(S/√B)



CMS Preliminary
bbττ (ττ channel), 138 fb-1 (13 TeV)
Drell-Yan
Single H
Data
tt
Others
Background (post-fit)
QCD
Uncertainty (post-fit)
Signal (r = 3.33, 95% CL)
Events
Data / Bkg.
Pre-fit expected log10(S/√B)



CMS Preliminary
bbττ, 138 fb-1 (13 TeV)
κλ = κt = 1
κV = κ2V = 1
Observed
Median expected
68% expected
95% expected
2016
Expected 10.6
Observed 8.92
2017
Expected 11.7
Observed 9.47
2018
Expected 8.16
Observed 5.51
Run 2
Expected 5.22
Observed 3.33
95% CL limit on σ(pp → HH (incl.)) / σTheory



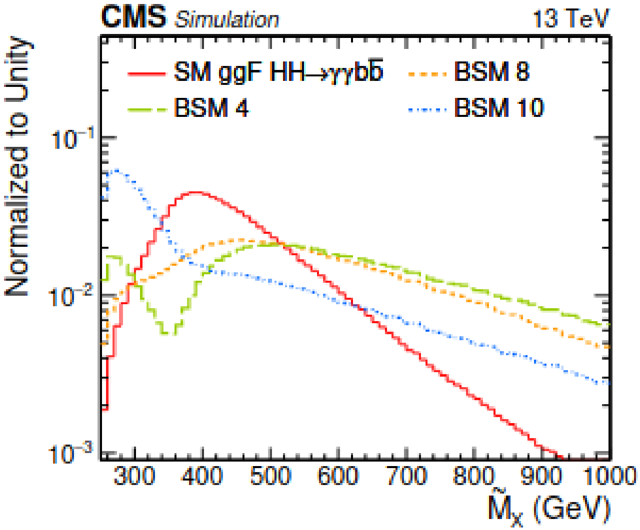
CMS Preliminary
bbττ, 138 fb-1 (13 TeV)
κλ = κt = 1
κV = κ2V = 1
Observed
Median expected
68% expected
95% expected
2016
Expected 357
Observed 283
2017
Expected 392
Observed 280
2018
Expected 226
Observed 241
Run 2
Expected 154
Observed 124
95% CL limit on σ(pp → qqHH) / σTheory

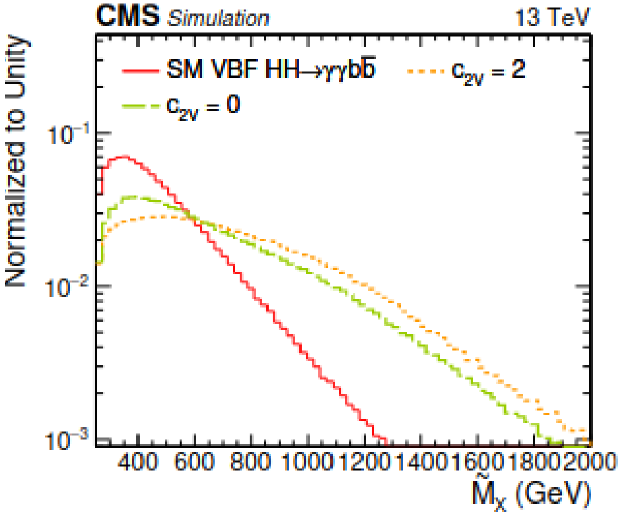
$\widetilde{M}_X$

- Dijet-diphoton mass very sensitive to anomalous couplings

$$\widetilde{M}_X = m_{\gamma\gamma jj} - (m_{jj} - m_H) - (m_{\gamma\gamma} - m_H)$$

