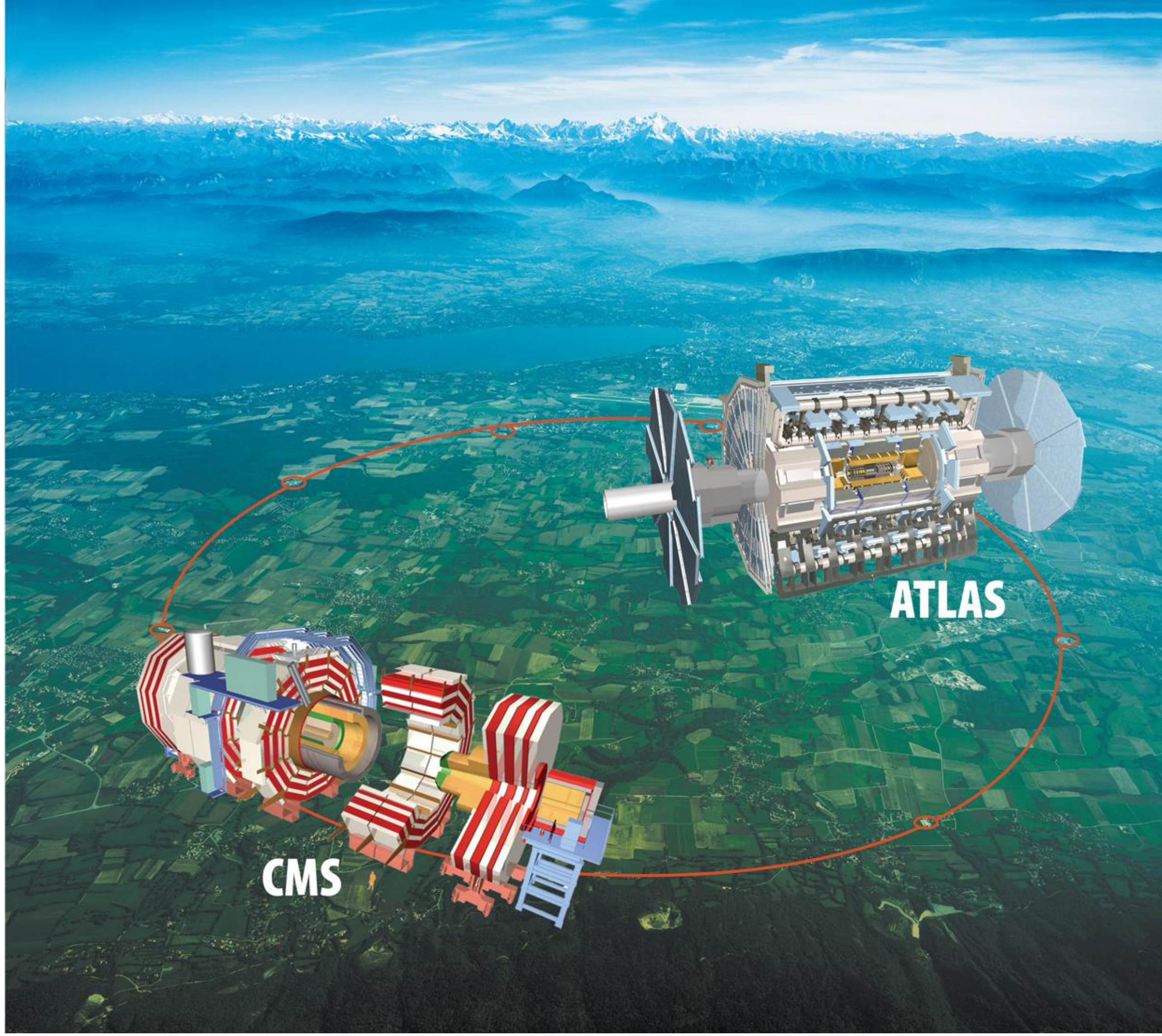
Higgs Physics in ATLAS and CMS



Rainer Mankel (DESY)
for the ATLAS + CMS collaborations

Corfu Summer Institute: Workshop on the Standard Model and Beyond,
28 Aug-7 Sep 2023, Corfu (Greece)

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Introduction

- The Higgs boson H observed in 2012 at a mass of 125 GeV gave striking support to the principle of spontaneous symmetry breaking in the electroweak theory → origin of elementary particles' masses
- Its discovery opened a rich field of research to address various questions, including:

Precise mass and dynamics of production & decay?

Do rare decay channels exist?

Anomalous couplings?

Do Yukawa interactions preserve lepton flavor?

Shape of Higgs potential?

Trilinear and quartic couplings?

Extended Higgs sector?

Outline

Matching the previous questions

- Higgs boson mass and couplings
- Rare decay H→Zγ
- Higgs boson production at very high p_T
- Differential cross sections
- Higgs pair production and self-coupling

Precision measurements of the H boson properties

- Search for resonant Higgs boson production
- Search for low-mass Higgs bosons
- Search for flavor-violating Higgs boson decays

Searches for BSM Higgs boson physics

Precision measurements of the H boson properties

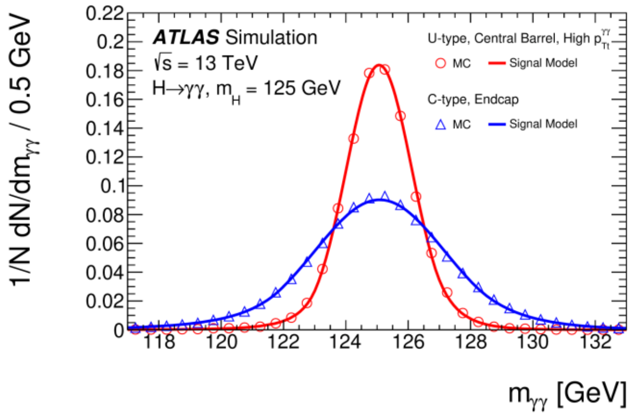
Measurement of Higgs boson mass: H→γγ

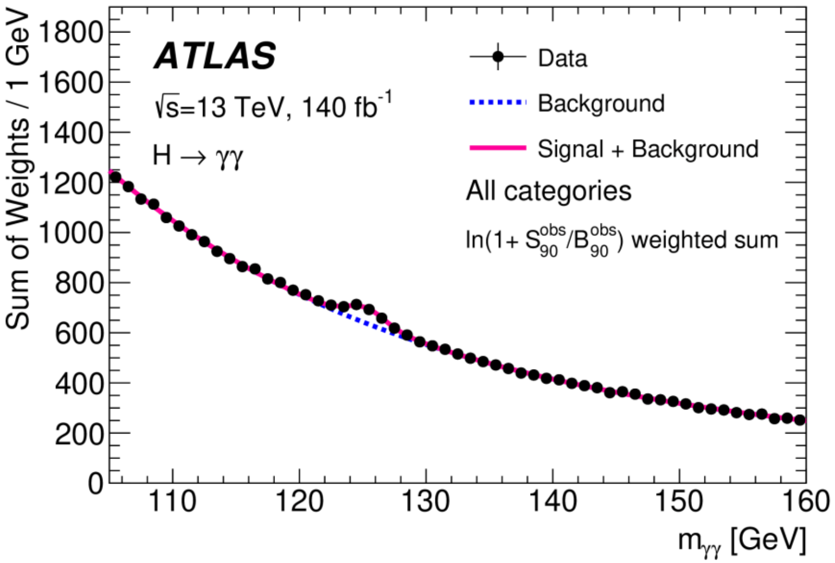
And combination with H→ 4ℓ

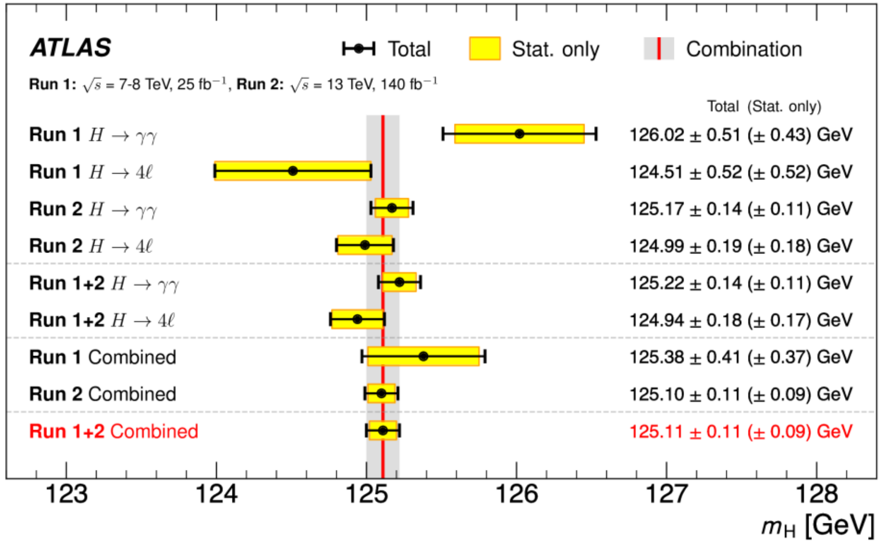
NEW!

arxiv:2308.07216 submitted to Phys.Lett. B
arxiv:2308:04775

- Precise knowledge of H mass essential e.g. for theory predictions
- Photon calibration has been dramatically improved: 320 MeV → 80 MeV systematic uncertainty







Full Run 2 result $H \to \gamma\gamma$:	$m_H = 125.17 \pm 0.11\ (stat.) \pm 0.09\ (syst.)\ GeV = 125.17 \pm 0.14\ GeV$
Combination $\mathrm{H} \to \gamma\gamma + H \to 4\ell$, Run 1+2:	$m_H = 125.11 \pm 0.09\ (stat.) \pm 0.06\ (syst.)\ GeV = 125.11 \pm \mathbf{0.11\ GeV}$

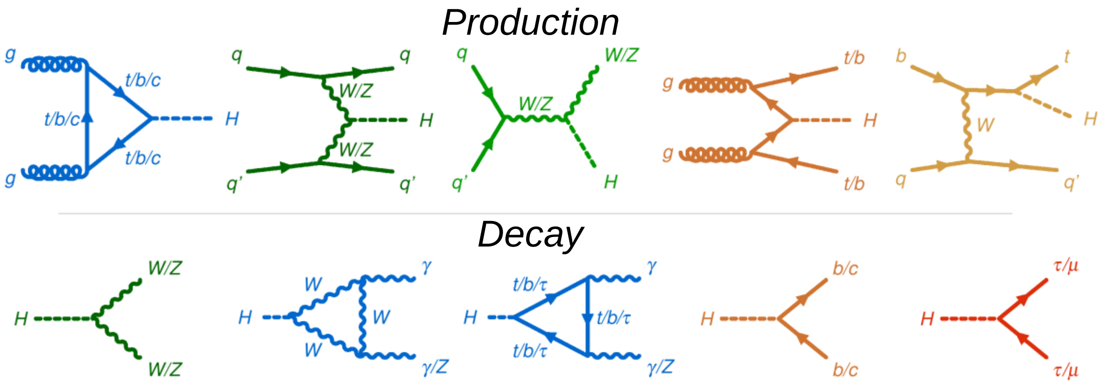
→ Most precise m_H measurement to date (0.09% precision)

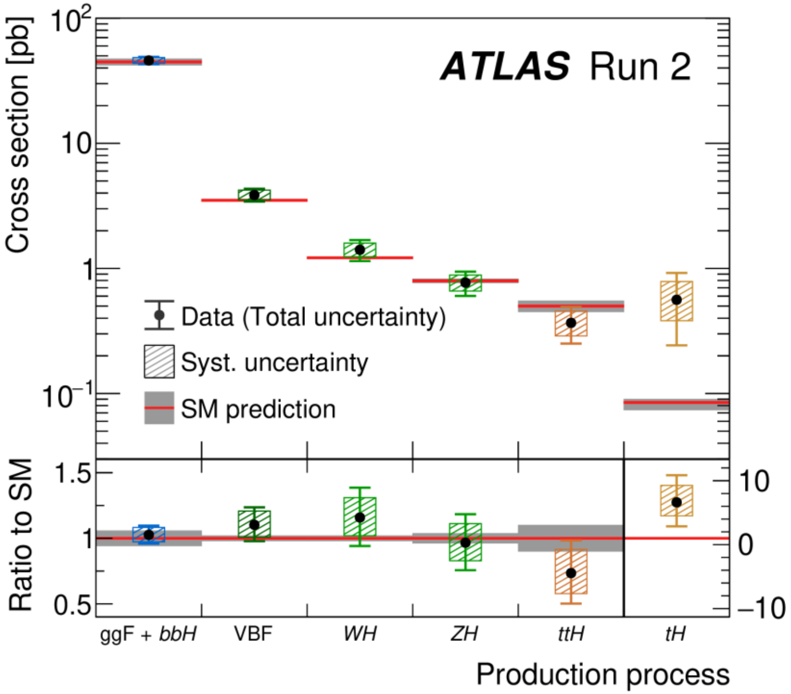
Higgs production and decay

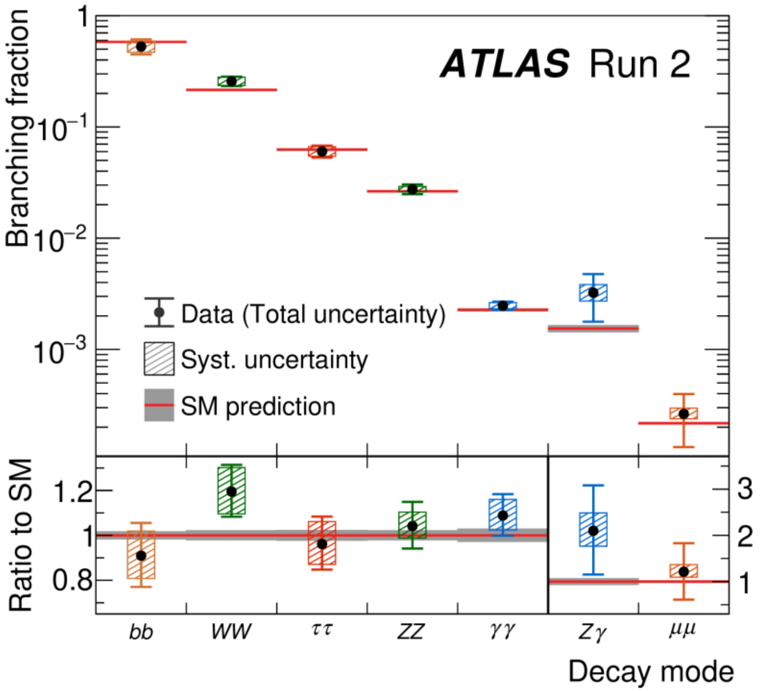
ATLAS Nature 607 (2022) 52-59

- Production and decay channels of the H boson have been intensively studied

➔ At Run 2 precision, production cross sections and decay branching fractions agree well with SM







Higgs couplings

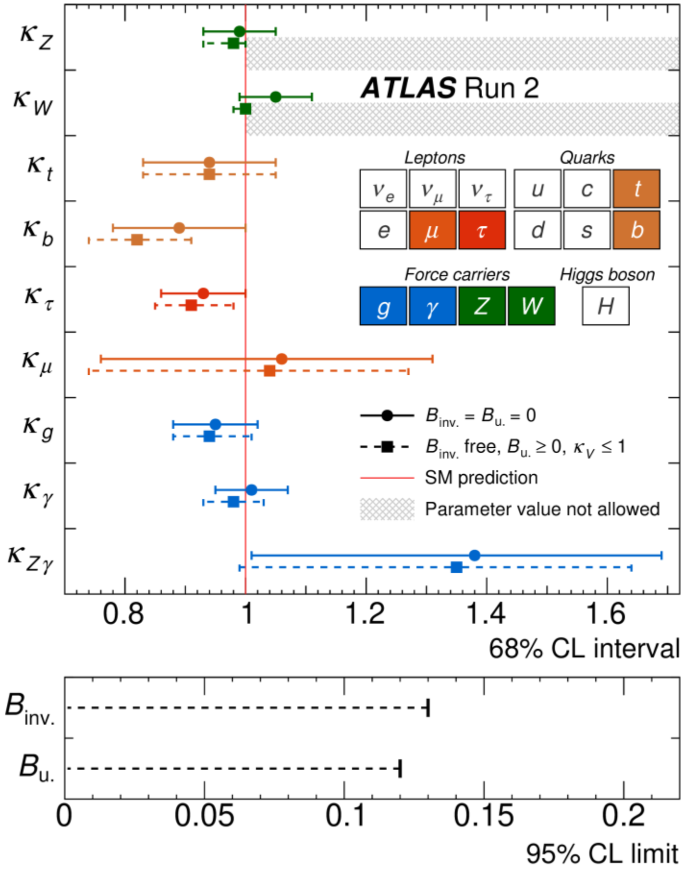
ATLAS Nature 607 (2022) 52-59

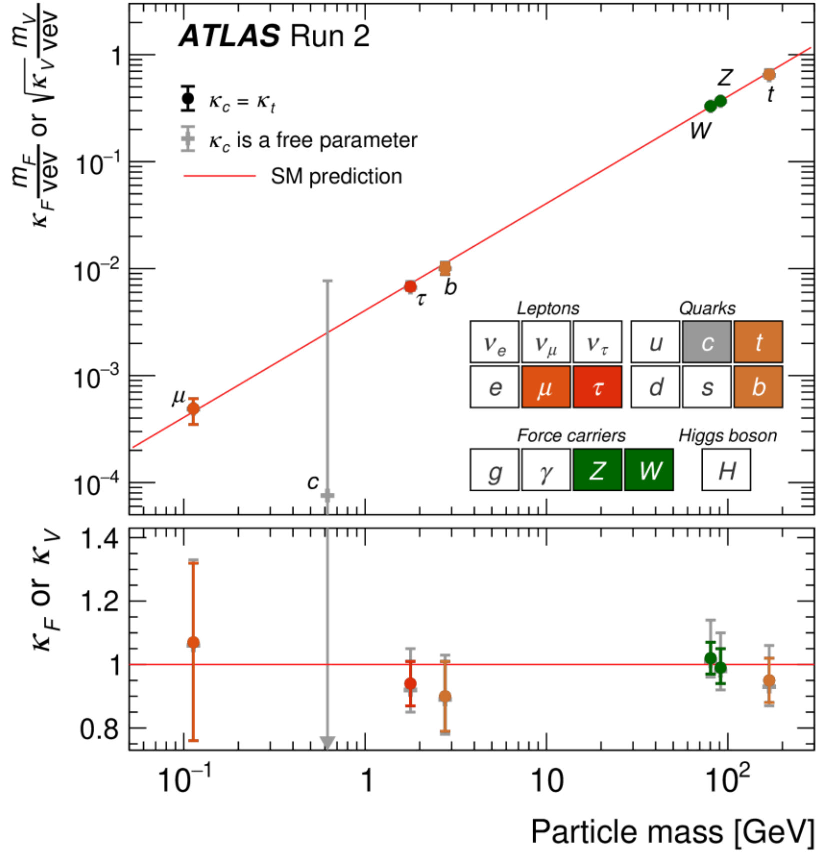
- Combination of production and decay measurements is used to determine modifiers of reduced H couplings to fermions and bosons

➔ All measured couplings agree with the SM predictions

➔ Scaling with m_F and m_V^2 as expected

➔ Strong constraints on invisible / undetectable decays of the H boson beyond the SM





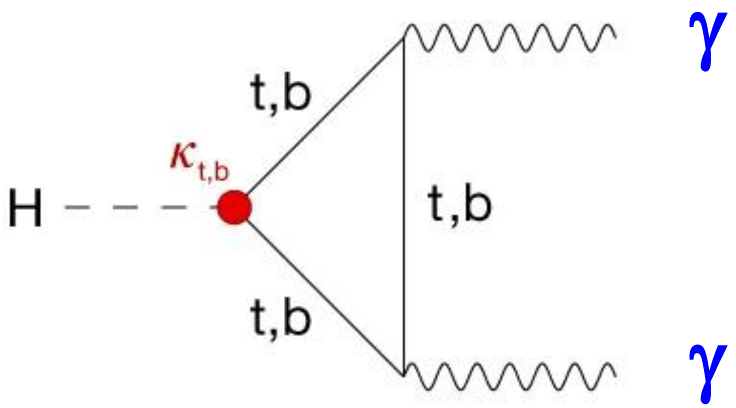
for CMS couplings results, see Nature 607 (2022) 60-68

The decay H→Zγ

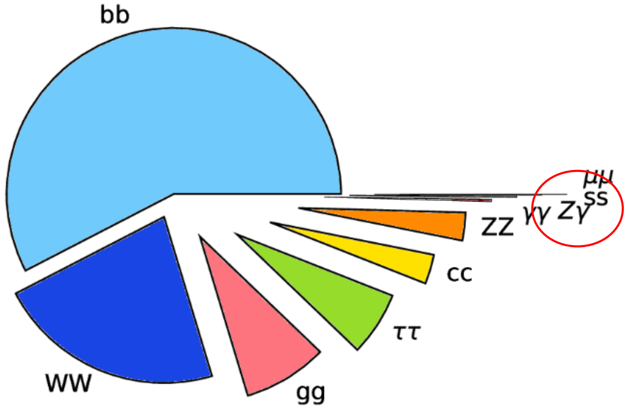
One of the rarest accessible decays

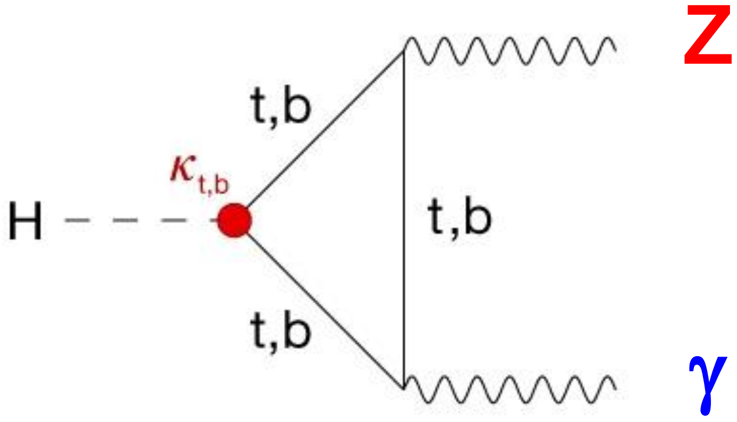
NEW!

