Recent Results in Higgs Physics

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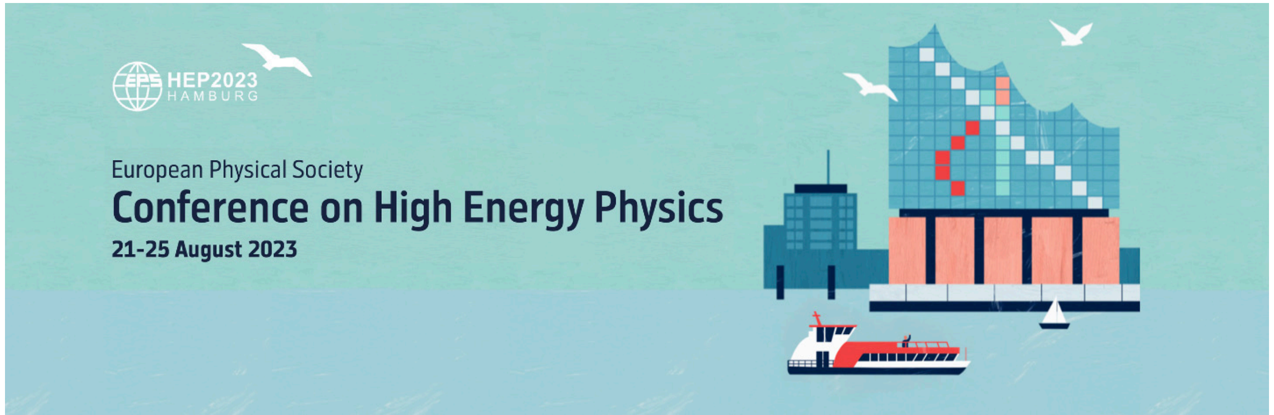
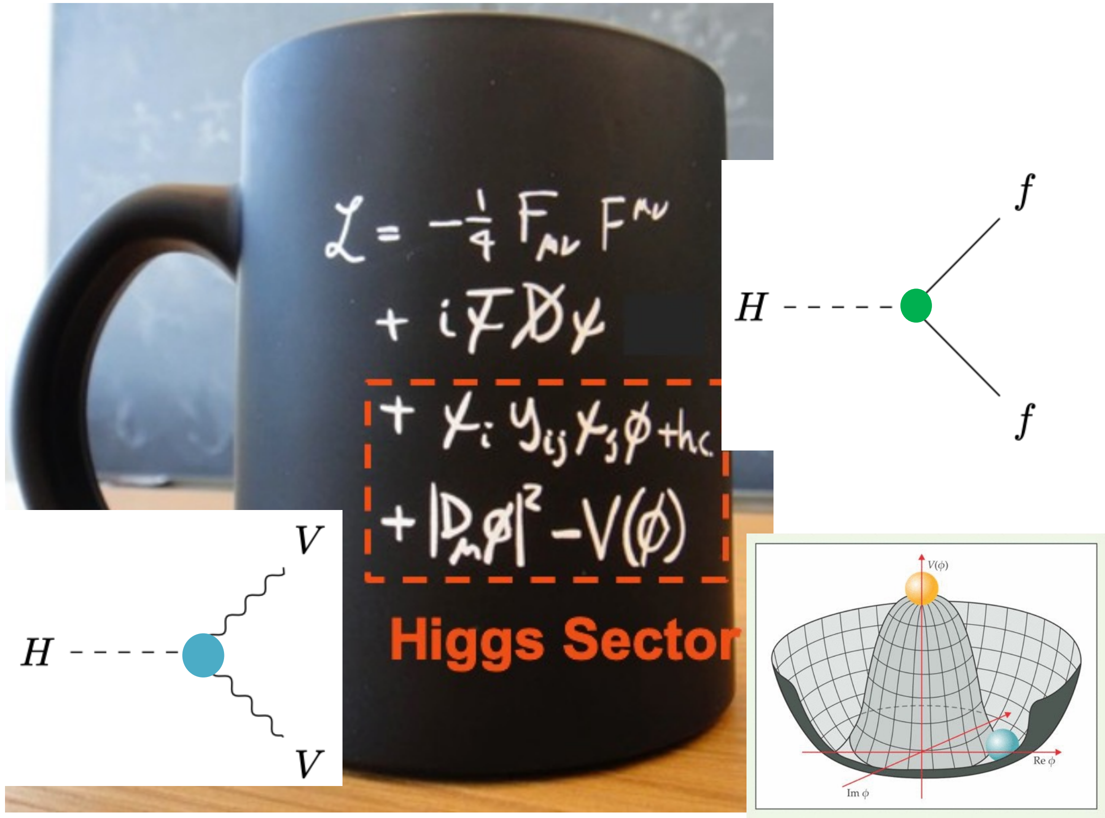
on behalf of the ATLAS and CMS Collaborations

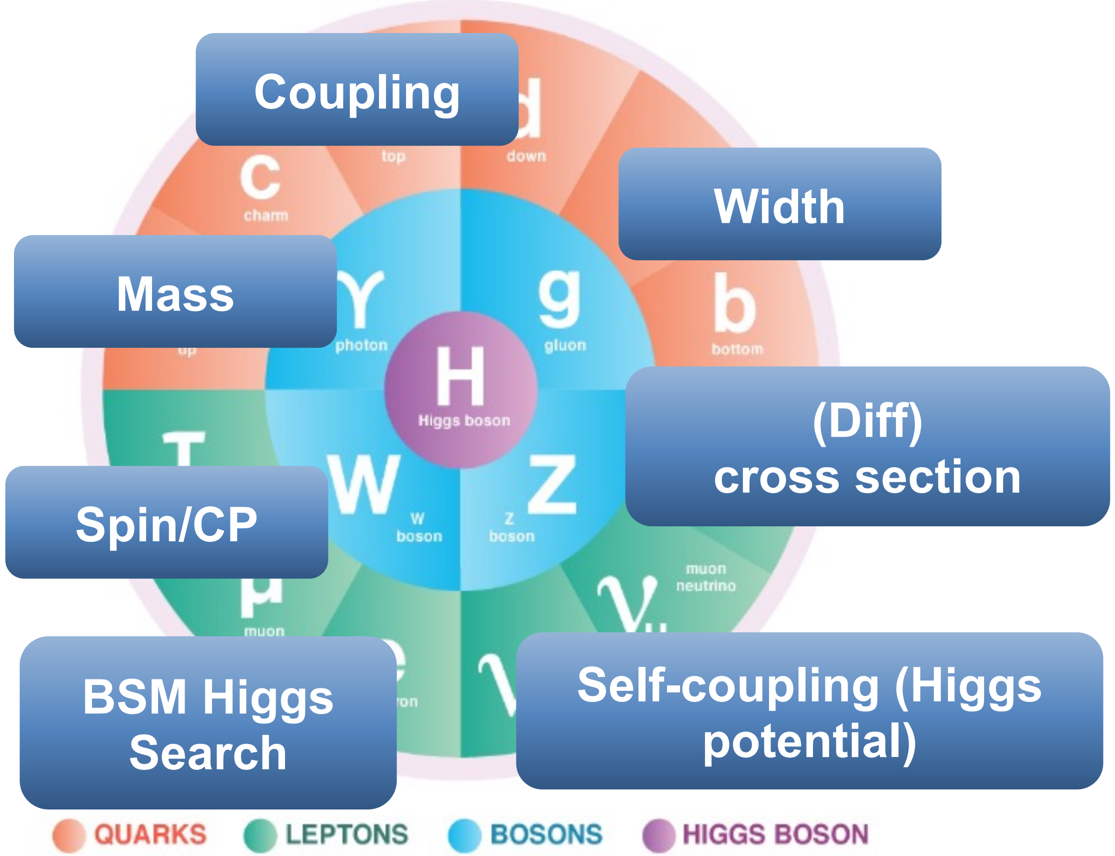


Introduction ~Higgs Physics ~

(*)not including neutrino mass

- In the Standard Model, 15* unpredictable parameters out of 19* are related to the Higgs sector
- Crucial to understand Higgs boson's properties in various measurements
  ➔ Connect to the unresolved questions in the Universe





Run2 achievements and Run 3 status

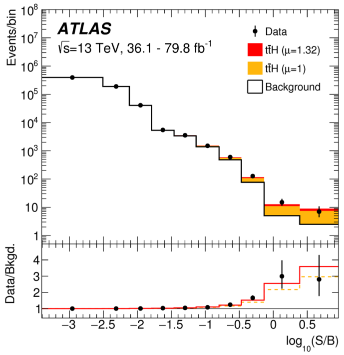
[ATLAS public page](#)

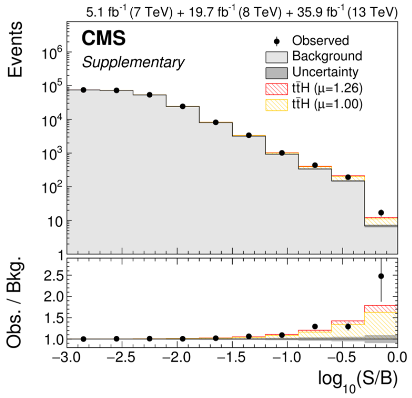
[CMS public page](#)

Run 2
13 TeV

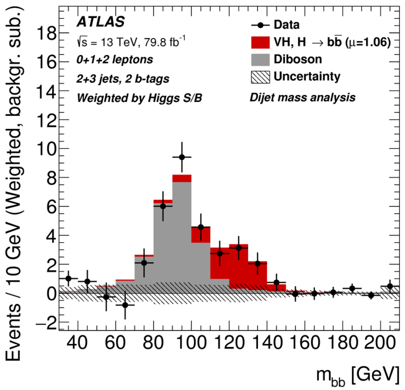
Partial data
~80fb^{-1}

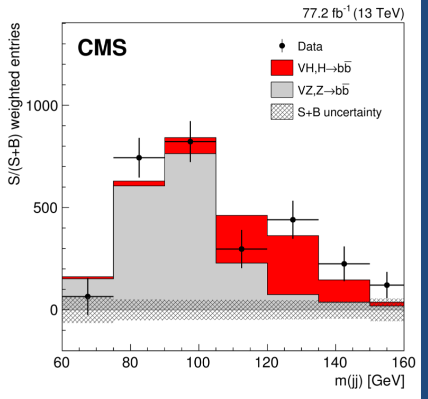
ttH observation





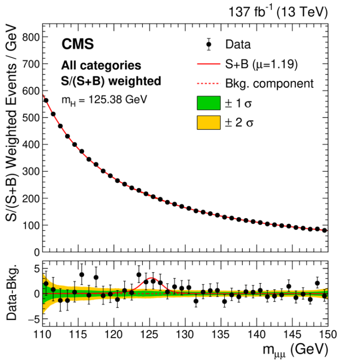
VH, H→bb observation



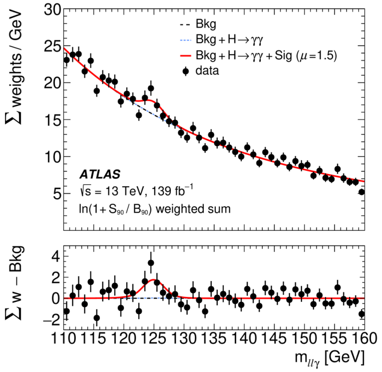


Full data
~140fb^{-1}

H→μμ evidence



H→llγ evidence



Run 3
13.6 TeV

~60fb^{-1}

- ✓ Observed major production/decay processes in Run1 and Run2
- ✓ Large LHC data opens the door to access **rare Higgs processes** and **difficult corners of phase spaces**

Run2 achievements and Run 3 status

Run 2
13 TeV

ttH c

VH

H→

Partial data
~80fb^{-1}

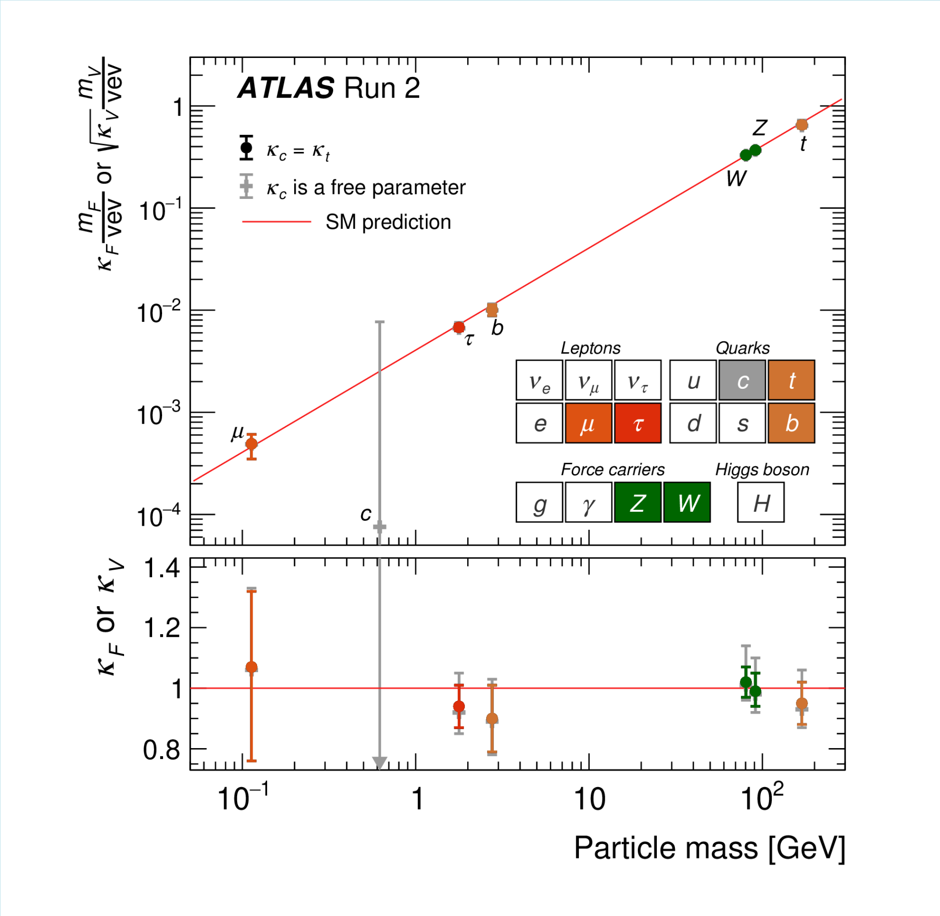
Full data
~140fb^{-1}

Higgs@10

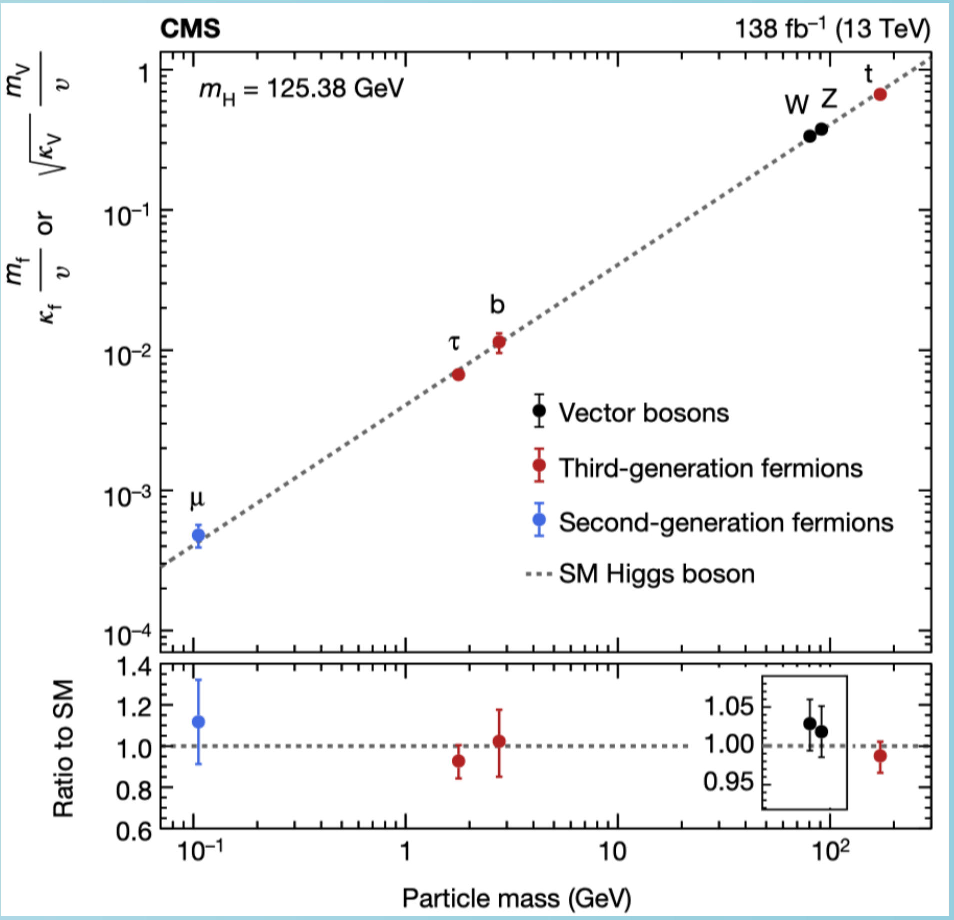
Run 3
13.6 TeV

~60fb^{-1}

Nature 607, 52-59 (2022)



Nature 607, 60-68 (2022)



Higgs couplings agree with SM over 3 order of magnitude in mass!!

This talk picks up highlights of recent Higgs results

Mass Measurement

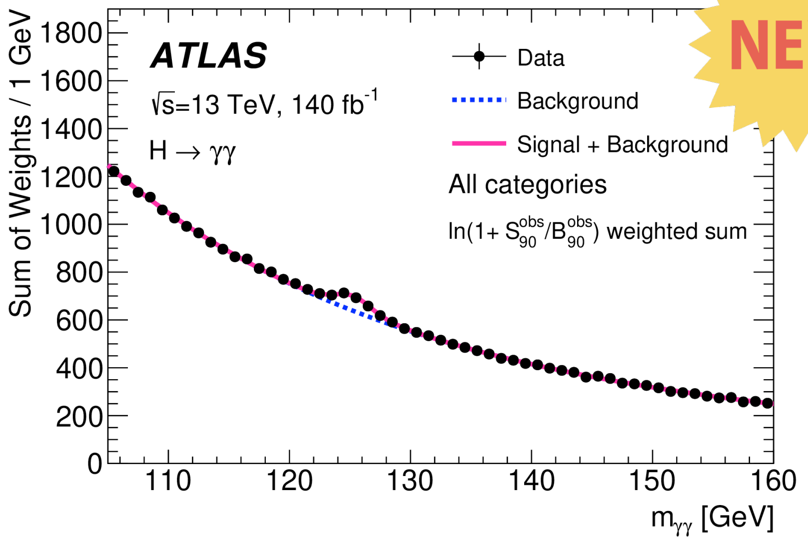
[Stefano's talk](#) [arXiv:2308.07216](#) [arXiv:2308.04775](#)

NEW

2023/8/20

- Fundamental parameter in the SM, it determines production and decay rates of Higgs
➔Need to measure experimentally
- H→γγ has excellent mass resolution
  - Extensive efforts on the photon energy calibration in Run2
  - Reduce photon energy scale/resolution uncertainties

<u>**320 MeV (previous Run 2 results) ➔ 80 MeV**</u>



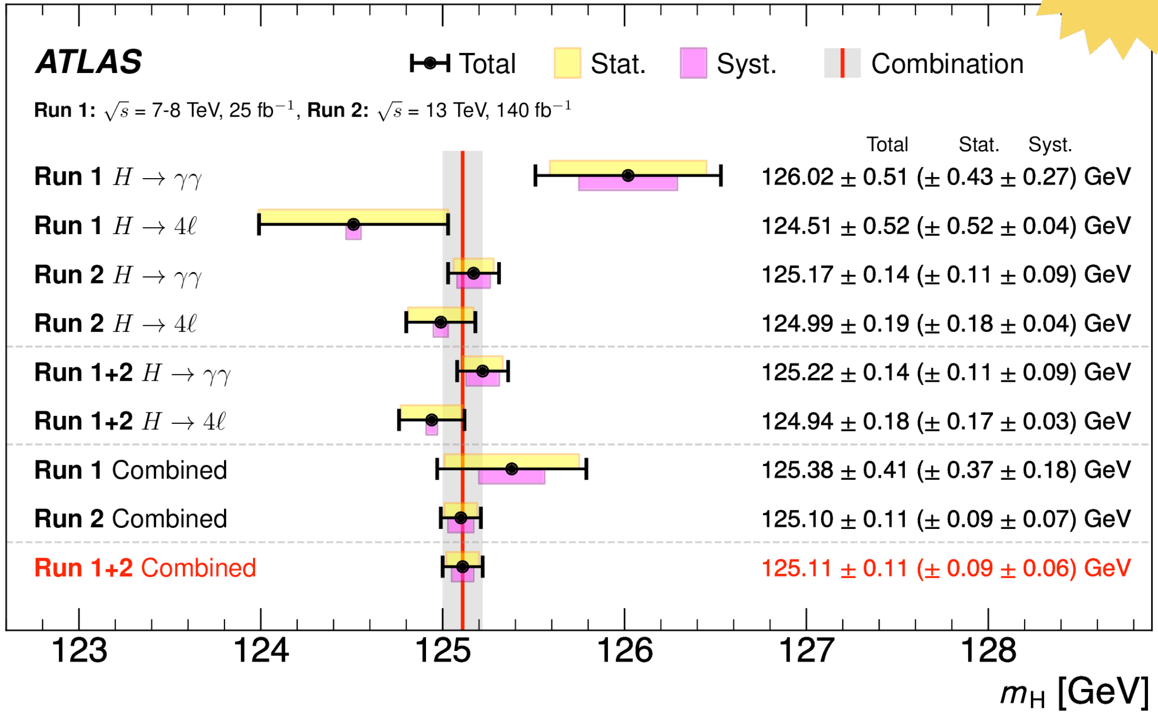
NEW

Measured Higgs mass with H→γγ (Run 1+2)

125.22±0.11(stat)±0.09(syst) GeV
(0.11% precision!)

Combine H→γγ and H→ZZ→4l channels (Run1+Run2)

125.11±0.09(stat)±0.06(syst) GeV
(0.09% precision!)

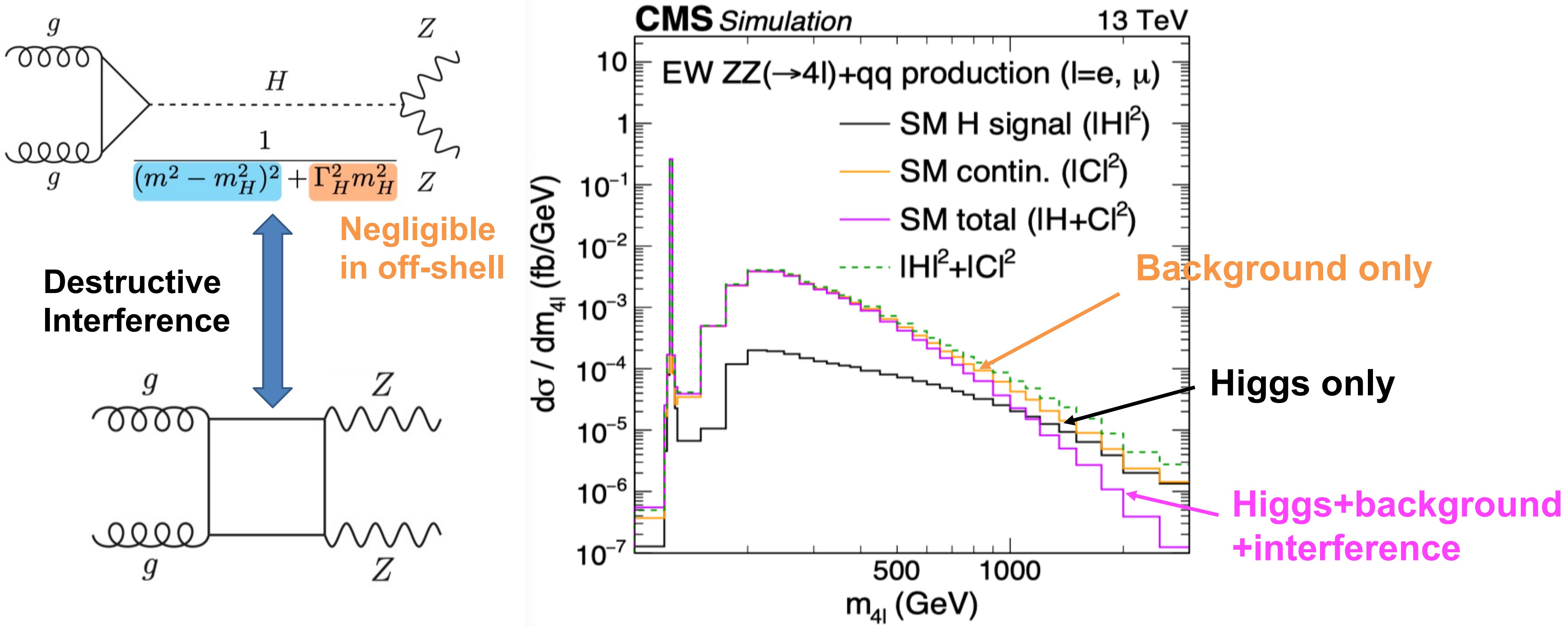


Width measurement

CMS *Nat. Phys. 18 (2022) 1329*
ATLAS arXiv:2304.01532

Stefano and Fillipo's talk

- Higgs boson natural width : Γ_H^{SM} ~4 MeV
  - Direct measurement is very difficult at the LHC
- Can measure Higgs width from on-shell/off-shell processes in H→ZZ



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Stefano and Fillipo's talk

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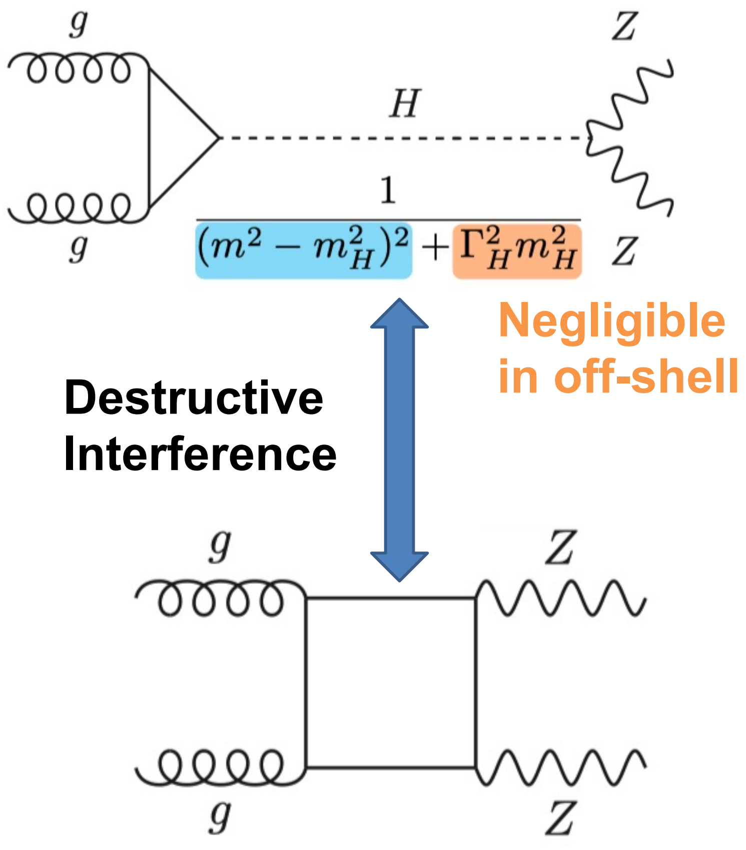
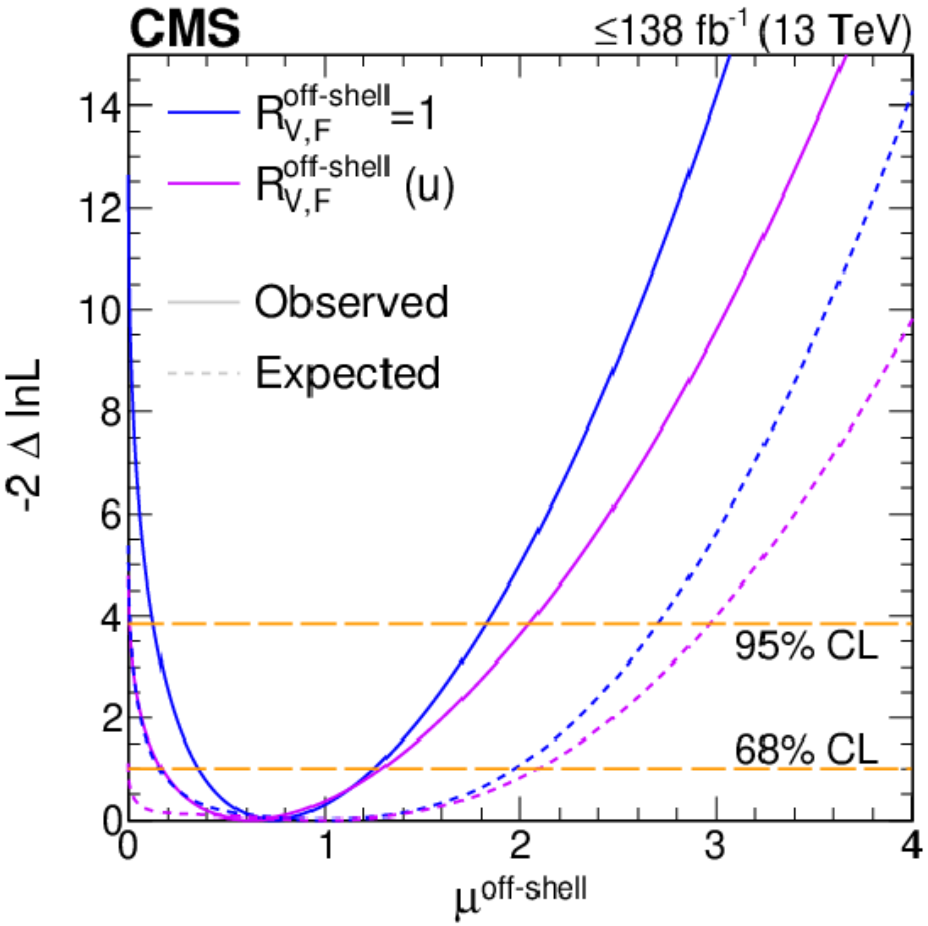


$$\frac{1}{(m^2 - m_H^2)^2 + \Gamma_H^2 m_H^2}$$



$$\mu = \frac{N_{obs}^{evernts}}{N_{exp,SM}^{events}}$$

Observed non-zero offshell signal at
3.6σ (CMS),
3.3σ(ATLAS)

