Probing Higgs boson self-couplings with the non-resonant HH production at the LHC

Speaker: Raffaele Gerosa

Institute: Università degli studi di Milano-Bicocca and INFN

On behalf of the ATLAS and CMS Collaborations

Higgs 2024 conference, 4th-8th November 2024, Uppsala University (Sweden)

The Higgs boson portrait

Many ***properties*** of the ***Higgs boson*** have been ***precisely measured*** with ***Run2 LHC data***

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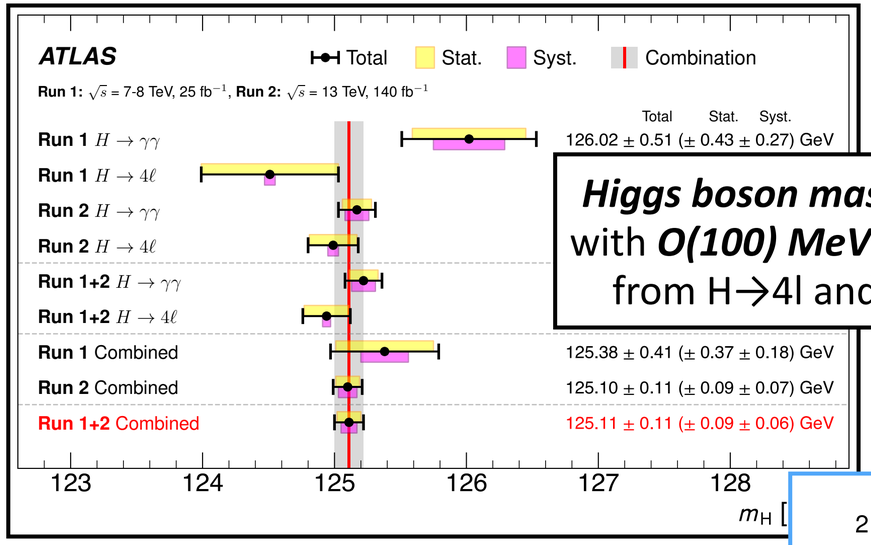
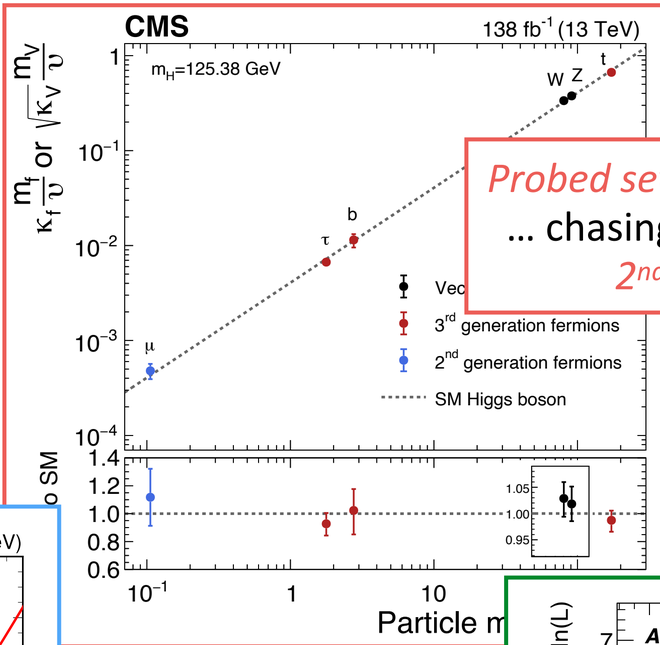
PRL 131 (2023) 251802



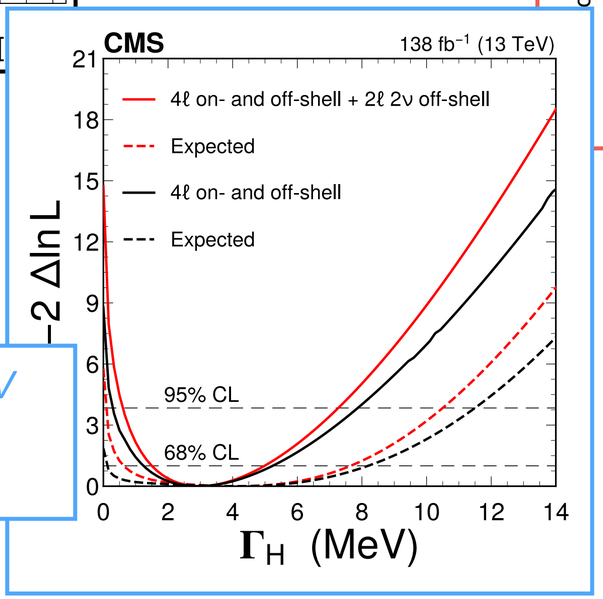
Higgs boson mass known with ***O(100) MeV*** precision from H→4l and H→***γγ***

Nature 607 (2022) 60-68



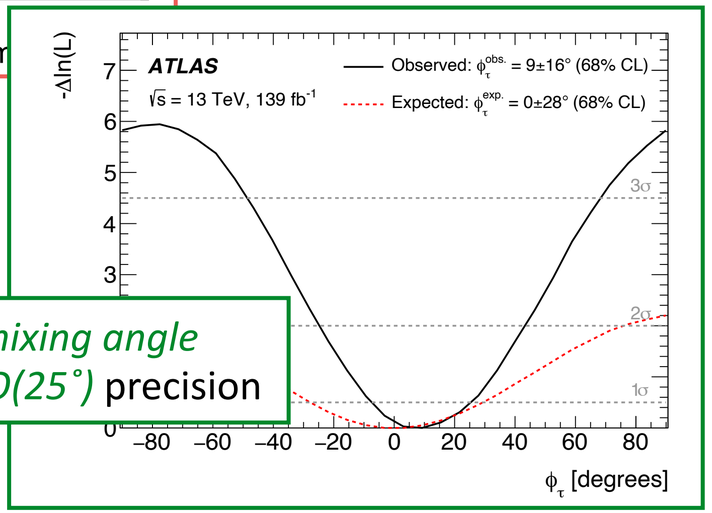
Probed several Higgs boson couplings
… chasing Yukawa interactions with *2nd fermion generation*

EPJC 83 (2023) 563



Higgs boson width known *O(2-3) MeV* precision from *on-shell* and *off-shell* measurements in H→ZZ decays

arXiv.2409.13663



Yukawa CP-mixing angle measured with *O(25°)* precision

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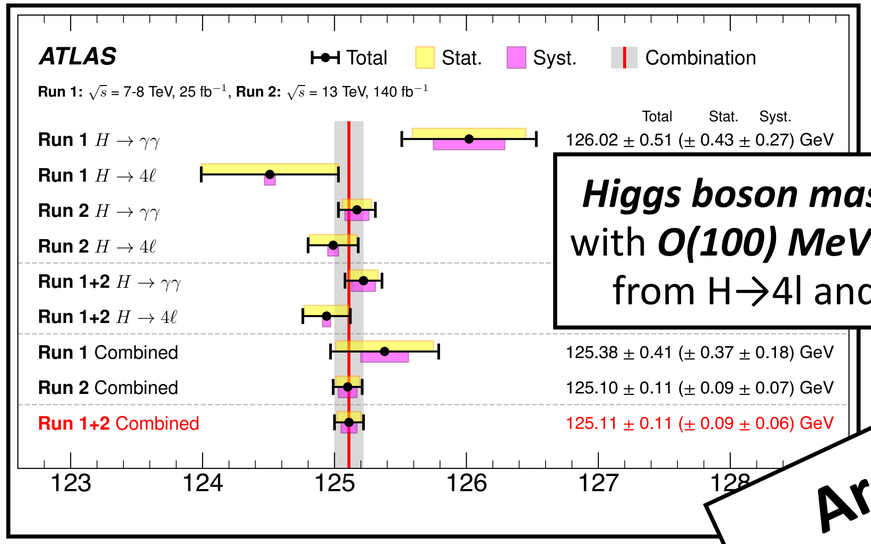

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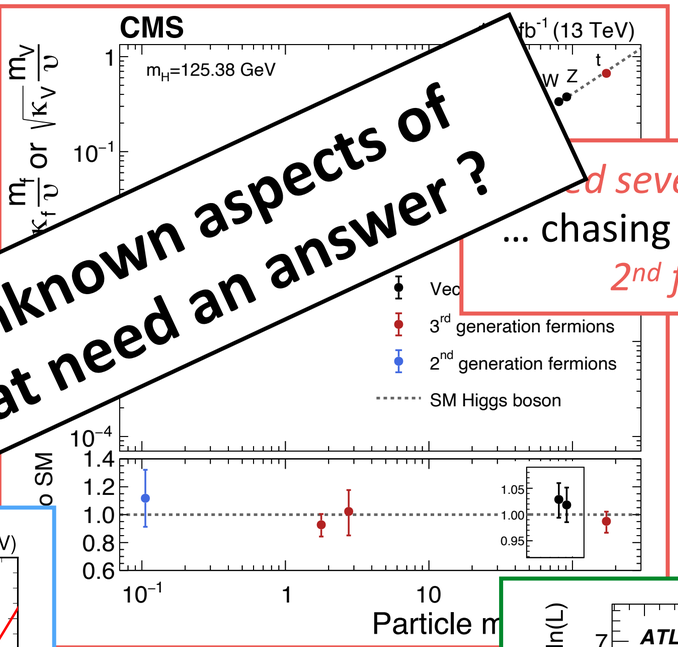
Are there are still unknown aspects of the Higgs sector that need an answer ?



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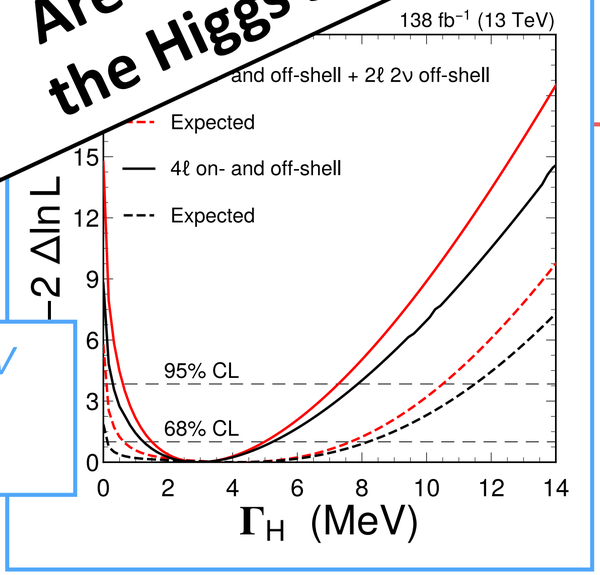

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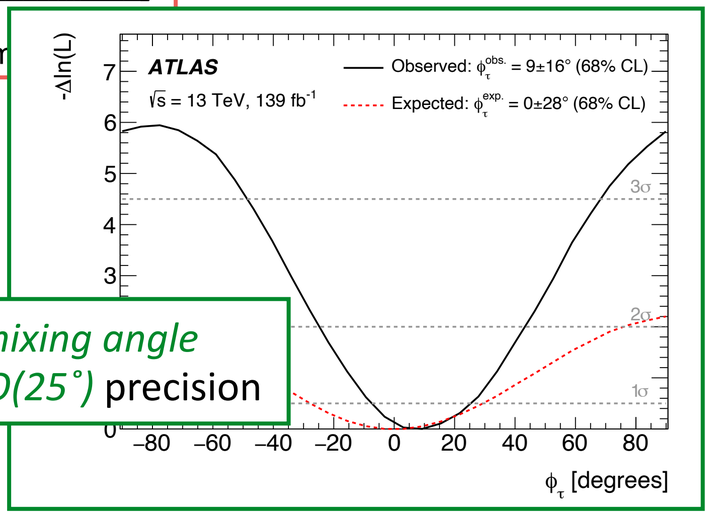

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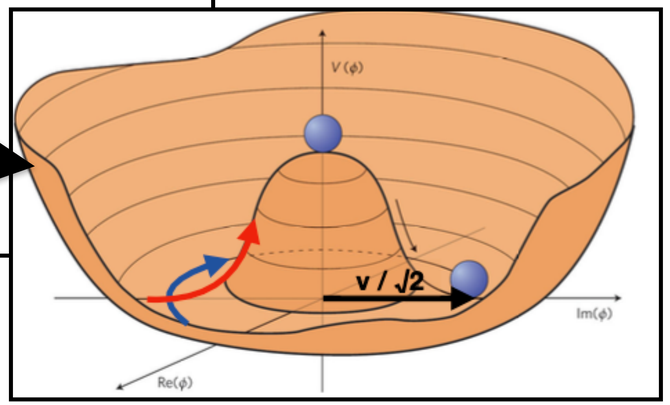
The Higgs boson potential

- The ***scalar sector*** is a ***cornerstone*** of the ***SM*** and is ***not yet fully established*** experimentally

- ***BEH mechanism:*** the Higgs field is a complex doublet invariant under SU(2) weak isospin symmetry
- The ***Higgs potential*** is given by $V(\Phi^\dagger\Phi) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$
- ***Spontaneous breaking*** of the EW symmetry (***EWSB***) originates a ***VEV ≠ 0***
- After EWSB → the ***ground state*** is ***degenerate*** under ***SU(2)*** transformations



$$\text{VEV} = v = \frac{\mu}{\sqrt{\lambda}} \qquad \mu = m_H^2/2$$

- *Expanding* the *potential around* then VEV $V(H) = \frac{1}{2}m_{\mathrm{H}}^2\mathrm{H}^2 + \lambda v\mathrm{H}^3 + \frac{1}{4}\lambda\mathrm{H}^4 - \frac{\lambda}{4}v^4$
- *Properties* of the scalar sector is *controlled* by λ → rules the *shape* of the *Higgs potential*
- The *parameter λ* is a *known value* in the SM theory given by $\lambda = \frac{m_{\mathrm{H}}^2}{2v^2} \approx \frac{1}{8} \approx 0.13$

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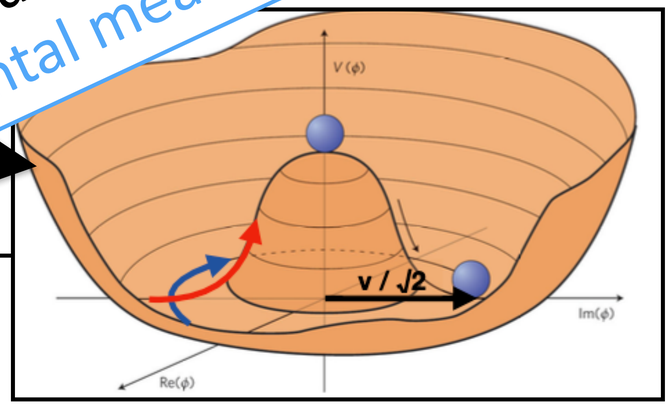

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- *Expanding* the *p* *V*

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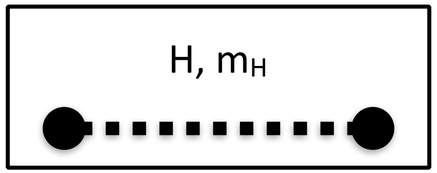
Even if λ is determined from m_H and VEV values,
deviations from SM are possible and motivate experimental measurements

How can we measure the self-coupling?

Mass term measured with O(100) MeV precision



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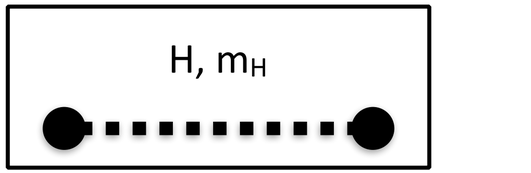

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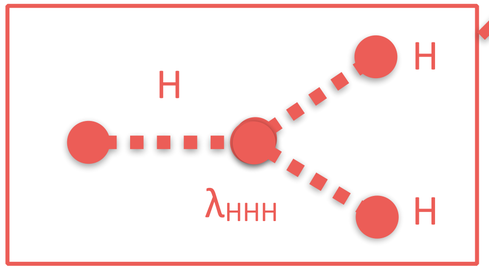

Direct measurements

- It can be *directly probed* via the non-resonant production of *HH pairs*
- *Direct measurements* are *theoretically robust* but experimentally *very challenging* because HH production is an *rare process*
- *HH* production *cross section* is about *1000 x smaller* than *single-H*

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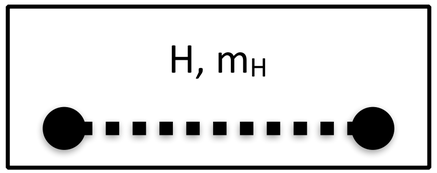

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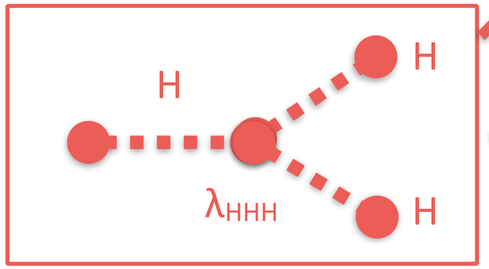

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- Extract λ_{HHH} from precise *single-H cross section* measurements
- *Limited* by *theory assumptions* needed to extract NLO dependence vs λ_{HHH}

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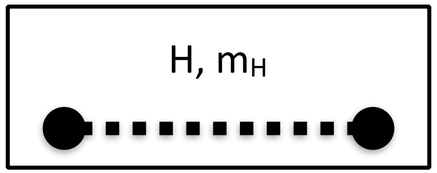

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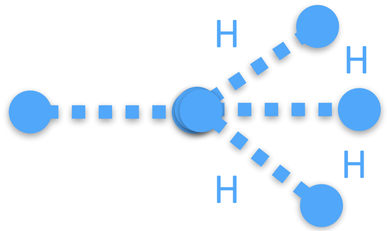
Quartic coupling



- Extremely rare → *out of reach for HL-LHC*
- Serves as additional probe for BSM

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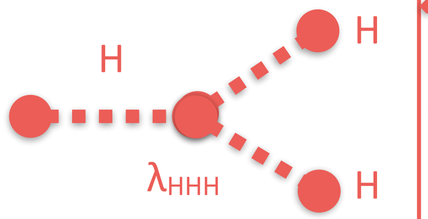

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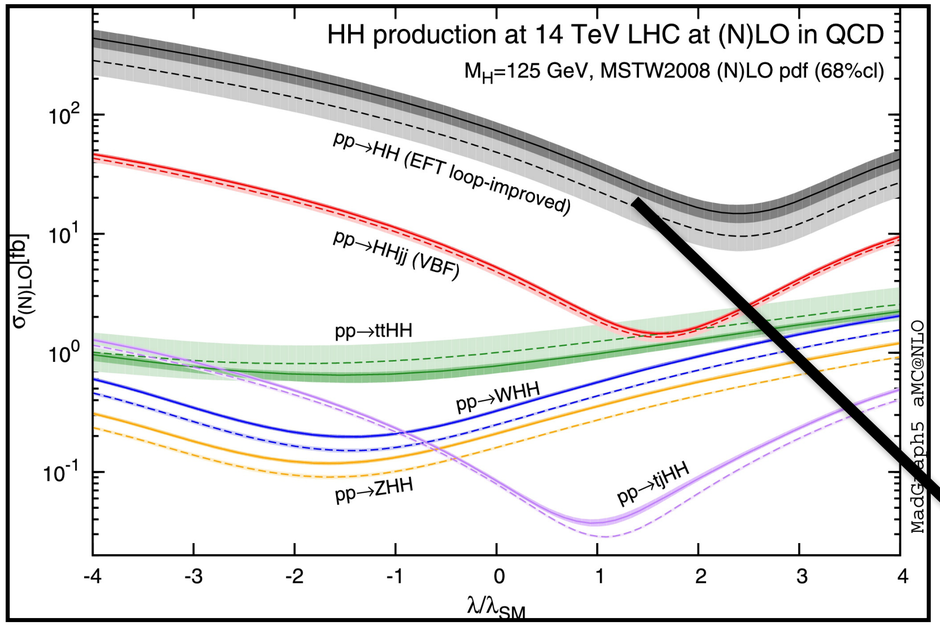
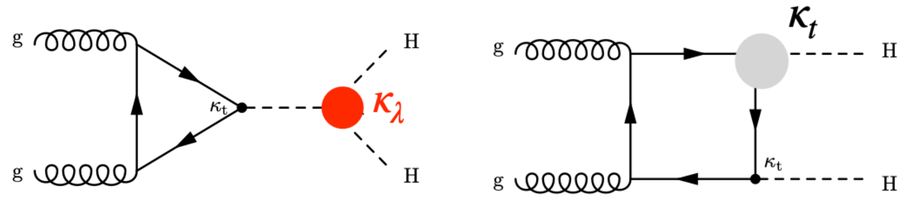
HH production at the LHC

- Total HH production ***cross section*** is about ***1000 x smaller*** than single-H
- HH pairs produced via ***different mechanisms*** → ***ggHH, VBF-HH, VHH,*** and ***ttHH*** in analogy with single-H production
- ***Cross-section*** for each mode ***can be*** precisely **parametrised** as a function of $\mathbf{k_\lambda = \lambda/\lambda_{SM}}$



gluon-fusion production (ggHH)

- ***Main production*** is ***gluon-fusion*** who drive the $\boldsymbol{\lambda_{HHH}}$ measurement
- ***Two diagrams @LO*** with similar magnitude showing with large ***destructive interference***



- Value of the ***self-coupling*** modifies both ***total*** and ***differential cross sections*** → $d\sigma/dm_{HH}$ strongly depends on k_λ

NNLO-QCD FT-approx + m_{top} uncertainty

$$\sigma_{ggHH}(k_\lambda = 1) = 34.13\ (30.77)\ \text{fb at}\ \sqrt{s} = 13.6\ (13)\ \text{TeV}$$

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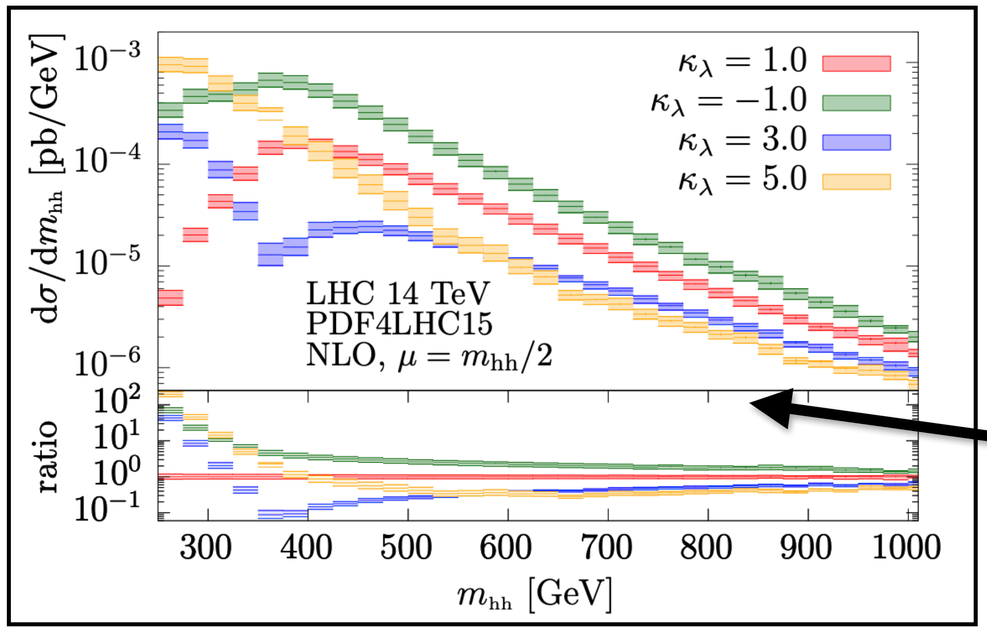
JHEP06(2019)066



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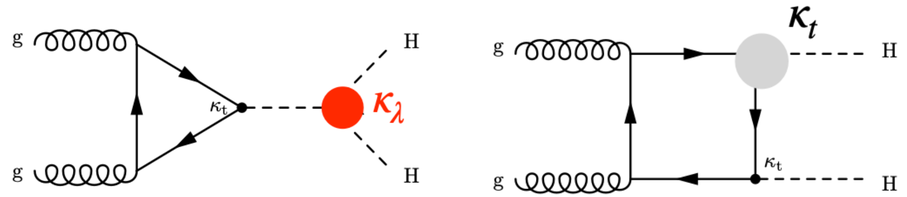

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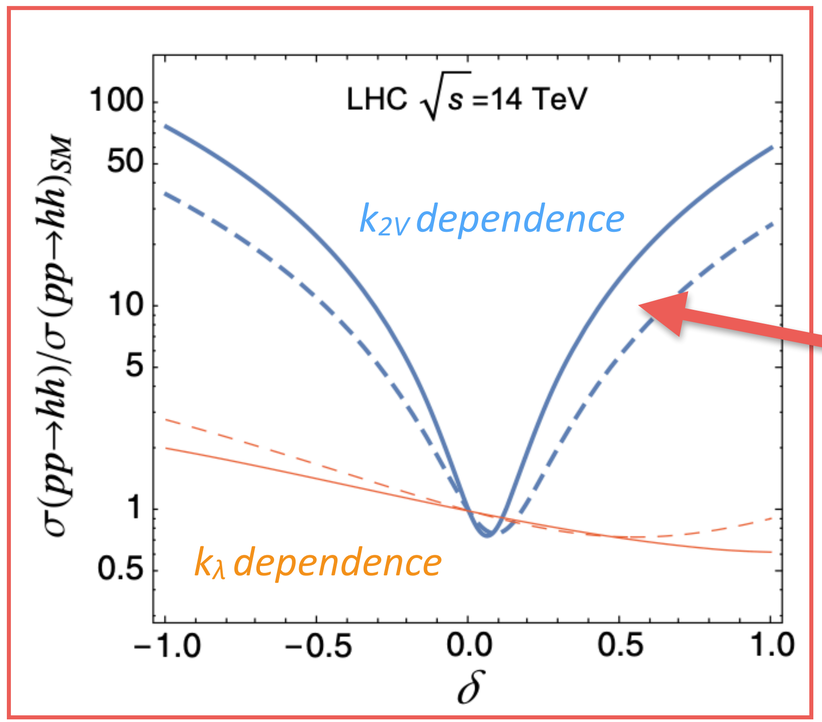
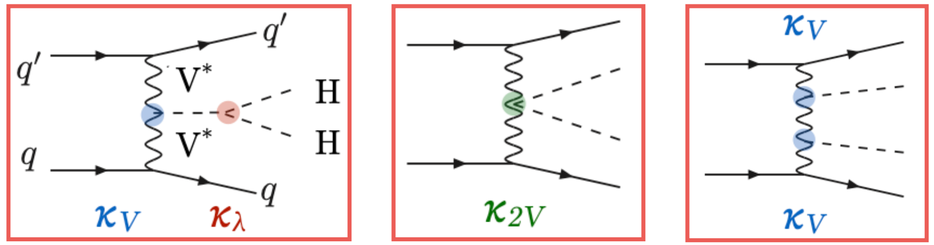
Eur.Phys.J. C77 (2017) no.7, 481



vector boson fusion (VBF-HH)

- *Three diagrams* contribute at LO: sensitive to k_λ and k_{2V}



- *VBF-HH* sensitive to the *self-coupling* but it represents a *unique probe* for *HHVV interactions* (k_{2V})
- *VBF-HH* production cross section is *10 x smaller* than *ggHH*

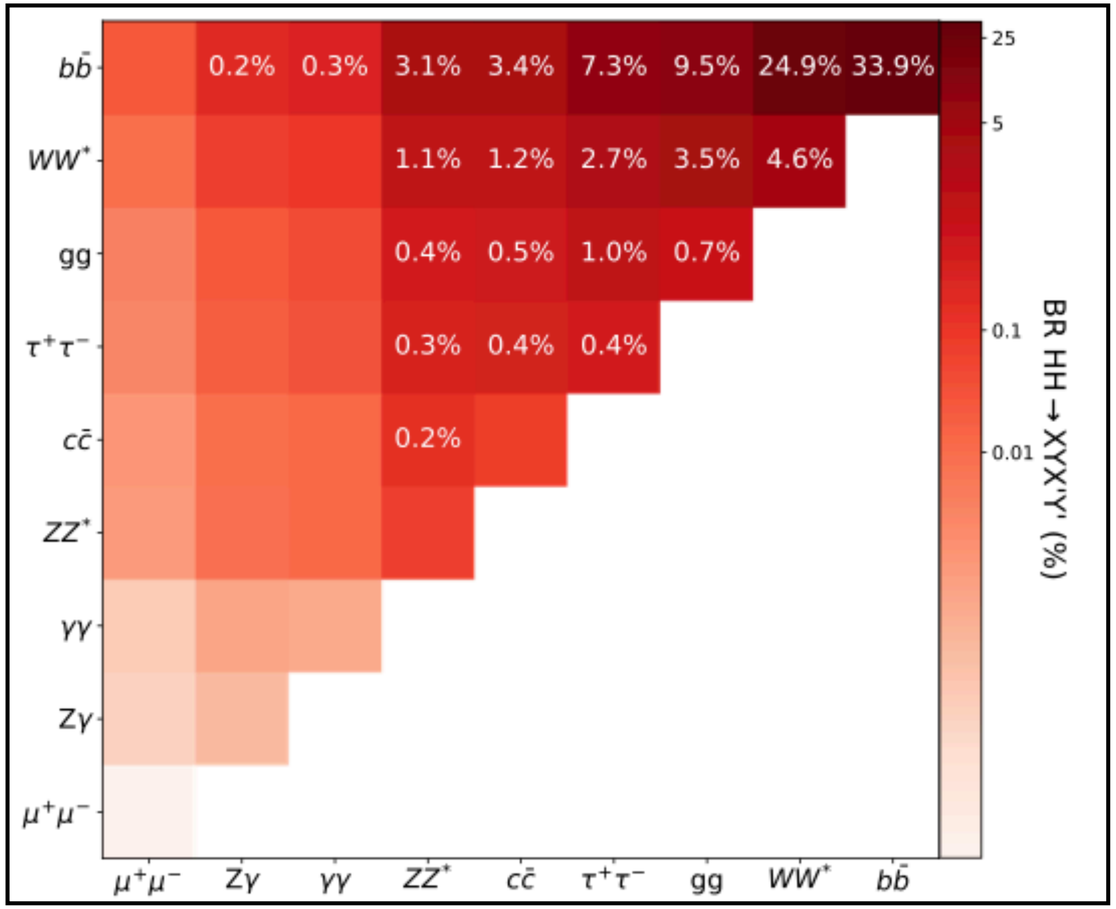
N3LO QCD + NLO EW

$$\sigma_{\mathrm{vbfHH}}(k_\lambda = 1) = 1.87\ (1.69)\ \mathrm{fb\ at}\ \sqrt{s} = 13.6\ (13)\ \mathrm{TeV}$$

- VBF-HH with k_{2V}=1 *beyond the LHC reach* due to its small x-sec

HH final state signatures

- ***Large set*** of ***final states*** due to rich Higgs boson decay signatures
- ***Branching ratios*** favour ***hadronic signatures***: H→bb, H→$\tau_h\tau_h$, etc
- ***S/B*** favours instead ***leptonic*** final states



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Broad experimental programme

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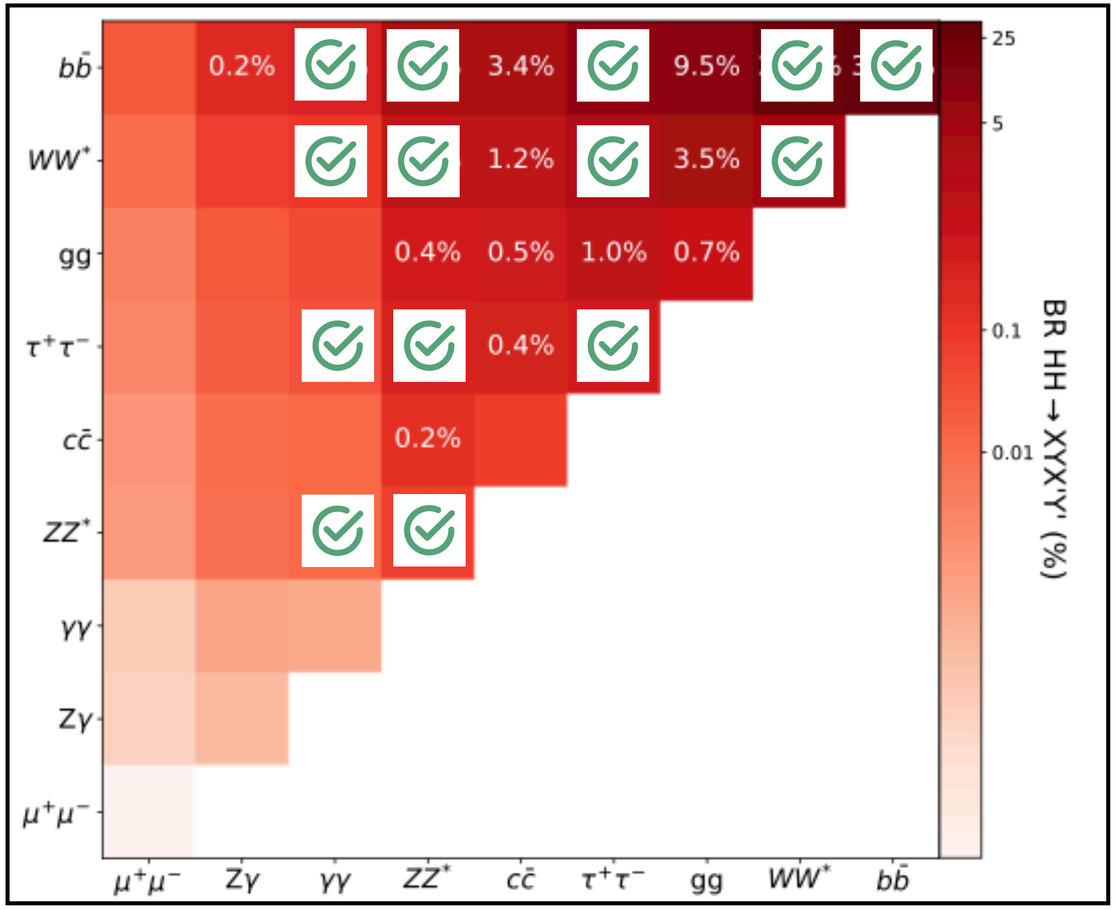
- *Note:* a parallel rich program of searches for new resonances decaying to HH exists and won't be covered by this talk



Published results based on "full" Run2 data

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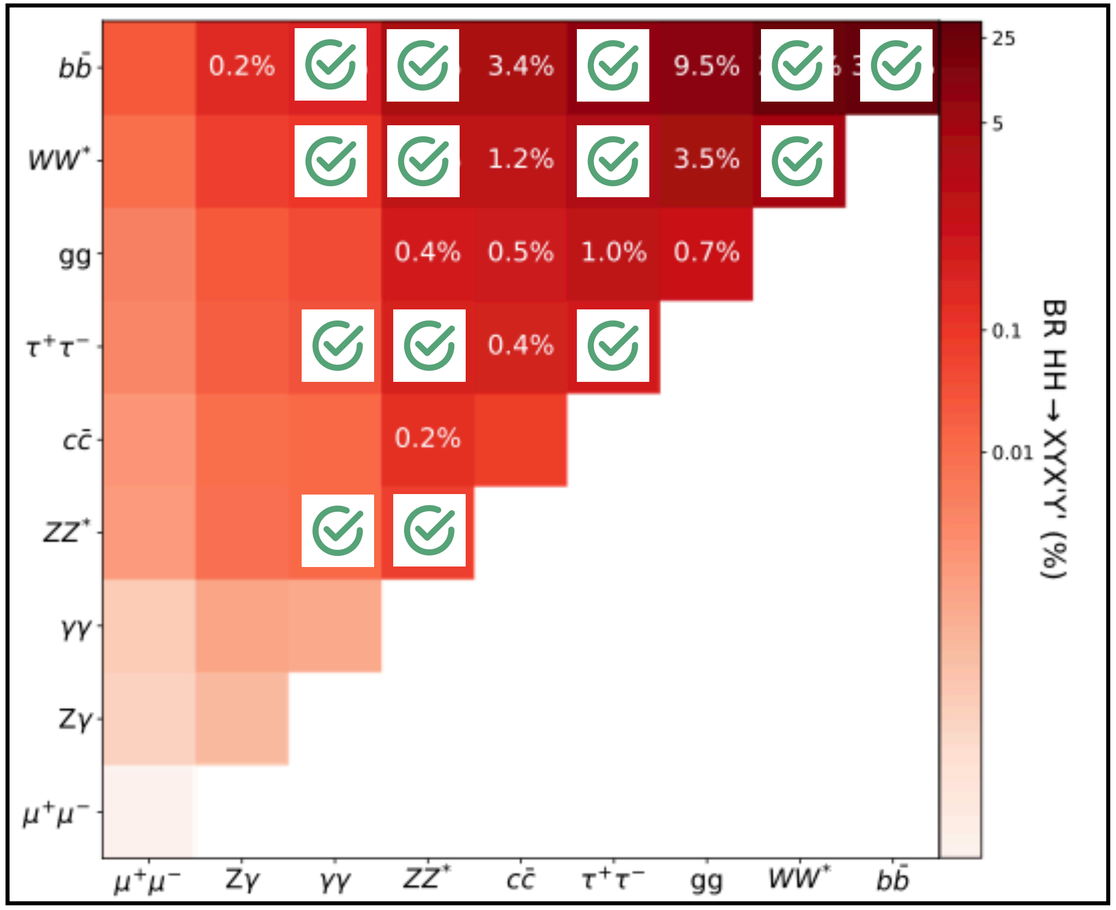
Sensitivity ranking

- *Sensitivity* driven by *three leading channels* → 4b, bb$\tau\tau$, and bb$\gamma\gamma$
- *Multi-lepton searches* follow in sensitivity covering several possible decay configurations: bbVV, $\tau\tau$VV, 4V, and 4τ
- *Very rare decay modes* are also explored like H→$\gamma\gamma$VV and H→$\gamma\gamma\tau\tau$



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HH → 4b: high BR but low S/B

Resolved HH→4b

- **Signal region:** four b-jets in central region from b-jet triggers
- **Key features:** hadronic backgrounds (QCD, top) needs to be highly rejected and controlled, with novel ML-techniques, from data at O(%) level

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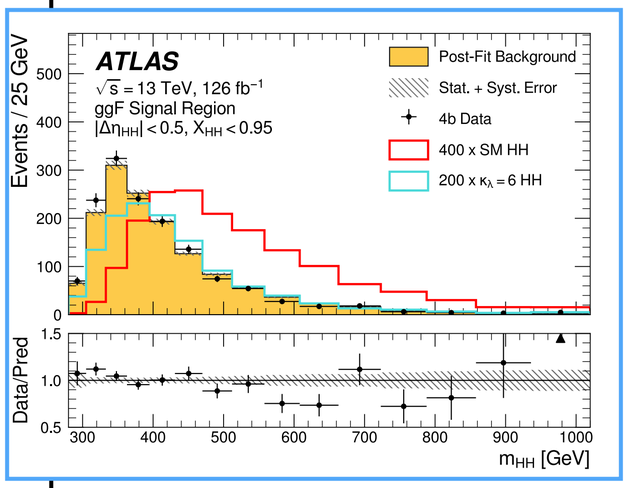
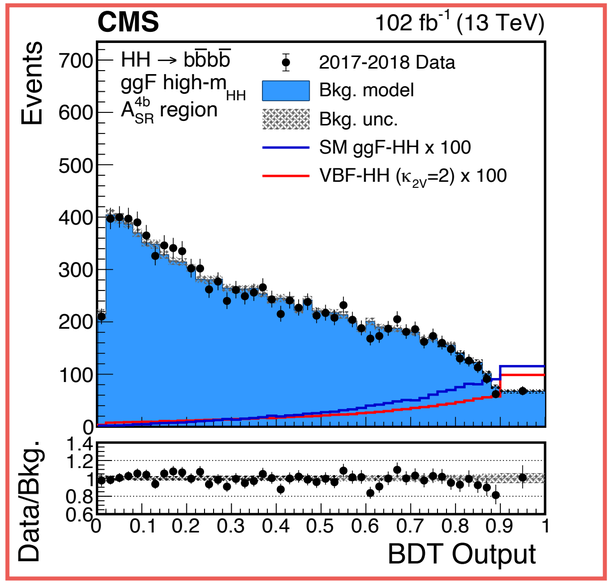