ATLAS-CONF-2023-005
CMS PAS HIG-23-002



- SM: $B(H \to \gamma\gamma) = 2.3 \cdot 10^{-3}$
- discovered in 2012

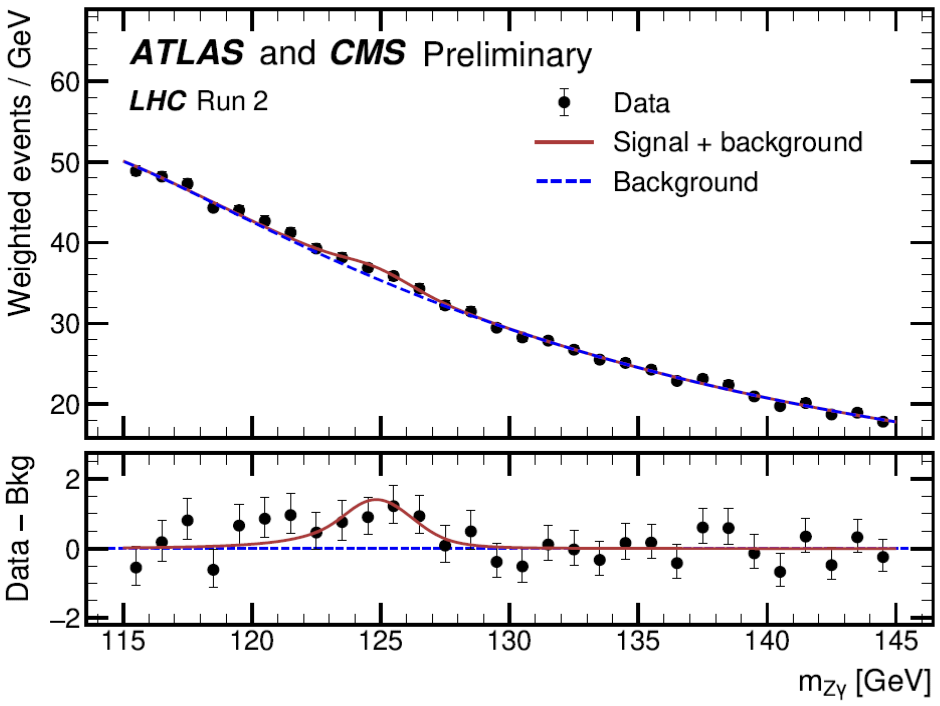


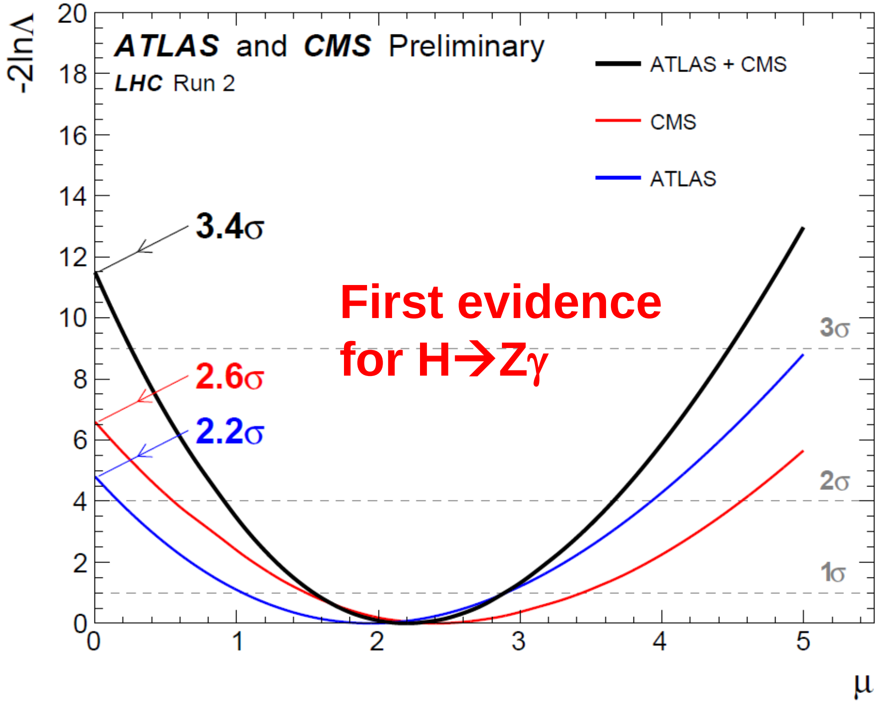


- SM: $B(H \to Z\gamma) = 1.5 \cdot 10^{-3}$
  - similar diagram
  - but $B(Z \to ee, \mu\mu)$ gives additional reduction factor of 0.066
  - ➔ more difficult to measure
- Sensitive to BSM effects which might modify the branching fraction relative to the SM

The decay H→Zγ (cont'd)

ATLAS-CONF-2023-005
CMS PAS HIG-23-002





~140 fb^{-1} per experiment!

μ = signal strength relative to SM

- Combination of analyses by ATLAS and CMS (each with $> 2\sigma$ significance)

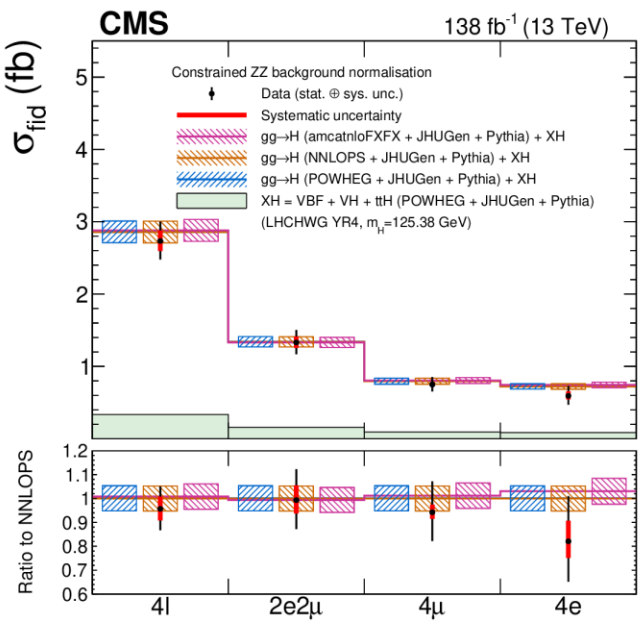
➔ Combined signal strength: $\mu = 2.2 \pm 0.7$ agrees with SM, combined significance $3.4\sigma\ obs.\ (1.6\sigma\ exp.)$

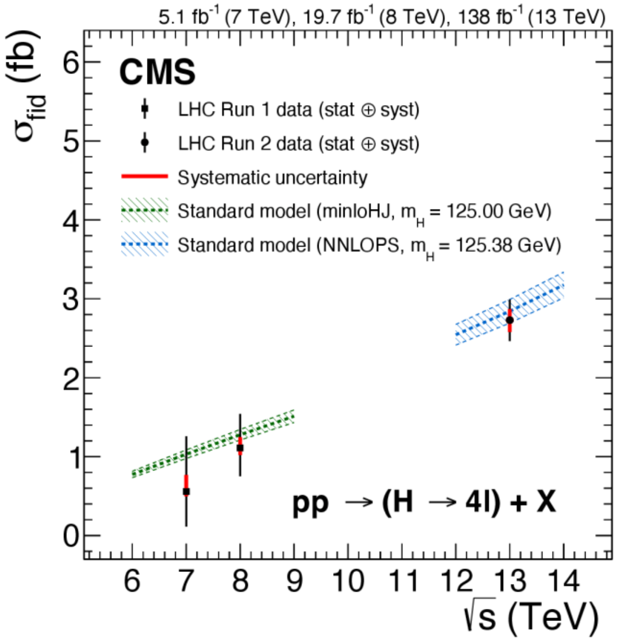
➔ First evidence for this Higgs boson decay mode

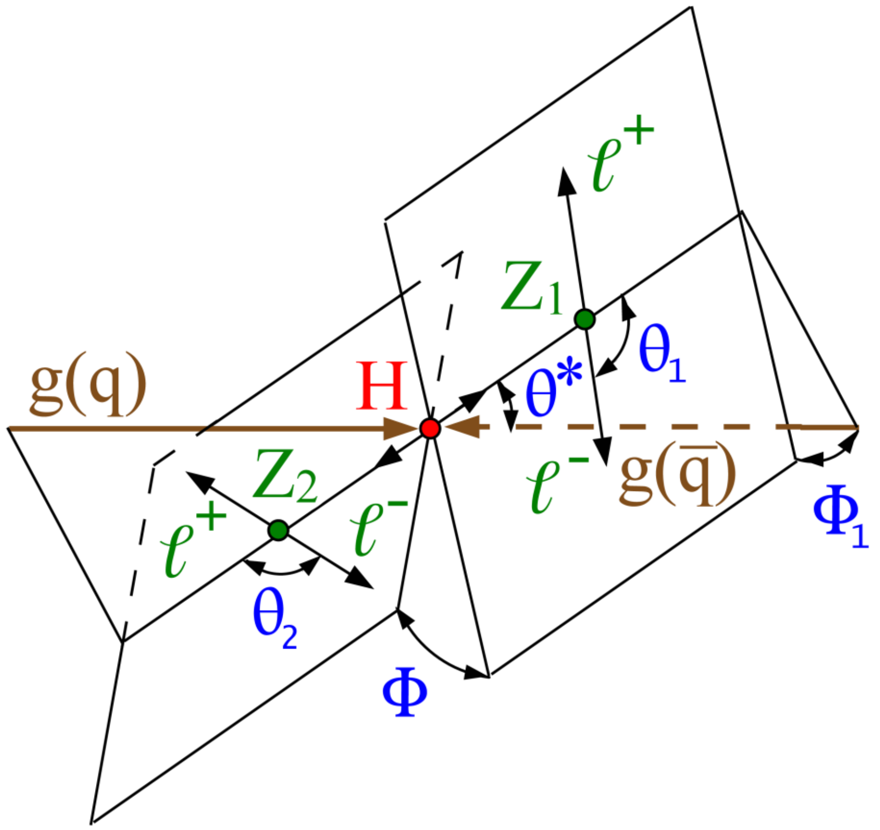
Differential cross sections in H→4ℓ

arxiv:2305.07532, accepted by JHEP

- ℓ =e, μ → Very clean signature, excellent resolution, analyzed with full Run 2 dataset
- Cross sections measured in fiducial kinematic region of detector minimize theory dependence → excellent agreement with SM



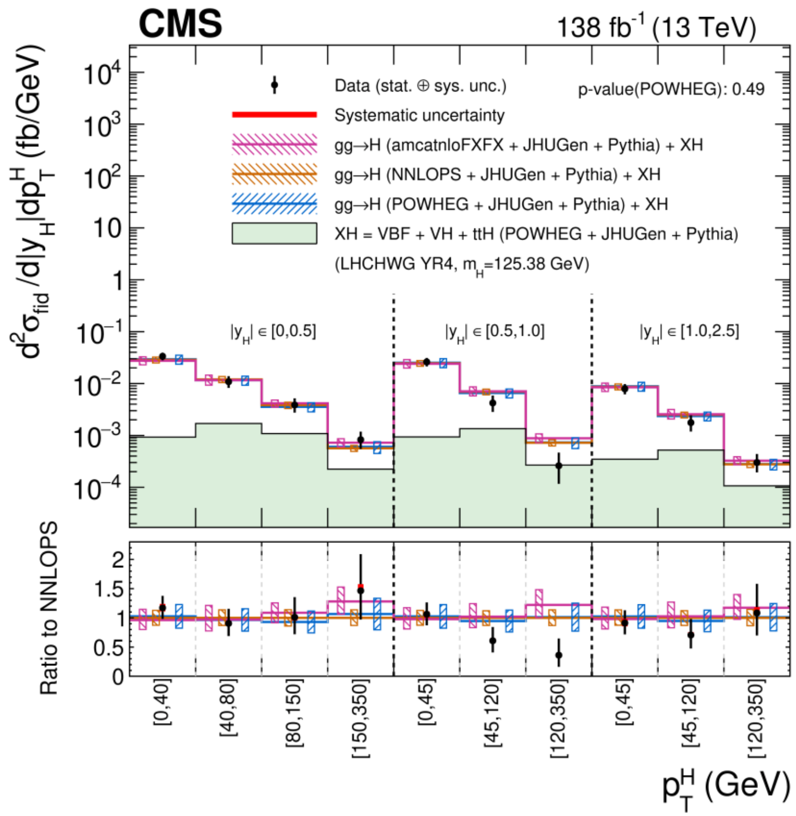


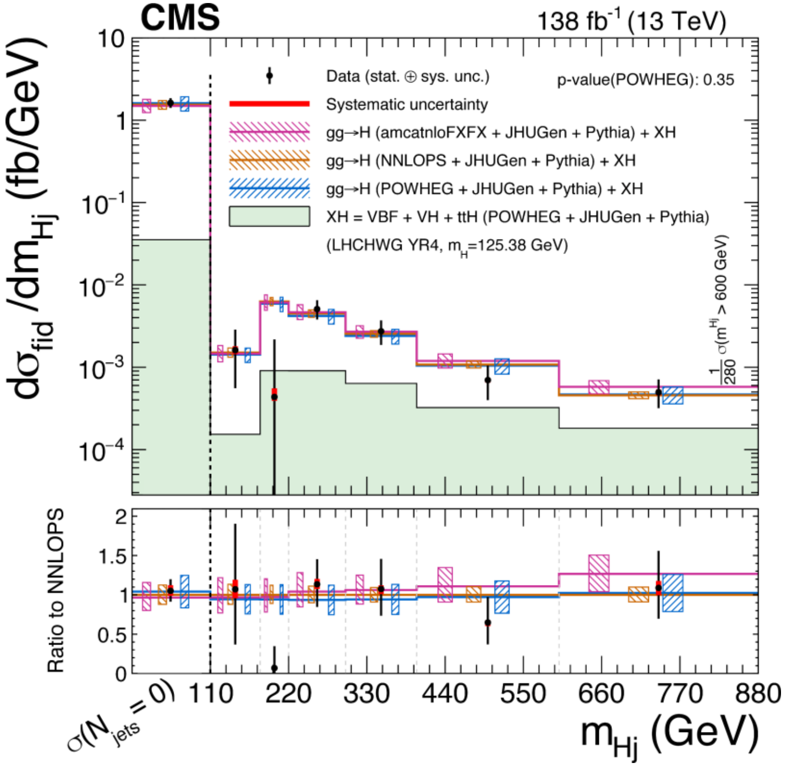


Differential cross sections in H→4ℓ (cont'd)

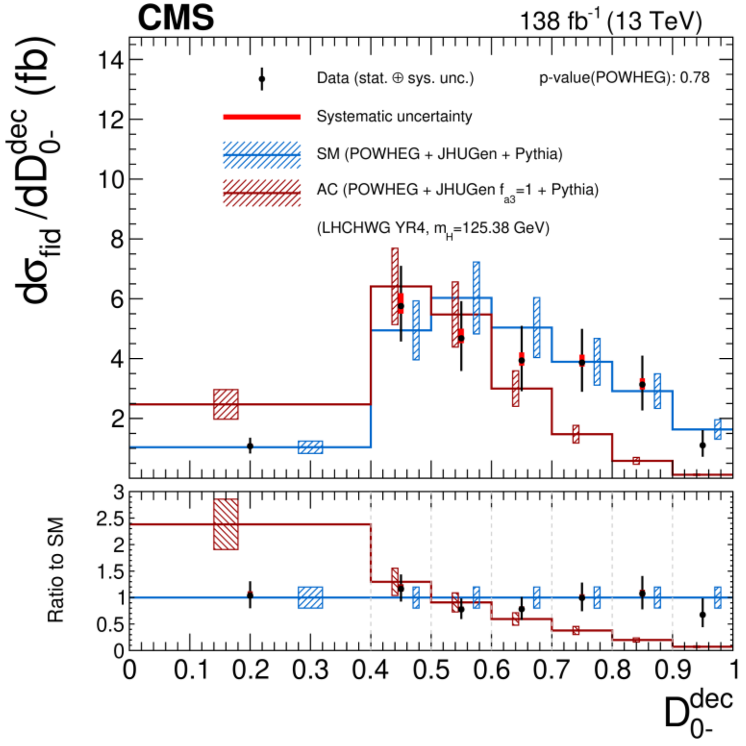
arxiv:2305.07532, accepted by JHEP

- Detailed (even double-) differential cross sections are measured, testing production models
  - ➔ dynamics of H boson and additional jets
  - ➔ constraining anomalous couplings





matrix element kinematic discriminant, sensitive to CP-odd H



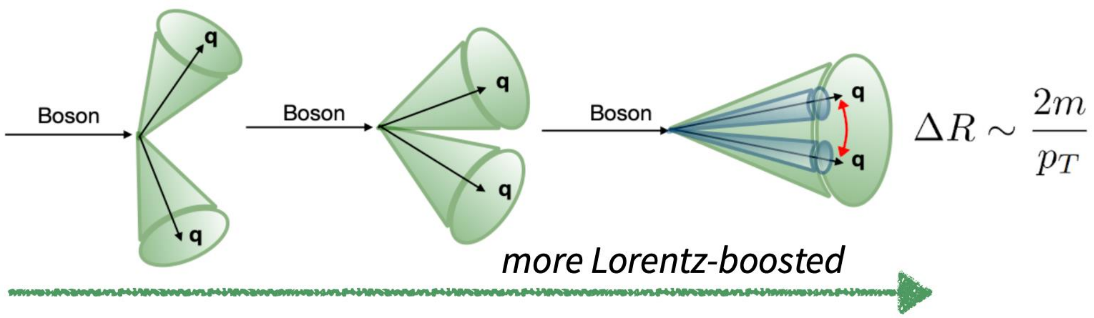
H production at very high p_T

Highly Lorentz-boosted H→ττ

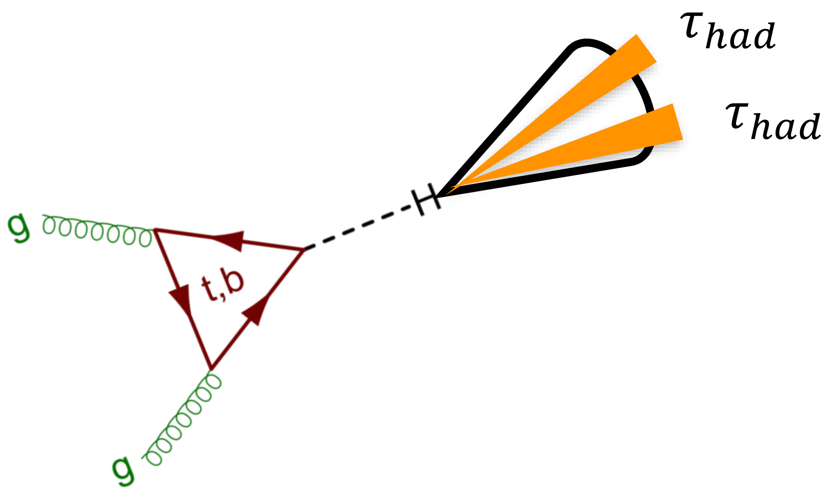
CMS PAS HIG-21-017

NEW!

