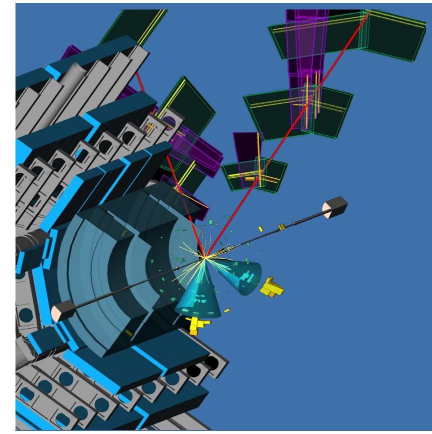
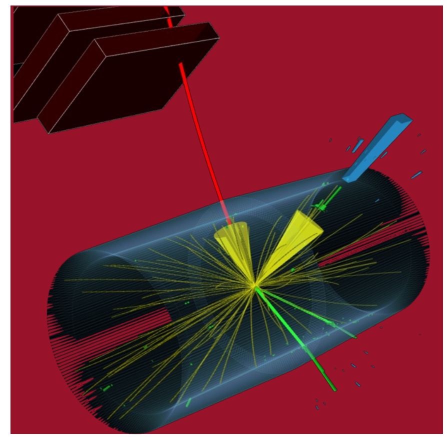
Higgs-Boson Couplings to 2nd Generation Fermions & Rare Higgs-Boson Decays





Elisabeth Schopf, on behalf of the ATLAS & CMS Collaborations

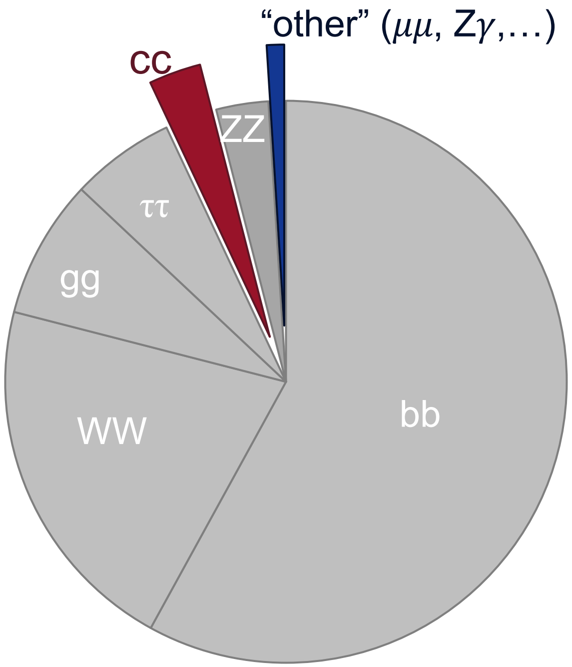
UNIVERSITY OF OXFORD

Higgs 2023, Beijing

CMS

ATLAS EXPERIMENT

Rare Interactions & Decays of the Higgs Boson

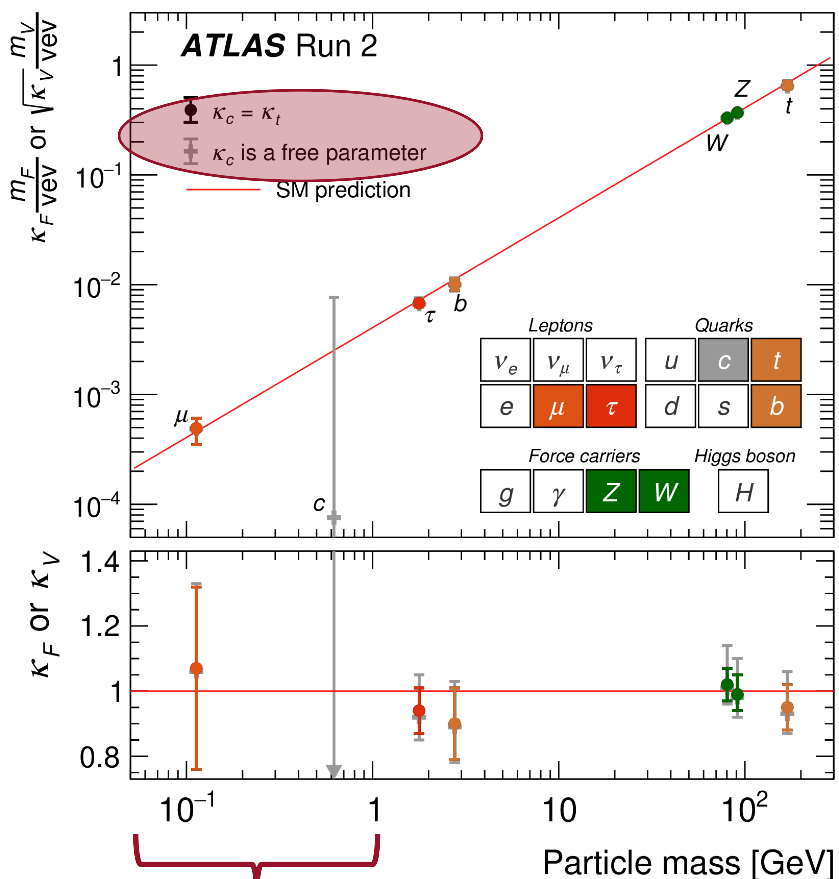


- Rare decays of the Higgs boson involve higher-order or highly supressed diagrams
  - Does new physics enter through these diagrams and modify the branching ratios?
- 2nd generation fermion couplings introduced as ad-hoc Yukawa terms
  - Does the Higgs-boson-fermion coupling hierarchy follow the fermion mass hierarchy? (expected in SM)

→ In this talk: ~4% of the Higgs boson decay "pie"

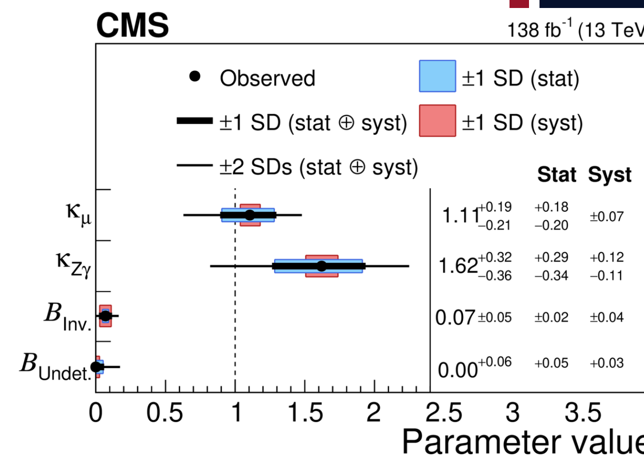
→ All results: full Run-2 data sets (up to 140 fb^{-1} of pp-collisions at 13 TeV)

+ Experimental Knowledge Overview



Nature 607, 52 (2022)

Only loose constraints on 2nd generation couplings!