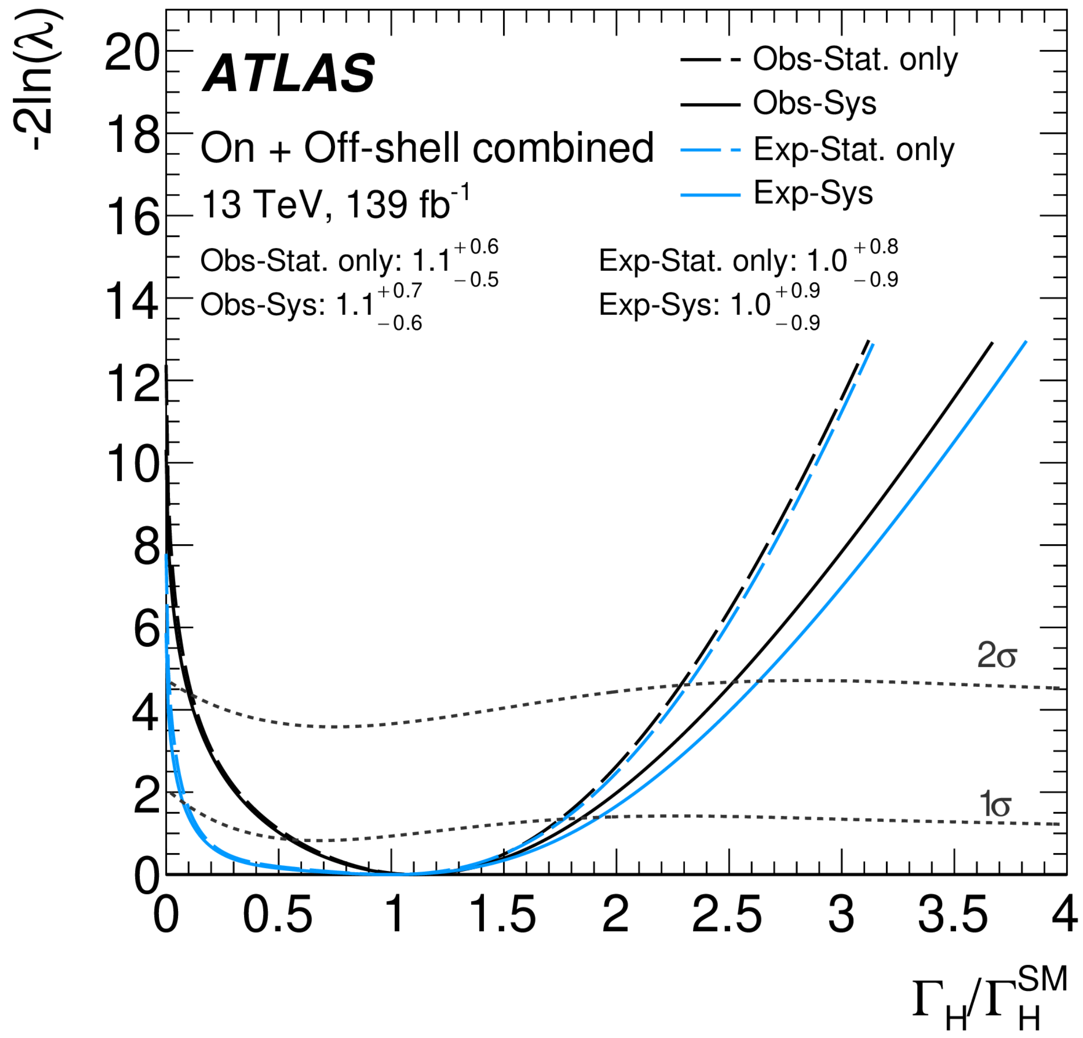
$\mu_{off-shell}$ = $0.62^{+0.68}_{-0.45}$ (CMS)

$\mu_{off-shell}$ = $1.1^{+0.7}_{-0.6}$ (ATLAS)

Width measurement

CMS *Nat. Phys. 18 (2022) 1329*
ATLAS arXiv:2304.01532
Stefano and Fillipo's talk

- Extract Higgs width with off-shell and on-shell H→ZZ measurement



$$\mu_{\mathrm{off-shell}} = \mu_{gg}\mu_{ZZ}$$

$$\mu_{\mathrm{on-shell}} = \mu_{gg}\mu_{ZZ}\frac{\Gamma_H^{SM}}{\Gamma_H}$$

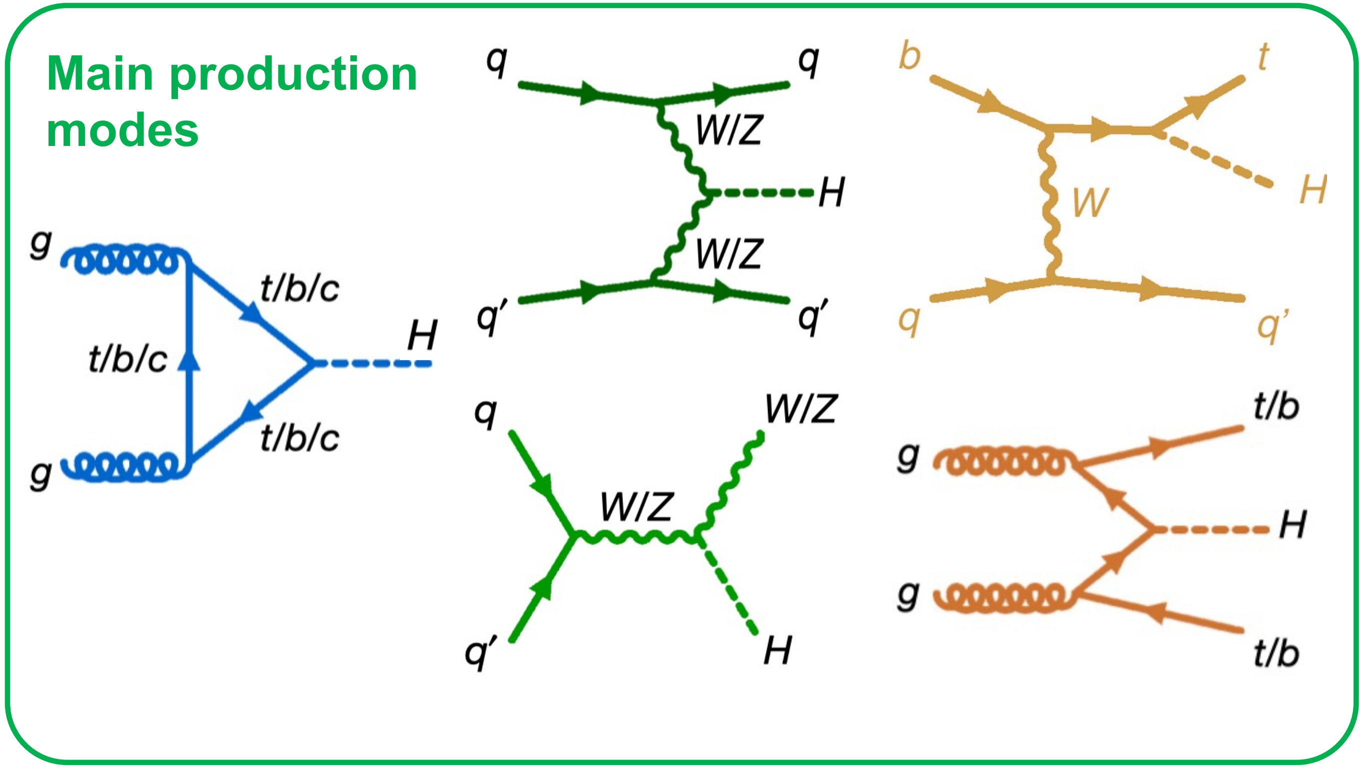
Assuming, couplings are identical in on-shell and off-shell

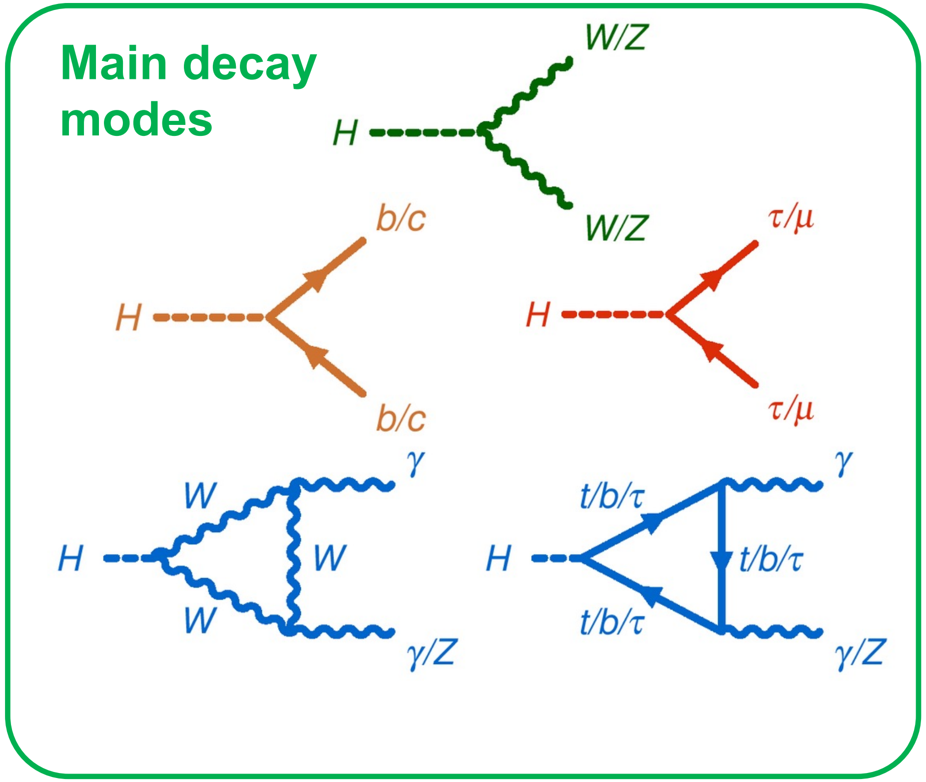
$$\frac{\mu_{\mathrm{off-shell}}}{\mu_{\mathrm{on-Shell}}} = \frac{\Gamma_H}{\Gamma_H^{SM}}$$

ATLAS
$\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV
(Exp. 4.1±3.7 MeV)

CMS
$\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV
(Exp. $4.1^{+4.0}_{-3.5}$ MeV)

Combined Higgs Measurements





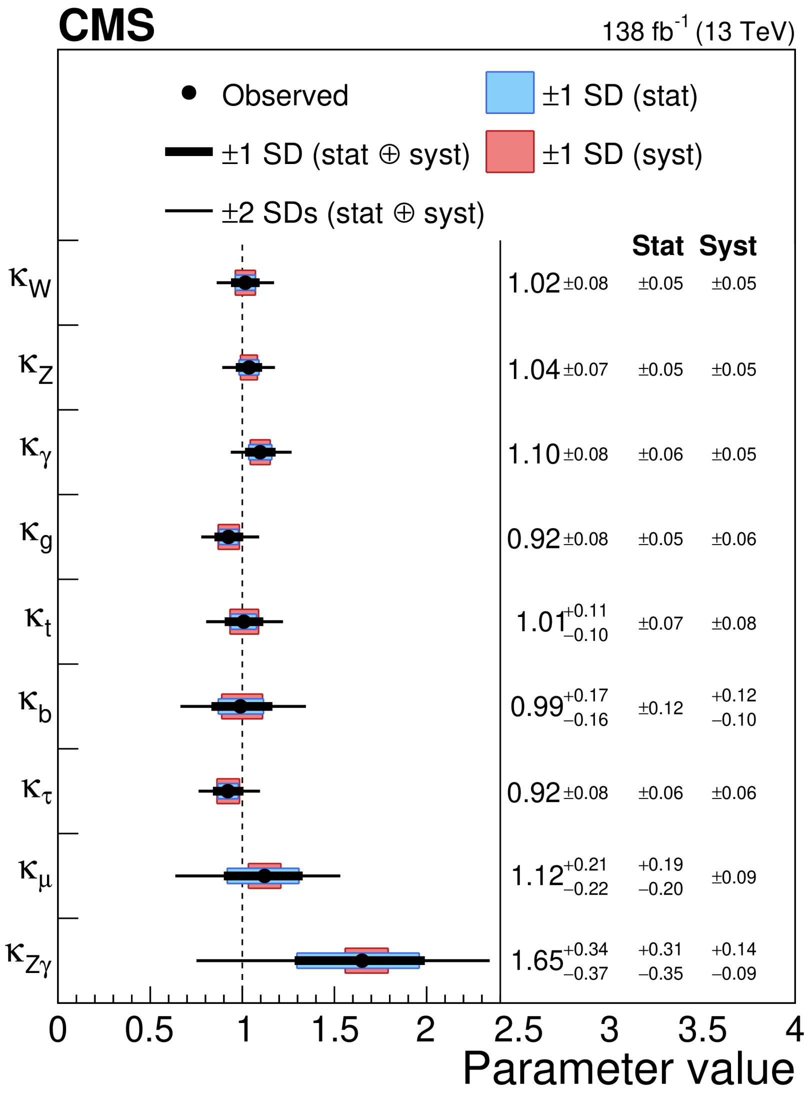
- Various production and decay modes have been studied in Higgs measurement

➔ Provides most precise Higgs coupling and cross-section measurements

Coupling Measurements

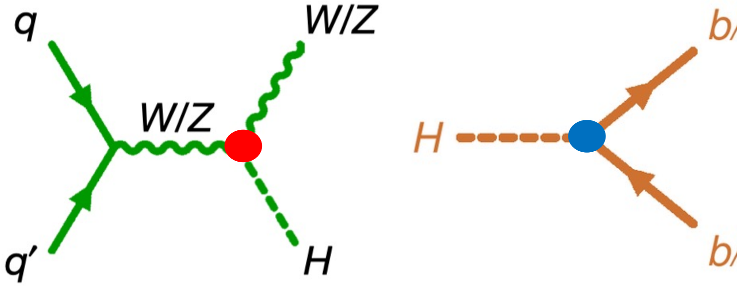
[Nature 607, 52-59 (2022)](#)
[Nature 607, 60-68 (2022)](#)

[Changqiao's talk](#)



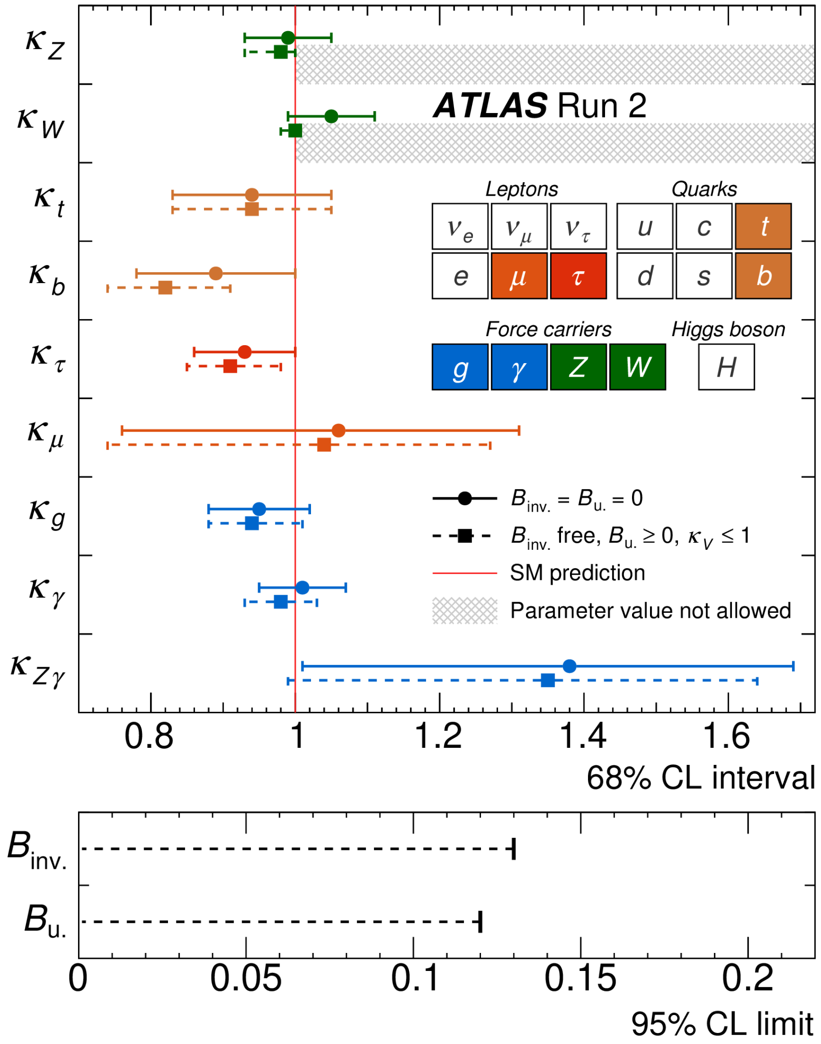
k-framework

$$\kappa = g_x^{measure} / g_x^{SM}$$



$$\sigma(pp \to VH) \cdot BR(H \to bb)$$
$$= k_{W/Z}^2 \cdot k_b^2 \times (\sigma_{SM} \cdot BR_{SM})$$

- $\kappa_{W/Z}$, κ_γ, κ_g, κ_τ ~6-8%
- κ_t, κ_b ~10%
- κ_μ ~20%
- $\kappa_{Z\gamma}$ ~40%



Combined cross-section measurement

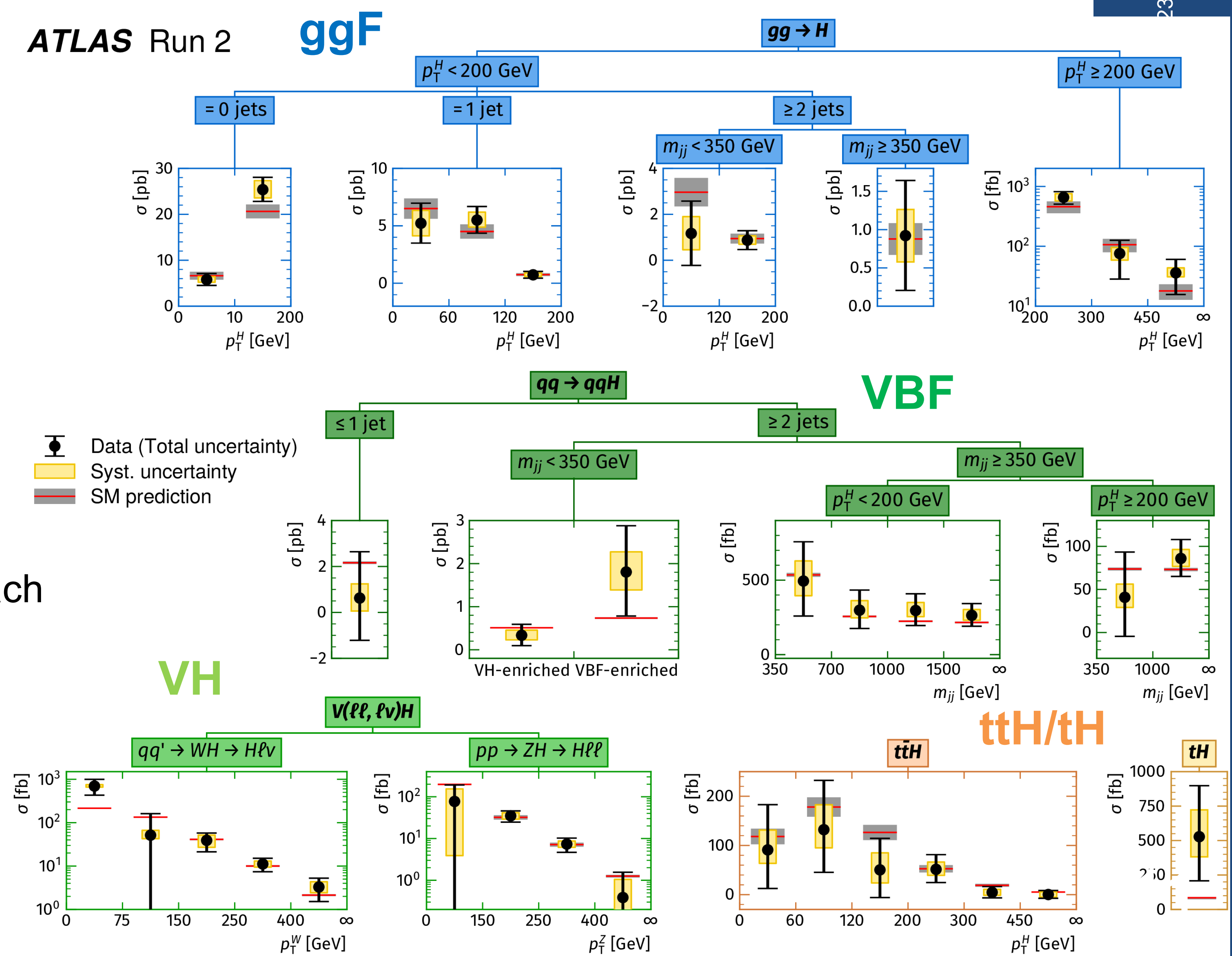
[Nature 607, 52-59 (2022)](#)

[Changqiao's talk](#)

- Cross-section measurement moving from inclusive to kinematic properties ("simplified template cross sections", STXS)

- STXS is powerful framework
  - Combine all decay modes for each production processes

➔ Access to BSM sensitive phase space (e.g. high p_T^H)



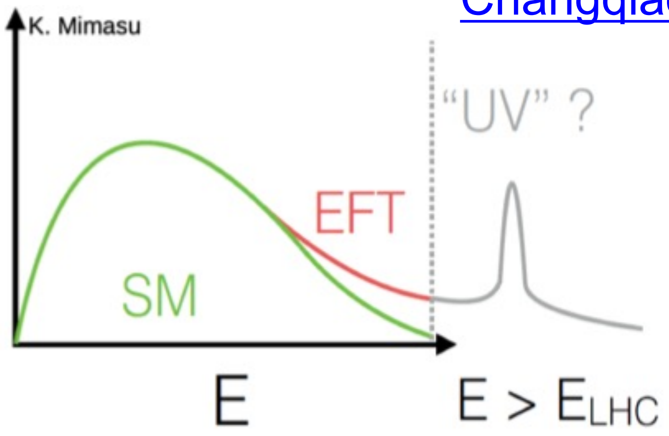
SMEFT interpretation

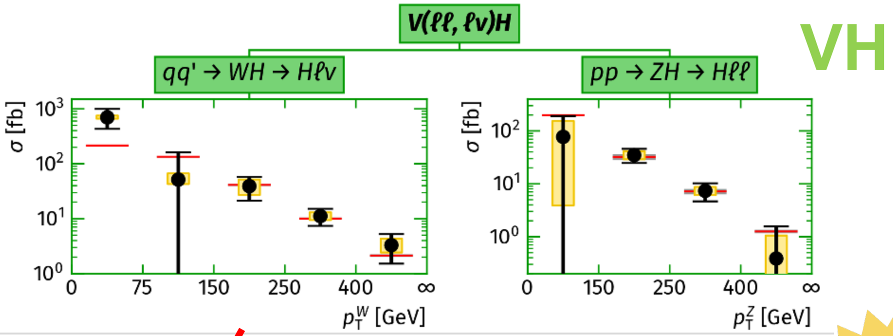
- SMEFT is generic extension of SM and describes BSM effects even beyond LHC energy

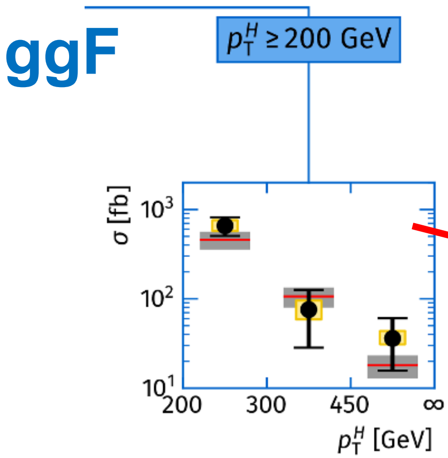
$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_{i}^{N_{d=6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \dots$$

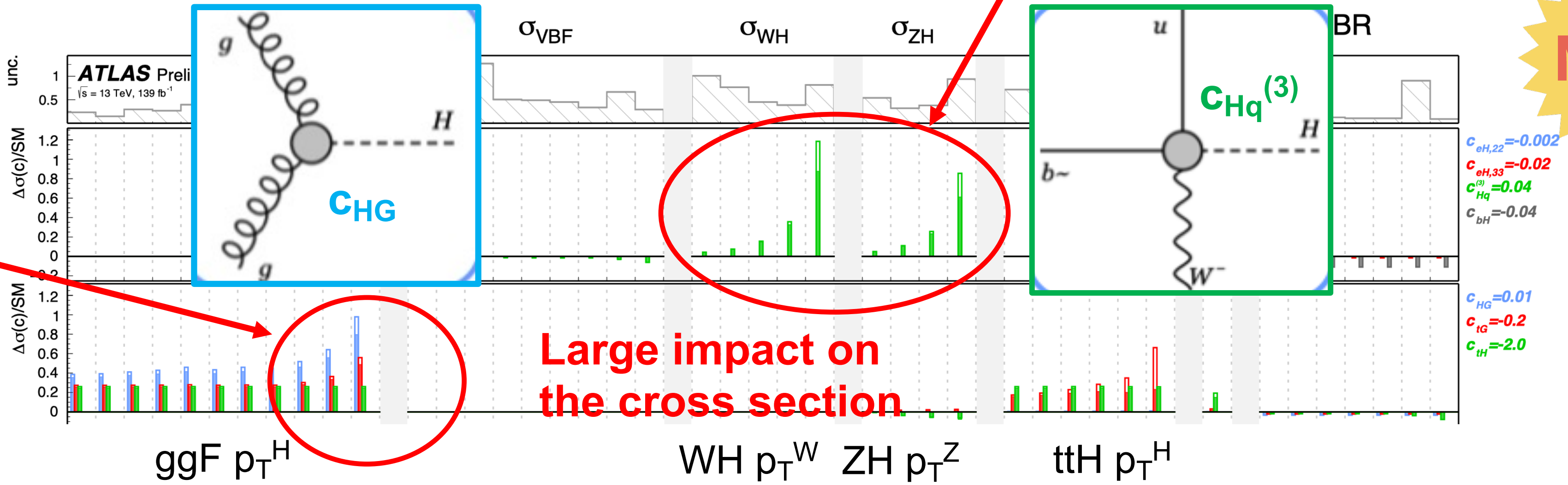
Wilson coefficient

- STXS measurements provide many observables ➔ Sensitive to various Wilson coefficients









