HIGGS@LHC

XLVIII INTERNATIONAL MEETING
ON FUNDAMENTAL PHYSICS

María Cepeda

BENASQUE, SEPTIEMBRE 2021

HIGGS@LHC

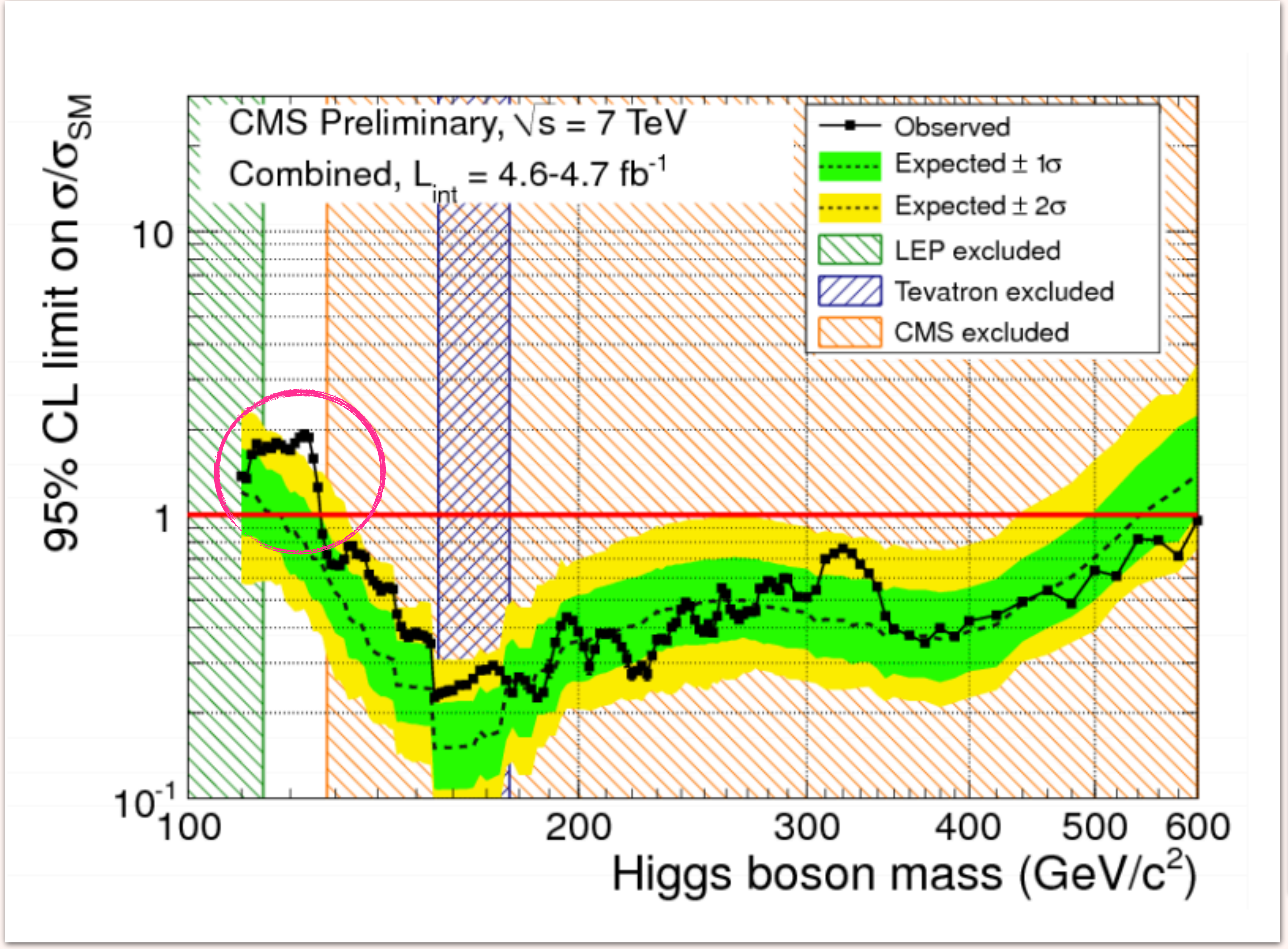
What have we learnt about the Higgs in the last 10 years?

XLVIII INTERNATIONAL MEETING
ON FUNDAMENTAL PHYSICS

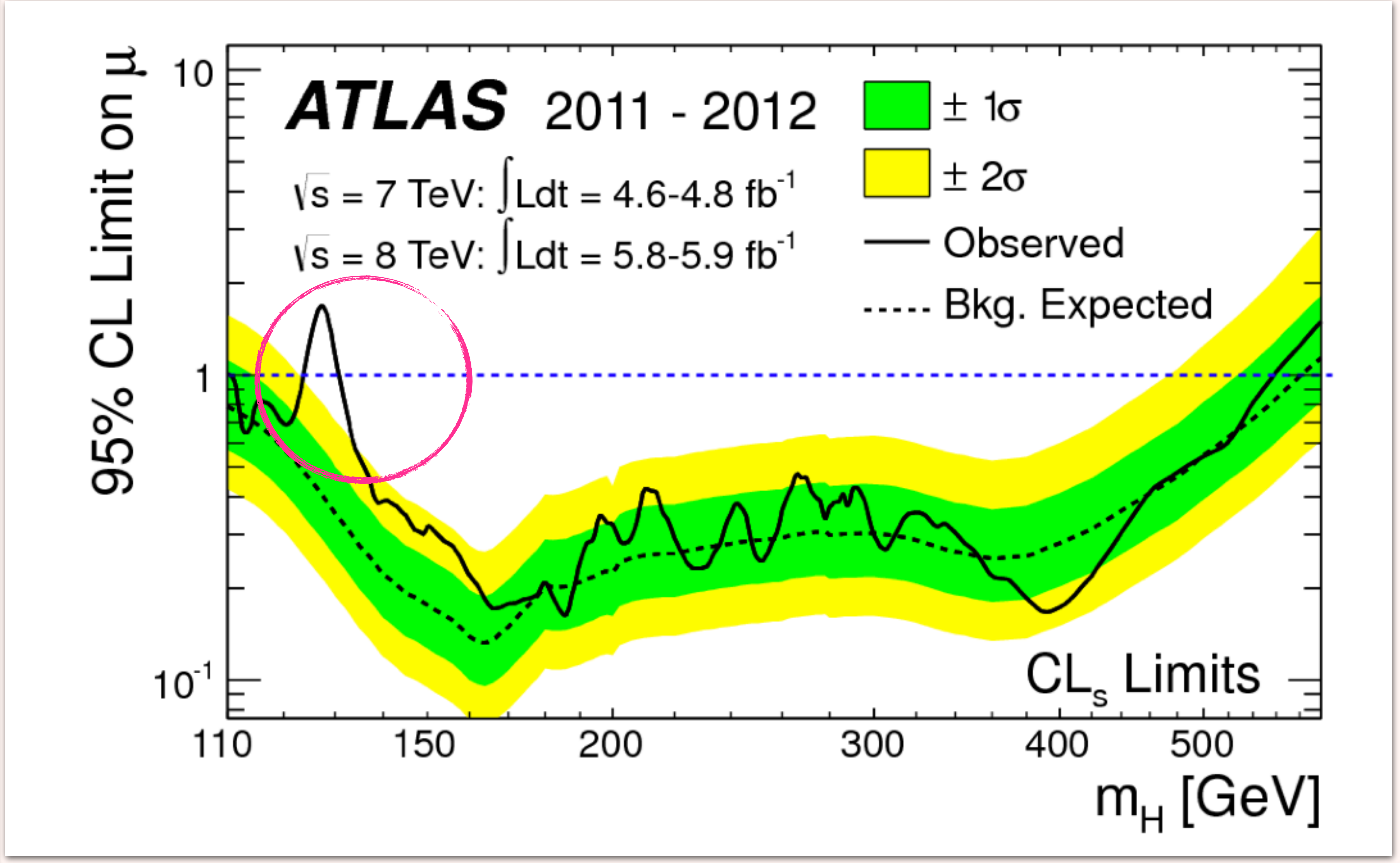
María Cepeda

BENASQUE, SEPTIEMBRE 2021

IT'S ONLY BEEN TEN YEARS...

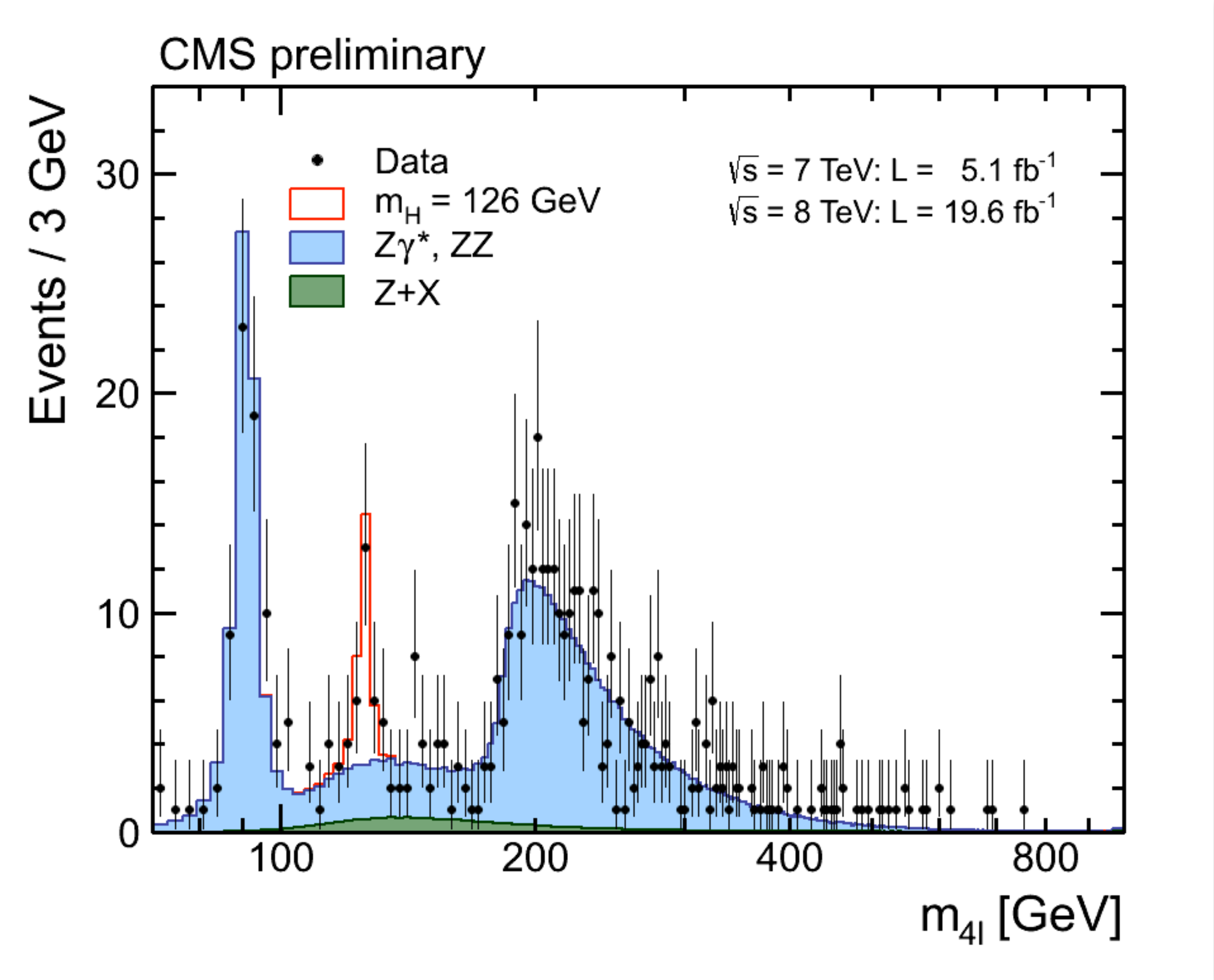


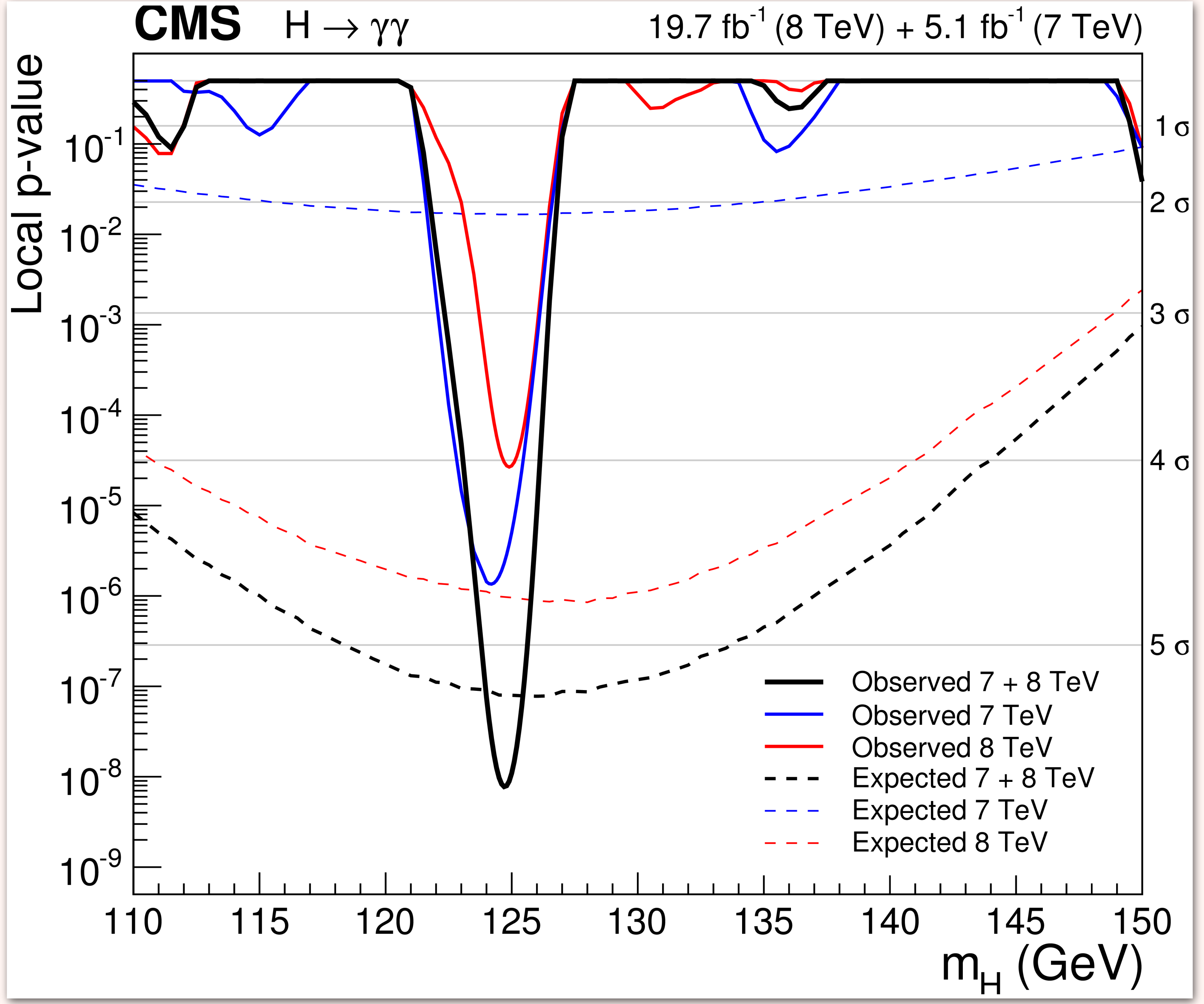
Status at the end of 2011

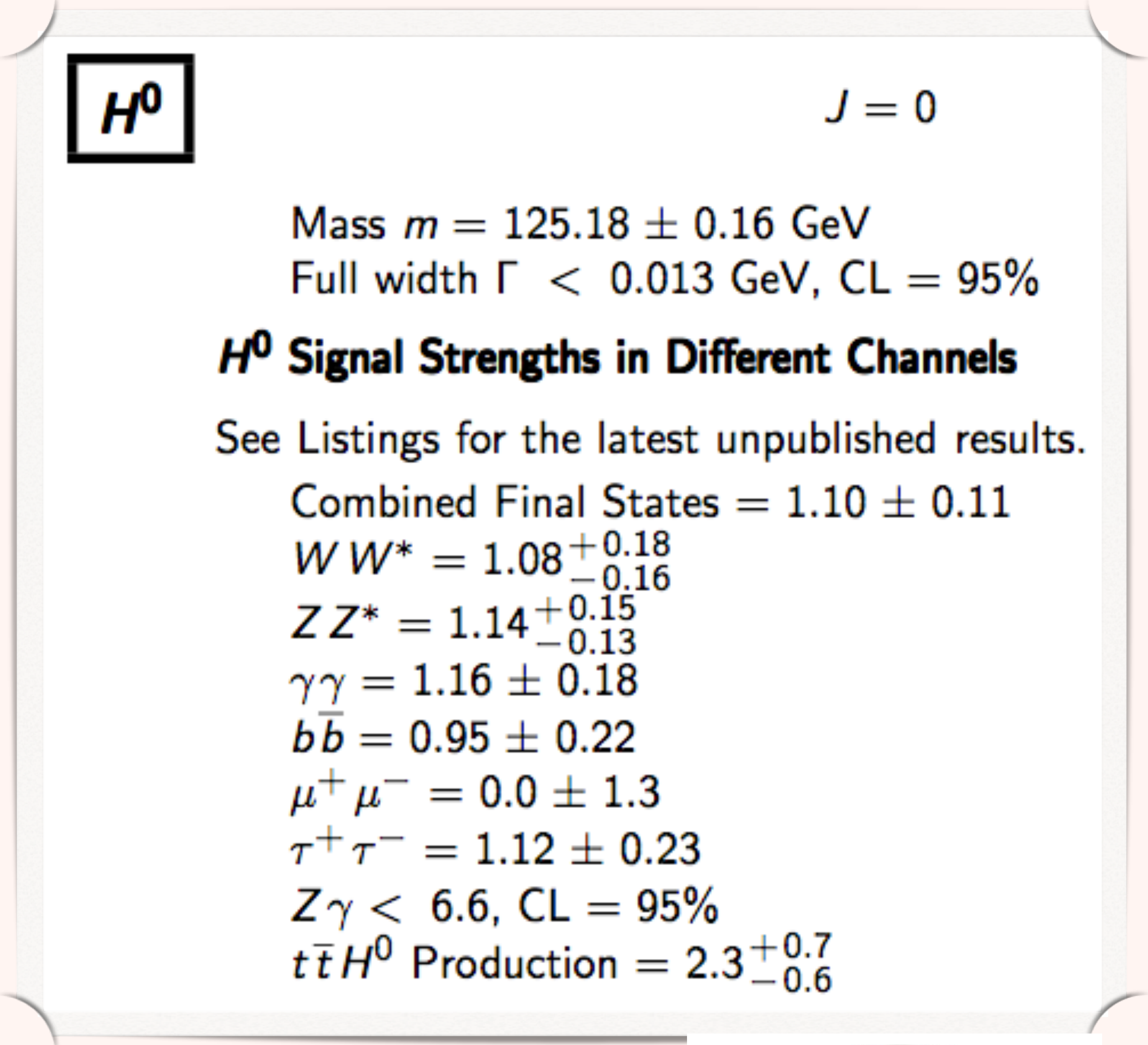


June 2012

AND WE'VE COME A LONG WAY SINCE OBSERVATION







H^0 $J = 0$

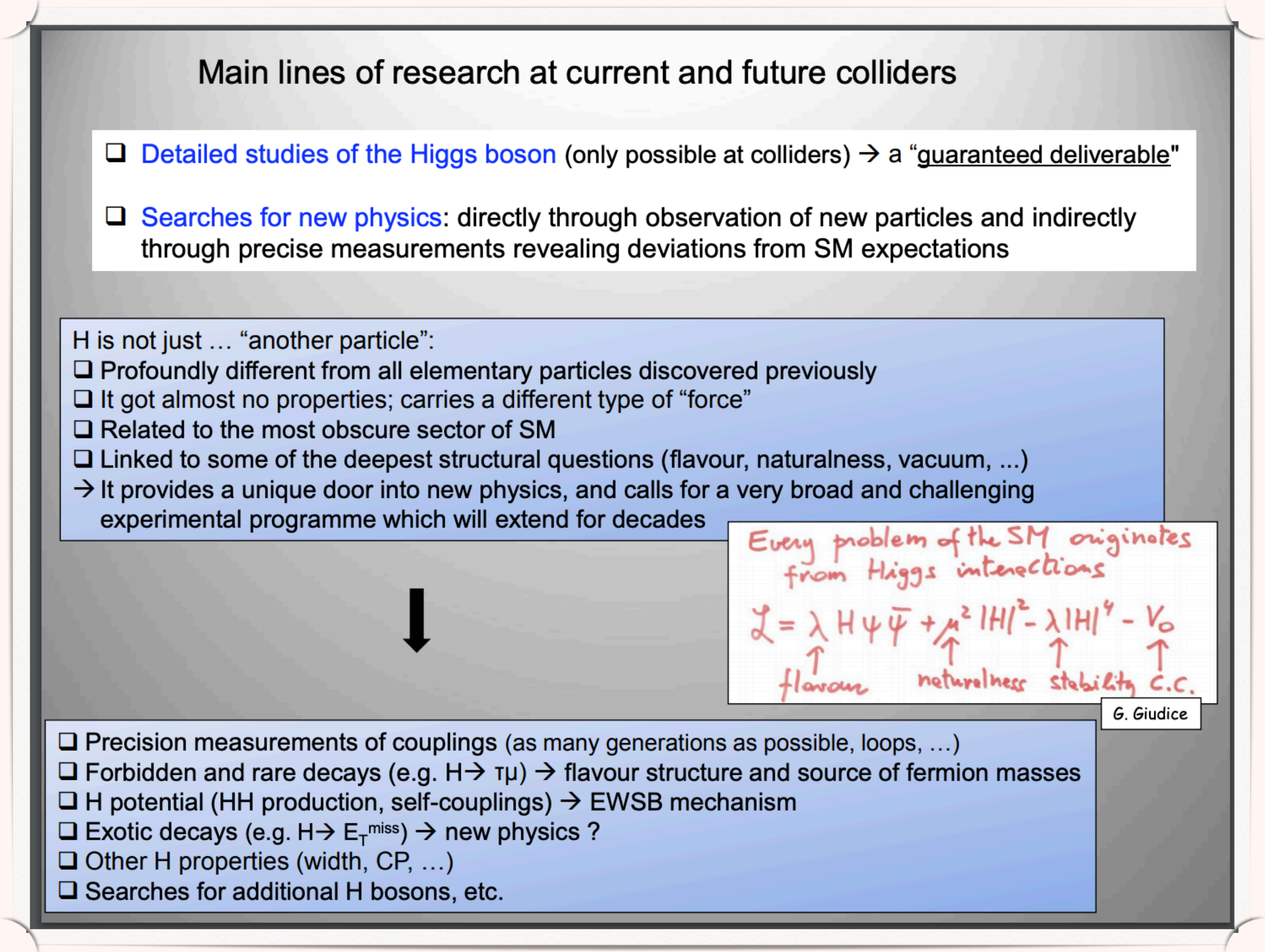
Mass $m = 125.18 \pm 0.16$ GeV
Full width $\Gamma < 0.013$ GeV, CL = 95%

H^0 Signal Strengths in Different Channels

See Listings for the latest unpublished results.

Combined Final States $= 1.10 \pm 0.11$
$WW^* = 1.08^{+0.18}_{-0.16}$
$ZZ^* = 1.14^{+0.15}_{-0.13}$
$\gamma\gamma = 1.16 \pm 0.18$
$b\bar{b} = 0.95 \pm 0.22$
$\mu^+\mu^- = 0.0 \pm 1.3$
$\tau^+\tau^- = 1.12 \pm 0.23$
$Z\gamma < 6.6$, CL = 95%
$t\bar{t}H^0$ Production $= 2.3^{+0.7}_{-0.6}$

THE DISCOVERY WAS ONLY THE START



Main lines of research at current and future colliders

- ☐ Detailed studies of the Higgs boson (only possible at colliders) → a "guaranteed deliverable"
- ☐ Searches for new physics: directly through observation of new particles and indirectly through precise measurements revealing deviations from SM expectations

H is not just … "another particle":
- ☐ Profoundly different from all elementary particles discovered previously
- ☐ It got almost no properties; carries a different type of "force"
- ☐ Related to the most obscure sector of SM
- ☐ Linked to some of the deepest structural questions (flavour, naturalness, vacuum, ...)

→ It provides a unique door into new physics, and calls for a very broad and challenging experimental programme which will extend for decades

Every problem of the SM originates from Higgs interactions

$$\mathcal{L} = \underset{\text{flavour}}{\underset{\uparrow}{\lambda}} H \psi \bar{\psi} + \underset{\text{naturalness}}{\underset{\uparrow}{\mu^2}} |H|^2 - \underset{\text{stability}}{\underset{\uparrow}{\lambda}} |H|^4 - \underset{\text{C.C.}}{\underset{\uparrow}{V_0}}$$

G. Giudice

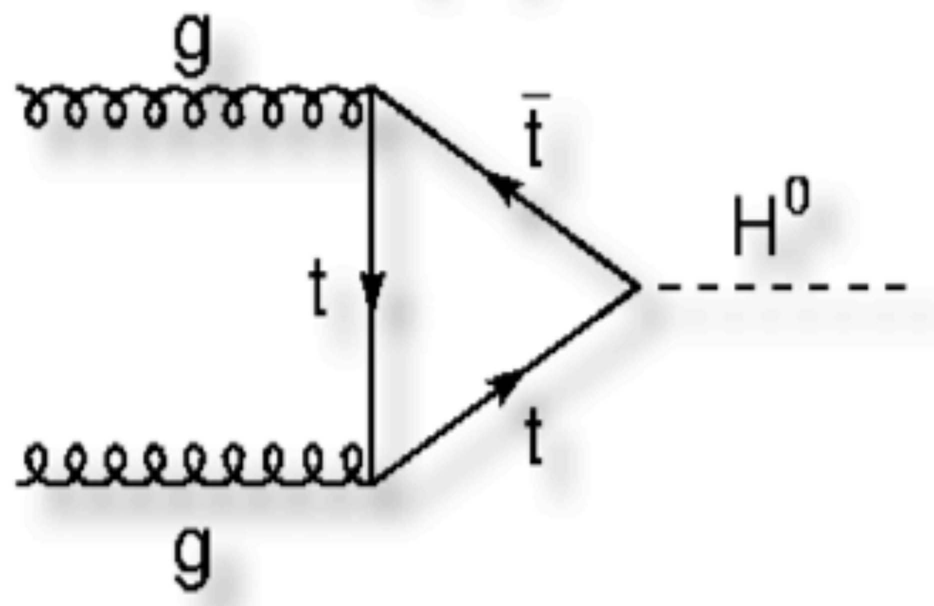
- ☐ Precision measurements of couplings (as many generations as possible, loops, …)
- ☐ Forbidden and rare decays (e.g. H→ τμ) → flavour structure and source of fermion masses
- ☐ H potential (HH production, self-couplings) → EWSB mechanism
- ☐ Exotic decays (e.g. H→ E_T^{miss}) → new physics ?
- ☐ Other H properties (width, CP, …)
- ☐ Searches for additional H bosons, etc.

Fabiola Giannotti @ LHCP 2021

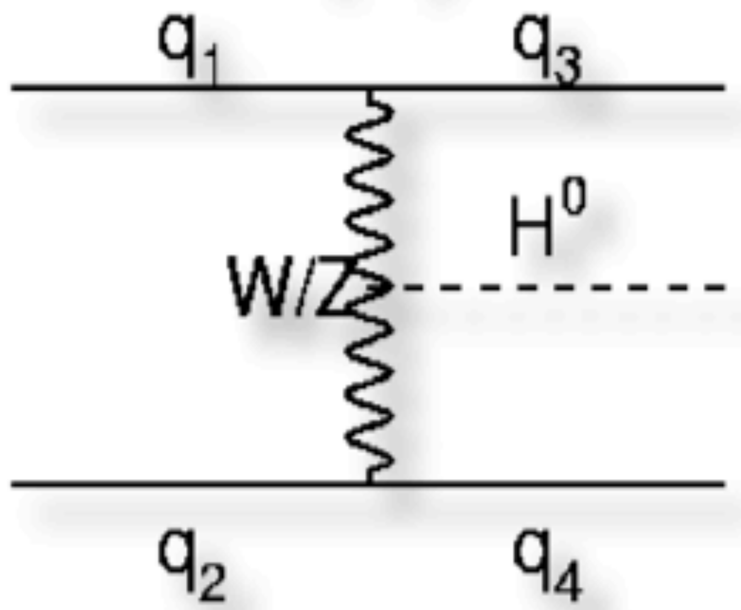
Understanding the nature of the Higgs boson is one of the main goals of particle physics today

How much do we really know in 2021 about the boson?

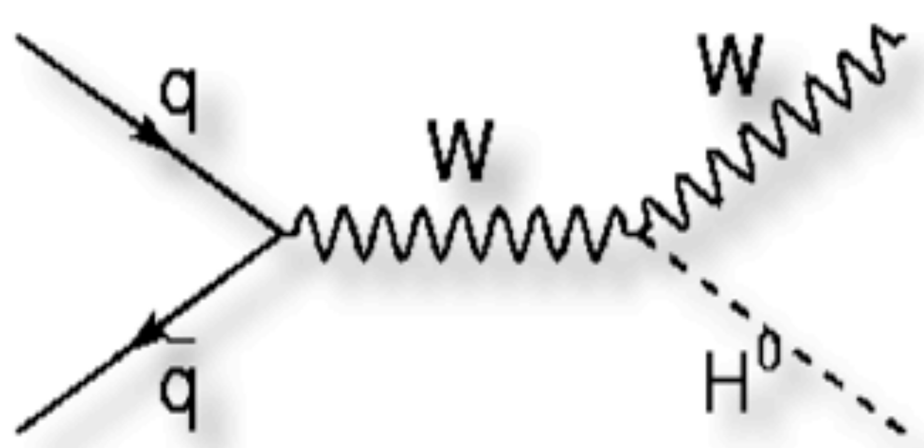
THE LHC EXPERIMENTS ARE UNIQUE TOOLS, ABLE TO EXPLORE HIGGS PRODUCTION AND DECAY IN DETAIL



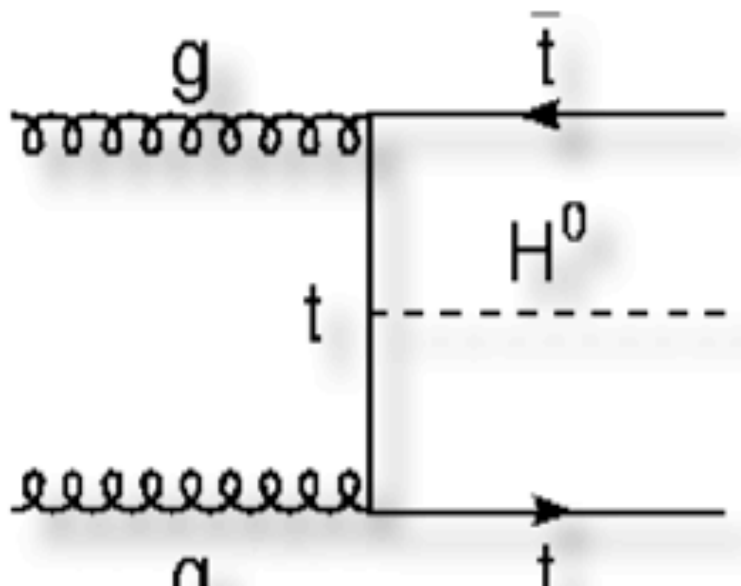
gluon fusion, ggH



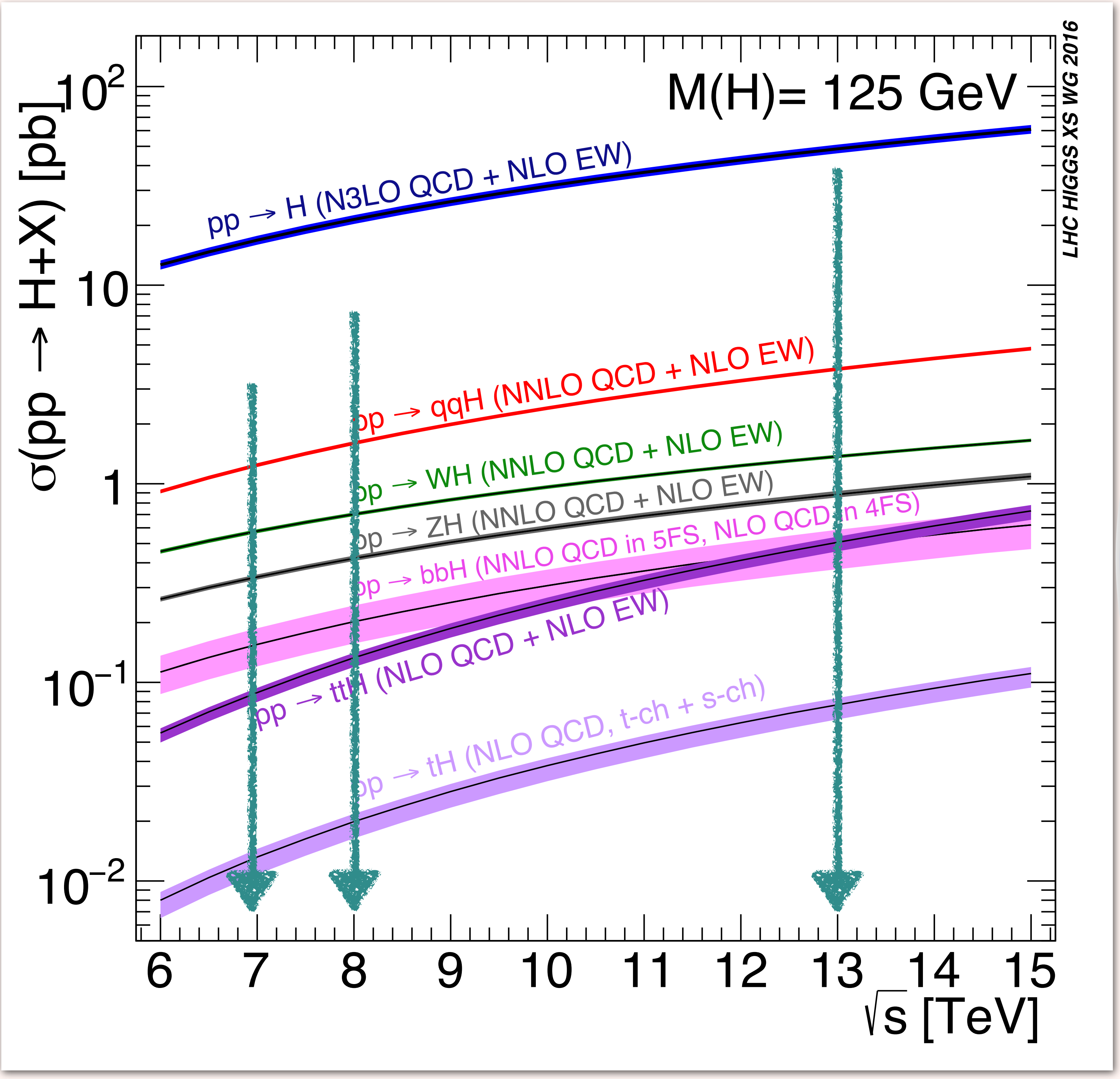
VBF, qqH (V=W,Z)

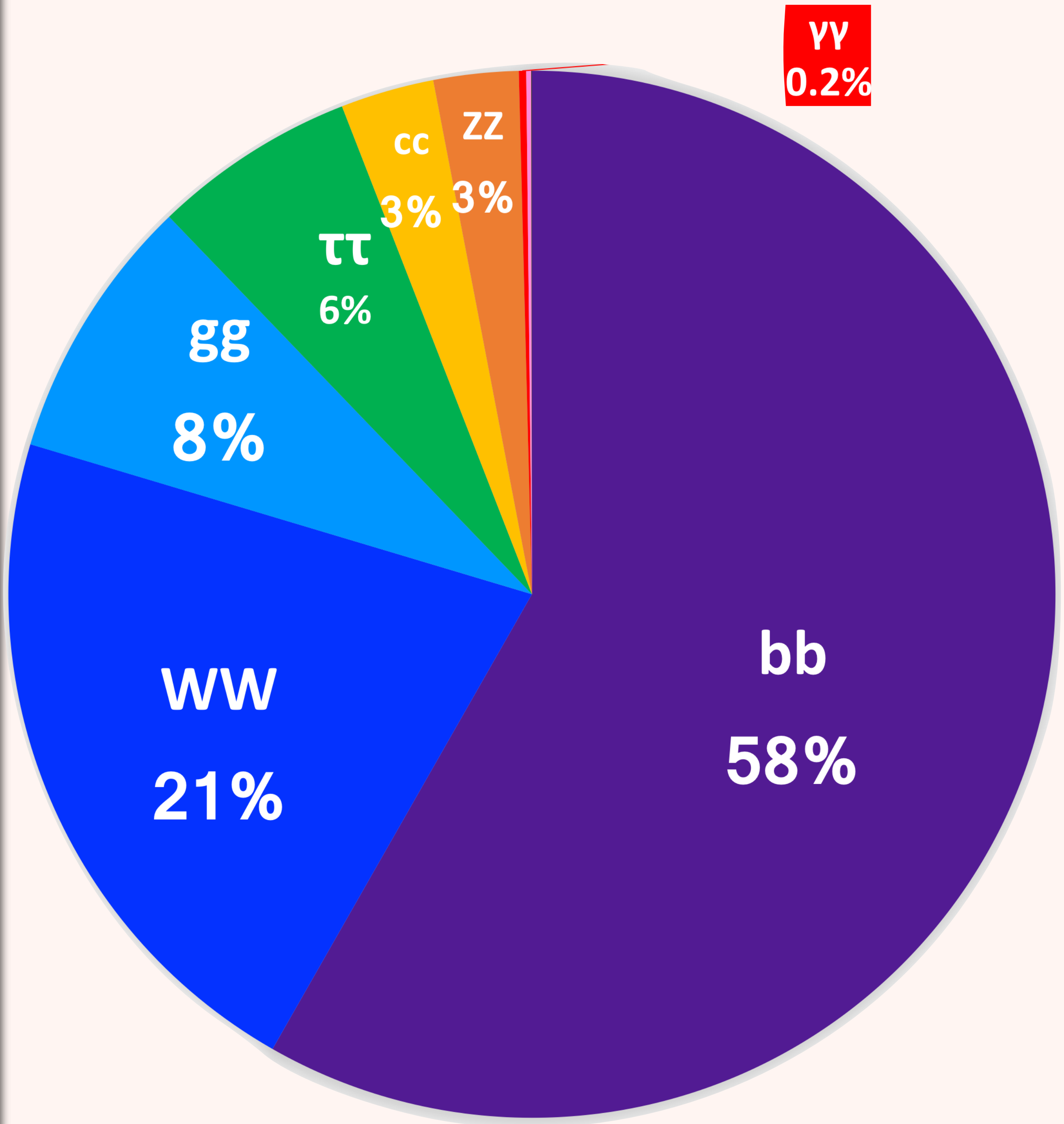


Higgs-strahlung, VH



Top associated production

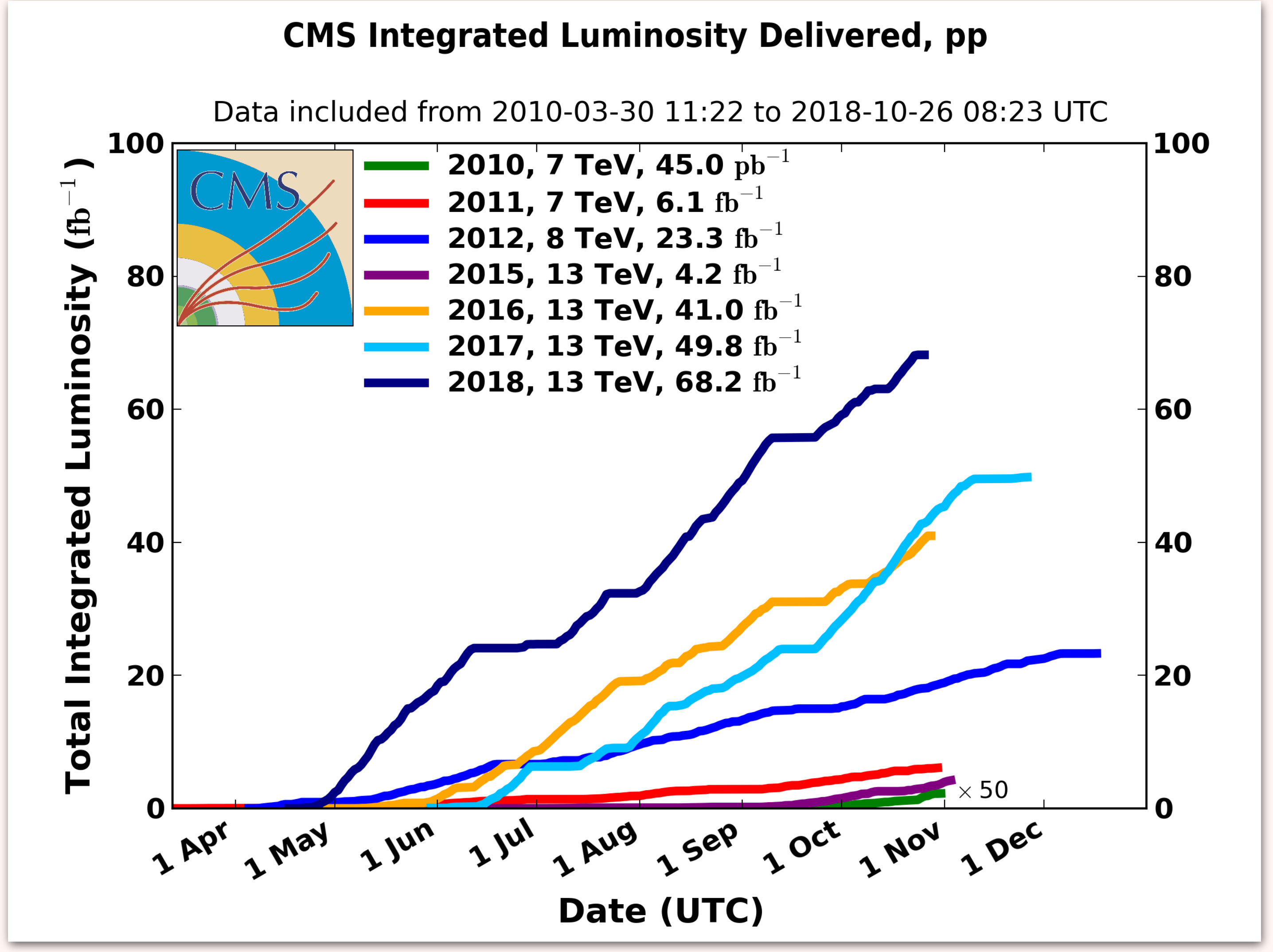


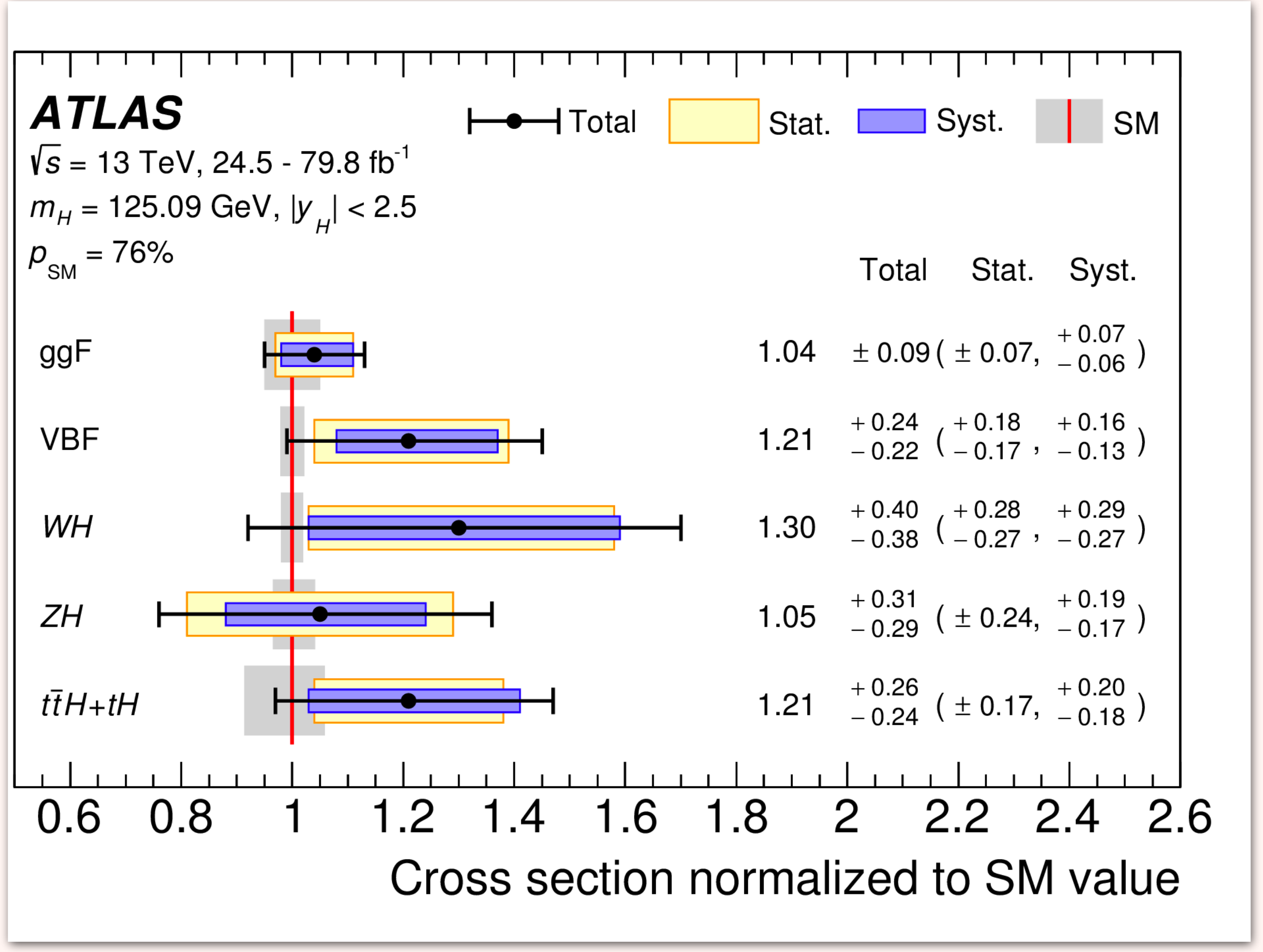


https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG

PRECISION HIGGS PHYSICS ALL AROUND

- With the third run of the LHC about to start, we are still working on finishing the analysis of the close to 150 fb^{-1} of 13TeV pp Run2 collisions available for analysis.
- We have really exploited the millions of Higgs bosons produced in each LHC experiment: the main Higgs production & decay modes have been observed or show evidence with Run2 statistics. We have moved to precision measurements in almost all cases.
- So far excellent agreement with the Standard Model prediction. Similar performance in CMS and ATLAS: Single experiment partial Run2 results more precise already than Run1 ATLAS+CMS.





WHAT HAVE WE LEARNT ABOUT THE HIGGS SO FAR, AND WHAT DO WE EXPECT TO LEARN IN RUN3?

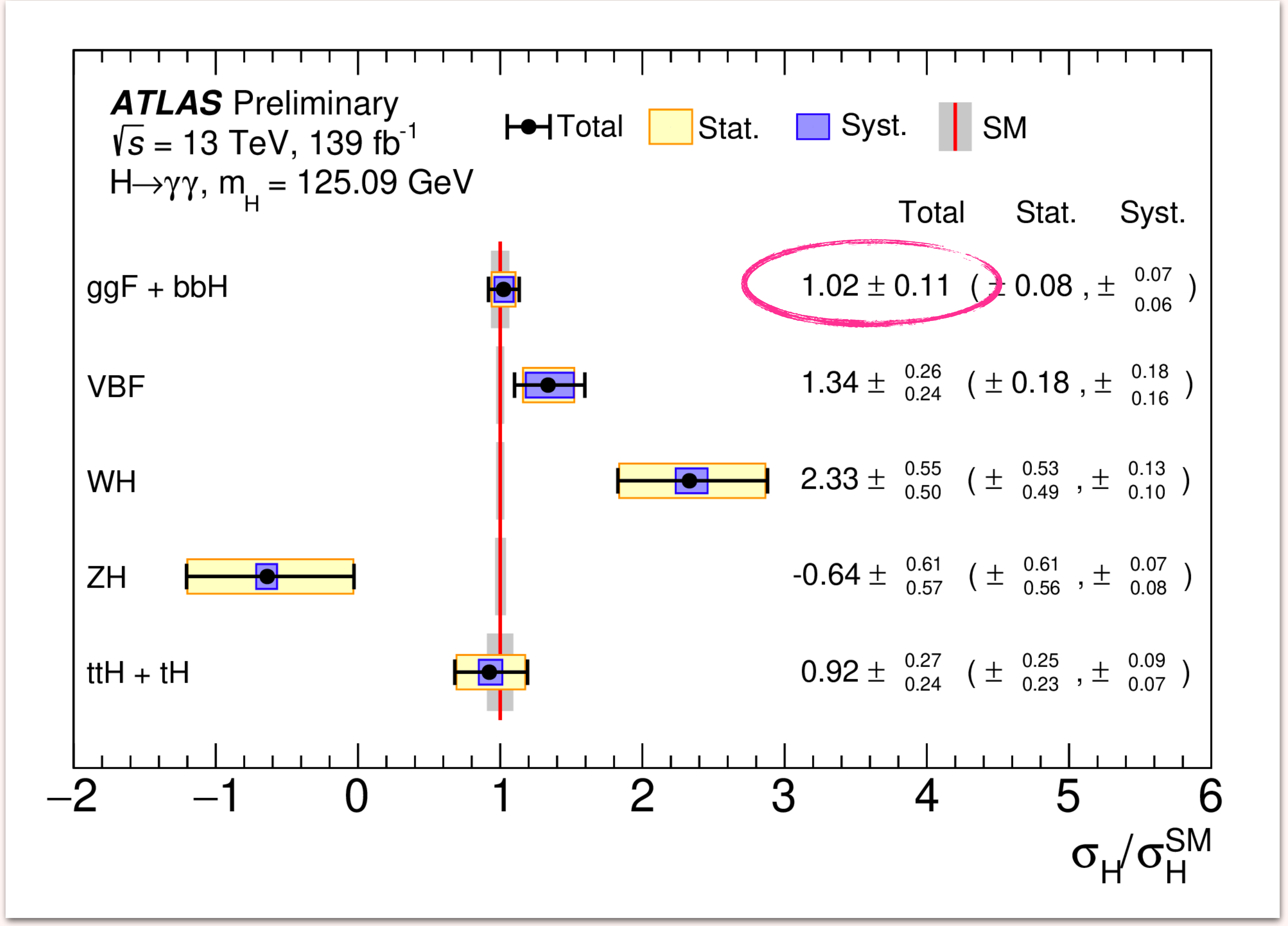
- Precision Measurements: Mass&Width, CP, Differential & Fiducial Cross Sections
- Does the Higgs couple to the Second Generation?
- Does the Higgs couple to itself?
- Can we ‘see’ rare processes (production or decay)
- Is the Higgs the SM Higgs?
- Is the Higgs alone?

