Double Higgs production at the LHC

Louis Portales (LLR, CNRS)
for the ATLAS & CMS collaborations
PANIC2021 – Lisbon (online) – 05/09/2021

HH production

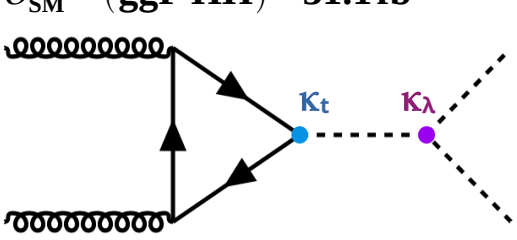
- **Non-resonant production**
  - Box & triangle diagrams destructive interference
    → **Small production cross-section**
  - Access to κ_t, κ_λ, κ_V, κ_{2V}
    → **Direct probe of Higgs potential**
    → **NP could appear as non-SM couplings**

Trilinear self-coupling (HH production)

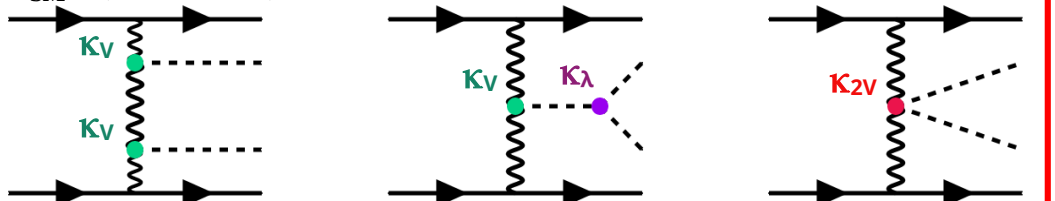
Quartic self-coupling Not (yet) accessible

$$V(H) = V_0 + \frac{1}{2} m_H^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4$$

$\sigma_{SM}^{NNLO}(\text{ggF HH}) = 31.1\,\text{fb}$



$\sigma_{SM}^{N^3LO}(\text{VBF HH}) = 1.73\,\text{fb}$



HH production

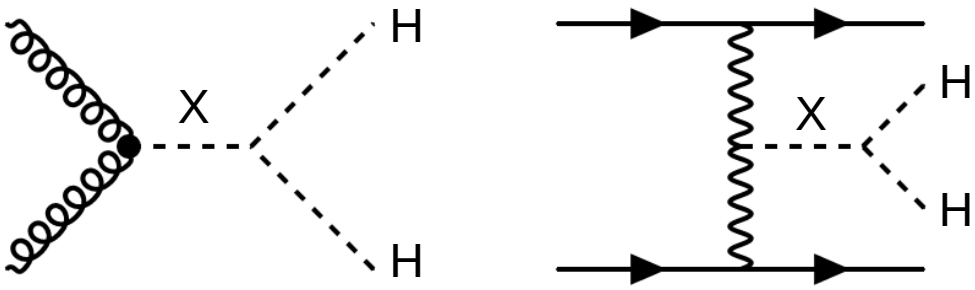
- **Non-resonant production**
  - Box & triangle diagrams destructive interference

    → **Small production cross-section**
  - Access to κ_t, κ_λ, κ_V, κ_{2V}

    → **Direct probe of Higgs potential**

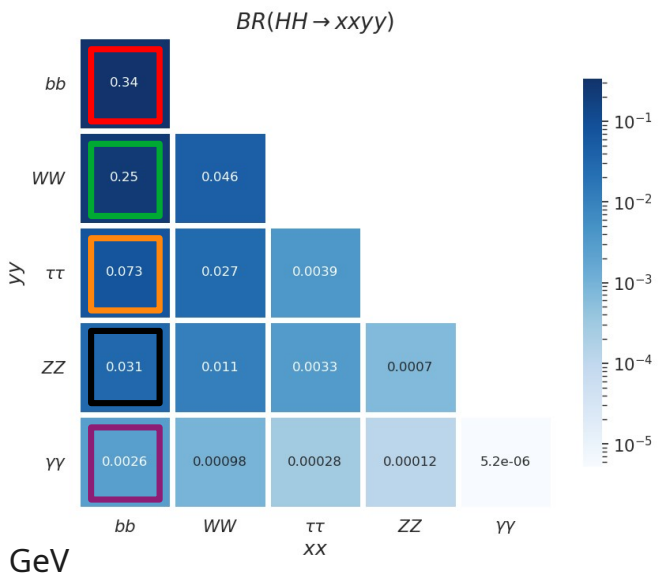
    → **NP could appear as non-SM couplings**
- **Resonant production**
  - Looking for bumps in m_{HH} distributions
  - Predicted by many BSM models

    → WED, HMSSM, 2HDM, …
  - Typically **spin-0/2 resonances** with m_X>250 GeV



HH production

- **Non-resonant production**
  - Box & triangle diagrams destructive interference
    → **Small production cross-section**
  - Access to κ_t, κ_λ, κ_V, κ_{2V}
    → **Direct probe of Higgs potential**
    → **NP could appear as non-SM couplings**
- **Resonant production**
  - Looking for bumps in m_{HH} distributions
  - Predicted by many BSM models
    → WED, HMSSM, 2HDM, …
  - Typically **spin-0/2 resonances** with $m_X \geq 250$ GeV
- **Final states**
  - Large variety, various branching ratios
    → Usually taking advantage of **large BR(H→bb)**



ATLAS
PLB 801 (2020) 135145 (non-res.)
ATLAS-CONF-2021-016 (res. + non-res.)
JHEP 11 (2020) 163 (boosted res.)
ATLAS-CONF-2021-030 (res.+non-res.)
JHEP 07 (2020) 108 (VBF res. + non-res.)
ATLAS-CONF-2021-035 (res.)
ATL-PHYS-PUB-2021-031 (summary plots)

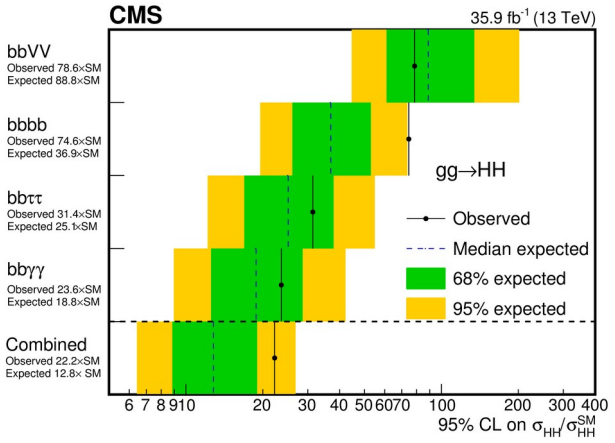
CMS
JHEP 03 (2021) 257 (non-res.)
HIG-20-014 (res. X→YH)
HIG-20-005 (resolved res.)
B2G-21-001 (boosted VBF non-res.)
B2G-20-004 (boosted res.)
SUS-20-004 (HH+MET)
HIG-20-004 (non-res.)
B2G-20-007 (res.)

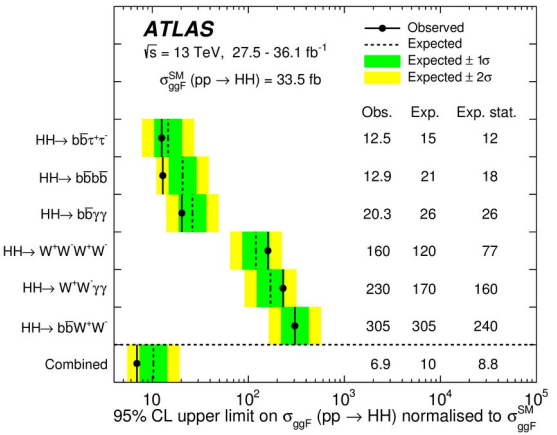
Mainly focusing on full Run-2 results

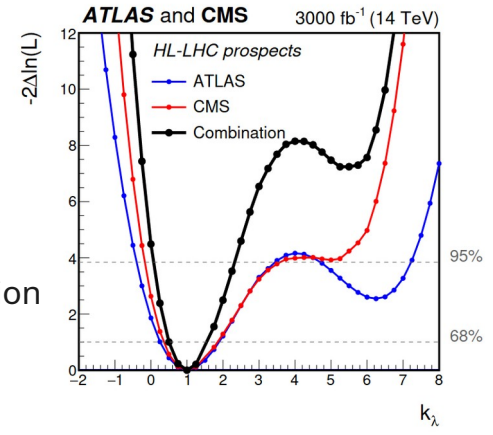
Combinations & prospects

ATLAS
PLB 800 (2020) 135103
CMS
PRL 122 (2019) 121803
HL-LHC
arXiv:1902.00134

- **36 fb^{-1} HH combinations**
  - **ATLAS**:
    - → 6 channels combined
    - → Leading channel: bbττ
  - **CMS**:
    - → 4 channels combined
    - → Leading channel: bbyy
  - Reached limit of ~10 times SM prediction
- **Extrapolation performed for HL-LHC**
  - Based on available 36 fb^{-1} results
  - Single-experiment and ATLAS+CMS combination
    - → Evidence expected, but no observation
    - → Exclusion of κ_λ=0 at 95% CL expected