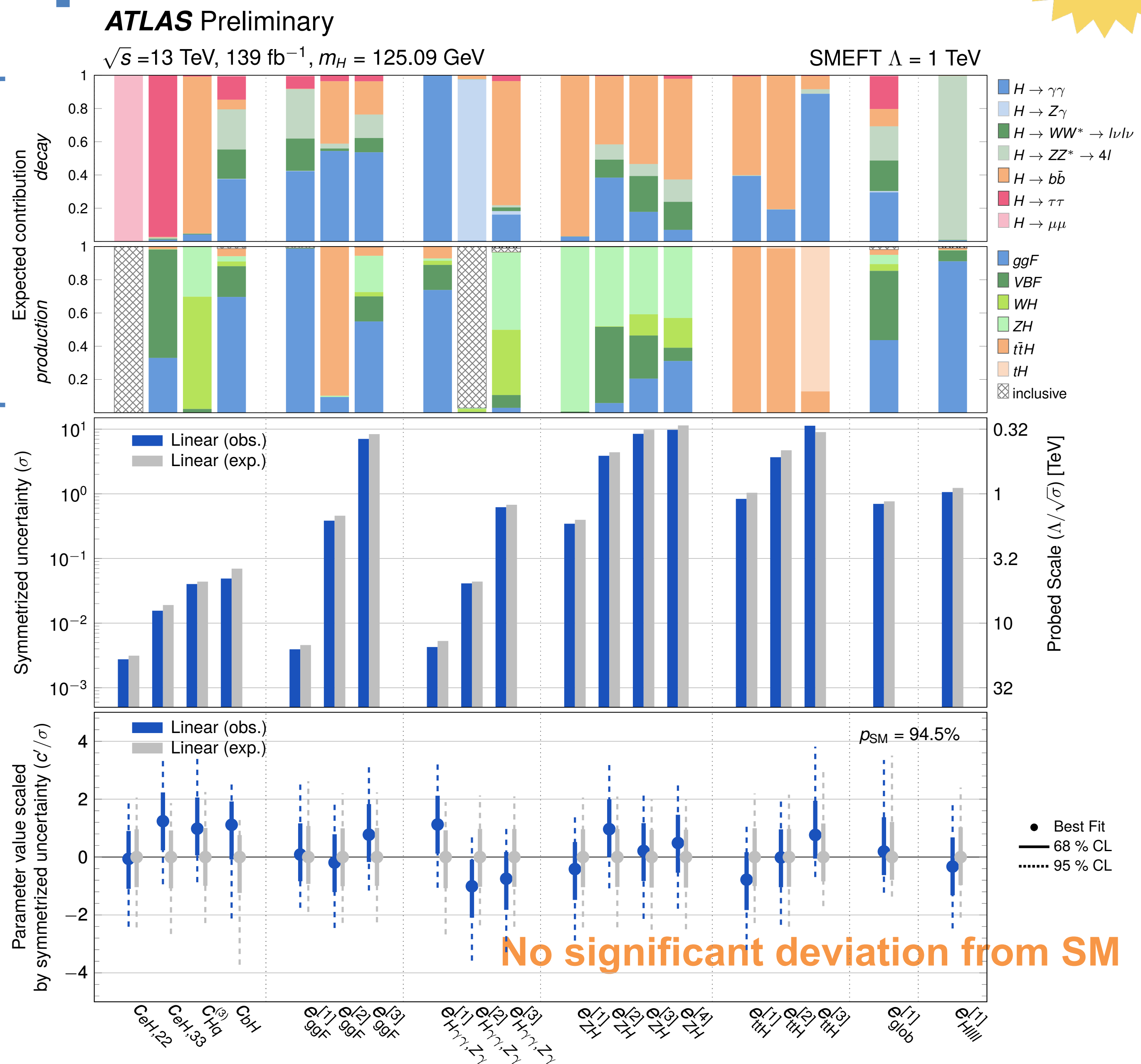
NEW

SMEFT/BSM interpretation

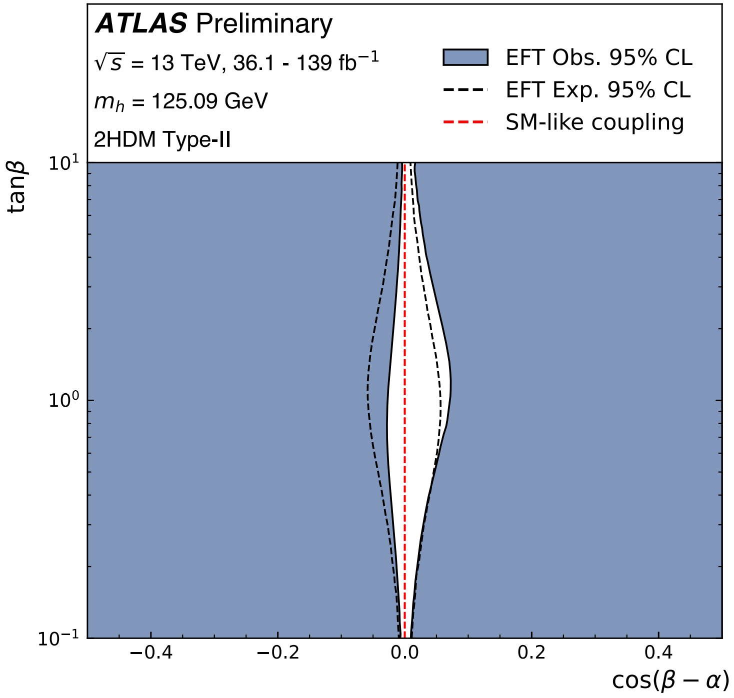
[ATLAS-CONF-2023-52](#)
[Changqiao's talk](#)

NEW

Various production/decay modes contribute to constrain different EFT parameters



No significant deviation from SM



ttH/tH, H→bb measurement

CMS-PAS-HIG-19-011

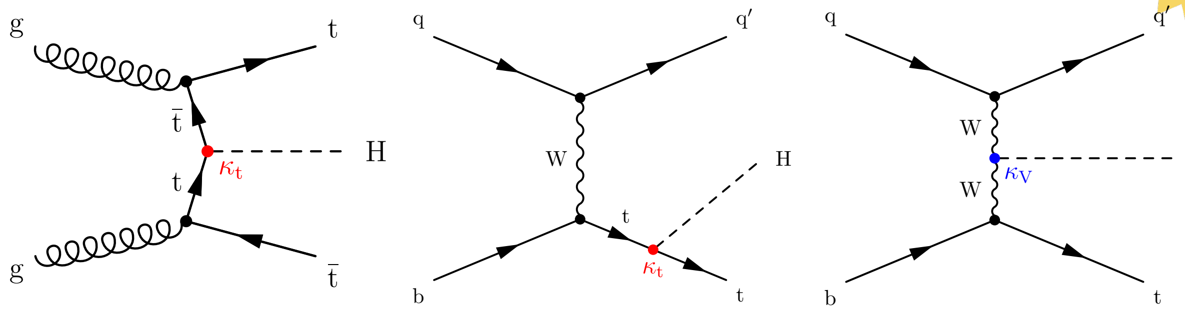
Pascal's talk

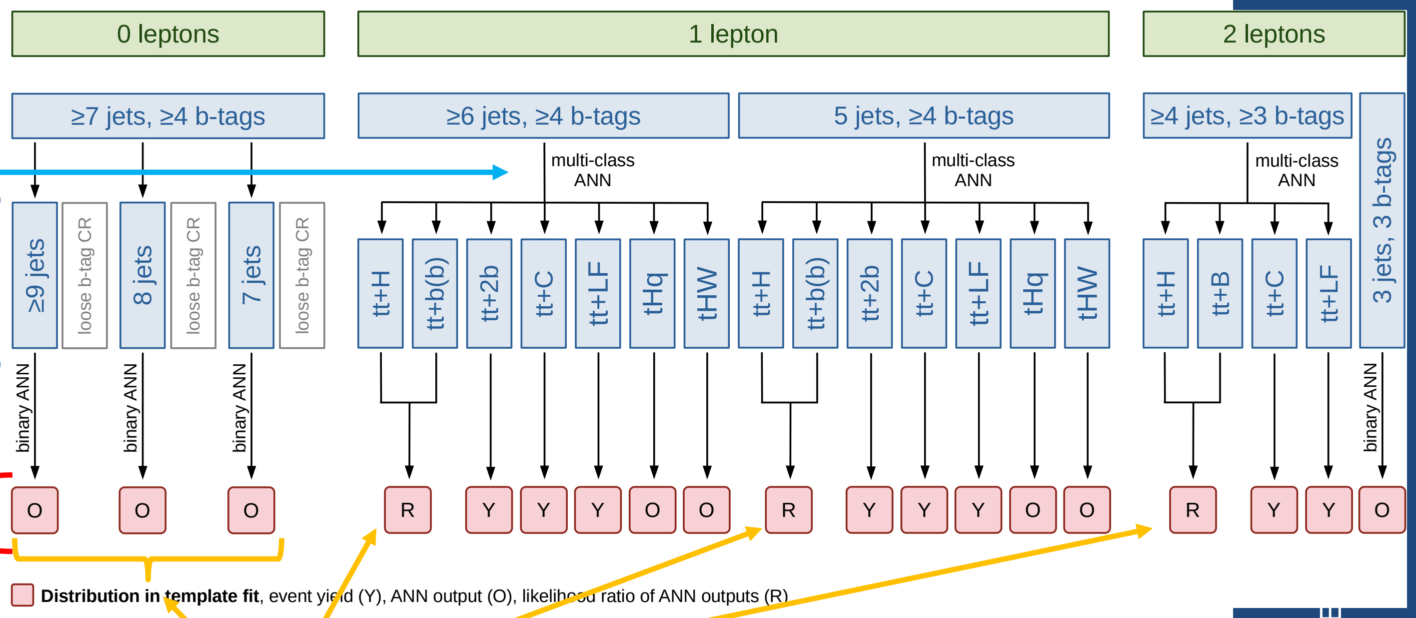
NEW

- Direct access to Higgs-top coupling

Analysis strategy

- Optimized analyses by top decay
- Categorized by the number of jets and the number of b-jets
- Classified into ttH/tH and tt+jets backgrounds by multi-class ANNs
- Background estimation
  - Multi-jet by data-driven method
  - tt+jets are controlled by each background category
- Final discriminant:
  - ANN information or yield



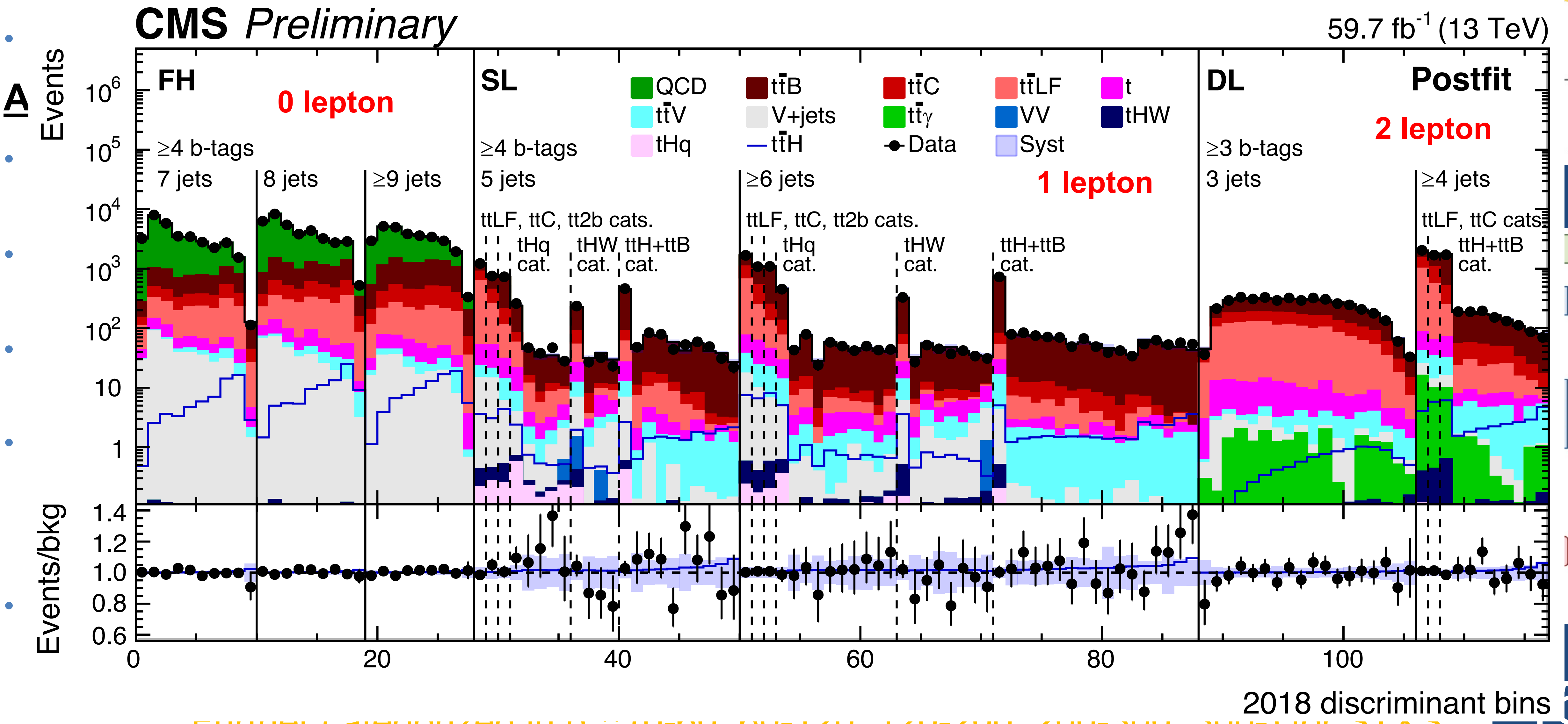


Further categorized in p_T^H (0-60, 60-120, 120-200, 200-300, 300-) for STXS

ttH/tH, H→bb measurement

CMS-PAS-HIG-19-011
Pascal's talk

NEW



Further categorized in p_T^H (0-60, 60-120, 120-200, 200-300, 300-) for STXS

CMS-PAS-HIG-19-011

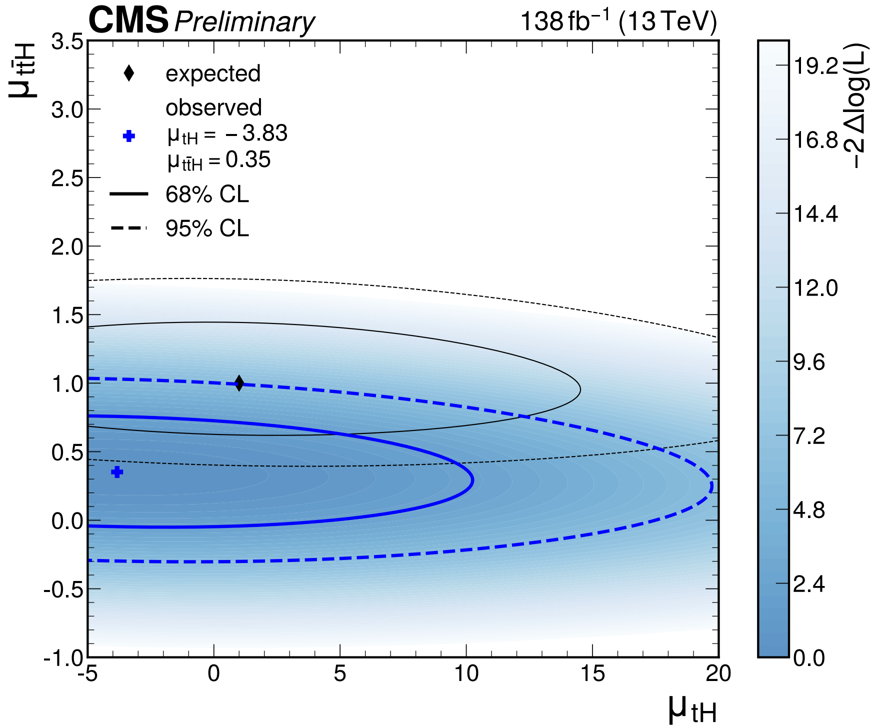
Pascal's talk

NEW

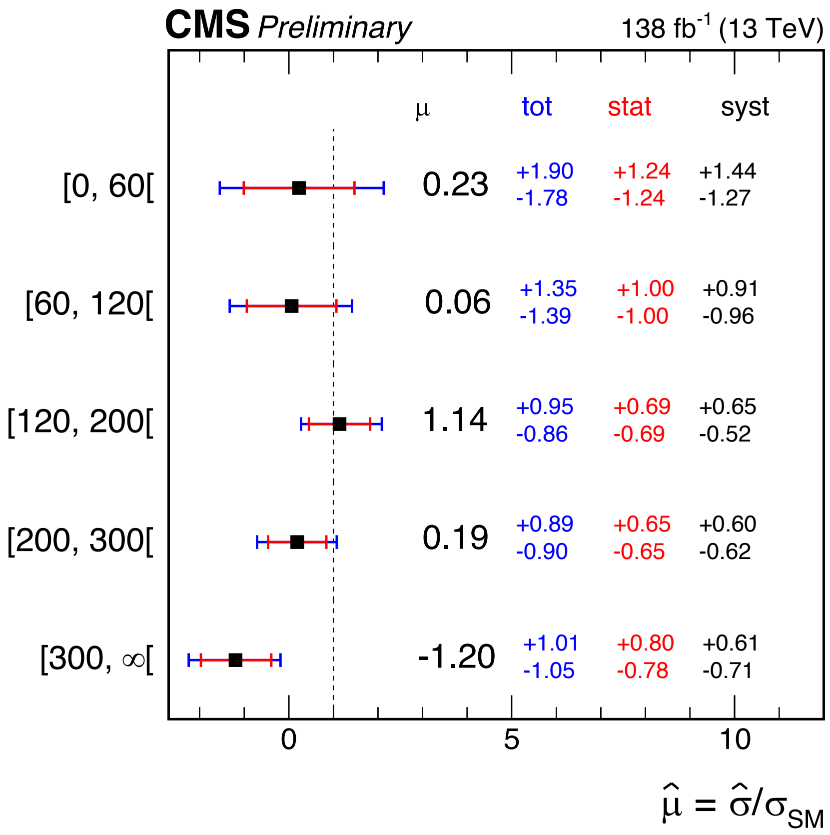
ttH/tH, H→bb measurement

- Inclusive signal strength for ttH and tH
  - $\mu_{ttH} = 0.33 \pm 0.26$(stat+sys)
    - Compatibility with SM is 2.4σ
  - 95% CL upper limit on μ_{tH} 14.6 (exp. $19.3^{+9.2}_{-6.0}$)

μ_{tH} and μ_{ttH} simultaneous measurement



ttH STXS (p_T^H) measument



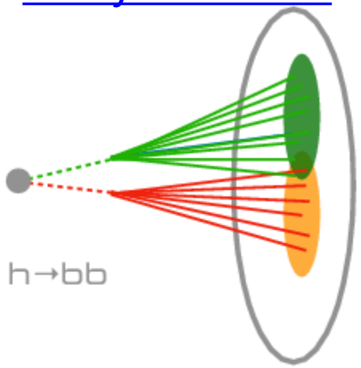
Compatibility with SM model p-value 0.21 (1.3σ)

Boosted topology opens new window

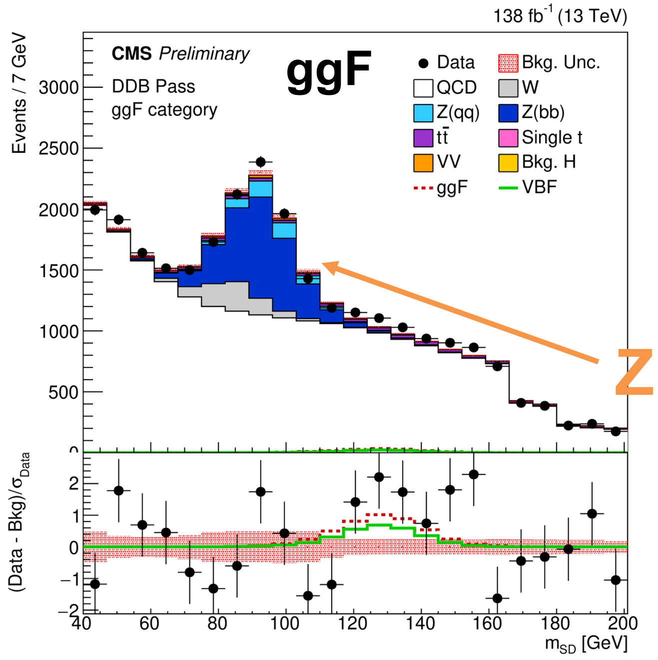
CMS-PAS-HIG-21-020

Chayanit's talk

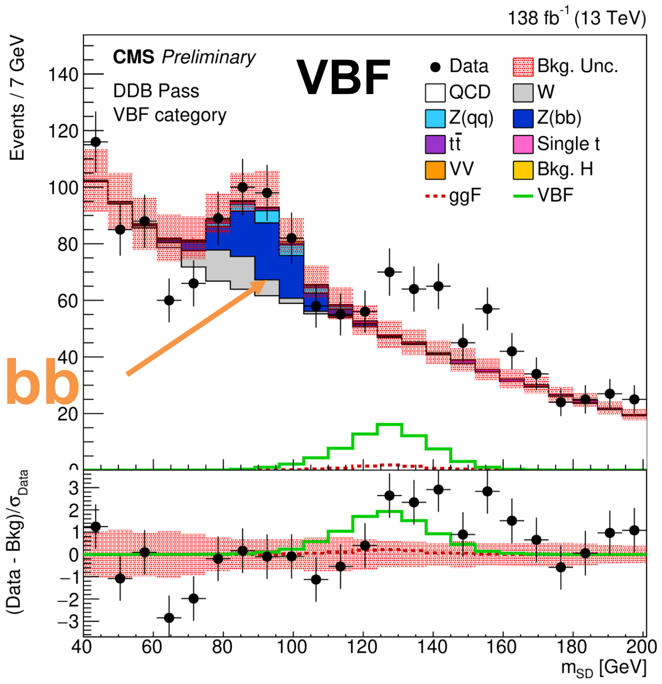
- Search for boosted VBF and ggF production in H→bb decay
- Requirement of highly boosted Higgs ($p_T^H > 450$ GeV)
  - Dedicated X(H,Z)→bb tagger to distinguish signal from QCD jets
  - Separate VBF and ggF categories

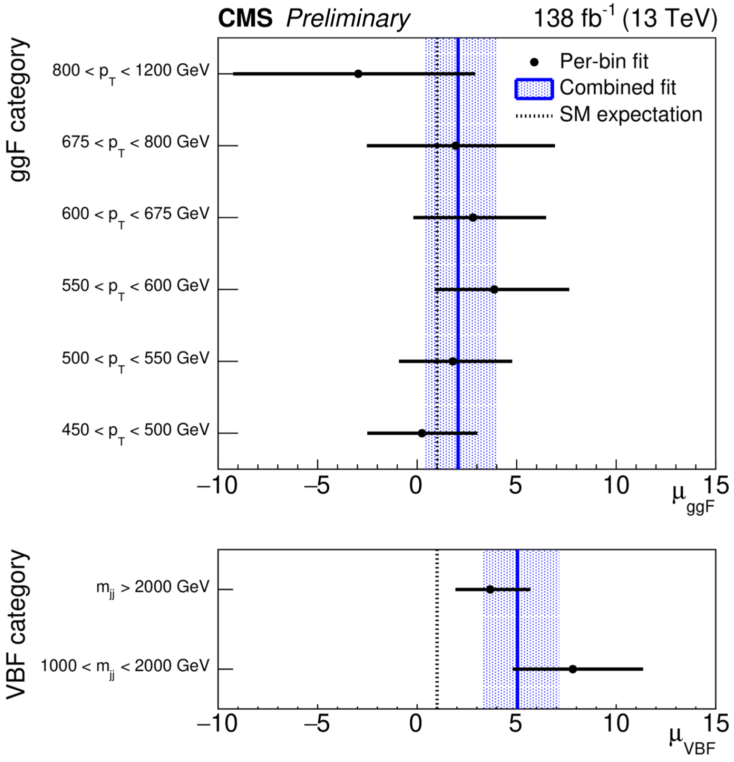


NEW



Z→bb





$\mu_{ggF} = 2.1^{+1.9}_{-1.7}$
Significance 1.2σ(0.9σ exp.)

$\mu_{VBF} = 5.0^{+2.1}_{-1.8}$
Significance 3.0σ(0.9σ exp.)

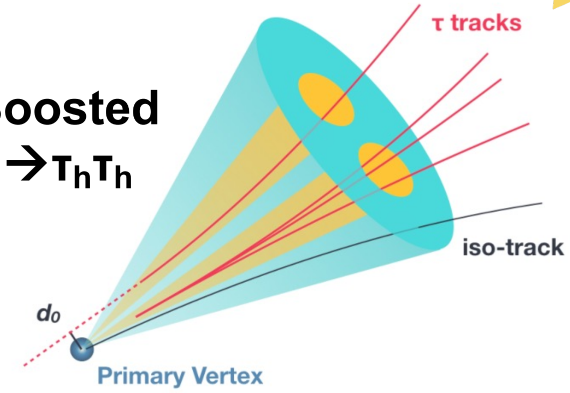
Another boosted Higgs in H→ττ

[CMS-PAS-HIG-21-017](CMS-PAS-HIG-21-017)
Chayanit's talk

NEW

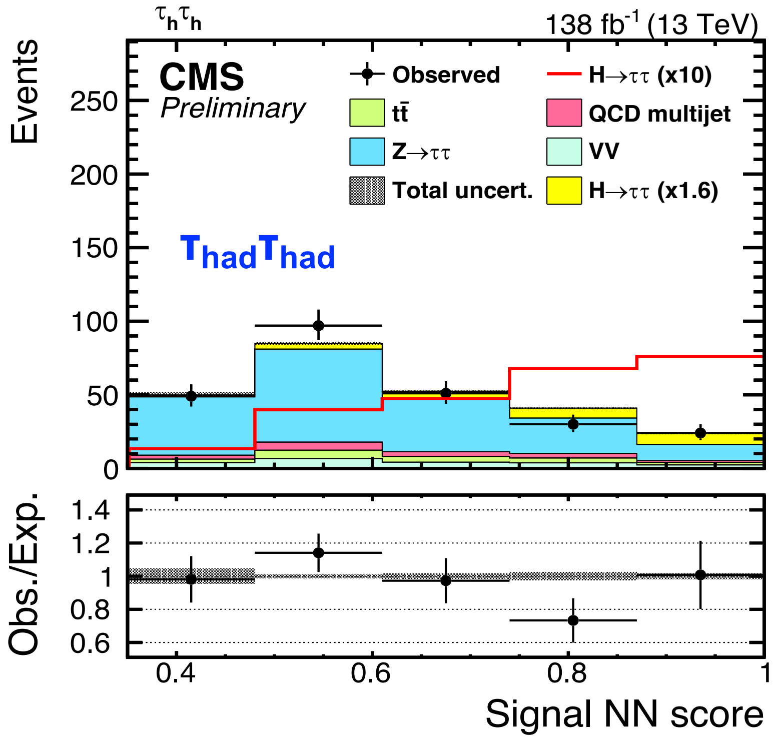
- Improved high p_T H→ττ (p_T^H > 250 GeV) reconstruction with dedicated algorithm to identify close-by τ leptons
- NN output as final discriminant to distinguish background
- Measure differential fiducial cross-section in high p_T^H

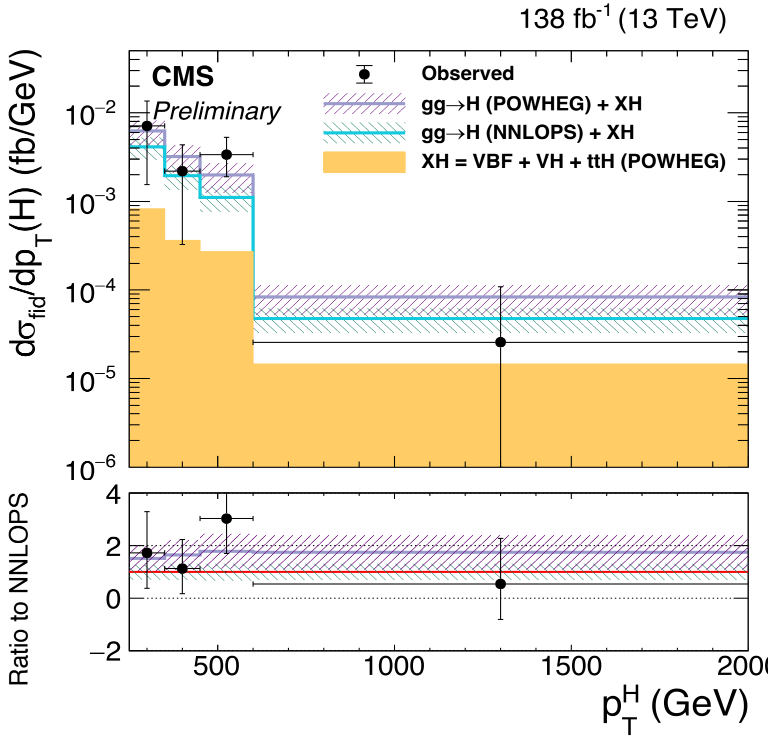
Boosted $H \to \tau_h\tau_h$



Observed significance 3.5σ (exp. 2.2σ)

Signal strength $\mu = 1.64^{+0.68}_{-0.54}$



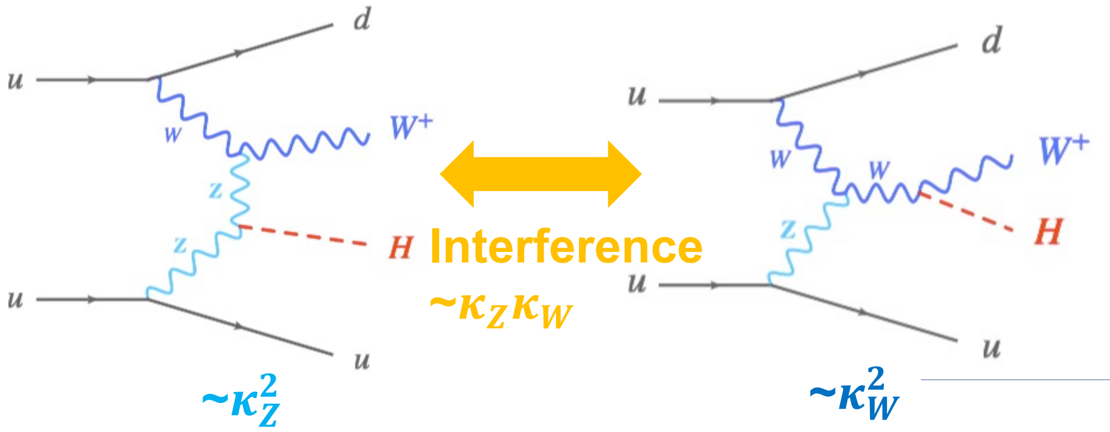


Relative sign of W/Z coupling

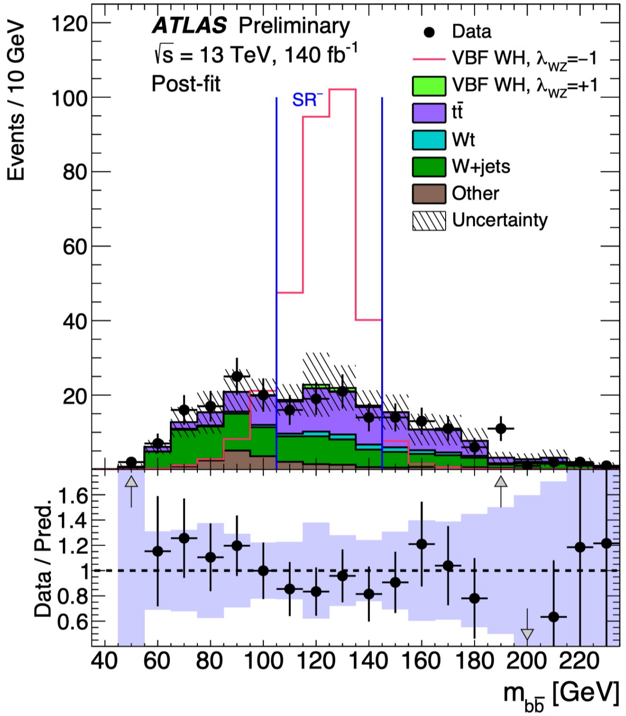
ATLAS-CONF-2023-57
John's talk

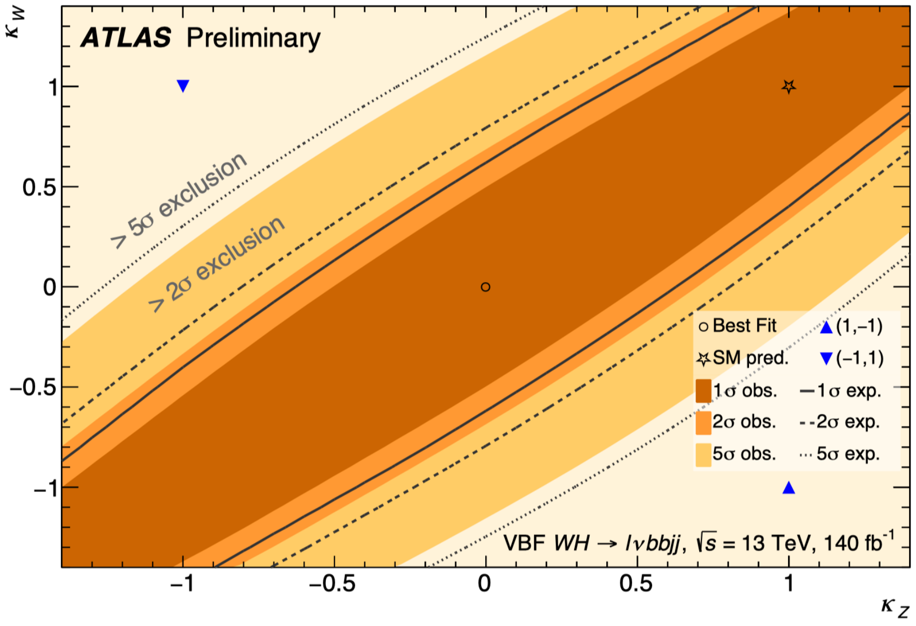
NEW

- VBF WH process is sensitive to $\lambda_{WZ}(=\kappa_W/\kappa_Z)$ sign
  - σ(VBF WH) enhanced by a factor of ~6 for negative λ_{WZ}
- Positive λ_{WZ} in the SM (custodial symmetry)
  ➔ Observation of negative sign would be clear BSM
- Simple counting analysis with VBF topology and WH→lνbb selection



$$\sigma_{\mathrm{VBF,WH}} \propto \kappa_Z^2|\mathcal{M}_Z|^2 + \kappa_W^2|\mathcal{M}_W|^2 - 2\kappa_Z^2\lambda_{WZ}\mathcal{R}|\mathcal{M}_Z\ \mathcal{M}_W|$$