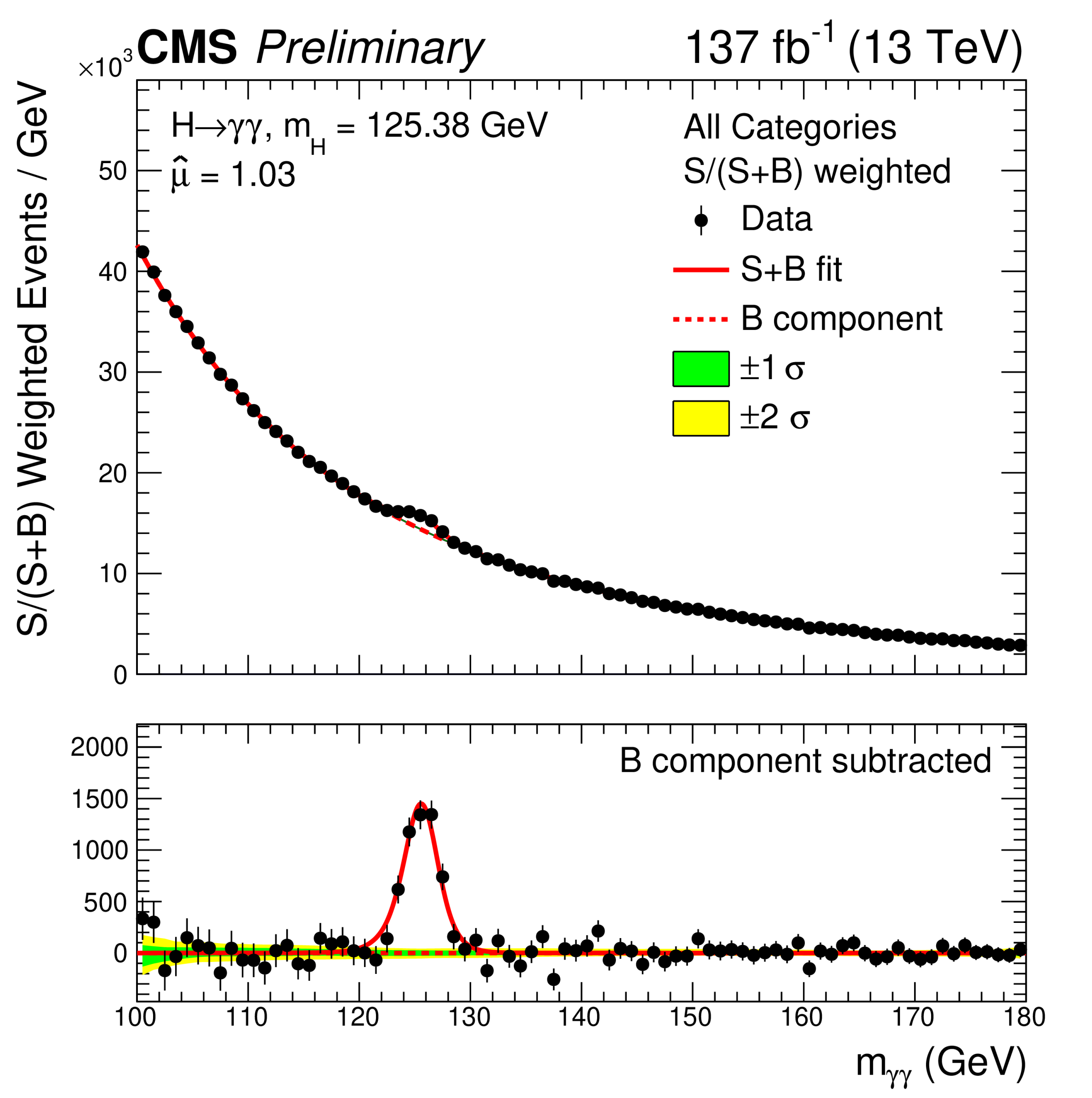
THE SECOND RUN OF THE LHC: PRECISION IN HIGGS MEASUREMENTS

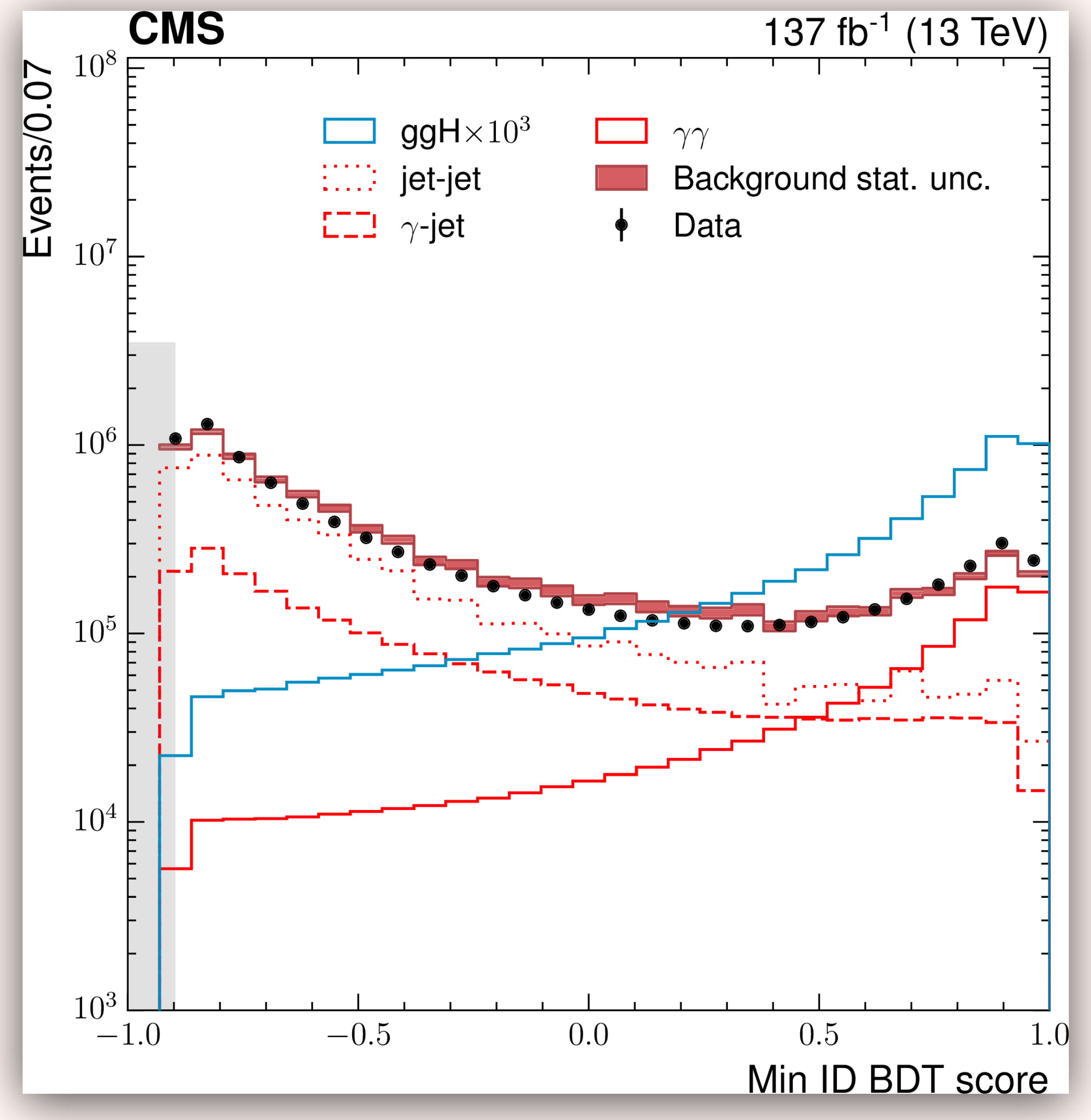
PRECISELY MEASURING THE HIGGS: $H \to \gamma\gamma$

- $H \to \gamma\gamma$ alone able to measure the Higgs signal strength to 10% (stat similar to syst for ggF)
- Probing ggF, VBF, VH, ttH, tH
- Exploit the cleanliness of the signature (excellent diphoton resolution) to do precision physics

	Lumi	**Precision**
CMS, JHEP 07 (2021) 027	Full Run2	μ=1.12±0.09
ATLAS-CONF-2020-026	Full Run2	σxBR = 127 ± 10 fb

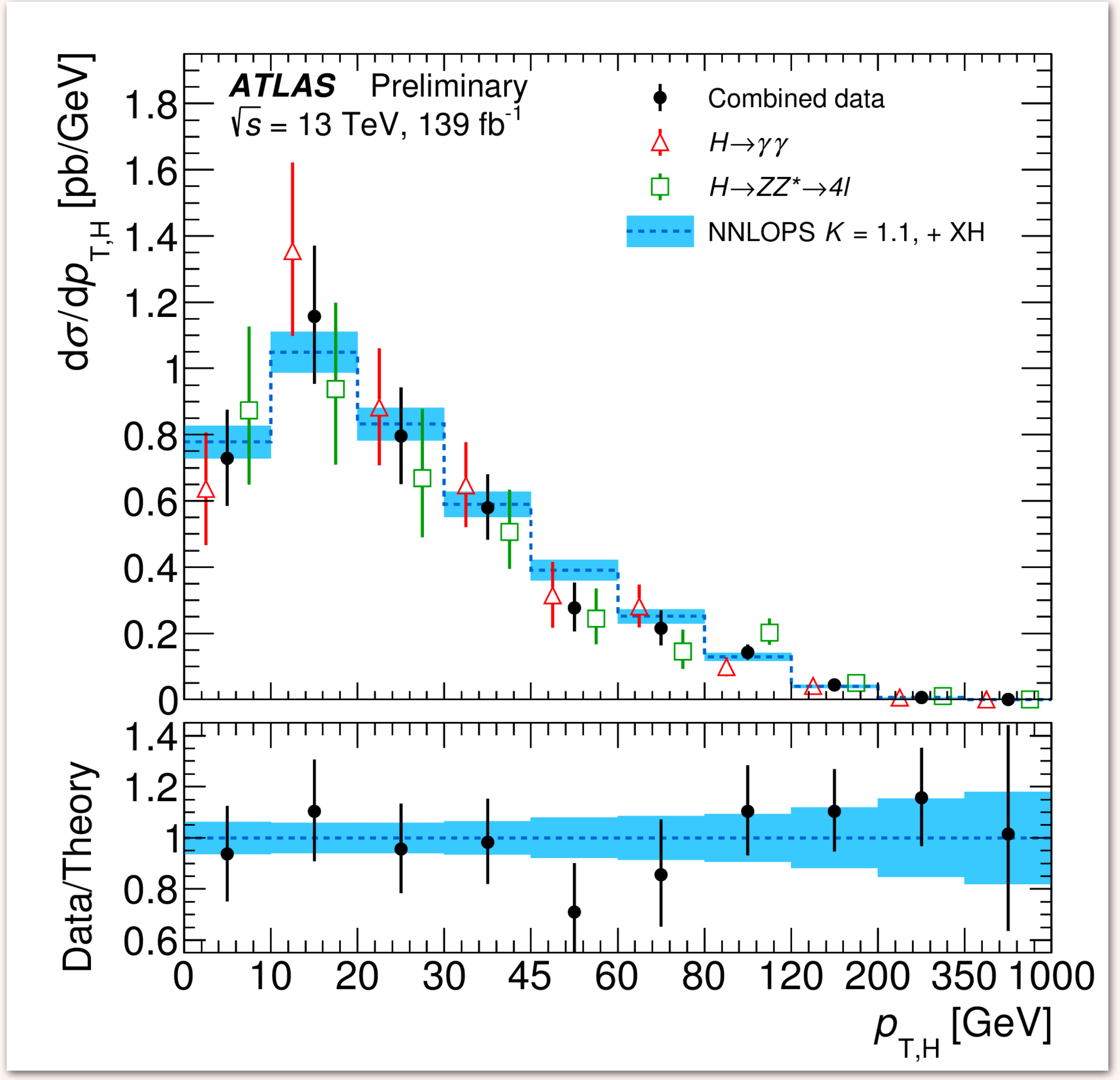


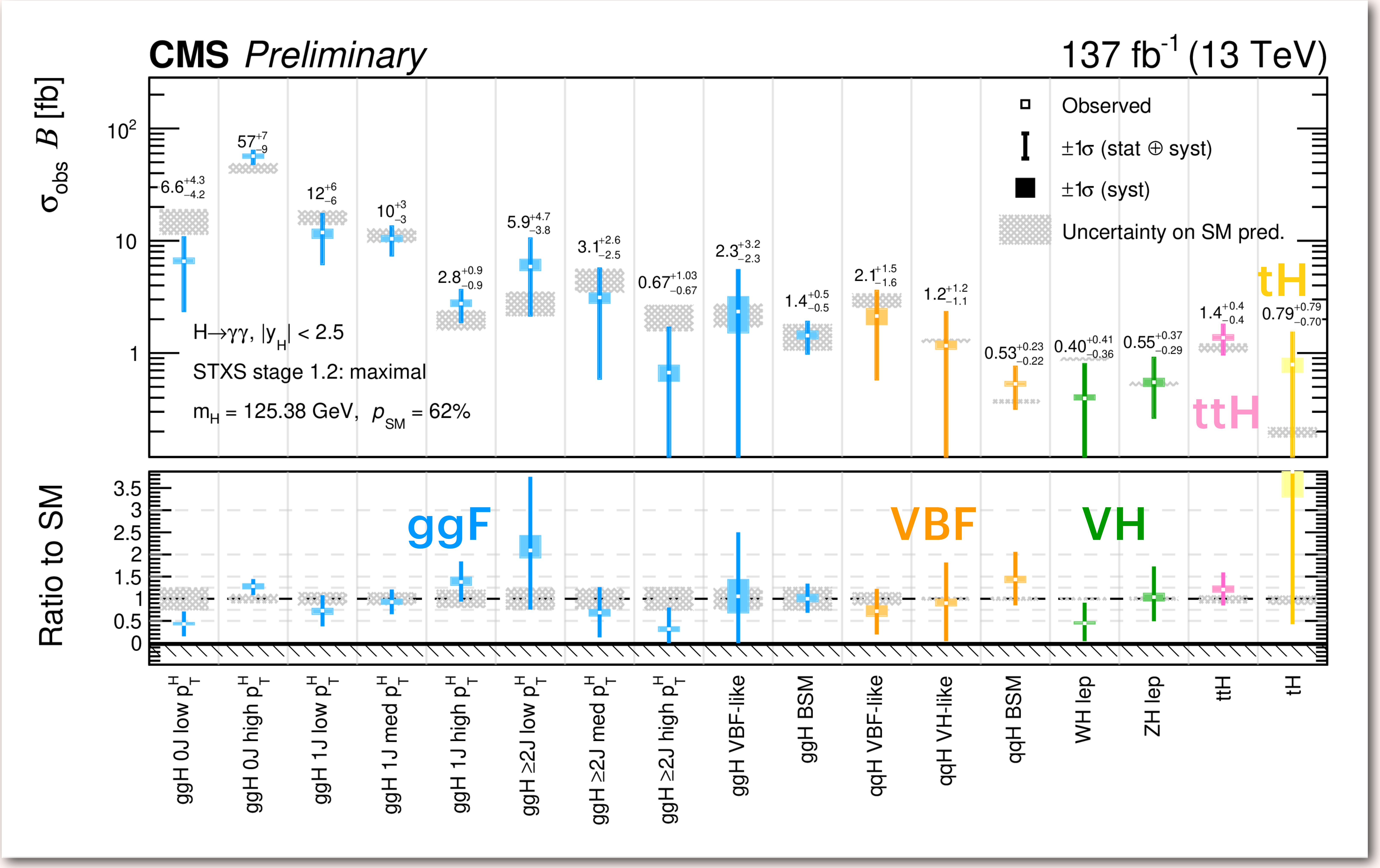




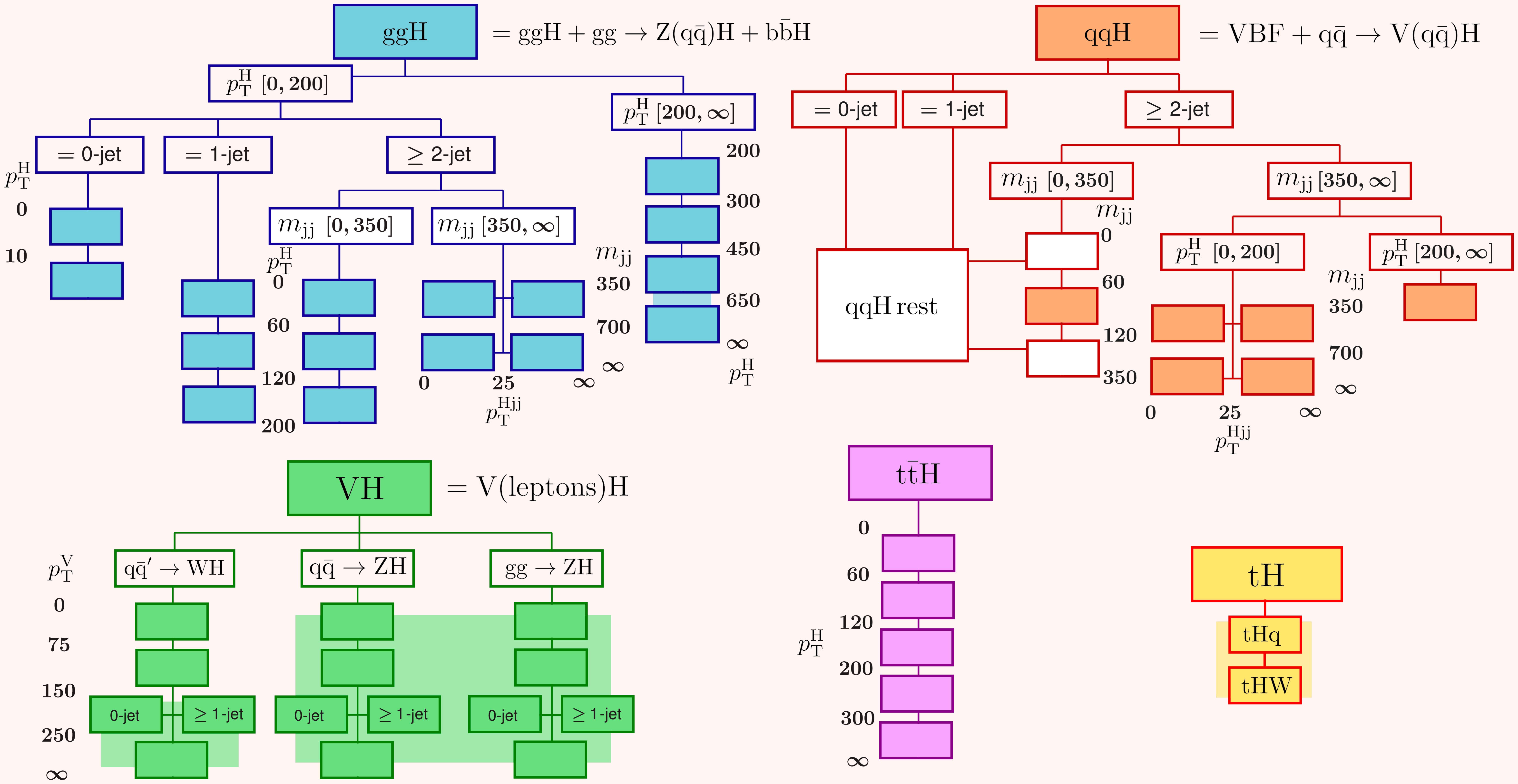
FROM RATES AND SIGNAL STRENGTHS TO FIDUCIAL AND DIFFERENTIAL CROSS SECTIONS

- Measuring cross sections differentially or in specific bins of phase-space with high precision





WHAT ARE STXS?



- Higgs kinematics can be sensitively modified by BSM physics

- "Simplified Template Cross Sections" approach: Measure cross sections separated into production modes, inclusively over the Higgs decays, in specific regions of phase-space ("bins"), defined in terms of specific kinematic variables (p_T^H, m_{jj}, p_T^{Hjj}, p_T^V)

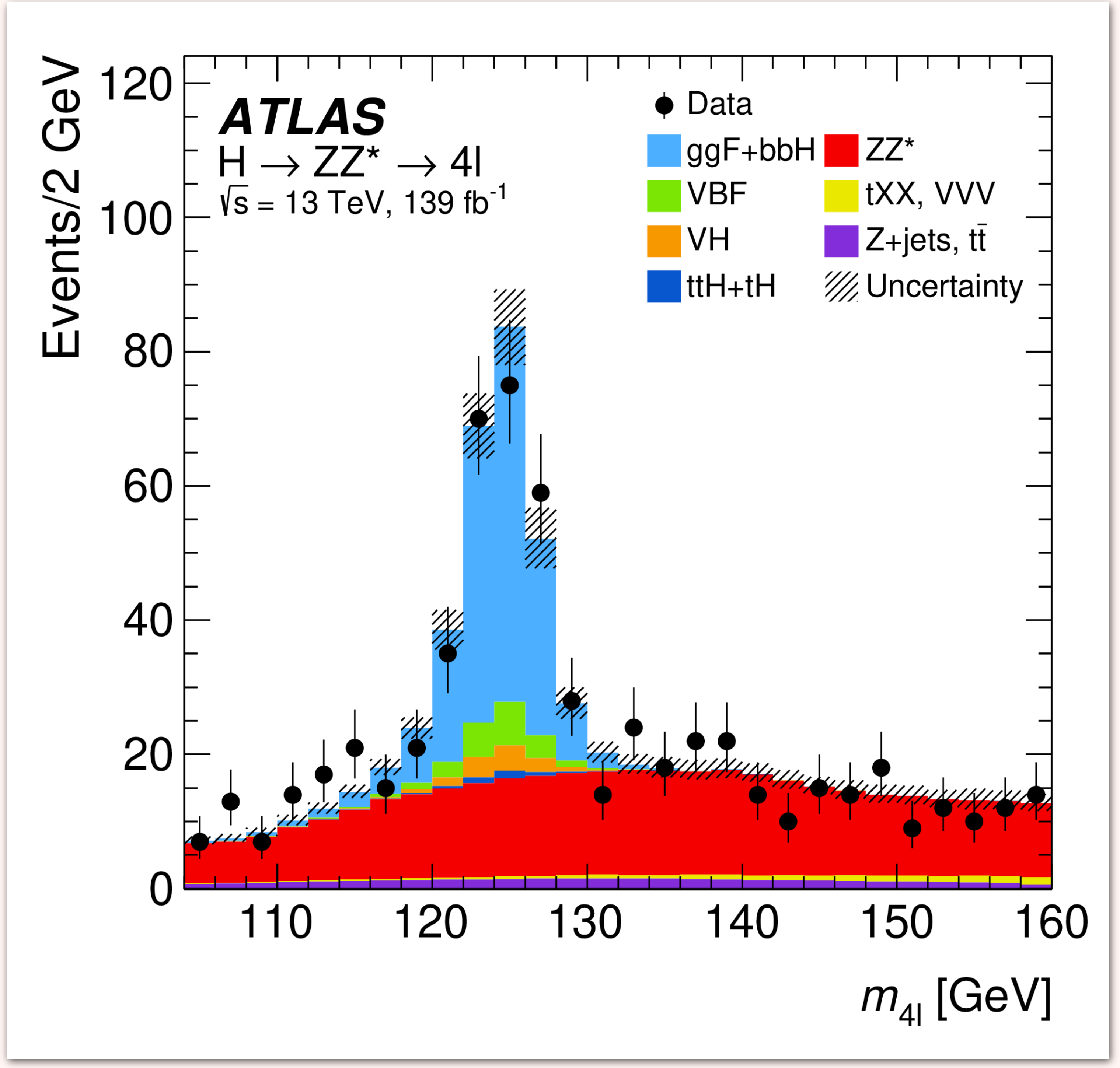
- STXS provide a largely model-independent way to test for BSM deviations in kinematic distributions.

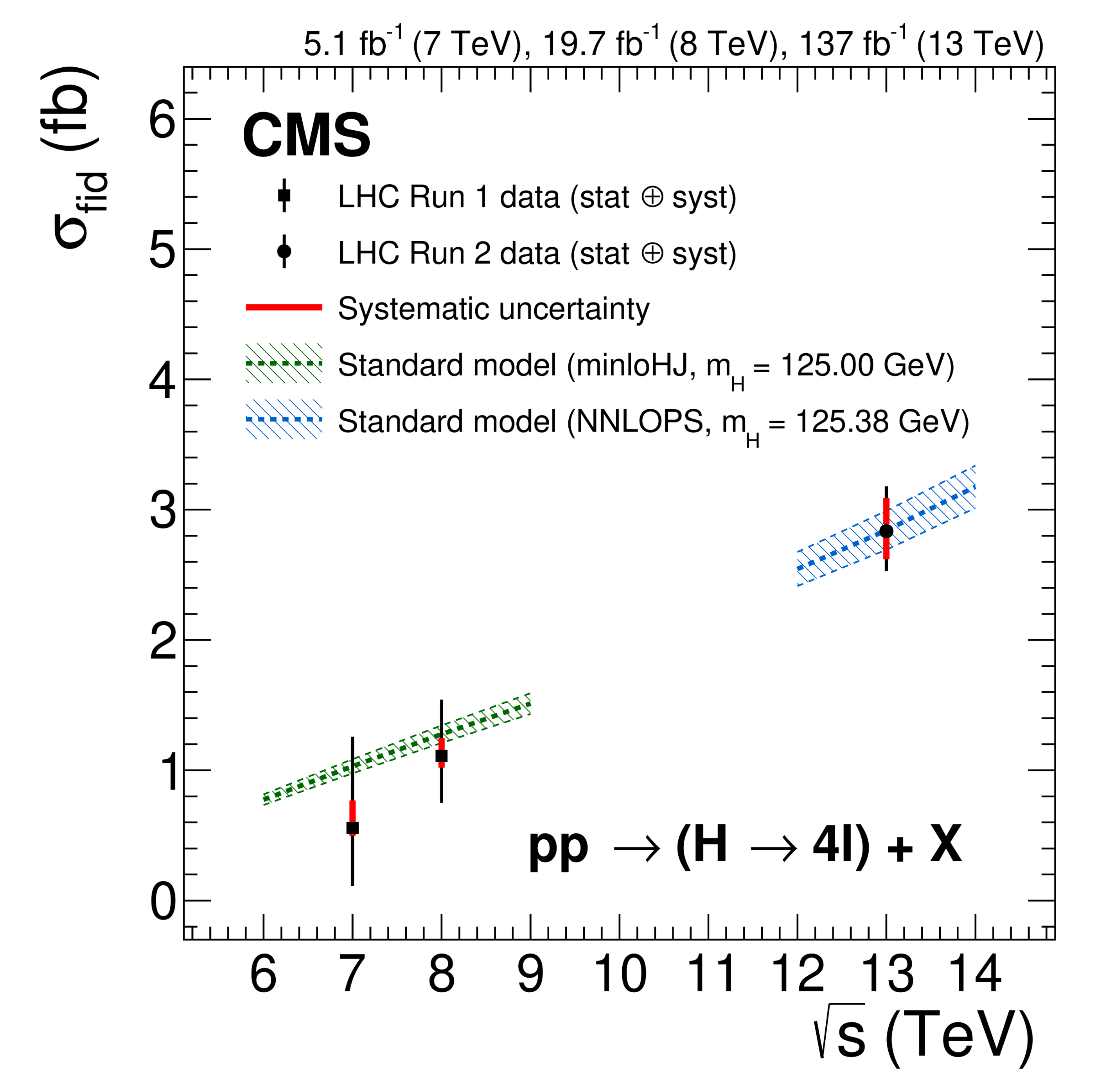
- Specific bins defined in coordination with the theoretical community

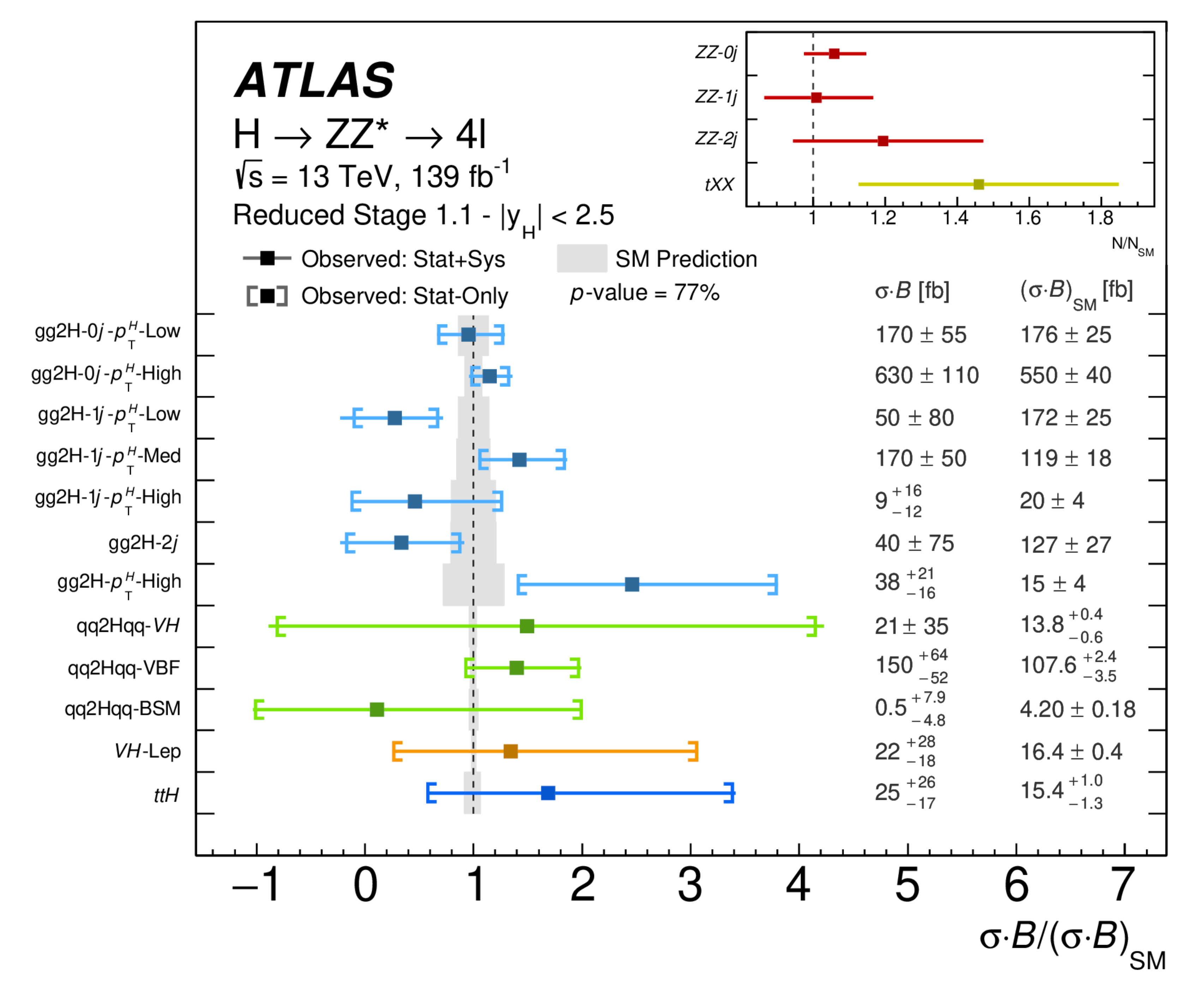
PRECISELY MEASURING THE HIGGS: HZZ

- Signal strengths also at the 10% level
- Exploiting the cleanest Higgs channel: Probing ggF, VBF, VH, ttH
- Measurements of fiducial and differential cross sections, STXS, EFT interpretations,…

	Lumi	Precision
CMS, Eur. Phys. J. C 81 (2021) 488	Full Run2	μ=1.01±0.11
ATLAS, Eur. Phys. J. C 81 (2021), 398 Eur. Phys. J. C 80 (2020) 942	Full Run2	$\mu = 0.94^{+0.11}_{-0.12}$







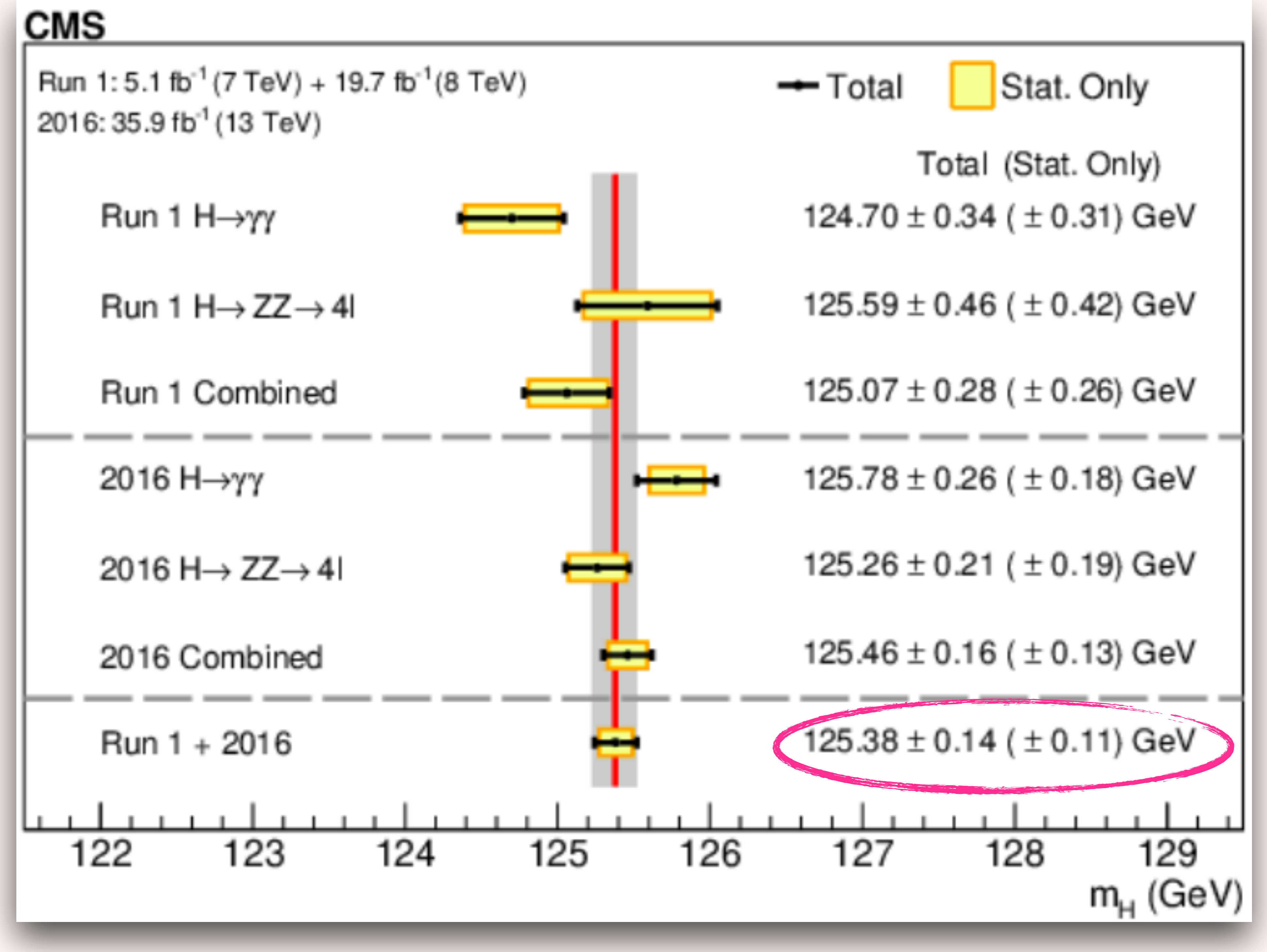
HOW WELL DO WE KNOW THE HIGGS MASS?

- Only free parameter in the SM, and already very precisely measured by CMS and ATLAS

- The precision with which we can measure m_H is directly linked to the reconstruction (energy scale and resolution) of photons and leptons

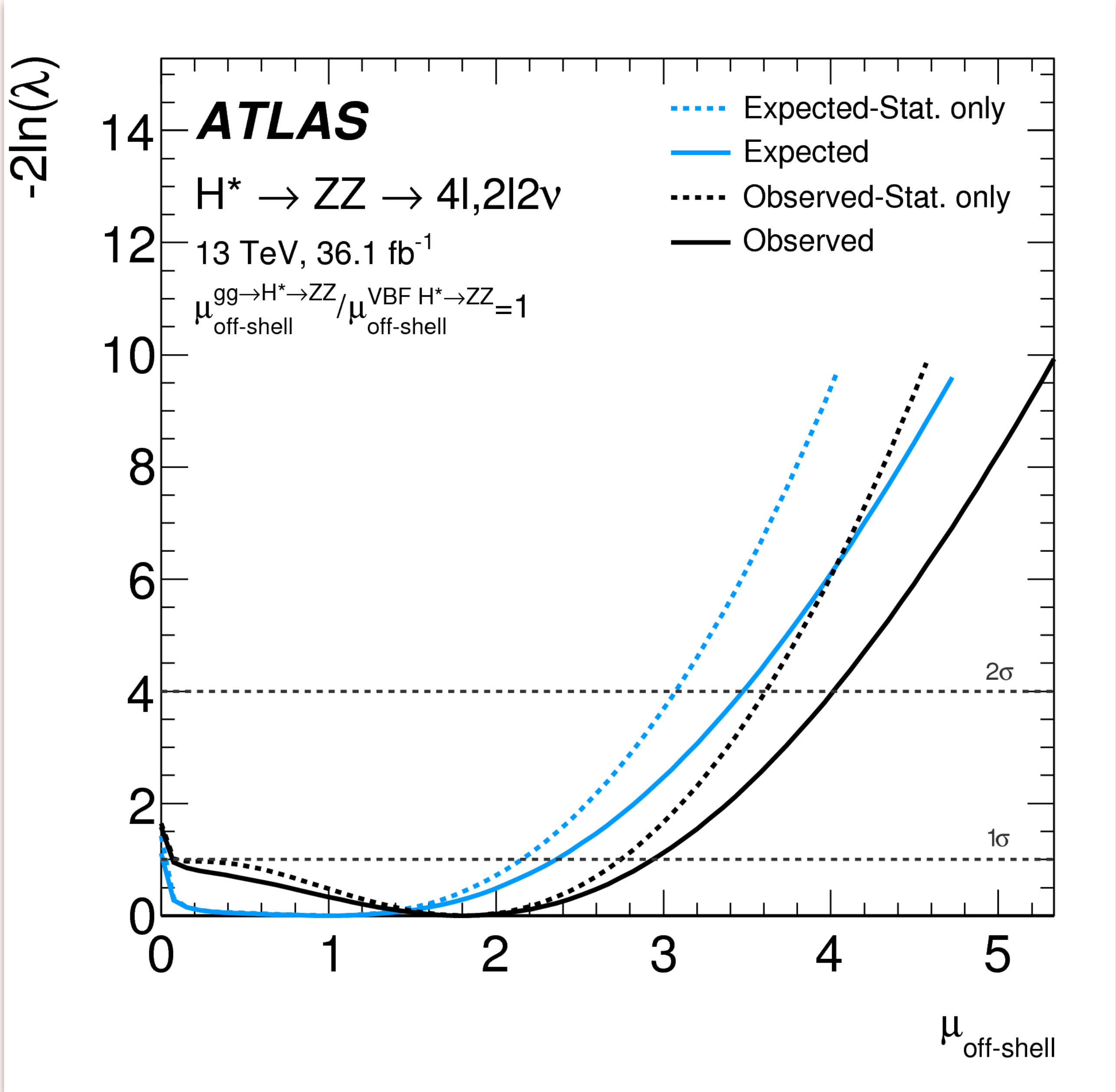
- How well can we measure m_H in the future?

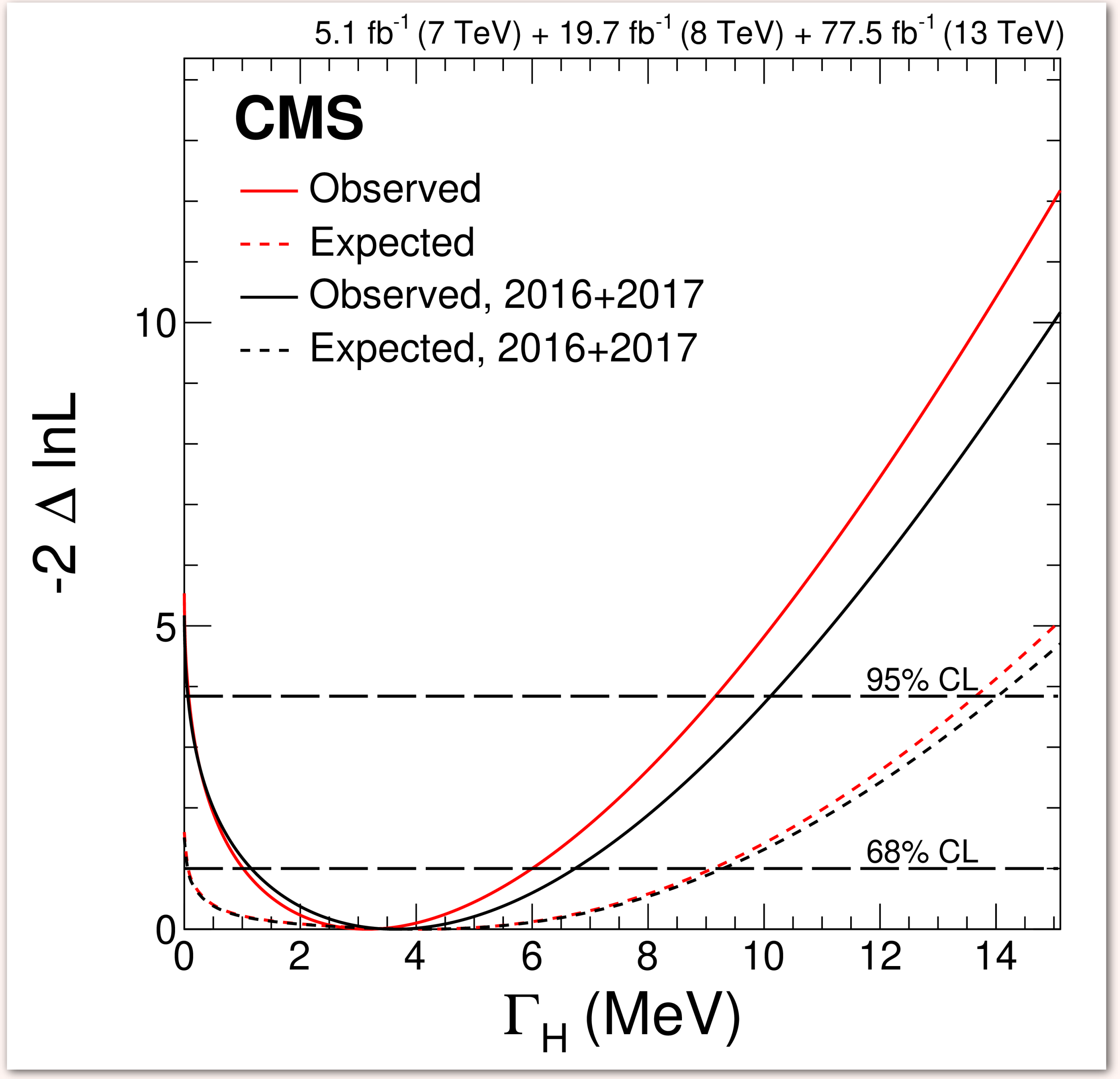
	Lumi	**Measurement**
ATLAS+CMS Run1 Combination Phys. Rev. Lett. 114 (2015) 191803	5.1 fb-1 @ 7 TeV, 19.7 fb-1 @ 8TeV	$125.09 \pm 0.24\ GeV\ (0.19\%)$
CMS: 4l + DiPhoton Phys. Lett. B 805 (2020) 135425	Run1 + 36 fb^{-1}	$125.38 \pm 0.14\ GeV\ (0.11\%)$
ATLAS: 4l ATLAS-CONF-2020-005	139 fb^{-1}	$124.92 \pm 0.19(stat)^{+0.09}_{-0.06}(syst)\ GeV\ (0.17\%)$



HOW WELL DO WE KNOW THE HIGGS WIDTH?

