Higgs Boson Measurements

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on behalf of the ATLAS and CMS Collaborations

EUROPEAN PHYSICAL SOCIETY HEP2019

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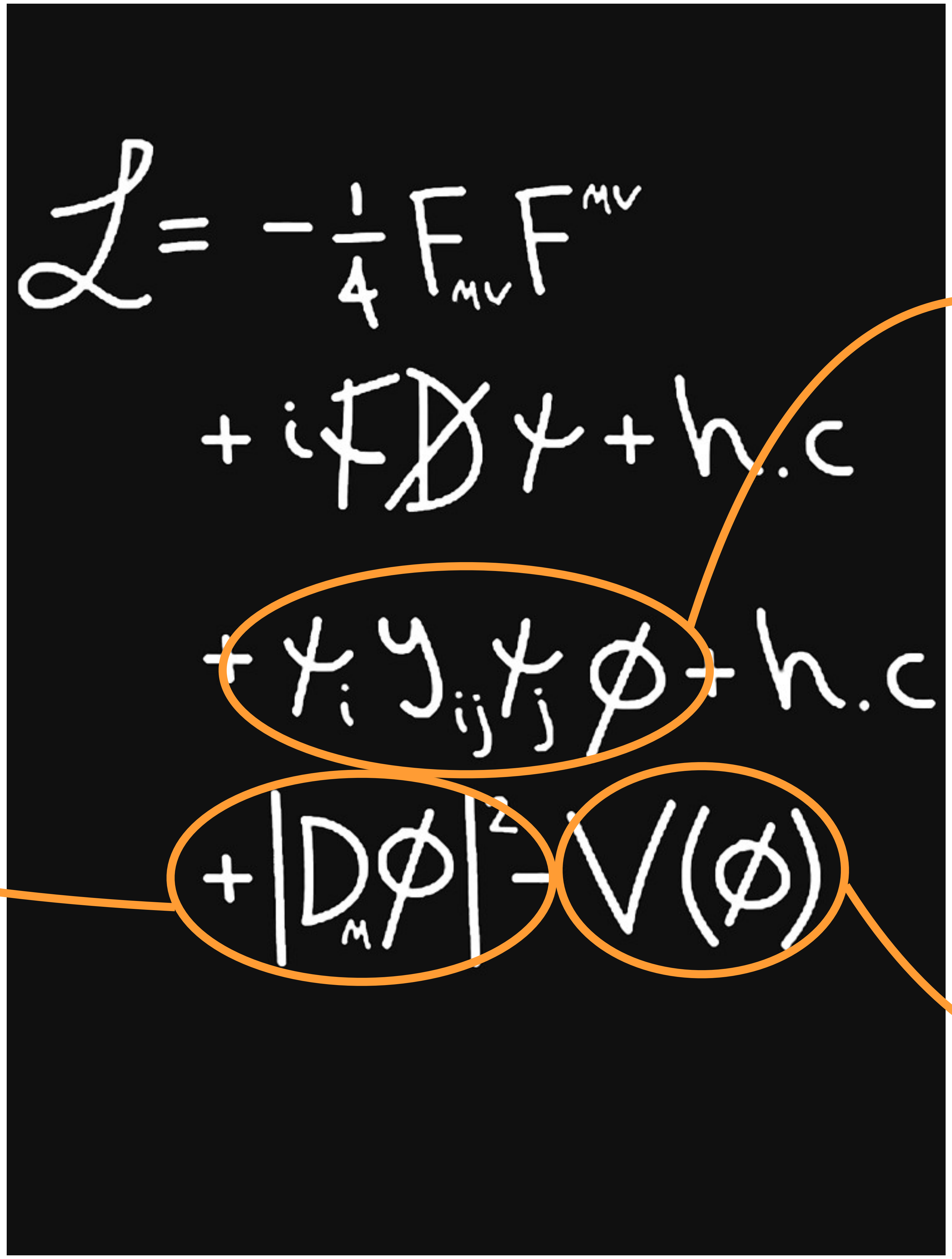
THE HIGGS SECTOR IS SPECIAL

The Higgs boson is a fundamental scalar particle (spin 0) and
its theory is unlike anything else we have seen in nature

A gauge interaction
much like what we have seen before



A Yukawa interaction
unlike anything we have probed before

A potential $V(\phi) \sim -\mu^2(\phi\phi^\dagger) + \lambda(\phi\phi^\dagger)^2$
the keystone of the BEH mechanism and SM, never probed

Inspired by G. Salam's LHCP2018 talk

THE HIGGS BOSON TIMELINE AT THE LHC

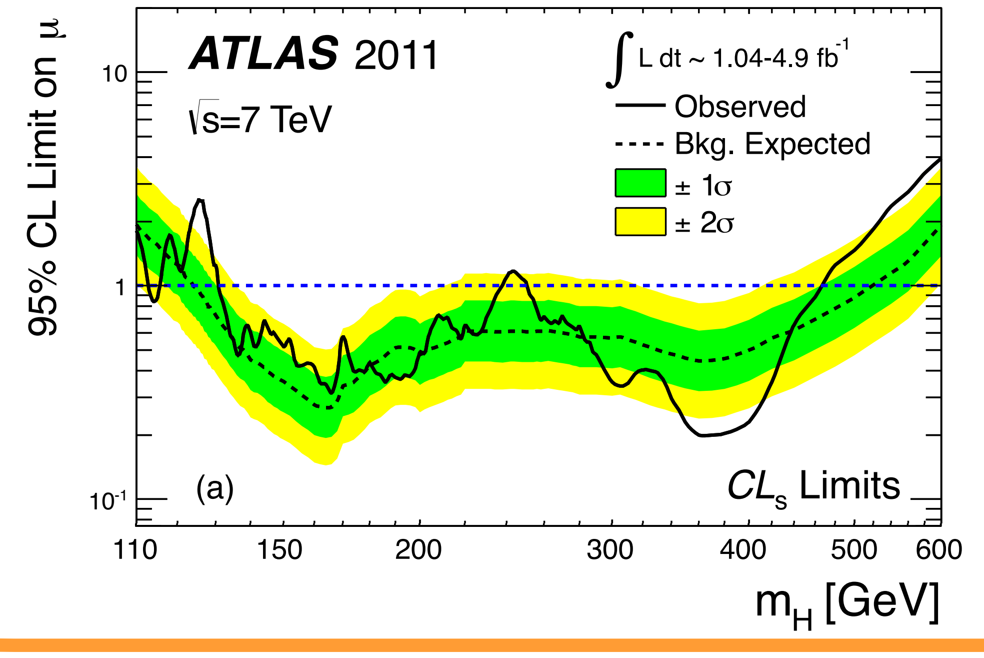
THE HIGGS BOSON TIMELINE AT THE LHC

LHC — Run1 7-8 TeV — Run2 13 TeV — Last EPS-HEP (HEP2017) — High Luminosity LHC

2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | …2038

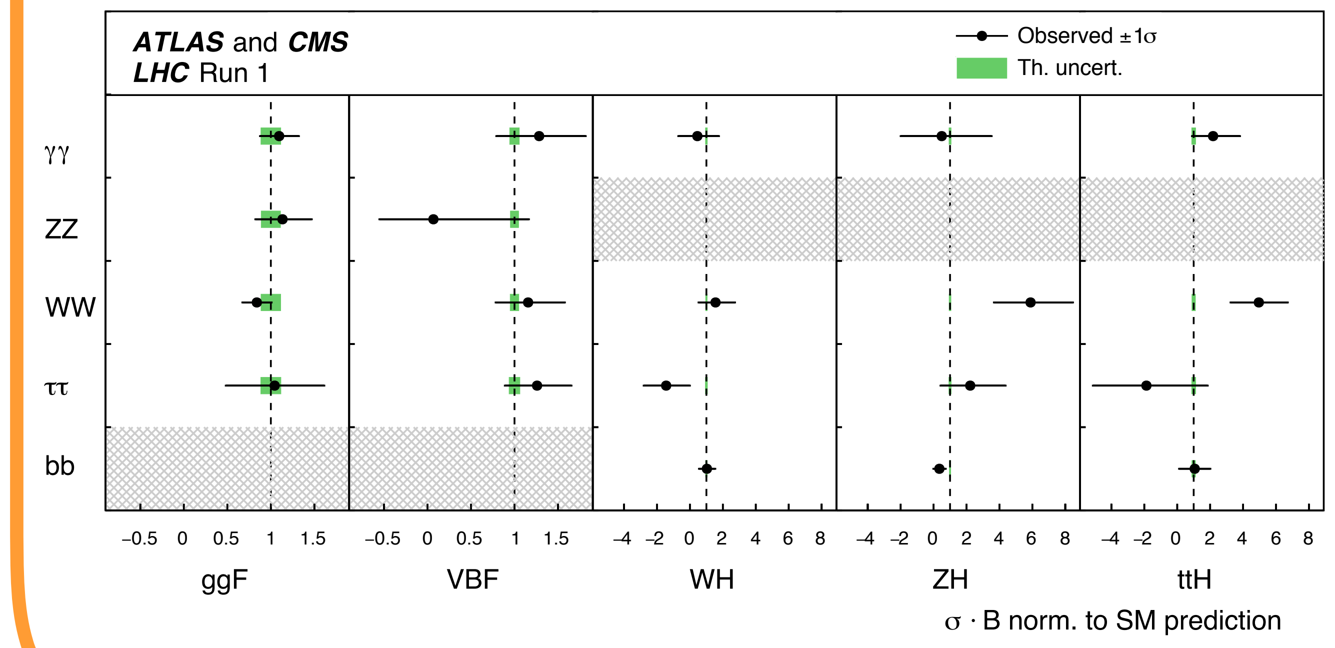
Higgs boson searches

"if the SM Higgs boson exists, is most likely to have a mass constrained to 115-130 GeV "



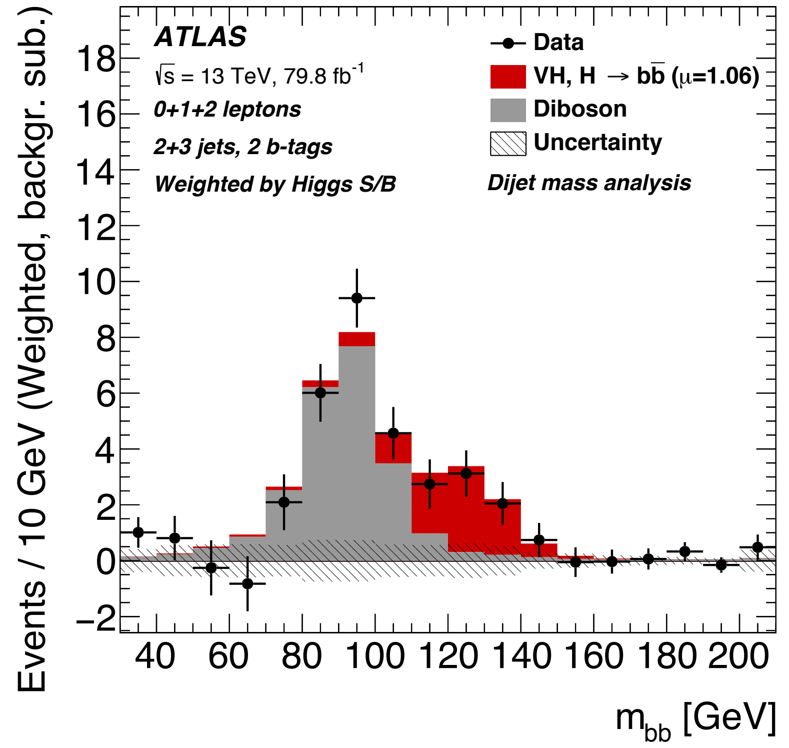
LHC combination

In one word "SM like"

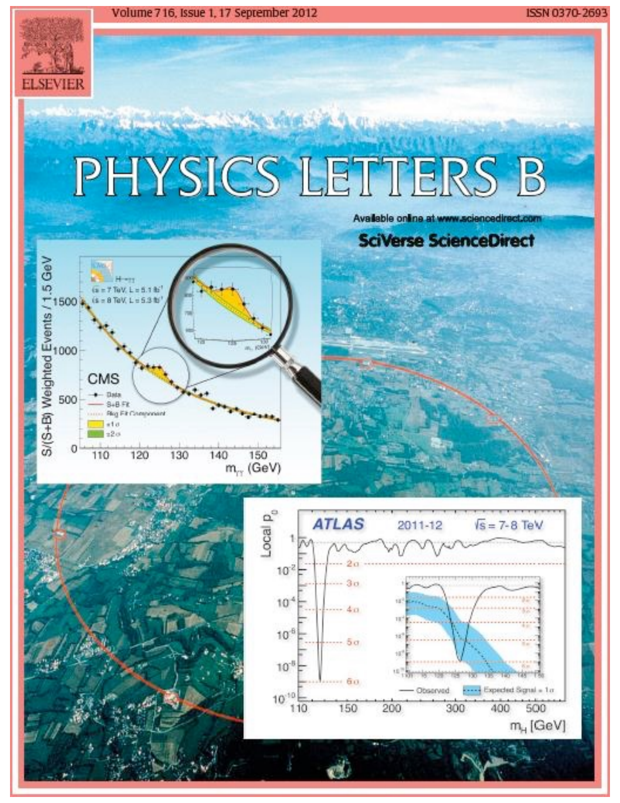


3rd-generation fermion couplings

H-τ, H-t, H-b observed

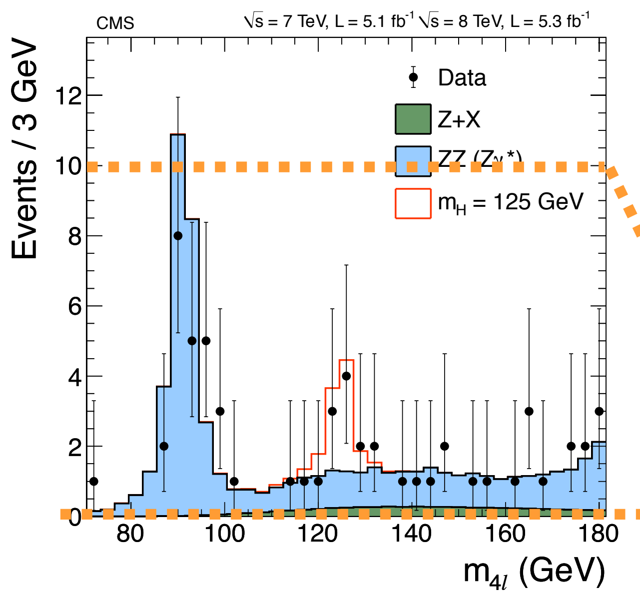


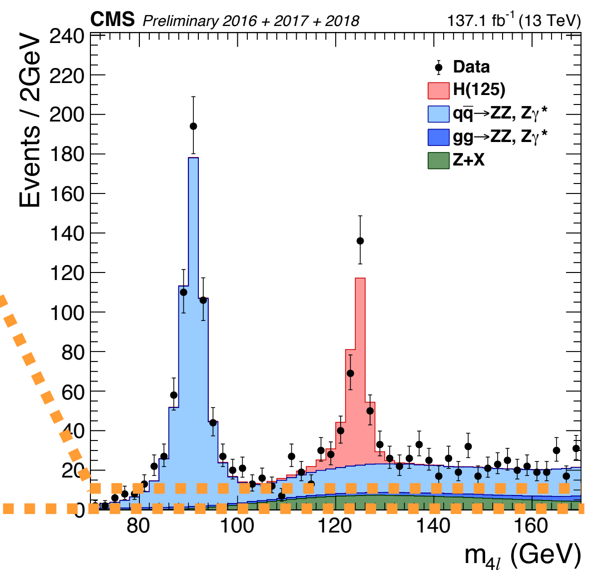
Higgs boson observation



Towards the precision physics era

discovery ⟶ full Run2





THE HIGGS BOSON TIMELINE AT THE LHC

LHC

Run1

7-8 TeV

Run2

13 TeV

Last EPS-HEP

High Luminosity LHC

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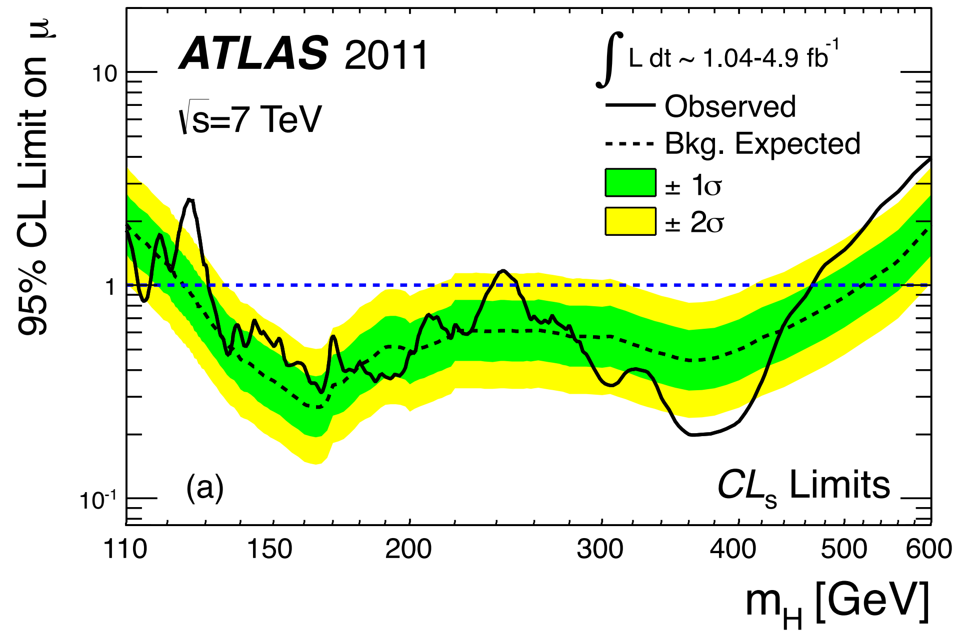

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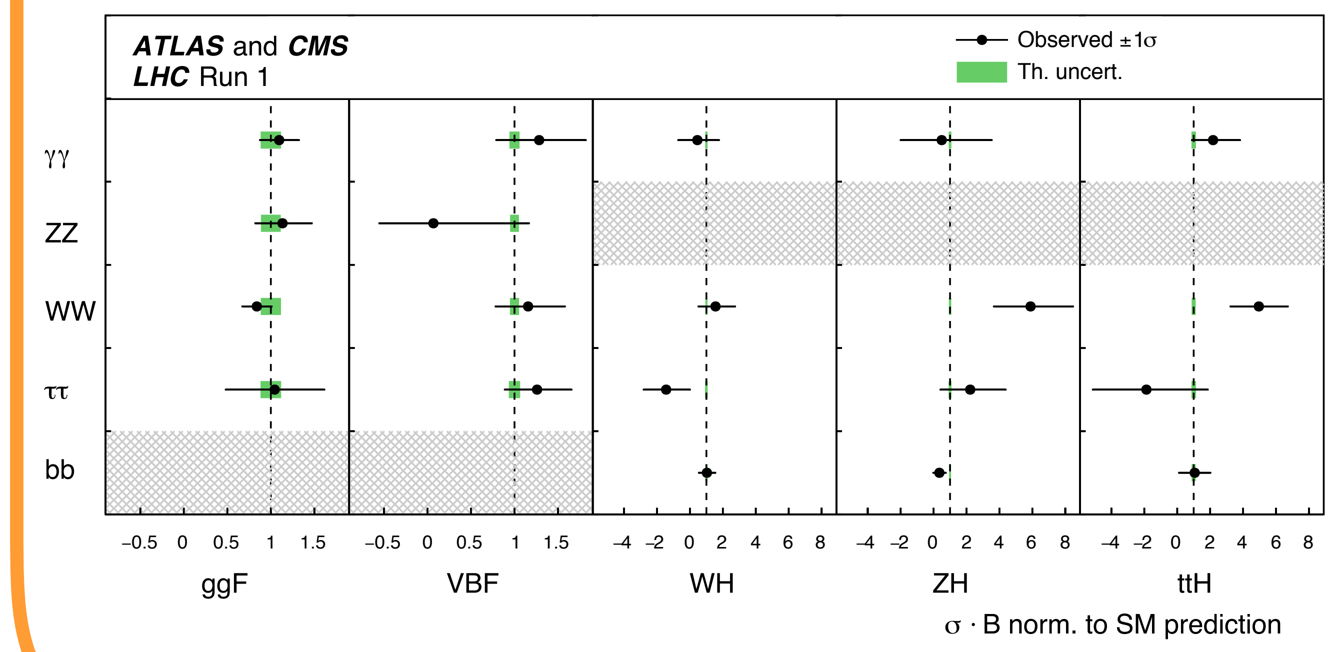

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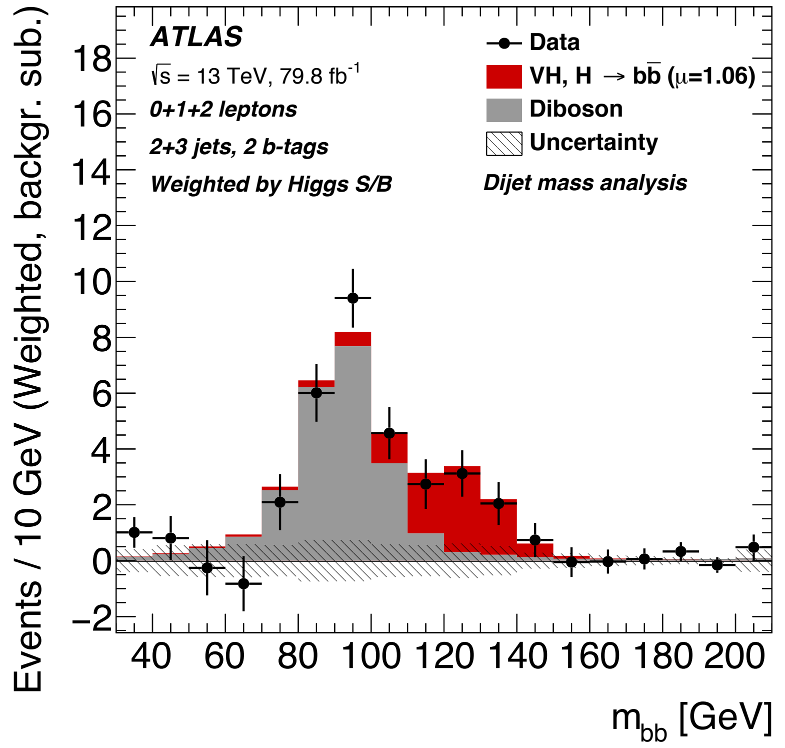

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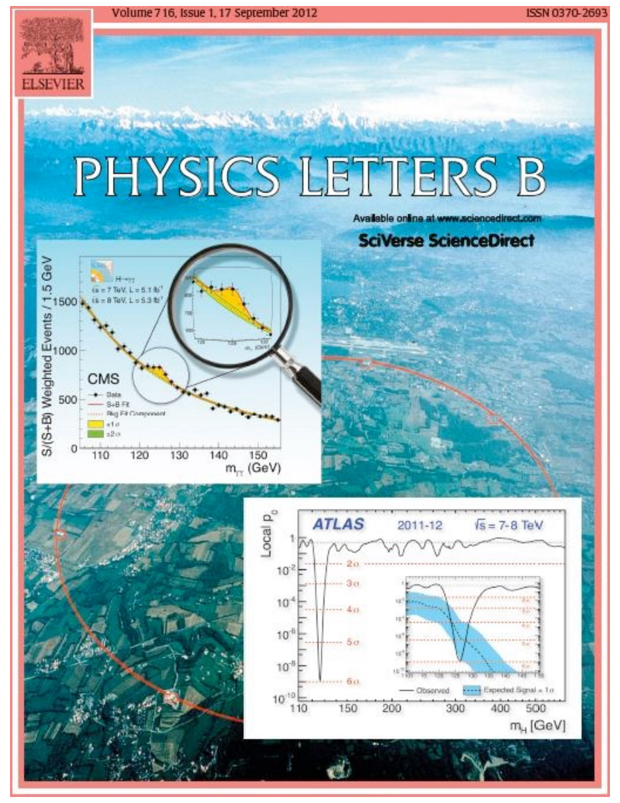

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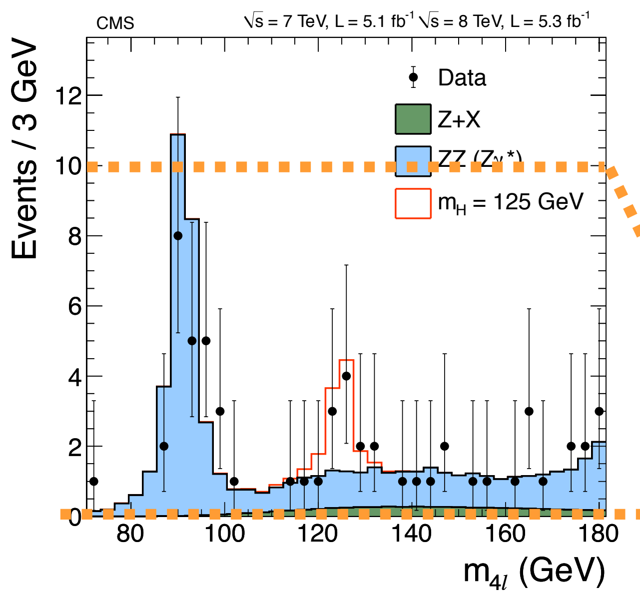
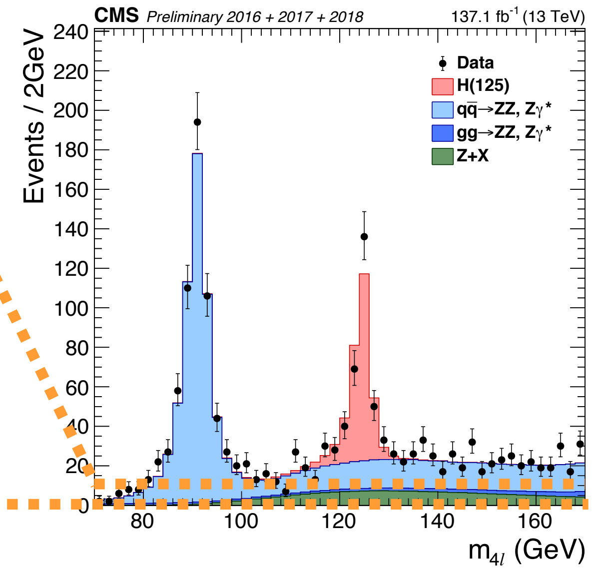
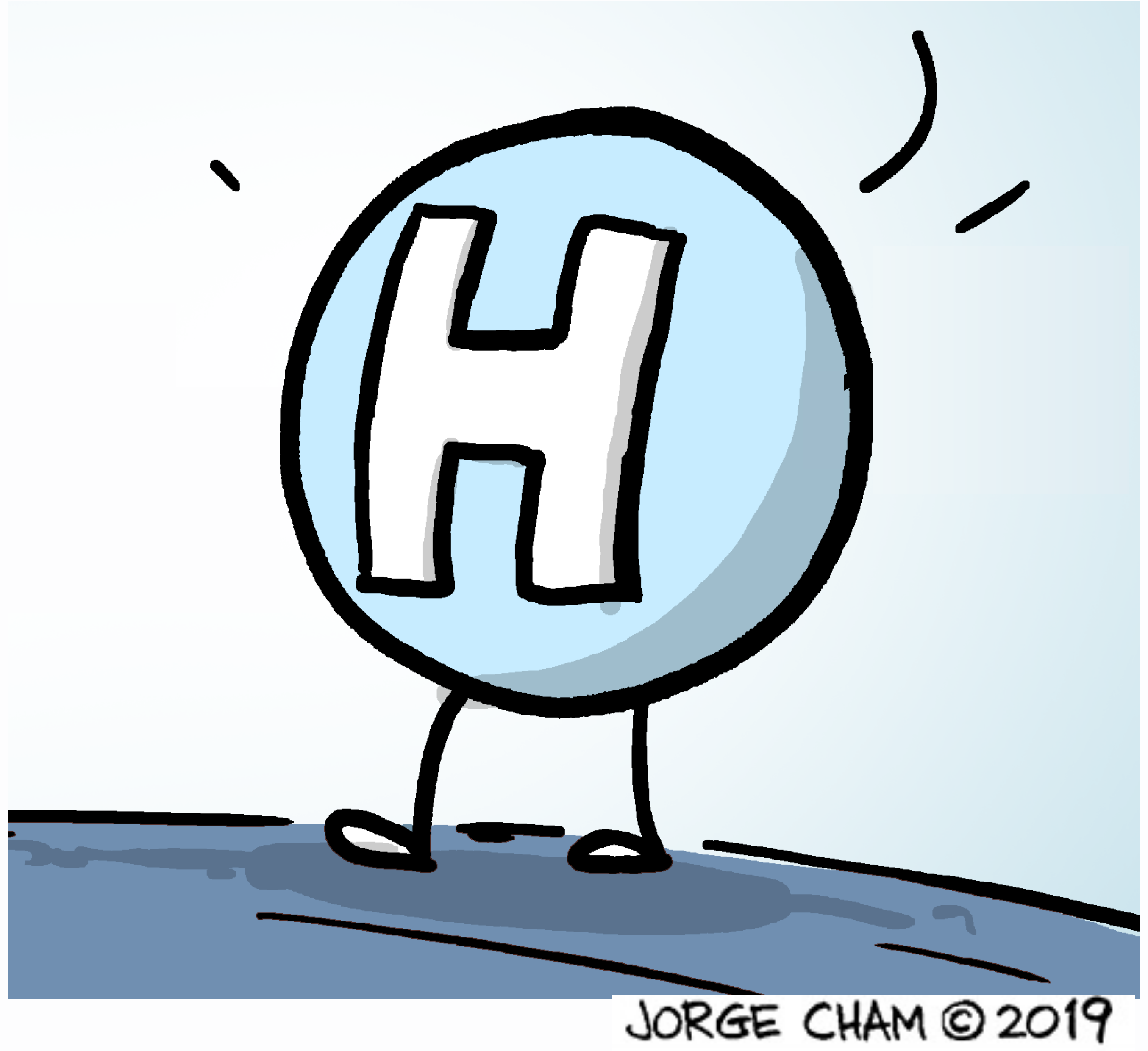




TODAY

EUROPEAN PHYSICAL SOCIETY HEP2019

The Higgs Boson Landscape Nowadays

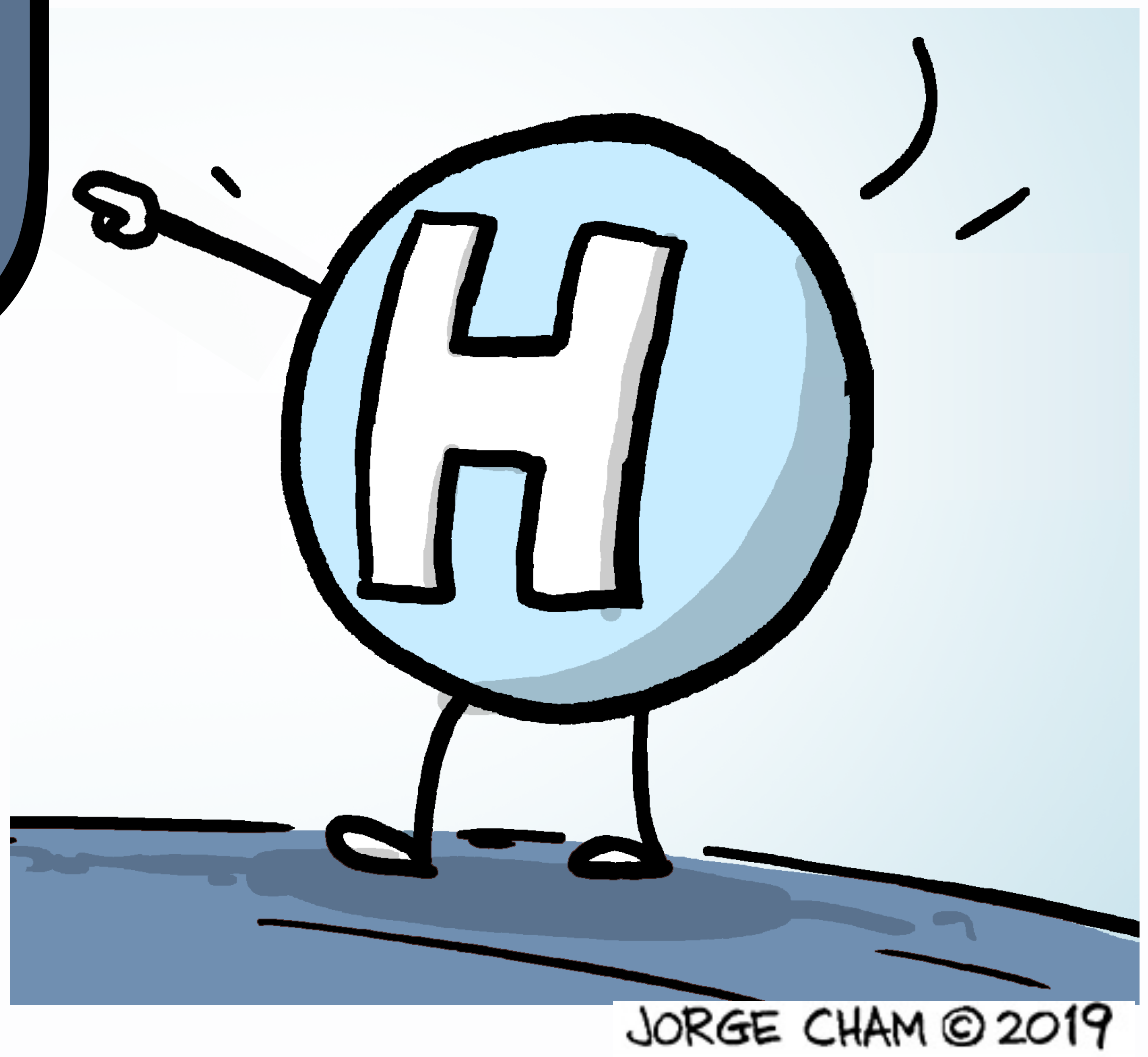


THE HIGGS BOSON LANDSCAPE NOWADAYS

The H profile

exploiting H-Z, H-W, and H-γ interactions

- Mass and width
- Coupling properties
- Inclusive/Differential cross sections
- Quantum numbers (Spin, CP)
- Combination



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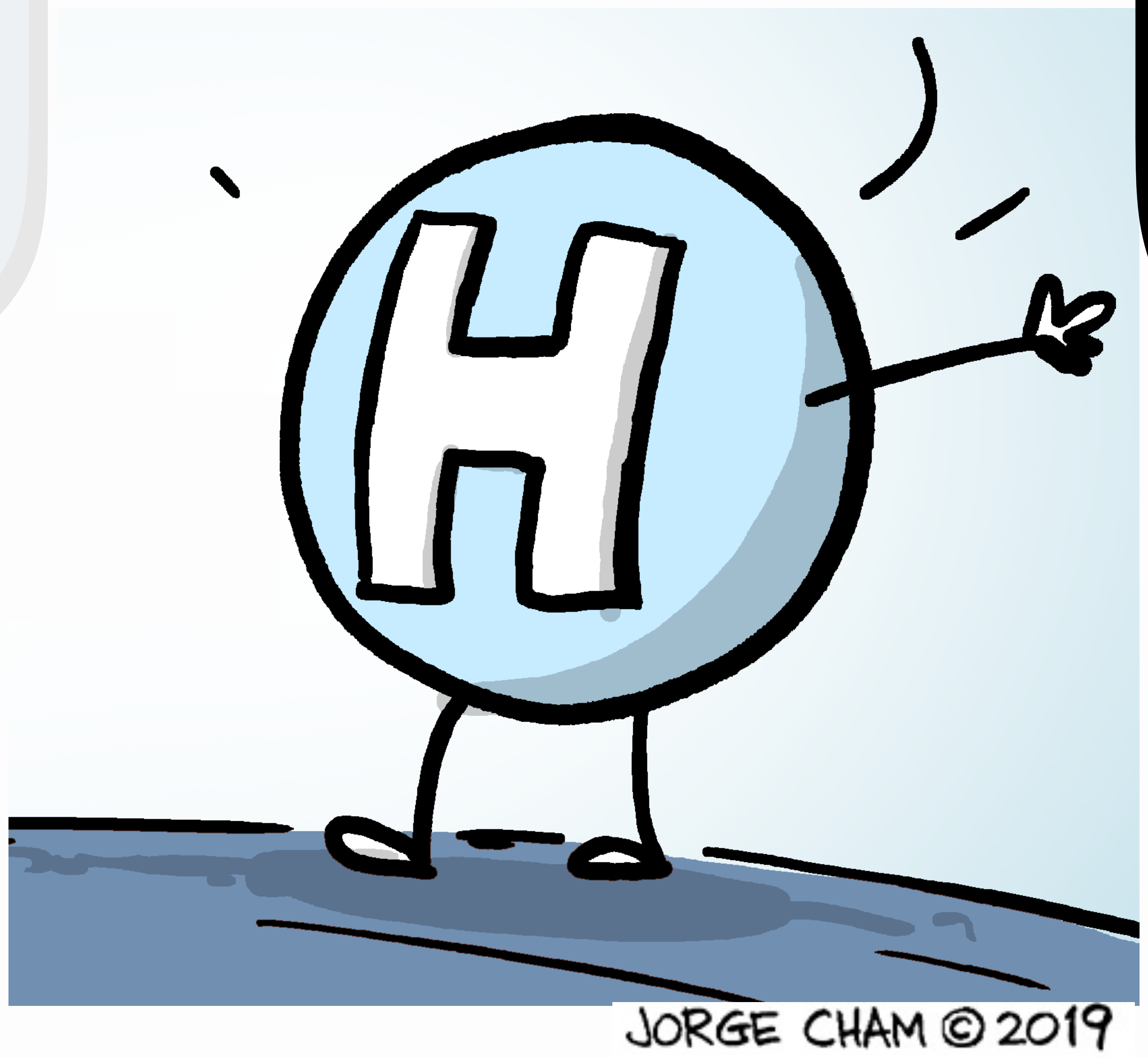