ATLAS: 95% CL on μ_{HH} is 5.3 (8.1) x SM

PhysRevLett.129.081802



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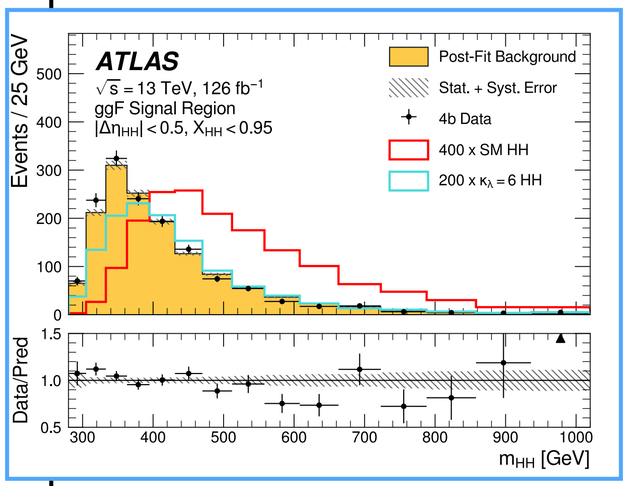

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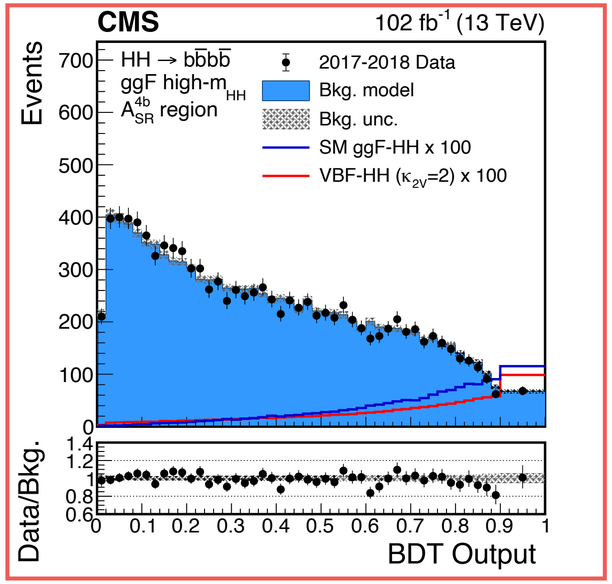

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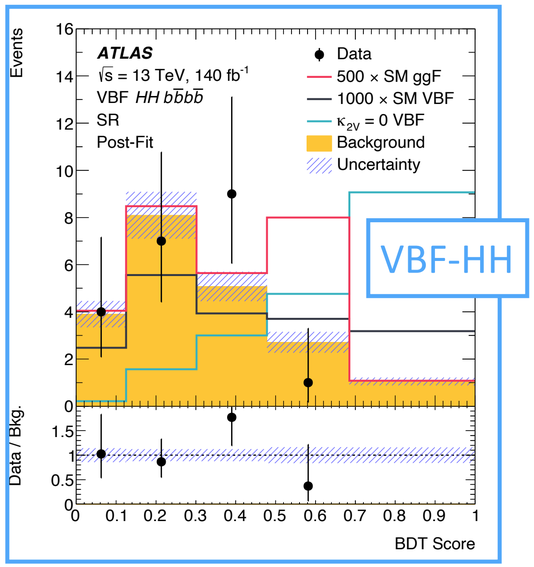
Boosted HH→4b

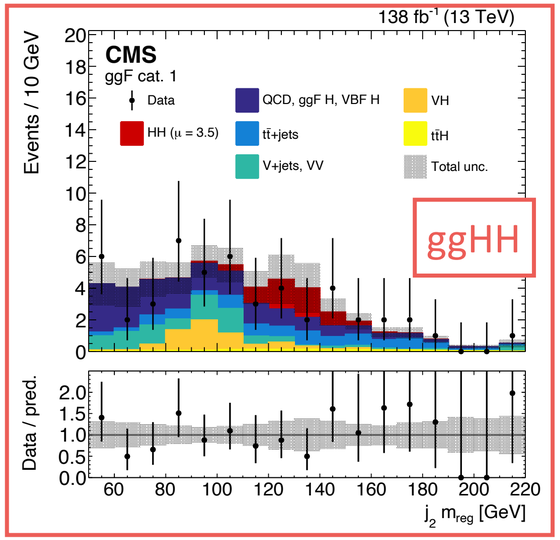
- **Signal region:** high p_T region where H→bb decay products are contained in a single large-R jet
- **Key features:** S/B enhanced via powerful ML H→bb taggers, bkg estimate is data-driven, statistically limited analysis

PLB.2024.139007



VBF-HH→4b provides best constraints on k_{2V}

PhysRevLett.131.041803



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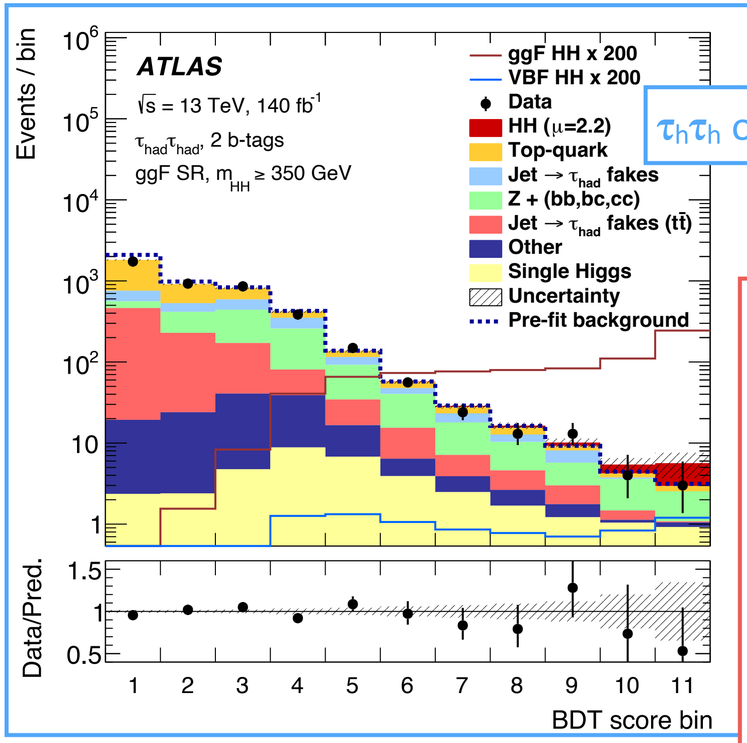
HH → bbττ: mid BR and ≈ good S/B

- ***Signal regions*** explore hadronic and semi-leptonic final states (**μτ$_h$, eτ$_h$,** and **τ$_h$τ$_h$**) ≈ 90% of HH→bbττ expected events
- ***Event categories*** based on ττ ***decay*** modes, ***production mode*** (ggHH, VBF-HH), ***boost*** of ***H→bb*** (CMS), and ***m$_{HH}$*** (ATLAS)
- ***Irreducible backgrounds from simulation***
  - Top-backgrounds: ttbar, single-top, etc
  - ***Z(ττ)+b-jets*** from simulation + ***corrections*** from ***Z → μμ*** in ***data***
- ***Reducible backgrounds estimated from data***
  - Mostly from ***mis-identified τ$_h$*** in QCD multi-jet and W(lv)+jets events
- ***Signal extraction*** from a fit to a ***BDT/DNN discriminant*** trained in each event category
- *Sensitivity driven by τ$_h$τ$_h$ category*

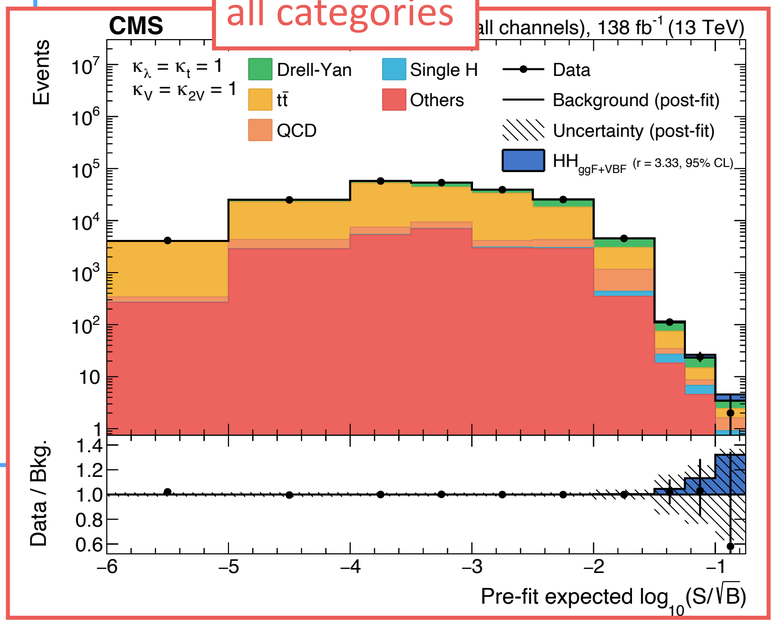


τ$_h$τ$_h$ only

PhysRevD.110.032012

PLB.2022.137531

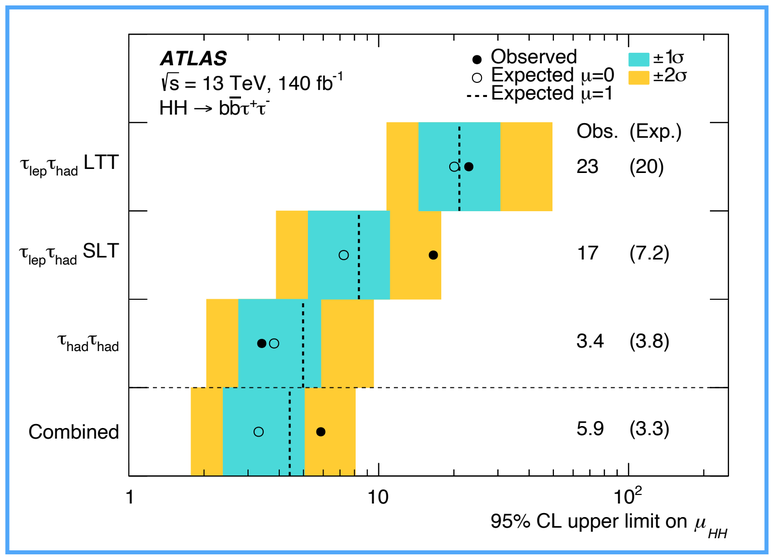
all categories



HH → bbττ: mid BR and ≈ good S/B

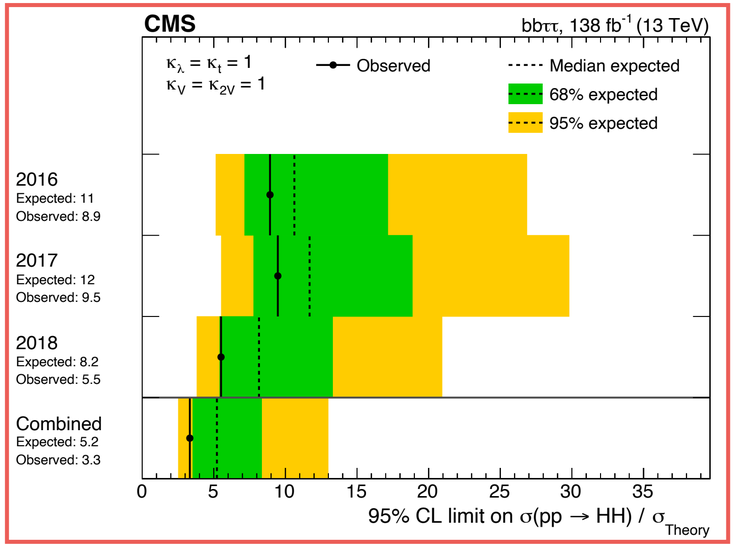
- ***Signal regions*** explore hadronic and semi-leptonic final states (**μτ$_h$, eτ$_h$,** and **τ$_h$τ$_h$**) ≈ 90% of HH→bbττ expected events
- ***Event categories*** based on ττ ***decay*** modes, ***production mode*** (ggHH, VBF-HH), ***boost*** of ***H→bb*** (CMS), and ***m$_{HH}$*** (ATLAS)
- ***Irreducible backgrounds from simulation***
  - Top-backgrounds: ttbar, single-top, etc
  - ***Z(ττ)+b-jets*** from simulation + ***corrections*** from ***Z → μμ*** in ***data***
- ***Reducible backgrounds estimated from data***
  - Mostly from ***mis-identified τ$_h$*** in QCD multi-jet and W(lv)+jets events
- ***Signal extraction*** from a fit to a ***BDT/DNN discriminant*** trained in each event category
- *Sensitivity driven by τ$_h$τ$_h$ category*

ATLAS: 95% CL on μ$_{HH}$ is 5.9 (3.3) x SM



PhysRevD.110.032012

CMS: 95% CL on μ$_{HH}$ is 3.3 (5.2) x SM



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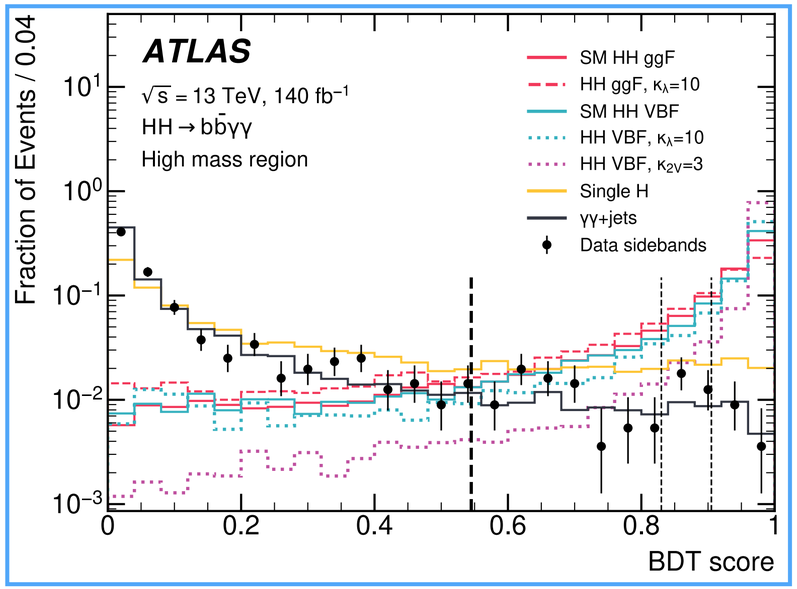
HH → bbγγ: low BR but best S/B

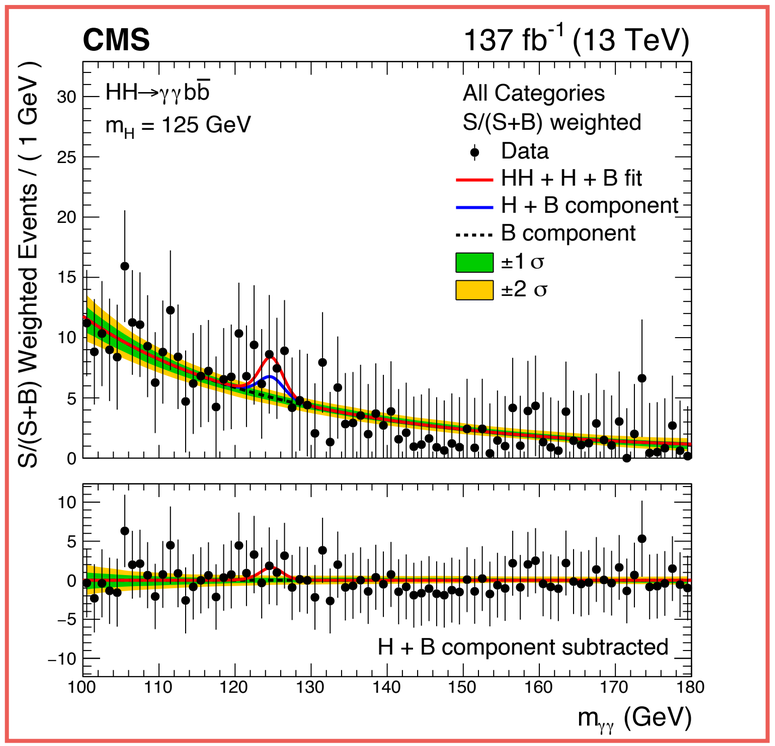
- The ***HH→bbγγ*** is a ***rare decay*** channel (BR ≈ 0.3%) but provides the ***best purity*** (S/B) among HH signatures
- ***Exclusive*** event ***categories*** designed based on m_{HH} (ATLAS) , ***production mode*** (CMS), and ***signal purity***
- ***Signal purity*** enhanced by using ***BDT*** discriminants featuring event ***kinematics*** and ***resolution*** of jets and photons (CMS)
- ***Main backgrounds*** from ***γγ*** / ***γ***+jets & single-H
- ***Rejection*** of ***ttH*** via hadronic W and top tagging (ATLAS) or ttH BDT killer (CMS)
- ***Signal extracted*** via a fit to $m_{\gamma\gamma}$ (ATLAS) and $m_{\gamma\gamma}$+m_{bb} (CMS) distributions
- *Statistically limited analysis!*

JHEP01(2024)066



ATLAS: 95% CL on μ_{HH} is 4.0 (5.0) x SM

JHEP03(2021)257

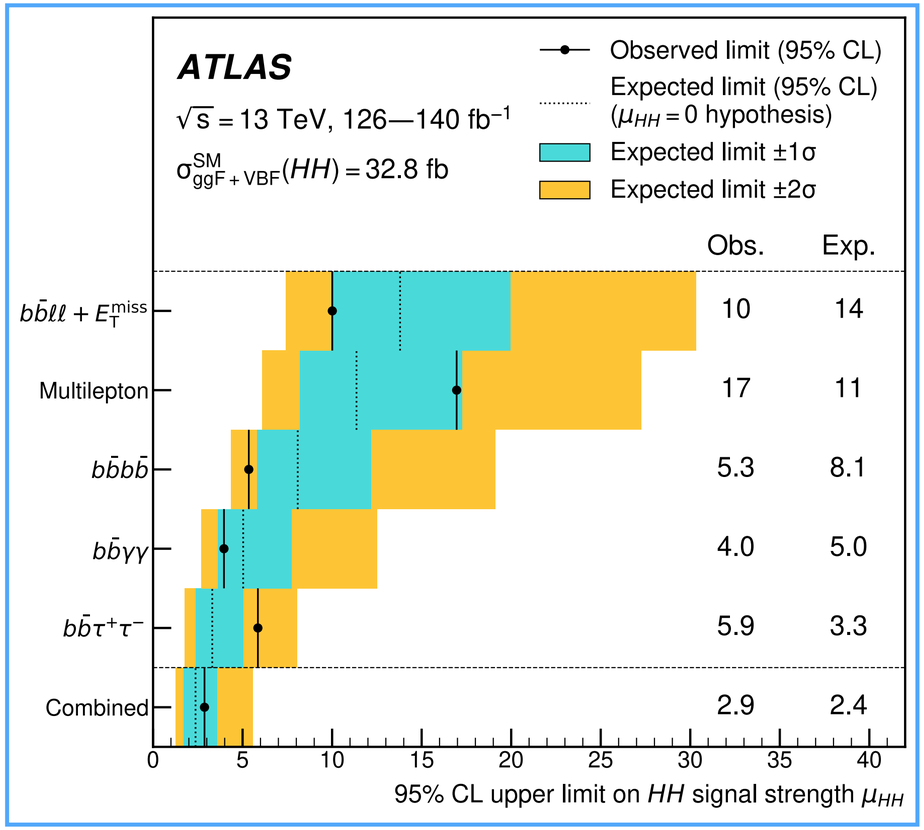


CMS: 95% CL on μ_{HH} is 8.4 (5.5) x SM

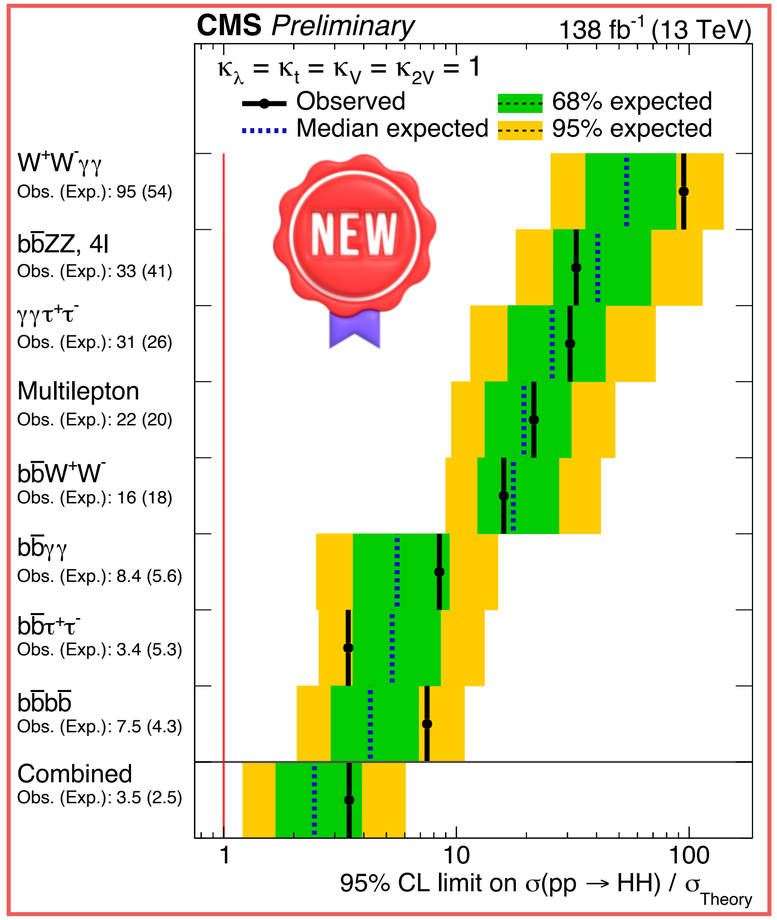
HH combination: pp→HH cross-section k_λ=1

- Observed and expected 95% CL upper limits on $\mu_{HH} = \sigma(pp \to HH)/\sigma_{SM}(k_\lambda=1)$ with full Run2 luminosity

PhysRevLett.133.101801



ATLAS: 95% CL on μ_{HH} is 2.9 (2.4) x SM



CMS: 95% CL on μ_{HH} is 3.4 (2.5) x SM

- *New CMS result* that supersedes previous Run2 combinations and *provides more interpretations*

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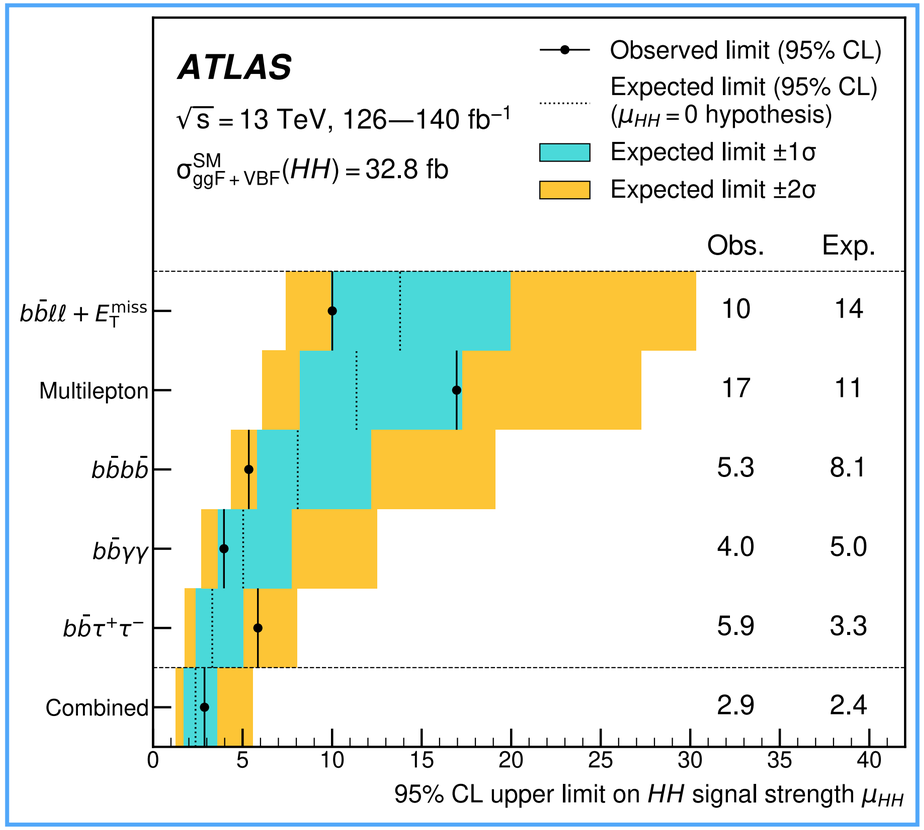

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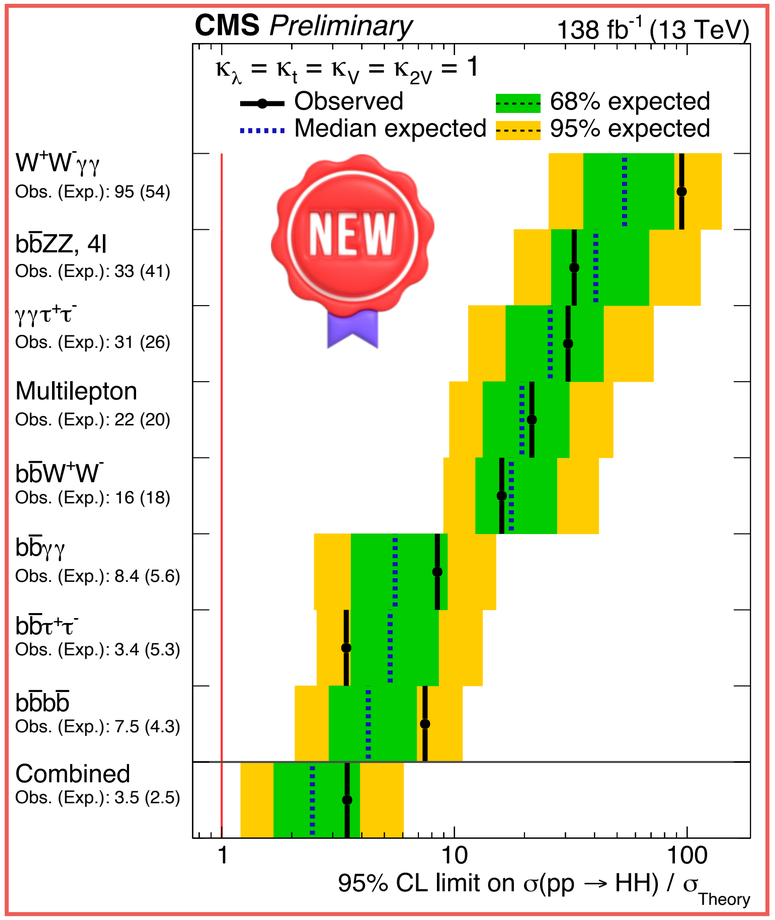
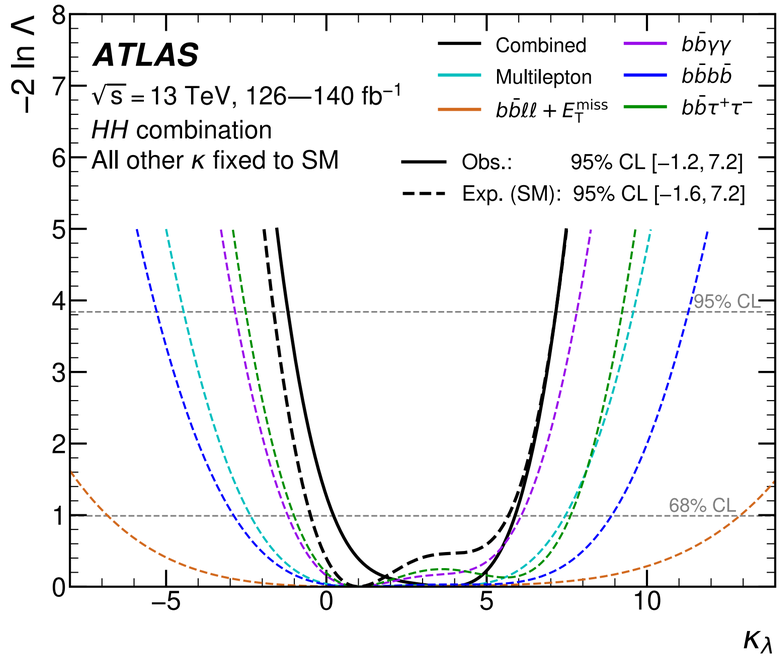


CMS: 95% CL on μ_{HH} is 3.4 (2.5) x SM

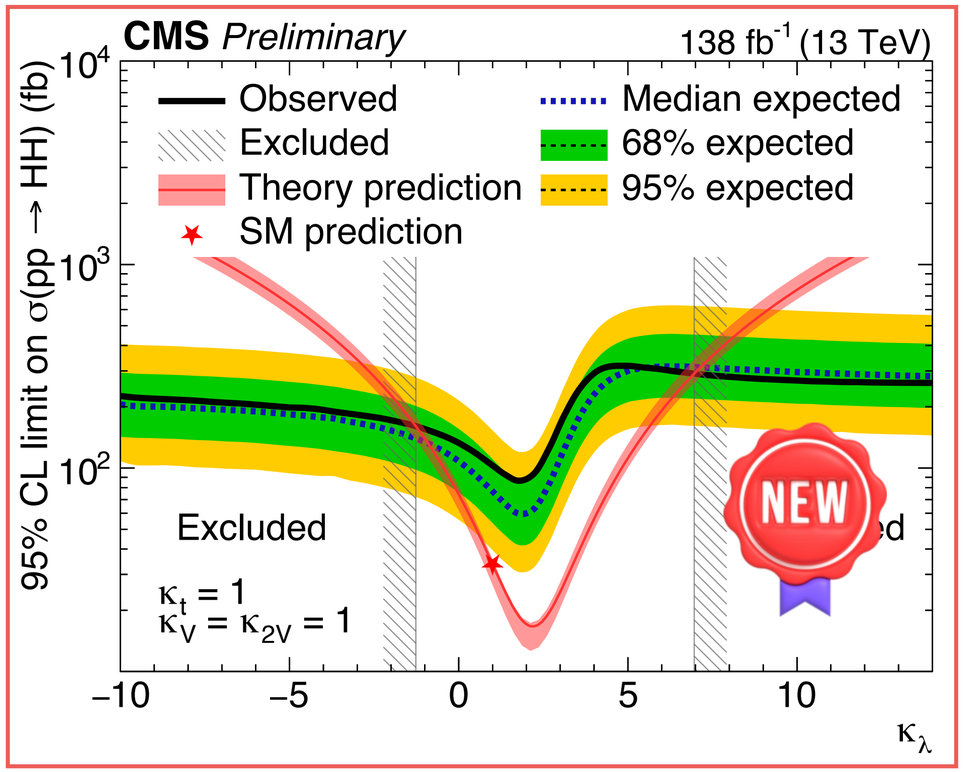
- *New CMS result* that supersedes previous Run2 combinations and *provides more interpretations*
- ***Similar sensitivity*** between ATLAS and CMS but ***different hierarchy*** in the analyses performance
- Results still ***statistically limited***
- However ***background modelling*** and ***theoretical uncertainties*** on σ_{ggHH} have a quite relevant impact

HH combination: self-coupling

PhysRevLett.133.101801



ATLAS: -1.2 (-1.6) < k_λ < 7.2 (7.2) at 95% CL from Log(L)



CMS: -1.4 (1.0) < k_λ < 7.0 (7.2) from 95% CL UL on σ/σ_{SM}

- ***Combination improves significantly*** the k_λ-constraint power of individual analysis
- ***Progressively closing*** the allowed region for ***anomalies*** in ***Higgs self-coupling***

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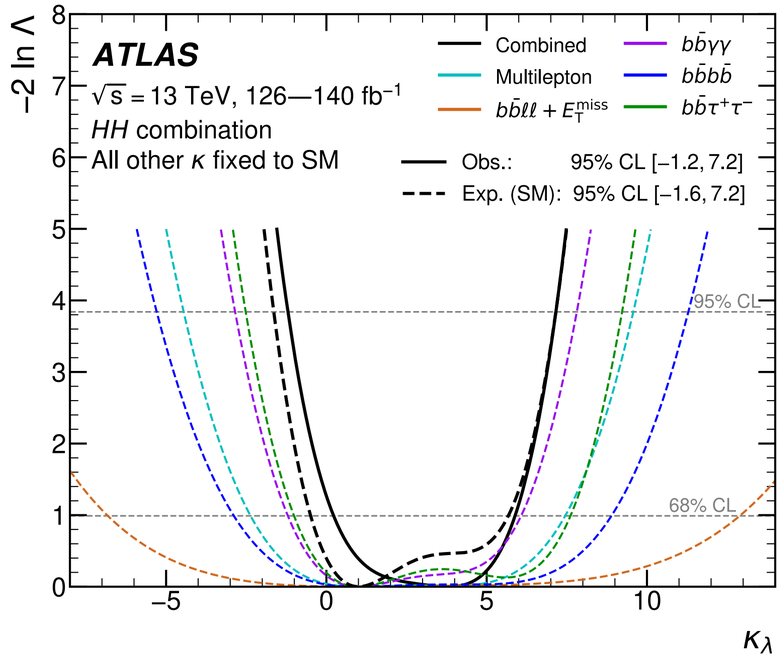
PhysRevLett.133.101801



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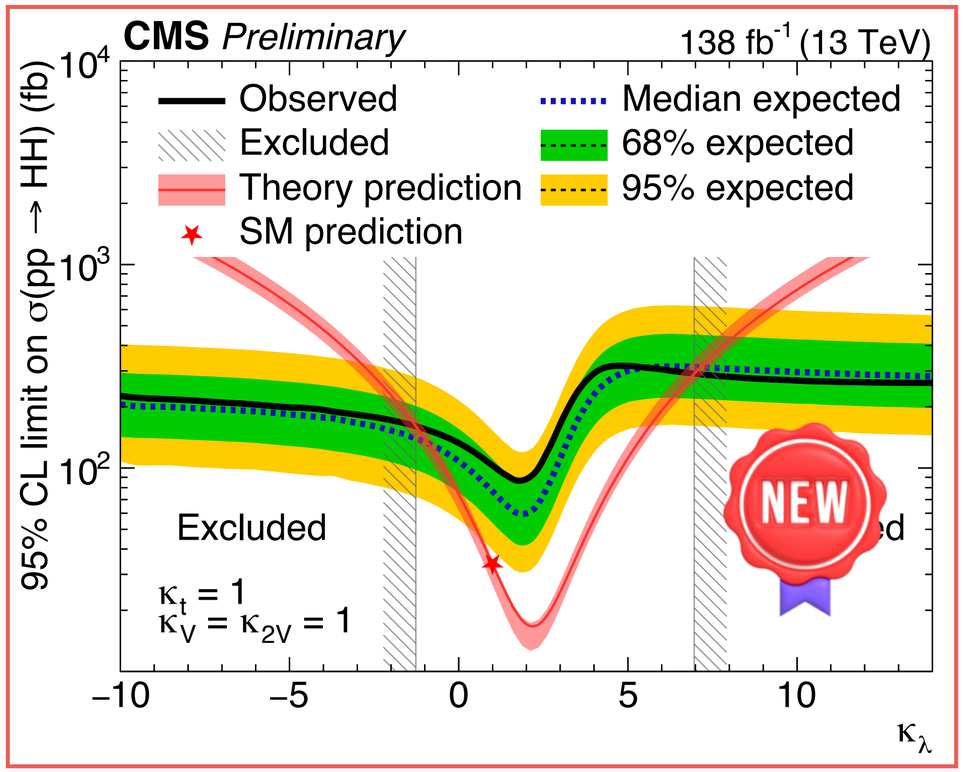

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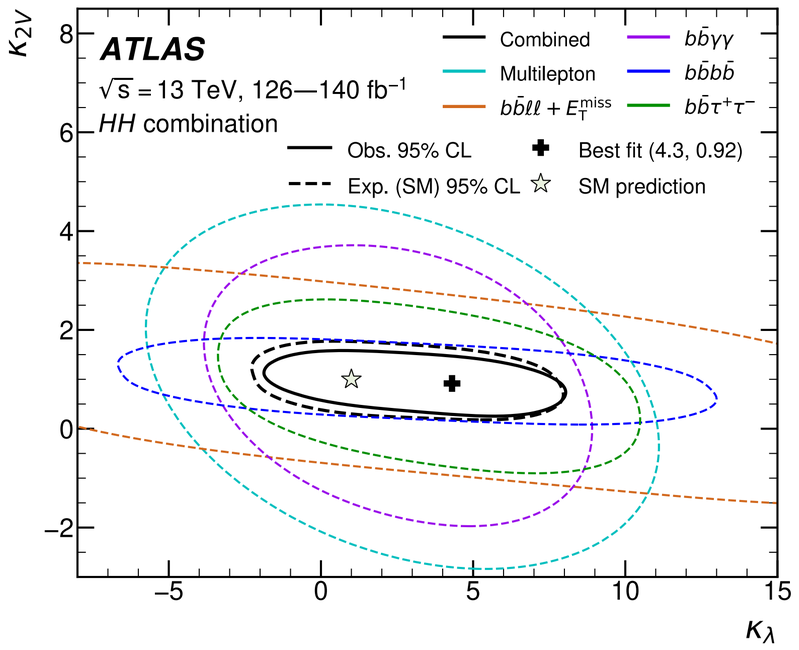
- ***Combination improves significantly*** the k_λ-constraint power of individual analysis
- ***Progressively closing*** the allowed region for ***anomalies*** in ***Higgs self-coupling***
- ***Resolved signatures*** are powerful for $\mathbf{k_\lambda < 0}$ and $\mathbf{k_\lambda > 2}$
- ***Boosted signatures*** enhance the sensitivity for k_λ around the SM
- ***Hardest region*** corresponds to $\boldsymbol{k_\lambda}$ in ***[4,7]***

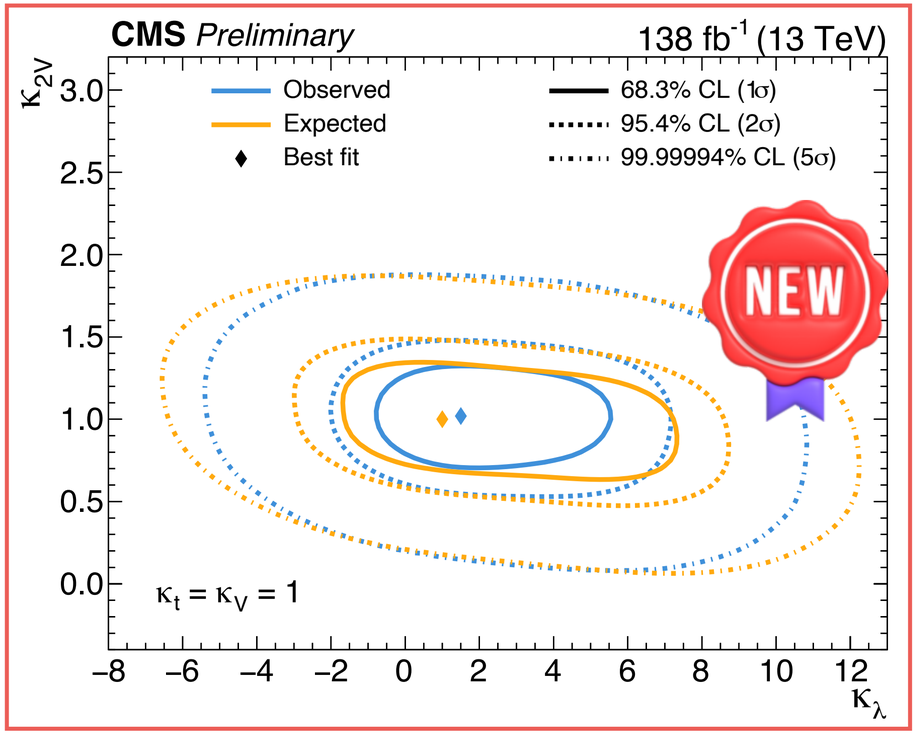
HH combination: HHH and HHVV interactions