- Γ_H (SM)= 4 MeV
- Direct measurement: < 1.1 GeV (95% CL) (CMS)
- H→ZZ→4l: measure through the relative on-shell and off-shell production rates (model dependent)





$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(m^2_{ZZ}-m^2_H)^2+m^2_H\Gamma^2_H},$$

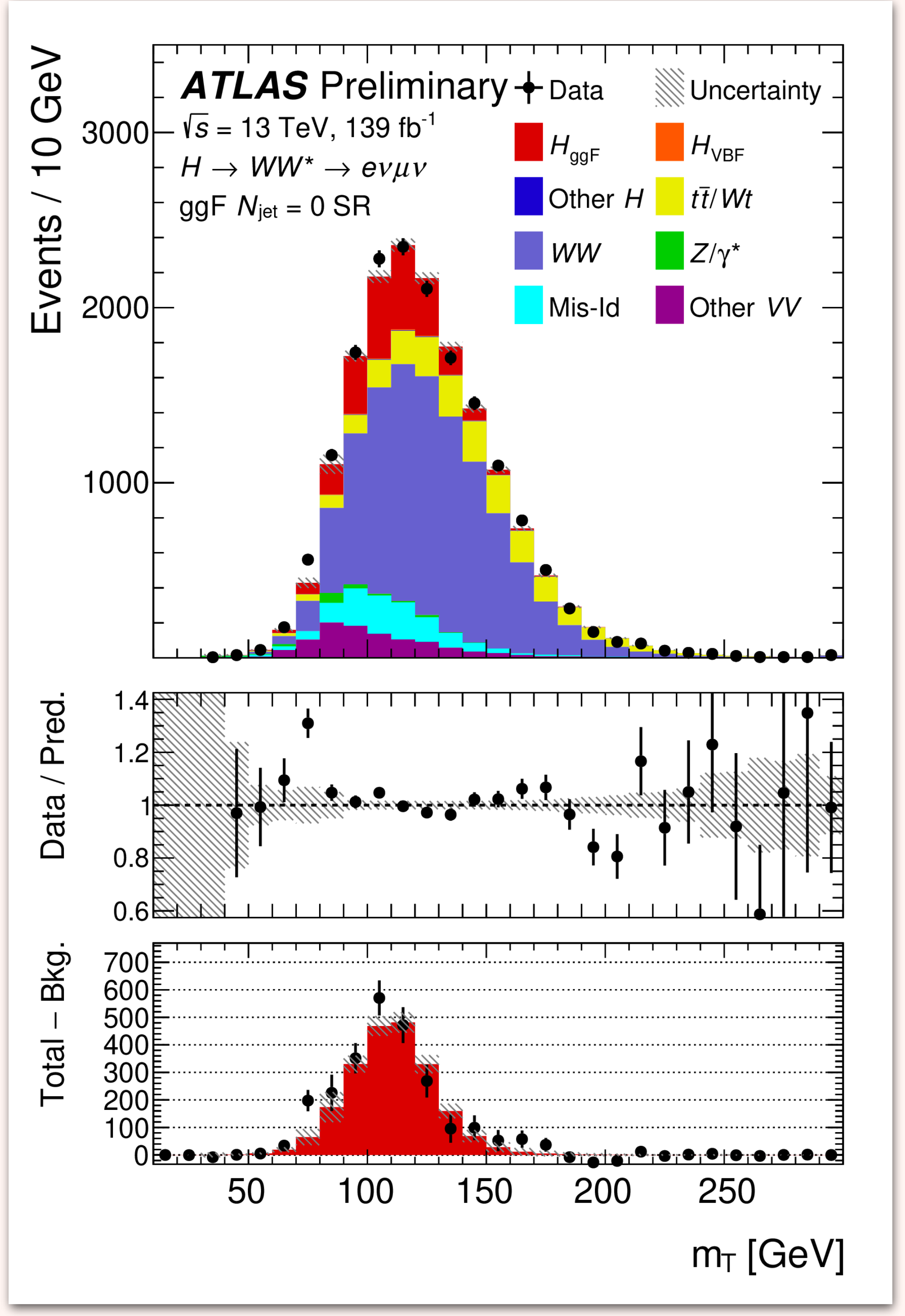
$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH}g^2_{HZZ}}{m_H\Gamma_H} \quad \text{and} \quad \sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(2m_Z)^2}.$$

$m_{ZZ} \sim m_H$
(On-shell production)

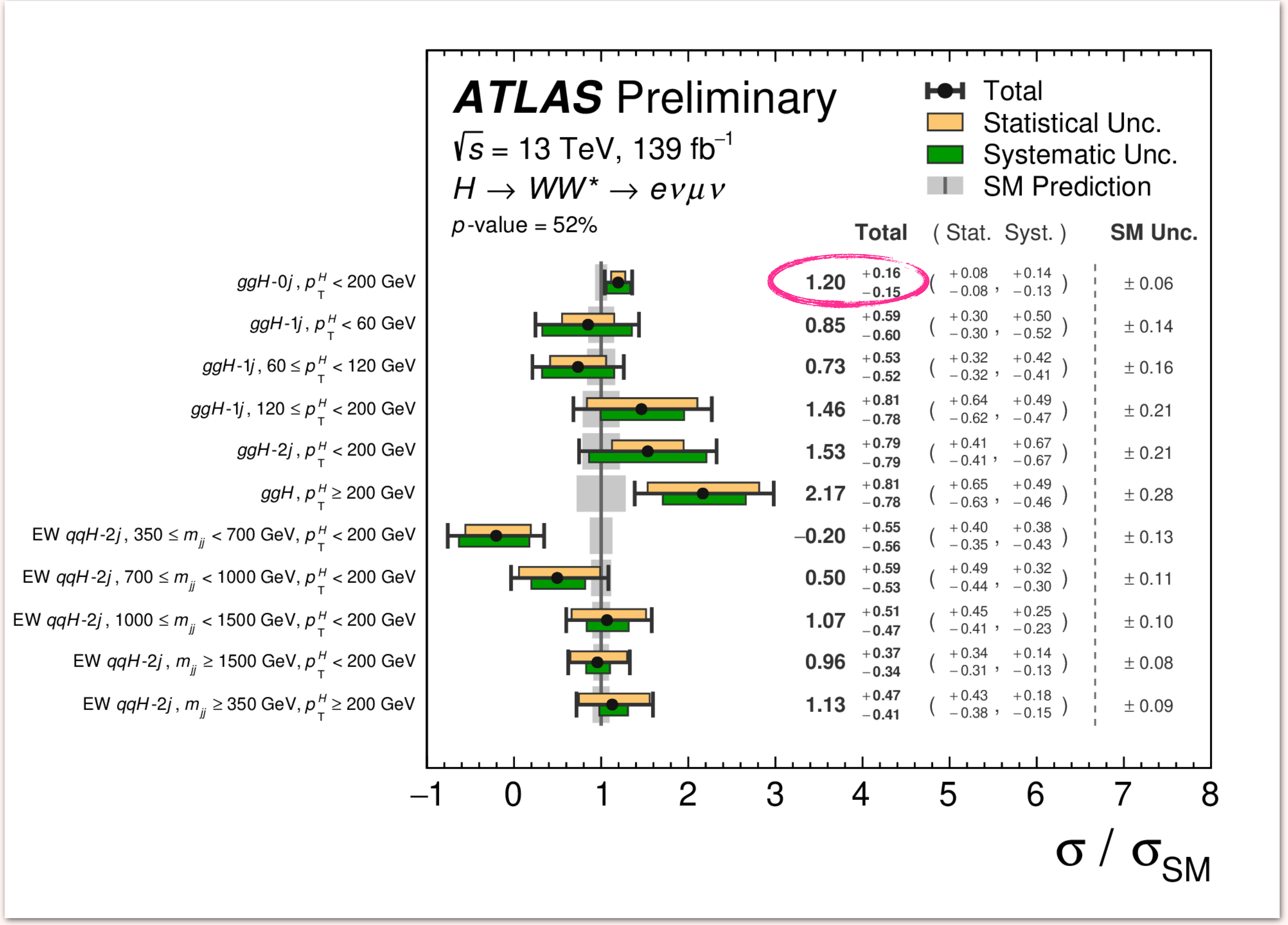
$m_{ZZ} > m_{ZZ}$
(Off-shell production)

	Lumi	Latest Result on Γ_H
CMS, Phys. Rev. D 99 (2019) 112003	Run1+ 77.5 fb^{-1}	$3.2^{+2.8}_{-2.2}\ (4.1^{+5.0}_{-4.0})\ MeV$ Γ_H < 9.16 (13.7) MeV (95% CL)
ATLAS, Phys. Lett. B 786 (2018) 223	36 fb^{-1}	Γ_H < 14.4 (15.2) MeV (95% CL)

HIGGS DECAYS TO W BOSONS



- Much larger Br, but experimentally more complicated: neutrinos in the W decay
- Main signature e+mu+MET with veto on b-jets
- Cross sections (inc. STXS) for ggF, VBF, WH, ZH

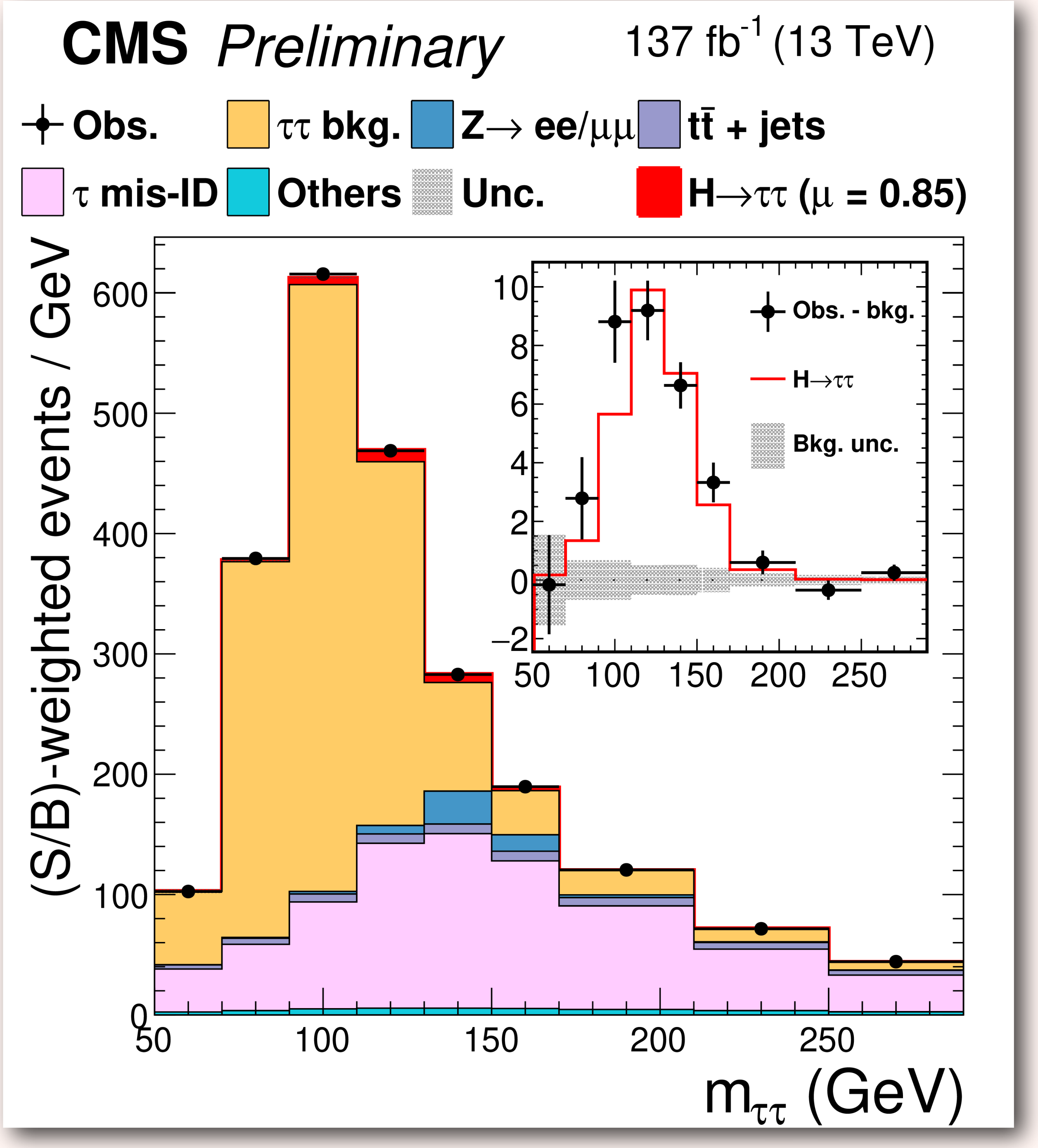


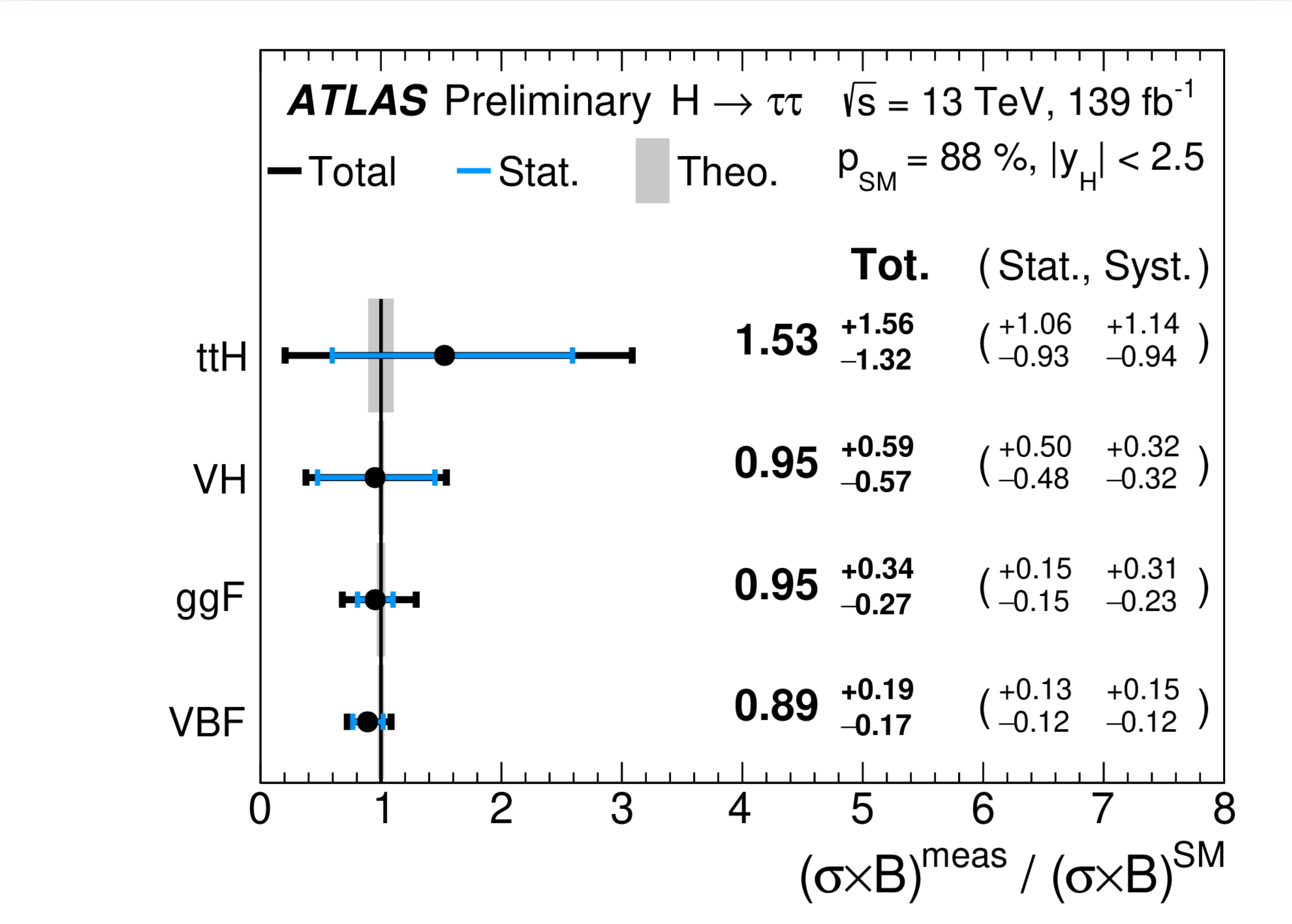
	Lumi	Precision
CMS, Phys. Lett. B 791 (2019) 96 HIG-19-017 (VH, fullRun2)	36 fb^{-1} 137 fb^{-1}	ggF+VBF+VH (2016): $\mu=1.28^{+0.18}_{-0.17}$ VH (full Run2): $\mu=2.11^{+0.46}_{-0.43}$
ATLAS-CONF-2021-014	Full Run2	ggF: σxBR = 12.4±1.5pb VBF: σxBR = $0.79^{+0.19}_{-0.16}$ pb

- Also differential distributions (CMS JHEP 03 (2021) 003), CP interpretations (ATLAS-CONF-2020-055)

PRECISION IN LEPTON DECAYS: $H \rightarrow \tau\tau$

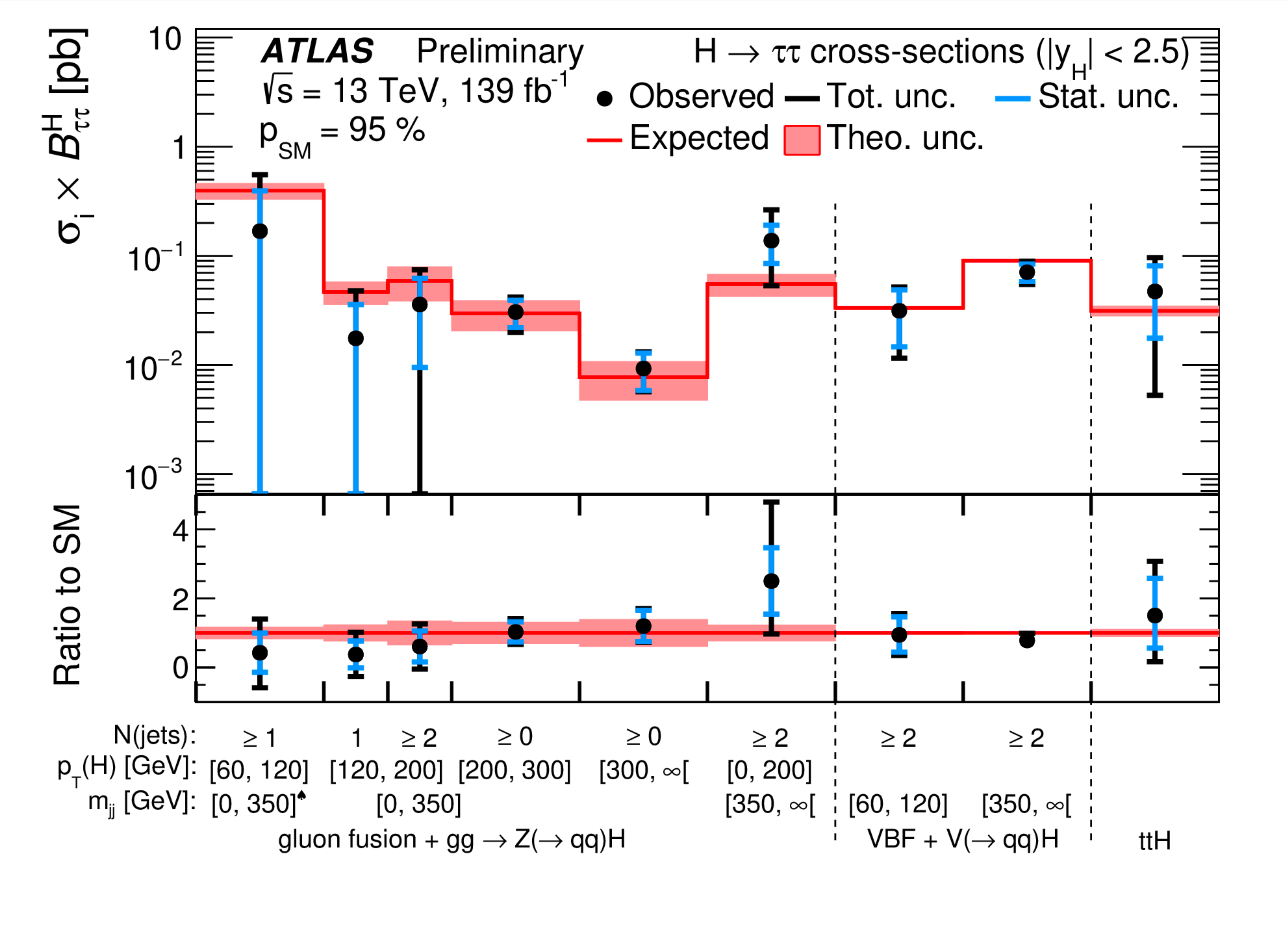
- Coupling to leptons!
- GGF and VBF with precision ~20%
- Sophisticated Z$\tau\tau$ background modelling techniques exploiting the data
- Tau identification is key (efficiency, misidentification rate)

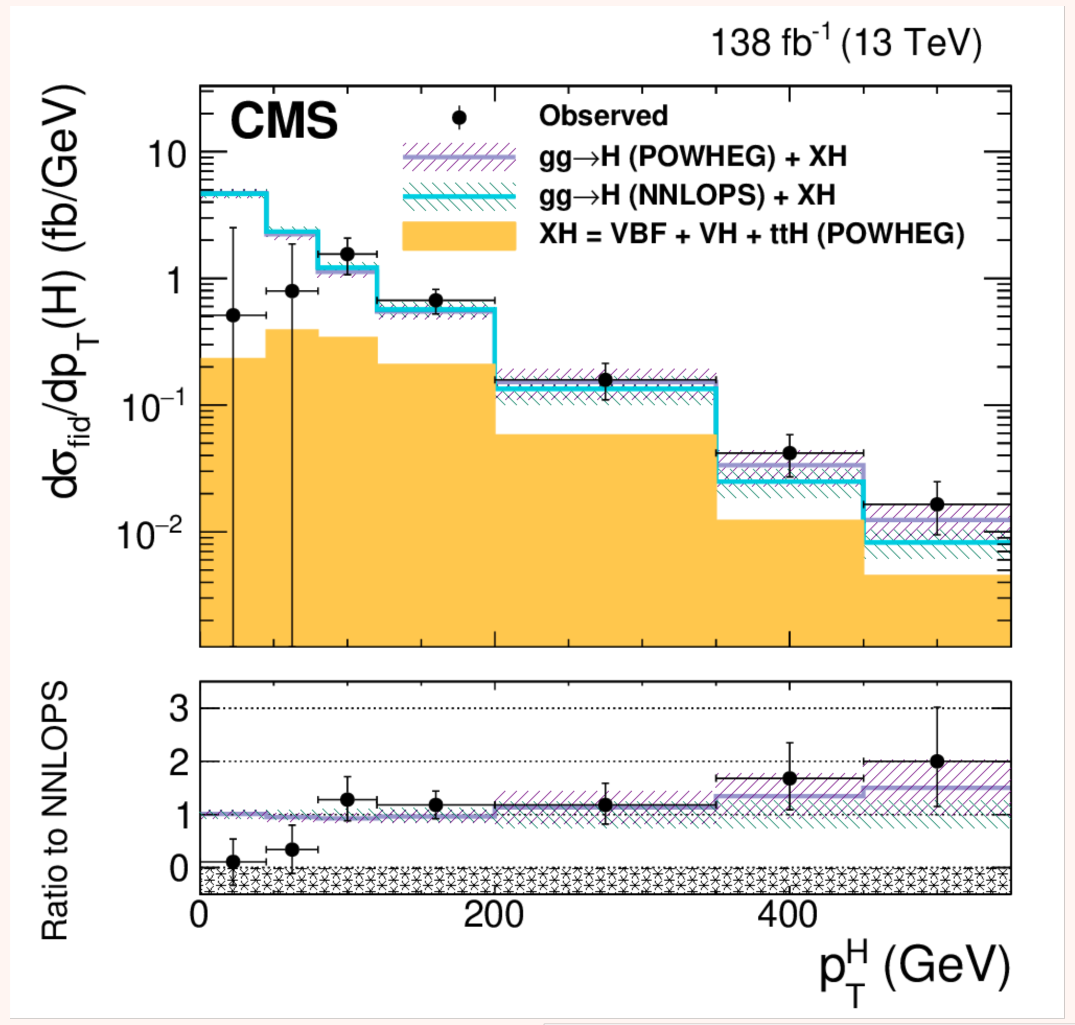


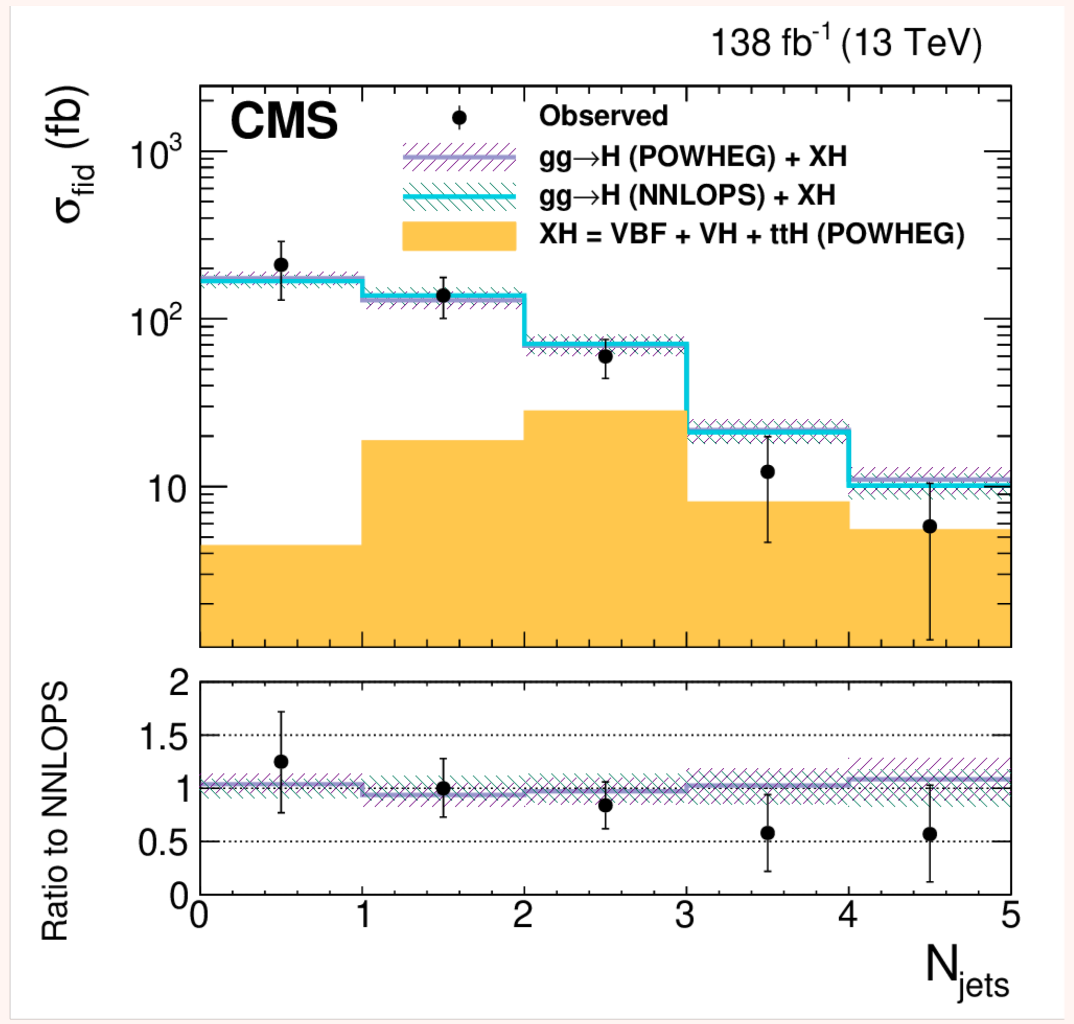


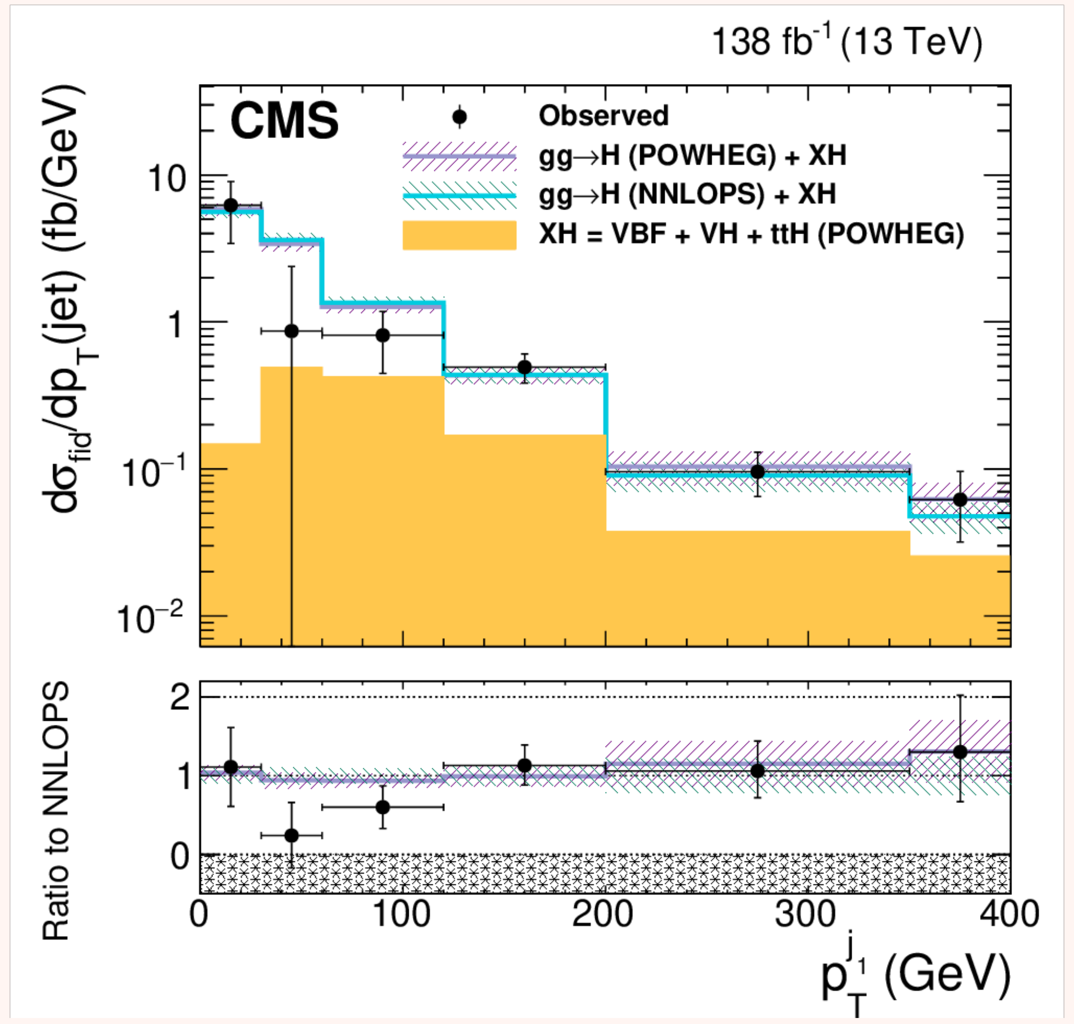
	Lumi	Precision
CMS, HIG-20-015 HIG-19-010	137 fb^{-1}	$\mu=0.85^{+0.12}_{-0.11}$
ATLAS-CONF-2021-014	Full Run2	$\sigma \times BR = 2.90 \pm 0.21(stat)^{+0.37}_{-0.32}$ pb

MOVING TO DIFFERENTIAL DISTRIBUTIONS







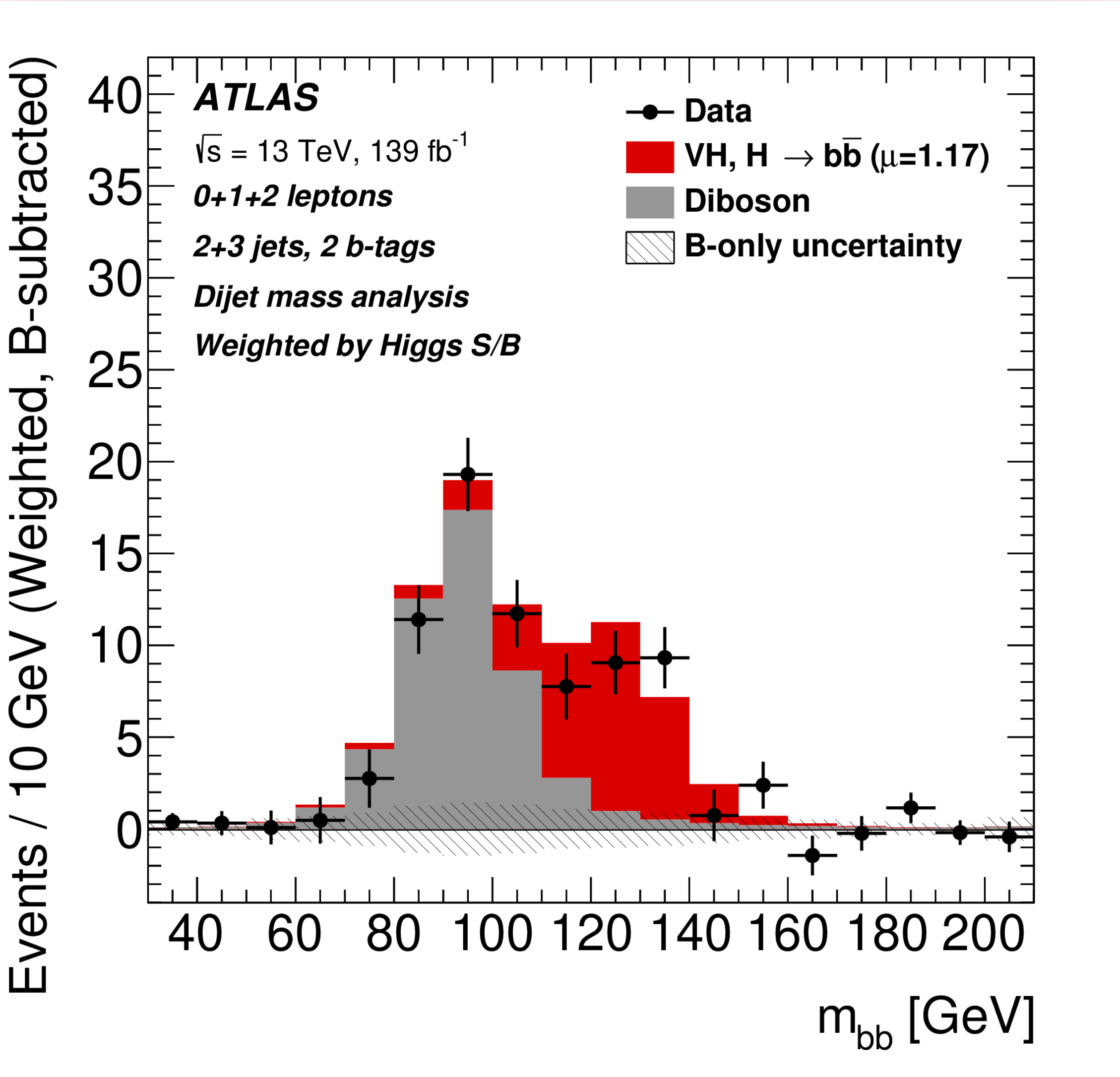


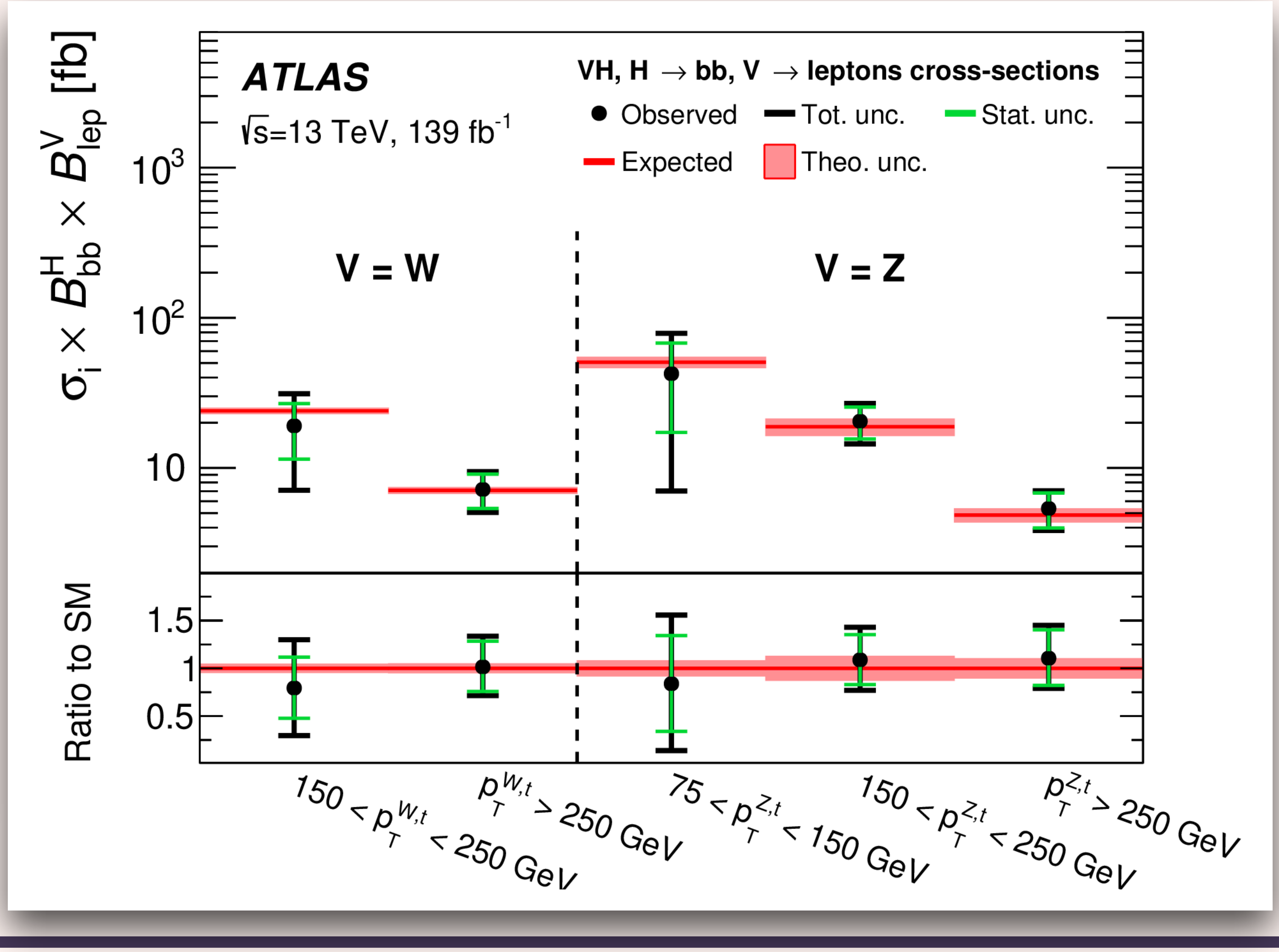
H→bb: FROM VH TO BEYOND

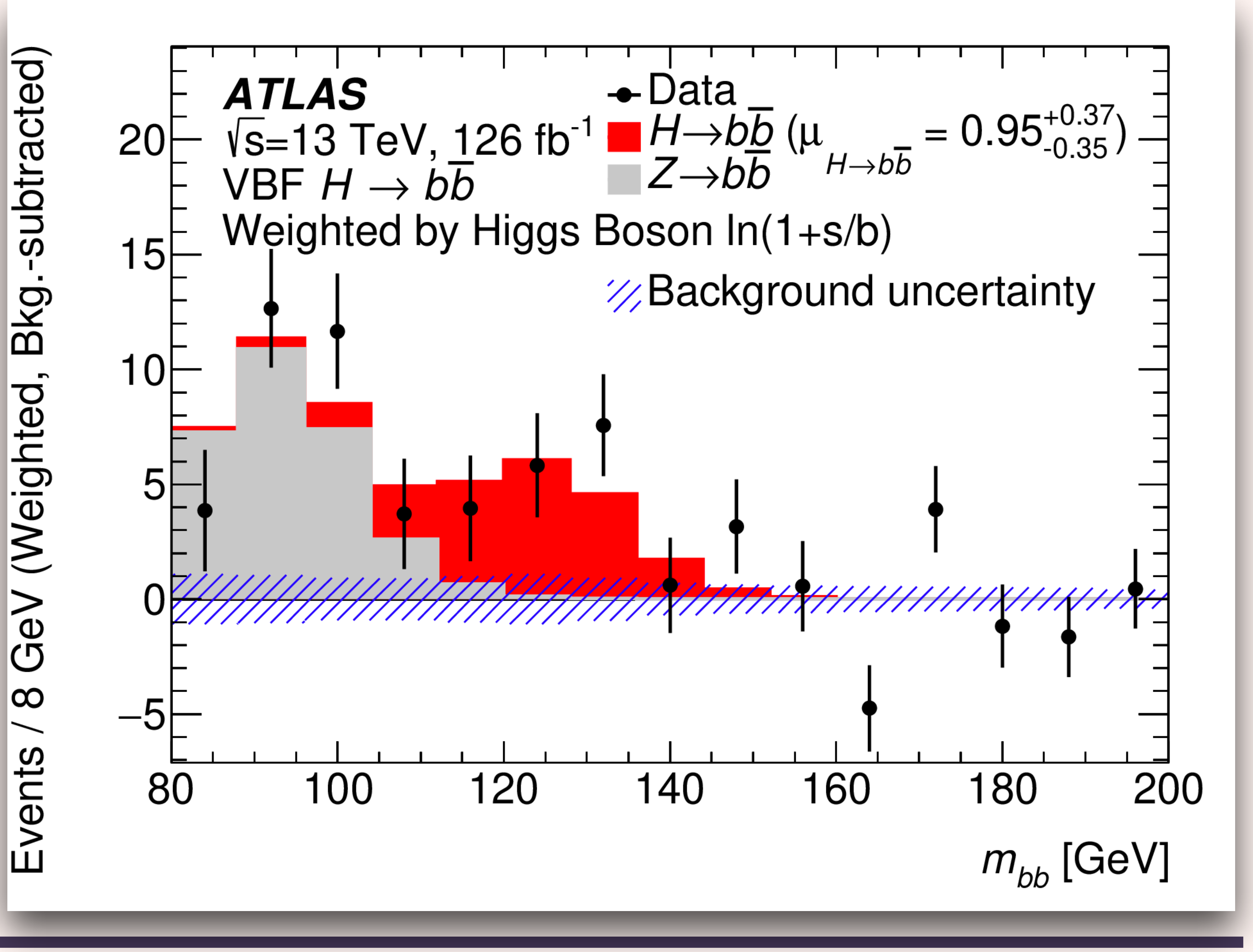
- VH Hbb observation well established already
  - ~20% uncertainty in VH signal strength, measurements in STXS bins, boosted VH measurements
- VBF Hbb at evidence level already (2.9 σ VBF production alone, 3.0 σ including VBF+γ)

ATLAS: Eur. Phys. J. C 81 (2021) 178 , Eur. Phys. J. C. 81 (2021) 537, JHEP 03 (2021) 268 , Phys. Lett. B 816 (2021) 136204 , ATLAS-CONF-2021-010

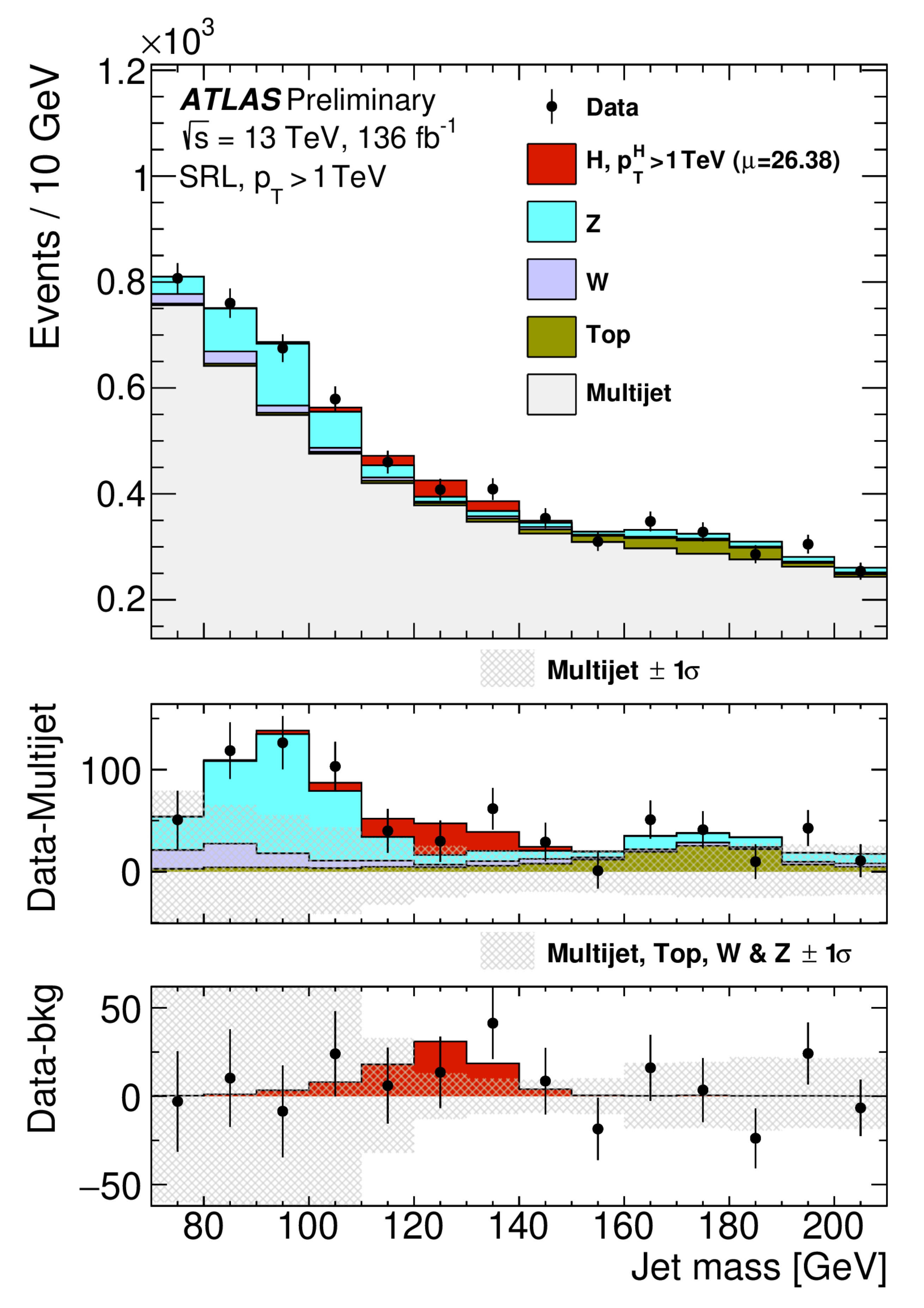
CMS: JHEP 12 (2020) 085, CSBS 4 (2020) 10 , Phys. Rev. Lett. 121 (2018) 121801





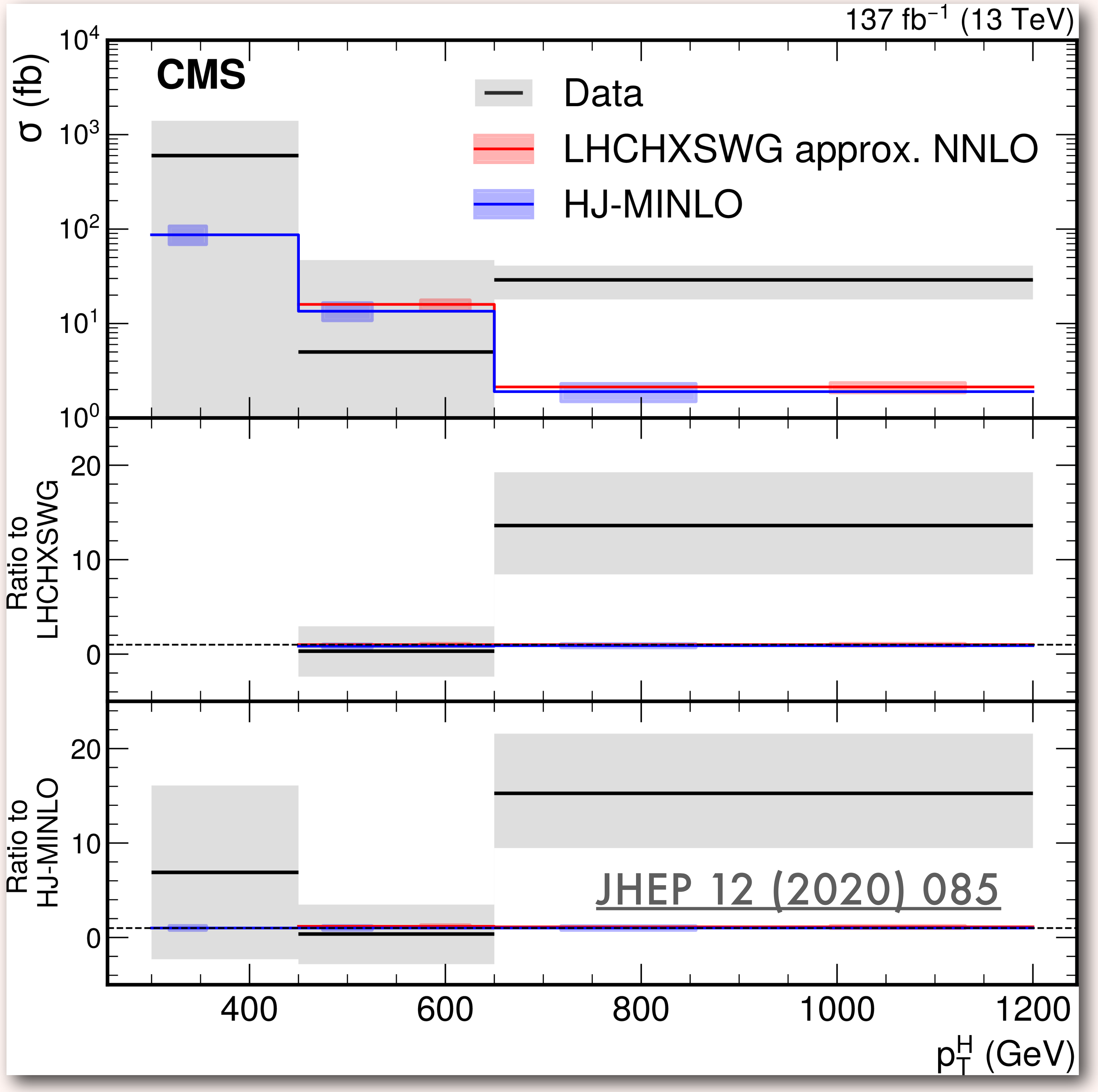


HBB: HOW HIGH WE CAN REACH IN HIGGS PT?