Negative λ_{WZ} excluded >8σ
➔ Consistent with SM

Rare H→Zγ decay ATLAS+CMS

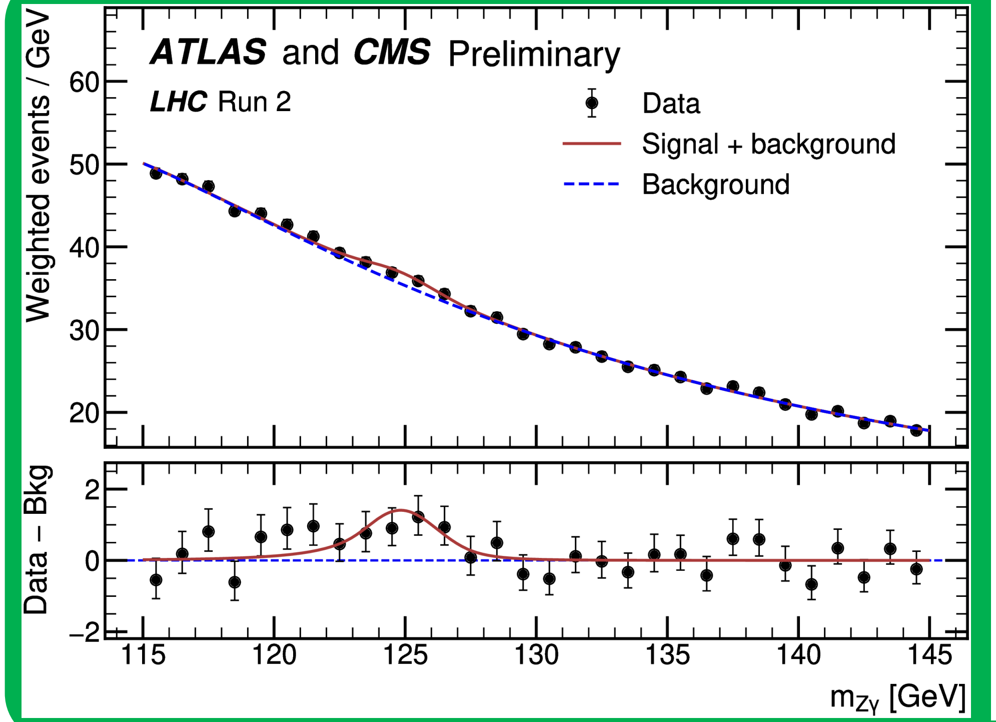
ATLAS-CONF-2023-025
CMS-PAS-HIG-23-002
Changqiao's talk

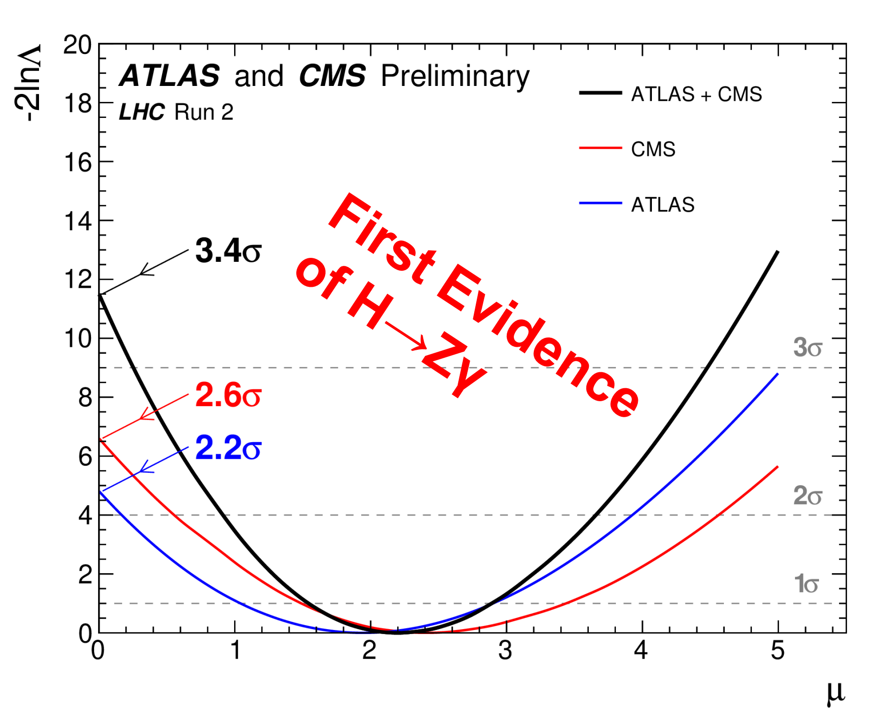
- Rare decay mode $B(H\rightarrow Z\gamma) \sim 1.5\times10^{-3}$

ATLAS
- $\mu=2.0^{+1.0}_{-0.9}$
- Significance 2.2σ (1.2σ exp.)

CMS
- $\mu=2.4^{+1.0}_{-0.9}$
- Significance 2.6σ (1.1σ exp.)

NEW





3.4σ (1.6σ exp.)

μ=2.2±0.7 (1.9σ compatibility with SM)

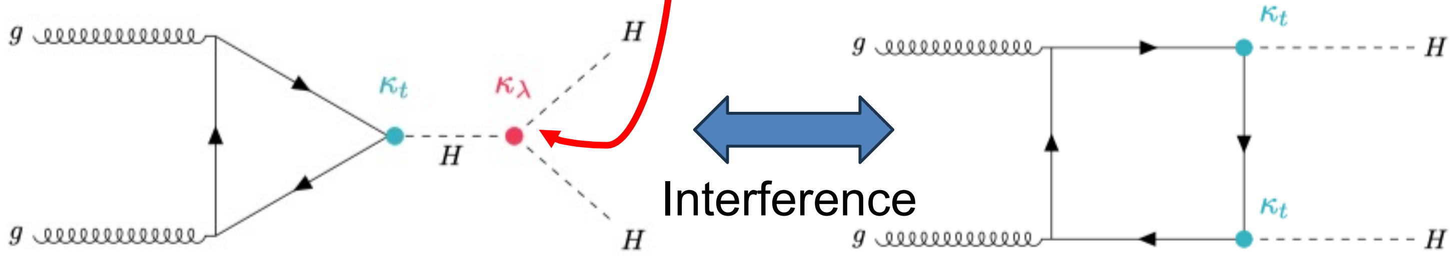
Higgs self-coupling measurement

- Higgs self-coupling λ, shaping Higgs potential may connect to the stability of the Universe

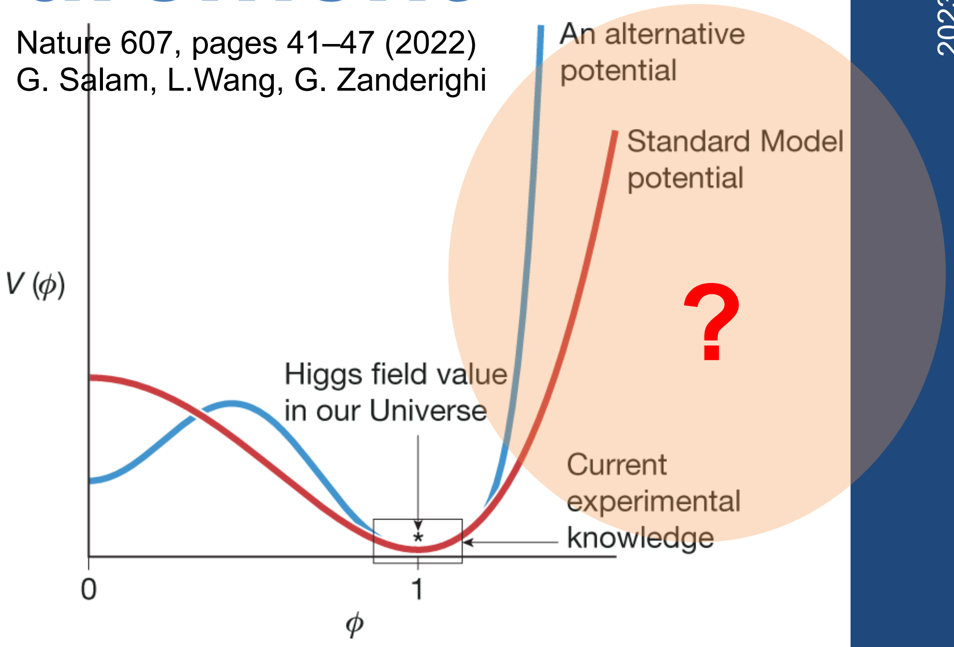
$$V(h) = \boxed{\lambda v^2 h^2} + \boxed{\lambda_3 v h^3} + \boxed{\frac{1}{4}\lambda_4 h^4} + \cdots$$

Higgs mass term

Higgs self-coupling



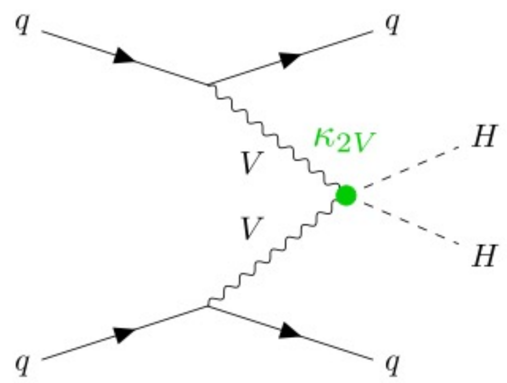
Nature 607, pages 41–47 (2022)
G. Salam, L.Wang, G. Zanderighi



- λ_3 ($\kappa_\lambda = \lambda_3/\lambda_{3,SM}$) is accessible via Higgs pair production
  - Not well-constraint experimentally

In SM $\lambda(=\lambda_3=\lambda_4)=\frac{m_h^2}{2v^2}\sim 0.13$

- **σ(pp→HH) ~30fb ➔ >1000 lower than σ(pp→H)**
- Two Higgs boson decays give variety of final states
  - Golden channels: HH→4b, HH→bbττ, HH→bbγγ



VBF provides unique quartic coupling κ_{2V}

One of next biggest targets in Higgs measurements

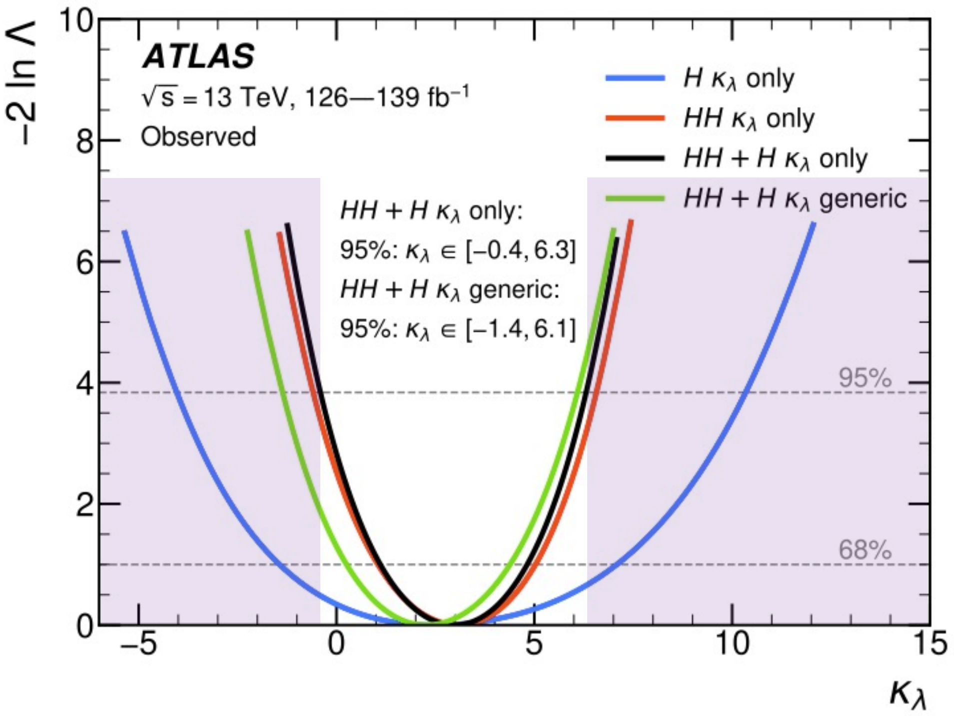
Combined HH measurement

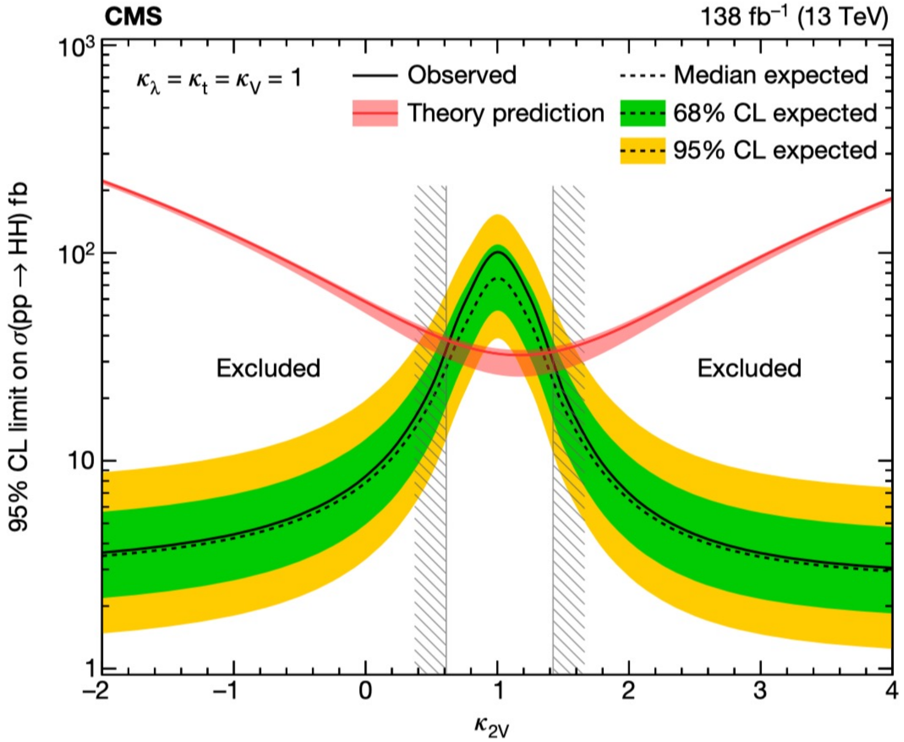
[Phys. Lett. B 843 (2023) 137745](#)
[Nature 607, 60-68 (2022)](#)
[Saswati](#) and [Viviana](#)'s talks

- **ATLAS: HH→4b, bbγγ, bbττ**
  - Combined with single Higgs measurements via NLO EW correction
  - μ_{HH}: 2.4 × SM (2.9 × SM exp.) at 95% CL
  - $-0.4 < \kappa_\lambda < 6.3$ at 95% CL (HH+H combination)

- **CMS: HH→4b, bbγγ, bbττ, bbZZ, multi-lepton**
  - μ_{HH}: 3.4 × SM (2.5 × SM exp.) at 95% CL
  - $-1.2 < \kappa_\lambda < 6.5$ ($-2.3 < \kappa_\lambda < 7.9$ exp.) at 95% CL
  - $0.67 < \kappa_{2V} < 1.38$ at 95% CL

(κ_{2V}=0 excluded at 6.6σ)





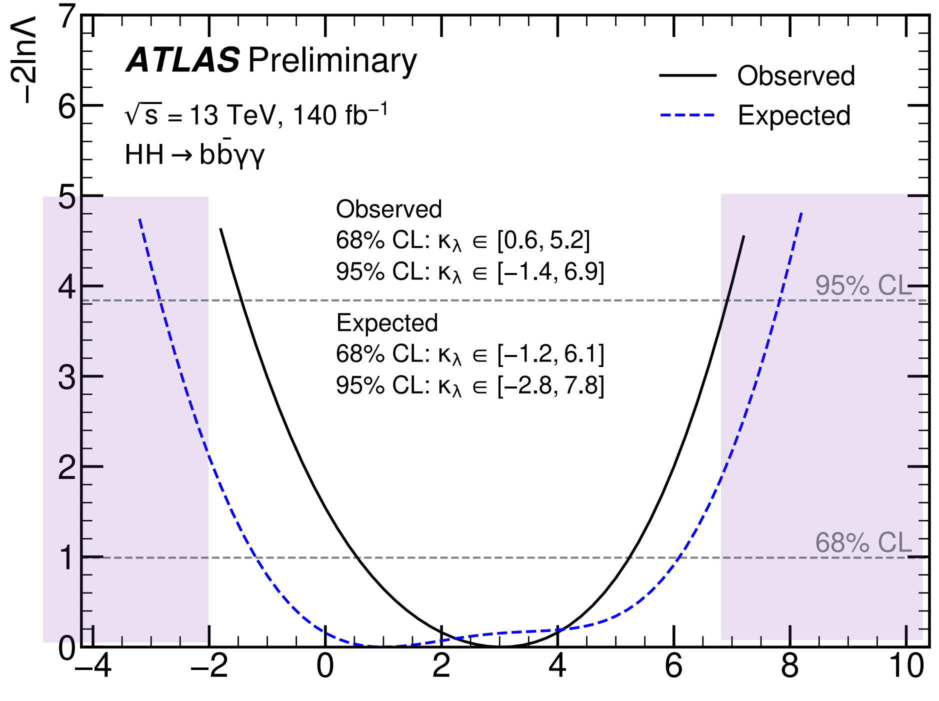
Search for DiHiggs in bbγγ

ATLAS-CONF-2023-050

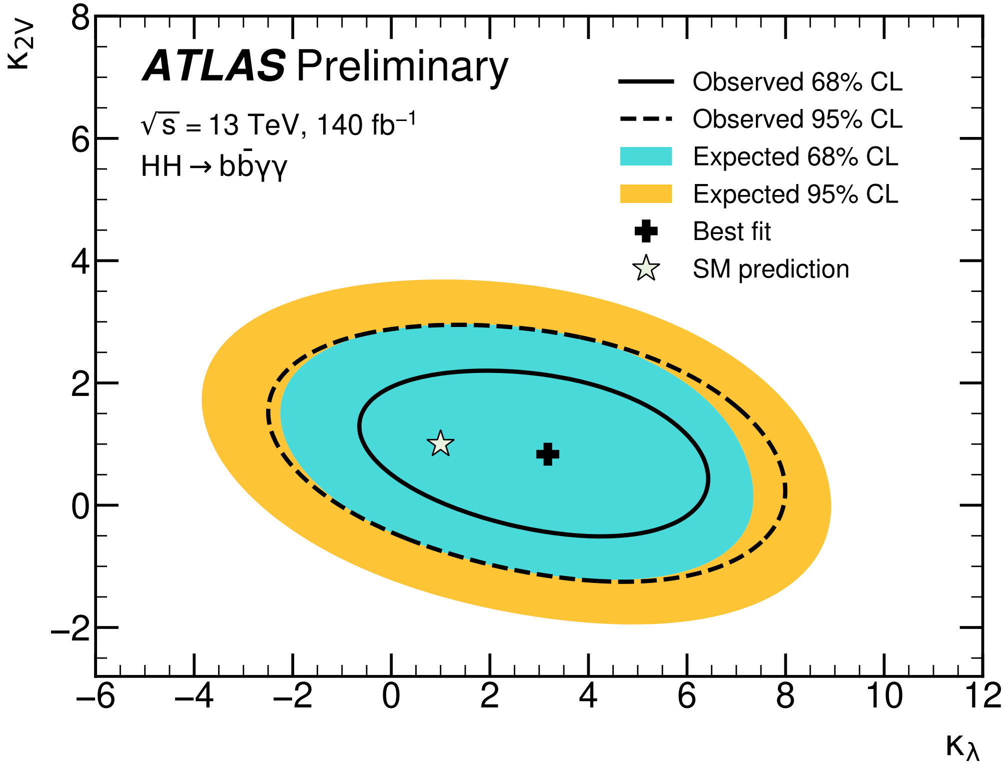
Viviana's talk

- Clean H→γγ signature and excellent $m_{\gamma\gamma}$ resolution to discriminate HH signal from continuum γγ background
- Introduced VBF-jet tagger to improve jet assignment
  ➔ More sensitive to VBF HH
- Event categorization using BDT scores
- **μ_{HH} < 4.0 (6.4 exp.) at 95% CL**

NEW



$-1.4 < \kappa_\lambda < 6.9$ at 95% CL



First Run 3 Higgs Measurement

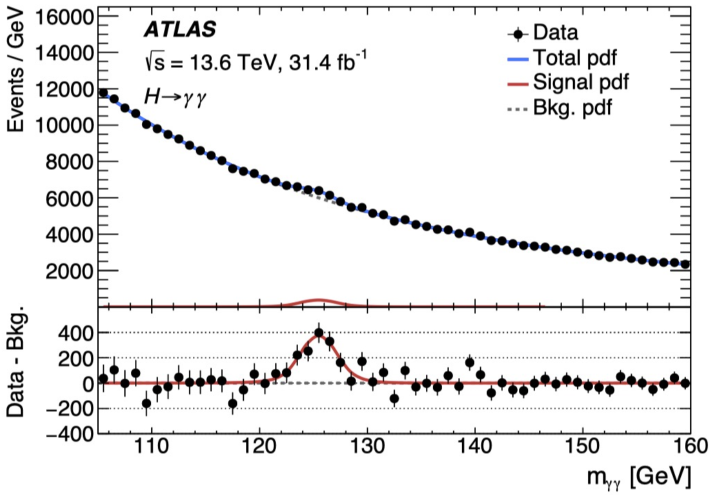
arXiv:2306.11379

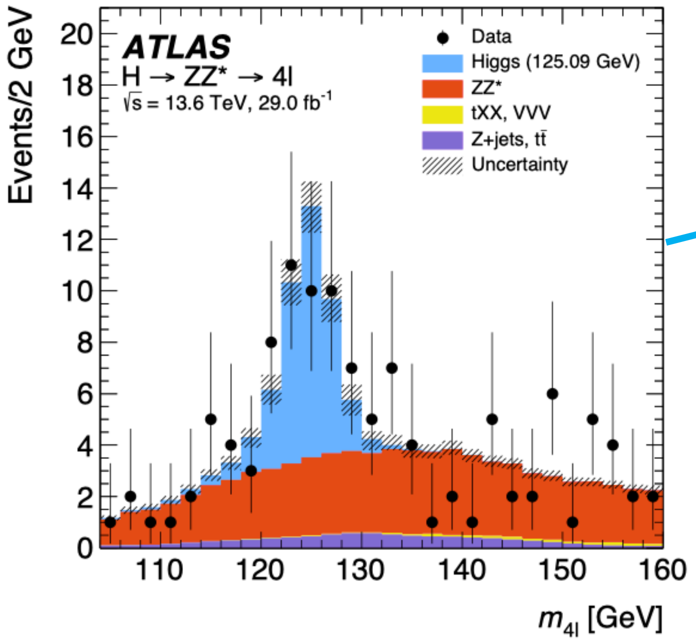
Maria's talk

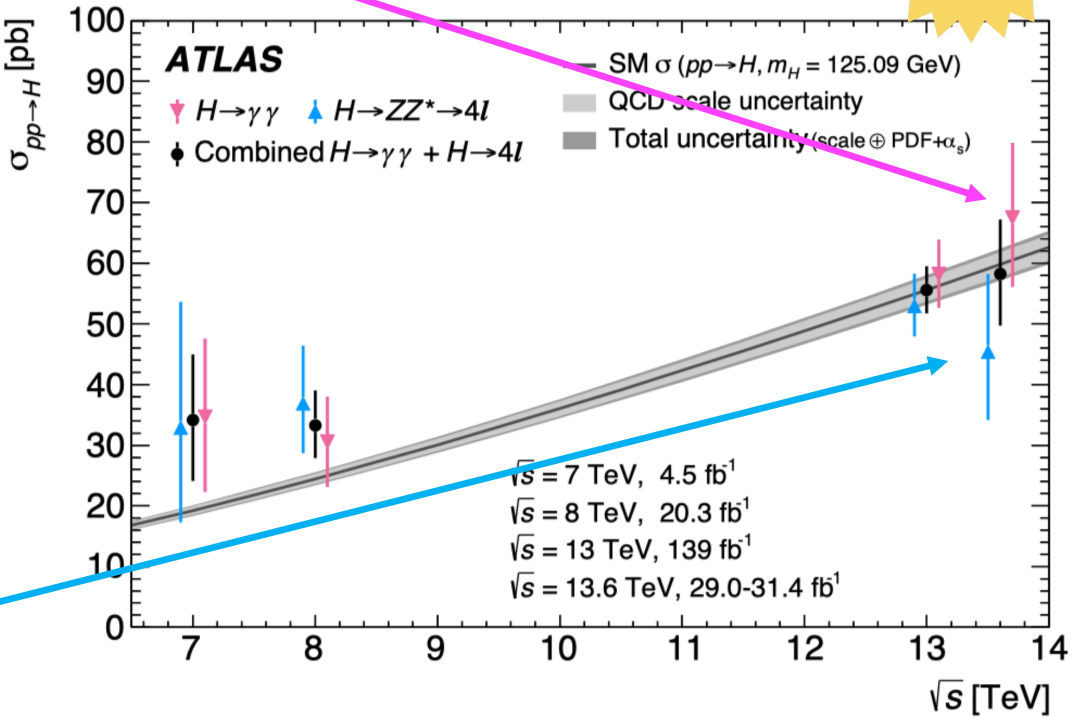
NEW

- Measure fiducial and total cross section with H→γγ, H→ZZ→4l channels at 13.6 TeV in 2022 data
- Measured total cross-section
  - 67^{+12}_{-11} pb for H→γγ
  - 46±12 pb for H→ZZ→4l
  - **58.2±8.8 pb for combined**

➔ **Good agreement with SM prediction (59.9±2.6pb)**

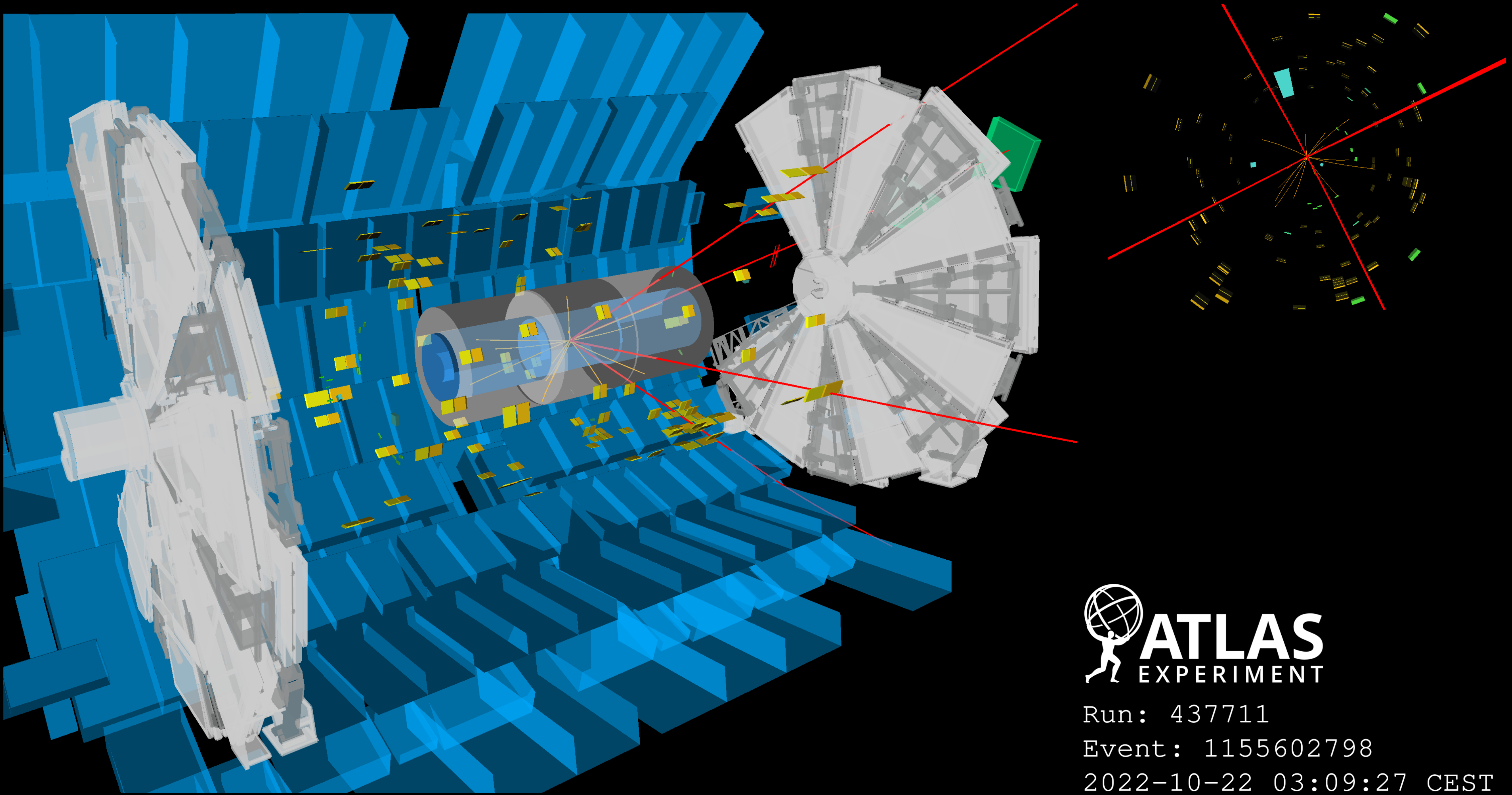






Re-observed at 13.6 TeV!!
More data coming for precise measurement in Run3

H→ZZ→4μ Candidate at 13.6 TeV!