- ***Event categories*** targeting ***ggHH*** and ***VBF-HH*** modes are ***complementary*** → allow to ***measure simultaneously k_λ*** and ***k_{2V}***

PhysRevLett.133.101801



ATLAS: 0.6 < k_{2V} < 1.5 (7.2) at 95% CL



CMS: 0.7 < k_{2V} < 1.4 (7.2) at 95% CL

- Both ATLAS (CMS) largely ***exclude*** the hypothesis of ***k_{2V} = 0*** at about 4 (6.5) σ
- ***k_{2V}*** mostly ***constrained*** by the boosted ***VBF HH→4b***

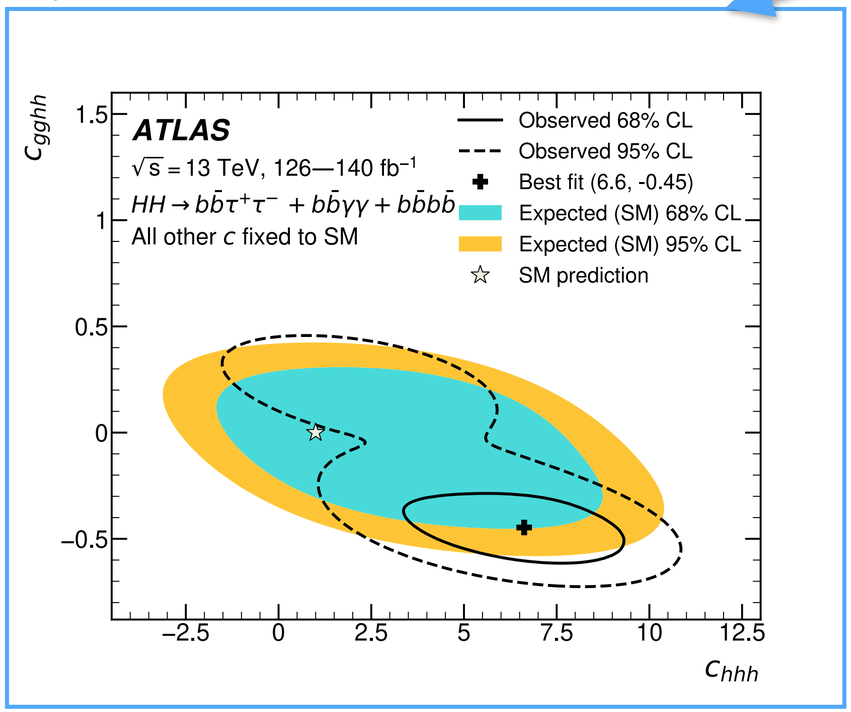
  PLB.2024.139007

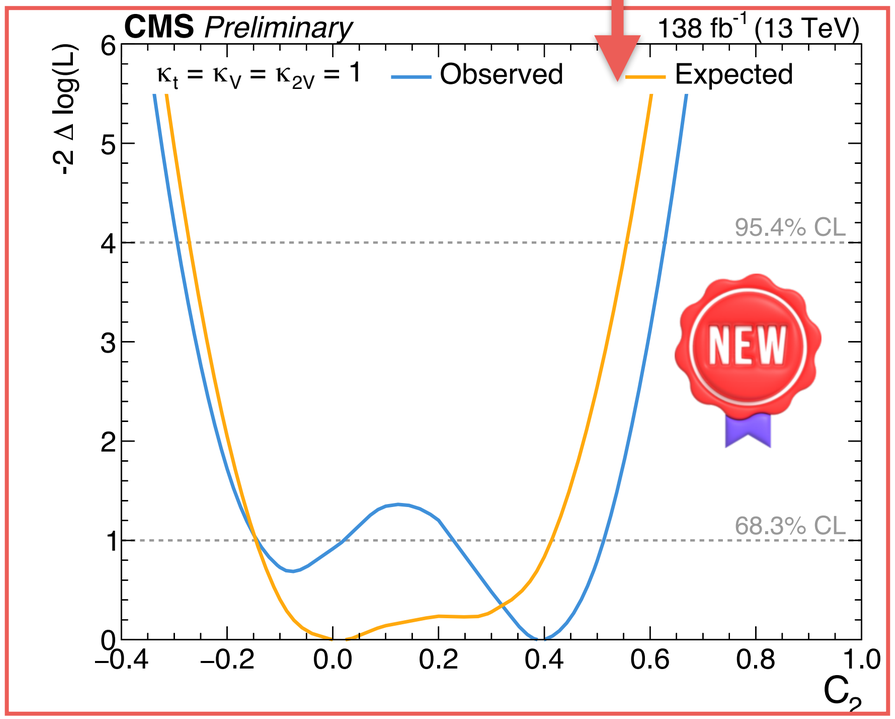
  PhysRevLett.131.041803
- ***Complementary role*** played by ***different analyses*** to constrain at best the 2D parameter space

HH combination: HEFT interpretation

- Parametrising ***BSM physics*** in ***HH*** solely with ***coupling modifiers*** (k_λ, k_{2V}, k_t, k_V) has ***limitations***
- The ***"Higgs Effective Field Theory" (HEFT)*** provides a ***complete basis*** for anomalous interactions in ***single-H*** and ***HH***
- ***Five HEFT operators*** modifies the dynamics of ggHH process @ LO: $c_{tth} \Leftrightarrow k_t$, c_{gghh}, $c_{hhh} \Leftrightarrow k_\lambda$, c_{gghh}, c_{tthh} (c_2)

PhysRevLett.133.101801





No significant deviations from the SM hypothesis have been observed … no indirect hints of new physics

Single-H + HH combination

- ***Single-H analyses*** used as an ***indirect precision*** tool for $\boldsymbol{\lambda_{HHH}}$ through ***NLO effects***
- Both single-H ***inclusive x-sec*** (ggH, VBF, VH, ttH) and ***differential distributions*** sensitive to $\boldsymbol{\lambda_{HHH}}$
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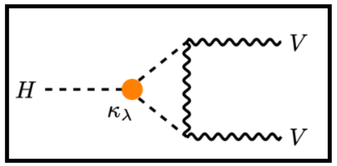

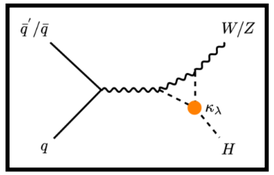

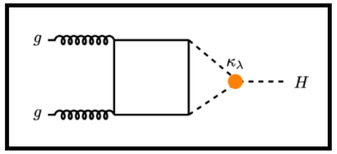

JHEP 1612, 080 (2016)

EPJ C (2017) 77 887

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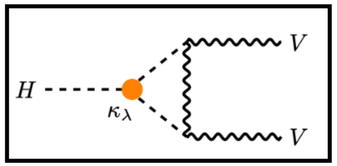

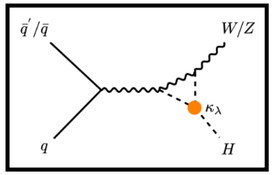

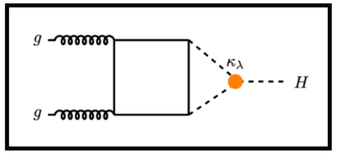

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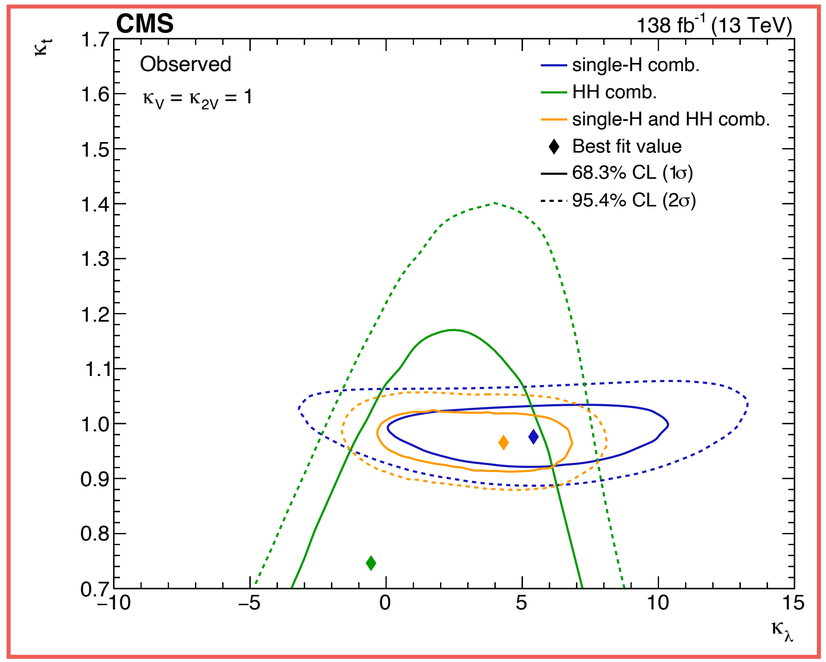
arXiv.2407.13554



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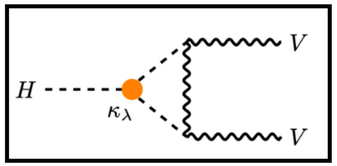

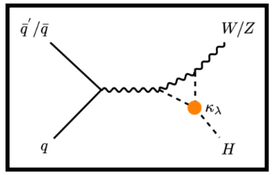

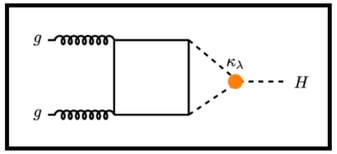

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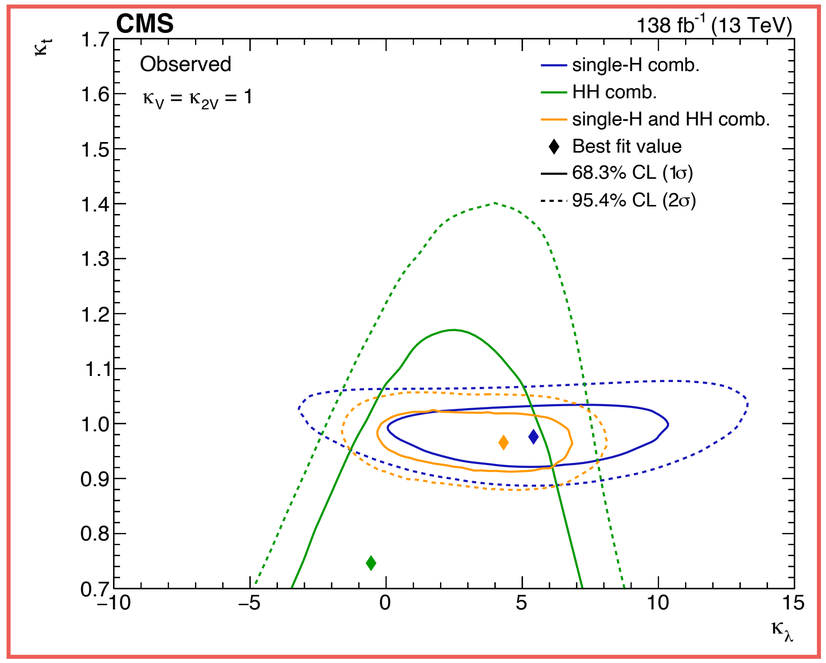
arXiv.2407.13554



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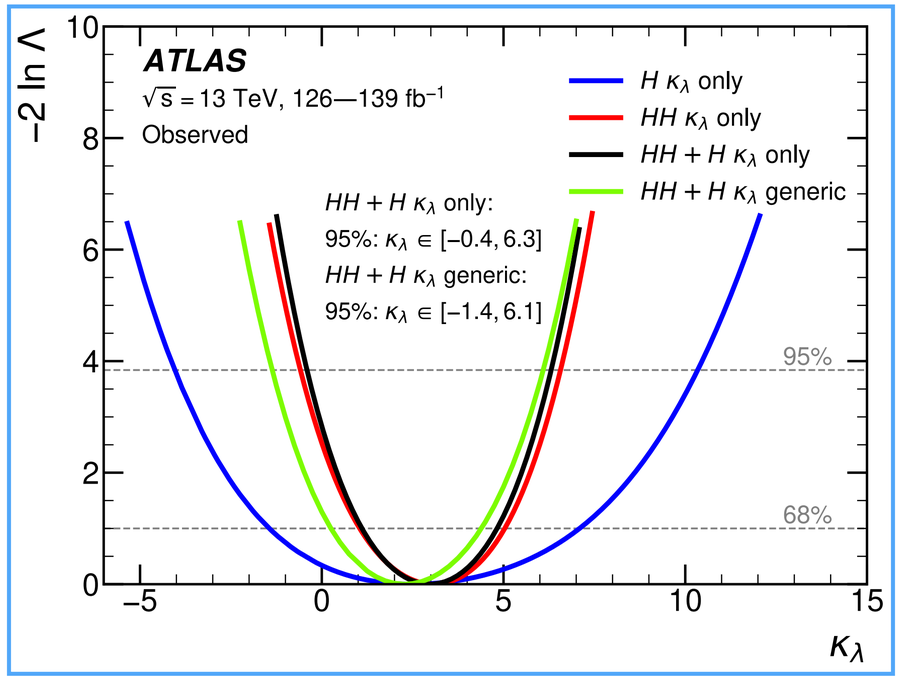

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Degeneracy of k_λ with k_V and k_f in single-H solved by direct HH searches

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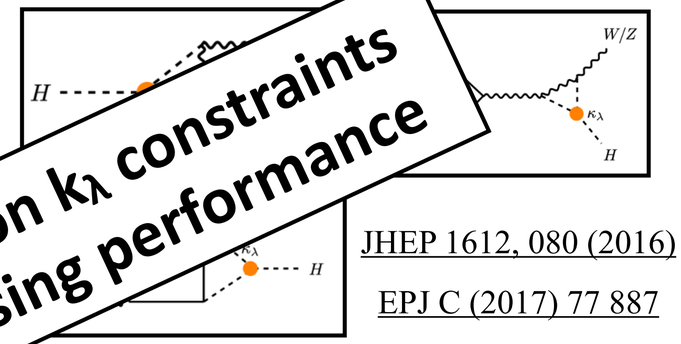

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Simultaneous fit of H+HH provides small improvements on κ_λ constraints but one can relax assumptions on κ_V and κ_f without loosing performance

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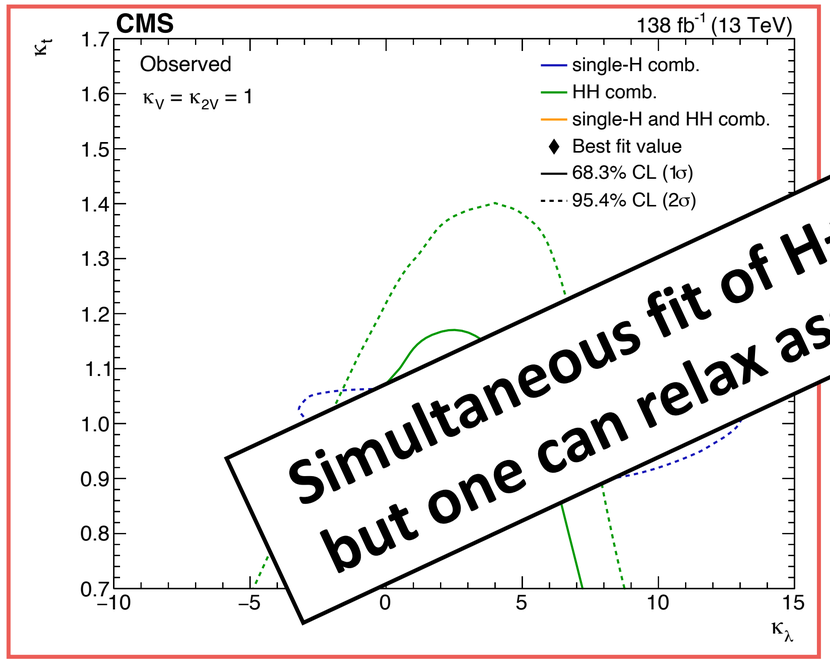

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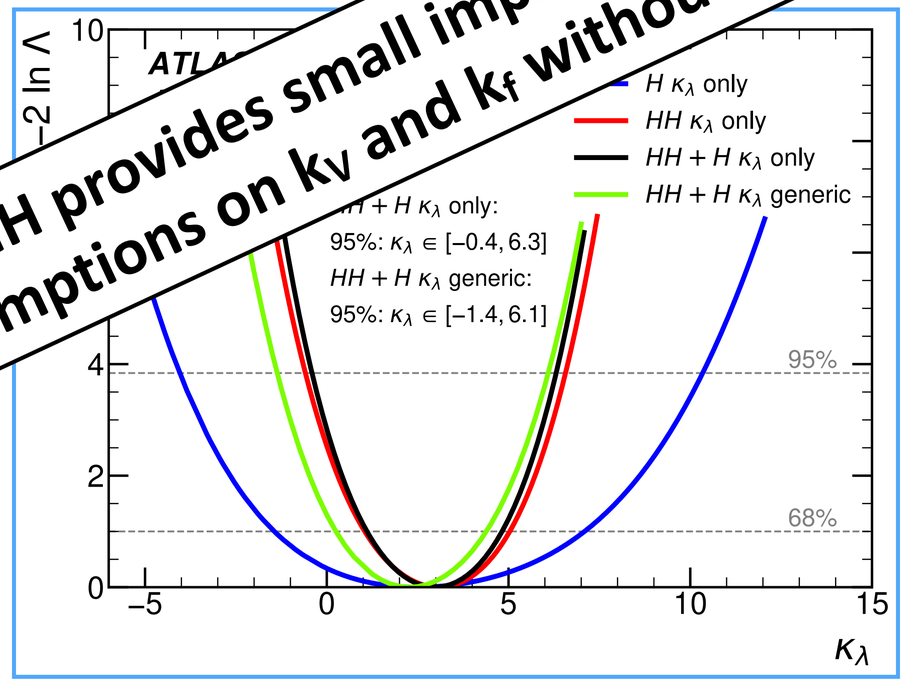
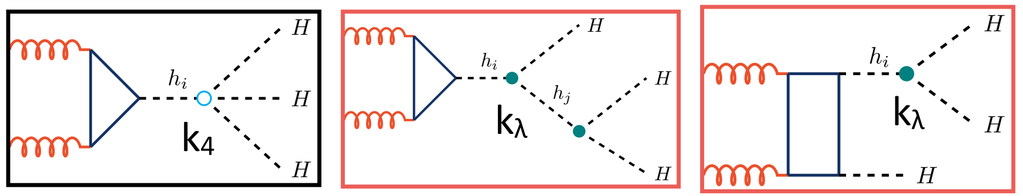


Degeneracy of k_λ with k_V and k_f in single-H solved by direct HH searches

Search for HHH→6b at 13 TeV

- ***First constraints*** on Higgs ***quartic (k_4)*** gauge ***coupling*** exploring HHH→6b
- ***Leading mode*** for non-resonant production of HHH is ***gluon-fusion***
- ***Signal region*** has 6 b-jet, ***control regions*** with either 5 or 4 b-jet
- ***Higgs candidates*** are constructed via a mass-based pairing algorithm
- *Signal purity* improved via a DNN based on selected jet kinematic features
- *Background estimate* is data-driven predicting yields in each DNN bin from (5b,4b)
- *Signal extraction* via a simultaneous fit to DNN across 5b and 6b

σ(gg-HHH) at NNLO-QCD is 0.079 fb @ 13 TeV



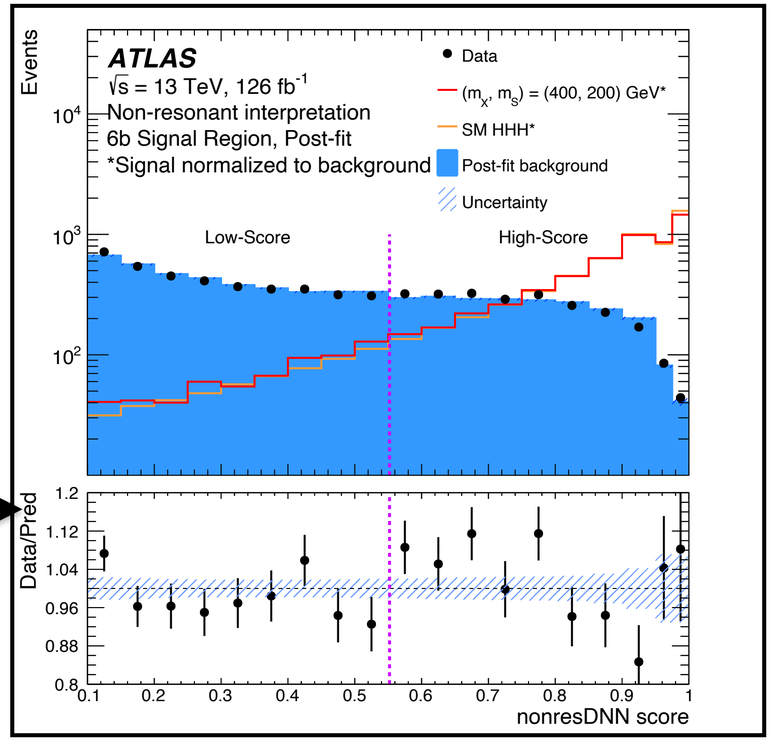
HHH also sensitive to k_λ

At 95% CL no phase-space within unitary bound is excluded

95% CL UL on μ_{HHH} is < 750 x SM

-230 < k_4 < 240 at 95% CL for k_λ = 1

arXiv:2411.02040



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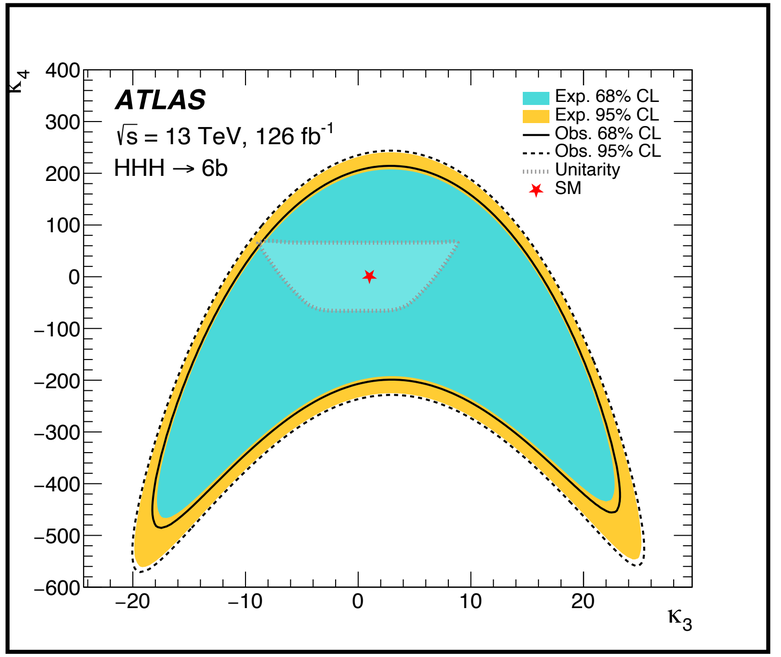

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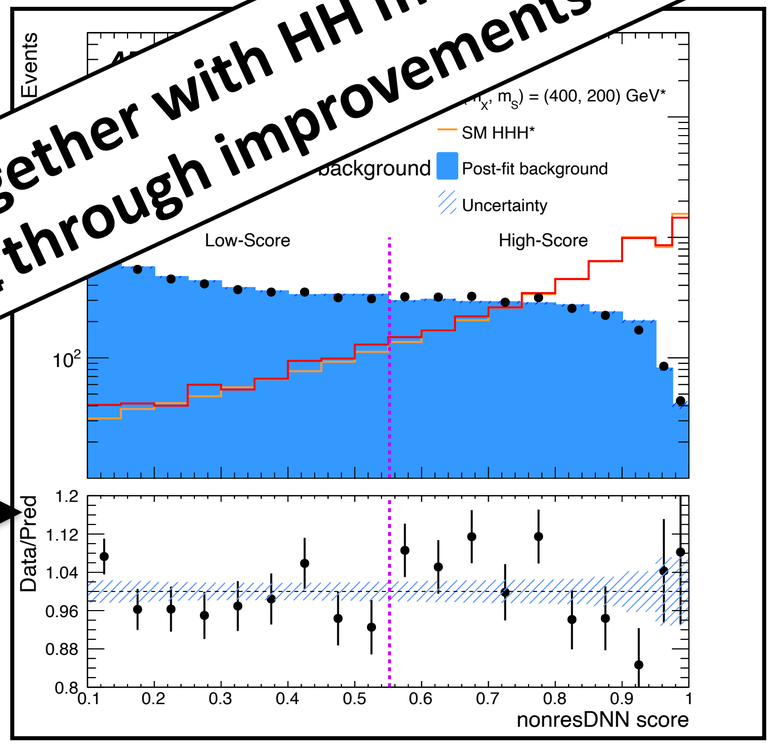
σ(gg-HHH) at NNL… …079 fb @ 13 TeV

HHH also sensitive to k_λ

Need to be fit together with HH measurements to better constrain k_4 through improvements in k_λ bounds

arXiv:2411.02040



At 95% CL no p… …within unitary bou… …xcluded

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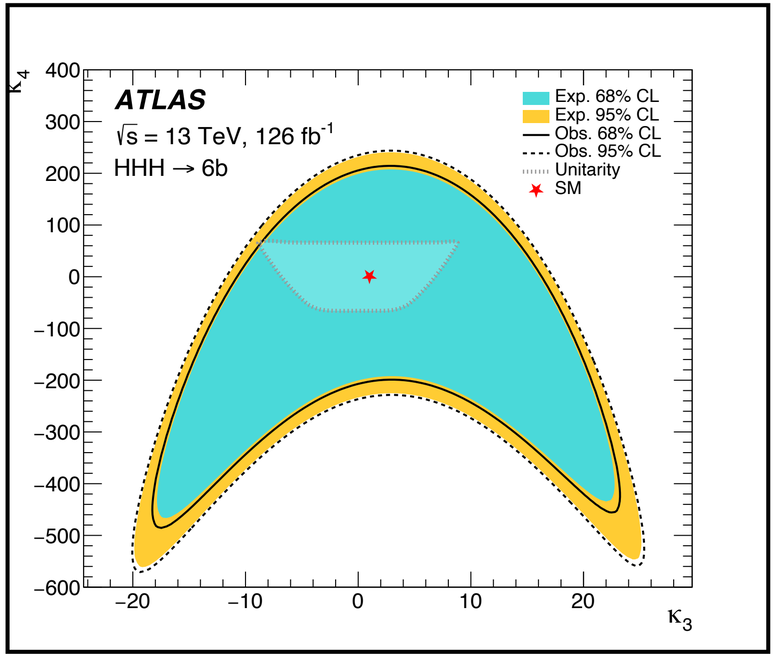
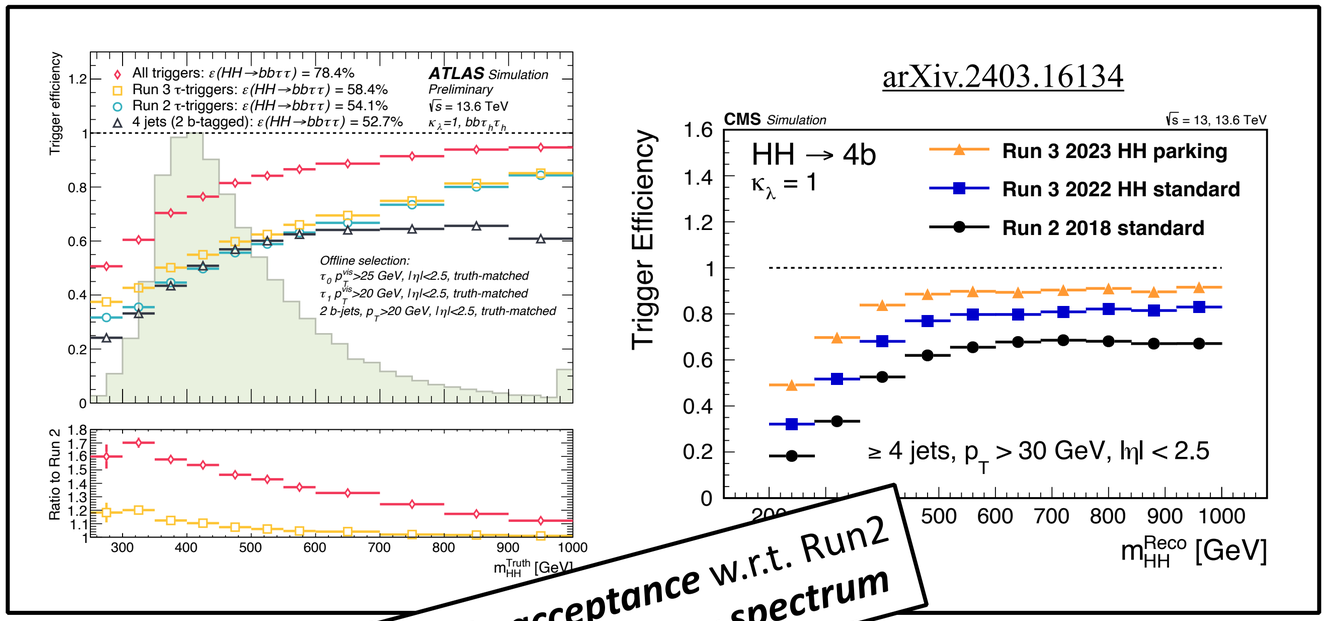


Run3 prospects from ATLAS and CMS

- ***Run3*** will ***at least triple*** the size of pp-collision data set → already ≈ 180 fb^{-1} collected at 13.6 TeV
- Both ATLAS and CMS introduced ***several improvements that will impact their HH program:*** hadronic triggers, b-jet and τ_h tagging, jet energy resolution, boosted H→ bb tagging + mass reconstruction, etc.

Improved triggers for HH → 4b and HH→bb$\tau_h\tau_h$

ATL-COM-DAQ-2023-100



arXiv.2403.16134

Large gain in acceptance w.r.t. Run2 triggers over the full m_{HH} spectrum

Run3 prospects from ATLAS and CMS

- ***Run3*** will ***at least triple*** the size of pp-collision data set → already ≈ 180 fb^{-1} collected at 13.6 TeV
- Both ATLAS and CMS introduced ***several improvements that will impact their HH program:*** hadronic triggers, b-jet and τ_h tagging, jet energy resolution, boosted H→ bb tagging + mass reconstruction, etc.

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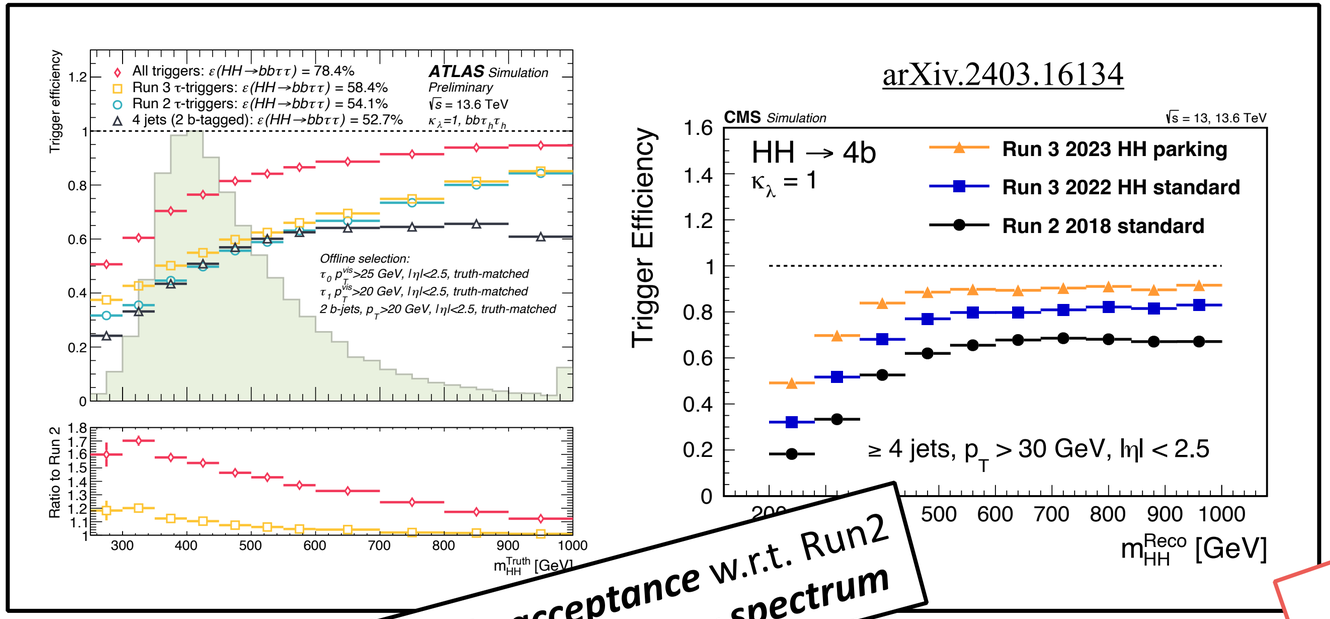
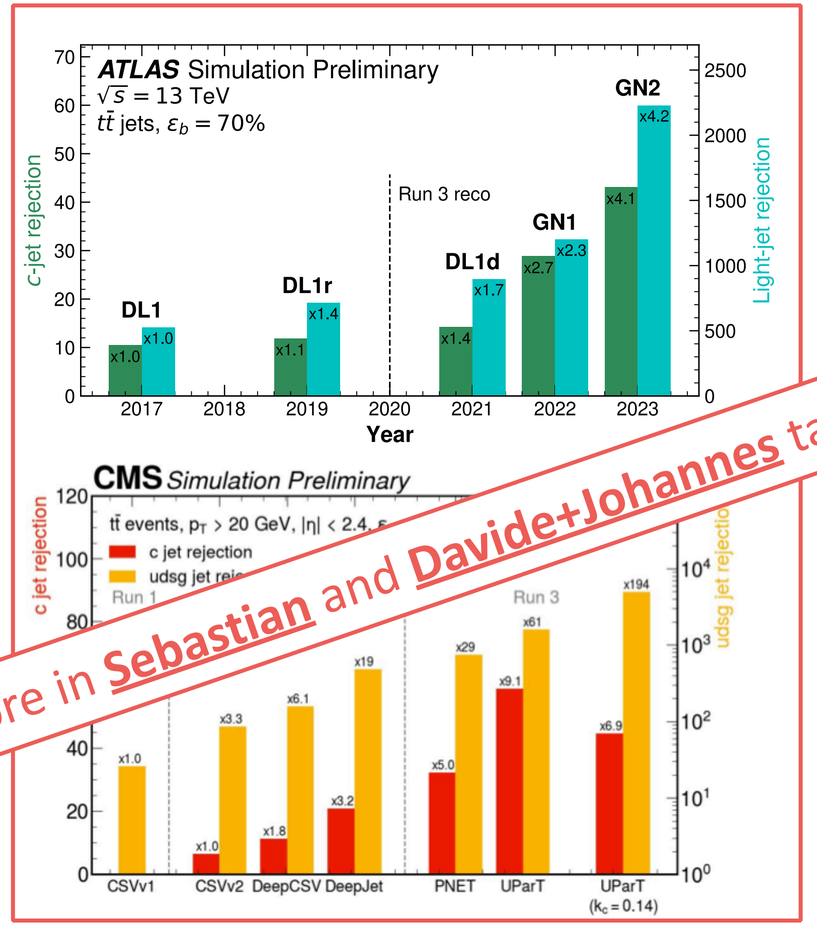
ATL-COM-DAQ-2023-100



Large gain in acceptance w.r.t. Run2 triggers over the ***full m_{HH} spectrum***

Improvements in b-tagging



FTAG-2023-01

CMS-DP-2024-066

More in **Sebastian** and **Davide+Johannes** talks

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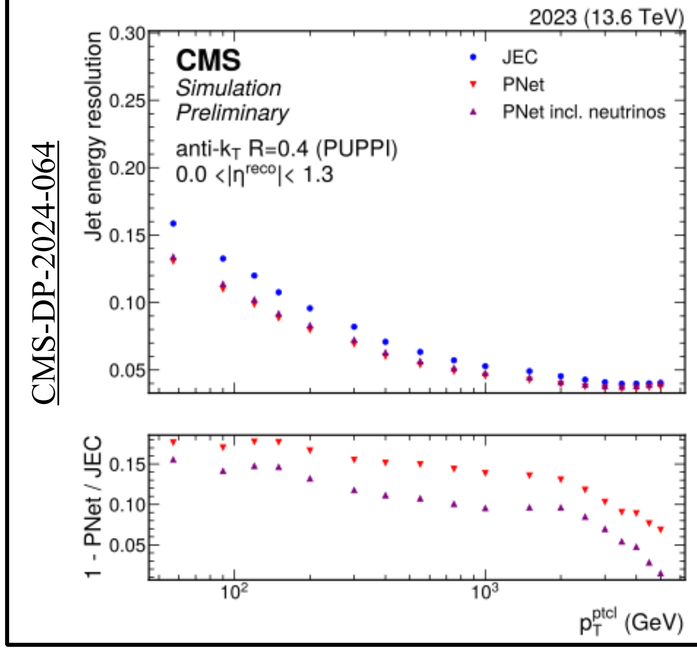
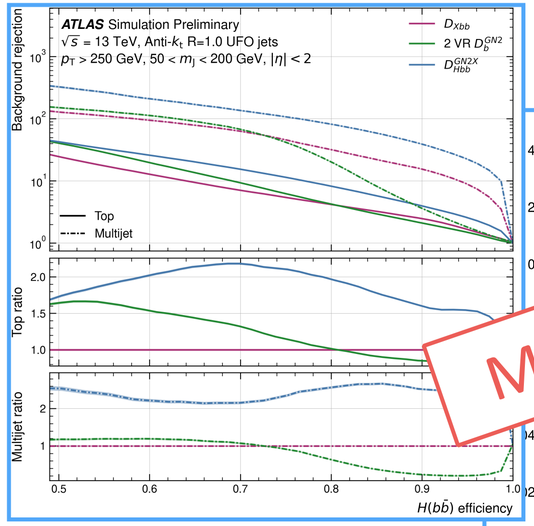
Jet energy resolution

- ***ML-based p_T calibration*** improves by ***5-20%*** the resolution of uds/g jets and even-more for b/c jets



Boosted H→bb tagging + mass regression

- ATLAS: transformer-based GNN for H→bb(cc) tagging and m_H regression
- CMS: ParT for tagging and m_H regression → improved performance and larger number of boosted signatures including H→VV→4q



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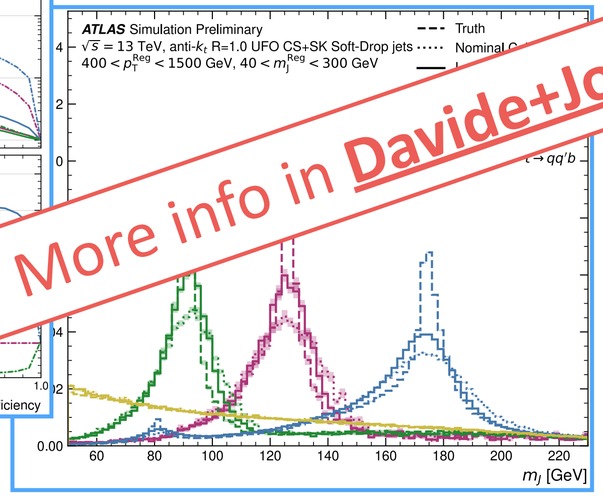

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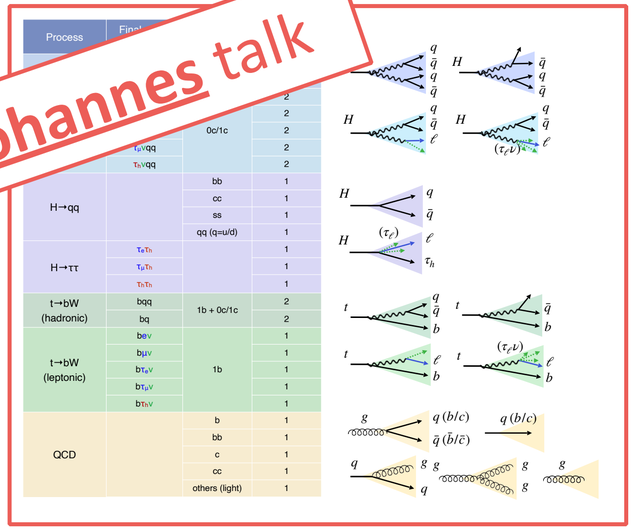
More info in **Davide+Johannes** talk



CMS-PAS-HIG-23-012

Summary and outlook

- ***Di-Higgs production*** is a ***key probe*** of the ***EWSB*** mechanism
  - Allows to access the ***Higgs-boson self-coupling*** with LHC data → probe the shape of the ***Higgs field potential***
  - Allows to access another rare ***quartic gauge coupling*** → ***HHVV interactions***

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- ATLAS and CMS performed a *large set* of *analysis* with Run2 data covering:
  - *Most relevant decay channels* in terms of branching ratio and expected S/B
  - The two main HH production modes: *gluon-fusion* (leader in k_λ) and *VBF* (leader in k_{2V})
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- *Run3 prospects:*
  - The expected *95% CL UL on* μ_{HH} is about *2.5 x SM* per experiment with *Run2*
  - *Assuming* that results will *scale with luminosity* → *1.5 x SM* per experiment (*Run2+Run3*)
  - Combining ATLAS + CMS results → *1 x SM (Run2+Run3)* → *2σ significance*
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Summary and outlook

- ***Di-Higgs production*** is a ***key probe*** of the ***EWSB*** mechanism
  - Allows to access the ***Higgs-boson self-coupling*** with LHC data → probe the shape of [illegible] ***otential***
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Can we dream for an evidence for HH before the startup of HL-LHC ??