- Less dependent on dijet and diphoton resolutions



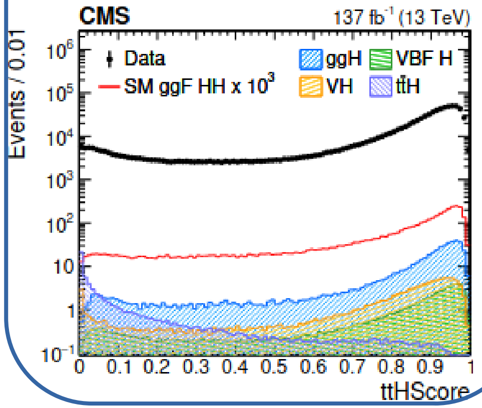


Category	MVA	$\widetilde{M}_X$ (GeV)
VBF CAT 0	0.52–1.00	>500
VBF CAT 1	0.86–1.00	250–500
ggF CAT 0	0.78–1.00	>600
ggF CAT 1		510–600
ggF CAT 2		385–510
ggF CAT 3		250–385
ggF CAT 4	0.62–0.78	>540
ggF CAT 5		360–540
ggF CAT 6		330–360
ggF CAT 7		250–330
ggF CAT 8	0.37–0.62	>585
ggF CAT 9		375–585
ggF CAT 10		330–375
ggF CAT 11		250–330

ttH rejection

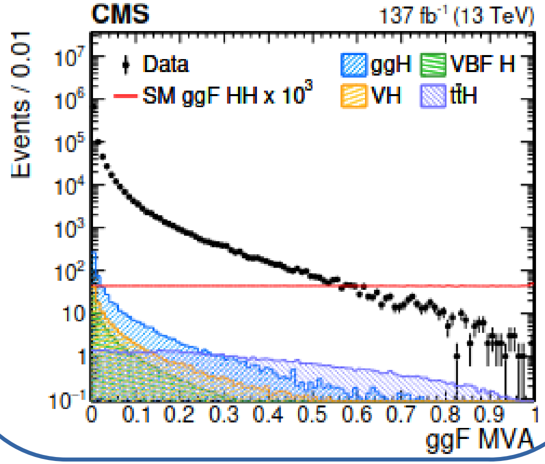
- ttH major resonant background in high purity regions
- ttHScore → classifying DNN
- Angular and discrimination from W boson decays variables
- ttHScore > 0.26 for GGF (VBF) categories

  → 80 (85) % ttH rejection
  → 95 (90) % HH efficiency



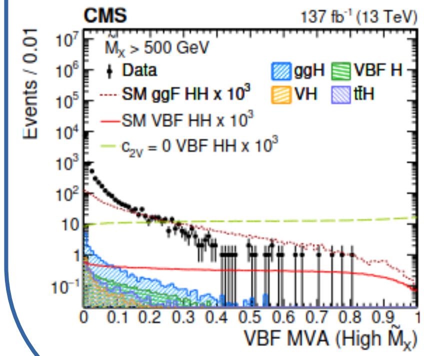
GGF classification

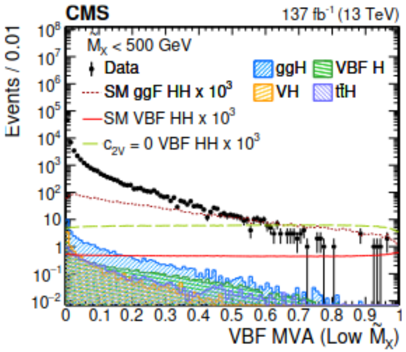
- Multiclass BDT trained between GGF bbɣɣ (mixture of SM+ BSM), ɣ+jets and ɣɣ+jets (MC)
- Inputs :
  - Kinematic variables (dimensionless)
  - Object identification variables
  - Object resolution variables
- Signal events : inversely weighted by resolution



