Overview of recent Higgs boson with the ATLAS detector

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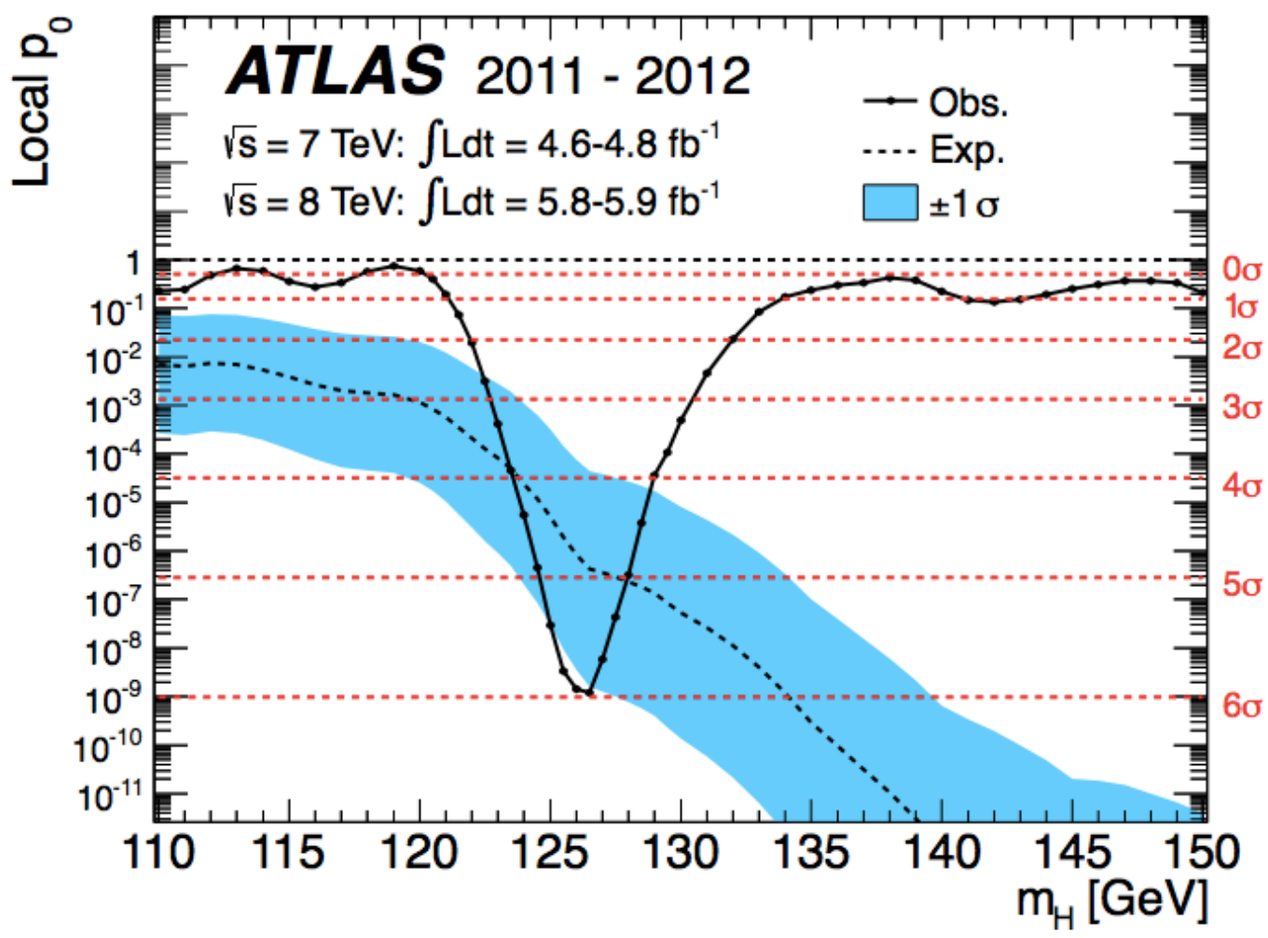
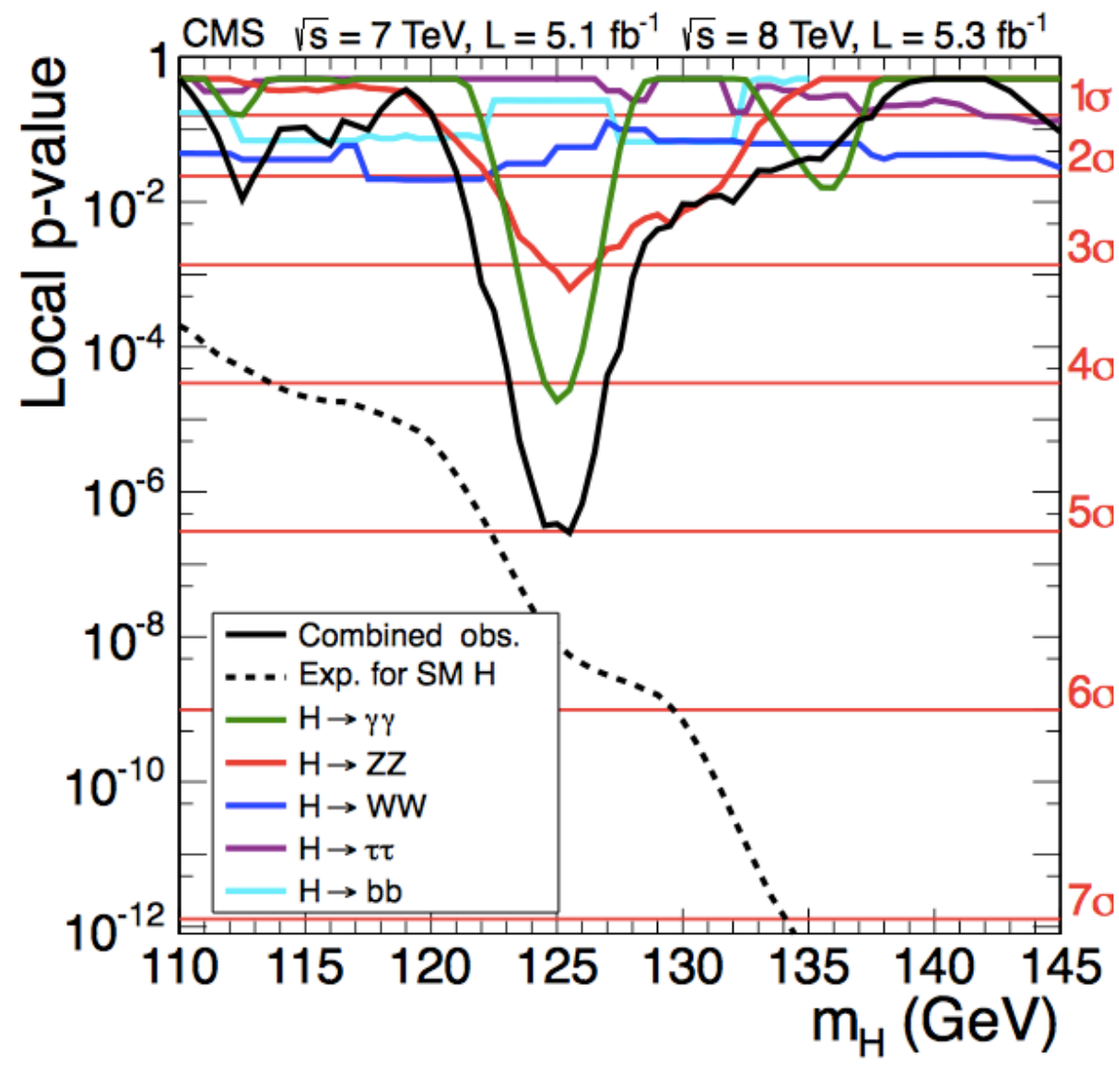
Higgs discovery at the LHC

A scalar boson compatible with the SM Higgs has been discovered in run I as shown by the combination of ATLAS and CMS run I results

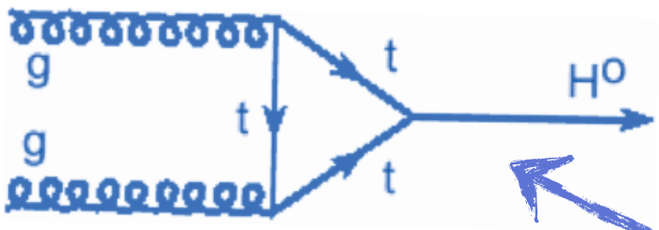
Greatest achievement of run I

- concentrated effort on its properties:
  - magnitude of couplings
  - mass measurements
  - spin/CP





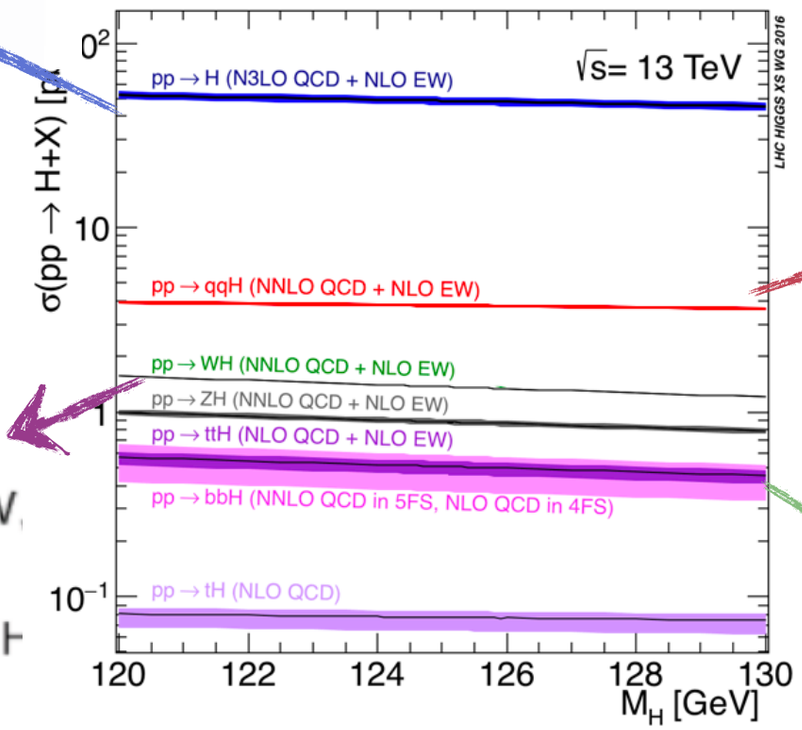
Where do we stand



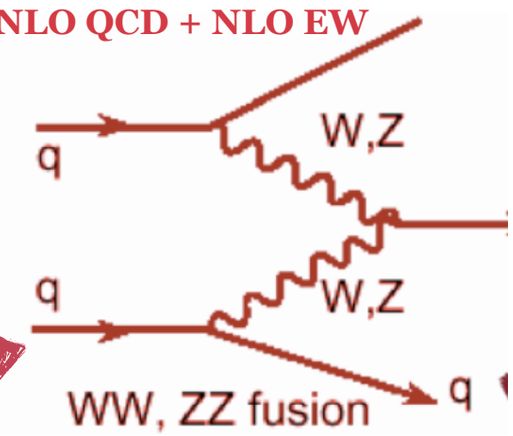
ggF: NNNLO+NNLL QCD + NLO EW

WH: NNLO QCD + NLO EW

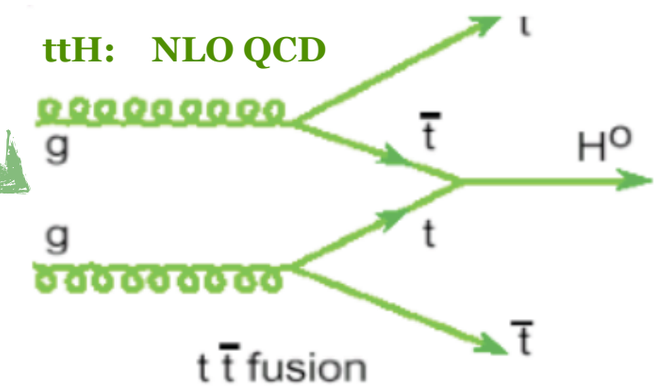
ZH: NNLO QCD + NLO EW

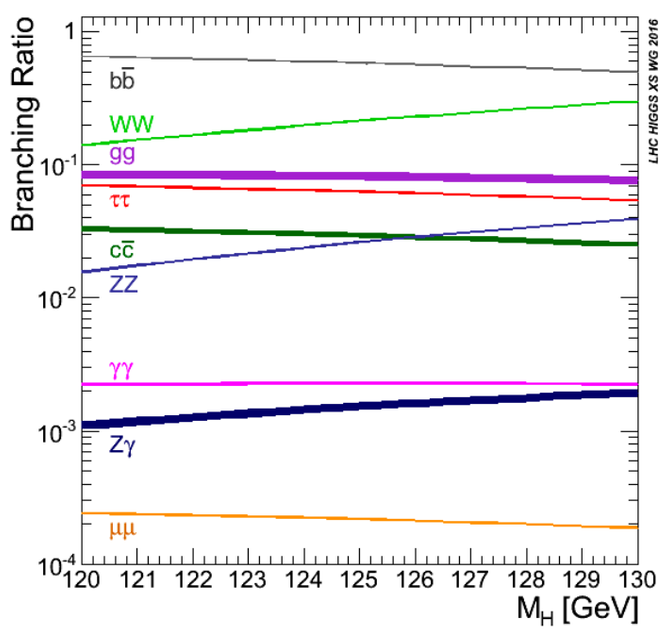


NNLO QCD + NLO EW



ttH: NLO QCD





	BR(%)
bb	**57**
WW	**22**
ττ	**6.2**
ZZ	**2.8**
γγ	**0.23**
Zγ	**0.15**

Increase in run 3 @ 13.6 TeV

ggF	+7.5%
VBF	+7.9%
WH	+6.2%
ZH	+6.9%
ttH	+12.6%
HH	+11%

Higgs History: where are we?

- Since the discovery we have a factor 30 more statistical power
- we have a permil precision on the Higgs mass
- The scenario with no off-shell production of the Higgs is ruled out and its width measured at ~2 MeV precision

We are :

- measuring couplings to bosons and fermions
- investigating the couplings to the second generation
- measuring the signal strength for Higgs production with a 6% precision
- a precision on various couplings that ranges from 3-10%
- evidence that the Higgs couples with the particle mass and that it has spin 0
- at the level of sensitivity of testing x-sections at the level of 2-3 times the SM for the di-higgs production

Let's walk through all of this together!

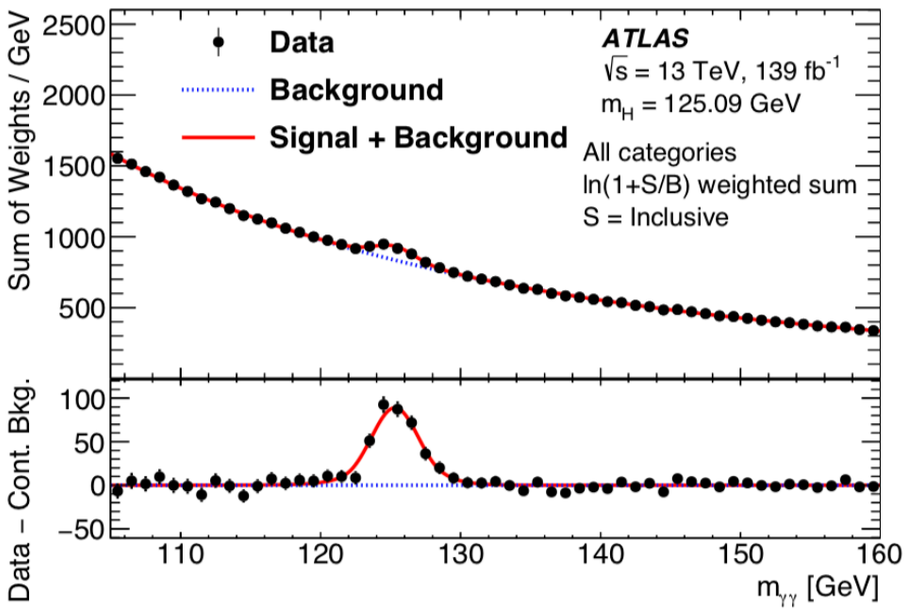
Higgs decays to vector bosons

Higgs→$\gamma\gamma$

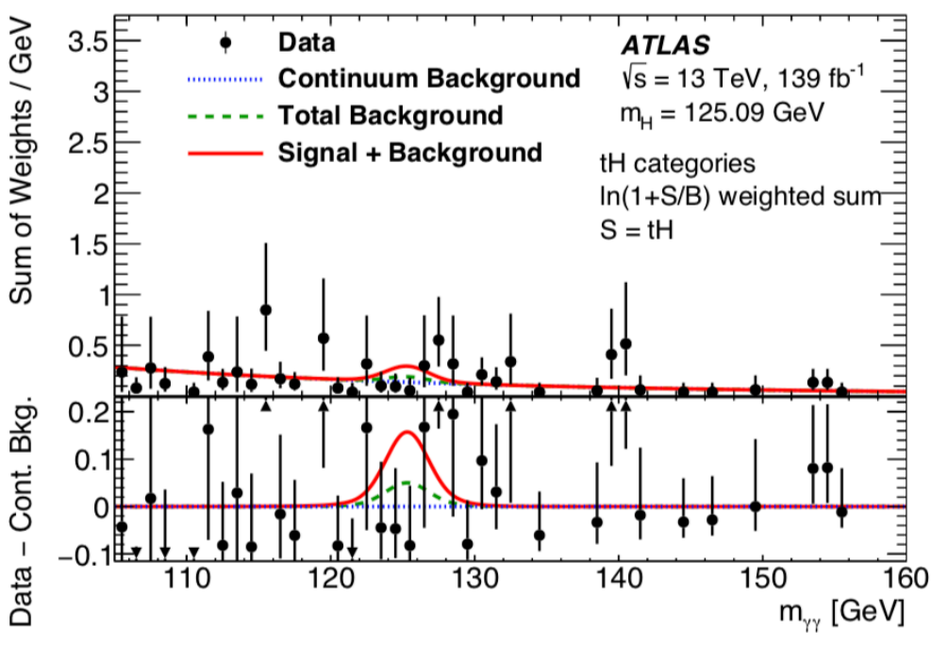
ArXiv:2207.00348

10 % precision

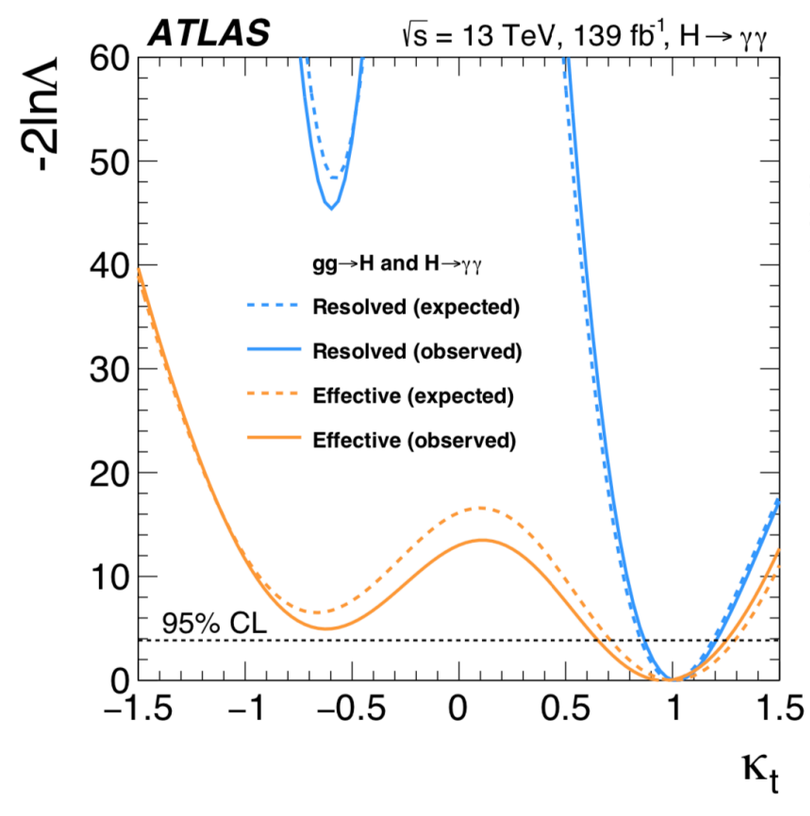
$$\mu = 1.04^{+0.10}_{-0.09} = 1.04 \pm 0.06\ (\text{stat.})^{+0.06}_{-0.05}\ (\text{theory syst.})\ ^{+0.05}_{-0.04}\ (\text{exp. syst.}).$$



- An upper limit of 10xSM obs (6.8 exp) prediction is set for the associated production process of a Higgs boson with a single top quark, which has a unique sensitivity to the sign of the top quark Yukawa coupling.
- Sensitivity to the sign of the κt modifier to the top quark coupling in the tH process leads to an exclusion of the κt <0 region with a significance of 2.2σ



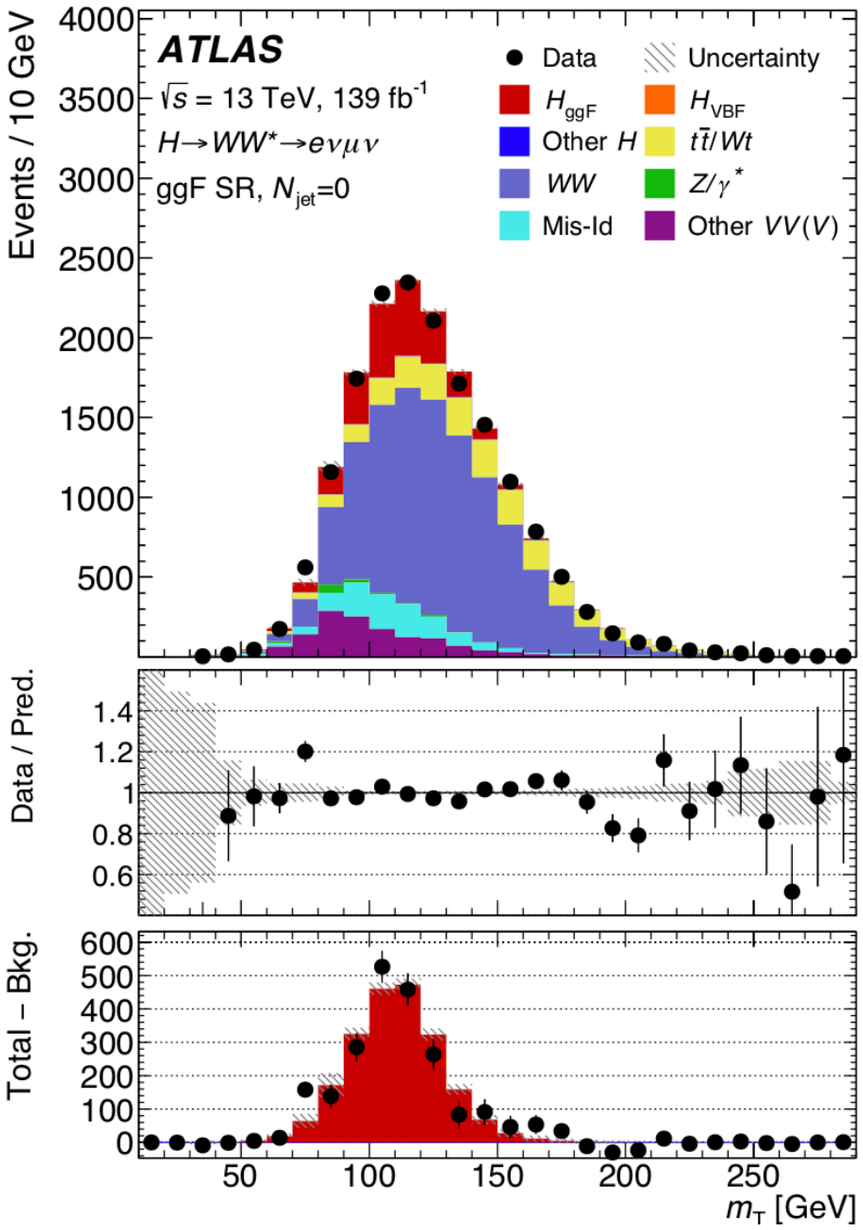
(f) tH



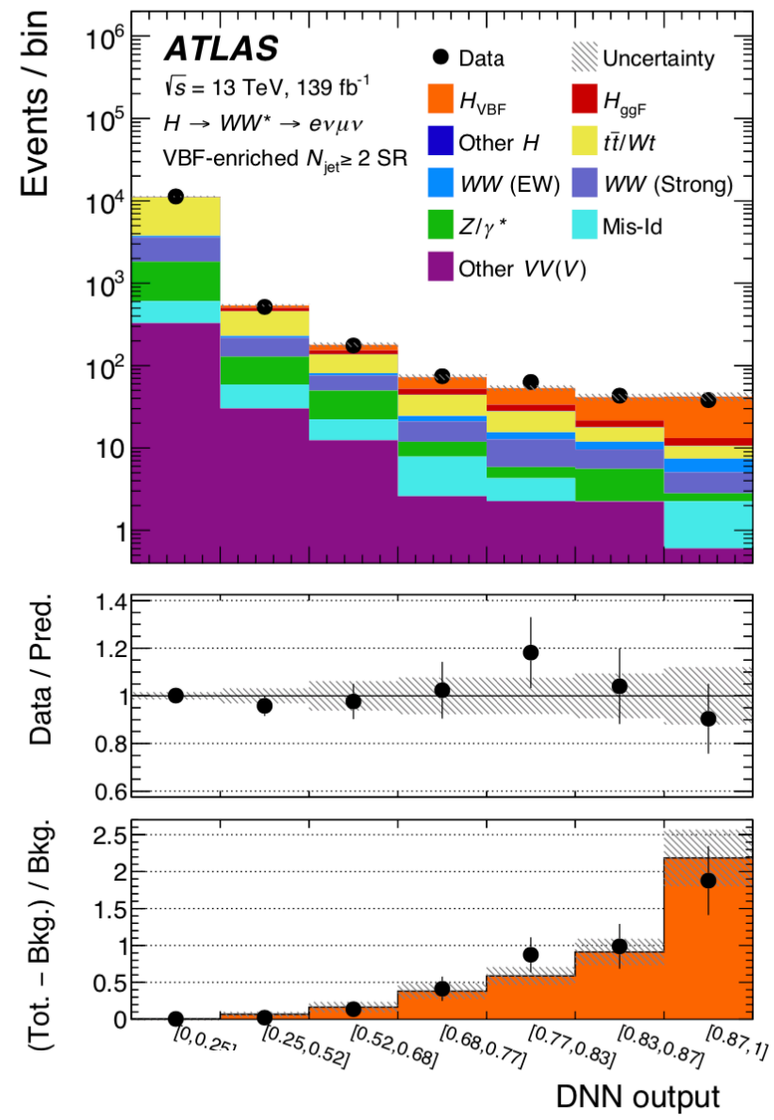
The $H \rightarrow \gamma\gamma$ and $gg \rightarrow H$ loops are either parameterized as a function of κt (blue) or fixed to their SM expectation (orange)

H→WW*

ArXiv:2207.00338



- Targeting only ggF and VBF and 11 STXS 1.2 bins
- only different flavor
- Simultaneous fit of signal and control regions, using mT or DNN (ggF vs VBF) as observable

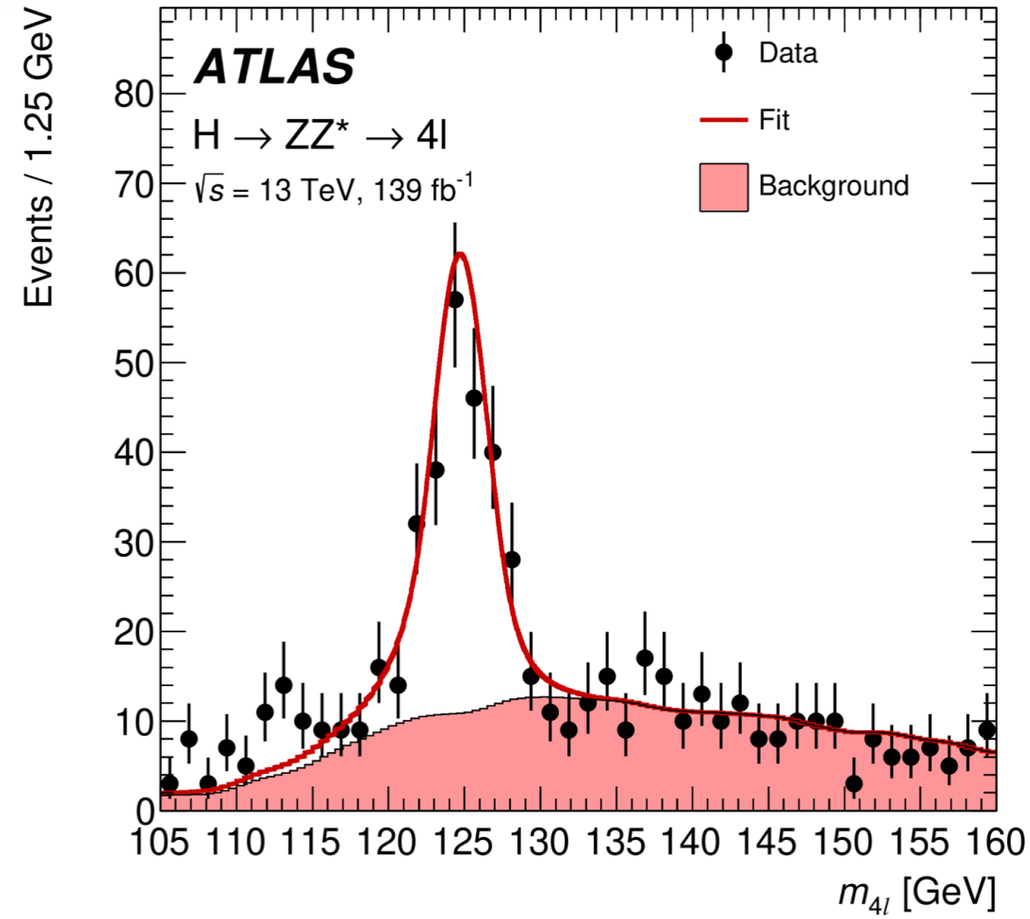


10 % precision

	Total	(Stat.,	Syst.)	SM Unc.
μ=	$1.09^{+0.11}_{-0.11}$	$^{+0.06}_{-0.06}$,	$^{+0.10}_{-0.09}$)	± 0.07