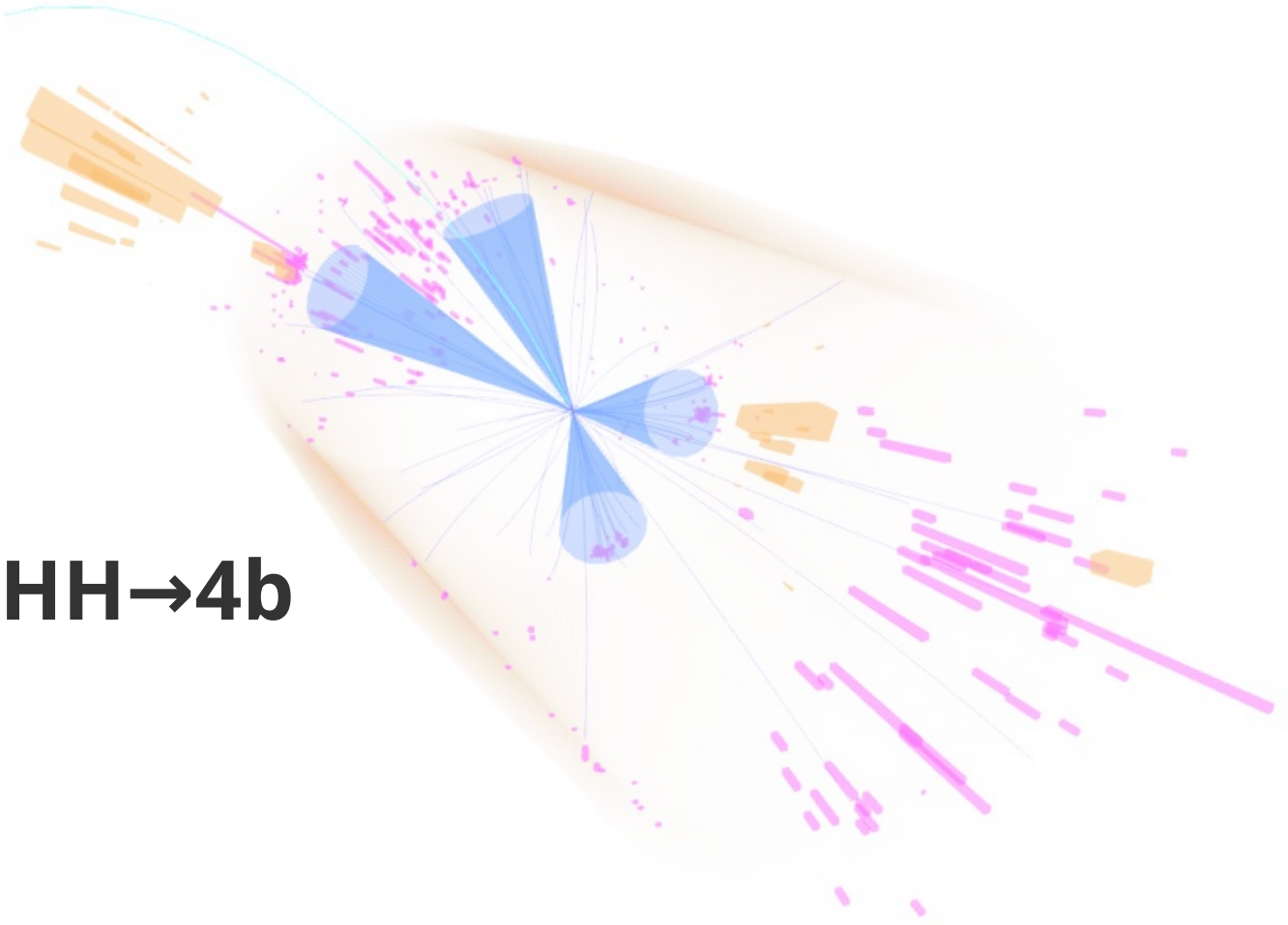




HL-LHC prospect (14 TeV, 3 ab^{-1})

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined		Combined	
	4.5		4.0	

HH→4b



ATLAS

PLB 801 (2020) 135145 (non-res.)
ATLAS-CONF-2021-016 (res. + non-res.)
JHEP 11 (2020) 163 (boosted res.)
ATLAS-CONF-2021-030 (res. + non-res.)
JHEP 07 (2020) 108 (VBF res. + non-res.)
ATLAS-CONF-2021-035 (res.)
ATL-PHYS-PUB-2021-031 (summary plots)

CMS

JHEP 03 (2021) 257 (non-res.)
HIG-20-014 (res. X→YH)
HIG-20-005 (resolved res.)
B2G-21-001 (boosted VBF non-res.)
B2G-20-004 (boosted res.)
SUS-20-004 (HH+MET)
HIG-20-004 (non-res.)
B2G-20-007 (res.)

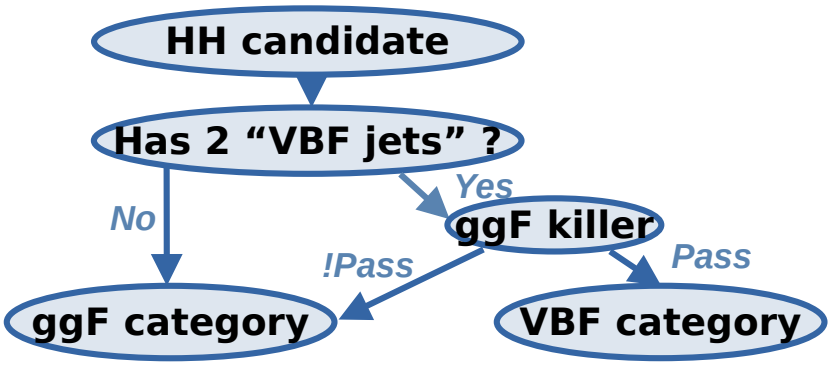
HH→4b – Non-resonant (resolved)

- **HH→ 4b**
  - ⊕ Larger HH BR (~34%)
  - ⊖ Large QCD background (multijet)
  - ⊖ Non-trivial combinatorics (b-jet pairing)

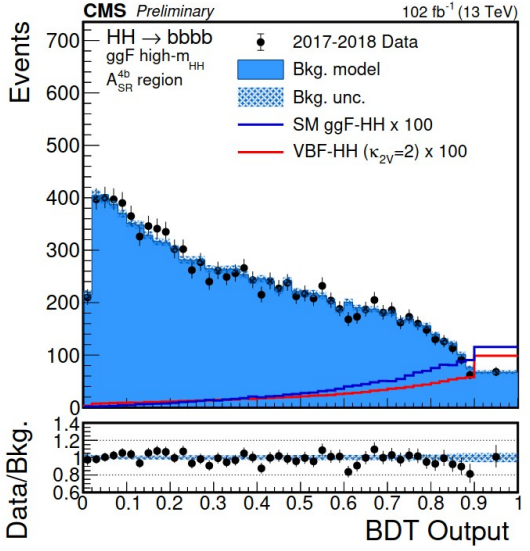
Data-driven estimate

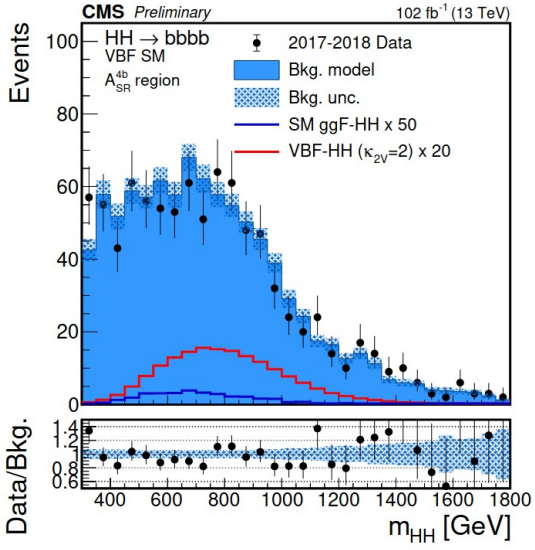
Distance-based pairing

$$d = \frac{|m_{H_1} - k m_{H_2}|}{(1+k^2)}$$



- **Resolved analysis**
  - ≥4 jets (3 b-tagged)
  - ggF/VBF categorisation
    - → BDT-based ("ggF-killer")
  - m_{HH} categories for ggF
    - → Dedicated BDT discriminant
  - ggF-killer categories for VBF
    - → m_{HH} used as discriminant





HH→4b – Non-resonant (resolved)

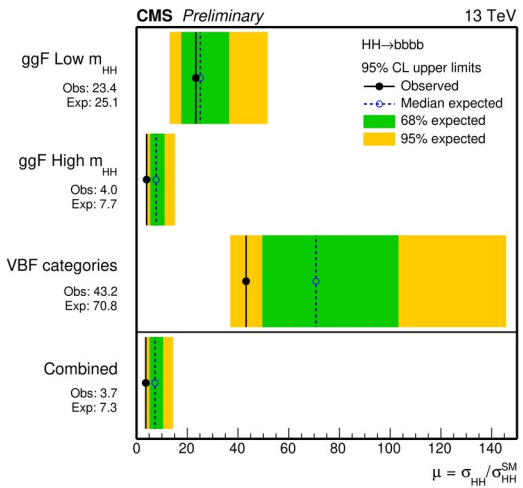
Observed (expected) 95% CL:

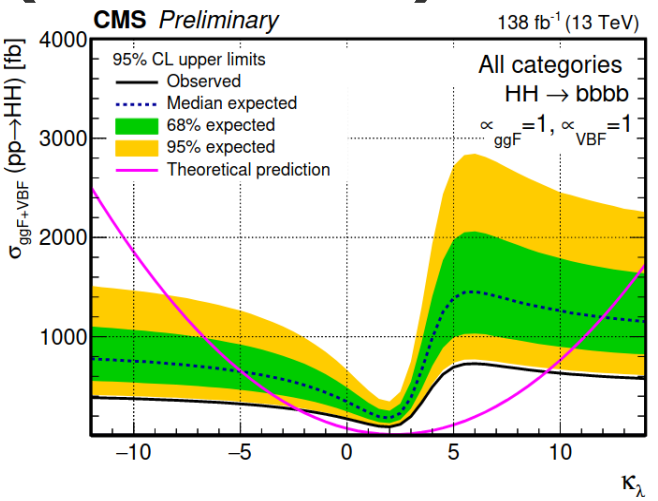
→ **σ(HH)** < 3.6 (7.3) σ_{SM}

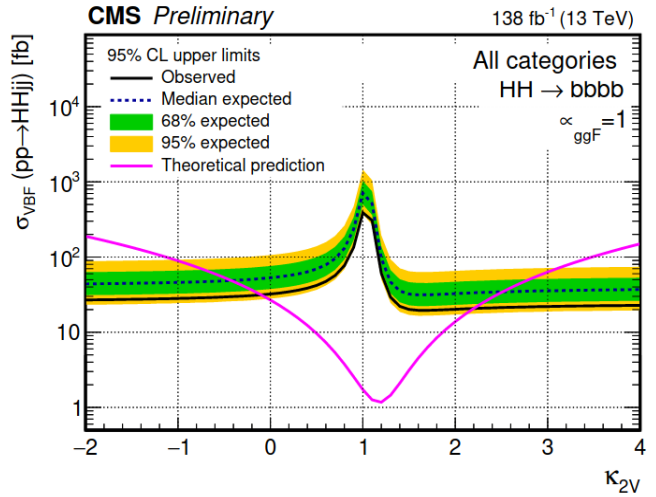
→ -2.3 < κ_λ < 9.4 (-5.0 < κ_λ < 12.0)

→ -0.1 < κ_{2V} < 2.2 (0.4 < κ_{2V} < 2.5)

~ 5x improvement w.r.t previous analysis !





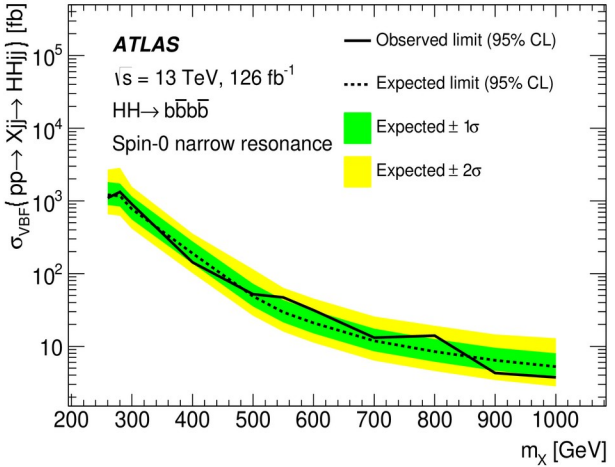


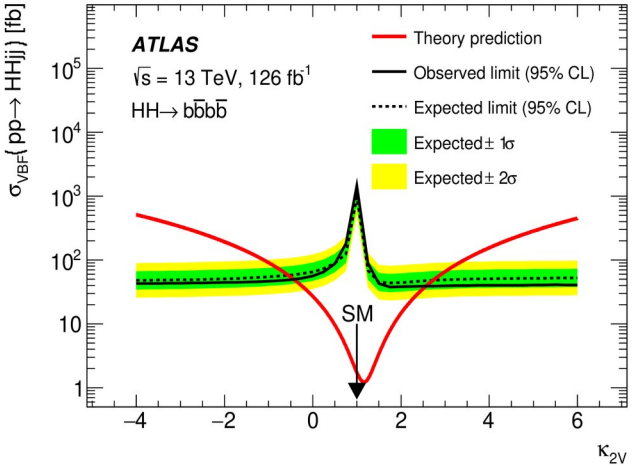
ATLAS
(JHEP 01 (2019) 030)
JHEP 07 (2020) 108

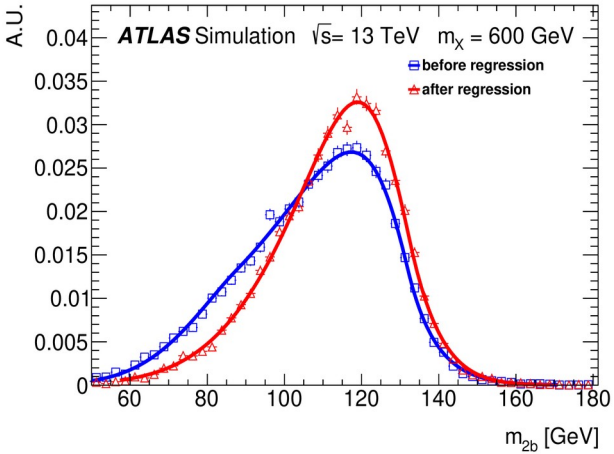
HH→4b – Resolved VBF

- **Based on partial Run 2 ggF analysis**
  - ≥4 b-jets
    → BDT-based identification
  - VBF specific: 2 opposite-η "VBF jets"
  - BDT-based b-jet energy regression
  - Main backgrounds:
    → QCD: Data-driven in side-band region
    → $t\bar{t}$: normalisation from data
  - Limit setting from fit on m_{HH}
    → Resonant: no significant excess
    max 1.5 σ local significance @ 550 GeV
  - → Non-resonant:

-0.43 < κ_{2V} < 2.56 (0.55 < κ_{2V} < 2.72) observed (expected)

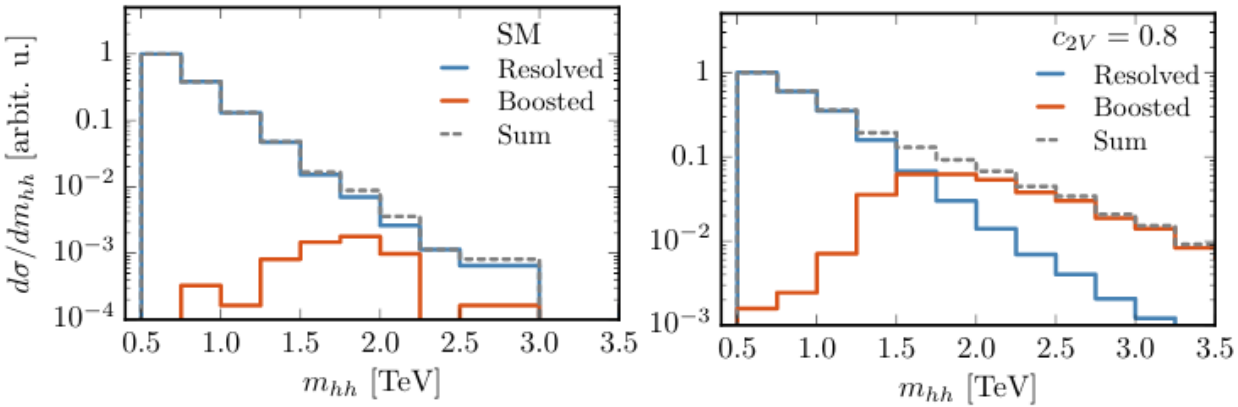




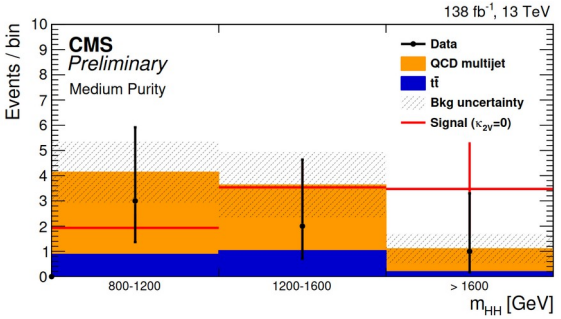


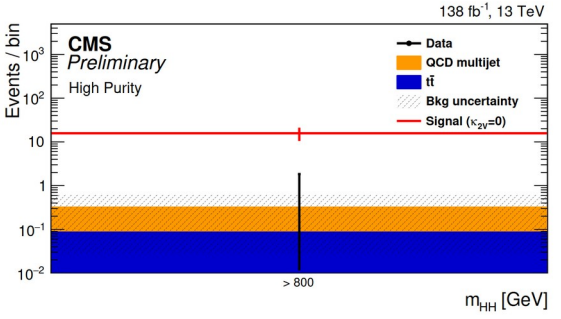
HH→4b – Non-resonant (boosted VBF)

Eur.Phys.J. C77 (2017) no.7, 481



- **Boosted VBF HH→bbbb**
  - **Boosted regime** → ***high sensitivity to*** κ_{2V}
  - High pT Higgs bosons → collimated decays
    - → 2 R=0.8 anti-k_T jets in final state
    - → No combinatorics issues
    - → Large **QCD background** (sideband estimate)
  - NN-based H→bb identification – ***ParticleNet***
    - → Multi-class ($b\bar{b}$, $c\bar{c}$, QCD) ***Graph neural network***
    - → $D_{bb} = \frac{P(H \to bb)}{P(H \to bb) + P(QCD)}$
    - → Used to define 3 purity-based categories
    - → Also used for **mass regression**