- Measure H production for $p_T^H > 250\ GeV$
  - boosted topology → decay products are collimated
  - four main decay channel combinations used: $\tau_e\tau_\mu$, $\tau_e\tau_{had}$, $\tau_\mu\tau_{had}$, $\tau_{had}\tau_{had}$
  - dedicated algorithm based on substructure techniques used to separate the two τ_{had} candidates



- Resulting signal strength wrt SM: $\mu = 1.64^{+0.68}_{-0.54}$
  - ➔ in agreement with SM
  - significance: 3.5 σ (2.2 σ exp.)



➔ First measurement of highly boosted H→ττ

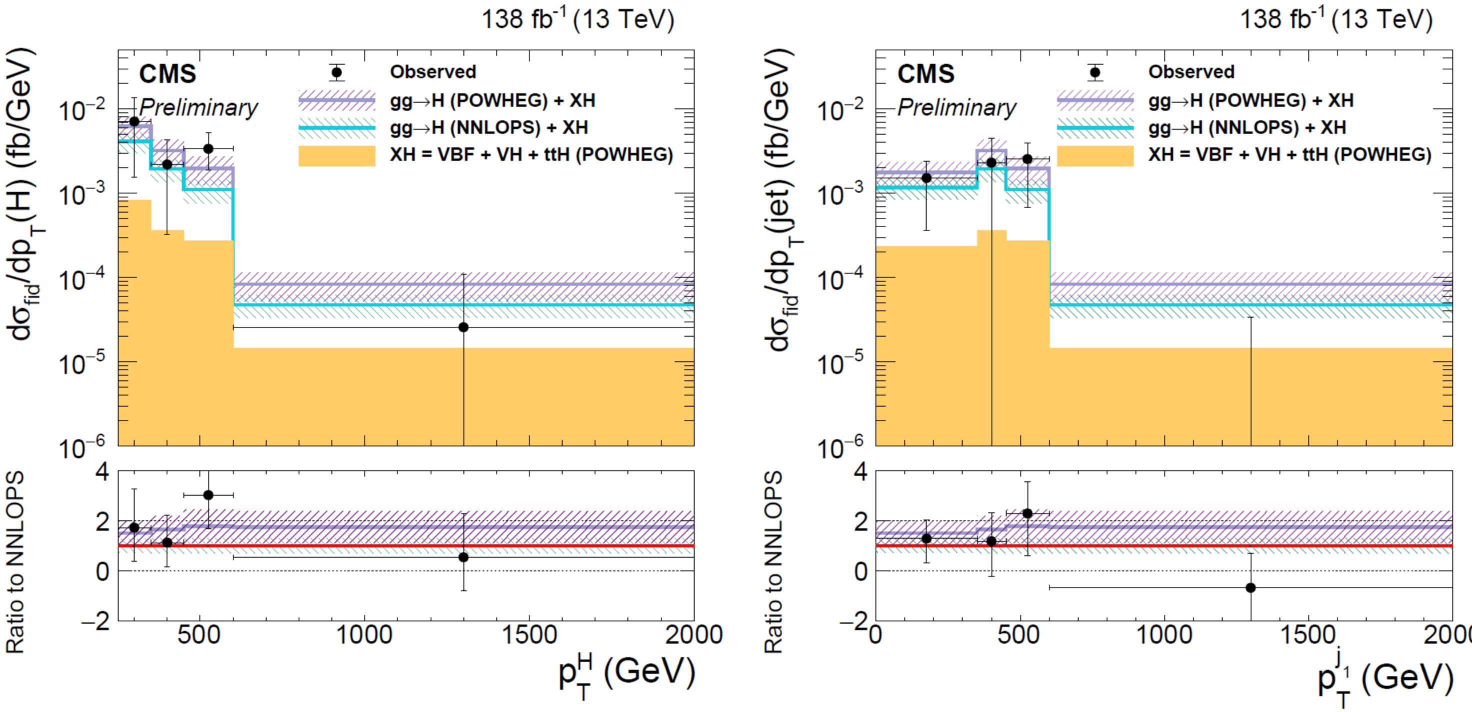
H production at very high p_T (cont'd)

Highly Lorentz-boosted H→ττ

NEW!

CMS PAS HIG-21-017

- In addition, measure fiducial differential cross sections
  - as functions of p_T^H and p_T of leading jet, four bins each



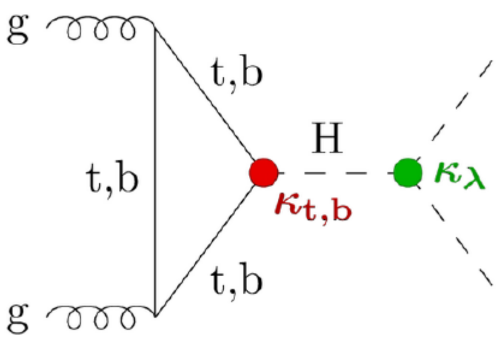
- Comparison with models (two generators for gluon fusion process)

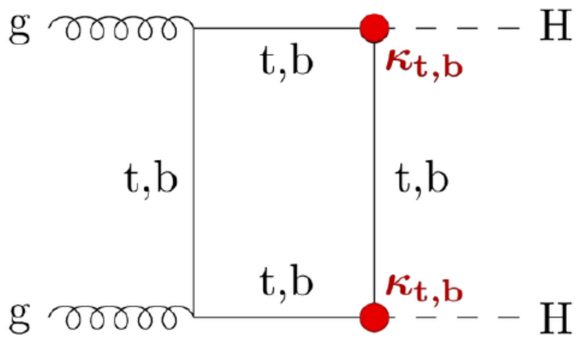
Pair production of Higgs bosons

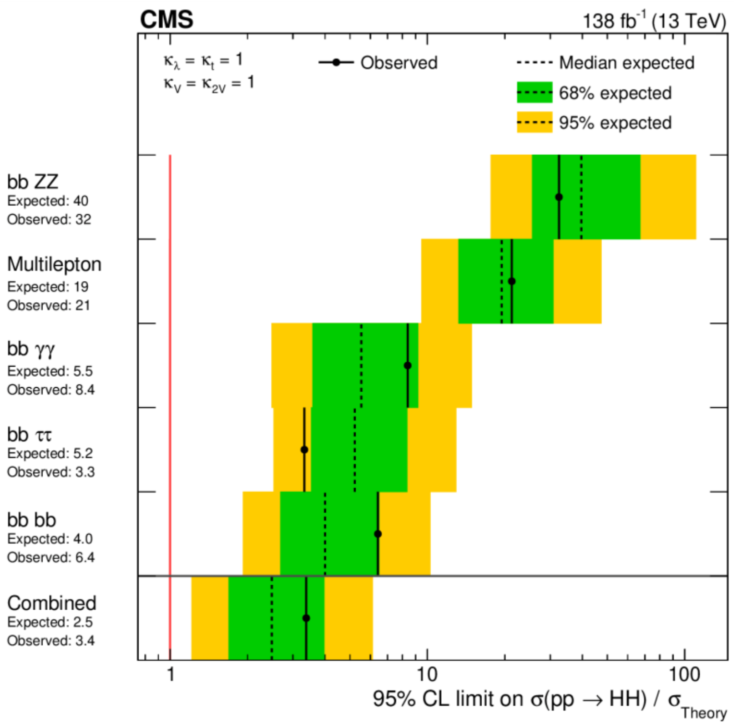
ATLAS Phys.Lett. B 843 (2023) 137745
CMS Nature 607 (2022) 60-68

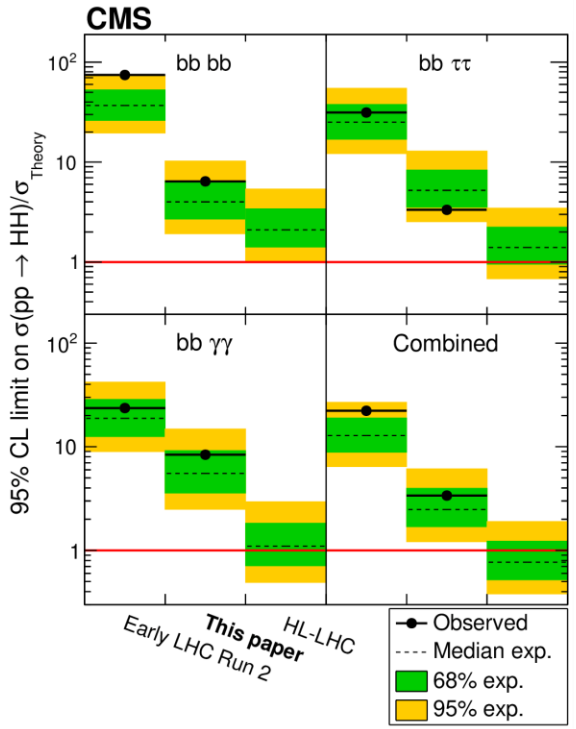
- Fundamental test of the SM
- Directly sensitive to the trilinear Higgs coupling
  - destructive interference, small cross section
- Full Run 2, σ_{HH} relative to SM:
  - $\mu_{HH} < \begin{cases} 3.4\ (2.5\ exp.)\ \ CMS \\ 2.4\ (2.9\ exp.)\ \ ATLAS \end{cases}$ $@95\%\ CL$
- Strong improvement wrt initial Run 2 results with 2016 data (35.9 fb^{-1})
  - luminosity, enhanced methodology

➔ At HL-LHC, expect to establish HH production at SM level





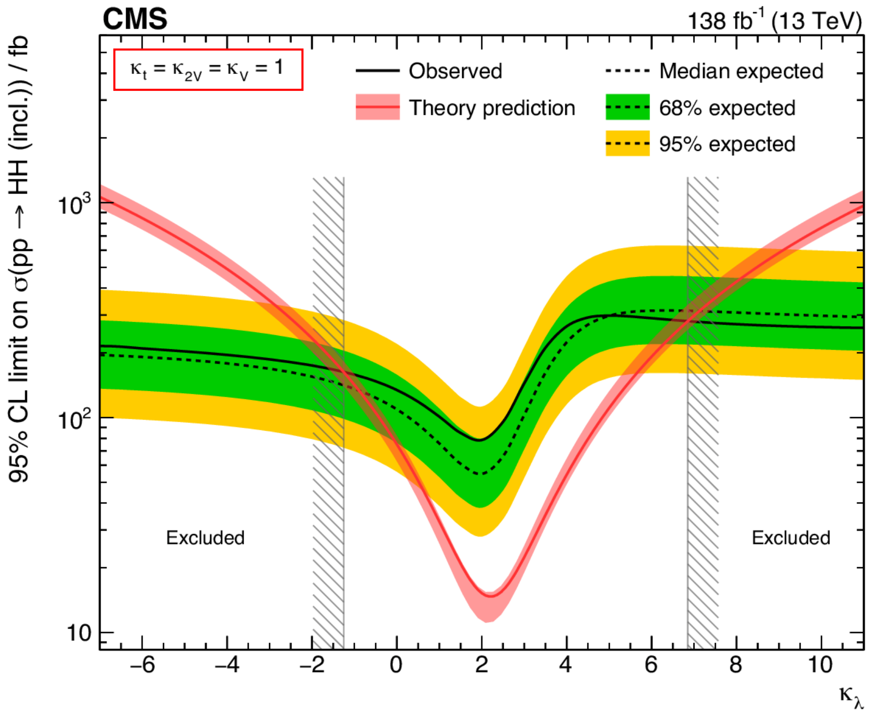


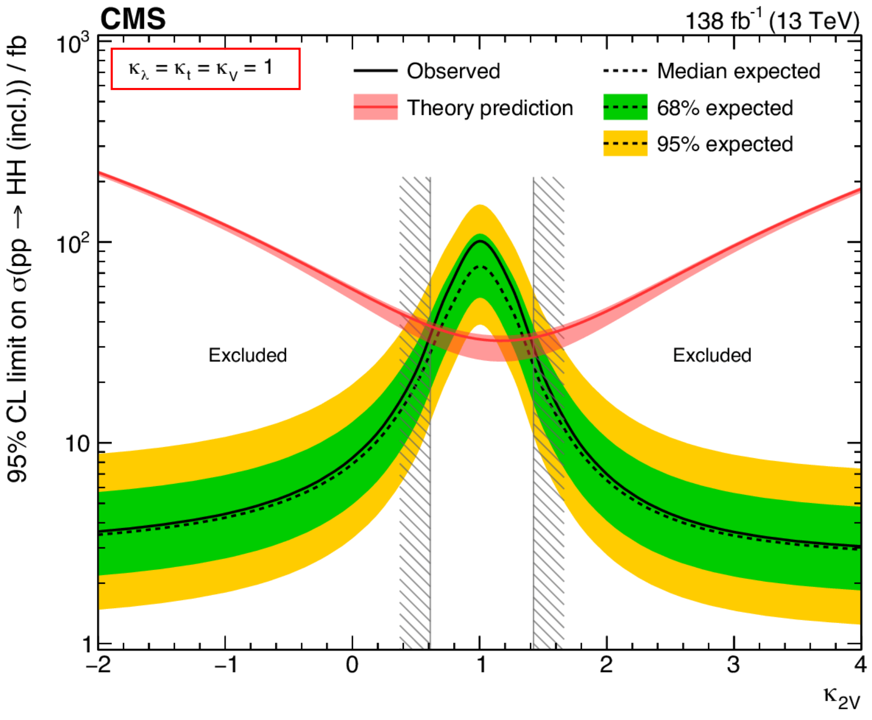


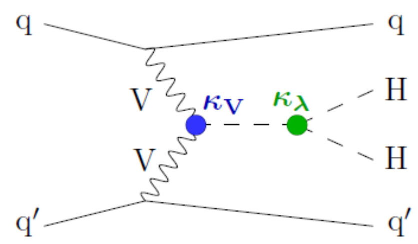
Pair production of Higgs bosons (cont'd)

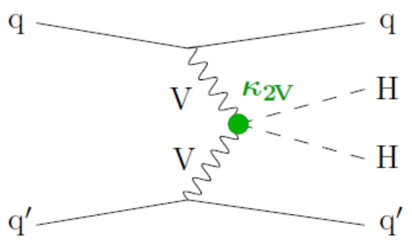
ATLAS Phys.Lett. B 843 (2023) 137745
CMS Nature 607 (2022) 60-68

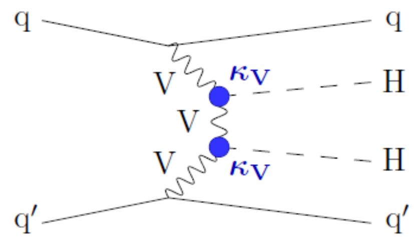
- Strong constraints on the modifier of the trilinear Higgs coupling, κ_λ
  - $-0.6 < \kappa_\lambda < 6.6$ (ATLAS), $-1.24 < \kappa_\lambda < 6.49$ (CMS), @ 95% CL
- VBF production also establishes non-zero quartic VVHH coupling at 6.6 σ
  - $0.1 < \kappa_{2V} < 2.0$ (ATLAS), $0.67 < \kappa_{2V} < 1.38$ (CMS), @ 95% CL





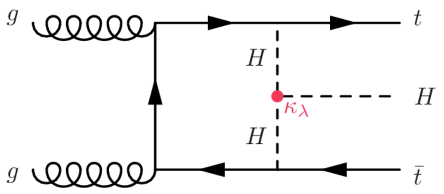


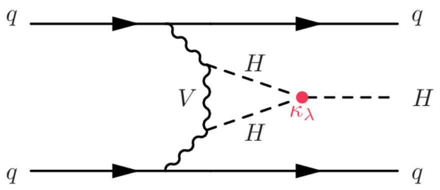


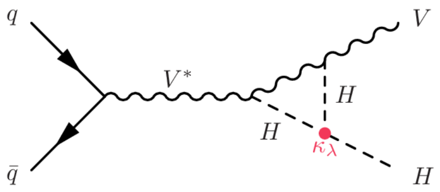


Combining single- and double-Higgs production

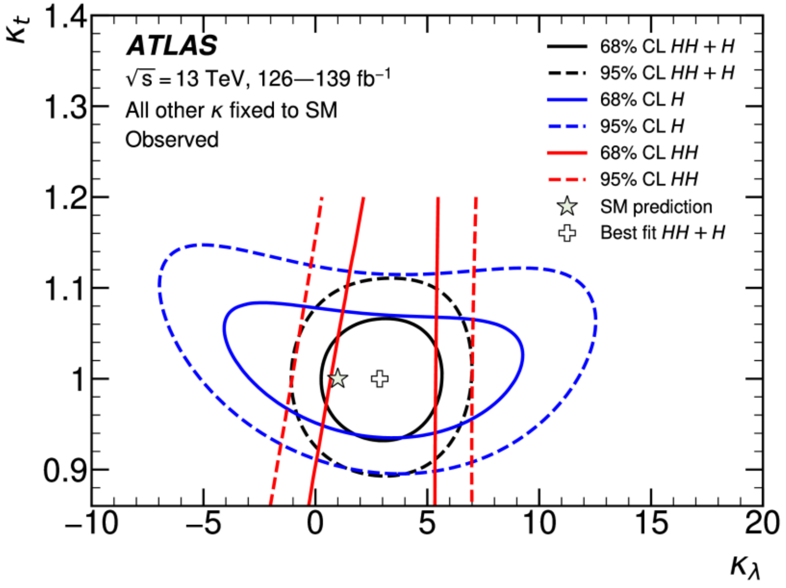
ATLAS Phys.Lett. B 843 (2023) 137745

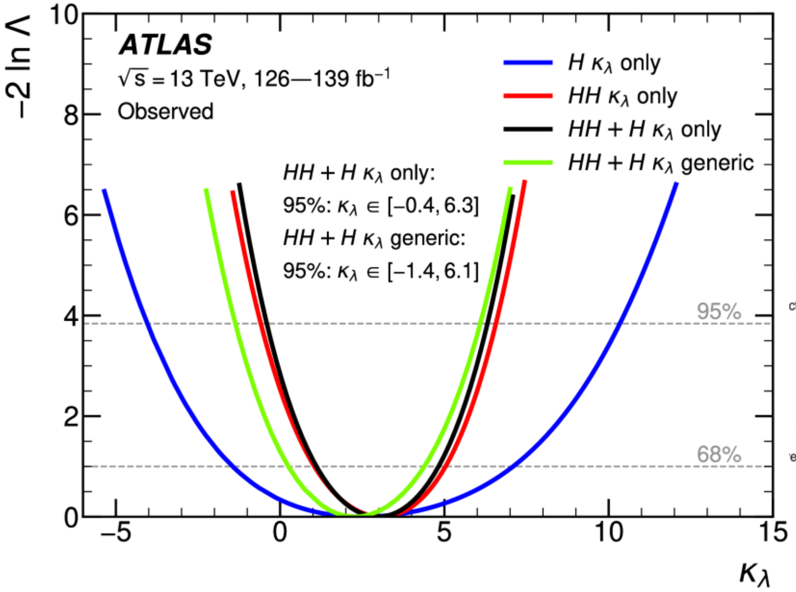




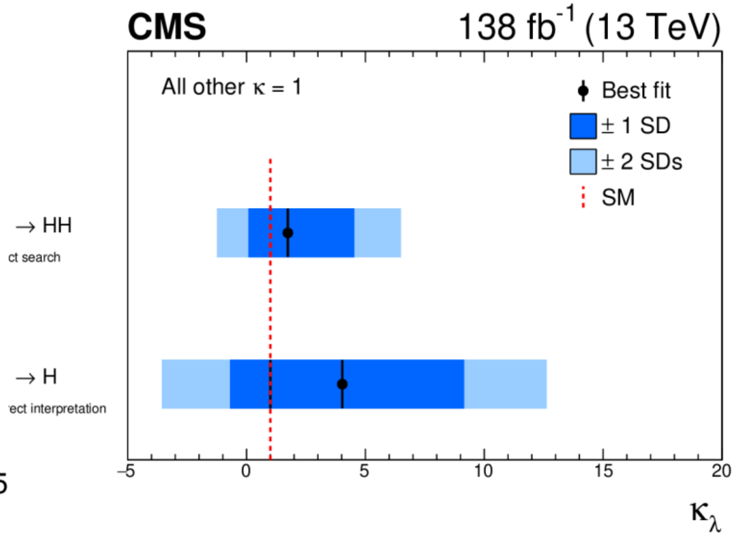


- Also single-Higgs boson production is sensitive to the trilinear Higgs coupling by means of NLO corrections
- Combined results of H + HH production (ATLAS):
  - assuming SM for all other H interactions: $-0.4 < \kappa_\lambda < 6.3$ @ 95% CL obs. ($-1.9 < \kappa_\lambda < 7.6$ exp.)
- Addition of single H analyses allows relaxing of assumptions on coupling modifiers like κ_t