H→ZZ→4l

ArXiv:2207.00320



precise muon and electron momentum calibration

m_H =124.94±0.17(stat.)±0.03(syst.)GeV

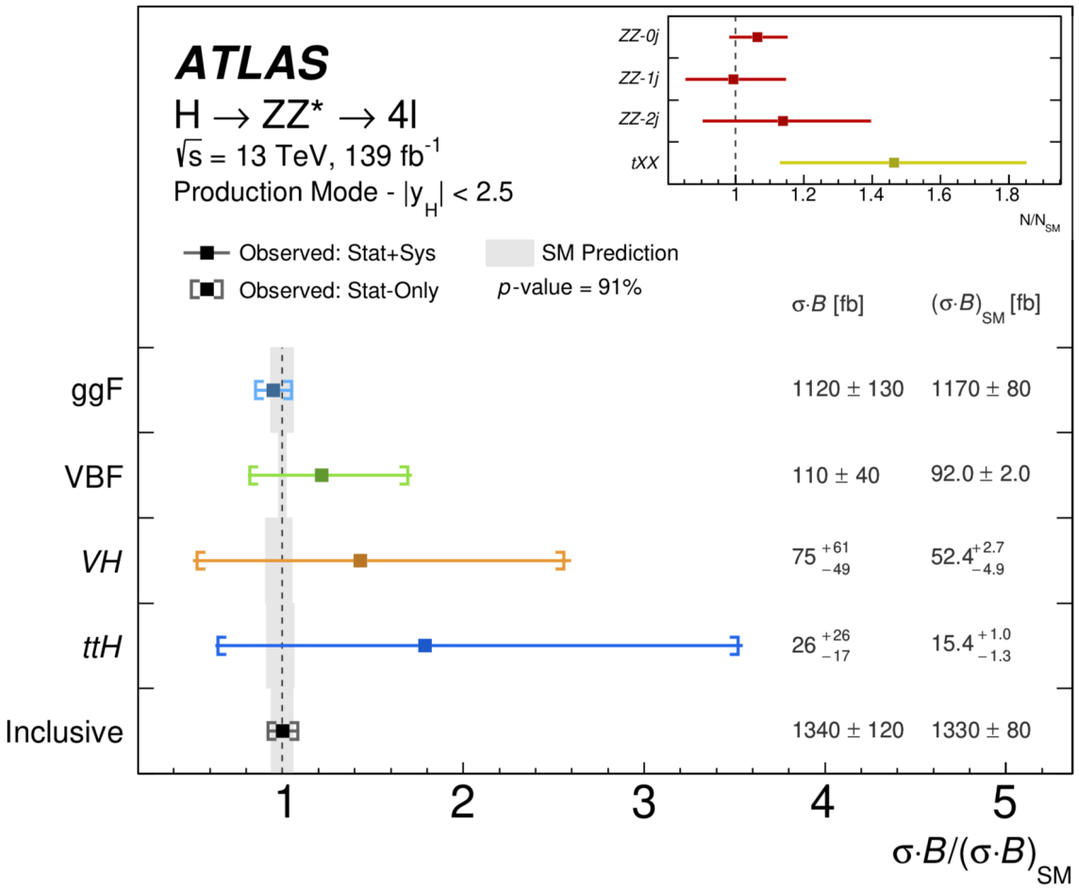
combined with run I 0.14% precision (per mill level !) on the higgs mass`

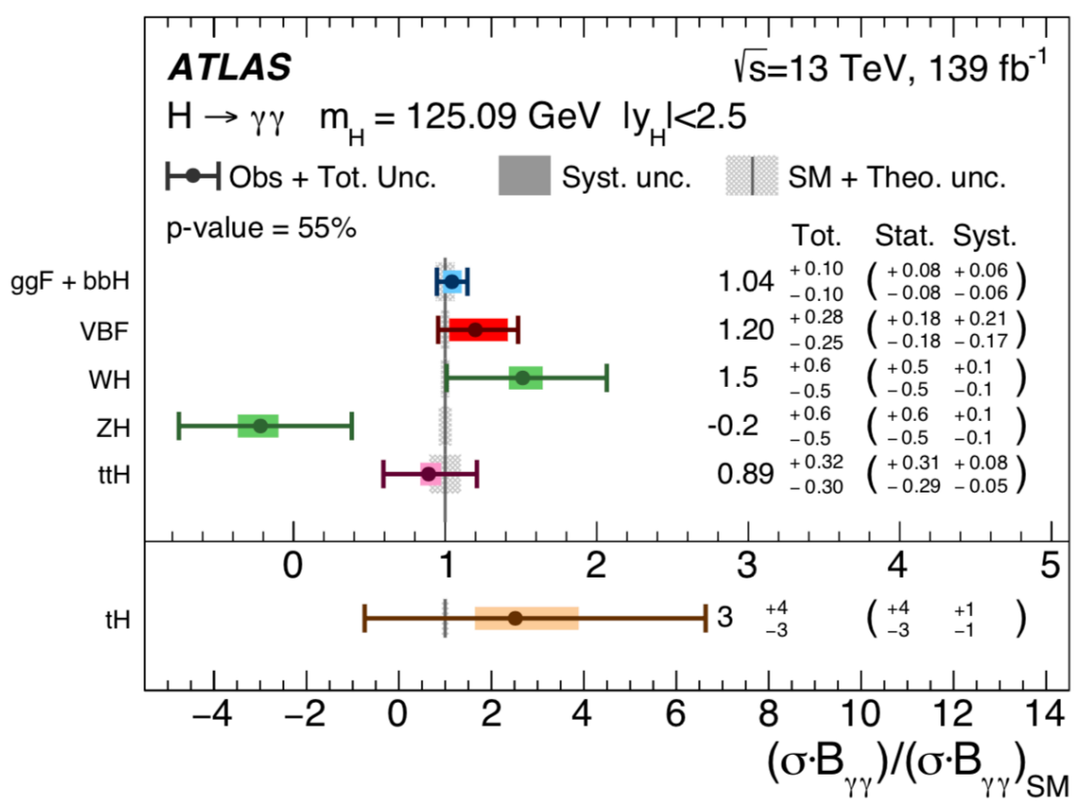
$$\mu = 1.01 \pm 0.08(\text{stat.}) \pm 0.04(\text{exp.}) \pm 0.05(\text{th.})$$

Eur. Phys. J. C 80 (2020) 957

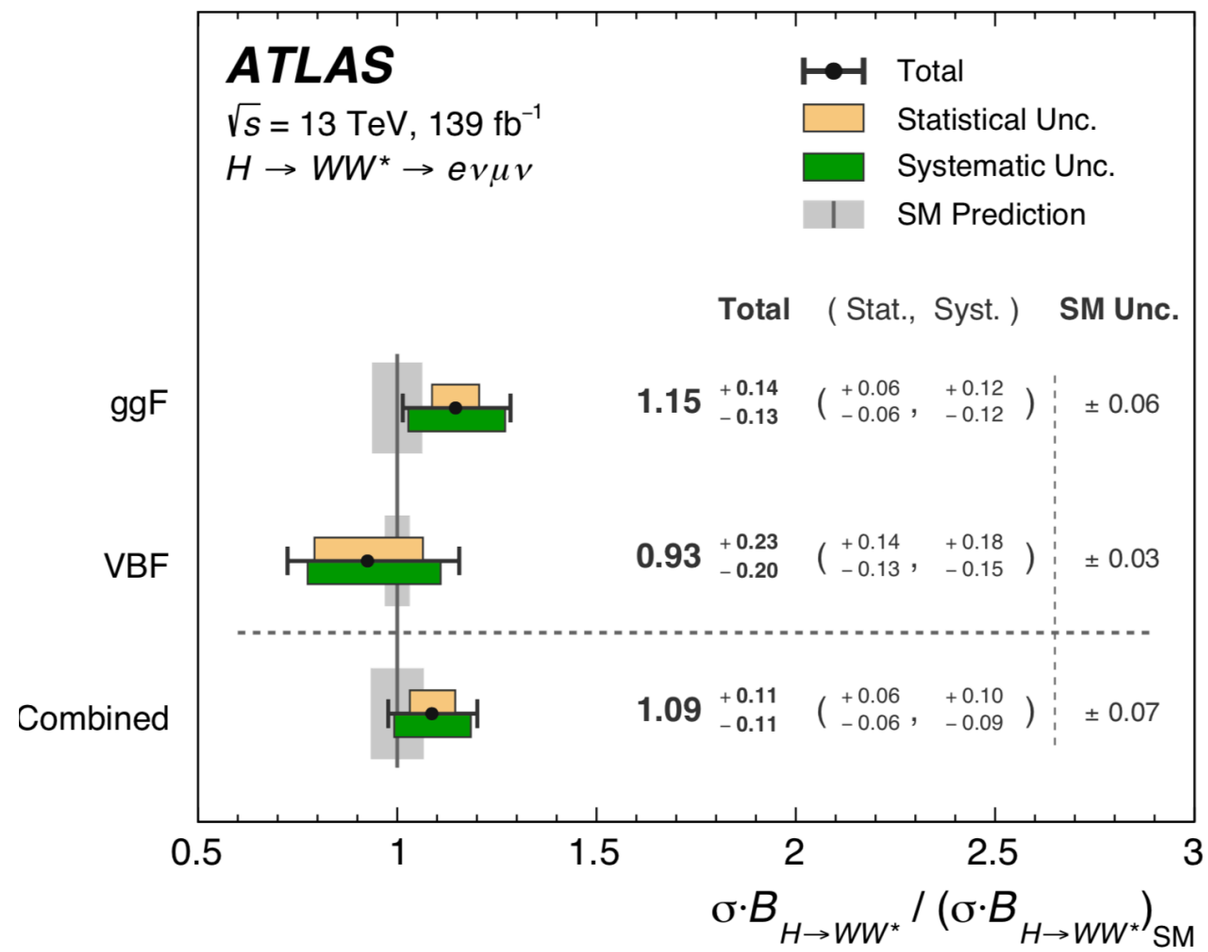
precision on μ ~ 10%

Production modes





→ theory uncertainties start to matter



Measurement precision

- 10% uncertainty on ggF
- 20-30% on VBF
- 35% ttH(yy)

Simplified Template X-Sections

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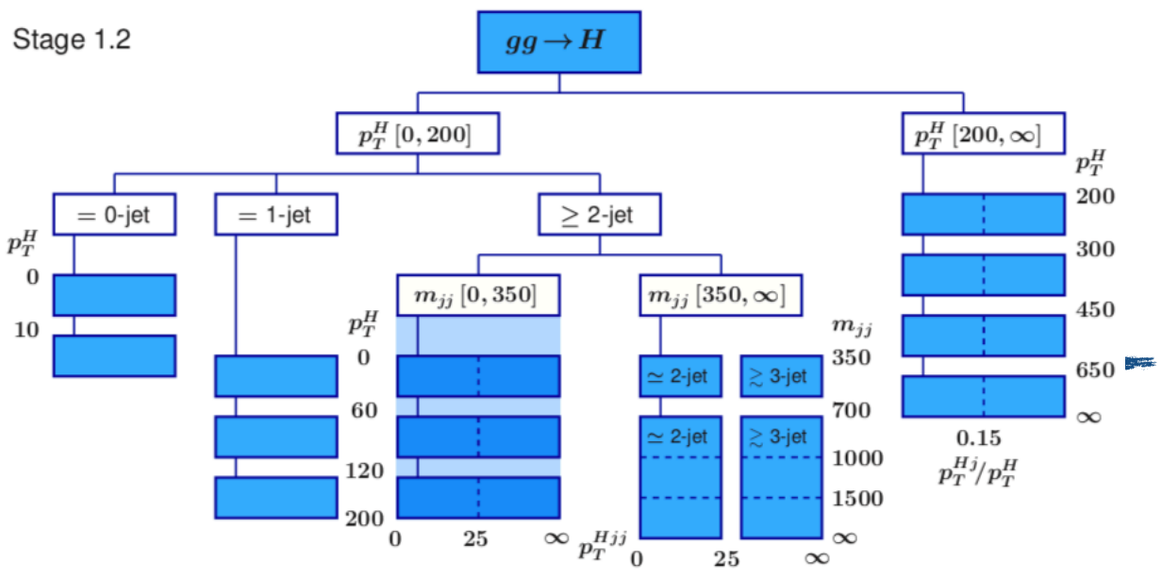
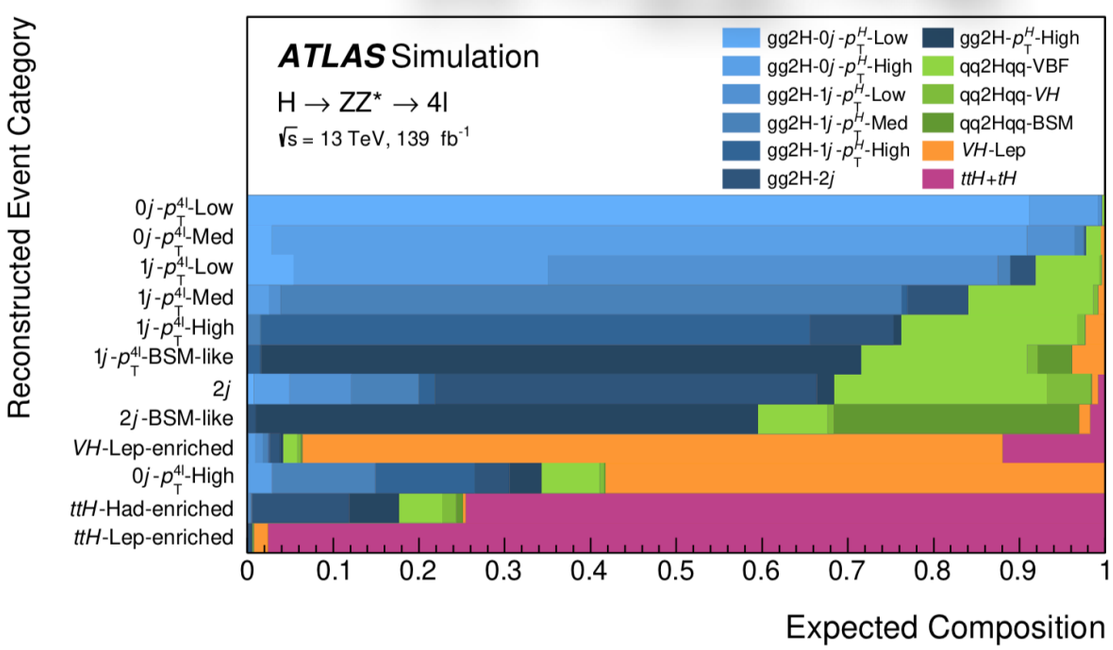


Fiducial exclusive regions of phase space, specific to different production modes, inclusive in decay. Bins minimize the dependence on theoretical uncertainties that are directly folded into the measurements.

"Simplified" not fully differential; residual acceptance changes / model dependence allowed, but reduced

H→ZZ→4l

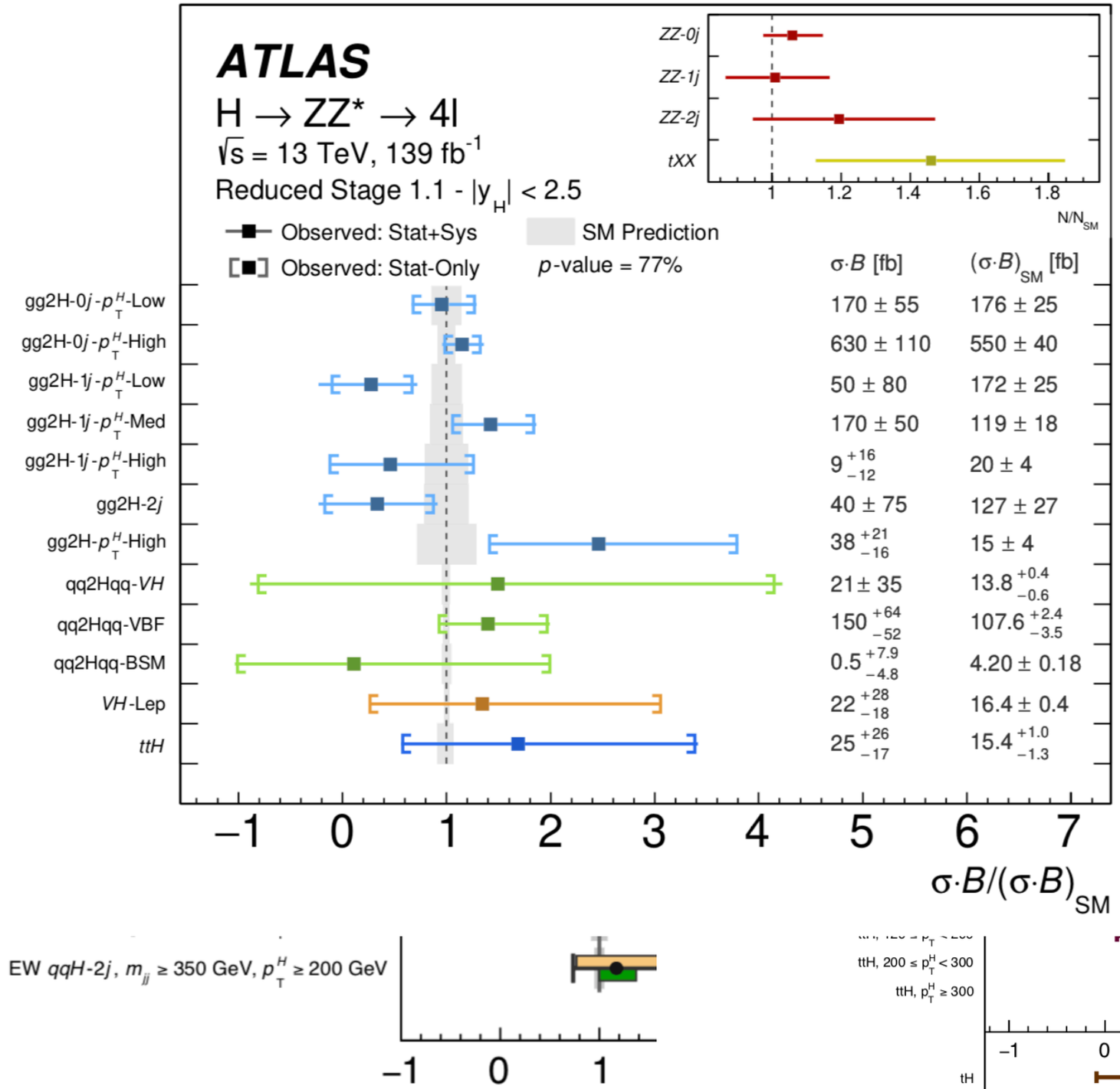


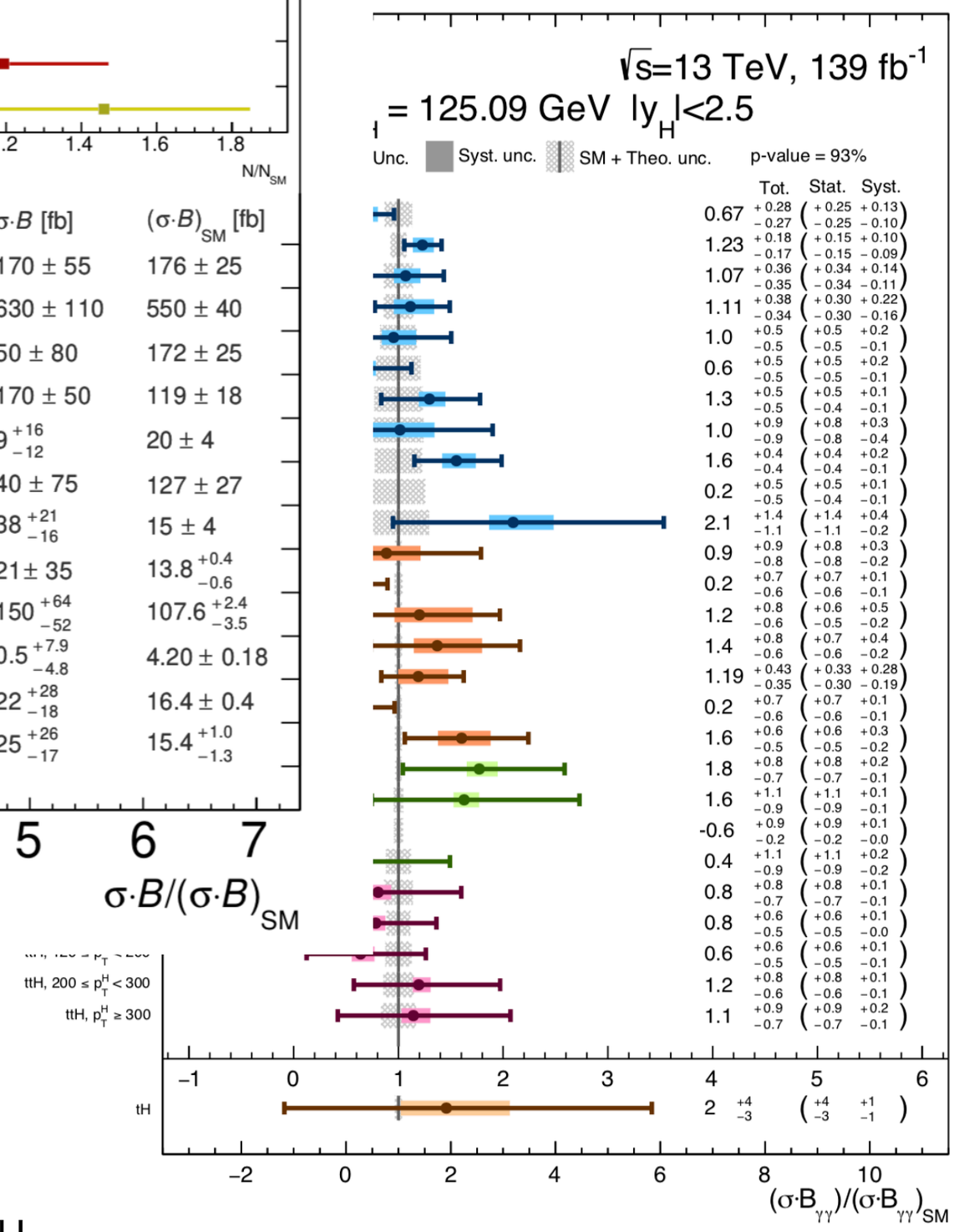
- only theory uncertainties having to deal with the bins migrations remain
- The bins are chosen to be sensitive to new physics and the granularity will increase with time and experience.

- Here statistical uncertainties are the limiting factor

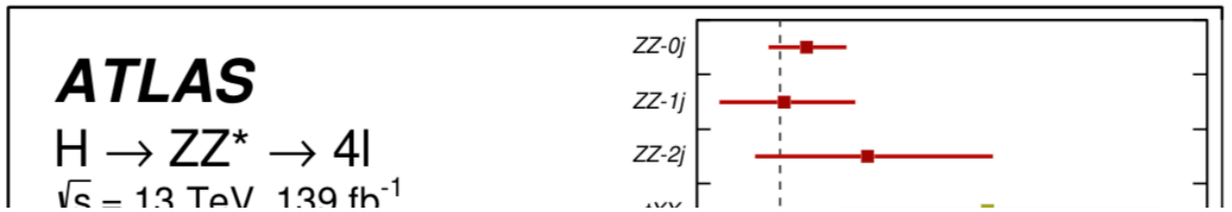
Simplified Template X-sections

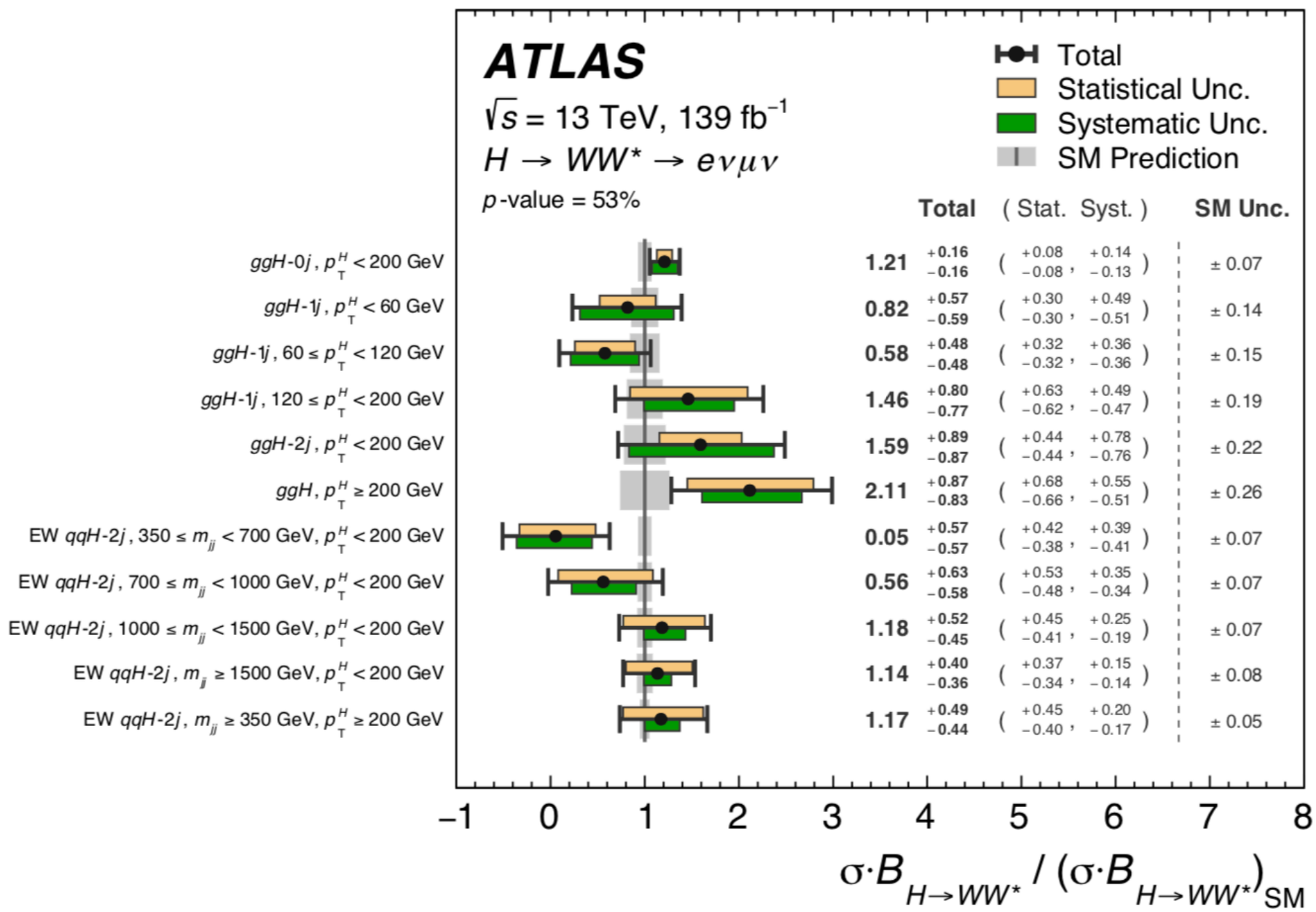
Several STXS 1.2 bins for ggF and VBF at < 50% from single channel