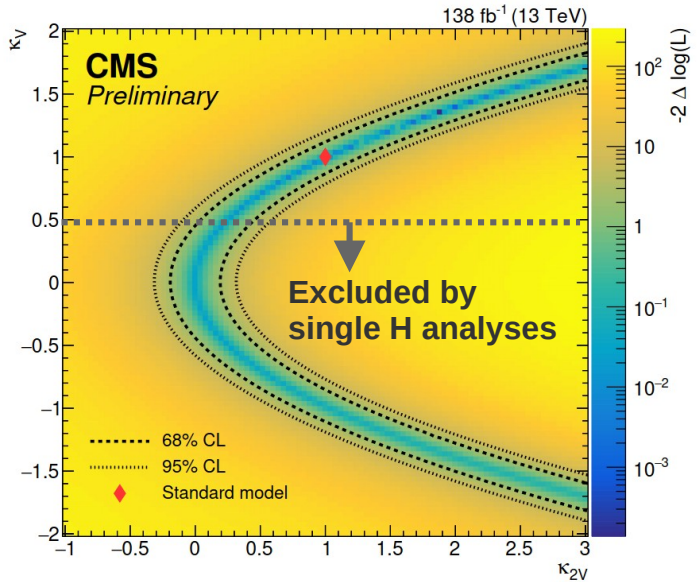


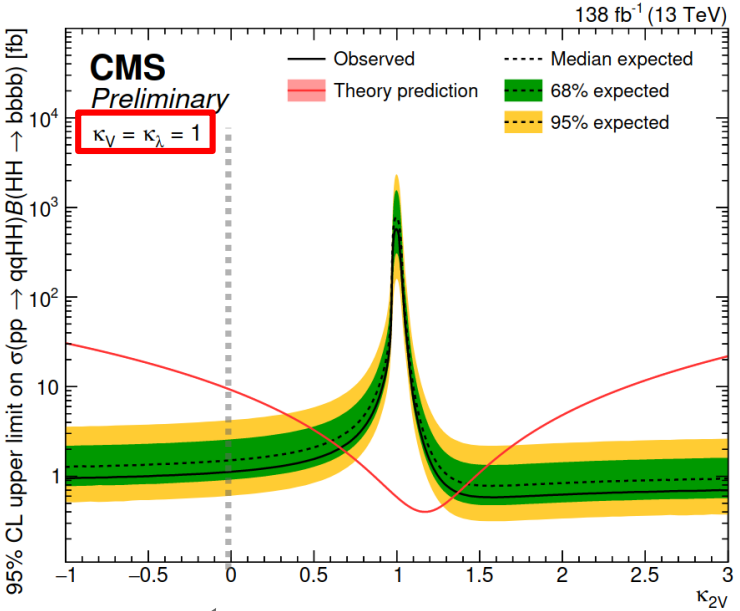
HH→4b – Non-resonant (boosted VBF)

Observed (expected) 95% CL:

→ $0.8 < |\kappa_V| < 1.2$ $(0.8 < |\kappa_V| < 1.2)$

→ $0.6 < \kappa_{2V} < 1.4$ $(0.6 < \kappa_{2V} < 1.4)$





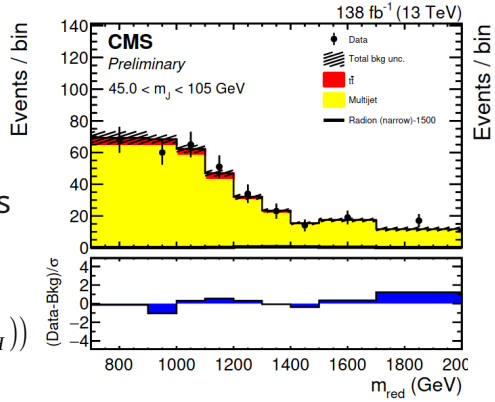
>99.99% CL exclusion !

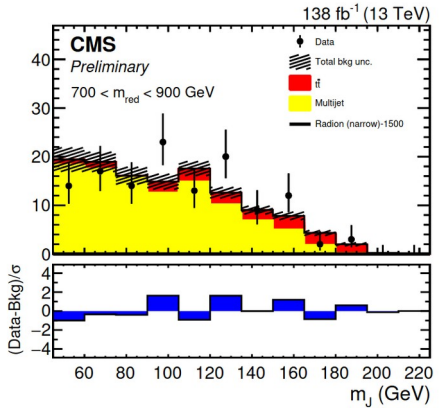
HH→4b – Resonant

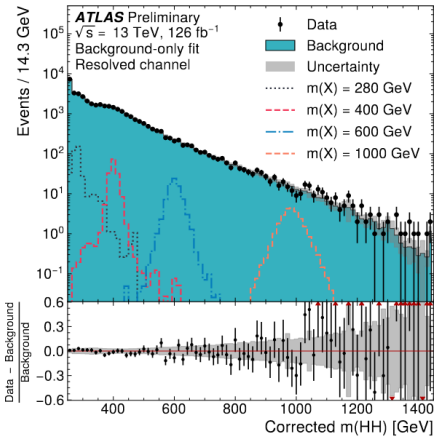
DeepAK8 JINST 15 (2020) P06005

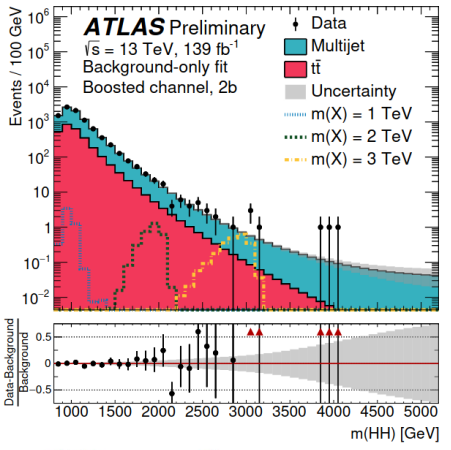
ATLAS
ATLAS-CONF-2021-035
CMS
B2G-20-004

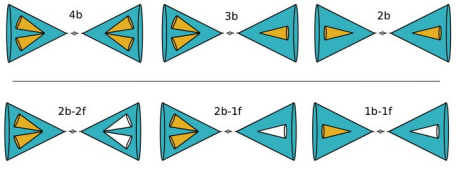
- **CMS: (Semi-)boosted**
  - 2 R=0.8 anti-k_T jets or 1 R=0.8 jet + 2 b-tagged R=0.4 jets
  - NN-based identification and categorisation – ***DeepAK8***
  - Limits from 2D fit: m_{J1} vs $m_{red}\left(=m_{JJ}-\left(m_{J1}-m_H\right)-\left(m_{J2}-m_H\right)\right)$
- **ATLAS: Resolved+boosted**
  - **Resolved analysis (250-1500 GeV)**
    - → 4 b-tagged R=0.4 jets (2 b-tag QCD CR)
    - → BDT-based H→bb pairing
    - → Elliptical mH1 vs mH2 cut (SR / QCD-CR)
  - **Boosted analysis (900-3000 GeV)**
    - → 2 R=1.0 jets (≥1 b-tagged)
    - → b-tagged based categorisation (+ elliptical mass cut)
  - Limits from m_{HH} fit (both Resolved & boosted)