CMS Nature 607 (2022) 60-68

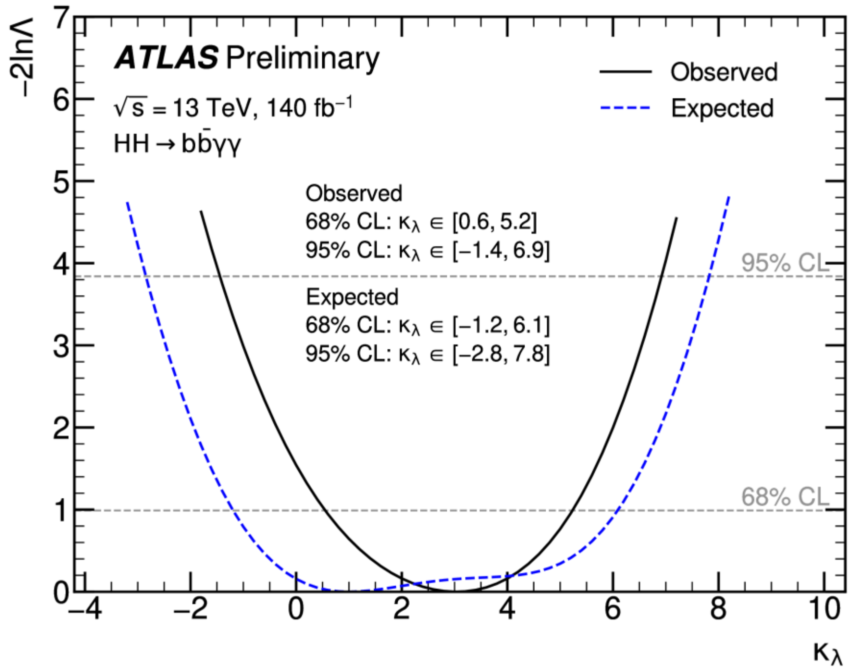


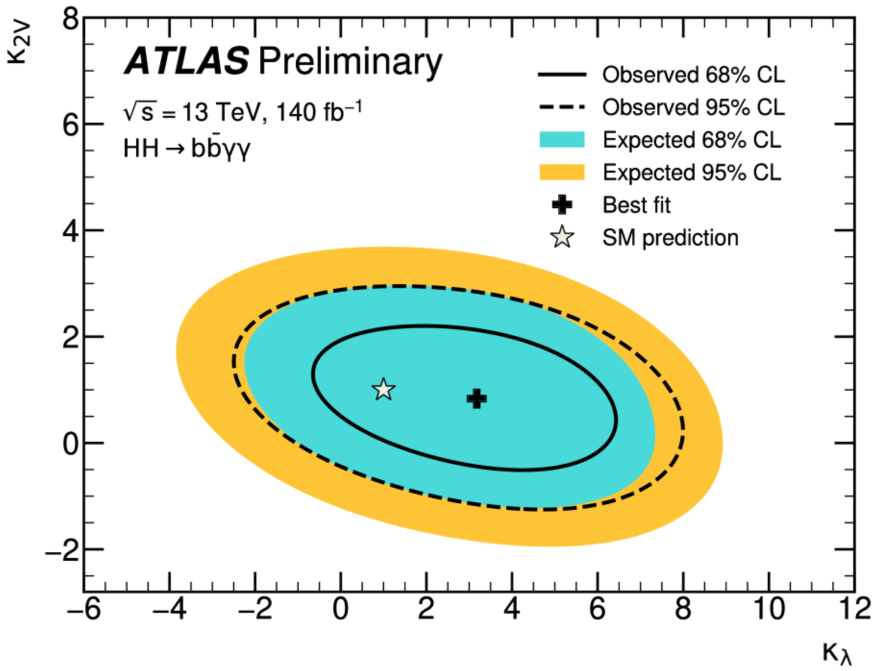
Improved search for HH in the $bb\gamma\gamma$ channel

NEW!

ATLAS-CONF-2023-050

- Supersedes and expands the previous ATLAS analysis
  - event classification based on multivariate classifier → improved sensitivity to κ_λ and κ_{2V}
  - interpretation within effective field theory (HEFT, SMEFT)





all other coupling modifiers fixed to SM predictions

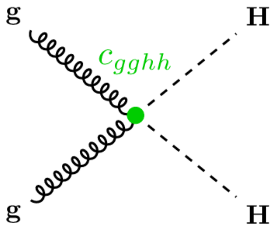
➔ $\mu_{HH} < 4.0\ (6.4\ exp.)$ at 95% CL. $-1.4 < \kappa_\lambda < 6.9$ at 95% CL

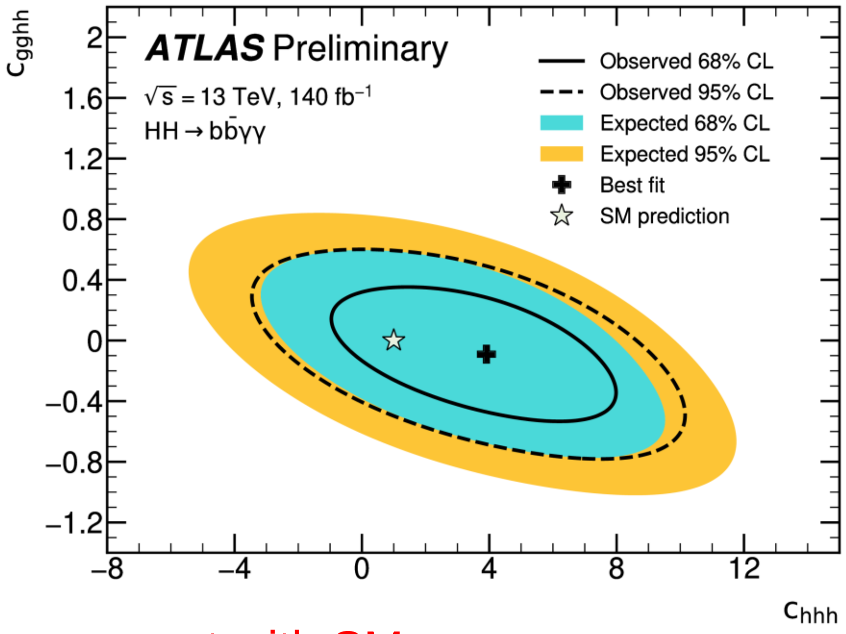
Improved search for HH in the bbγγ channel (cont'd)

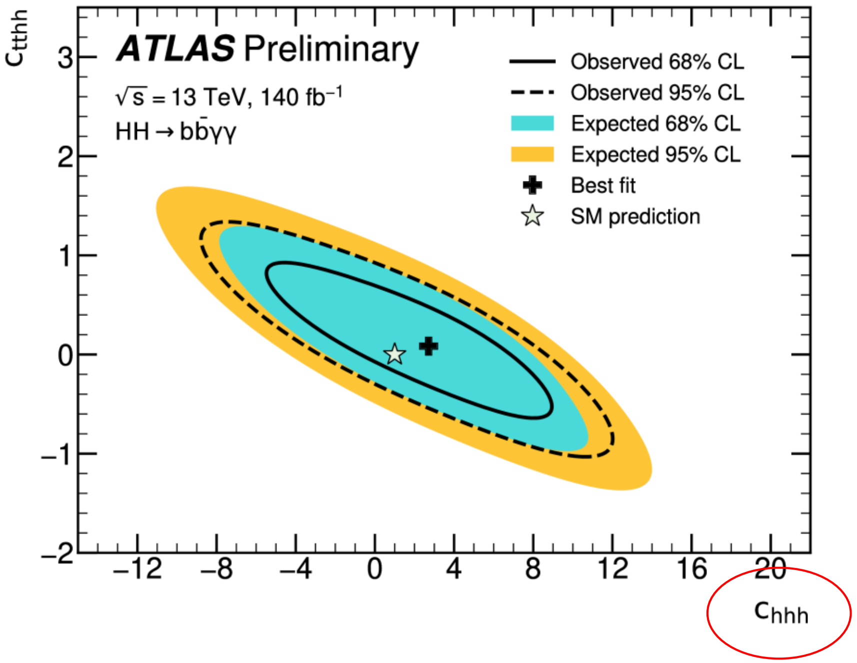
ATLAS-CONF-2023-050

NEW!

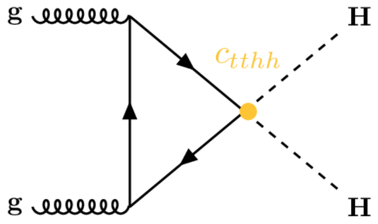
- This analysis is also used to search for anomalous contributions from extensions of the SM
  - described by Wilson coefficients of operators describing these anomalous interactions
  - here: constraints on Wilson coefficients of Higgs effective field theory (HEFT)







$\leftarrow \kappa_\lambda$



All other coefficients fixed to SM predictions

No impact on H boson production and decay at tree level

➔ Perfect agreement with SM

Searches for BSM Higgs boson physics

Higgs physics beyond the Standard Model

Only a small selection

➢ Extended Higgs sectors

- NMSSM: two Higgs doublets and one singlet
  - three CP-even (one of them H), two CP-odd and two charged Higgs bosons
- Two Higgs doublet models (2HDM)
  - two CP-even Higgs bosons (one of them H), one CP-odd and two charged Higgs bosons
  - in general, lepton flavor non-conservation possible

Signatures:

X→SH
X→HH
light scalars (m<125 GeV)

Signatures:

H→eμ, H→τμ, H→τe decays

➢ Warped extra dimensions (WED)

- heavy resonances:
  - spin 0: Radion (R)
  - spin 2: Kaluza-Klein graviton (G)

Signatures:

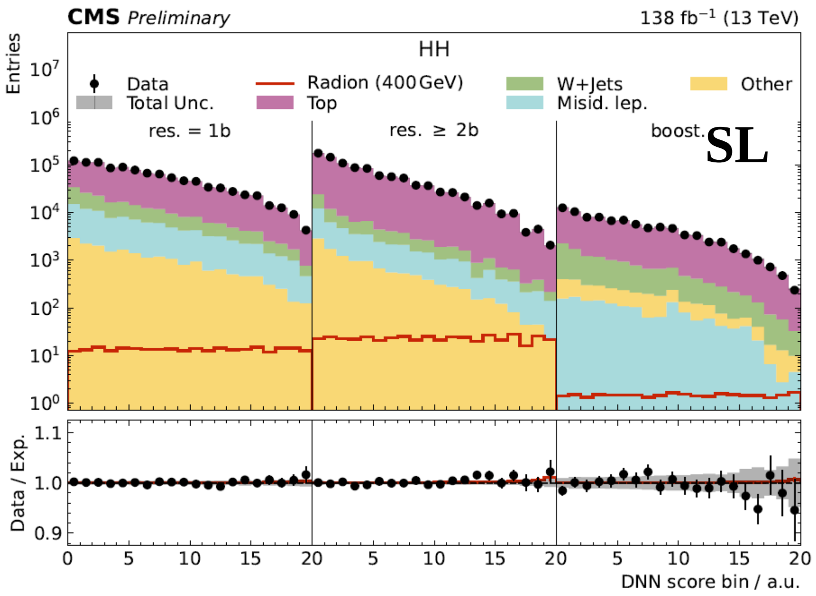
R→HH
G→HH

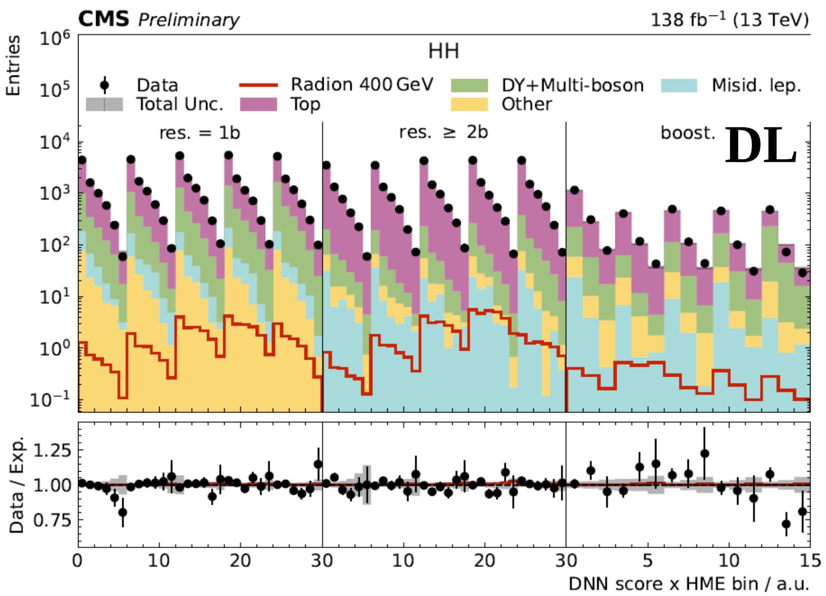
Search for X → HH → bb WW

Going beyond the "big three" (bbbb, bbγγ, bbττ)

CMS PAS HIG-21-005

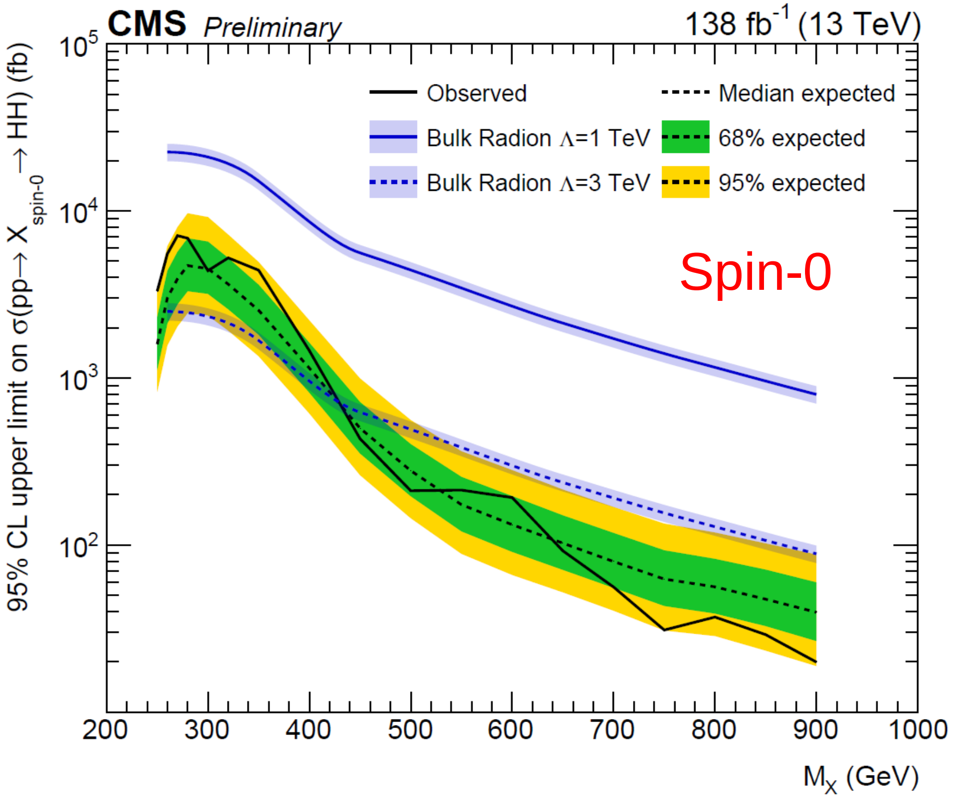
- Motivated by Warped Extra Dimensions and Extended Higgs sector models
- HH → bbWW channel has the second largest combined branching fraction
  - single-lepton $(bb\ell\nu qq)$ and di-lepton $(bb\ell\nu\ell\nu)$ final states (non-resonant analysis not shown)
- Multiclass DNN to classify events according to processes
- Signal extraction by simultaneous fit to all signal and background DNN discriminant distributions

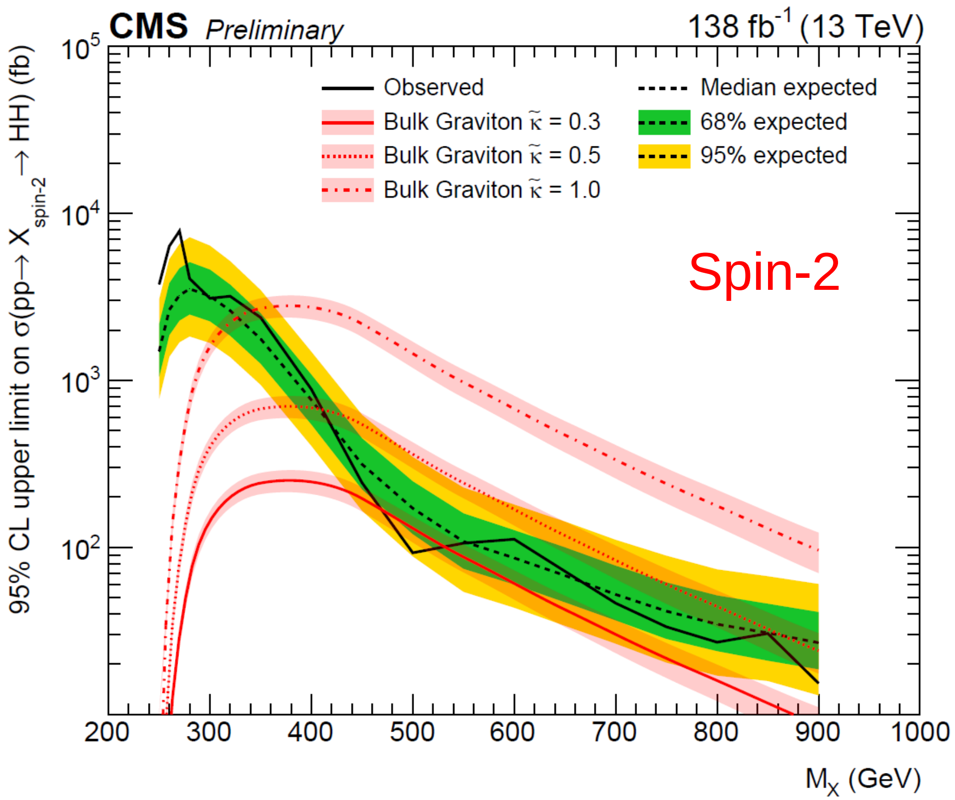




Search for X→HH→bbWW (cont'd)

- Upper limits for X → HH cross section between 250–900 GeV for spin-0 and spin-2 assumption
- Compared to warped extra dimension models (bulk radion and graviton)