ATLAS EXPERIMENT
Run: 437711
Event: 1155602798
2022-10-22 03:09:27 CEST

Summary

- Full Run 2 dataset and new analysis techniques opened the door of more precise Higgs measurements
  - Higgs mass precision ~ 0.09%
  - Major couplings < 10% precision
  - Access to rare production/decay processes
  - Measuring cross-sections in higher p_T^H regions
  - Self-coupling constraints improved significantly (SM will be within reach in future runs!)

Precise/various Higgs property measurements provide deeper and deeper understanding of the SM!!

- Run3 Higgs physics just started
  - Much larger dataset than Run 2 is expected
    ➔ New physics may appear in coming years

Stay tuned for Run 3 results!!

EPS Parallel session talks

- Higgs boson mass and width measurement with the ATLAS detector **by Stefano**
- Measurements of Higgs boson couplings and simplified template cross sections in bosonic final states (WW, ZZ, yy) at the ATLAS experiment **by Theodota**
- Measurements of the Higgs boson couplings and their interpretations in fermionic decay modes at the ATLAS experiment **by Punit**
- Measurements of Higgs boson production in association with top quarks at the ATLAS experiment **by Thomas**
- Higgs boson properties (mass/width) at CMS **by Filippo**
- Higgs boson CP property measurements at the ATLAS experiment **by Christian**
- Boosted Higgs boson measurements at CMS **by Chayanit**
- Combined measurement of Higgs coupling, cross section measurement and interpretation at the ATLAS experiment **by Changqiao**
- Higgs boson anomalous couplings and EFT at CMS **by Matteo**
- Standard Model Effective-Field Theory in final states with multiple Higgs and gauge bosons **by Roberto**
- Rare Higgs boson production and decay at CMS **by Rocco**
- Measurement of rare Higgs boson production and decay modes at the ATLAS experiment **by John**
- Probing the nature of electroweak symmetry breaking with Higgs boson pairs in ATLAS **by Viviana**
- Higgs self coupling: status and projections at CMS **by Saswati**
- Measurements of inclusive and differential cross section measurement in bosonic final states at the ATLAS experiment **by Maria**
- Higgs boson inclusive cross section and coupling measurements (incl STXS) at CMS - fermionic channels **by Horssaal**
- Higgs boson inclusive cross section and coupling measurements (incl STXS) at CMS - bosonic channels **by Roberto**
- Higgs boson differential/fiducial cross section measurements at CMS **by Chen**

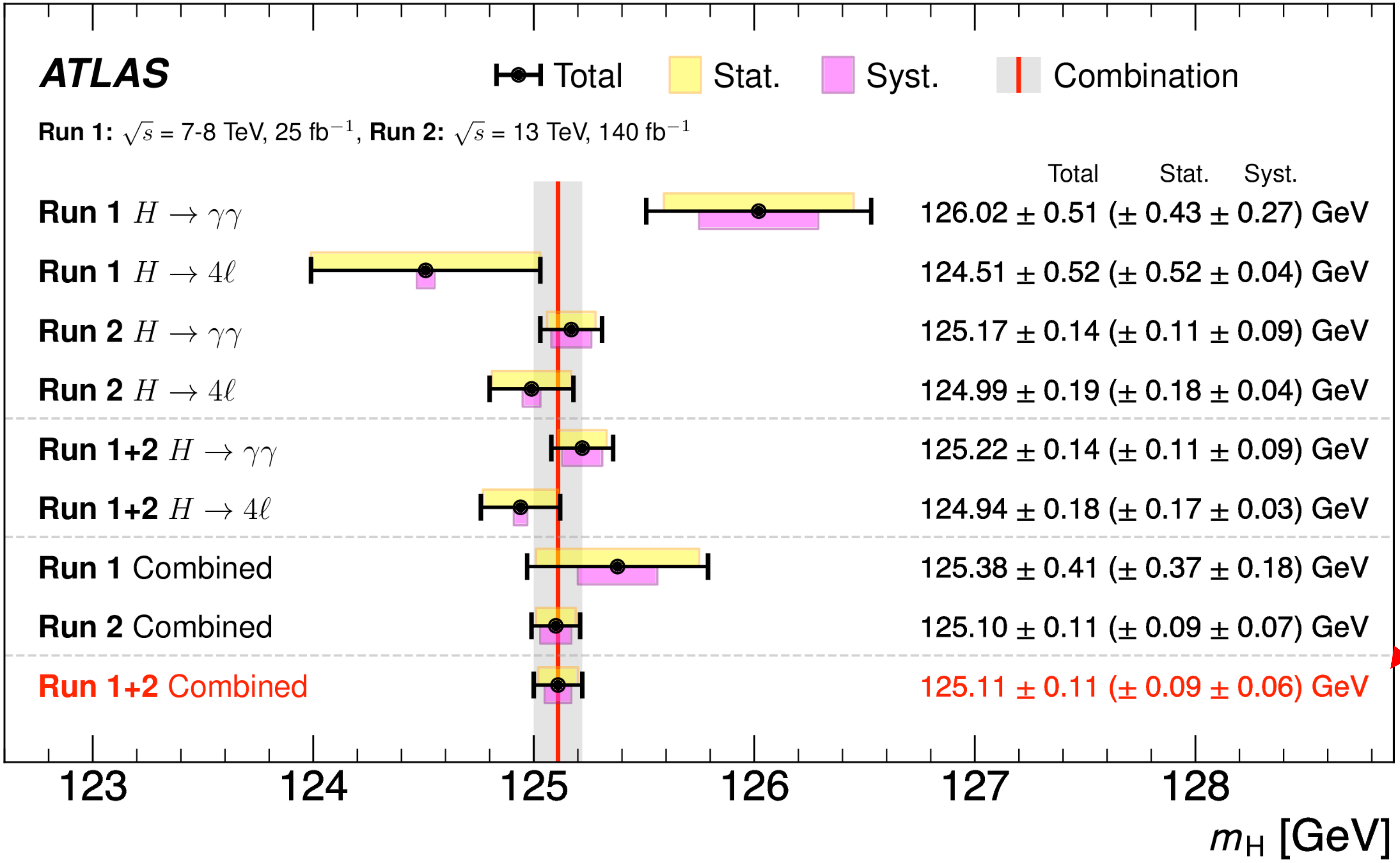
Backup

Combined Mass Measurement

arXiv:2308.04775

- Combine H→γγ and H→ZZ→4l mass measurements

NEW



Measurements of two channels in Run1 and Run2 are compatible with p-value 0.18

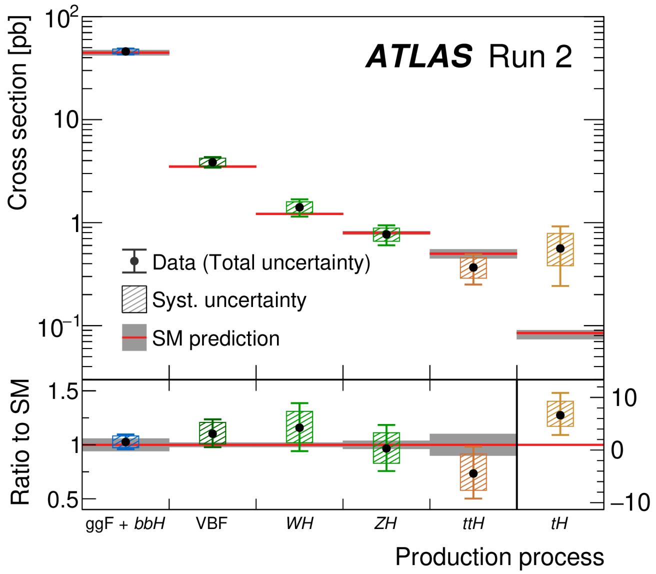
0.09% precision!

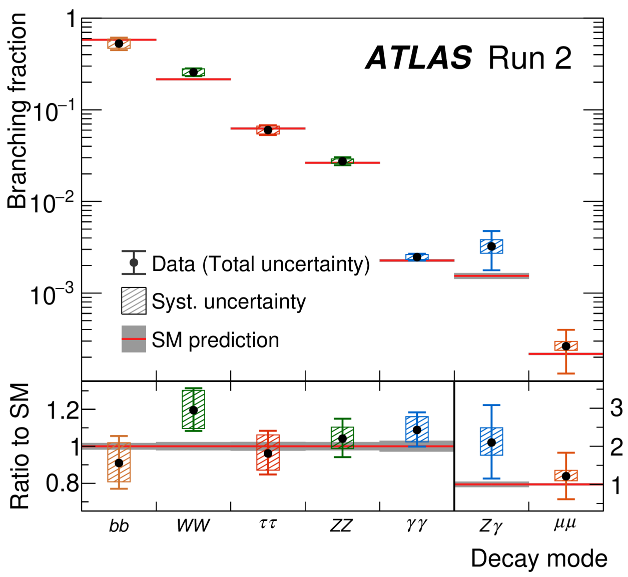
- Statistically dominated
- Dominant systematic: Photon energy scale/resolution

Inclusive cross section/branching fraction

[Nature 607, 52-59 (2022)](#)
[Nature 607, 60-68 (2022)](#)

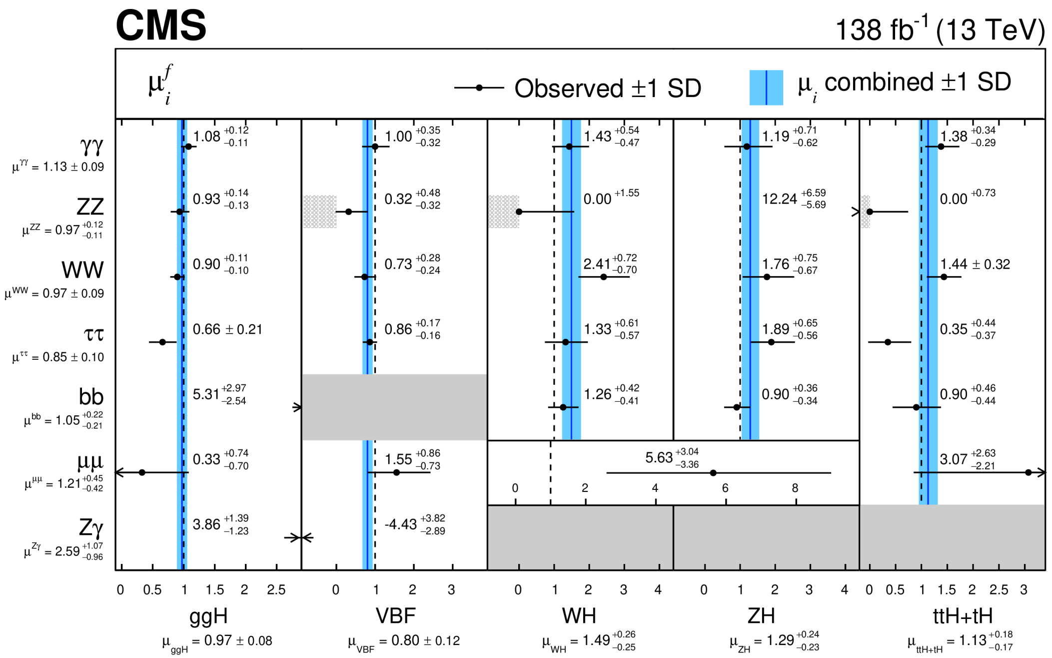
- **Higgs production**
  - Top 5 production modes has been observed with > 5σ sensitivity
  - **ggF, VBF: ~7-12% precision**
  - **WH/ZH, ttH: 20% precision**
  - tH(95% upper limit) : ~10×SM





- **Higgs decay**
  - **WW/ZZ/γγ ~10% precision**
  - **ττ ~10% precision**
  - **bb ~15-20% precision**
  - μμ ~40-60% precision: ATLAS(CMS) observed significance ~2(3)σ
  - Zγ ~100% precision

$$\mu_i^f = \frac{\sigma_i}{\sigma_i^{SM}} \times \frac{B_f}{B_f^{SM}}$$



No significant deviation from SM

ATLAS ttH, bb results

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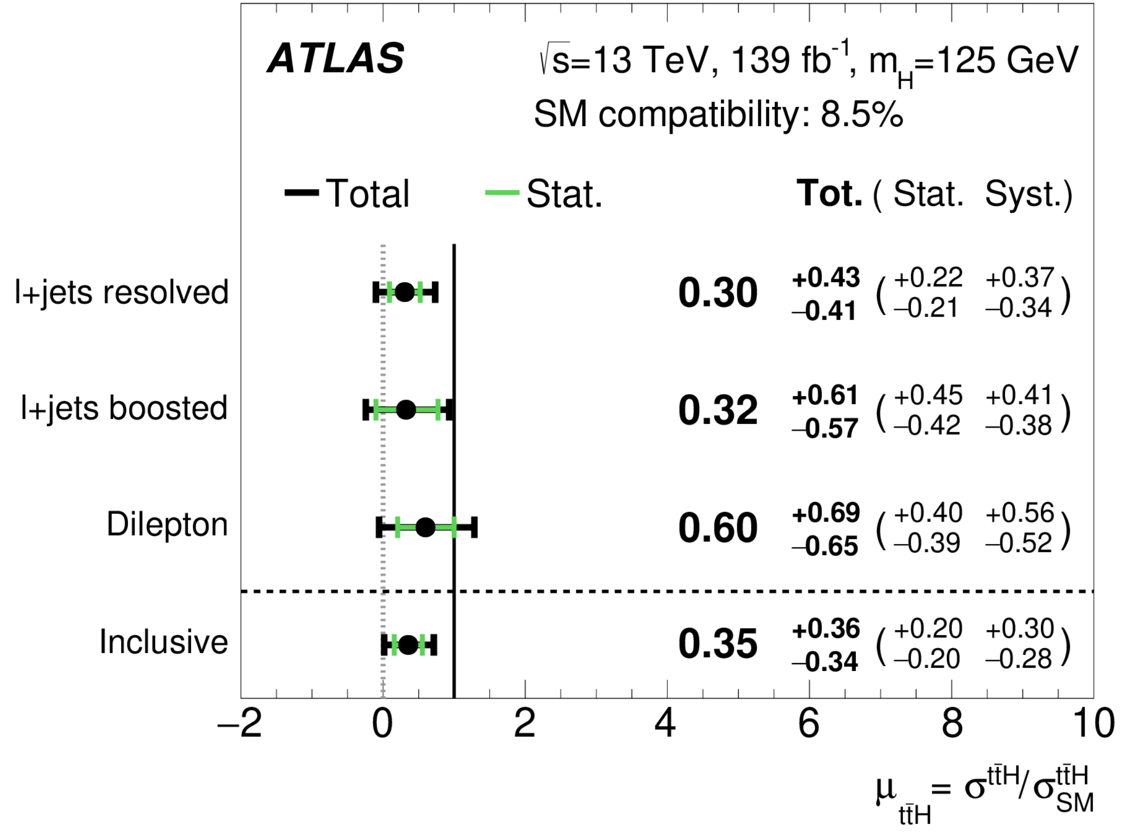
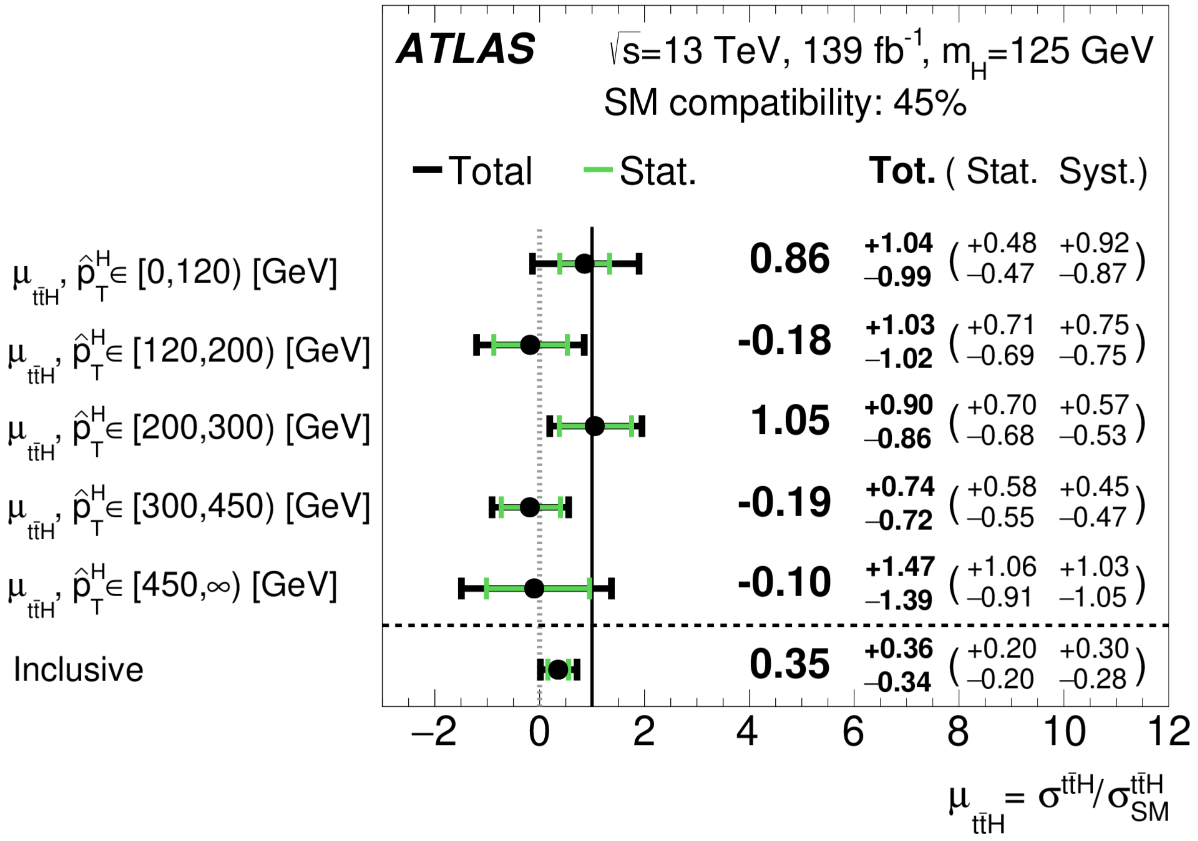
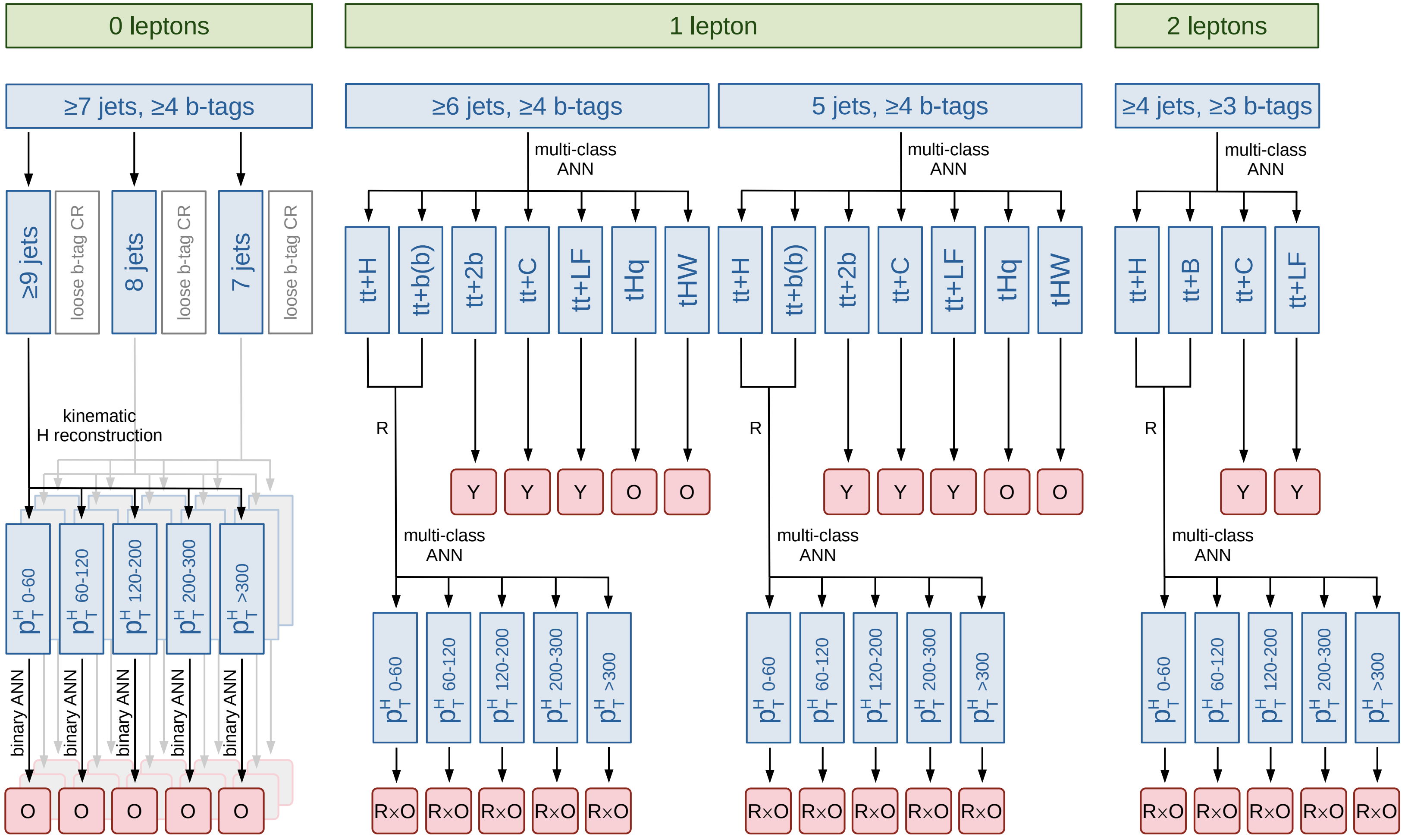




CMS ttH/tH, H→bb update

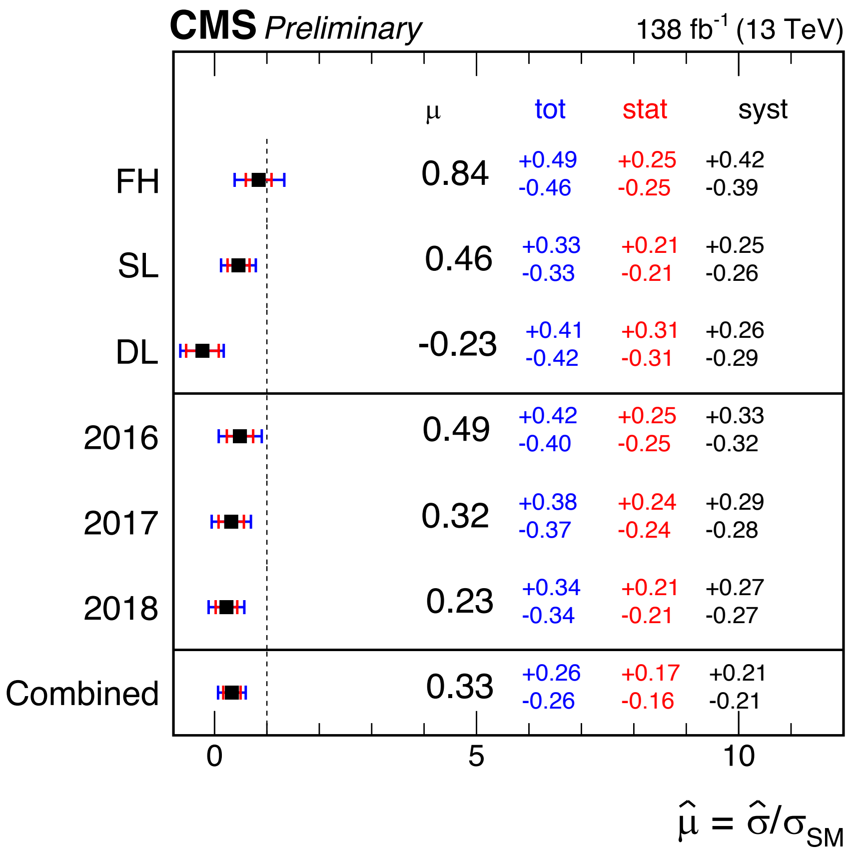
- STXS analysis strategy (removed 2 lepton 3jets category due to limited sensitivity)



Distribution in template fit, event yield (Y), ANN output (O), likelihood ratio of ANN outputs (R)