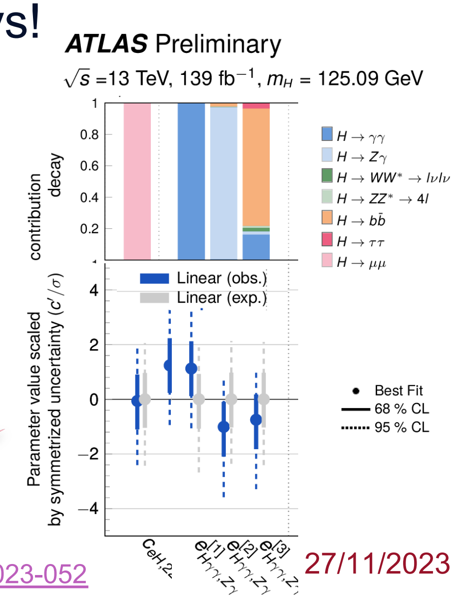


Nature 607 (2022) 60-68

Probing H decays with increasing precision and more and more rare decays → Narrowing down window for undetected decays!

Rare decays uniquely sensitive to certain directions in EFT coupling modifier space!

2023

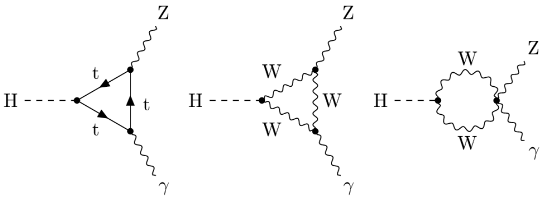


ATLAS-CONF-2023-052

Rare Decays

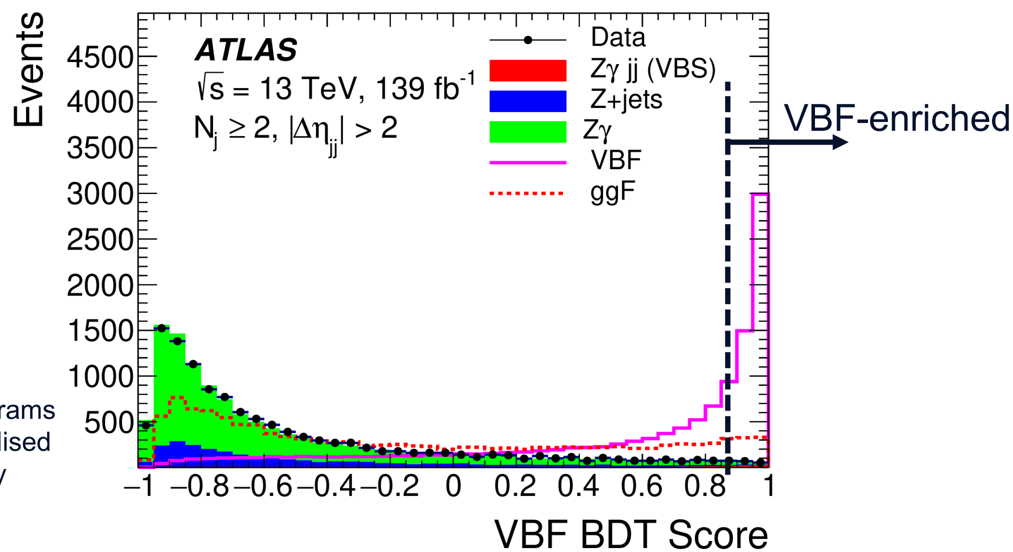
+ H→Zγ Decays

- SM BR(H→Zγ) = 0.15%



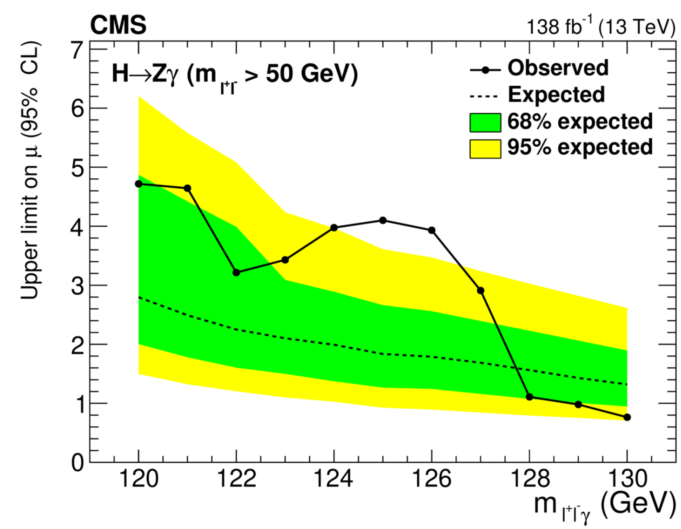
- Targeting **Z(ee/μμ)+γ** final states
  - Requiring on-shell Z-boson → select (tightly) events within mass window
  - Improvements to mass resolution (FSR correction, kinematic fit)

- **Several categories of varying signal-to-background ratios** (split by production mode, mass resolution) + **machine learning** classifiers