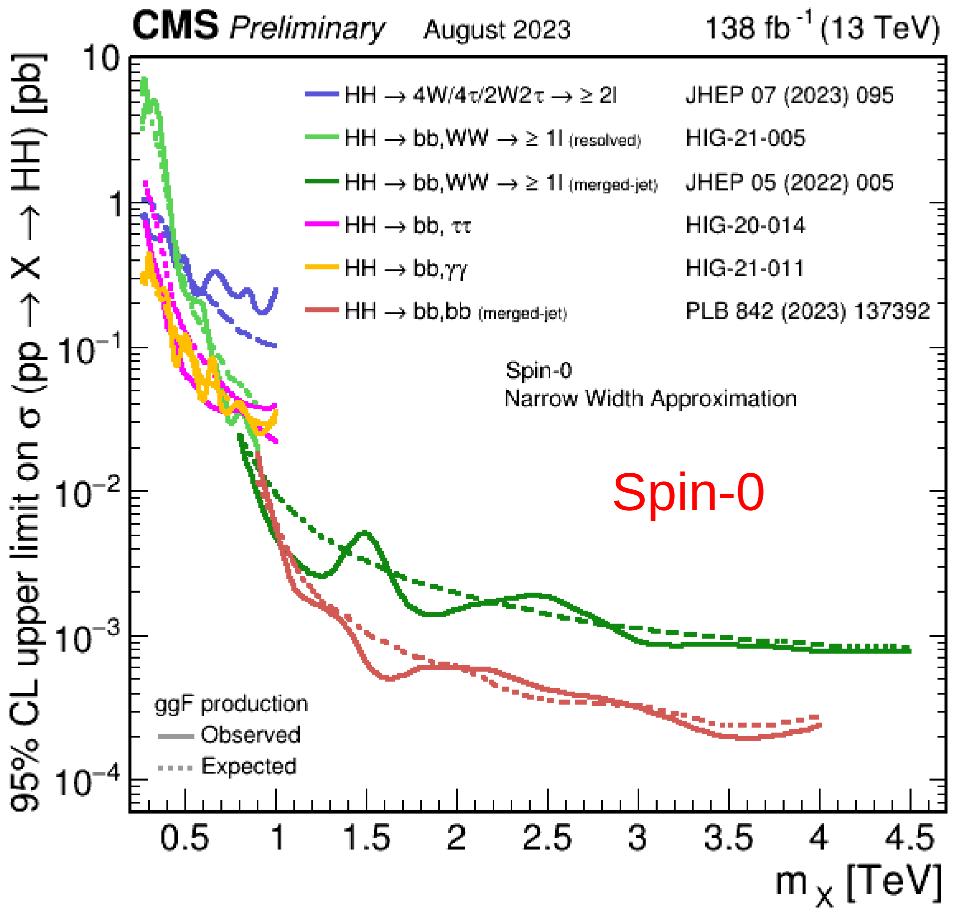


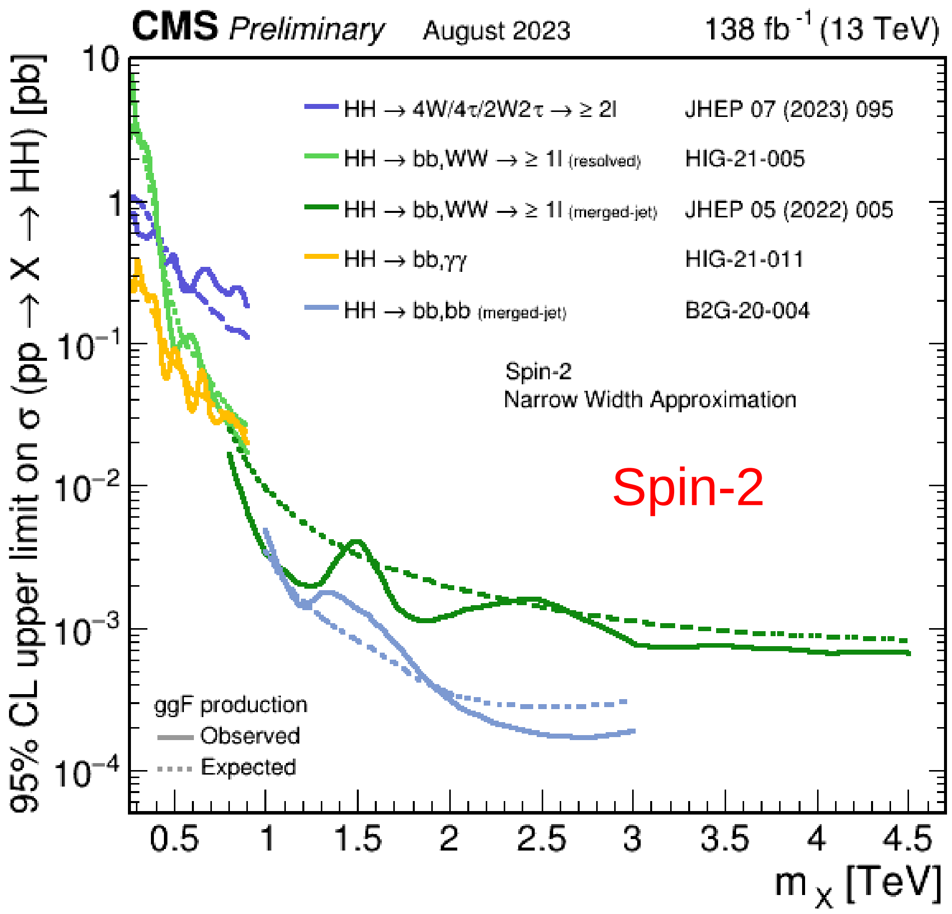


Comparison of X→HH analyses

NEW!

https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryResultsHIG



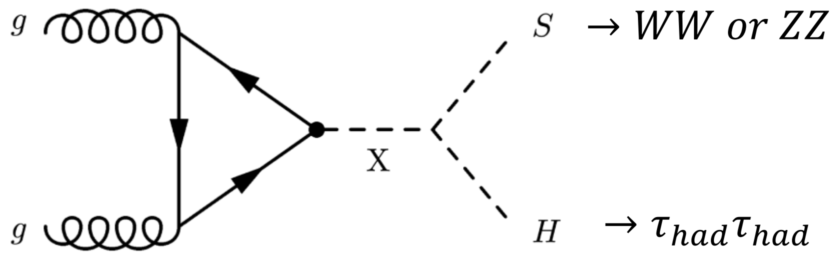


- Combination of many channels gives the best sensitivity to resonant Higgs production

Search for X → SH → VV ττ

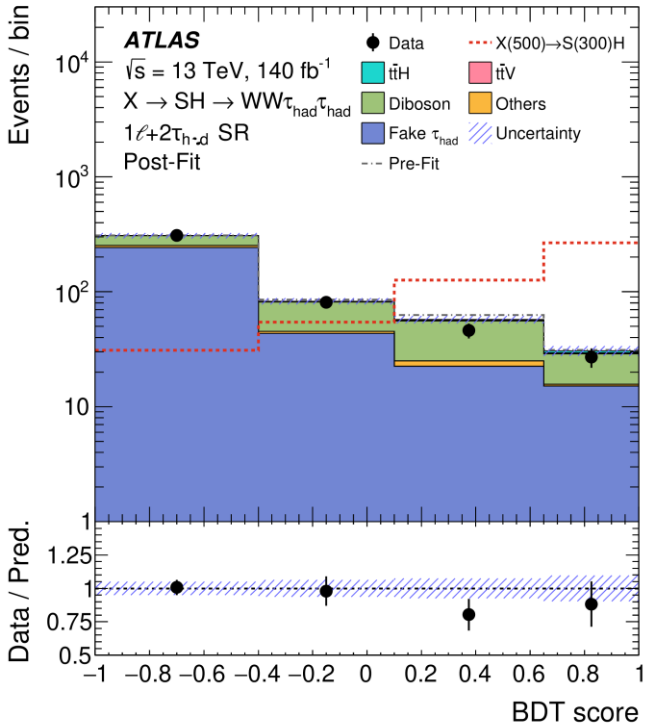
Extending to non-bb decay modes

arxiv:2307.11120

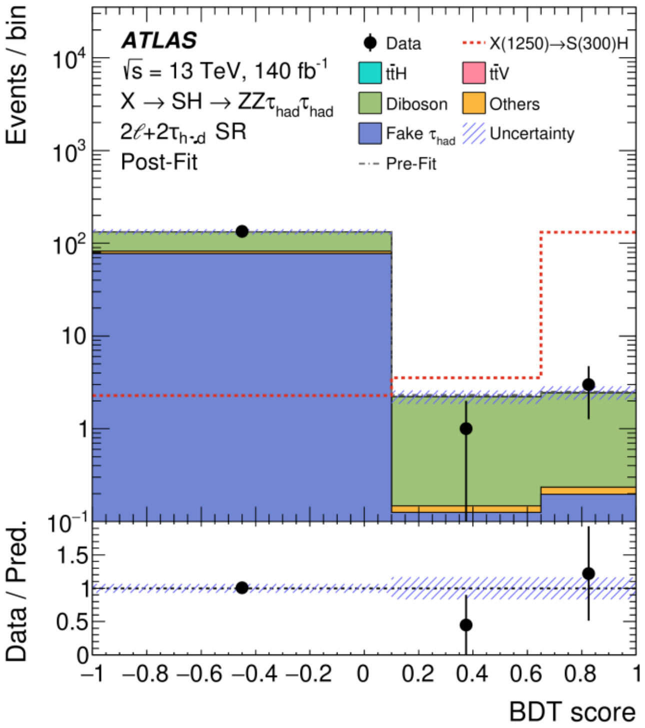


- Motivation: extended Higgs sectors (e.g. NMSSM) with additional neutral (pseudo-) scalars X and S
- Signature:
  - $H \rightarrow \tau_{had}\tau_{had}$
  - $S \rightarrow WW \; or \; ZZ$, with 1-2 leptons in final state
- Three signal regions: $WW \; 1\ell \; 2\tau_{had}$, $WW \; 2\ell 2 \; \tau_{had}$, $ZZ \; 2\ell \; 2\tau_{had}$
- BDTs to separate signal and background
  - 12 BDTs parametric in m_X (one per signal region and S mass point)
- Combined signal extraction from all BDT score distributions per (m_X, m_S) point

m_X=500 GeV, m_S = 300 GeV



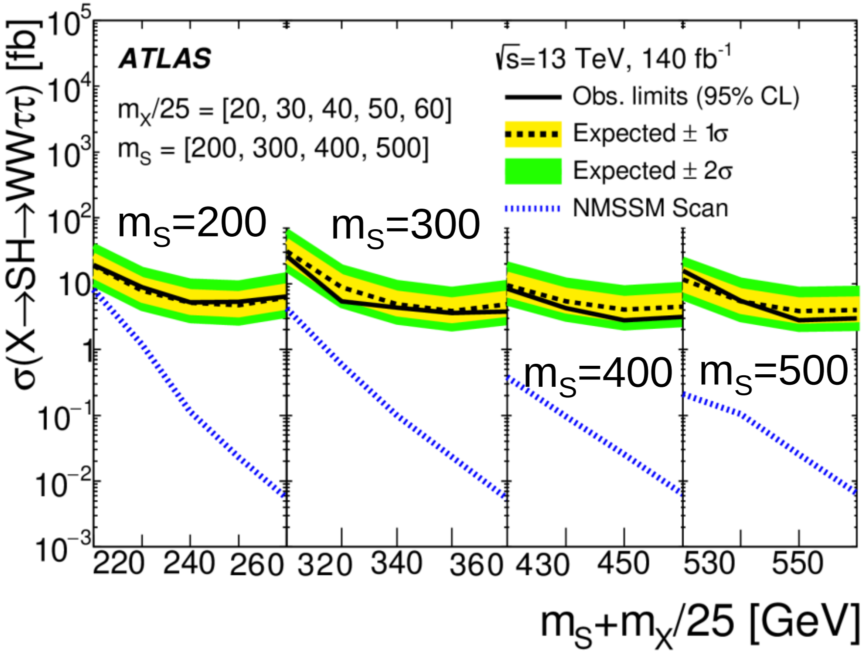
m_X=1250 GeV, m_S = 300 GeV

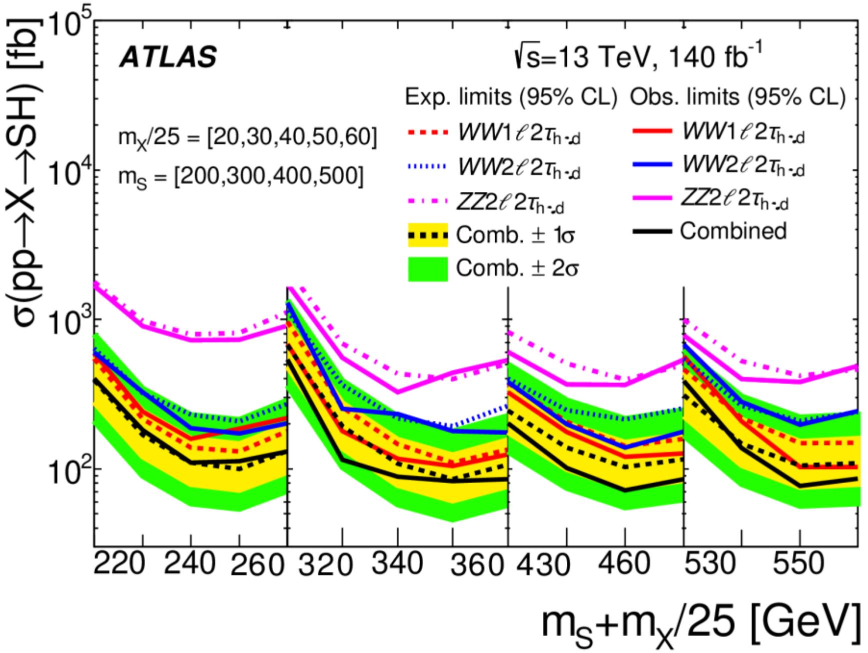


Search for X → SH → VV ττ (cont'd)

arxiv:2307.11120

- B(S→VV) are not known. Assume values of SM H boson at this mass → large
- Unrolled upper limits from (m_X, m_S) space





→ No significant excess seen at any mass combination. Most sensitive category: $WW\ 1\ell\ 2\tau_{had}$

→ Approaching the maximally allowed NMSSM cross sections

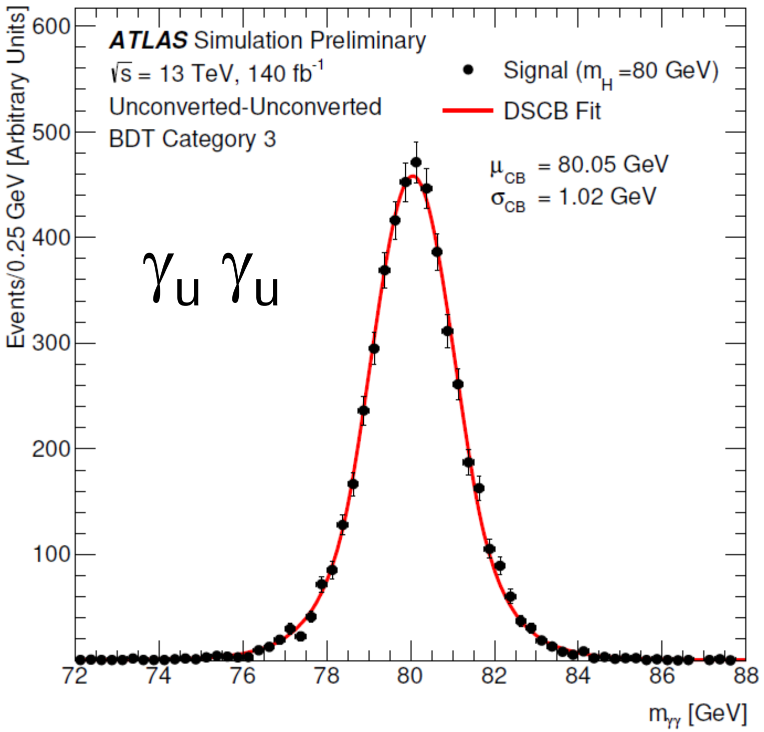
Search for low-mass Higgs bosons

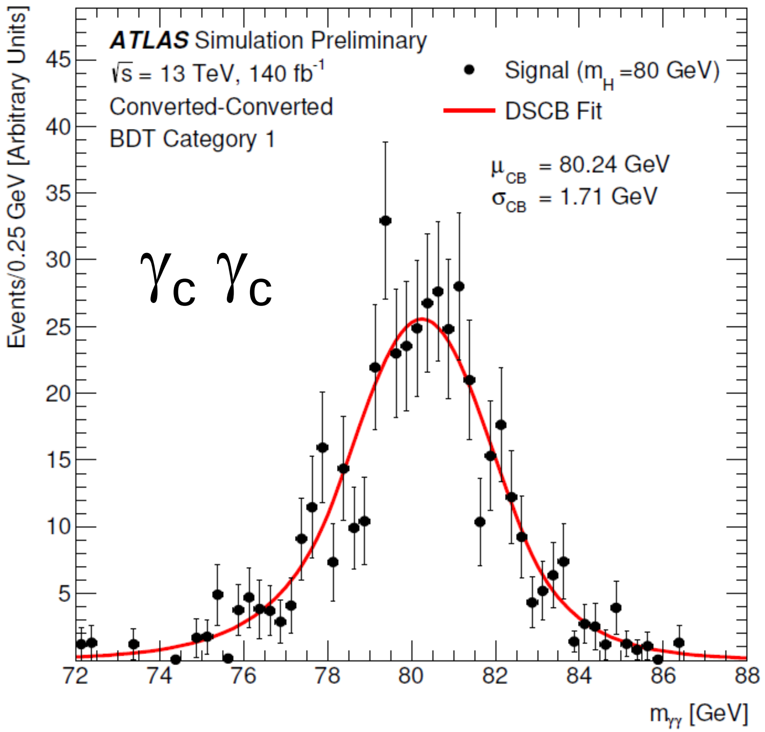
H → $\gamma\gamma$

NEW!