Discovery→Properties

3rd-generation fermion

- H-τ interaction in decay (H$\tau\tau$)
- H-t interaction in production (ttH)
- H-b interaction in decay (Hbb)

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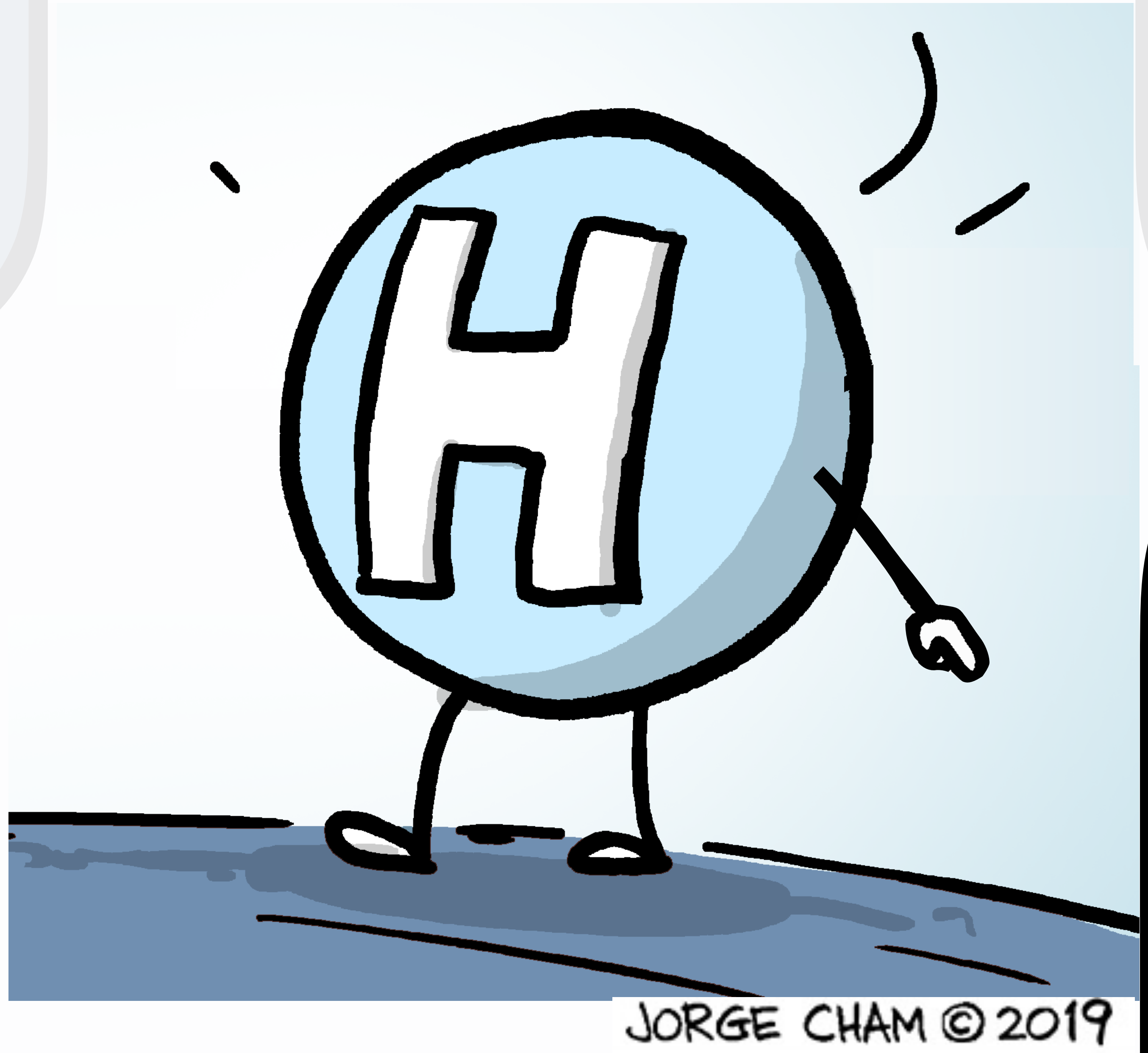

Rare decays/production

- 2nd -generation fermion
- Decay to mesons
- tHq/tHW
- Self coupling (HH production)
- Invisible decays

The Higgs Boson Landscape Nowadays

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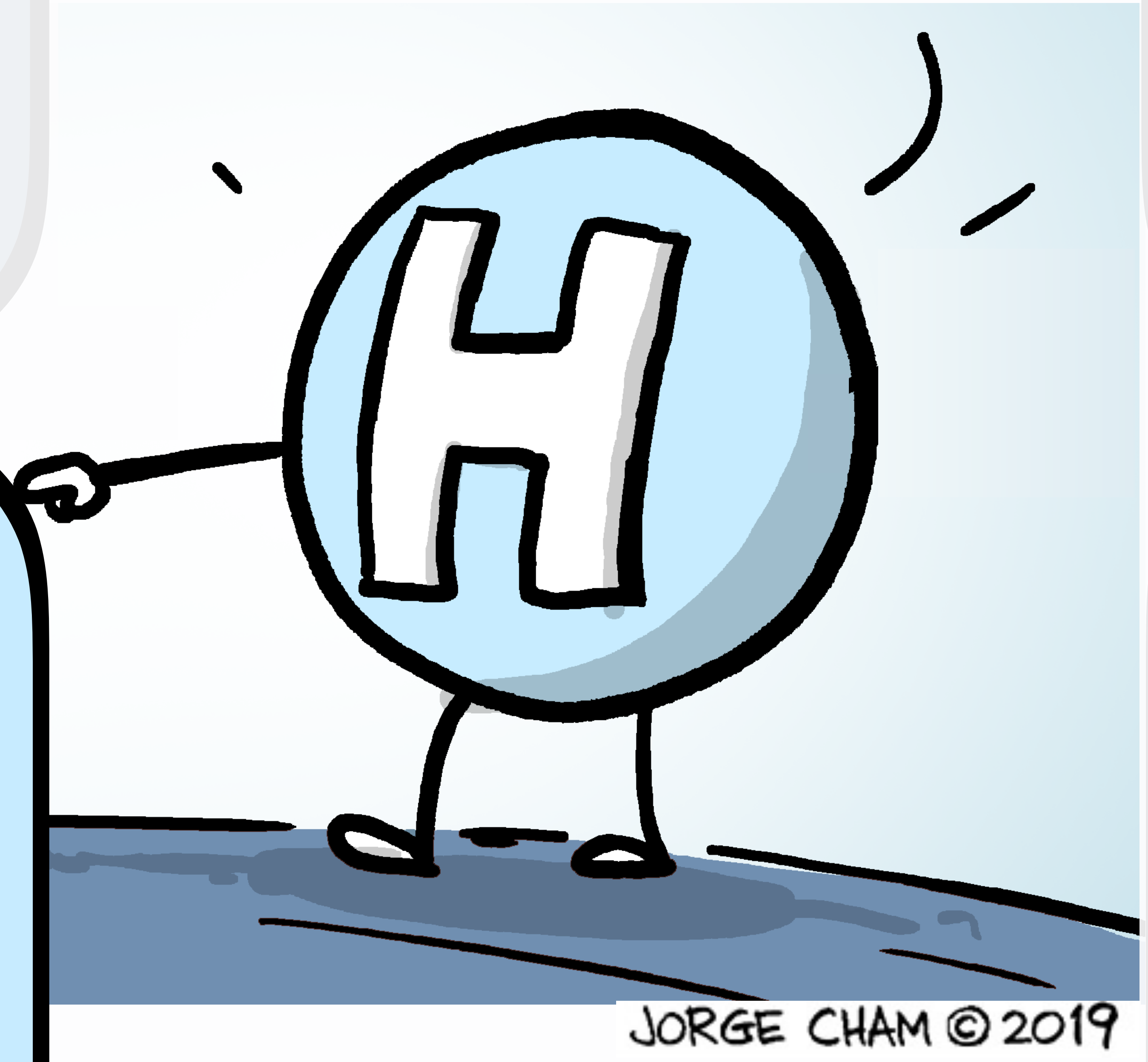

BSM Searches

- Additional scalars (charged, heavy, light)
- Exotic decays
- Anomalous couplings

Rare decays/production

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The Higgs Boson Landscape Nowadays

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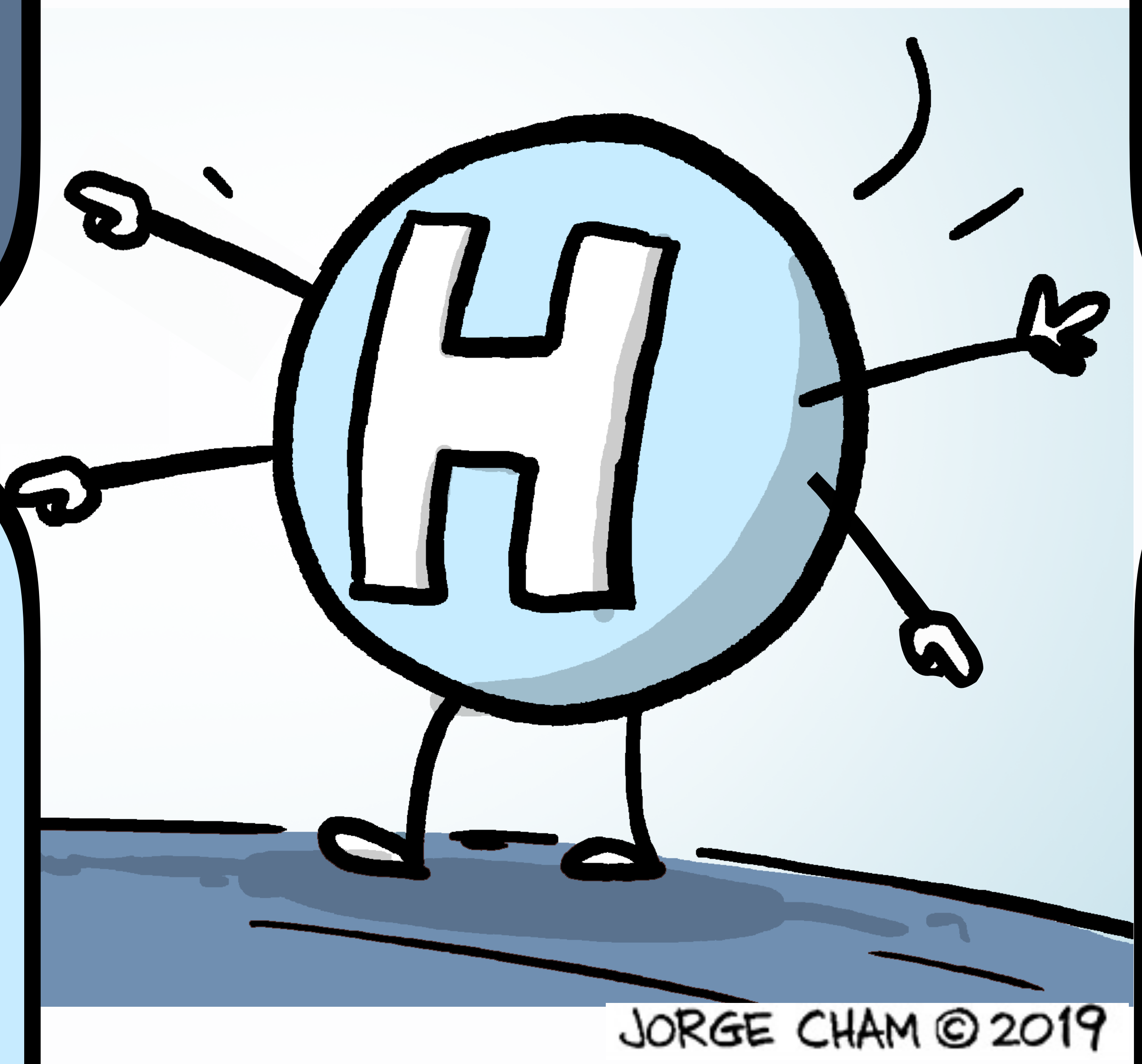


BSM Searches(*)

- Additional scalars (charged, heavy, light)
- Exotic decays
- Anomalous couplings

Rare decays/production

- 2nd -generation fermion
- Decay to mesons(*)
- tHq/tHW(*)
- Self coupling (HH production)
- Invisible decays(*)

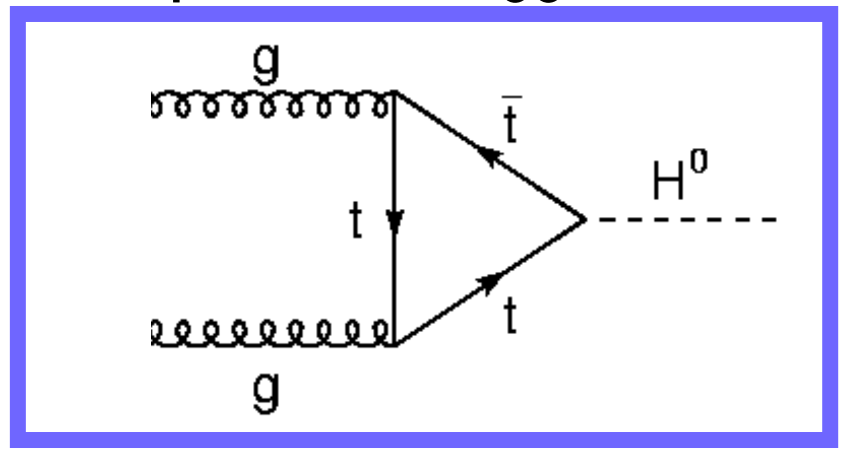
(Almost) all the results shown today are new since last EPS-HEP conference, some (NEW!) have been released in the last days

(*) In backup

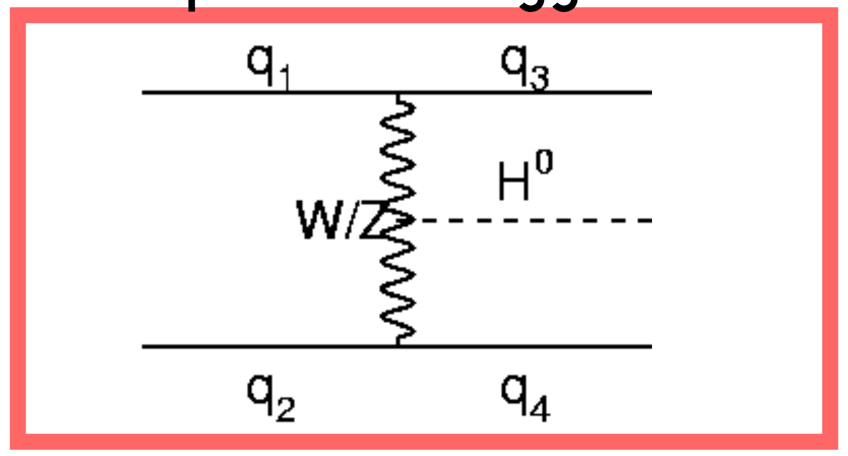
THE HIGGS BOSON PRODUCTION AND DECAY

"just a reminder"

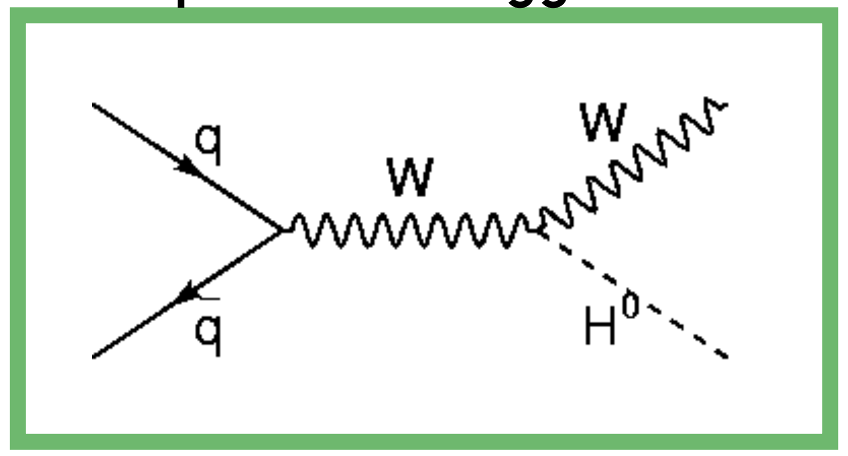
σ=49 pb / 6.9M Higgs in 140fb^{-1}



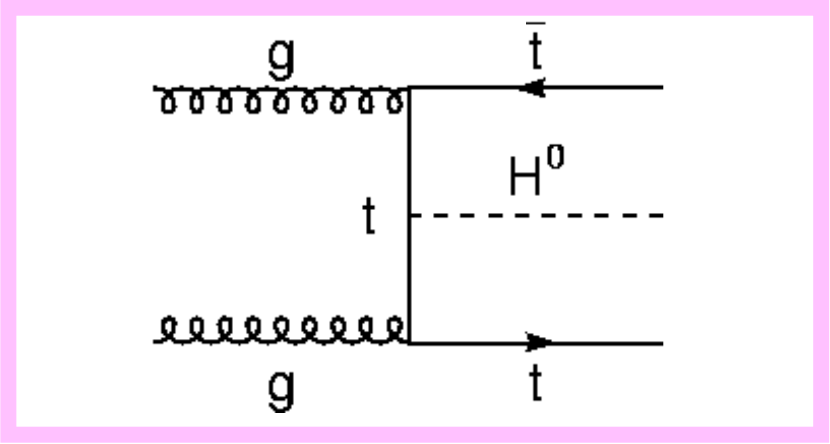
σ=3.8 pb / 520k Higgs in 140fb^{-1}

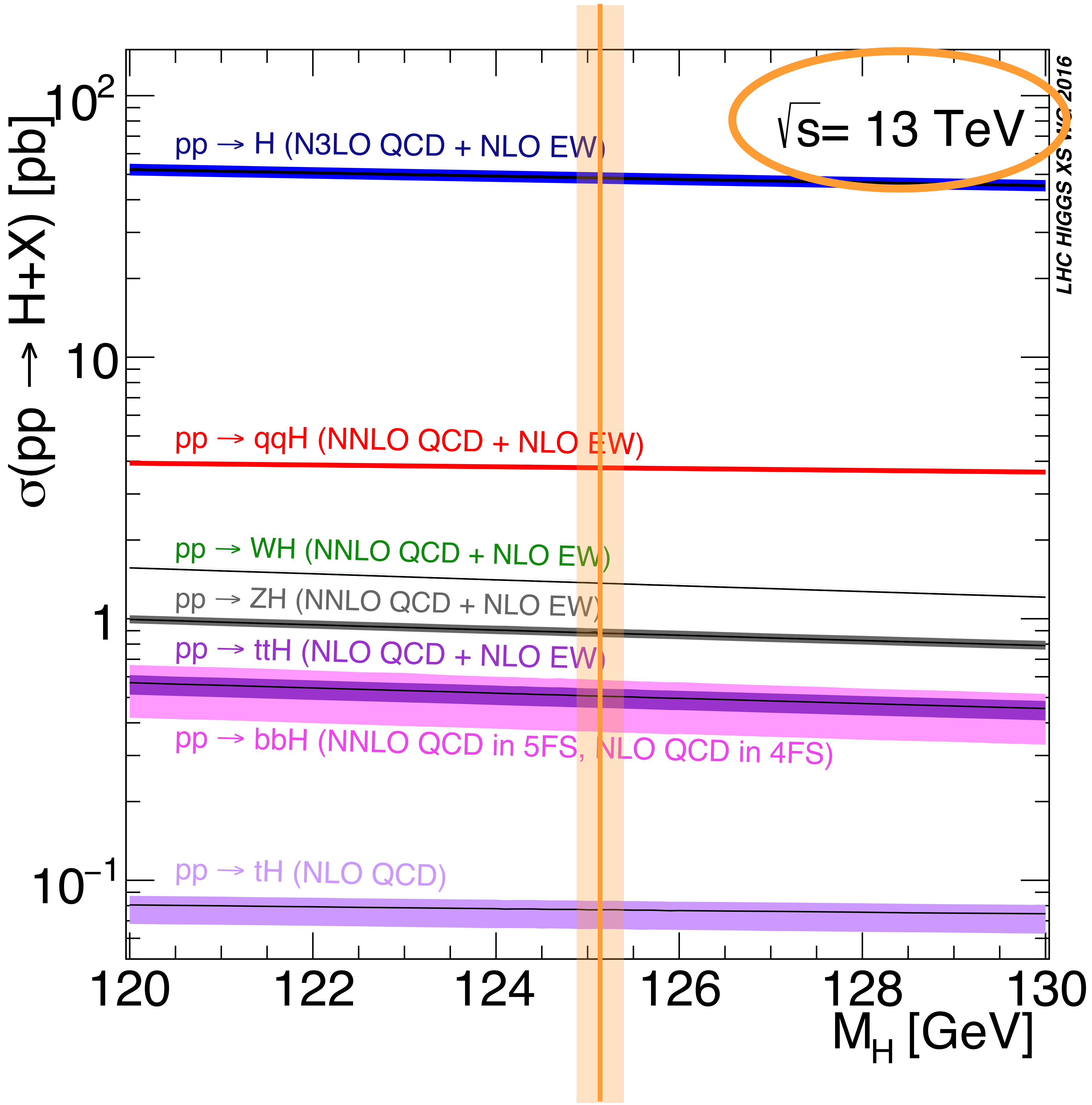


σ=2.3 pb / 320k Higgs in 140fb^{-1}



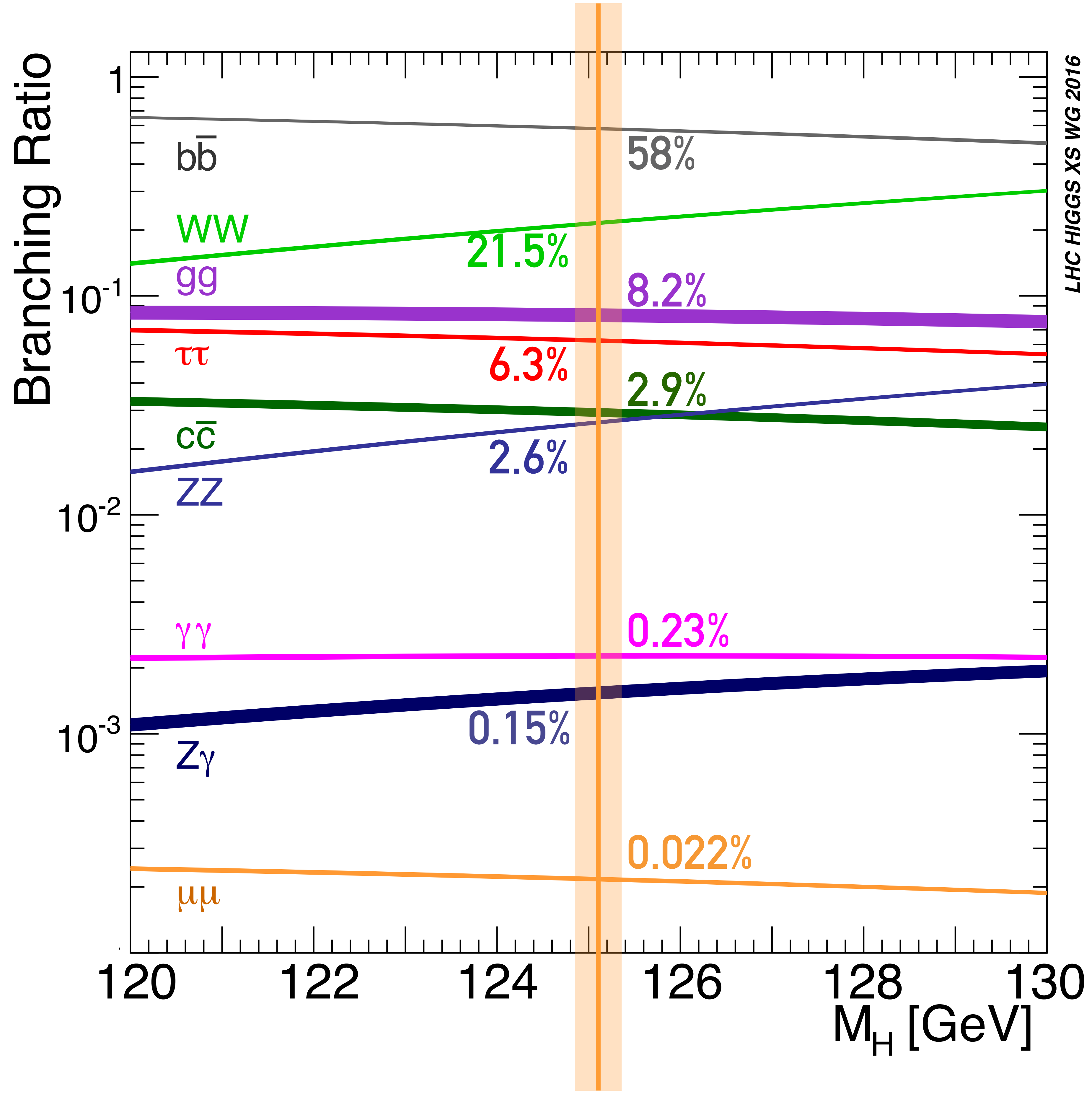
σ=0.5 pb / 70k Higgs in 140fb^{-1}





125.09 ± 0.24 GeV

LHC Run1 measurement



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LHC Run1 measurement

The H Profile

THE HIGGS BOSON MASS

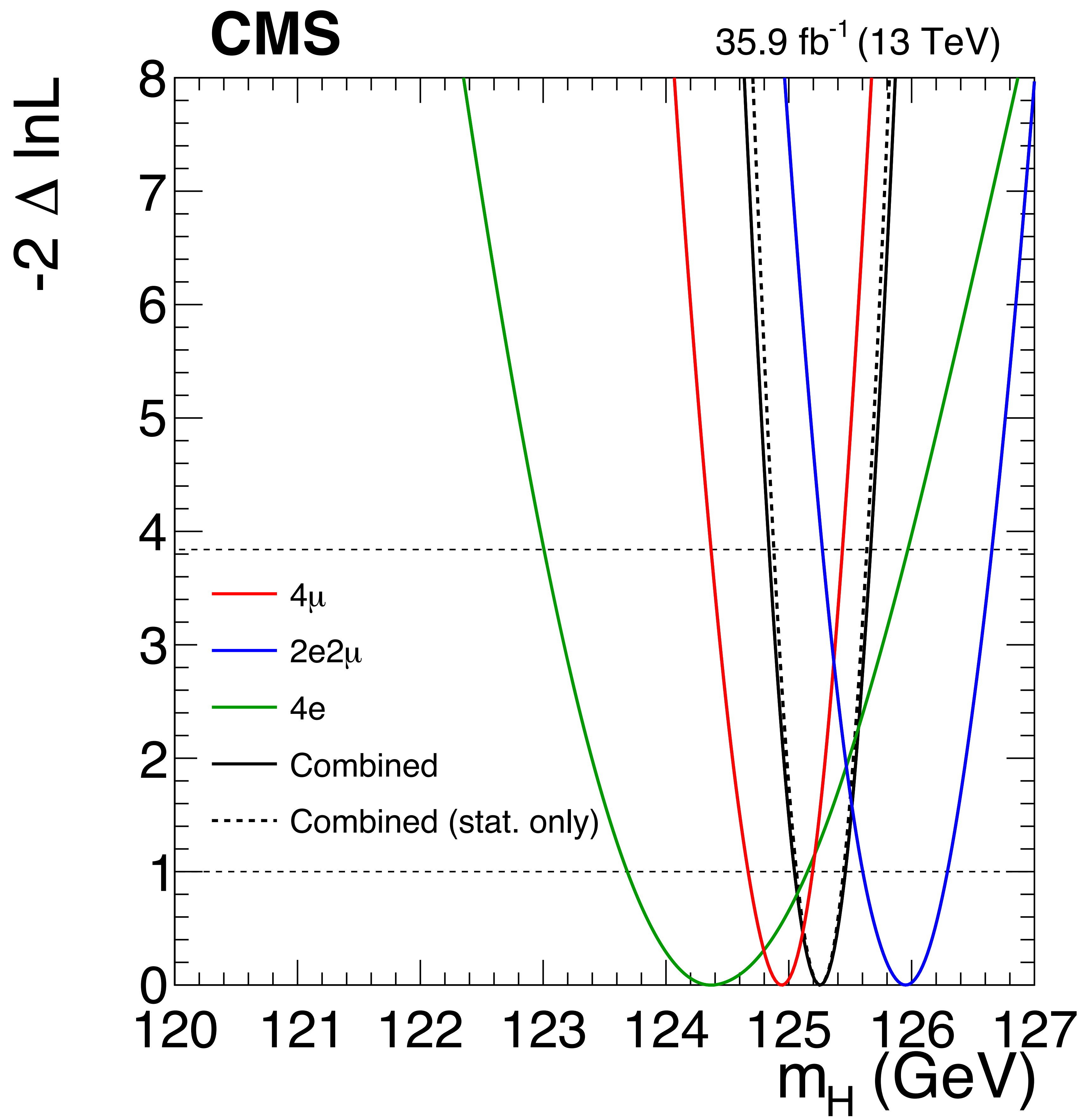
JHEP 11(2017)047
PLB 784(2018)345

m_H the single parameter that completely determined SM the Higgs sector

"Mass Peaks" → "Mass Measurements"

using high resolution channels ($4\ell+\gamma\gamma$)

	m_H ± tot (± stat ± syst)
ATLAS $4\ell+\gamma\gamma$ (Run1+ 36/fb Run2)	124.97 ± 0.24 (± 0.16 ± 0.18) GeV
CMS 4ℓ (36/fb Run2)	125.26 ± 0.21 (± 0.20 ± 0.08) GeV
LHC $4\ell+\gamma\gamma$ (Run1)	125.09 ± 0.24 (± 0.21 ± 0.21) GeV



~200 MeV precision, measurements dominated by statistical uncertainties

Among the most precise EWK parameters

The H Profile

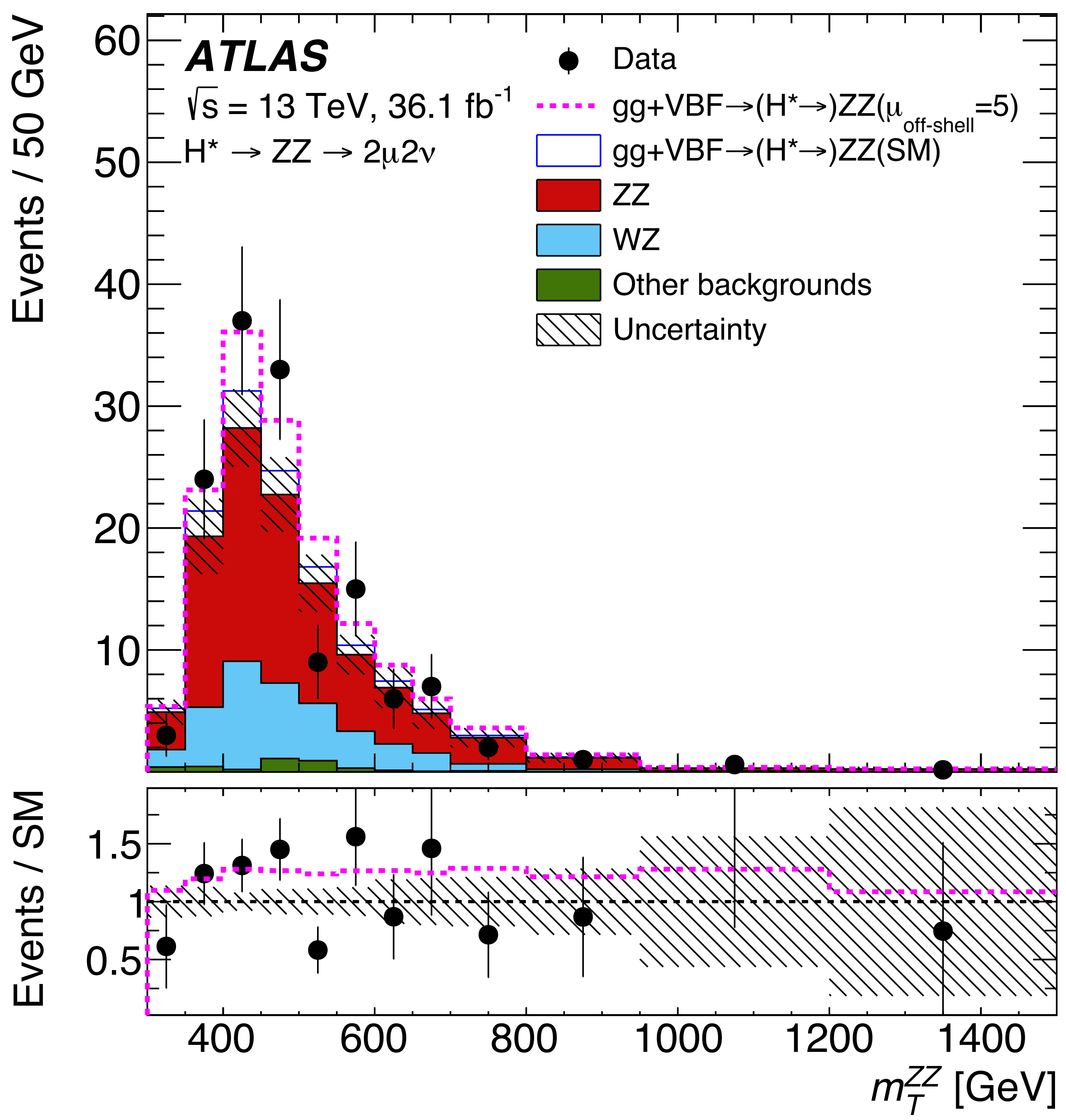
THE HIGGS BOSON WIDTH

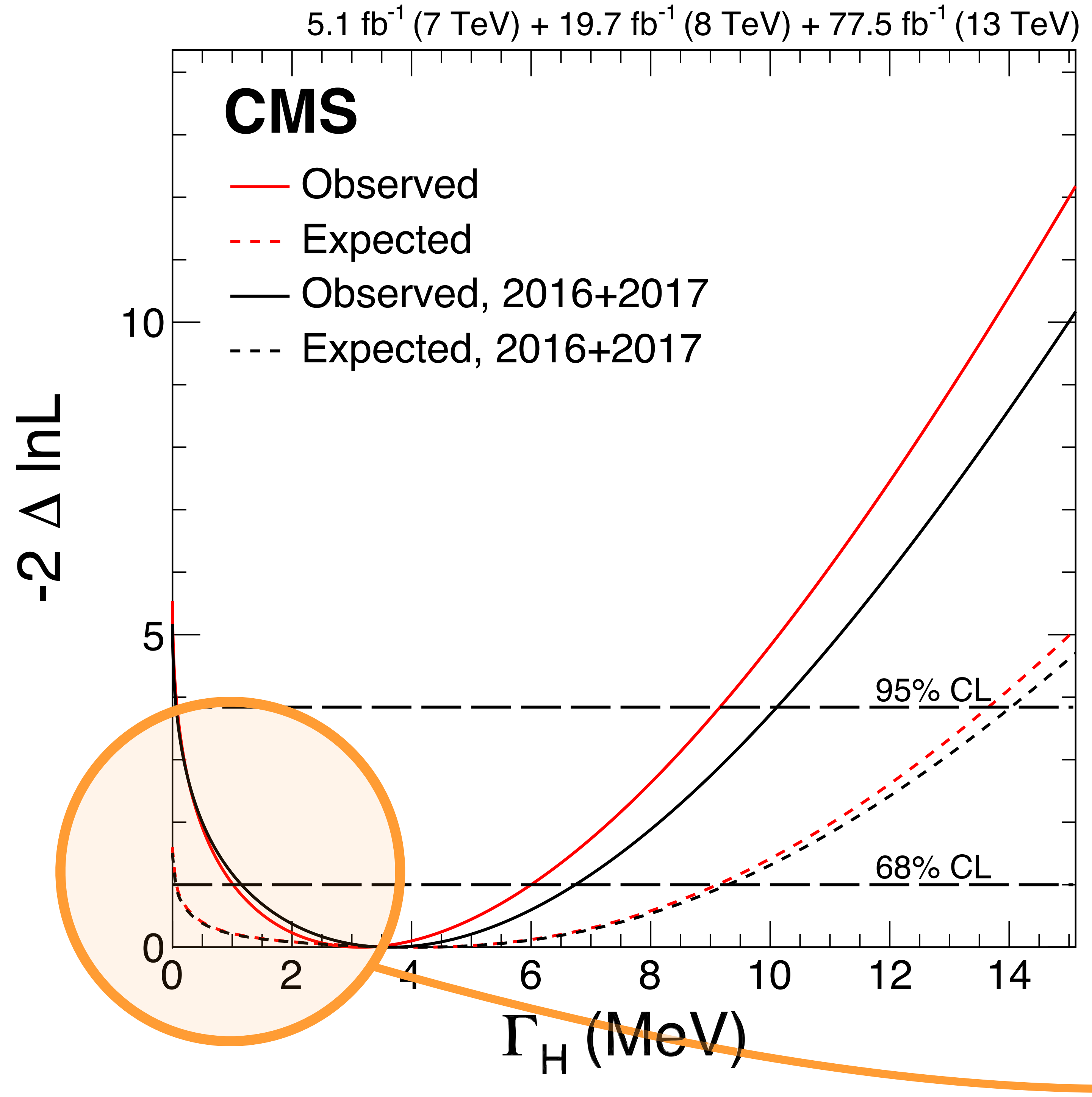
PRD 99(2019)112003
PLB 786 (2018) 223

A crucial parameter for BSM searches, in SM $c\tau_H = 48$ fm, small width $\Gamma_H = 4.1$ MeV