Histograms normalised to unity

Phys. Lett. B 809 (2020) 135754

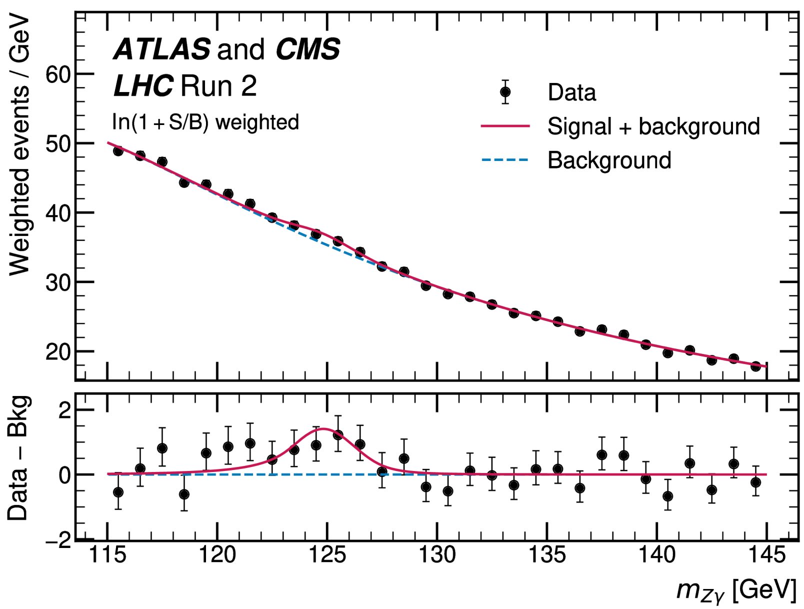


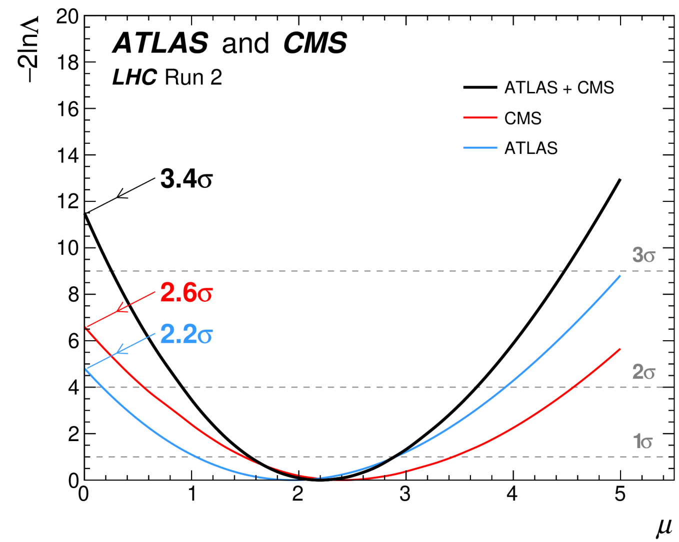
JHEP 05 (2023) 233

Evidence for H→Zγ Decays

2023

- ATLAS and CMS observe excess compatible with SM decay of **H→Zγ**
  - ATLAS observed (expected) significance: 2.2σ (1.2σ)
  - CMS observed (expected) significance: 2.7σ (1.2σ)
- Combination of both measurements → Evidence! 3.4σ, $\mu = 2.2 \pm 0.7$



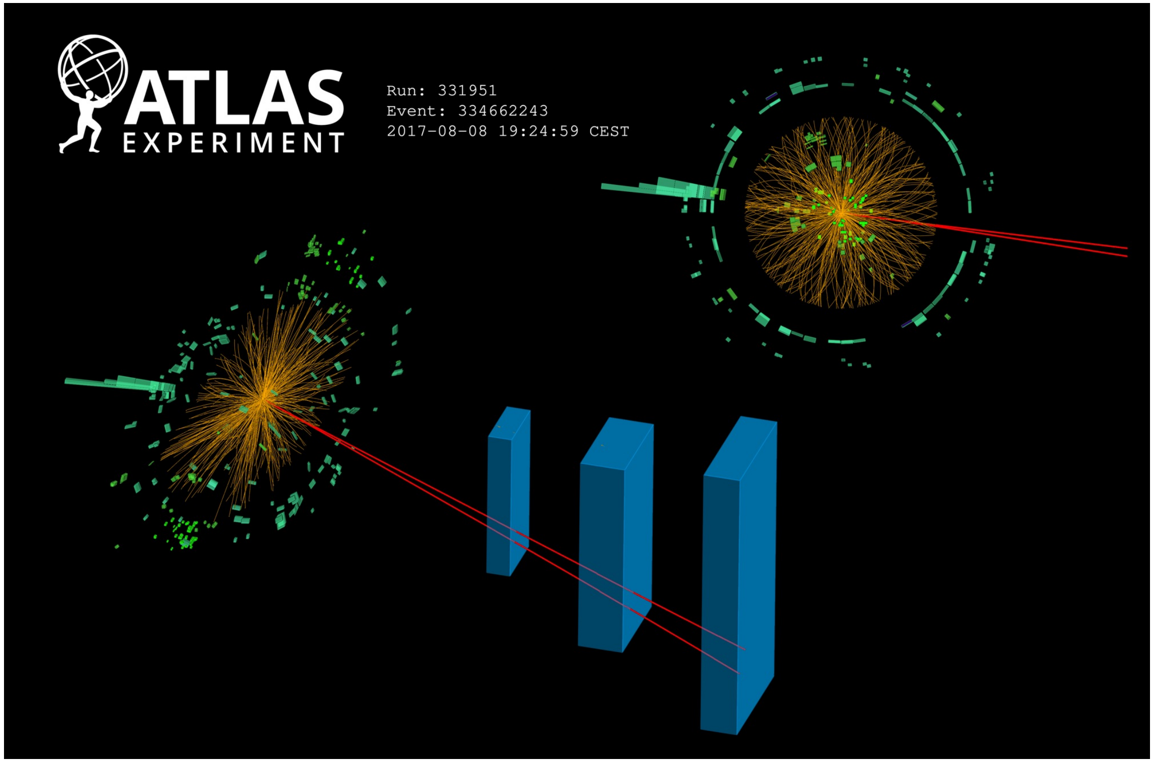


→ **Compatible with SM within 1.9 σ**

H→$\ell\ell\gamma$ with $m_{\ell\ell}$<30 GeV

$\ell\ell$ = ee or $\mu\mu$

→ No on-shell Z-boson, orthogonal to H→Zγ



SM BR~10^{-5}

Low p_T leptons → Custom calibration and classification for "merged" ee events (overlapping calorimeter showers)

$$\mu = 1.5 \pm 0.5$$

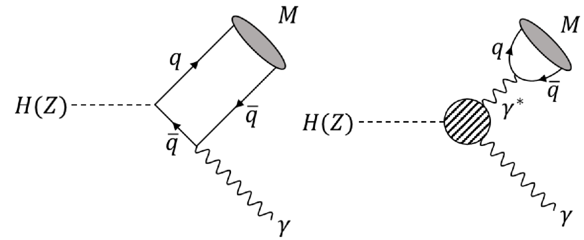
Observed significance: 3.2 σ

Evidence!

[Phys. Lett. B 819 (2021) 136412]

+ H→Quarkonia Decays

(H→meson+γ, H→meson+Z, H→2mesons)



Extremely rare decays in the SM

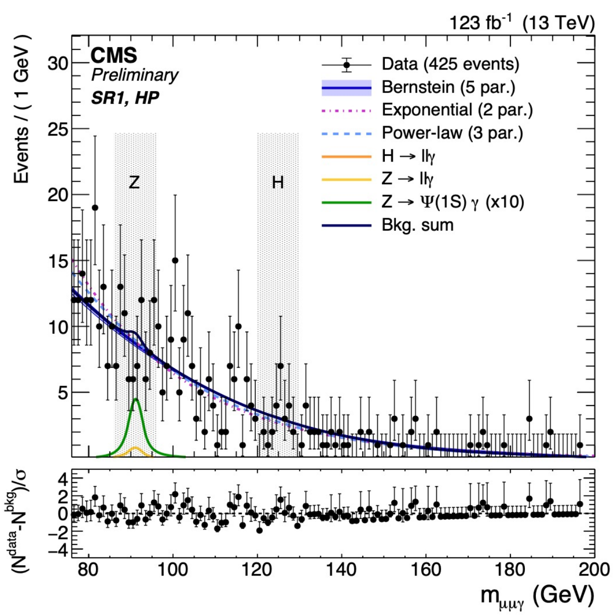
Sensitivity to couplings to light quarks, but
strong interference between diagrams → no direct scaling of decay rate with κ_q

2023

ATLAS latest result:
Phys. Lett. B 847 (2023) 138292

Channel	Meson content	BR upper limit (obs.)	SM BR
H→$\omega\gamma$	b=c=s=0	5.5 x 10^{-4}	1.5 x 10^{-6}
H→K*γ	s=1	2.2 x 10^{-4}	<10^{-11}

using custom triggers!