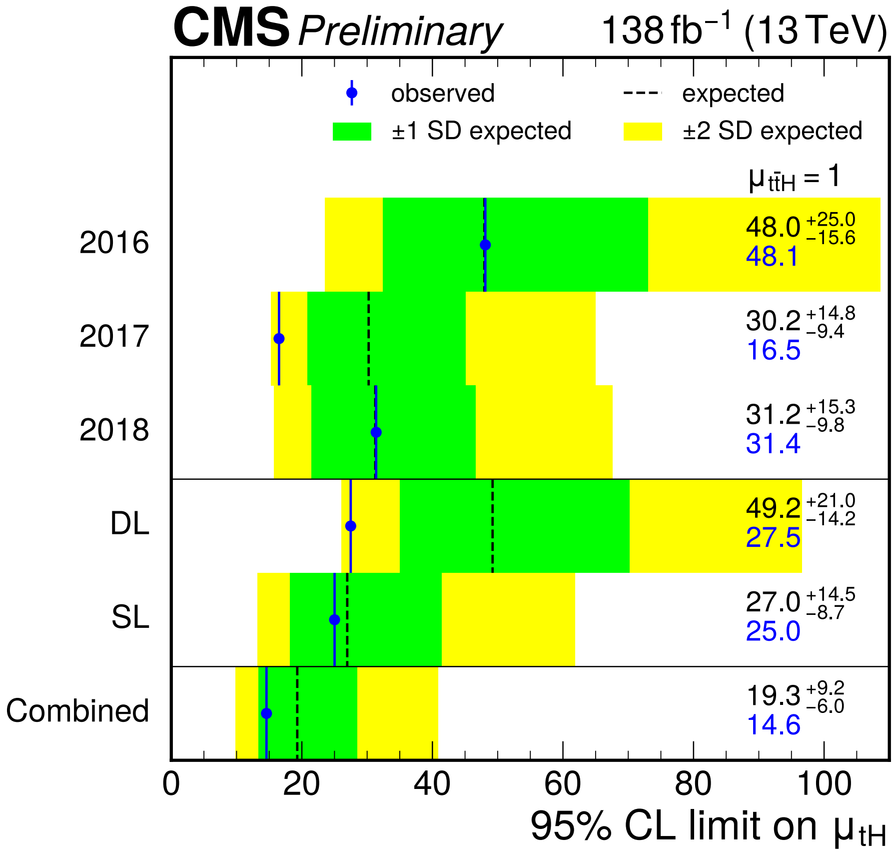
CMS ttH/tH, H→bb update

- Inclusive signal strength measurement

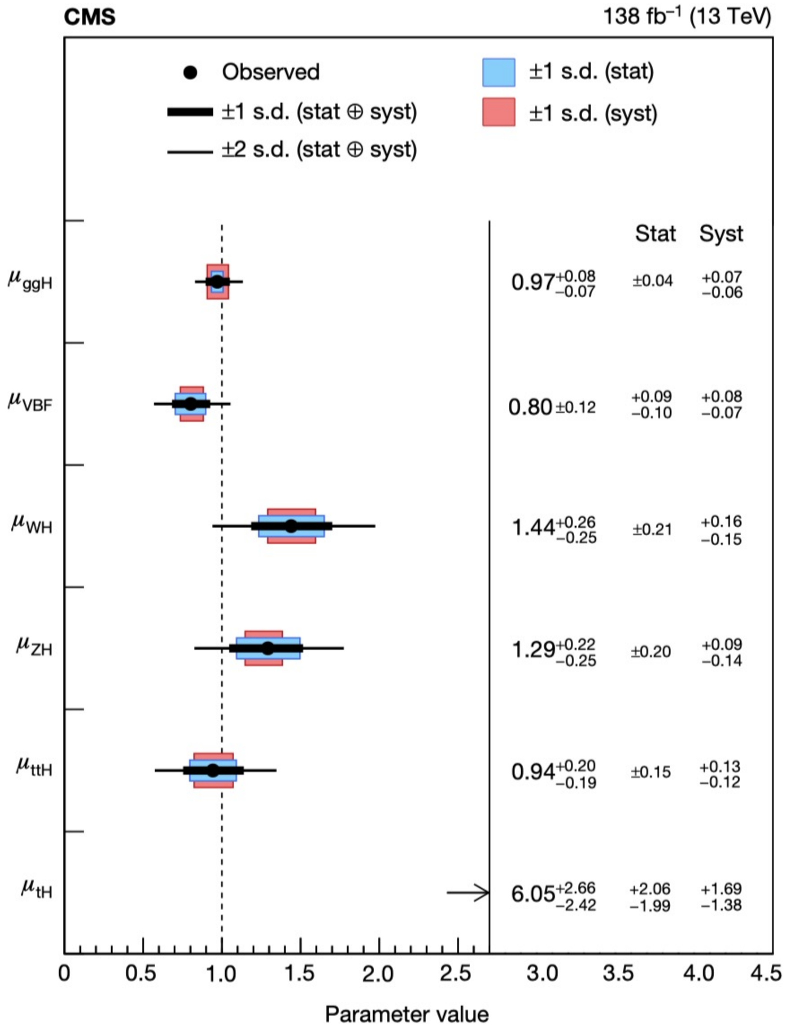


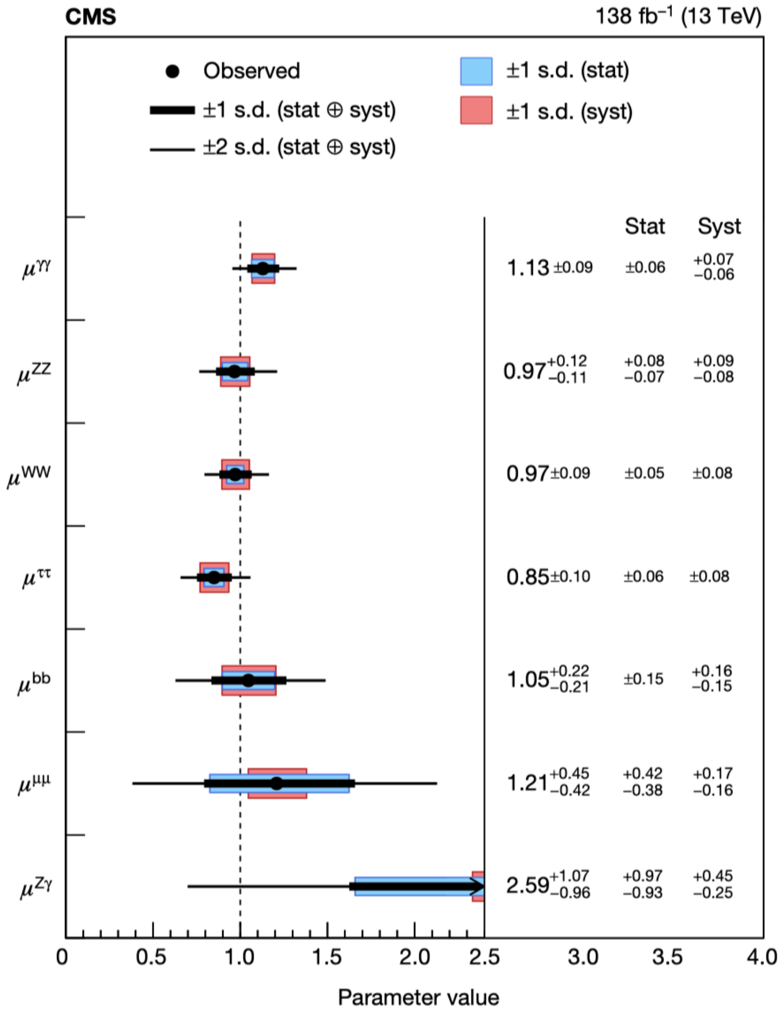
Uncertainties are uncorrelated between channels and years

- 95% CL upper limit on the tH signal sterength



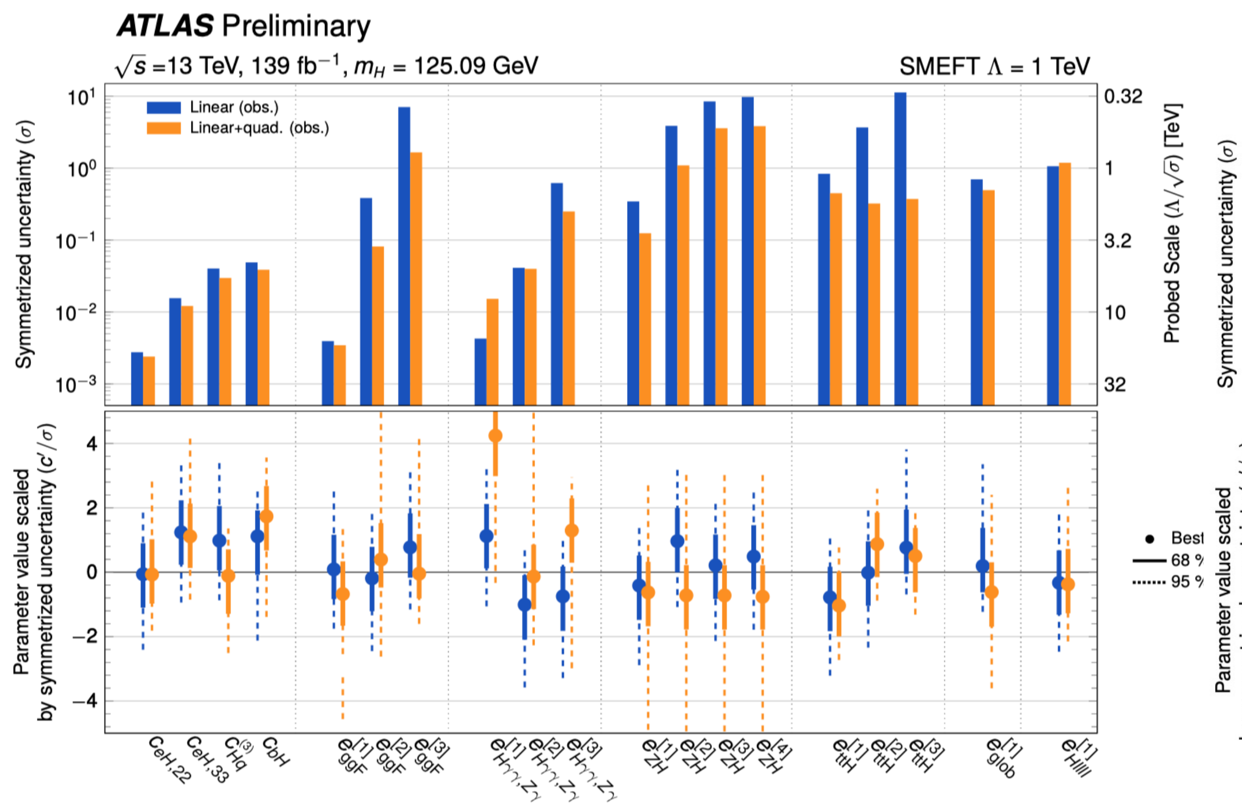
Higgs combined results



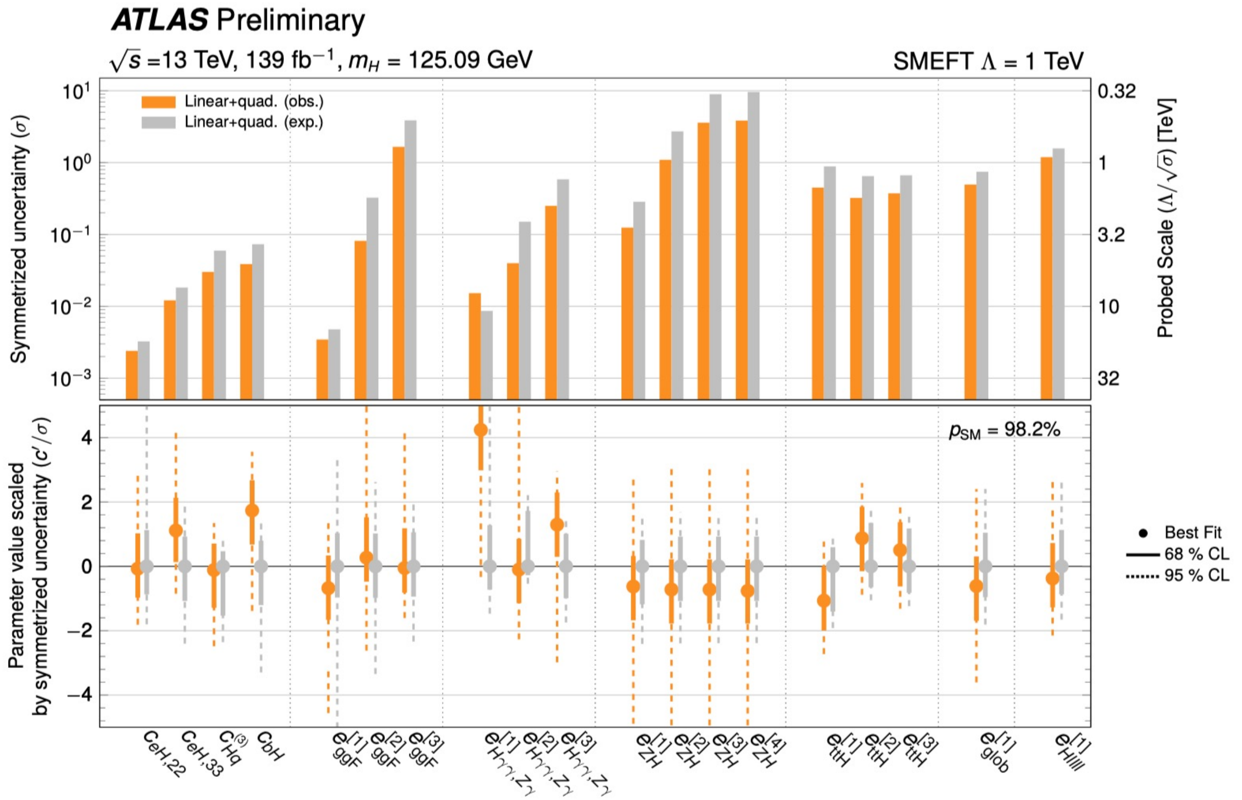


EFT interpretation

- Comparison between linear and linear+quad parametrizations

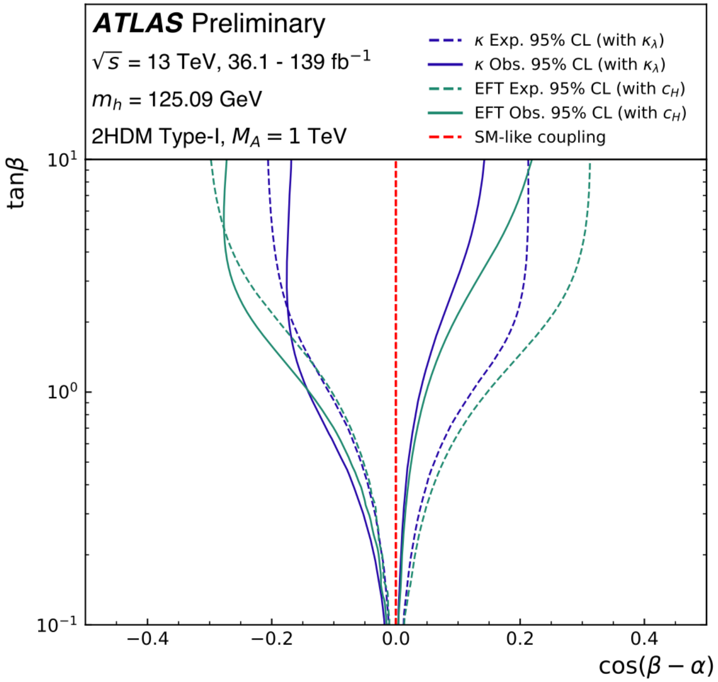


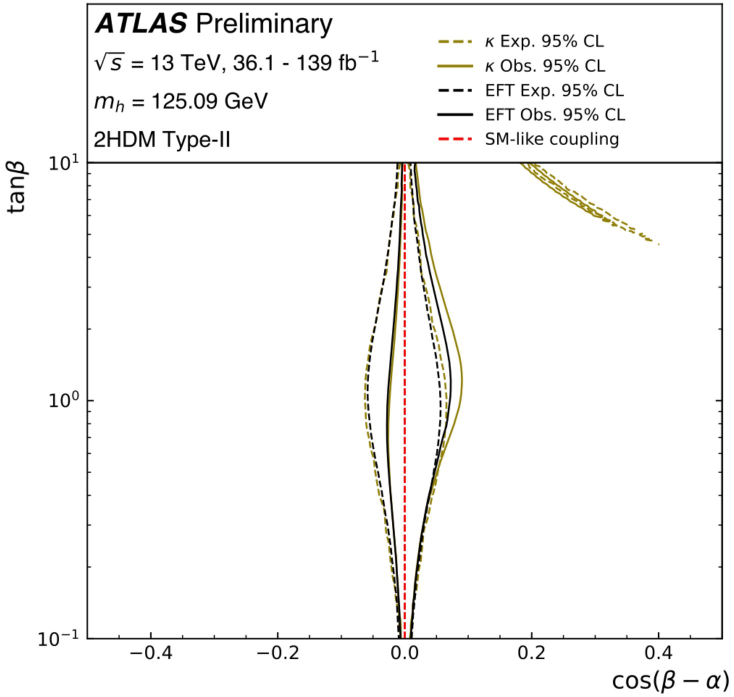
- Observed and expected sensitivity for lienar+quad parametrizations

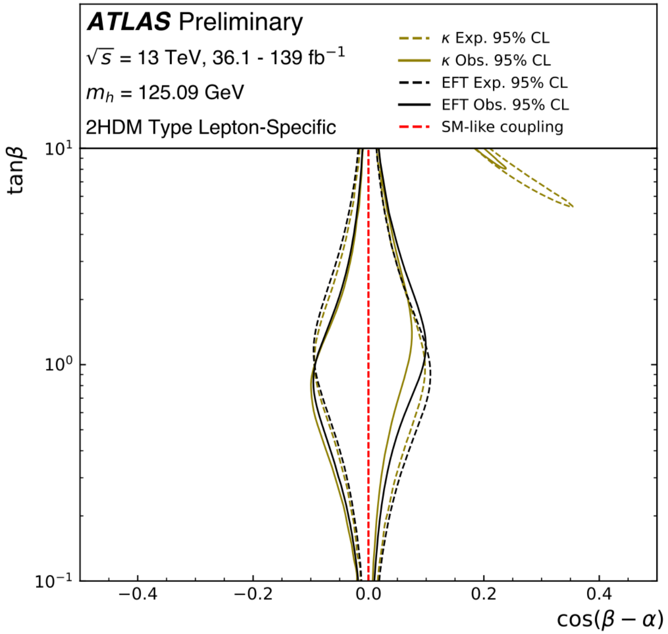


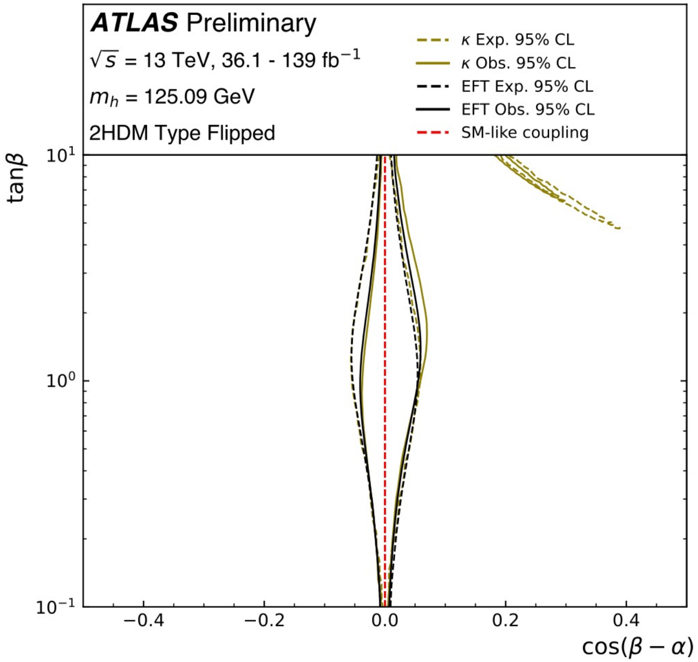
2023/8/20

EPS-HEP 2023 @ Hamburg

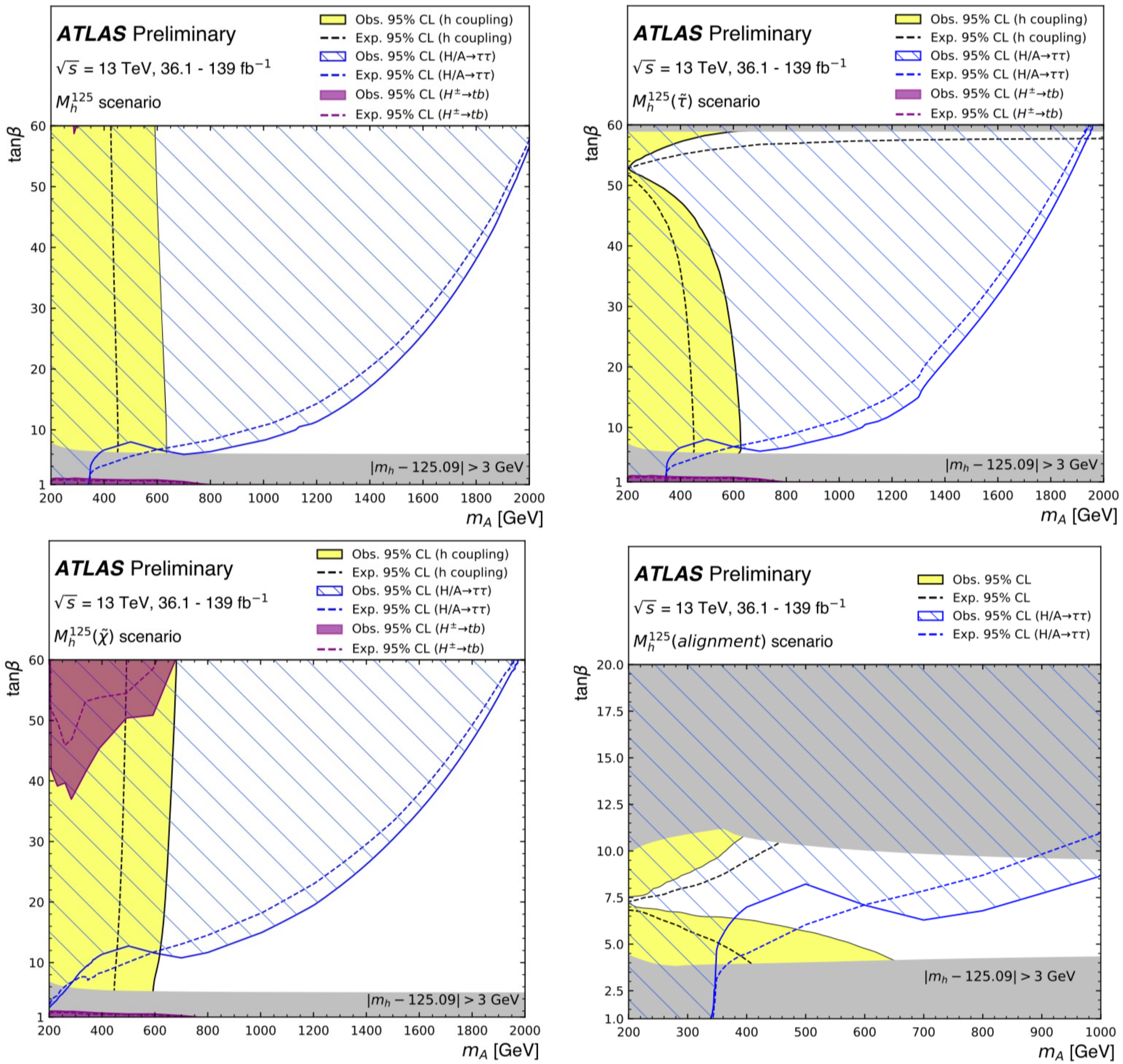

ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 36.1 - 139 fb^{-1}
m_h = 125.09 GeV
2HDM Type-I, M_A = 1 TeV
κ Exp. 95% CL (with κ_λ)
κ Obs. 95% CL (with κ_λ)
EFT Exp. 95% CL (with c_H)
EFT Obs. 95% CL (with c_H)
SM-like coupling
tanβ
10^1
10^0
10^{-1}
−0.4
−0.2
0.0
0.2
0.4
cos$(\beta-\alpha)$


ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 36.1 - 139 fb^{-1}
m_h = 125.09 GeV
2HDM Type-II
κ Exp. 95% CL
κ Obs. 95% CL
EFT Exp. 95% CL
EFT Obs. 95% CL
SM-like coupling
tanβ
10^1
10^0
10^{-1}
−0.4
−0.2
0.0
0.2
0.4
cos$(\beta-\alpha)$

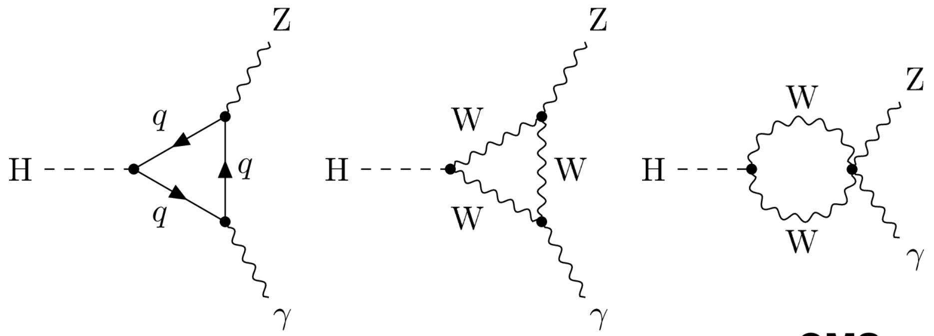

ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 36.1 - 139 fb^{-1}
m_h = 125.09 GeV
2HDM Type Lepton-Specific
κ Exp. 95% CL
κ Obs. 95% CL
EFT Exp. 95% CL
EFT Obs. 95% CL
SM-like coupling
tanβ
10^1
10^0
10^{-1}
−0.4
−0.2
0.0
0.2
0.4
cos$(\beta-\alpha)$


ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 36.1 - 139 fb^{-1}
m_h = 125.09 GeV
2HDM Type Flipped
κ Exp. 95% CL
κ Obs. 95% CL
EFT Exp. 95% CL
EFT Obs. 95% CL
SM-like coupling
tanβ
10^1
10^0
10^{-1}
−0.4
−0.2
0.0
0.2
0.4
cos$(\beta-\alpha)$

BSM interpretation

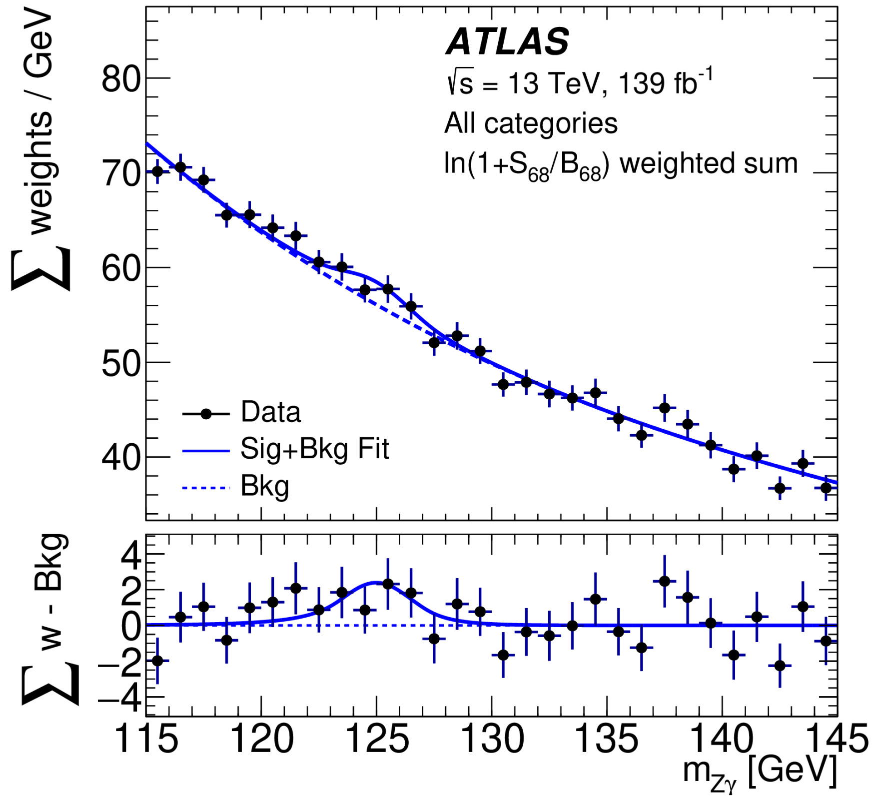


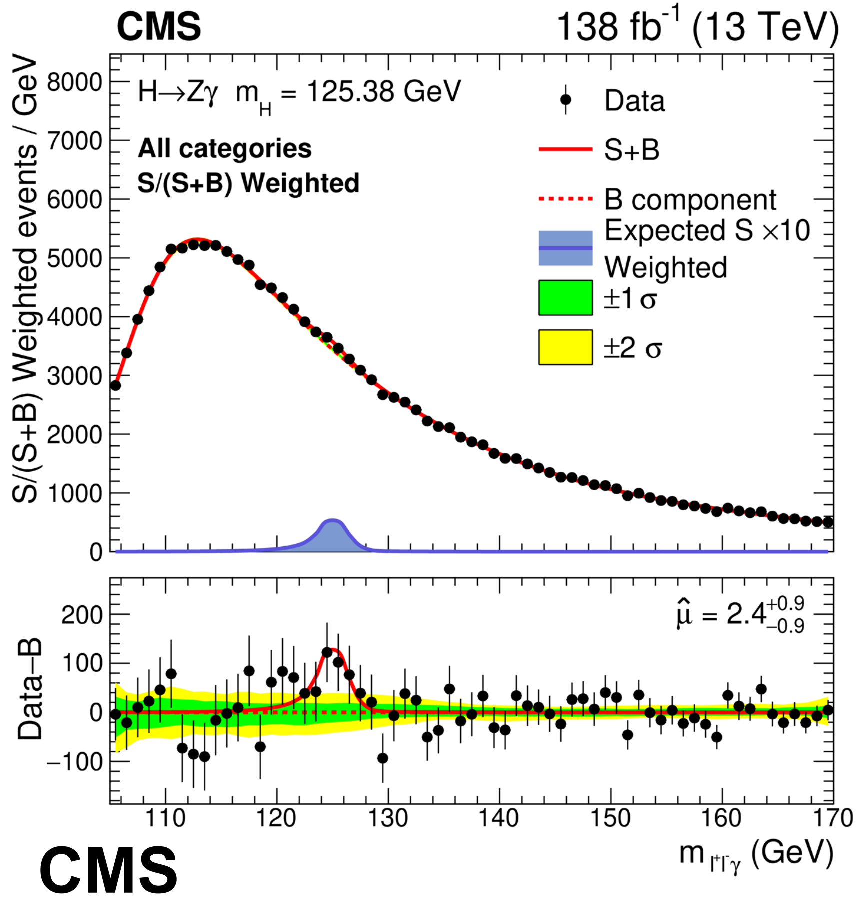
H→Zγ



[Phys. Lett. B 809 (2020) 135754](#)

[JHEP 05 (2023) 233](#)





ATLAS

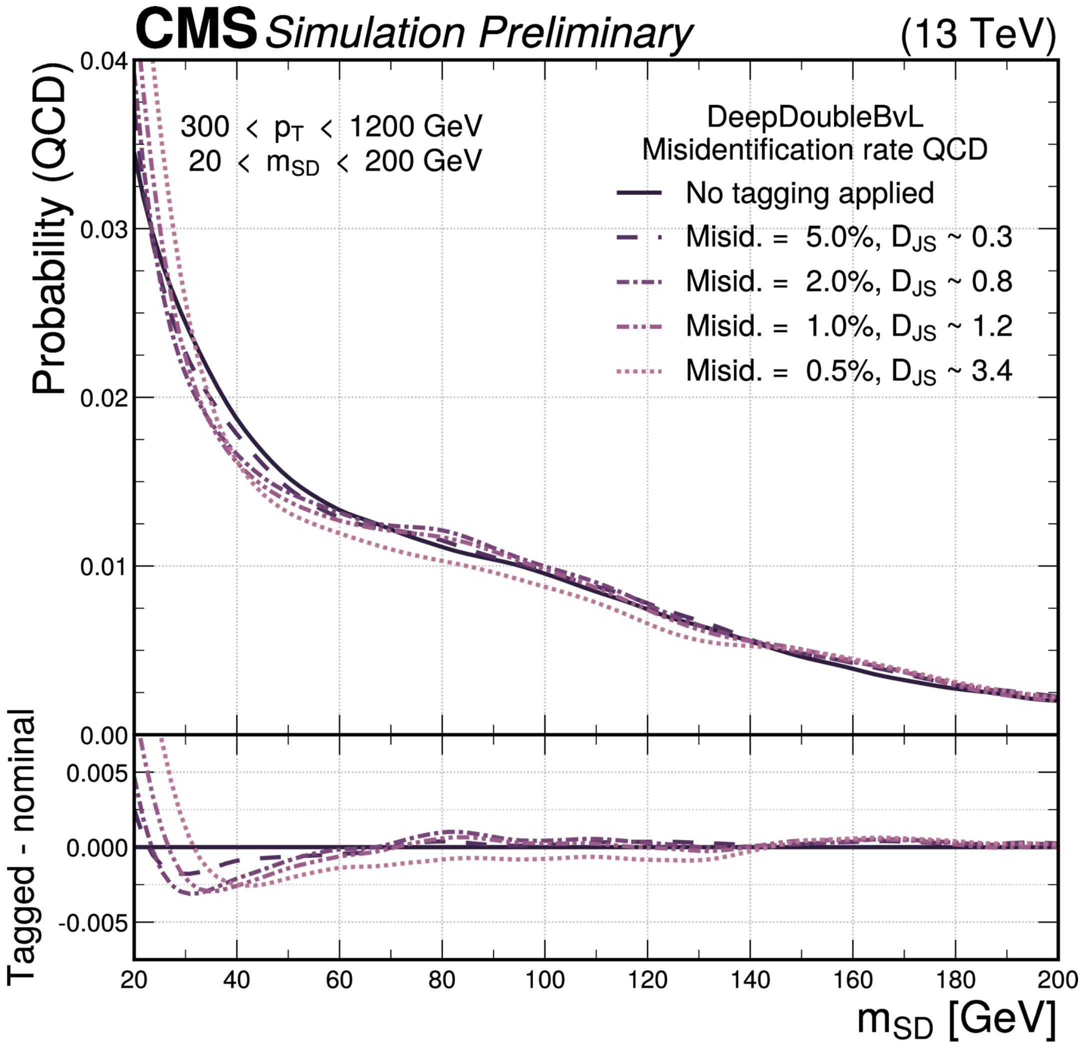
- $\mu=2.0^{+1.0}_{-0.9}$
- Significance 2.2σ (1.2σ exp.)