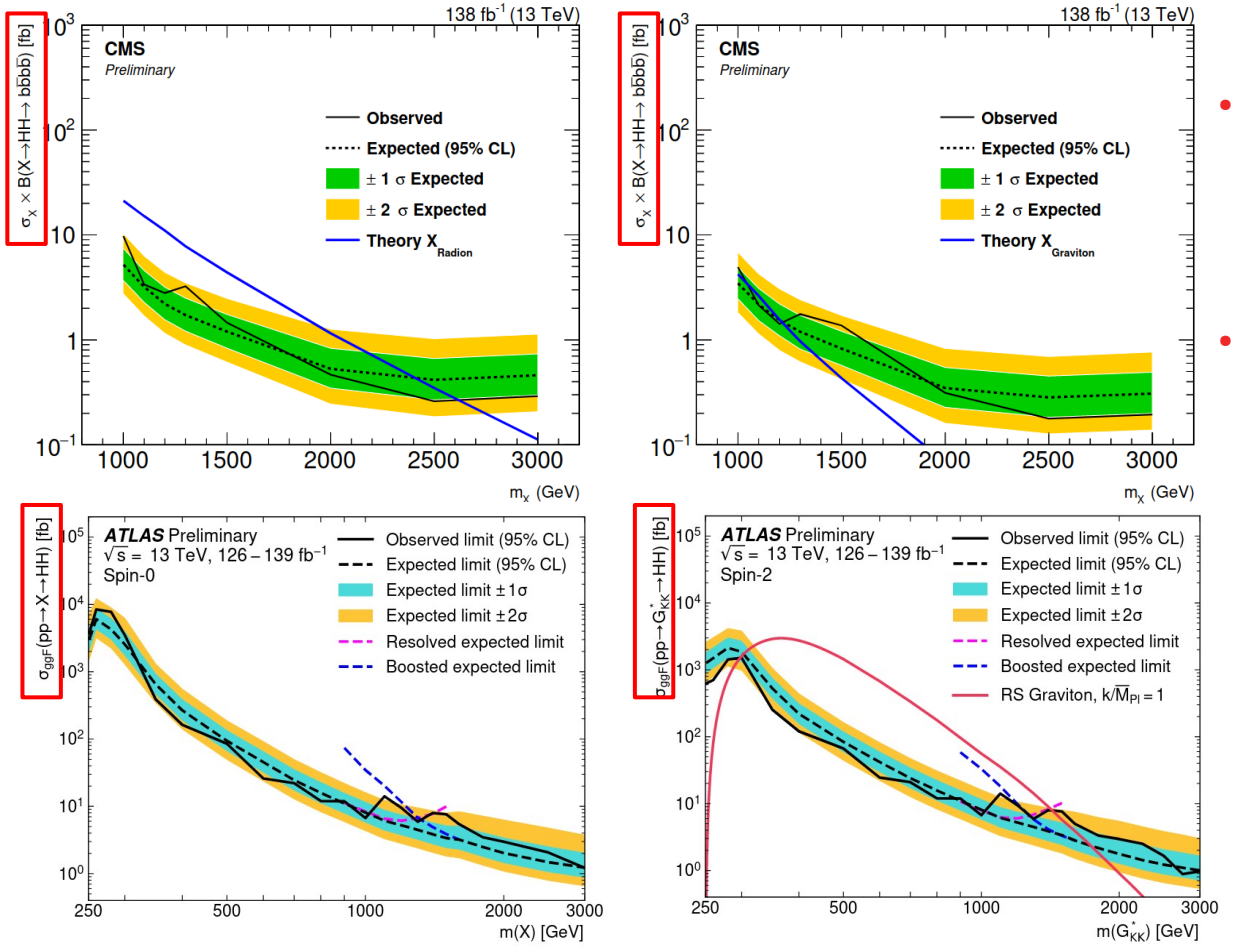






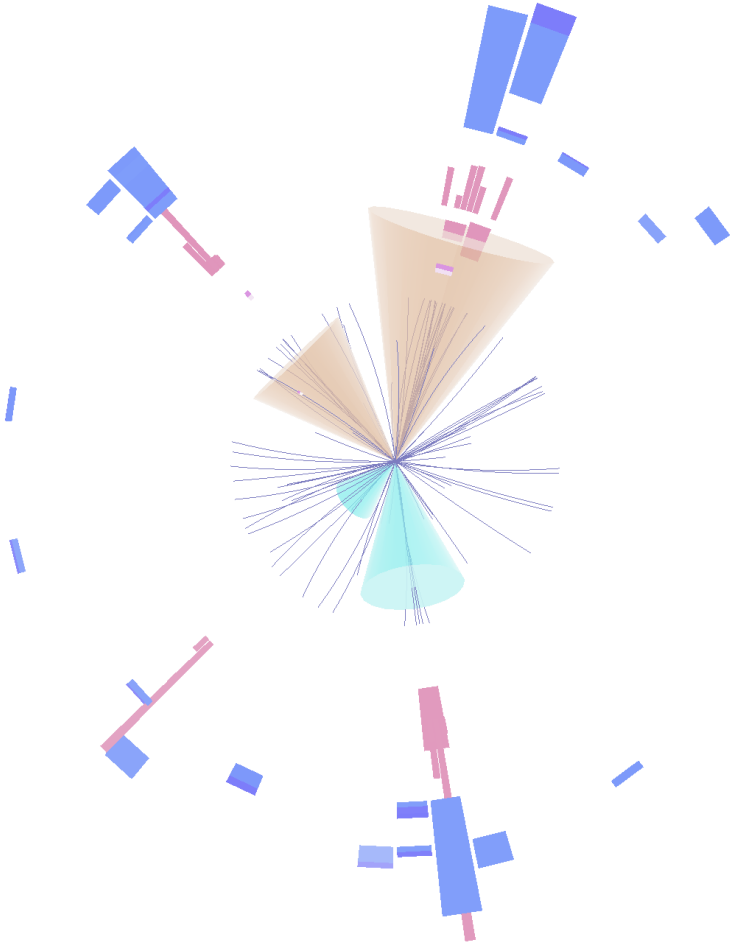
HH→4b – Resonant

ATLAS
ATLAS-CONF-2021-035
CMS
B2G-20-004



- **No significant excess**
  - ATLAS: max 2.6 σ (1.0 σ) local (global) (Spin 0)
    2.7 σ (1.2 σ) local (global) (Spin 2)
    @ 1.1 TeV
- **Comparable limits**
  - **CMS** spin-2 observed (expected):
    → σ x BR(X→HH) (3 TeV) ~ 0.58 (**0.88**) fb
    → σ x BR(X→HH) (1 TeV) ~ 14.7 (**8.8**) fb
  - **ATLAS** spin-2 observed (expected):
    → σ x BR(X→HH) (3 TeV) ~ 1.0 (**1.0**) fb
    → σ x BR(X→HH) (1 TeV) ~ 8.0 (**8.0**) fb

HH→bbττ



ATLAS

PLB 801 (2020) 135145 (non-res.)
ATLAS-CONF-2021-016 (res. + non-res.)
JHEP 11 (2020) 163 (boosted res.)
ATLAS-CONF-2021-030 (res. + non-res.)
JHEP 07 (2020) 108 (VBF res. + non-res.)
ATLAS-CONF-2021-035 (res.)
ATL-PHYS-PUB-2021-031 (summary plots)

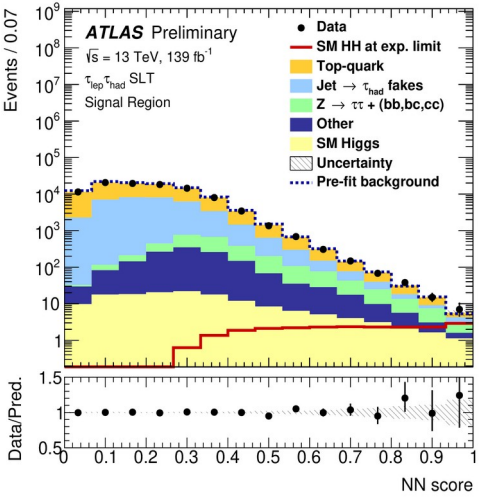
CMS

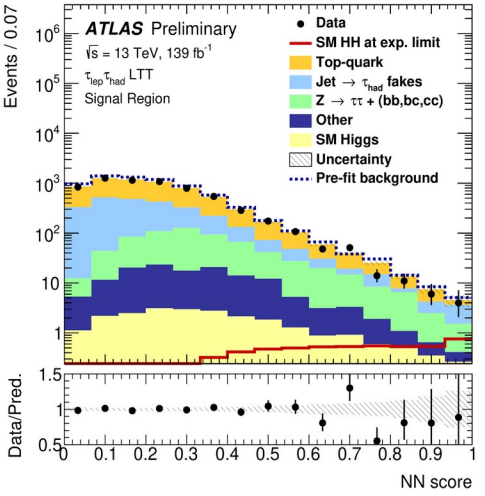
JHEP 03 (2021) 257 (non-res.)
HIG-20-014 (res. X→YH)
HIG-20-005 (resolved res.)
B2G-21-001 (boosted VBF non-res.)
B2G-20-004 (boosted res.)
SUS-20-004 (HH+MET)
HIG-20-004 (non-res.)
B2G-20-007 (res.)

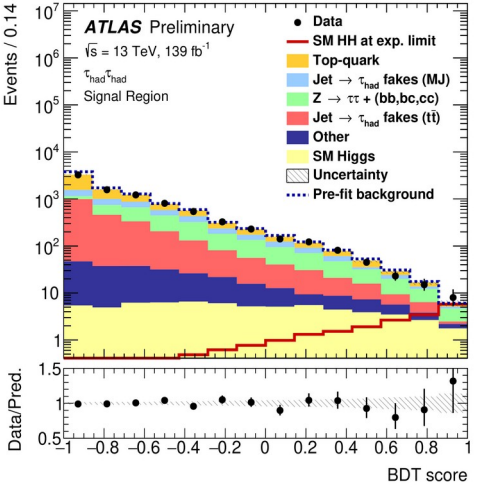
HH→bbττ – Resolved

- **HH→bbττ**
  - $\tau_{had}\tau_{had}$ + $\tau_{lep}\tau_{had}$ decays (lep = e,μ)
    → ~88% of all decays
  - Categorisation based on di-τ decay modes and triggers
    → $\tau_{had}\tau_{had}$: Single/di-τ_{had}
    → SLT $\tau_{lep}\tau_{had}$: Single-lepton triggers
    → LTT $\tau_{lep}\tau_{had}$: Lepton+τ_{had} triggers
  - Data-driven fake τ backgrounds ($t\bar{t}$, QCD) estimation
  - True τ backgrounds ($t\bar{t}$, Z+HF) normalisation from data
- **Non-resonant analysis**
  - BDT ($\tau_{had}\tau_{had}$) + DNNs ($\tau_{lep}\tau_{had}$) for signal extraction
  - **σ(ggF+VBF)** < 3.87 (4.65) **σ_{SM}**

~ 3x improvement w.r.t previous analysis ! (best limit to date)