Direct measurements (on-shell line shape, lifetime) limited by detector resolutions, the way out are indirect measurements (couplings, off-shell production)

$$\frac{\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \dfrac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}}{\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \dfrac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}}$$





	obs. 95% CL on Γ_H
ATLAS $4\ell+2\ell2\nu$ (36/fb Run2)	$\Gamma_H < 14.4$ MeV
CMS 4ℓ (Run1 + 77/fb Run2)	$0.08 < \Gamma_H < 9.16$ MeV

Start to place a lower bound on Γ_H

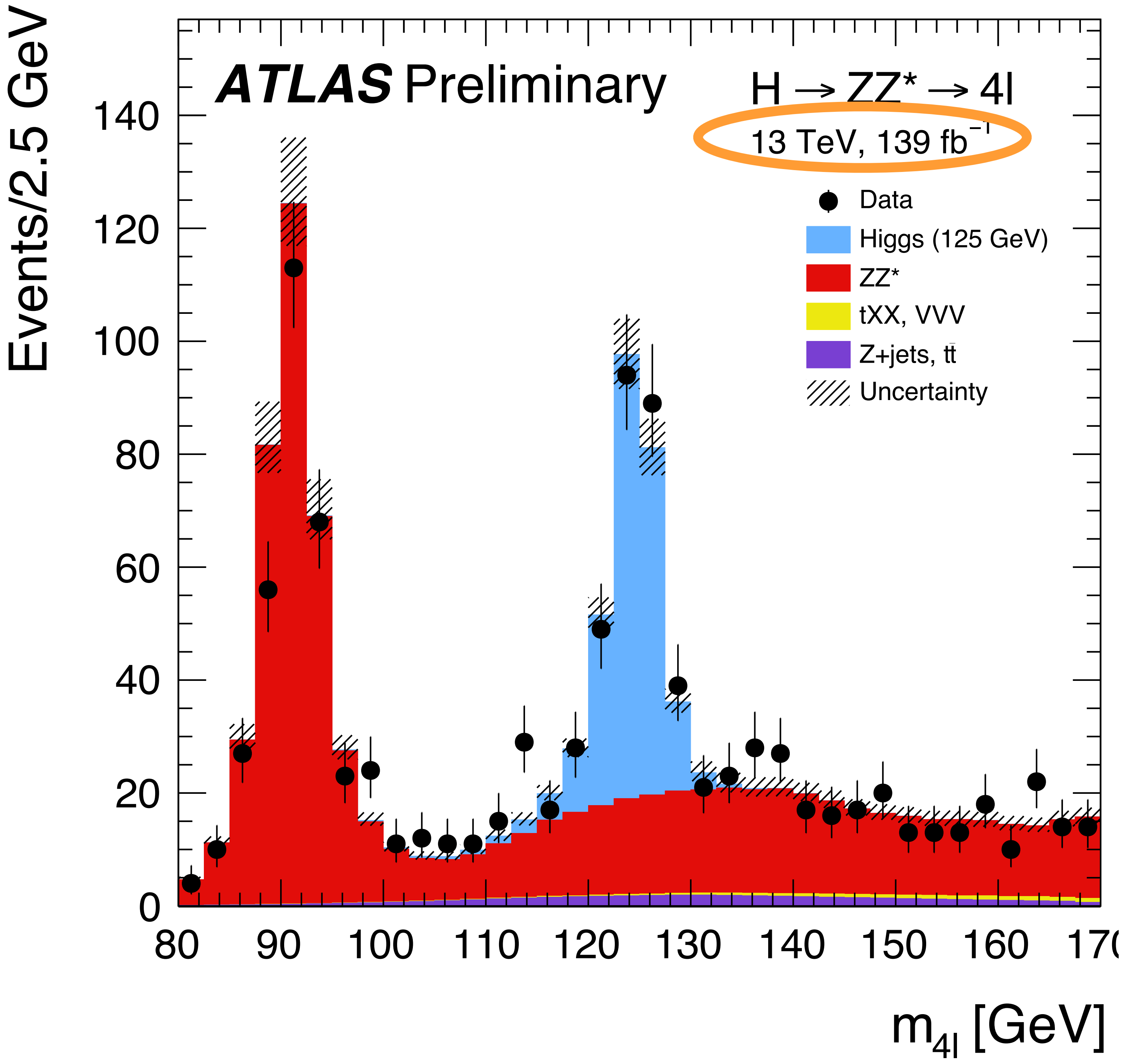
The H Profile

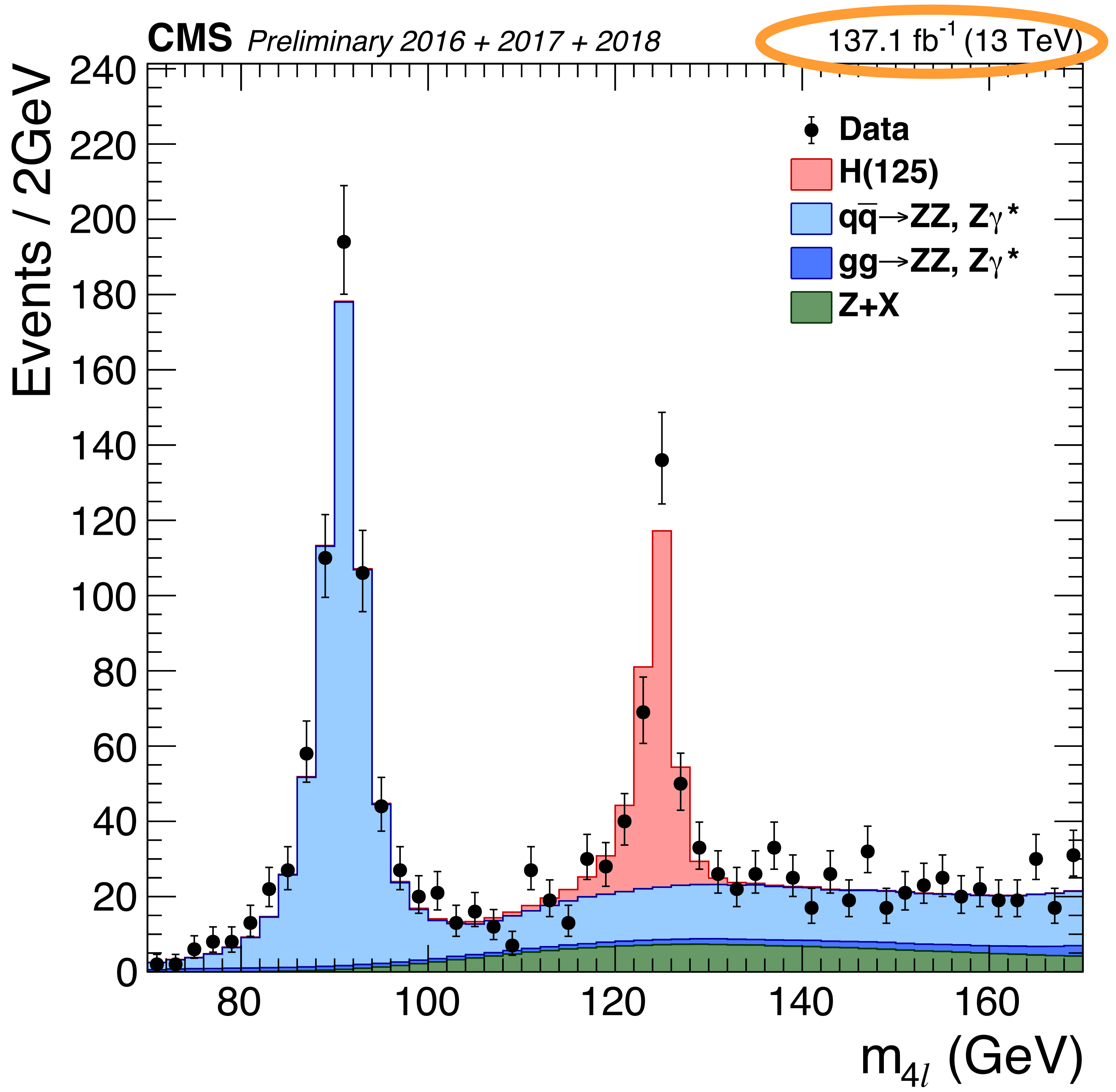
Coupling Properties with H→ZZ→4l

CMS-PAS-HIG-19-001
NEW! CONF-HIGG-2019-025

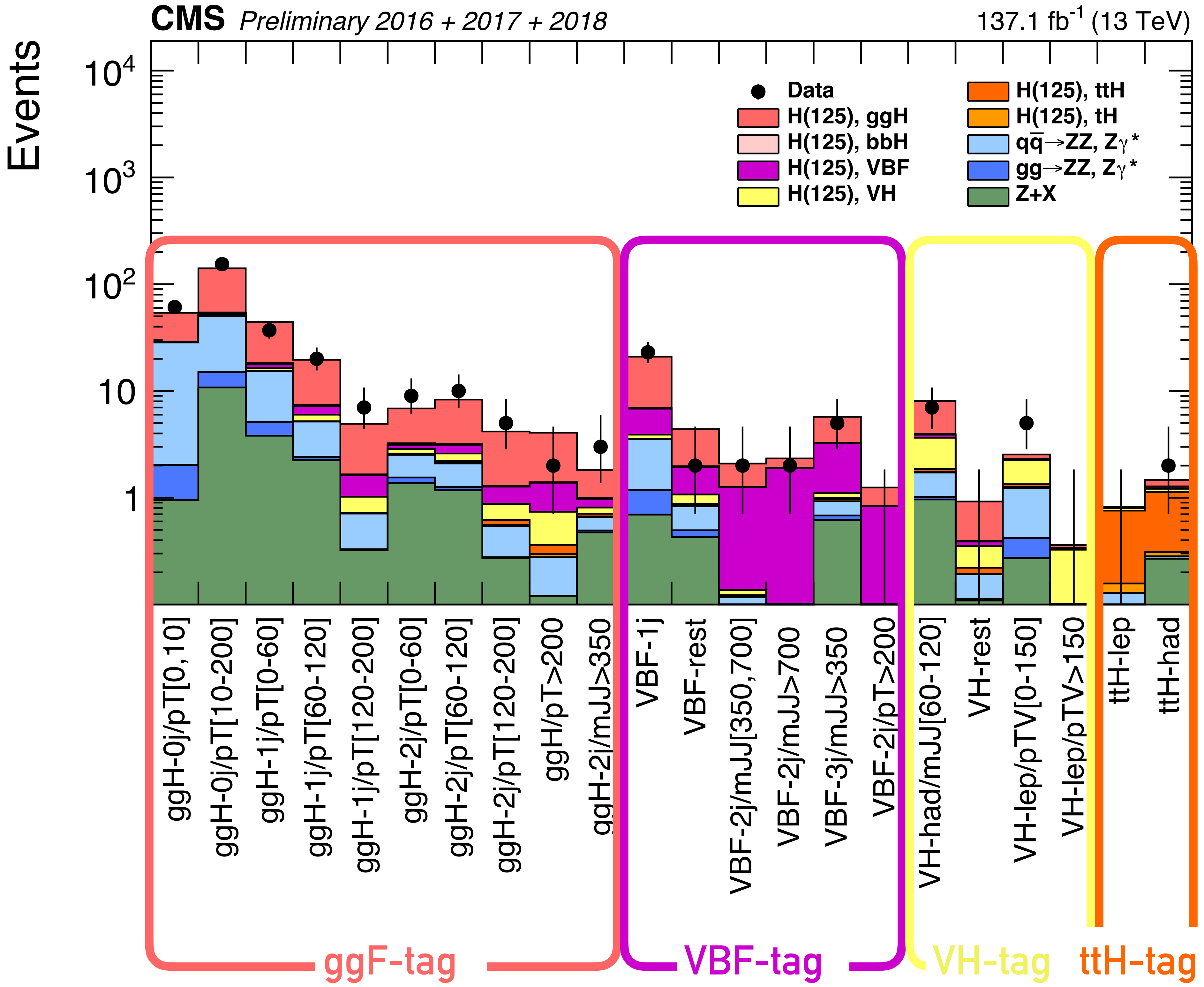
Final state has been updated with full LHC Run2 dataset

>200 signal events per experiment





Production tags based on full event topology and MVA/ME discriminants exploiting full decay and production information



	global signal strength (μ)(*)	
ATLAS 4ℓ (full Run2)	$1.04^{+0.12}_{-0.10}$ (tot)	$[^{+0.09}_{-0.08}$ (stat) $^{+0.04}_{-0.03}$ (exp) $^{+0.06}_{-0.05}$ (th)$]$
CMS 4ℓ (full Run2)	$0.94^{+0.11}_{-0.10}$ (tot)	$[^{+0.07}_{-0.07}$ (stat) $^{+0.08}_{-0.07}$ (syst)$]$

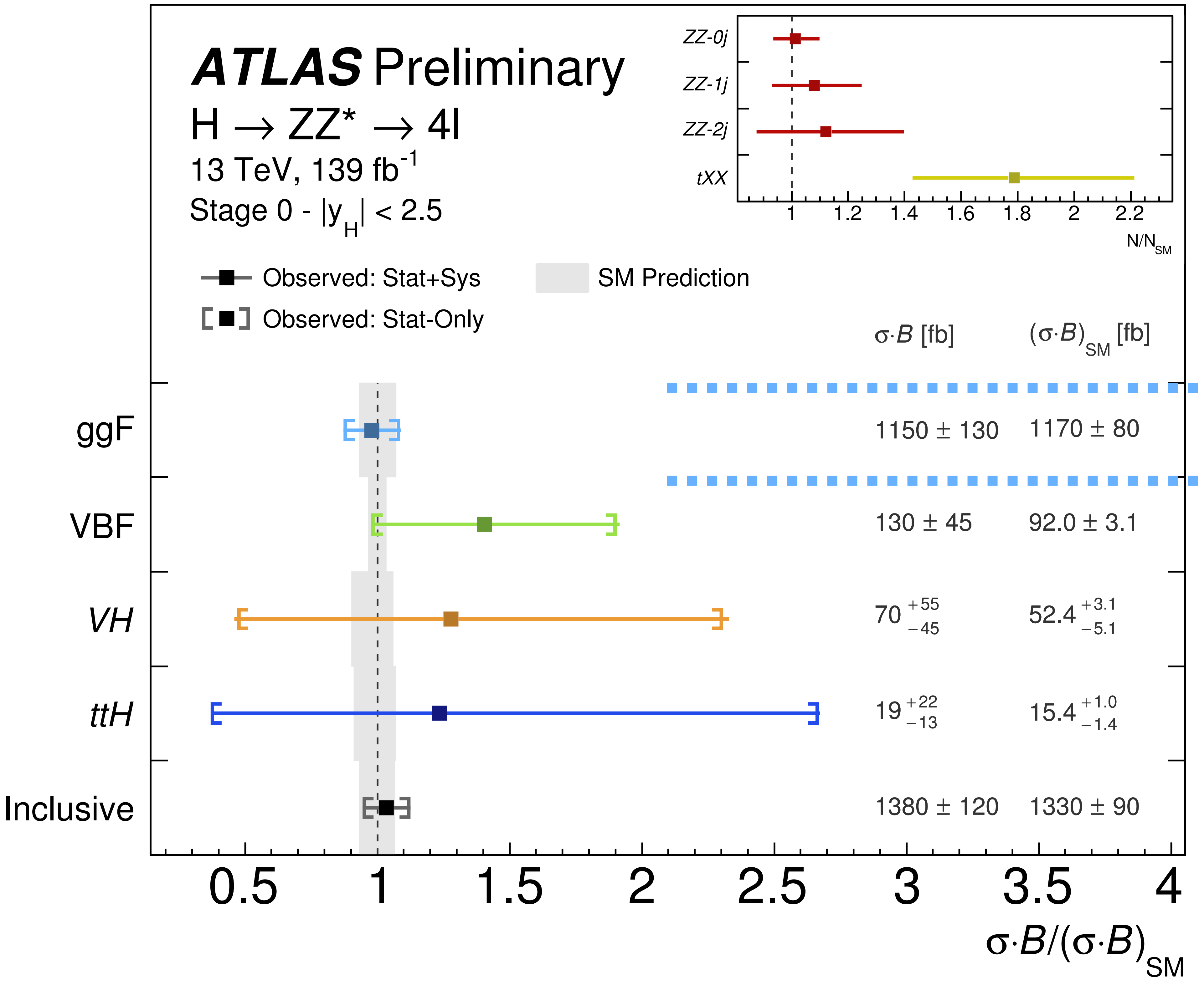
(*) signal strength defined as the ratio of the measured Higgs boson rate to its SM prediction

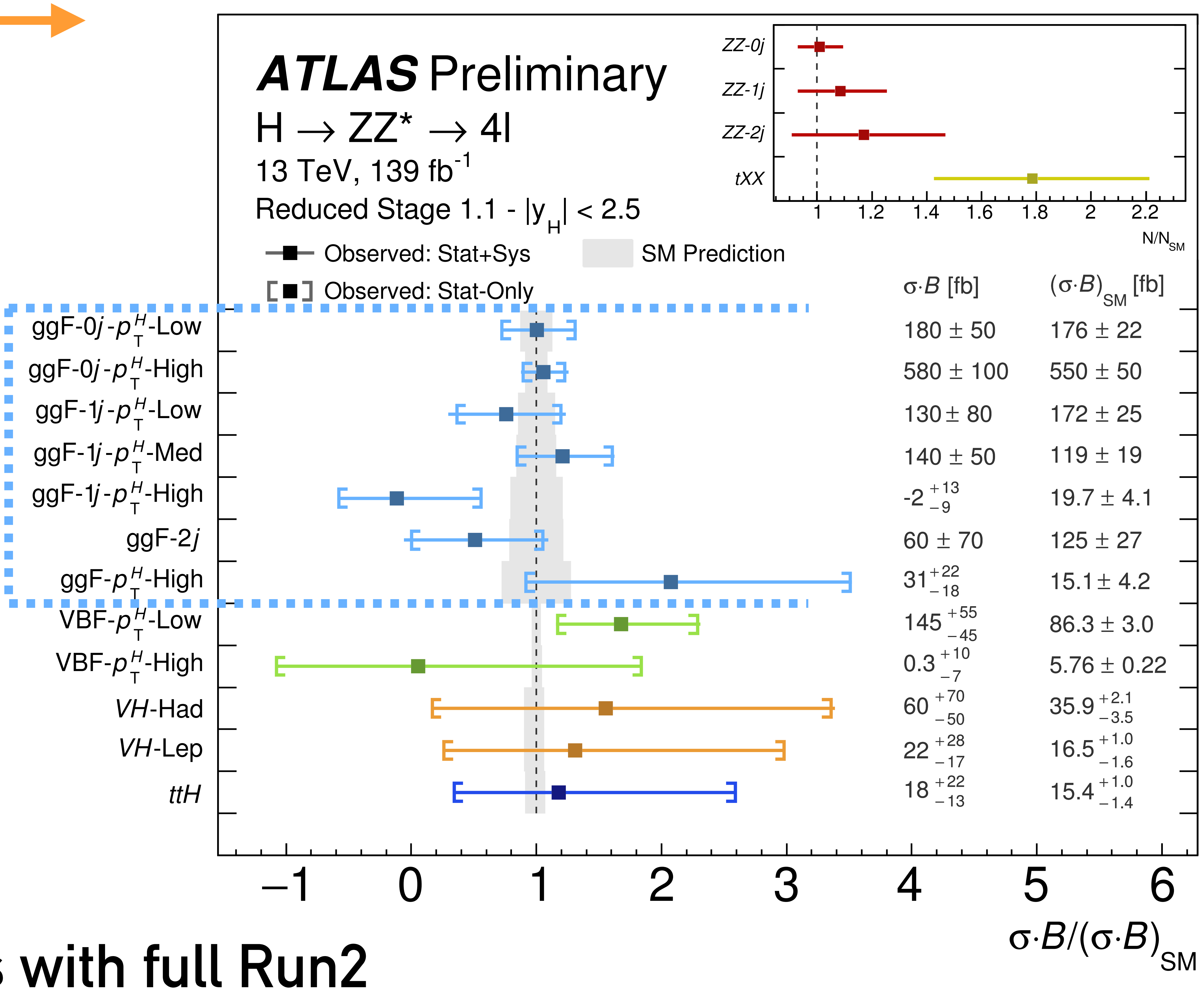
COUPLING PROPERTIES WITH H→ZZ→4l

CMS-PAS-HIG-19-001
NEW! CONF-HIGG-2019-025

Simplified Template XS (STXS) framework : measure Higgs boson cross sections per production modes and in different regions of the kinematics phase space

From "Stage 0" just Higgs boson production bins… … to "Stage 1.1" bins with finer split of kinematics regions





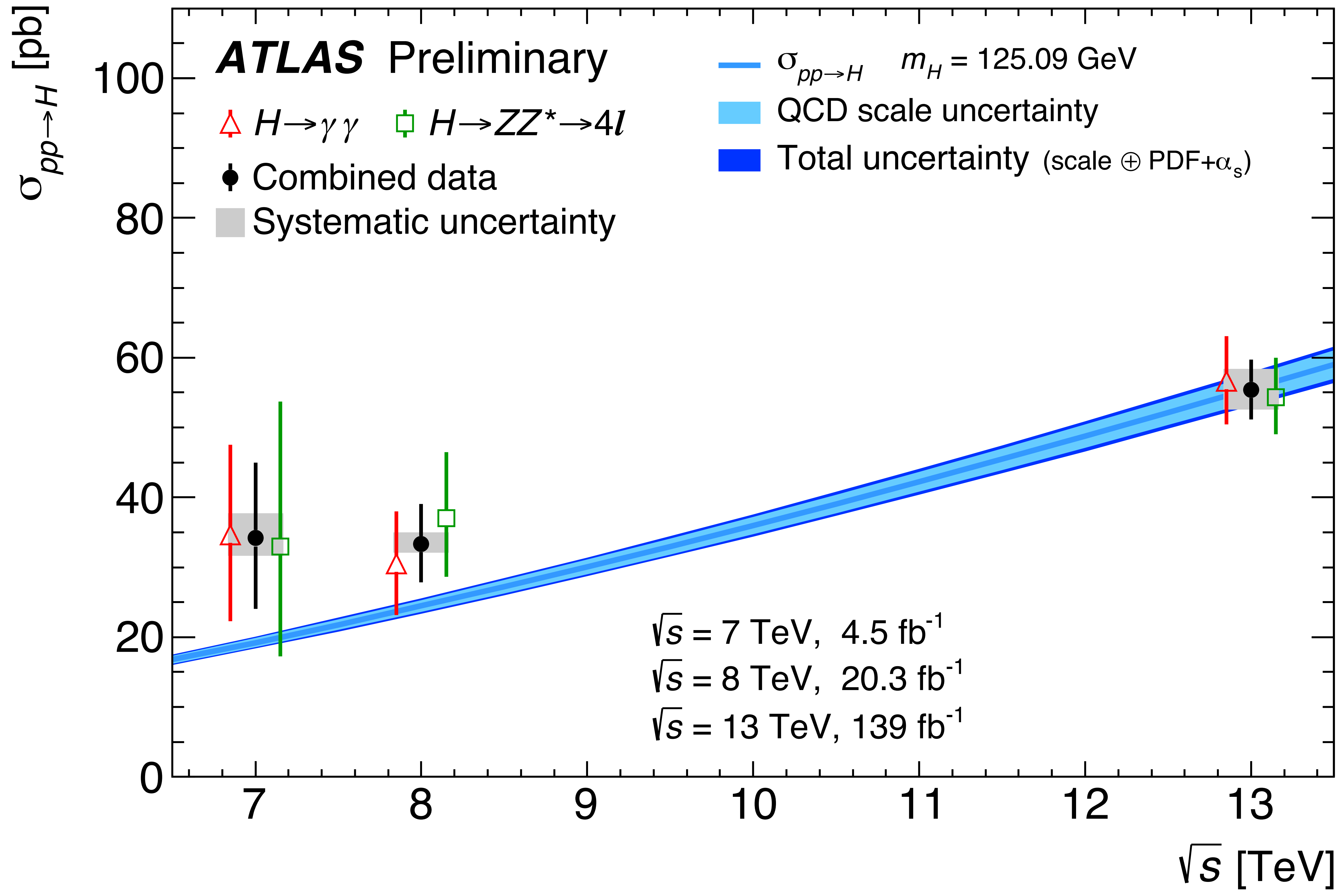
Similar CMS results with full Run2

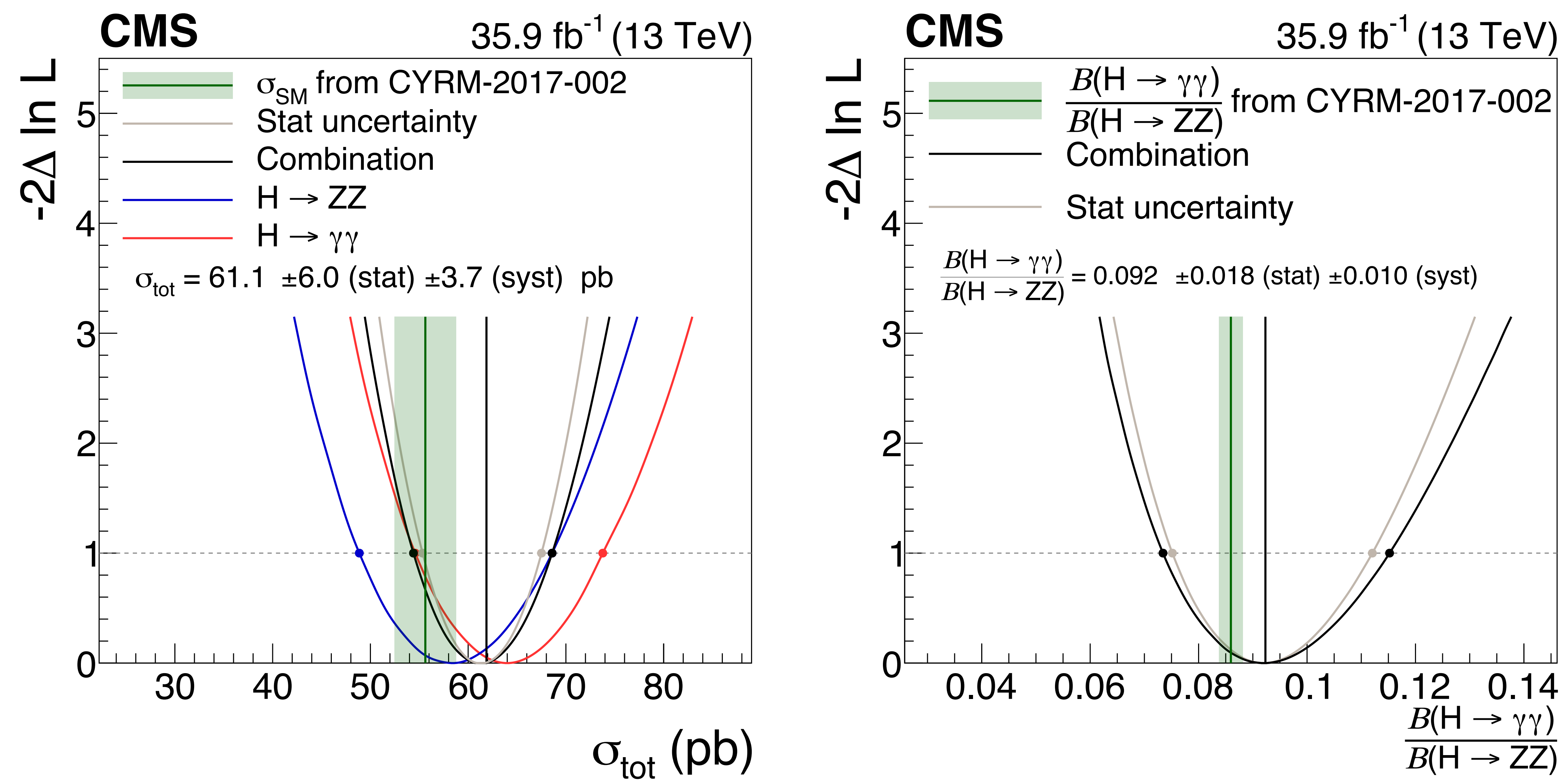
The H Profile

Total Cross Section Measurements

PLB 792(2019)369
NEW! CONF-HIGG-2019-032

Obtained from $H \to ZZ \to 4l$, $H \to \gamma\gamma$, and their combination. The ratio of BRs for two decay channels is measured.





	Total H production xsec
ATLAS $\gamma\gamma$ (full Run2)	$56.7^{+6.4}_{-6.2}$ pb
4ℓ (full Run2)	$54.4^{+5.6}_{-5.4}$ pb
Combination	$55.4\ ^{+3.1}_{-3.1}$ (stat) $^{+3.0}_{-2.8}$ (syst) pb
CMS $\gamma\gamma$ (36/fb Run2)	$64.4^{+9.6}_{-9.6}$ pb
4ℓ (36/fb Run2)	$58.2^{+9.8}_{-9.8}$ pb
Combination	$61.1\ ^{+6.0}_{-6.0}$ (stat) $^{+3.7}_{-3.7}$ (syst) pb
SM prediction	55.6 ± 2.5 pb

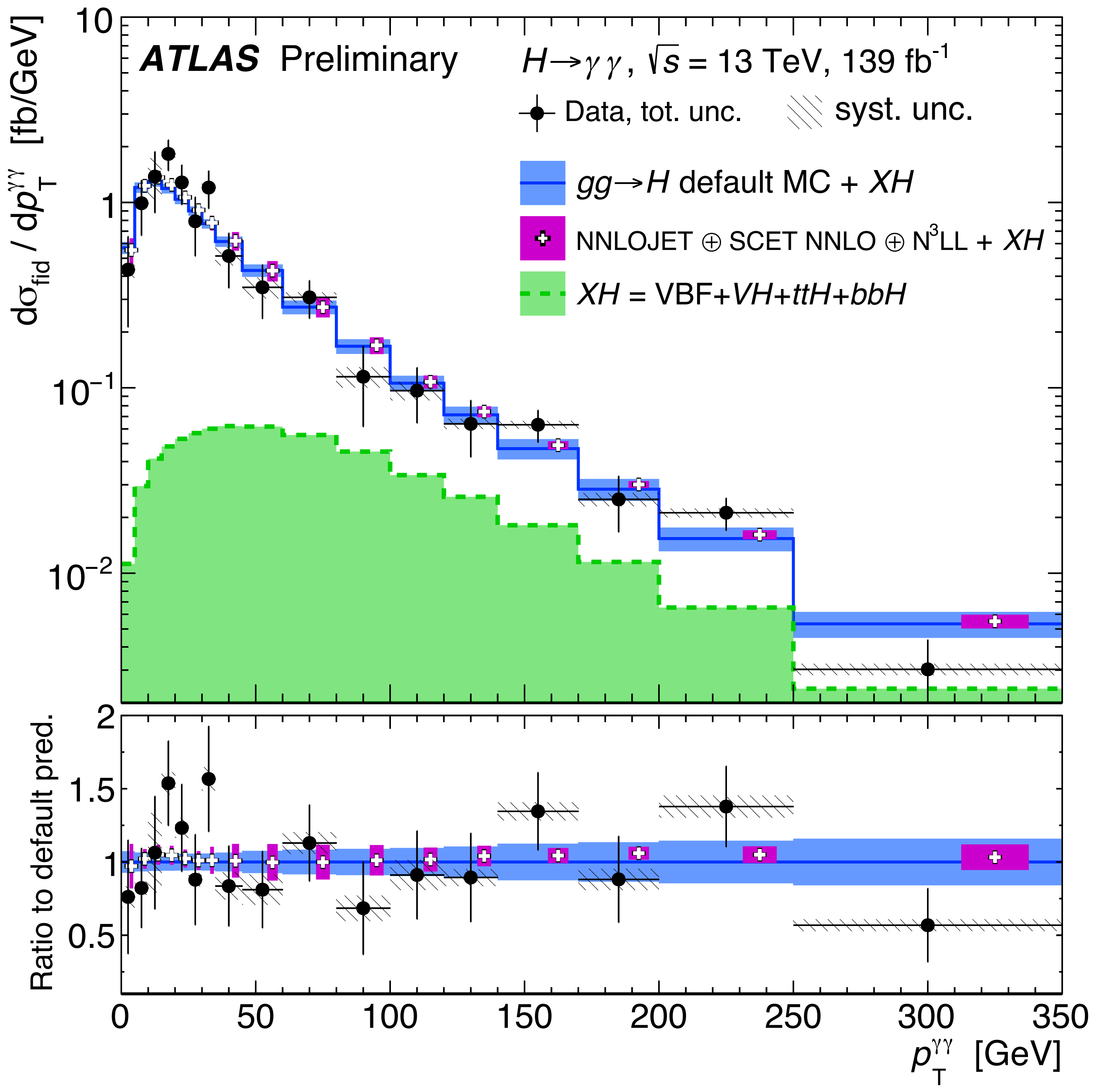
In agreement with the SM prediction

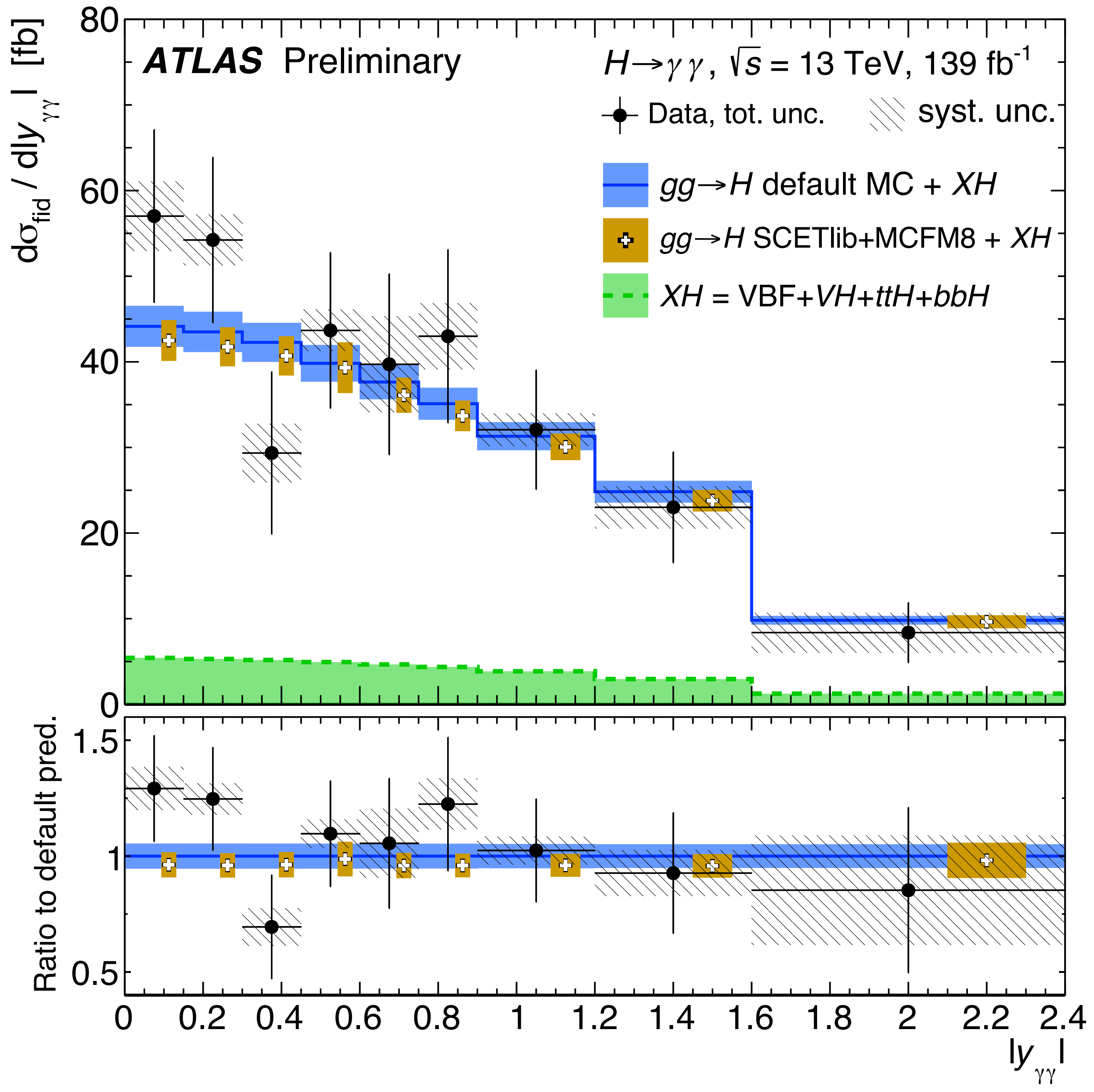
DIFFERENTIAL CROSS SECTION MEASUREMENTS

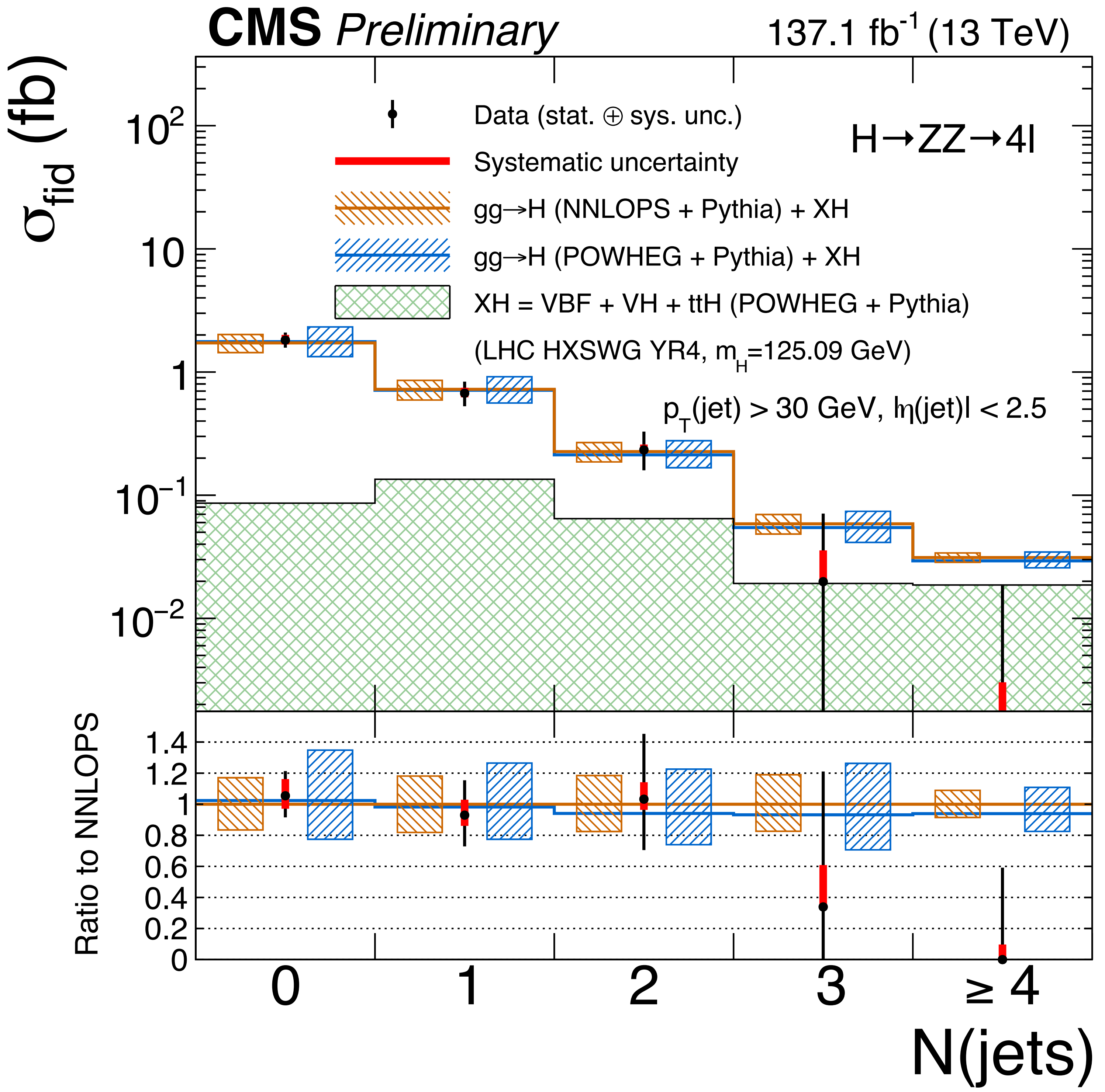
CMS-PAS-HIG-19-001
CONF-HIGG-2019-029

Finer granular measurements in specific observables

Measure a large numbers of distributions ($p_T^{\gamma\gamma}$, $p_T^{4\ell}$, $|Y_{\gamma\gamma}|$, $|Y_{4\ell}|$, N_{jets}, p_T^{jet1}, m_{jj}, $\Delta\varphi_{jj}$, ...) and compare with various predictions