SMP-22-012

NEW for Higgs2023

CMS: full Run 2 H→Ψ(nS)γ

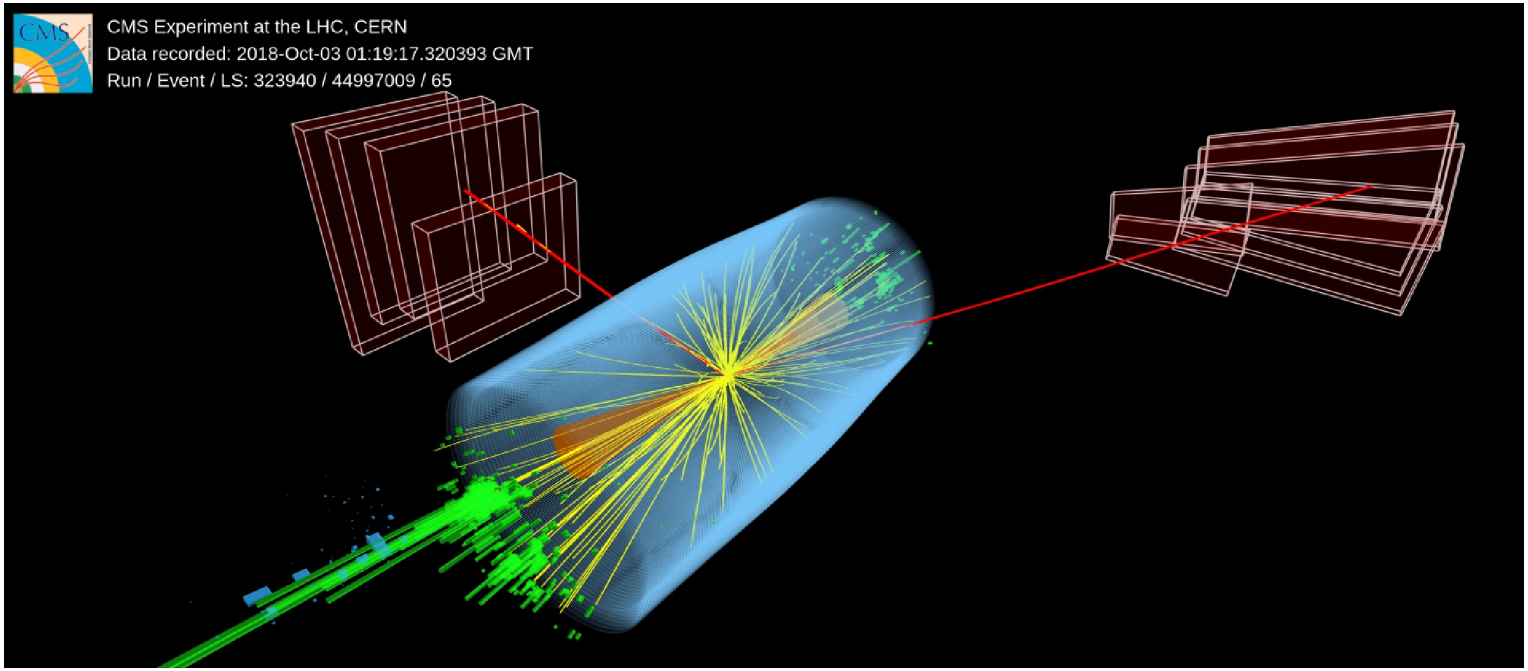
Signal-background multivariate likelihood discriminant using angular observables (no correlation with mass)
Additional VBF H, bbH and ttH categories

Channel	Meson content	BR upper limit (obs.)	SM BR
H→Ψ(1S)γ	cc	2.6 x 10^{-4}	3.01 x 10^{-6}
H→Ψ(2S)γ	cc	9.9 x 10^{-4}	1.03 x 10^{-6}

→ Interpretation: -157 < κ_c/κ_γ < 199

2nd Generation Fermion Couplings

Higgs Boson Decays to Muons



SM BR(H→$\mu\mu$)=0.02%

High background rates

Sensitivity highly correlated with di-muon-mass resolution

Phys. Lett. B 812 (2021) 135980

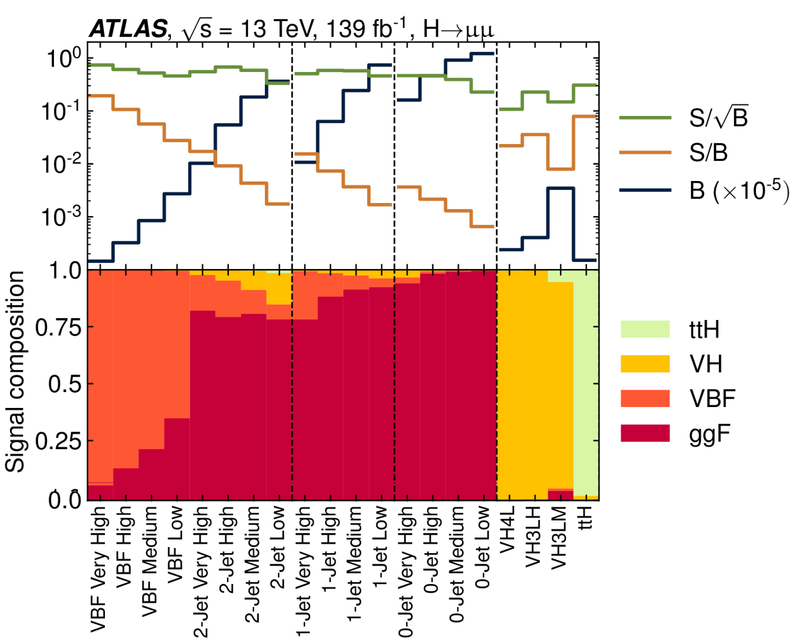
ATLAS: Search for H→$\mu\mu$ Decays

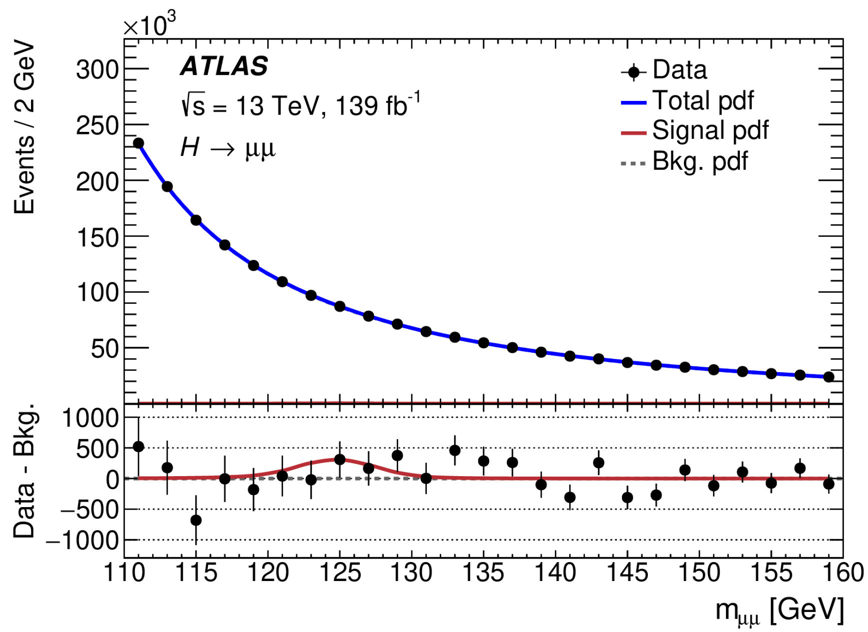
Separate analysis channels for all major production modes