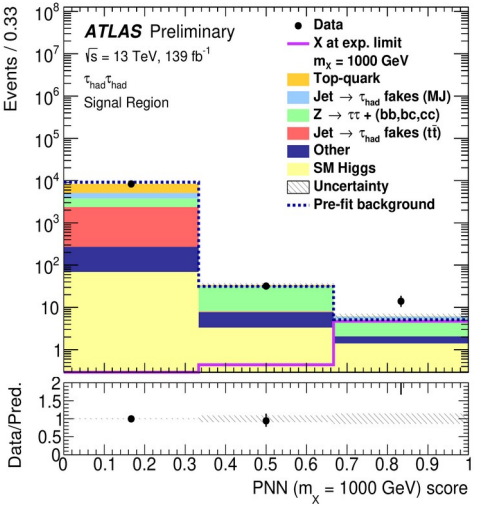


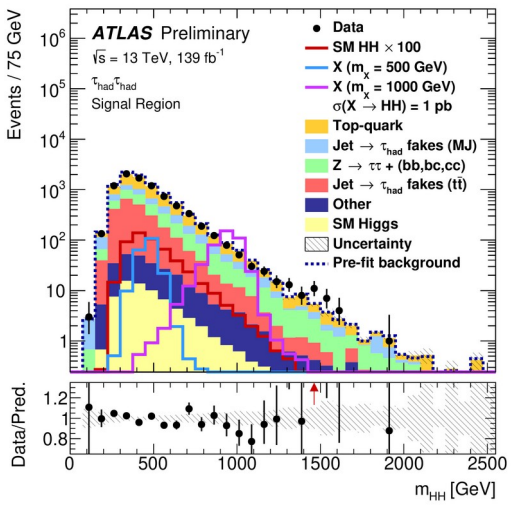


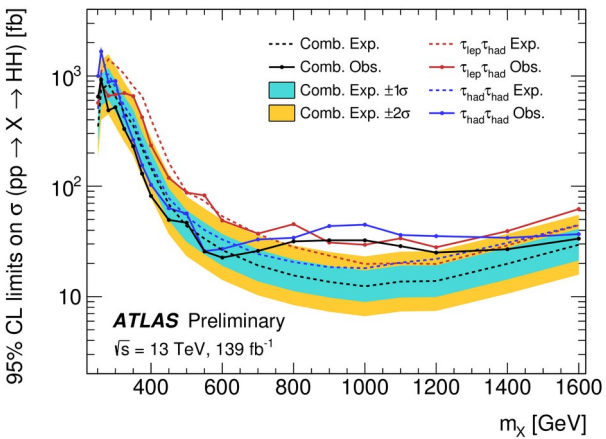


HH→bbττ – Resolved

- **HH→bbττ**
  - $\tau_{had}\tau_{had}$ + $\tau_{lep}\tau_{had}$ decays (lep = e,μ)
    → ~88% of all decays
  - Categorisation based on di-τ decay modes and triggers
    → $\tau_{had}\tau_{had}$: Single/di-τ_{had}
    → SLT $\tau_{lep}\tau_{had}$: Single-lepton triggers
    → LTT $\tau_{lep}\tau_{had}$: Lepton+τ_{had} triggers
  - Data-driven fake τ backgrounds ($t\bar{t}$, QCD) estimation
  - True τ backgrounds ($t\bar{t}$, Z+HF) normalisation from data
- **Resonant analysis**
  - Parametric (in m_X) NN for signal extraction
  - Largest excess @ 1 TeV: 3.1 σ (2.1 σ) local (global)

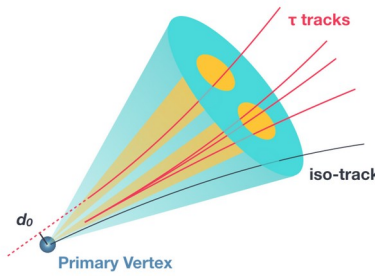


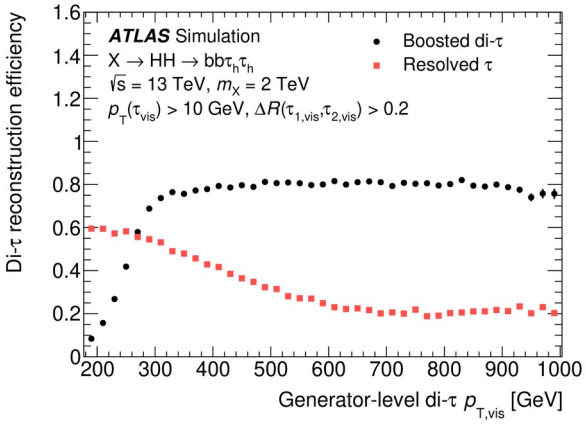


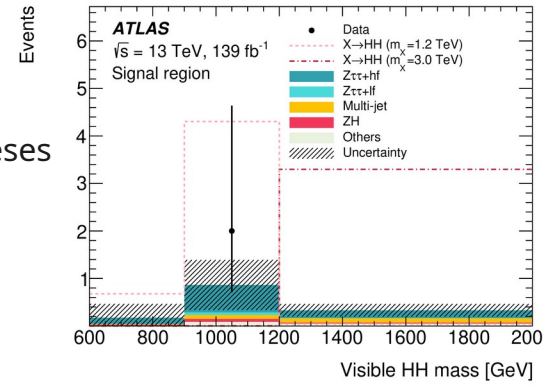


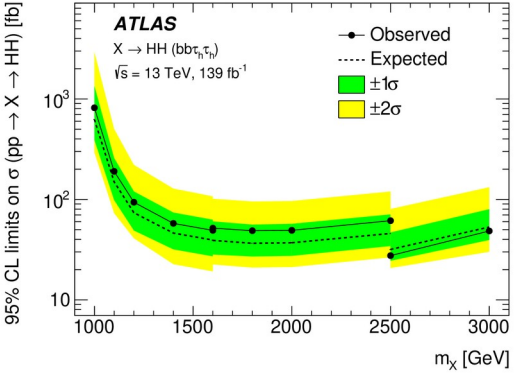
HH→bbττ – Boosted

- **High-mass resonant search**
  - Looking for boosted bb and $\tau_{had}\tau_{had}$ pairs
    - → bb: b-tagged R=1.0 jet
    - → $\tau_{had}\tau_{had}$: R=0.1 jet, R=0.2 sub-jets (dedicated reconstruction)
      BDT-based identification vs QCD jets
  - Data-driven QCD background estimate + di-τ tagger efficiency corrections
  - Limits from m_{HH} fit
    - → In signal region with $60<m_J<160$ GeV
    - → $m_{HH}^{vis}>900$ (1200) GeV for $m_X \geq 1.6$ (2.5) TeV hypotheses
    - → No significant excess found

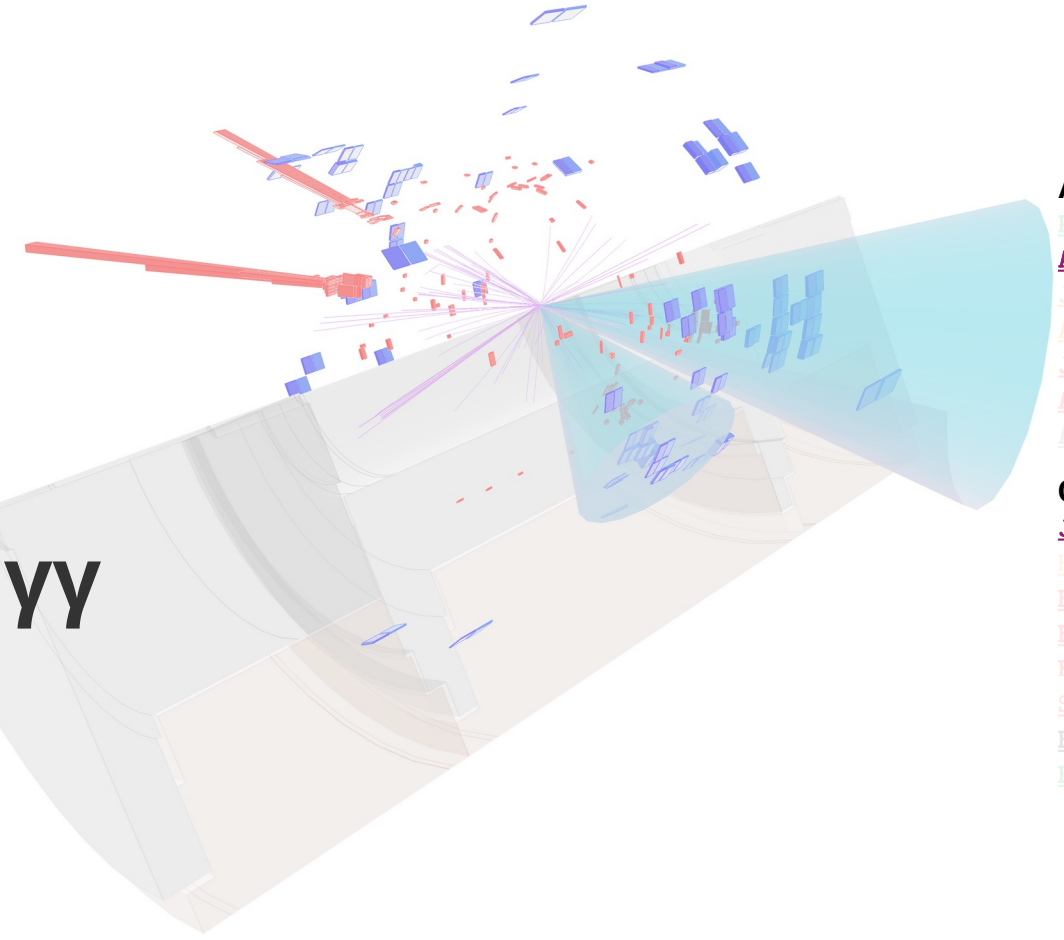








HH→bbyy



ATLAS

PLB 801 (2020) 135145 (non-res.)
ATLAS-CONF-2021-016 (res. + non-res.)
JHEP 11 (2020) 163 (boosted res.)
ATLAS-CONF-2021-030 (res. + non-res.)
JHEP 07 (2020) 108 (VBF res. + non-res.)
ATLAS-CONF-2021-035 (res.)
ATL-PHYS-PUB-2021-031 (summary plots)

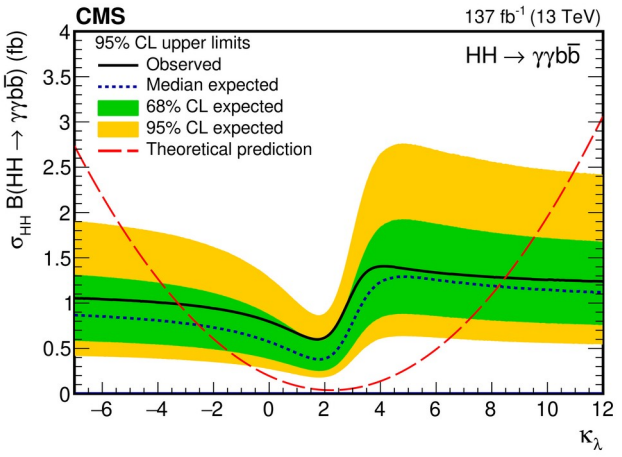
CMS

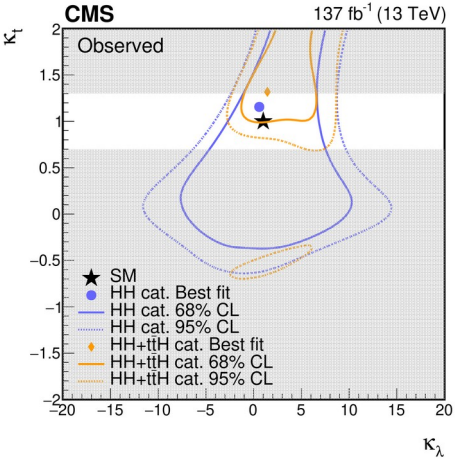
JHEP 03 (2021) 257 (non-res.)
HIG-20-014 (res. X→YH)
HIG-20-005 (resolved res.)
B2G-21-001 (boosted VBF non-res.)
B2G-20-004 (boosted res.)
SUS-20-004 (HH+MET)
HIG-20-004 (non-res.)
B2G-20-007 (res.)