These measurements allow to constrain Wilson coefficients of an effective Lagrangian and coupling not directly accessible (e.g charm-H interaction)

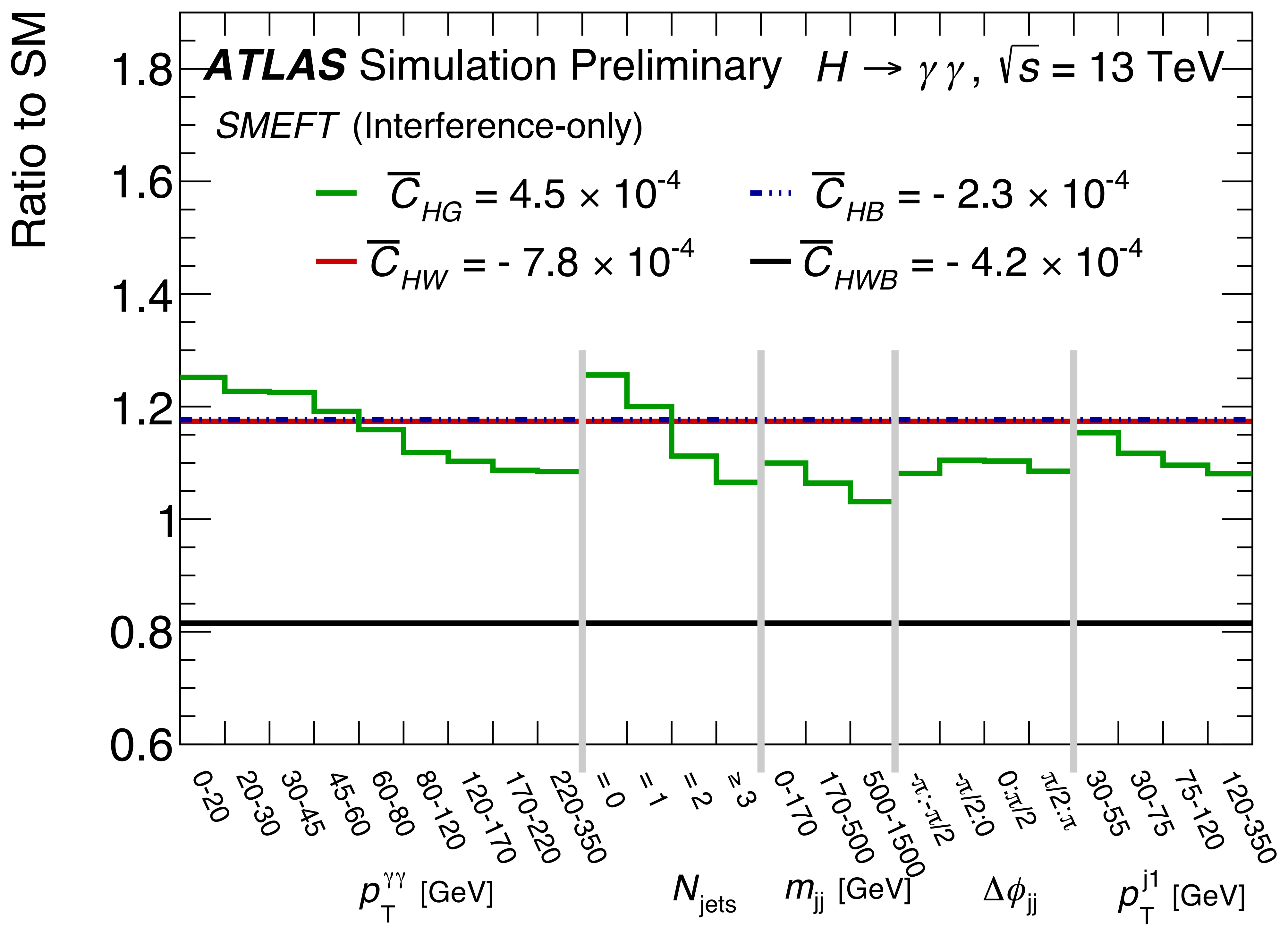
The H Profile

ANOMALOUS INTERACTIONS SEARCH WITH EFT

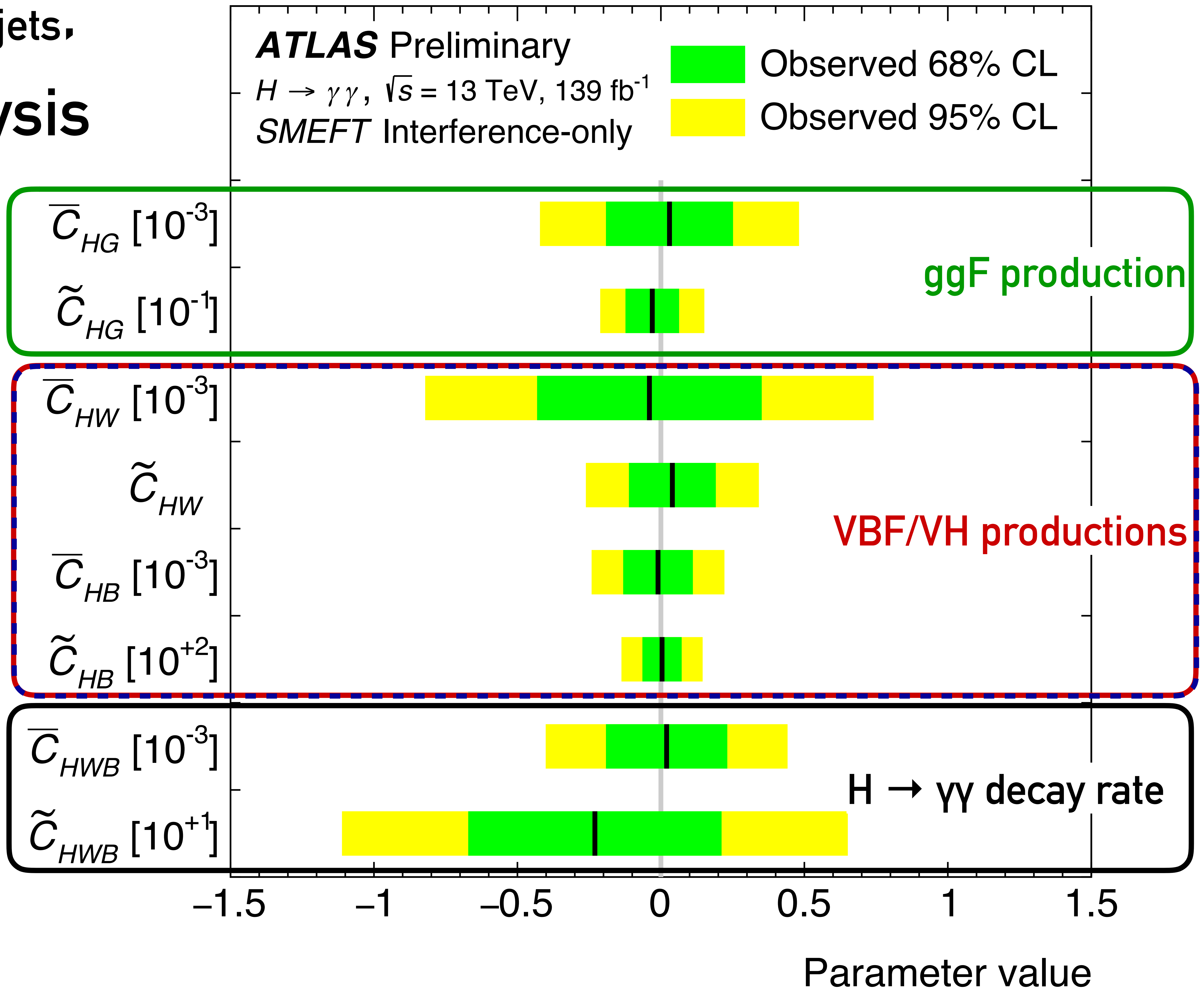
NEW! CONF-HIGG-2019-029

Using the 5 differential distributions ($p_T^{\gamma\gamma}$, N_{jets}, m_{jj}, $\Delta\varphi_{jj}$, p_T^{jet1}) measured in the $H\rightarrow\gamma\gamma$ analysis

Interpretations in SHIL and SMEFT bases



The effect on differential distributions of the four CP-even coefficients in the SMEFT basis



Constraints one Wilson coefficient at the time, the other coefficients are assumed to vanish

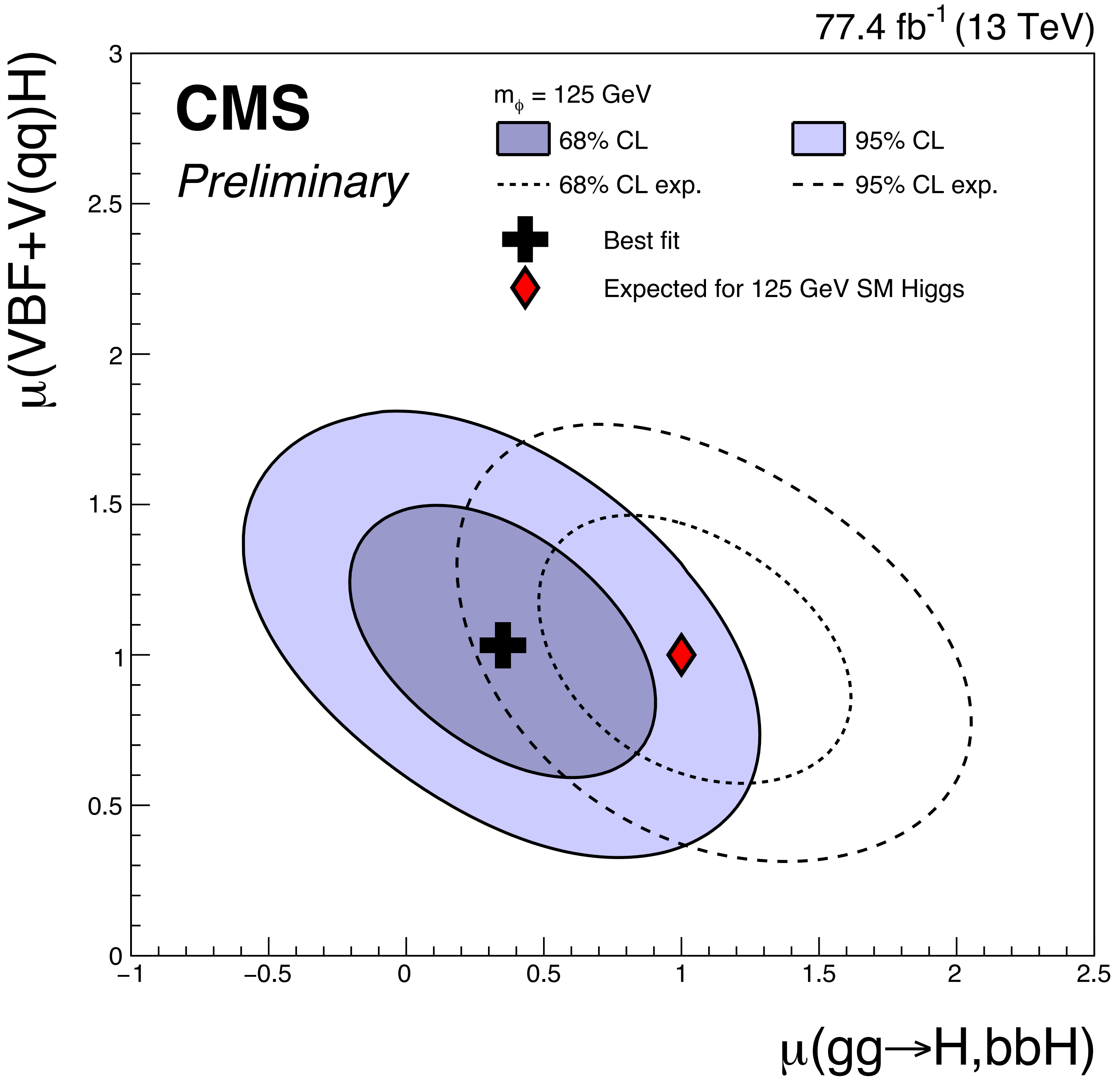
The H Profile

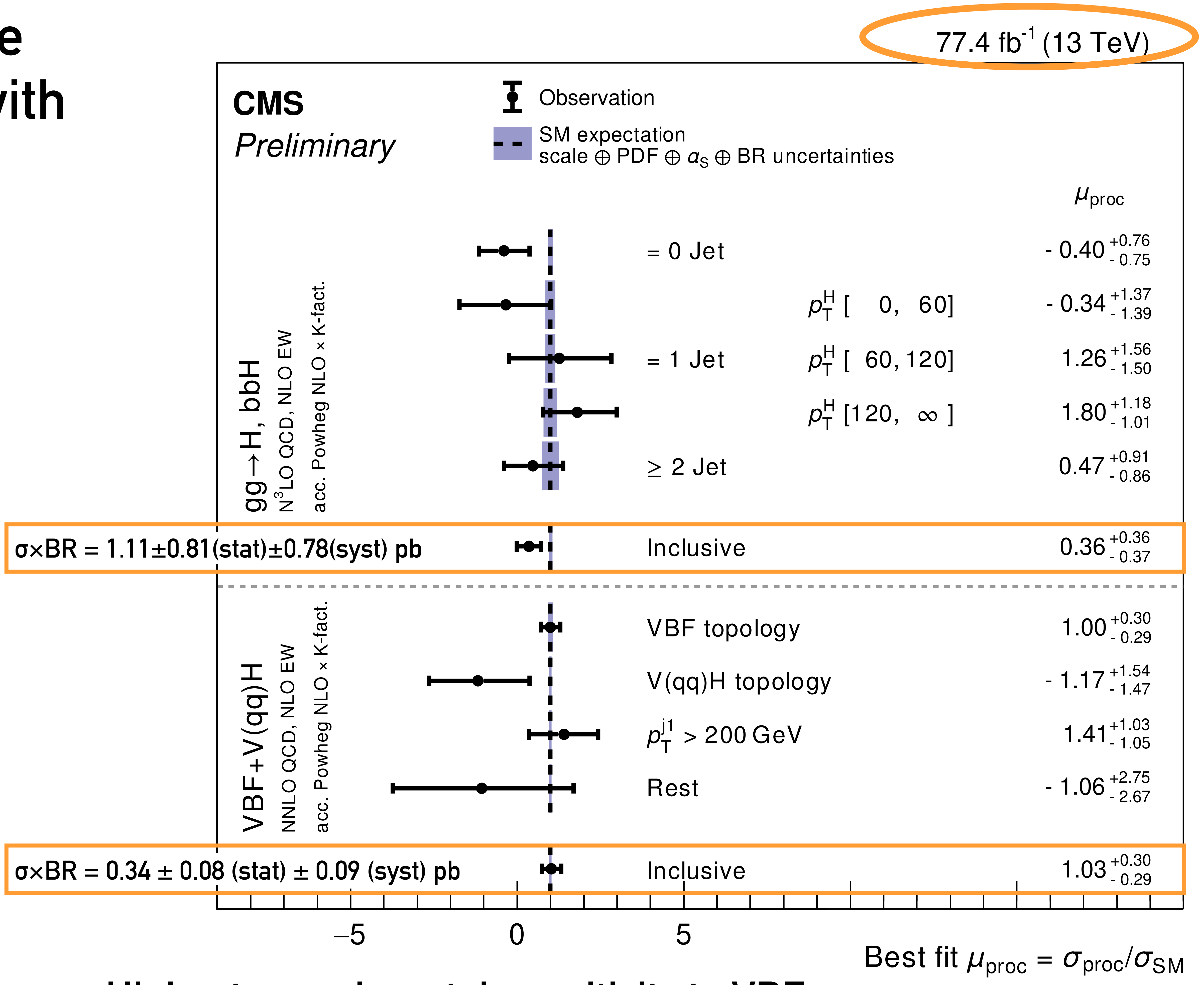
Discovery → Properties

3rd–Generation Fermion Coupling : τ–H

After the single experiments independent observations → perform cross section measurements split by production modes and in different kinematic regimes (STXS)

Improvements in the CMS 77/fb analysis: machine learning for categorization, 90% of backgrounds with data-driven methods





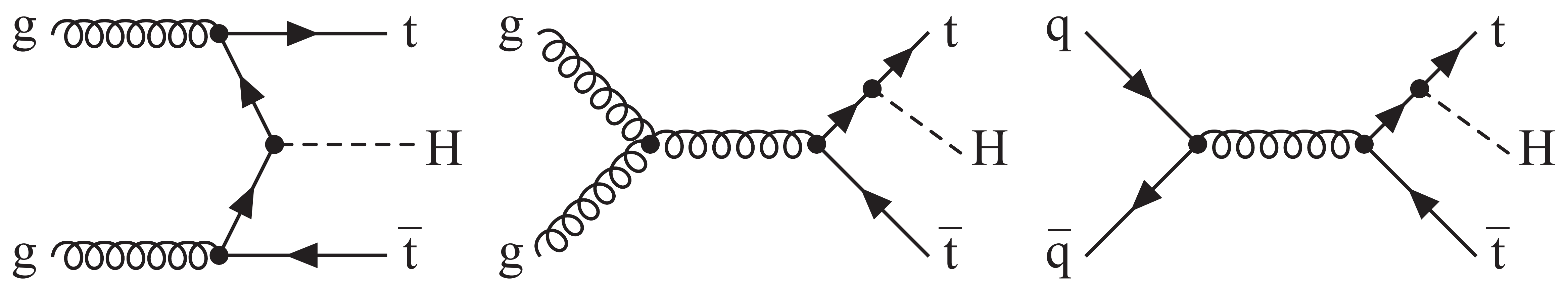
Highest experimental sensitivity to VBF

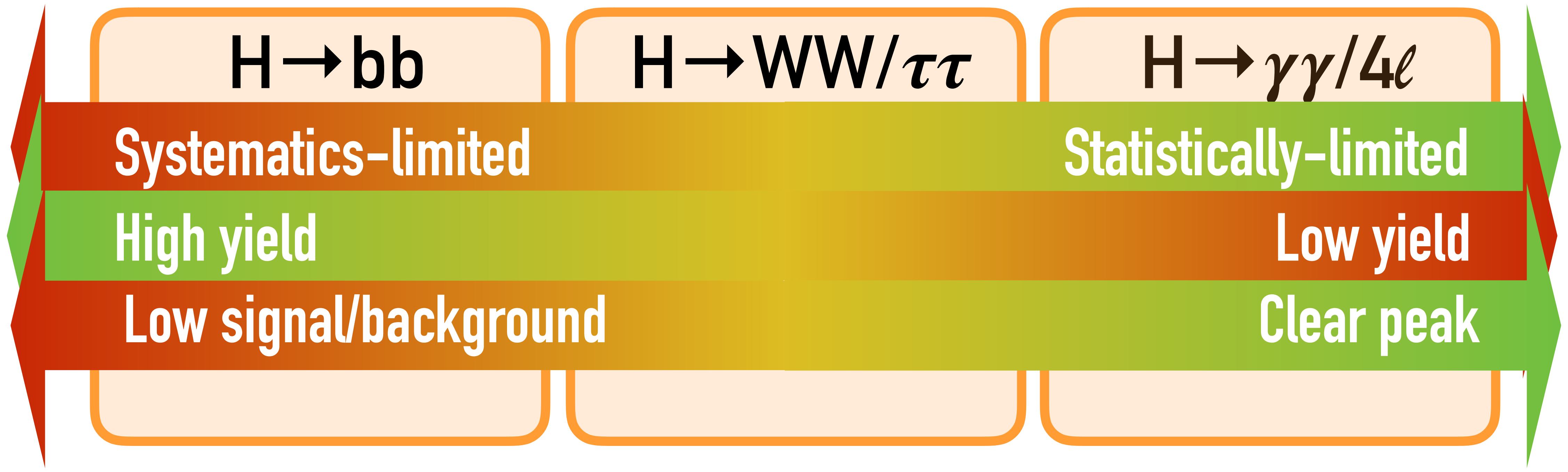
Discovery→Properties

3rd–GENERATION FERMION COUPLING : t–H

PRL 120(2018)231801
PLB 784(2018)173

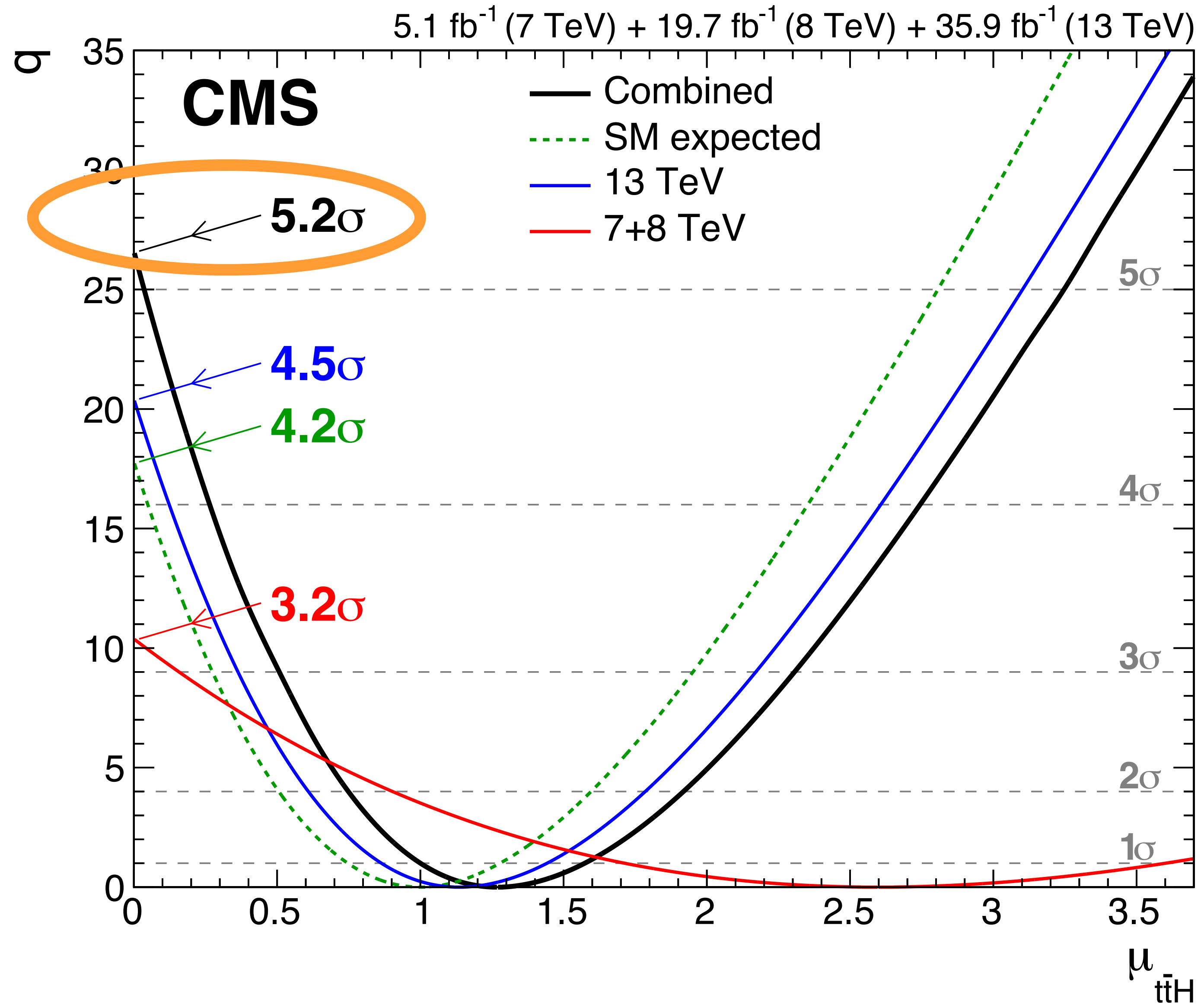
Only directly accessible when H is produced in association with 1 or >1 top quarks

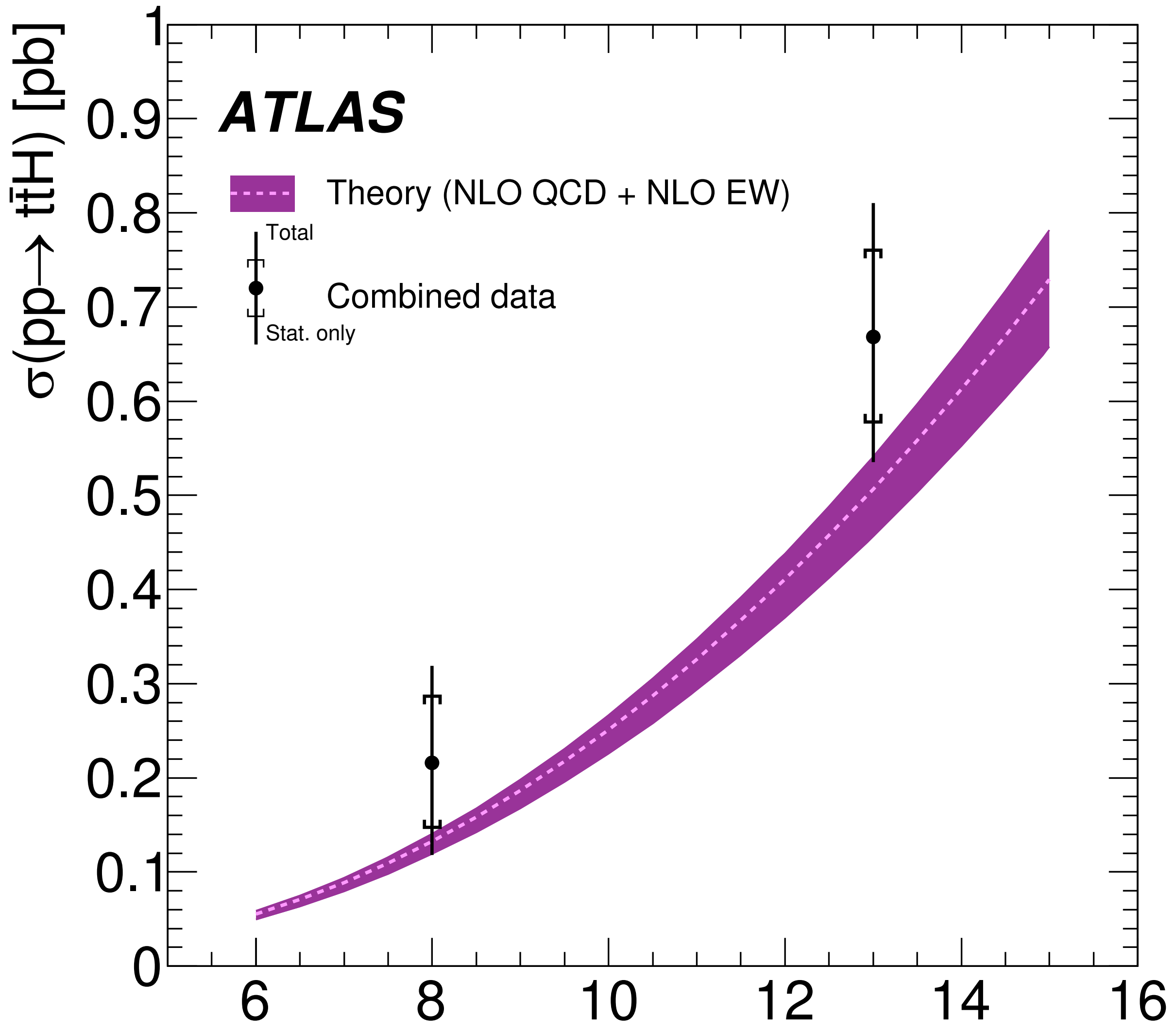




Direct observation in 2018!