ATLAS-CONF-2023-035

- Extended Higgs sectors might contain additional spin-0 bosons with m<125 GeV
  - could manifest themselves in the $\gamma\gamma$ channel
- Due to the material between interaction point and electromagnetic calorimeter, a significant fraction of the photons convert to e^+e^- pairs
  - energy resolution
  - more difficult separation from electrons
- Important aspect:
  - background from Drell-Yan production (Z→e^+e^- decays)



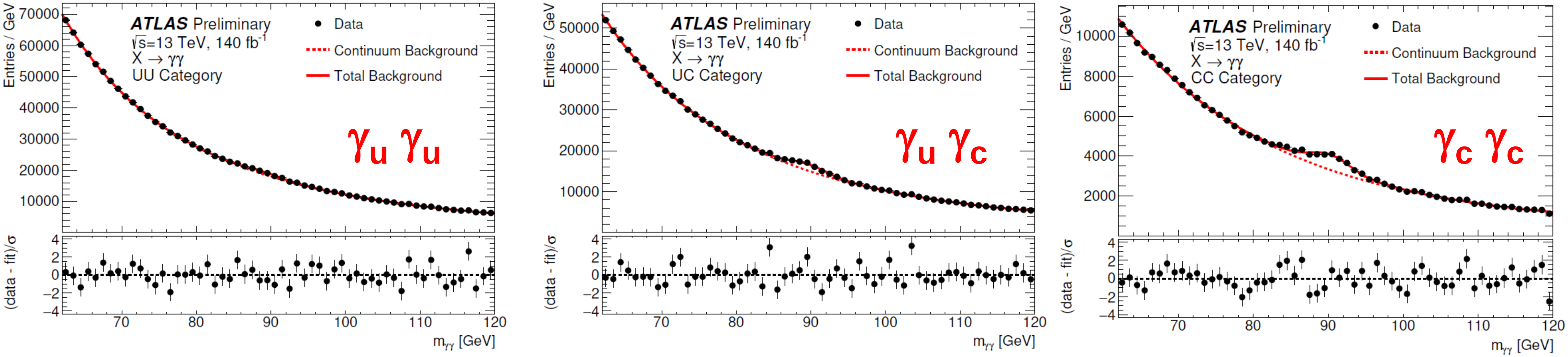


Search for low-mass Higgs bosons (cont'd)

H → $\gamma\gamma$

ATLAS-CONF-2023-035

- Three conversion categories: $\gamma_u \gamma_u$, $\gamma_u \gamma_c$, $\gamma_c \gamma_c$
- Background modelling:
  - Non-resonant (continuum) background: shape and normalization determined from data
  - Resonant (Drell-Yan) background: Z→ee events from data with corrections determined from simulation

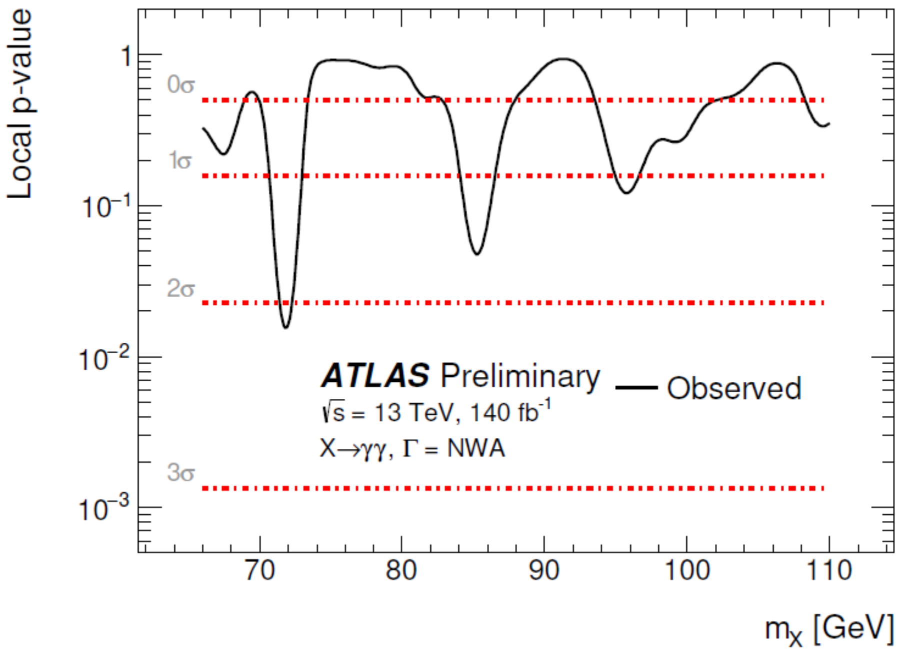


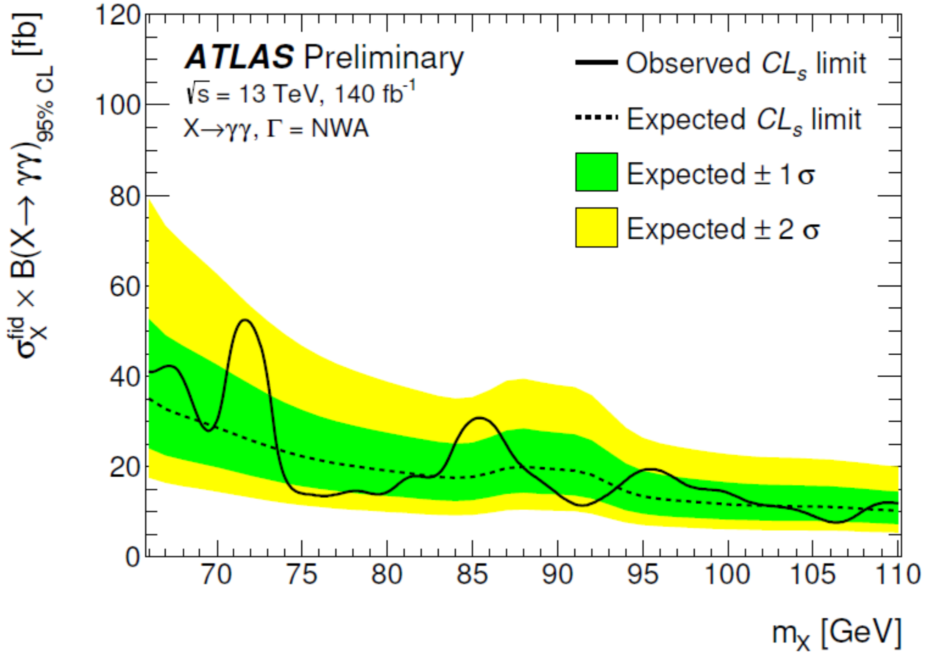
➔ Distributions are well described by SM background

Search for low-mass Higgs bosons (cont'd)

H → γγ

ATLAS-CONF-2023-035





➔ No significant excess observed at any mass (model-independent search)

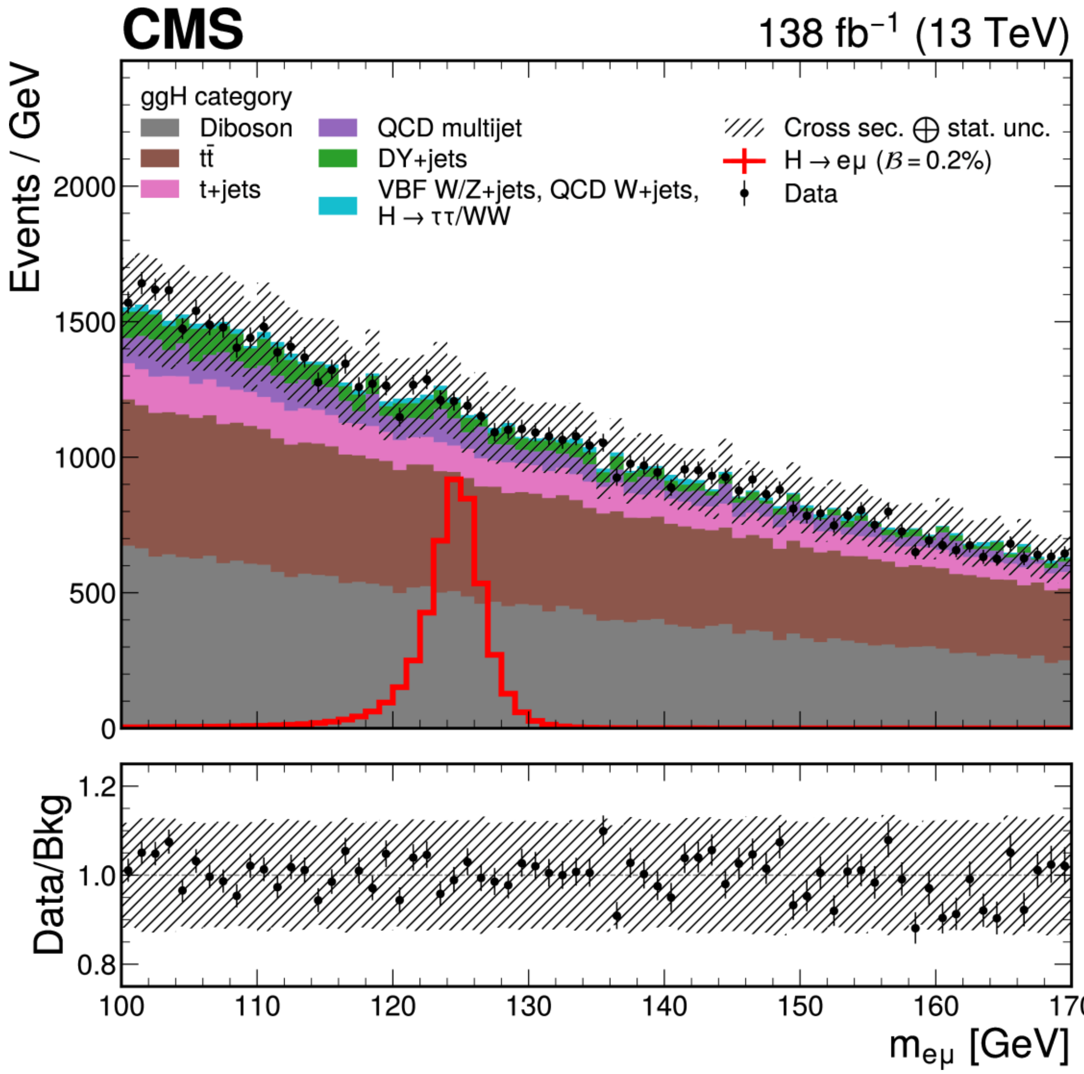
- A multivariate analysis trained with SM-like H→γγ gives more stringent, model-dependent limits (not shown)

Search for lepton-flavor violating H decays

H→eμ

arxiv:2305.18106

- In the SM, the H boson decays to lepton pairs of the same flavor
- In BSM models, e.g. in certain 2HDM variants, Yukawa couplings which do not conserve lepton-flavor are possible
  - flavor-violating decays of H boson at 125 GeV
  - new bosons at other masses appearing in such final states
- Here: search for H→eμ in gluon-fusion and VBF
- Choose mass window beyond the peak from ttbar production → smoothly falling background
- Categorization with signal/background discriminating BDT → in total 6 categories

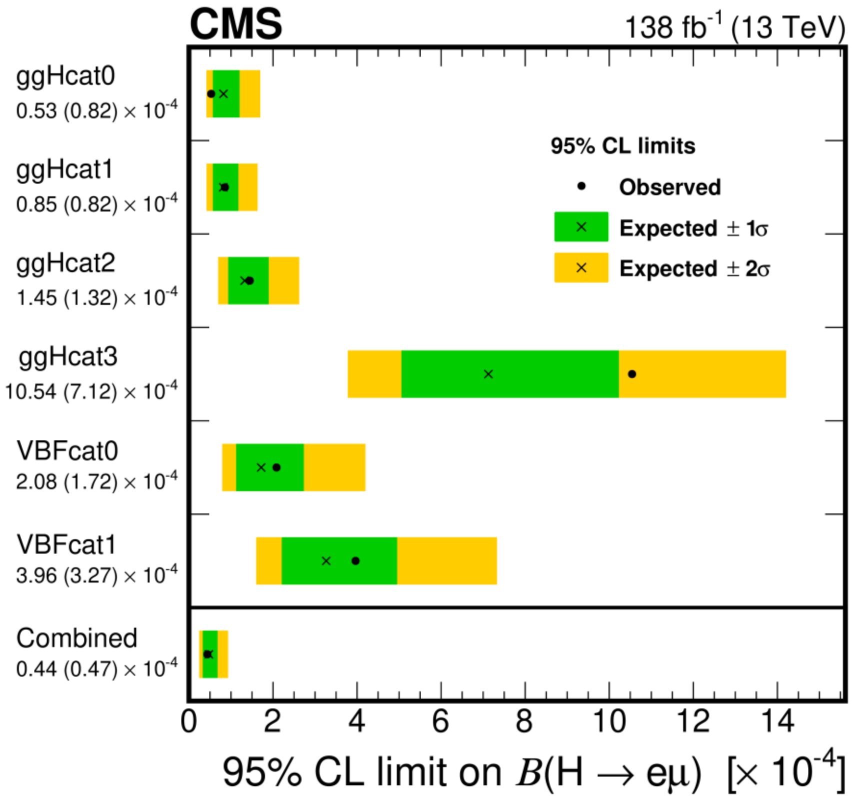


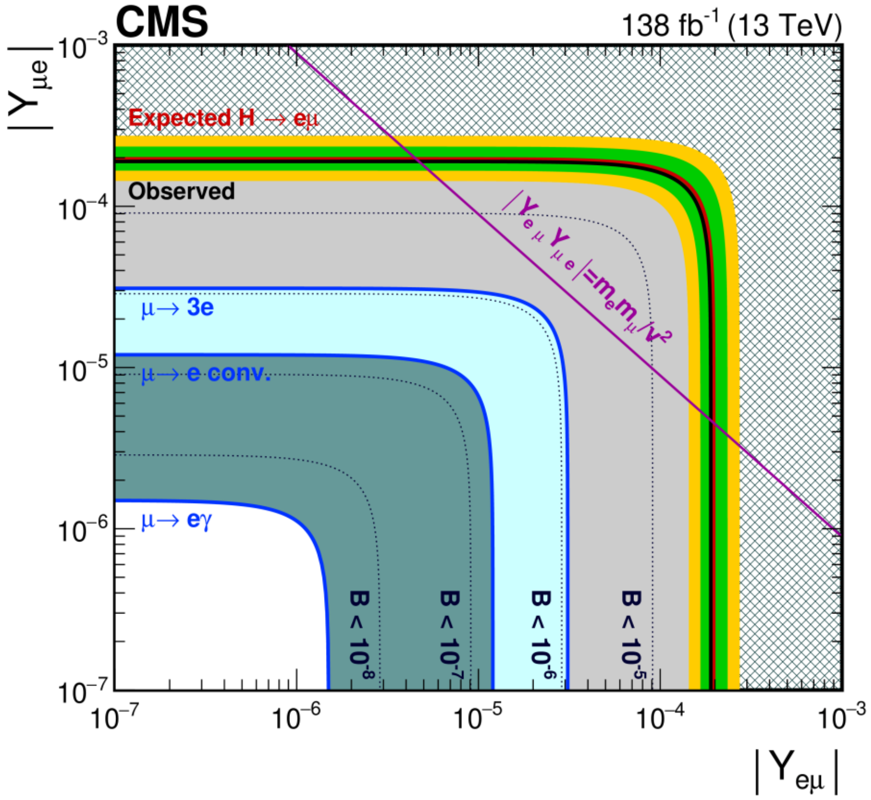
Search for lepton-flavor violating H decays (cont'd)

H→eμ

arxiv:2305.18106

- ➔ No excess observed for H→eμ at m=125 GeV
- ➔ B(H→eμ) < 4.4 (4.7) · 10^{-5} obs.(exp.) at 95% CL → most stringent direct limit so far





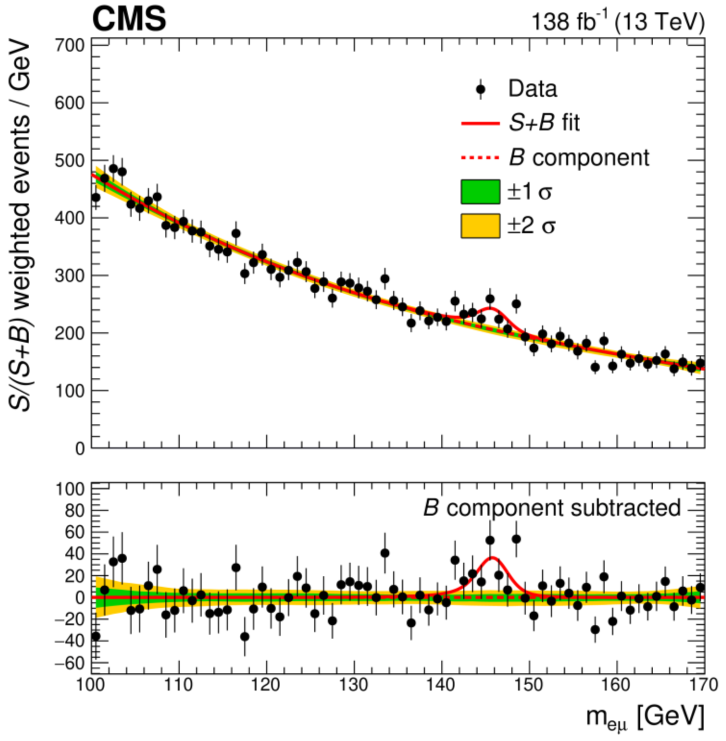
for recent results on H→eτ and H→μτ from ATLAS, see arXiv:2302.05225, JHEP 07 (2023) 166

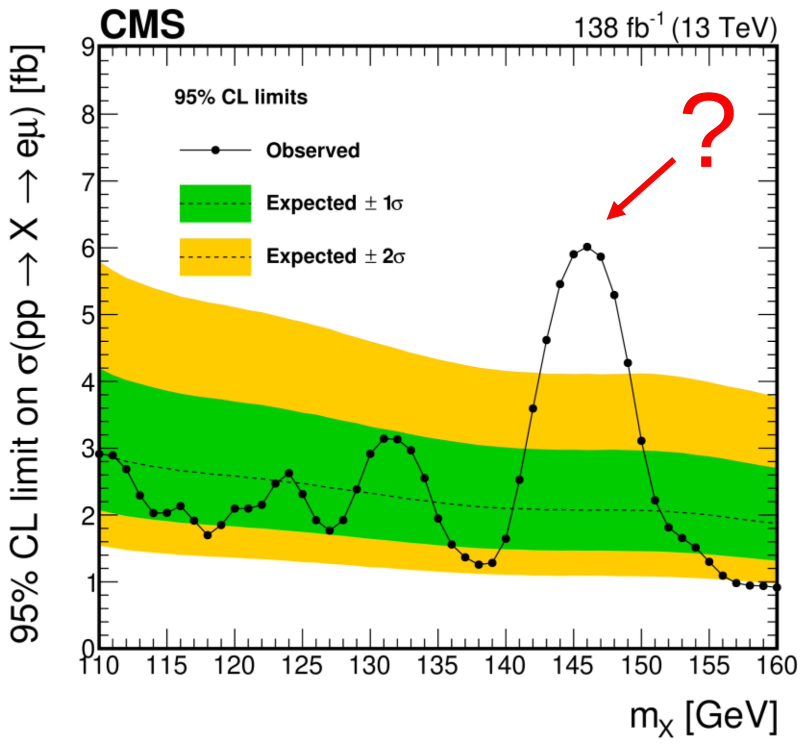
Search for lepton-flavor violating H decays (cont'd)

H→eμ

arxiv:2305.18106

- At a larger mass of ~146 GeV, a mild excess is seen
  - ➔ significance 3.8 σ local (2.8 σ global) → might be a fluctuation, need more data to conclude
  - ➔ first result of a direct X→eμ search with $M_X < 2m_W$





Summary

- Properties of H boson measured with unparalleled precision by ATLAS + CMS
  - Crucial recent updates on key questions in the Higgs sector
  - Currently all property measurements are a formidable confirmation of electroweak symmetry breaking as predicted in the SM

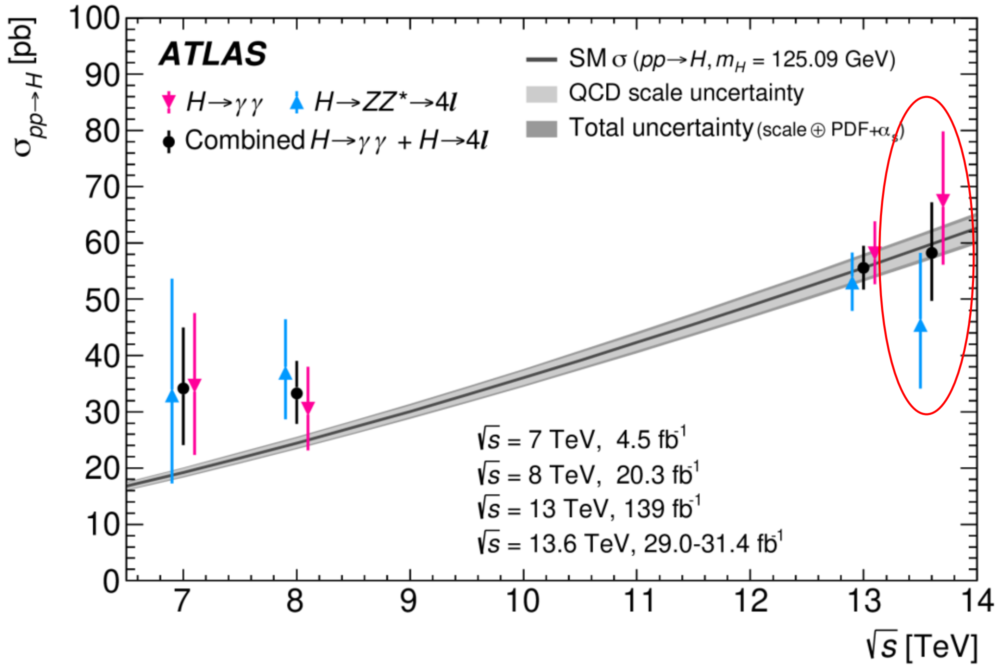
- Widely cast net searching for signatures of BSM physics involving Higgs bosons
  - Approaching the ultimate precision from Run 2
  - Some mild excesses observed whose nature needs to be clarified with further data and additional analyses