ATLAS-CONF-2021-010

- Boosted ggF Hbb analysis.
- AK8 jets & jet substructure techniques: soft-drop SD mass algorithm
- Enhanced sensitivity to BSM at high P_T
- Measurements of the cross section in bins of pt from 450-500 GeV up to 800-1200 GeV
- Parallel Z→bb measurements as control analyses

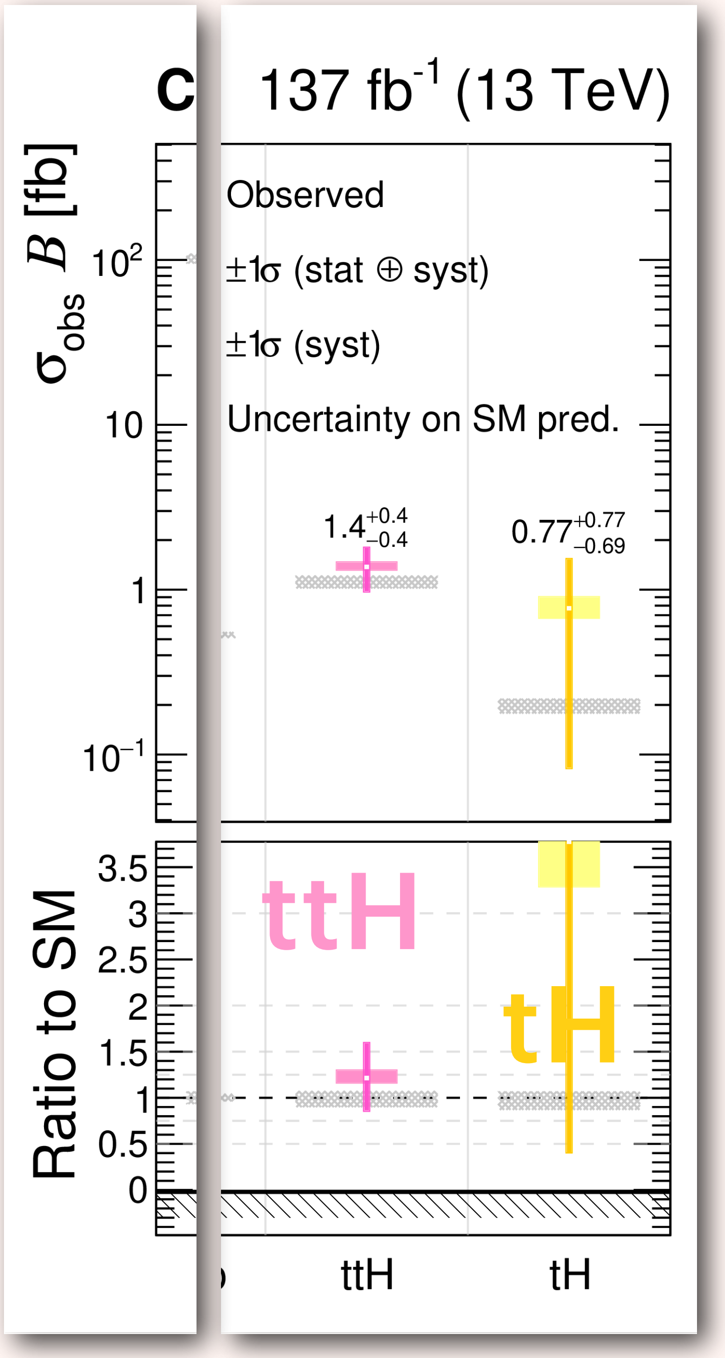


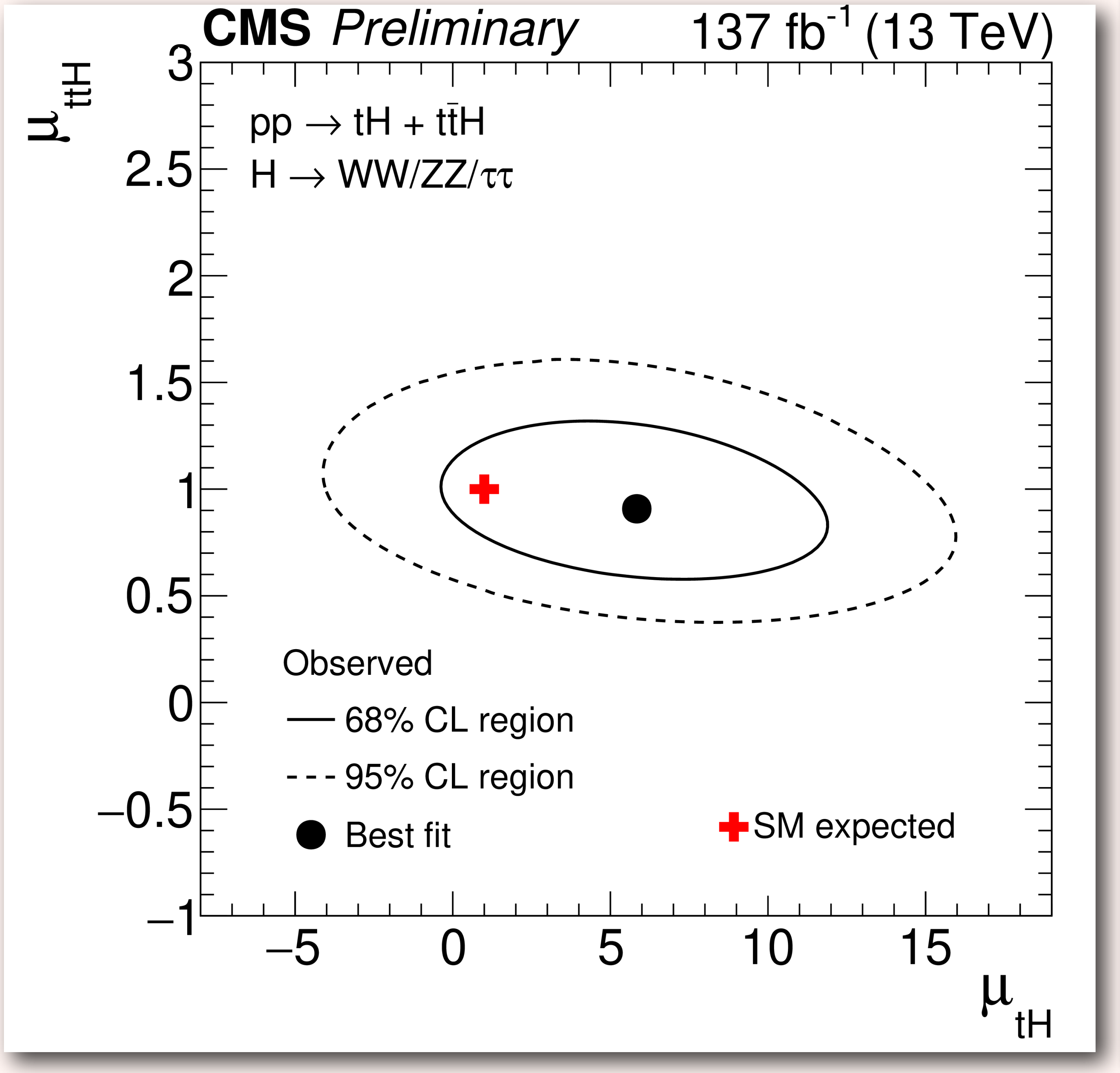
JHEP 12 (2020) 085

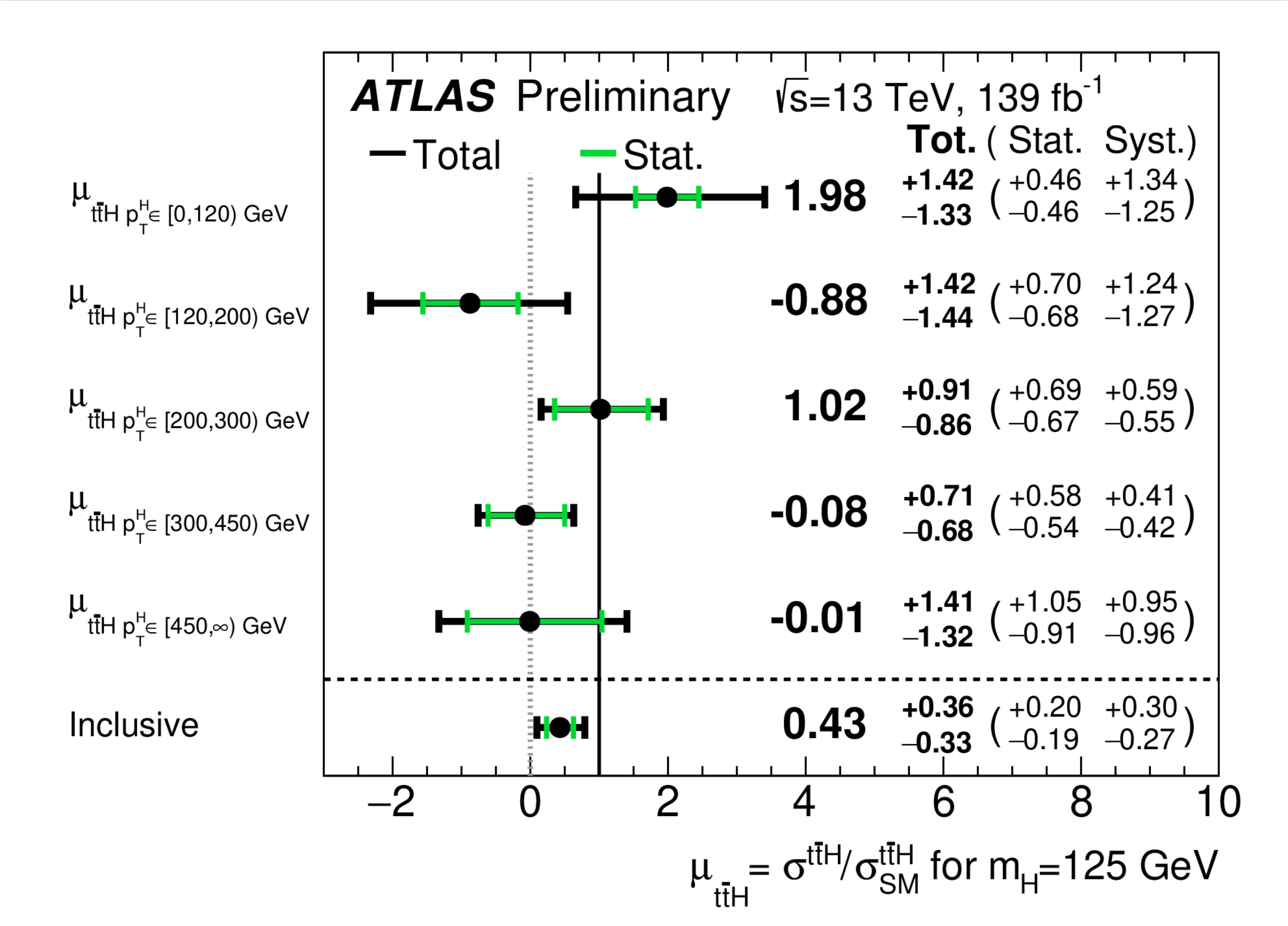
TTH AND TH

- Rare production, very complicated final states
  - Now sensitive enough for STXS measurements and CP constraints
- ttH: Variety of final states: Hγγ, Hbb, Hττ, Multilepton
  - Currently most sensitive: CMS Multilepton $\mu_{ttH} = 0.92 \pm 0.19(stat)^{+0.17}_{-0.13}(syst)$

- tH:
  - Hgg: 95%CL UL of 14(8)xSM (CMS), 8xSM (ATLAS)
  - Multilepton (CMS): $\mu_{tH} = 5.7 \pm 2.7(stat) \pm 3.0(syst)$







PRL 125 (2020) 061801

EPJC 81 (2021) 378

JHEP 07 (2021) 027

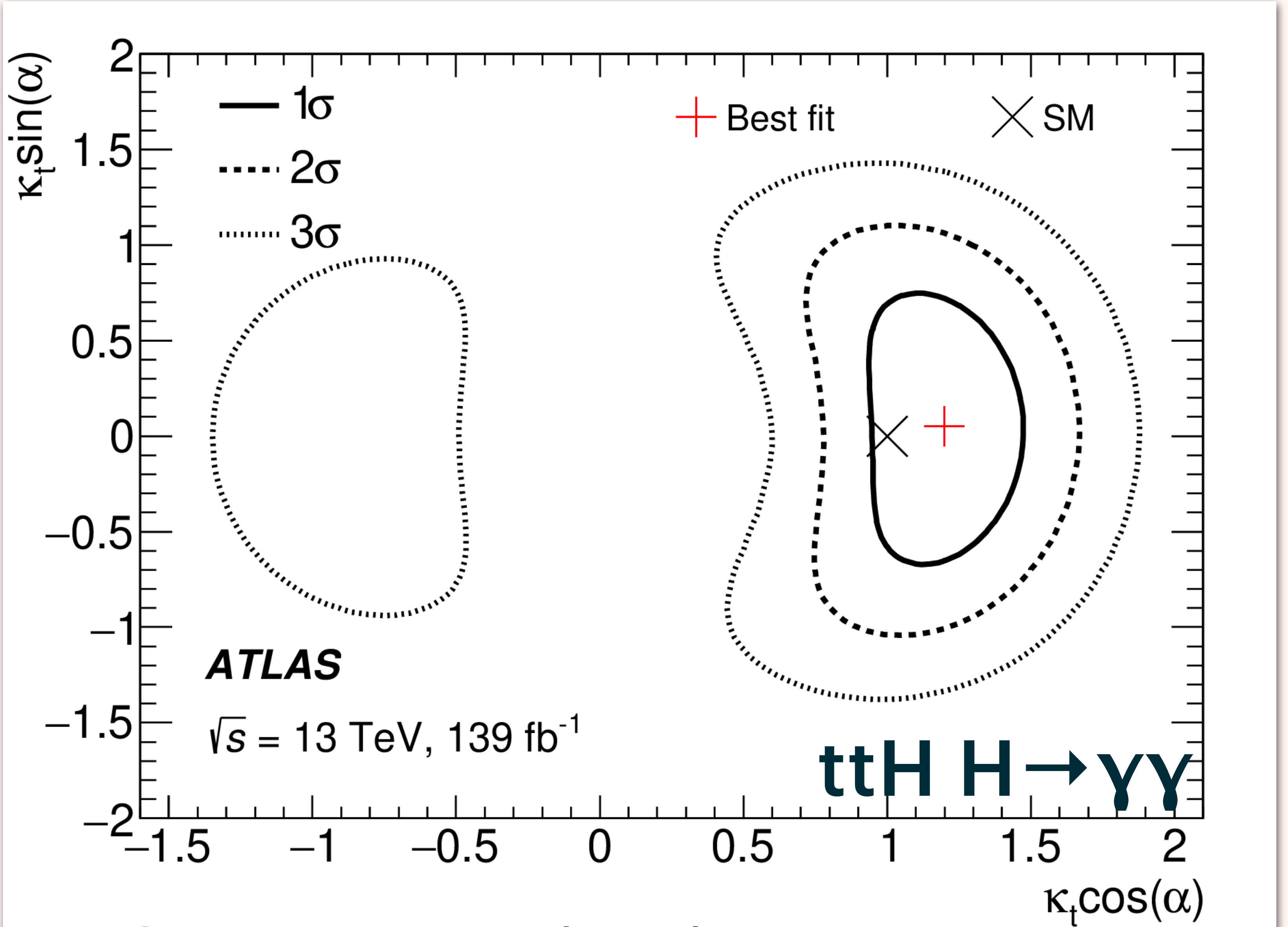
PRL 125 (2020) 061802

ATLAS-CONF-2020-058

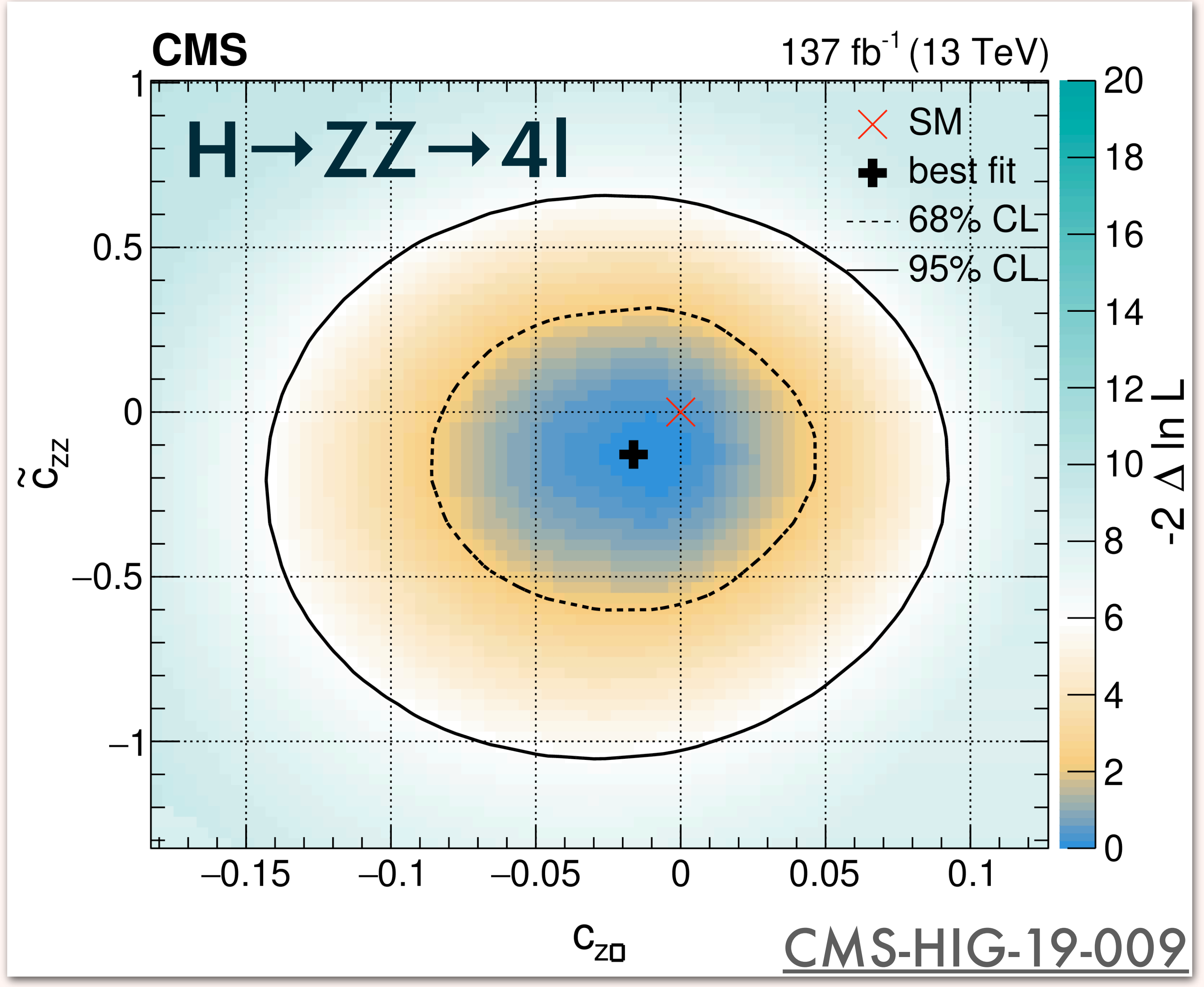
ATLAS-CONF-2021-014

HIGGS & CP

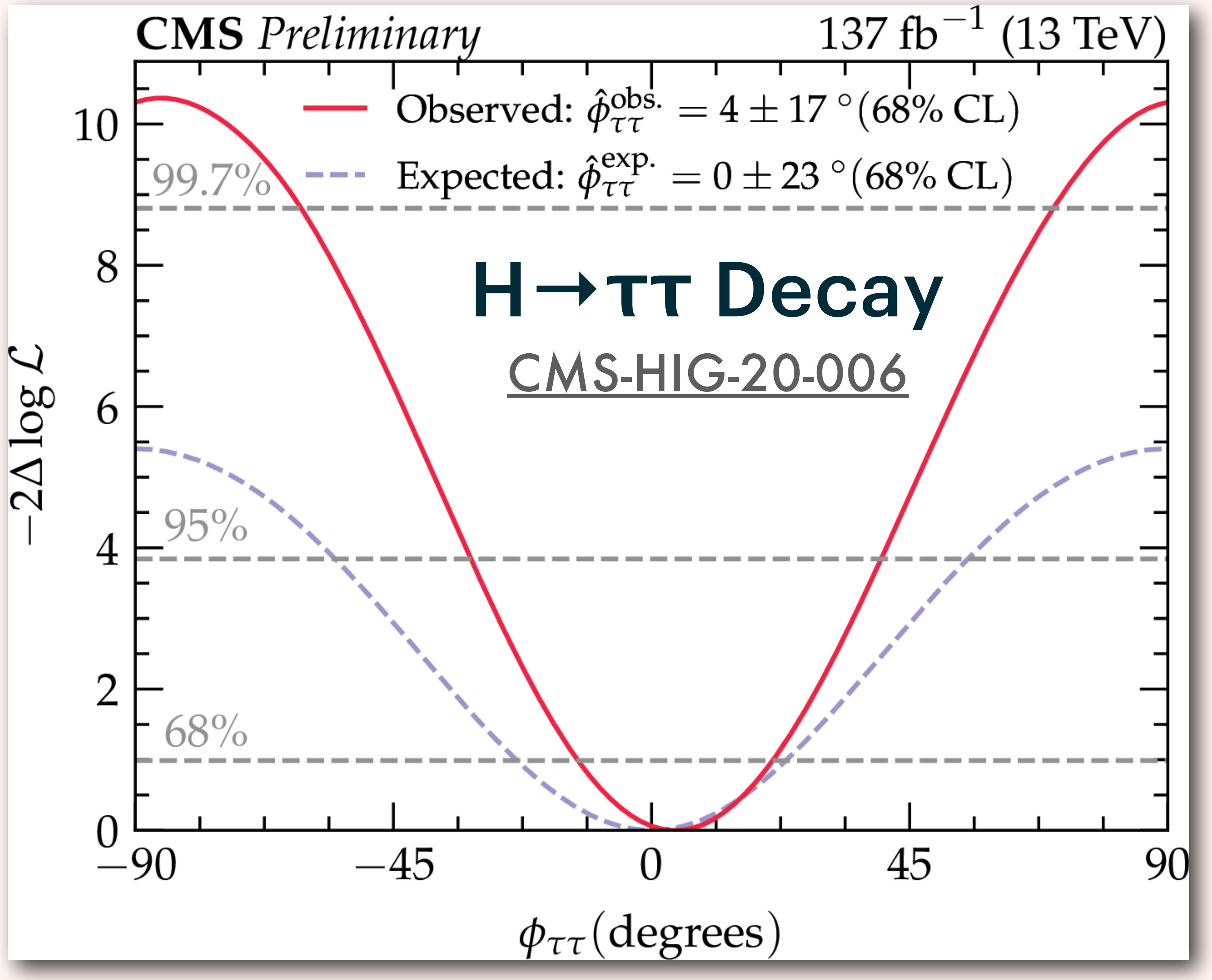
- Spin-parity quantum number of Higgs boson consistent with the SM , J^{cp} = 0++ . Does the Higgs sector have a new source of CP violation?
- Plenty of recent searches for CP in **production** and **decay.** Results also expressed in terms of SMEFT coefficients.
- So far no surprises: good agreement with SM



Phys. Rev. Lett. 125 (2020) 061802



CMS-HIG-19-009



CMS-HIG-20-006

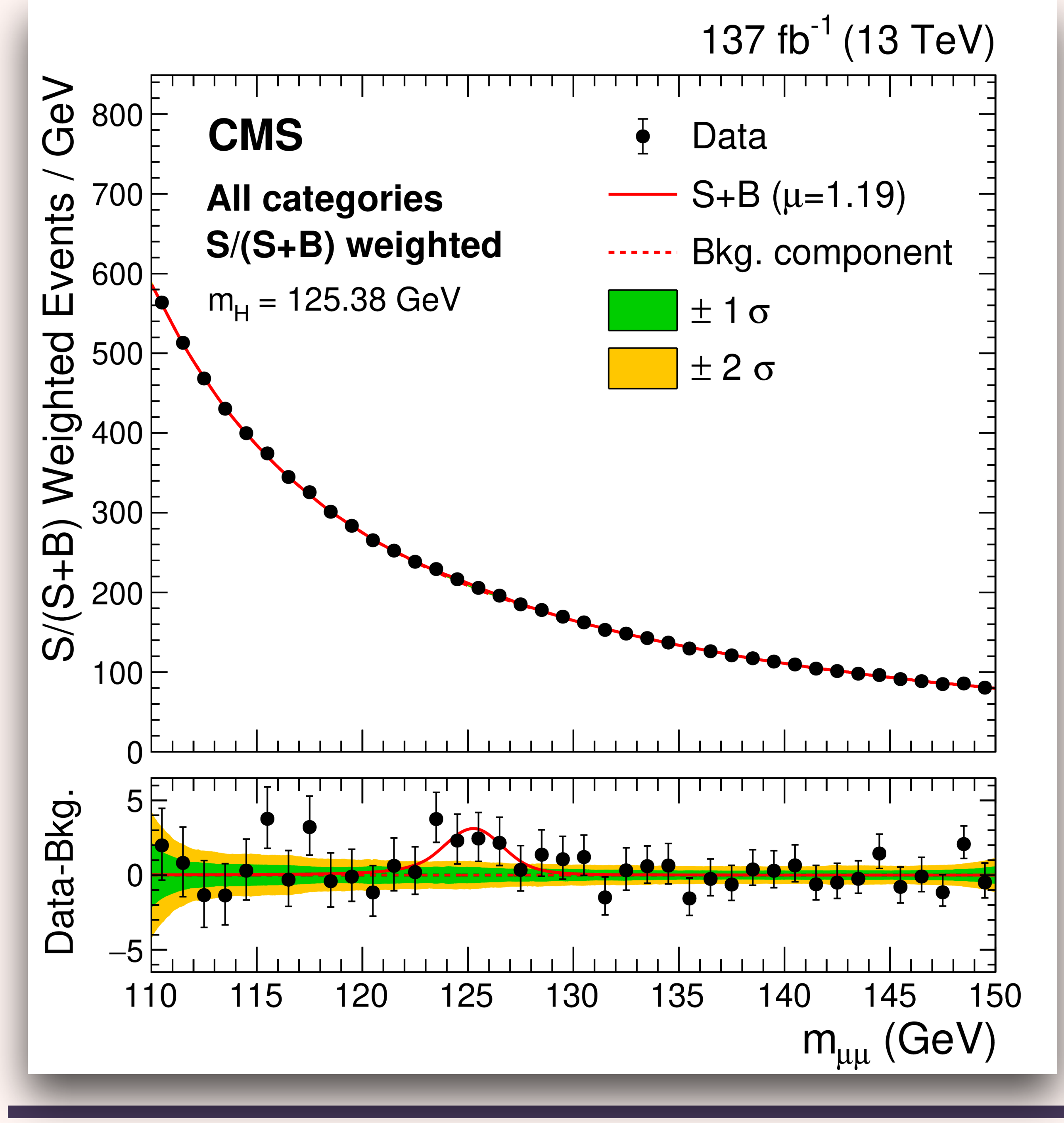
HUNTING FOR RARE PROCESSES

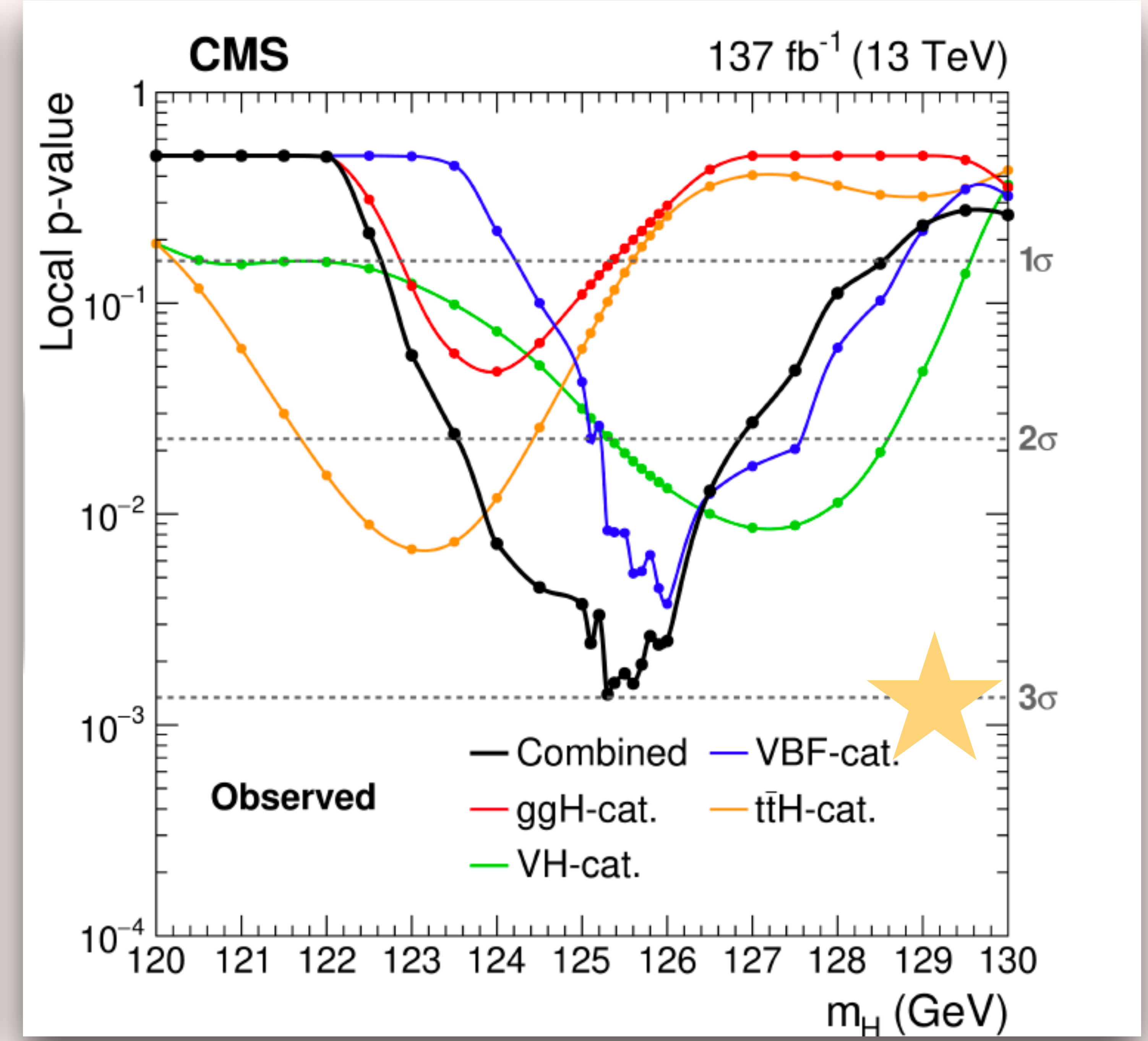
COUPLING TO THE SECOND GENERATION: H→μμ

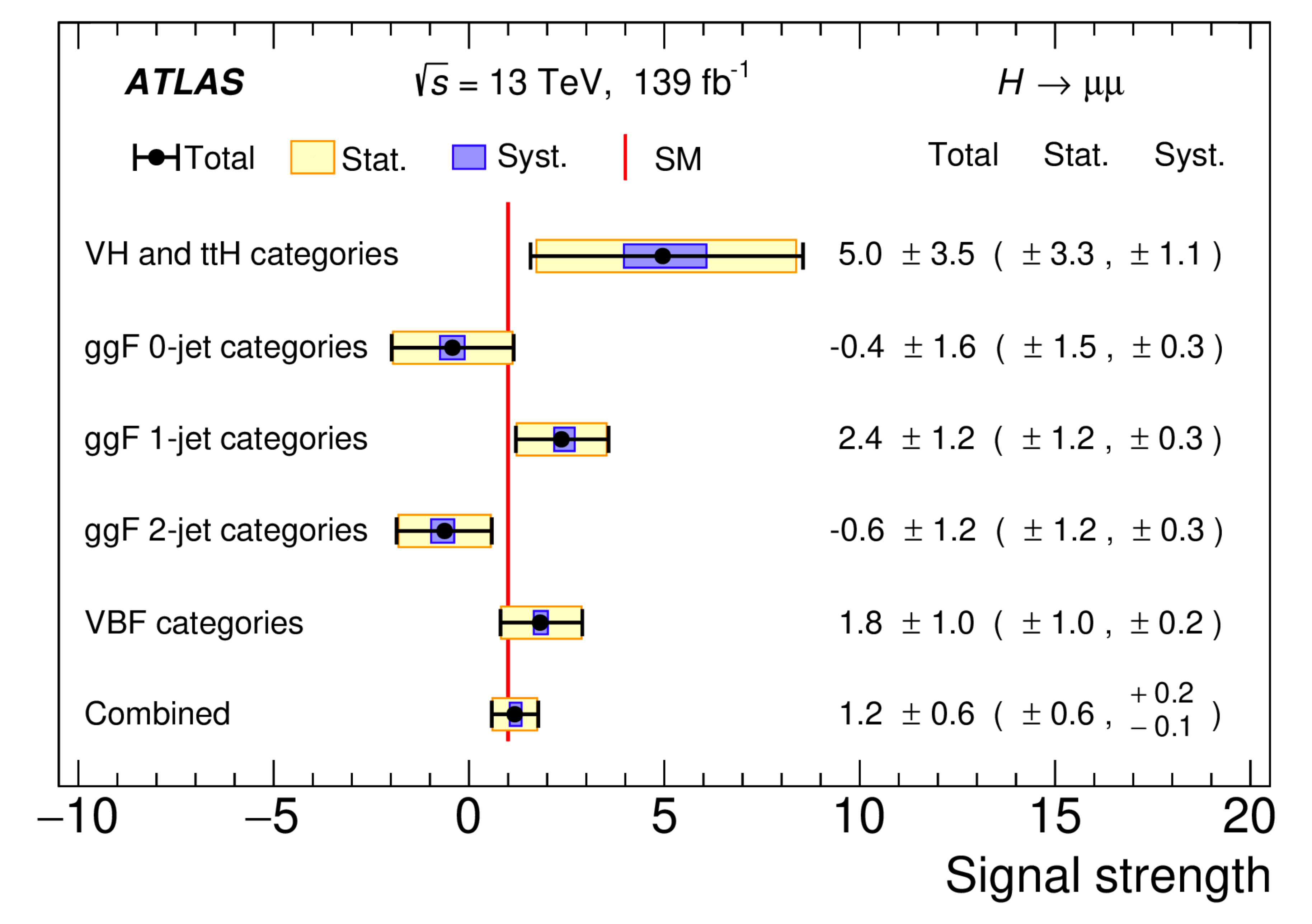
- **Highlight of 2020: evidence for the coupling to the second generation!**

- Clean analysis, good signal resolution: the challenge lies in the very small branching ratio, to identify the signal over the smoothly falling, huge Z dominated background
- Statistically limited

	Lumi	Precision
CMS, JHEP 01 (2021) 148	Full Run2	$\mu=1.19^{+0.40}_{-0.39}$ (stat)$^{+0.15}_{-0.14}$ (syst) 3.0(2.5)σ
ATLAS: Phys. Lett. B 812 (2021) 135980	Full Run2	$\mu=1.2\pm0.6$ 2.0(1.7)σ







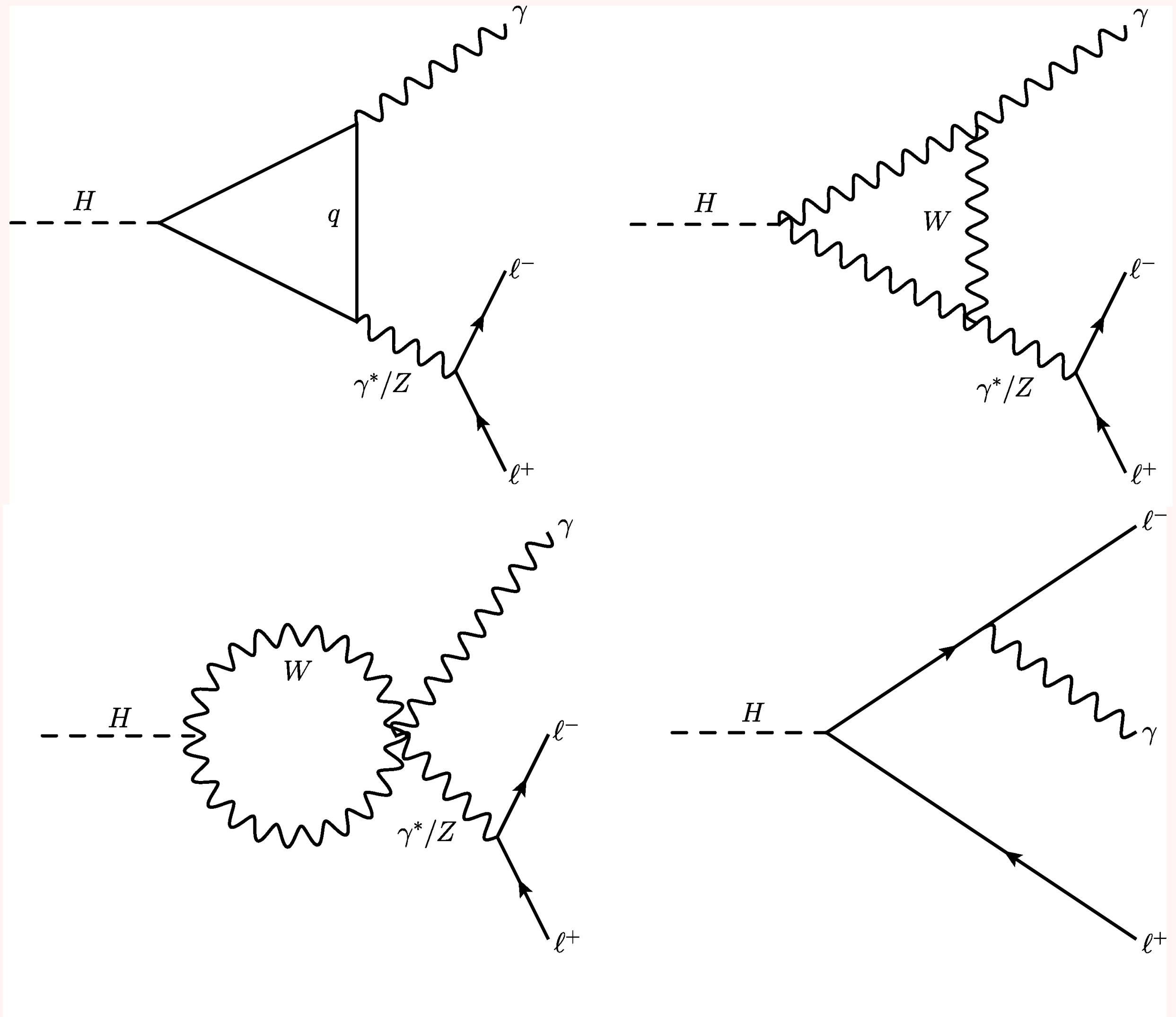
EVIDENCE FOR H→llγ

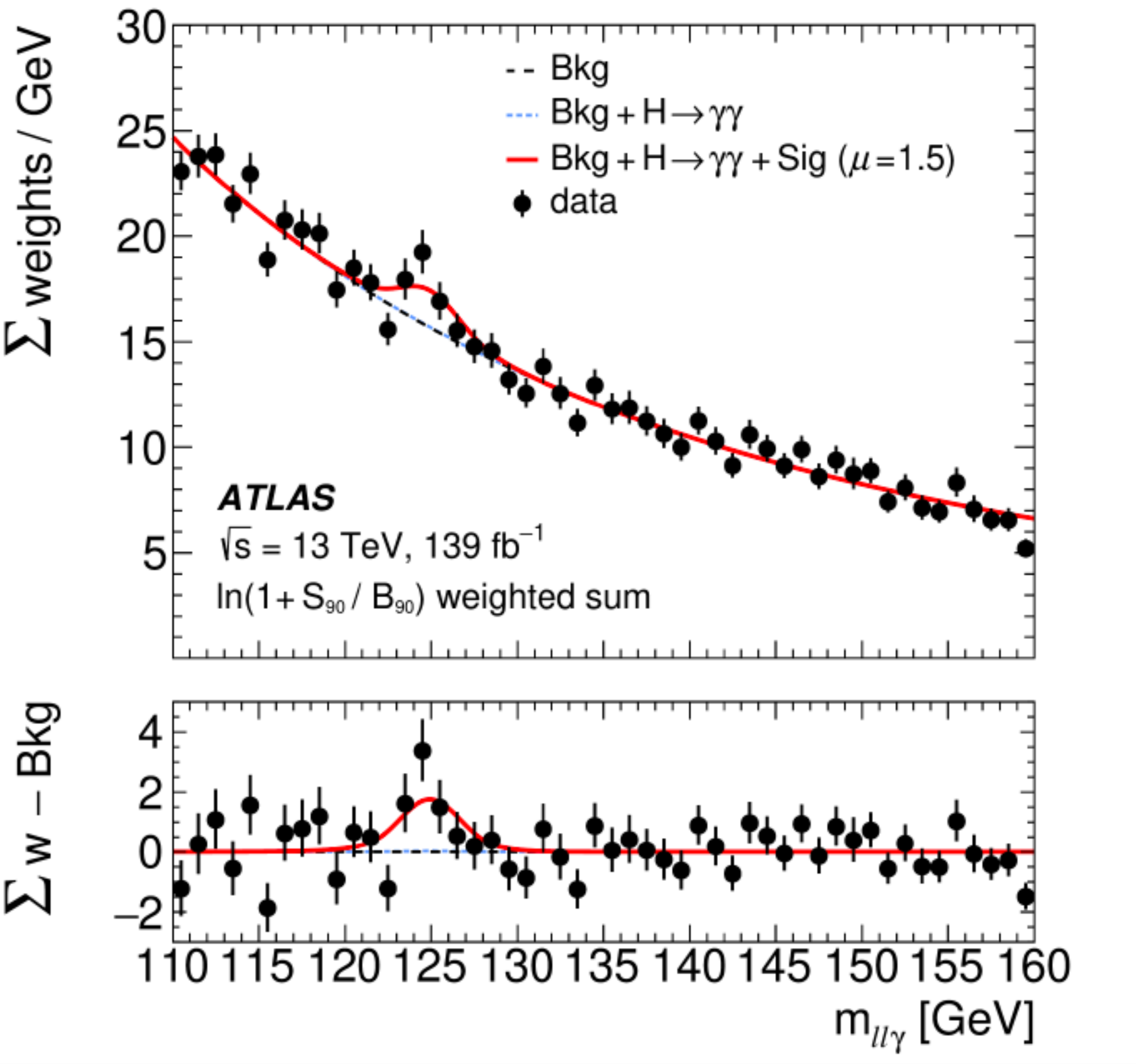
- Dedicated triggers and reconstructions
- Including main production modes (ggF; VBF, VH, ttH)
- Categorisation based on topology and lepton flavour

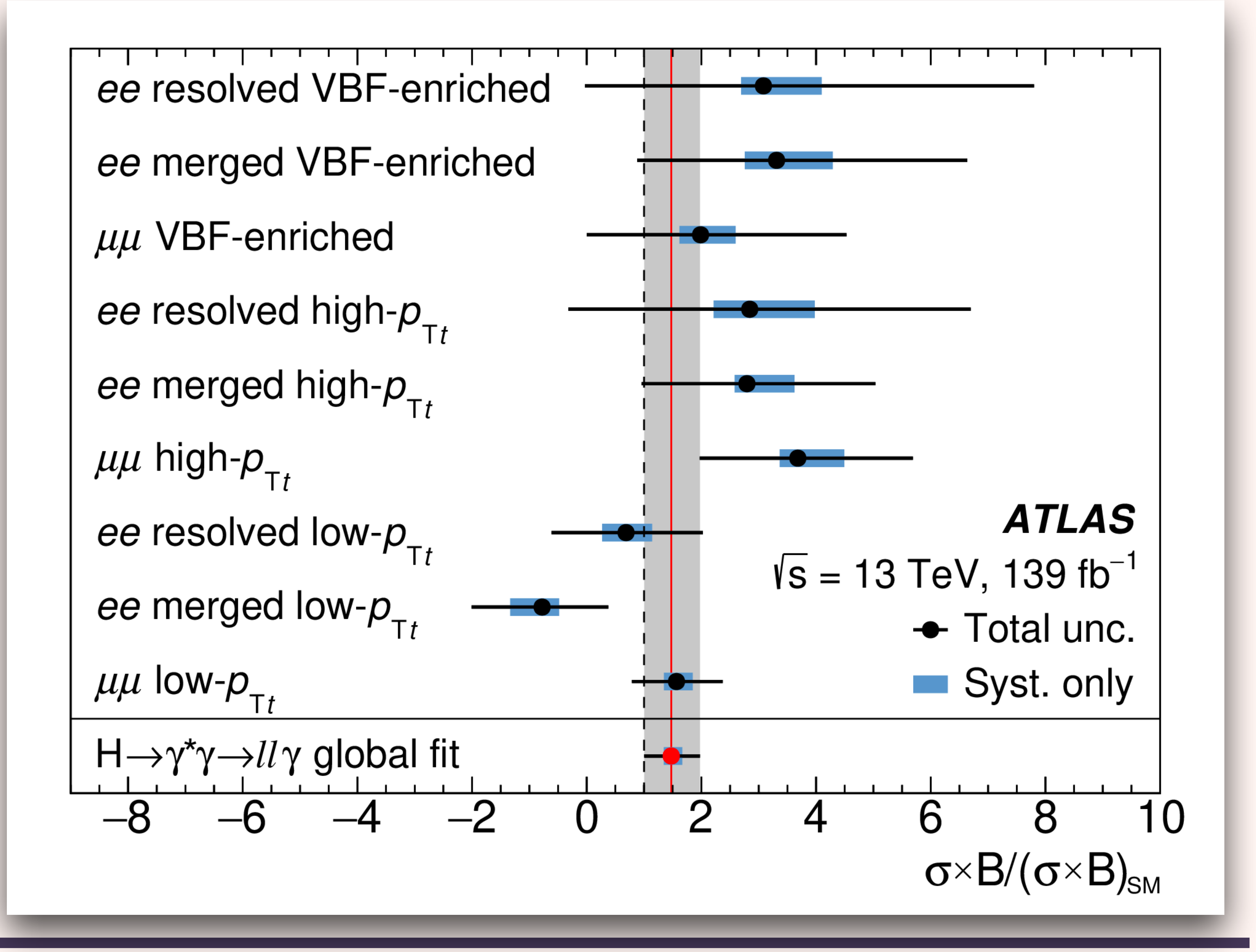
ATLAS, full Run2:

H→llγ (Dalitz): 3.2(2.1)σ , $\mu=1.5 \pm 0.5$ (Phys. Lett. B 819 (2021) 136412)

H→Zγ : 2.2 (1.2), σ , $\mu=2.0^{+1.0}_{-0.9}$ (Phys. Lett. B 809 (2020) 135754)



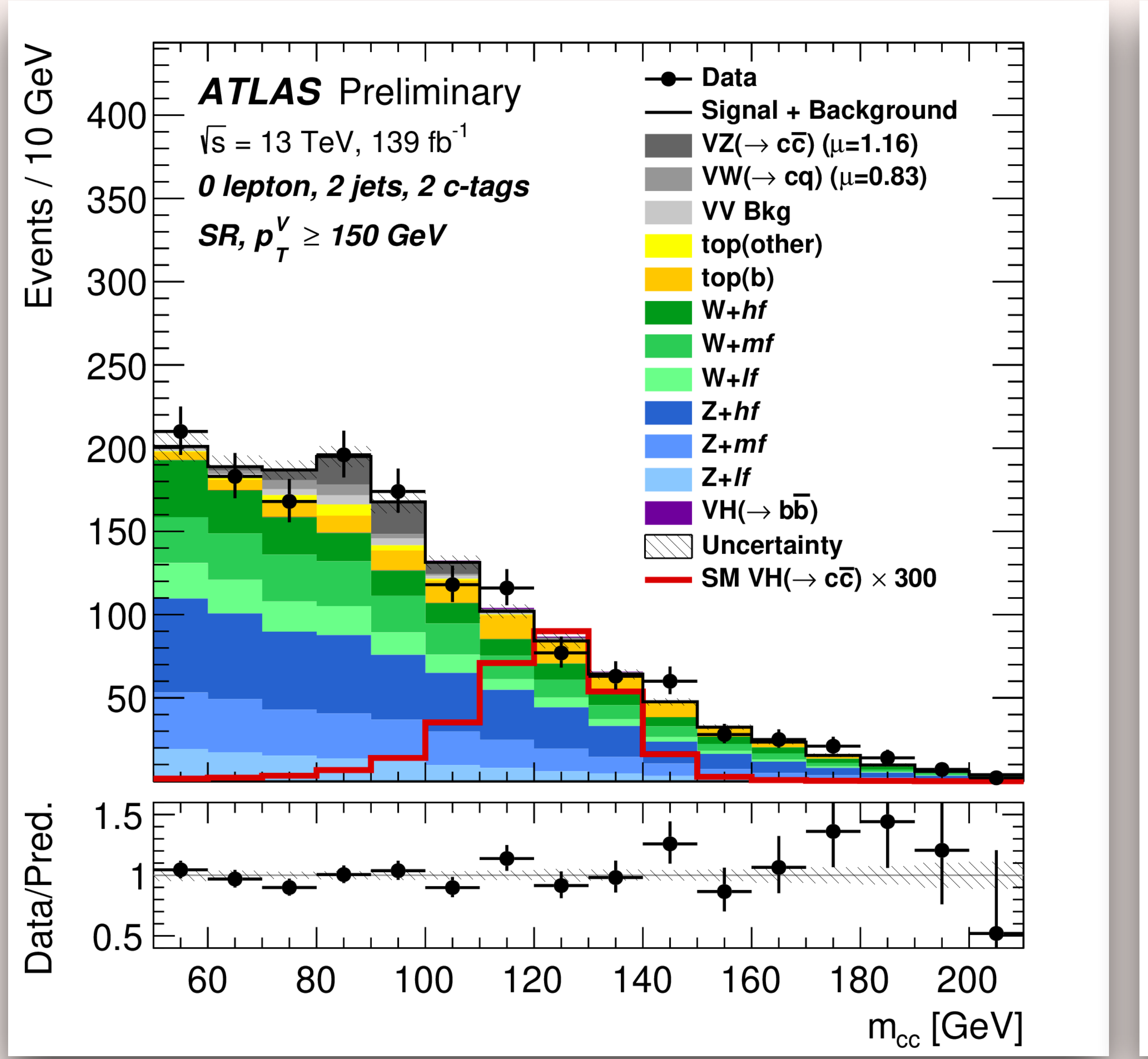


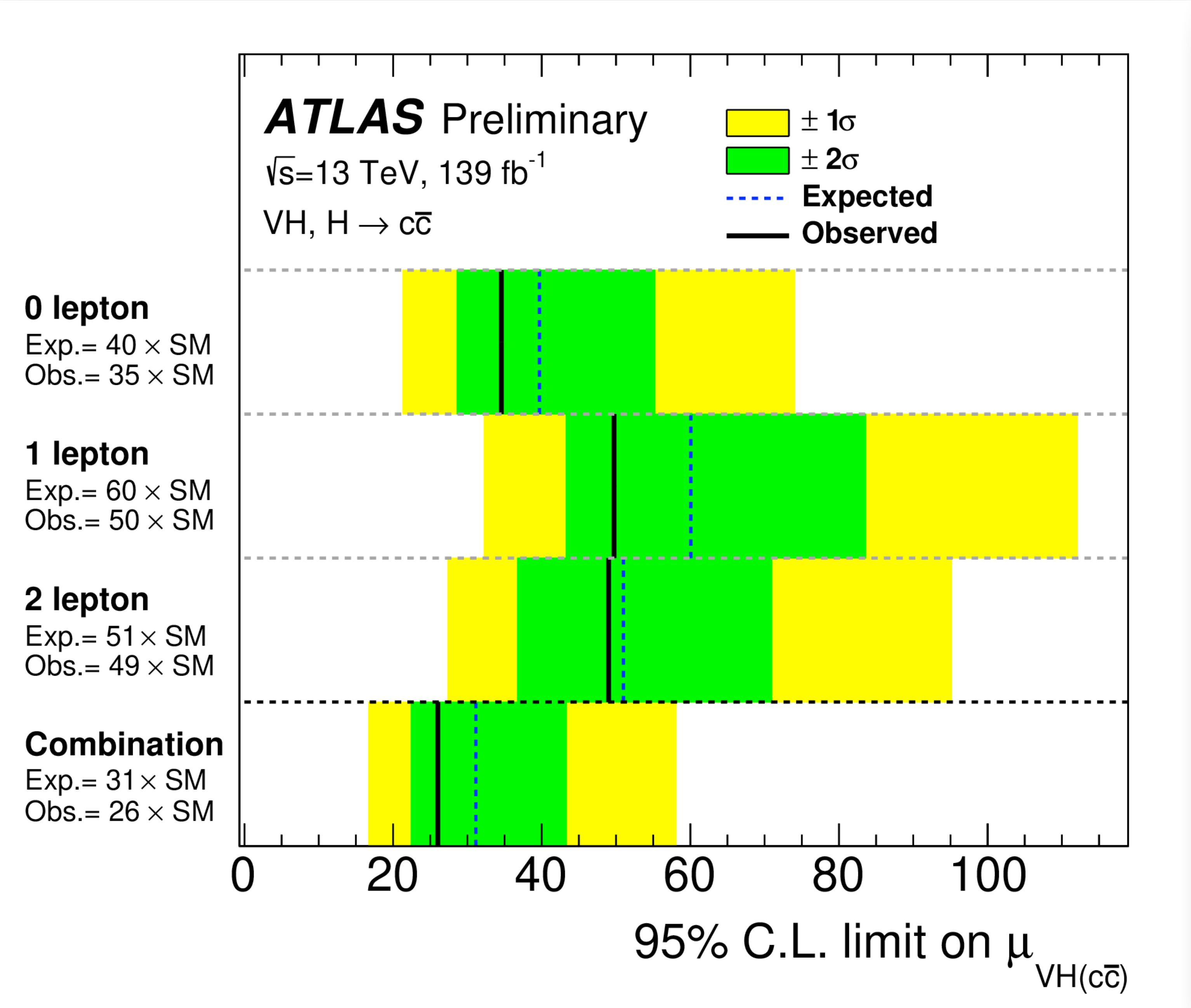


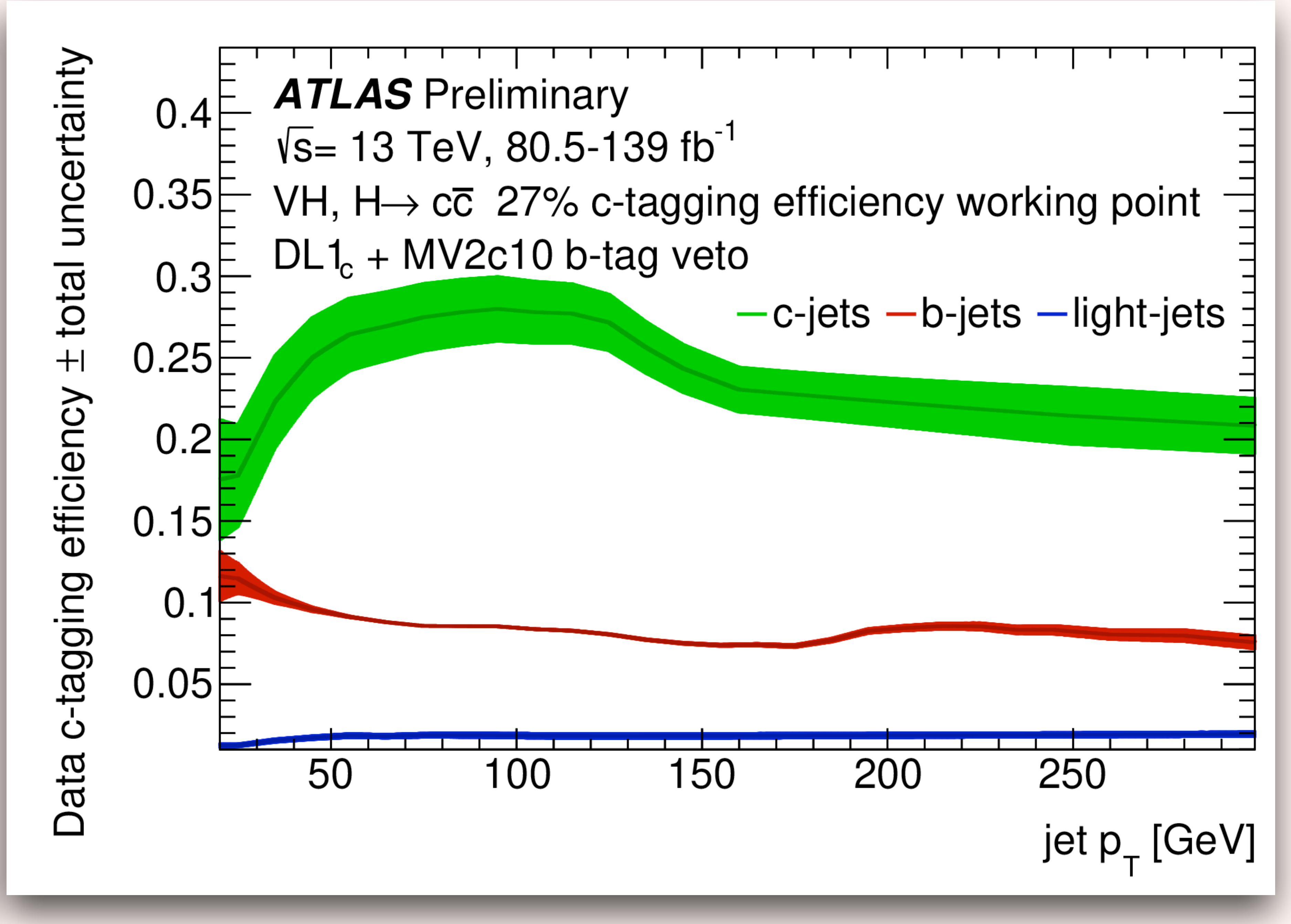
HOW CHARMING IS THE HIGGS?