From the combination of various final states





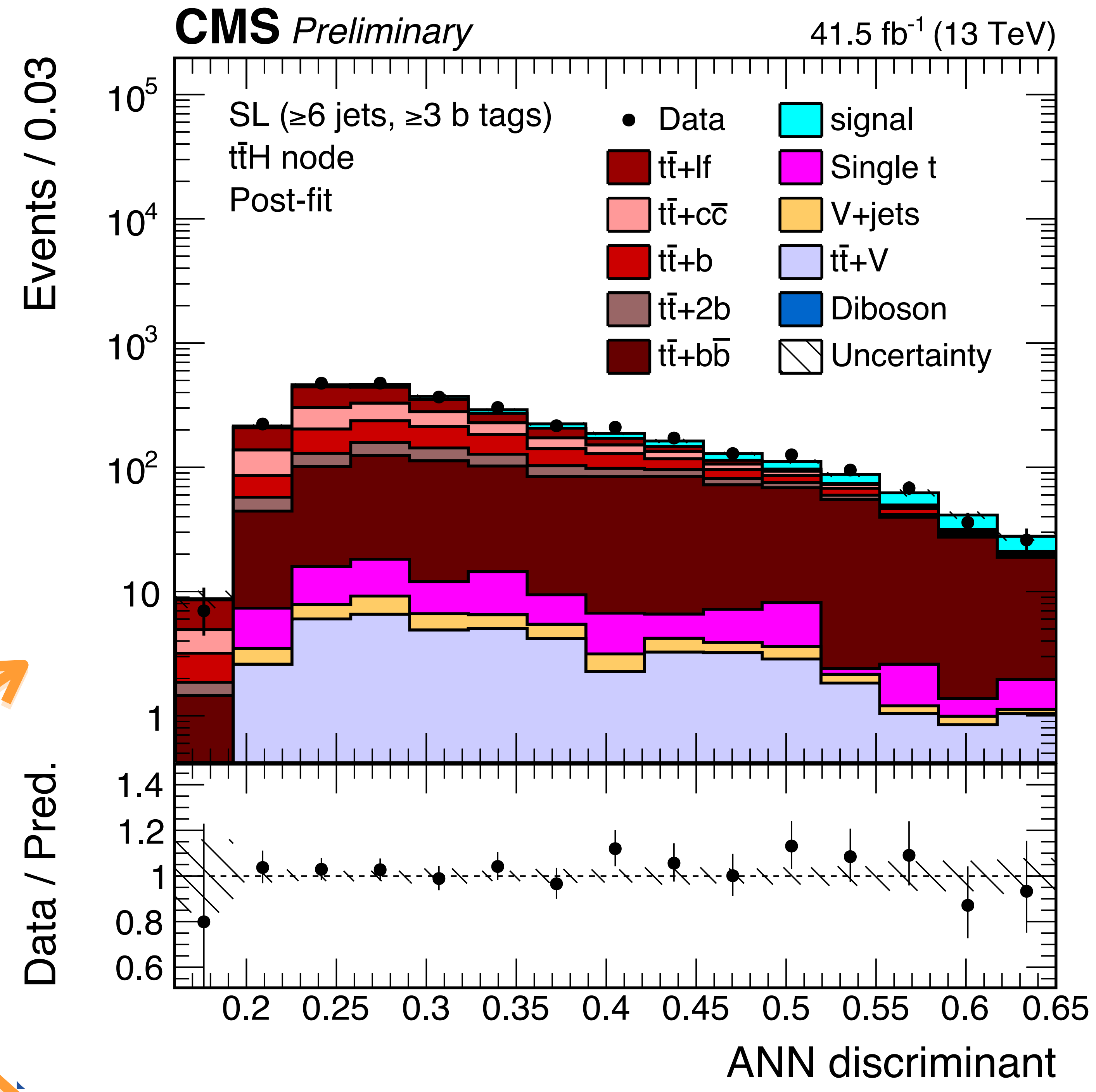
	signal strength
ttH comb (Run1+80/fbRun2)	$1.32^{+0.28}_{-0.26}$
ttH comb (Run1+36/fbRun2)	$1.26^{+0.31}_{-0.26}$

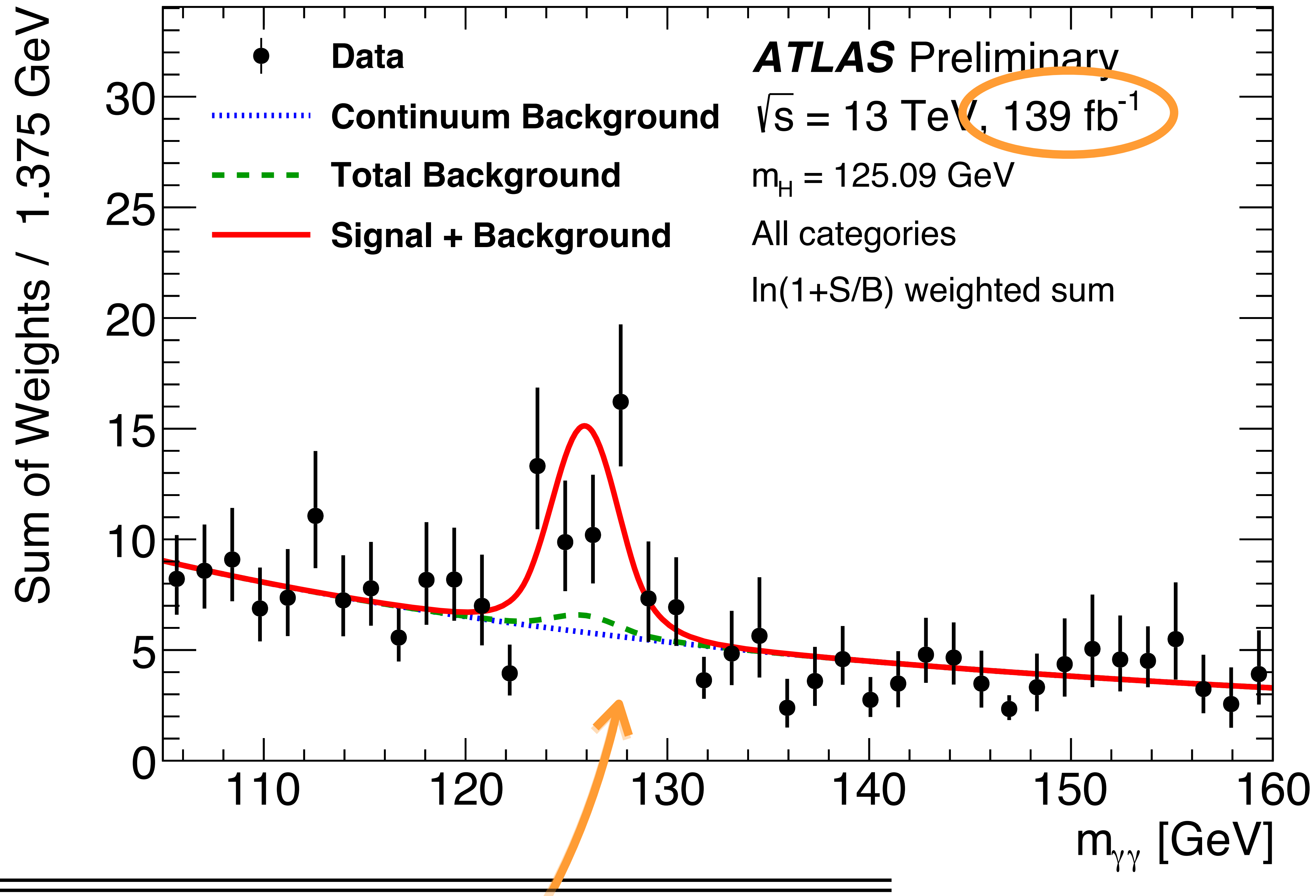
Adding more (full Run2) data direct observation in most of the final states

ttH MEASUREMENTS

CMS-PAS-HIG-18-031
ATLAS-CONF-2019-004

Analyses improved, usage of sophisticated methods for signal identification





		ttH(bb)	ttH(WW/$\tau\tau$)	ttH($\gamma\gamma$)	ttH(4ℓ)
ATLAS	lumi	36/fb	36/fb	139/fb	139/fb
	signal strength	$0.79^{+0.61}_{-0.60}$	$1.56^{+0.42}_{-0.40}$	$1.38^{+0.41}_{-0.36}$	$1.23^{+1.44}_{-0.86}$
CMS	lumi	77/fb	77/fb	77/fb	139/fb
	signal strength	$1.15^{+0.32}_{-0.29}$	$0.96^{+0.34}_{-0.31}$	$1.7^{+0.6}_{-0.5}$	$0.13^{+0.92}_{-0.13}$

More data added from ttH discovery analyses

3rd–GENERATION FERMION COUPLING : b–H

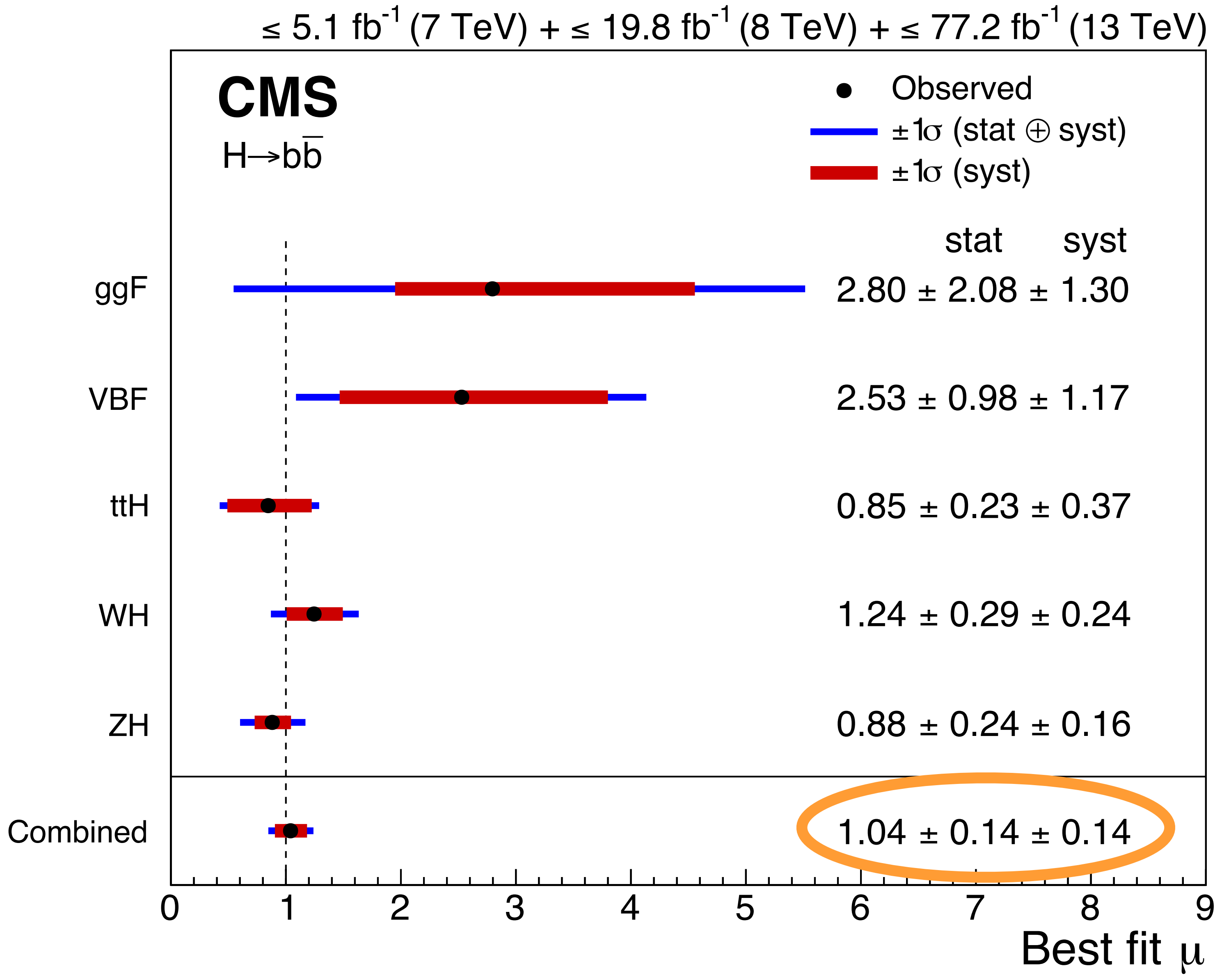
PRL 121(2018)121801
PLB 786(2018)59

Difficult channel despite large BR (58%) due to large bkg

Coupling established with a significance >5σ

VH production most sensitive but ggF, VBF and ttH play a role.

	signal strength
ATLAS Hbb (Run1+ 80/fb Run2)	1.01±0.20
CMS Hbb (Run1+ 77/fb Run2)	1.04±0.20



Discovery→Properties

3rd–GENERATION FERMION COUPLING : b–H

PRL 121(2018)121801
PLB 786(2018)59
JHEP 05(2019)141

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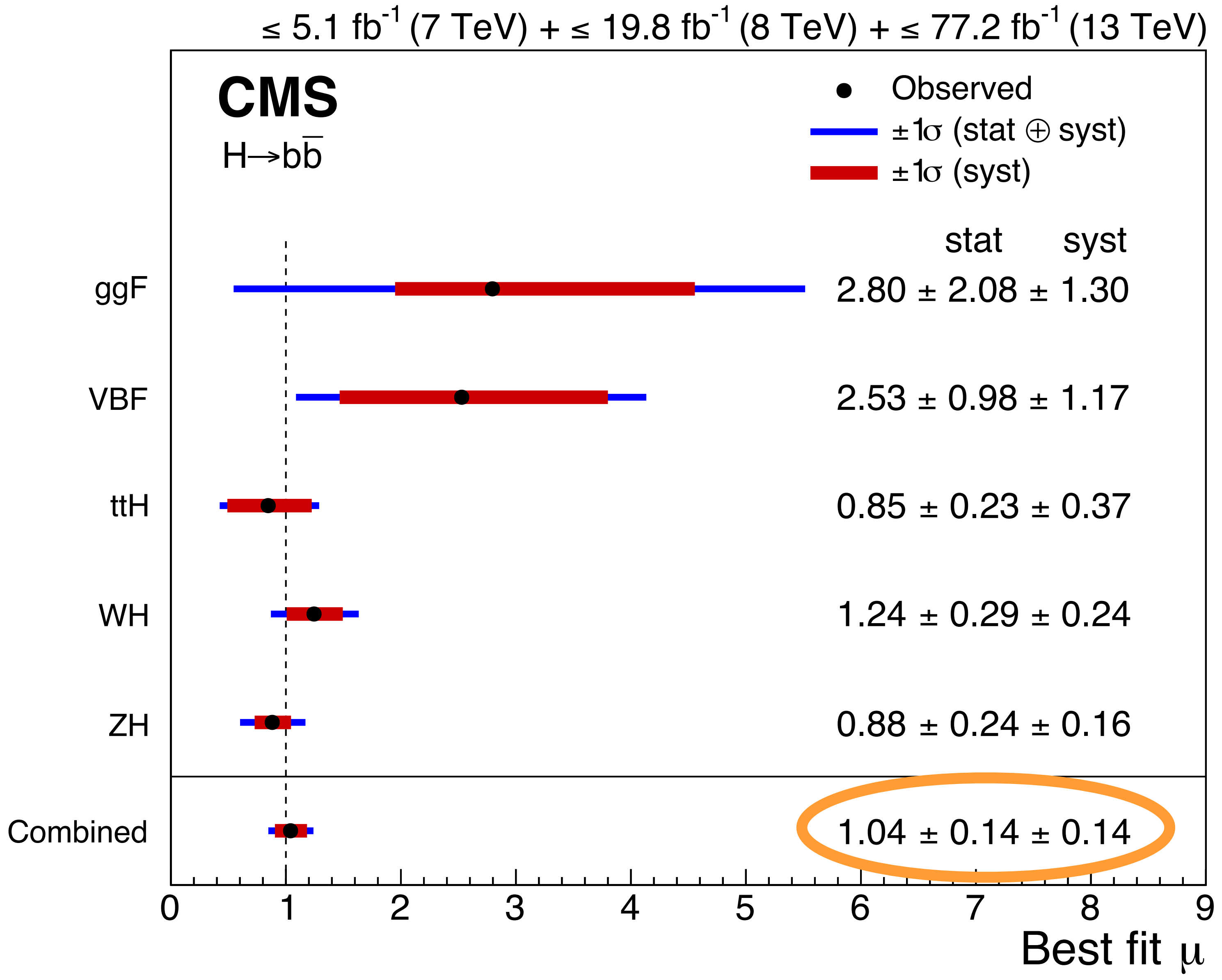
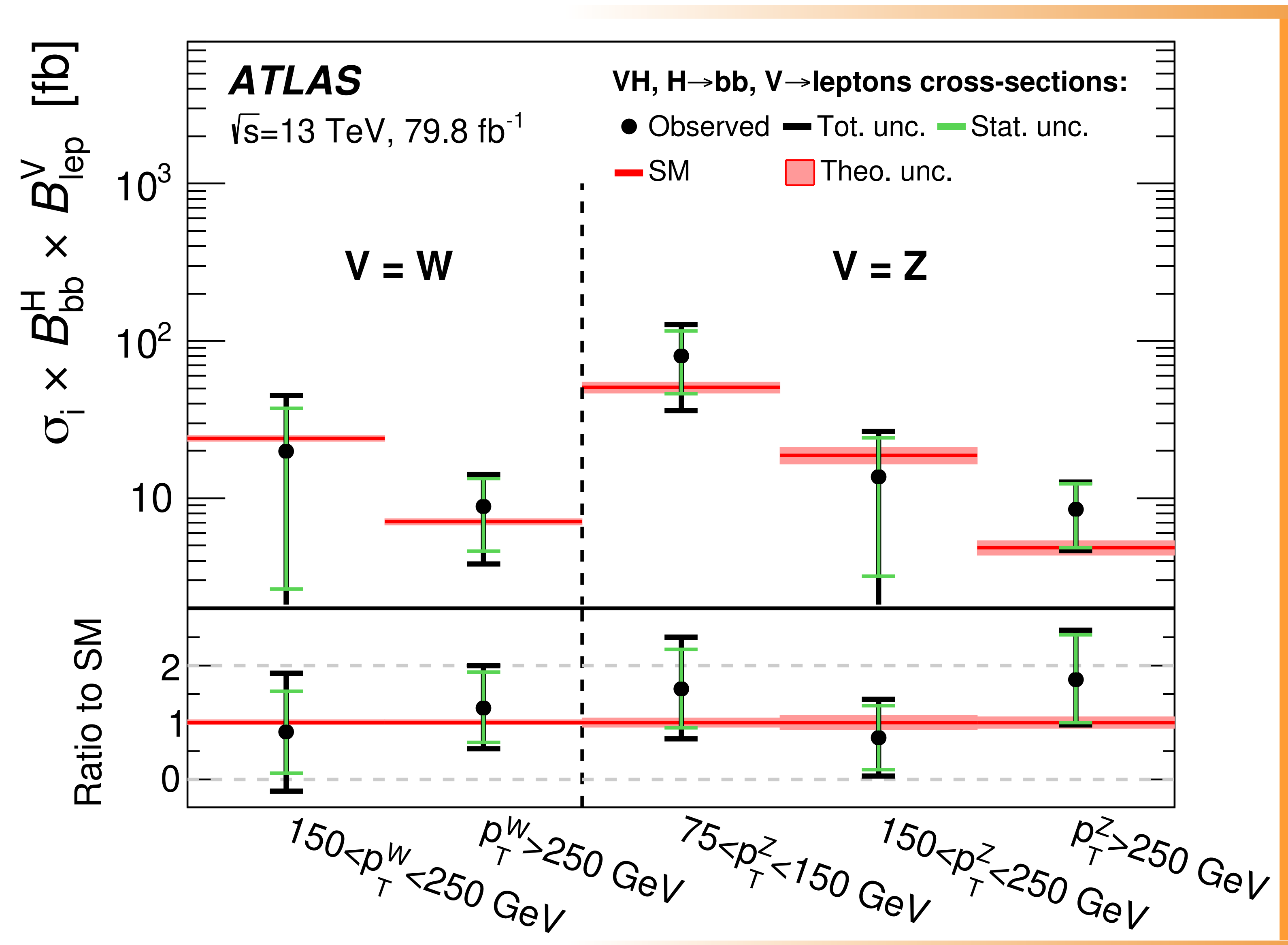
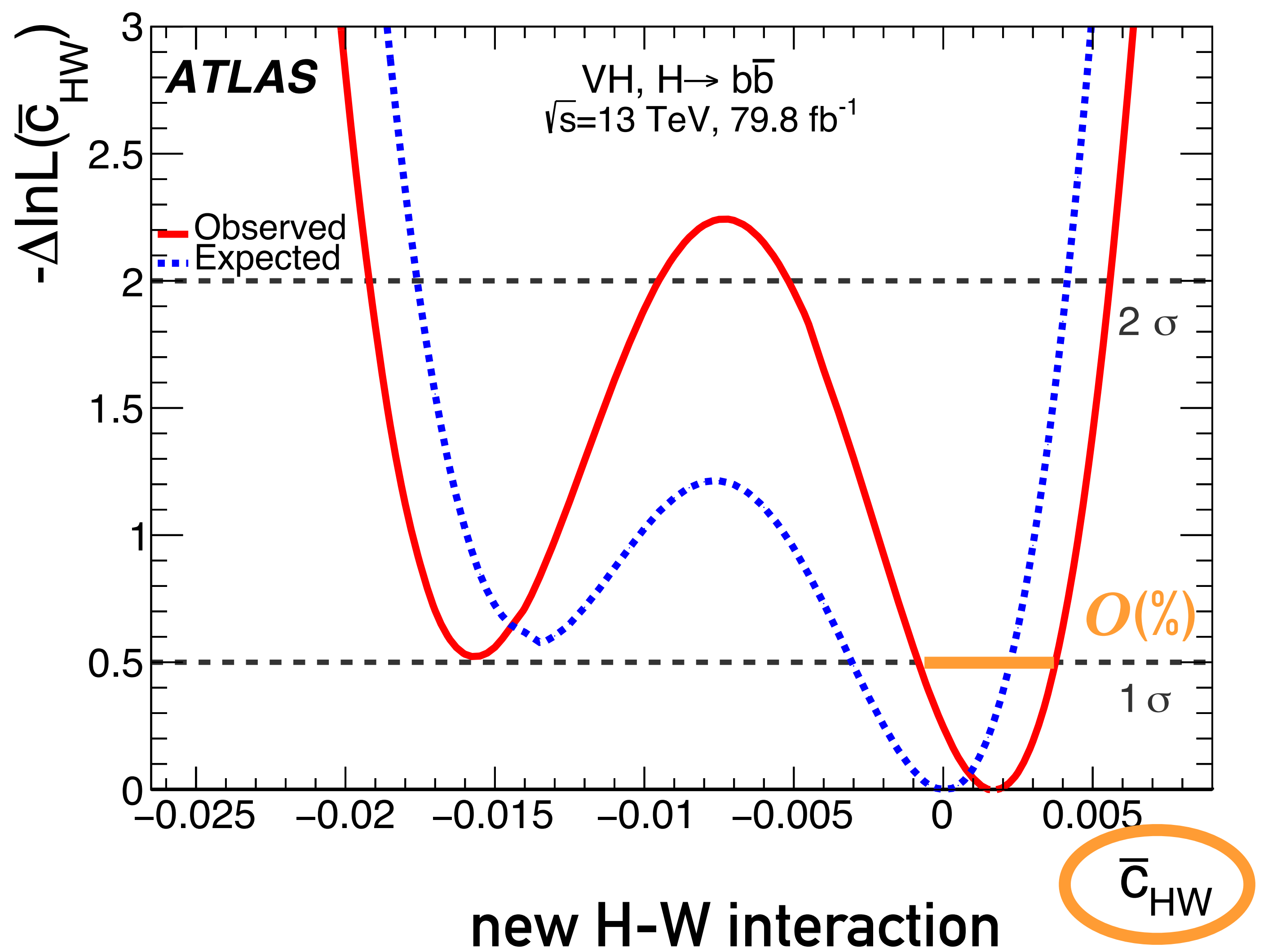


Moving towards measurements of differential σ_{VH} that has sensitivity to p_T^V



EFT interpretation →



new H-W interaction

Discovery→Properties

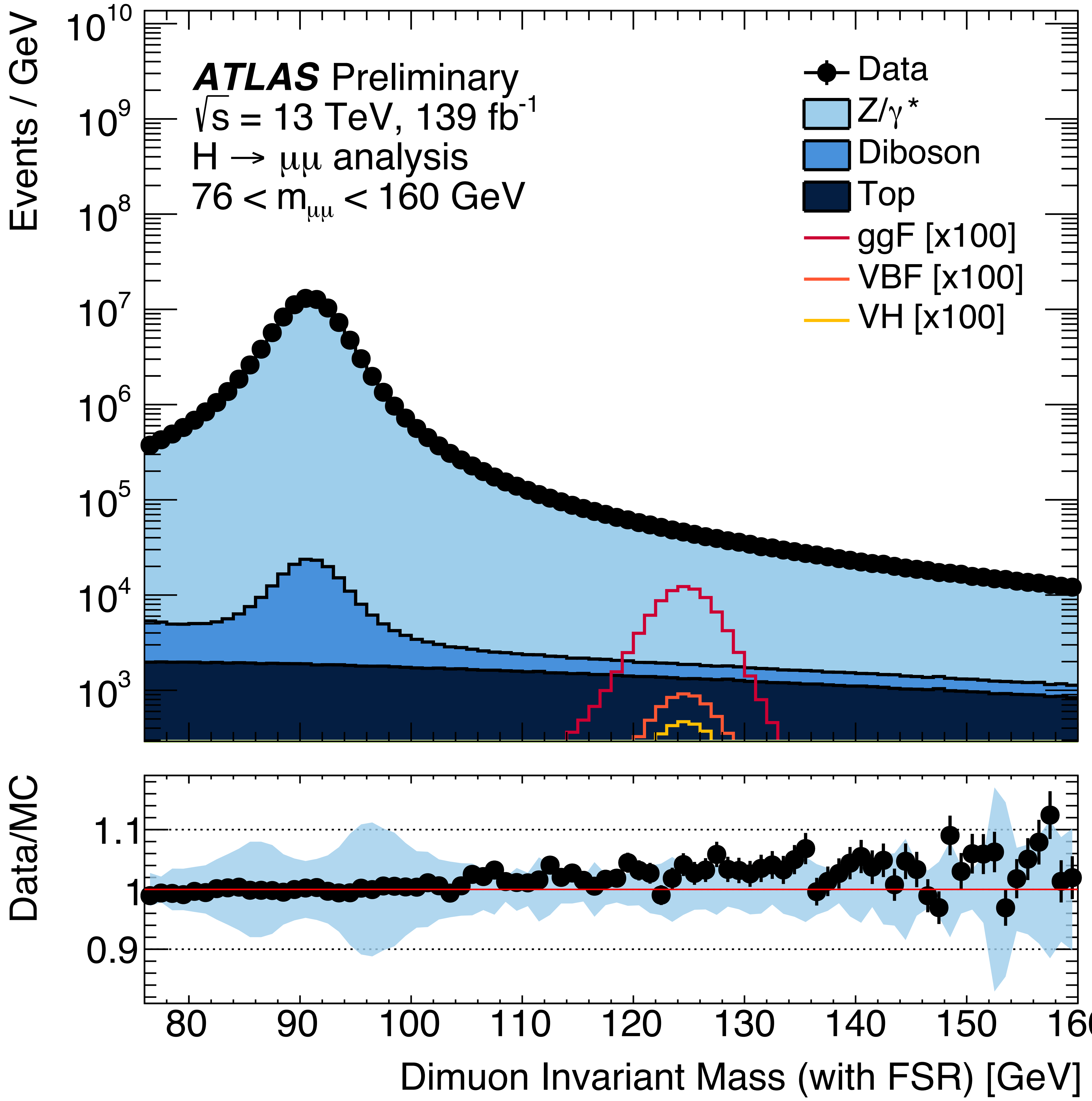
Rare Decays and Productions

2nd–GENERATION FERMION COUPLING : μ–H

PRL 122(2019)021801
NEW! CONF-HIGG-2019-028

H→μμ analysis, μ are the easiest object to identify and measure, but :

- small BR(H→μμ)=2×10^{-4} → $\mathcal{O}$(5-6) evt/fb^{-1}
- large backgrounds: Z/γ^*, Diboson, Top
- small S/(S+B) regime ~0.2%



Rare decays/production

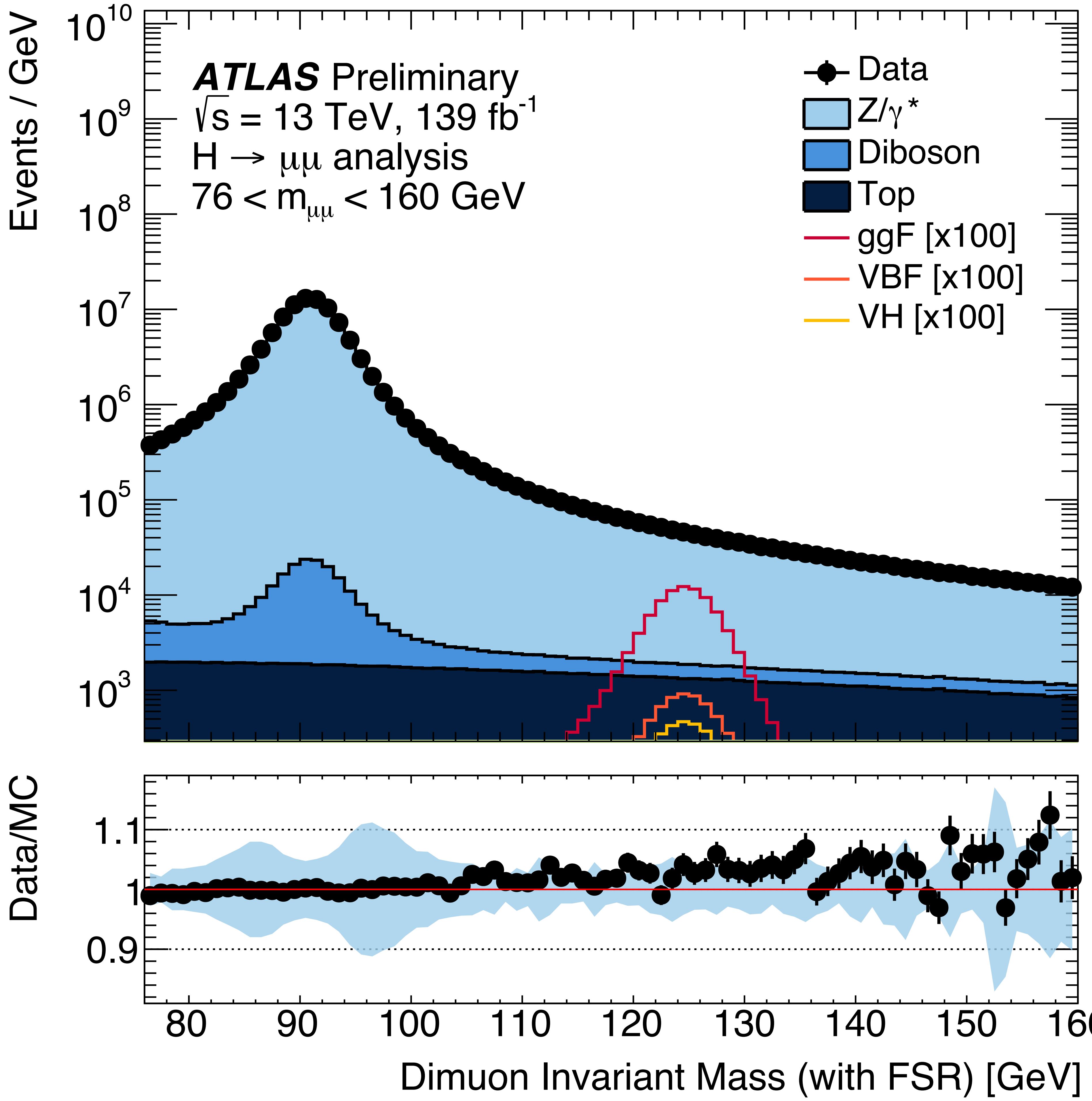
2nd–GENERATION FERMION COUPLING : μ–H

PRL 122(2019)021801
NEW! CONF-HIGG-2019-028

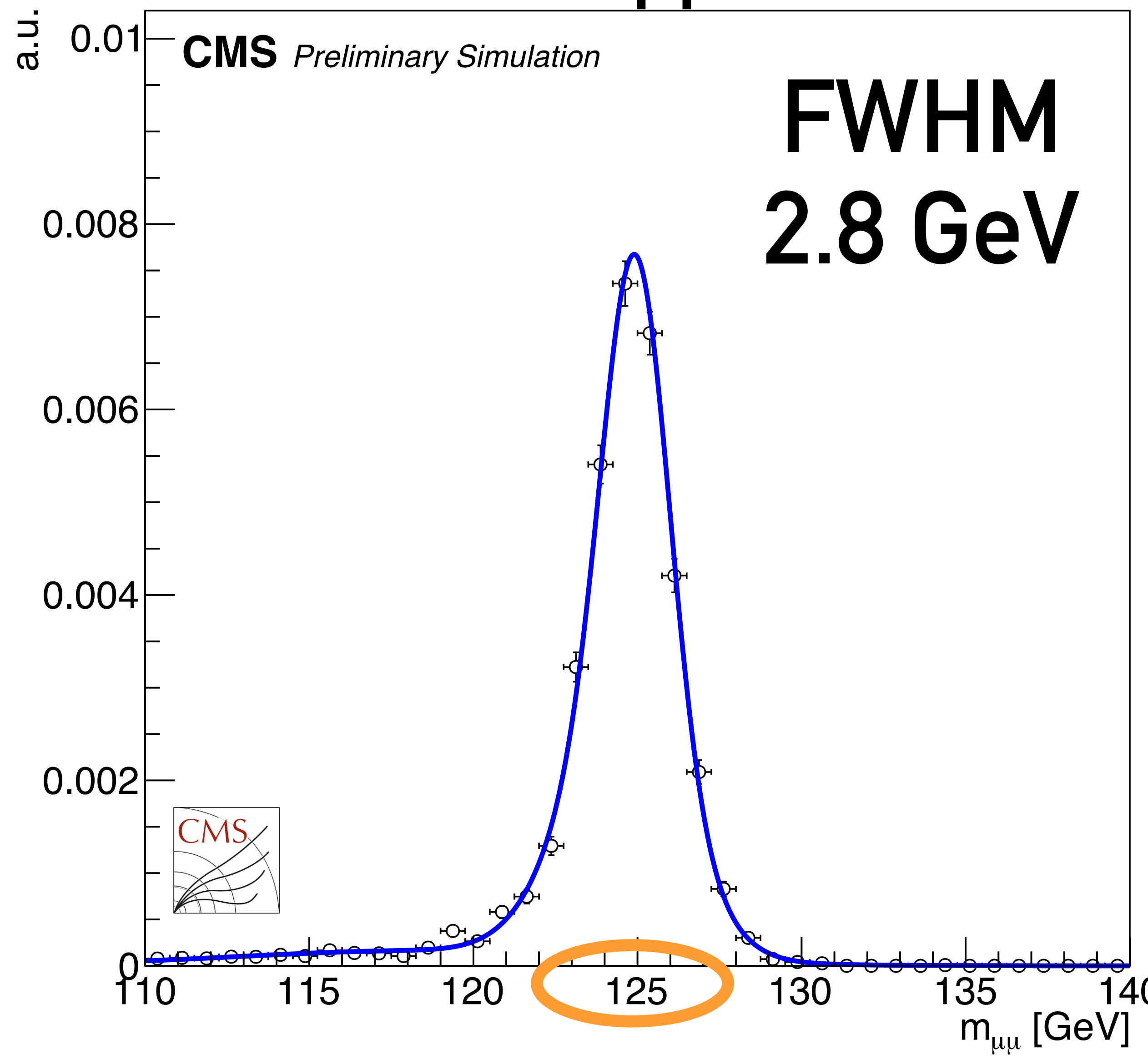
H→μμ analysis, μ are the easiest object to identify and measure, but :

- small BR(H→μμ)=2×10-4 → $\mathcal{O}$(5-6) evt/fb-1
- large backgrounds: Z/γ*, Diboson, Top
- small S/(S+B) regime ~0.2%

Critical good muon momentum resolution and sophisticated techniques to categorise and select events