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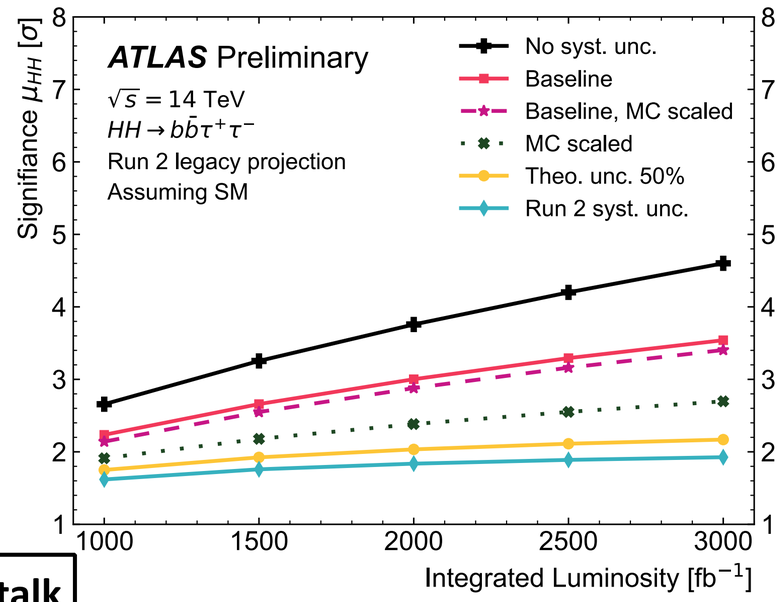
Backup material

HL-LHC most recent projections

- Both ATLAS and CMS recently **updated HL-LHC projections** for **HH measurements** on the latest Run2 results (140 fb^{-1})
- **Current projections** based on **luminosity extrapolation** of Run2 in different **scenarios** for **systematic** uncertainties

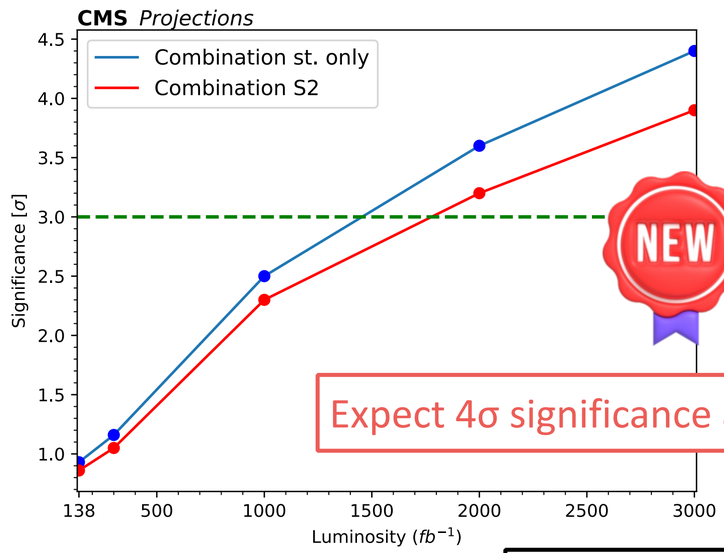
- Projection for ATLAS HH→bbττ analysis only
- Current analysis has expected significance of 2σ at 3 ab^{-1}
- Baseline analysis with recommended theory and experimental uncertainties → 3.5σ significance at 3 ab^{-1}

ATL-PHYS-PUB-2024-016



More in Alex's talk

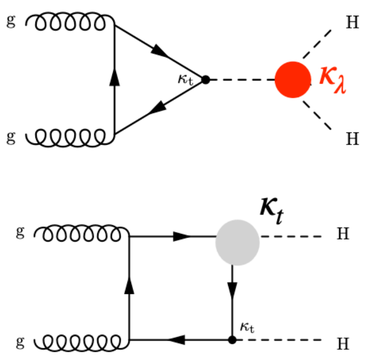
- Projection for the combination of CMS bbττ, bbγγ, 4b, multi-lepton, and bbWW
- Scenario 2 of systematic uncertainties scaling them by $\sqrt{L}$ until reaching a floor CYRM-2019-007.221

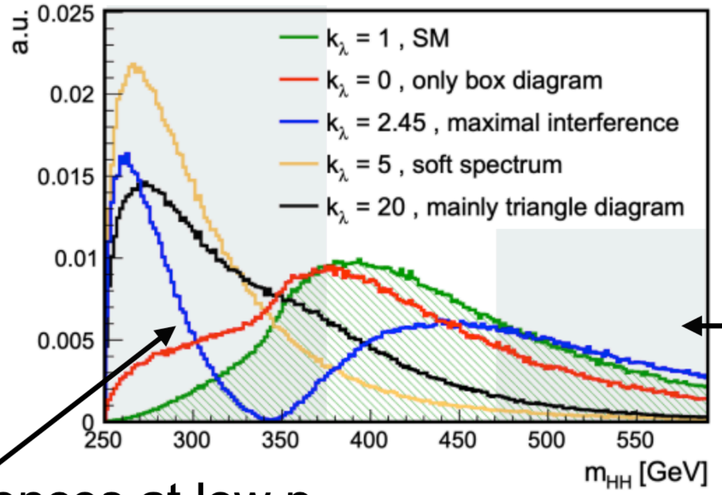


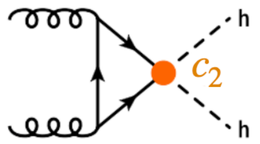
Expect 4σ significance at 3 ab^{-1}

More in Angela's talk

HH production properties



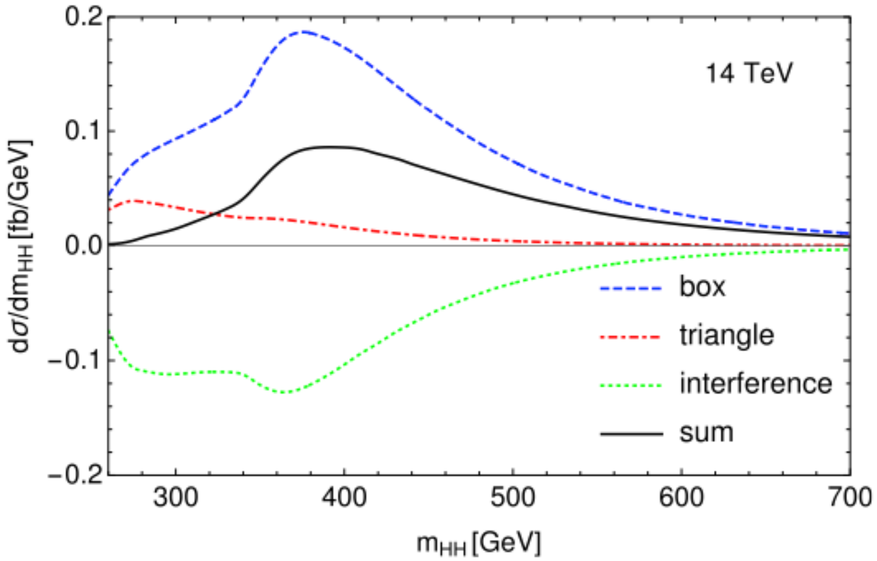


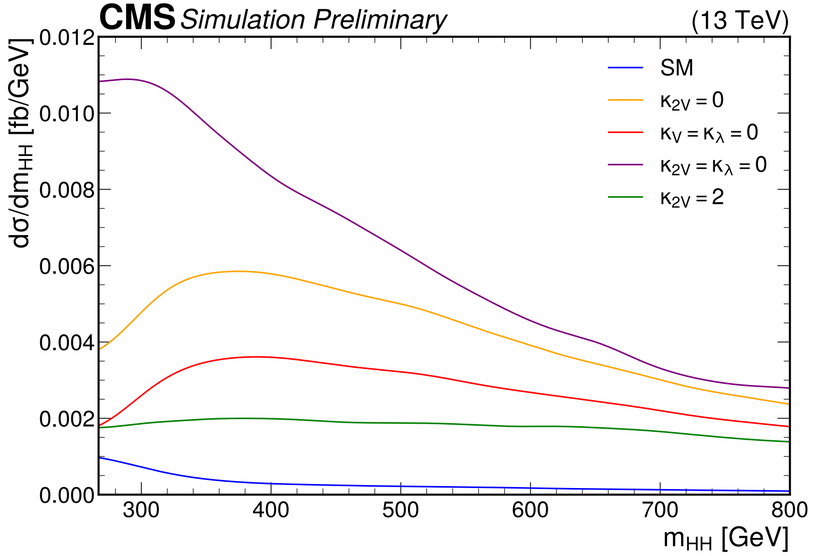


Activate new vertices: HEFT

I. Dutta talk

Modify λ_{hhhh} : differences at low p_T





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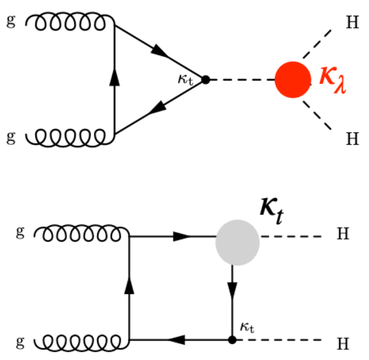

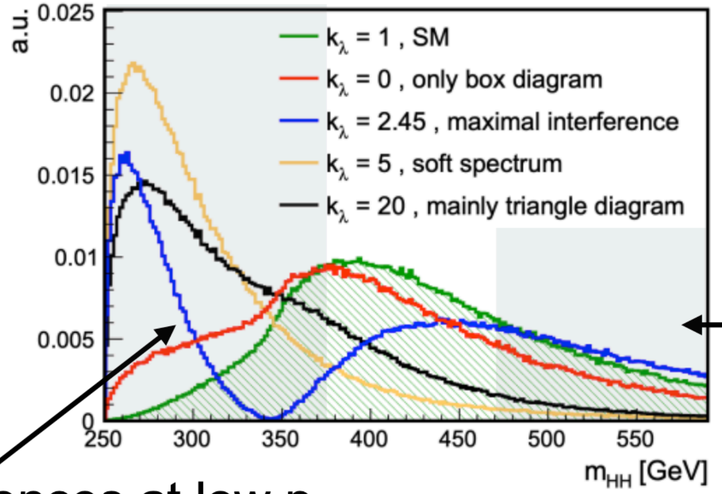

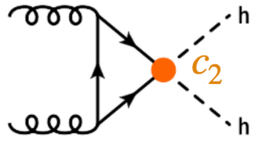

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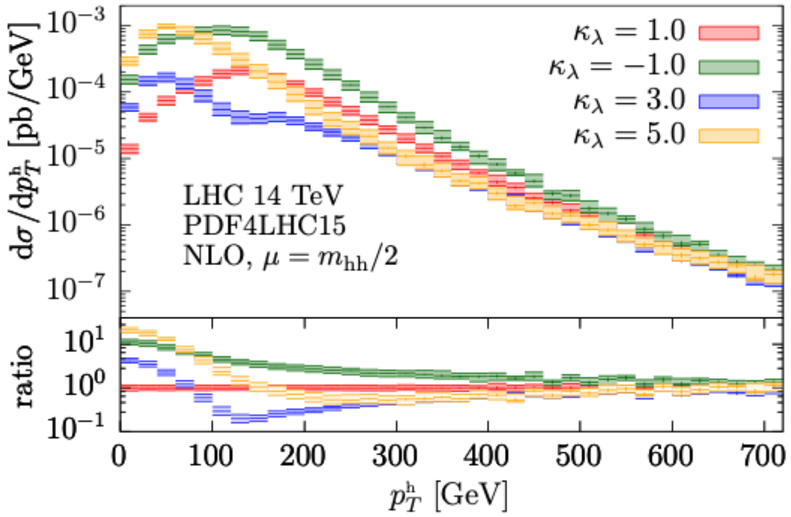
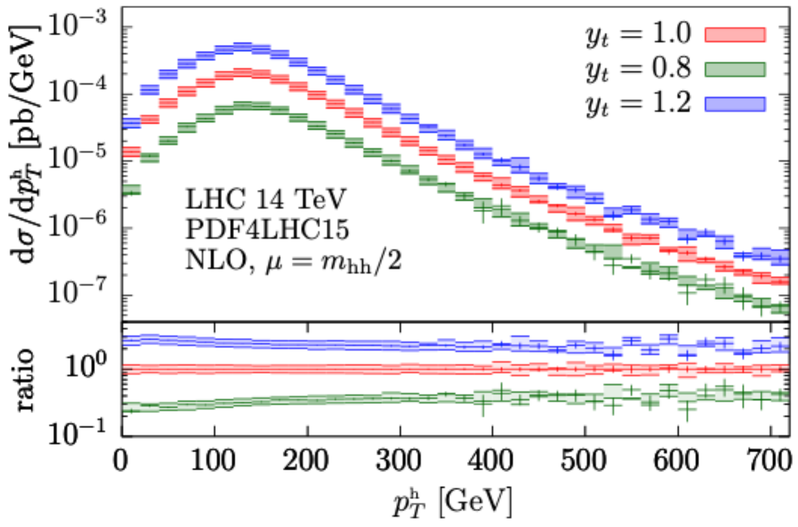
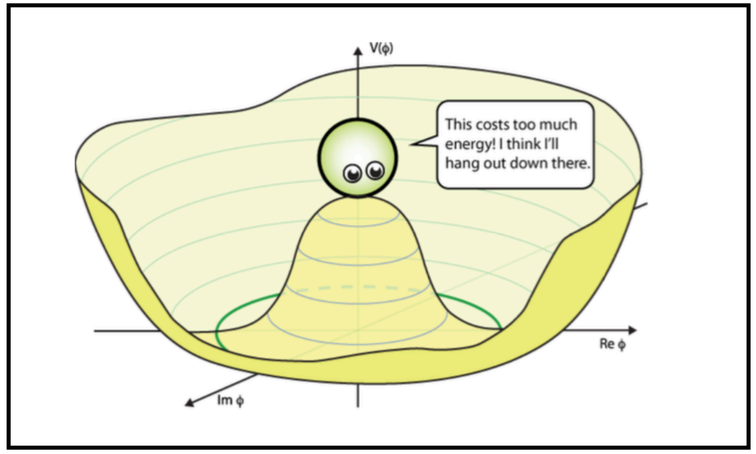
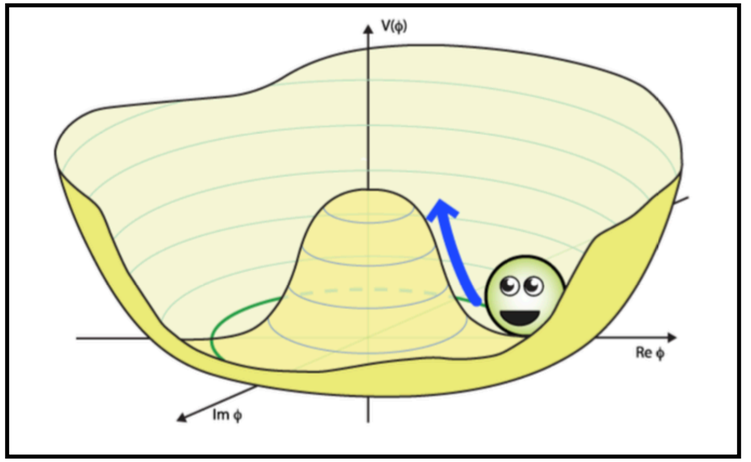
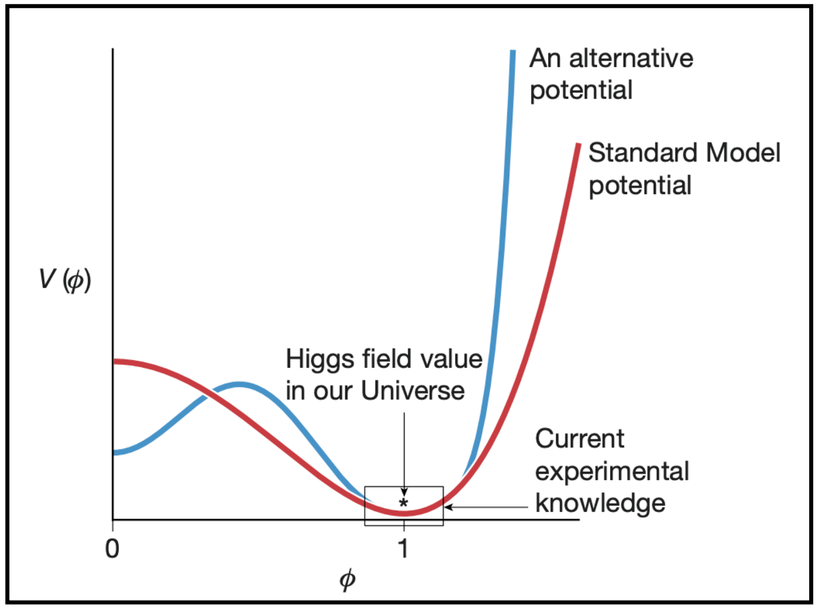




Higgs potential







Higgs potential

$$V(H) \simeq \begin{cases} -m^2 H^\dagger H + \lambda (H^\dagger H)^2 + \frac{c_6 \lambda}{\Lambda^2} (H^\dagger H)^3, & \text{Elementary Higgs} \\ -a \sin^2(\sqrt{H^\dagger H}/f) + b \sin^4(\sqrt{H^\dagger H}/f), & \text{Nambu-Goldstone Higgs} \\ \lambda (H^\dagger H)^2 + \epsilon (H^\dagger H)^2 \log \frac{H^\dagger H}{\mu^2}, & \text{Coleman-Weinberg Higgs} \\ -\kappa^3 \sqrt{H^\dagger H} + m^2 H^\dagger H, & \text{Tadpole-induced Higgs} \end{cases}$$

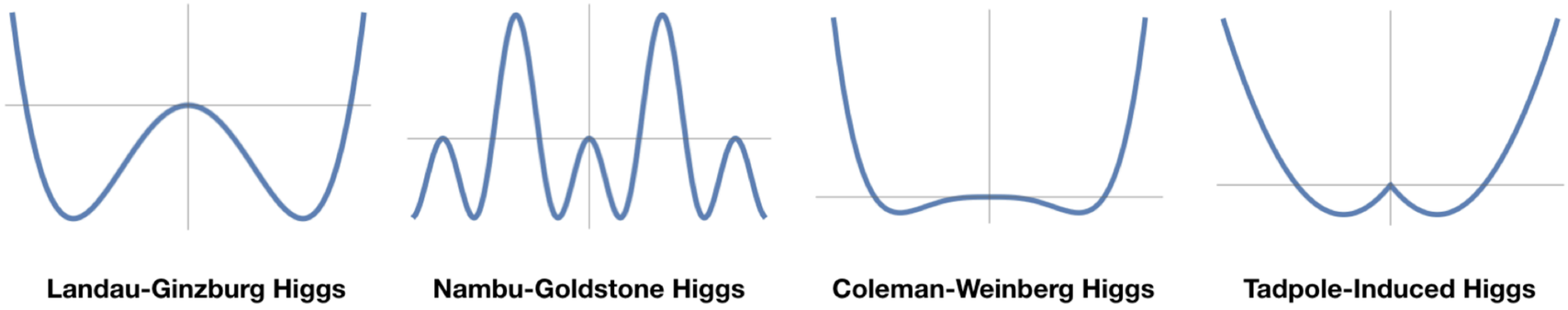
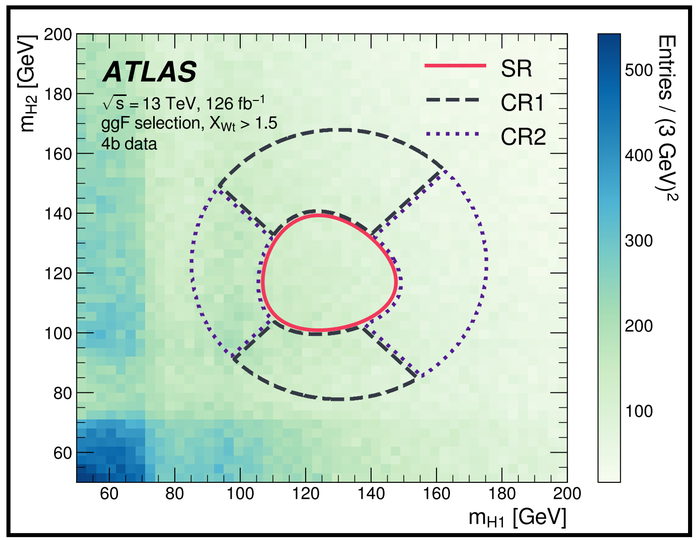
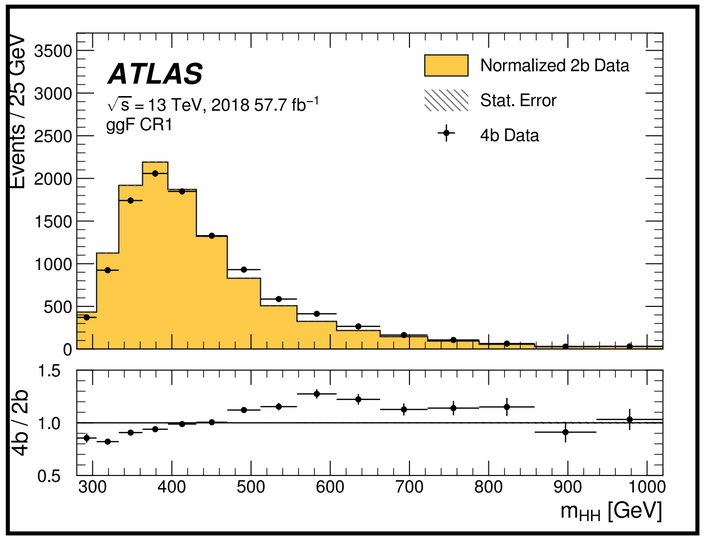
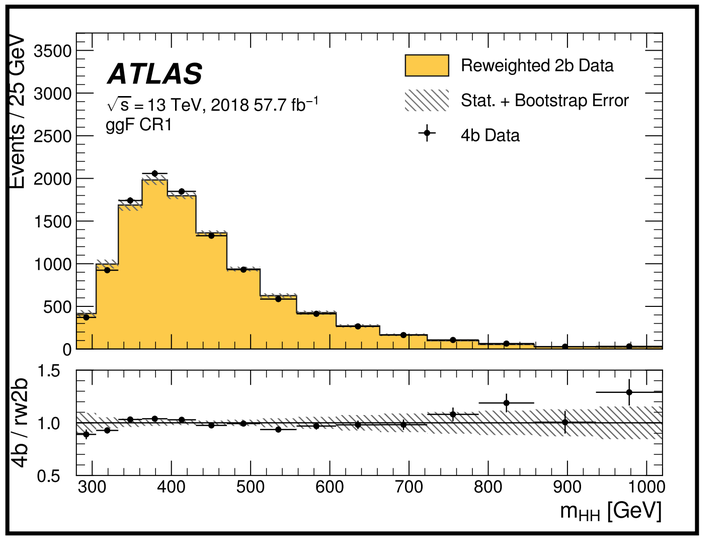


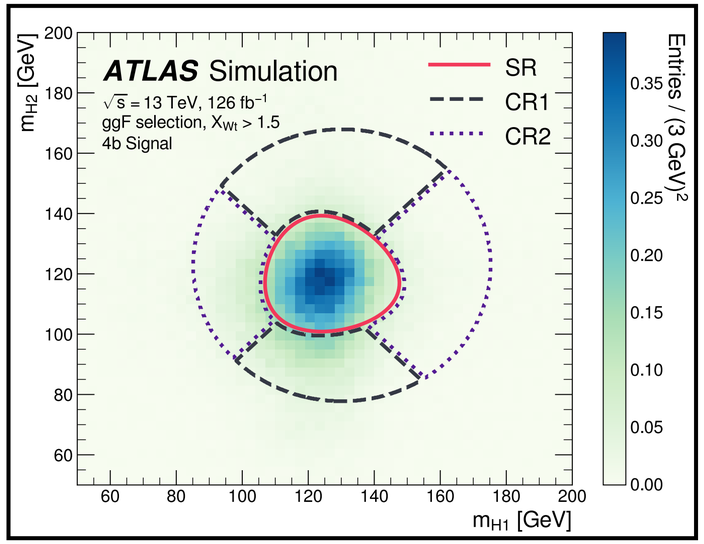
Figure 1: The shapes of Higgs potential for various scenarios studied in this work.

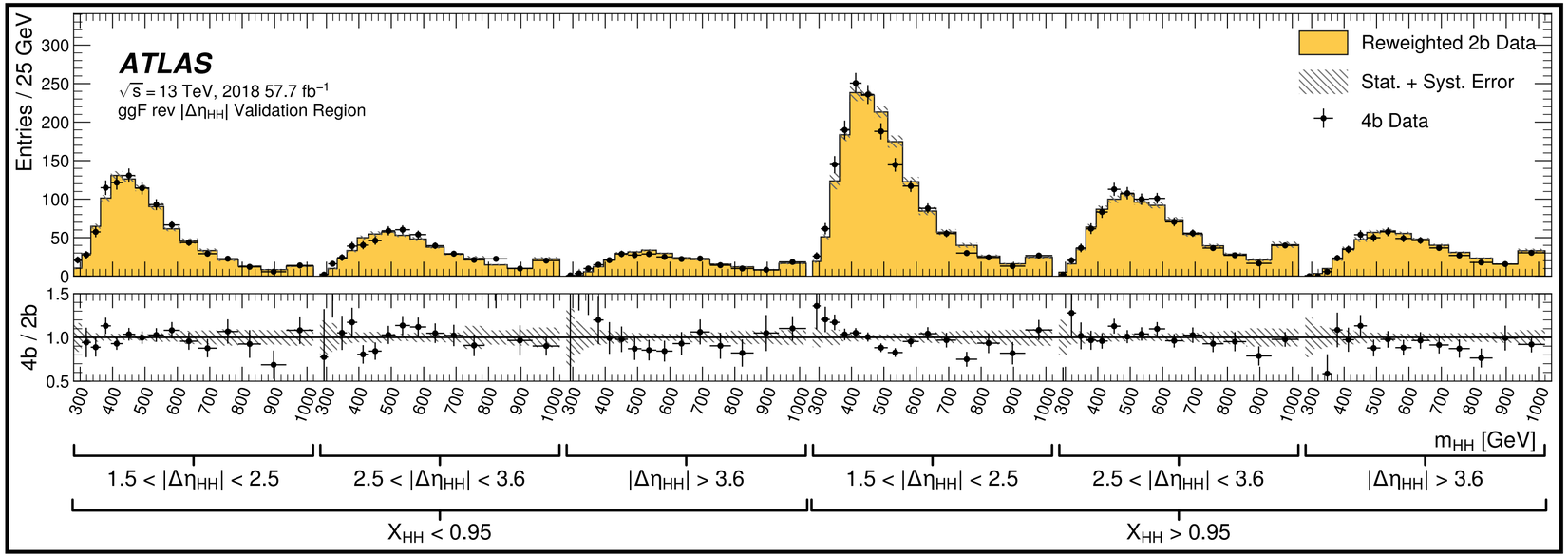
ATLAS HH→4b resolved











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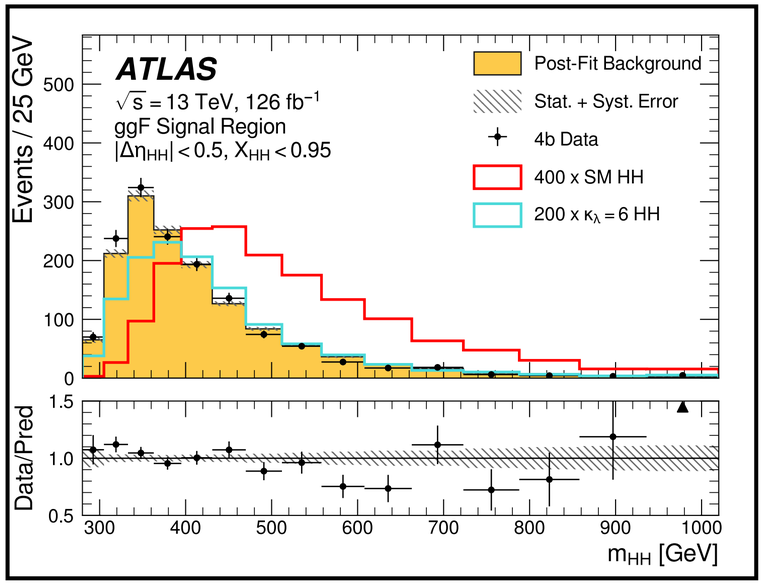
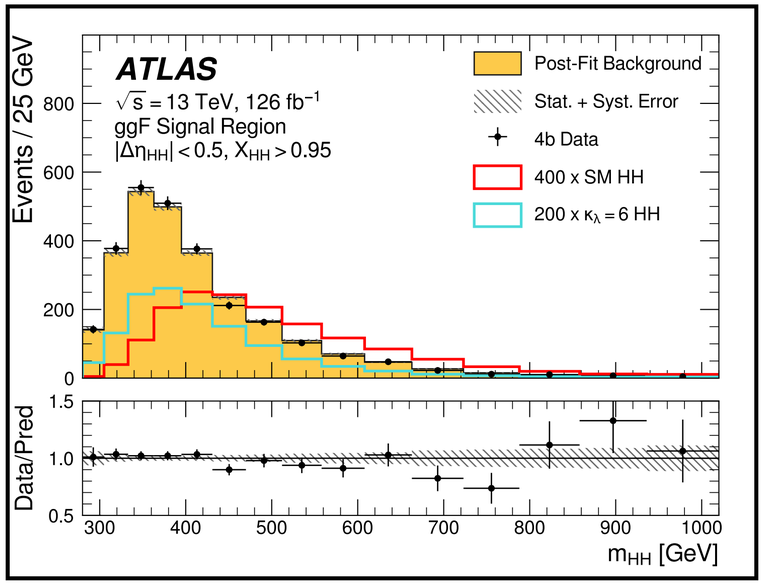
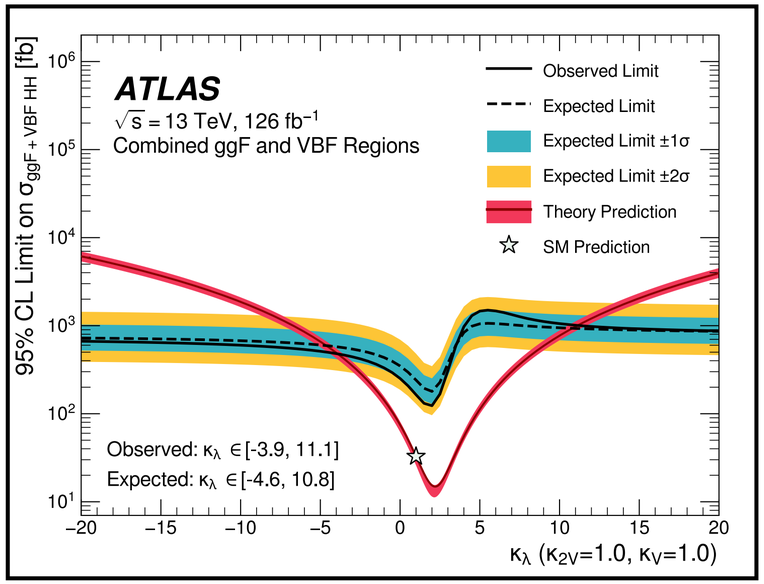
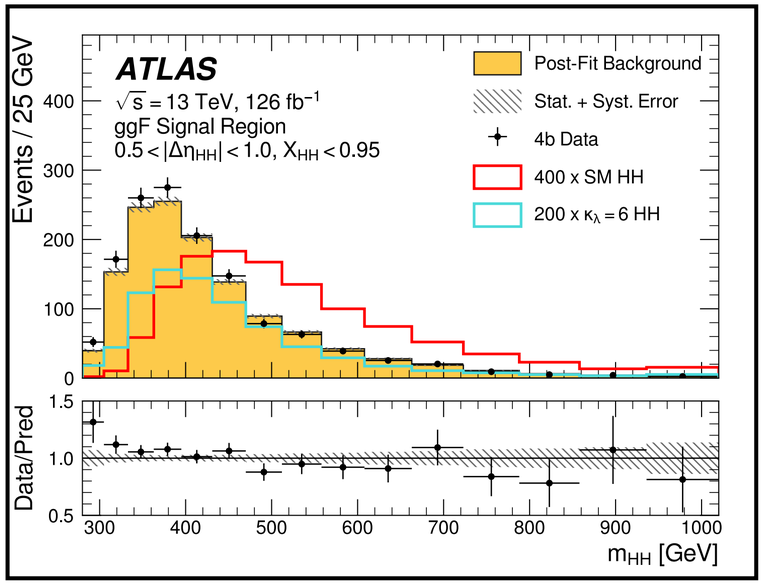
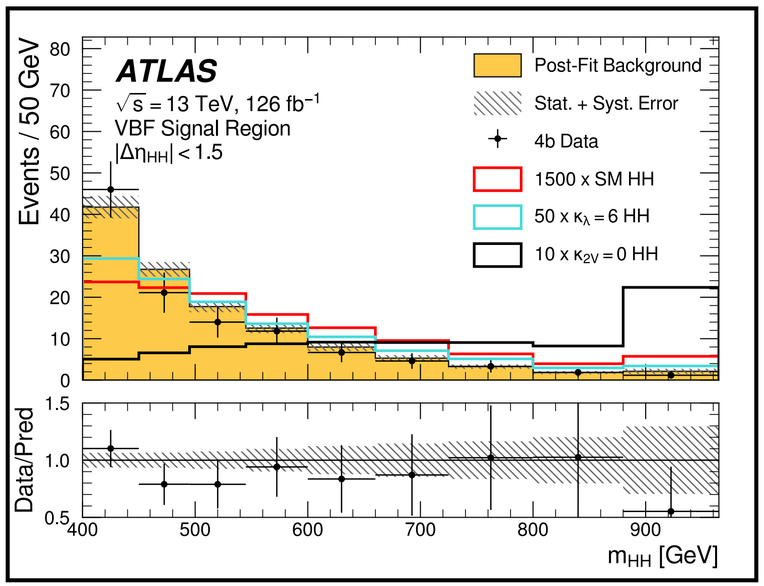
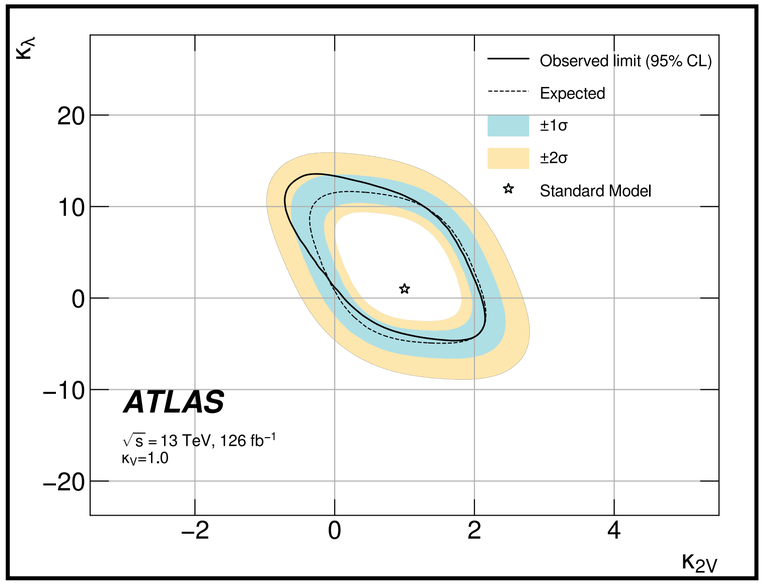