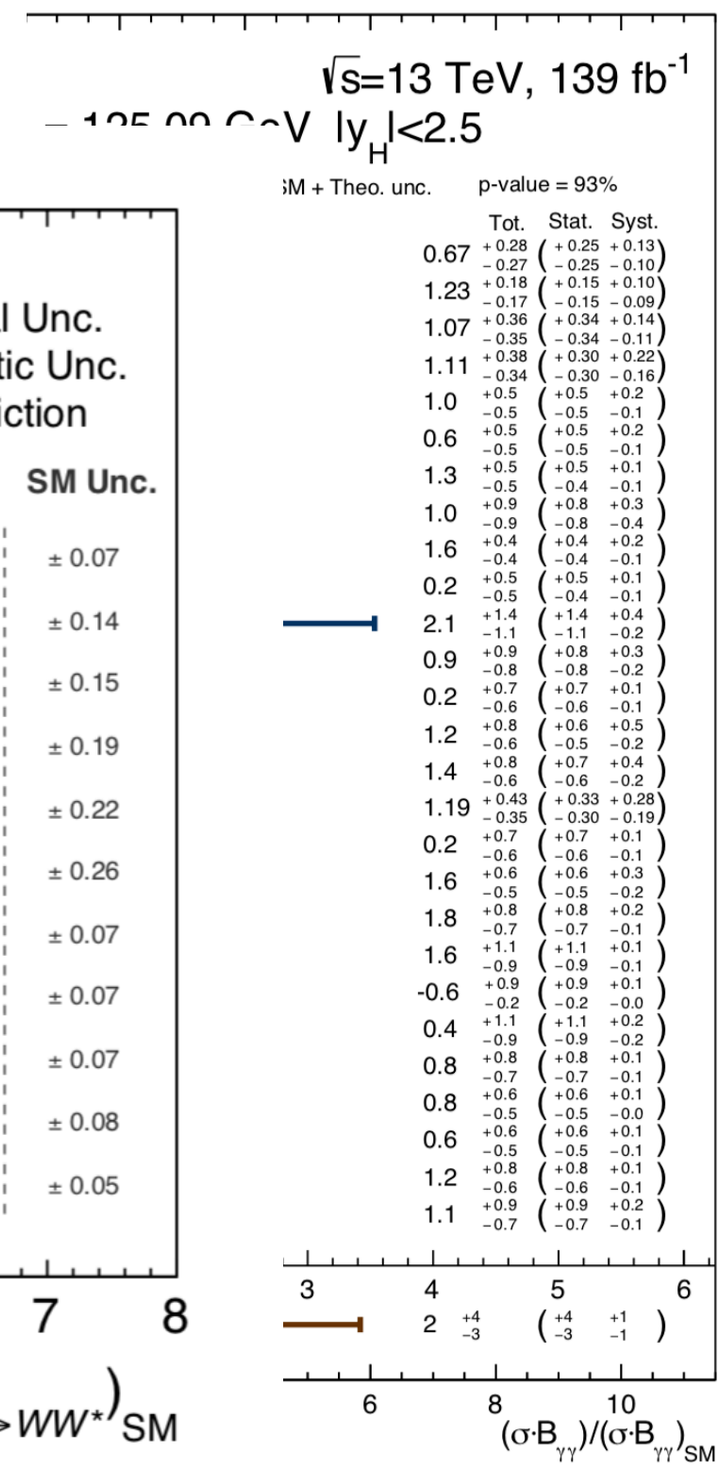




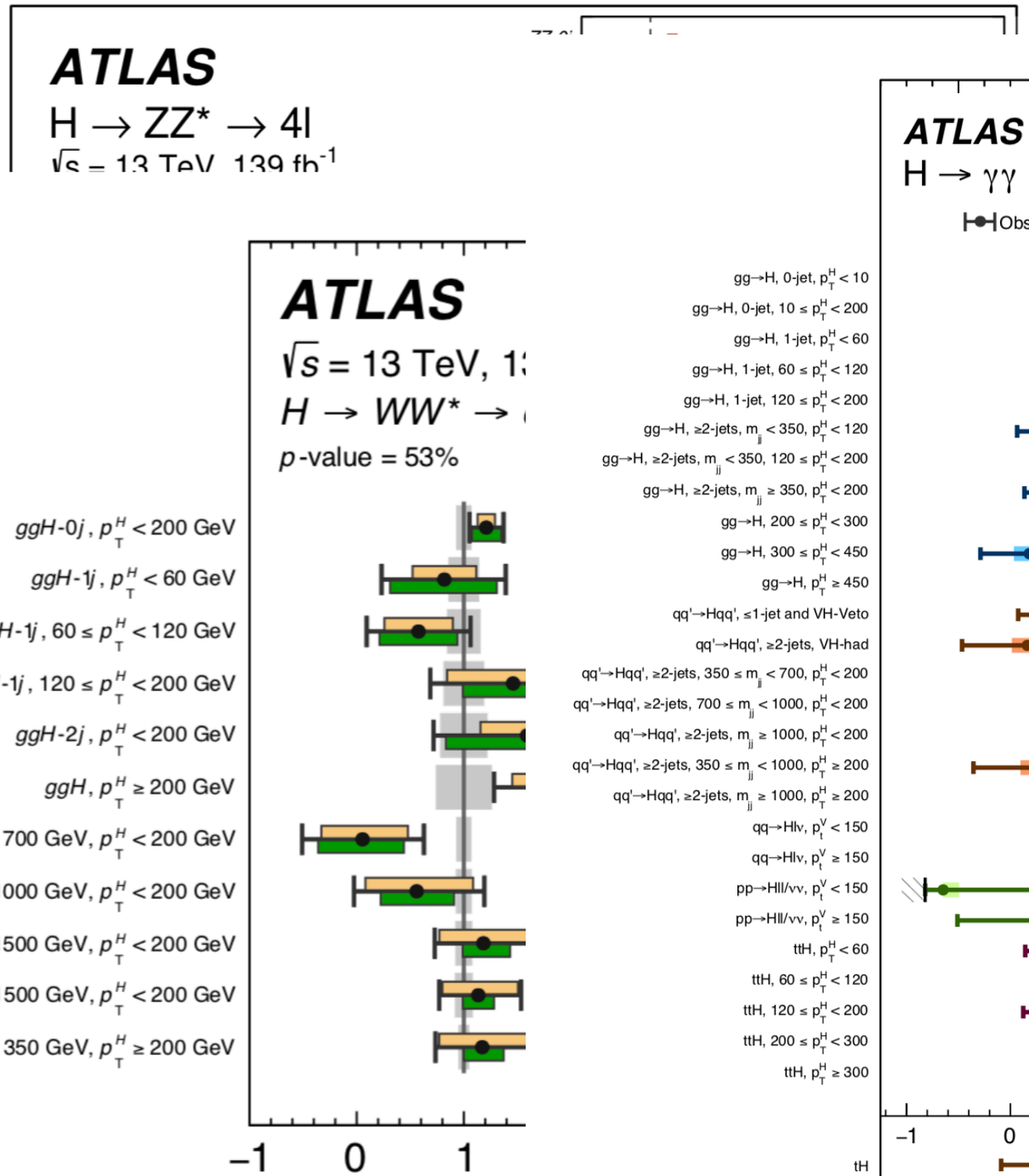
Simplified Template X-sections

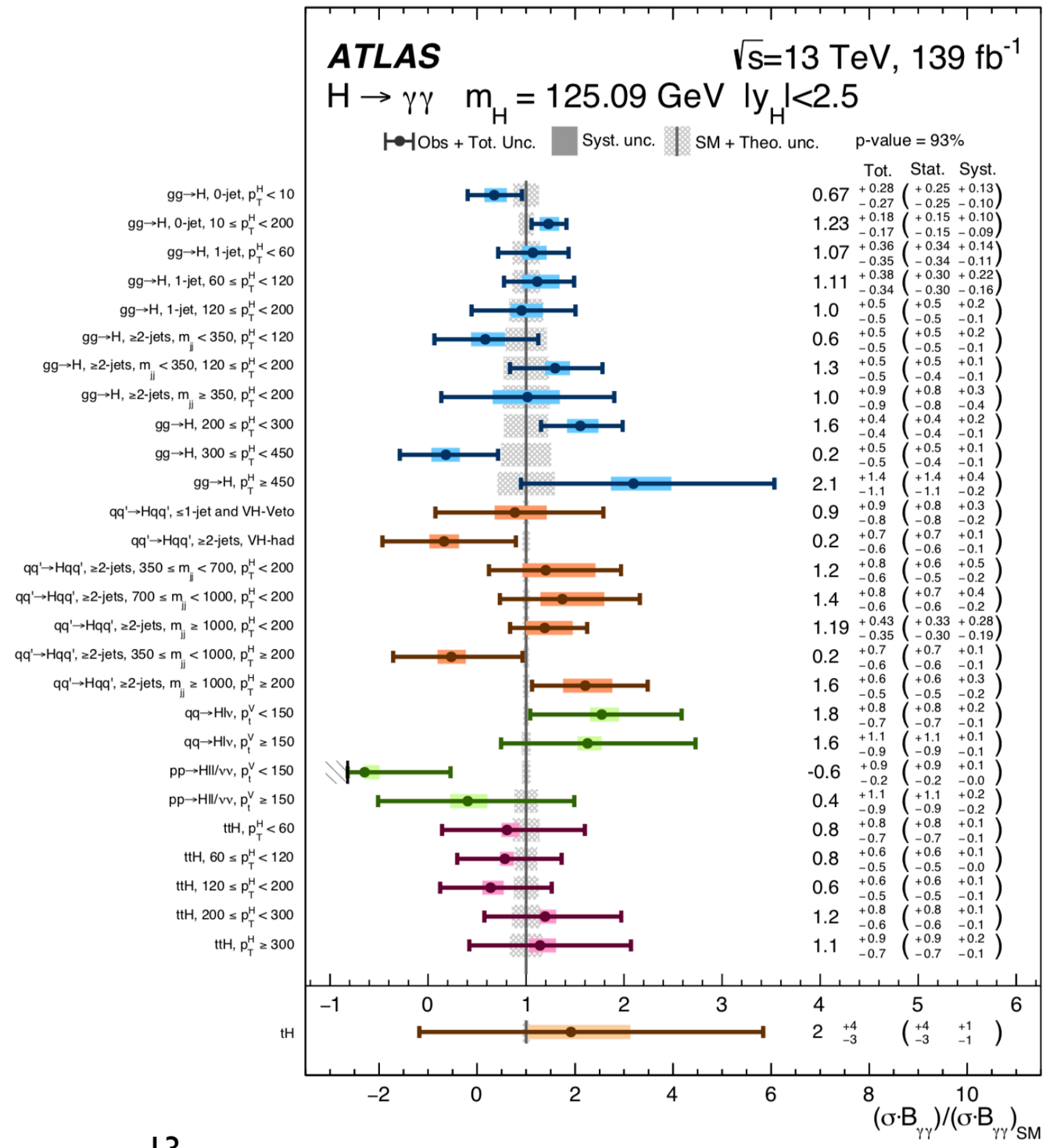






Simplified Template X-sections

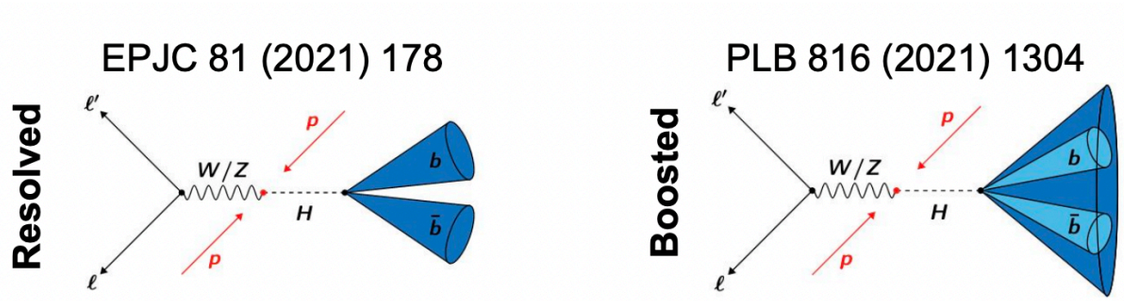


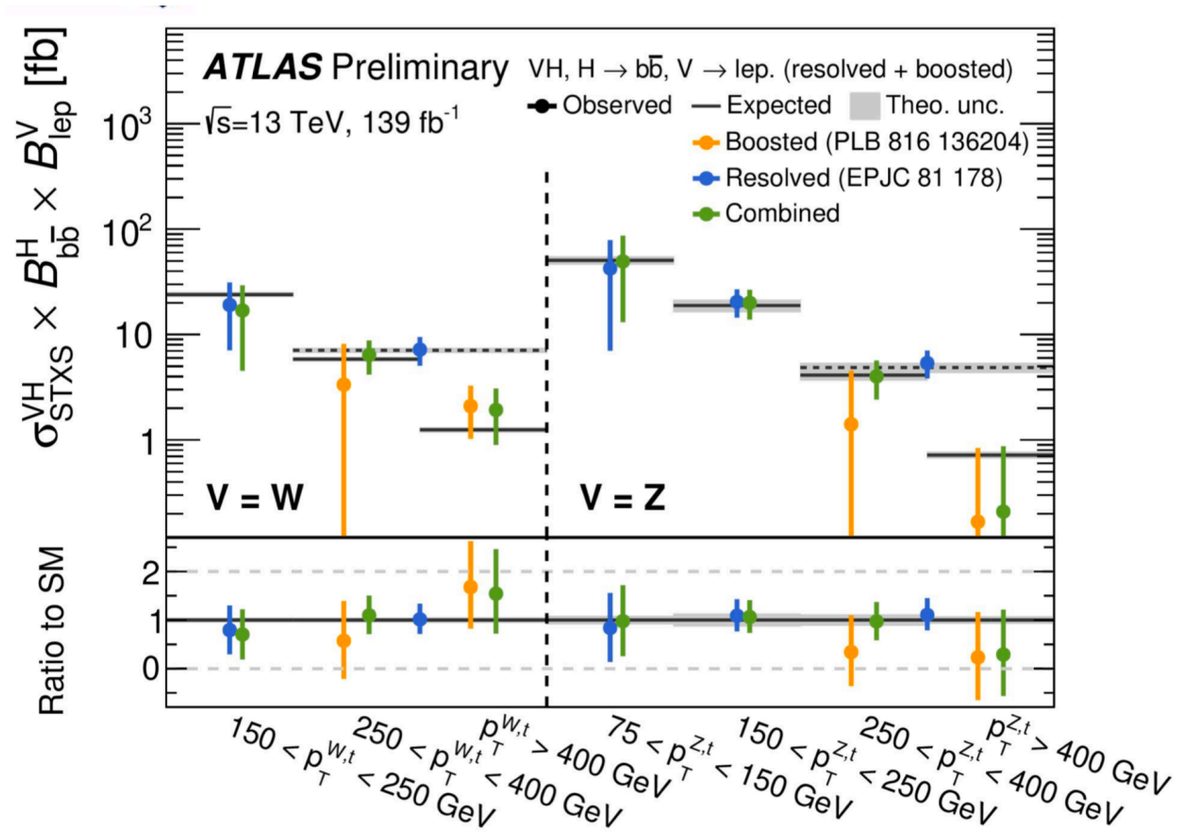


Higgs decays to fermions and ttH production

Vh→bb combination

ATLAS-CONF-2021-051

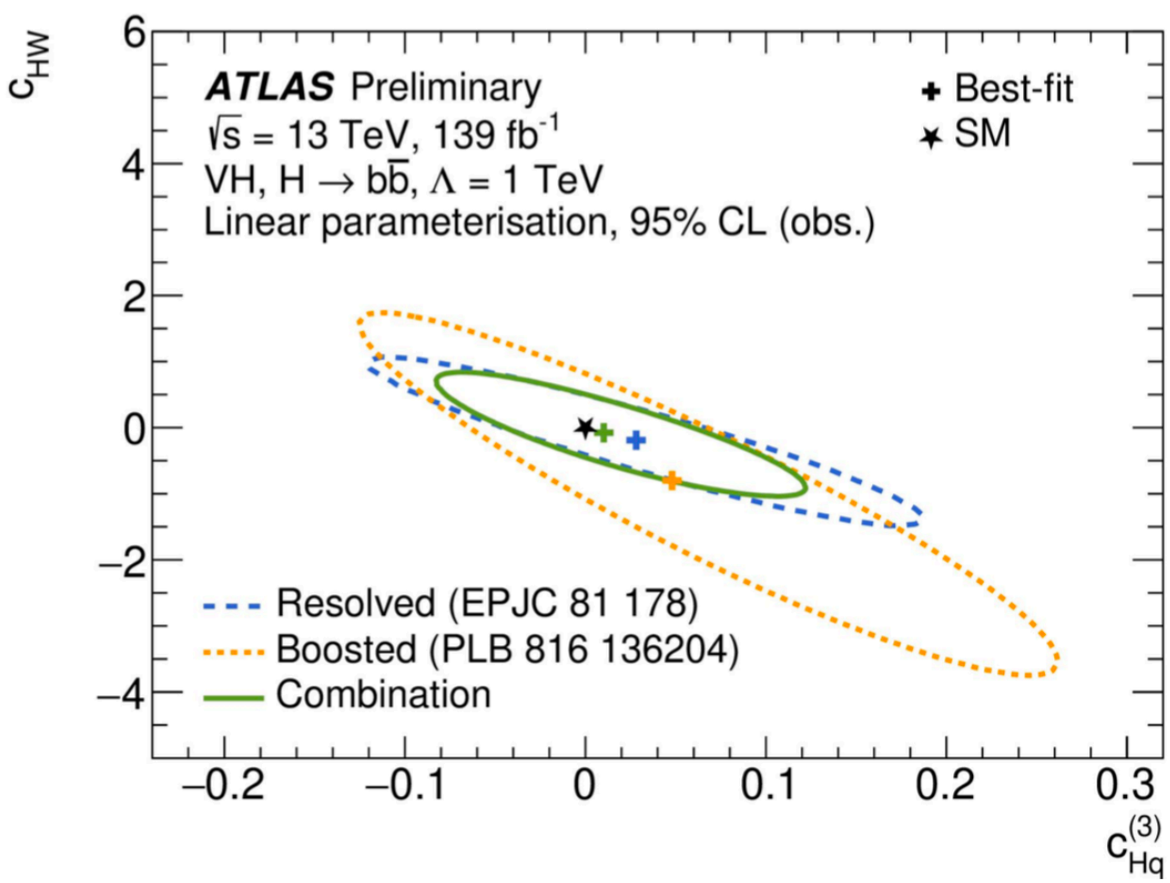




combine resolved & boosted

using $p_T V > 400$ GeV events for boosted only

O_{HW} is mainly responsible for overall modification of the VH cross-section.



$O_{Hq}^{(3)}$ has a strong p_T^V-dependent effect for both WH and ZH production,

Effective Field Theory:

Combination strengthens limits w.r.t. individual analyses.

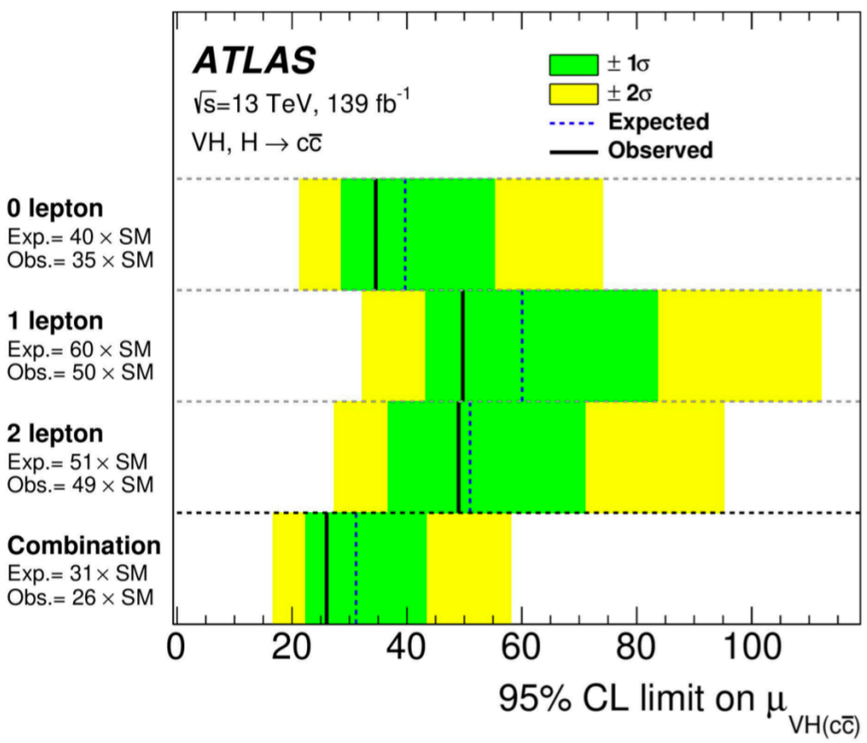
Wilson coefficients of operators of dimension 6

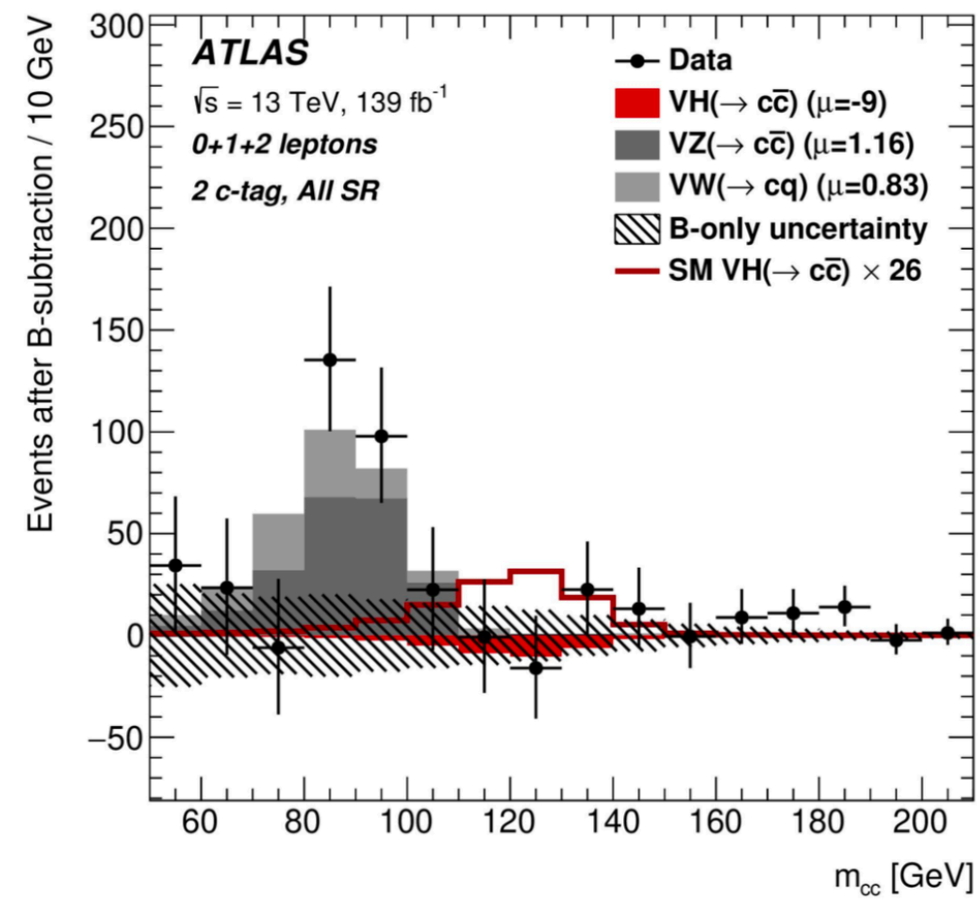
VH, H→cc

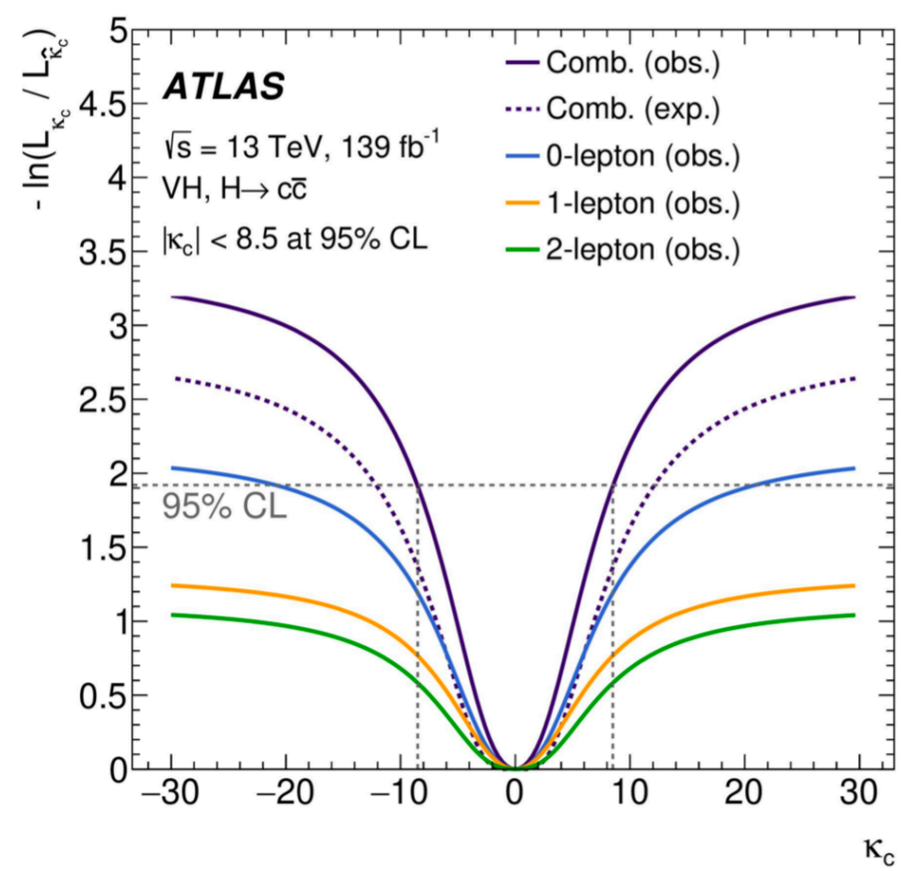
EPJC 82 (2022) 717

Optimized c-jet tagger
validation with di-boson channels

statistical and systematics
same magnitude







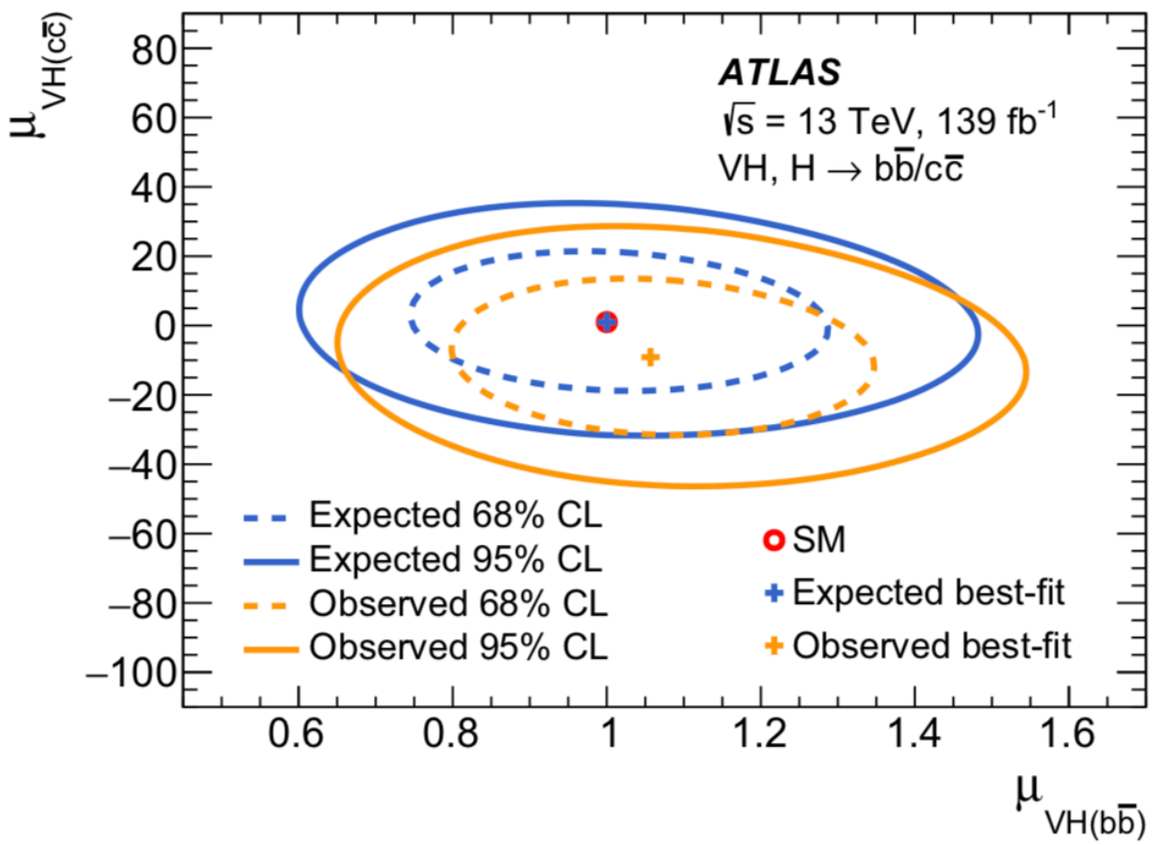
$|k_c| < 8.5$ @ 95% CL

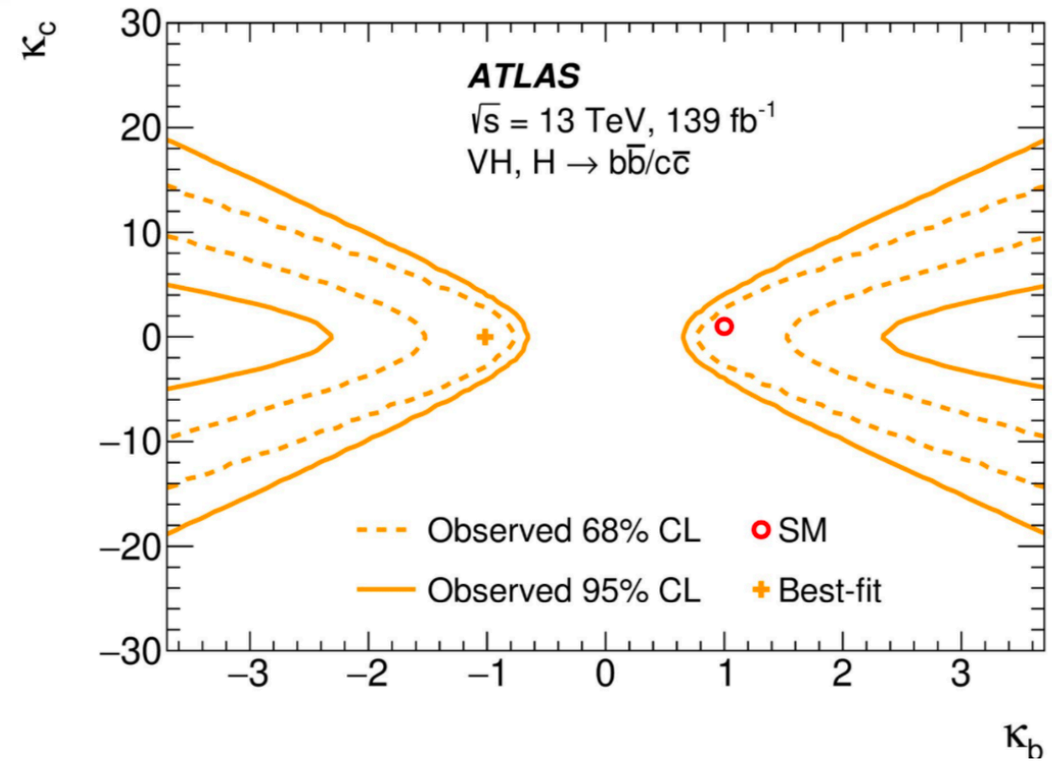
(other H couplings are SM like)