Sensitivity enhancement through:

→ **FSR correction**

→ **machine-learning** for defining analysis categories





$\mu = 1.2 \pm 0.6$ Observed significance: 2.0 σ

CMS: Evidence for H→$\mu\mu$ Decays

Separate analysis channels for all major production modes

Sensitivity enhancement through:

→ **FSR correction**

→ **machine-learning** as discriminant in VBF channel & for defining analysis categories in ggF, VH and ttH channels

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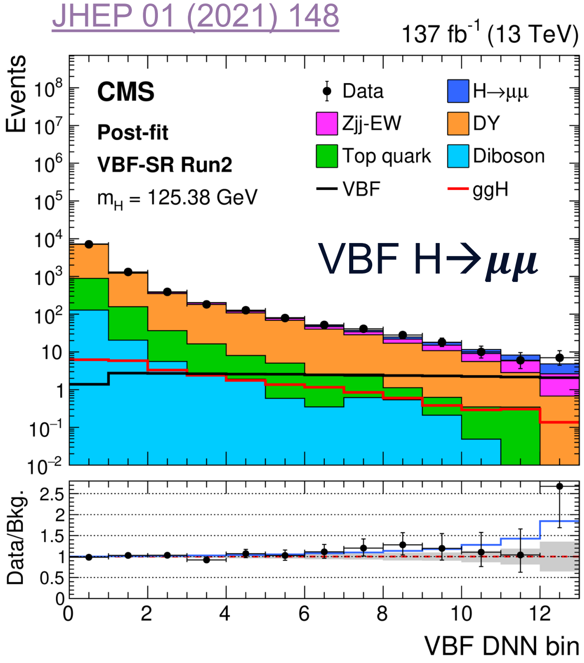
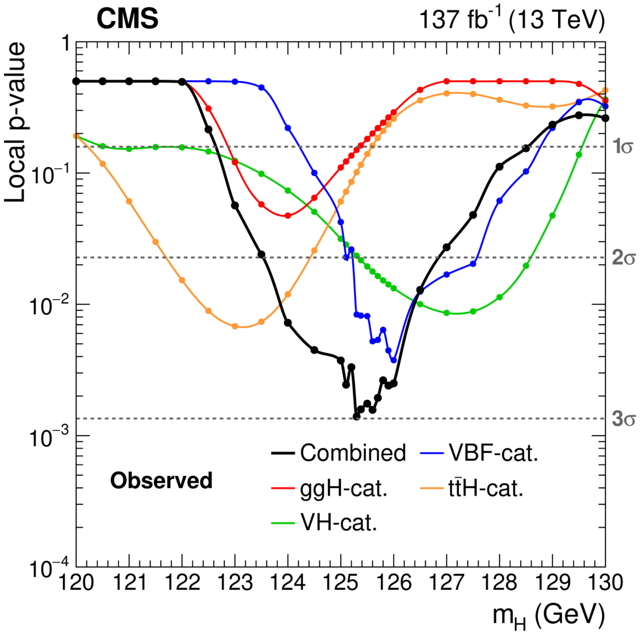


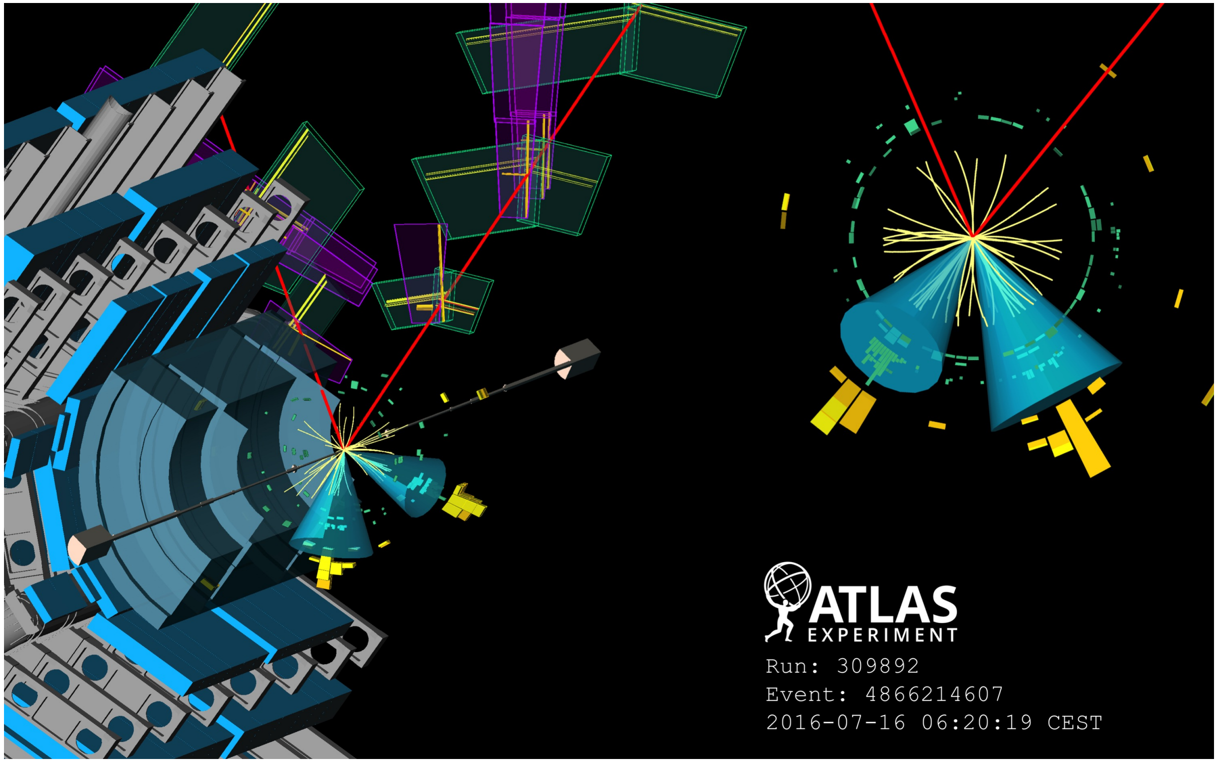


$$\mu = 1.19^{+0.40}_{-0.39}(\text{stat.})^{+0.15}_{-0.14}(\text{syst.})$$

Observed significance: 3.0 $\boldsymbol{\sigma}$ (2.5 $\boldsymbol{\sigma}$ expected)

→ Statistically limited analysis

Higgs Boson Decays to Charm Quarks



SM BR(H→cc)=3%

Experimentally challenging
→ c-jet identification
→ High background rates
→ Sizeable systematic uncertainties