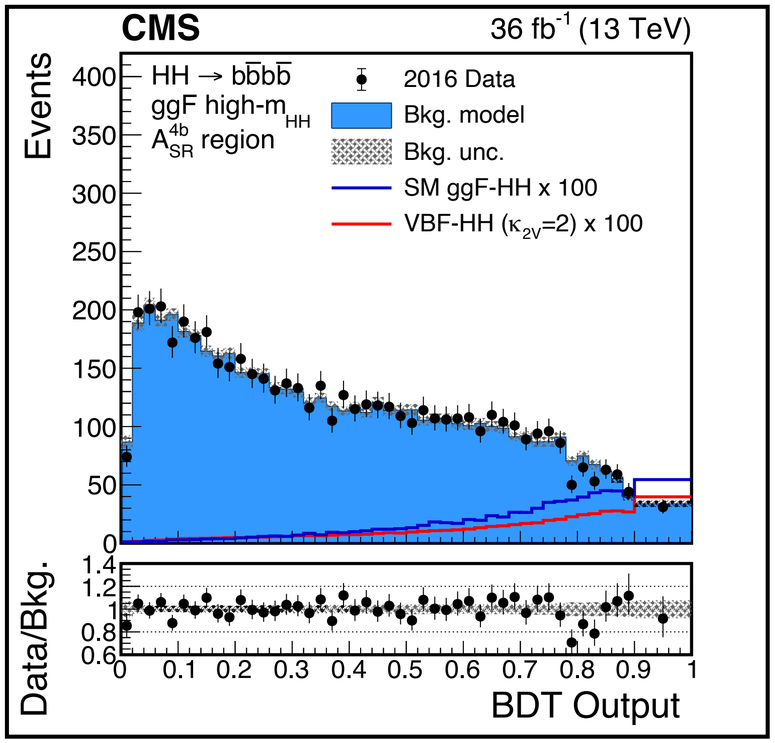


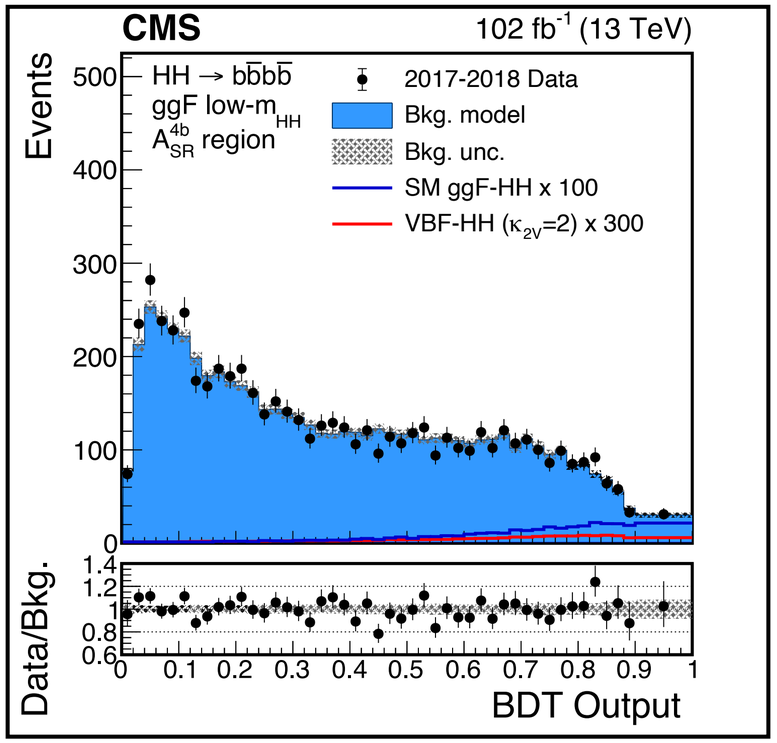


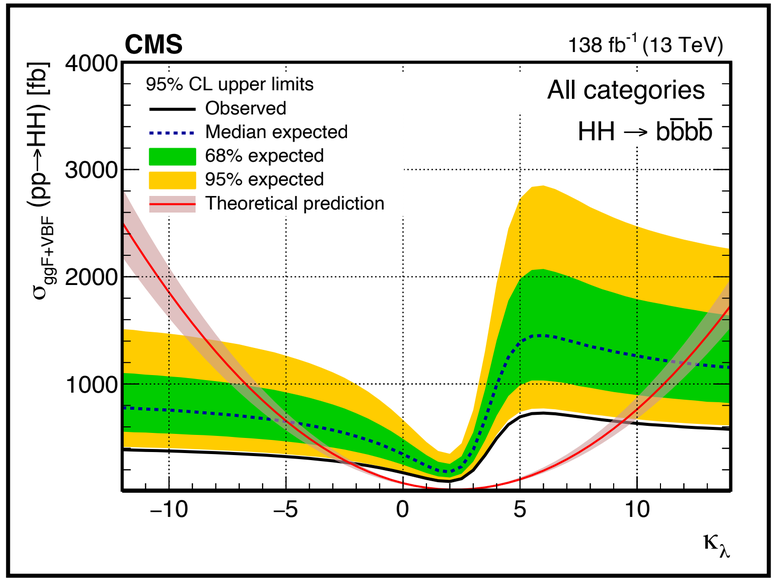


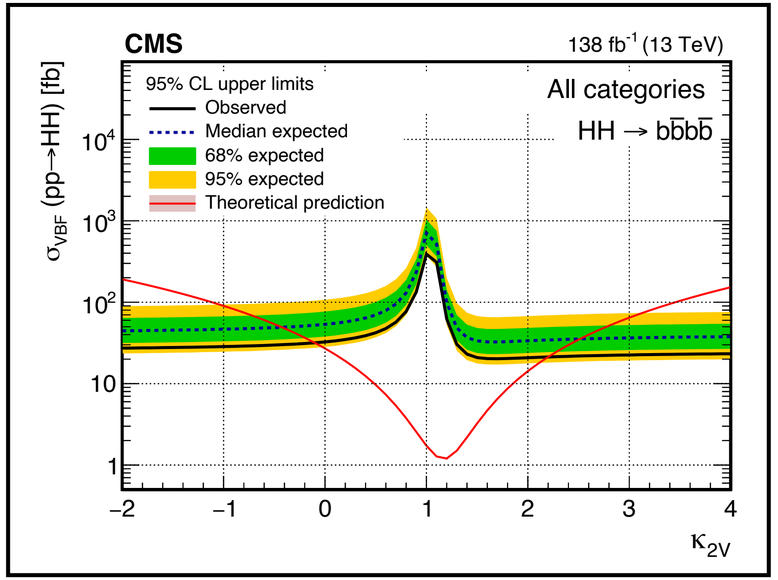


CMS HH→4b resolved

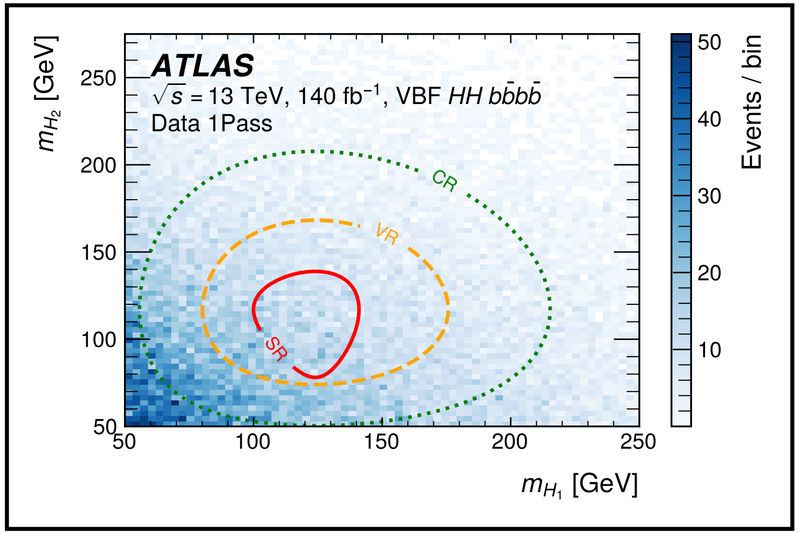


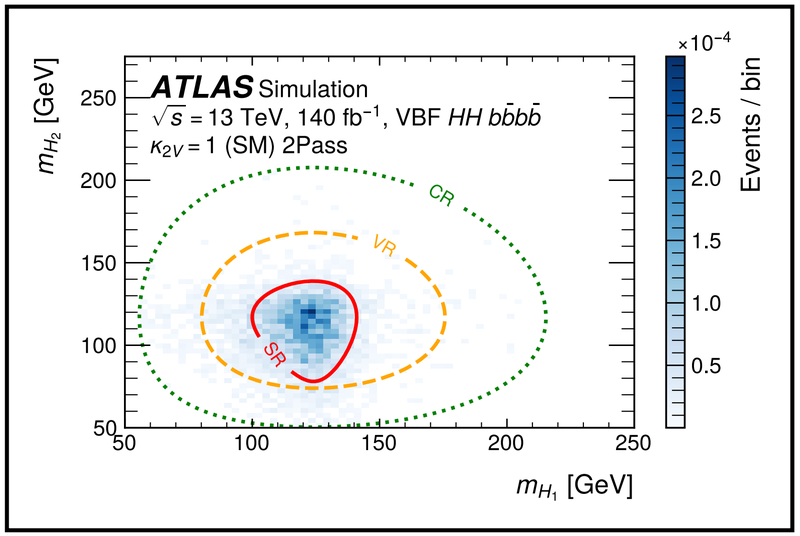


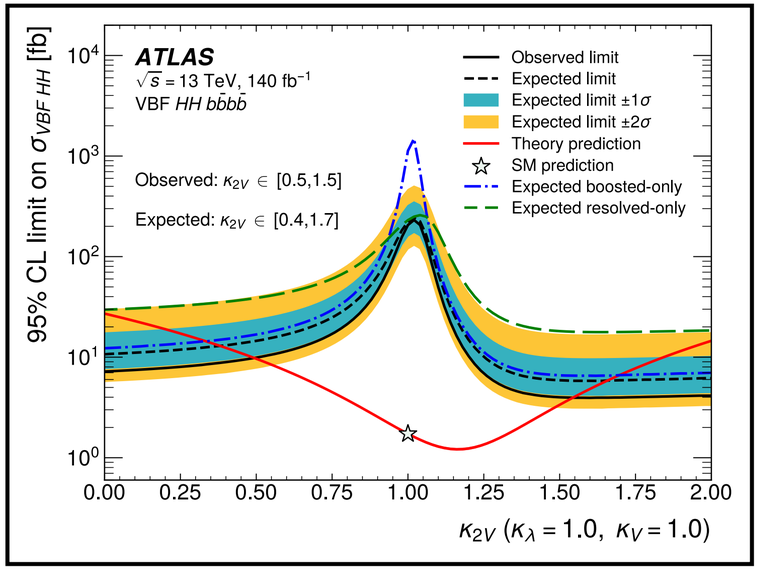


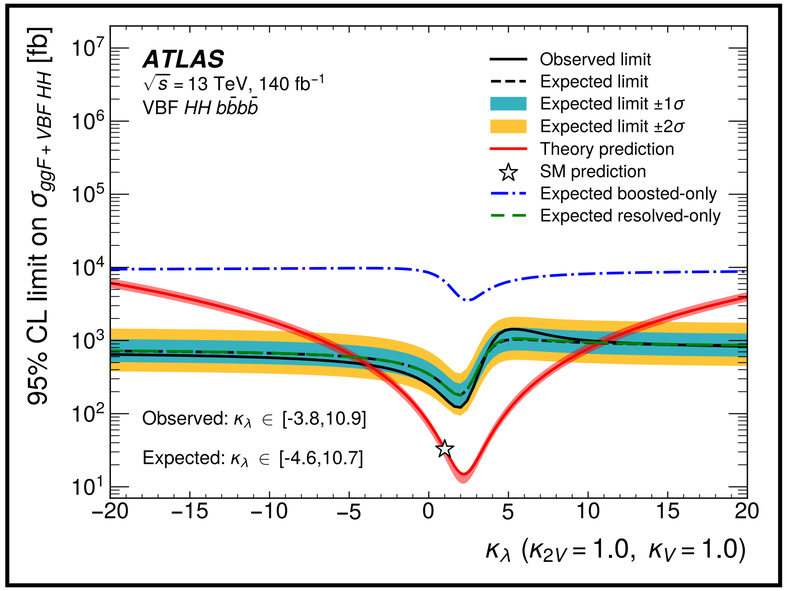


ATLAS VBF HH→4b boosted

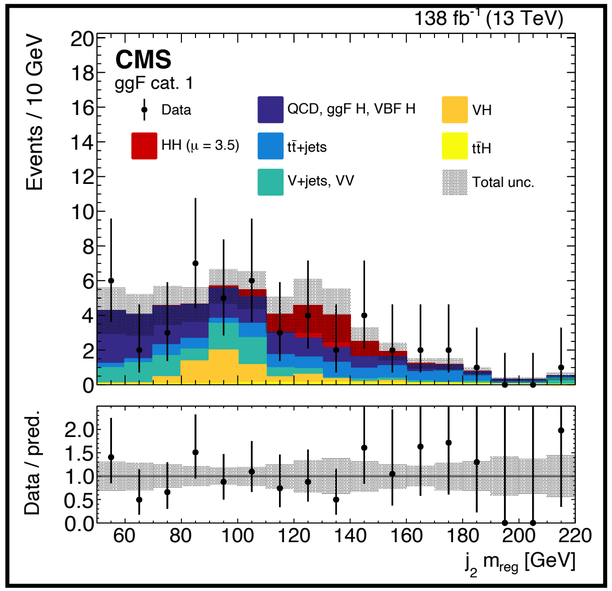


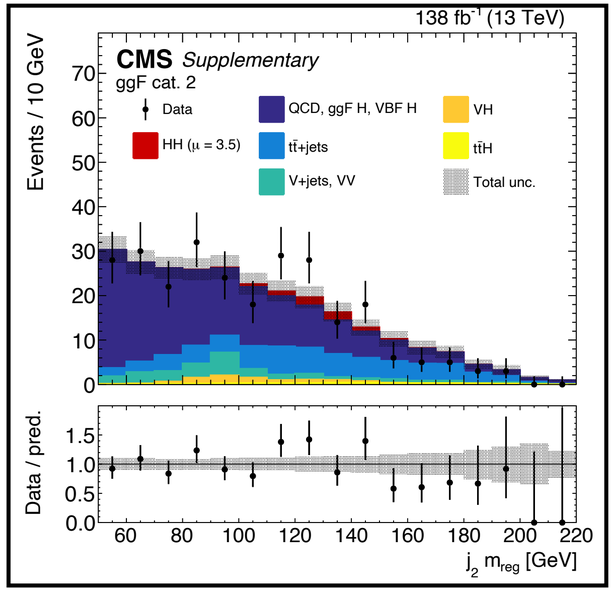


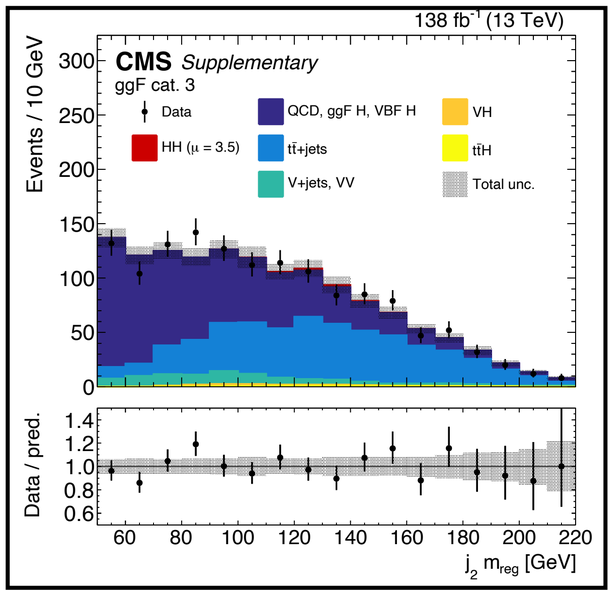


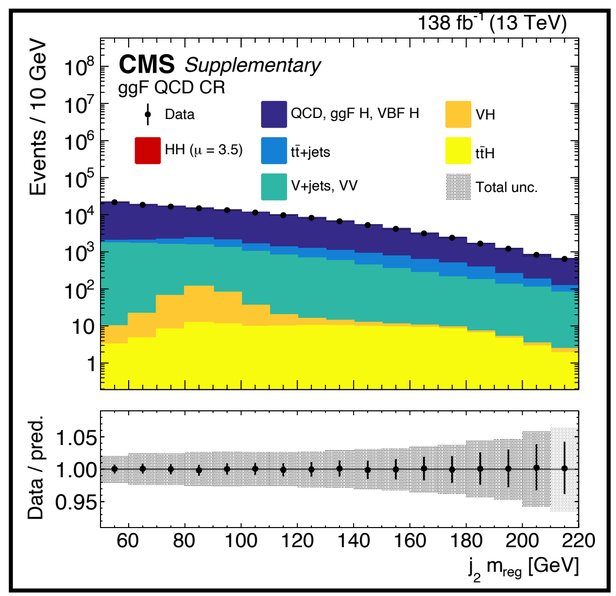


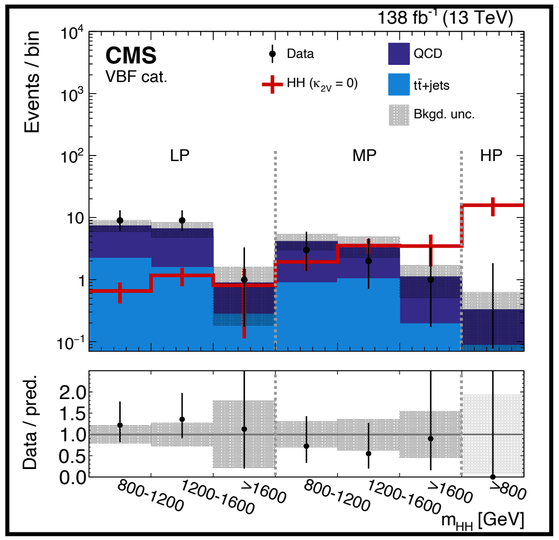
CMS HH→4b boosted

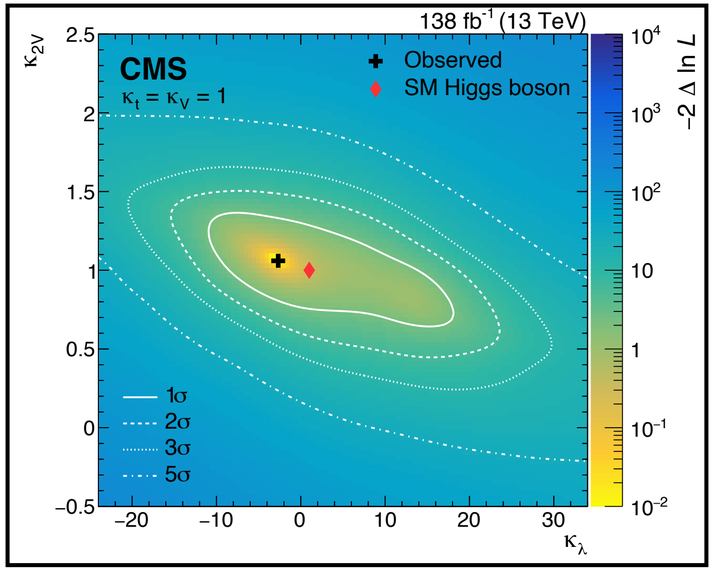


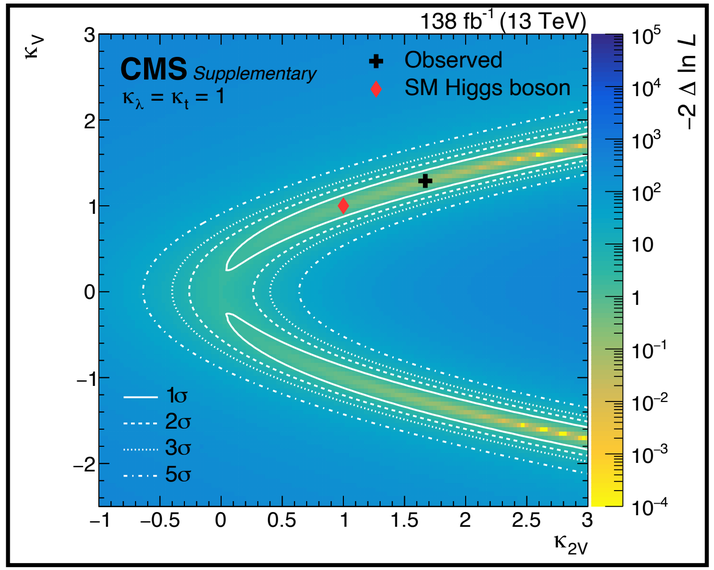




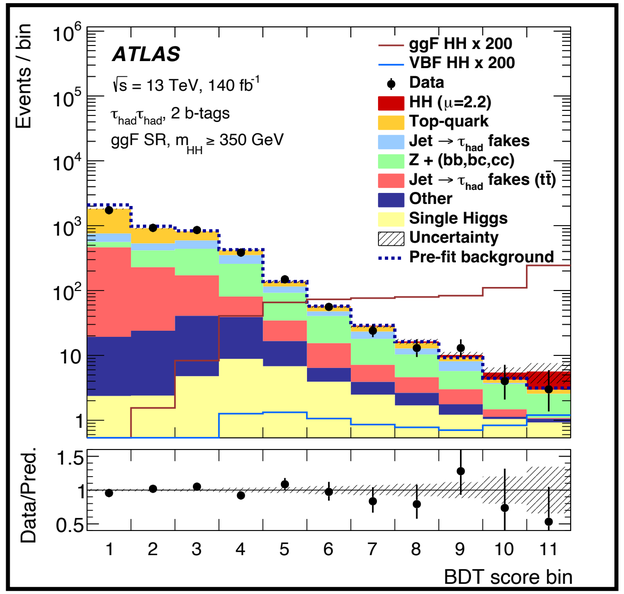


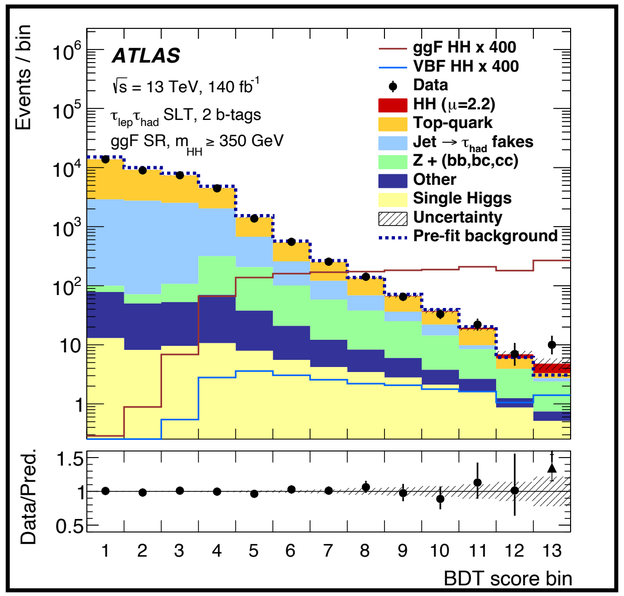


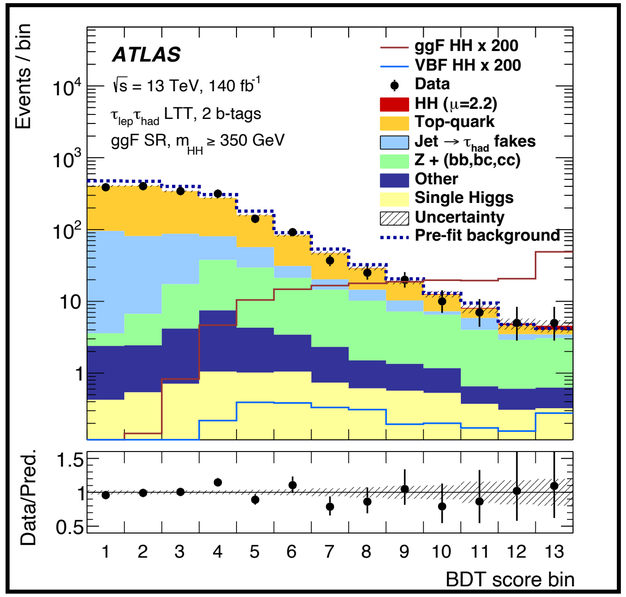


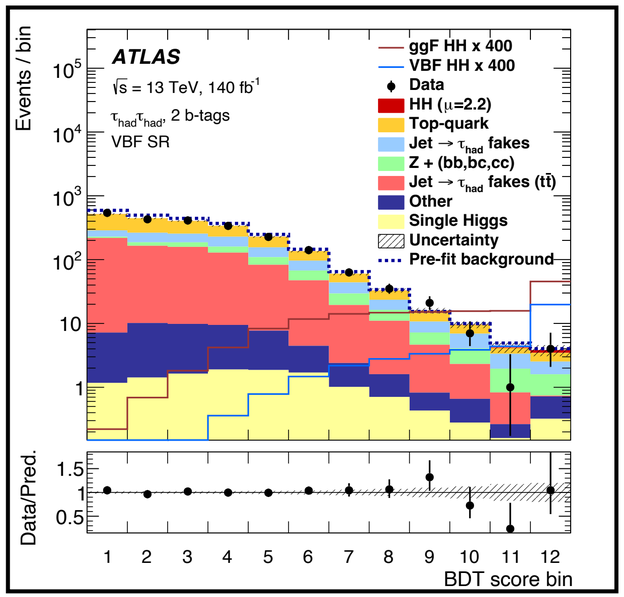


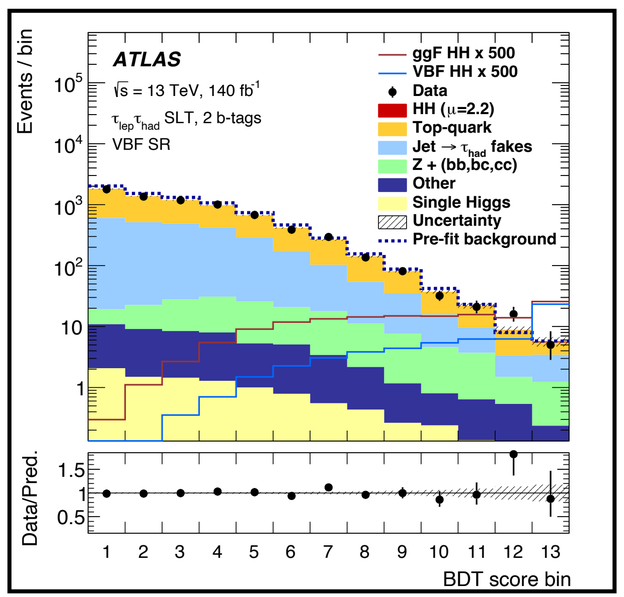
ATLAS HH→bbττ

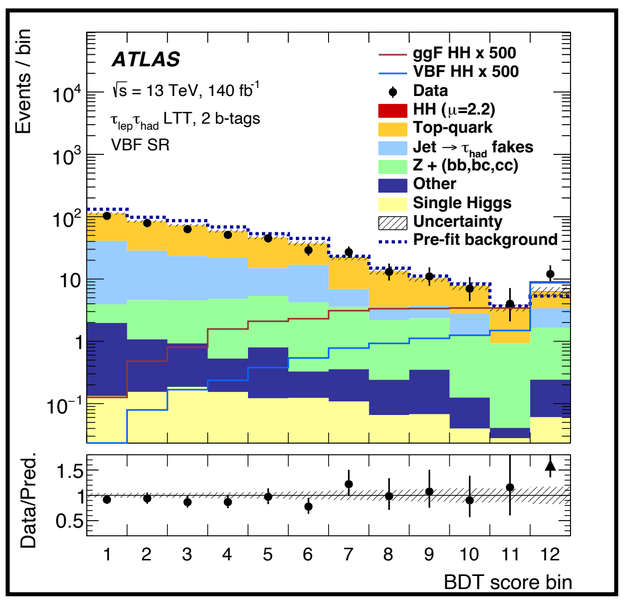




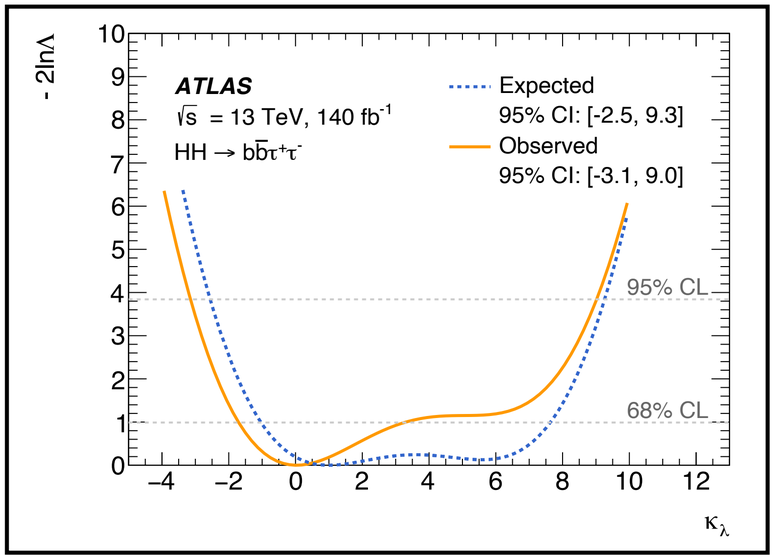


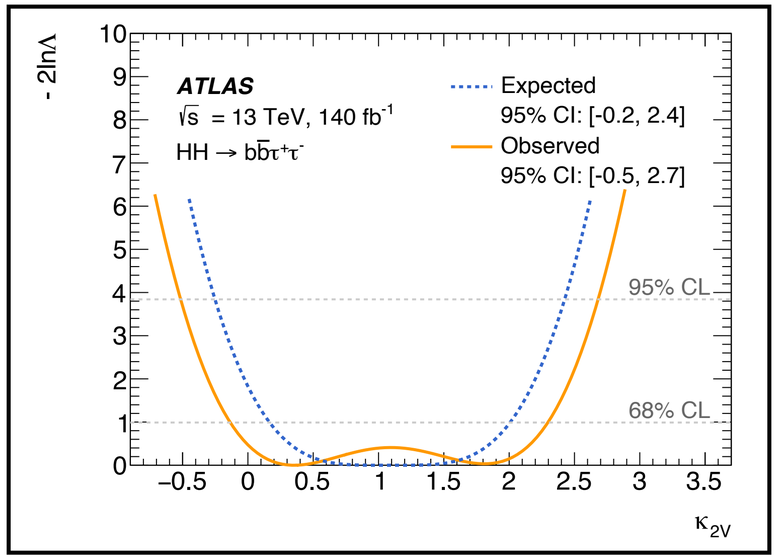


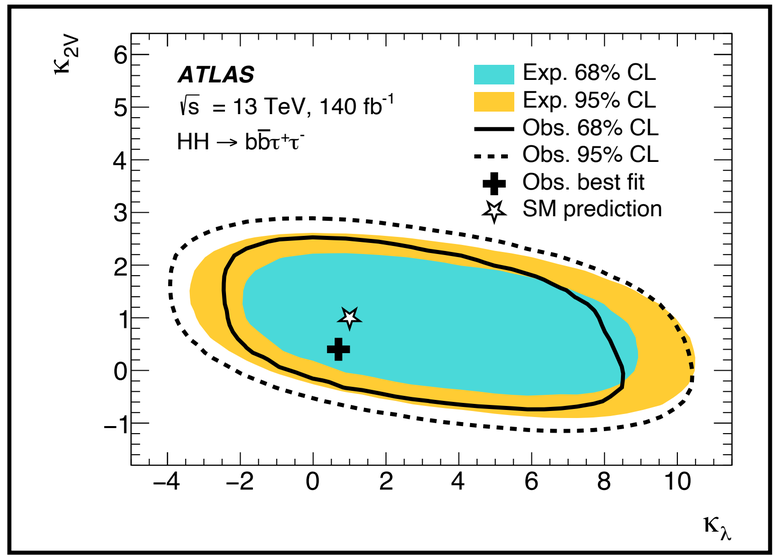


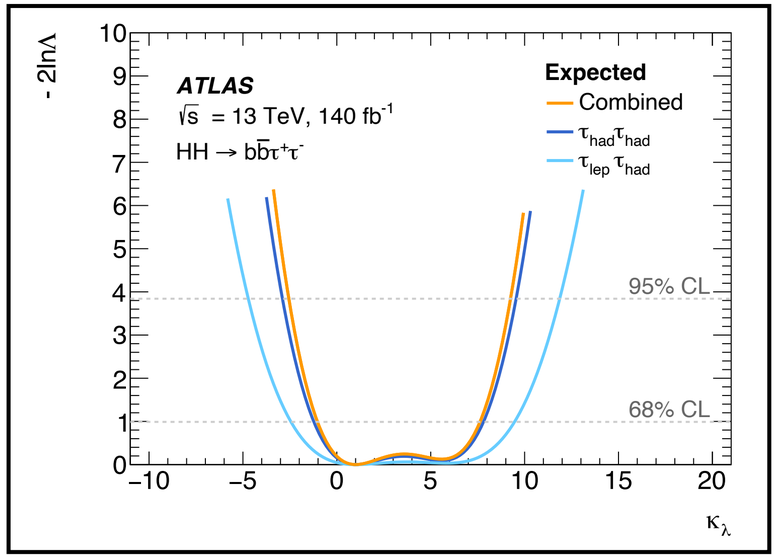


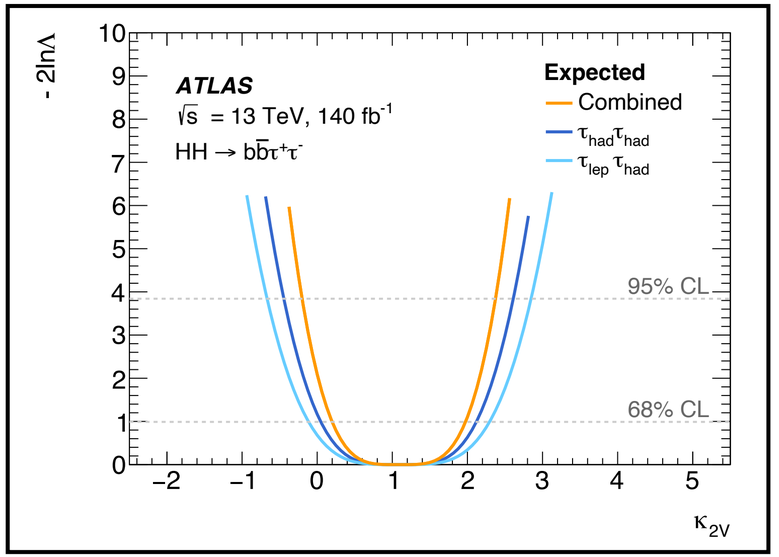
ATLAS HH→bbττ



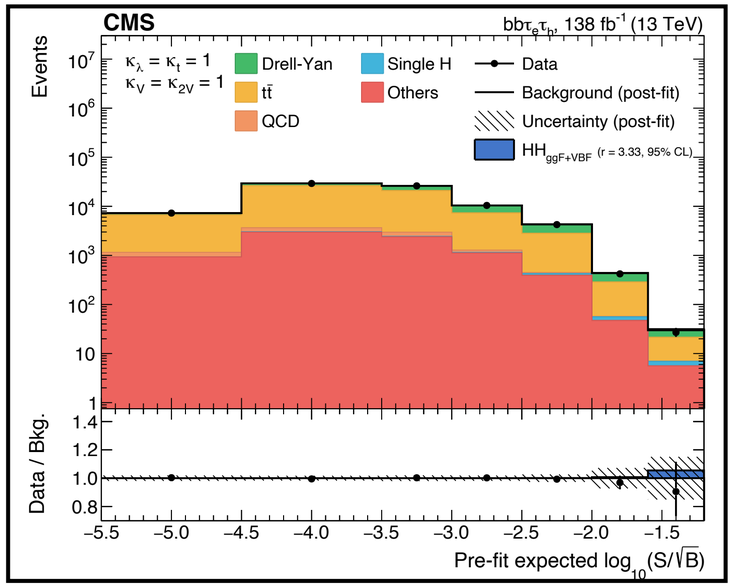


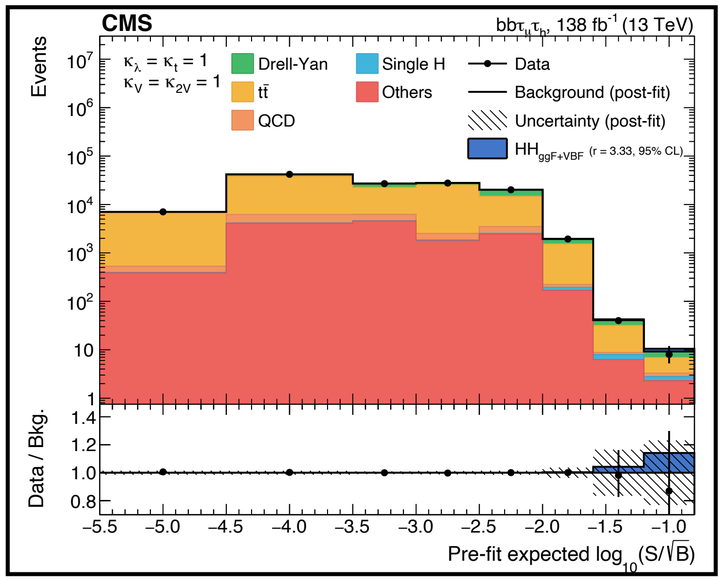


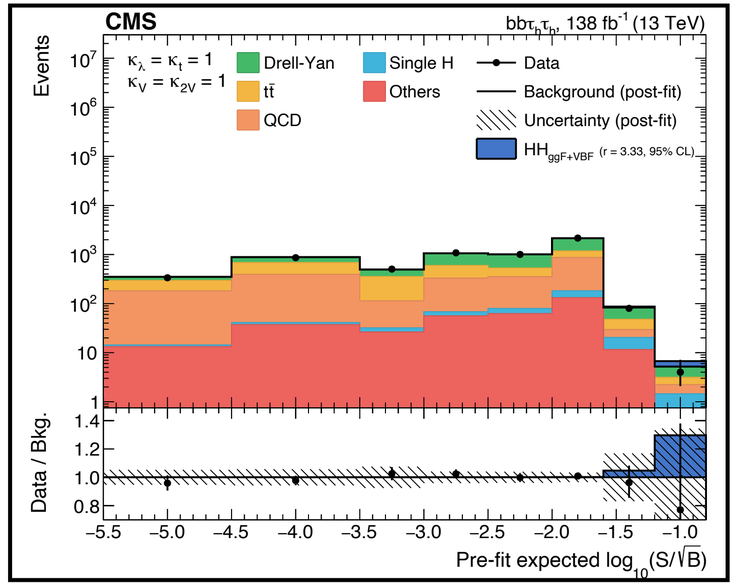


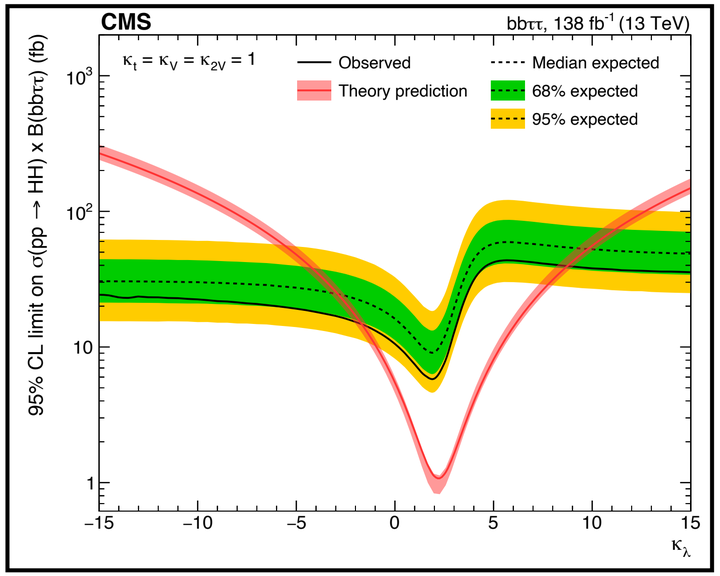


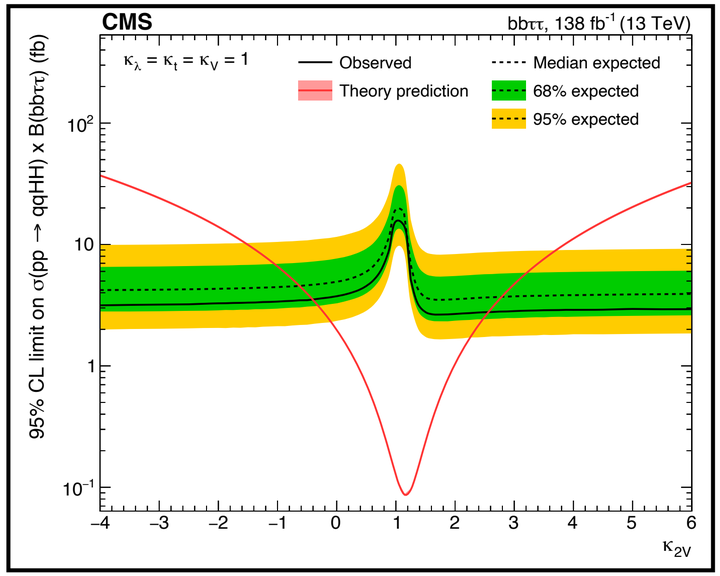
CMS HH→bbττ


CMS
bbτeτh, 138 fb-1 (13 TeV)
κλ = κt = 1
κV = κ2V = 1
Drell-Yan
Single H
Data
tt̄
Others
Background (post-fit)
QCD
Uncertainty (post-fit)
HHggF+VBF (r = 3.33, 95% CL)
Events
Data / Bkg.
Pre-fit expected log10(S/√B)