VBF classification

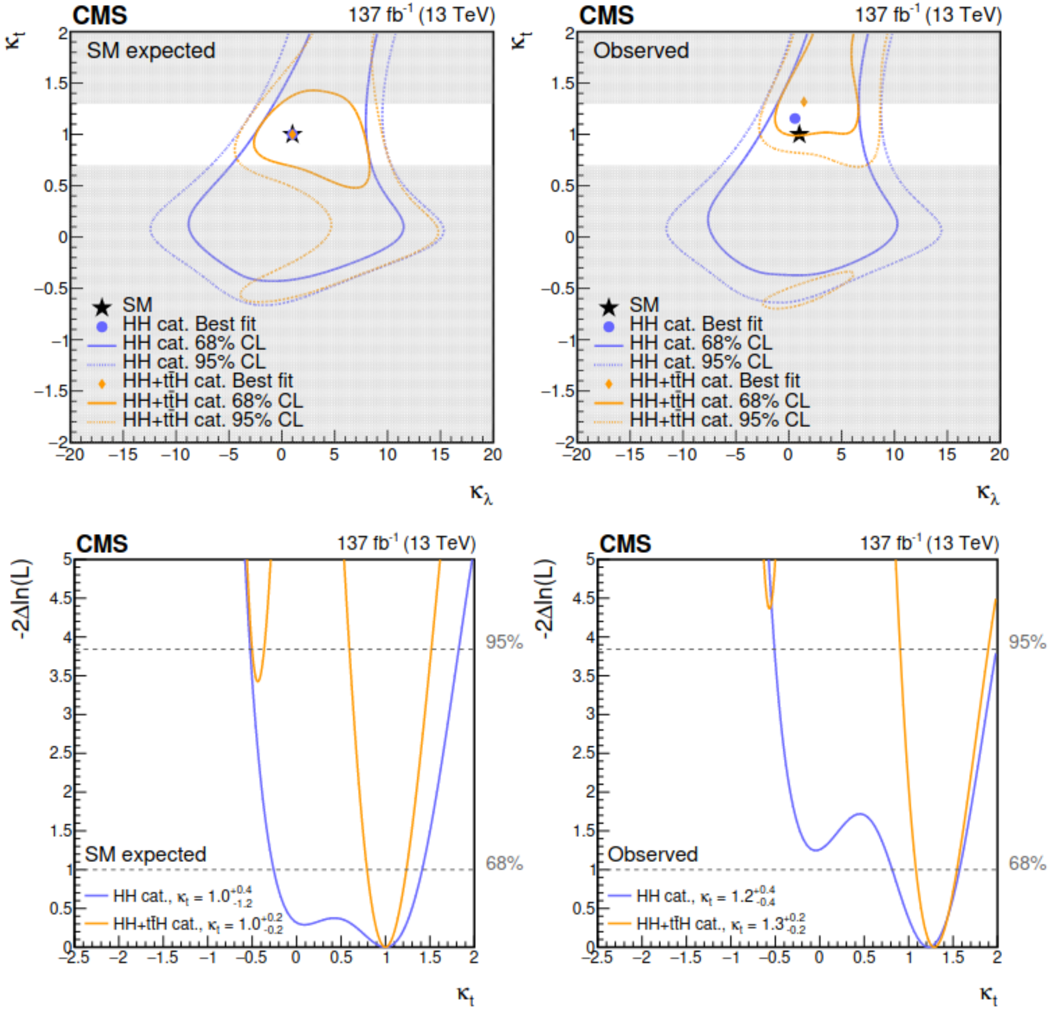
- Multiclass BDT trained between GGF (1/3 of events), VBF and ɣ(ɣ) + jets (MC)
- Inputs :
  - VBF features of the two forward jets : kinematic + angular
  - HH system variables
  - Centrality
- Signal events : inversely weighted by resolution
- One BDT for each of the 2 subcategories