- **What about the coupling to second gen quarks?**
- Difficult measurement: not only a matter of statistics. Exploit VH channel, and rely on c-tagging developments and ML.
- VZ (Z->cc), VW (W->cq) control analysis

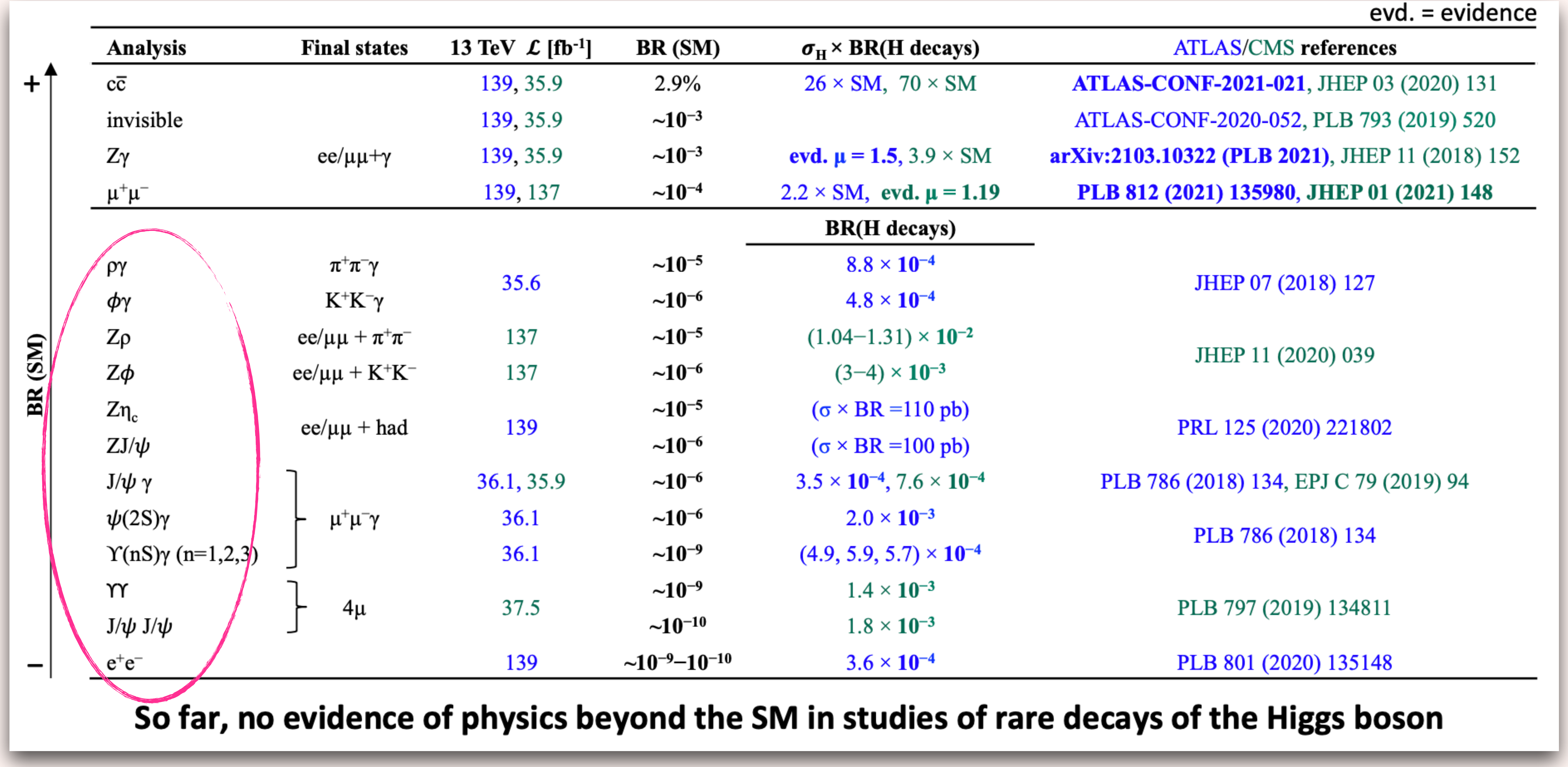
	Lumi	Latest limits @ 95% CL
CMS: JHEP 03 (2020) 131	2016	μ(VH, Hcc)<70(37)xSM
ATLAS-CONF-2021-021	Full Run2	μ(VH, Hcc)<26(31)xSM $\lvert\kappa_c\rvert$<8.5(12.4)







OTHER RARE DECAYS



evd. = evidence

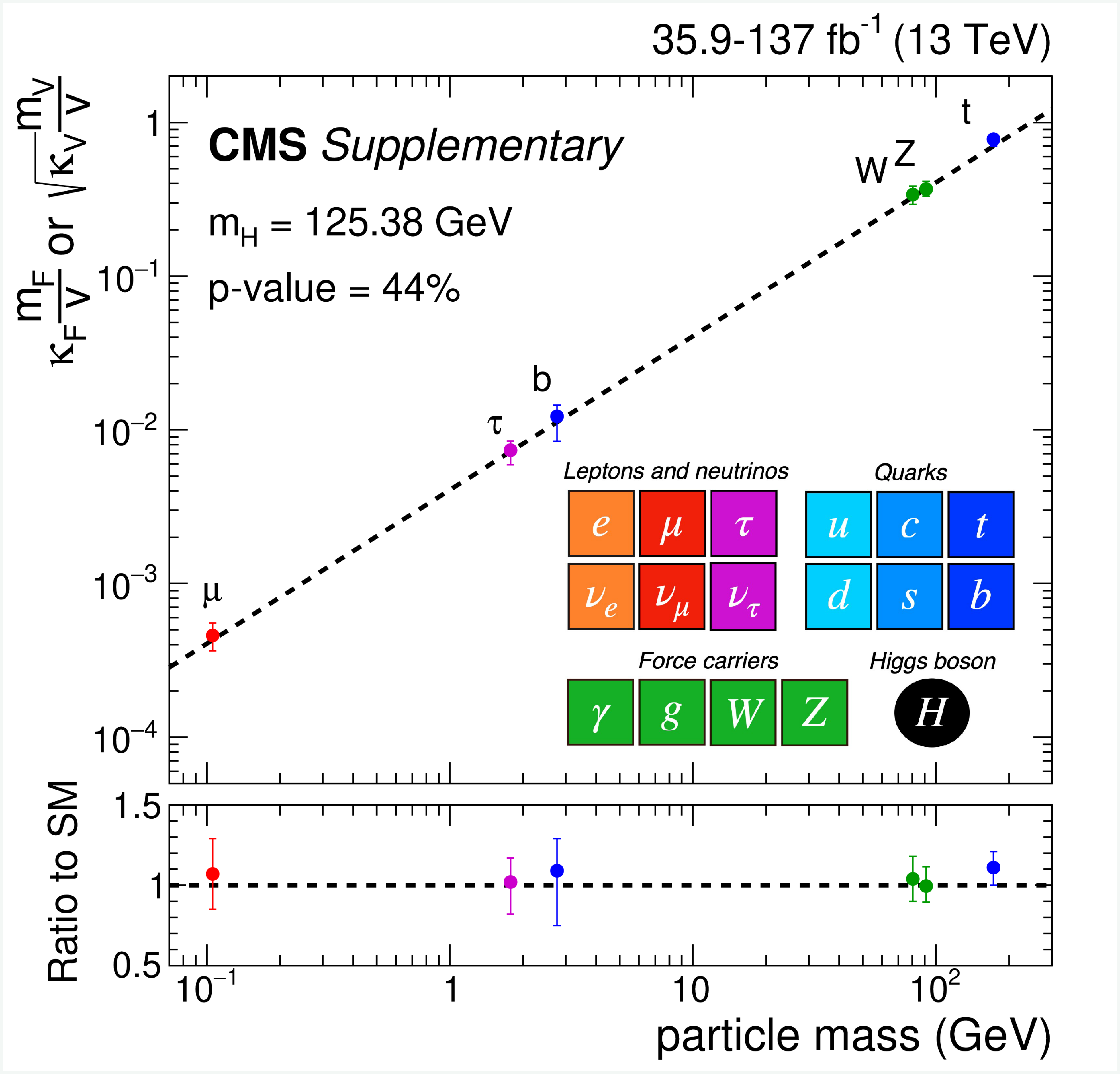
Analysis	Final states	13 TeV $\mathcal{L}$ [fb^{-1}]	BR (SM)	σ_H × BR(H decays)	ATLAS/CMS references
$c\bar{c}$		139, 35.9	2.9%	26 × SM, 70 × SM	**ATLAS-CONF-2021-021**, JHEP 03 (2020) 131
invisible		139, 35.9	$\sim 10^{-3}$		ATLAS-CONF-2020-052, PLB 793 (2019) 520
$Z\gamma$	ee/μμ+γ	139, 35.9	$\sim 10^{-3}$	**evd. $\mu = 1.5$**, 3.9 × SM	**arXiv:2103.10322 (PLB 2021)**, JHEP 11 (2018) 152
$\mu^+\mu^-$		139, 137	$\sim 10^{-4}$	2.2 × SM, **evd. $\mu = 1.19$**	**PLB 812 (2021) 135980, JHEP 01 (2021) 148**
				BR(H decays)	
$\rho\gamma$	$\pi^+\pi^-\gamma$	35.6	$\sim 10^{-5}$	8.8×10^{-4}	JHEP 07 (2018) 127
$\phi\gamma$	$K^+K^-\gamma$		$\sim 10^{-6}$	4.8×10^{-4}	
$Z\rho$	ee/μμ + $\pi^+\pi^-$	137	$\sim 10^{-5}$	$(1.04{-}1.31) \times 10^{-2}$	JHEP 11 (2020) 039
$Z\phi$	ee/μμ + K^+K^-	137	$\sim 10^{-6}$	$(3{-}4) \times 10^{-3}$	
$Z\eta_c$	ee/μμ + had	139	$\sim 10^{-5}$	(σ × BR =110 pb)	PRL 125 (2020) 221802
ZJ/ψ			$\sim 10^{-6}$	(σ × BR =100 pb)	
$J/\psi\ \gamma$	$\mu^+\mu^-\gamma$	36.1, 35.9	$\sim 10^{-6}$	3.5×10^{-4}, 7.6×10^{-4}	PLB 786 (2018) 134, EPJ C 79 (2019) 94
$\psi(2S)\gamma$		36.1	$\sim 10^{-6}$	2.0×10^{-3}	PLB 786 (2018) 134
$\Upsilon(nS)\gamma$ (n=1,2,3)		36.1	$\sim 10^{-9}$	$(4.9, 5.9, 5.7) \times 10^{-4}$	
$\Upsilon\Upsilon$	4μ	37.5	$\sim 10^{-9}$	1.4×10^{-3}	PLB 797 (2019) 134811
$J/\psi\ J/\psi$			$\sim 10^{-10}$	1.8×10^{-3}	
e^+e^-		139	$\sim 10^{-9}{-}10^{-10}$	3.6×10^{-4}	PLB 801 (2020) 135148

So far, no evidence of physics beyond the SM in studies of rare decays of the Higgs boson

Summary by Imma Riu @ LHCP2021

SO WHAT HAVE WE HAVE LEARNT?

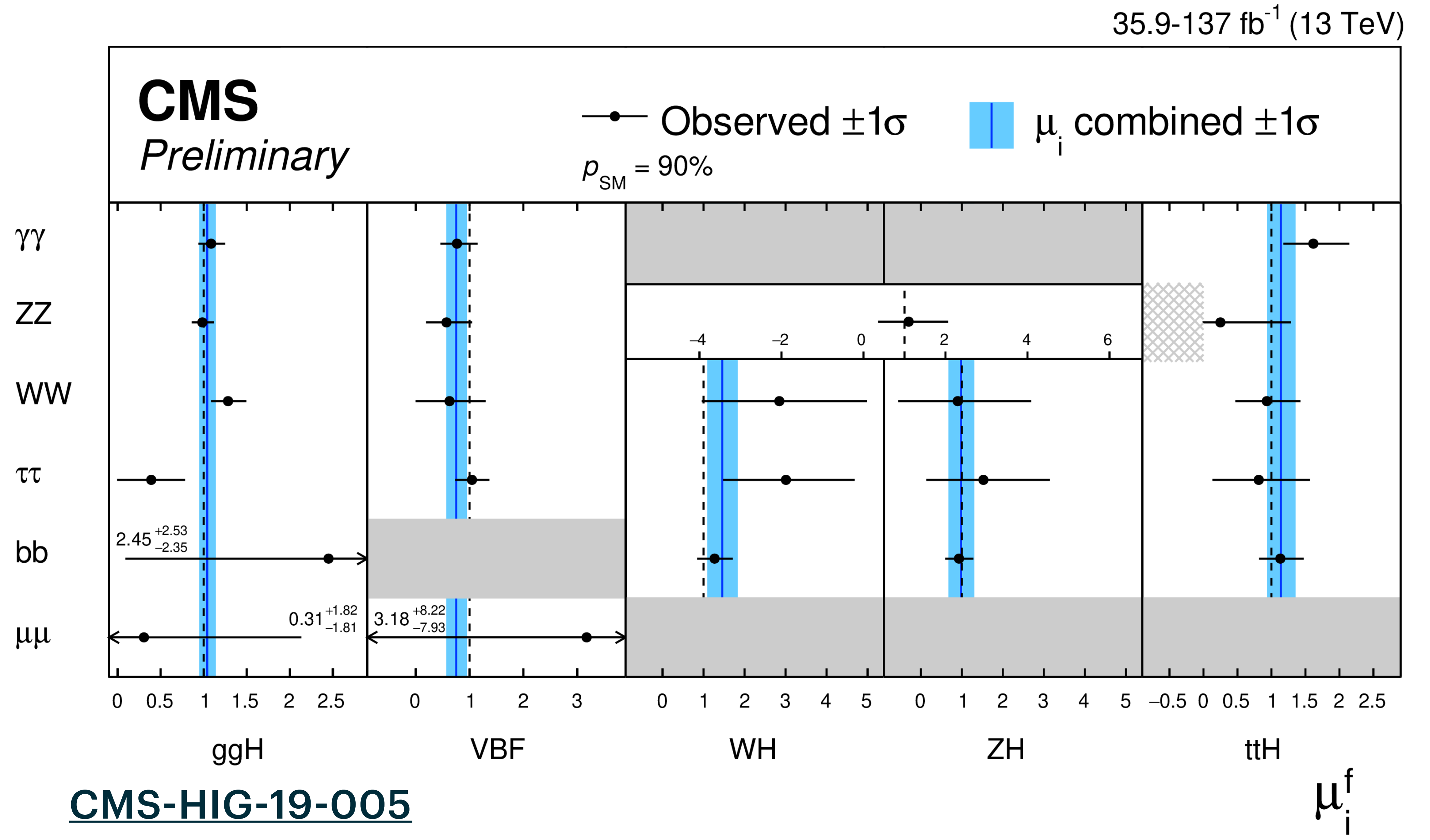
- Let’s recap:
  - Measurements of Mass (to 0.11%!), Width, CP
  - Main production modes explored in depth by now, with precise measurements of the signal strength/cross section (down to 10% precision)
  - Coupling to the SM particles well established for the main decay modes, and already at evidence level for several of the statistically dominated ones (eg: muons)
  - Measurements going differential, and towards precision in properties
  - Interpretations in terms of Effective Field Theories (EFT) start to be the norm
  - Rarer processes starting to become accessible



Can we put together all the information to have a global view of Higgs@LHC?

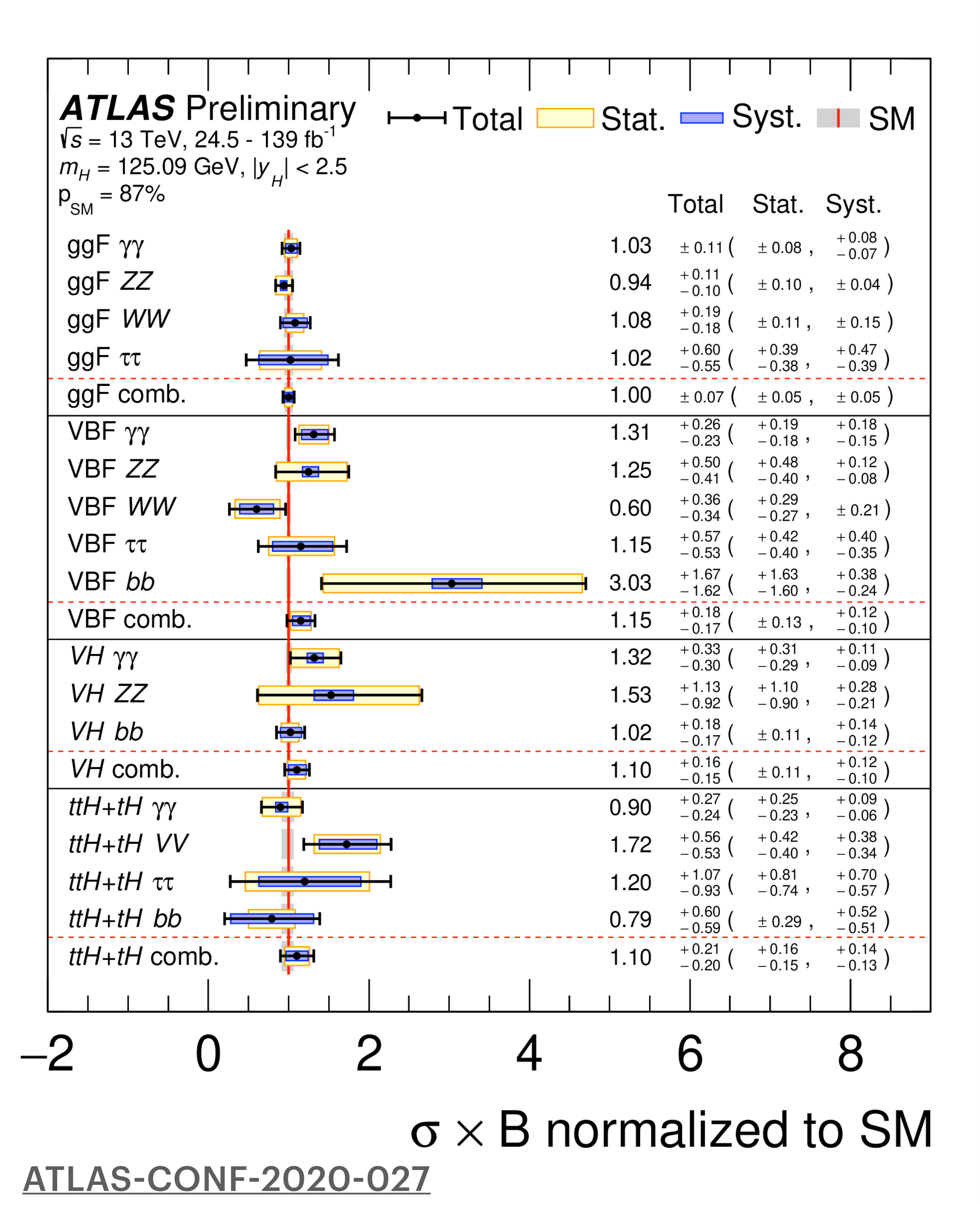
GLOBAL VIEW OF HIGGS PRODUCTION

- **Combining the information from the main decay channels presented until now we can obtain a detailed view of the Higgs agreement with the SM prediction**
- Global measurement of the signal strength today, with partial Run2 stats:
  - **ATLAS best fit to μ=1.06±0.07 (ATLAS-CONF-2020-027)**
  - **CMS best fit to μ=$1.02^{+0.07}_{-0.06}$ (CMS-HIG-19-005)**
- Many measurements: Cross Sections (including STXS), Branching ratios, Couplings



CMS-HIG-19-005

$$\mu_i^f \equiv \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i \cdot \mathrm{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$



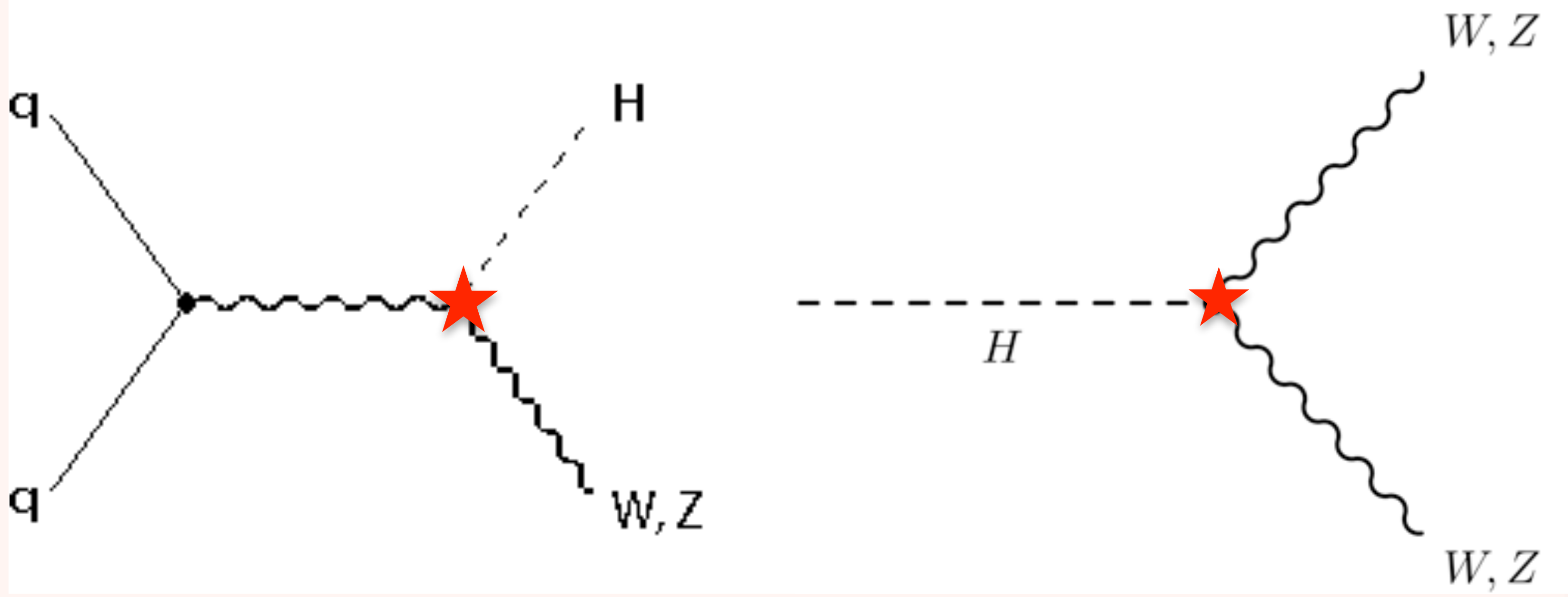
ATLAS-CONF-2020-027

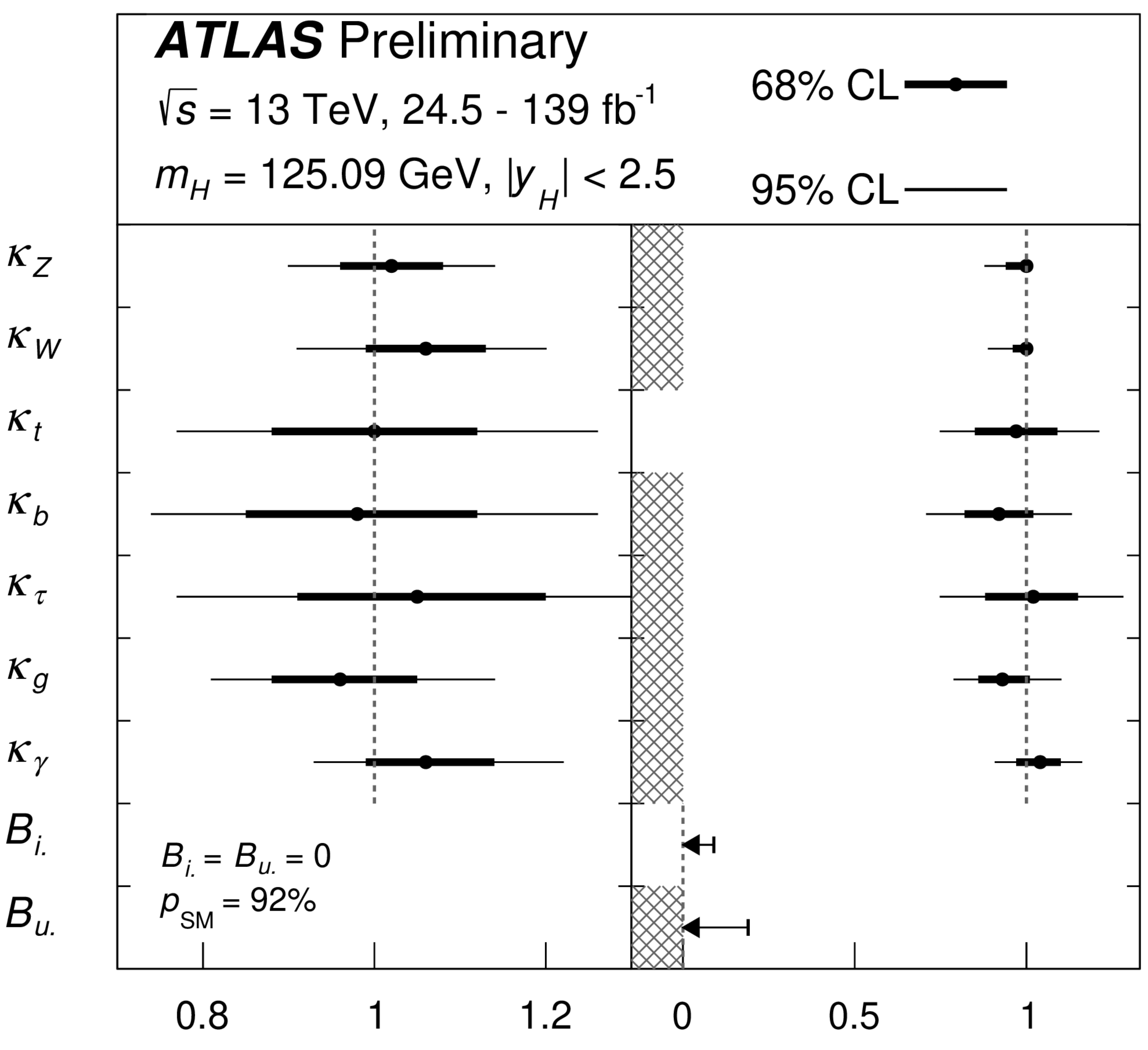
HOW WELL DO WE KNOW THE HIGGS COUPLINGS?

- In the Kappa Framework (simple parametrisation widely used by LHC experiments), **already known to 6-15%** (still with partial Run2 statistics)

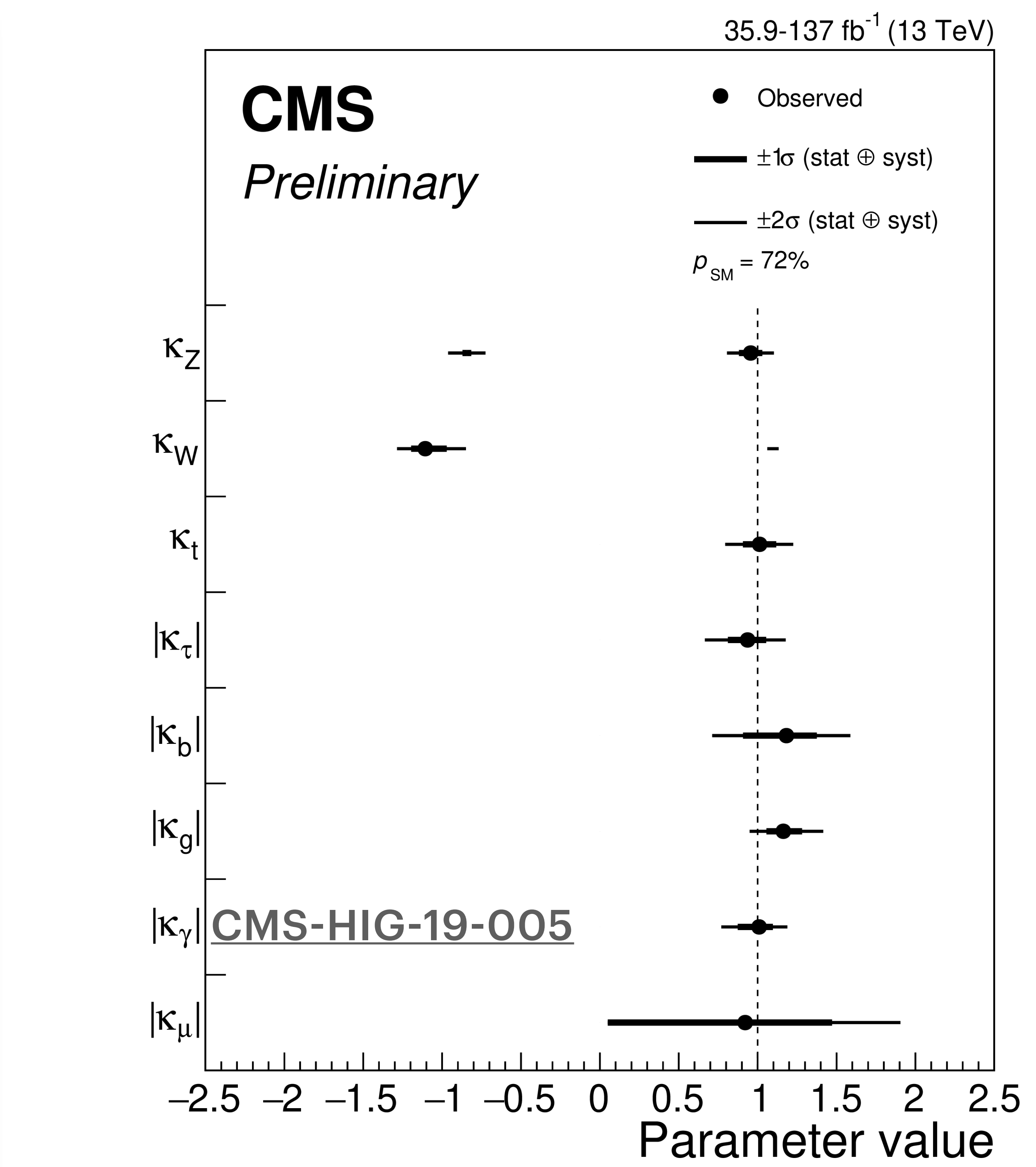
$$\sigma(i \to H \to f) = \frac{\sigma_i(\kappa_j)\cdot\Gamma_f(\kappa_j)}{\Gamma_H(\kappa_j)}$$

$$\sigma_i = \kappa_i^2(\vec{\kappa})\cdot\sigma_i^{SM} \qquad \Gamma^f = \kappa_f^2(\vec{\kappa})\cdot\Gamma^{f,SM}$$





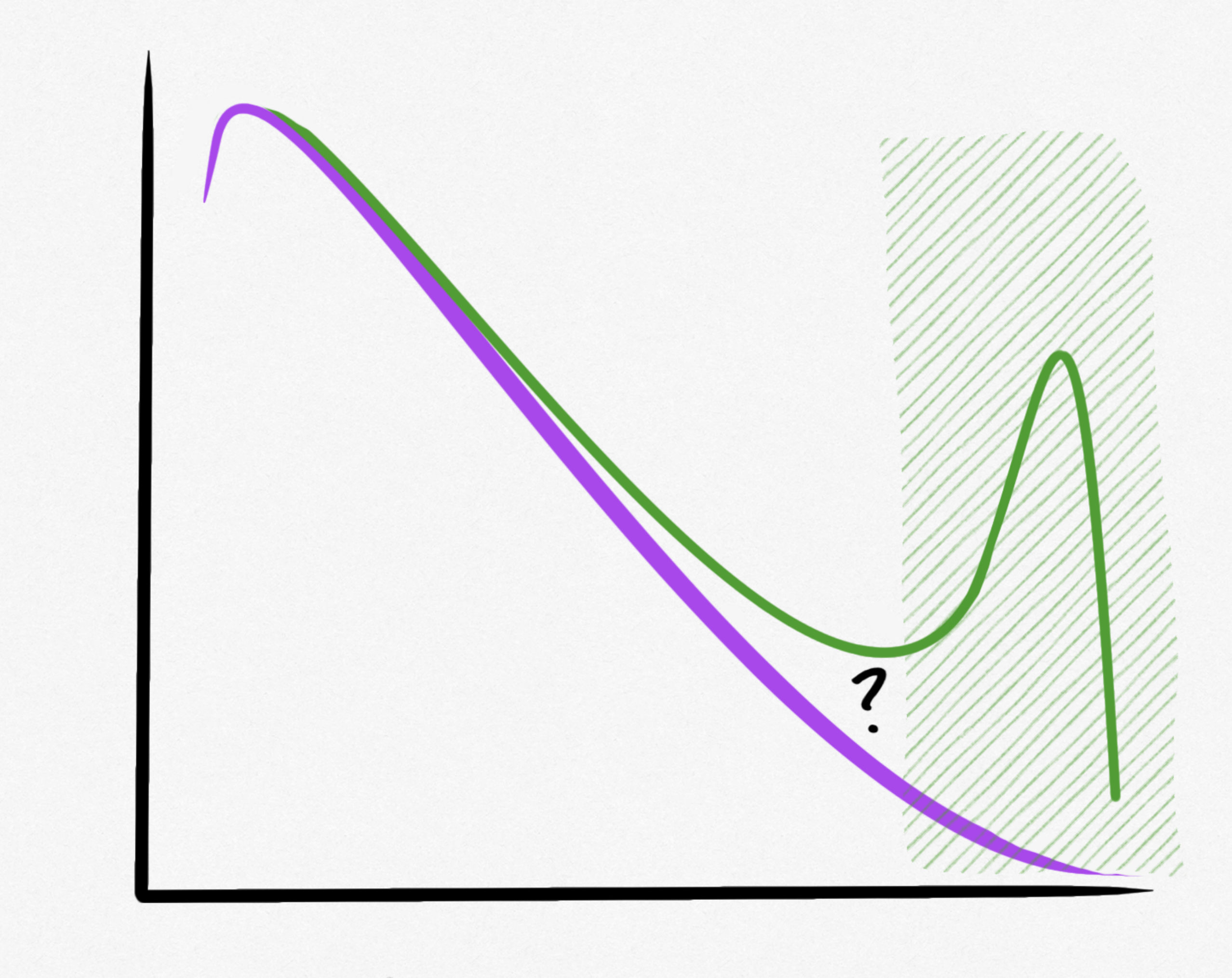
ATLAS-CONF-2020-027



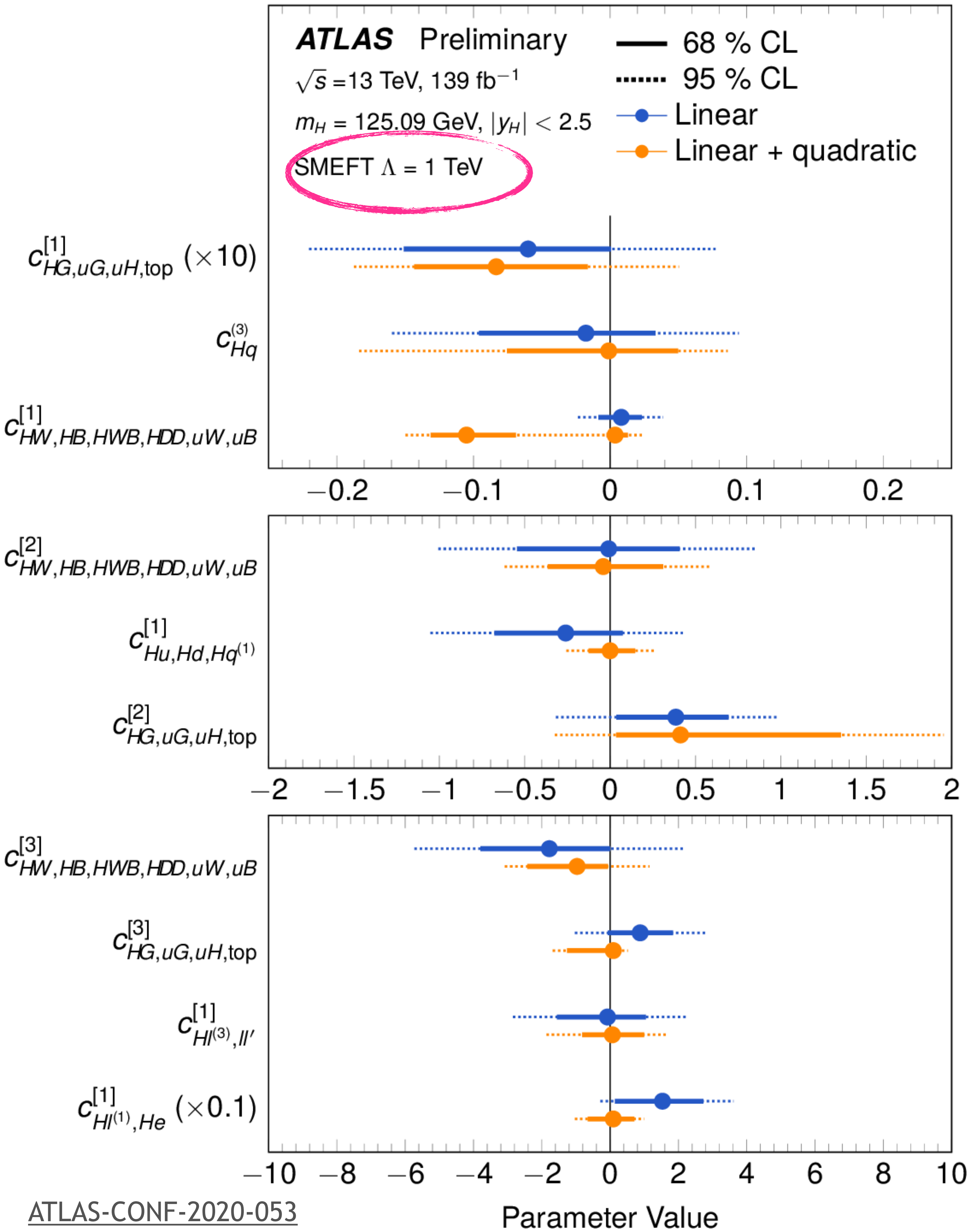
CMS-HIG-19-005

HOW WELL DO WE KNOW THE HIGGS COUPLINGS?

- Experiments moving beyond kappas to target Effective Field Theories (EFT): parameterise the low-energy effects of new physics at higher scales
- Going forward: we need to stop thinking about measuring Higgs couplings in isolation. Start targeting global approaches that eventually will involve all precision data available

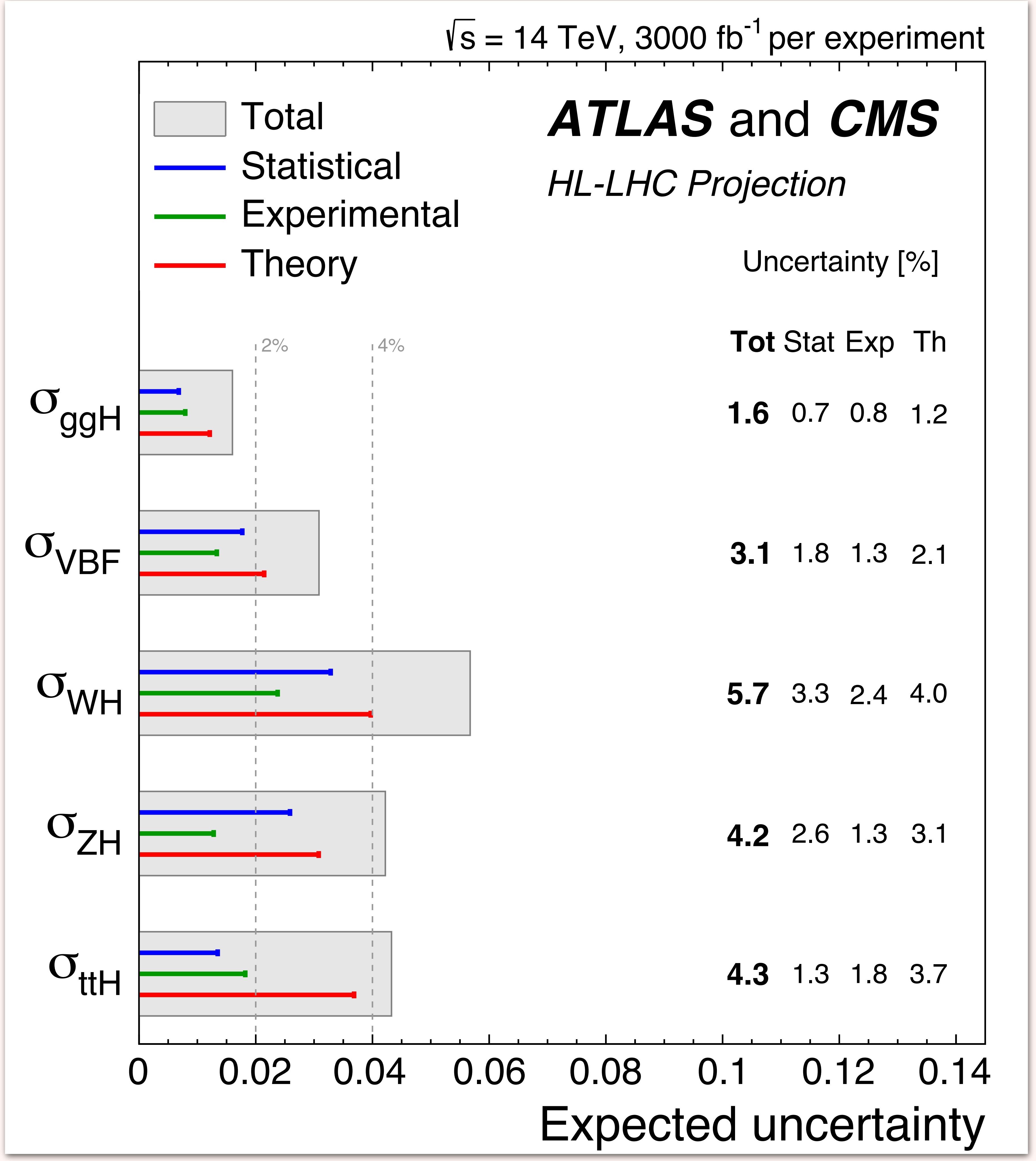


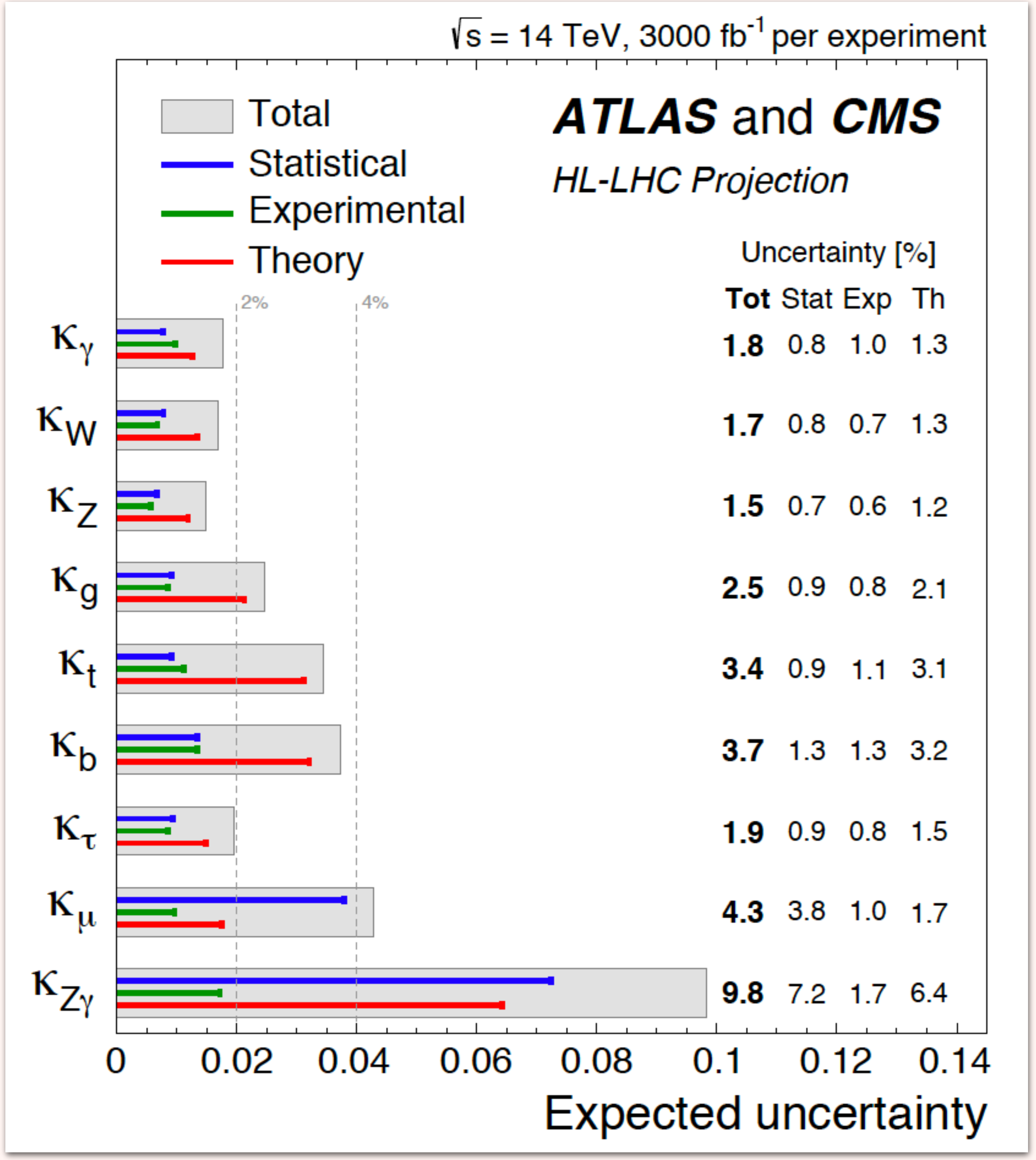
$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_{j}^{N_{d8}} \frac{b_j}{\Lambda^4} O_j^{(8)} + \dots ,$$



ATLAS-CONF-2020-053

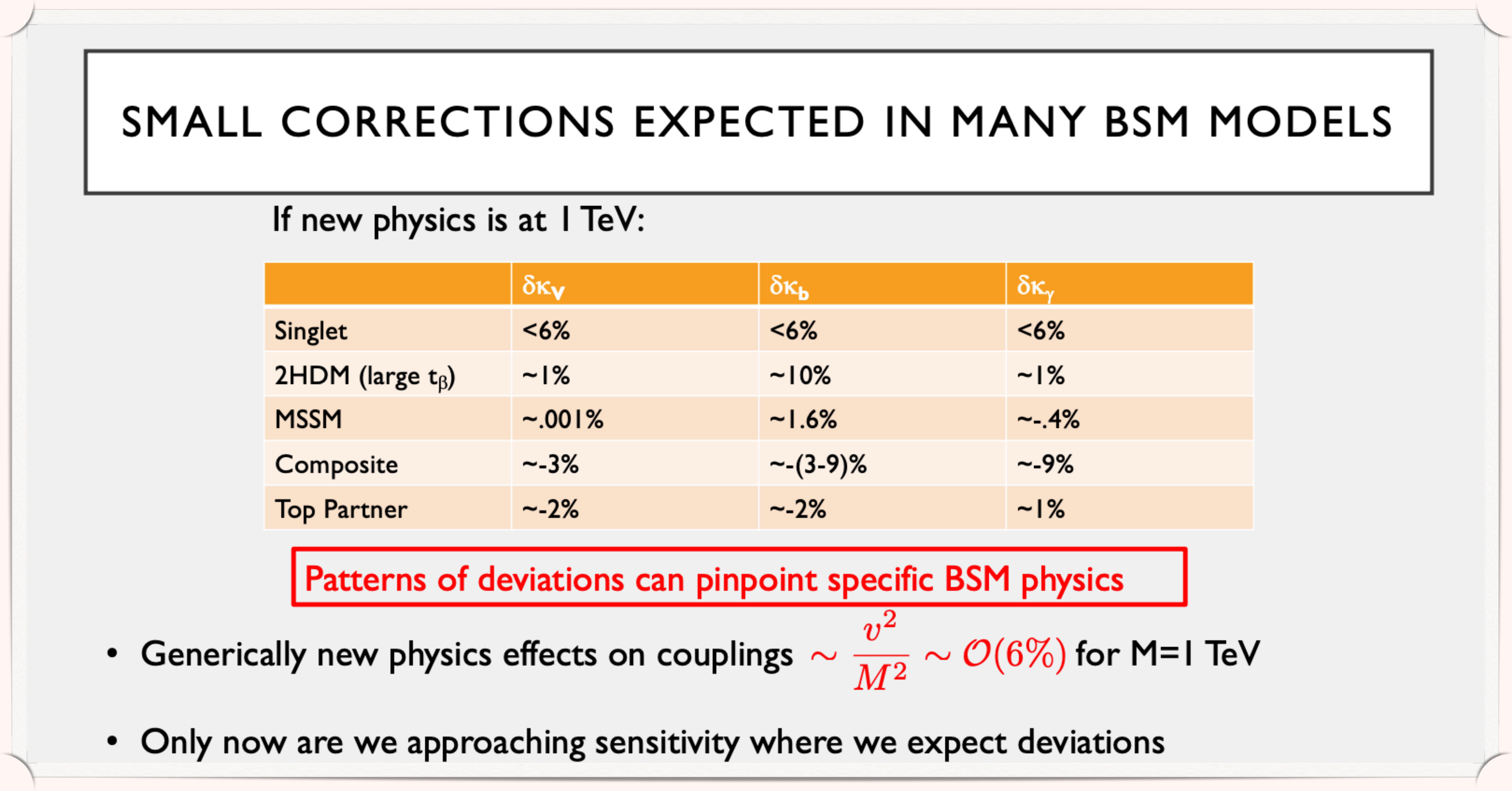
HOW WELL *CAN* WE KNOW THE HIGGS COUPLINGS?