VH, H→cc and H→bb combination

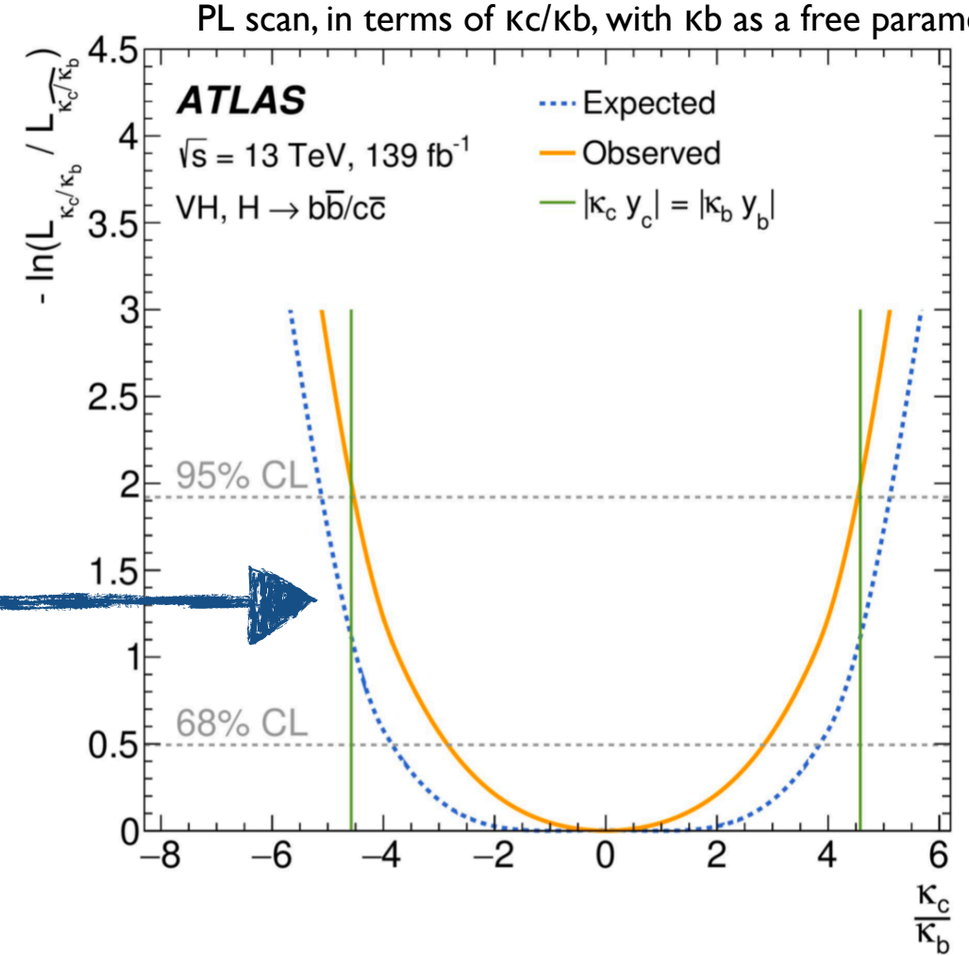
EPJC 82 (2022) 717

Orthogonal analyses
|kc/kb| < 4.5 @ 95% CL





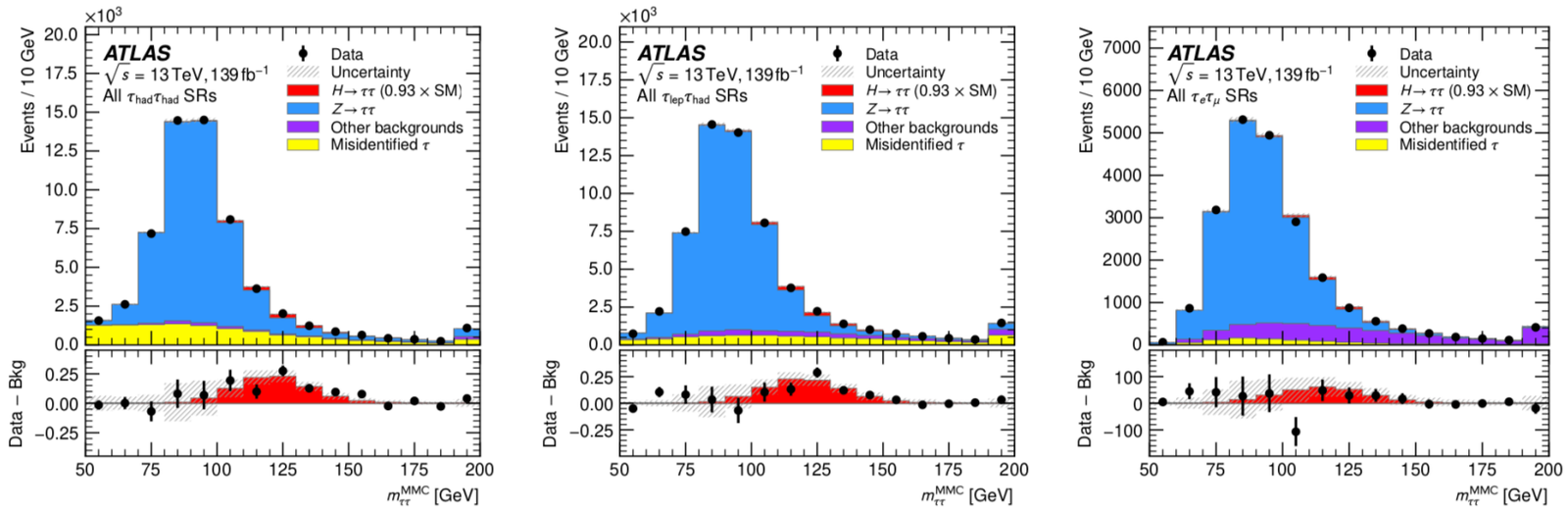
PL scan, in terms of κc/κb, with κb as a free parameter



Higgs-charm coupling is weaker than Higgs-bottom coupling @ 95% CL

H→ $\tau\tau$

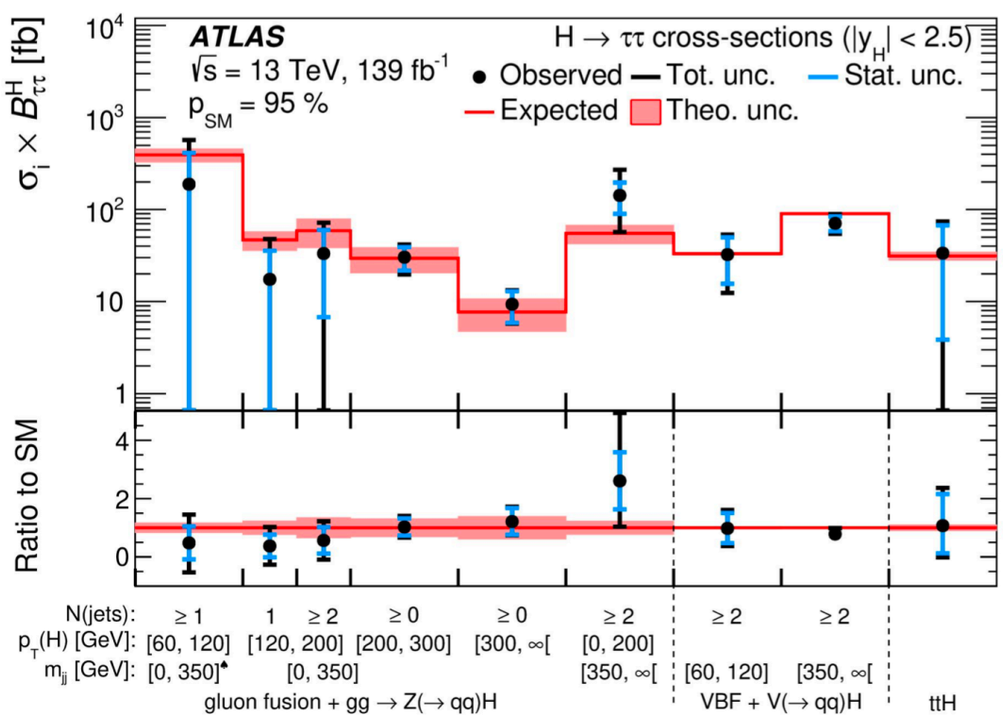
JHEP 08 (2022) 175

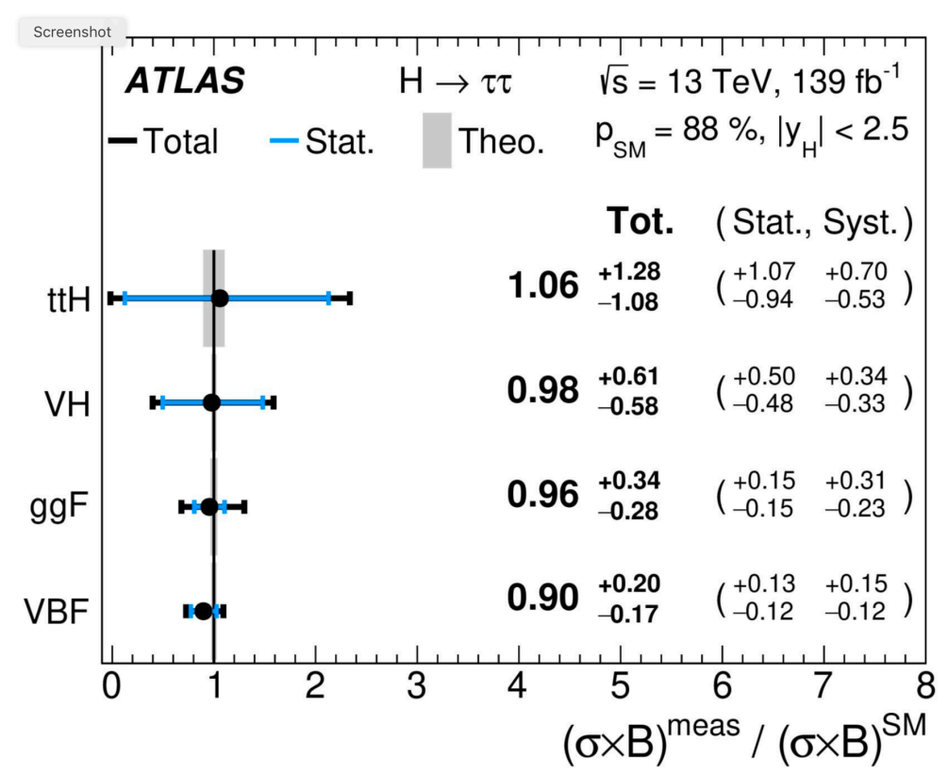


(a) $\tau_{had}\tau_{had}$ (b) $\tau_{lep}\tau_{had}$ (c) $\tau_e\tau_\mu$

best precision for p_T~200-300 and~300-400 GeV regions sensitive to BSM

Inclusive H -> $\tau\tau$ cross section measured with a precision of 13%



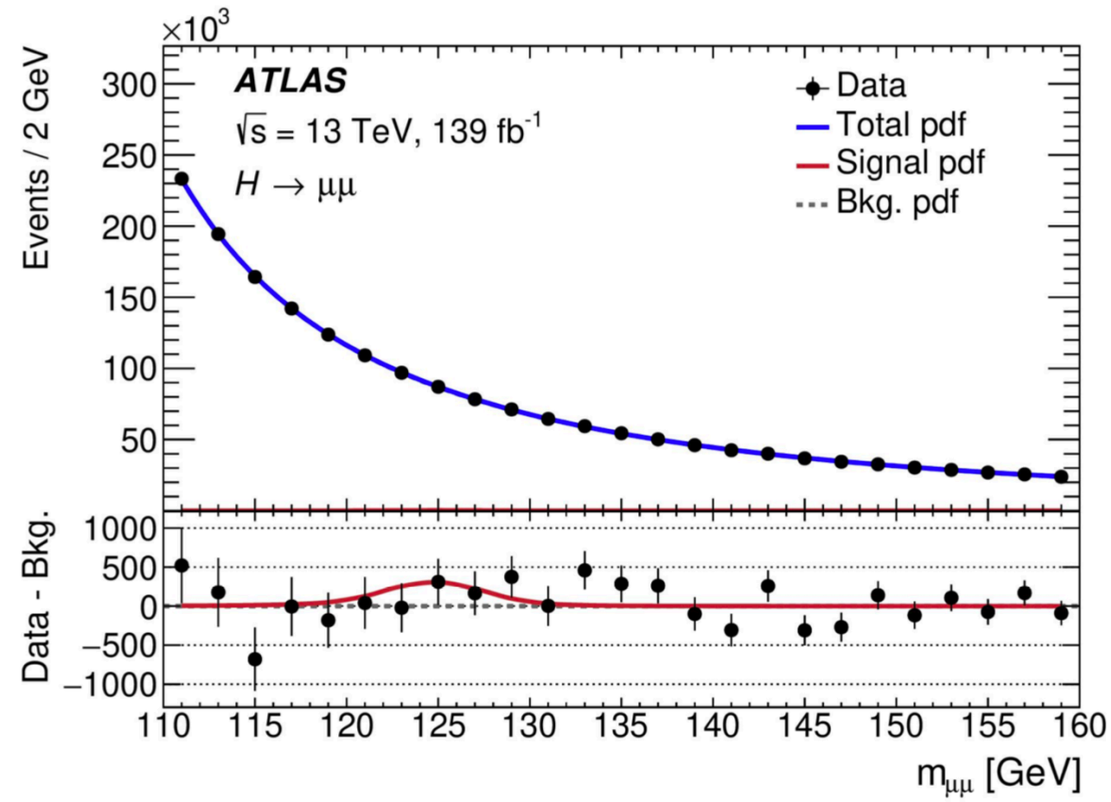


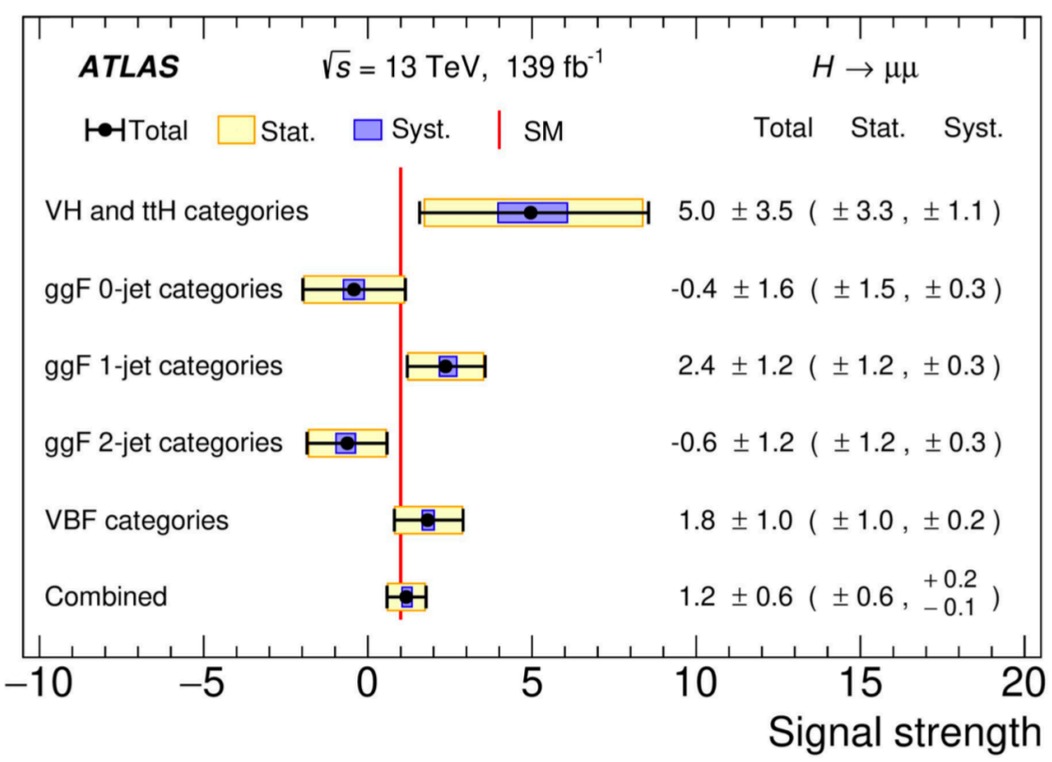
H→μμ

PLB 812(2021) 135980

Z→μμ main background
statistically limited

VBF category is the most powerful!





Observed (expected) significance of 2.0 (1.7) σ

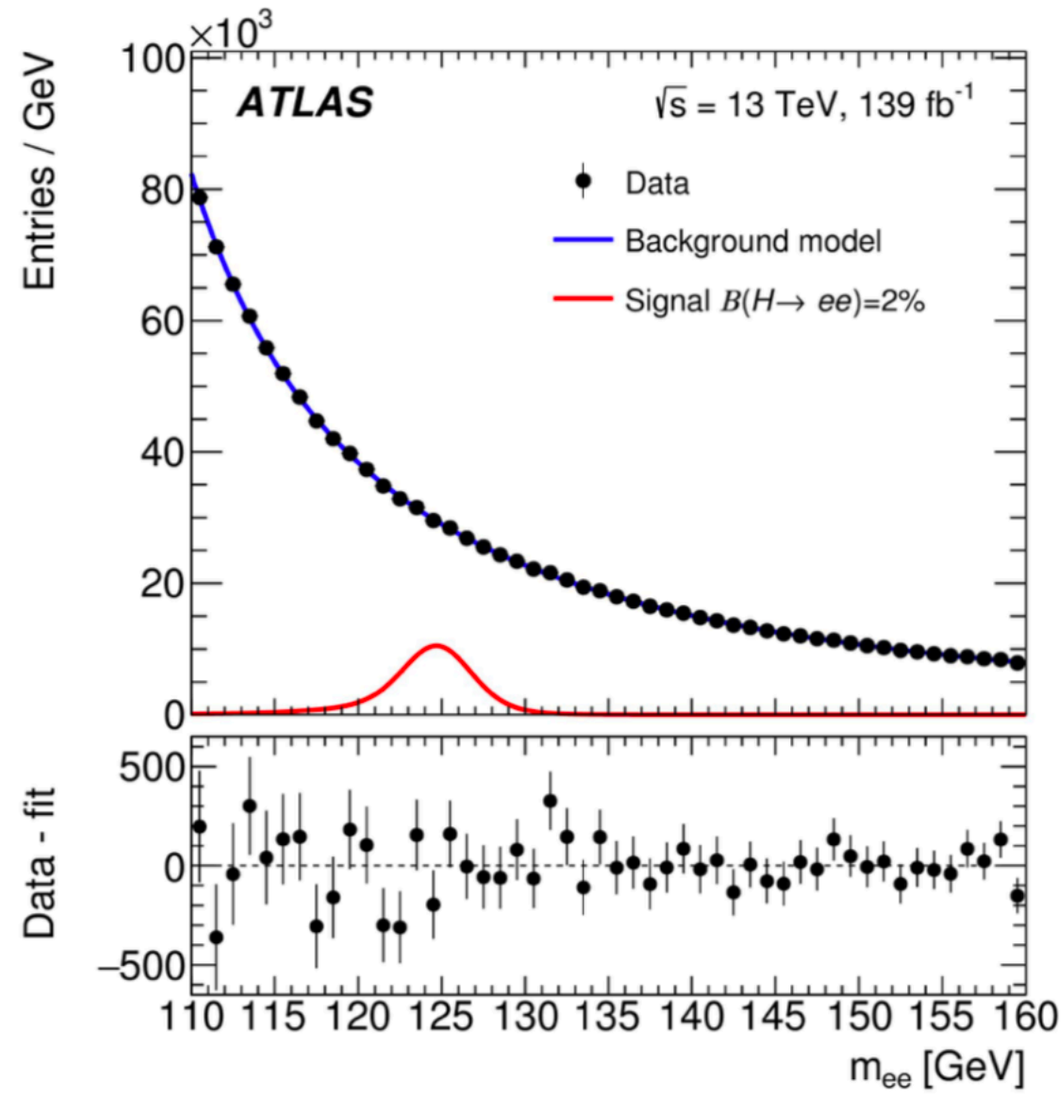
Important in run 3: in reach 3 sigma per experiment and 5 in combination.

H→ee

PLB 801(2020) 135148

Z→ee main background
statistically limited
similar analysis strategy as H→μμ

Observed (expected) limit at 95% CL:
$BR_{H\text{->}ee} < 3.6\ (3.5) \times 10^{-4}$



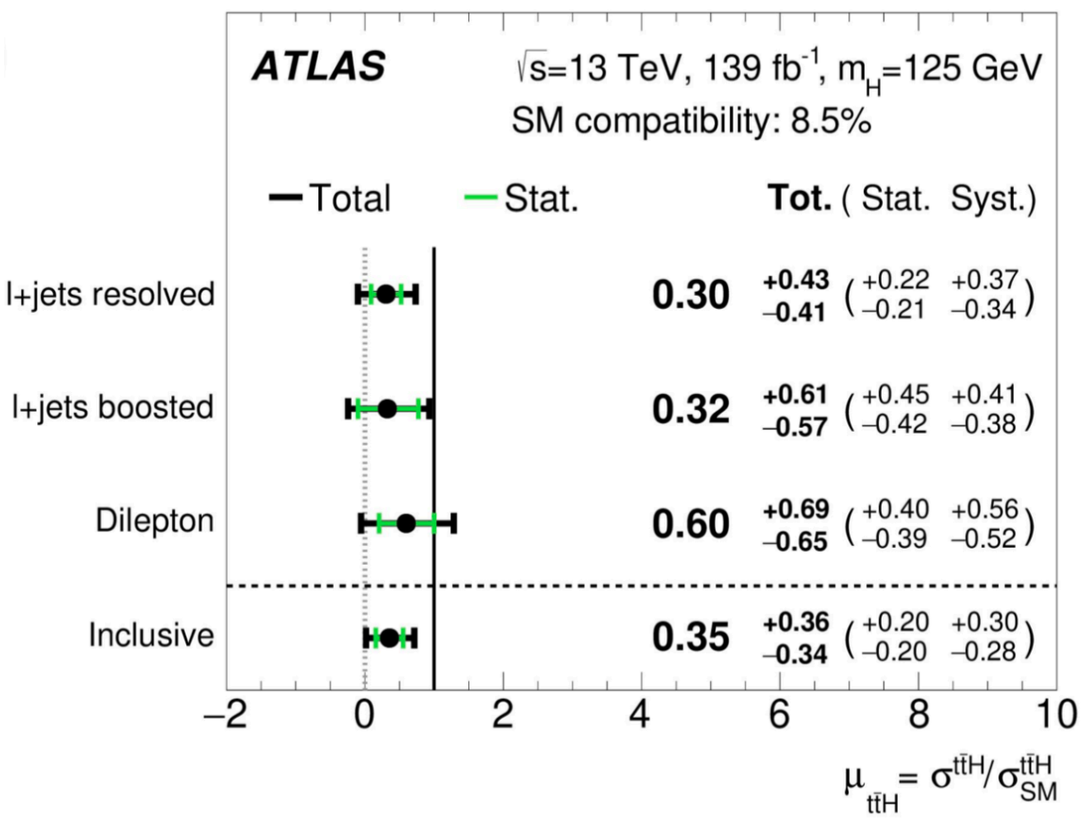
the Higgs boson is around 40,000 times less likely to decay into electrons as it is into muons

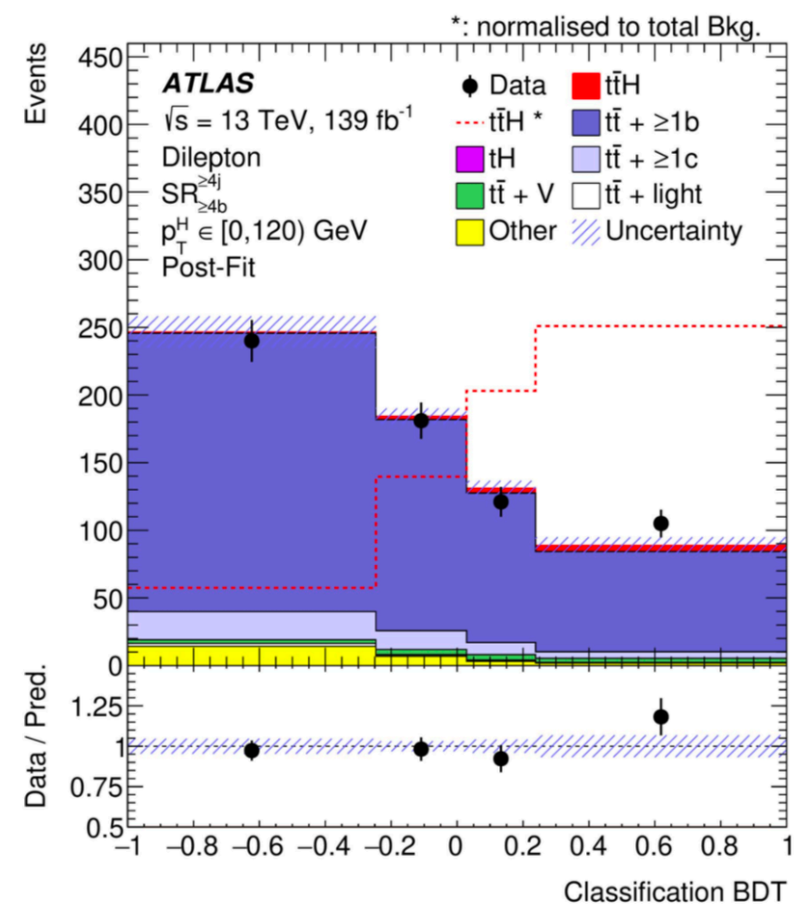
ttH(bb)

JHEP 06 (2022) 097

- The top Yukawa coupling probed with this channel, 1 or both tops decaying leptonically.
- Events classified according to the number of leptons, jets and b-jets
- Machine learning techniques to aid the signal/background discrimination

- significance of 1σ obs (2.1σ exp)



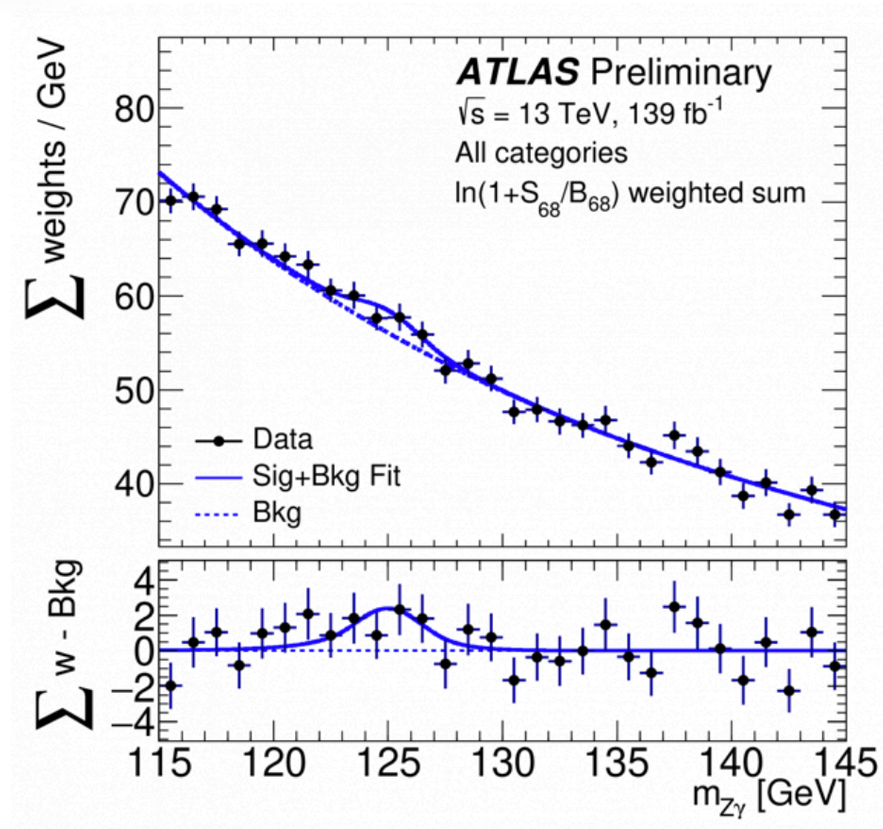


H → Zy and yy*

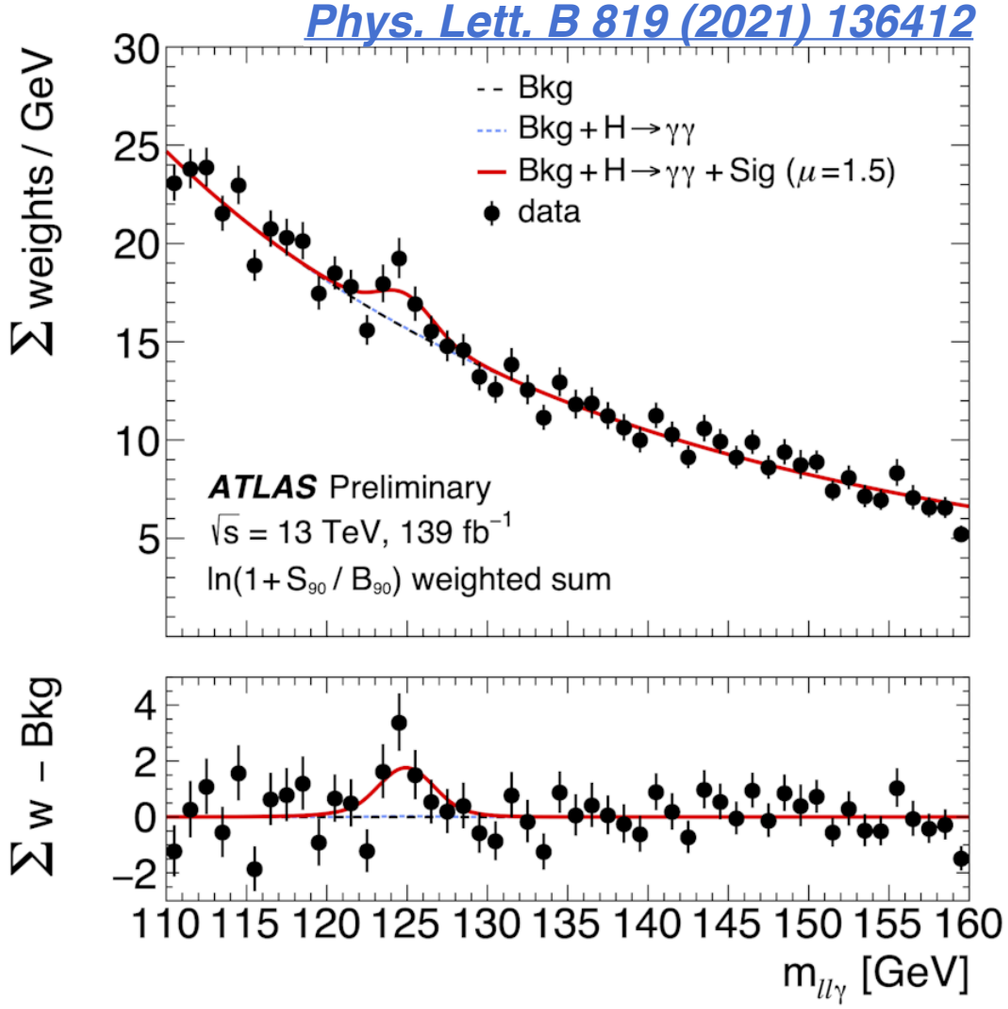
Phys. Lett. B 809 (2020) 135754

The SM predicts 0.15% of Higgs to decay to Zγ comparable to the decay to two photons (Z BR bosons decay to leptons) makes this more challenging.