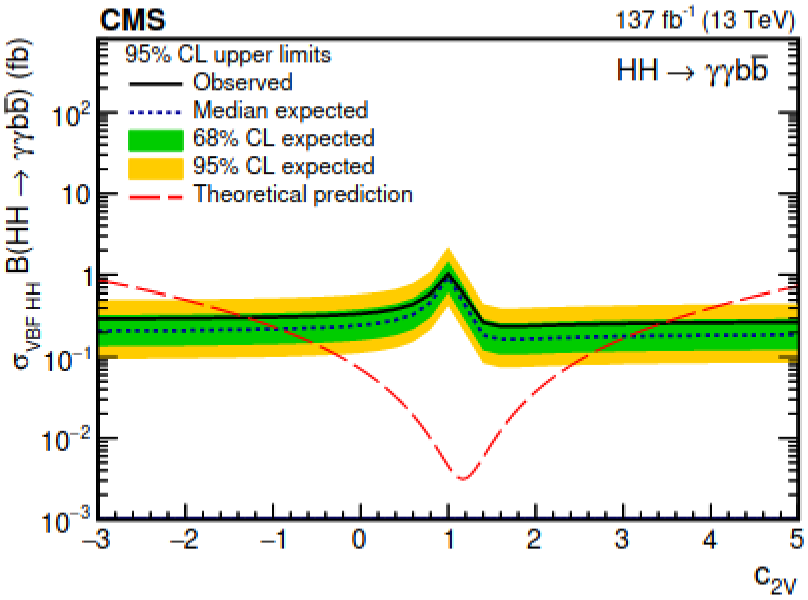




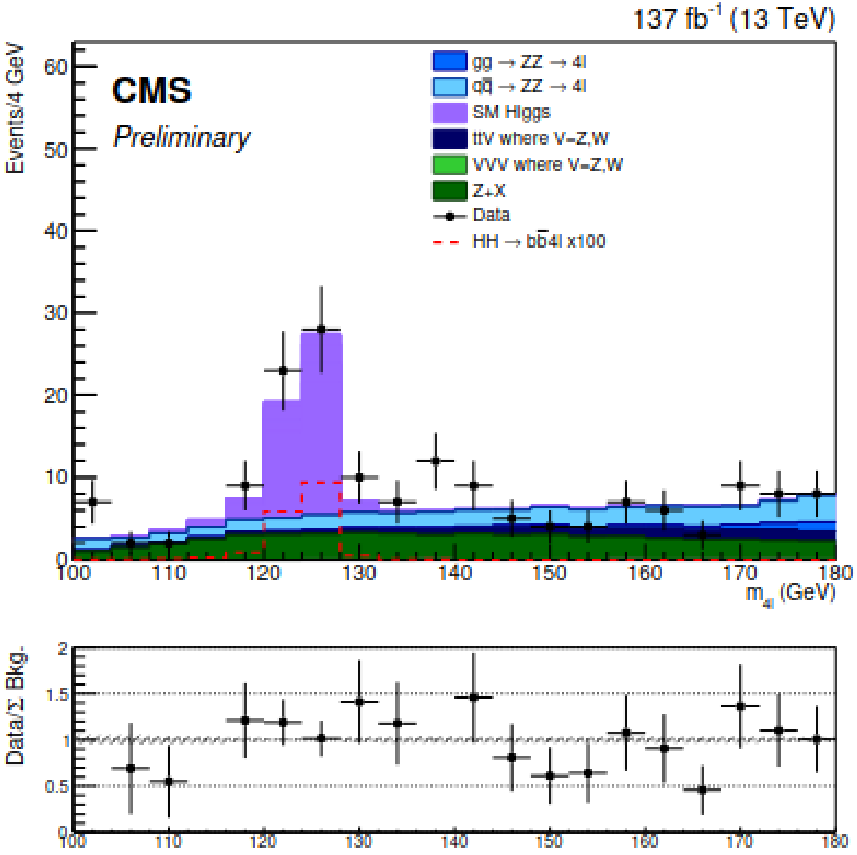
HH→bbɣɣ

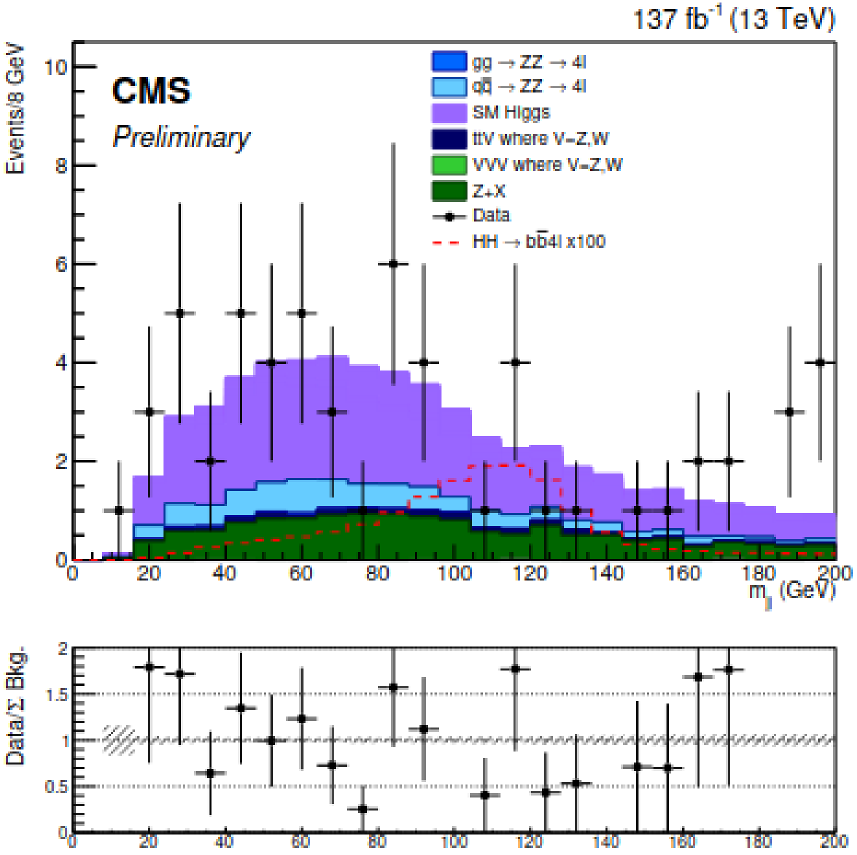
JHEP03(2021)257





arXiv:2206.10657





Data-driven Z+X

- Probabilities for misidentification of electrons and muons

$$f_e \;/\; f_\mu$$

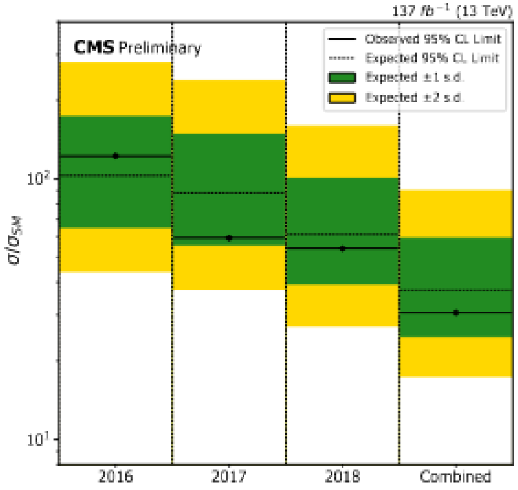
- Measured with Z(ll) + e/μ + jets events