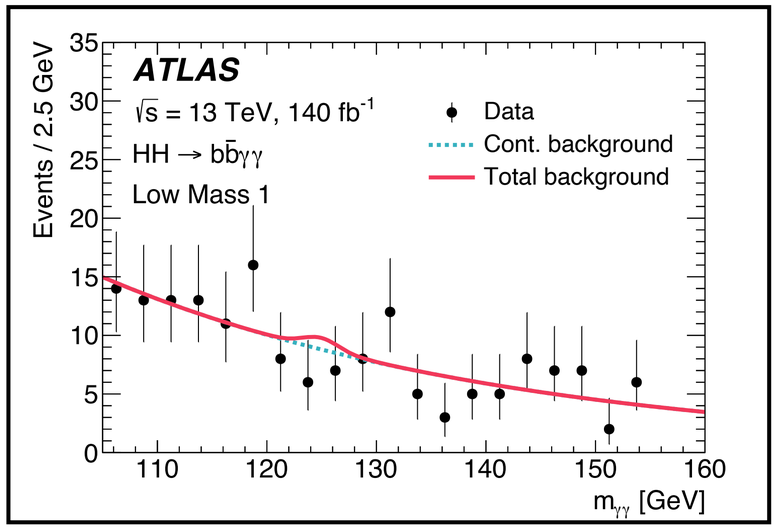

CMS
bbτμτh, 138 fb-1 (13 TeV)
κλ = κt = 1
κV = κ2V = 1
Drell-Yan
Single H
Data
tt̄
Others
Background (post-fit)
QCD
Uncertainty (post-fit)
HHggF+VBF (r = 3.33, 95% CL)
Events
Data / Bkg.
Pre-fit expected log10(S/√B)

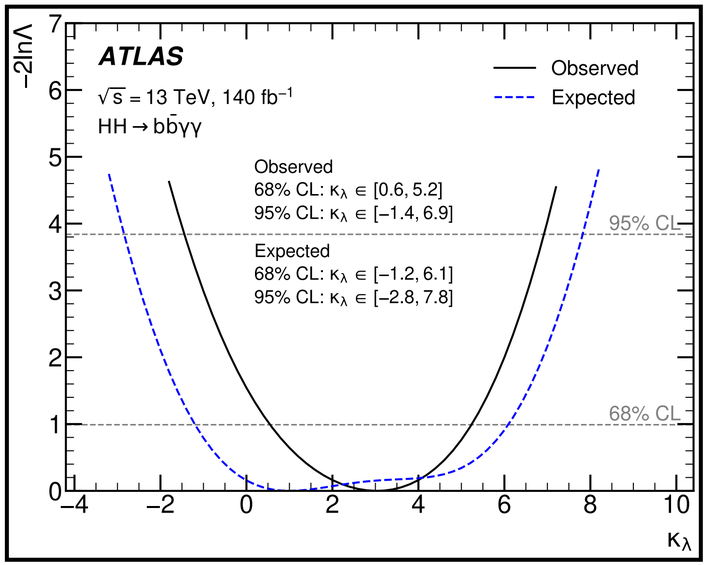

CMS
bbτhτh, 138 fb-1 (13 TeV)
κλ = κt = 1
κV = κ2V = 1
Drell-Yan
Single H
Data
tt̄
Others
Background (post-fit)
QCD
Uncertainty (post-fit)
HHggF+VBF (r = 3.33, 95% CL)
Events
Data / Bkg.
Pre-fit expected log10(S/√B)

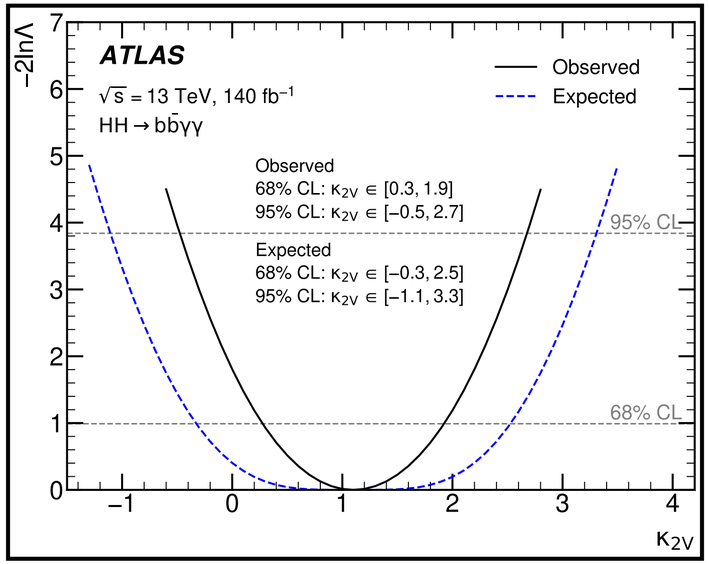

CMS
bbττ, 138 fb-1 (13 TeV)
κt = κV = κ2V = 1
Observed
Median expected
Theory prediction
68% expected
95% expected
95% CL limit on σ(pp → HH) x B(bbττ) (fb)
κλ

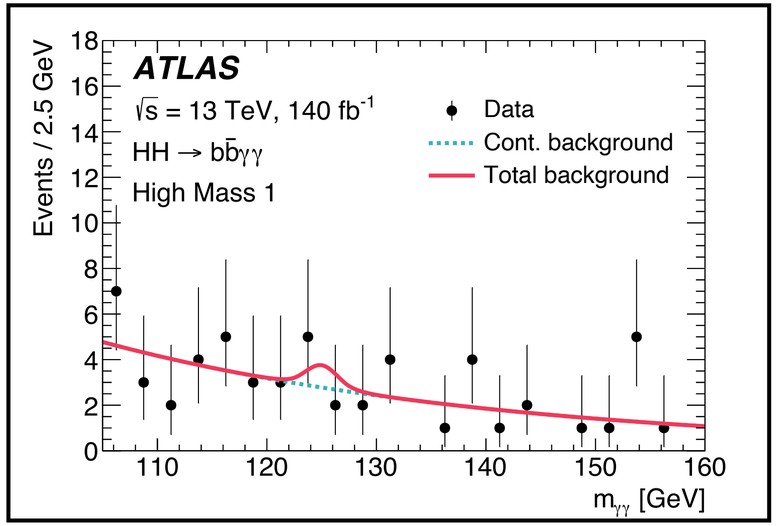

CMS
bbττ, 138 fb-1 (13 TeV)
κλ = κt = κV = 1
Observed
Median expected
Theory prediction
68% expected
95% expected
95% CL limit on σ(pp → qqHH) x B(bbττ) (fb)
κ2V

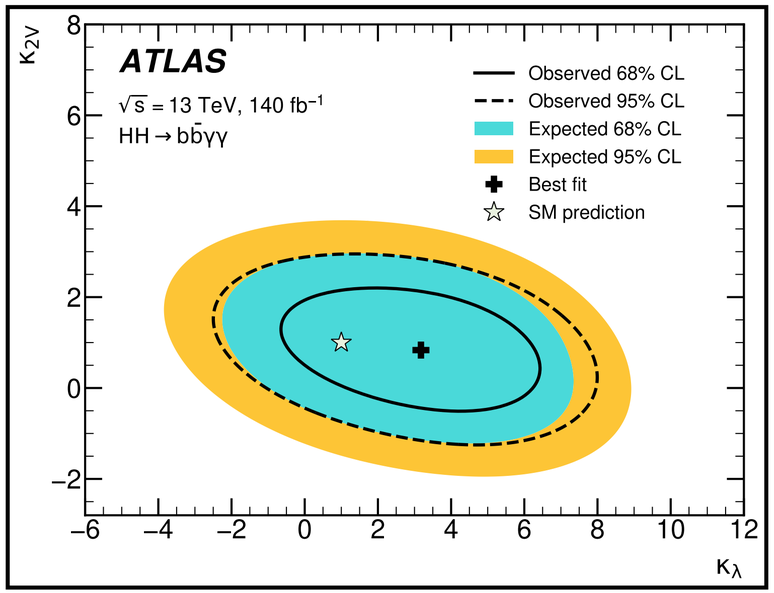
ATLAS HH→bbγγ



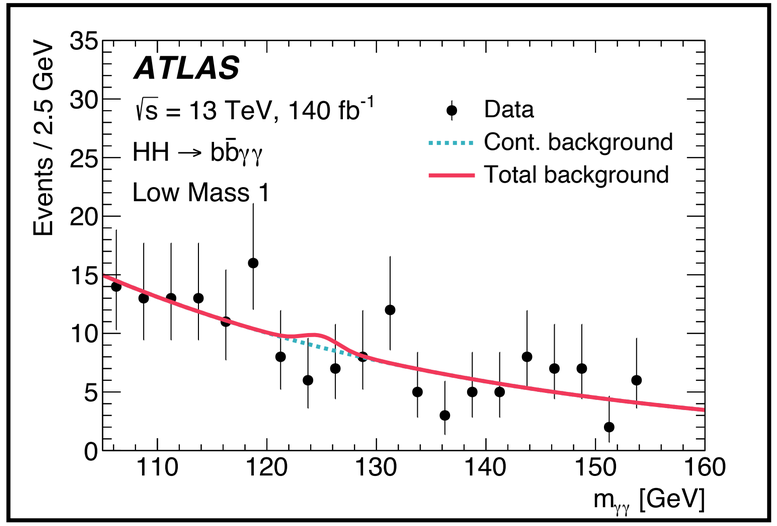


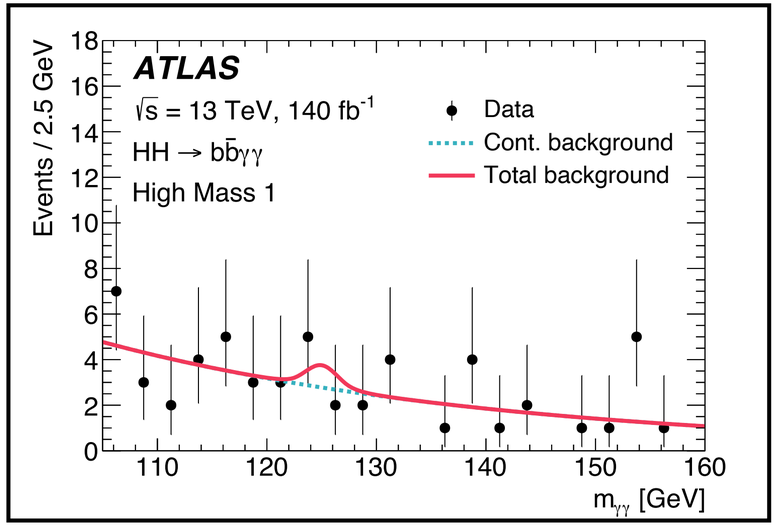


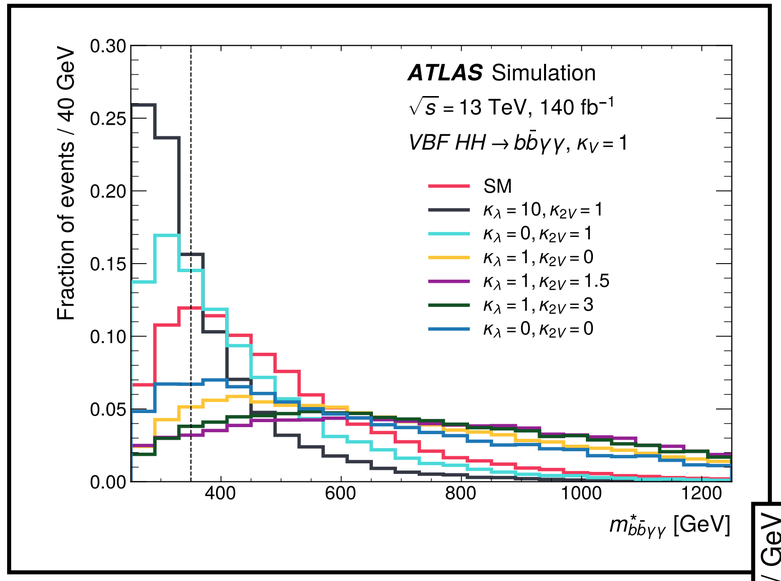


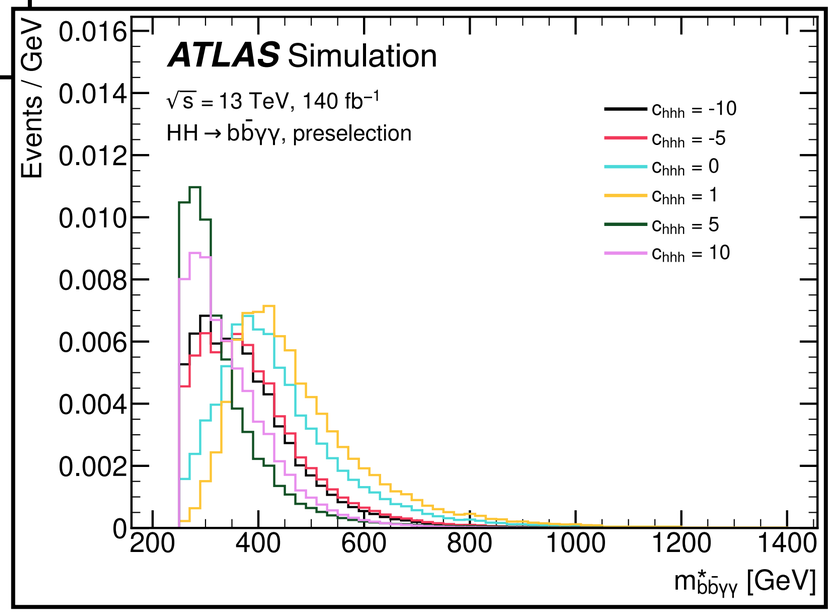


ATLAS HH→bbγγ

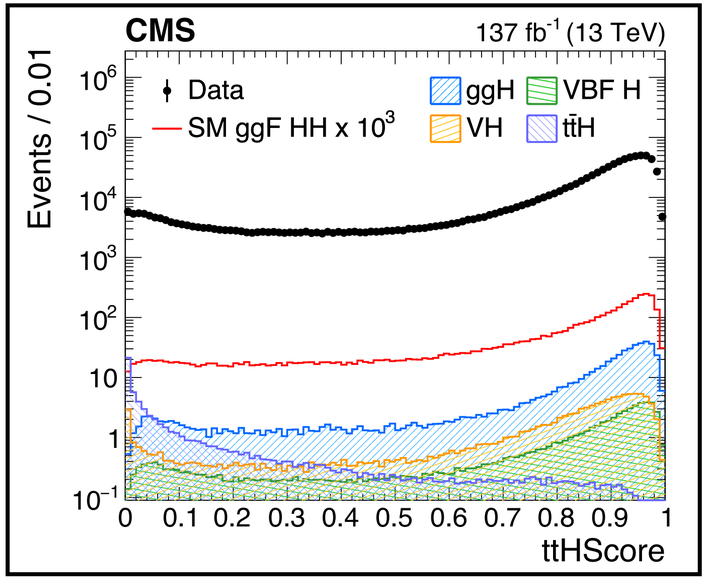


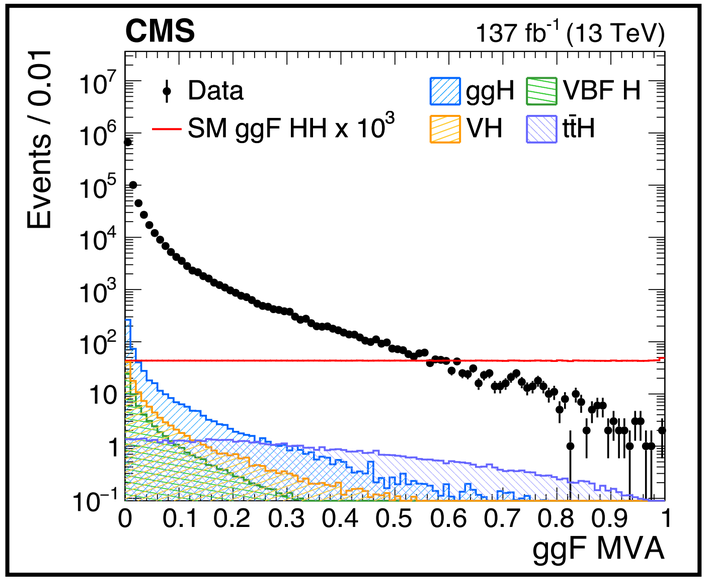


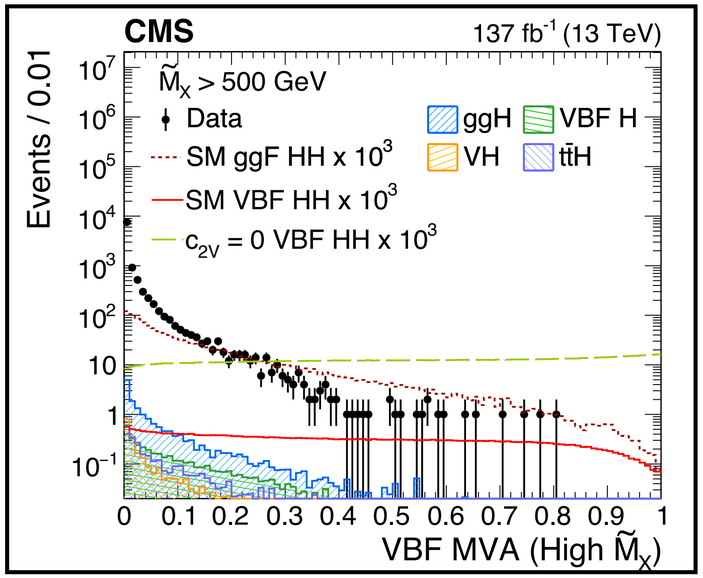


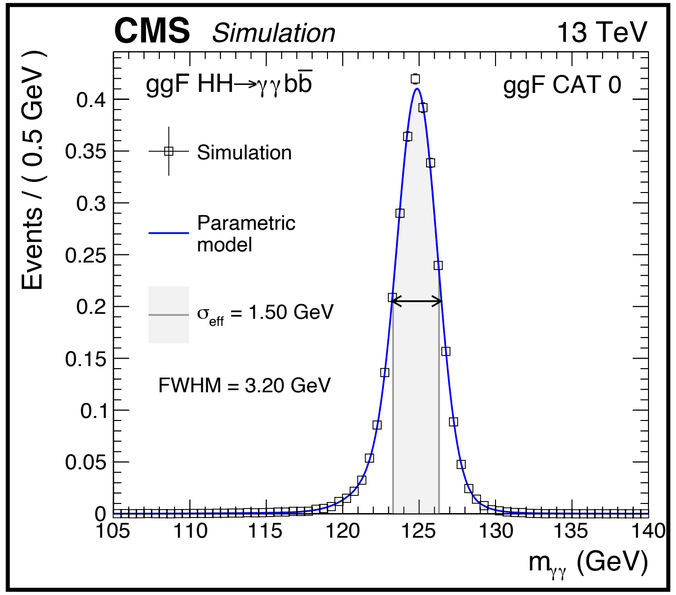


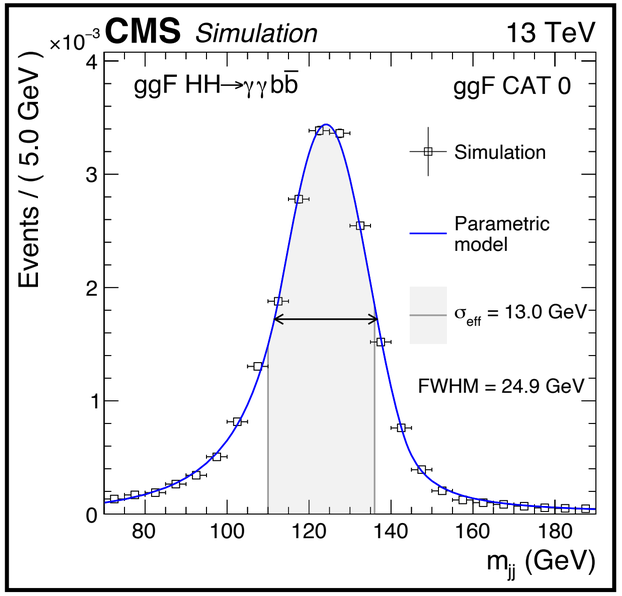
CMS HH→bbγγ


CMS
137 fb^{-1} (13 TeV)
Data
SM ggF HH x 10^3
ggH
VBF H
VH
tt̄H
Events / 0.01
ttHScore

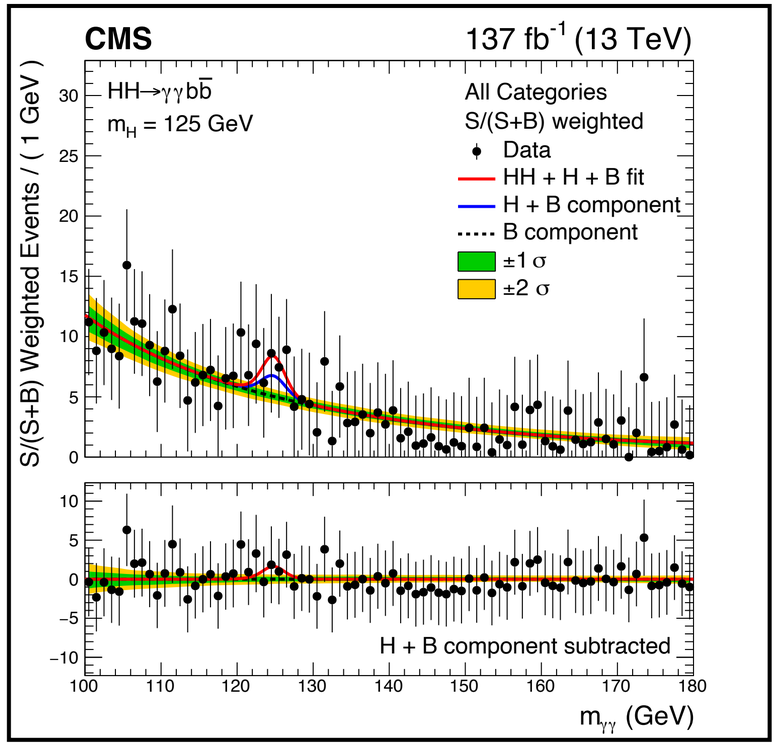

CMS
137 fb^{-1} (13 TeV)
Data
SM ggF HH x 10^3
ggH
VBF H
VH
tt̄H
Events / 0.01
ggF MVA

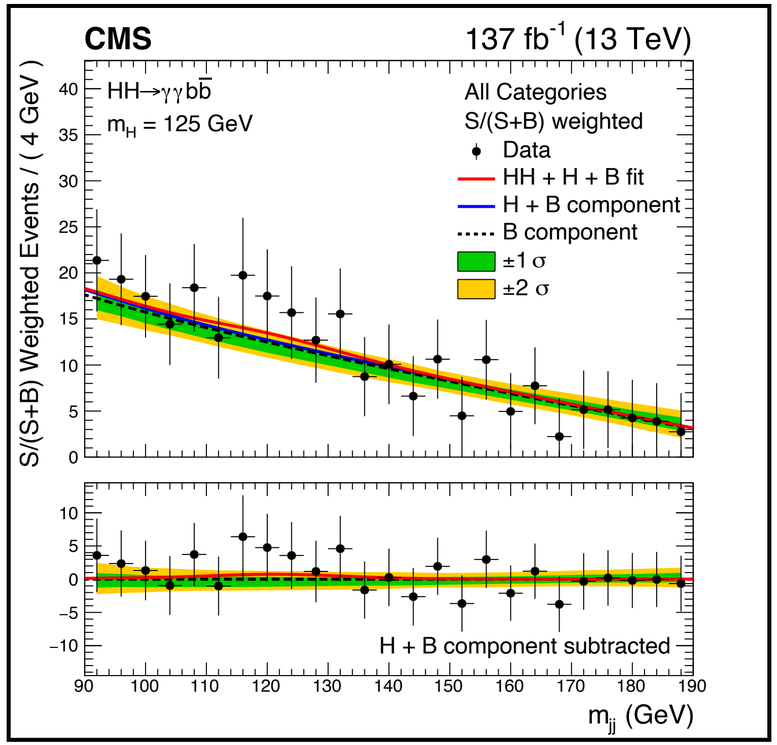

CMS
137 fb^{-1} (13 TeV)
$\tilde{M}_X$ > 500 GeV
Data
SM ggF HH x 10^3
SM VBF HH x 10^3
c_{2V} = 0 VBF HH x 10^3
ggH
VBF H
VH
tt̄H
Events / 0.01
VBF MVA (High $\tilde{M}_X$)

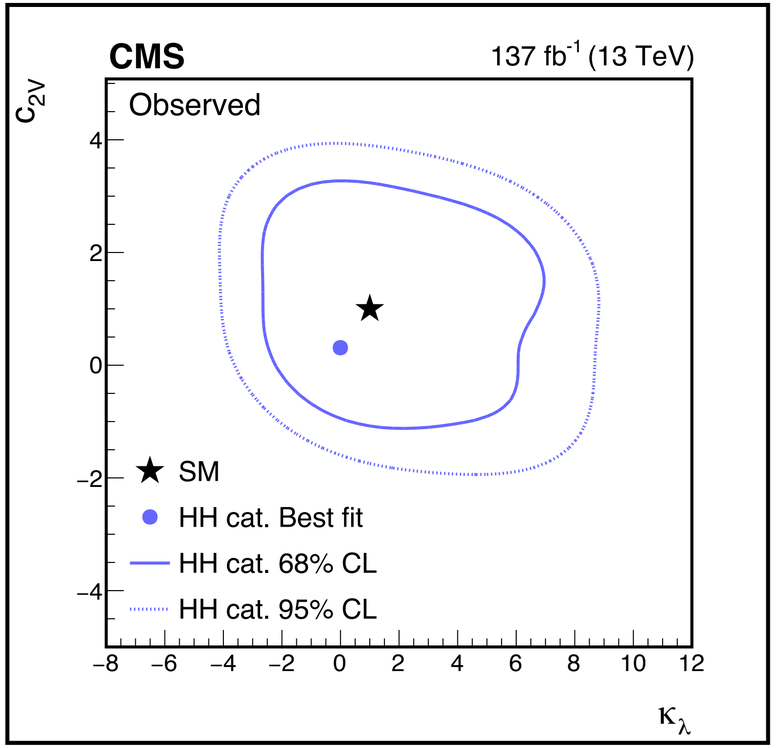

CMS Simulation
13 TeV
ggF HH→γγbb̄
ggF CAT 0
Simulation
Parametric model
σ_{eff} = 1.50 GeV
FWHM = 3.20 GeV
Events / (0.5 GeV)
$m_{\gamma\gamma}$ (GeV)


CMS Simulation
13 TeV
×10^{-3}
ggF HH→γγbb̄
ggF CAT 0
Simulation
Parametric model
σ_{eff} = 13.0 GeV
FWHM = 24.9 GeV
Events / (5.0 GeV)
m_{jj} (GeV)

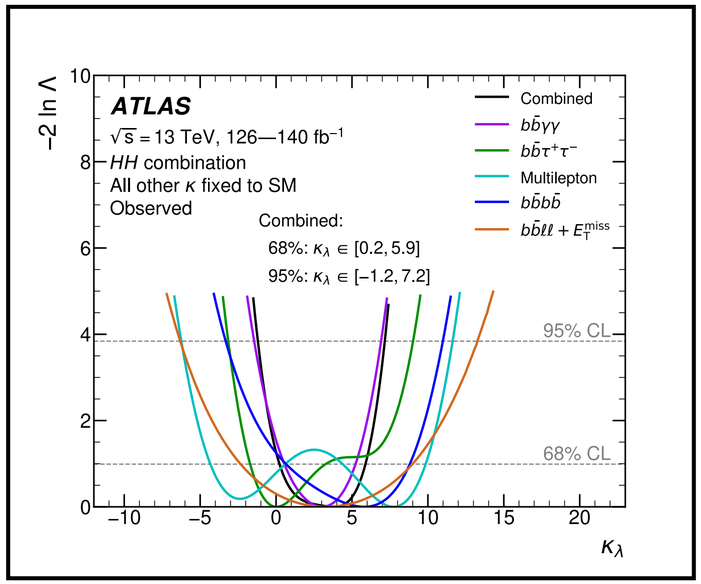
CMS HH→bbγγ

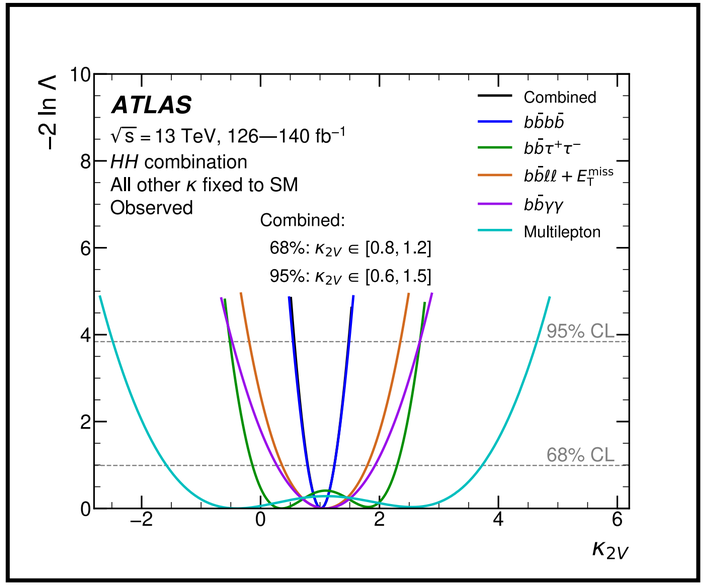

CMS
137 fb-1 (13 TeV)
HH→γγbb̄
mH = 125 GeV
All Categories
S/(S+B) weighted
Data
HH + H + B fit
H + B component
B component
±1 σ
±2 σ
S/(S+B) Weighted Events / (1 GeV)
H + B component subtracted
mγγ (GeV)

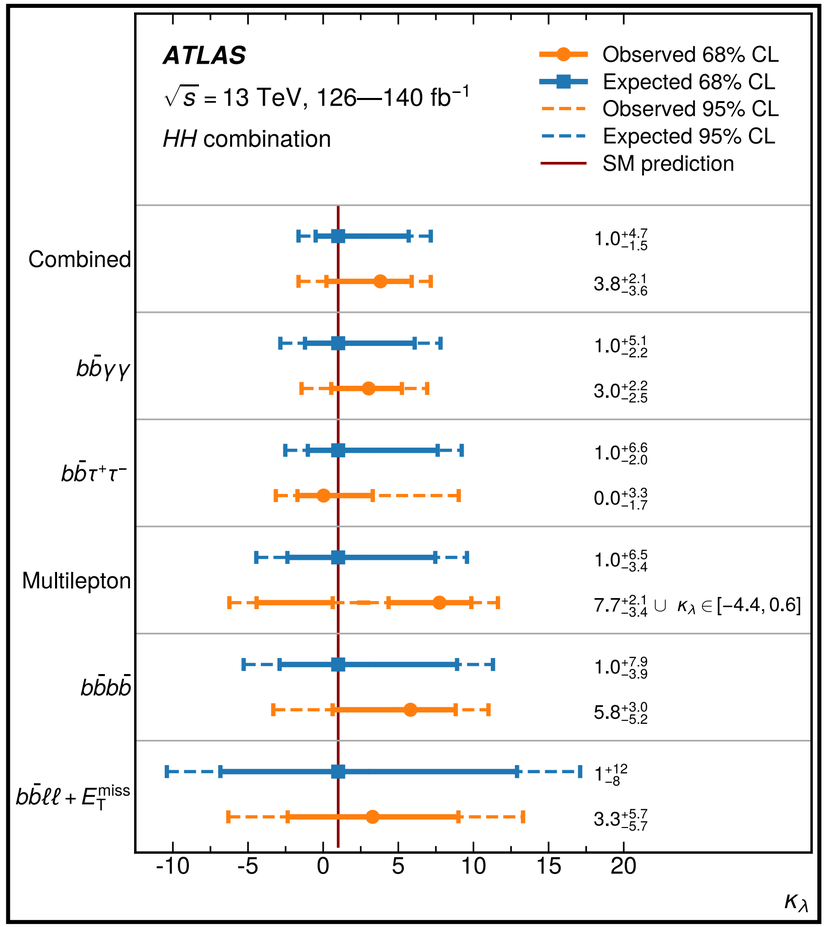

CMS
137 fb-1 (13 TeV)
HH→γγbb̄
mH = 125 GeV
All Categories
S/(S+B) weighted
Data
HH + H + B fit
H + B component
B component
±1 σ
±2 σ
S/(S+B) Weighted Events / (4 GeV)
H + B component subtracted
mjj (GeV)

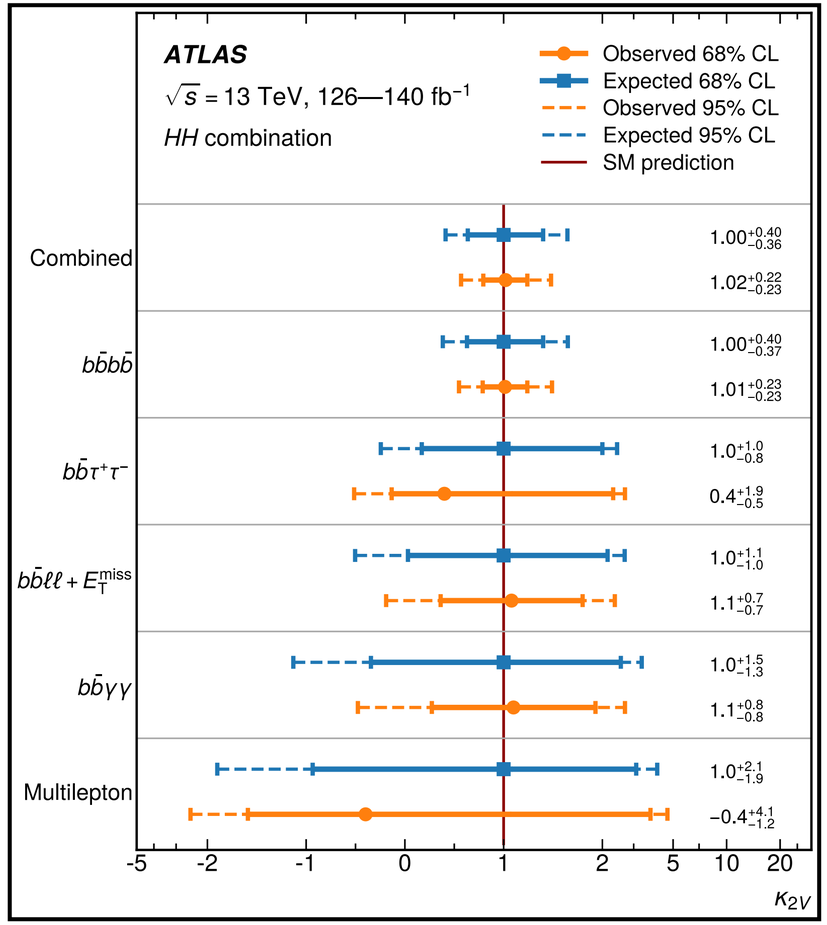

CMS
137 fb-1 (13 TeV)
Observed
c2V
SM
HH cat. Best fit
HH cat. 68% CL
HH cat. 95% CL
κλ