- significance of 2.2σ obs(1.2σ exp)
- 95%CL upper limit at 3.6xSM obs (2.6xSM exp)



Phys. Lett. B 819 (2021) 136412

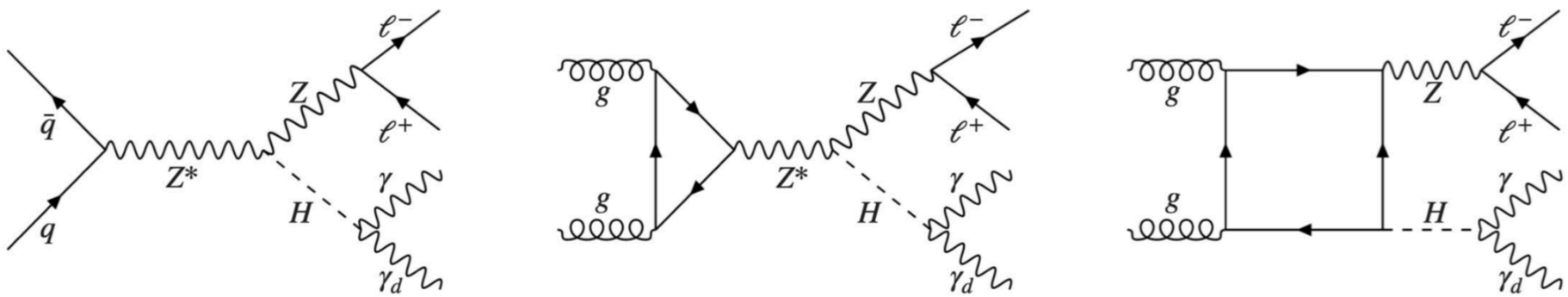


γ* is a virtual particle with(non zero) mass, decays instantly to two leptons
mℓℓ<30 GeV (typically <1 GeV)
high pT, small leptons separation ~cm
(challenge for electrons)

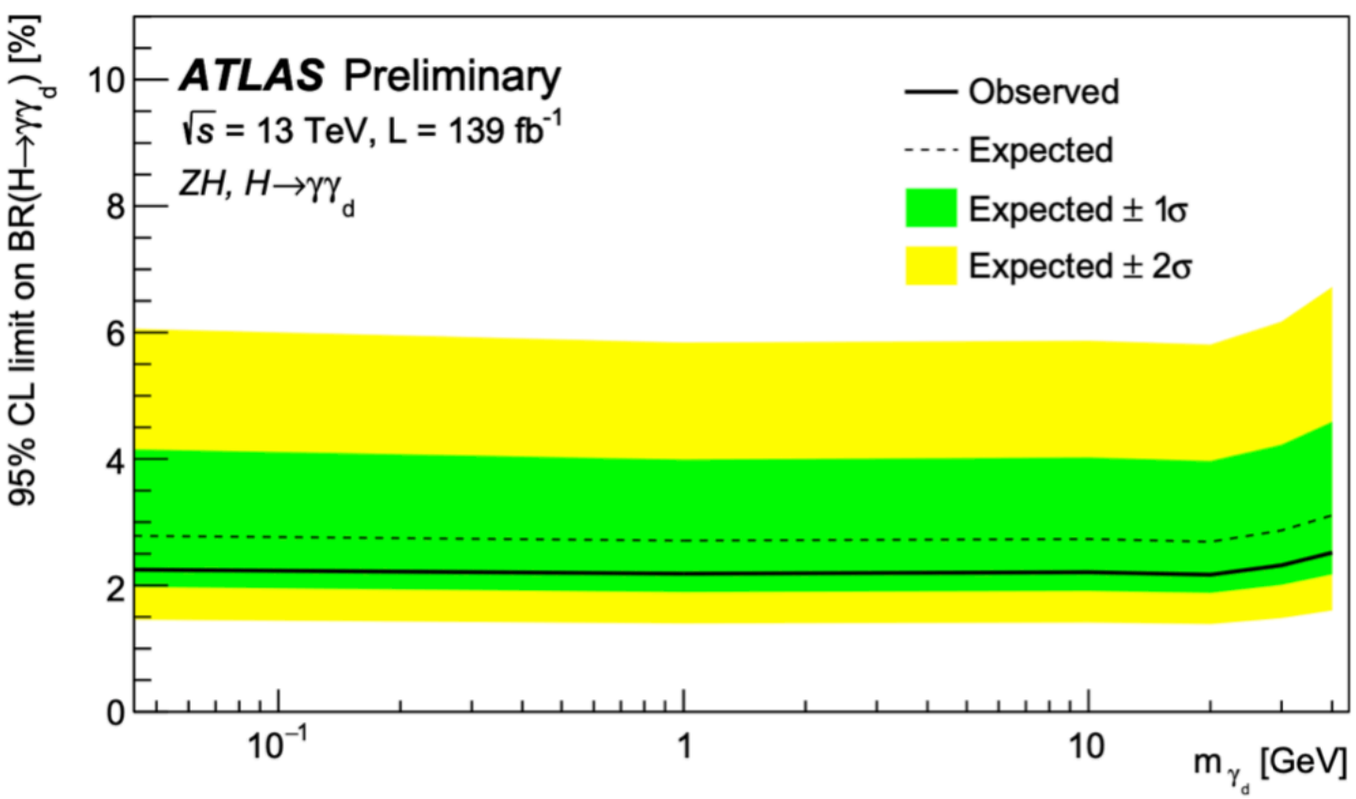
significance of 3.2 σ obs (2.1 σ exp)

Rare decays H → $\gamma\gamma_d$

ATLAS-CONF-2022-064



Exploiting ZH channel, scanning over dark photon mass 0-40 GeV



No excess observed, limit set on BR(H → $\gamma\gamma_d$)

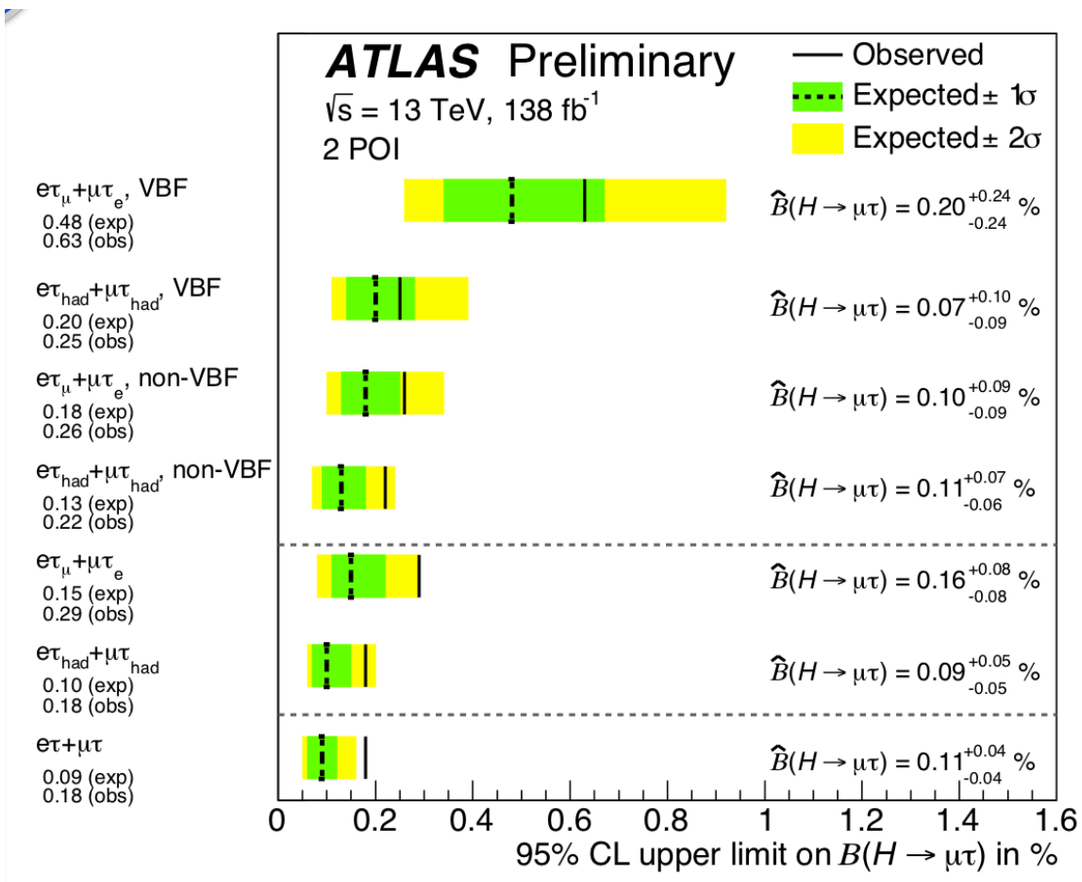
For massless γ_+, BR(H→ $\gamma\gamma_+$) of 2.28% (2.82 expected) at 95% CL

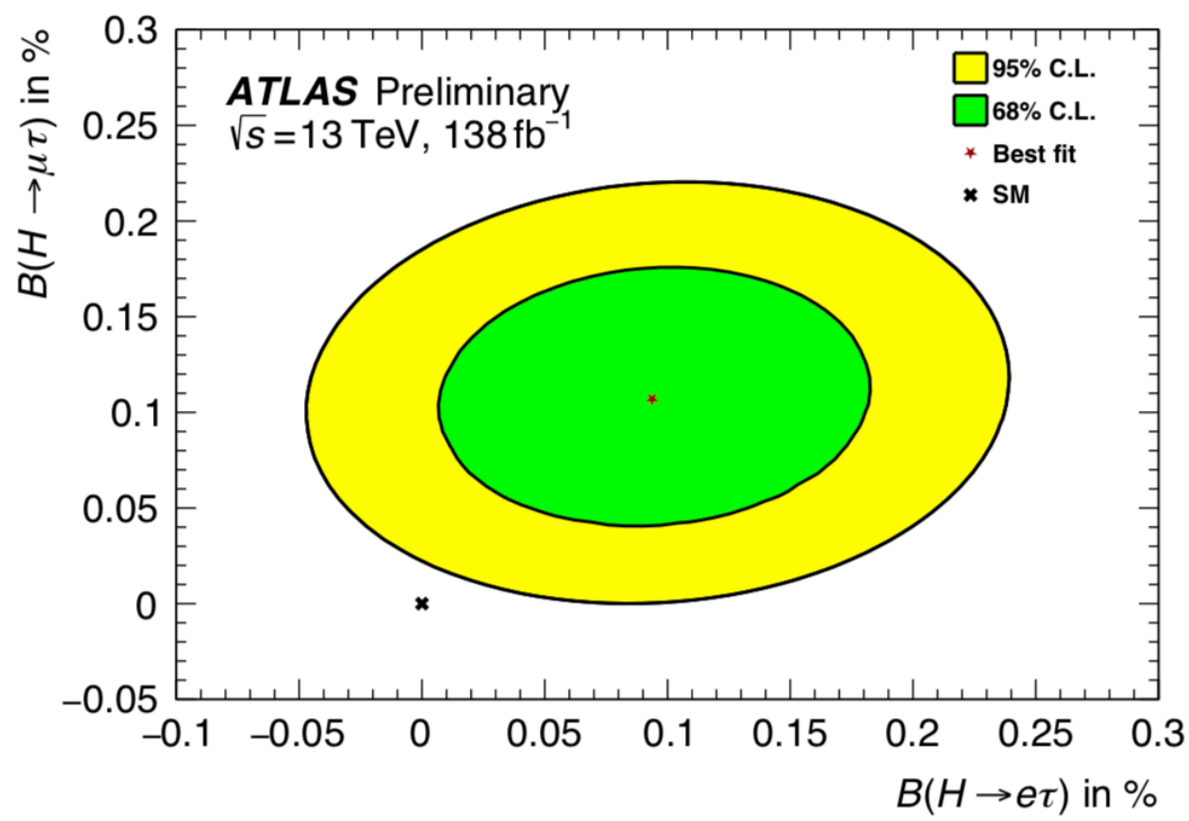
Rare decays H → eτ/μτ

ATLAS-CONF-2022-060

Search for two LFV signals , H → eτ and H → μτ,

Simultaneous fit of H → eτ and H → μτ signal: 2.5 σ excess Br(H → μτ) and 1.6 σ for Br(H → eτ)
H → eτ. BR<0.19% (0.11%) H → μτ BR< 0.18% (0.09 %) @ 95% C.L
compatibility with SM within 2.2 σ
Br(H → μτ)- Br(H → eτ) = 0.25±0.10 %, non significant





Higgs Combination

Nature 607, 52–59 (2022)

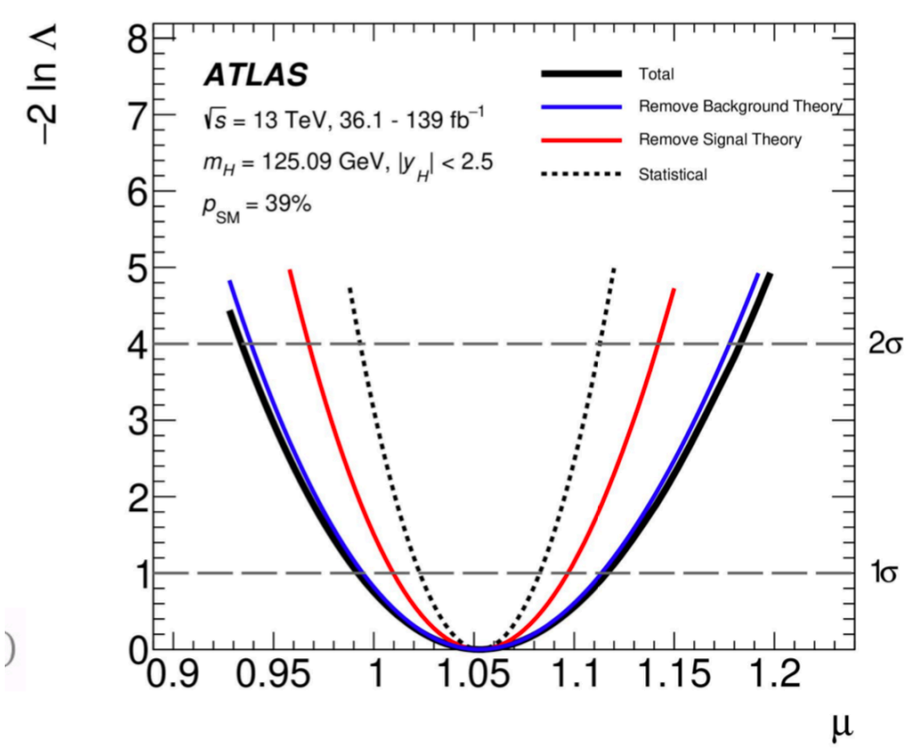
	ggHb	qqH	VH	ttH/tH
H→$\gamma\gamma$	✔	✔	✔	✔
H→ZZ	✔	✔	✔	✔
H→WW	✔	✔	✔	✔
H→$\tau\tau$	✔	✔	✔	✔
H→bb	✔	✔	✔	✔
H→$\mu\mu$	✔	✔	✔	✔
H→cc			✔	
H→Zγ	✔	✔	✔	✔
H→inv		✔	✔	

Missing channels

P.Francavilla

	ttH	tH	ggF	VBF	WH	ZH
γγ	139	139	139	139	139	139
ZZ* (4l)	139		139	139	139	
WW*			139	139	36.1	36.1
bb	139		incl. boost: 139	126	139	139
ττ	139		139	139	139	
ttH multilept	80					
cc					139	
μμ	139				139	
Zγ	(inclusive) 139					
inv				139		Z(ll)H: 139
			Not in Kinematic (NO STXS)			
			Only for Kinematic (ONLY STX			
			Only for floating kc			
			K models with Binv & Bu			

Missing VH, H → WW with full Run-2
ttH, H → multi lepton [performing ttW measurement program]
Additional modes for H → invisible

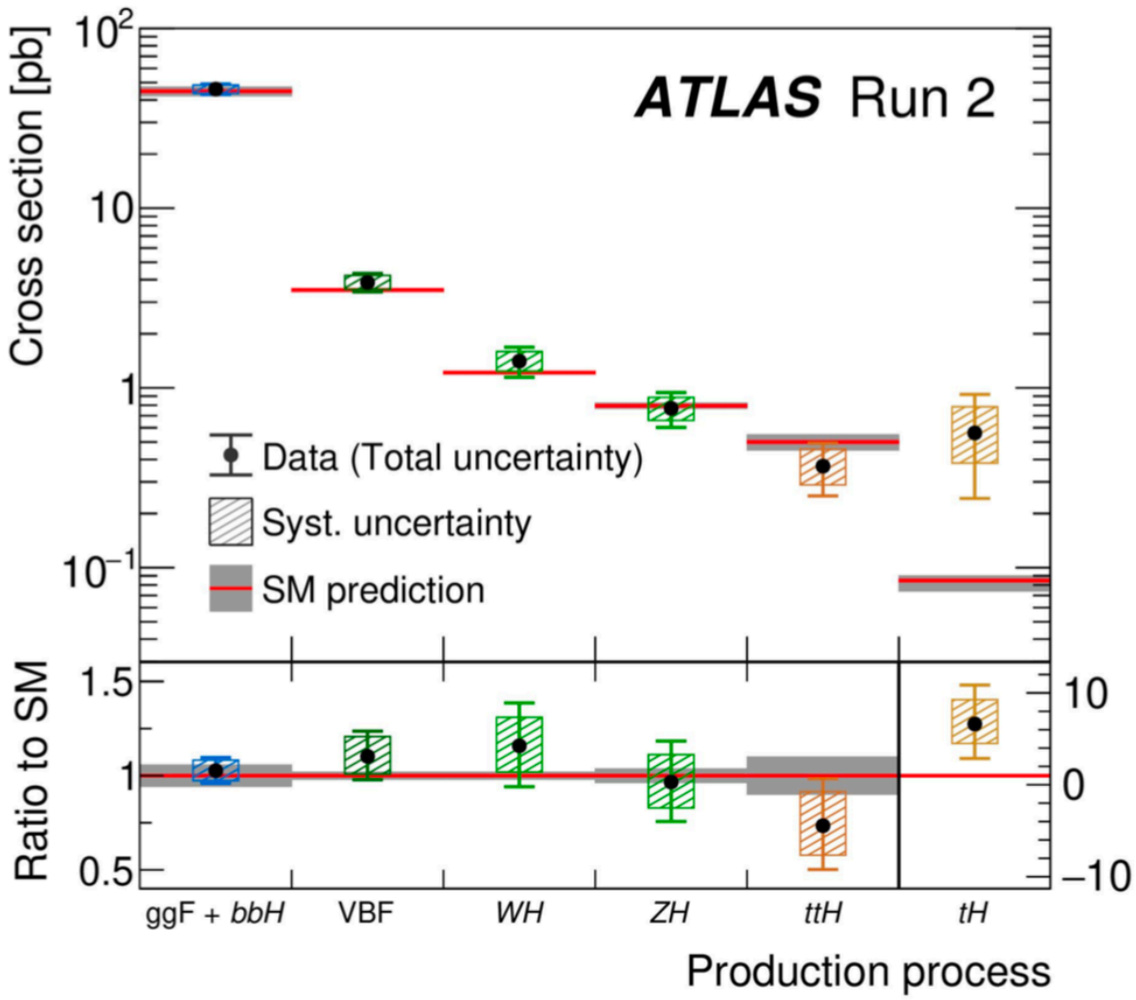


Measurement at 6%!

$$\mu = 1.05 \pm 0.06 = 1.05 \pm 0.03\,(\text{stat.}) \pm 0.03\,(\text{exp.}) \pm 0.04\,(\text{sig. th.}) \pm 0.02\,(\text{bkg. th.}).$$

Production x-sections

individual channels
- 10% uncertainty on ggF
- 20-30% on VBF



decays are assumed to be SM
ggF precision 7%
VBF precision 12%

Main production modes observed

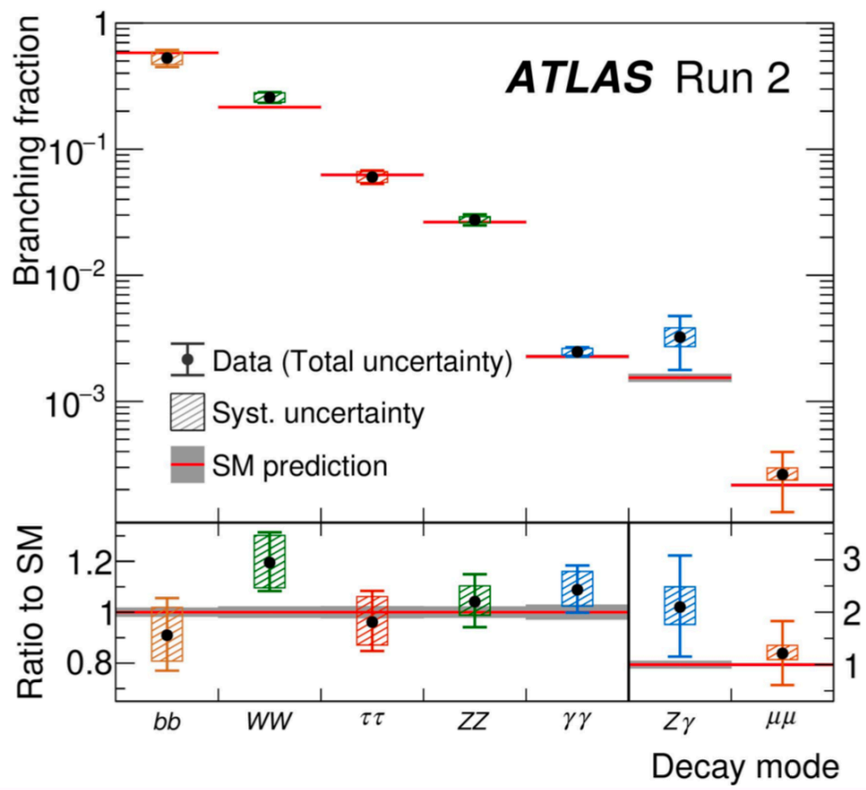
- WH 5.8σ (5.1σ expected),
- ZH with 5.0σ (5.5σ)
- ttH+tH with 6.4σ (6.6σ)

C

SM decays assumed

Decays

SM prod modes assumed

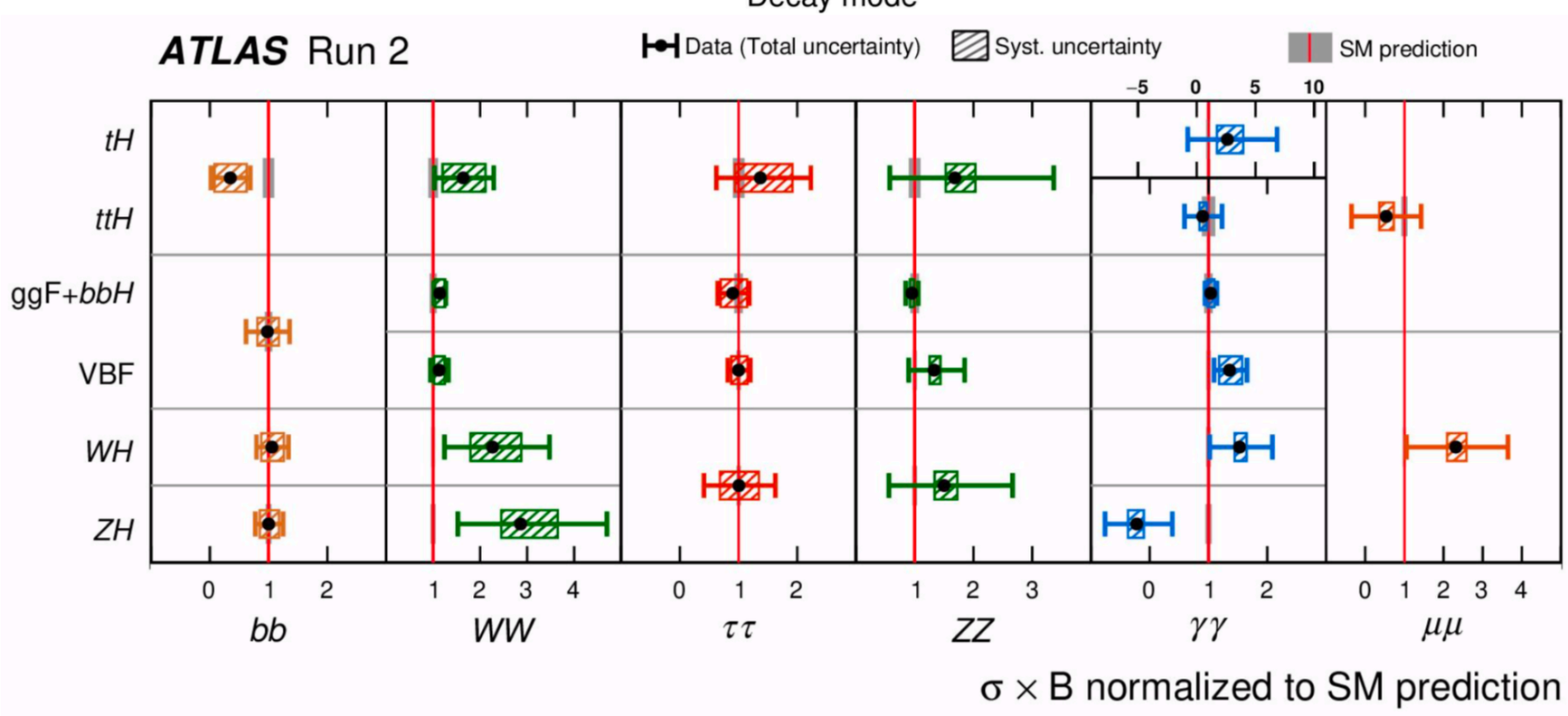


All major decay modes have been observed:

- BR(bb) precision of 14%
- BR(ττ), BR(WW), BR(ZZ) and BR(γγ) now at precision of 10-12%

Rare production modes:

- H→μμ @2.0σ (1.7σ)
- H→Zγ @ 2.2σ (1.2σ)



full picture:
production and decay!

kappa framework

LO modifier to probe for deviations from SM

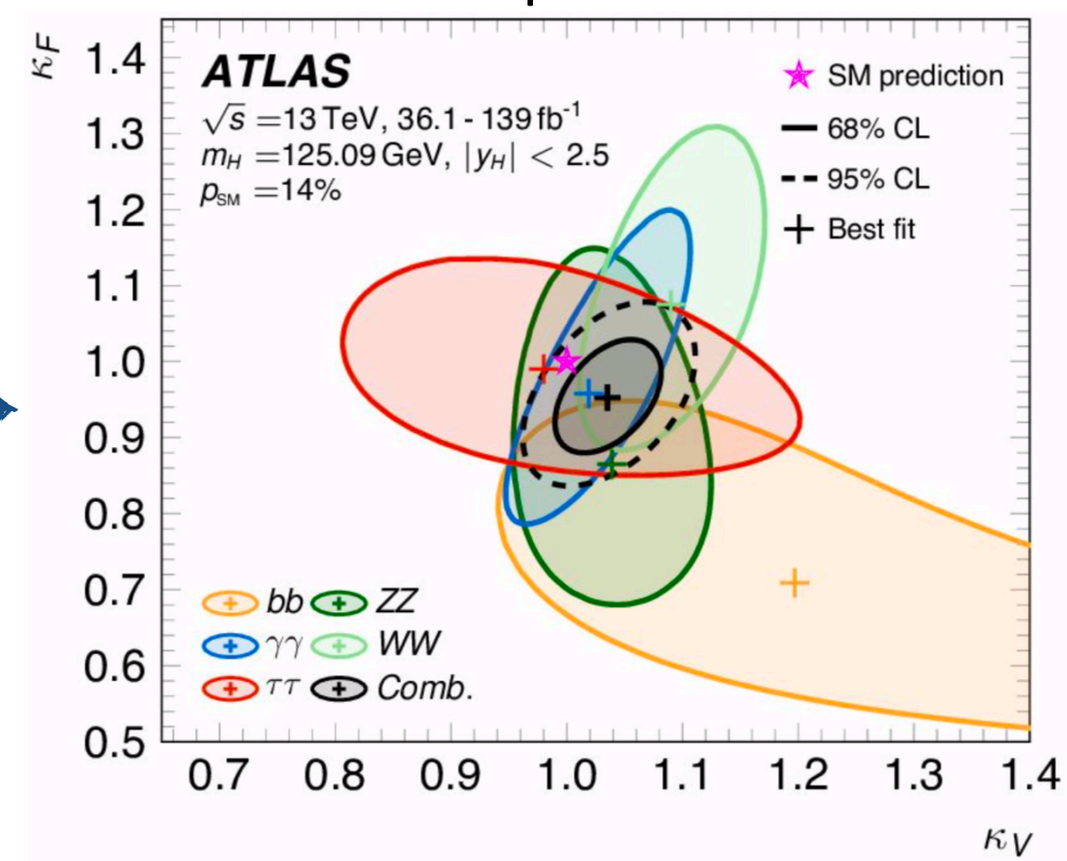
$$\sigma(i \to H \to f) = \sigma_i B_f = \frac{\sigma_i(\kappa)\Gamma_f(\kappa)}{\Gamma_H(\kappa, B_{\text{inv.}}, B_{\text{u.}})},$$

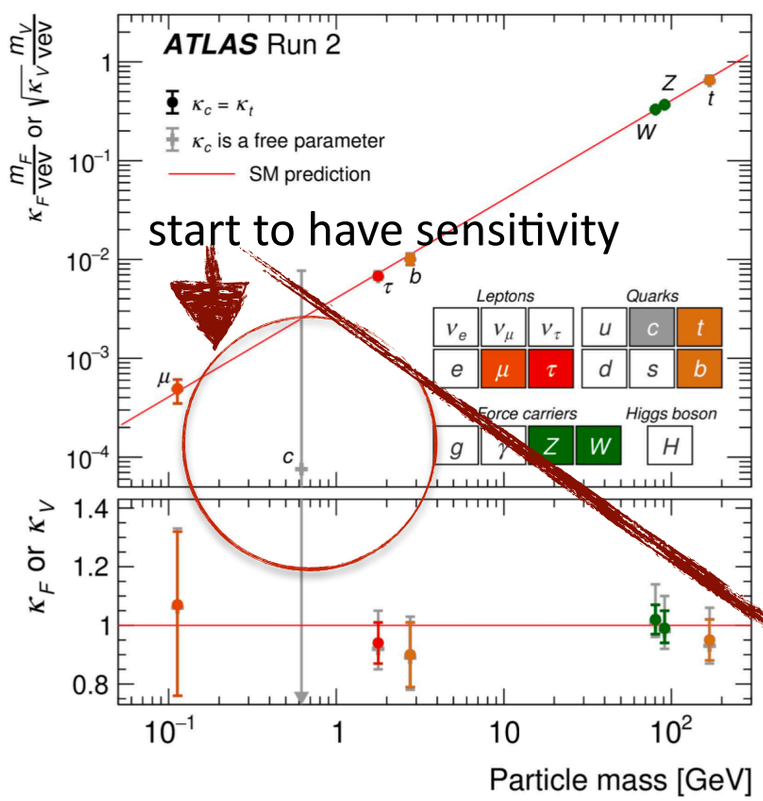
using 1 coupling modifier for fermions and one for vector bosons

$$\kappa_V = 1.035^{+0.031}_{-0.031}$$
$$\kappa_F = 0.95^{+0.05}_{-0.05}$$

3/5% precision respectively

p-value 14%





SM compatibility 72%

All modifiers assumed to be positive

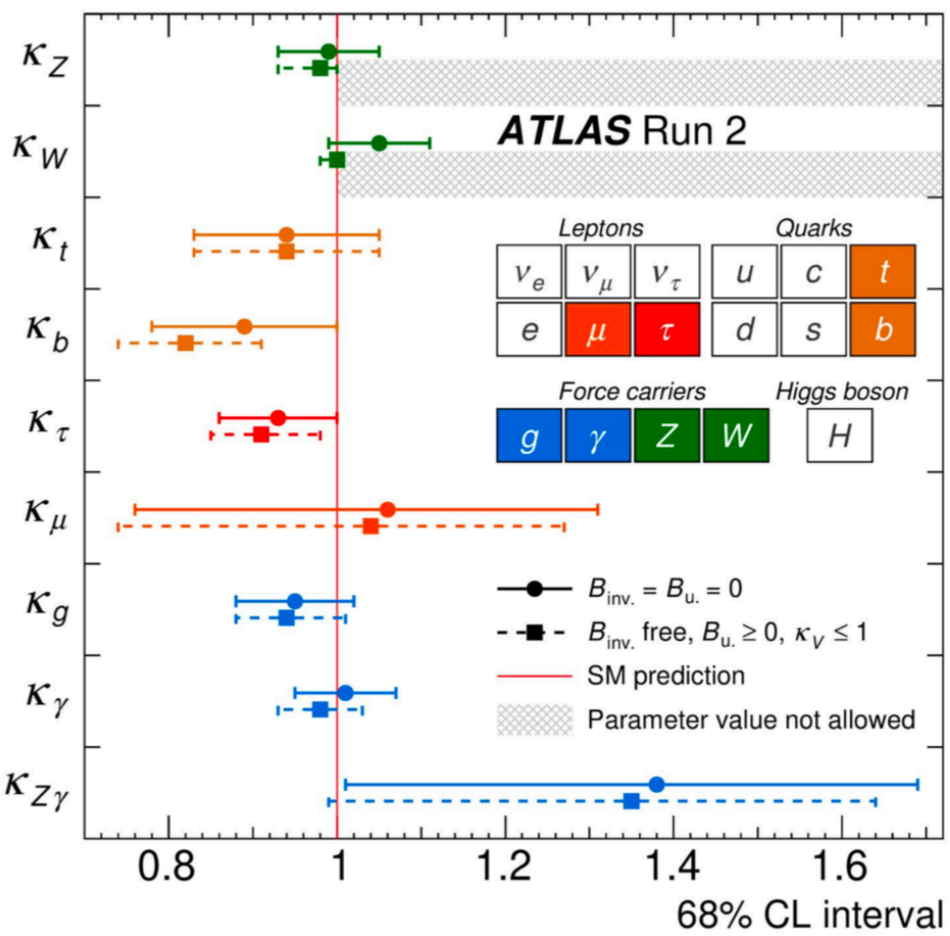
- Only SM particles in loop processes
- No invisible or undetected non-SM Higgs decays
- κc=κt colored markers (κc free-floating grey)

coupling precision

- Fermions (t, b, τ): 7% -12%
- Vector bosons (W, Z): 5%
- Upper limit on κc of 5.7 (7.6) x SM at 95% CL

kappa framework

Allowing for non SM particles in the loops now
with effective couplings strength
with and without invisible and undetected non-SM Higgs decays.
Still good agreement with the SM