Outlook

- More Run 2 results still to come
- Run 3 will strongly increase the impact in Higgs boson physics
  - first measurements already done
  - further accumulation of integrated luminosity to surpass Run 2 precision
- Beyond Run 3, HL-LHC will paint the ultimate picture of the Higgs boson

arxiv:2306.11379

H in Run 3

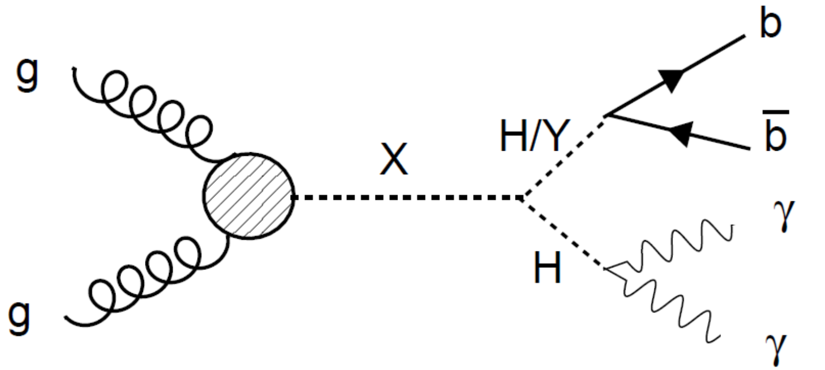


Backup

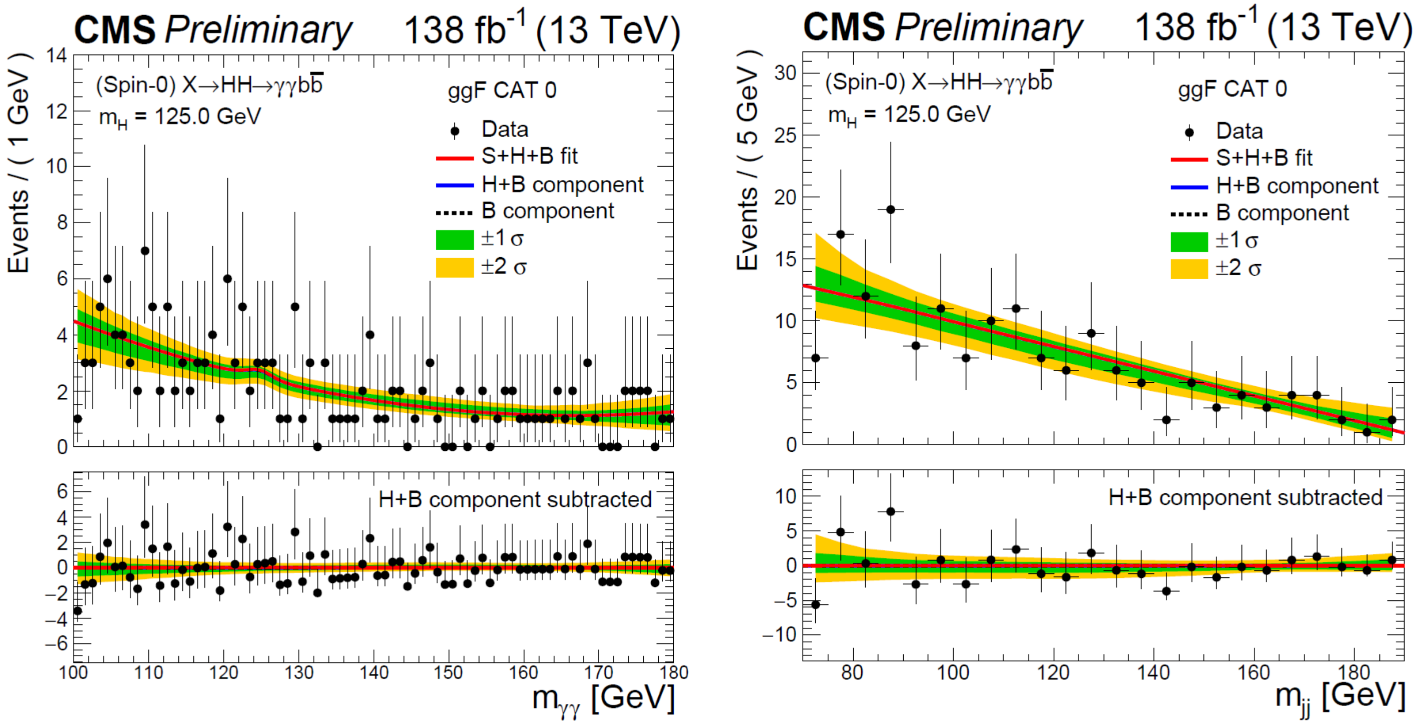
Search for X → YH → bb $\gamma\gamma$

Resonant production of Higgs bosons

CMS PAS HIG-21-011



- Motivation: extended Higgs sectors (e.g. NMSSM) with additional neutral (pseudo-)scalars X and Y
  - warped extra dimensions in case of Y=H
- A growing experimental field… many channels still uncovered
- Reconstruct $m_{\gamma\gamma\,bb}$ taking nominal values of m_H and m_Y into account
- Signal extraction in 2D space of ($m_{\gamma\gamma}$, m_{jj}) after M_X selection



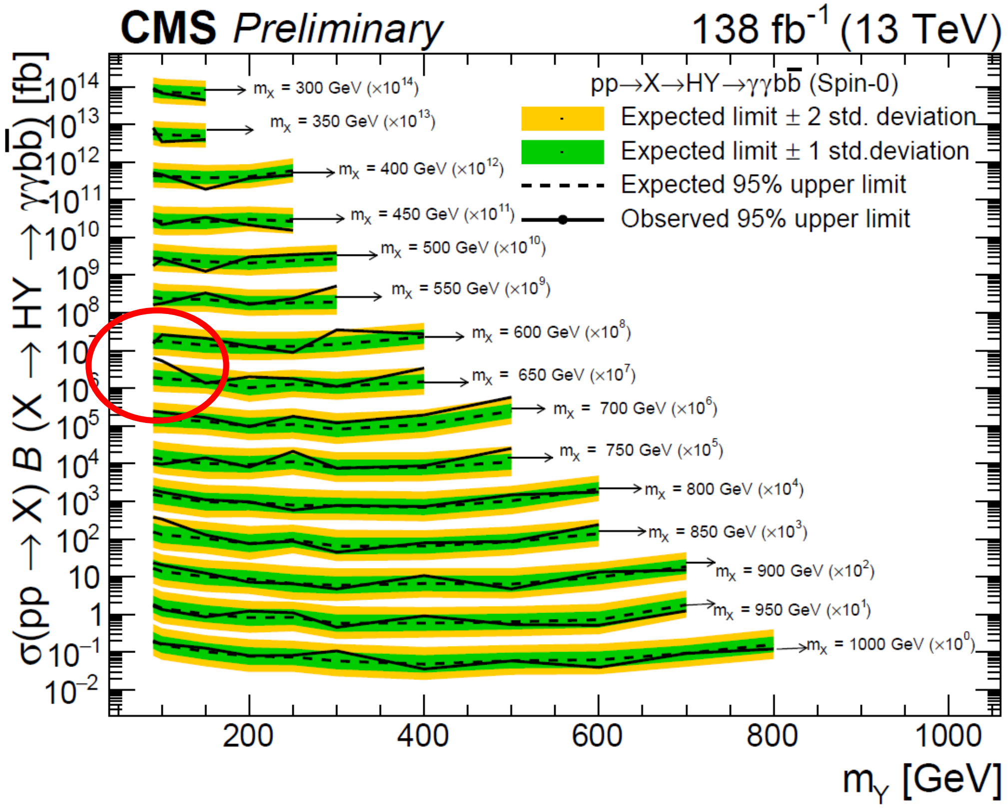
for m_X = 400 GeV

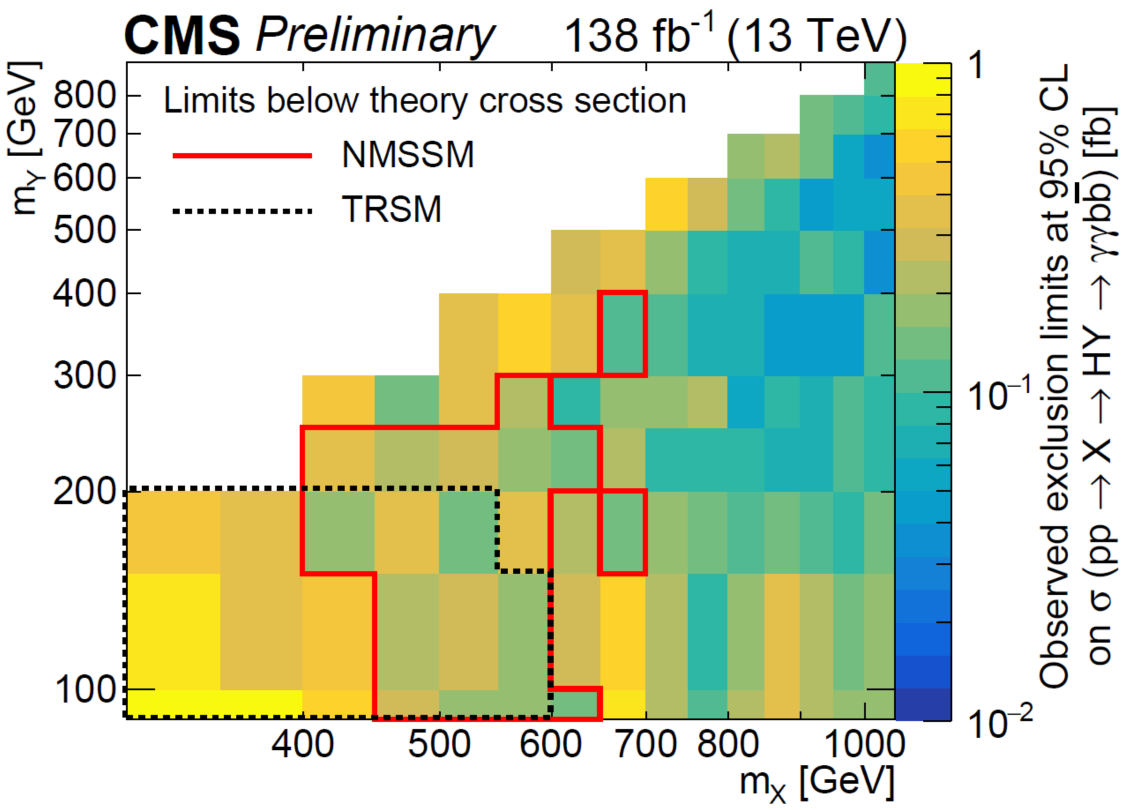
Search for X → YH → bb γγ (cont'd)

Resonant production of Higgs bosons

CMS PAS HIG-21-011

- Mild deviation from background-only hypothesis with local (global) significance of 3.8 σ (2.8 σ) for m_X = 650 GeV and m_Y = 90 GeV.
- Exclusions in parameter space of NMSSM and TRSM models



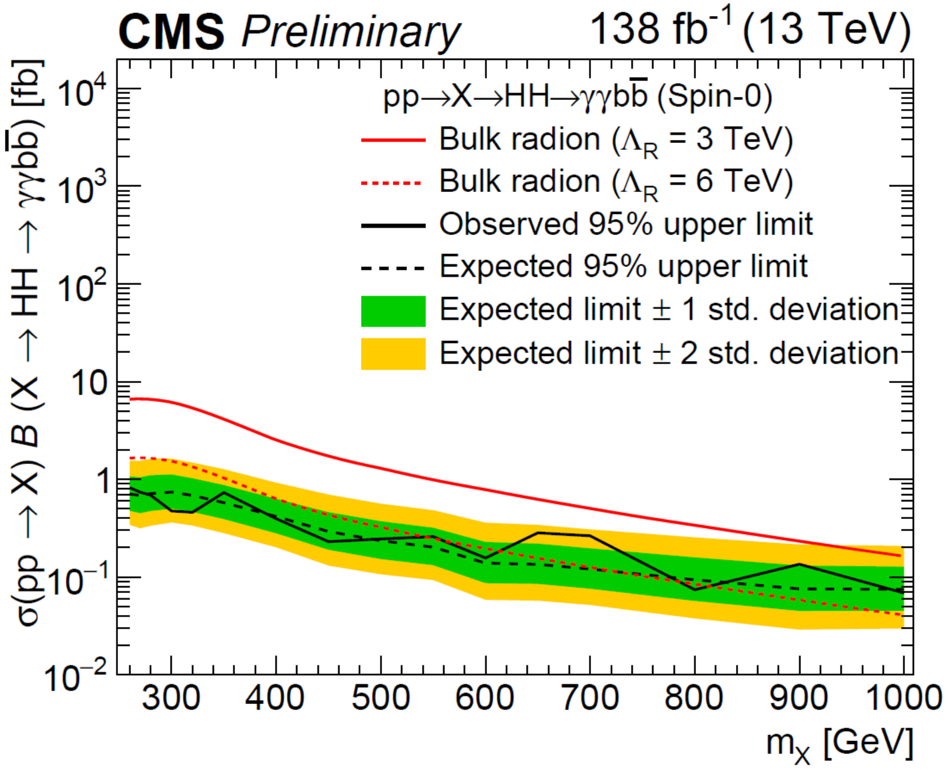


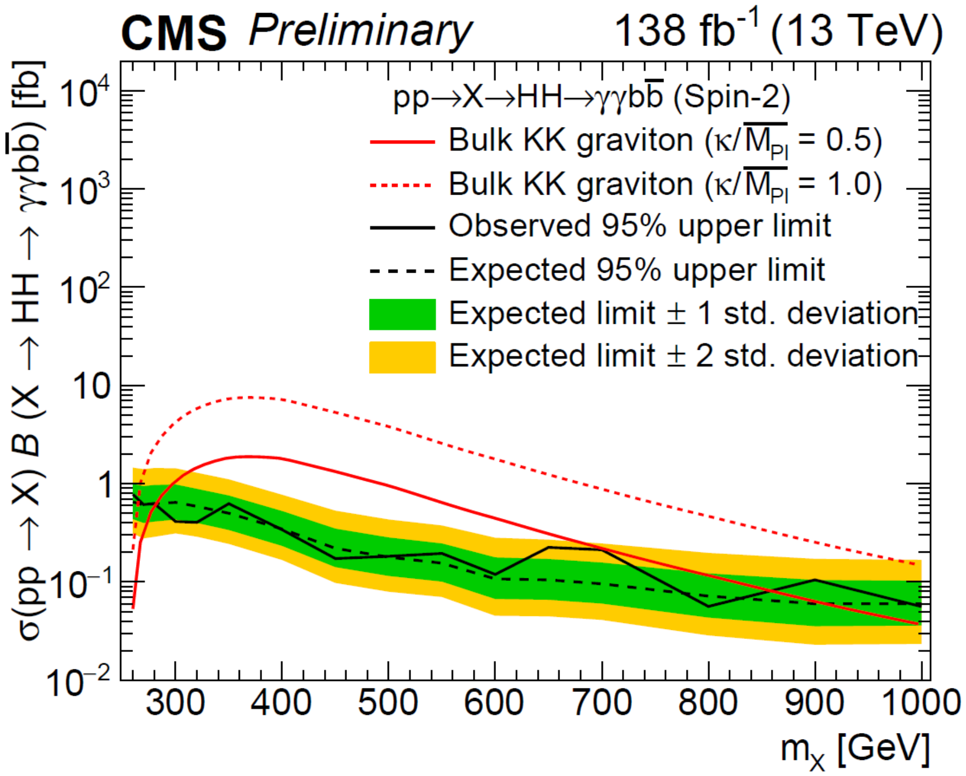
Resonant production of Higgs bosons (cont'd)

Symmetric case: X → HH decays

CMS PAS HIG-21-011

- ➔ In the symmetric case (Y=H), strong exclusion limits in particular in the low m_X regime
- ➔ Bulk radion (spin 0) and Kaluza Klein graviton (spin 2) excluded for specific parameters

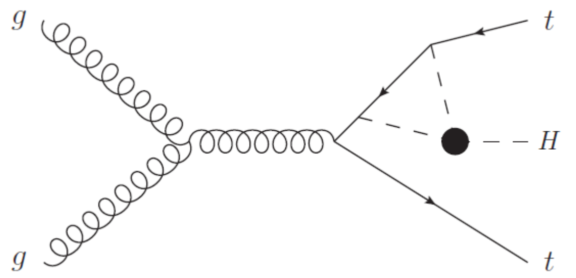


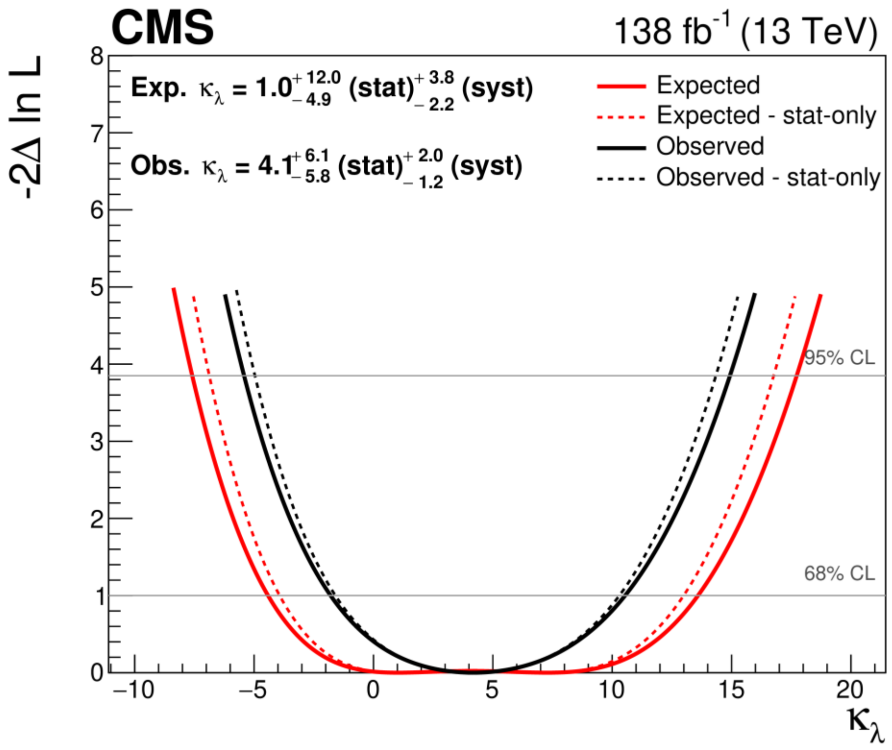


Differential cross sections in H→4ℓ (cont'd)