ATLAS HH combination

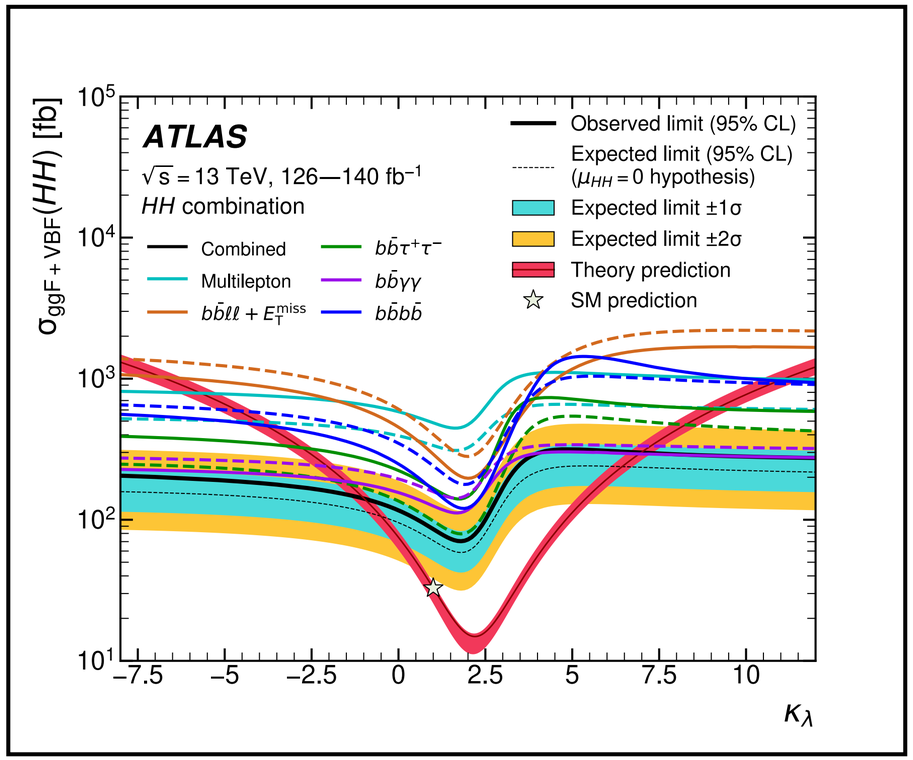


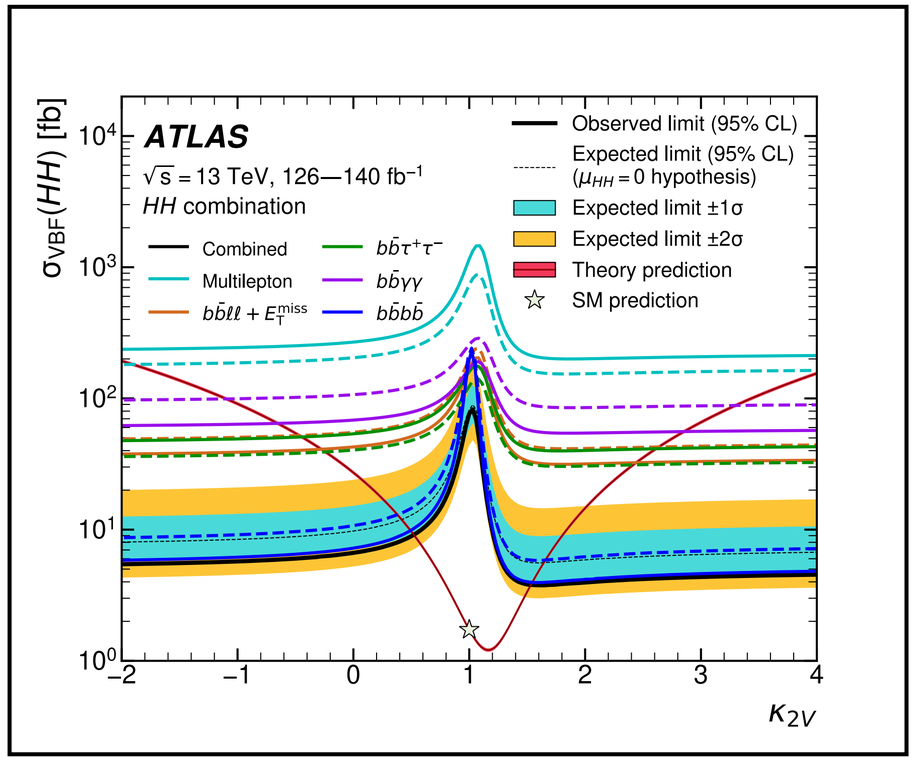




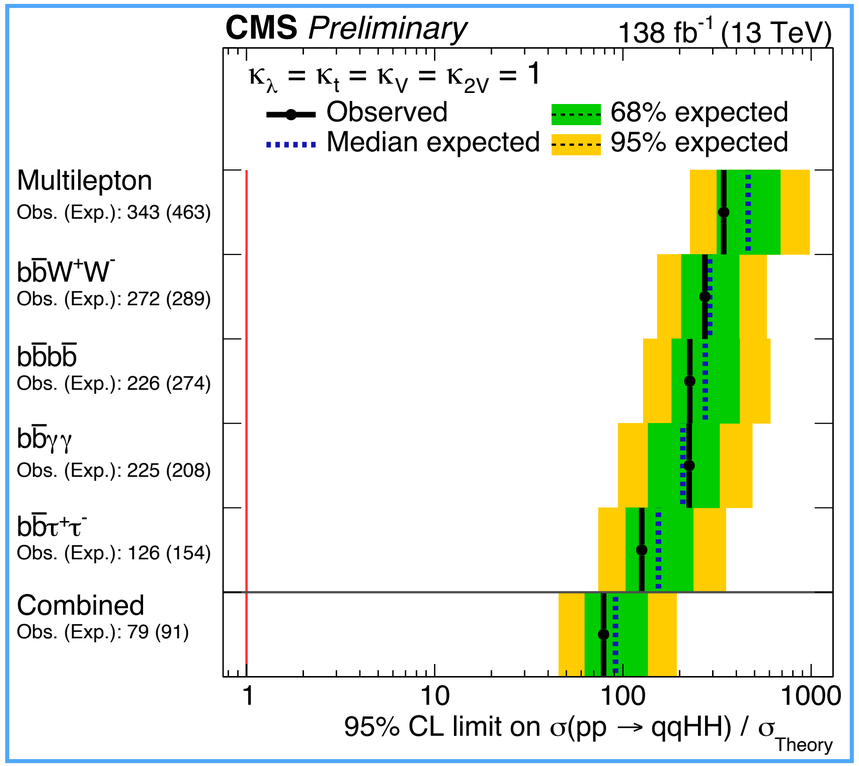


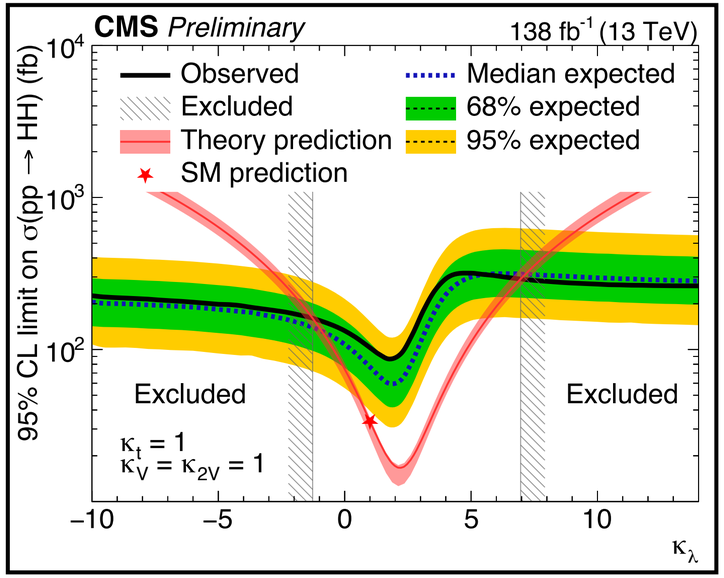
ATLAS HH combination

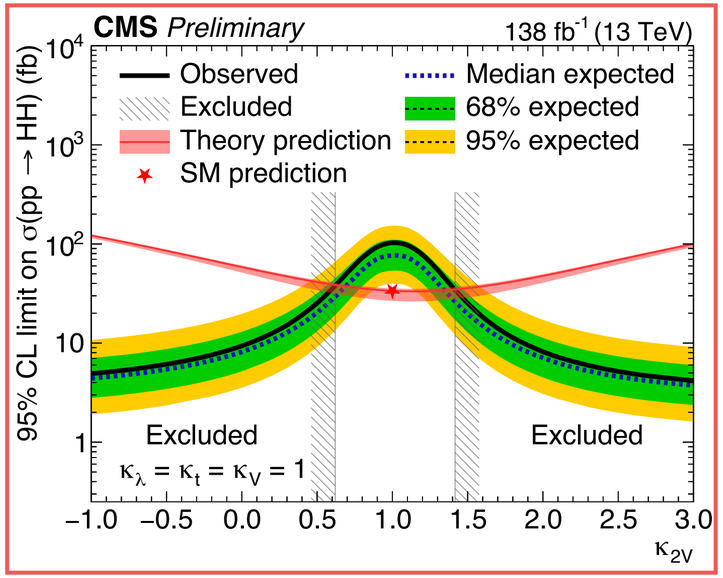


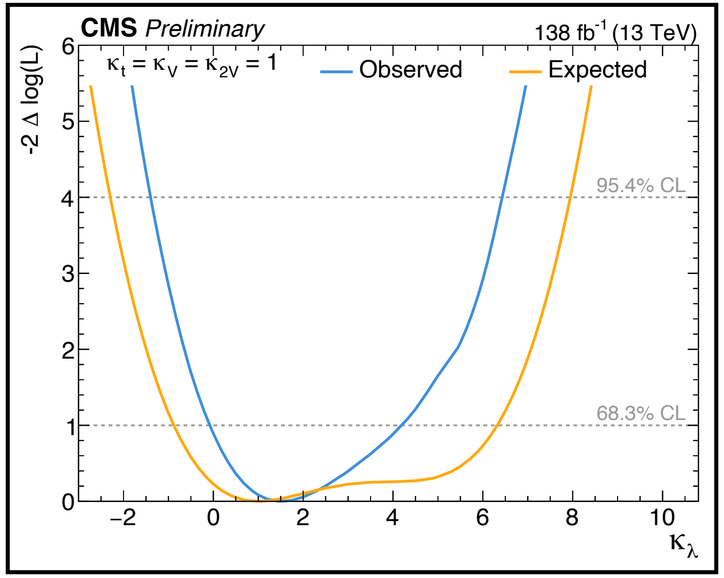


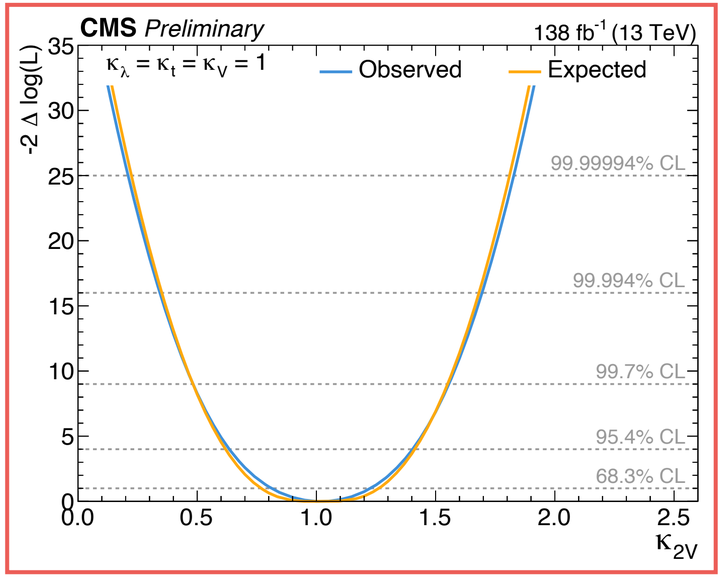
CMS HH combination



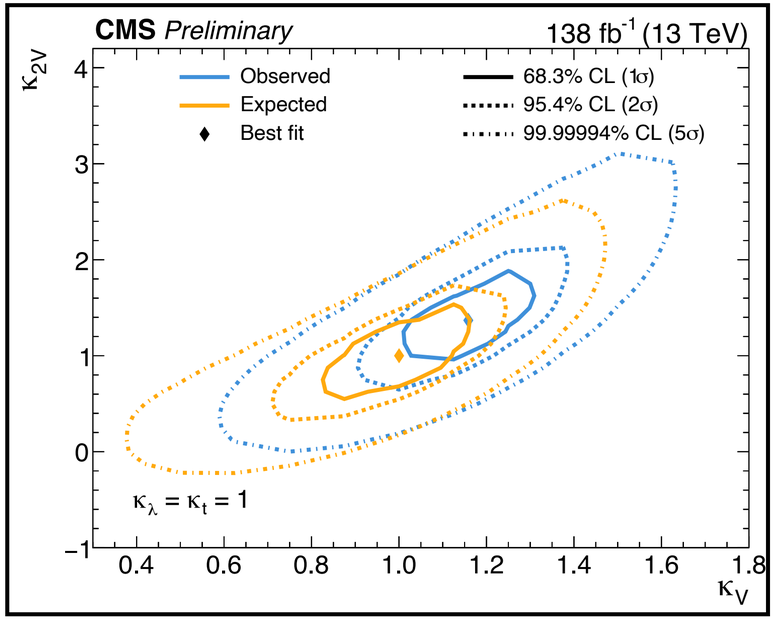


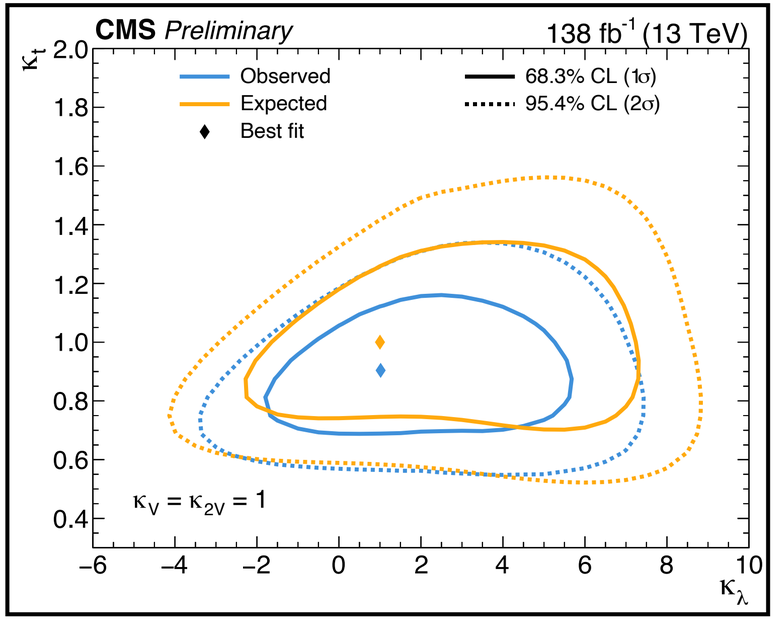


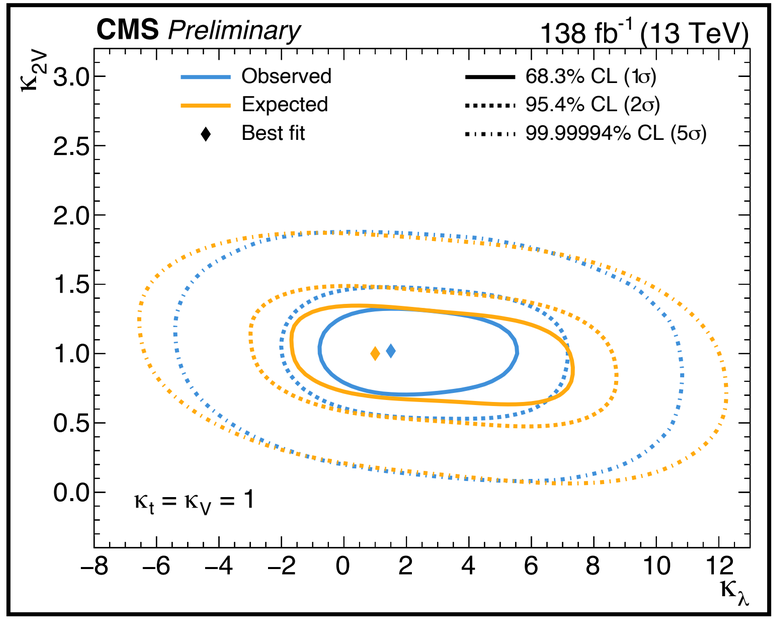




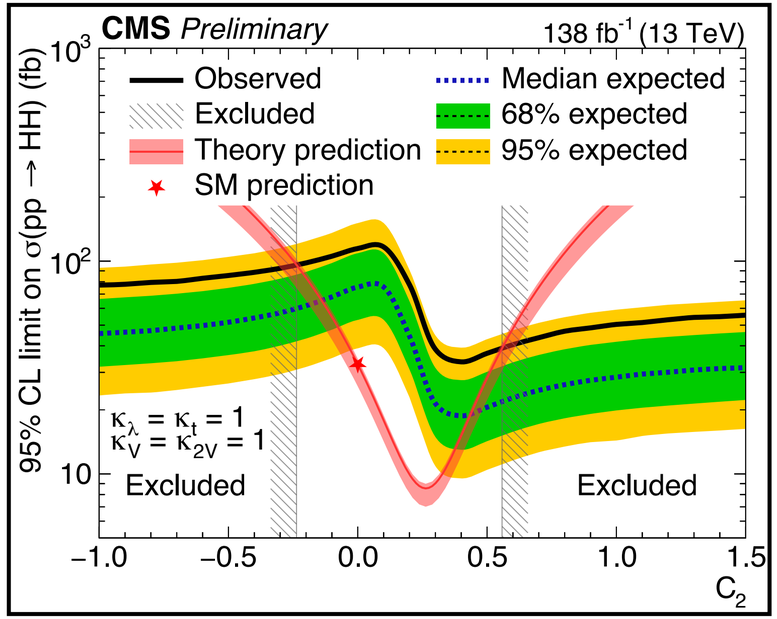
CMS HH combination

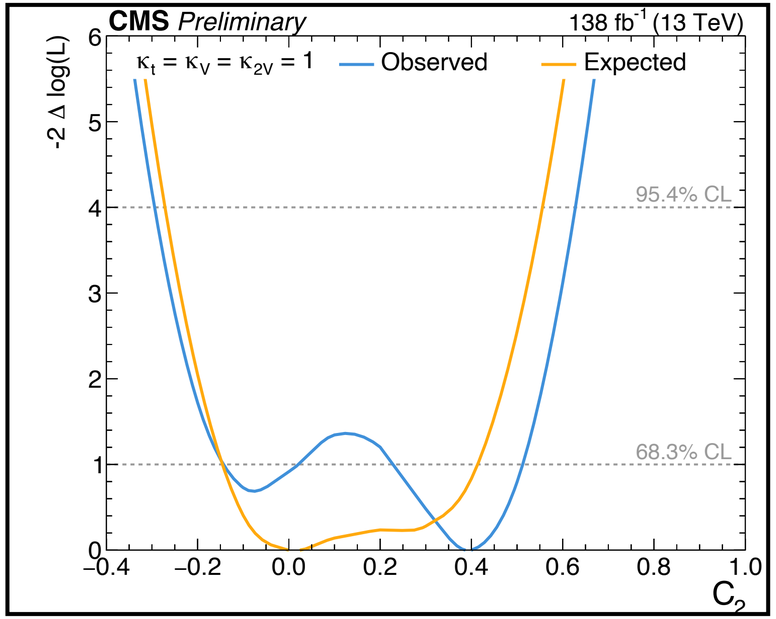


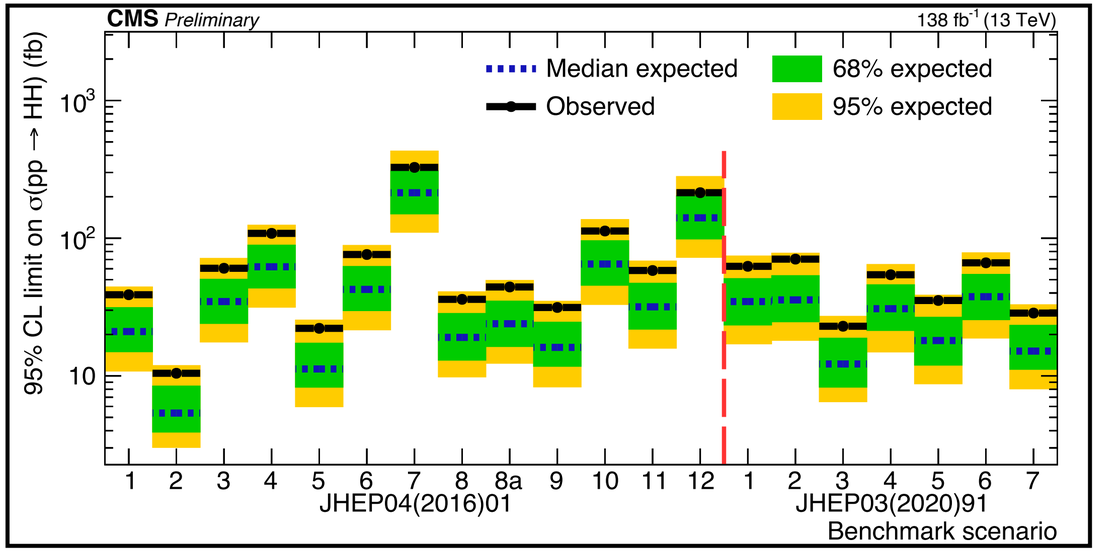




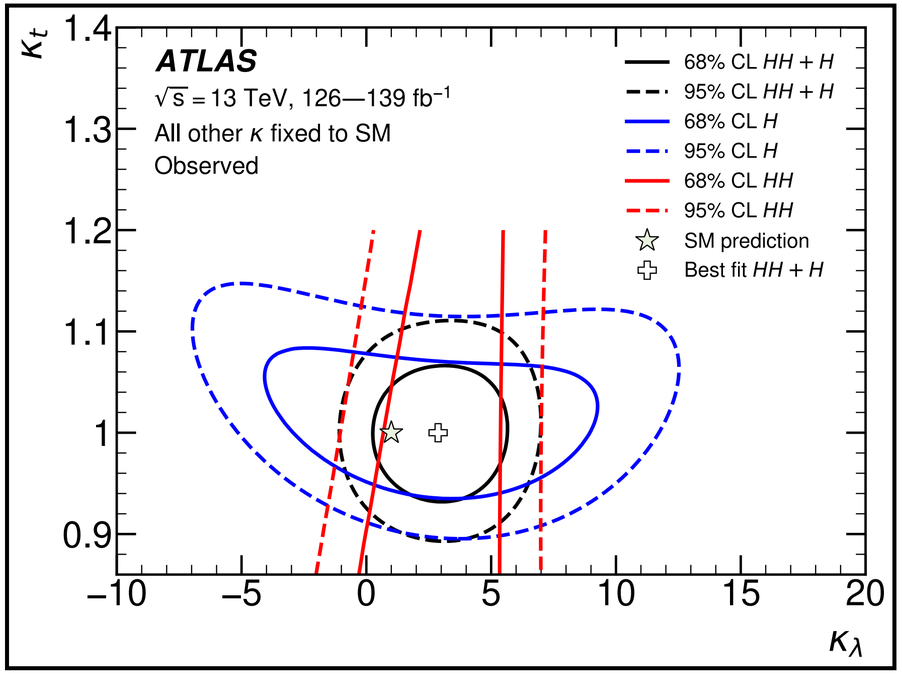
CMS HH combination

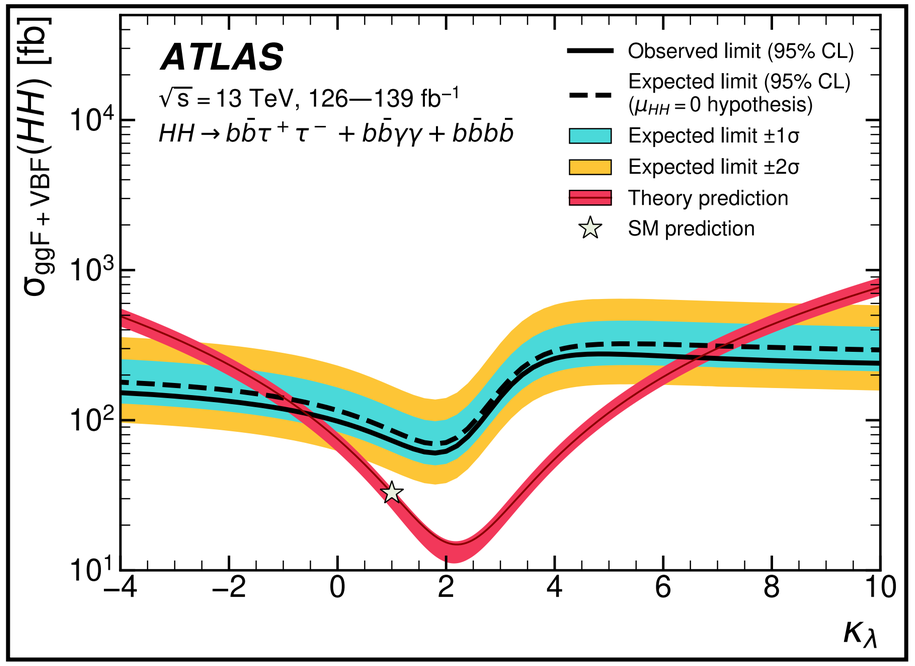




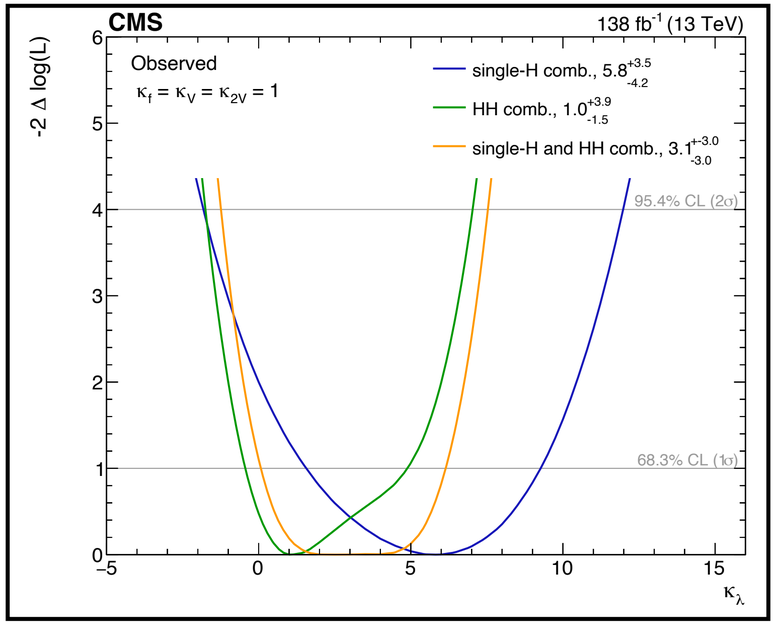


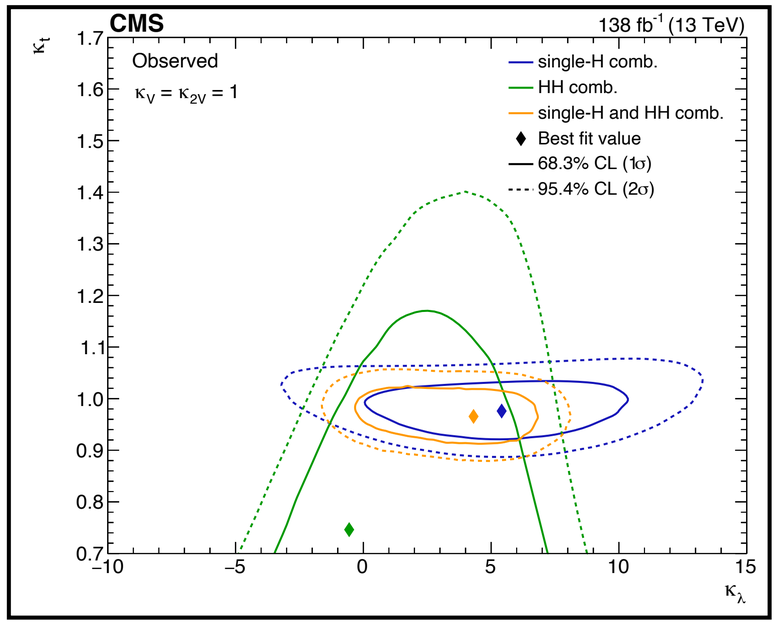
ATLAS H+HH combination

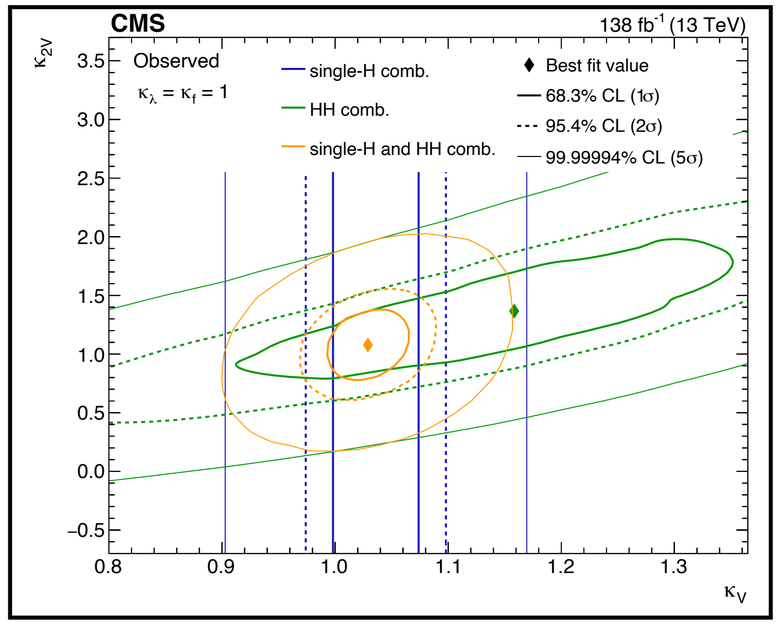




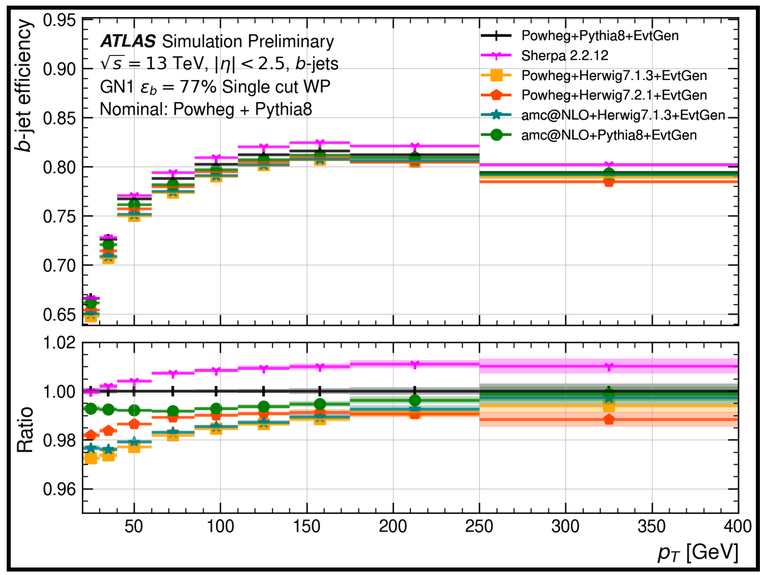
CMS H+HH combination

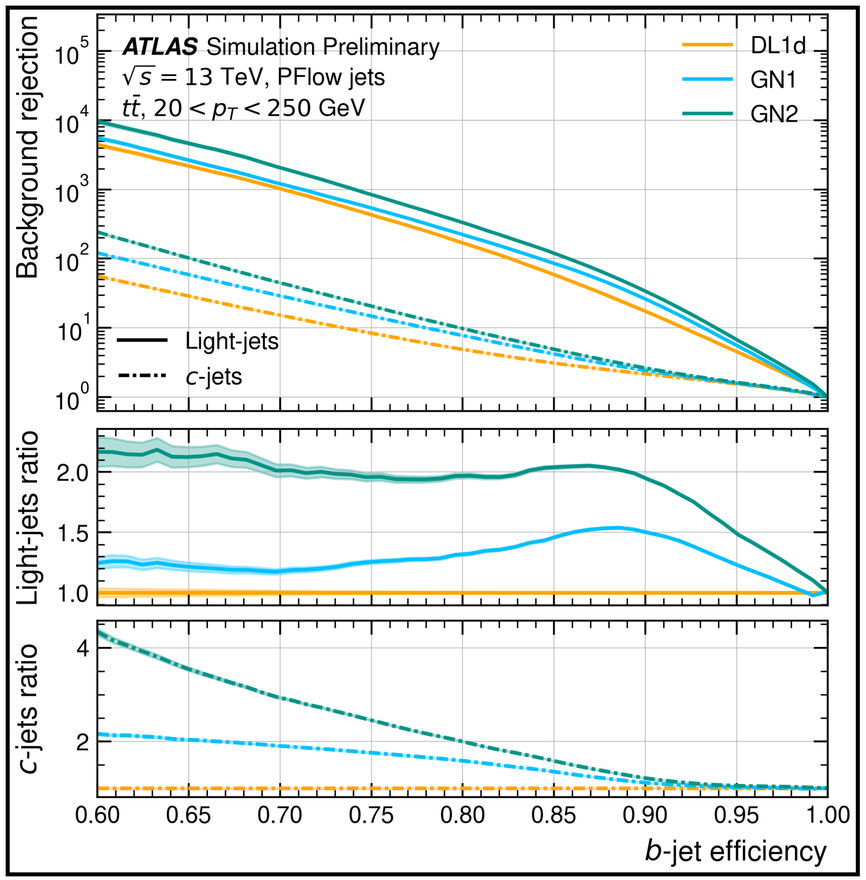


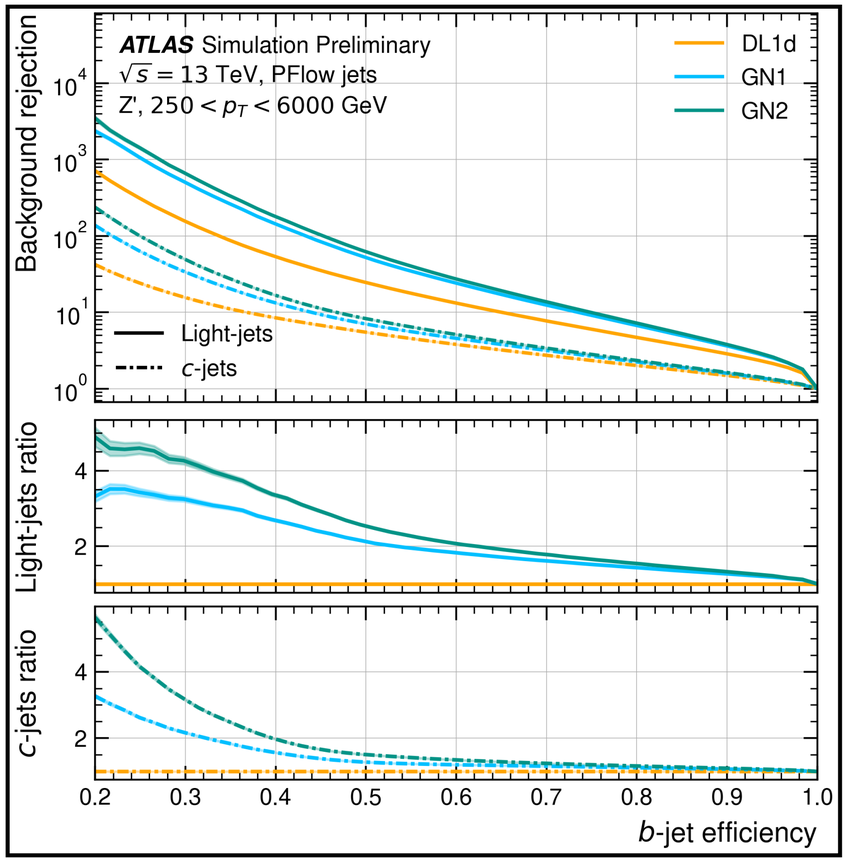




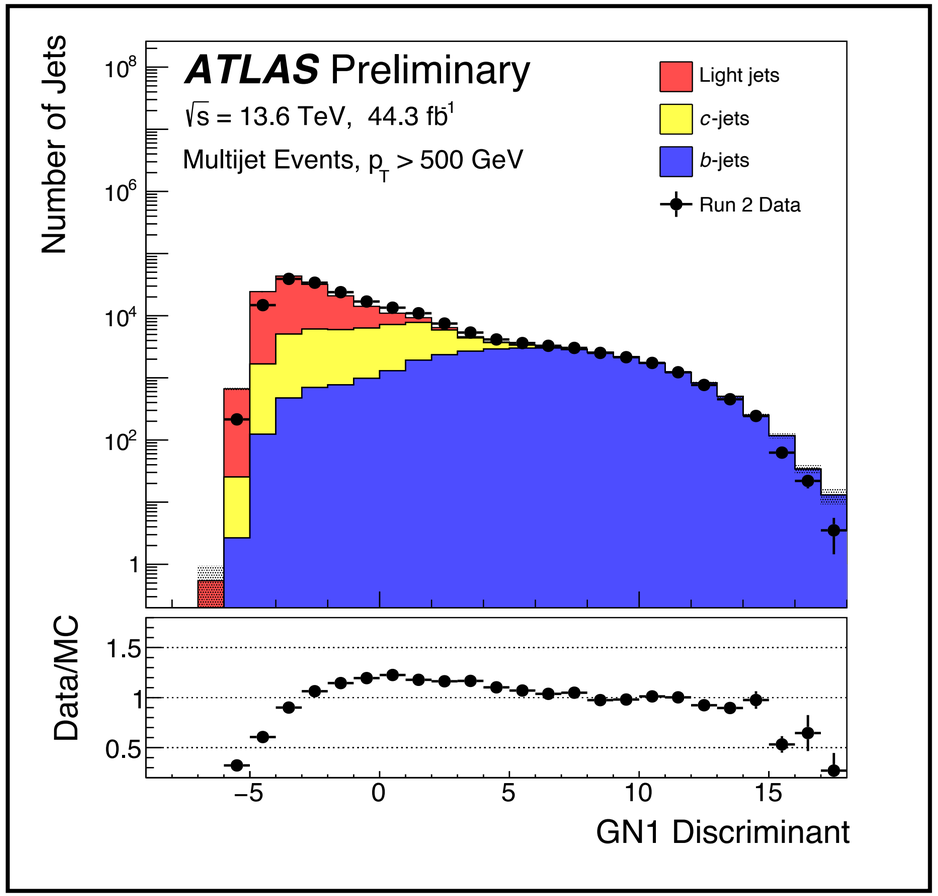
ATLAS b-tagging Run3

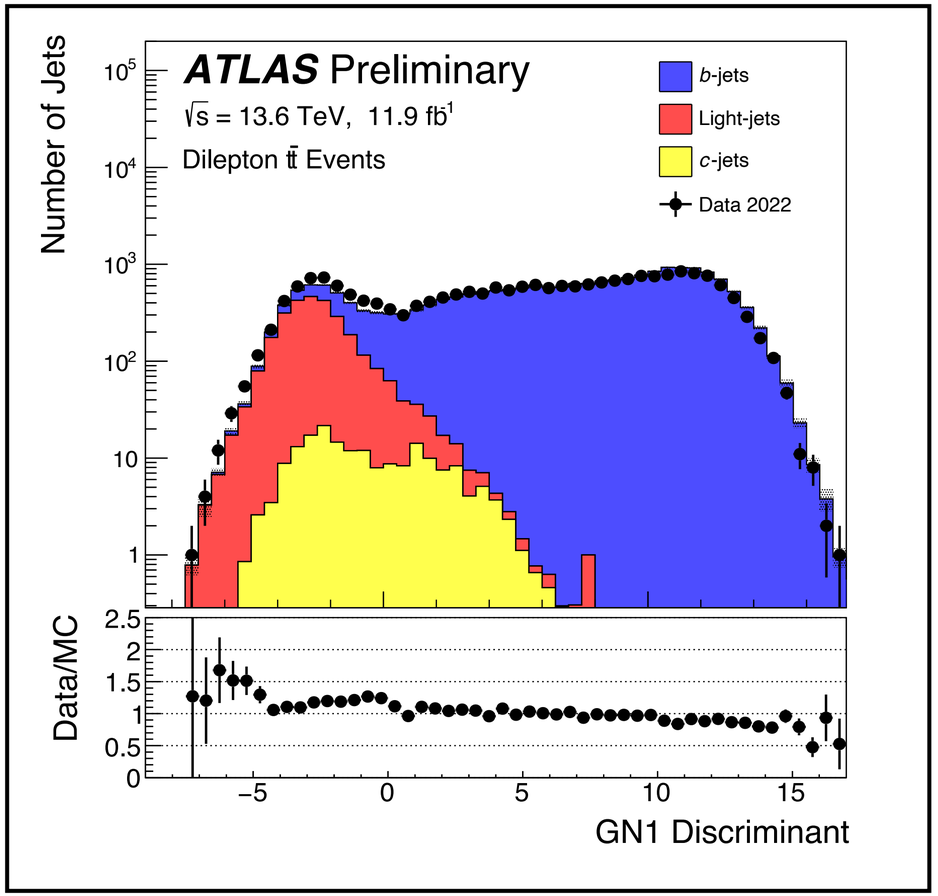




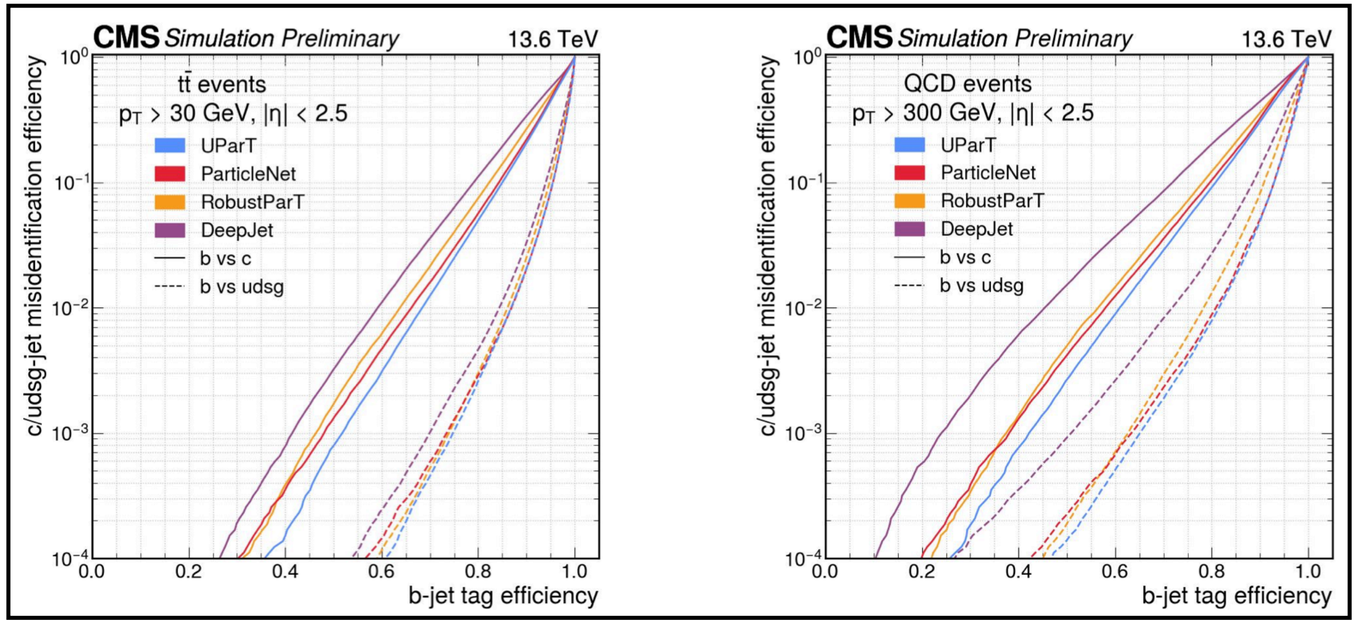


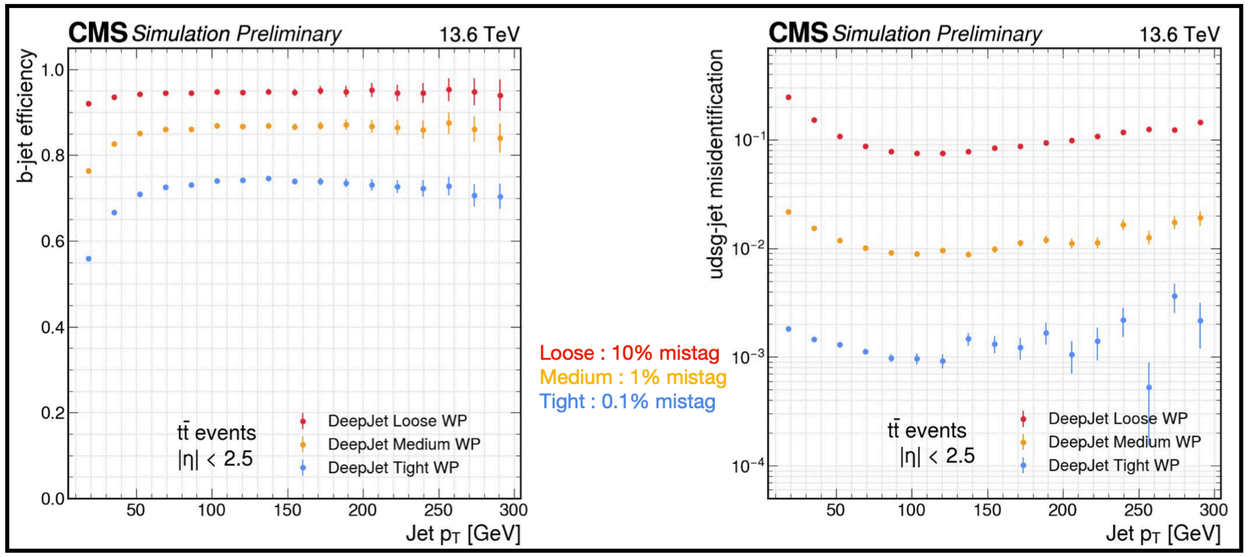
ATLAS b-tagging Run3

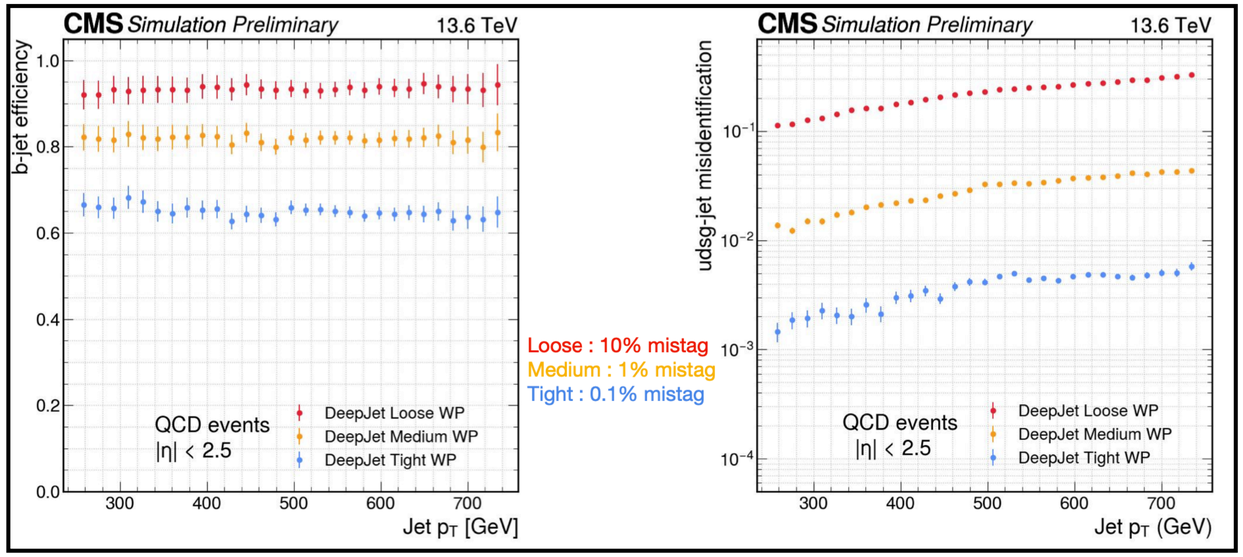




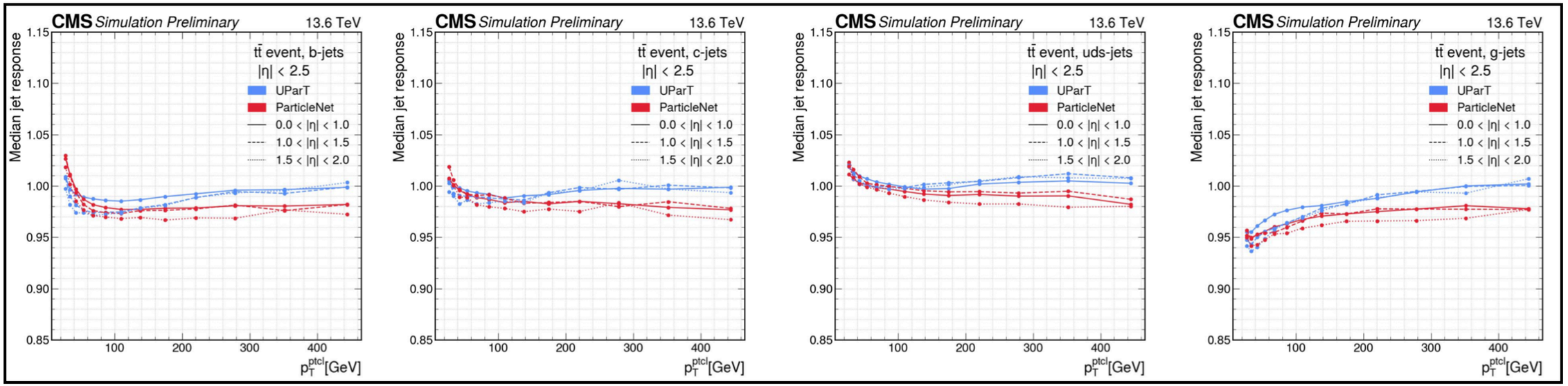
CMS b-tagging and regression Run3

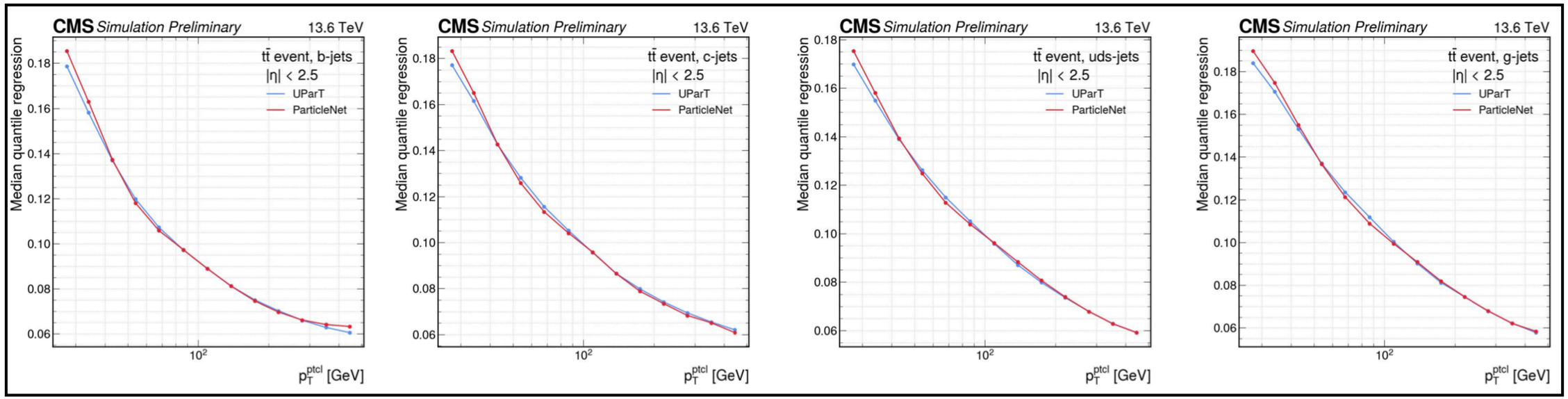




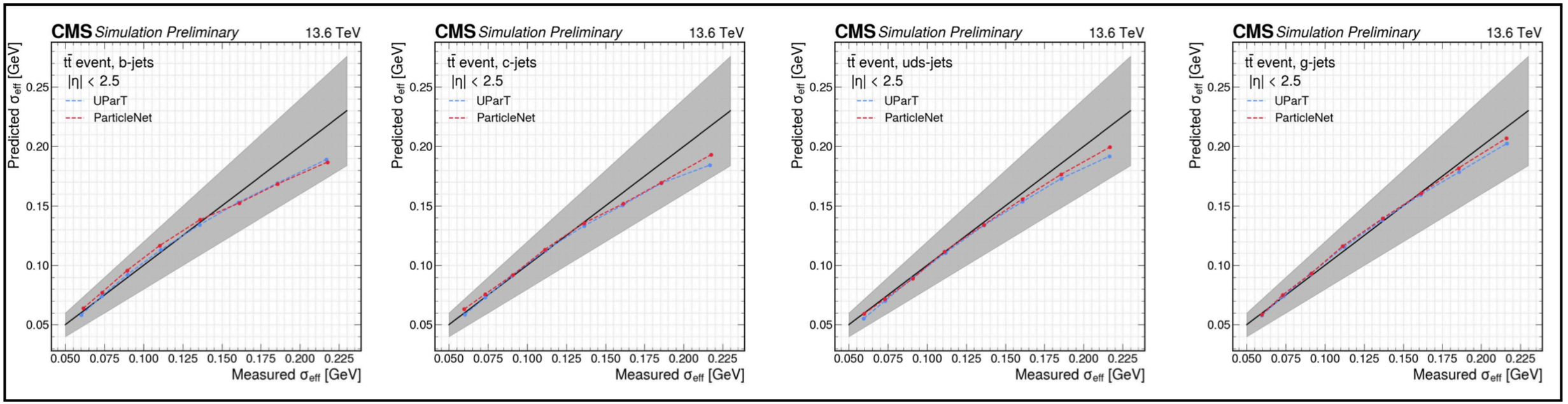


CMS b-tagging and regression Run3

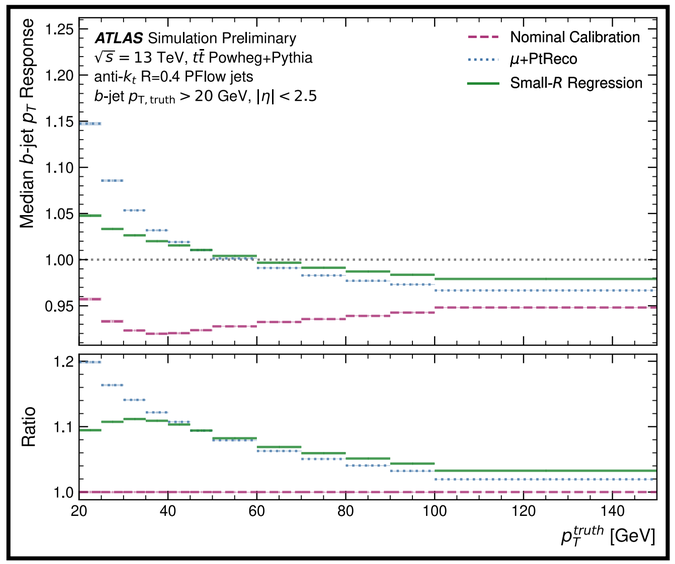


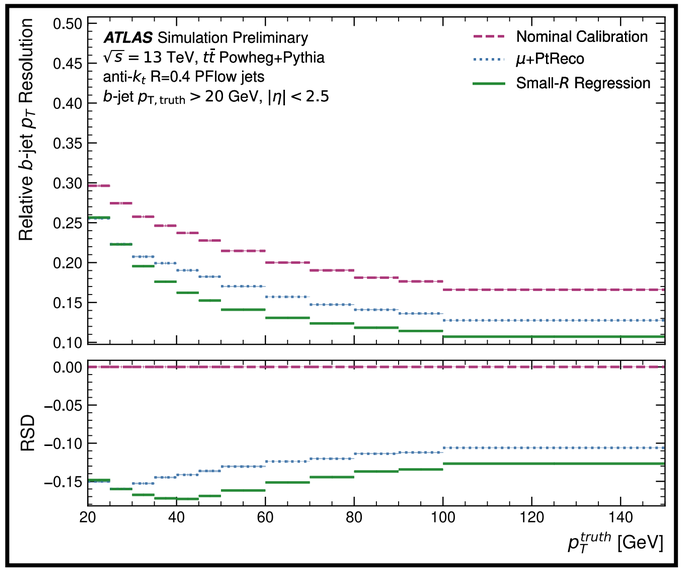


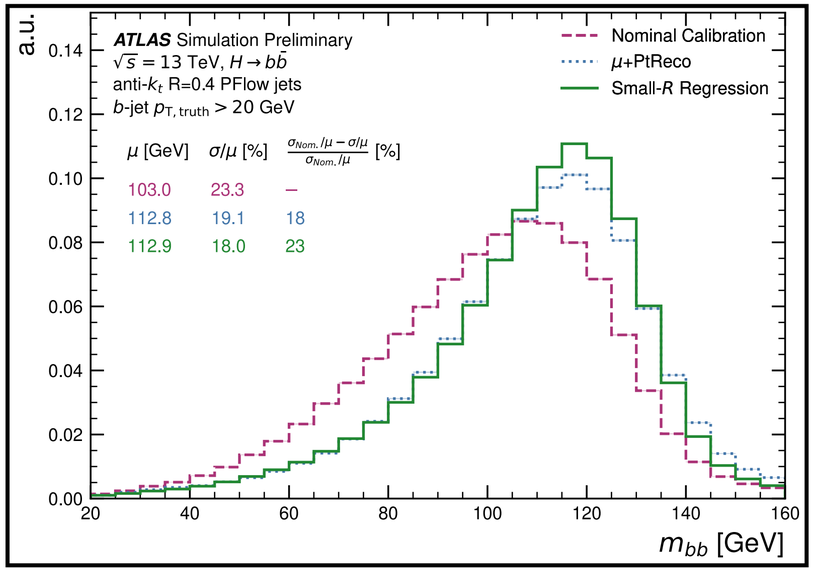
CMS b-tagging and regression Run3

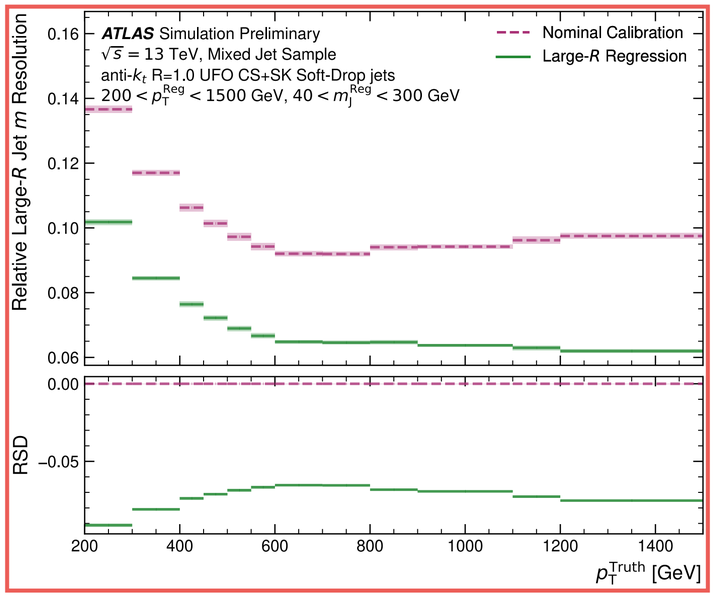


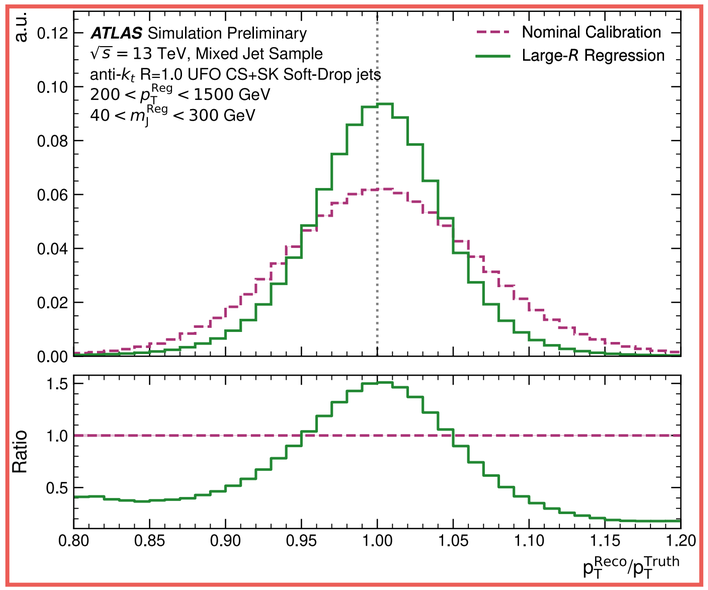
ATLAS jet energy / mass regression



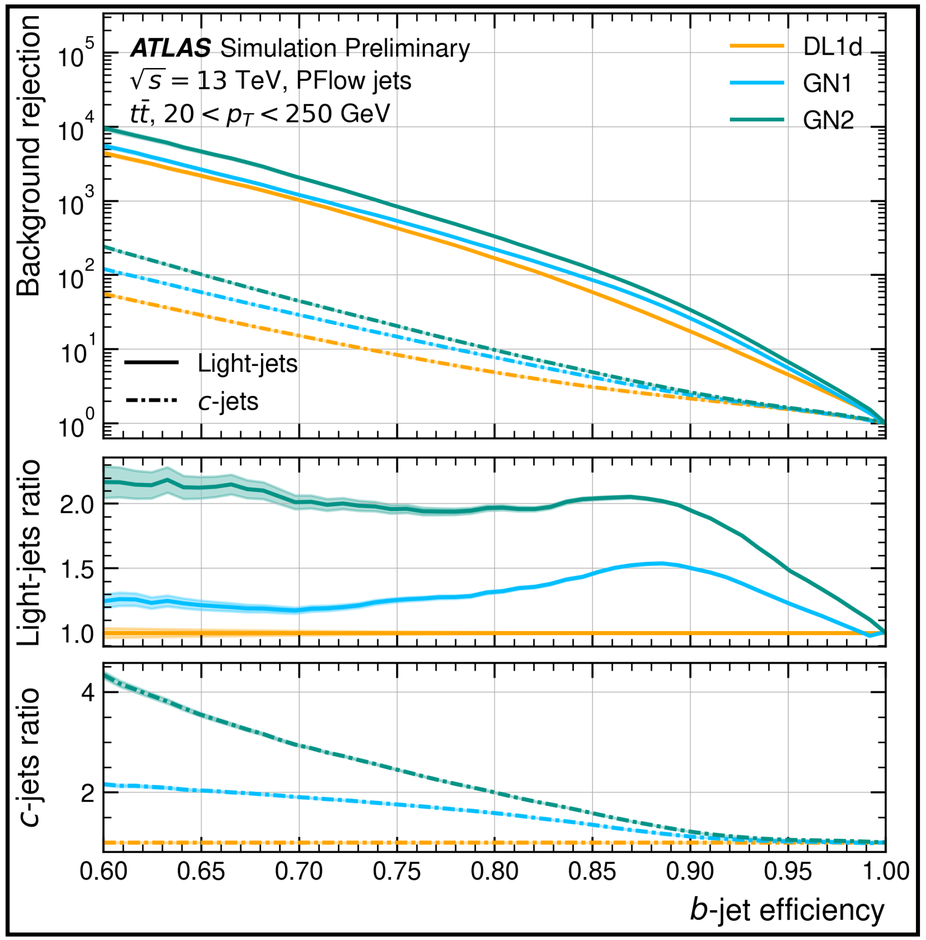


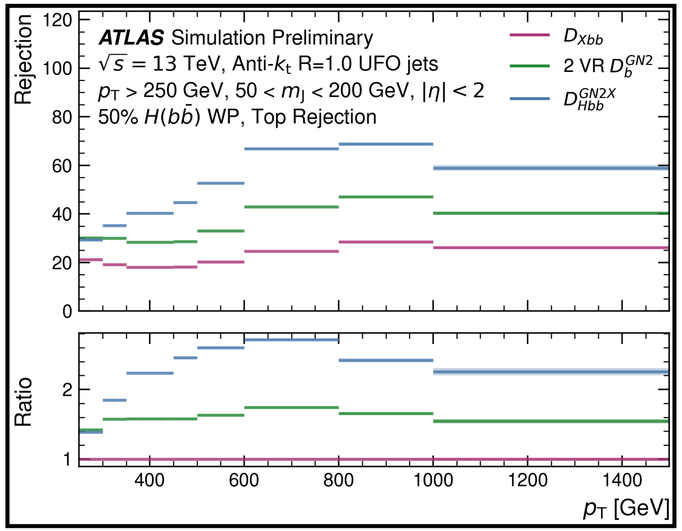


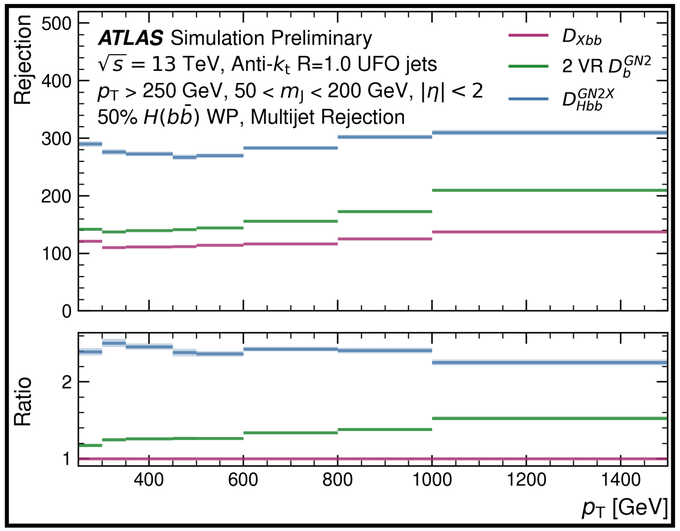


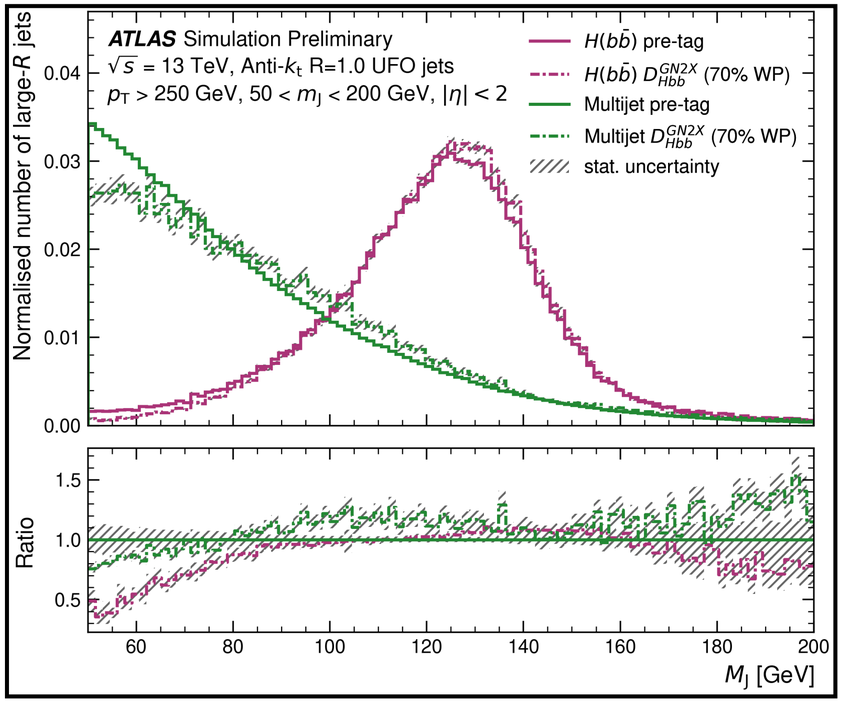


ATLAS boosted H→bb tagging

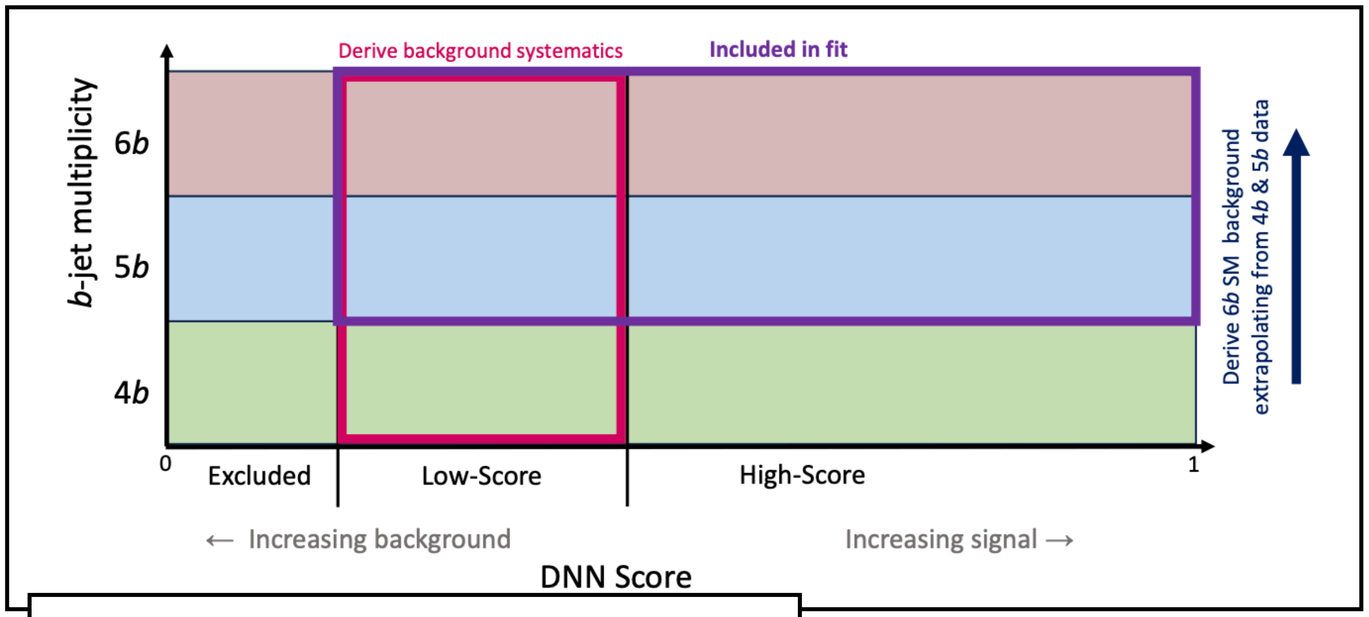








ATLAS HHH→6b



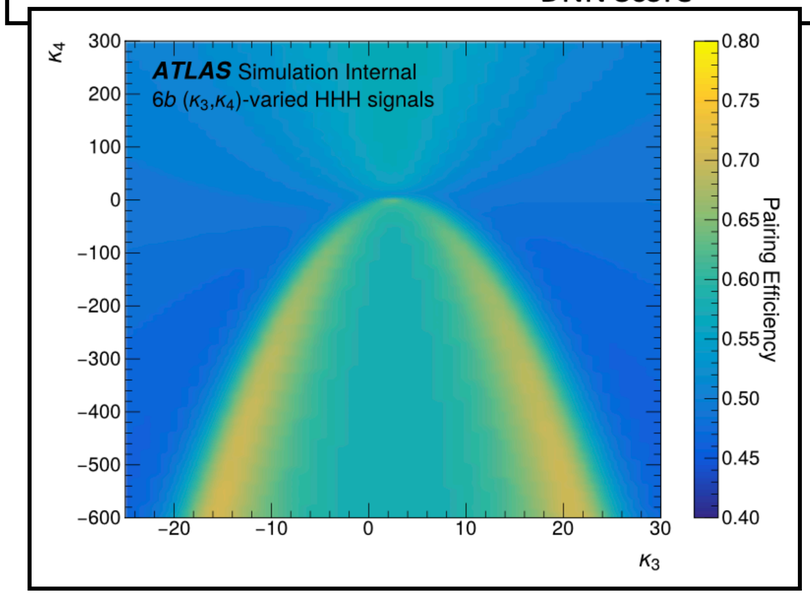


Table 1: Summary of the input variables used in each DNN. Check marks denote which input is used for each DNN.

Variable	Definition	nonres	res	heavyres
m_H-radius	Euclidean distance between the event and the pairing center (120, 115, 110) GeV in the (m_{H1}, m_{H2}, m_{H3}) volume.	✓		✓
m_{H1}	Reconstructed mass of the highest p_T Higgs boson candidate.	✓		✓
RMS(m_{jj})	Root-mean-squared (RMS) of the invariant mass of all possible jet pairs that can form a Higgs boson candidate.	✓		✓
RMS(ΔR_{jj})	RMS of the angular separation between all possible jet pairs that can form a Higgs boson candidate.	✓	✓	✓
RMS(η)	RMS of the pseudo-rapidity of the Higgs boson candidates.	✓		✓