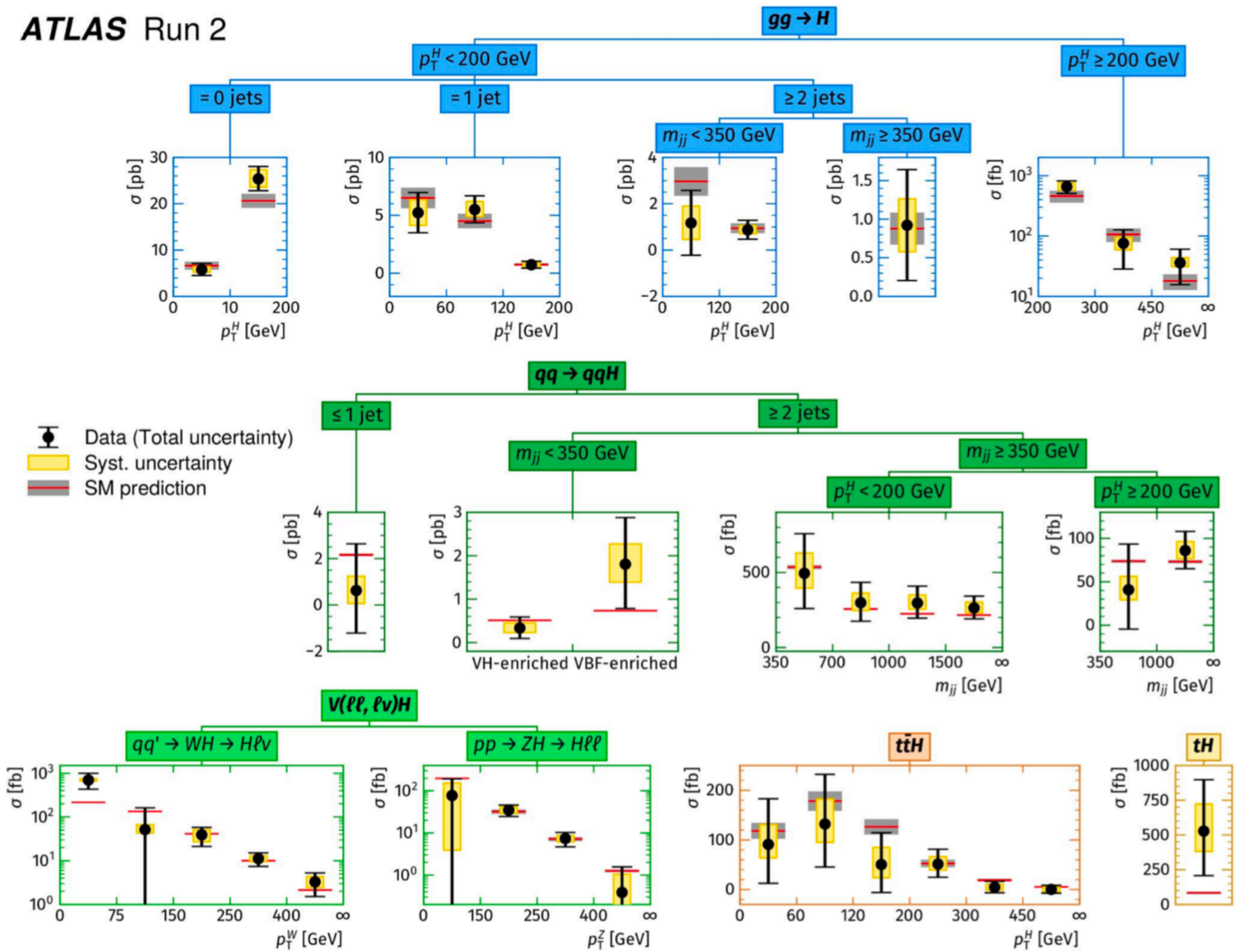
If we live the BR to inv and undetected floating
Upper limits on B_{inv} of 0.13 (0.08) and
$B_{undetected}$ of 0.12 (0.21) at 95% CL

@LHC cannot directly measure total width

need |κV | < 1 assumption to extract BR_{und}.

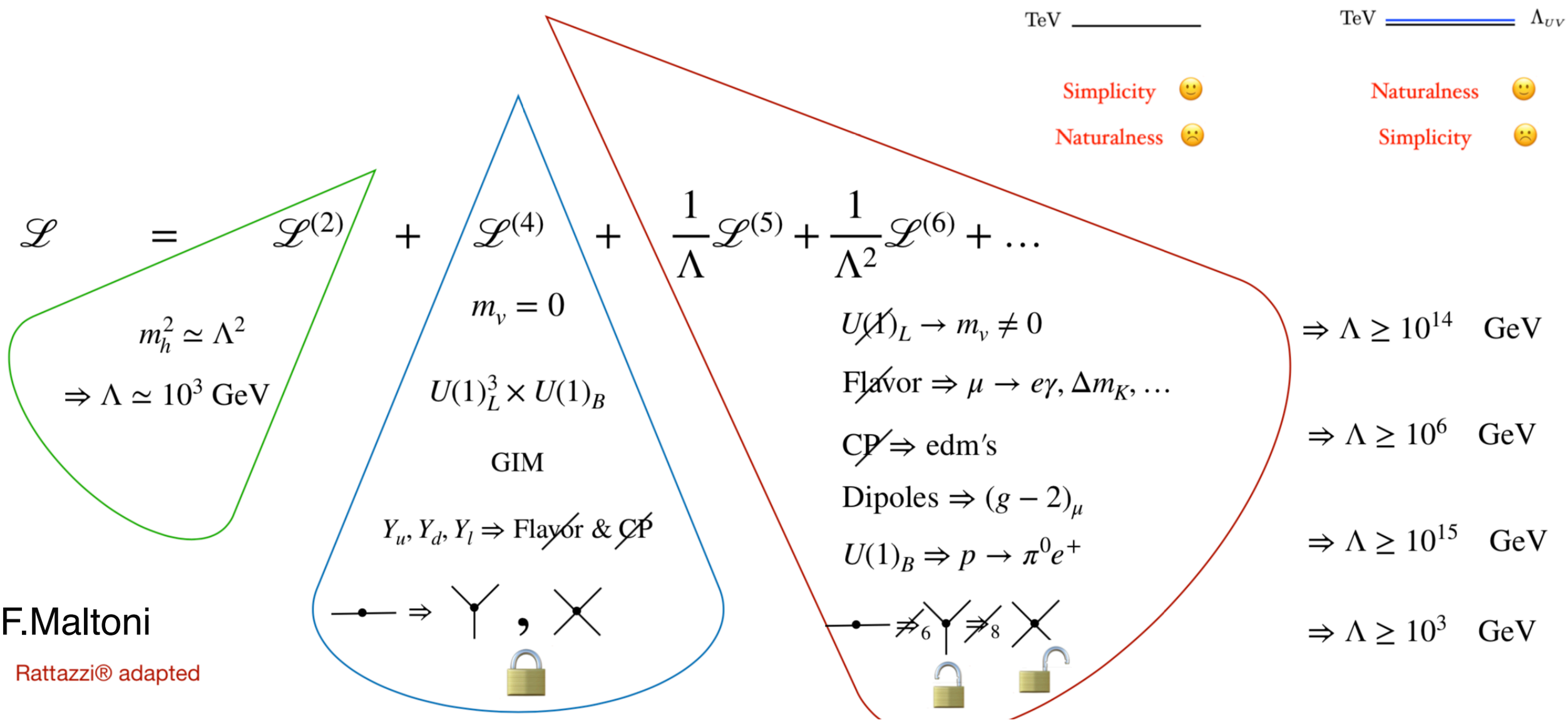
global STXS

p-value 92%



Effective Field Theory

- EFT is a formal expansion of he lagrangian in terms of the new physics scale. Higgs EFT based measurements takes all possible leading (dim6) deviations from heavy new physics into account .
- Parametrize deviations from the SM in this way in order to find evidence of New Physics



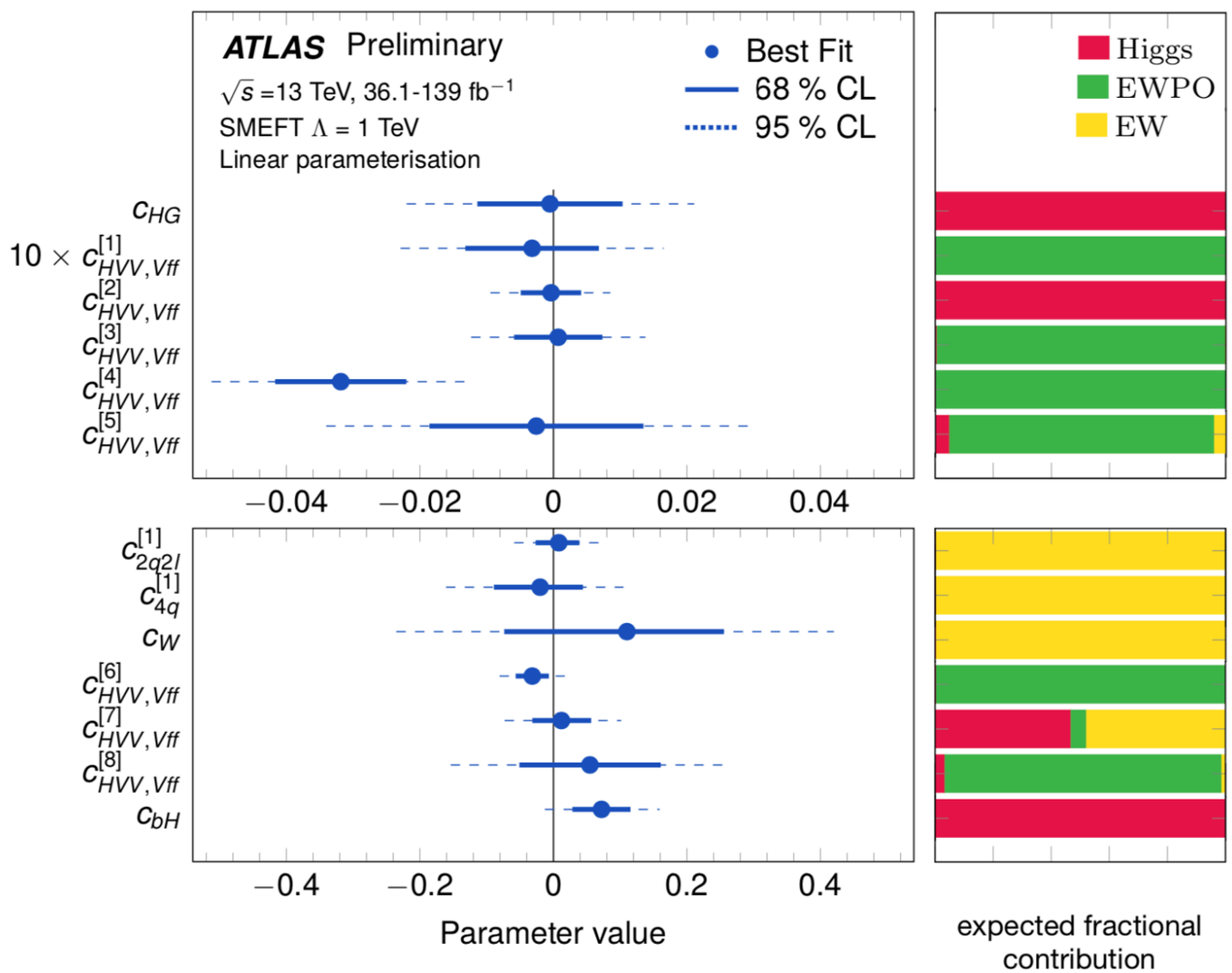
EFT interpretations

Higgs + EW + precision observables SMEFT global fit

ATL-PHYS-PUB-2022-037

- ATLAS Higgs STXS measurement (ATLAS-CONF-2021-053)
- ATLAS differential cross-section measurements of weak boson production (ATL-PHYS-PUB-2021-022)
- LEP + SLC electroweak precision observables (EWPO) (Phys. Rept. 427 (2006) 257), 8 observables included

Measurement for 6 Wilson coefficients + 22 linear combinations (rotations performed from Warsaw basis to linear combinations of operators with sensitivity)



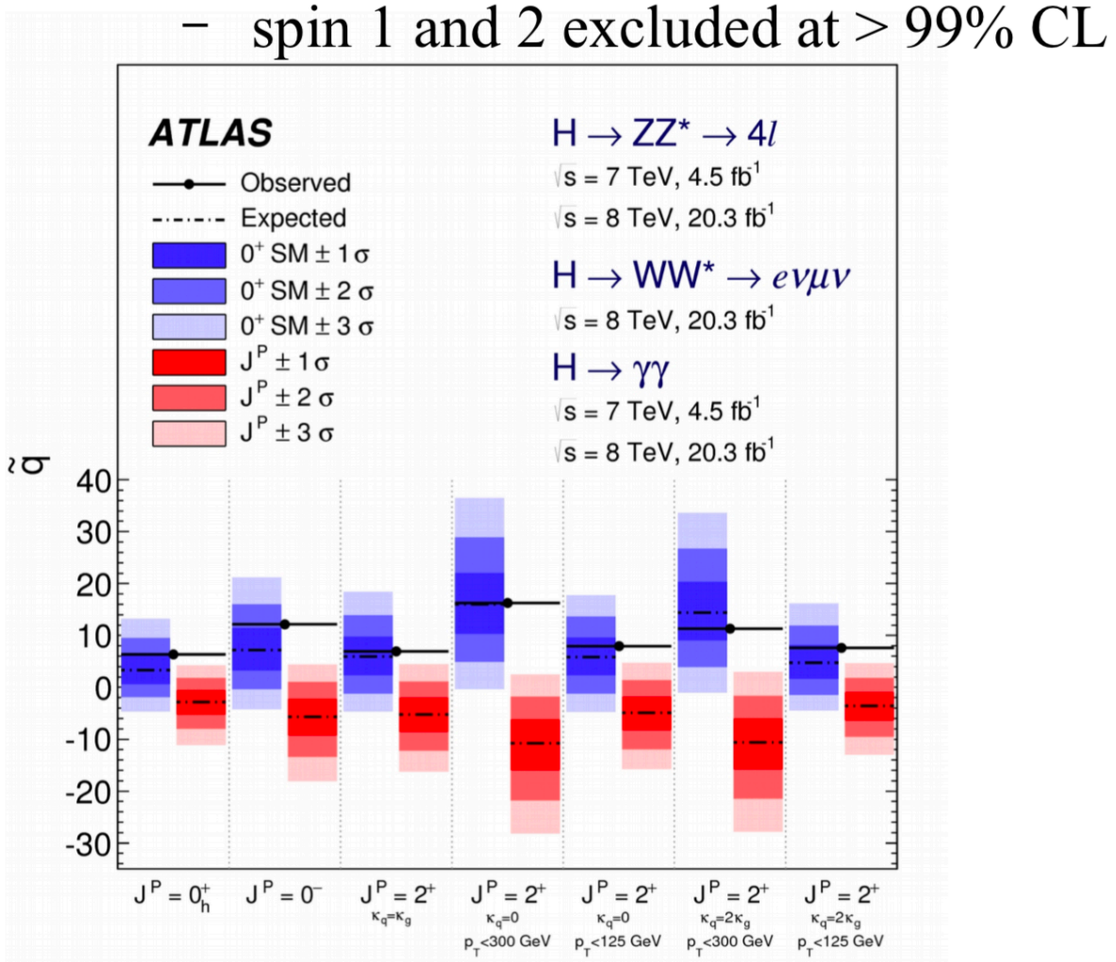
largest deviation from SM: $c^{[4]}_{HVV,VFF}$

from known $A^{0,b}_{FB}$, $A^{0,c}_{FB}$ discrepancies

There is a growing number of EFT interpretations made by ATLAS

CP violation

- Spin/parity: $J^{PC} = 0^{++}$
  - spin 1 and 2 excluded at > 99% CL



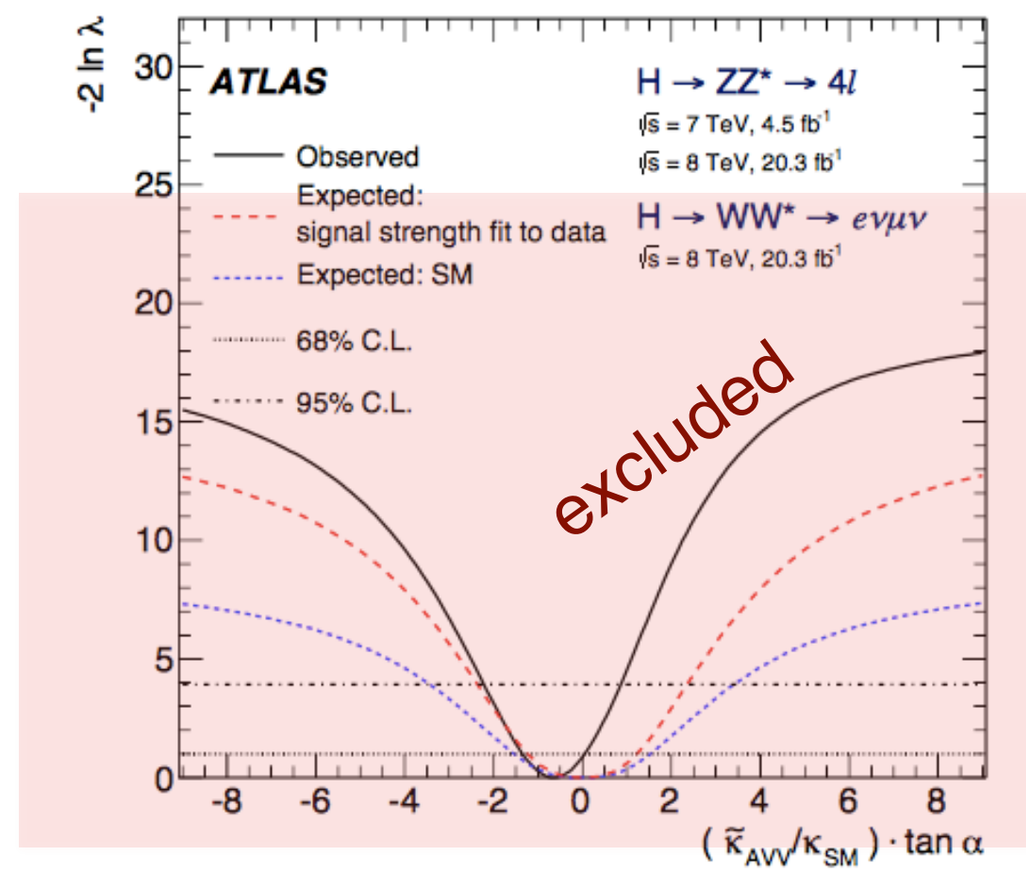
In bosonic couplings parametrized with higher order terms suppressed by powers of Λ (scale of new physics)

$$\mathcal{L}_{VVH} = \mathcal{L}_{VVH,SM} + \frac{1}{\Lambda^2} c\, \phi \widetilde{V}_{\mu\nu} V^{\mu\nu} + \ldots$$

Fermionic couplings affected at tree level (more important for heavier fermions due to higher coupling)

α CP- even and CP-odd mixing angle

$$\mathcal{L}_{ffH} = \kappa'_f y_f \phi \bar{\psi}_f (\cos\alpha + i\gamma_5 \sin\alpha)\psi_f$$



CP odd increasing

H-top Coupling in ttH/tH production H→bb

ATLAS-CONF-2022-016

Channel (PSR)	Final SRs and CRs	Classification BDT selection	Fitted observable
Dilepton ($PSR^{\geq 4j, \geq 4b}$)	$CR_{no\text{-}reco}^{\geq 4j, \geq 4b}$	–	$\Delta\eta_{\ell\ell}$
	$CR^{\geq 4j, \geq 4b}$	BDT∈ [−1, −0.086)	b_4
	$SR_1^{\geq 4j, \geq 4b}$	BDT∈ [−0.086, 0.186)	b_4
	$SR_2^{\geq 4j, \geq 4b}$	BDT∈ [0.186, 1]	b_4
ℓ+jets ($PSR^{\geq 6j, \geq 4b}$)	$CR_1^{\geq 6j, \geq 4b}$	BDT∈ [−1, −0.128)	b_2
	$CR_2^{\geq 6j, \geq 4b}$	BDT∈ [−0.128, 0.249)	b_2
	$SR^{\geq 6j, \geq 4b}$	BDT∈ [0.249, 1]	b_2
ℓ+jets ($PSR_{boosted}$)	$SR_{boosted}$	BDT∈ [−0.05, 1]	Classification BDT score

$$b_2 = \frac{(\vec{p}_1 \times \hat{n}) \cdot (\vec{p}_2 \times \hat{n})}{|\vec{p}_1||\vec{p}_2|}$$

$$b_4 = \frac{p_1^z p_2^z}{|\vec{p}_1||\vec{p}_2|}$$

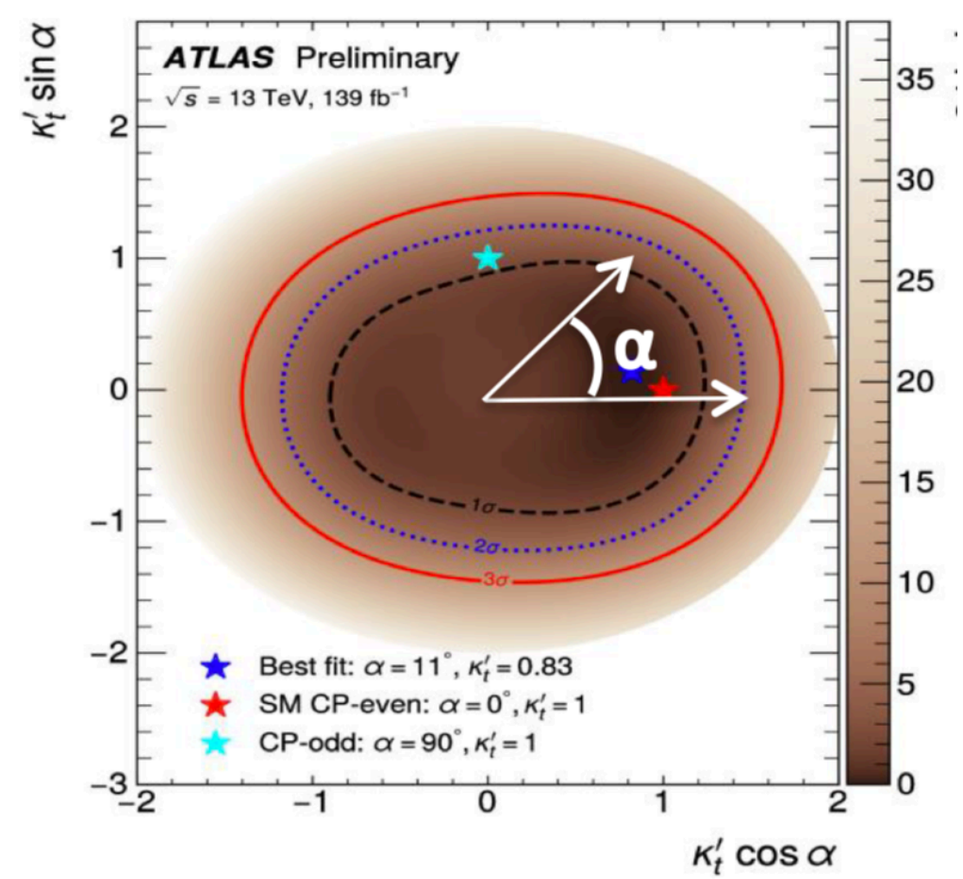
h->bb final state

Systematics-dominated analysis:

Dominant uncertainties from tt+≥1b modelling: NLO matching, PS and hadronisation, flavour scheme

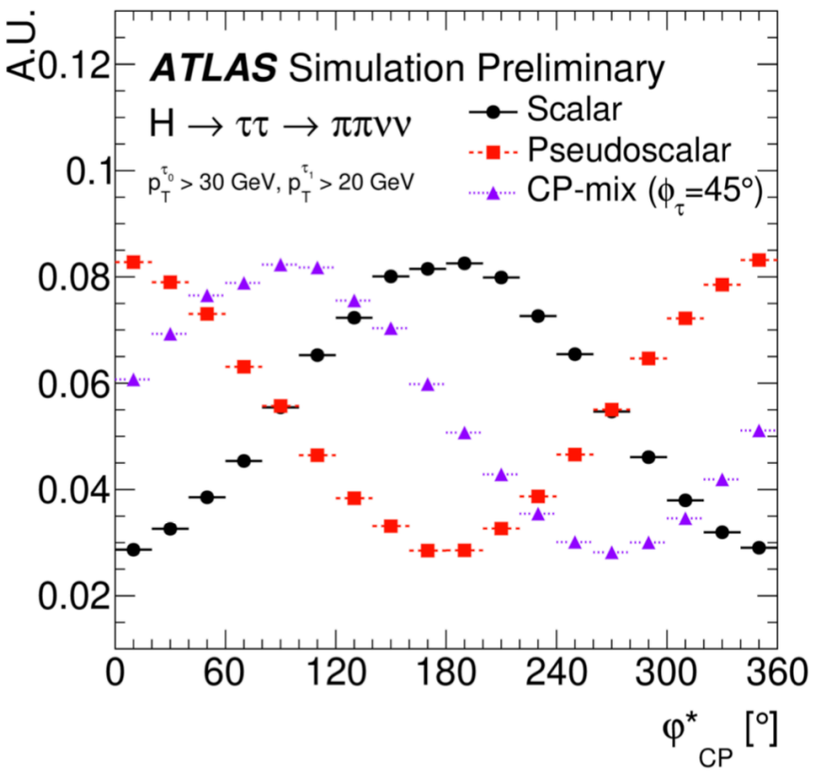
Pure CP-odd (α = 90°) disfavoured at 1.2 σ

$$\mathcal{L}_{ffH} = \kappa'_f y_f \phi \bar{\psi}_f (\cos\alpha + i\gamma_5 \sin\alpha)\psi_f$$



H-τ Coupling in inclusive production

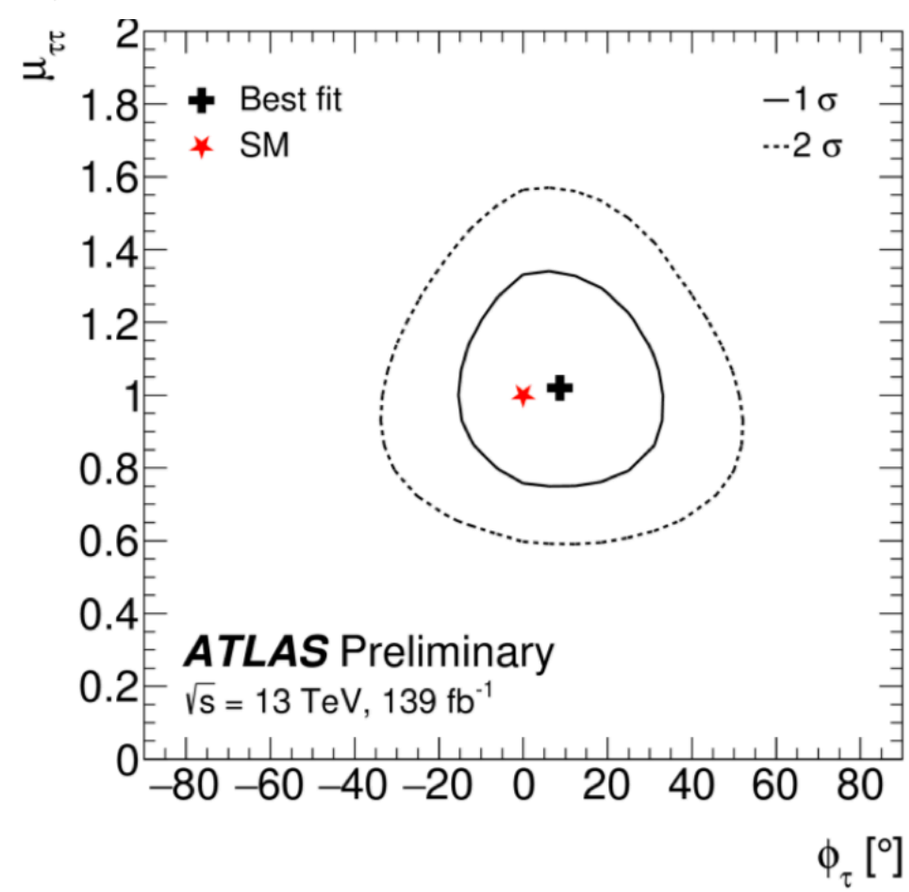
ATLAS-CONF-2022-032



Decay channel	Decay mode combination	Method	Fraction in all τ lepton pair decays
$\tau_{lep}\tau_{had}$	ℓ-1p0n	IP	8.1%
	ℓ-1p1n	IP-ρ	18.3%
	ℓ-1pXn	IP-ρ	7.6%
	ℓ-3p0n	IP-a_1	6.9%
$\tau_{had}\tau_{had}$	1p0n-1p0n	IP	1.3%
	1p0n-1p1n	IP-ρ	6.0%
	1p1n-1p1n	ρ	6.7%
	1p0n-1pXn	IP-ρ	2.5%
	1p1n-1pXn	ρ	5.6%
	1p1n-3p0n	ρ-a_1	5.1%