CMS

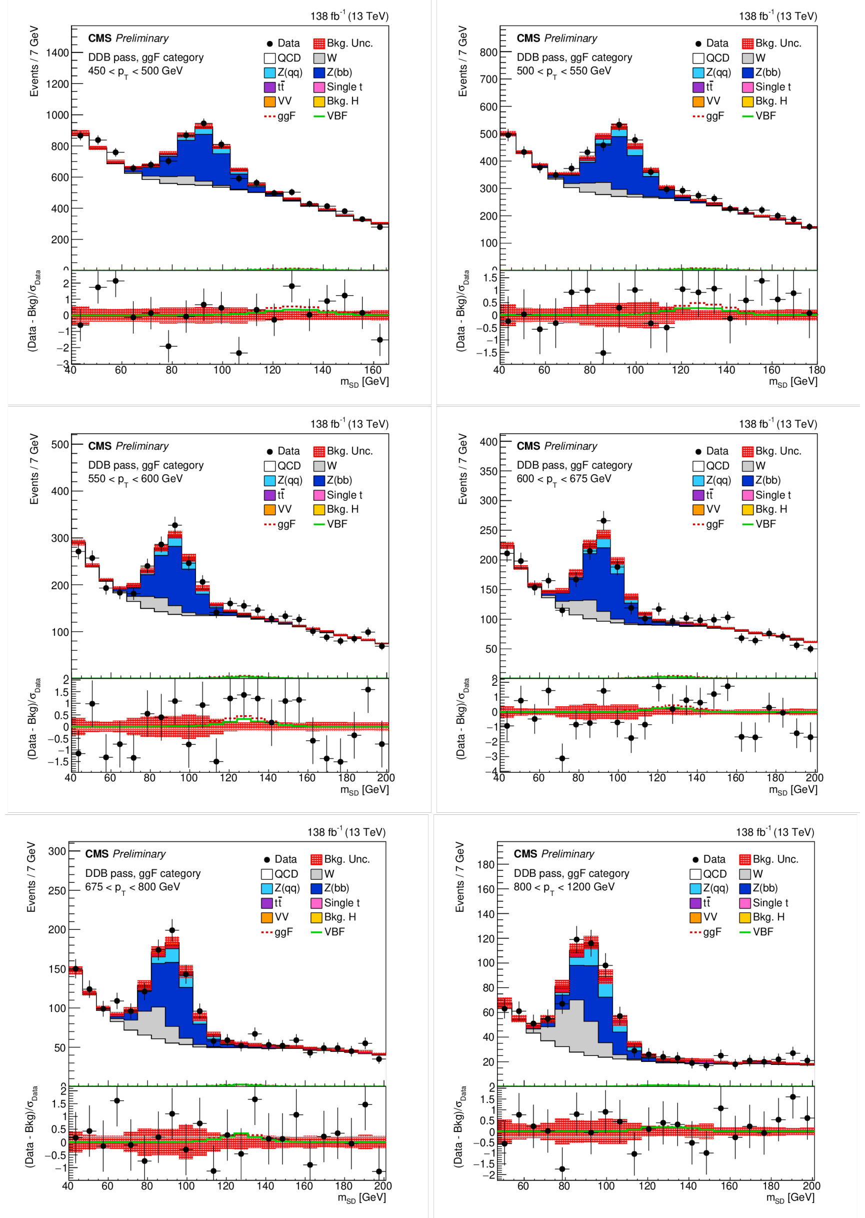
- $\mu=2.4^{+1.0}_{-0.9}$
- Significance 2.6σ (1.1σ exp.)

Boosted VBF H→bb

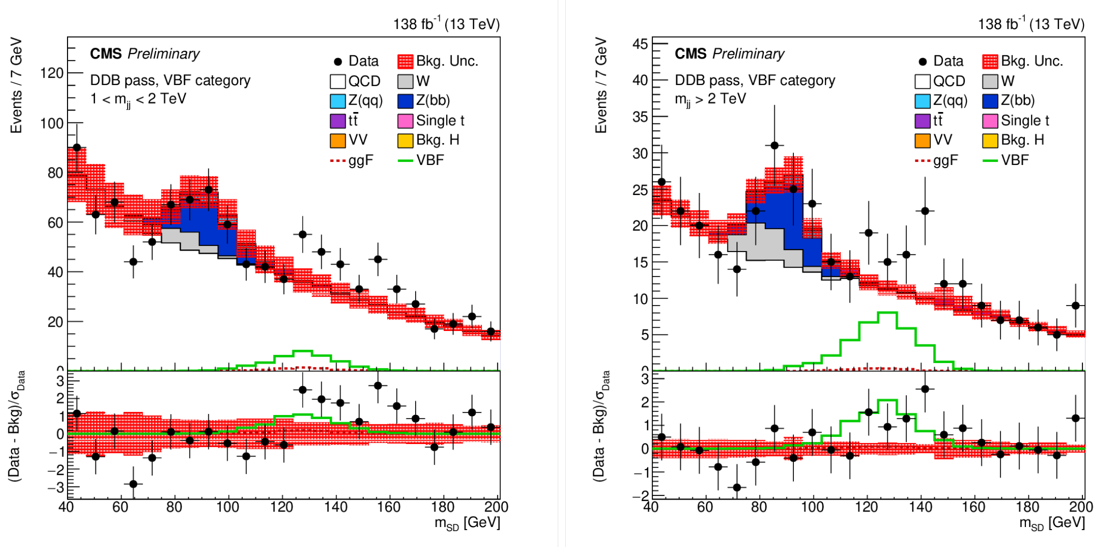
- DeepDoubleVbL-v2(DDB) tagger
  - Distinguish H→bb from QCD jets
  - Low-level quantities: SV, track and particle flow candidates withing the large radius jet (D=0.8)
    ➔ Large improvement w.r.t. previous tagger
  - DDB tagger eff 75%, QCD mis-tag rate 1%
  - Decorrelate tagger discriminant from soft drop mass



Boosted VBF H→bb

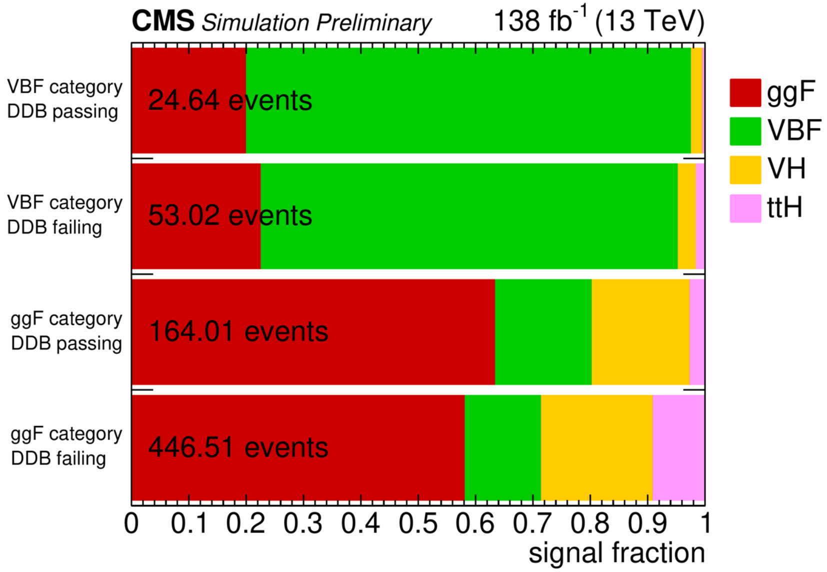


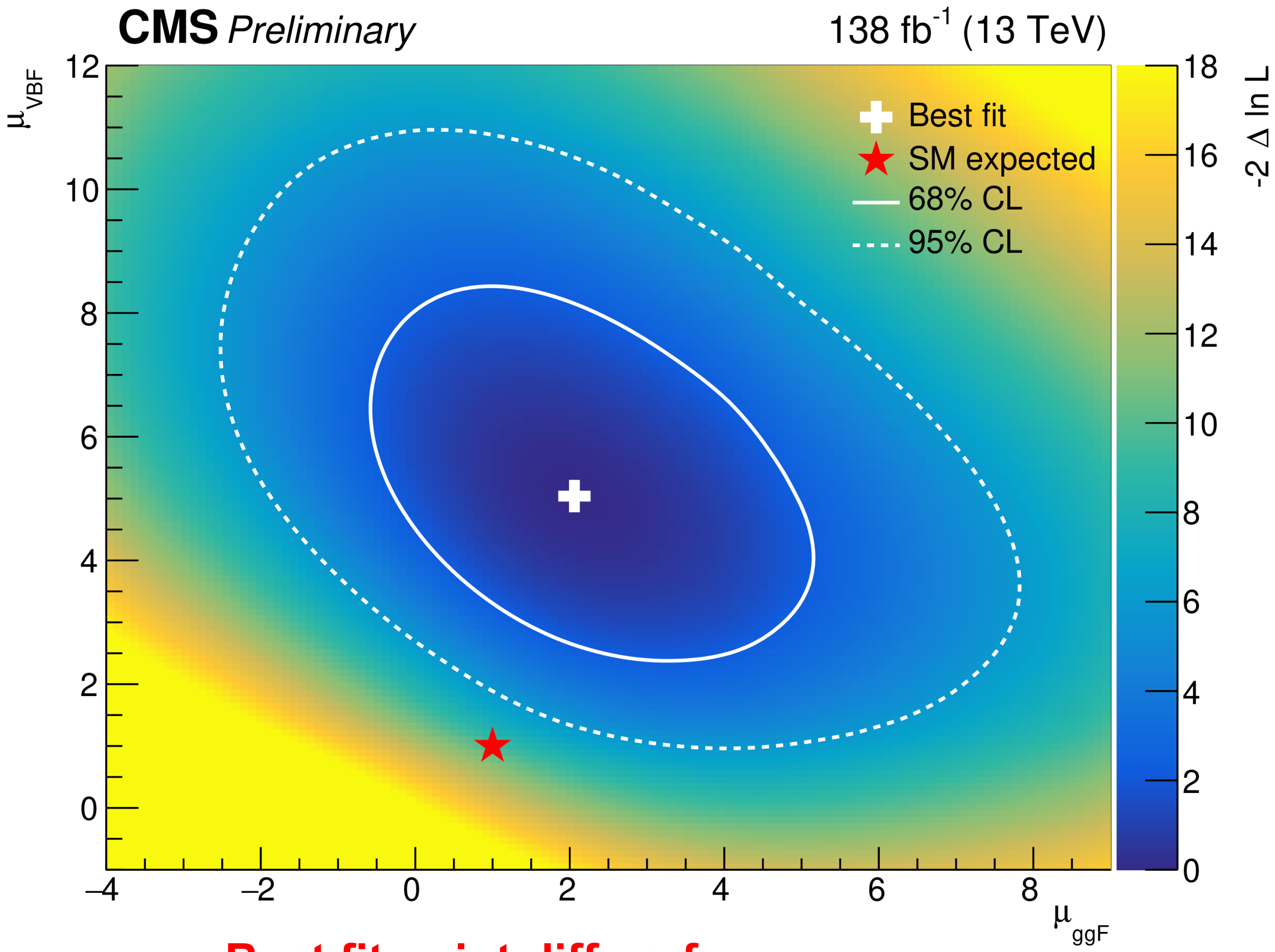
- Fitted ggF p_T^H categories (450-500, 500-550, 550-600, 600-675, 675-800, 800-1200)



- Fitted VBF categories (1 < m_{jj} < 2 TeV, m_{jj} > 2 TeV)

Boosted VBF H→bb

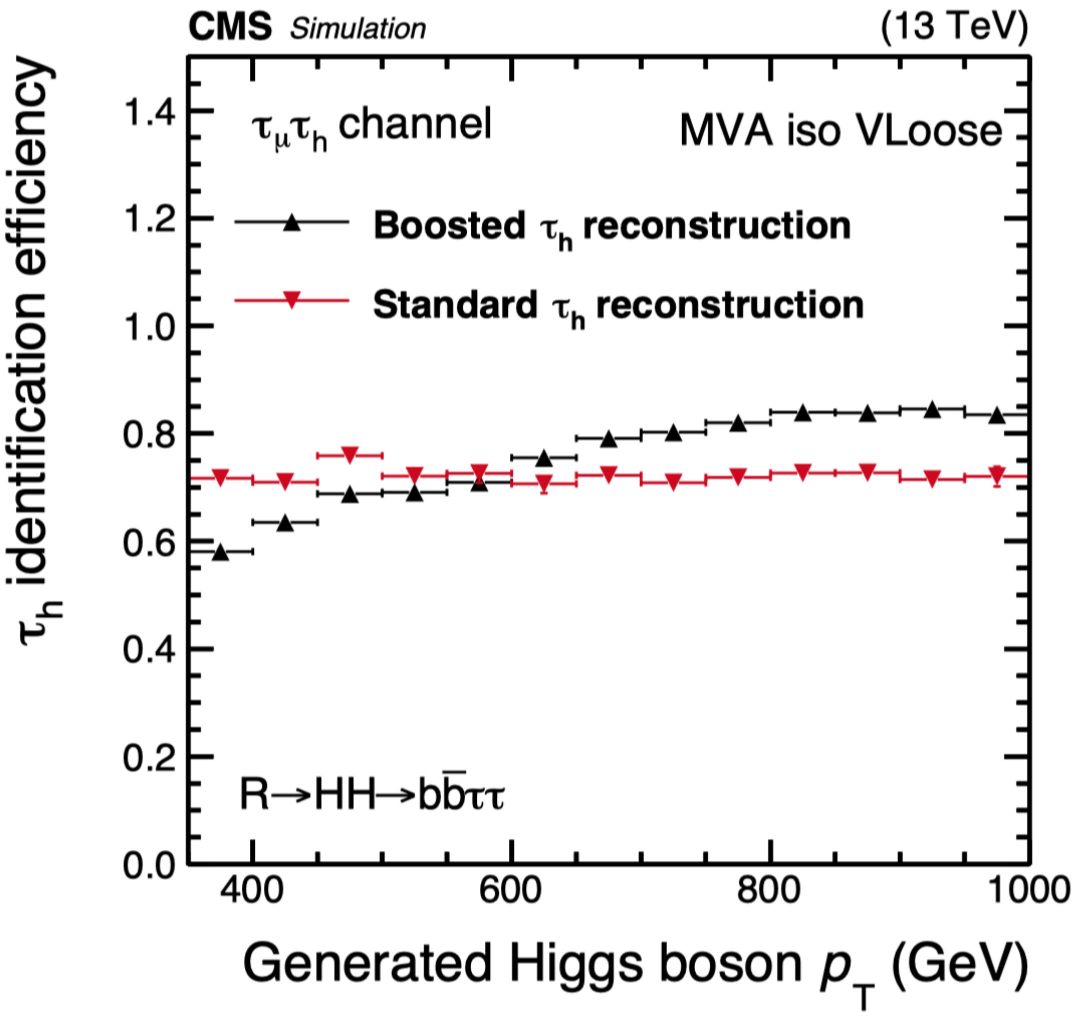


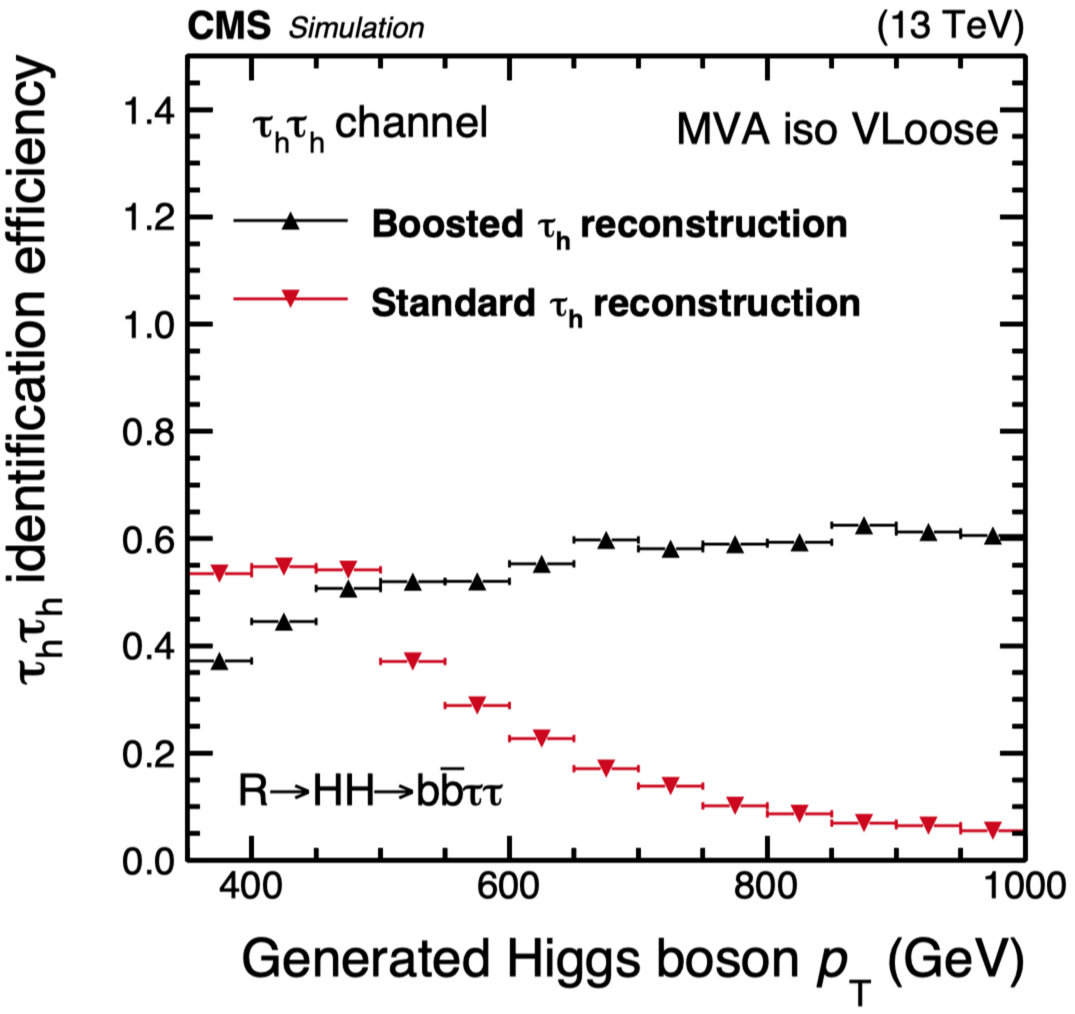


Best fit point differs from the SM by 2.6σ
null hypothesis by 3.9σ

Boosted H→ττ

JINST 13 (2018) P10005

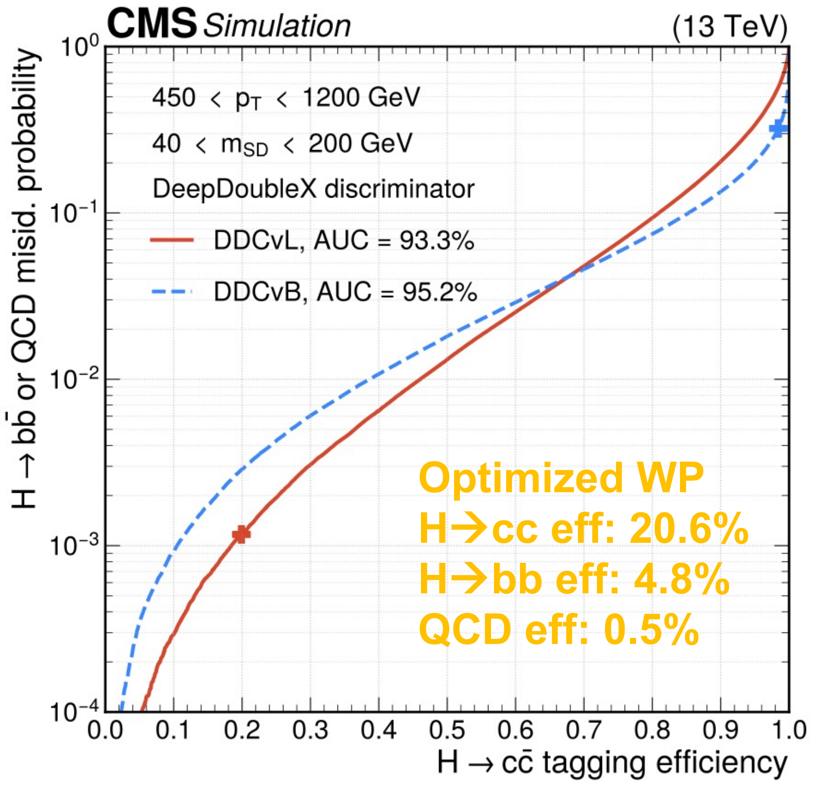




Boosted topology for rare decay mode

HIG-21-012

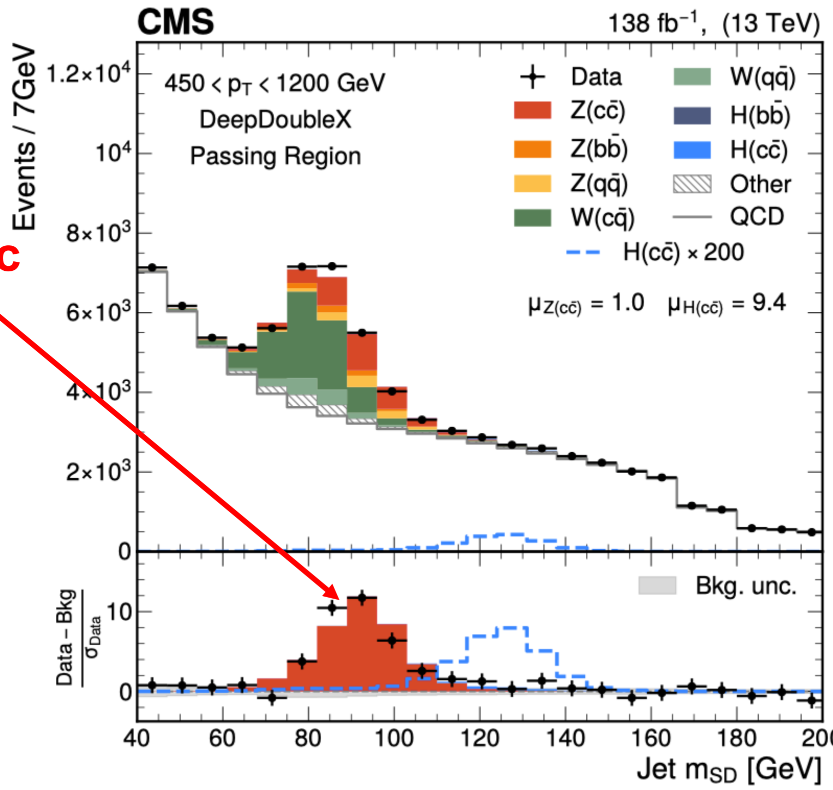
- $H \rightarrow cc$ is very challenging signature
  - Low branching ratio (2.9%), difficulty of c-tagging and huge background rate
  - $H \rightarrow cc$ tagging with recent ML techniques very promising in boosted region (p_T^H> 450 GeV)
  - DeepDoubleCvL(DDCvL) and DeepDoubleCvB(DDCvB) tagging
  - Tagger decorrelates with soft-drop mass (m_{SD})



Optimized WP
$H \rightarrow cc$ eff: 20.6%
$H \rightarrow bb$ eff: 4.8%
QCD eff: 0.5%

$\mu_{Z(\rightarrow cc)} = 1.0^{+0.19}_{-0.17}$
Observation of $Z \rightarrow cc$ in boosted region

$\mu_{H \rightarrow cc} = 9.4^{+20.3}_{-19.9}$
95% CL upper limit 47×SM (39×SM exp.)