Skewness ΔA_{jj}	Skewness of $\cosh(\Delta\eta_{ik}) - \cos(\Delta\phi_{ik})$, where i, k are all possible jet pairs that can form a Higgs boson candidate.		✓	
H_T^{6j}	Scalar sum of the p_T of the 6 jets selected to reconstruct the 3 Higgs boson candidates.		✓	
$\cos\theta$	In the (m_{H1}, m_{H2}, m_{H3}) coordinate system, θ is the angle between the vector from the origin to the event's reconstructed mass of the Higgs boson candidates, and vector from the origin to (120, 115, 110) GeV.		✓	
Aplanarity$_{6j}$	The fraction of p_T from the 6 jets selected to reconstruct the 3 Higgs boson candidates lying outside the plane formed by the 2 highest p_T jets.	✓	✓	✓
Sphericity$_{6j}$	Isotropy of the momenta of the 6 jets selected to reconstruct the 3 Higgs boson candidates.		✓	
Transverse Sphericity$_{6j}$	Isotropy of the p_T of the 6 jets used for Higgs reconstruction, with respect to the $x-y$ plane.	✓		
Sphericity	Isotropy of the momenta of all jets in the event.			✓
$\eta - m_{HHH}$ fraction	$\frac{\sum_{i,k} 2p_T^i * p_T^k * (\cosh(\Delta\eta(ik)) - 1)}{m_{HHH}^2}$ where i, k are all possible jet pairs that can form a Higgs boson candidate, and m_{HHH} is the reconstructed tri-Higgs invariant mass.		✓	
ΔR_{H1}	Angular separation between the jets paired to form the highest p_T Higgs boson candidate.	✓	✓	✓
ΔR_{H2}	Angular separation between the jets paired to form the second-highest p_T Higgs boson candidate.	✓	✓	✓
ΔR_{H3}	Angular separation between the jets paired to form the lowest p_T Higgs boson candidate.	✓	✓	✓

ATLAS HHH→6b

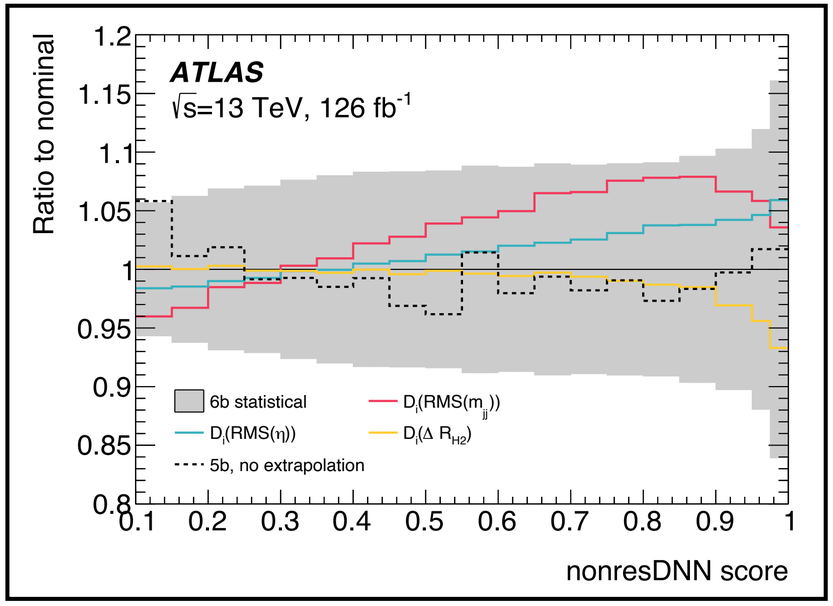
$$N_i^{6b,\,\text{predicted}} = \mu_{\text{NF}} \cdot B_i \cdot \left(\frac{(N^{5b}/N^{4b})_i}{N^{5b}/N^{4b}} \right),$$

$$D(v) = \left(\frac{(N^{6b}/N^{5b})(v)}{N^{6b}/N^{5b}} \right)_{\text{Low-Score}} \div \left(\frac{(N^{5b}/N^{4b})(v)}{N^{5b}/N^{4b}} \right)_{\text{Low-Score}}$$

Differences between 6b and 5b w.r.t. 5b vs 4b vs each input variables of DNN

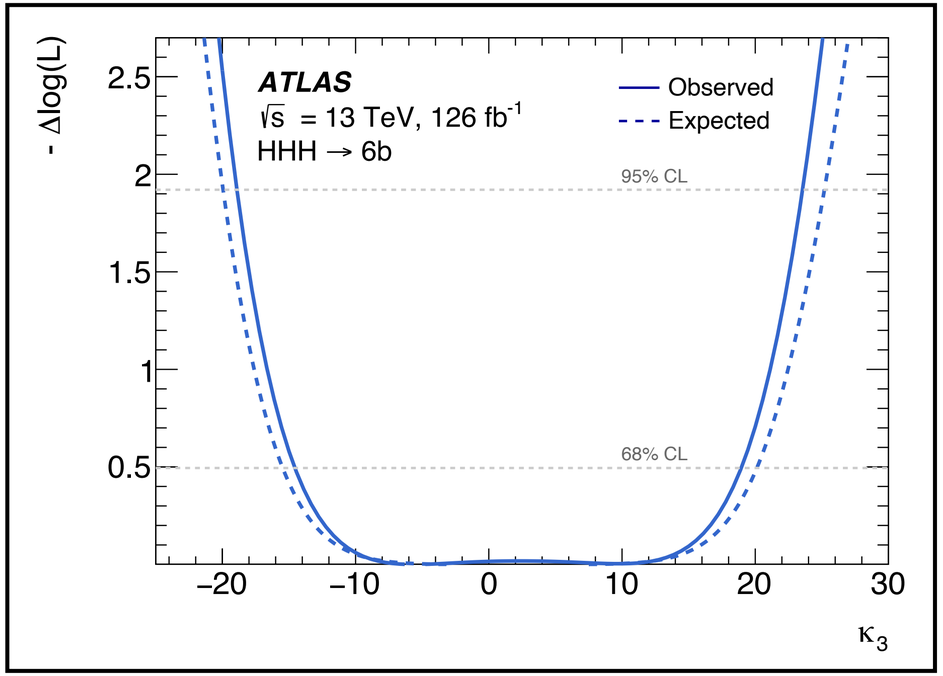
Non-closures are used to perturbate the input features and assess a variation on the final DNN template → 10 possible variations

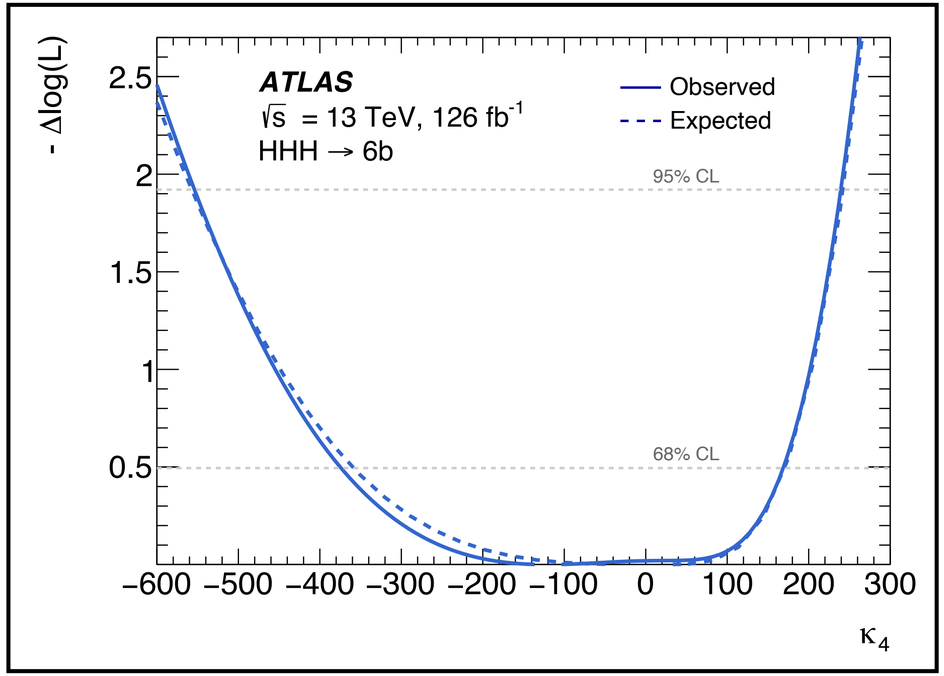
Finally a pruning procedure is allowed to only retain some principal components



Uncertainty source	Relative impact of systematic uncertainties [%]			
	SM-like	TRSM non-resonant	TRSM resonant	Heavy resonance
All uncertainties	24	20–46	33–42	24–53
Experimental	22	20–45	33–41	24–53
Detector response	7.4	6.6–14	16–24	4.1–15
Luminosity and pileup	<1	<1	<1	<1
Flavor tagging	3.2	2.8–5	6.9–8.8	1.5–5.6
Jet reconstruction	2.7	2.3–6.5	3.6–7.1	1.0–6.3
Trigger efficiency	2.0	1.8–3.5	6–10	1.4–4.2
Background modeling	16	14–36	18–30	20–45
Theoretical	1.5	<1	<1	<1
MC statistical	<1	<1	<1	<1

ATLAS HHH→6b


- Δlog(L)
ATLAS
√s = 13 TeV, 126 fb-1
HHH → 6b
Observed
Expected
95% CL
68% CL
κ3


- Δlog(L)
ATLAS
√s = 13 TeV, 126 fb-1
HHH → 6b
Observed
Expected
95% CL
68% CL
κ4