YpXn Y charged pions; X neutral pions

$$\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)H,$$



Angle reconstruction requires excellent performance:

- Particle flow based τ_{had} reconstruction
- π^0->γγ and vertex / impact parameter reconstruction

avoid rate constraint:

Pure CP-odd (ϕ_τ= 90°) disfavoured at 3.4 σ

Stat dominated, largest sys from jets

HVV Coupling in VBF

arXiv:2208.02338

New analysis in VBF H->yy,

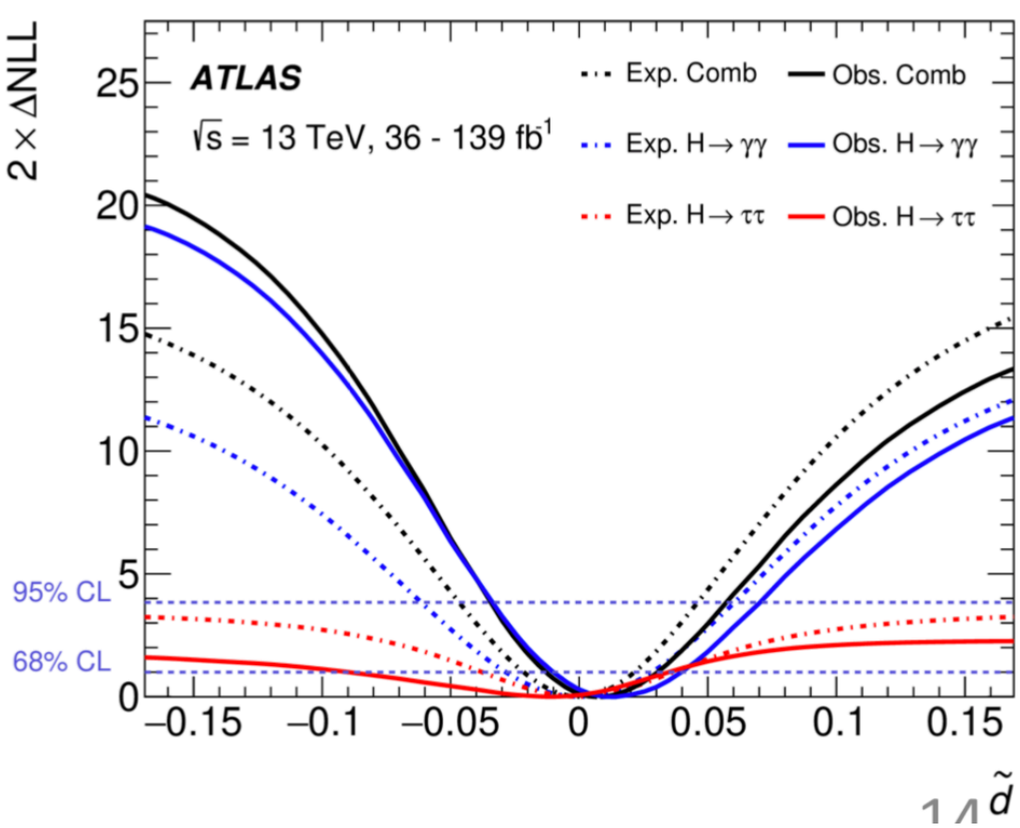
Strength of CP violation in VBF matrix element simplified as being dependent by a single parameter

$$\mathcal{M} = \mathcal{M}_{\text{SM}} + \tilde{d} \cdot \mathcal{M}_{\text{CP-odd}}$$

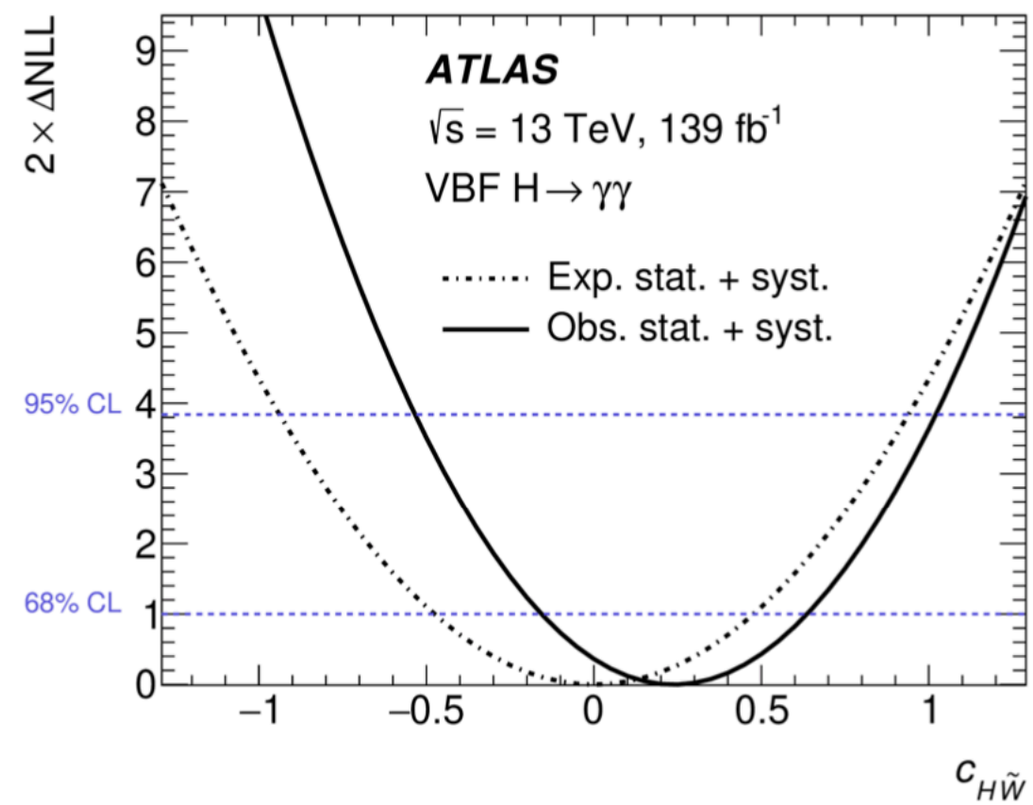
$$|\mathcal{M}|^2 = |\mathcal{M}_{\text{SM}}|^2 + \tilde{d} \cdot 2\,\text{Re}(\mathcal{M}^*_{\text{SM}}\mathcal{M}_{\text{CP-odd}}) + \tilde{d}^2 \cdot |\mathcal{M}_{\text{CP-odd}}|^2$$

$\tilde{d}$ is in HISZ basis and is further

Combined with previous analysis VBF H→ττ (36 fb^{-1})



$\tilde{C}_{HW}$ is in Warsaw basis

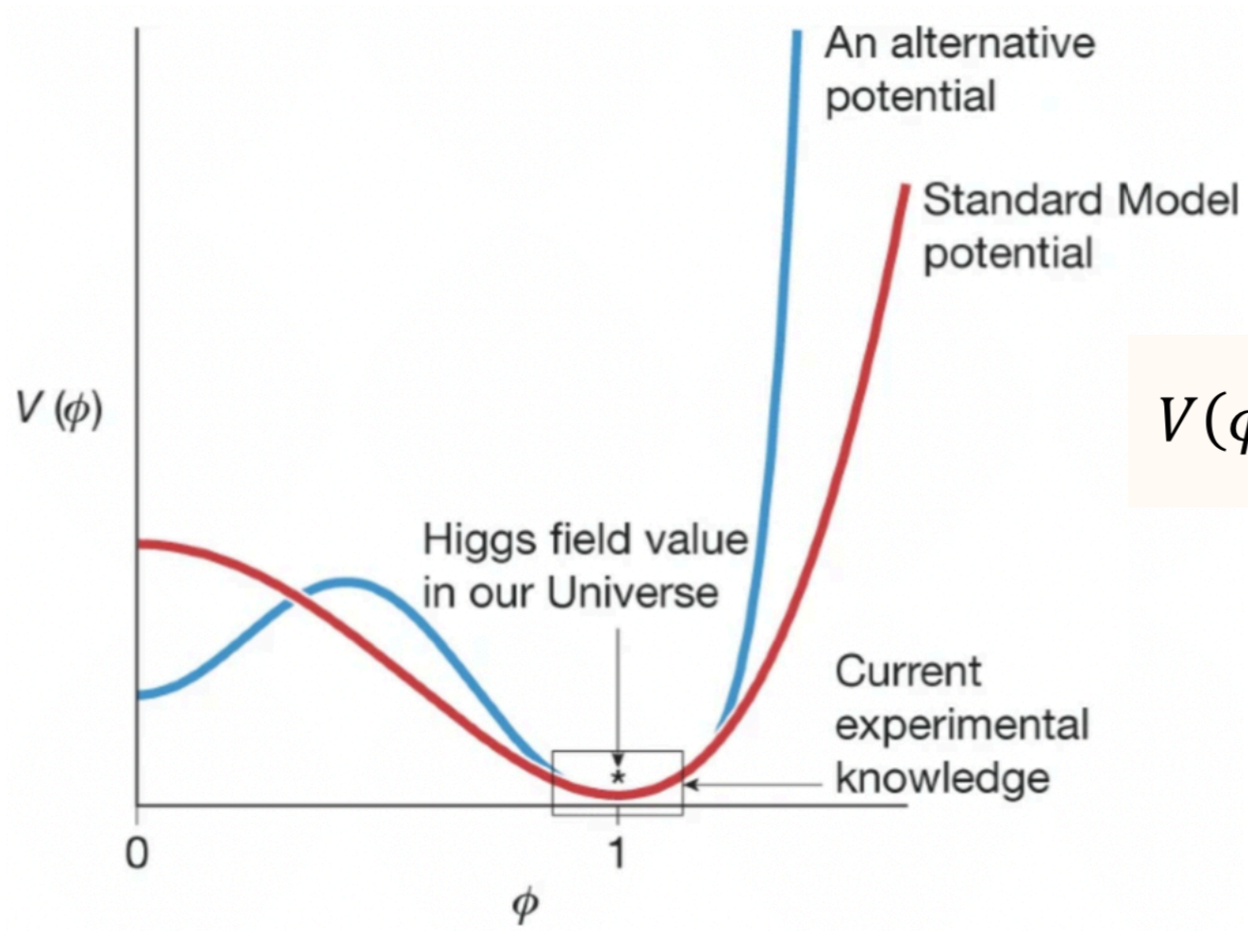


Strongest existing bounds on CP violation in HVV

Higgs potential and self couplings

Understanding the shape of the Higgs potential is fundamental

[G. Salam, Nature 607, 41–47 (2022)]



mass term, indicating a physical particle, the Higgs boson

$$V(\phi) = -\frac{\mu^4}{4\lambda} - \mu^2 H^2 + \lambda v H^3 + \cdots$$

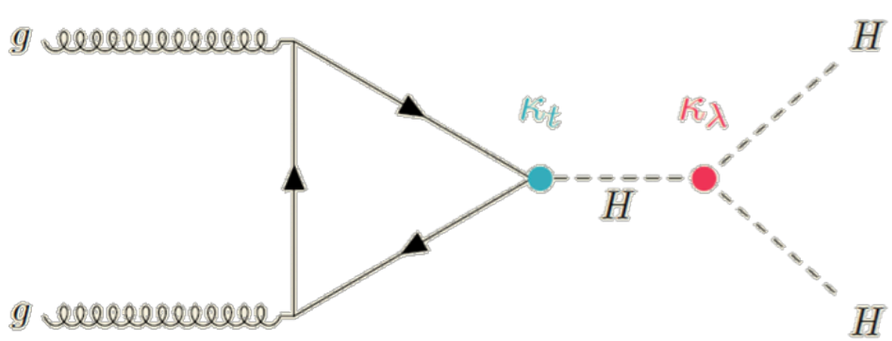
Higgs self-interaction term

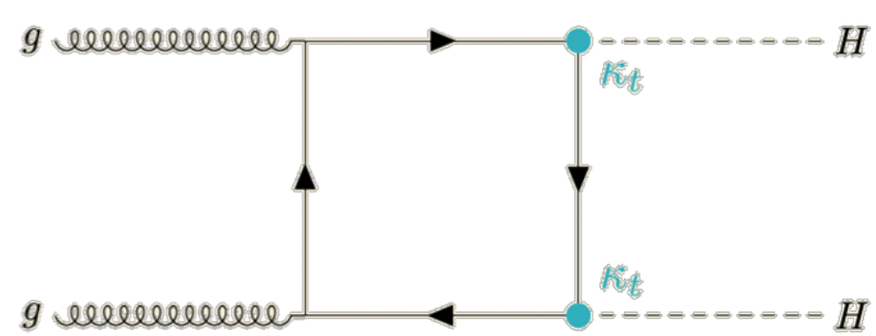
direct probing of Higgs self-interaction and the shape of Higgs potential

deviations from the SM would indicate new physics

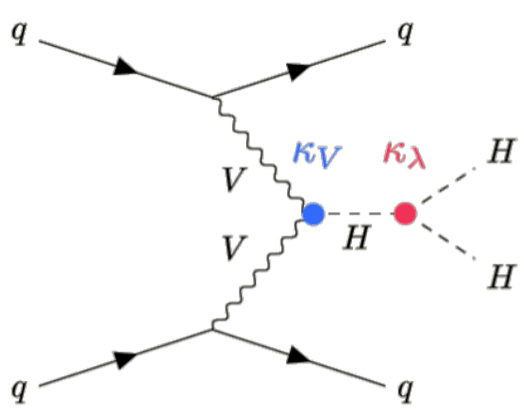
di-Higgs production at LHC

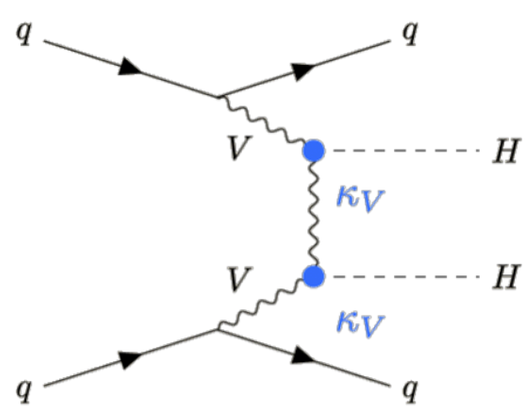
dominant production mode ggF $31fb[13TeV]$ with 2 diagrams that have distructive interference

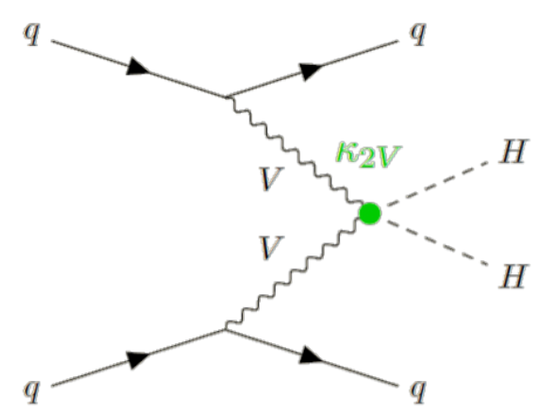




Vector-boson fusion $1.7fb$ $13TeV$ is the second dominant mode







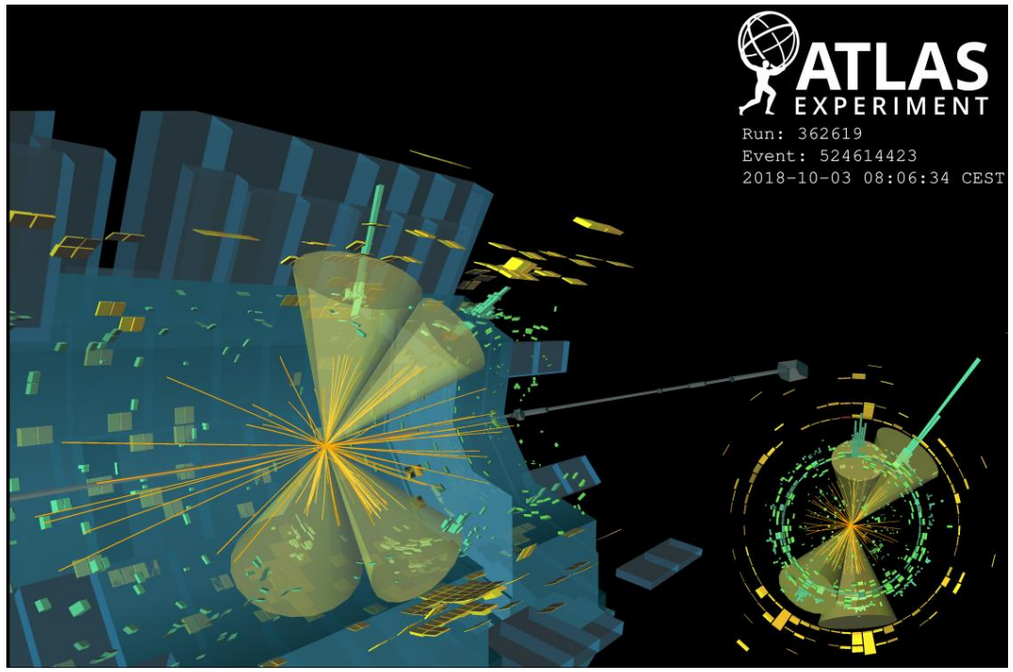
Associated productions, HHV, HHtt have much smaller production cross-sections

di-Higgs decay modes

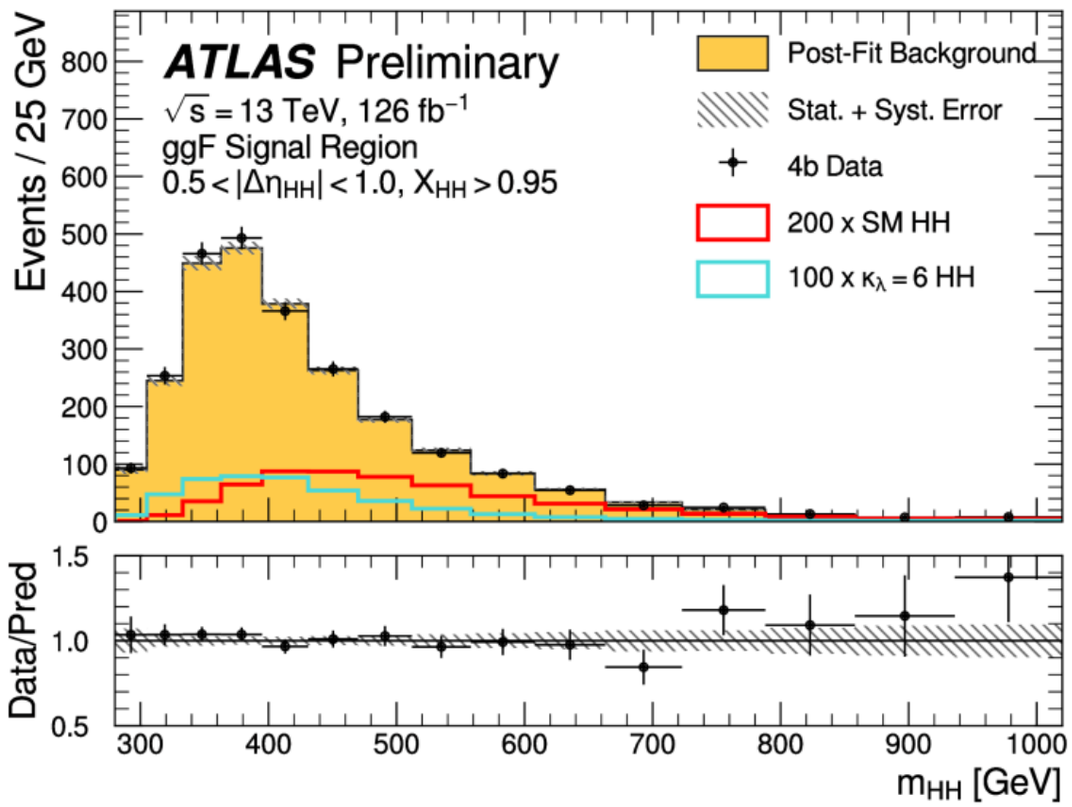
by Katharine Leney

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

HH → *bbbb*



ATLAS-CONF-2022-035



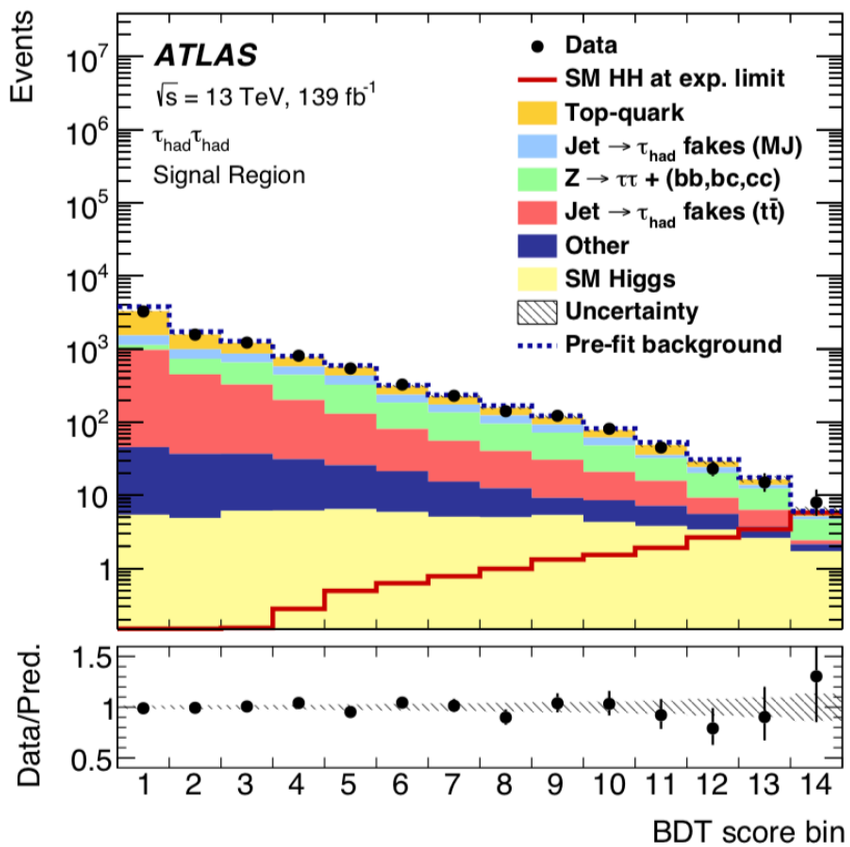
Highest BR, sensitive to high pT of the Higgs

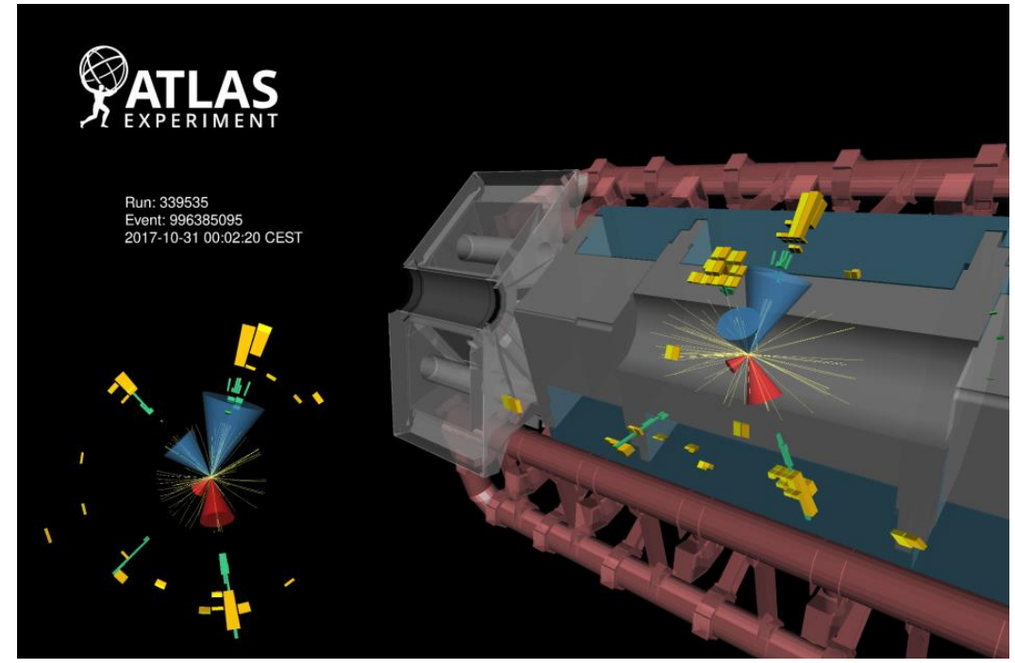
events are selected to have at least 4 jets with pT > 40 GeV, at least 2 of which are b-jets, which are quested to be compatible with the Higgs

	Observed Limit	-2σ	-1σ	Expected Limit	$+1\sigma$	$+2\sigma$
$\sigma_{\mathrm{ggF}}/\sigma_{\mathrm{ggF}}^{\mathrm{SM}}$	5.5	4.4	5.9	8.2	12.4	19.6
$\sigma_{\mathrm{VBF}}/\sigma_{\mathrm{VBF}}^{\mathrm{SM}}$	130.5	71.6	96.1	133.4	192.9	279.3
$\sigma_{\mathrm{ggF+VBF}}/\sigma_{\mathrm{ggF+VBF}}^{\mathrm{SM}}$	5.4	4.3	5.8	8.1	12.2	19.1

HH → $bb\tau\tau$

arXiv:2209.10910





both in $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$ channel
and in ggf+VBF production

		Observed	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$
$\tau_{had}\tau_{had}$	$\sigma_{ggF+VBF}$ [fb]	150	70	95	130	180	240
	$\sigma_{ggF+VBF}/\sigma^{SM}_{ggF+VBF}$	5.0	2.4	3.2	4.4	6.1	8.2
$\tau_{lep}\tau_{had}$	$\sigma_{ggF+VBF}$ [fb]	280	120	170	230	320	430
	$\sigma_{ggF+VBF}/\sigma^{SM}_{ggF+VBF}$	9.7	4.2	5.6	7.8	11	15
Combined	$\sigma_{ggF+VBF}$ [fb]	140	62	83	110	160	210
	$\sigma_{ggF+VBF}/\sigma^{SM}_{ggF+VBF}$	4.7	2.1	2.8	3.9	5.4	7.2