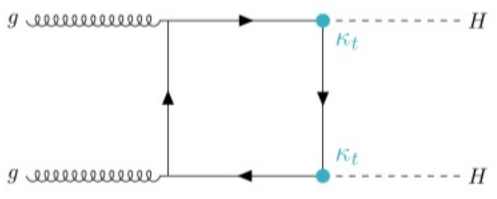
Higgs pair production at LHC

- pp→HH production cross section is quite small (**~30fb**) at even LHC
  - >1000 times lower than pp→H (**55.6pb**)
  - VERY challenging to observe HH signal (and measure λ_{HHH})

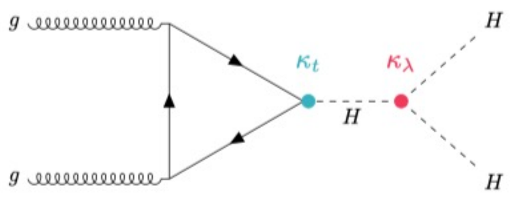
<u>Dominant processes</u>

<u>ggF (~31.05fb at NNLO QCD+NLO EW)</u>

$\kappa_x = \sigma/\sigma_{SM}$

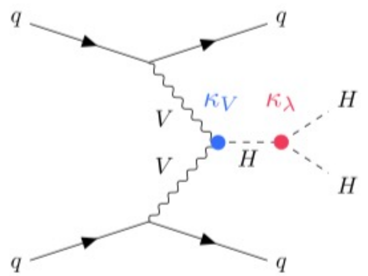


$\sigma \sim \kappa_t^2$

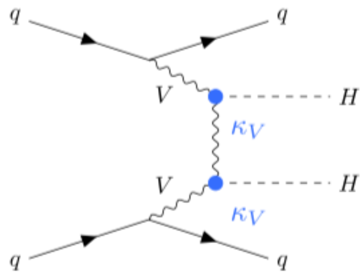


$\sigma \sim \kappa_t \times \kappa_\lambda$ (HHH coupling)

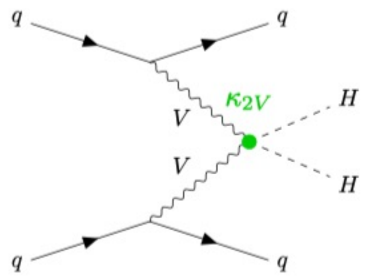
<u>VBF (~1.73fb at N³LO QCD)</u>



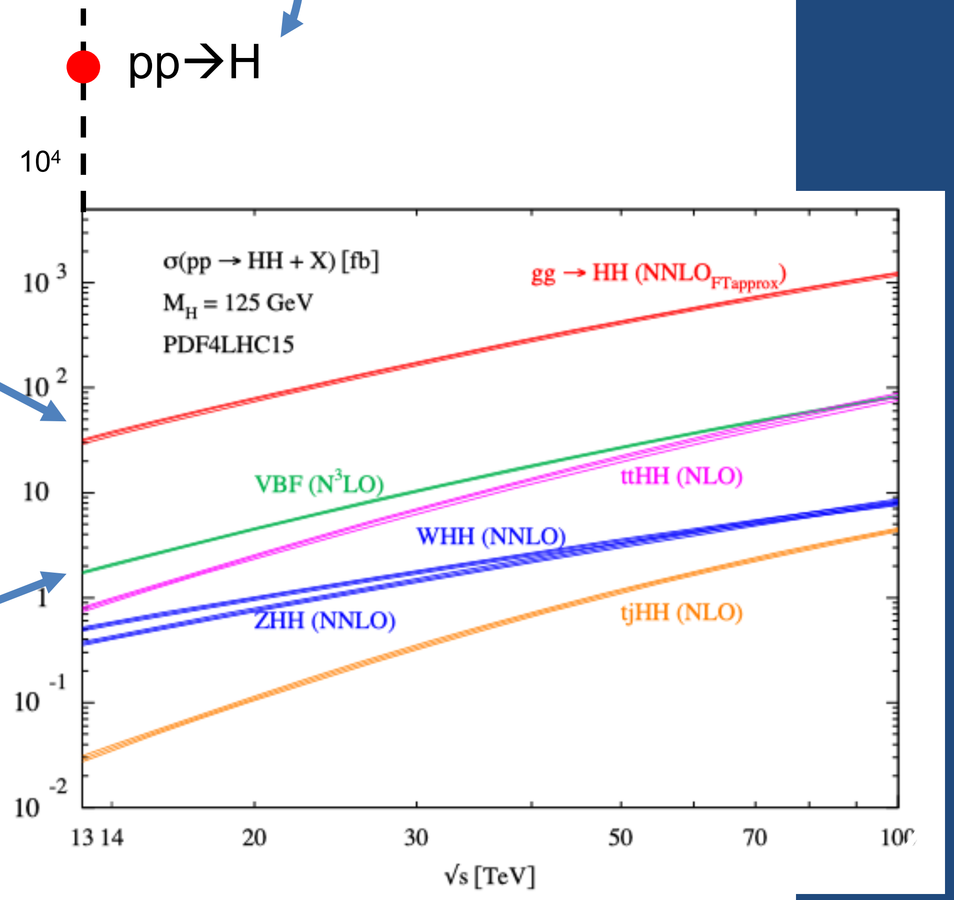
$\sigma \sim \kappa_V \times k_\lambda$



$\sigma \sim \kappa_V^2$



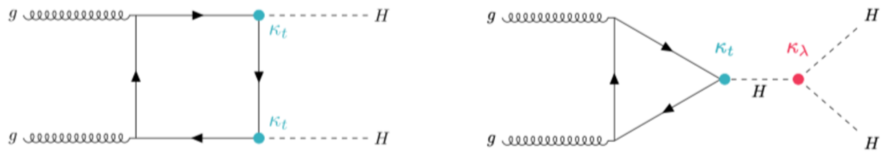
$\sigma \sim \kappa_{2V}$ (VVHH coupling)



DiHiggs production at LHC

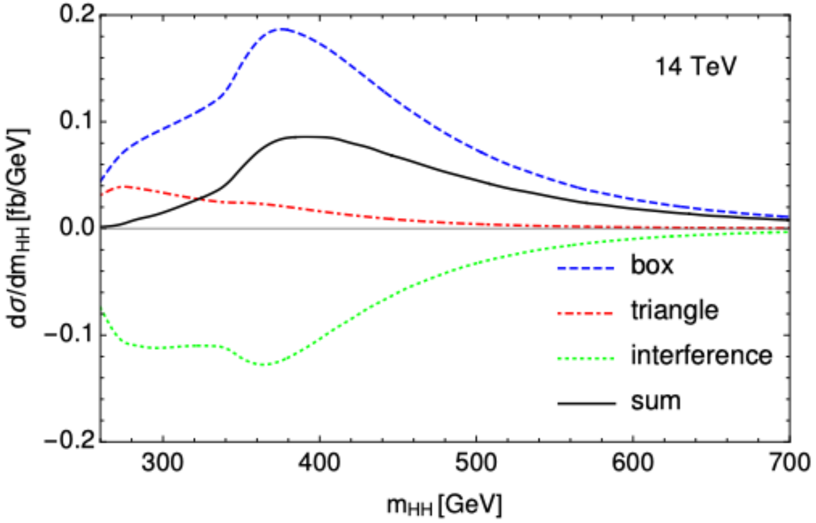
- pp→HH processes include diagrams with/without self-coupling
  - **Interfere non-κ_λ and κ_λ diagrams (destructive interference))**

ggF (~31.05fb at NNLO QCD+NLO EW) **$\kappa_x = \sigma/\sigma_{SM}$**

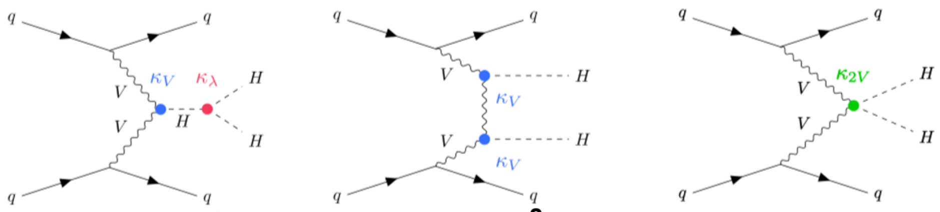


$\sigma \sim \kappa_t^2$ **$\sigma \sim \kappa_t * \kappa_\lambda$ (HHH coupling)**

Interference

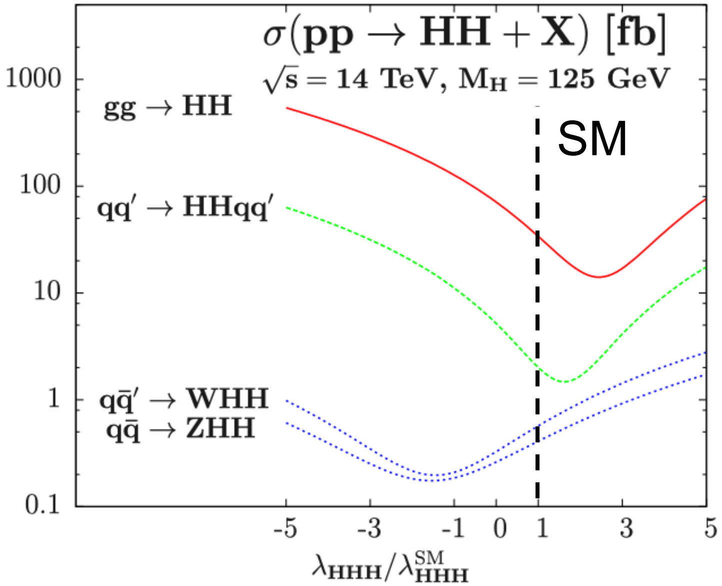


VBF (~1.73fb at N³LO QCD)



$\sigma \sim \kappa_V * \kappa_\lambda$ **$\sigma \sim \kappa_V^2$** **$\sigma \sim \kappa_{2V}$ (VVHH coupling)**

Interference

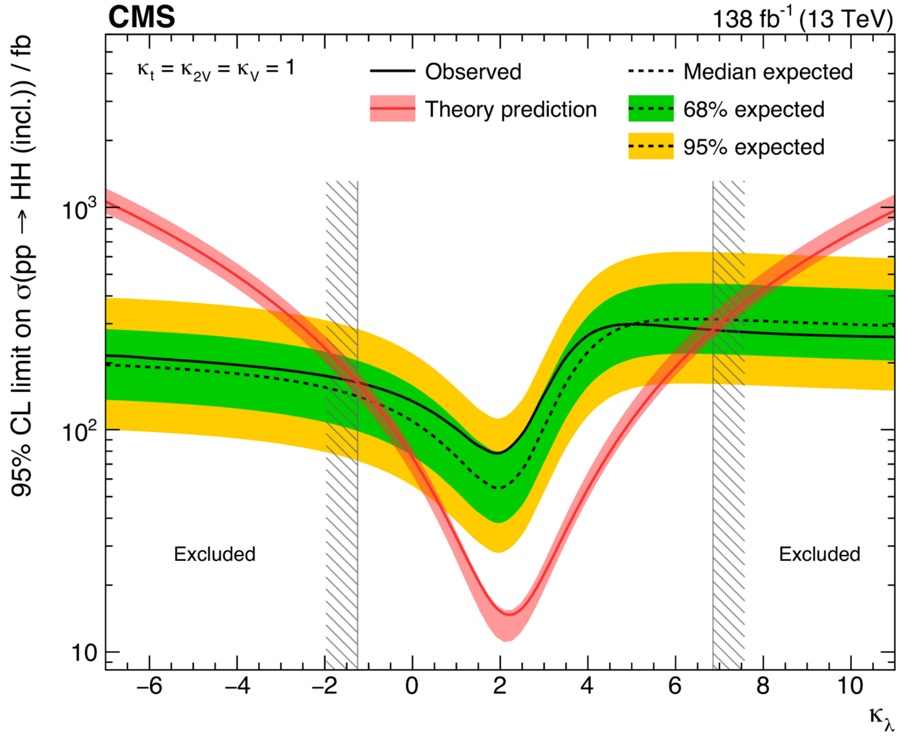


Cross section depends on κ_λ
"$\kappa_\lambda = 0$" is not lowest cross section

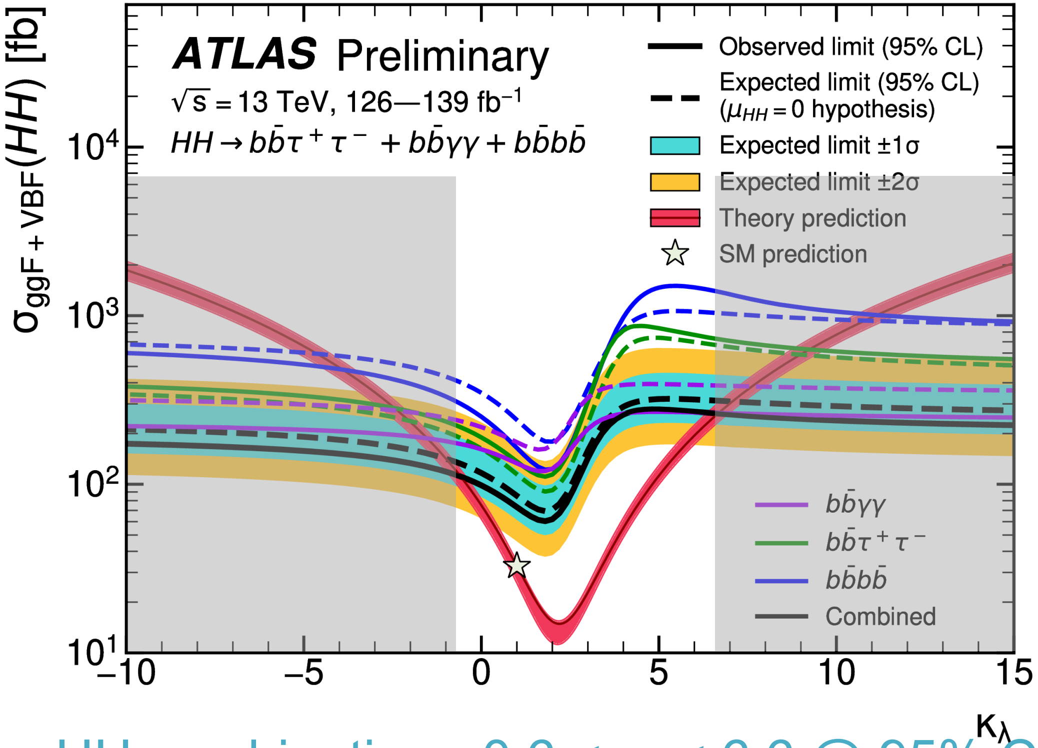
In ggF, minimum cross section at κ_λ = ~2.5

Combination: Limits on κ_λ

- Comparable constraints on k_λ in both experiments
- κ_λ=0 can be excluded in near future (analysis should be reoptimized for the targeting κ_λ)



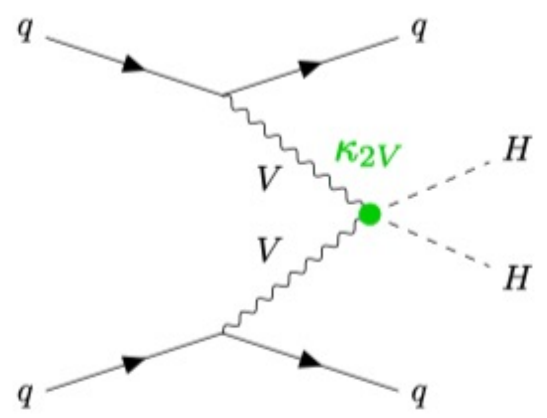
HH combination: -1.2 < κ_λ < 6.5 @ 95% CL

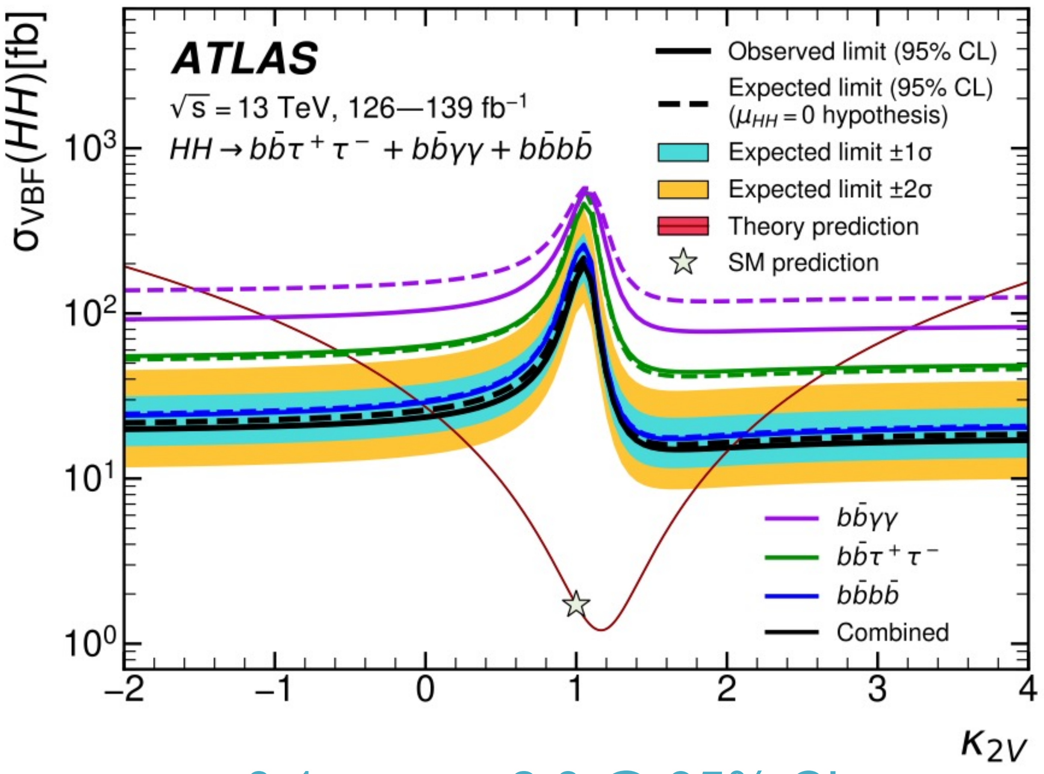


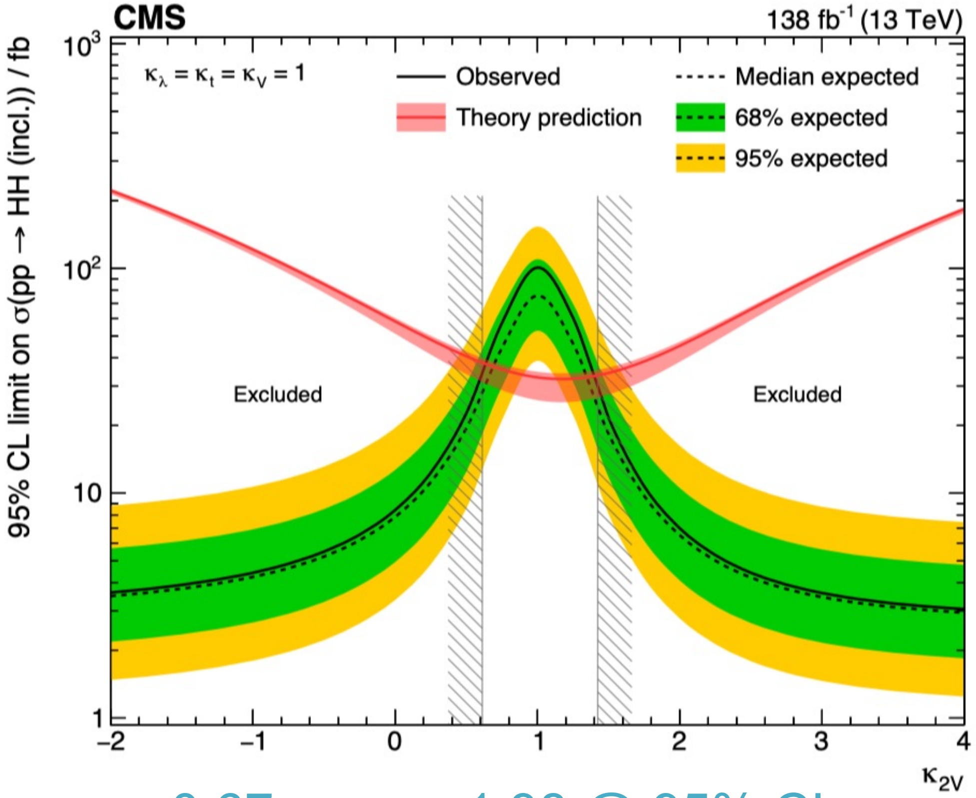
HH combination: -0.6 < κ_λ < 6.6 @ 95% CL

κ_{2V} limit

- VBF HH production is unique channel which is sensitive to quartic k_{2V} coupling







$0.1 < \kappa_{2V} < 2.0$ @ 95% CL

$0.67 < \kappa_{2V} < 1.38$ @ 95% CL

No significant deviation from SM. Non-zero k_{2V} excluded

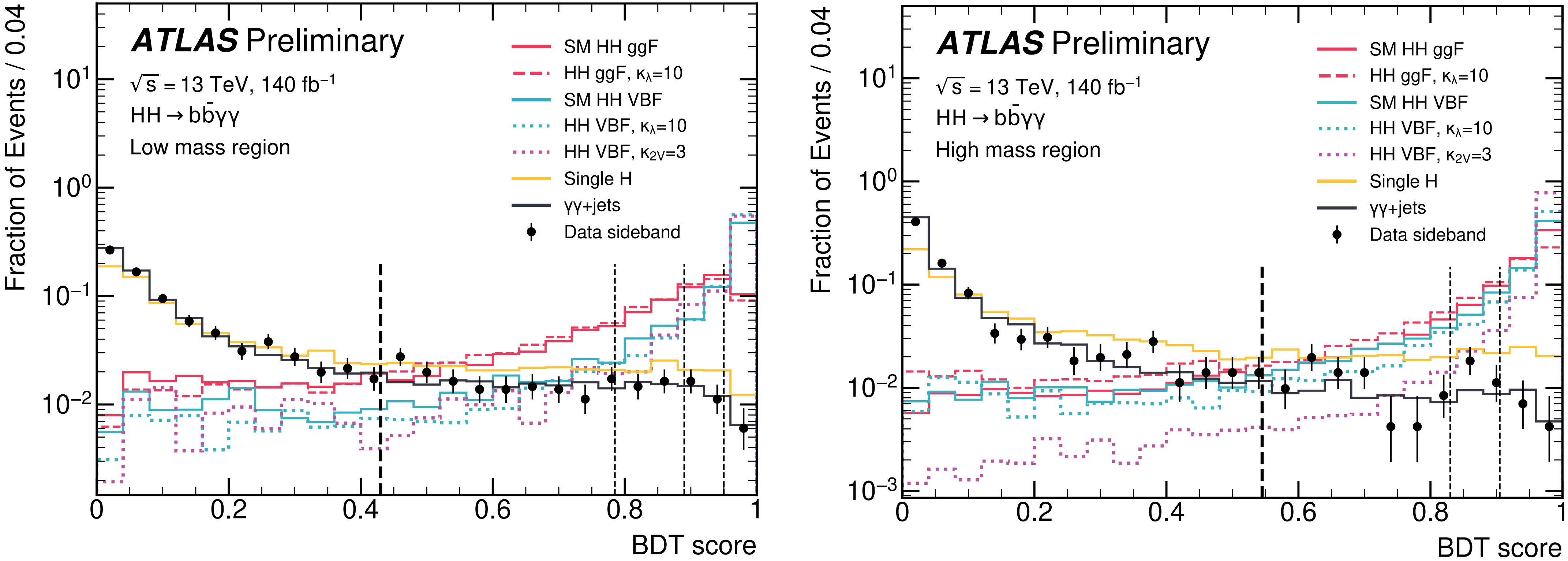
H+HH combinations

In the combination with single Higgs channel, not only stronger κ_λ constraint, more model independent κ_λ measurement is possible

Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single-H combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$
HH+H combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t, κ_V, κ_b, κ_τ floating	$-1.4 < \kappa_\lambda < 6.1$	$-2.2 < \kappa_\lambda < 7.7$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

HH→γγbb BDT categorization

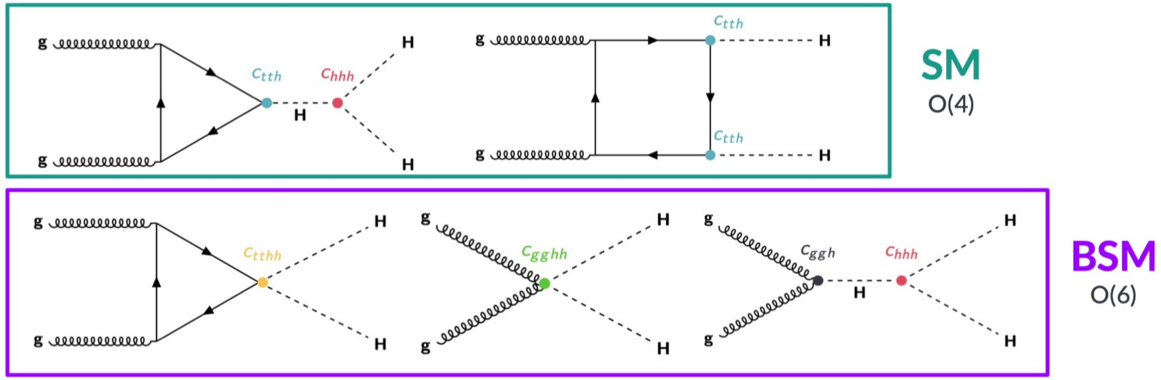
- VBF jet tagger BDT assigns correct BDT jet from reconstructed non b-jets (VBF jets are correctly identified in 95% of events)
- Event classification BDTs (HH signal vs other backgrounds) trained in low/high mass ($m_{bb\gamma\gamma^*}$ >350 GeV/< 350 GeV) to keep sensitivity in BSM kλ, k2V scenario
  - 3(4) categories for high/low mass



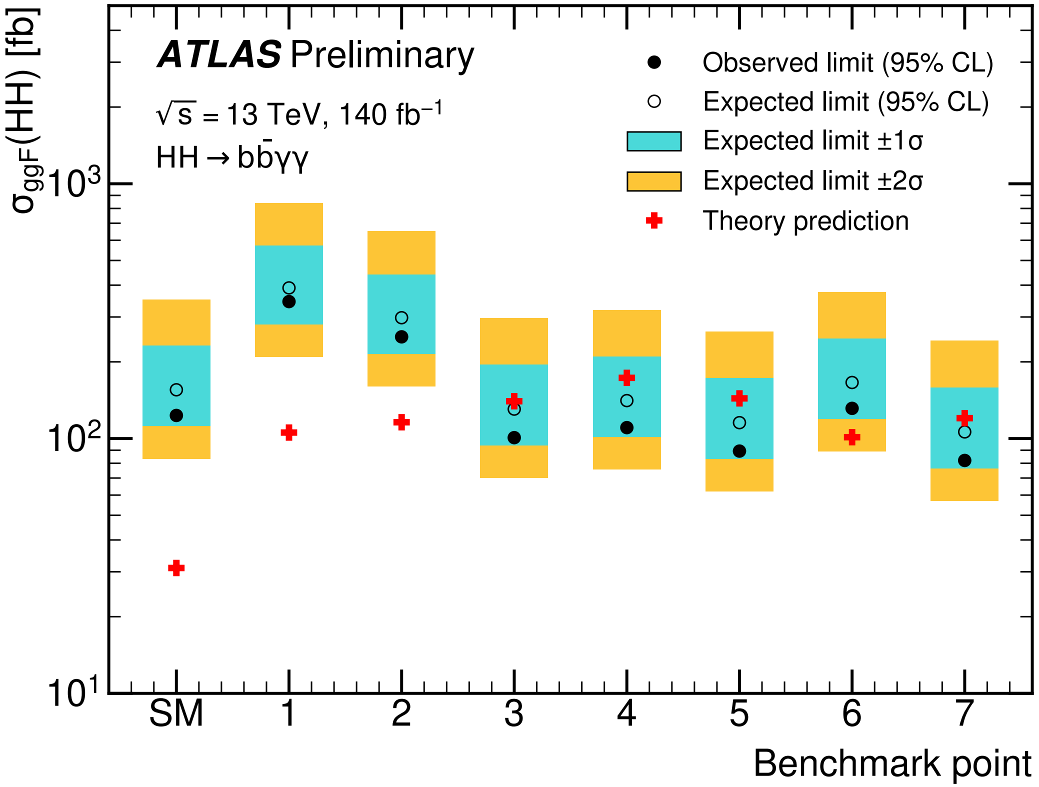
HH→γγbb EFT interpretation

- For EFT interpretation, only ggF HH production is considered, and VBF HH is assumed to be negligible

- HEFT and SMEFT interpretation is performed
  - In the HEFT case, 7 bench mark points are investigated with different c_{tthh}, c_{gghh} and c_{hhh} values



Benchmark	c_{hhh}	c_{tth}	c_{ggh}	c_{gghh}	c_{tthh}
SM	1	1	0	0	0
1	5.11	1.10	0	0	0
2	6.84	1.03	-1/3	0	1/6
3	2.21	1.05	1/2	1/2	-1/3
4	2.79	0.90	-1/3	-1/2	-1/6
5	3.95	1.17	1/6	-1/2	-1/3
6	-0.68	0.90	1/2	0.25	-1/6
7	-0.10	0.94	1/6	-1/6	1



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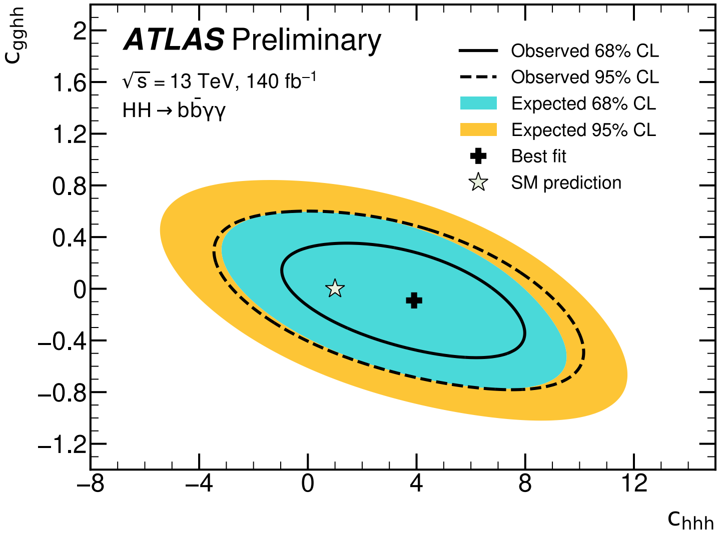

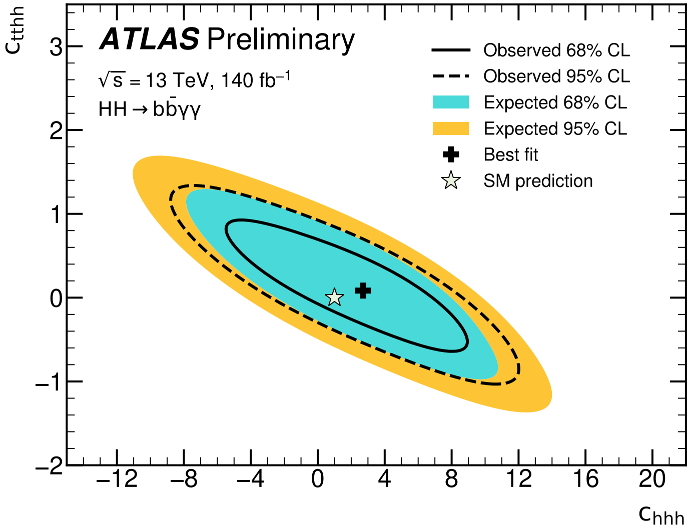

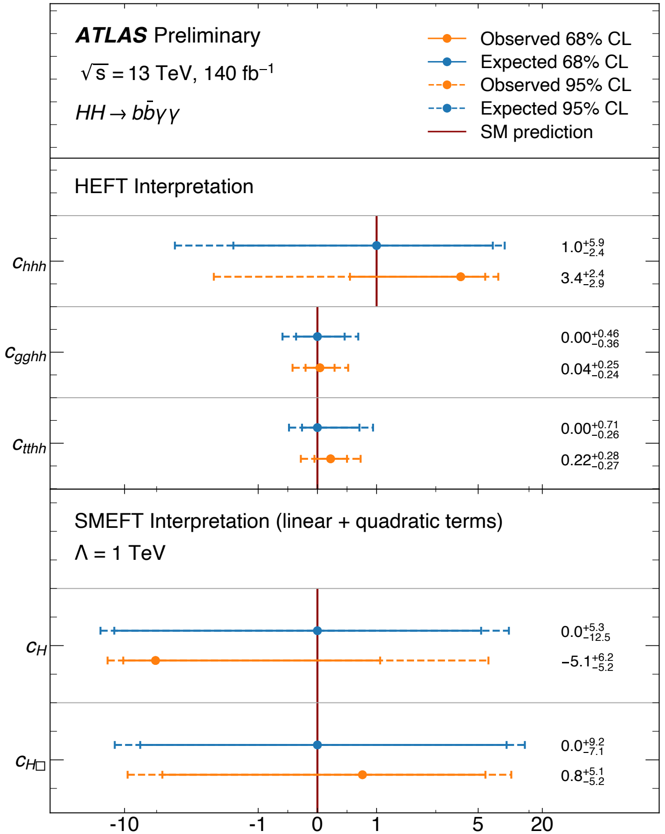

Wilson coefficient	95% CL Observed	95% CL Expected
c_{hhh}	[−1.8 , 7.7]	[−3.4 , 8.9]
c_{tthh}	[−0.28, 0.73]	[−0.48, 0.94]
c_{gghh}	[−0.42, 0.52]	[−0.59, 0.69]