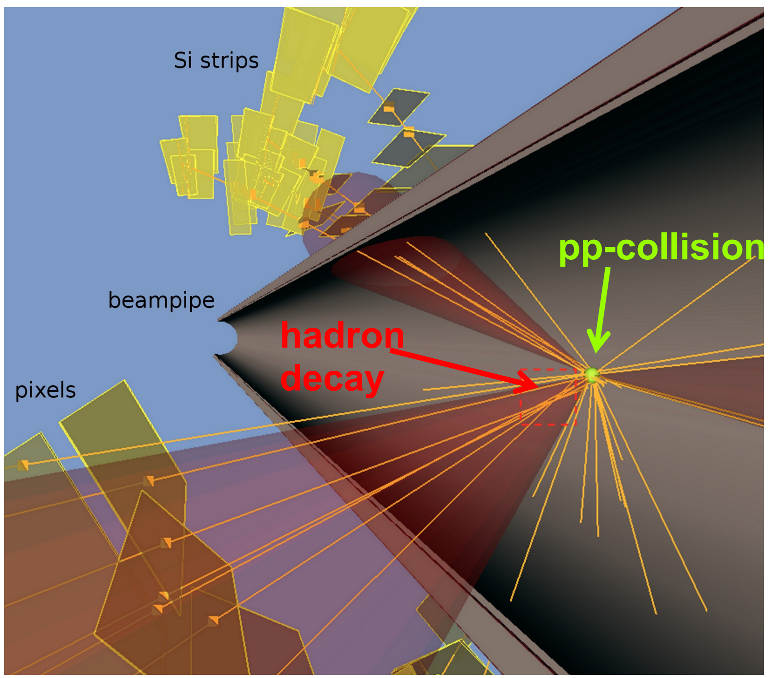
Most sensitive analyses: VH(cc) targeting Z($\nu\nu$)H(cc), W($\ell\nu$)H(cc), Z($\ell\ell$)H(cc)
Efficient triggering and background suppression

+ Identification ("Tagging") of c-jets

Hadrons containing c-quarks have measurable lifetime(*)

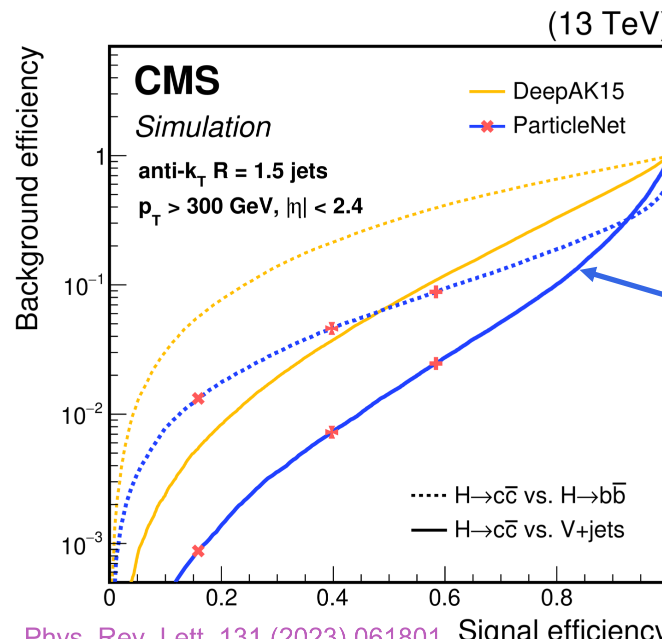
Information input in neural net (NN) algorithms → c-tagging ID algorithms combine NN output into discriminant for:

- → "jet tagging": single small (R=0.4) jets c-tagging ("resolved")
- → "Higgs tagging": large (R=1.0/1.5) jets ("boosted")



ATLAS event displays

Typical c-tagging efficiencies ~20-50% with still considerable mis-tag rates for background (~10%)



Phys. Rev. Lett. 131 (2023) 061801

GNN-based H→cc tagger

(*) c-hadrons: $c\tau$ ~120 to 300 μm b-hadrons: $c\tau$ ~450 to 500 μm

Phys. Rev. Lett. 131 (2023) 061801

+ H→cc Search in CMS

Targeting resolved (VH) and boosted topologies (VH, ggF)

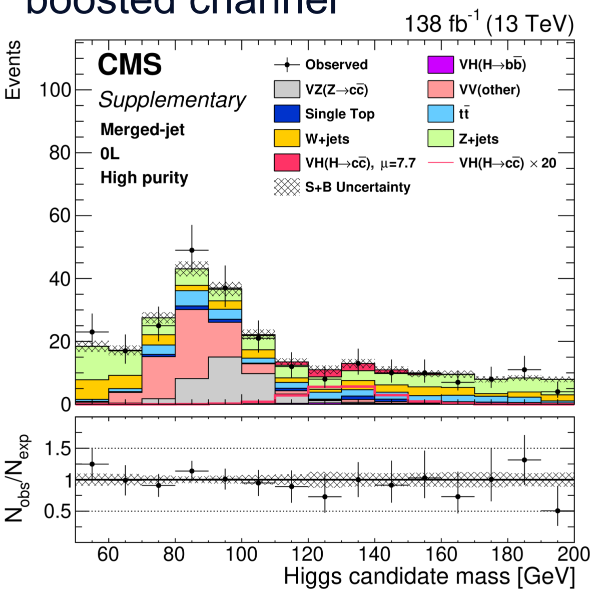
→ focus here on VH (ggF on page 18)

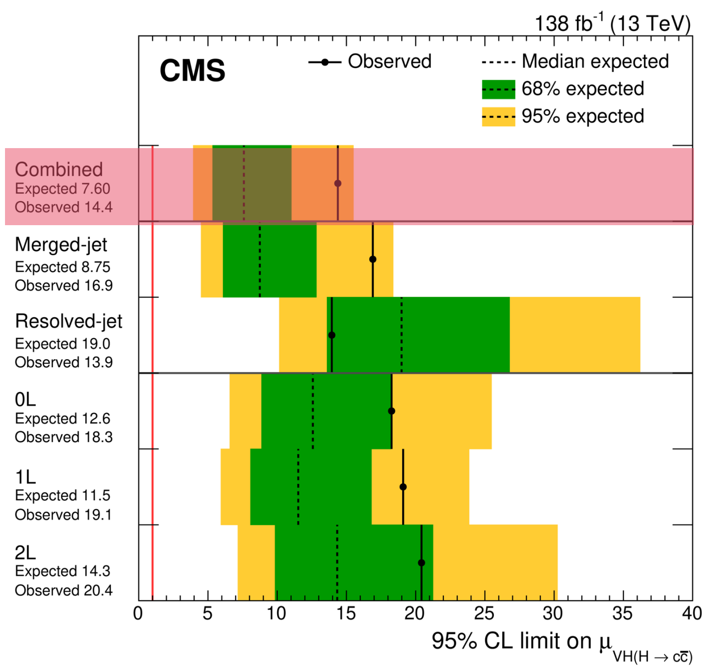
Sensitivity enhancement through extensive use of:

→ **machine-learning classifiers** for signal-background discrimination & analysis region definition

→ **c-tagging discriminant** as ML input & fit discriminant in control regions

Large-R jet mass in Z($\nu\nu$)H(cc) boosted channel





μ<14.4 * SM

1.1 < $|\kappa_c|$ < 5.5

→ Most sensitive H→cc search to date

VZ(cc) cross-check measurement: 5.7σ Observation!