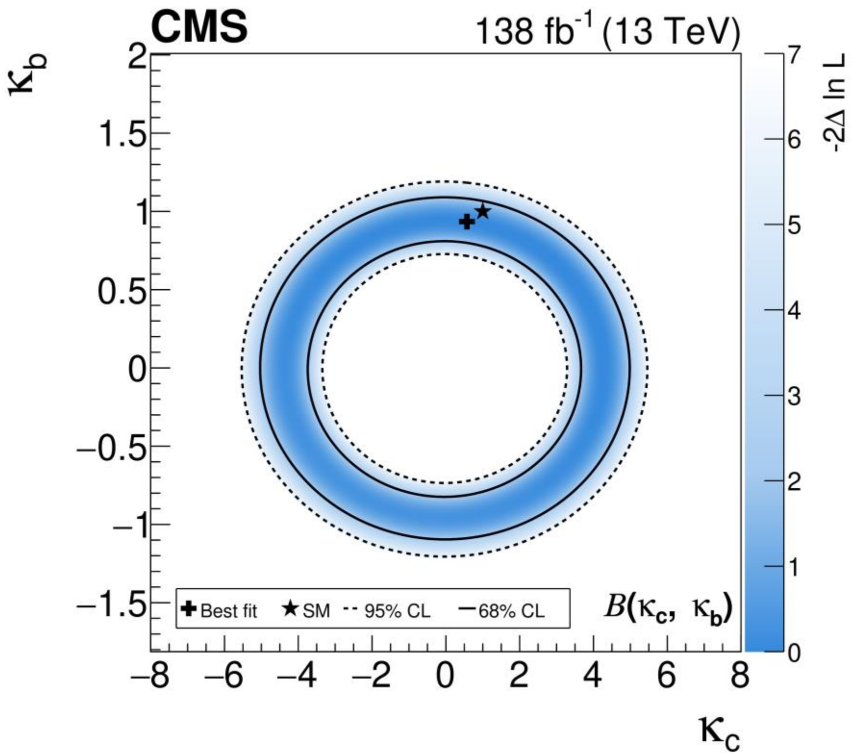
arxiv:2305.07532, accepted by JHEP

- Even possible to constrain the trilinear Higgs coupling from the p_T distributions
  - NLO corrections depending on κ_λ in ttH and VH modes → to be compared with results from HH production
- Gluon fusion process proceeds via quark loop → sensitive to H-c Yukawa coupling





arxiv:1607.04251

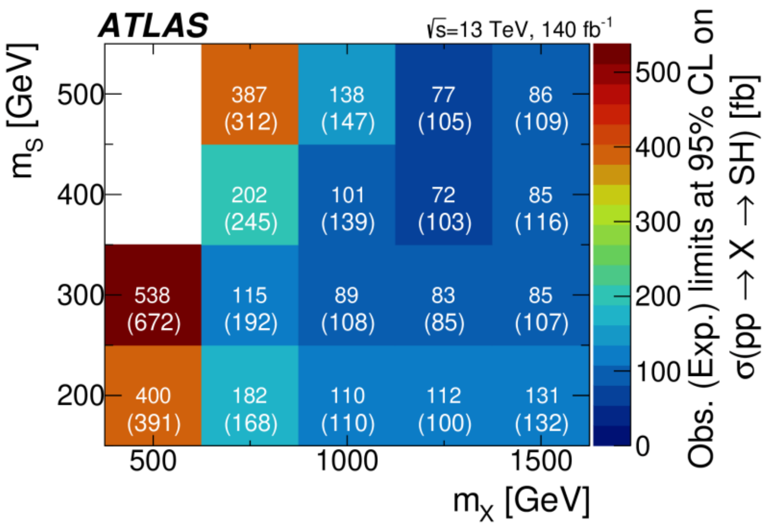


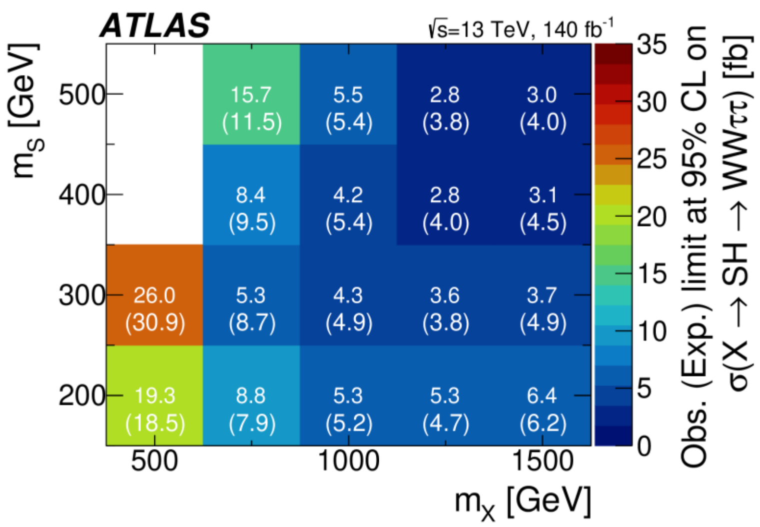
Resonant production of Higgs bosons (cont'd)

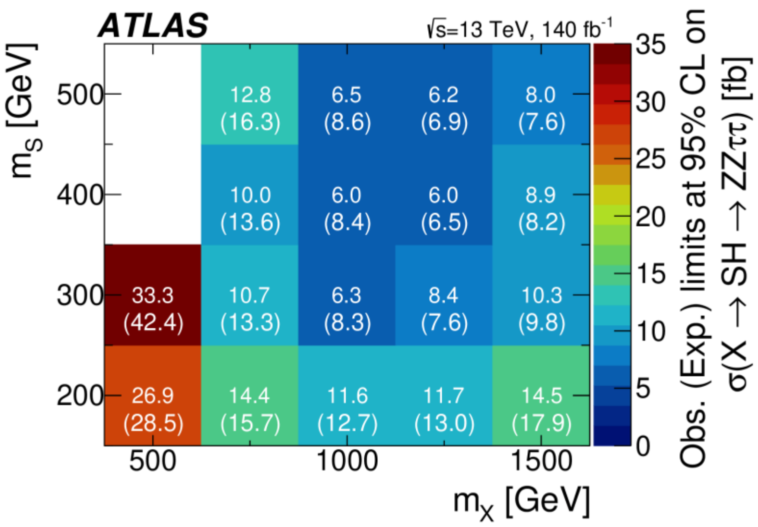
Search for X → SH decays

arxiv:2307.11120

- No significant excess seen at any mass combination
- B(S→VV) are not known. Assume values of SM H boson at this mass → large B(→VV)







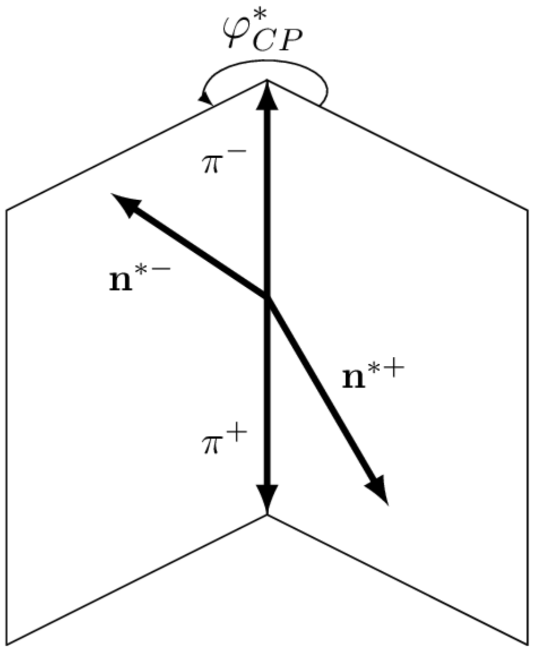
CP properties of Hτ Yukawa interaction

Eur. Phys. J. C 83 (2023) 563

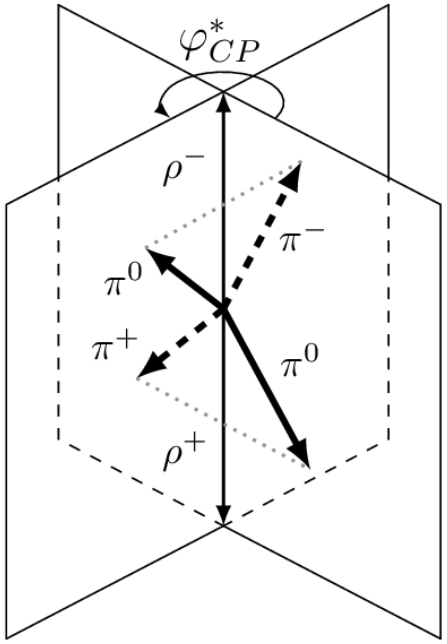
- SM H boson has CP=+1 → confirmed by experiment, but some CP= –1 admixture not excluded
- Can be tested through CP structure of Yukawa interaction
  - quantified by mixing angle ϕ_τ, where ϕ_τ =0 corresponds to the SM (pure CP=+1)
  - encoded in spin correlations in H→ττ decays
- CP-sensitive variable: angle between the decay planes of the two τ leptons, φ^*_{CP}
- Analysis focuses on 1- and 3-prong decays

Notation	Decay mode	Branching fraction
ℓ	$\ell^\pm \bar{\nu}\nu$	35.2%
1p0n	$h^\pm\nu$ $(\pi^\pm\nu)$	11.5% (10.8%)
1p1n	$h^\pm\pi^0\nu$ $(\pi^\pm\pi^0\nu)$	25.9% (25.5%)
1pXn	$h^\pm \geq 2\pi^0\nu$ $(\pi^\pm 2\pi^0\nu)$	10.8% (9.3%)
3p0n	$3h^\pm\nu$ $(3\pi^\pm\nu)$	9.8% (9.0%)

($\tau \to \pi\nu$)
($\tau \to \rho\nu$)
($\tau \to a_1\nu$)



impact parameter method

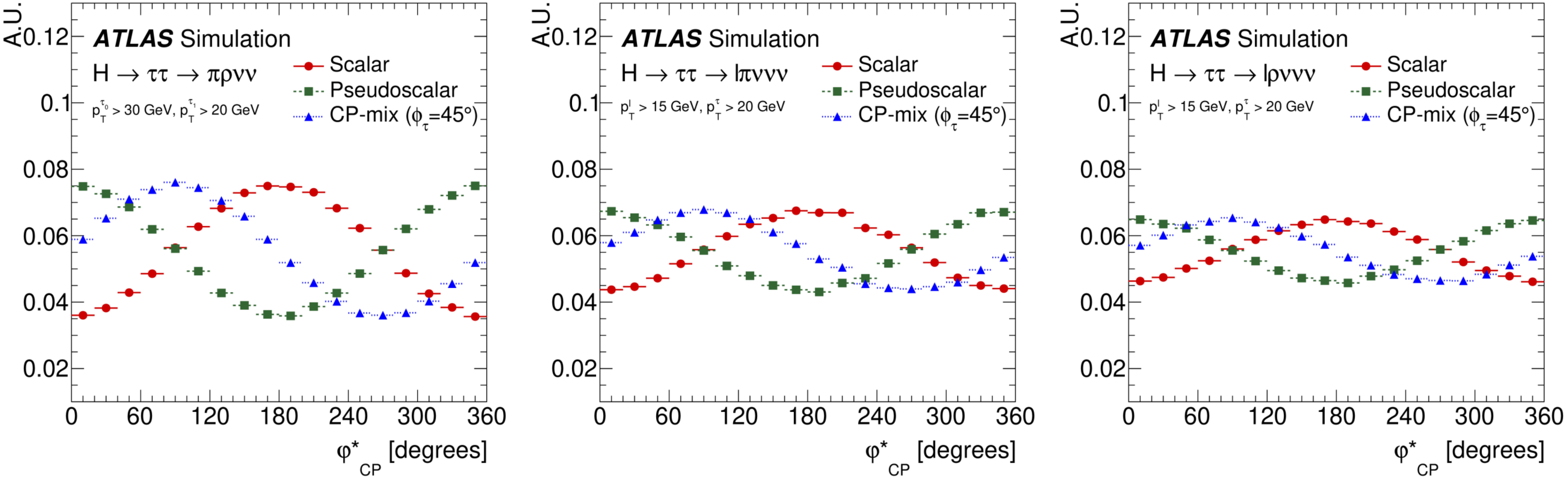


ρ decay plane method

CP properties of Hτ Yukawa interaction (cont'd)

Eur. Phys. J. C 83 (2023) 563

- Signature tested on simulation (before detector effects)
- Variation of mixing angle ϕ_τ results in a phase shift of modulation in φ^*_{CP} distribution
- Strength of effect varies depending on decay channel combination

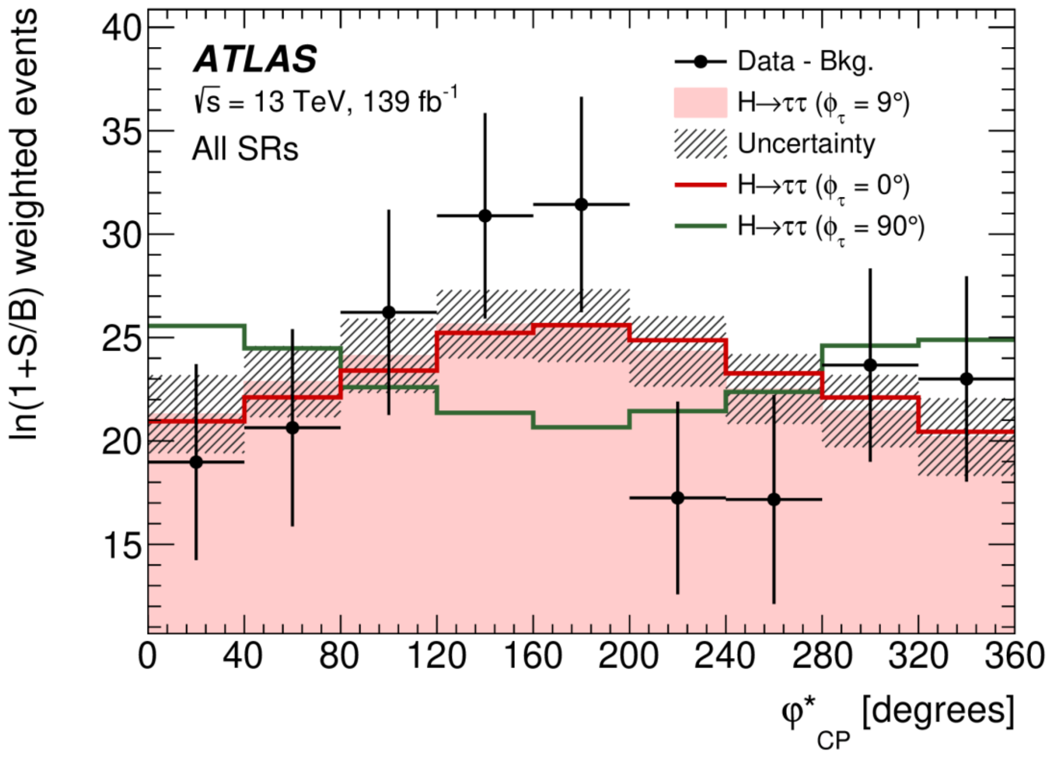


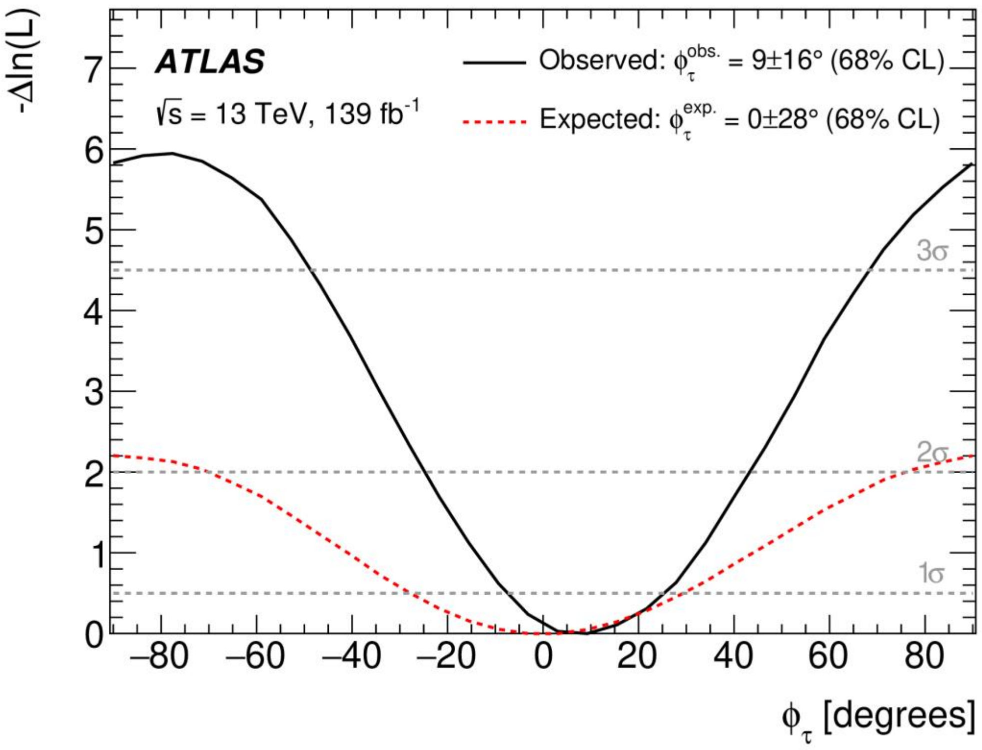
CP properties of Hτ Yukawa interaction (cont'd)

Eur. Phys. J. C 83 (2023) 563

➔ Combination of all data gives $\phi_\tau = 9° \pm 16°$ obs. ($0° \pm 28°$ exp.)

➔ The pure CP-odd hypothesis is excluded at a level of 3.4 σ

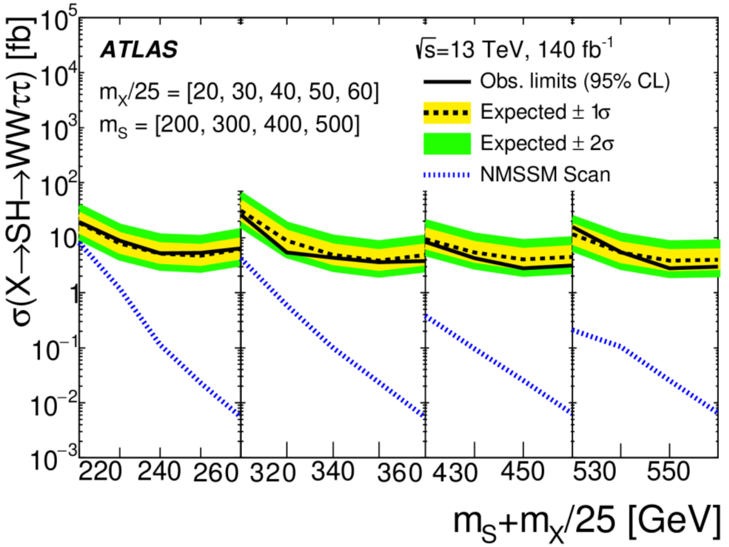


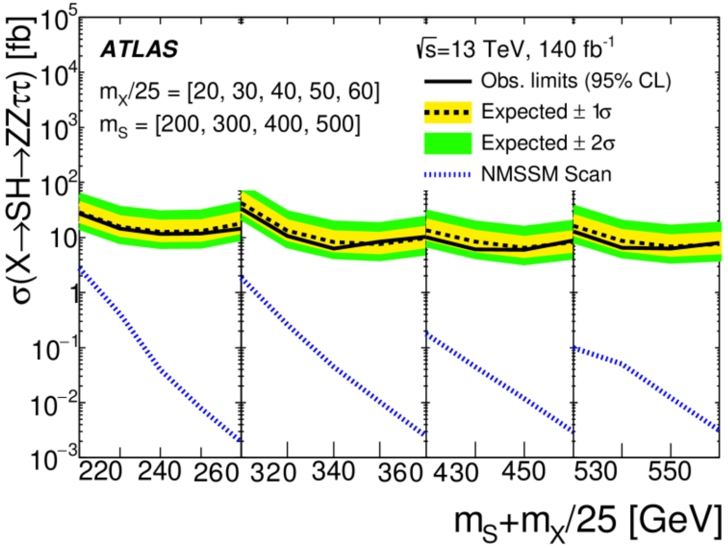


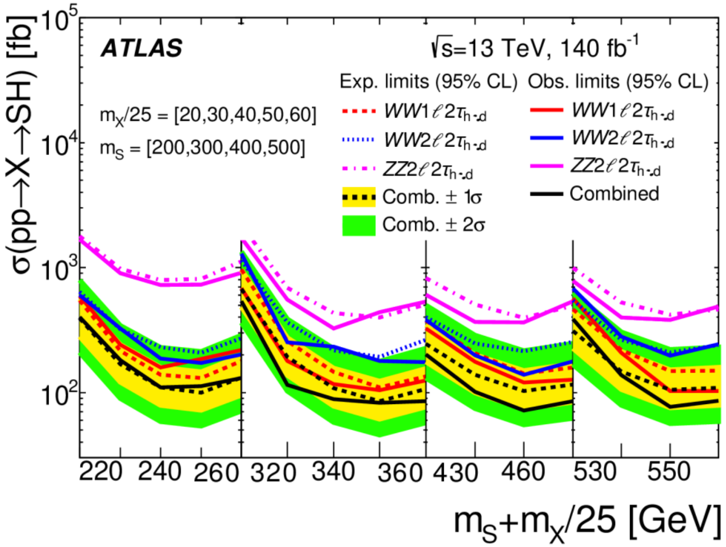
Resonant production of Higgs bosons (cont'd)

arxiv:2307.11120

Search for X → SH decays







for m_X = 400 GeV

Measurement of Higgs boson mass: H→ZZ*→4 ℓ

ℓ = e, μ

Phys. Lett. B 843 (2023) 137880

- Various improvements: increased dataset, improved muon momentum scale calibration
- Neural-network based classifier for S/B discrimination
- Full Run 2 result: $m_H = 124.99 \pm 0.18\ (stat.) \pm 0.04\ (syst.)\ GeV = 124.99 \pm 0.19\ GeV$
- Run 1 + Run 2: $m_H = 124.94 \pm 0.17\ (stat.) \pm 0.03\ (syst.)\ GeV = 124.94 \pm 0.18\ GeV$