HH→bbyy

ATLAS
ATLAS-CONF-2021-016
CMS
JHEP 03 (2021) 257

- **HH→ bbyy**
  - ⊖ Tiny BR (~0.26%)
  - ⊕ Fully reconstructed final state
  - ⊕ Excellent m_{yy} resolution
- **CMS analysis**
  - Non-resonant ggF+VBF
  - Fine categorisation
    - → Based on BDTs + reduced mass
    - → 12 ggF SR + 2 VBF SR
  - 2D m_{yy} vs m_{jj} fit for signal extraction





$$m_{\text{red}} = m_{\text{bb}\gamma\gamma} - (m_{\gamma\gamma} - m_H) - (m_{\text{bb}} - m_H)$$

Observed (expected) 95% CL:

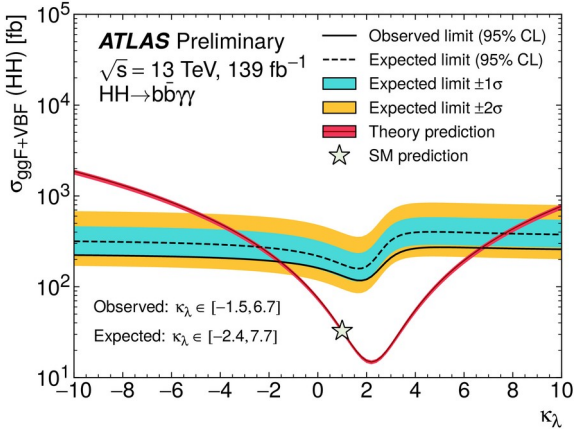
→ **σ(HH)** < 7.7 (5.2) **σ$_{SM}$**
→ **σ(VBF-HH)** < 225 (208) **σ$_{SM}$**
→ -3.3 < **κ$_λ$** < 8.5 (-2.5 < **κ$_λ$** < 8.2)
→ -1.3 < **κ$_{2V}$** < 3.5 (-0.9 < **κ$_{2V}$** < 3.1)

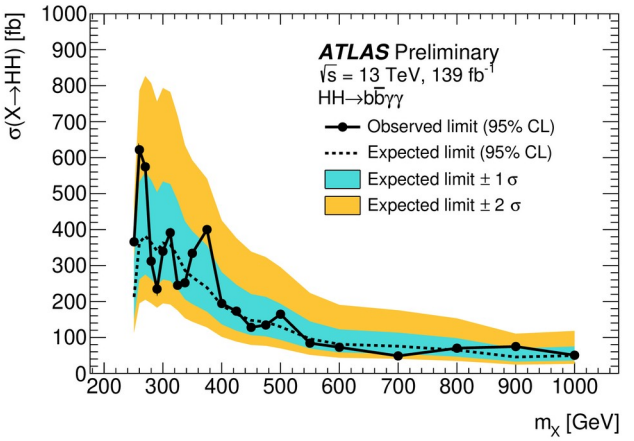
~ 4x improvement w.r.t previous analysis !

HH→bbyy

ATLAS
ATLAS-CONF-2021-016
CMS
JHEP 03 (2021) 257

- **HH→ bbyy**
  - ⊖ Tiny BR (~0.26%)
  - ⊕ Fully reconstructed final state
  - ⊕ Excellent m_{yy} resolution
- **ATLAS analysis**
  - Resonant + Non-resonant ggF+VBF
    → Analysis optimised for ggF
  - Categorisation based on MVA + m^*_{bbyy}
    → Non-resonant: high/low-mass, 2 dedicated BDT
    → Resonant: mass-independant BDT + m^*_{bbyy} windows
  - m_{yy} for signal extraction





$$m^*_{bb\gamma\gamma} = m_{bb\gamma\gamma} - (m_{\gamma\gamma} - m_H) - (m_{bb} - m_H)$$

Observed (expected) 95% CL:

→ **σ(HH)** < 4.1 (5.5) σ_{SM}

→ -1.5 < κ_λ < 6.7 (-2.4 < κ_λ < 7.7)

~ 5x improvement w.r.t previous analysis !

HH→bbVV

ATLAS

PLB 801 (2020) 135145 (non-res.)
ATLAS-CONF-2021-016 (res. + non-res.)
JHEP 11 (2020) 163 (boosted res.)
ATLAS-CONF-2021-030 (res. + non-res.)
JHEP 07 (2020) 108 (VBF res. + non-res.)
ATLAS-CONF-2021-035 (res.)
ATL-PHYS-PUB-2021-031 (summary plots)

CMS

JHEP 03 (2021) 257 (non-res.)
HIG-20-014 (res. X→YH)
HIG-20-005 (resolved res.)
B2G-21-001 (boosted VBF non-res.)
B2G-20-004 (boosted res.)
SUS-20-004 (HH+MET)
HIG-20-004 (non-res.)
B2G-20-007 (res.)

HH→bb4l – Non-resonant

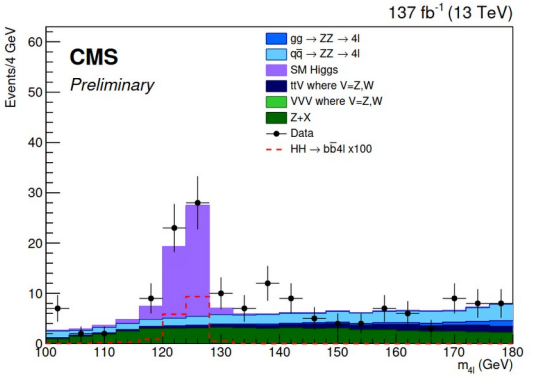
- **HH→bbZZ* → bb4l (l = e,μ)**
  - **First result in this channel**
  - BR = 0.014% !
  - But small background & clear signature

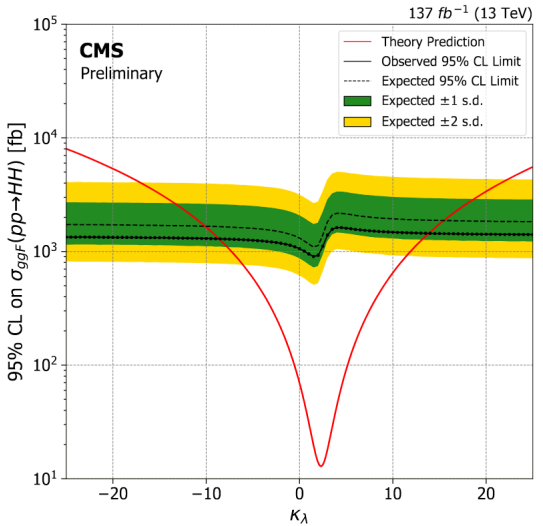
    → Main background: single-H
  - 2 pairs of OS leptons (4μ, 4e, 2e2μ), 2 b-tagged R=0.4 jets
  - SR definition: $|m_{4l} - 125| < 10$ GeV
  - Signal extraction through fit on BDT discriminant

Observed (expected) 95% CL:

→ **σ(ggF HH)** < 30 (37) σ_{SM}

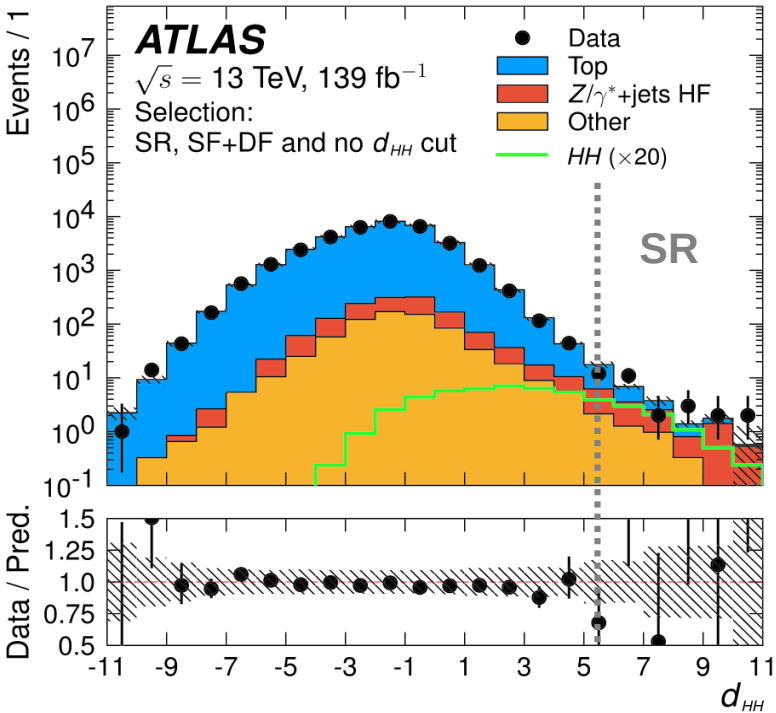
→ -9 < κ_λ < 14 (-11 < κ_λ < 16)