- Tight requirement

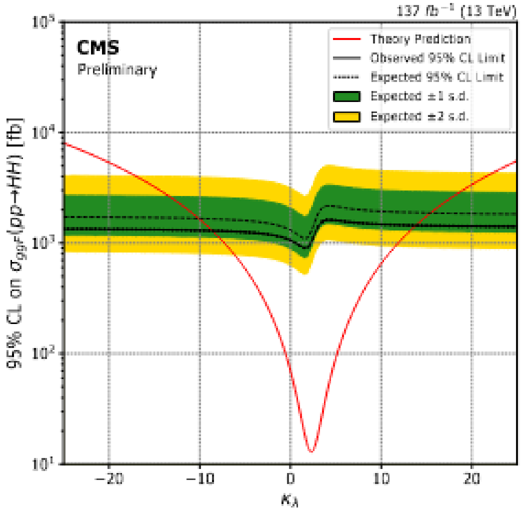
$$|M_{inv}(l_1 l_2) - M_Z| < \; 7 \text{ GeV}$$

- Misidentifications as bins of lepton pT

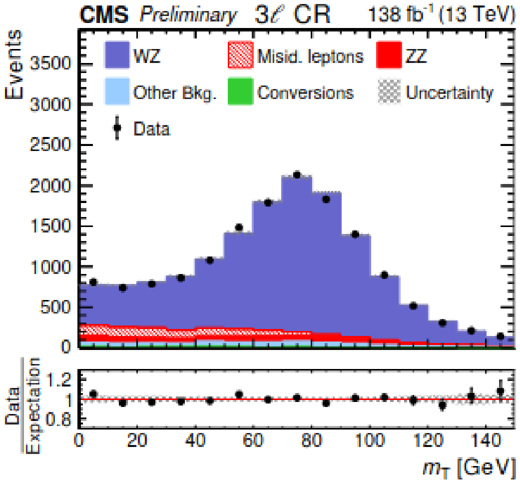
$$N_{SR}^{Z+X} = \Sigma \frac{f_i}{(1-f_i)}(N_{3P1F} - N_{3P1F}^{bkg} - N_{3P1F}^{ZZ}) + \Sigma \frac{f_i}{(1-f_i)} \frac{f_j}{(1-f_j)} N_{2P2F}$$