HH → $bb\gamma\gamma$

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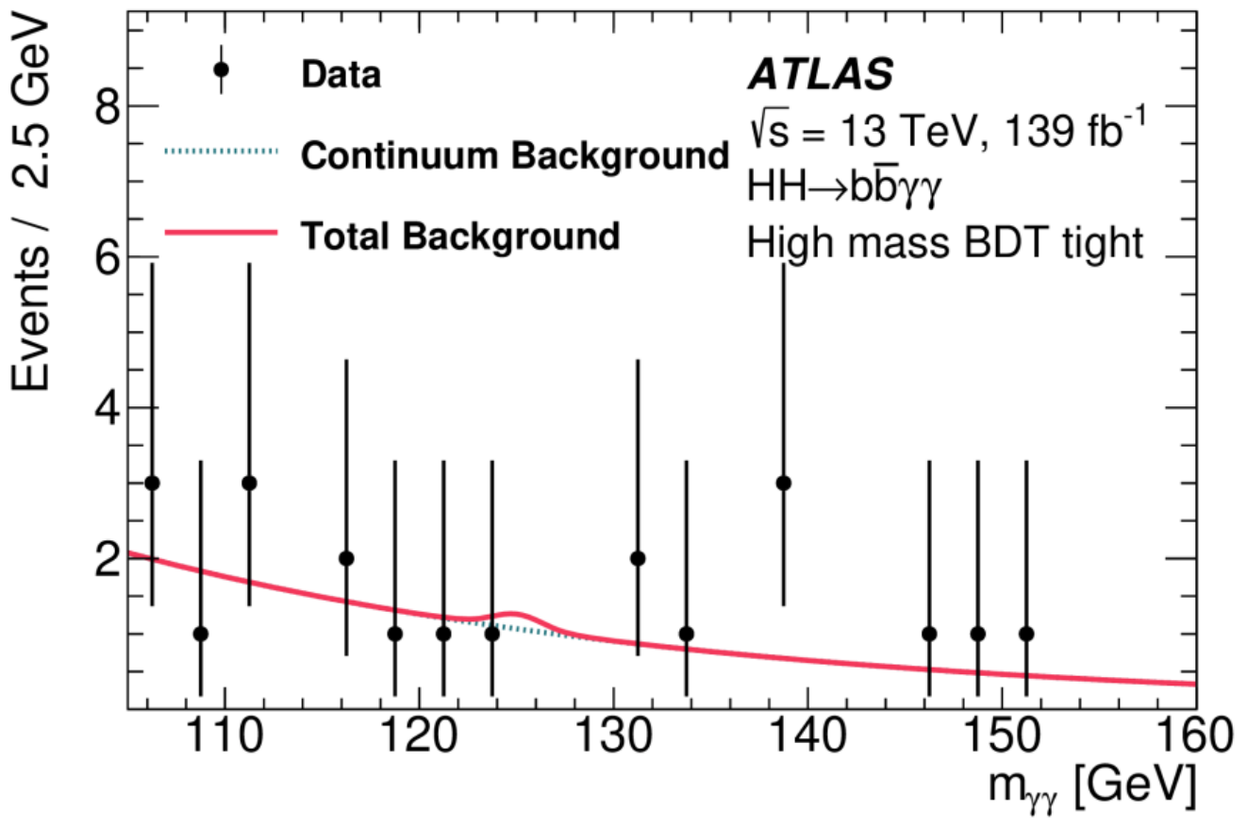
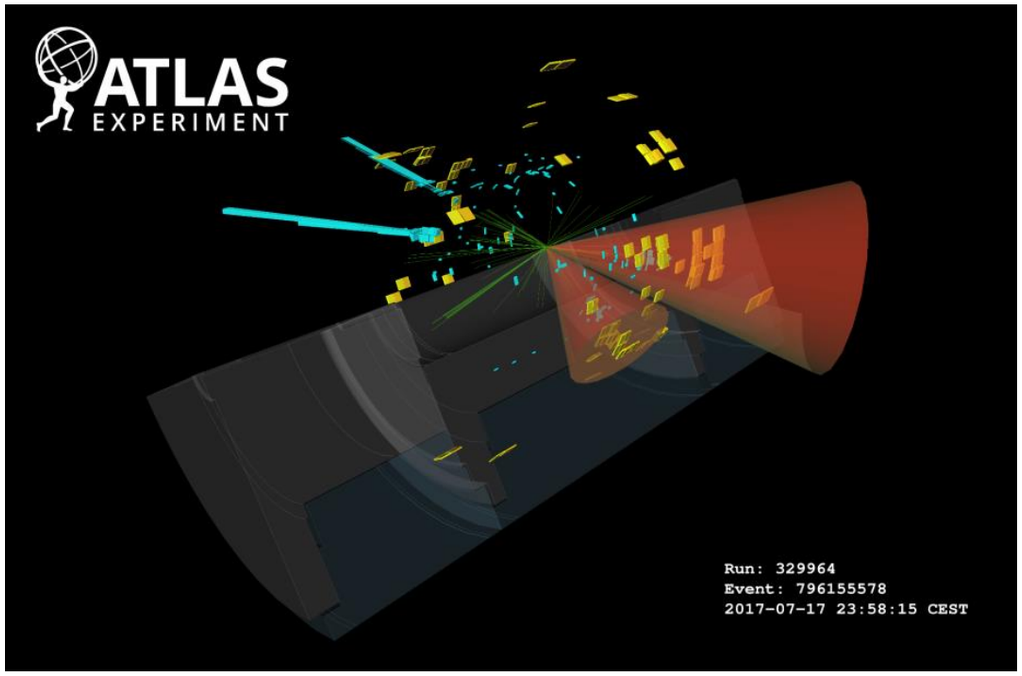
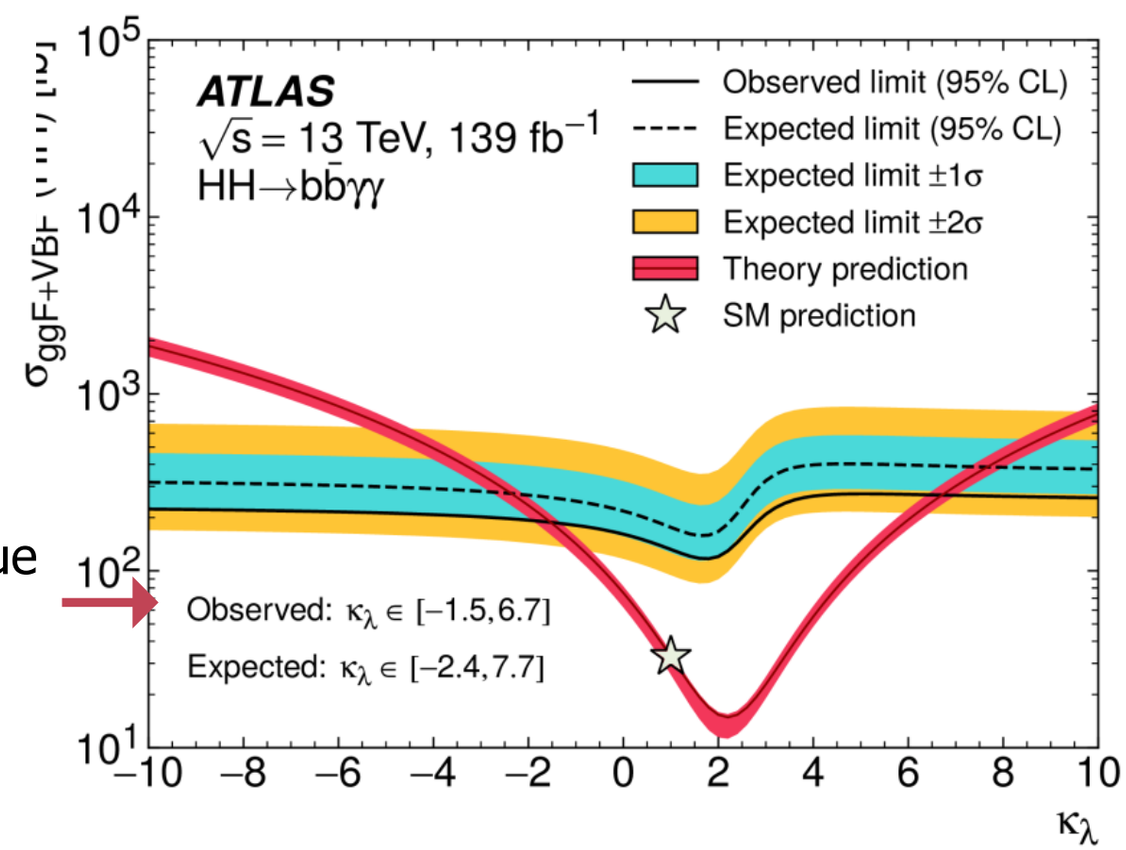




Signal/background modeling
- H / HH shape from simulation
- continuum background shape from data

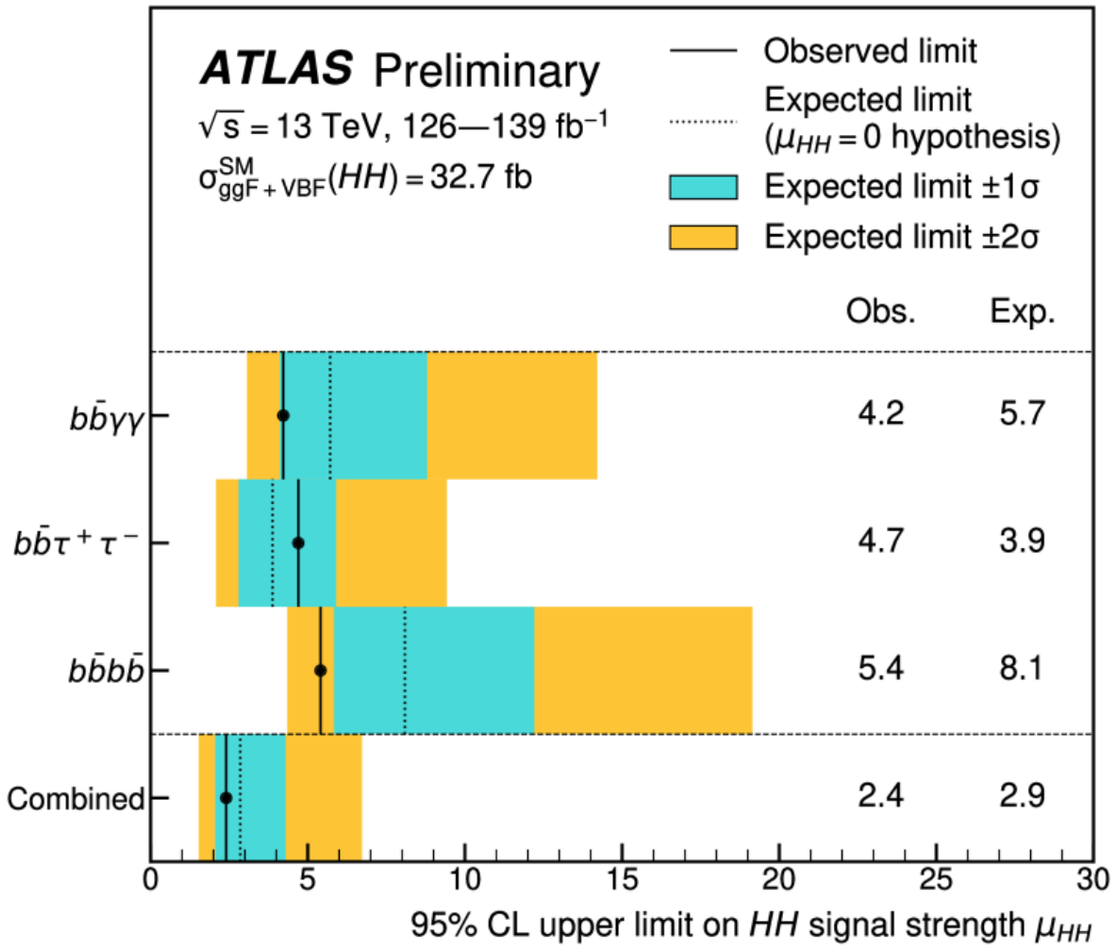
$\kappa\lambda$ = ratio of the Higgs boson self-coupling to its SM value

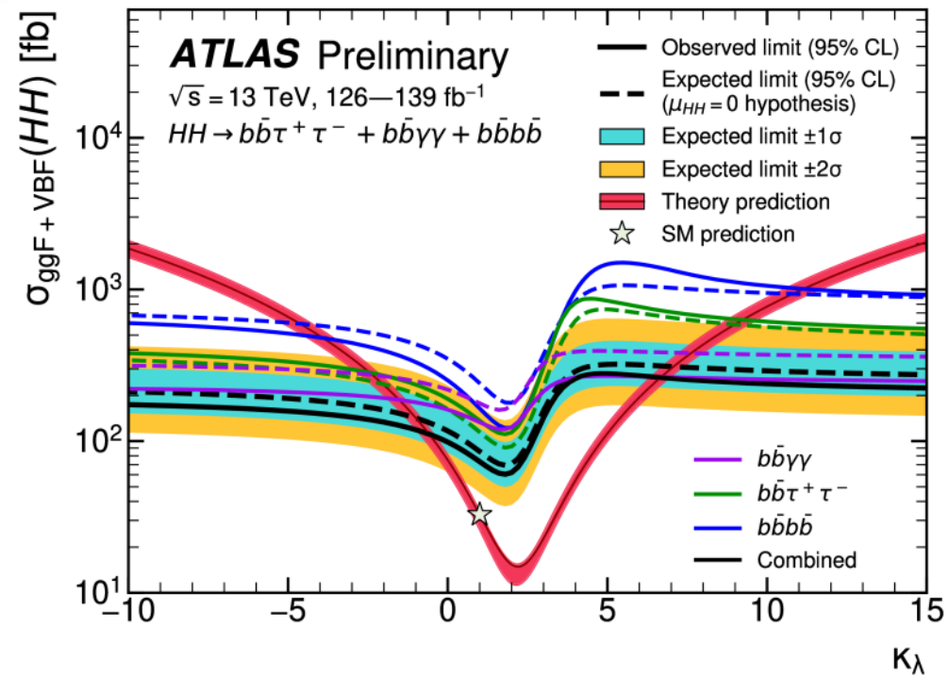


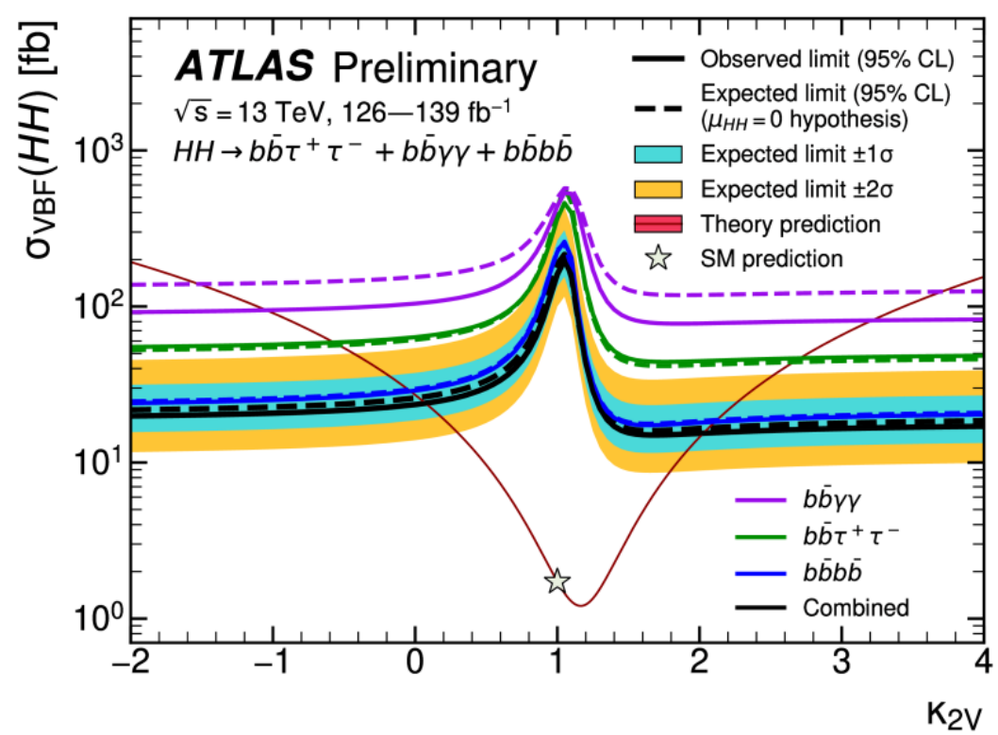
Limit on on σ 4.2 (4.7) times the SM prediction @ 95% CL

HH combination

ATLAS-CONF-2022-050







K_{2V} related to the $VVHH$ interaction vertex

Limit on on σ 2.4 (2.9) times the SM prediction at 95% CL

H+HH combination

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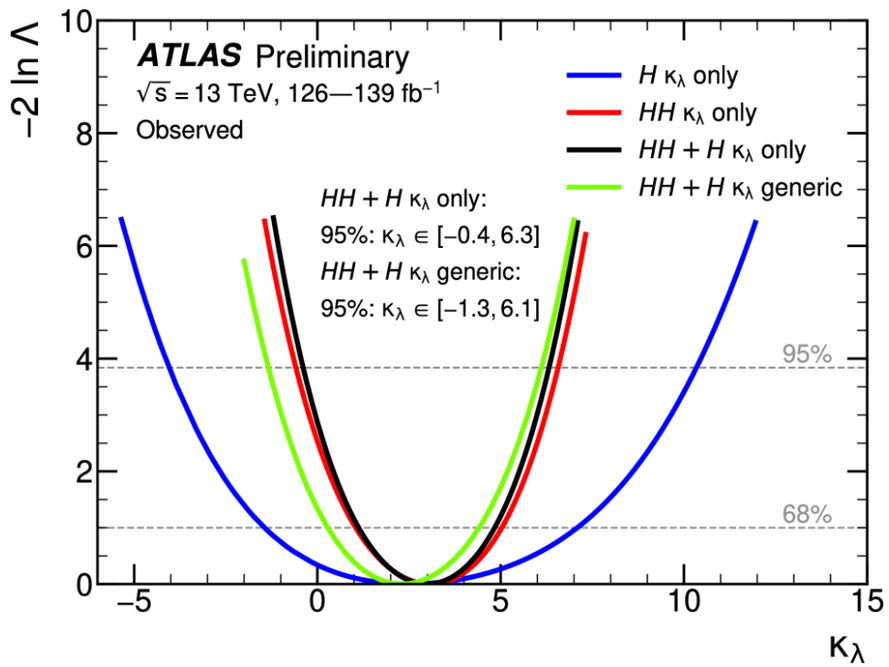
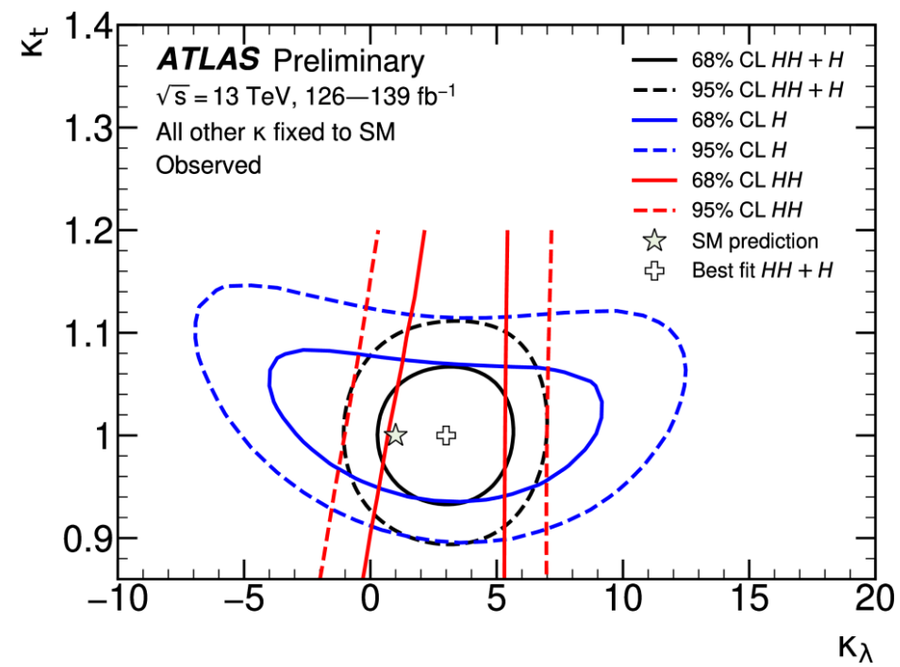


The combination with single Higgs allows the determination of $\kappa\lambda$ with other K



κ_λ from di-Higgs

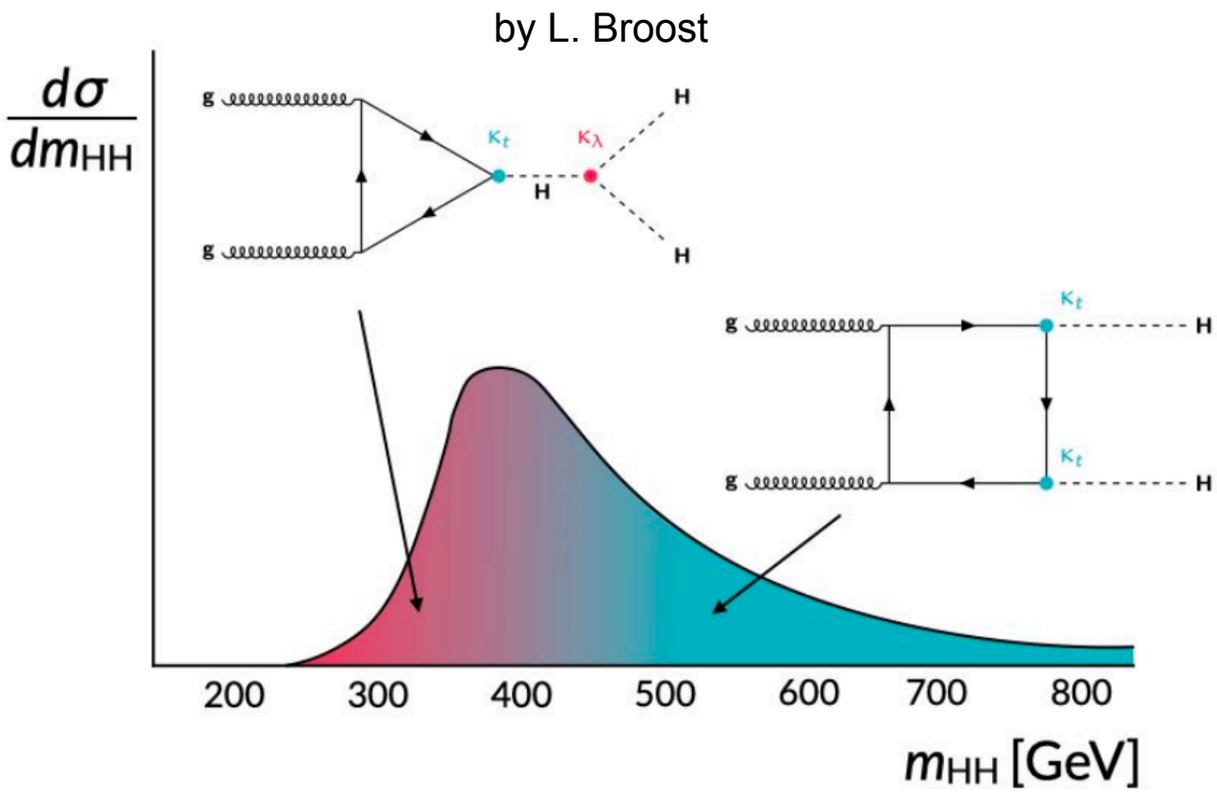
κ_t from single Higgs

- Profile $\kappa\lambda$ only: $-0.4 < \kappa\lambda < 6.3$ (95% CL)
- Profile $\kappa\lambda$, κt, κV, κb, $\kappa\tau$: $-1.3 < \kappa\lambda < 6.1$ (95% CL)

Single-Higgs constraint dominated by ggH rate therefore the theory uncertainty is important

κt, κb, κV, $\kappa\tau$ coupling modifiers wrt to the SM Higgs boson coupling to up-type quarks, to down-type quarks, to vector boson V and to leptons.

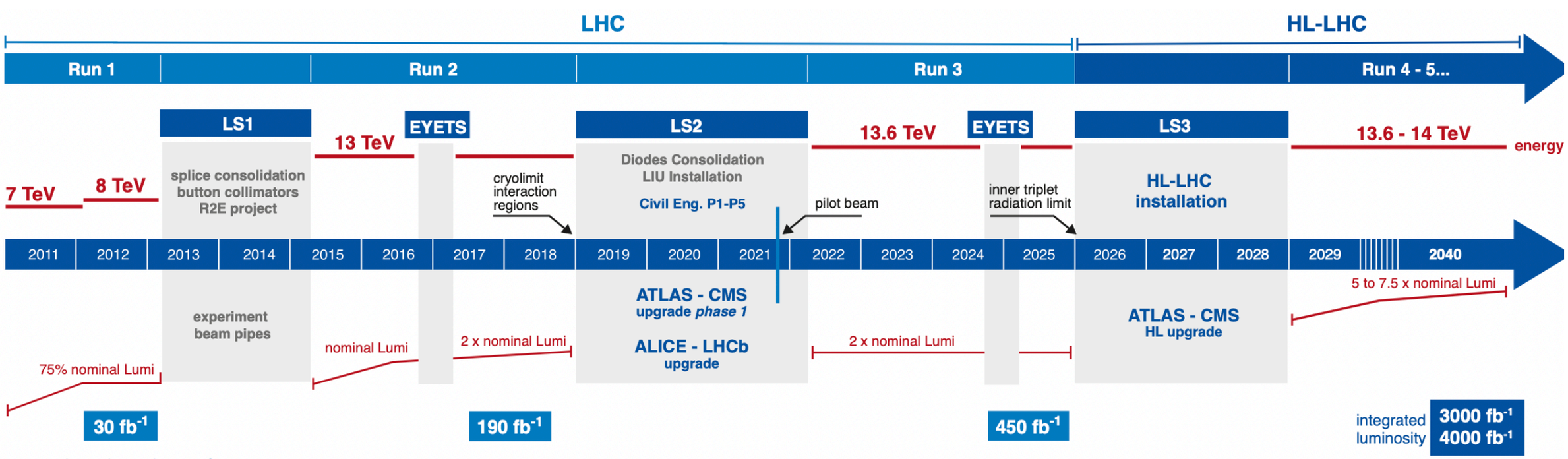
Prospects



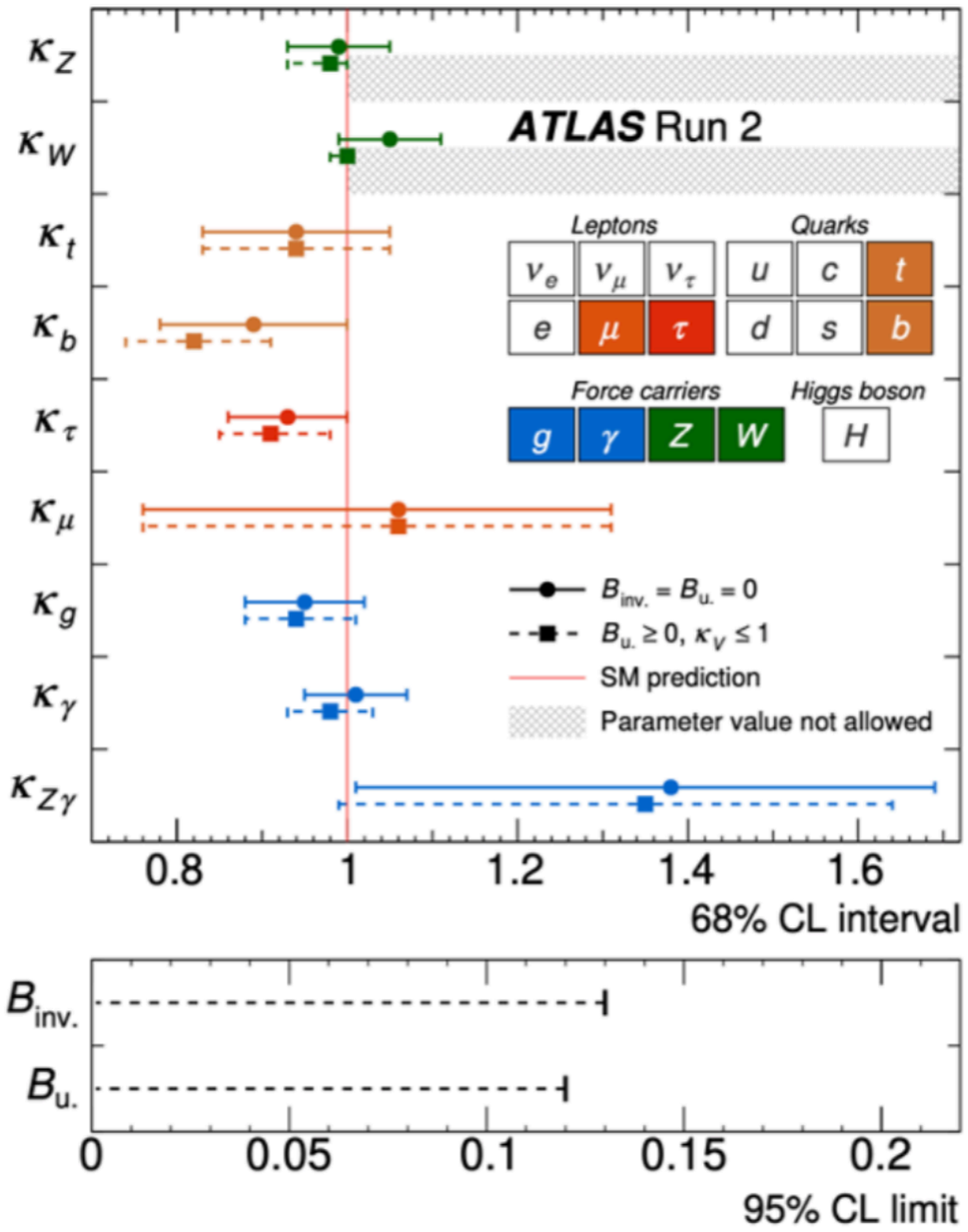
the low mHH regions drives sensitivity therefore lowering thresholds including trigger is fundamental, especially for the future

in run 3 possible sensitivity to 1xSM x-section

we might be able to observe at 5 sigma di-higgs production at HI-LHC

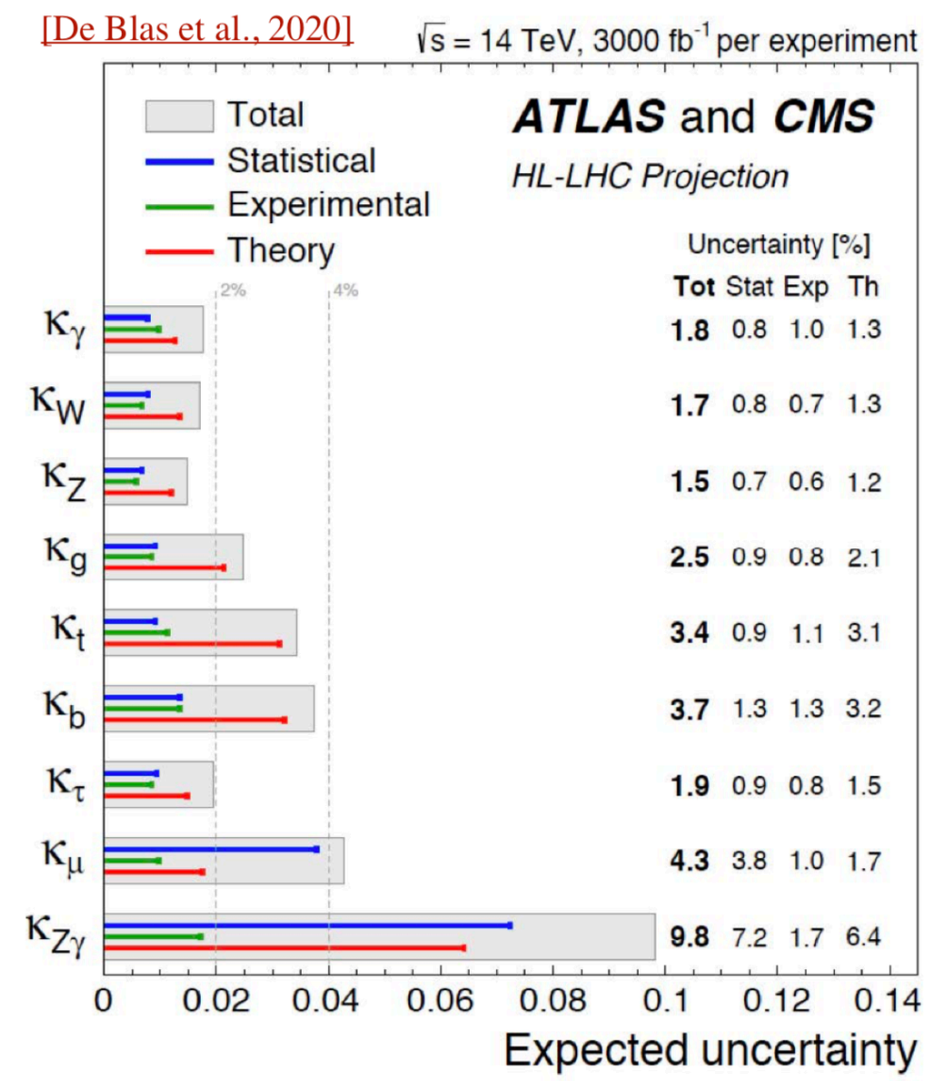


Longer term prospects



0-20%

2-4%



- Precision on cross-sections and κ modifiers between 2 and 4%
- limited by experimental and mostly theoretical systematics

To conclude: what is near the corner in run 3?

In general: measurements that are still statistically limited with Run 2 dataset

- Differential cross-section measurements
- Couplings to 2nd generation
  - $H \to \mu\mu$: first evidence by the CMS collaboration with Run 2 dataset: observed (expected) signal significance of 3.0σ (2.5σ)
  - ATLAS Run2 : observed (expected) signal significance of 2.0σ (1.7σ)
  - projected CMS analysis: 5σ can be achieved with L ≈ 300 fb-1 of data (at = 14 TeV) also sensitivity to VH(→ cc)

- Rare decay: $H \to Z(\to ee/\mu\mu)\gamma$:BR = 0.1×10-3
  full Run 2 significance: ATLAS: 2.2σ (expected 1.2σ)
  5σ expected at HL-LHC ⇒evidence could be expected at the end or run 3

- Rare decay: $H \to \gamma\gamma^*$: 3σ by single experiment in reach at run 3