H→μμ Simulation



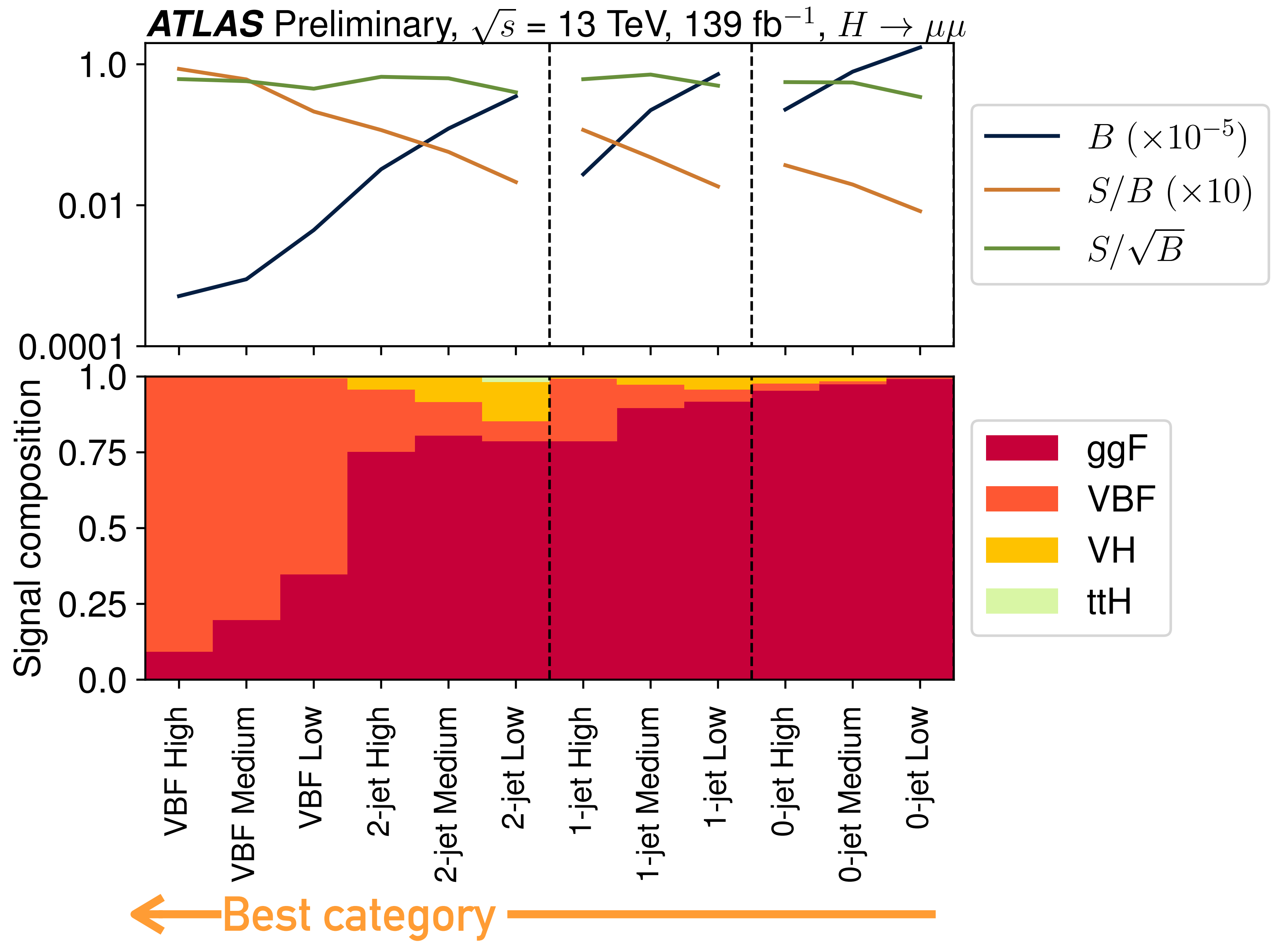
Rare decays/production

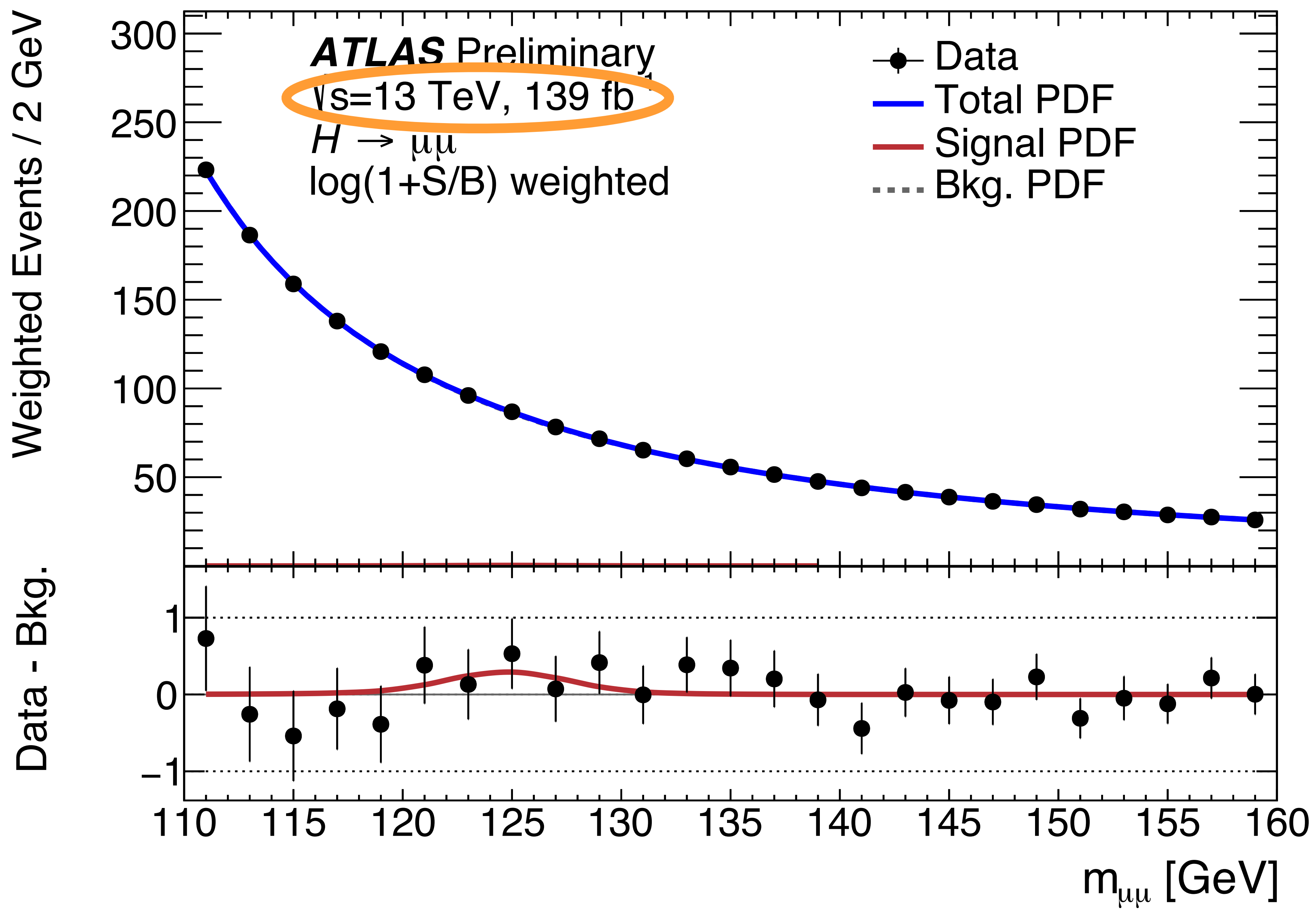
H→μμ RESULTS

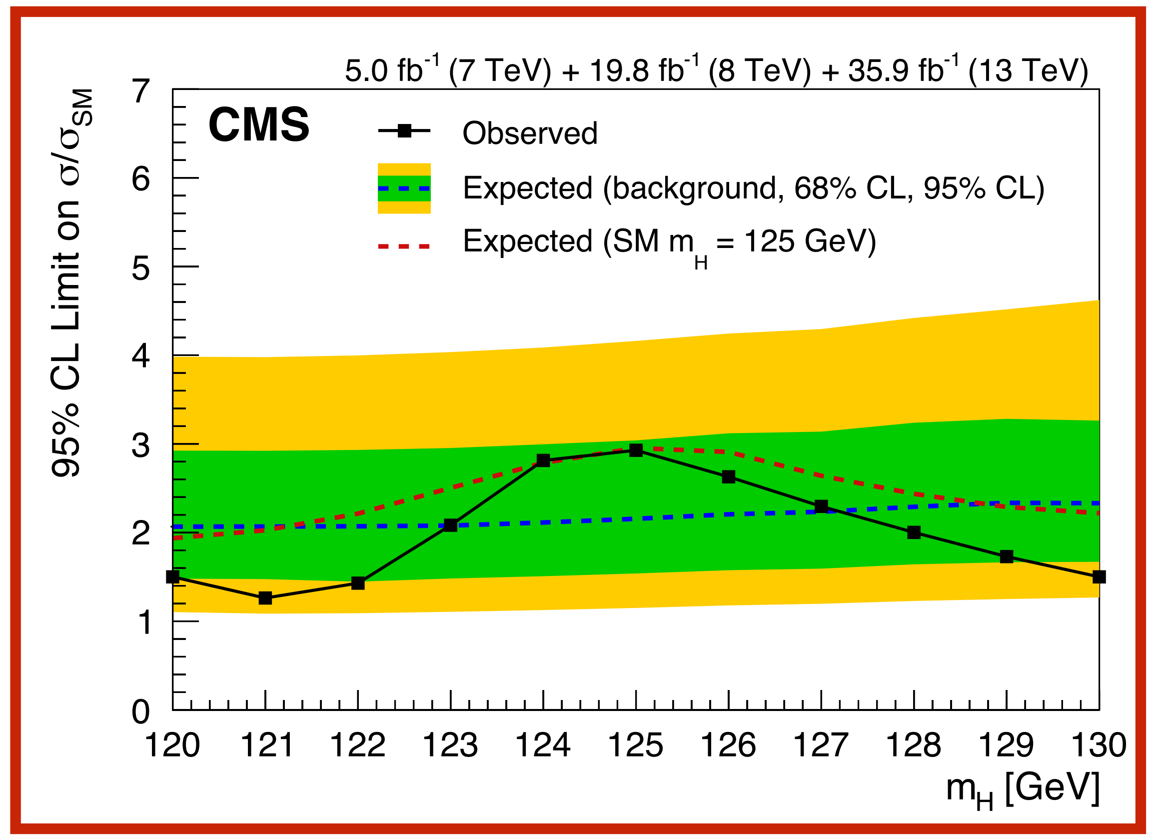
PRL 122(2019)021801
NEW! CONF-HIGG-2019-028

Signal and background yields are determined through a fit to $m_{\mu\mu}$ distribution

Improvements in ATLAS full Run2 analysis: BDT-based event classification, bkg modelling, FSR, rejection of pile-up jet







	obs(exp(*)) UL on σ/σ_{SM}	obs(exp) μ	obs(exp) sign
ATLAS 2μ (full Run2)	1.7(1.3)	0.5±0.7(1.0±0.7)	0.8σ(1.5σ)
CMS 2μ (Run1+36/fb Run2)	2.9(2.2)	1.0±1.0(1.0±1.0)	0.9σ(1.0σ)

Results statistically limited

(*) background-only UL, no H→μμ included

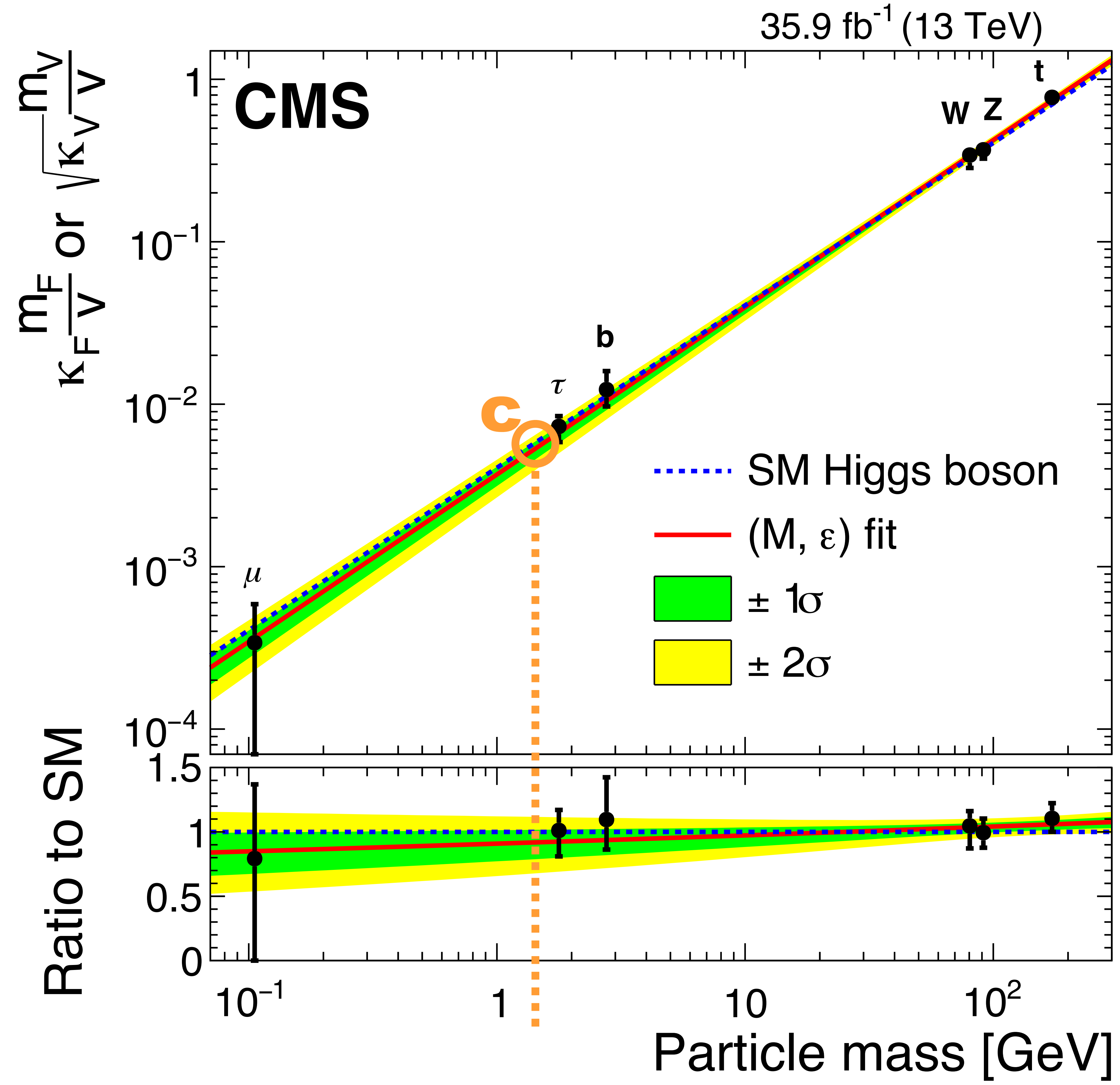
2^{nd}–GENERATION FERMION COUPLING : c–H

charm-Higgs coupling $\lambda_c \sim \lambda_\tau$, but way harder to probe :

- BR($H \to cc$)~0.05×BR($H \to bb$)
- $H \to bb$ is background
- large (hadronic) background
- charm jet ID is highly challenging

Complementary approaches exist :

- Direct search for $H \to cc$ decay
- Extract constraints on λ_c from kinematics
- Searches for charmonium decays: $H \to J/\Psi\gamma$
- Total width / global analysis

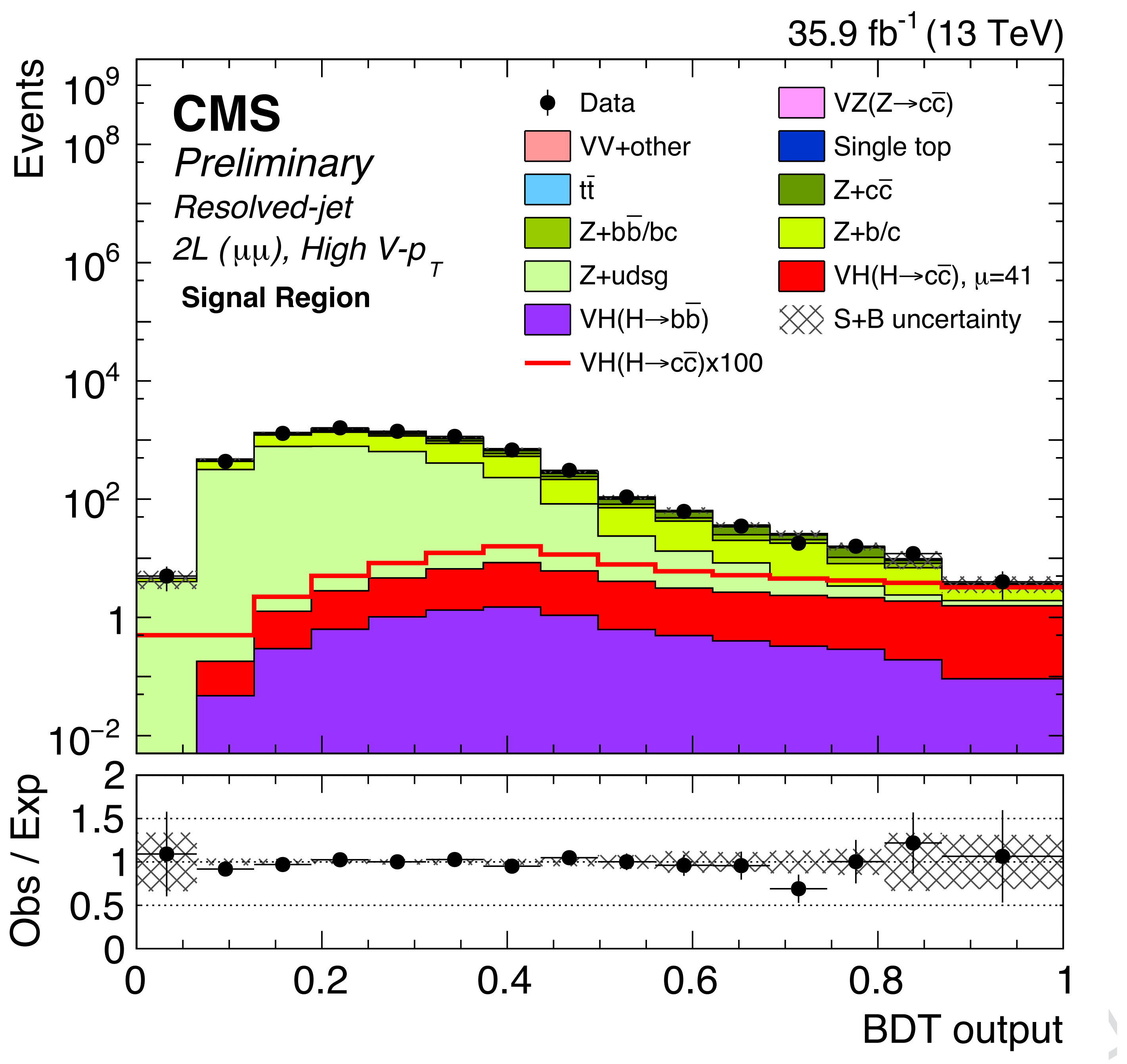


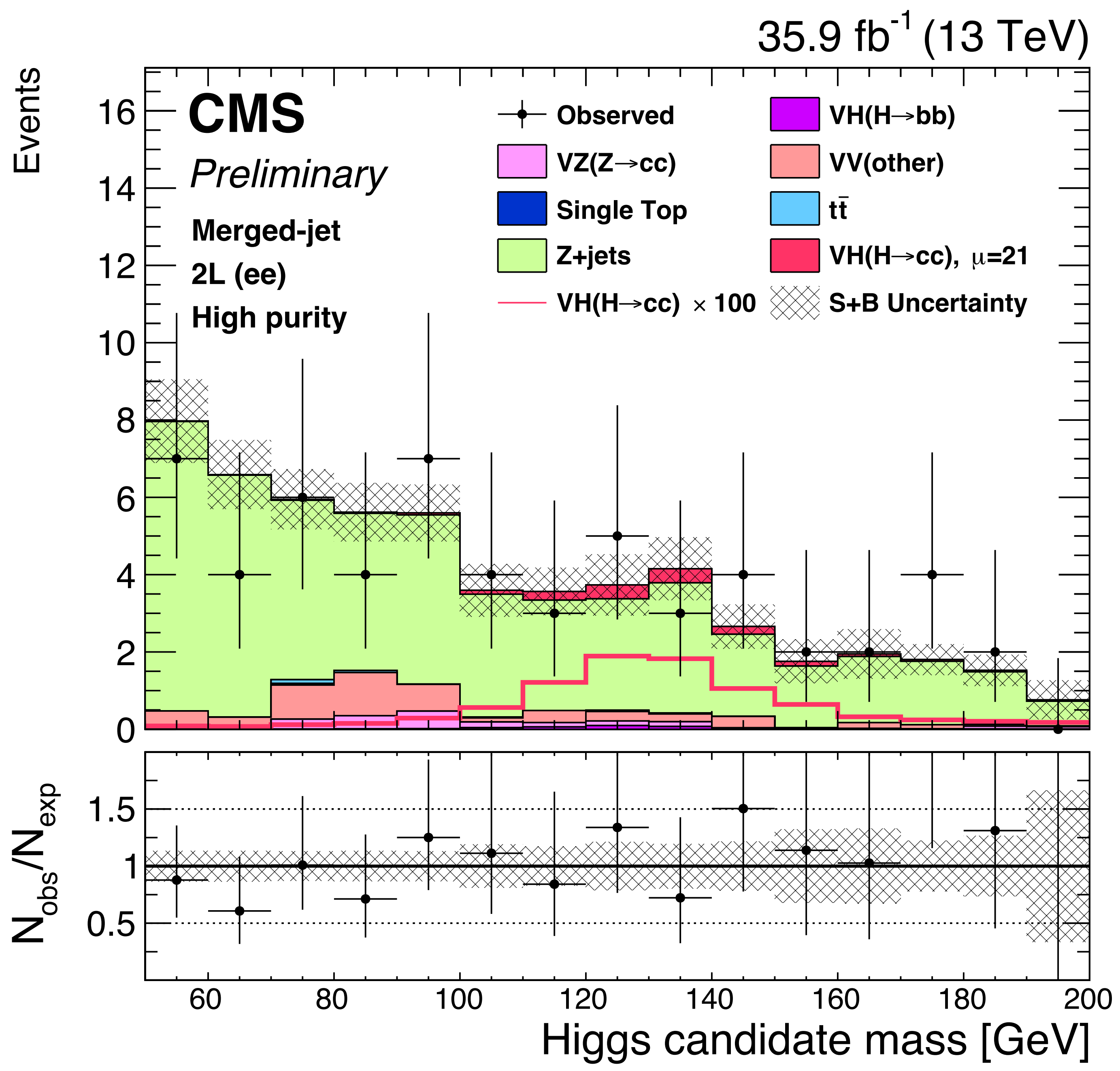
Rare decays/production

Direct Search H→cc

First direct H→cc search in CMS target the VH production

- Three exclusive channels to capture V decay modes
  0, 1, and 2 leptons ($Z\to\nu\nu$, $W\to\ell\nu$, and $Z\to\ell\ell$)
- Two approaches to explore the H→cc decay topology
  resolved (two jets R=0.4), merged (one large-R jet R=1.5)
- Advanced charm-tagging techniques exploited





	obs(exp) UL on σ/σ_{SM}
ATLAS VHcc (36/fb Run2)	110(150)(*)
CMS VHcc (36/fb Run2)	70(37)

Results are significantly improved

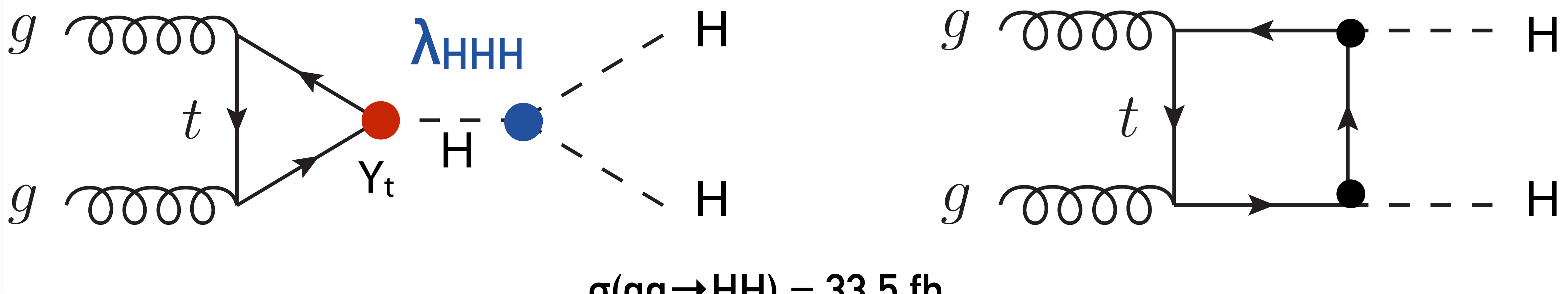
HL-LHC prospects UL on $\sigma/\sigma_{SM} < 6.3$
in the absence of syst unc.
by extrapolating ATLAS Run2 results

(*) only $Z\to\ell\ell$ + H→cc channel analysed

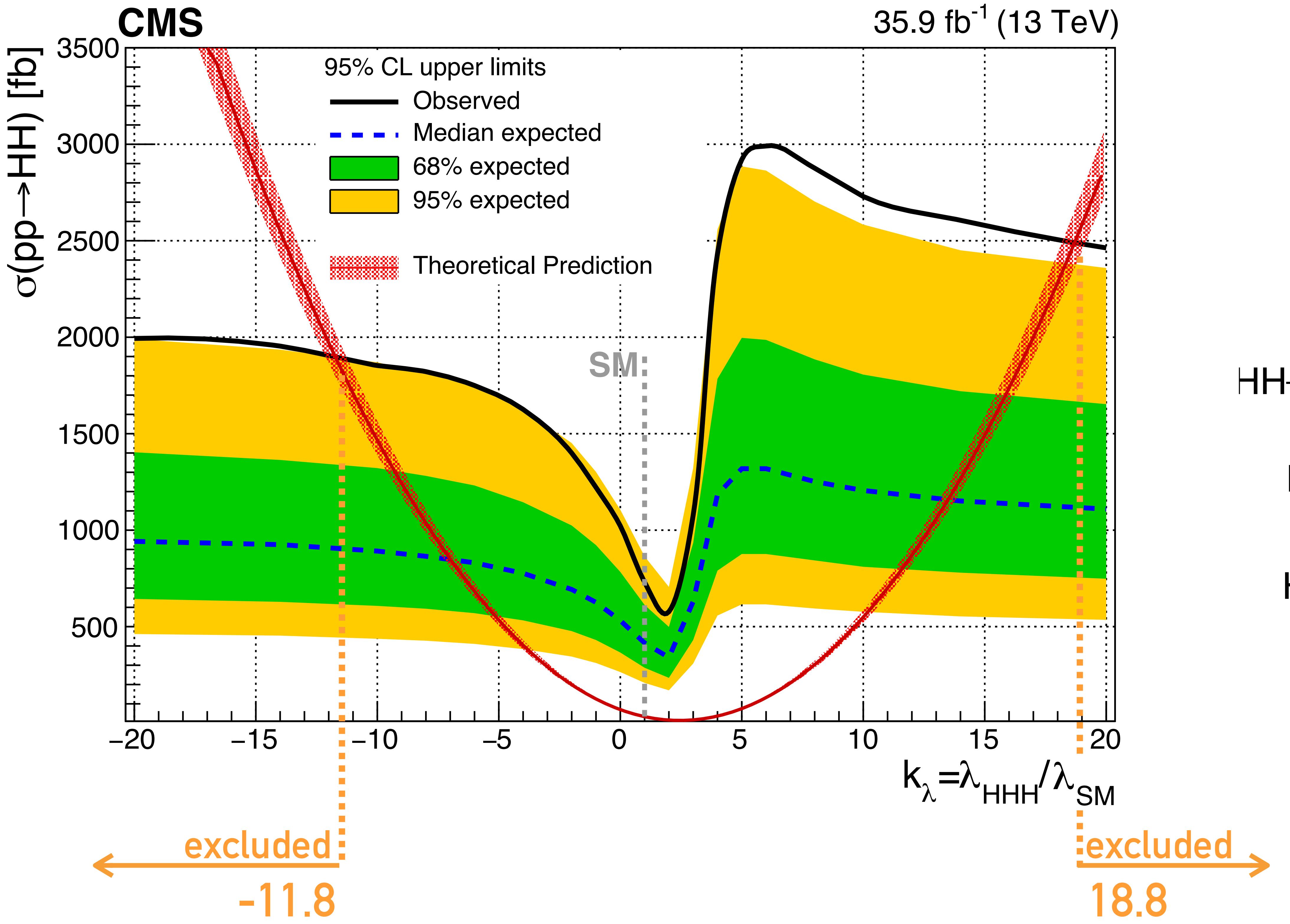
Probing the Higgs Boson Self-Coupling

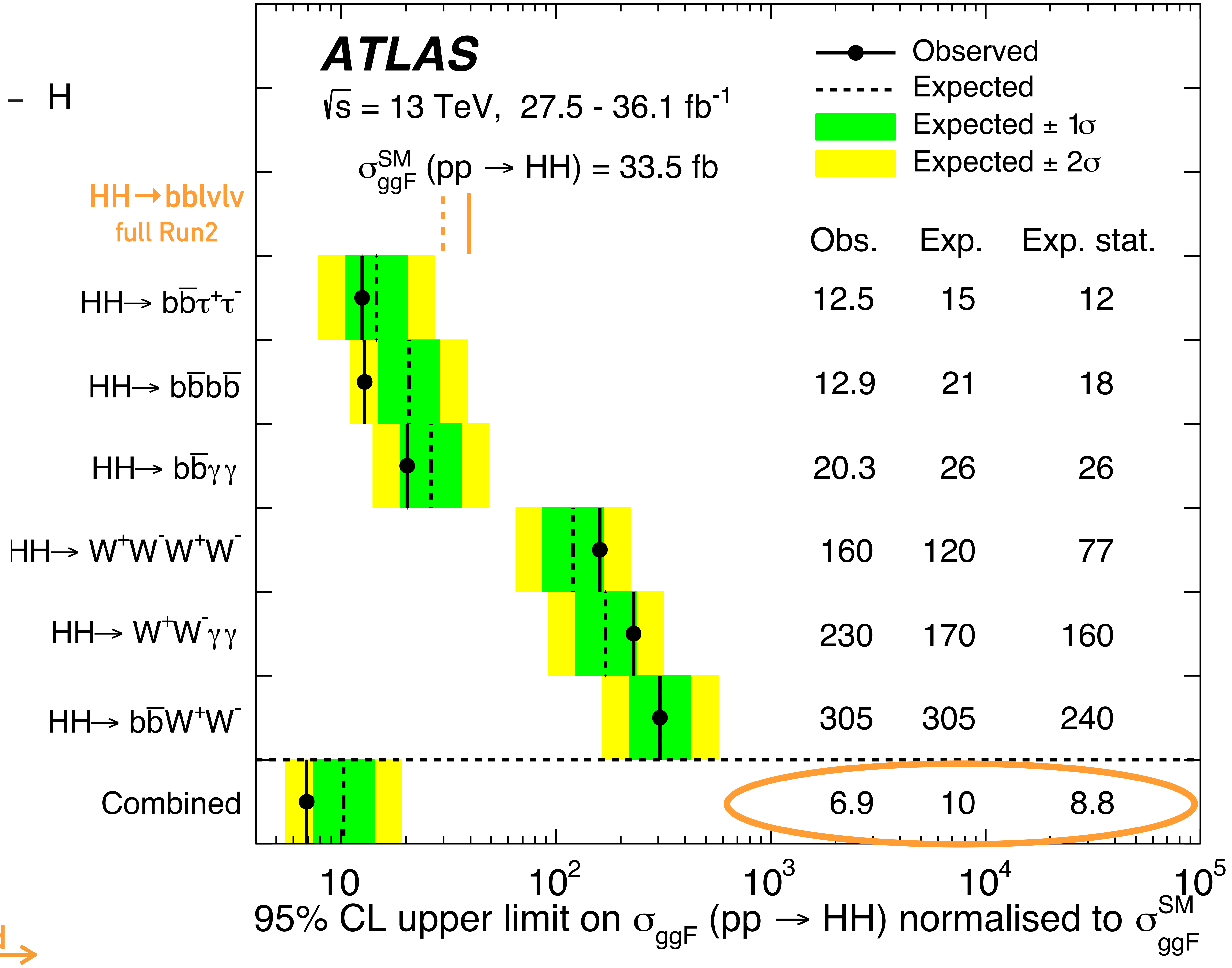
PRL 122(2019)121803
arXiv:1906.02025

Essential in EWSB, need to measure the Higgs boson trilinear coupling (λ_{HHH})



$\sigma(gg \to HH)$ = 33.5 fb
[@13 TeV, NNLO + NNLL with top mass effects]



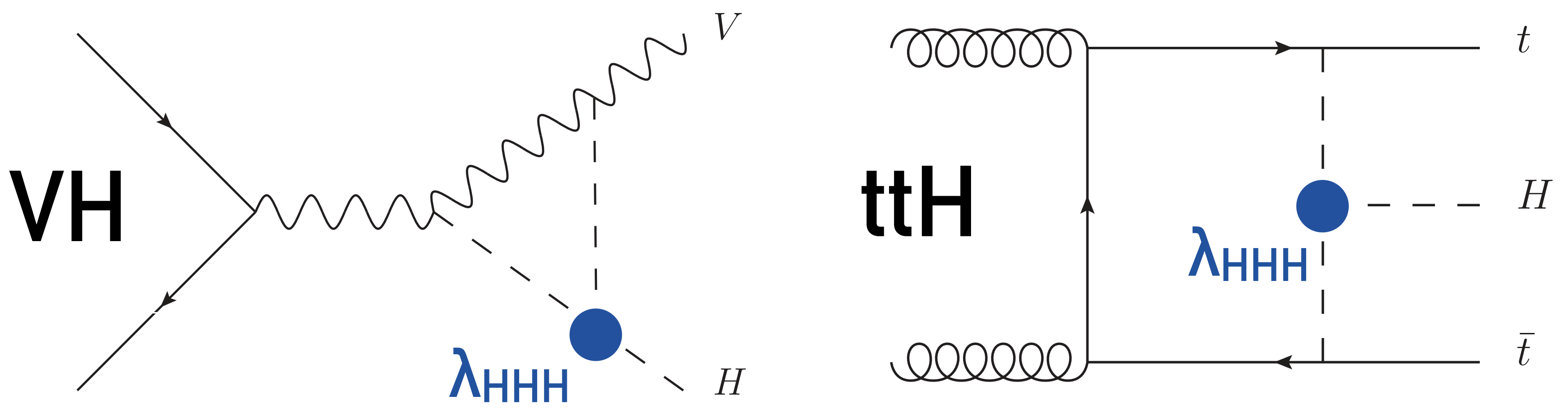


Presented a full Run2 VBF HH→bbbb analysis, strong constraints on the VVHH vertex

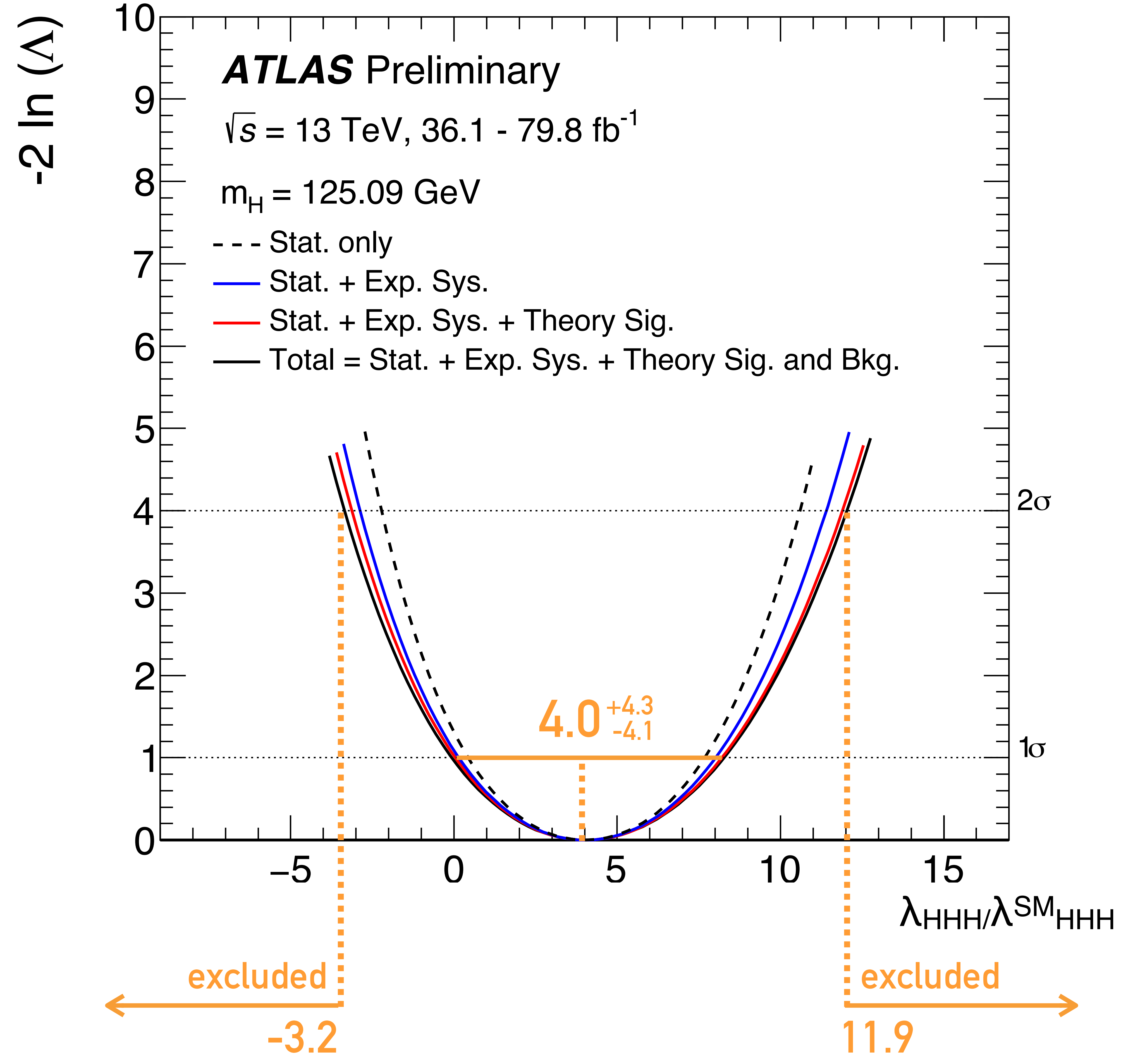
PROBING THE HIGGS BOSON SELF-COUPLING

ATL-PHYS-PUB-2019-009

Single Higgs boson productions, decays, and kinematics are sensitive to the self-coupling through EW corrections



Reinterpretation of the combined measurements gives some access to kinematic information



Measurement sensitive only under strict assumptions on other Higgs boson couplings

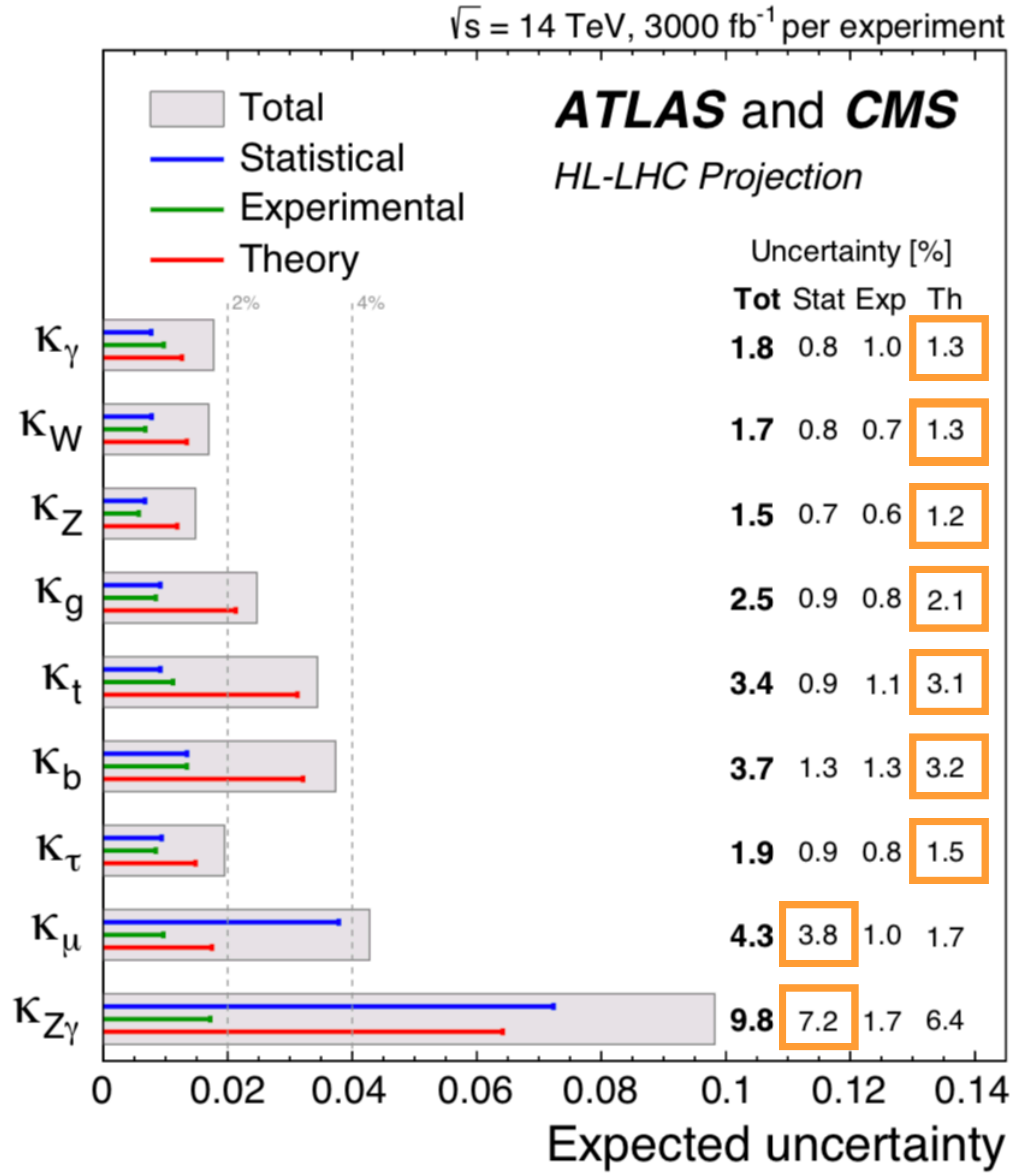
Complements direct determination from HH

Rare decays/production

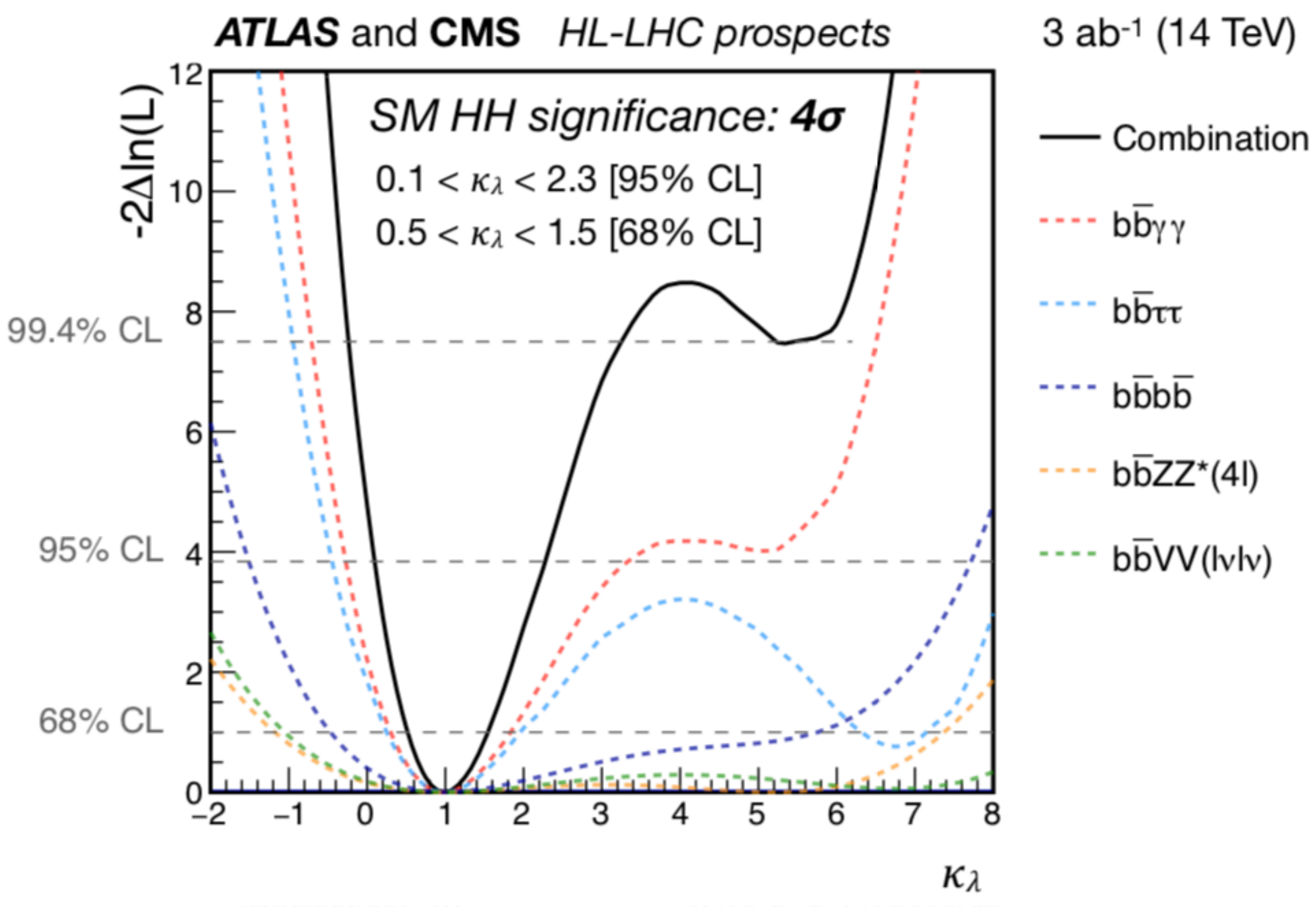
TOWARDS HL-LHC

arXiv:1902.00134

Couplings



Higgs boson self-coupling



In addition for Higgs BSM searches a substantial amount of parameter space (and masses) to be covered

The future

OUTLOOK AND CONCLUSIONS

The Higgs boson is “really” new physics.