VH,H→cc Search in ATLAS

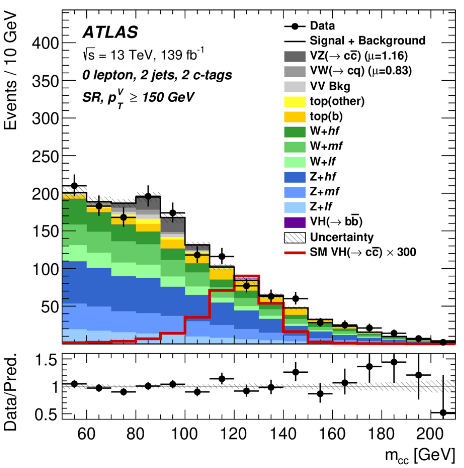
Targeting resolved topologies

b-veto+c-tagging → orthogonal to VH(bb) analyses

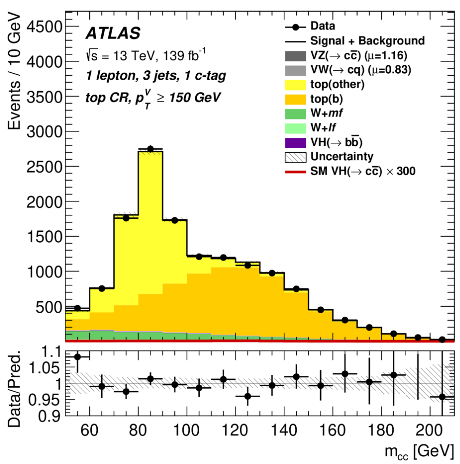
Mass-based analysis, i.e. m_{cc} used as discriminant

Extensive use of **background control regions**

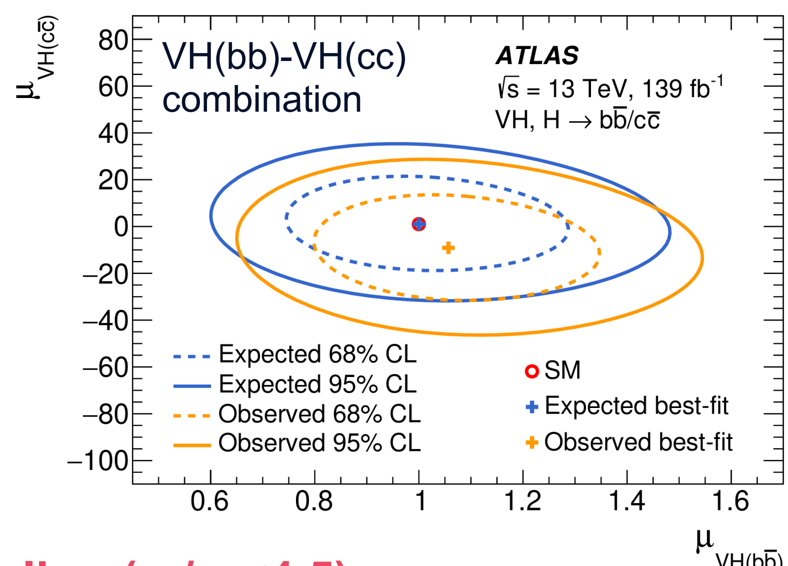
m_{cc} in $Z(\nu\nu)H(cc)$ channel



Top-quark control region



μ< 26 * SM (31 exp.), $|\kappa_c|$ < 8.5

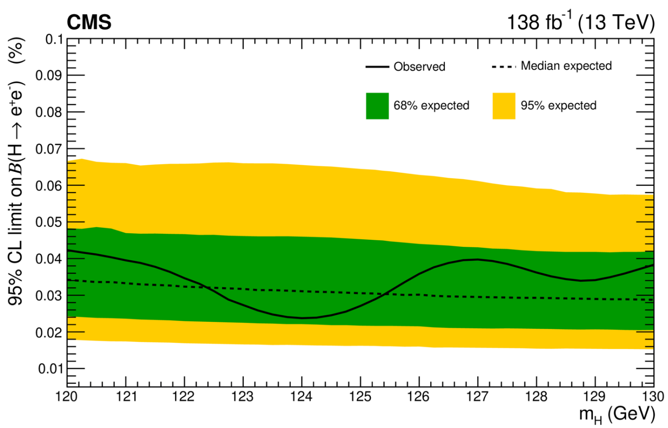


VH(bb)-VH(cc) combination confirms:

Higgs-charm-coupling < Higgs-bottom-coupling (κ_c/κ_b<4.5)

What about 1st generation couplings?

- Extremely tiny branching ratios / couplings in the SM
  - Limit setting on H→ee hand-in-hand with searches for lepton-flavour violating (LFV) Higgs decays
  - Indirect sensitivity in global combinations, H→Quarkonia, etc.

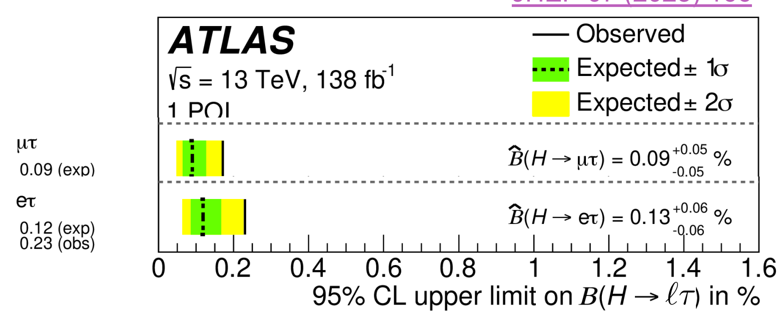


Phys. Lett. B 846 (2023) 137783

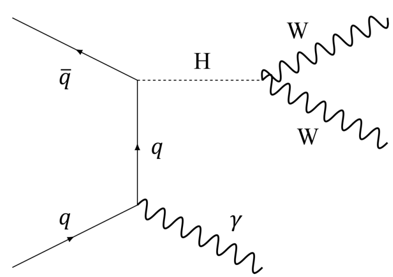
H→ee:
SM BR 5 x 10^{-9}
CMS: BR < 3.0 x 10^{-4}
ATLAS: BR < 3.6 x 10^{-4}

Phys. Lett. B 801 (2020) 135148

JHEP 07 (2023) 166



ATLAS: **LFV** decays



CMS: **H+γ production**

Process	κ_q limits obs. (exp.) at 95% CL
$u\bar{u} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	$\lvert\kappa_u\rvert \leq 16000\ (13000)$
$d\bar{d} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	$\lvert\kappa_d\rvert \leq 17000\ (14000)$
$s\bar{s} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	$\lvert\kappa_s\rvert \leq 1700\ (1300)$
$c\bar{c} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	$\lvert\kappa_c\rvert \leq 200\ (110)$