- We've only tapped a small fraction of the LHC potential as a Higgs-Hunting machine
- Target at the end of the HL-LHC: cross sections, branching ratios and kappas to the few percent level (except for stat-dominated final states)

HOW WELL *SHOULD* WE KNOW THE HIGGS COUPLINGS?



SMALL CORRECTIONS EXPECTED IN MANY BSM MODELS

If new physics is at 1 TeV:

	$\delta\kappa_V$	$\delta\kappa_b$	$\delta\kappa_\gamma$
Singlet	<6%	<6%	<6%
2HDM (large t_β)	~1%	~10%	~1%
MSSM	~.001%	~1.6%	~-.4%
Composite	~-3%	~-(3-9)%	~-9%
Top Partner	~-2%	~-2%	~1%

Patterns of deviations can pinpoint specific BSM physics

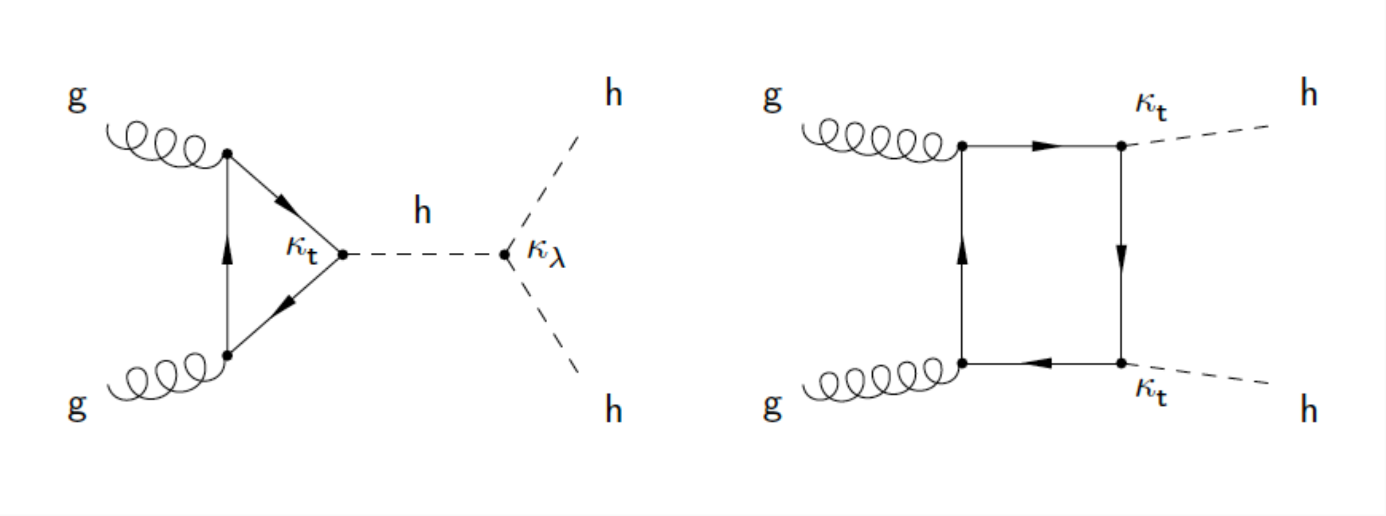
- Generically new physics effects on couplings $\sim \frac{v^2}{M^2} \sim \mathcal{O}(6\%)$ for M=1 TeV
- Only now are we approaching sensitivity where we expect deviations

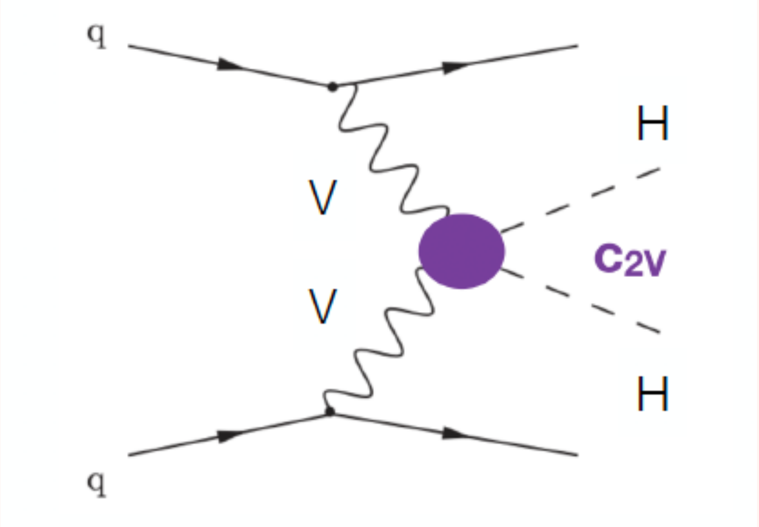
Sally Dawson

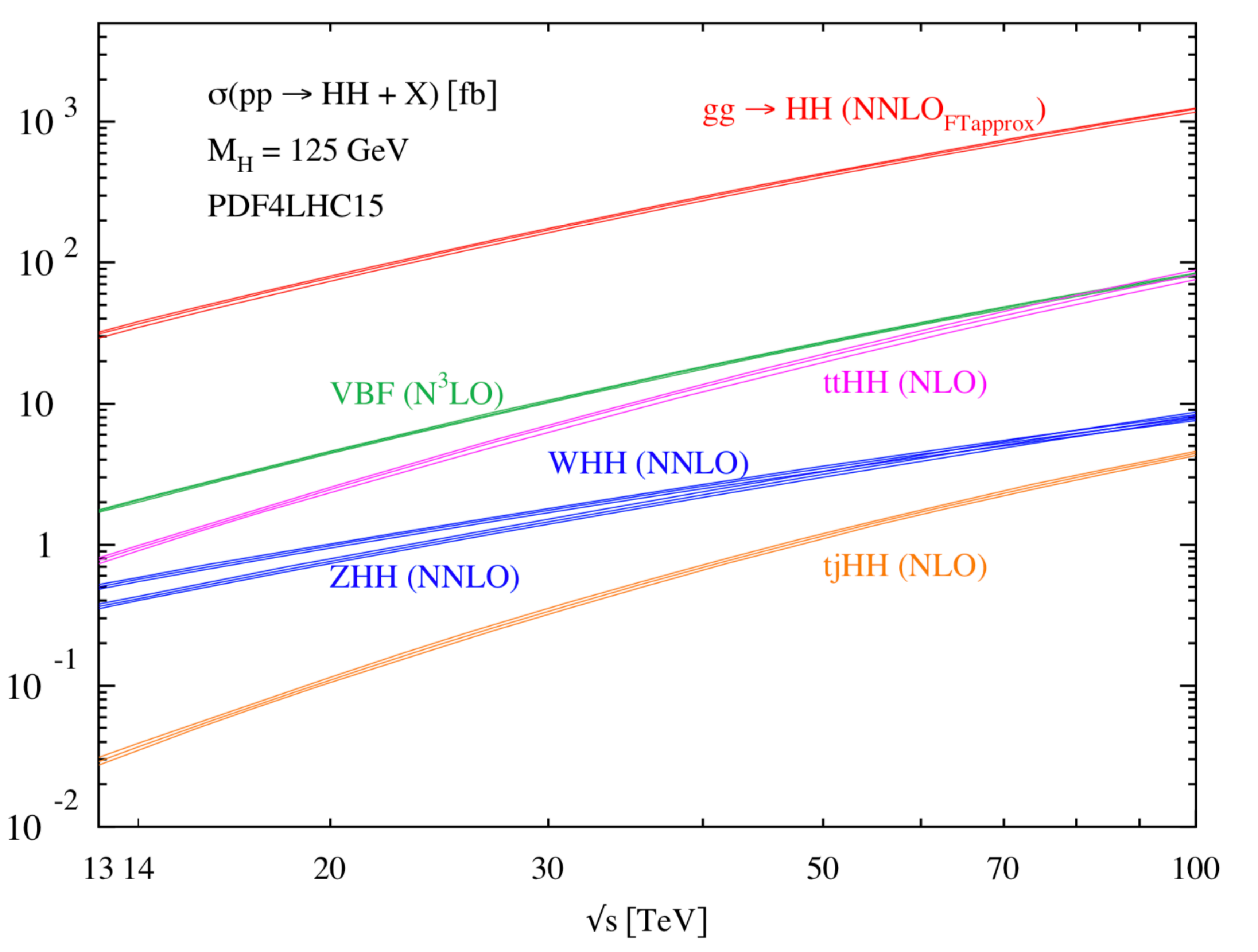
WHAT ABOUT THE HIGGS SELF-COUPLING?

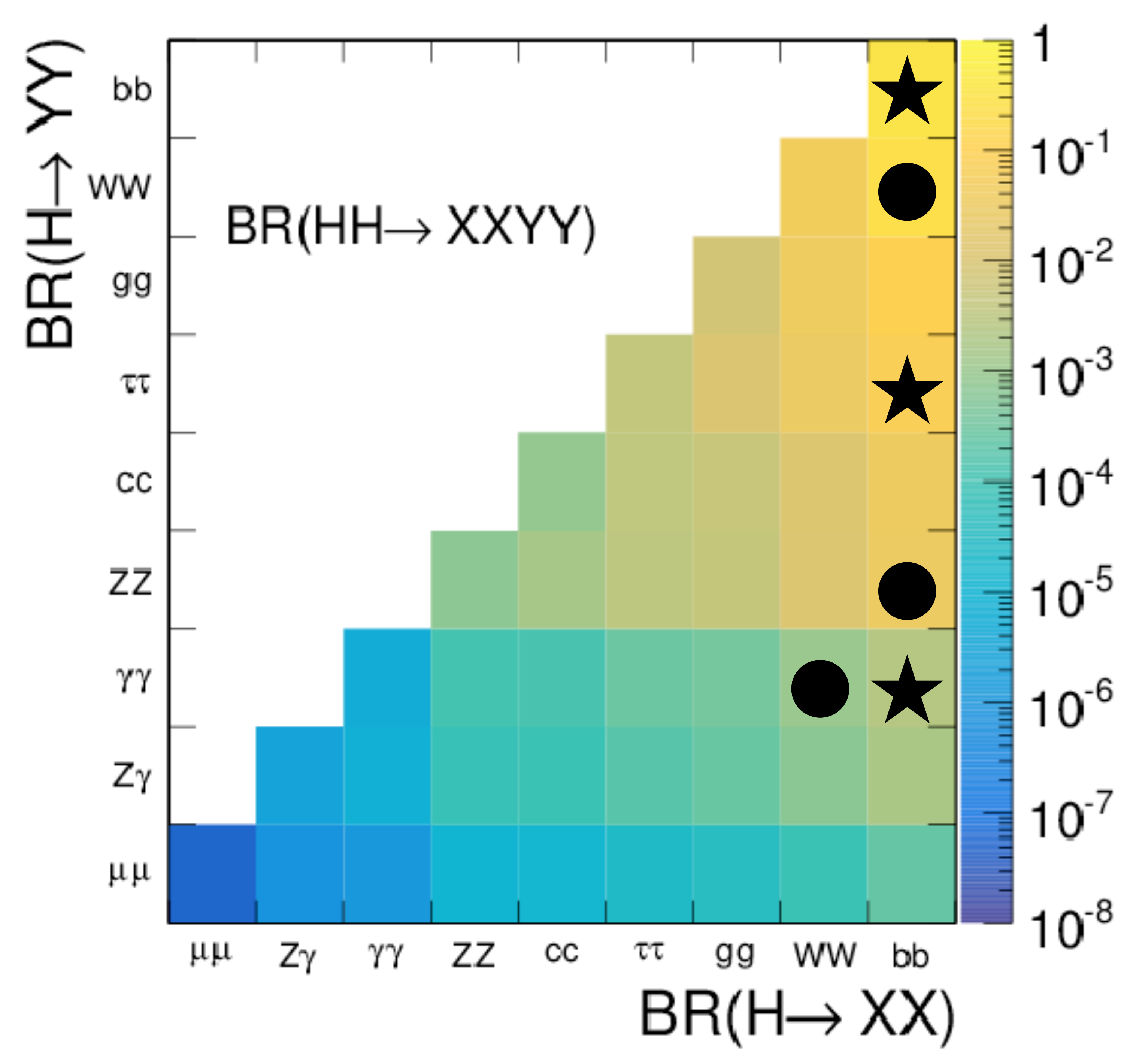
CAN WE ACCESS THE HIGGS SELF-COUPLING AT THE LHC?

- Main avenue at LHC (*): exploit HH production. Very small cross section, still ~5xSM (per analysis, per experiment)
    - Sensitive to BSM physics : Small changes on the couplings can lead to large changes in production
- Not only ggF: targeting VBF production we can look for deviations in the VVHH vertex







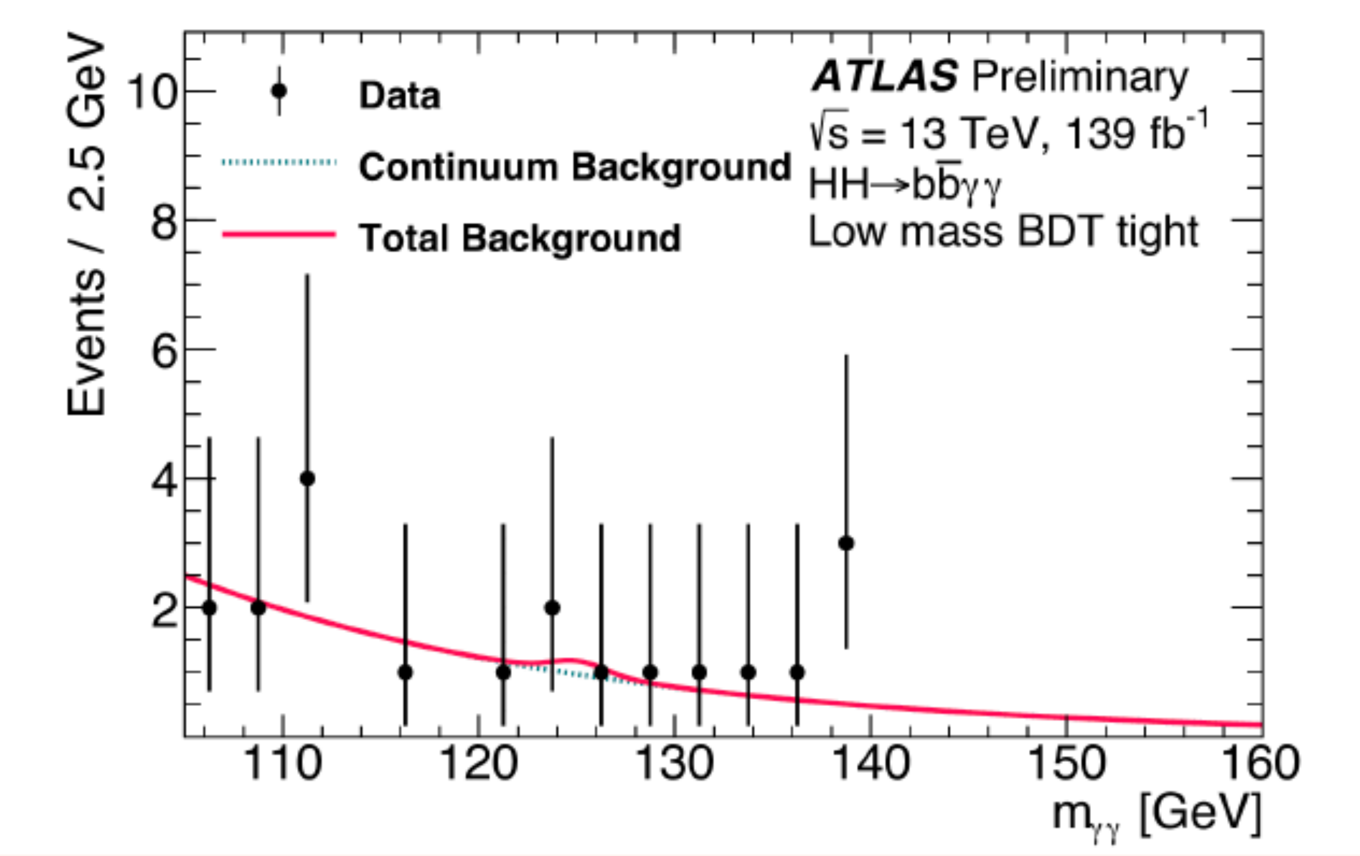


Exploit a combination of high BR decays with decays with good mass reconstruction or S/B for optimal sensitivity

(*) Also possible to extract constraints on the self coupling from single Higgs: I won’t discuss those today

$HH \rightarrow b\bar{b}\gamma\gamma$

- Small rate, but clean: one of the golden channels
- Exploits the excellent diphoton resolution of the detectors
- Categories designed to probe larger and smaller ranges of κ_λ, κ_{2V}



Cross section limits (@ 95 % CL):

CMS: JHEP03(2021)257

$\mu<7.7(5.2)\times SM$

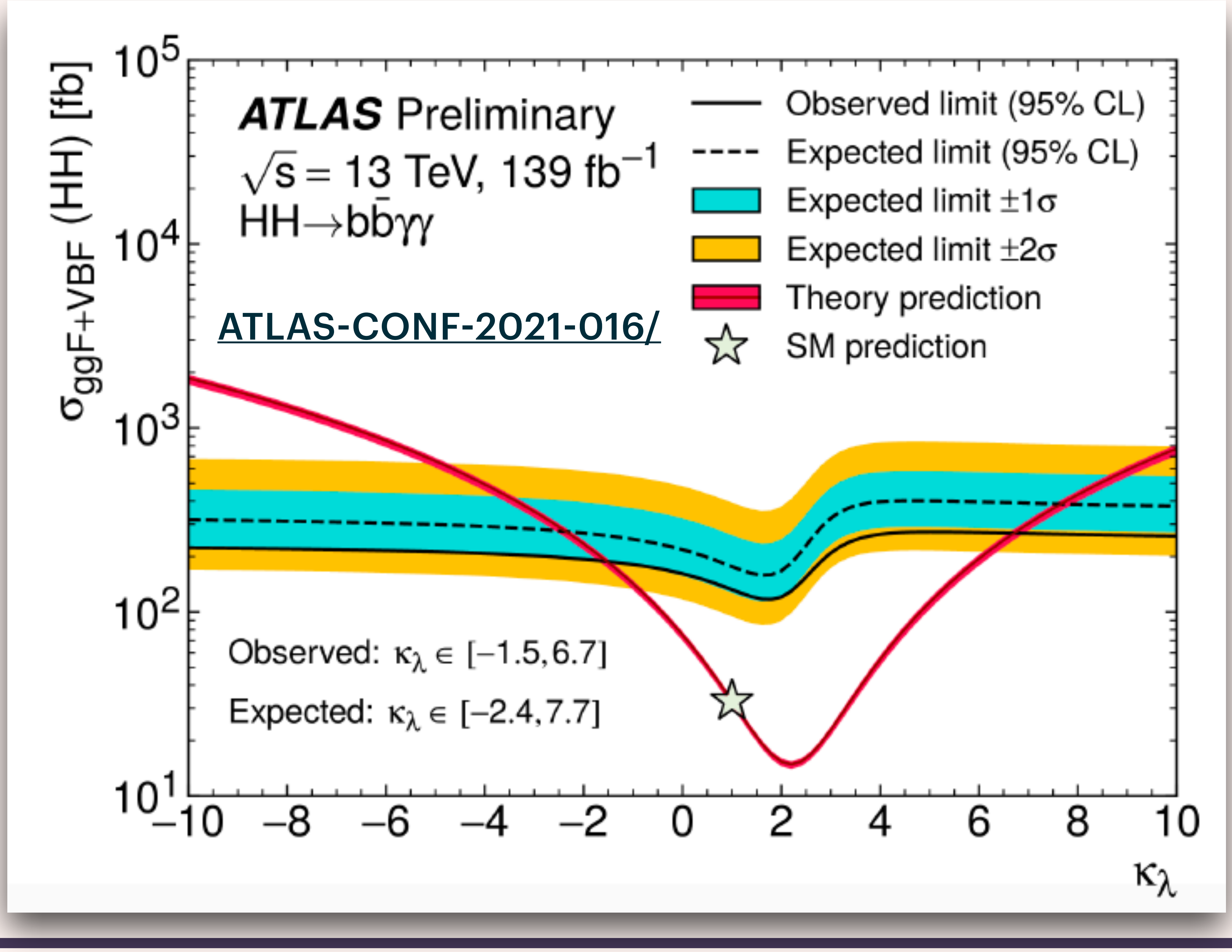
$-3.3<\kappa_\lambda<8.5$

$-1.3<\kappa_{2V}<3.5$

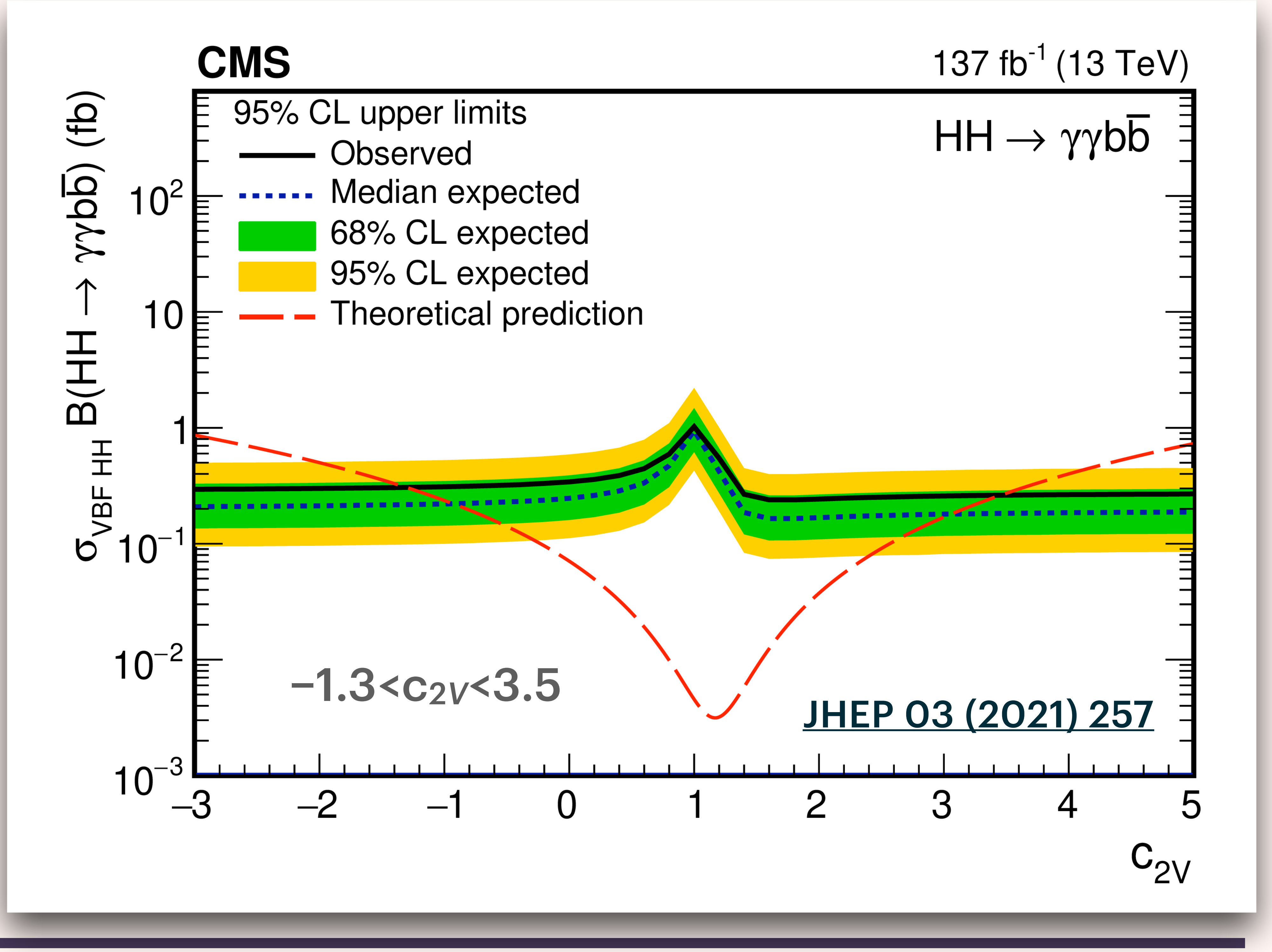
ATLAS: ATLAS-CONF-2021-016/

$\mu<4.1(5.5)$ x SM

$-1.5<\kappa_\lambda<6.7$



ATLAS-CONF-2021-016/



$-1.3<c_{2V}<3.5$

JHEP 03 (2021) 257

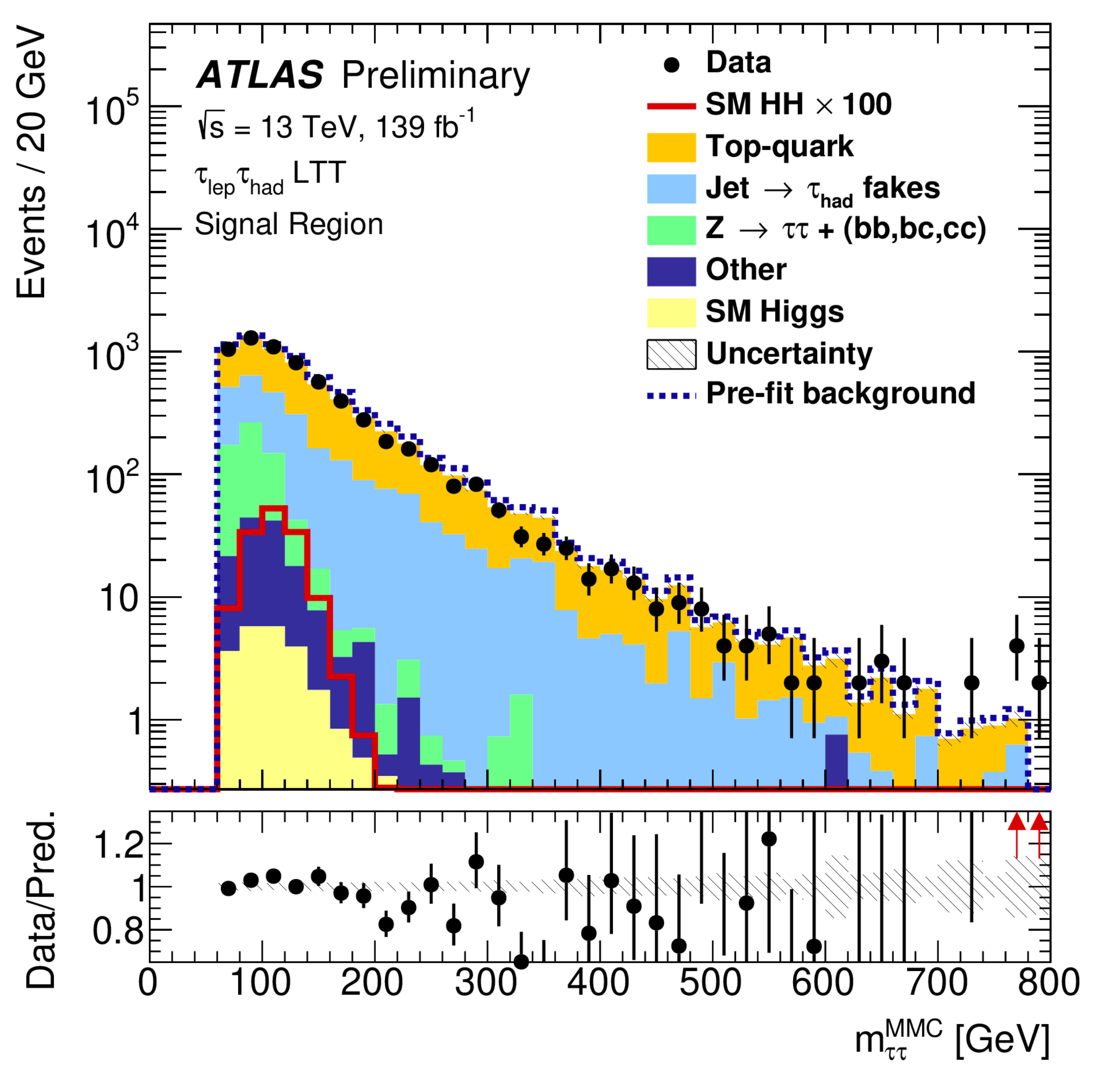
$HH \rightarrow b\bar{b}\tau\tau$

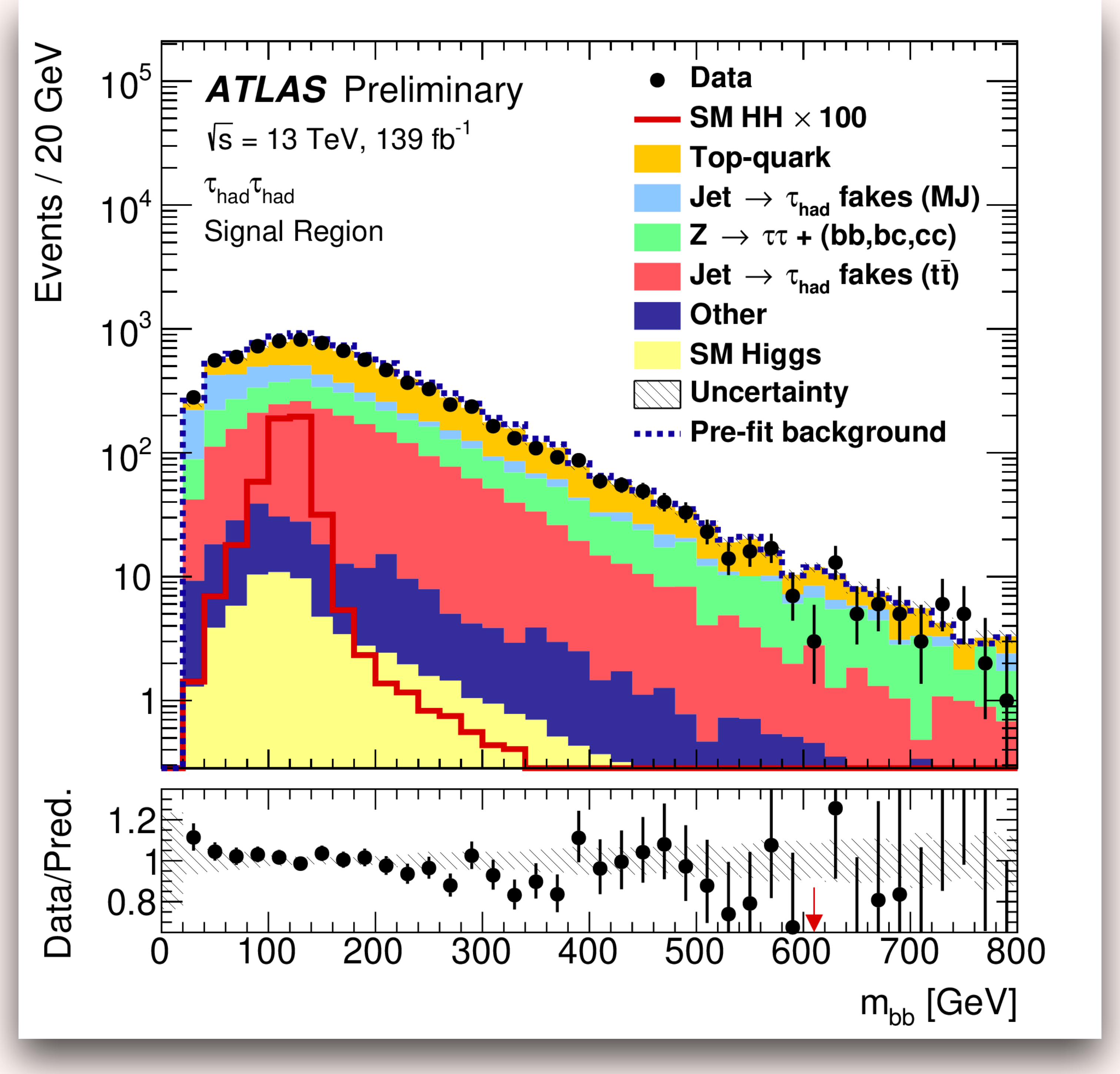
- Larger Branching ratio
- Relies on excellent tau identification
- Backgrounds ranging from ttbar to misidentified taus

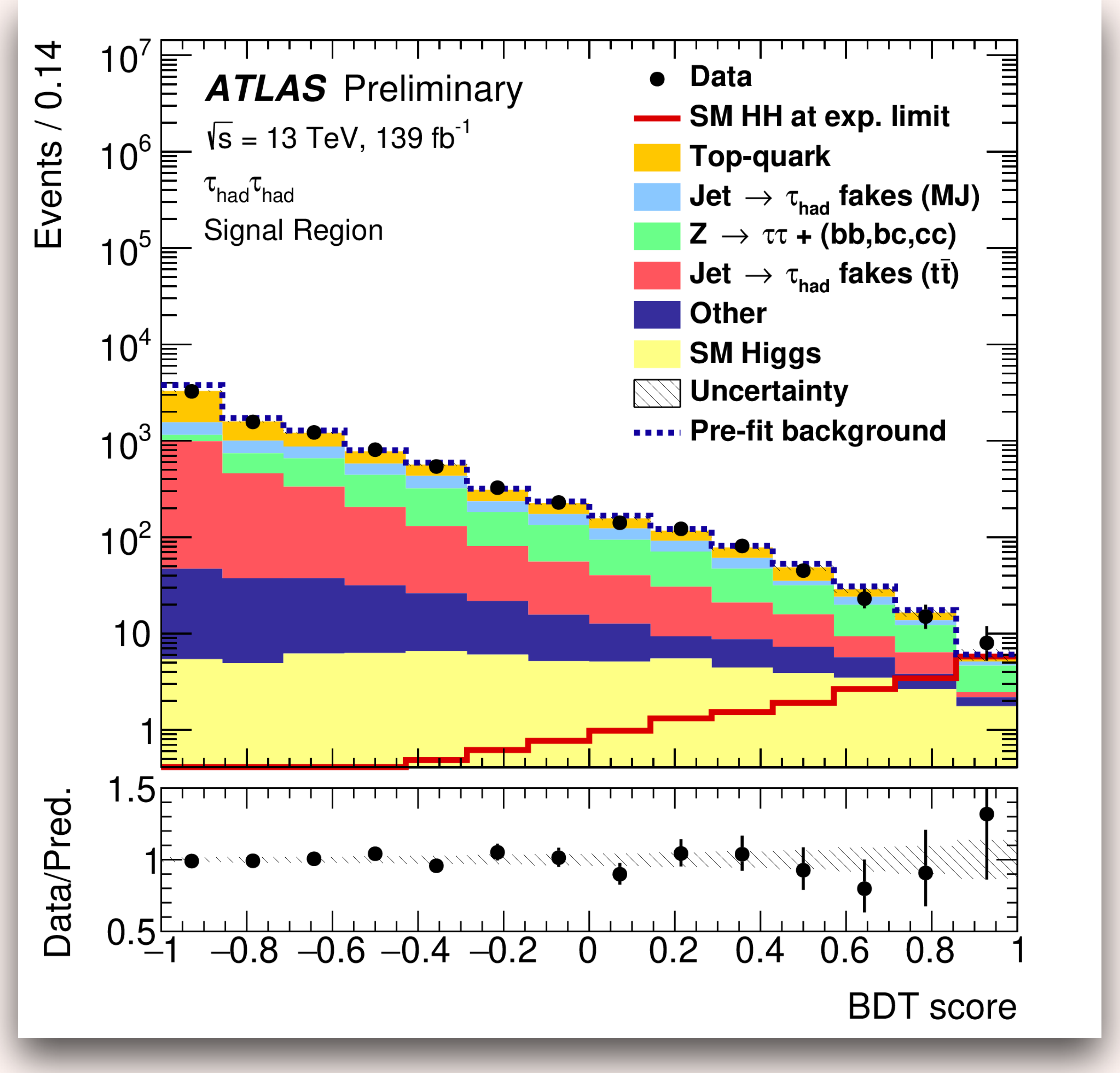
Cross section limits (@ 95 % CL):

ATLAS full Run2: ATLAS-CONF-2021-030 μ< 4.7(3.9)x SM

CMS 2016 only: Phys. Lett. B 778 (2018) 101 μ< 30(25)x SM







$HH \to b\bar{b}b\bar{b}$

- The 4b decay boasts the largest branching ratio, but that comes with a complicated background that is best modelled with data driven approaches
- Searches targeting ggF and VBF production using both resolved and boosted approaches

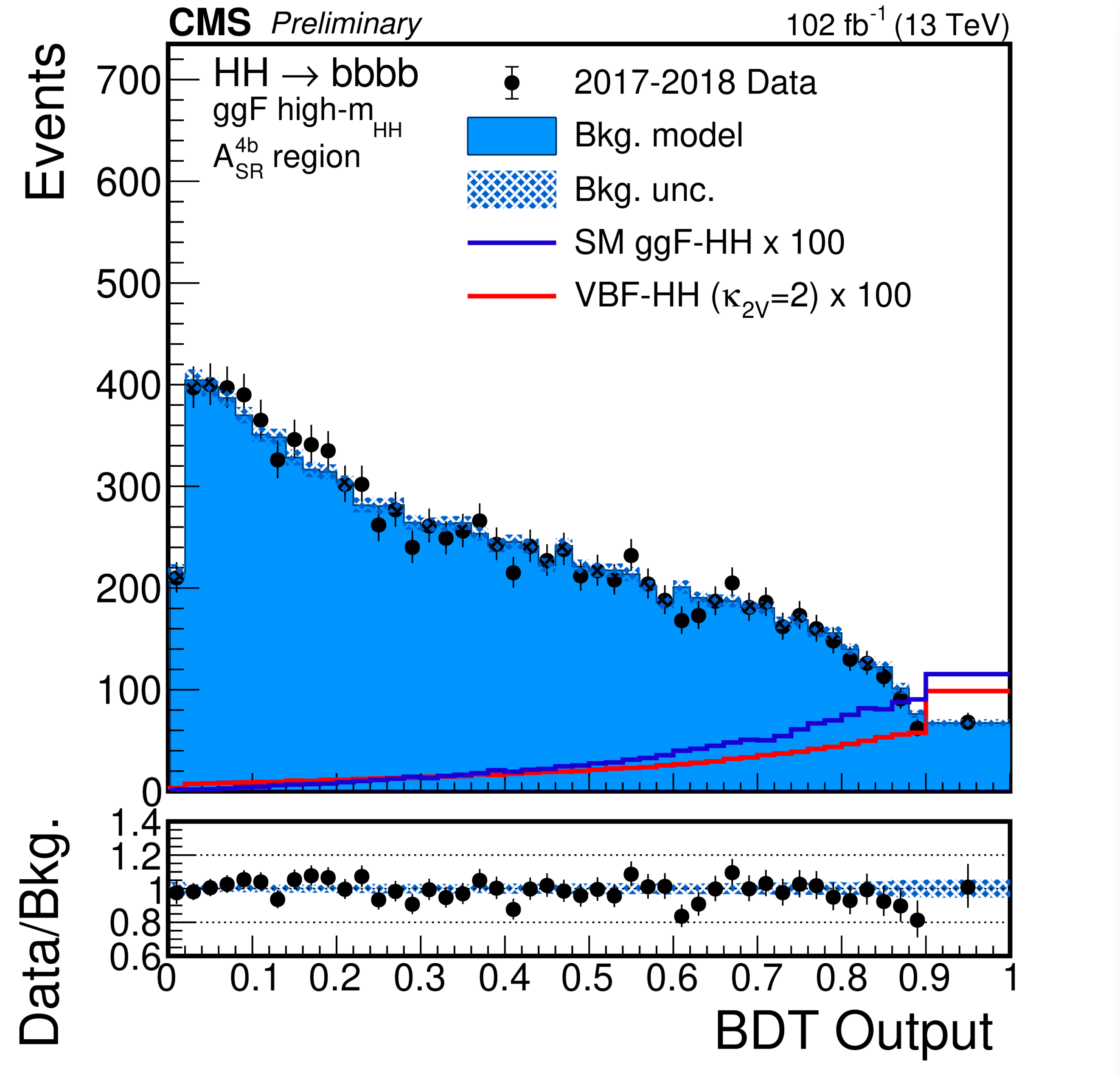
Cross section limits (@ 95 % CL):

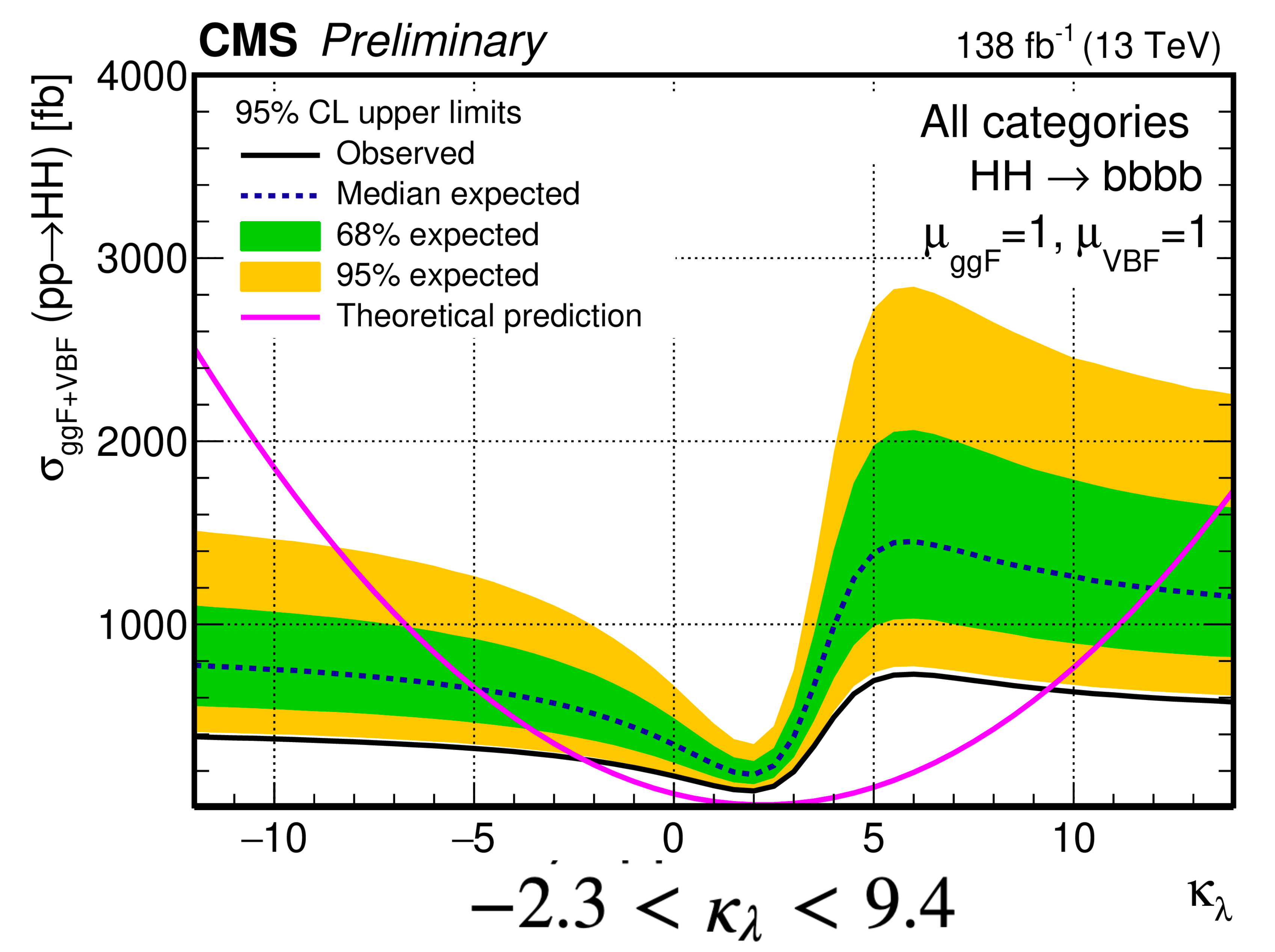
ATLAS: JHEP 07 (2020) 108 JHEP 01 (2019) 030

$\mu <$ 12.7 (20.7) x SM (2016) , $-0.43 < \kappa_{2V} < 2.56$ (full Run2)

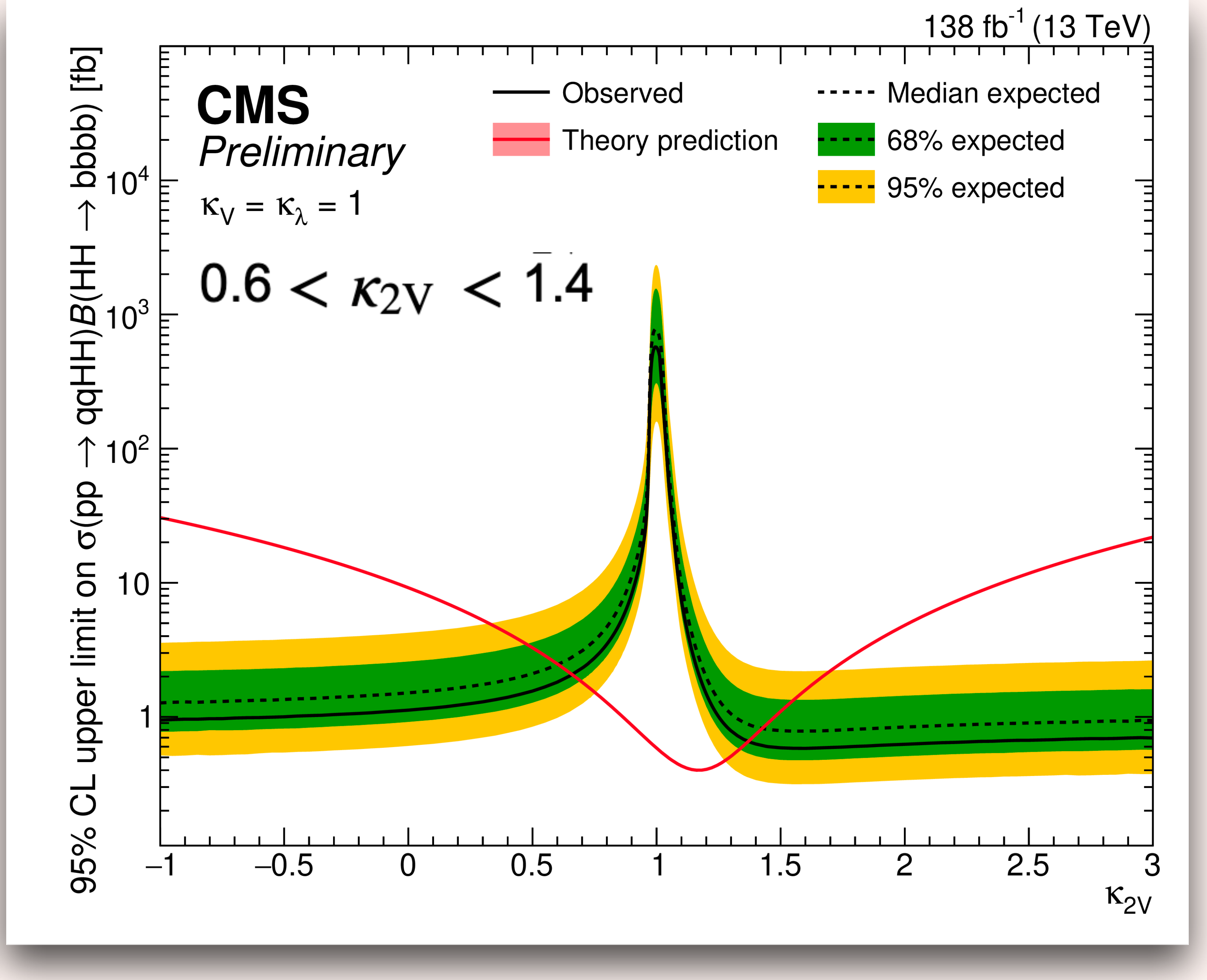
CMS Resolved full Run2: HIG-20-005 $\mu < 3.6(7.3)$xSM, $-2.3 < \kappa_\lambda < 9.4$, $-0.1 < \kappa_{2V} < 2.2$