A broad Higgs physics program is ongoing within ATLAS and CMS using the LHC Run2 dataset (<5% of the final HL-LHC integrate luminosity)

- Start of the precision era in the gauge sector (towards <10% uncertainties)
- Switch from discovery to properties measurements using the 3rd-generation couplings
- Focus on rare processes
  - evidence/observation of 2nd-generation coupling using LHC data
  - probe charm-H interaction and Higgs self-coupling towards HL-LHC
- Extensive BSM searches

OUTLOOK AND CONCLUSIONS

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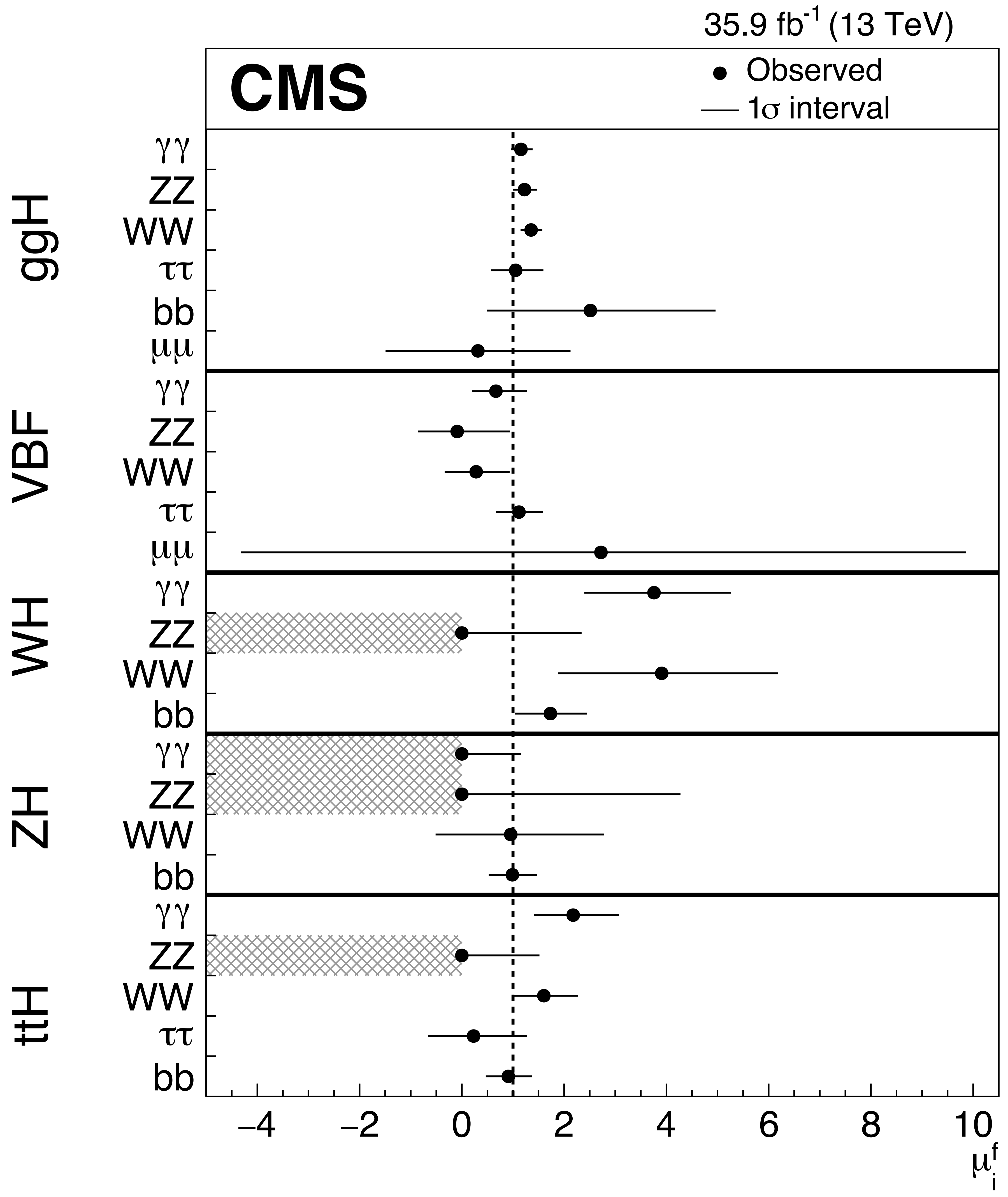
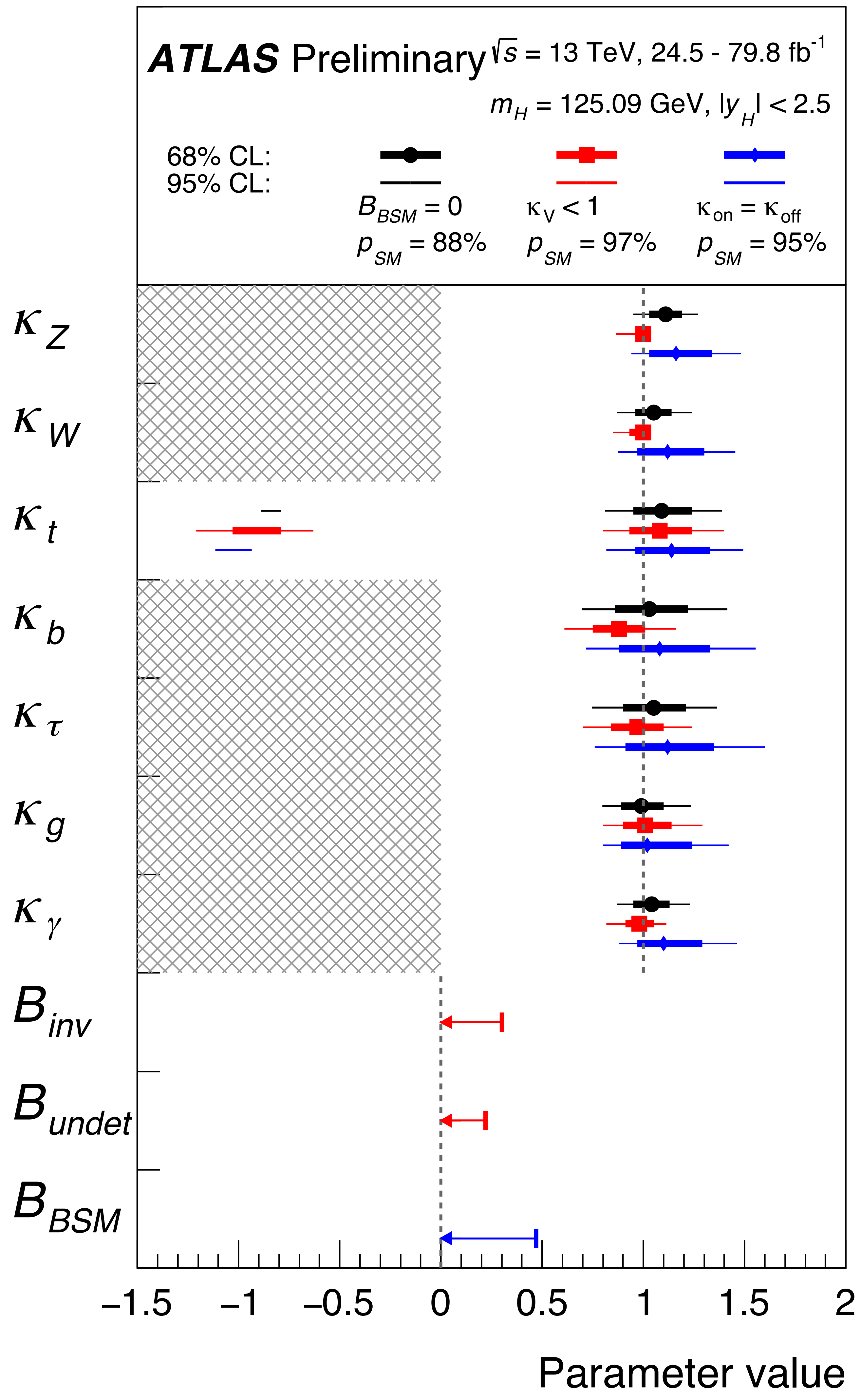
Backup

THE HIGGS BOSON COMBINATION

EPJC 79 (2019) 421019
CONF-HIGG-2019-028

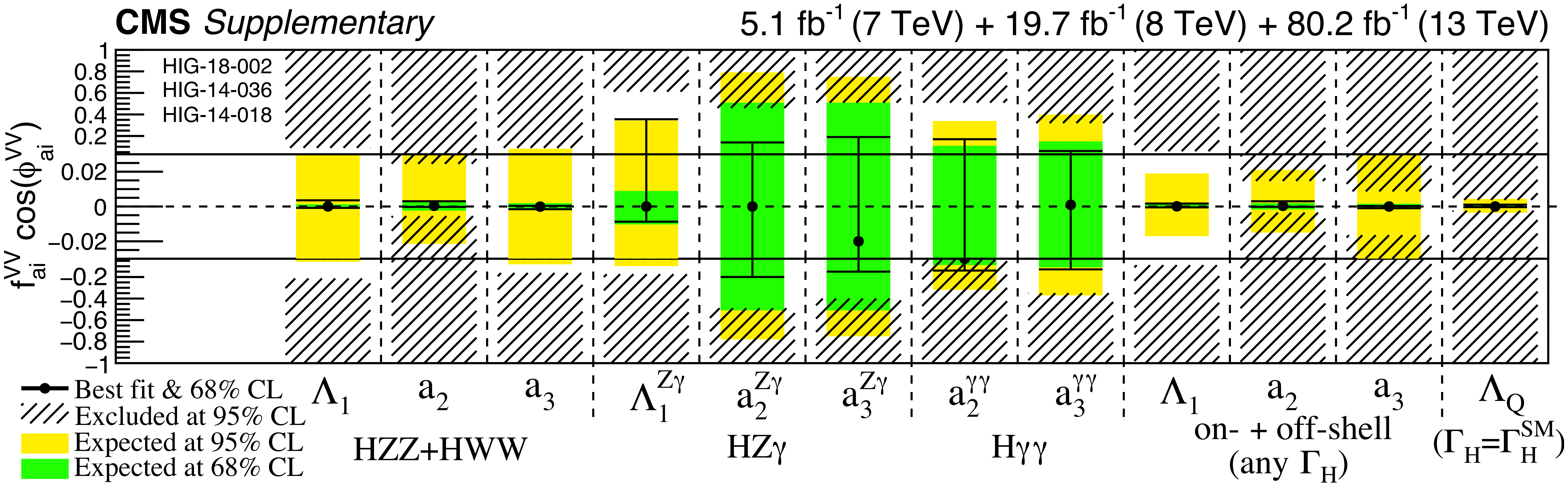




The H Profile

Quantum Numbers Spin

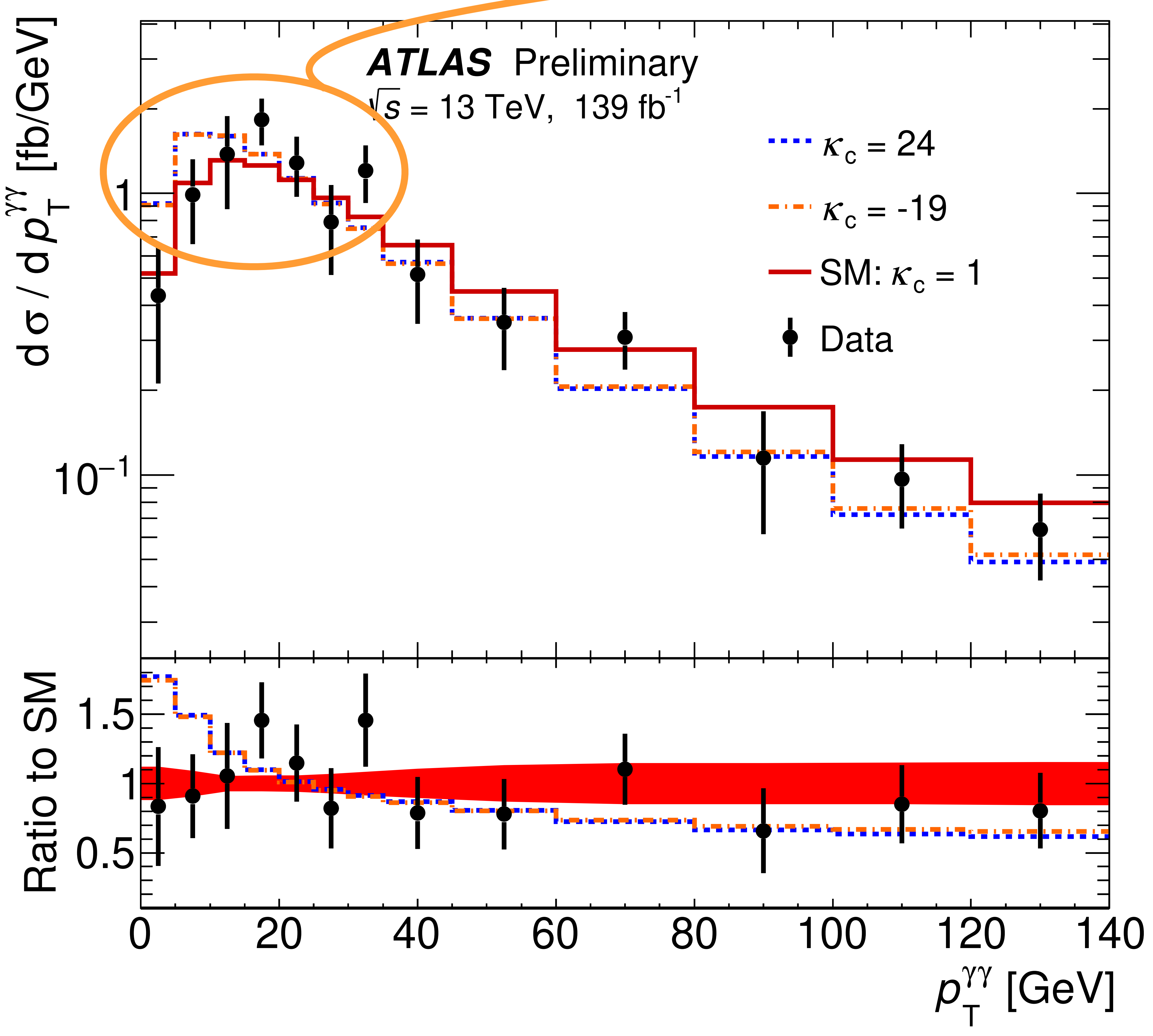
PRD 99(2019)112003



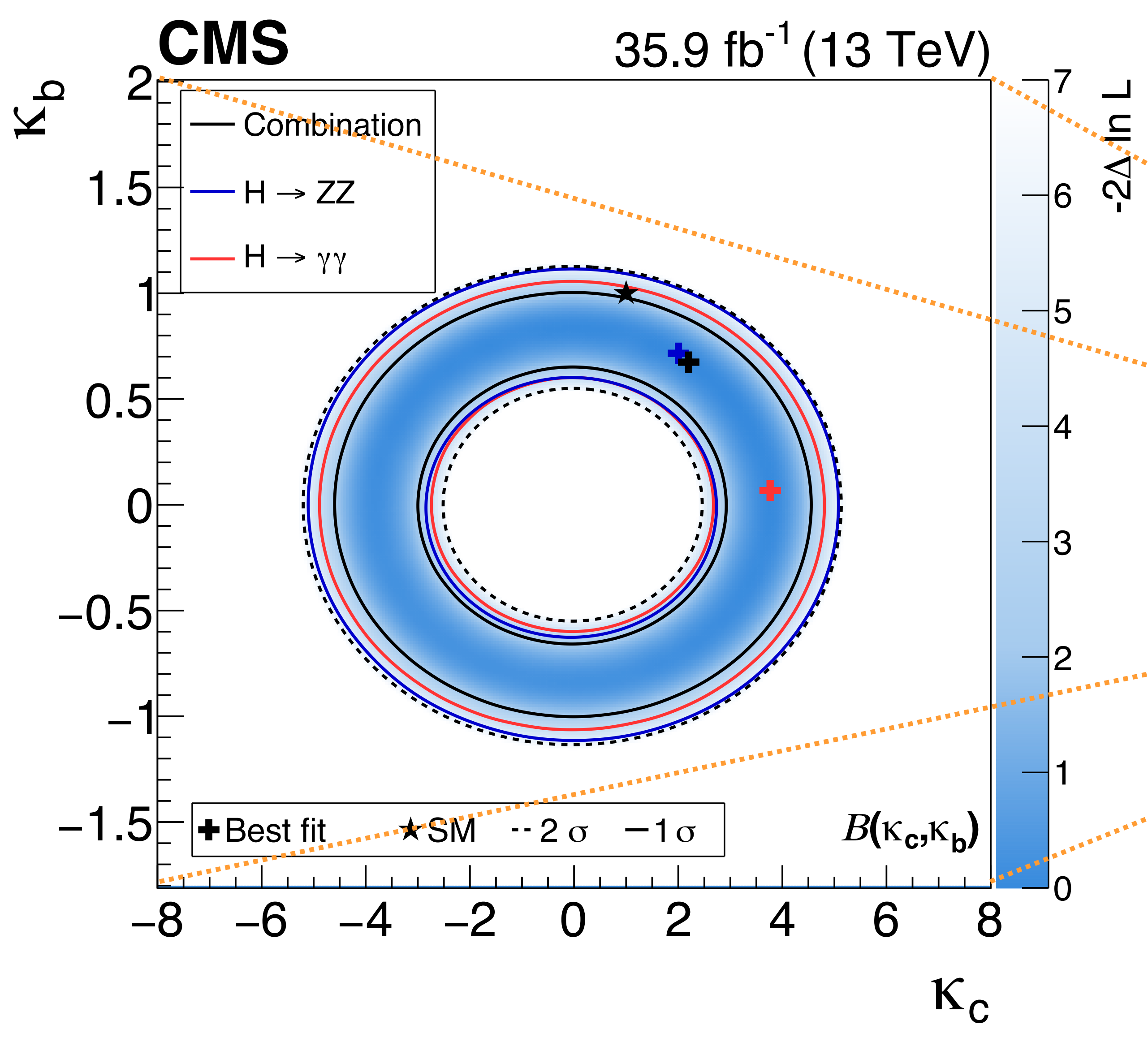
c–H Coupling from Kinematics

PLB 792(2019)369
NEW! CONF-HIGG-2019-046

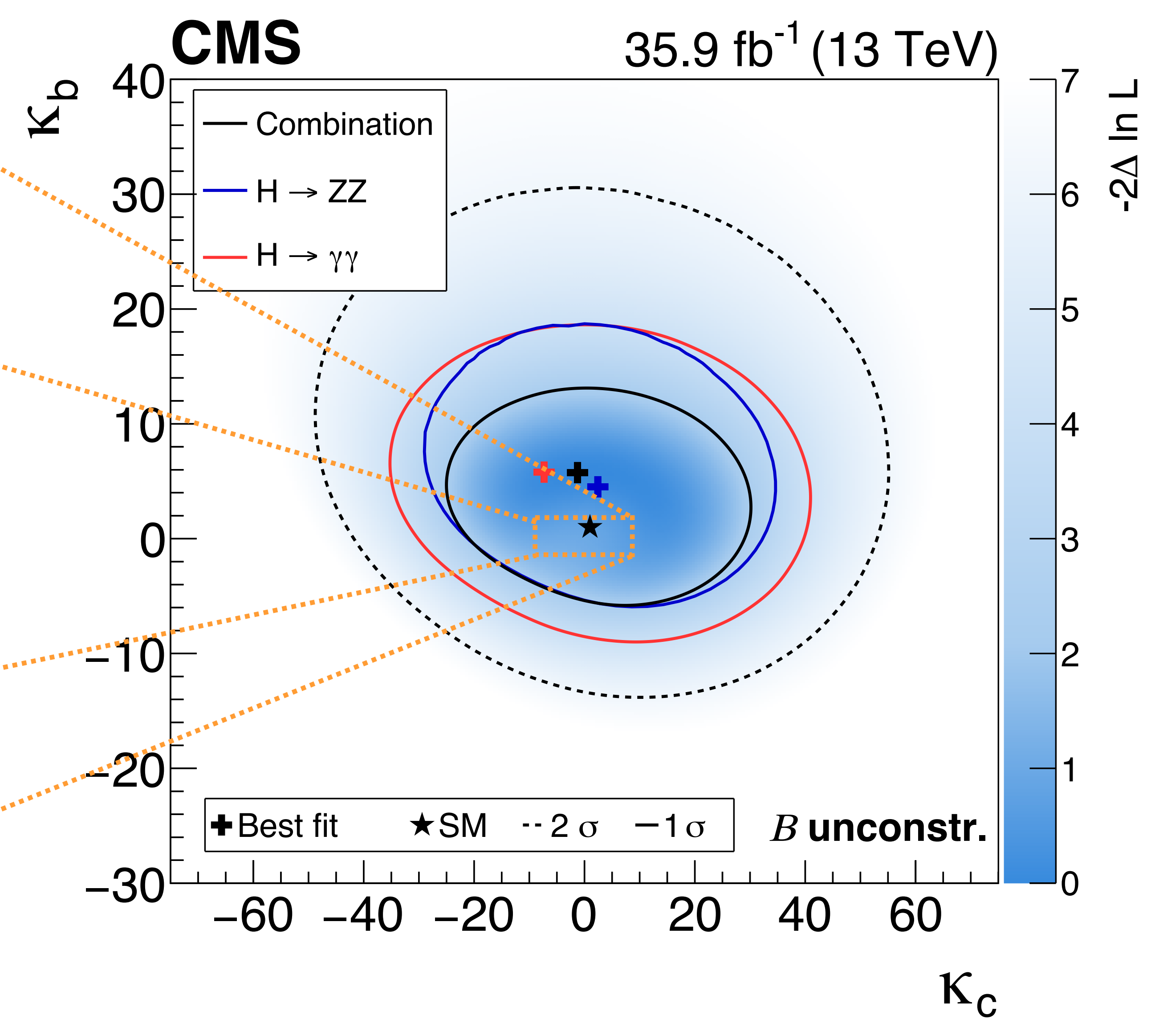
p_T^H shape and cross section are dependent on t-H, b-H, and c-H couplings
Effects from charm, mostly at low p_T^H



BRs(k_c,k_b)



BRs as nuisances



	obs. (exp.) 95% CL on k_c
ATLAS $\gamma\gamma$ (full Run2)	[-18, 24] ([-15, 19])(*)
CMS $4\ell+\gamma\gamma$ (36/fb Run2)	[-33, 38] ([-31, 36])(**)

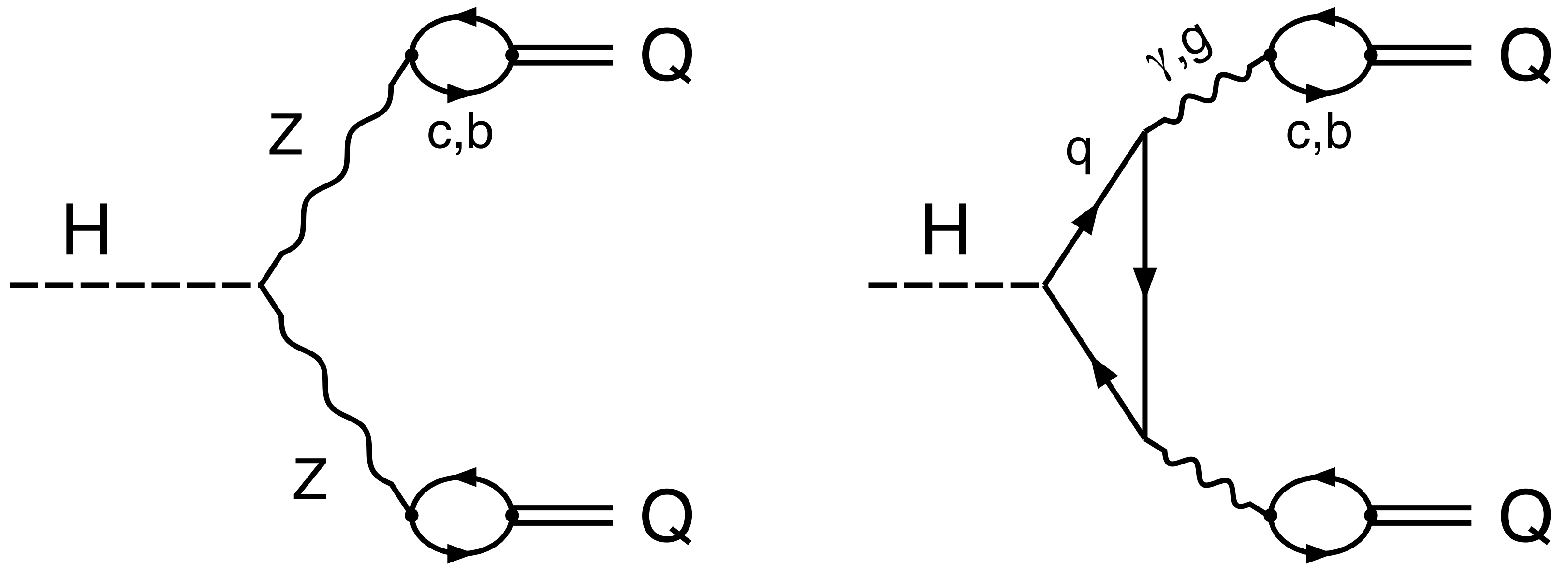
(*)BRs fixed to their SM expectations
(**)BRs as nuisances

Rare decays/production

H→J/Ψ J/Ψ AND H→ΥΥ

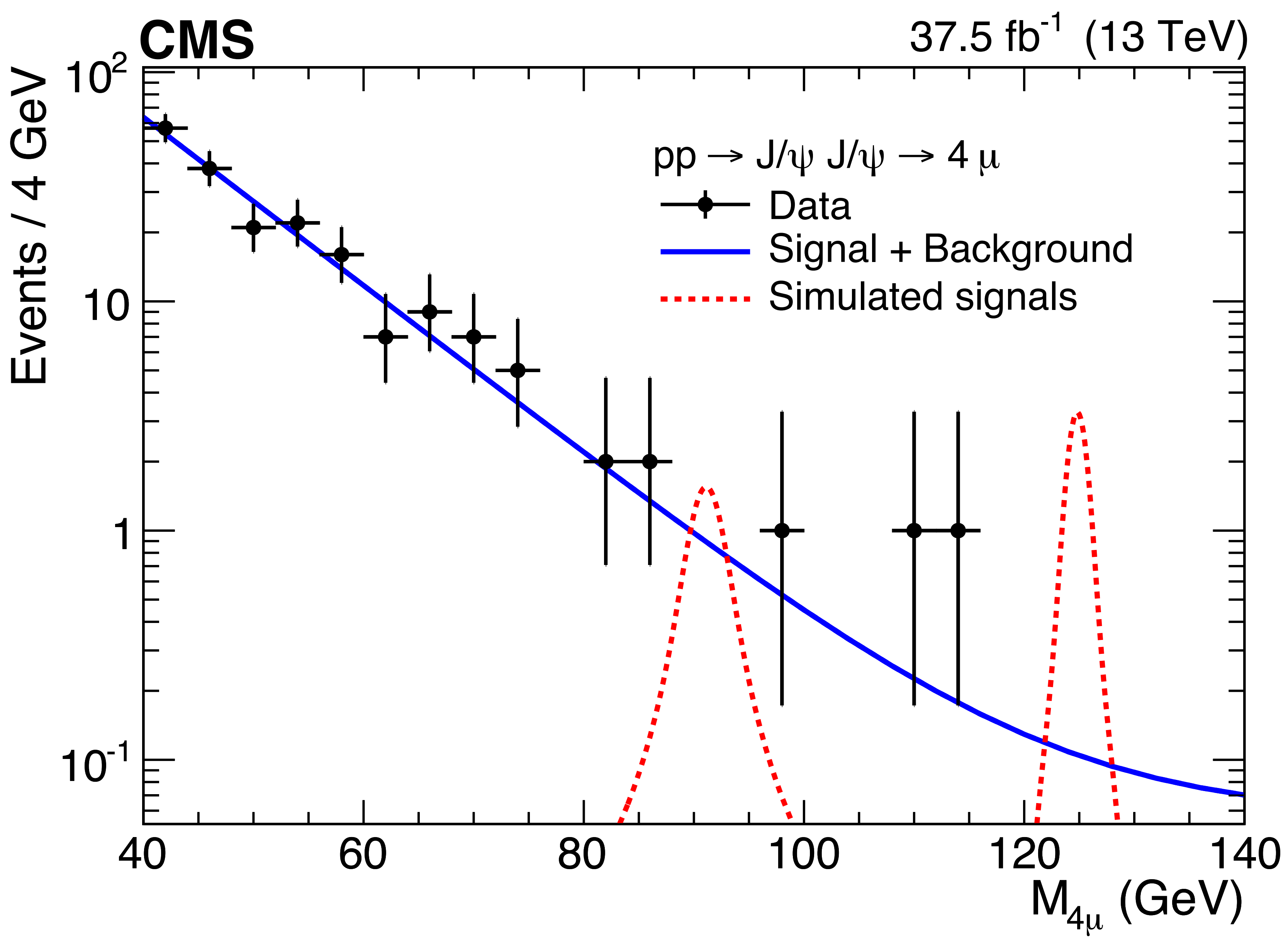
arXiv:1905.10408

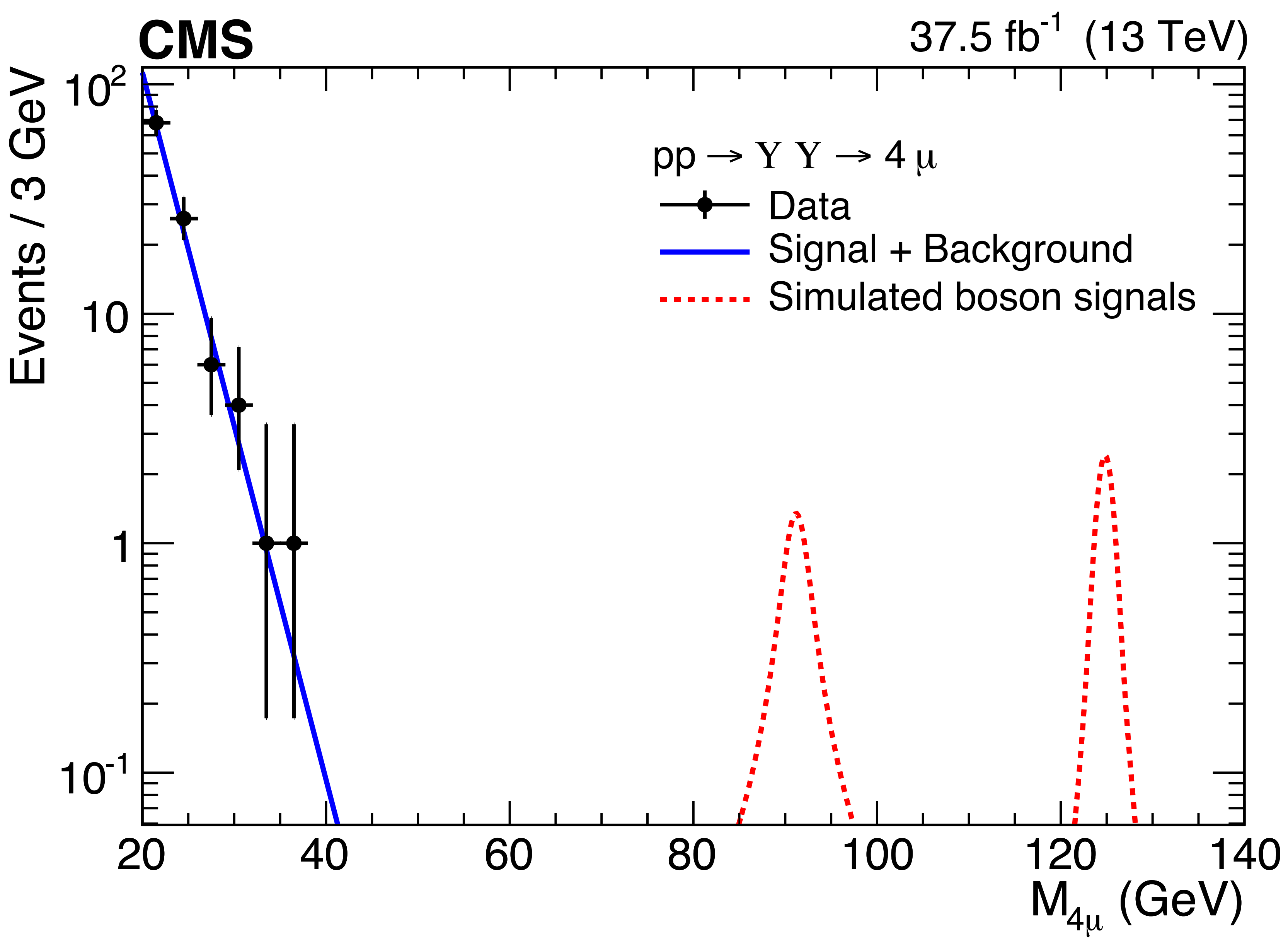
SM BRs inaccessible by many orders of magnitude.