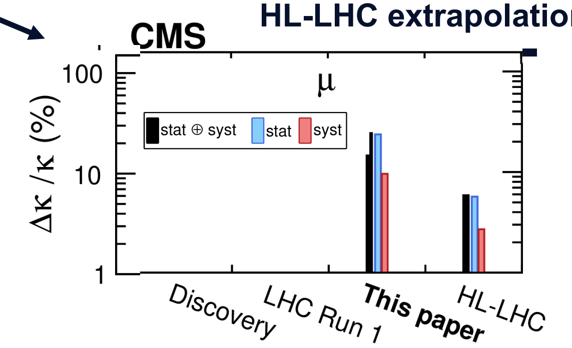
SMP-22-006

+ Setting up for the Future

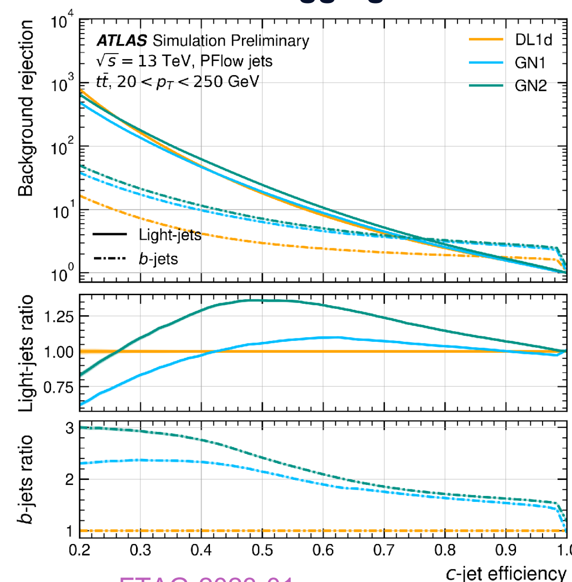
- Rare decays to leptons & bosons limited by statistical uncertainties → improve with more data
- H→cc will remain challenging
  - Great advancements in c-tagging using graph neural nets → small improvements in light-rejection go a long way ATL-PHYS-PUB-2021-039
    - Overcoming MC statistical limitations using (GNN) based statistical tagging ATL-PHYS-PUB-2022-041
  - Consider more production modes

Nature 607 (2022) 60-68

HL-LHC extrapolation



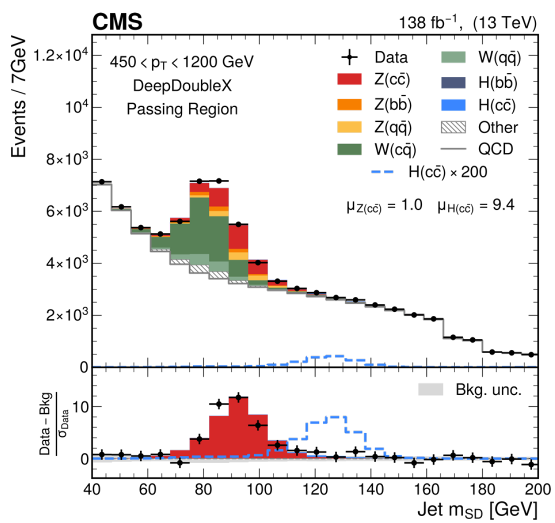
c-tagging evolution



FTAG-2023-01

CMS: Boosted all hadronic (ggF) H→cc μ<49 * SM

Phys. Rev. Lett. 131 (2023) 041801



Summary

- Rare couplings (1^{st} & 2^{nd} generation fermions) and rare decays of the Higgs boson are an active field of study

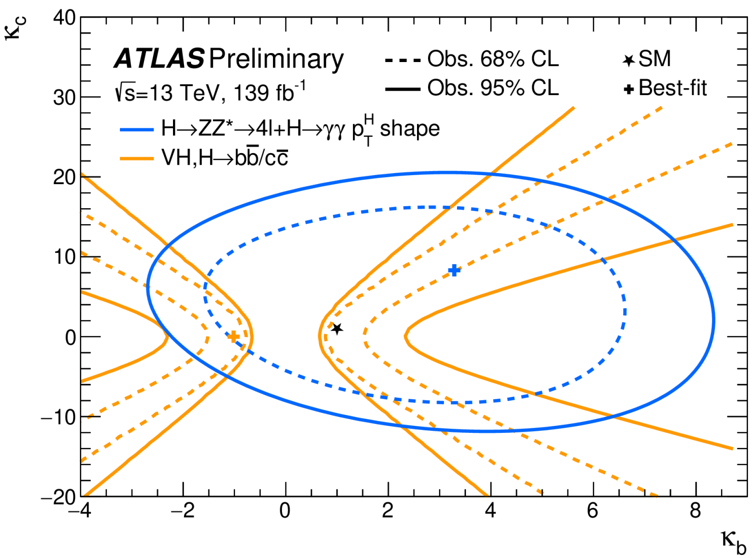
→ Important ingredient to understand Higgs-mechanism fully and probe for BSM effects in the Higgs sector

- Many experimental challenges:
  - Small expected (SM) production / decay rates
  - Reconstruction challenges (soft leptons, c-tagging, etc.)
  - Large background rates
- Many (new) channels probed in Run-2 and continuously improving experimental limits
  - In the process of laying ground-work for future analyses

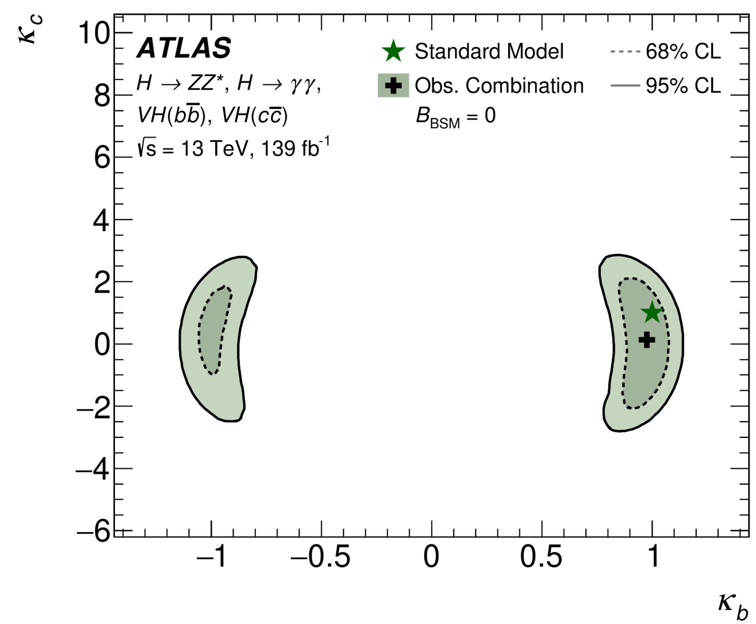
Thank you for your Attention!

Higgs-charm constraints from differential measurements

Overlay



Combination



Combining VH(bb) and VH(cc) with differential pTH measurements in H→ZZ and H→yy