HH→bblνlν – Non-resonant

- **HH→bblνlν**
  - Analysis optimised for bbWW*
    → Dominant signal
    → bbZZ* + bbττ included in signal definition
  - Multi-class DNN for event selection
    → $d_{HH} = \ln\left(\frac{P(HH)}{P(t)+P(Z\to ll)+P(Z\to \tau\tau)}\right)$
    → Optimised cuts for two flavour-based categories
    → $20 < m_{ll} < 60$ GeV, $110 < m_{bb} < 140$ GeV
  - Background controlled in mass side-bands
  - Counting experiment for signal extraction
    → Single bin per region (SRs + CRs)

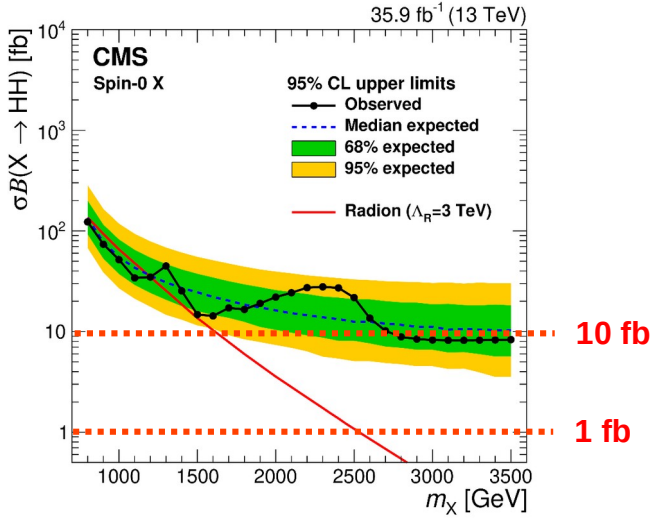


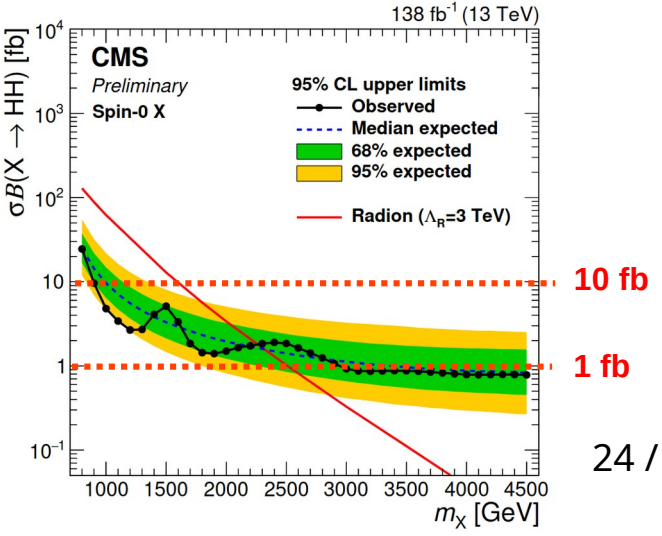
Observed (expected) 95% CL:

→ **σ(ggF HH)** < 40 (29) **σ_{SM}**

HH→bbWW – Resonant

- **High-mass X→HH→bbWW search**
  - 1 < mX < 4.5 TeV
    → Looking at boosted topologies
  - **H→bb**
    → R=0.8 "$b\bar{b}$" jet (***DeepAK8*** for identification)
  - **H→WW**
    → Single-lepton + R=0.8 "qq" jet (WW→lνqq)
  - → Di-lepton (WW→lνlν, ττ→lννlνν) – ***update w.r.t. 36 fb⁻¹ analysis***
  - Fine categorisation
    → Based on various properties (flavor, DeepAK8, substructure)
    → 8 Single-lepton + 4 Di-lepton categories
  - Limit setting from 2D (m_{bb},m_{HH}) fit
    → **~ 1 order of magnitude gained** w.r.t. 36 fb^{-1} analysis
    → **Scan range extended by 1 TeV !**

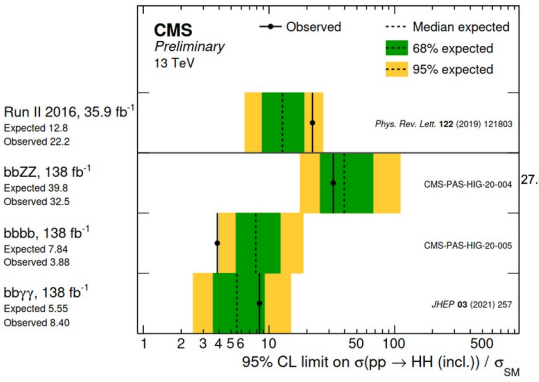


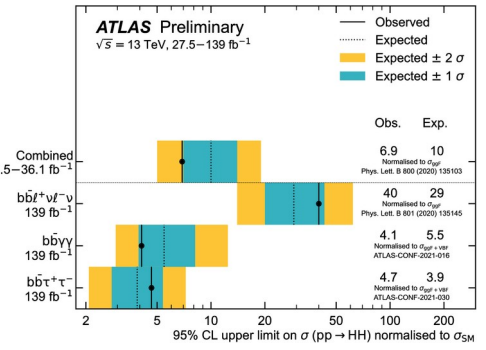


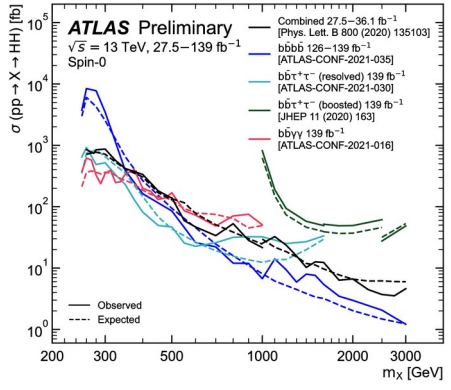
Summary

Summary

- **Large selection of new HH results using the full Run 2 datasets (~140 fb^{-1})**
  - Both non-resonant & resonant production
  - Different topologies (boosted & resolved)
  - Different production modes (ggF & VBF)
- **Unprecedented sensitivities**
  - **Highly improved limits (~3-10 x, both res. and non-res.)**
    → Naive luminosity scaling ~ 2 x
    → Single channels better than 36 fb^{-1} combinations
  - **Highly improved constraints on couplings**
    → $\kappa_{2V} \leq 0$ excluded !
- **Still much more data to come (Run 3 & HL-LHC)**
  - ***Lots of optimism for the future !***







Backup

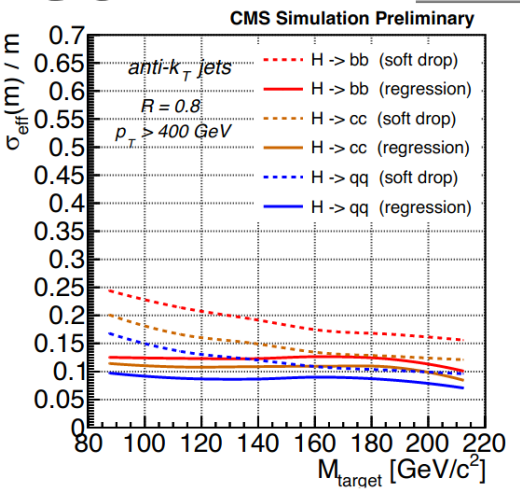
DeepAK8 vs ParticleNet

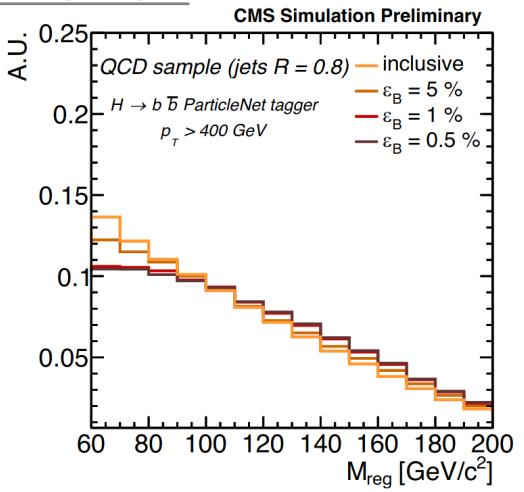
- **DeepAK8**
  - Particle-flow candidates+ secondary vertices as inputs
  - Convolutional neural network
  - Multi-category output: (H,t,W,Z)→(bb,cc,qq,4q)
- **ParticleNet**
  - Same inputs as DeepAK8
  - Graph neural network
  - ~ 2x improved bb vs QCD discrimination w.r.t. DeepAK8
  - Performance much less impacted when introducing **mass decorrelation**
  - **Used as mass regressor** with minimal modifications

  → Same inputs, training samples and overall architecture

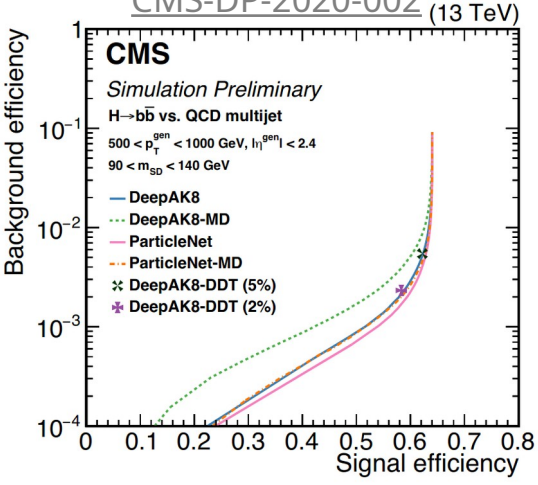
  → Different target: signal (pole) mass / background (particle level) SD mass

CMS-DP-2021-017





CMS-DP-2020-002



(13 TeV)