Four-muon final state

- Experimentally clean with very small SM backgrounds
- Excess at H or Z mass would be sign of BSM physics





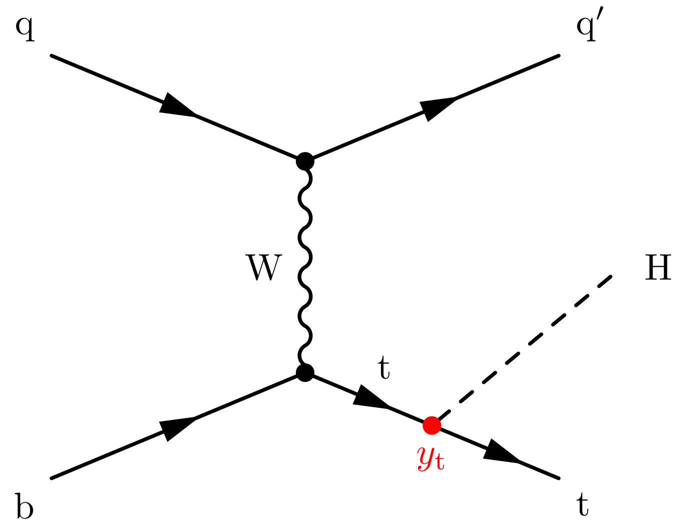
95% CL Upper Limits

Process	Observed	Expected
$\mathcal{B}(\mathrm{H} \to \mathrm{J}/\psi\mathrm{J}/\psi)$	1.8×10^{-3}	$(1.8^{+0.2}_{-0.1}) \times 10^{-3}$
$\mathcal{B}(\mathrm{H} \to \Upsilon\Upsilon)$	1.4×10^{-3}	$(1.4 \pm 0.1) \times 10^{-3}$
$\mathcal{B}(\mathrm{Z} \to \mathrm{J}/\psi\mathrm{J}/\psi)$	2.2×10^{-6}	$(2.8^{+1.2}_{-0.7}) \times 10^{-6}$
$\mathcal{B}(\mathrm{Z} \to \Upsilon\Upsilon)$	1.5×10^{-6}	$(1.5 \pm 0.1) \times 10^{-6}$

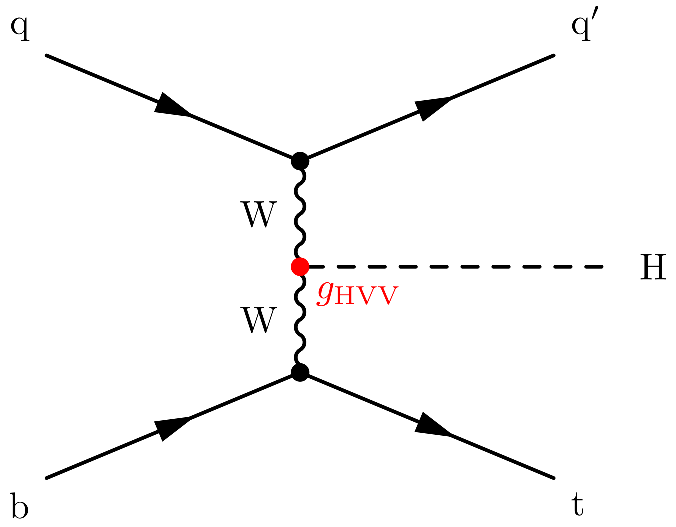
SEARCH FOR tHq/tHW PRODUCTION

PRD 99(2019)092005

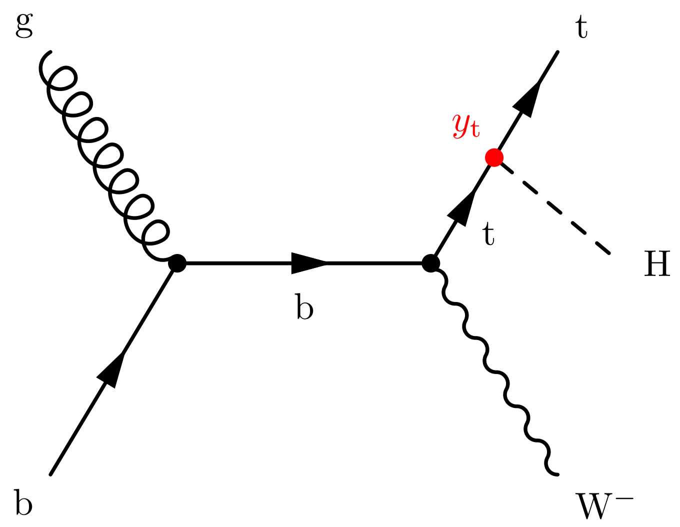
Process is highly sensitive to the absolute values of the Higgs-top Yukawa coupling, the Higgs boson coupling to vector bosons, and to their relative sign



σ(qb →tHq)=0.074 pb
t-channel

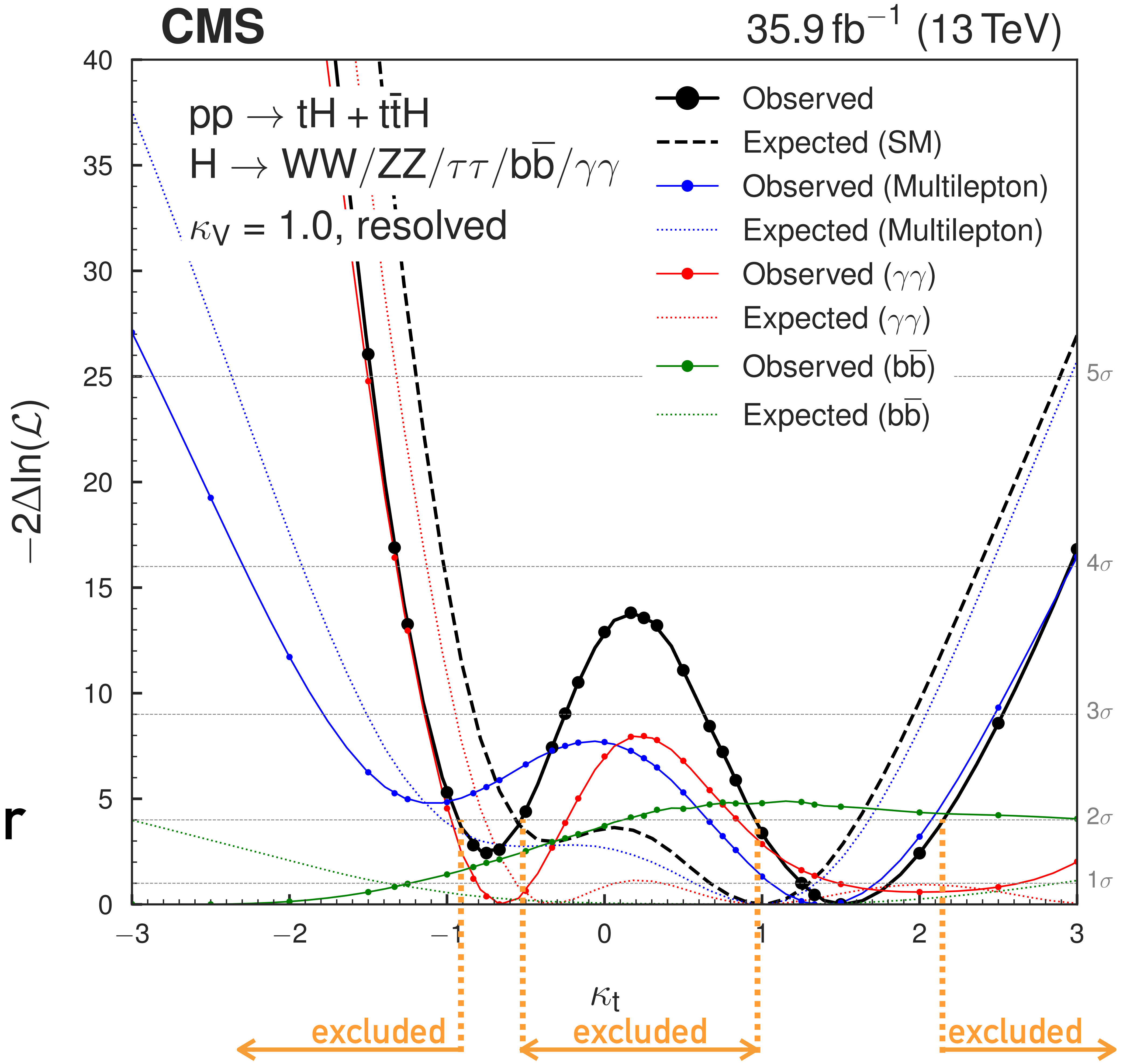


σ(qb →tHq)=0.003 pb
s-channel



σ(gb →tHW)=0.015 pb
W-associated

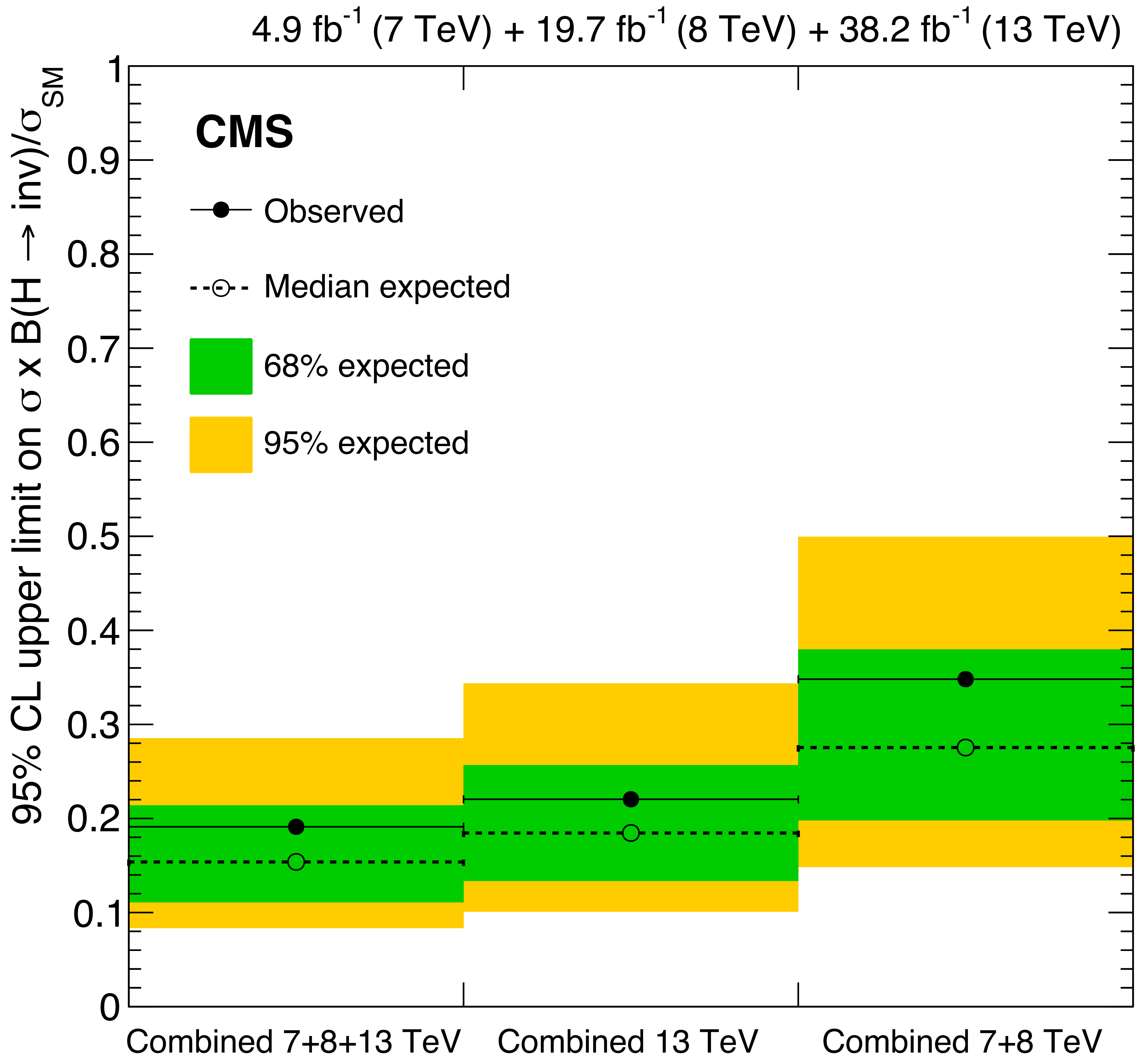
< 1/500th of ggF production

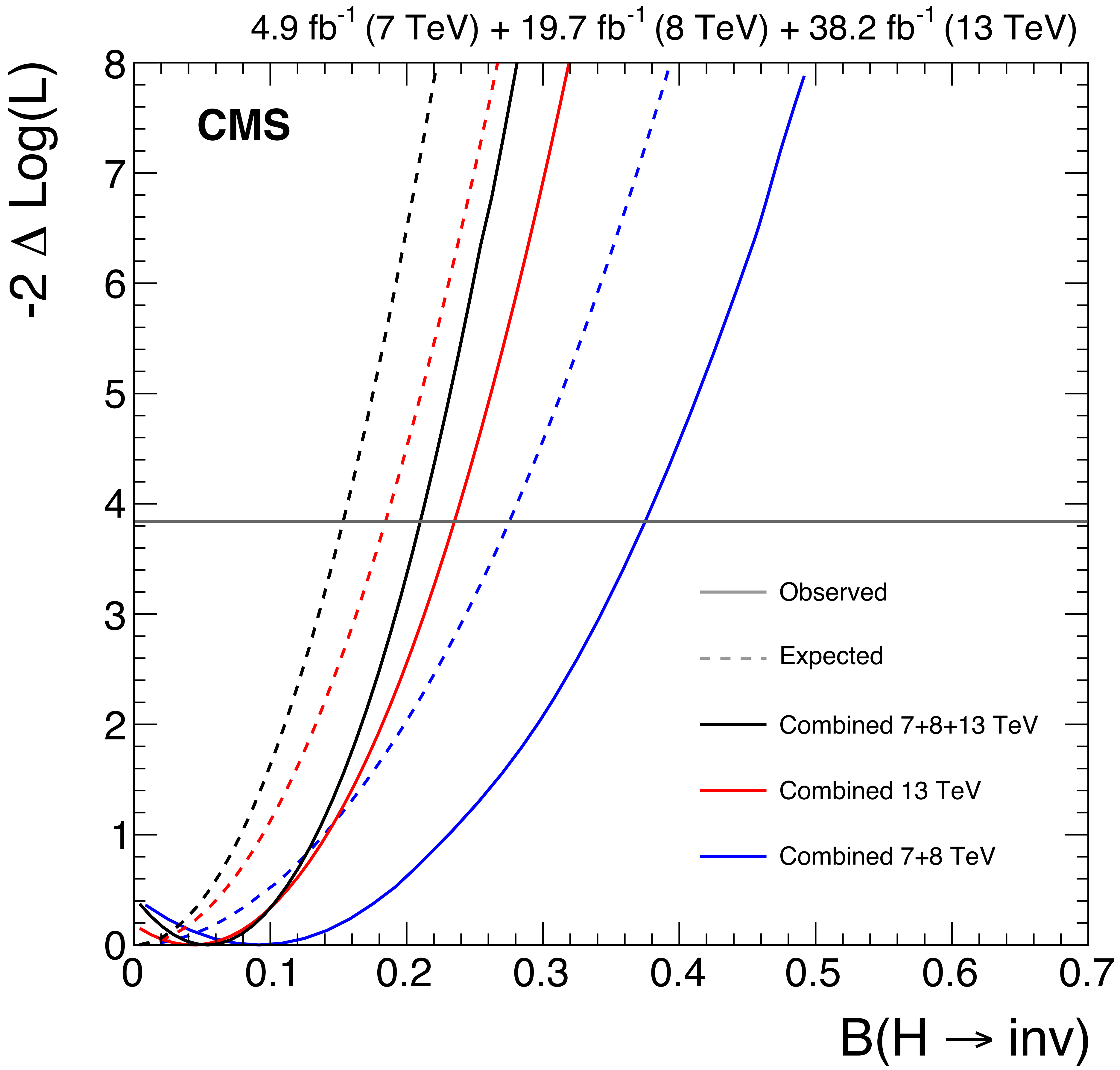


For a SM-like value of g_{HVV}, the data favor positive values of y_t

SEARCH FOR INVISIBLE DECAY

PLB 793(2019)520

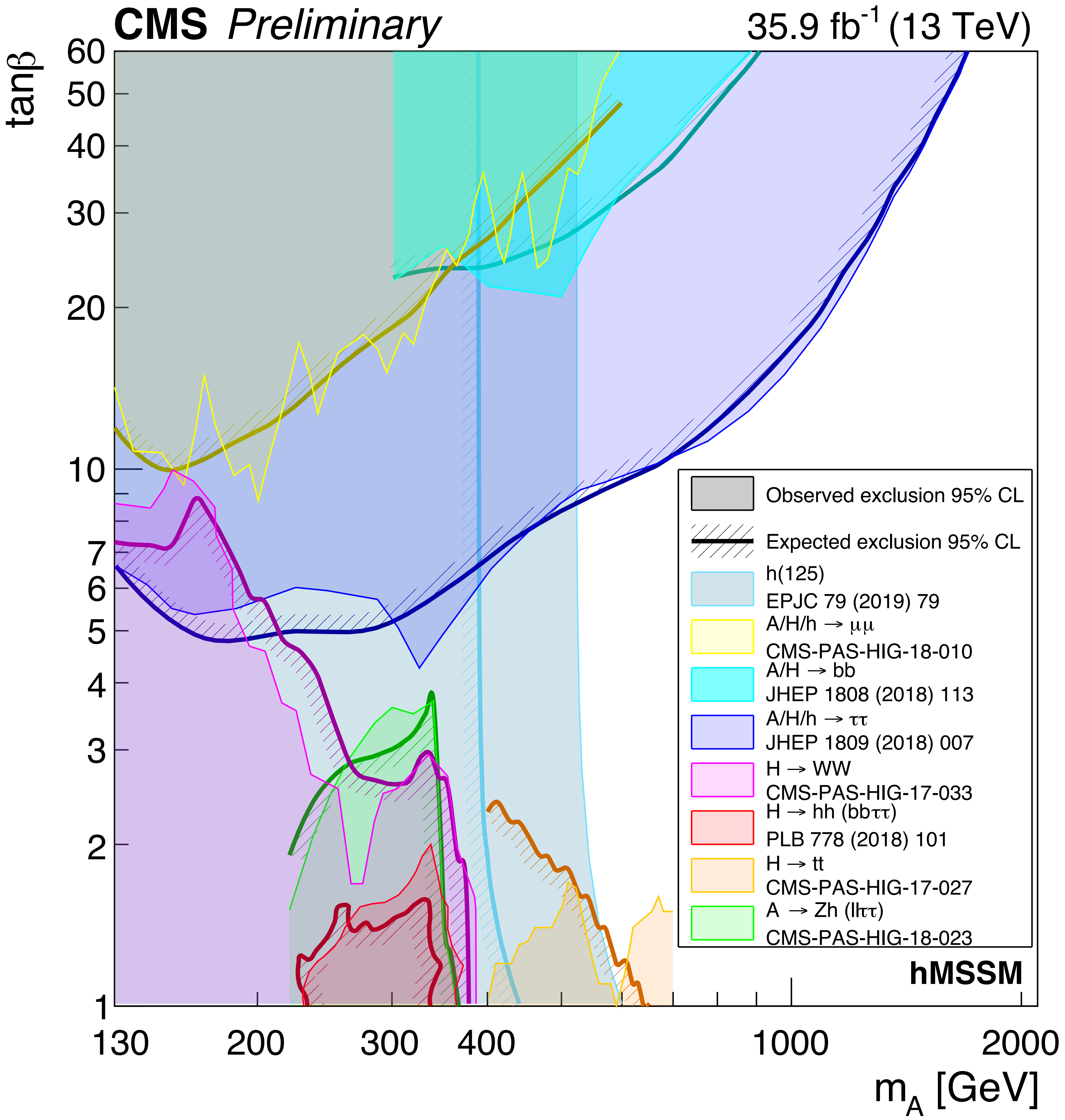


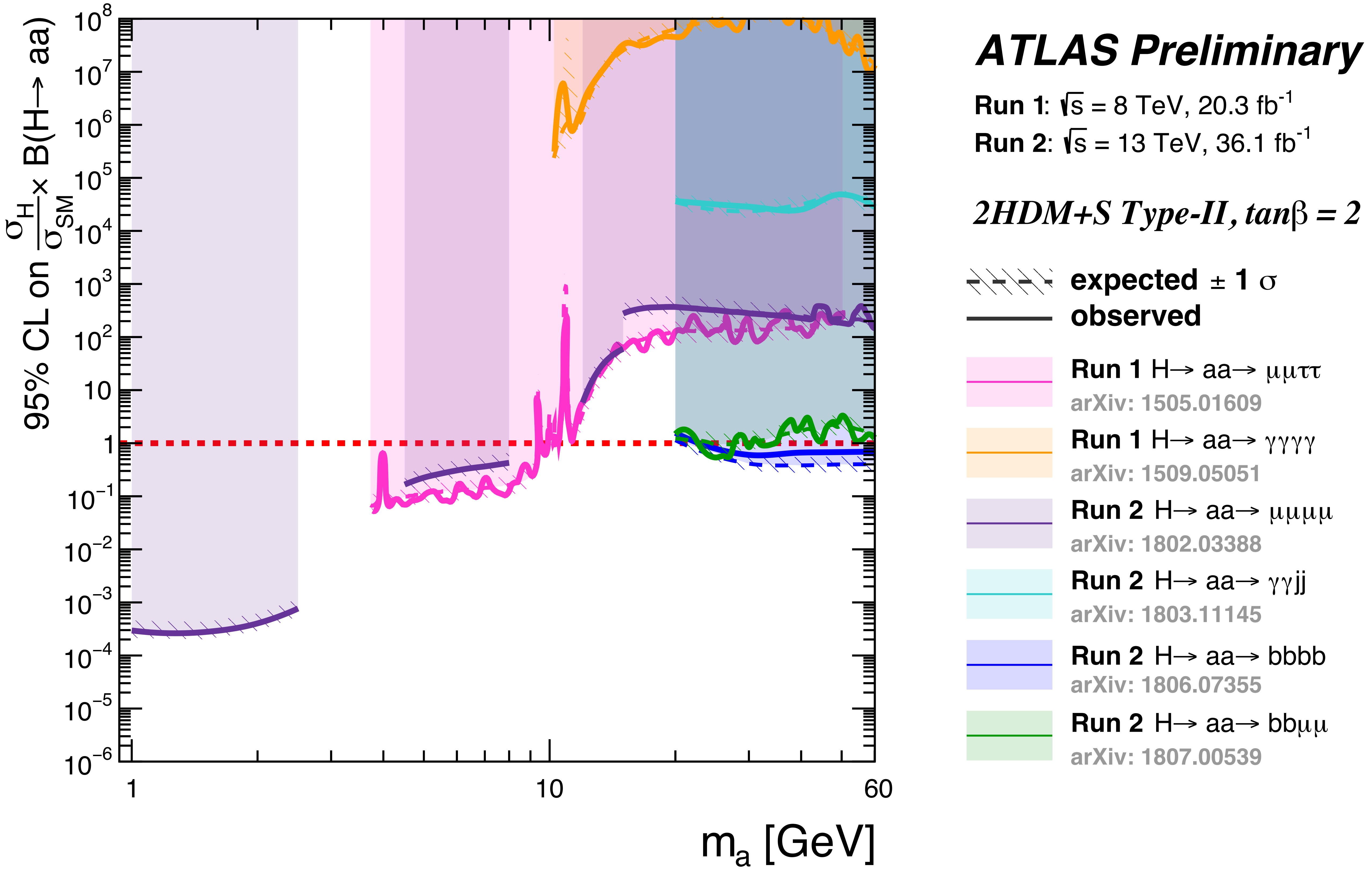


BSM SEARCHES

Variety of searches for additional Higgs bosons and exotic decays of H(125)

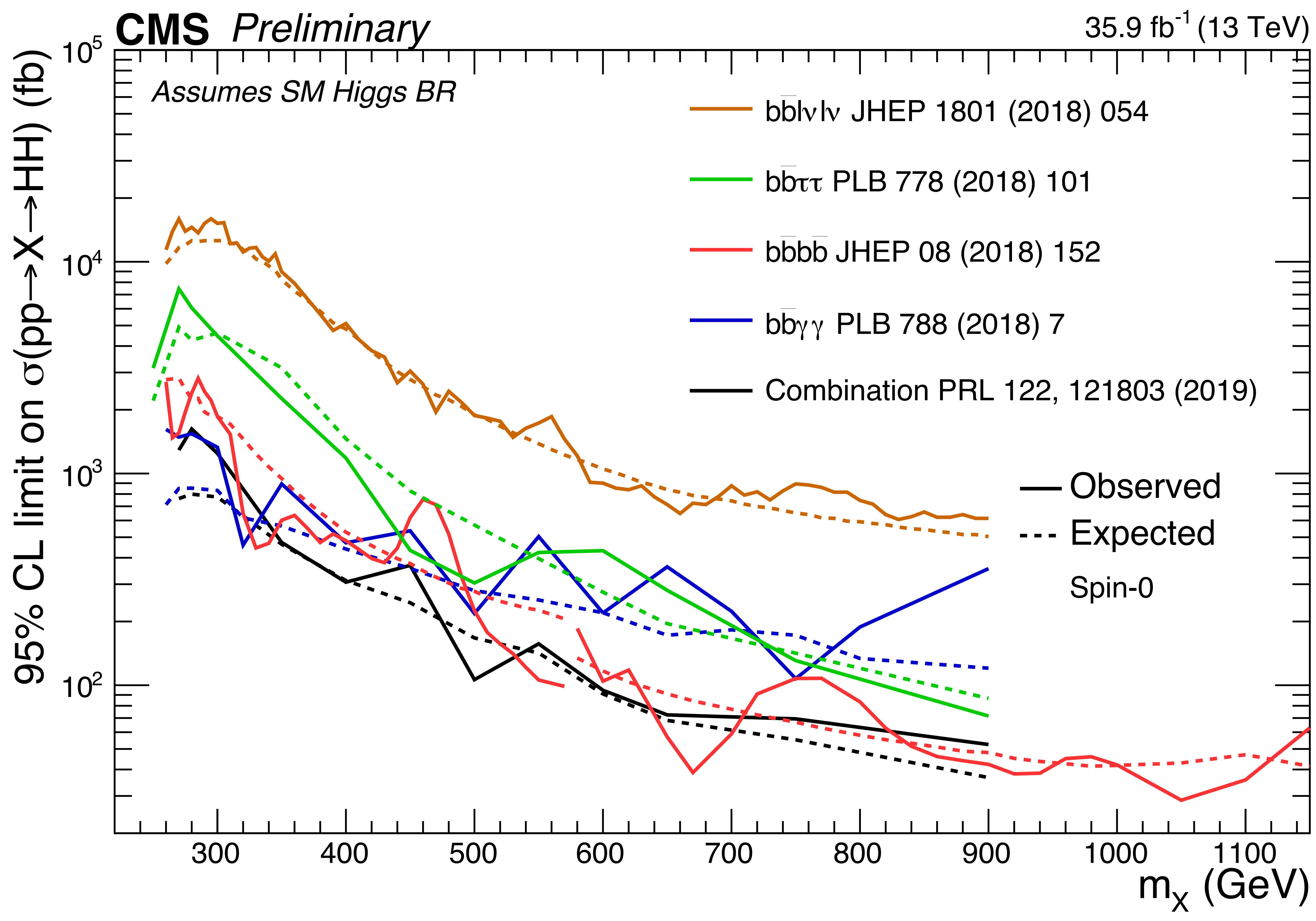
So far no excess or evidence and only exclusion in theory parameter space



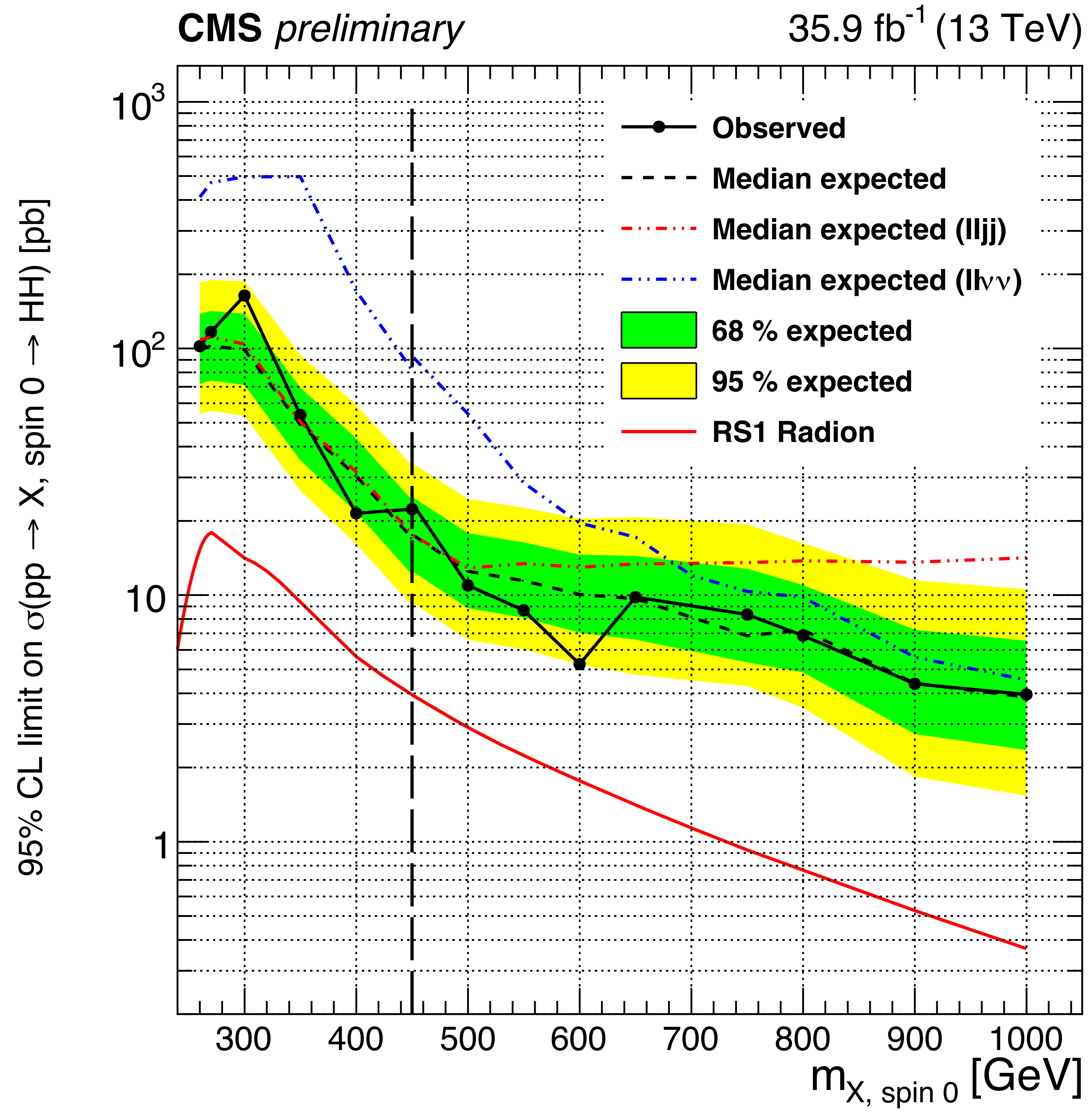


More material shown in the Higgs parallel sessions

HH Resonant Searches

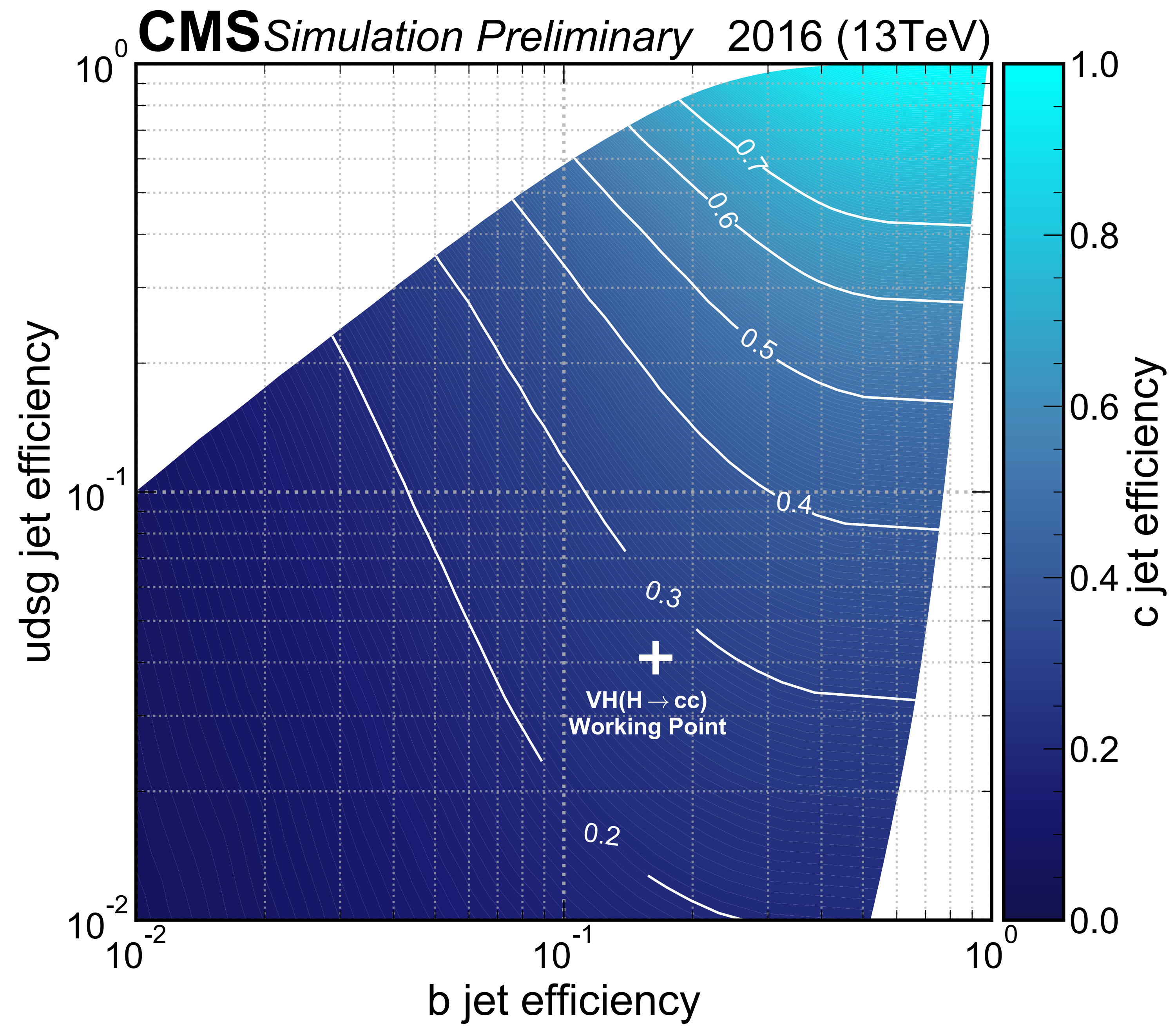


CMS-PAS-HIG-18-013



New HH→bbZZ analysis

CHARM–TAGGING TECHNIQUES



Resolved tagging

Fully connected DNN providing P(b), P(c), P(light) combined to create two discriminants

CvsL = P(c) / P(c) + P(light)

CvsB = P(c) / P(c) + P(b)

Calibration done using via a simultaneous fit to the 2D plane CvsB / CvsL in 3 background regions

Merged tagging

Complex DNN architecture for top, W, Z, Higgs decays, further splitted based on flavor content of decay mode

$$cc_{discriminant} = \frac{score(Z \to c\bar{c}) + score(H \to c\bar{c})}{score(Z \to c\bar{c}) + score(H \to c\bar{c}) + score(QCD)}$$

Calibration done using proxy jets, gluon splitting to cc with similar characteristics as signal jets