VBF Boosted full Run2: B2G-21-001 : $0.6 < \kappa_{2V} < 1.4$



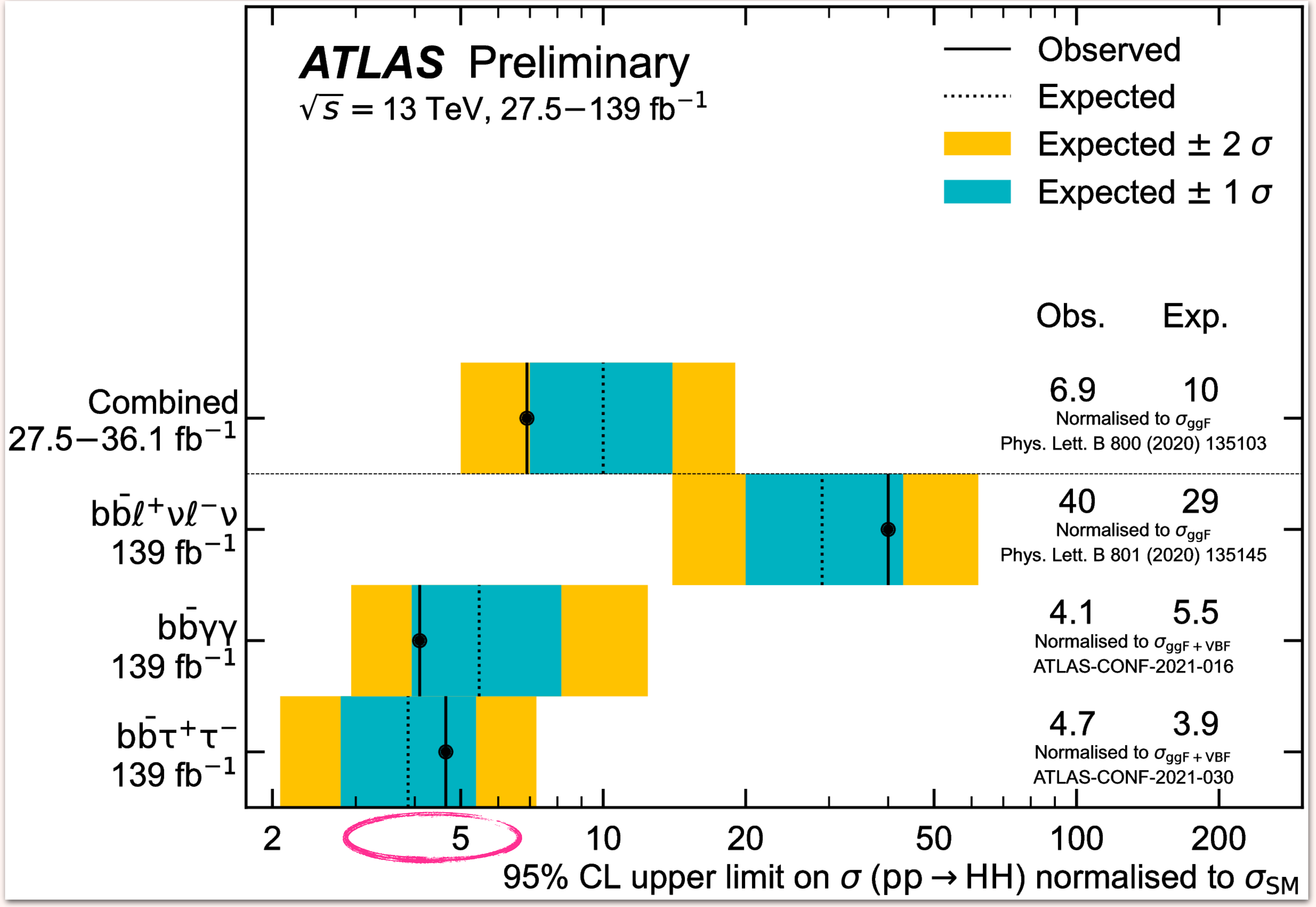


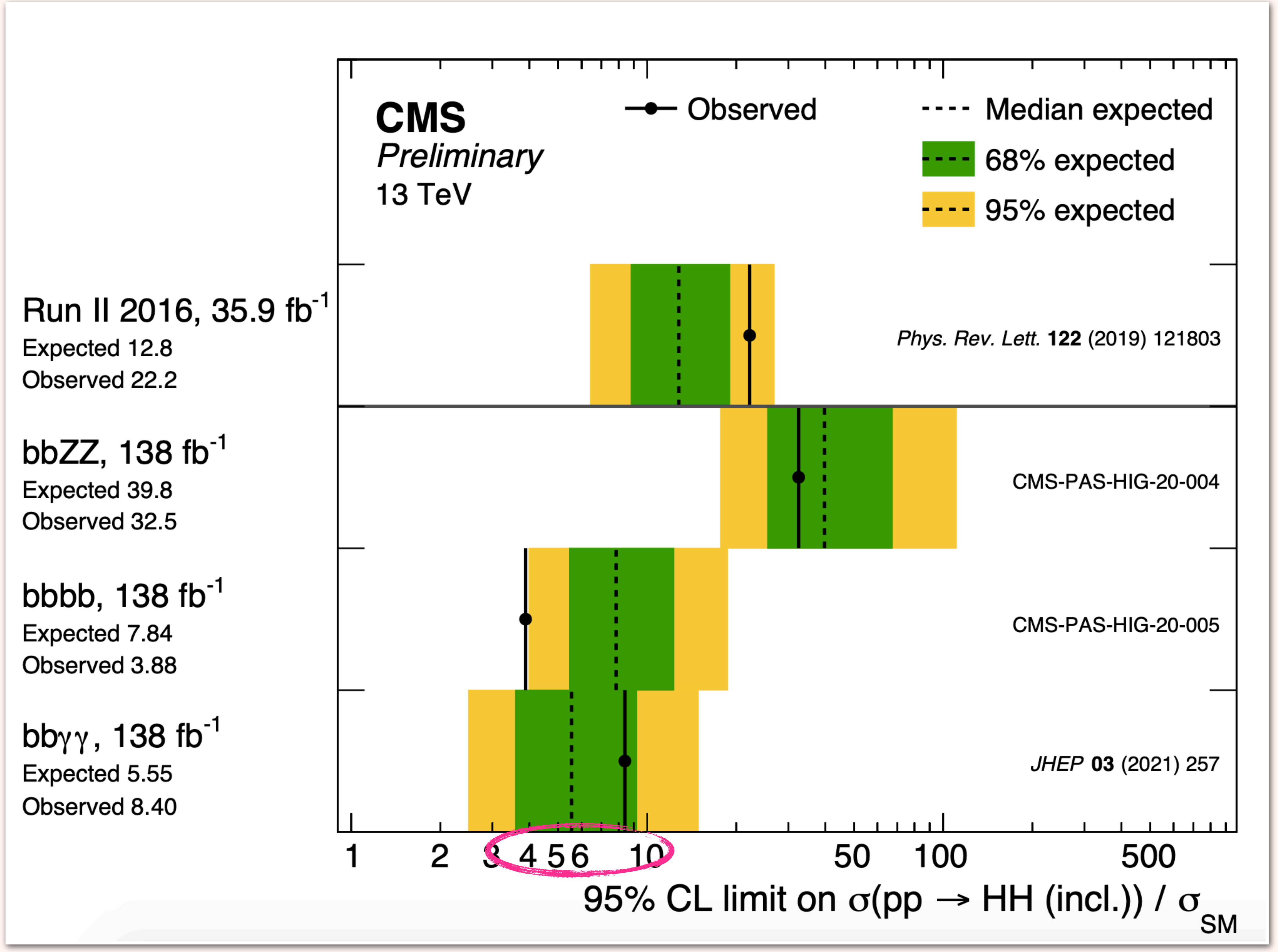
$-2.3 < \kappa_\lambda < 9.4$



$0.6 < \kappa_{2V} < 1.4$

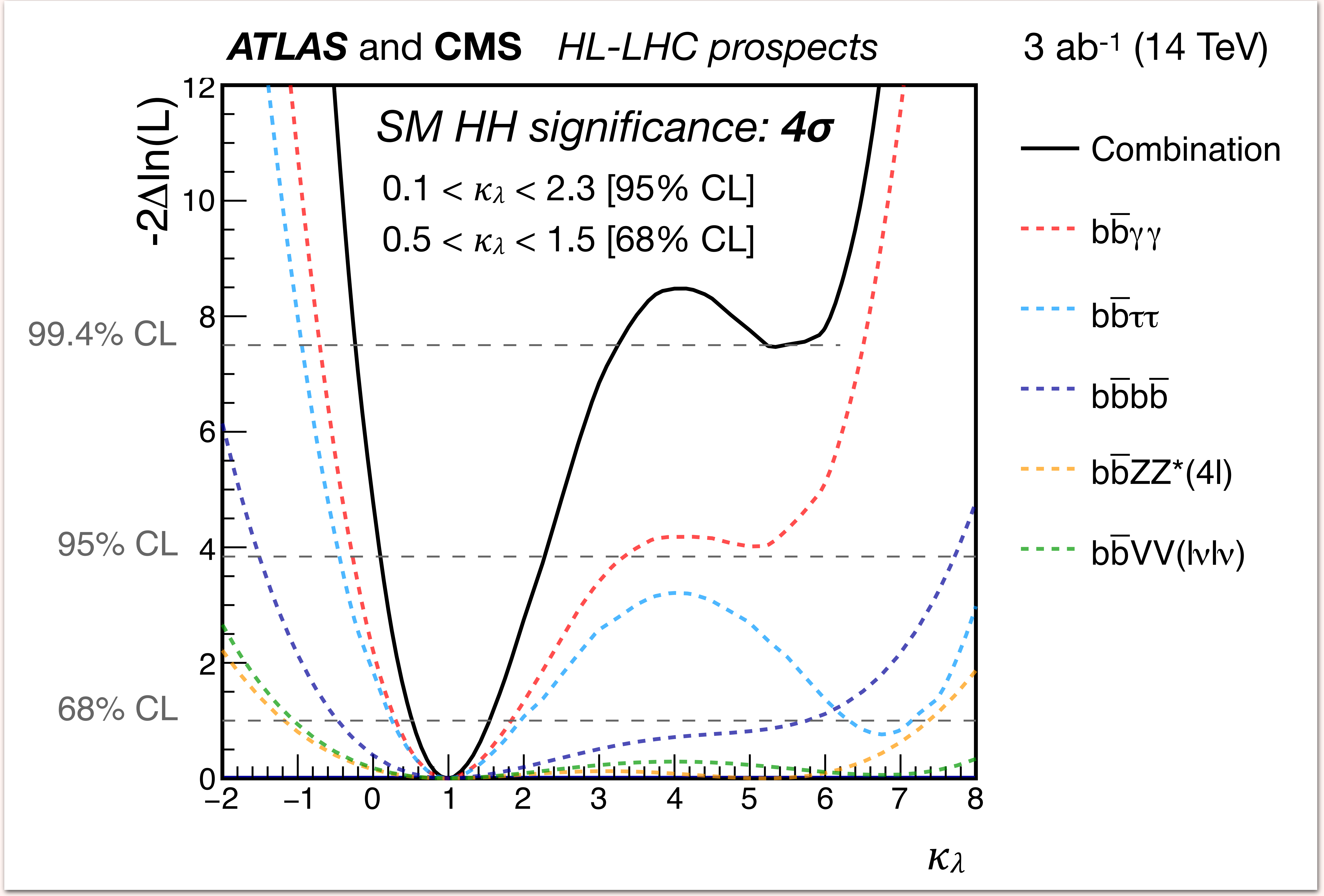
VIEW FROM THE TOP?





- Individual analysis now better than the 2016 combinations : the golden channels already at 4-5xSM
- Work ongoing towards the full Run2 picture, which should include not only cross section limits but also coupling constraints

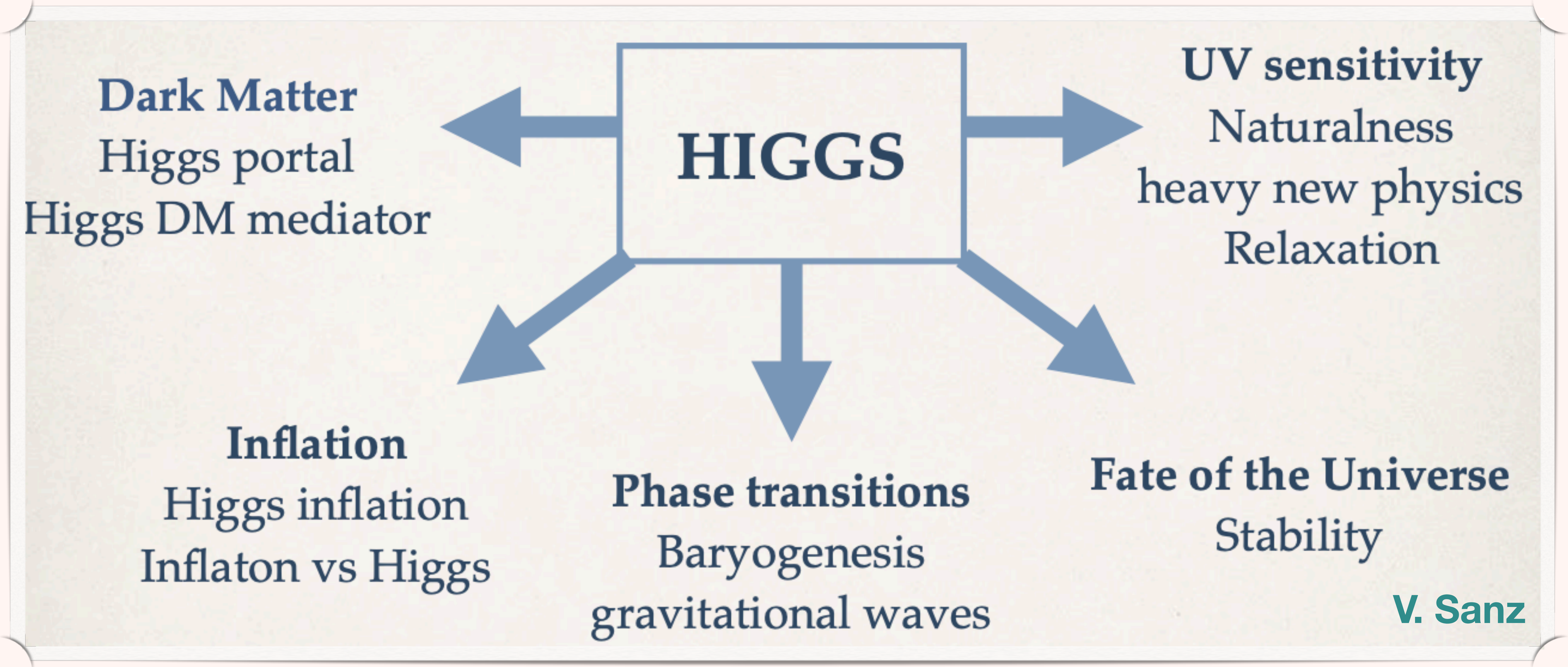
WHAT ABOUT THE FUTURE?



- **Combining the ATLAS and CMS results: a significance of 4 standard deviation can be achieved at the end of the HL-LHC (including systematic uncertainties).**
- 50% uncertainty on κ_λ
- Second minimum of the negative log-likelihood excluded at 99.4% CL

IS THE HIGGS THE PORTAL TO NEW PHYSICS?

SO, IS THIS HIGGS REALLY THE SM HIGGS BOSON?



HIGGS

Dark Matter
Higgs portal
Higgs DM mediator

UV sensitivity
Naturalness
heavy new physics
Relaxation

Inflation
Higgs inflation
Inflaton vs Higgs

Phase transitions
Baryogenesis
gravitational waves

Fate of the Universe
Stability

V. Sanz

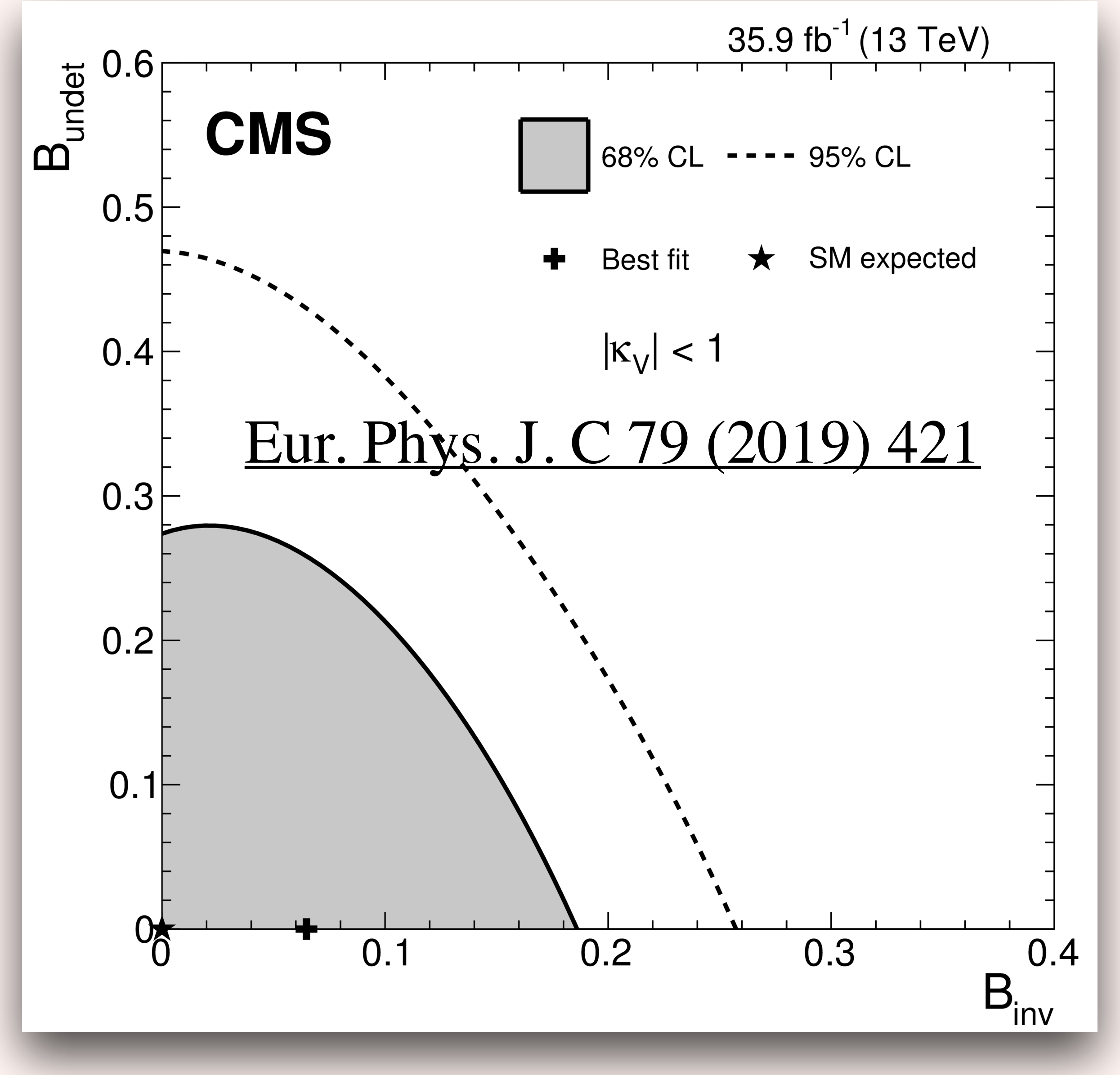
- The Higgs boson is the only particle of its kind, a mystery on itself, and a irreplaceable tool to find the connection to BSM physics
- From deviations on its behaviour or its couplings to the SM, to looking for Higgs partners or exotic decays: huge landscape of possible measurements and searches

CAN THE HIGGS DECAY UNUSUALLY?

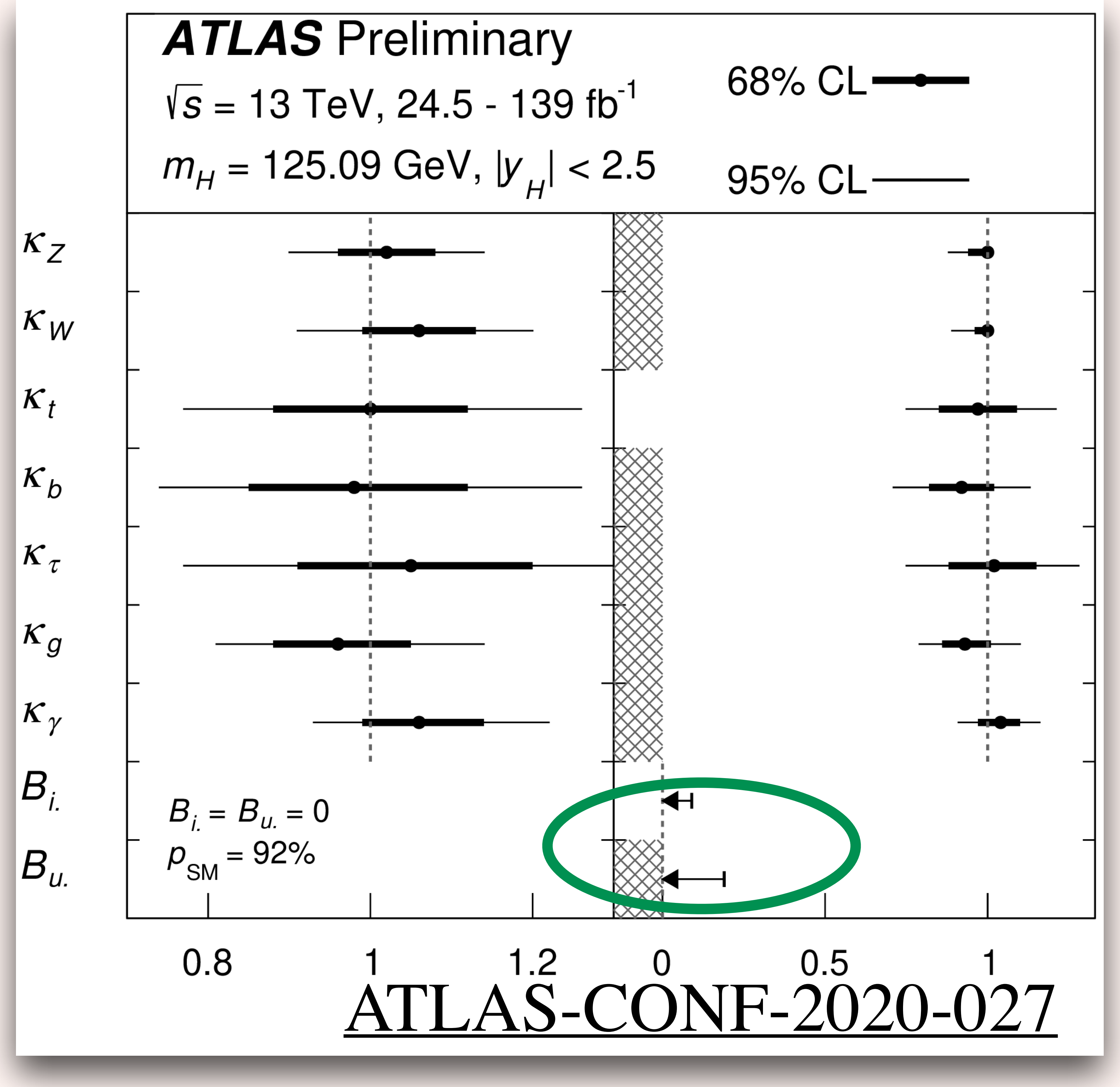
- We can derive constraints on the Exotic Higgs Branching ratio from the Higgs couplings measurements in the kappa framework, combining the information from all measured Higgs decay channels

- Warning: no direct measurement of the width. To probe the BSM BR an additional constrain needs to be imposed. Usually, $\kappa_{W,Z} \leq 1$.

$$\Gamma_H = \frac{\Gamma_H^{SM} \cdot \kappa_H^2}{1 - (BR_{inv} + BR_{undet})}$$



Eur. Phys. J. C 79 (2019) 421

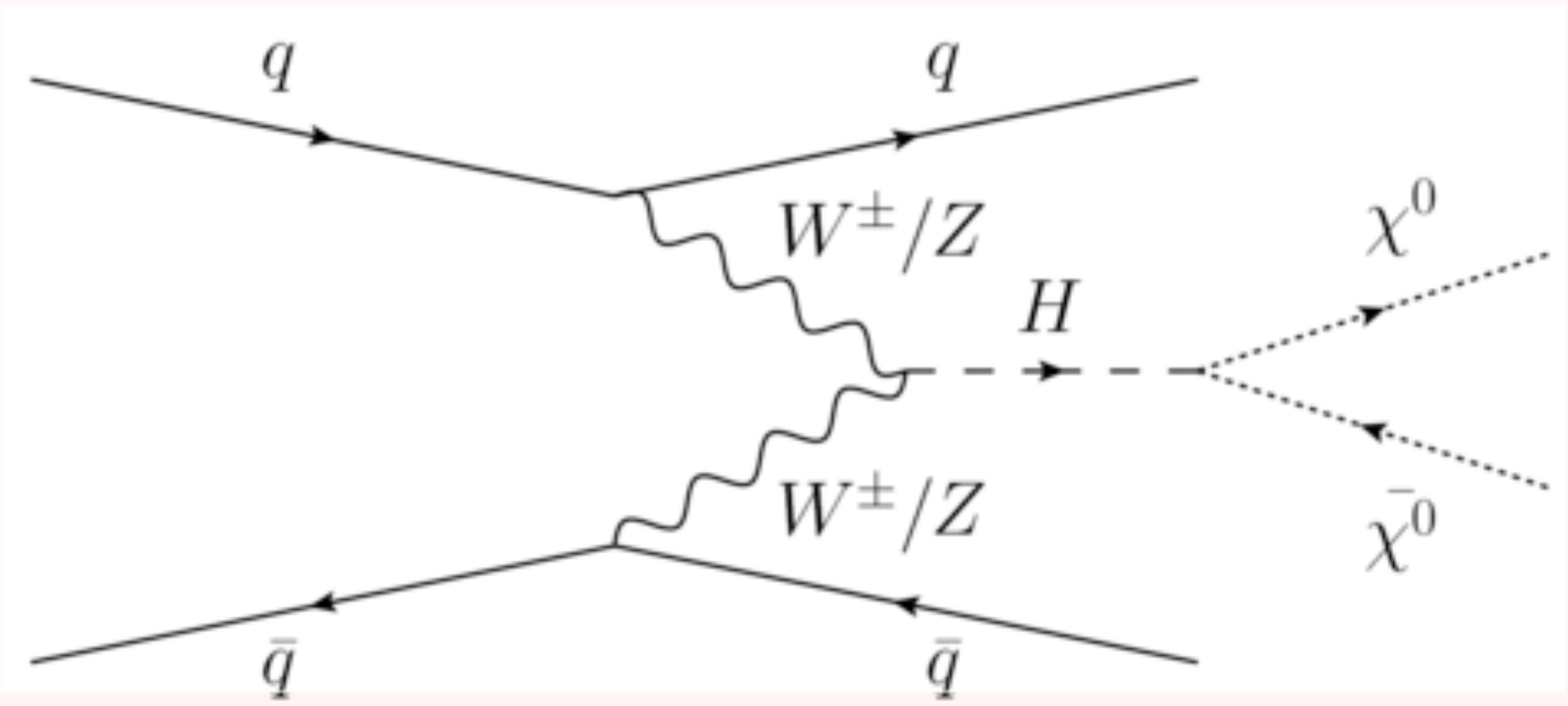


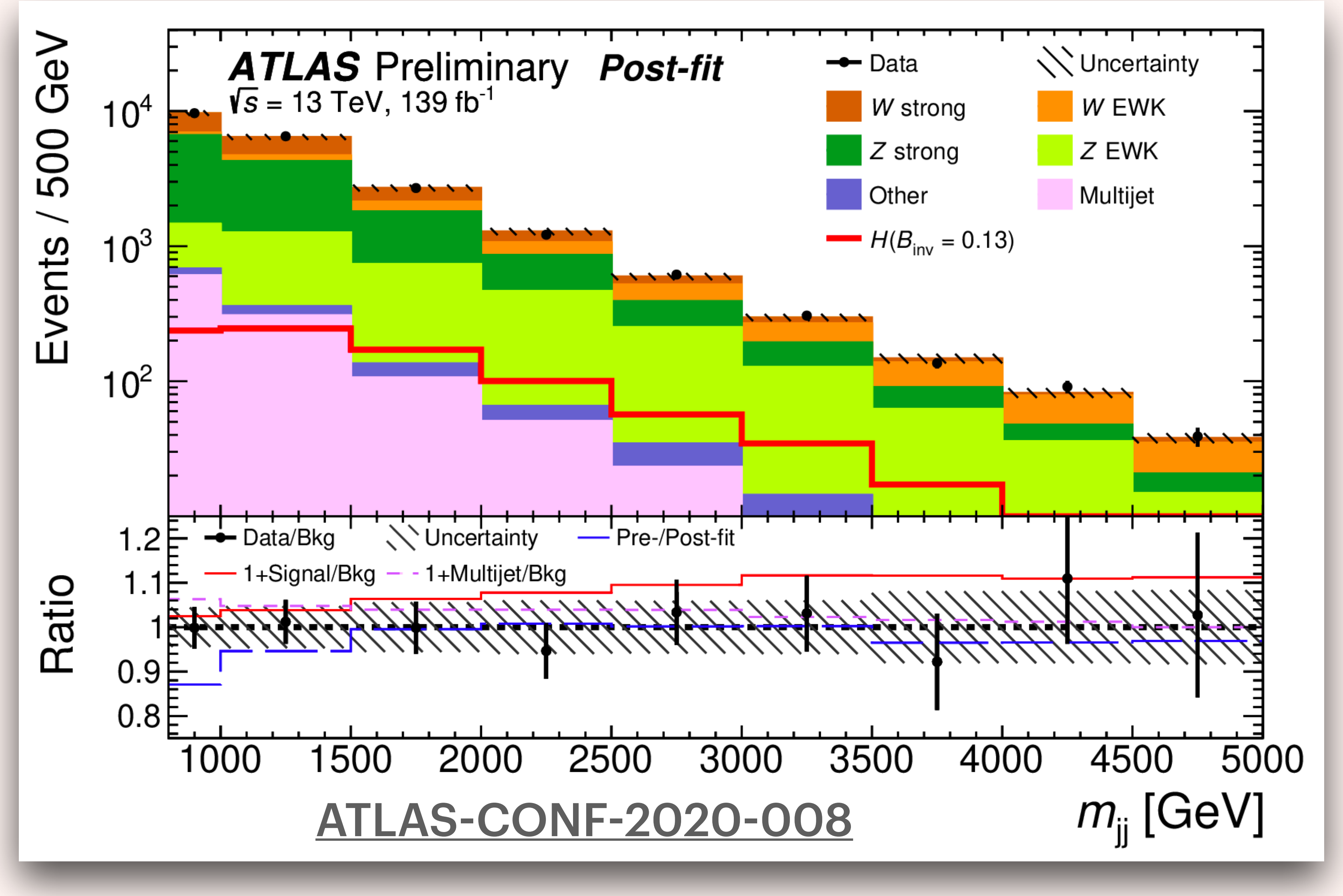
ATLAS-CONF-2020-027

B_{inv} < 9% and B_{undet} < 19% at 95% CL

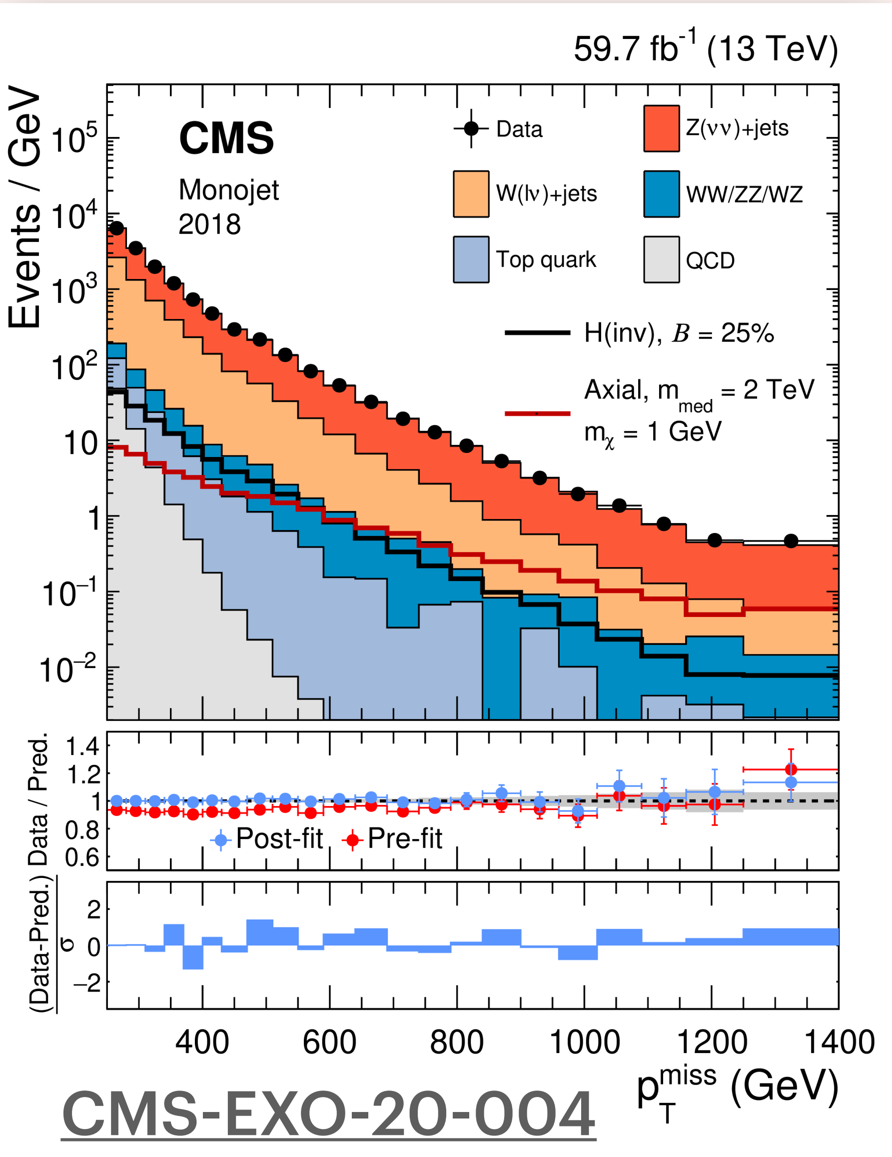
INVISIBLE HIGGS DECAYS

- Direct searches for Higgs decays to undetected particles → connection to Dark Matter (Higgs Portal)
  - Challenging signature: MET
  - Use associated production (WH and ZH) and especially weak vector boson fusion (VBF) to tag the events. Also target ggF, ttH production.
  - Background modelling (QCD/WJets/DY) is key

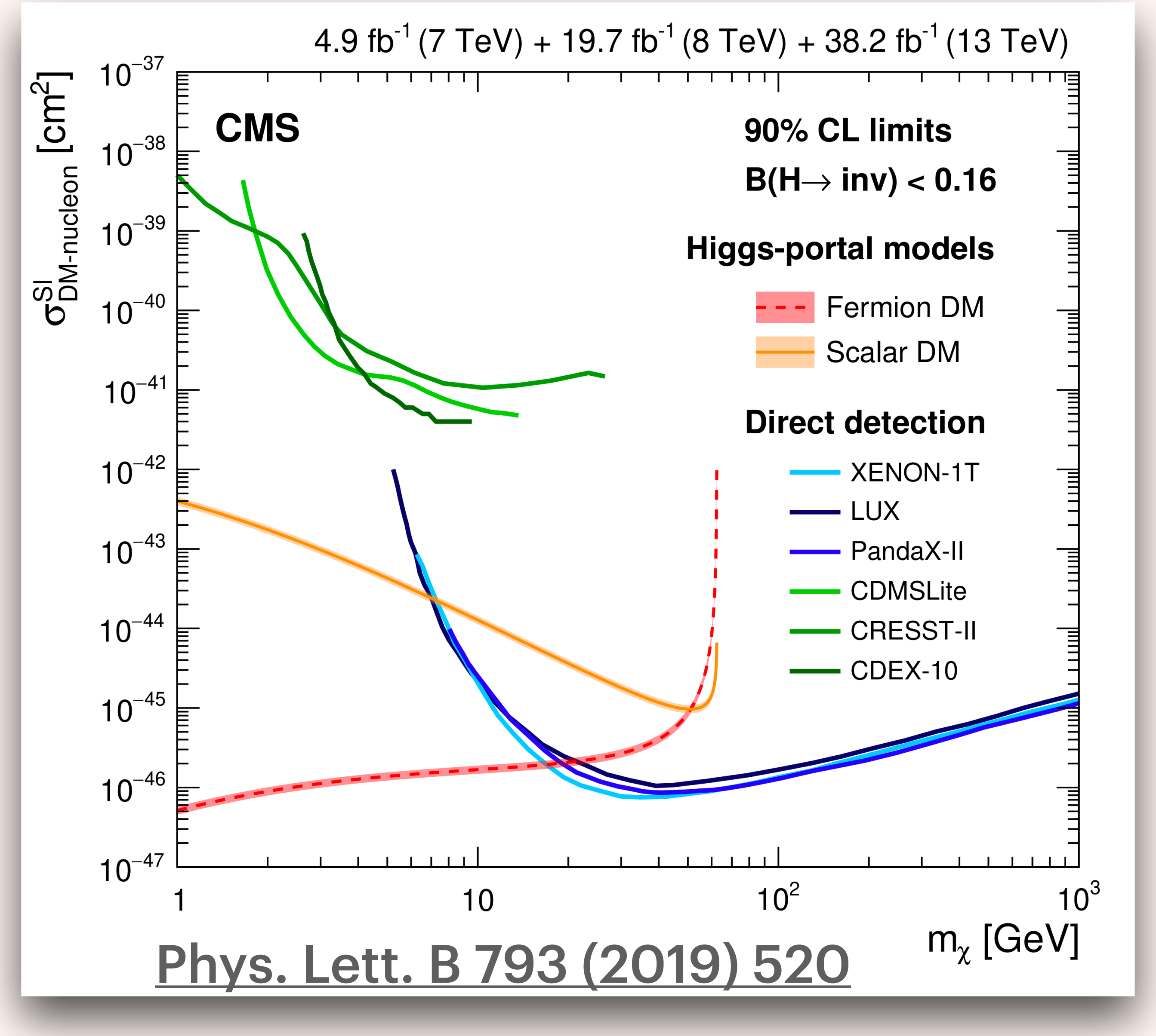




ATLAS-CONF-2020-008



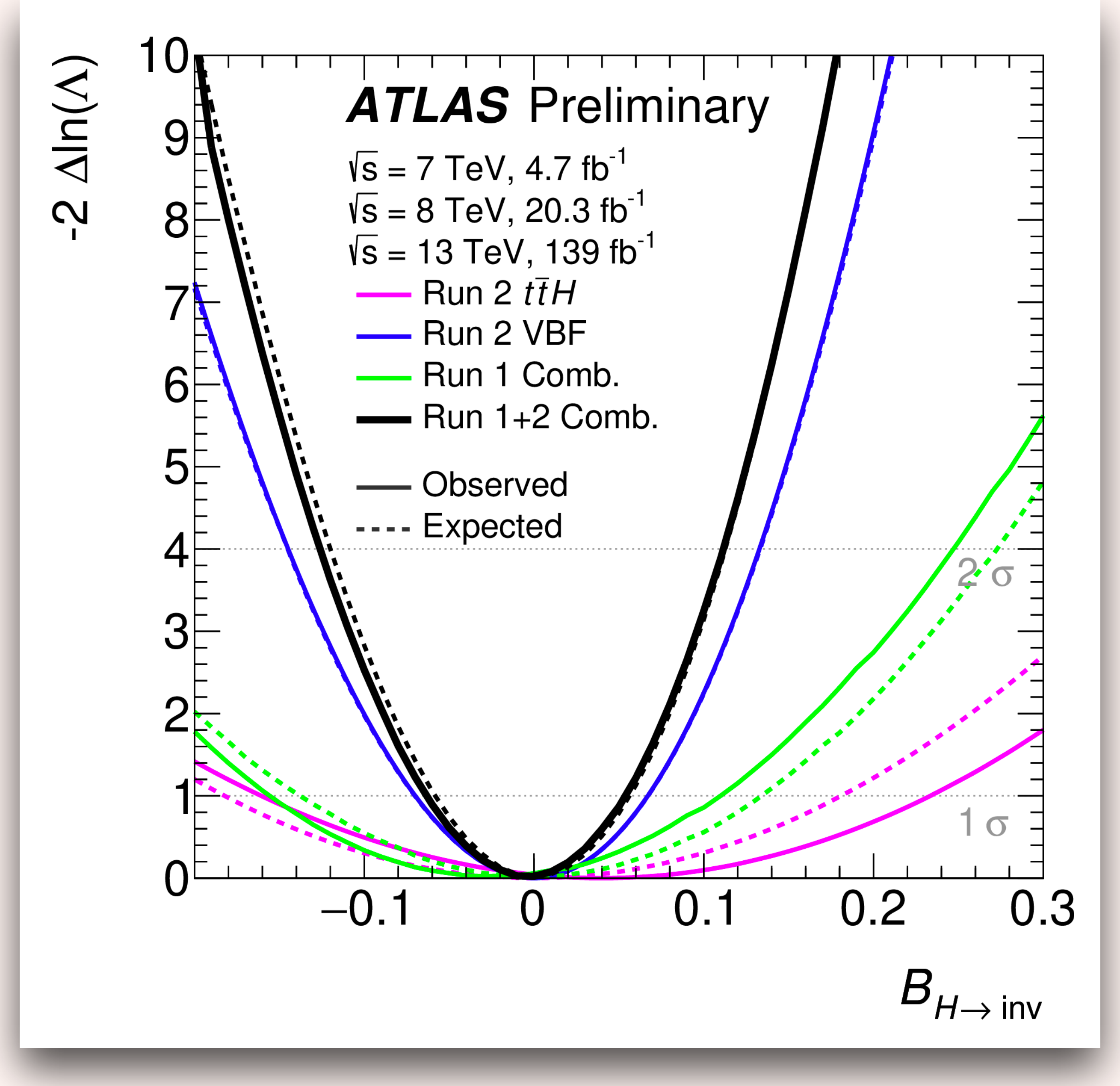
CMS-EXO-20-004



Phys. Lett. B 793 (2019) 520

INVISIBLE HIGGS DECAYS

		Lumi	95% CL Limit on Br$_{\mathrm{Inv}}$ (MH=125)
VBF	CMS Phys. Lett. B 793 (2019) 520	36 fb^{-1}	33% (25%)
	ATLAS ATLAS-CONF-2020-008	139 fb^{-1}	13 % (13%)
ZH	CMS Eur. Phys. J. C 81 (2021) 13	137 fb^{-1}	29% (25%)
	ATLAS ATLAS-CONF-2021-029	139 fb^{-1}	18% (18%)
MonoJet, MonoV	CMS CMS-EXO-20-004	137 fb^{-1}	27.8% (25.3%)
	ATLAS ATLAS-CONF-2020-048	139 fb^{-1}	63 % (57%)
TTH	CMS CMS-PAS-HIG-18-008	36 fb^{-1}	46% (48%)
	ATLAS ATLAS-CONF-2020-052	139 fb^{-1}	40% (36%)

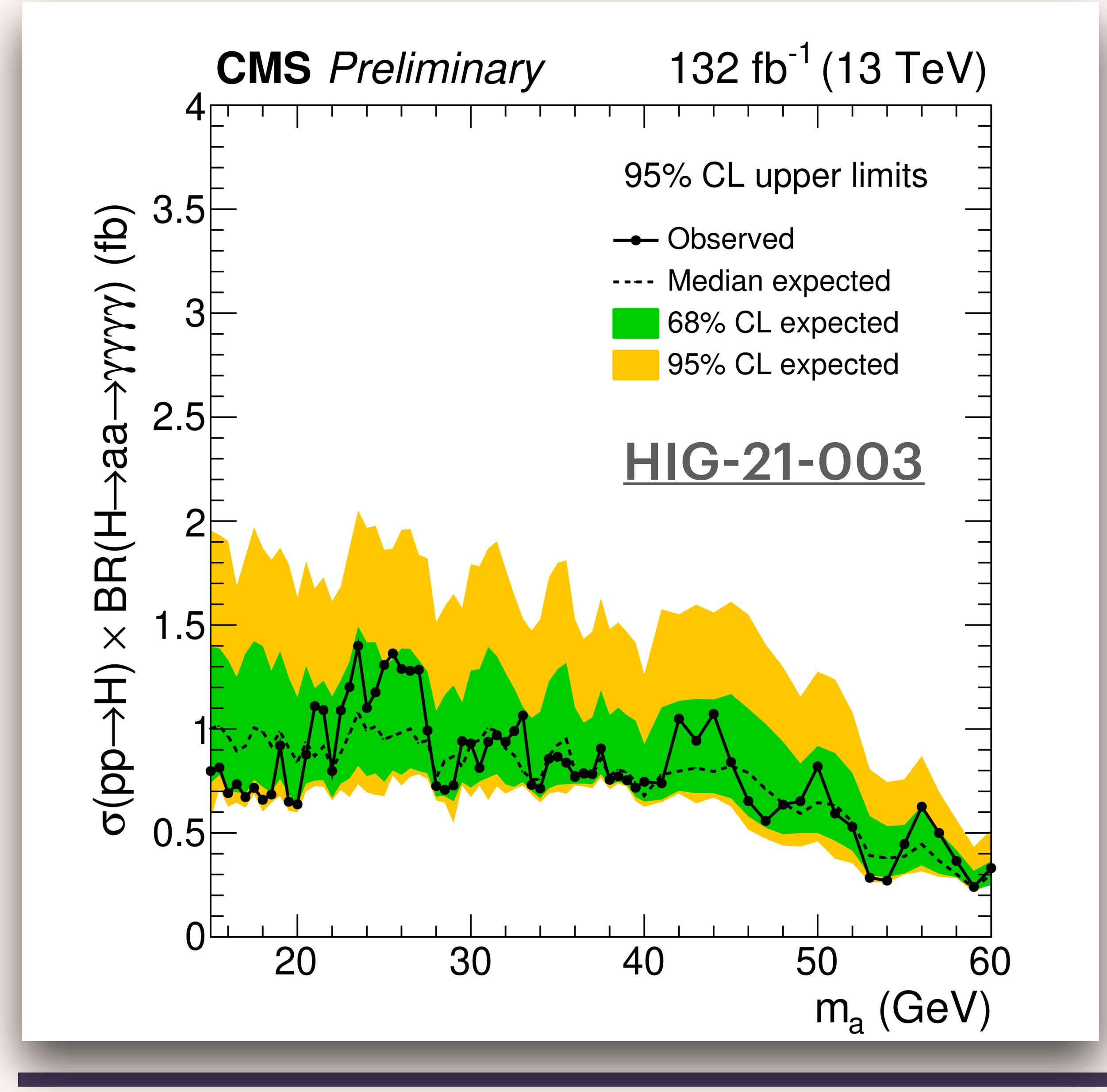


- **Current sensitivity: Br(H→Inv) ~ 10 %** (Best current UL @ 95% CL : Br<11% , ATLAS, VBF+ttH)

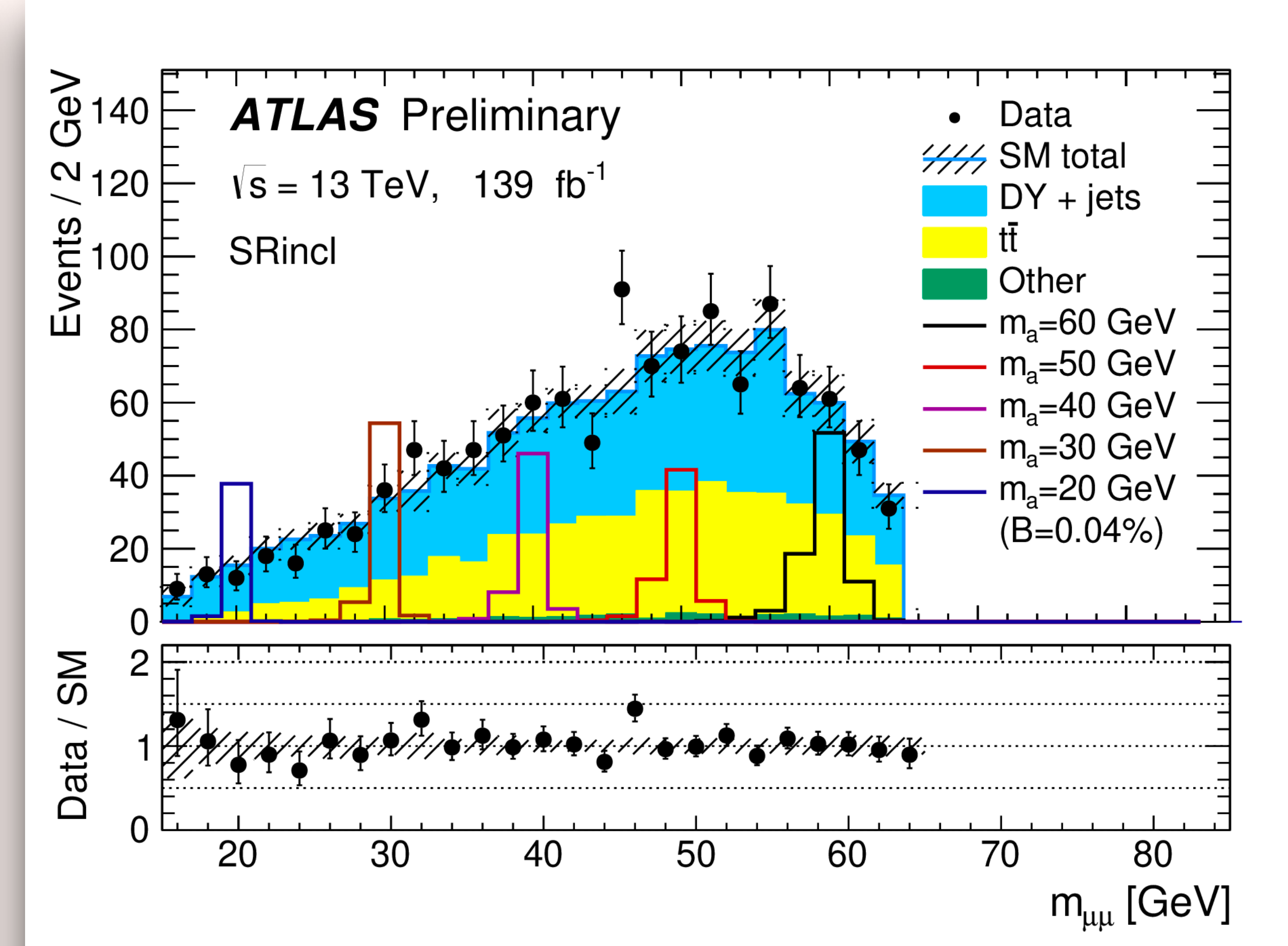
2HDM+S: LOOKING FOR H->AA

- With a large untagged branching ratio to explore, direct searches for exotic decays of the Higgs are an exciting, growing field