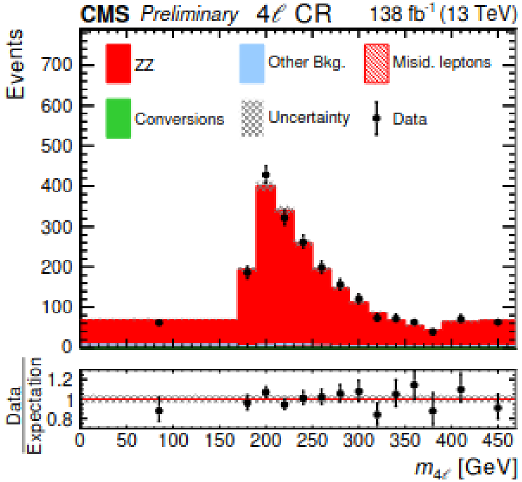
- N_{3P1F} and N_{2P2F} are observed number of events in the control regions Z + 2jets (additional pair of SF OS leptons)
  - 3P1F : one of the four leptons does not pass final selection
  - 2P2F : two leptons (not Z1) do not pass final selection





Trigger	Selection requirements for reconstructed e, μ, and τ_h objects
Single e	$p_T(e) > 27/32–35/32$ GeV (2016/17/18)
Single μ	$p_T(\mu) > 22–24/24–27/24$ GeV (2016/17/18)
Double e	$p_T(e) > 23, 12$ GeV
e + μ	$p_T(e) > 23$ GeV, $p_T(\mu) > 8$ GeV
μ + e	$p_T(\mu) > 23$ GeV, $p_T(e) > 8/12/12$ GeV (2016/17/18)
Double μ	$p_T(\mu) > 17, 8$ GeV
e + τ_h	$p_T(e) > 24$ GeV, $p_T(\tau_h) > 20–30/30/30$ GeV, $\lvert\eta(e, \tau_h)\rvert < 2.1$ (2016/17/18)
μ + τ_h	$p_T(\mu) > 19/20/20$ GeV, $p_T(\tau_h) > 20/27/27$ GeV, $\lvert\eta(\mu, \tau_h)\rvert < 2.1$ (16/17/18)
Double τ_h	$p_T(\tau_h) > 35–40, 35–40$ GeV, $\lvert\eta(\tau_h)\rvert < 2.1$
Triple e	$p_T(e) > 16, 12, 8$ GeV
Two e + μ	$p_T(e) > 12, 12$ GeV, $p_T(\mu) > 8$ GeV
Two μ + e	$p_T(\mu) > 9, 9$ GeV, $p_T(e) > 9$ GeV
Triple μ	$p_T(\mu) > 12, 10, 5$ GeV





HH→Multilepton

CMS-PAS-HIG-21-002

Misidentification background

- Misidentification probability for e,μ and τ_h

  $$f_i^l(p_T, \eta)$$

- Measured in Multijet events in Z→ μμ + jets

  → requiring 2 muons with $60 < M_{\mu\mu} < 120$ GeV

  → evaluate misidentification of jet as lepton/tau

- Applied as

  $$w = (-1)^{n+1} \prod_{i=1}^{n} \frac{f_i^{\ell}(p_{\mathrm{T}}, \eta)}{1 - f_i^{\ell}(p_{\mathrm{T}}, \eta)}$$

  → For both data and MC (subtracted)

Charge flip background

- Only necessary in 2lss category

  → N(2 leptons OS) >> N(2 leptons SS)

- Select events in the SR 2lss, except of the dilepton pair being OS

  → Weight applied to estimate charge flip bkg

- Probability measure in Z→ ee events

  (negligible for muons)