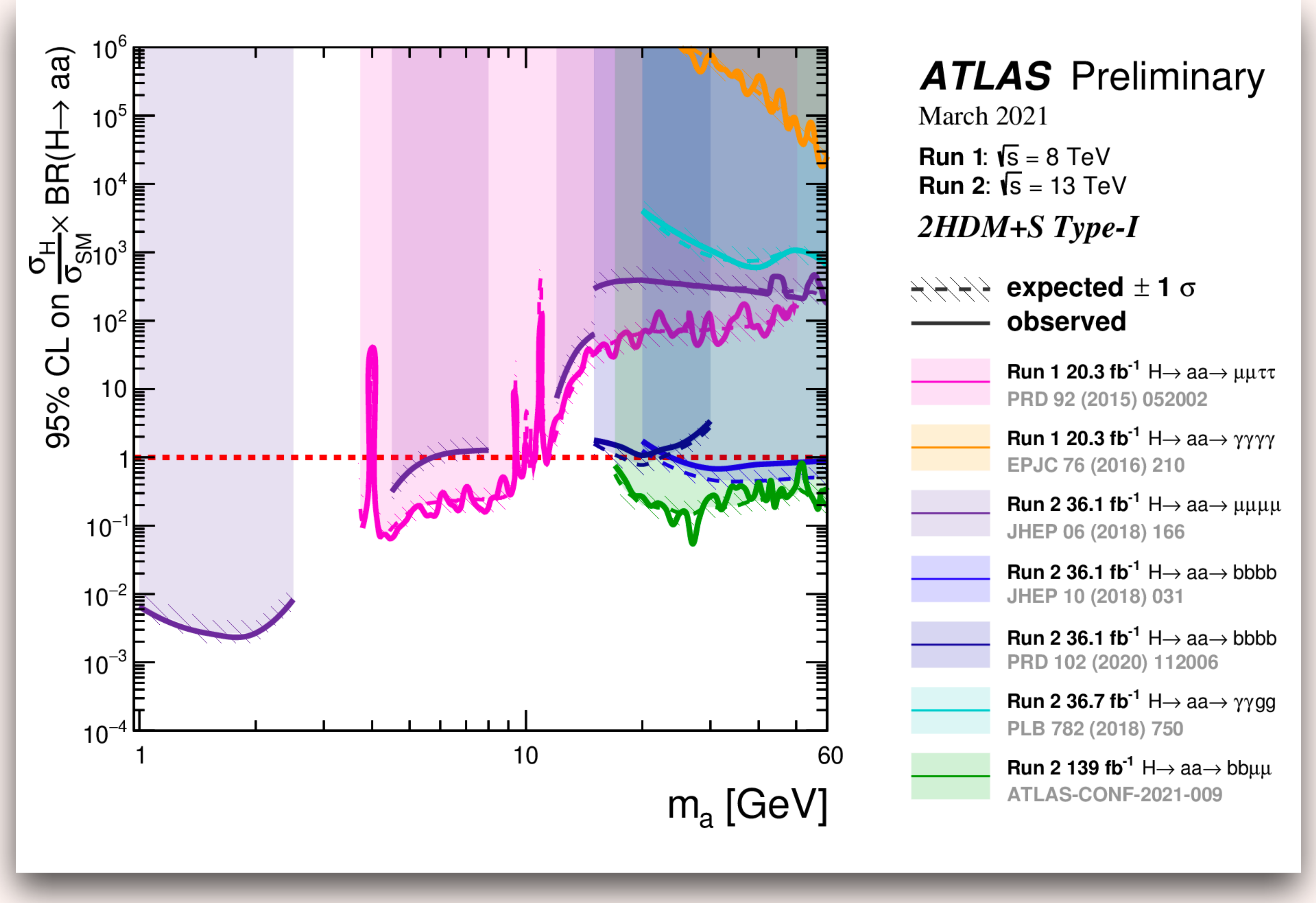
- A good example are the **searches for decays to (pseudo)scalars with lower mass than the Higgs: h->aa searches**, which can be interpreted in the 2HDM+S model (with one extra CP even scalar s and one extra CP odd scalar a)



HIG-21-003



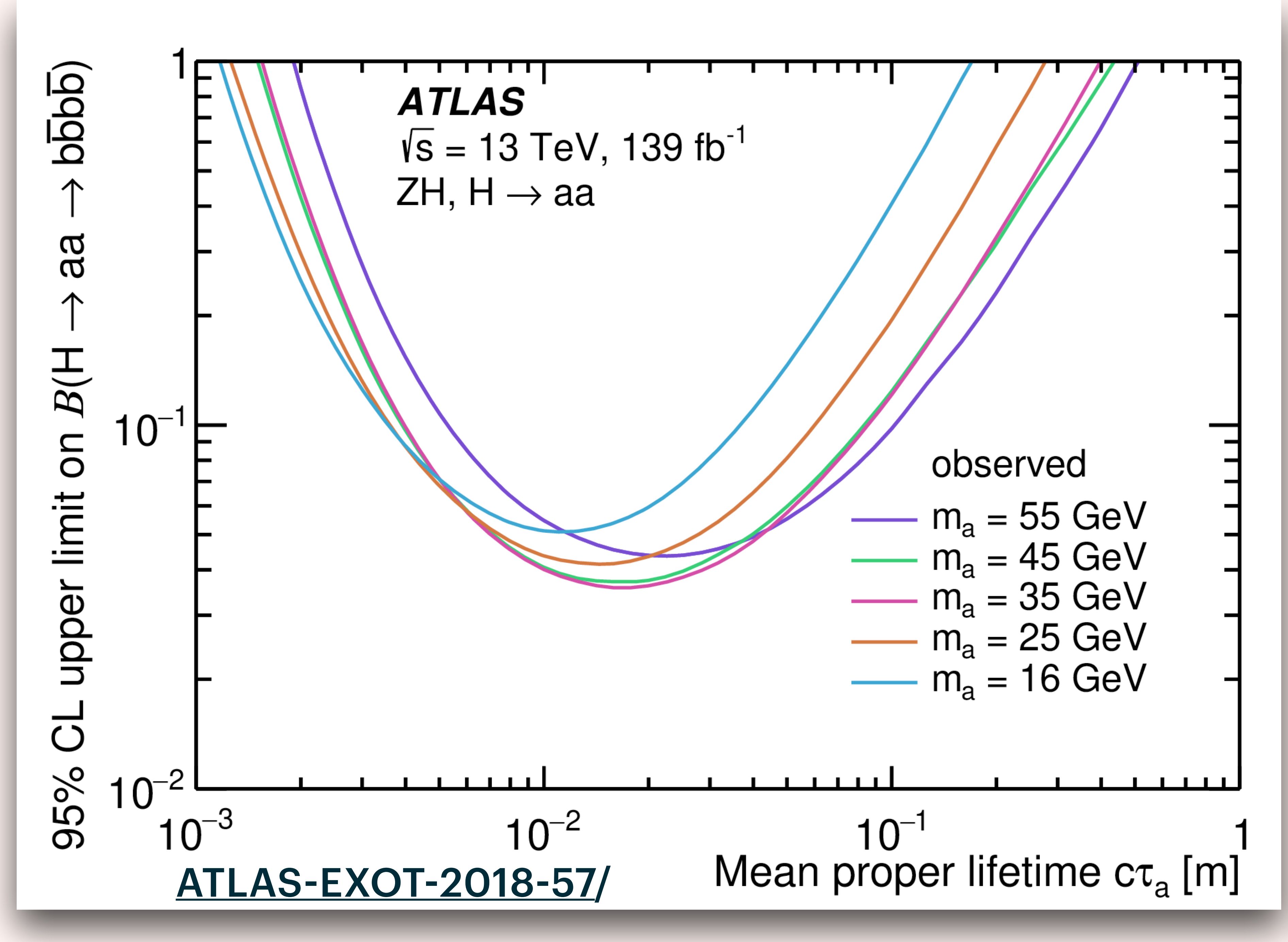
ATLAS-CONF-2021-009



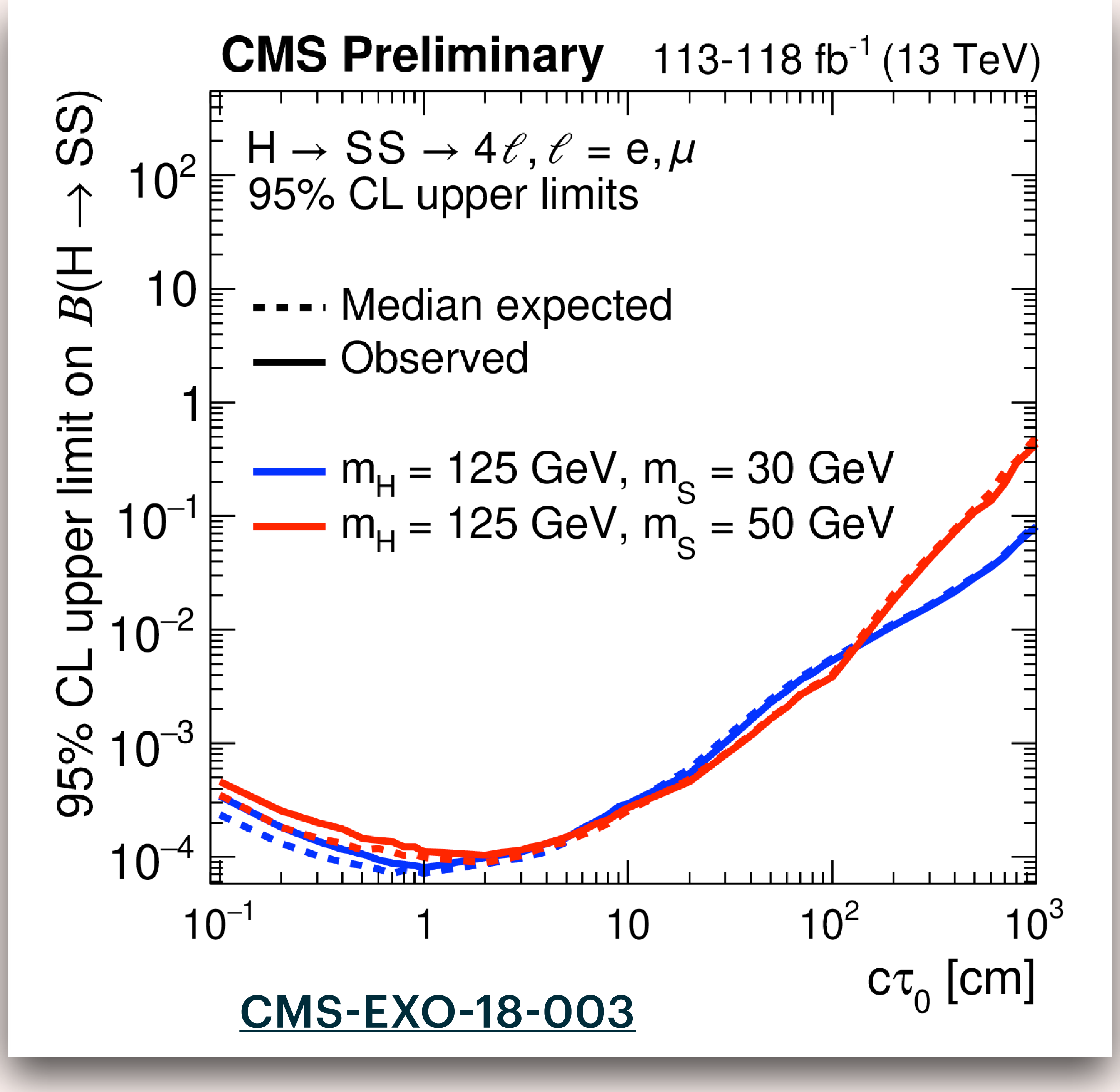
Large variety of final states targeted (b, tau, mu, photons,…)

WHAT ABOUT LONG LIVED HIGGS DECAYS?

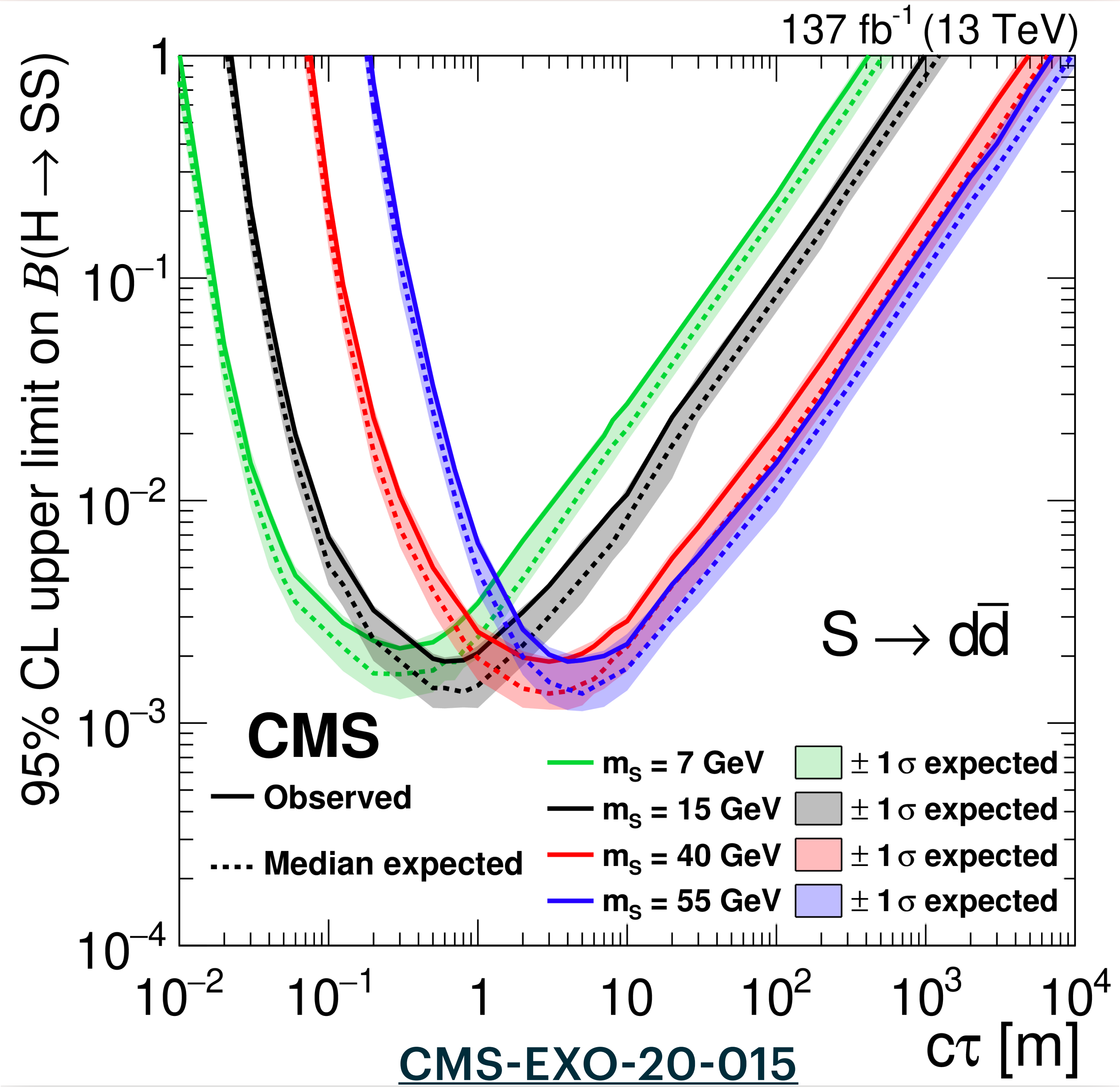
- Looking for exotic Higgs decays goes beyond the traditional h->aa/ss searches
- Expanding to probe for decays to Dark Bosons, ALPs, Long Lived particles is one of the next frontiers



ATLAS-EXOT-2018-57/



CMS-EXO-18-003

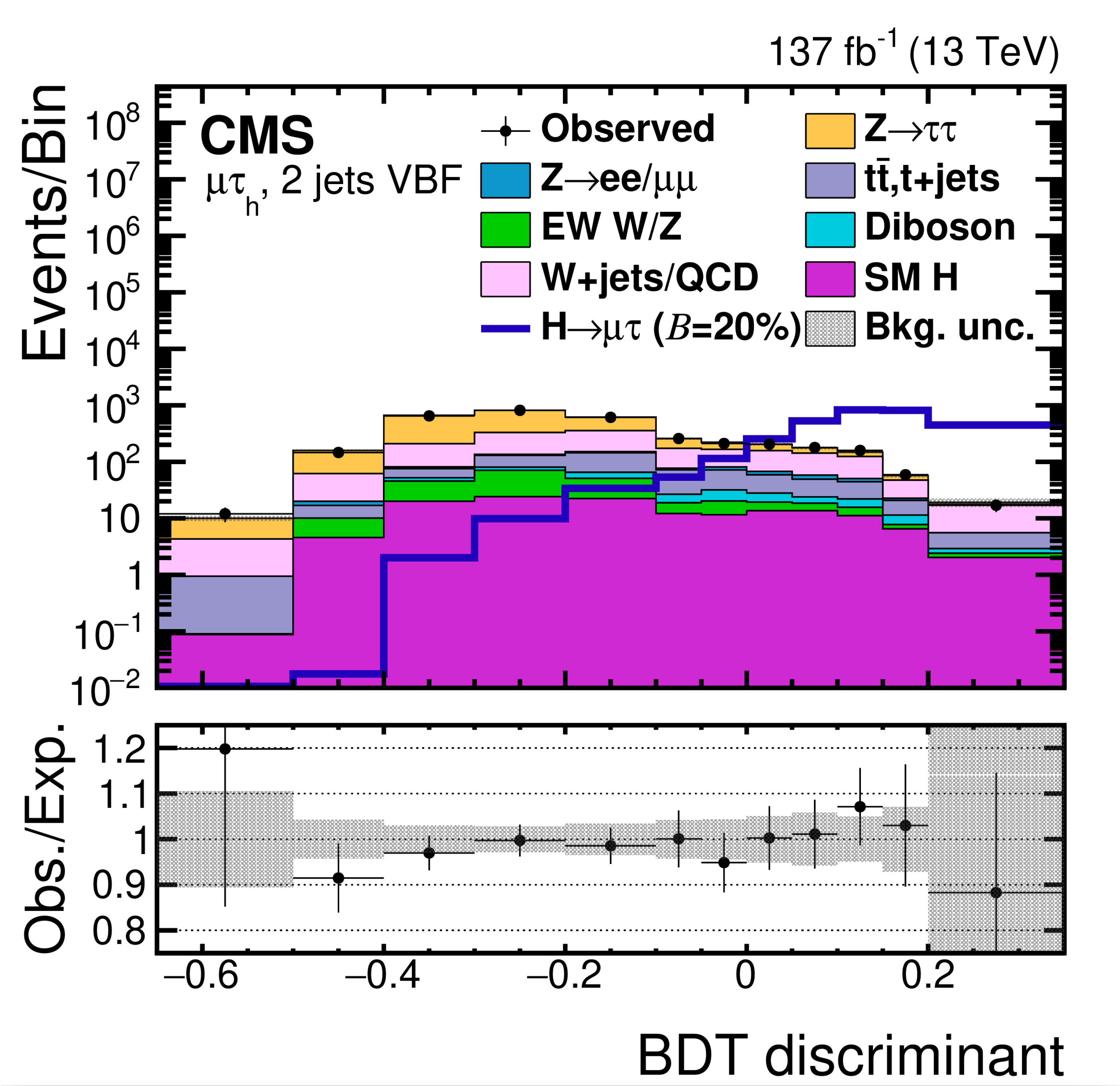


CMS-EXO-20-015

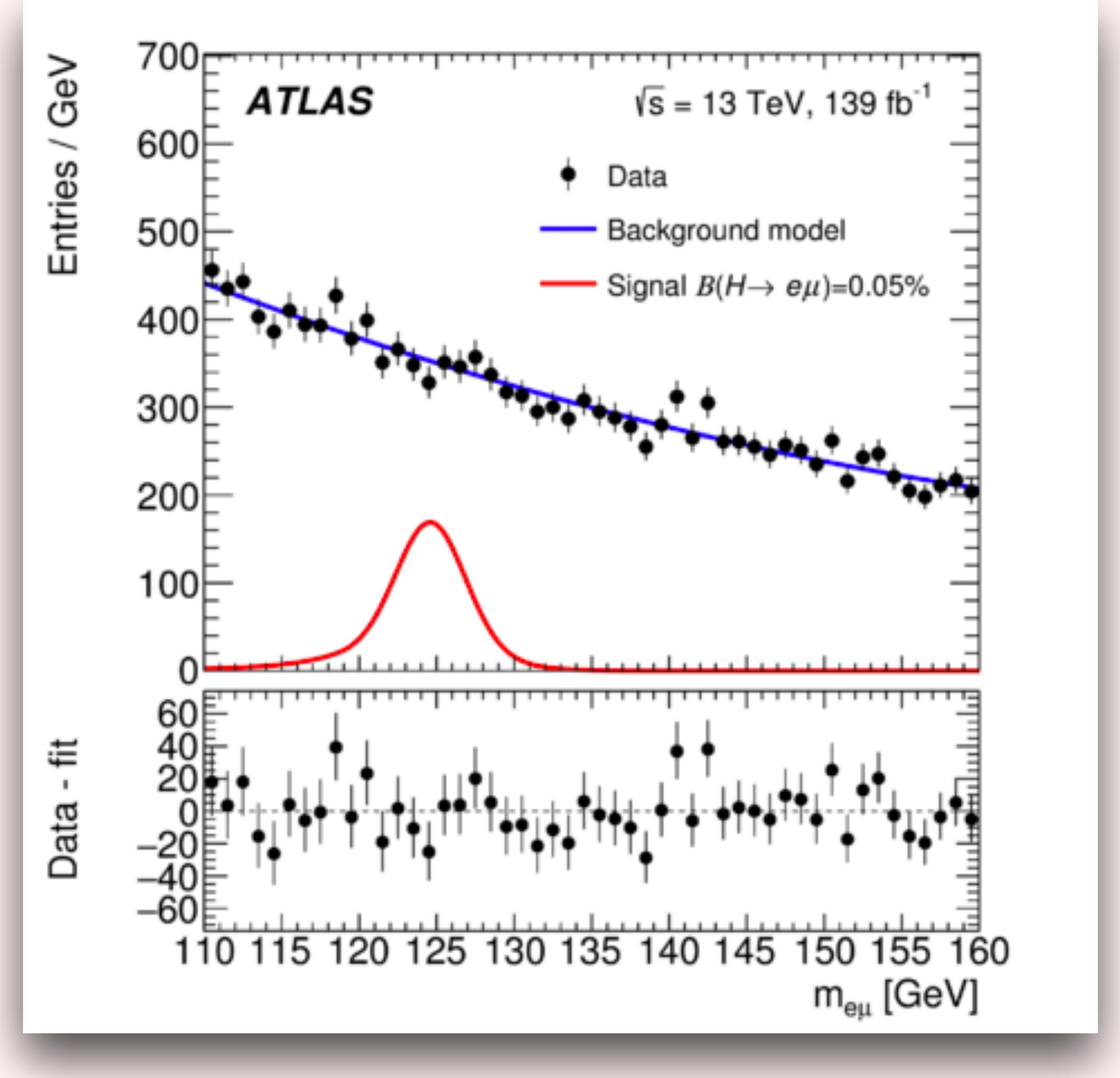
ANY SURPRISES WITH FLAVOUR?

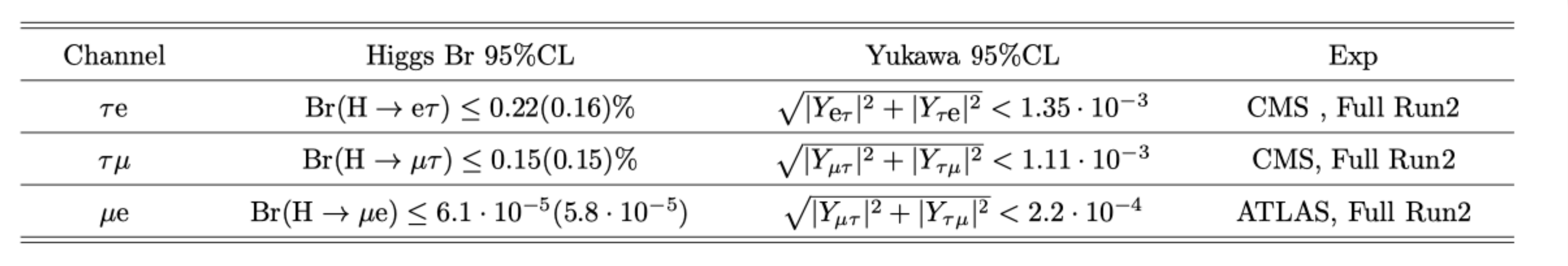
- In the SM, Higgs decays should conserve flavour: Higgs decays to pair of leptons of different flavour are forbidden
- **However we know well that the Flavour sector typically brings surprises. What happens if we mix Higgs & Flavour?**
- Look for Higgs decays to OF leptons

Phys. Rev. D 104, 032013



Phys. Lett. B 801 (2020) 135148





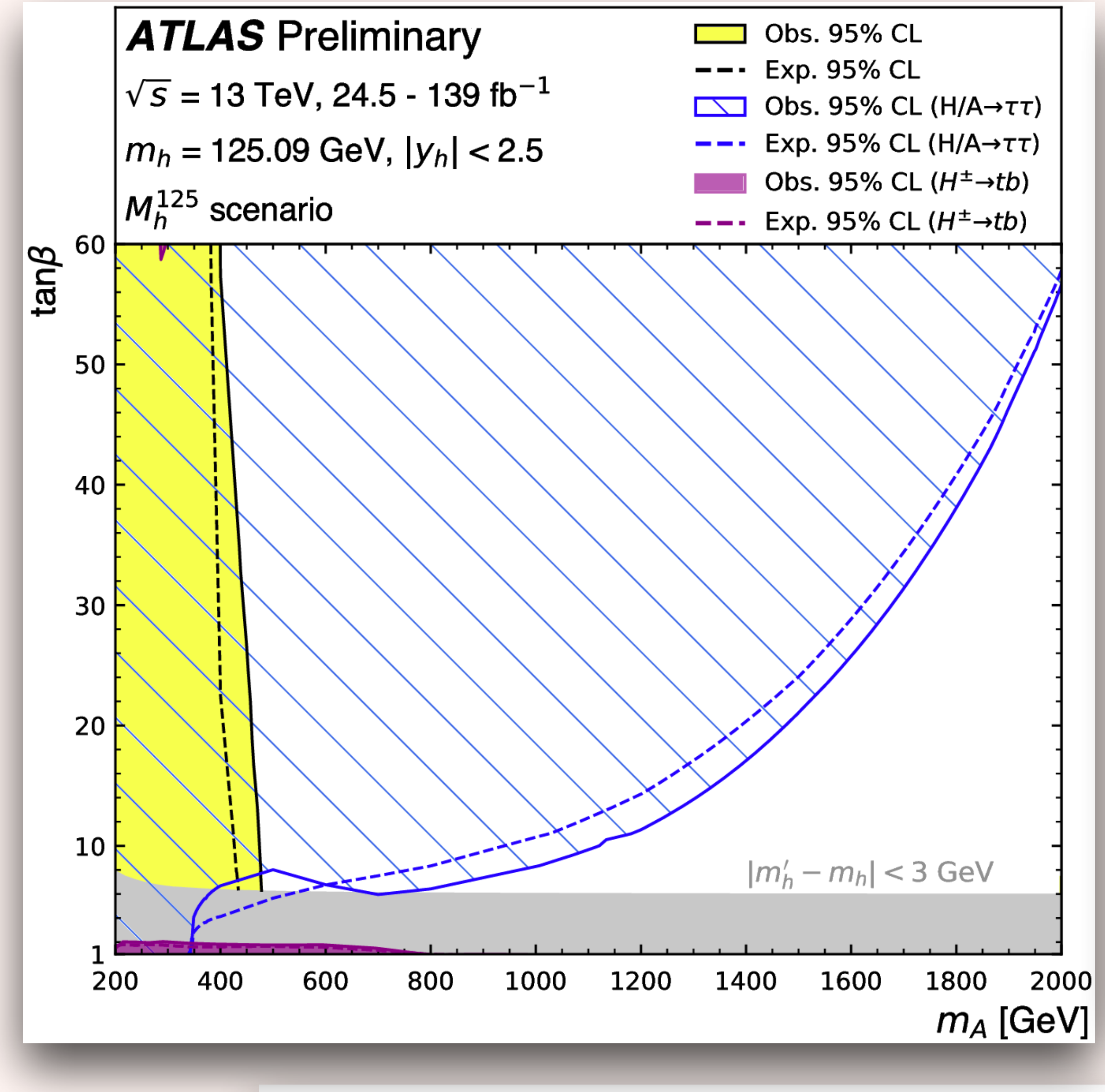
Channel	Higgs Br 95%CL	Yukawa 95%CL	Exp
τe	$\mathrm{Br(H \to e\tau)} \leq 0.22(0.16)\%$	$\sqrt{\vert Y_{e\tau}\vert^2 + \vert Y_{\tau e}\vert^2} < 1.35 \cdot 10^{-3}$	CMS , Full Run2
$\tau\mu$	$\mathrm{Br(H \to \mu\tau)} \leq 0.15(0.15)\%$	$\sqrt{\vert Y_{\mu\tau}\vert^2 + \vert Y_{\tau\mu}\vert^2} < 1.11 \cdot 10^{-3}$	CMS, Full Run2
μe	$\mathrm{Br(H \to \mu e)} \leq 6.1 \cdot 10^{-5}(5.8 \cdot 10^{-5})$	$\sqrt{\vert Y_{\mu\tau}\vert^2 + \vert Y_{\tau\mu}\vert^2} < 2.2 \cdot 10^{-4}$	ATLAS, Full Run2

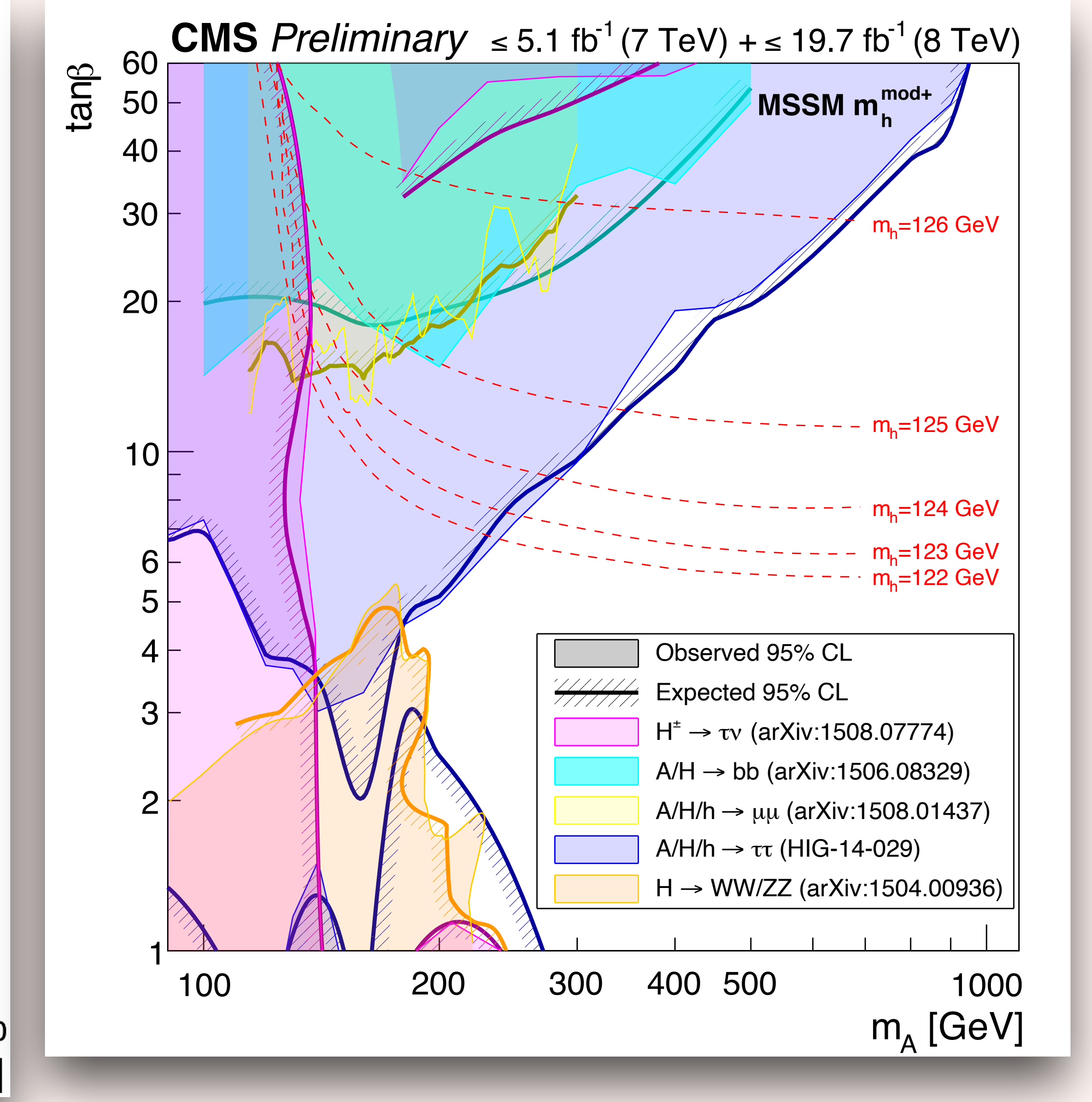
Previous Run1 or partial Run2 results by CMS and ATLAS not shown in the table

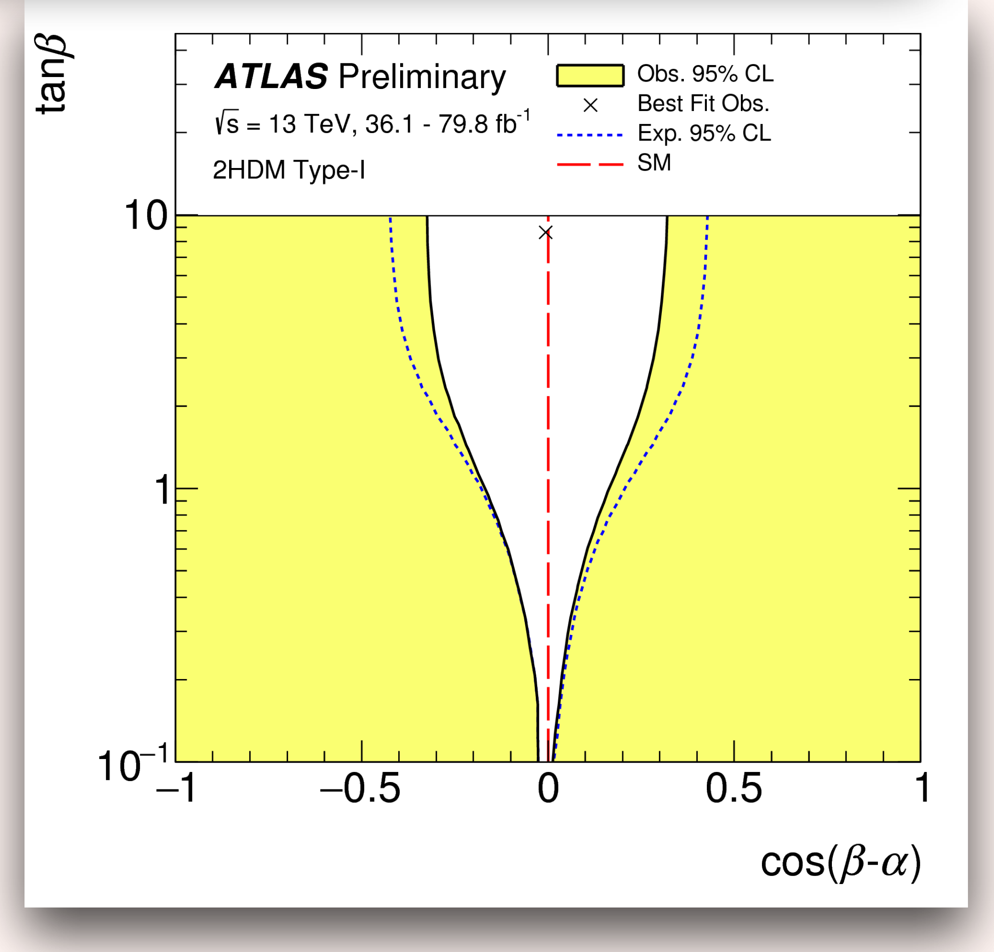
Hee limit also included in Phys. Lett. B 801 (2020) 135148 : Br(Hee)<3.6e-4 (3.5e-4)

IS THE HIGGS ALONE?

- **BSM models tell us that the Higgs does not like being lonely: looking for additional Higgses (at high or low masses, scalar pseudo scalar or charged) is a key part of the Higgs program of the LHC**
    - Very large phase space to cover, but caution: the fact that we observed and measured h(125) gives us large indirect constraints on new models
- Complementarity in the search approaches: look for many different channel topologies, emphasising model independent searches whenever possible
- So far no surprises, but there is still a lot of uncovered phase-space - especially at high mass and exploring unconventional topologies (eg: the mentioned long lived decays)

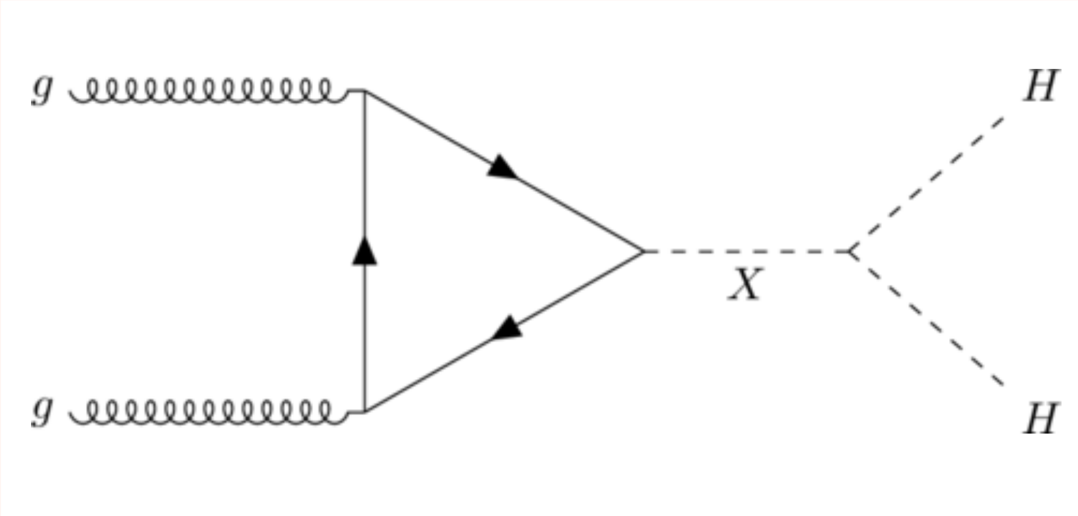




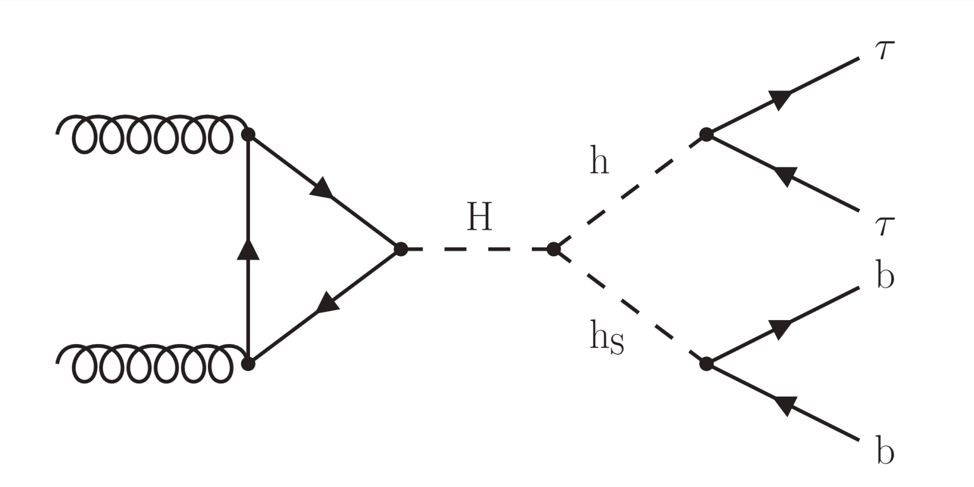


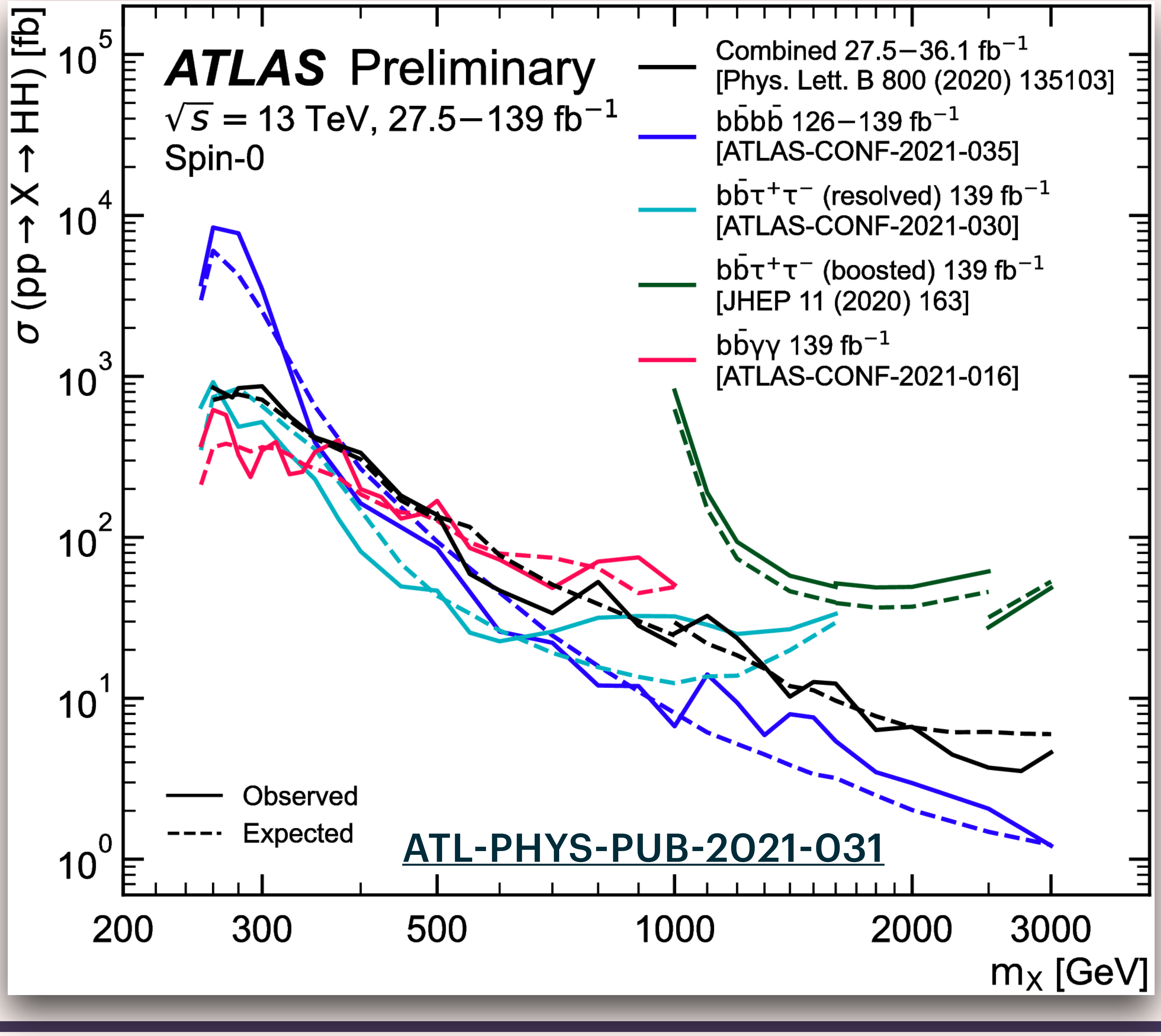
Expanding list of final states going towards Run3: merits another full hour talk to give them justice :)

JUST AN EXAMPLE: HH RESONANCES

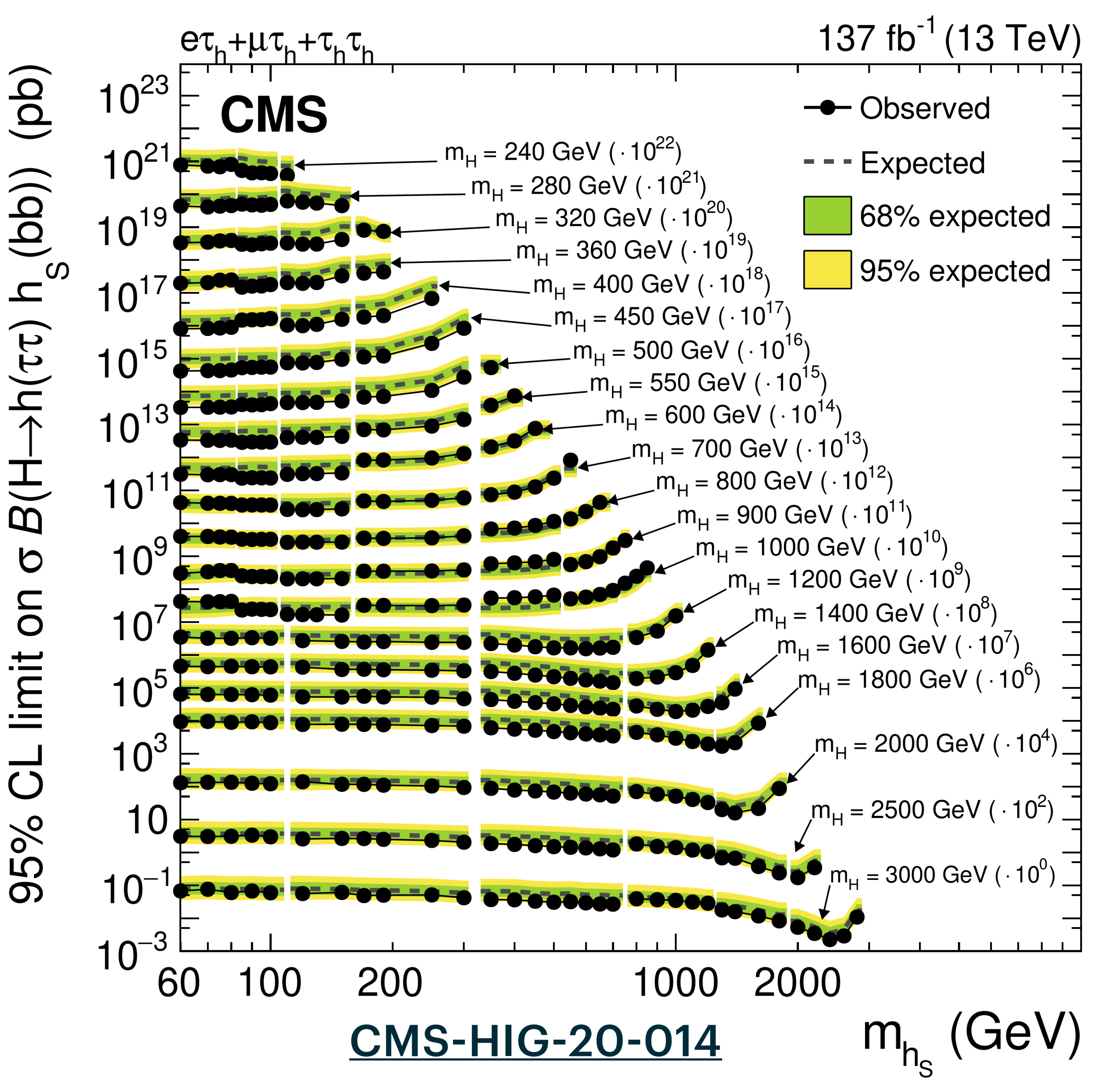


- Same final states and similar analysis techniques as the non resonant HH production analyses, with the advantage of profiting from the resonant topologies
- Traditional X->HH searches now also expanding to Extended Higgs Sector scenarios with H_1->H_2 h





ATL-PHYS-PUB-2021-031



CMS-HIG-20-014

CONCLUSIONS

- The LHC collaborations have ran a challenging Higgs physics program in Run2.
- The Higgs is today one of the best tools to explore the limits of the SM: we have measured cross sections and branching ratios, explored kinematics, and inspected the coupling to the SM particles, including itself.
- So far, no surprises: the Higgs remains stubbornly SM-like. However there is plenty of unexplored phase-space to search for anomalous behaviour, exotic decays or additional scalars: we have only explored a very small fraction of the full LHC dataset

→Look for surprises in the data to come in Run3 and in the HL-LHC

References for all the experimental results shown:
CMS
ATLAS SM Higgs **ATLAS BSM Higgs**

Theoretical predictions & LHC agreement for benchmarks:
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG