Recent Higgs physics results from the ATLAS experiment

"Higgs as a Probe of New Physics" Special Edition 2021 (HPNP2021)

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online ☹

Contents

Precision

- Higgs mass measurement (precision: ~0.15%)

- Higgs cross-sections measurements
  - including STXS and differential

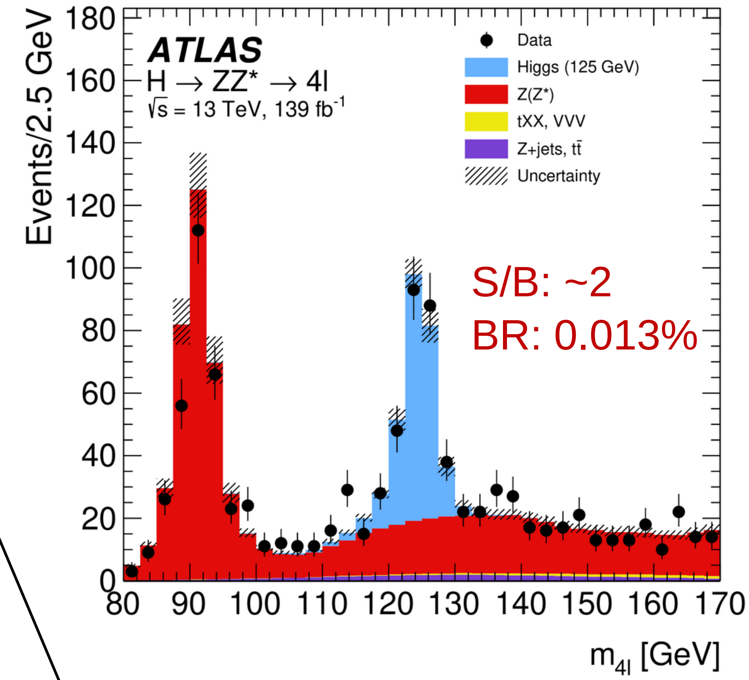
Becoming sensitive to...

- Higgs couplings
  - couplings modifiers (from combinations)
  - EFT
  - probe CP structure of top-Yukawa coupling

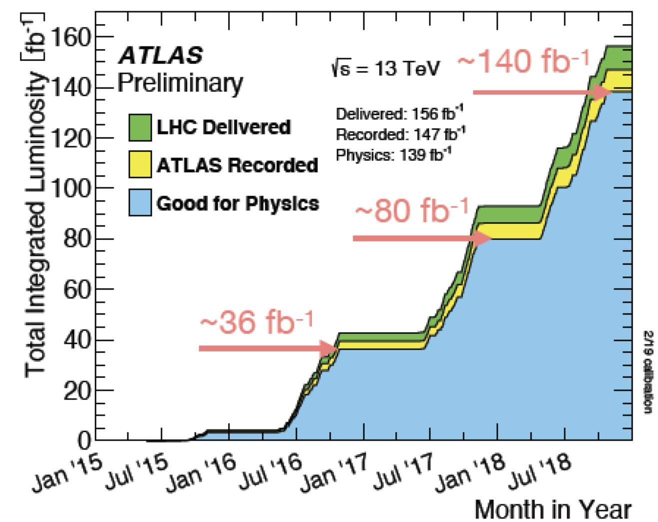
Searches...

- Rare Higgs decay modes:
  - H→μμ
  - H→Z/γ*→llγ
  - H→invisible (from VBF and ttH)

- Di-Higgs production



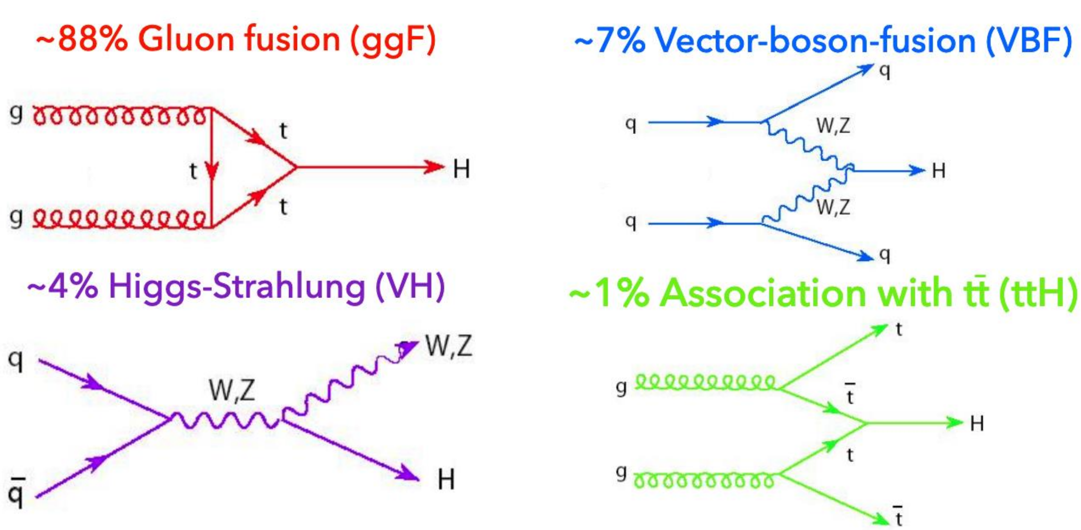
$$124.92 \pm 0.19(\text{stat.})^{+0.09}_{-0.06}(\text{syst.})\ \text{GeV}$$



ATLAS experiment has successfully collected ~140 fb^{-1} at 13 TeV in full Run 2
(dataset used in stage for publications: 36 / 80 / 140 fb^{-1})
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

Thanks to CERN accelerator/technical teams for the excellent LHC performance !
Next: expected ~150 fb^{-1} for Run 3 and ~3 ab^{-1} for HL-LHC

Production



ggF & VBF: observed in Run 1
WH, ZH & ttH: observed in Run 2

Decay

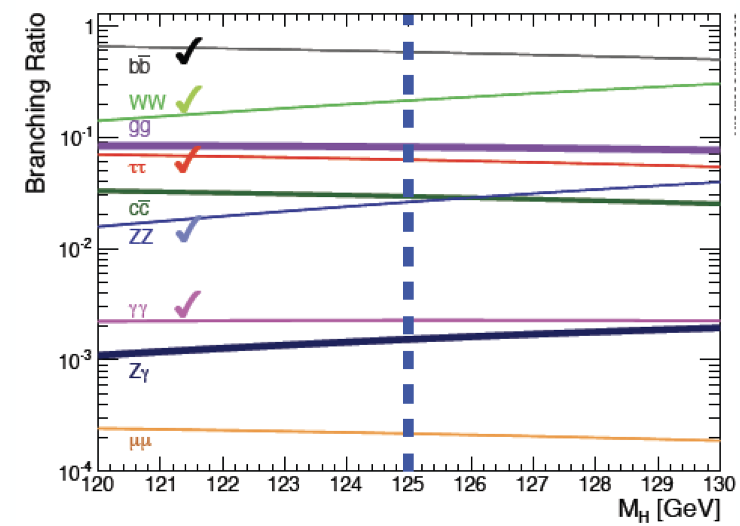
Mode	BR (125 GeV)
H→WW*	21.4%
H→ZZ* (→4l)	2.62% (~0.013%)
H→$\gamma\gamma$	0.23%
H→$\tau\tau$	6.27%
H→bb	58.2%
H→$\gamma^*\gamma$→llγ	0.010%
H→Zγ (→llγ)	0.15% (~0.010%)
H→$\mu\mu$	0.022%
H→cc	2.89%

Observed in Run 1 (clean final sate)

→ Observed in Run 2

Becoming sensitive with full Run 2 (~2-3σ)

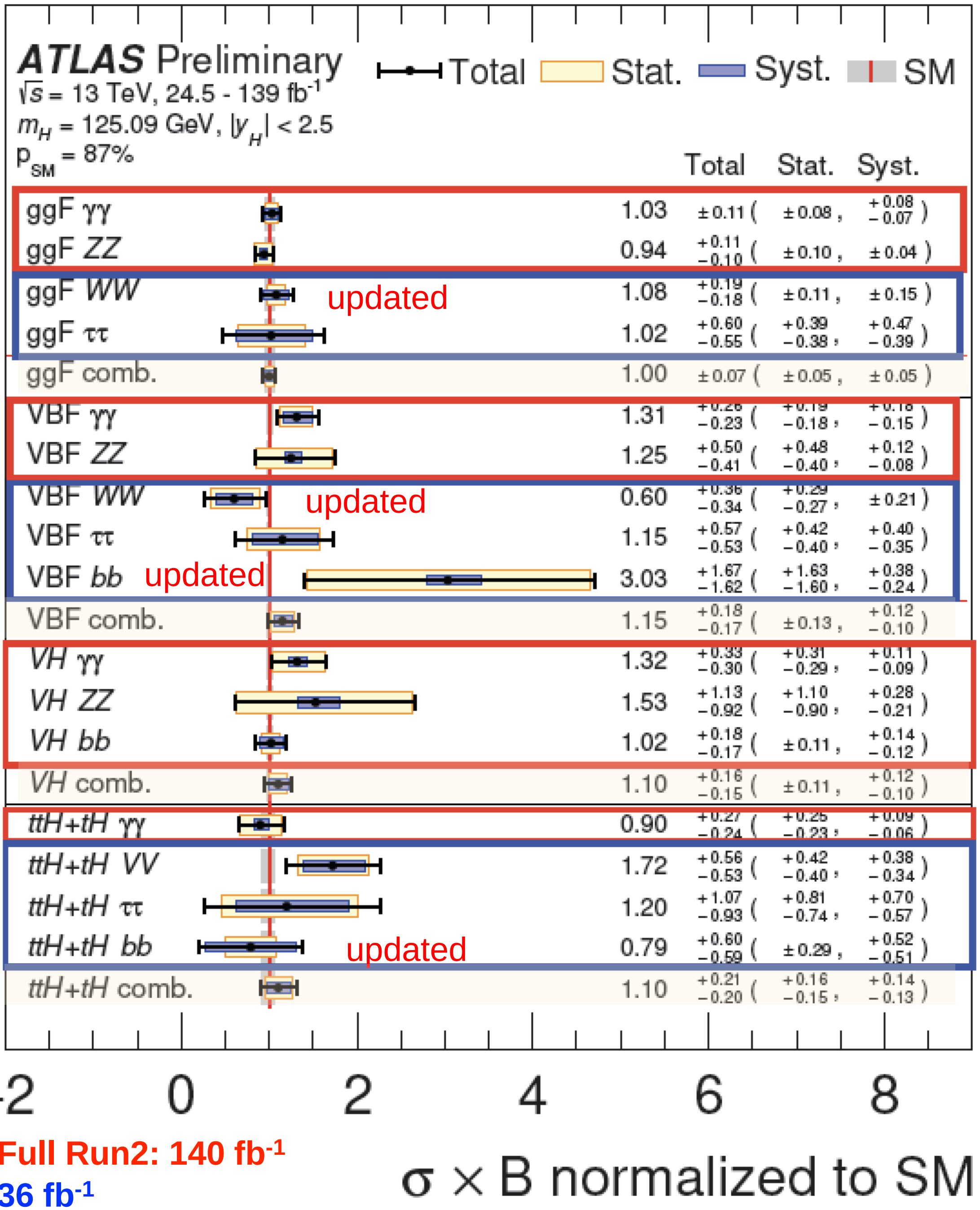
Run 3 or HL-LHC



Reaching more difficult and rare decay modes...

Cross-sections measured in several phase space regions.
Two complementary approaches are being explored:
* Simplified template cross sections
* Differential cross sections

ATLAS-CONF-2020-027



Full Run2: 140 fb-1

36 fb-1

✓ being studied
★ observed

	ggF	VBF	VH	ttH
H→WW	★	★	✔	✔
H→ZZ	★	✔	✔	✔
H→γγ	★	✔★	✔★	★
H→ττ	✔	★	✔	✔
H→bb	✔	✔	★	✔
H→cc			✔	
H→μμ	✔	✔	✓	✓
H->Z/γ*	✓	✓		
H->inv		✓		✓

Updated from T. Masubuchi @HPNP2019

Good agreement with SM

Precisions reached:

- inclusive Higgs: 6%
- ggH: 10-12% in 4l, $\gamma\gamma$, WW*
- VBF: 20% in $\gamma\gamma$, WW*
- VH: 15% in bb
- ttH: 25% in $\gamma\gamma$

Inclusive cross-sections: updates and main limitations

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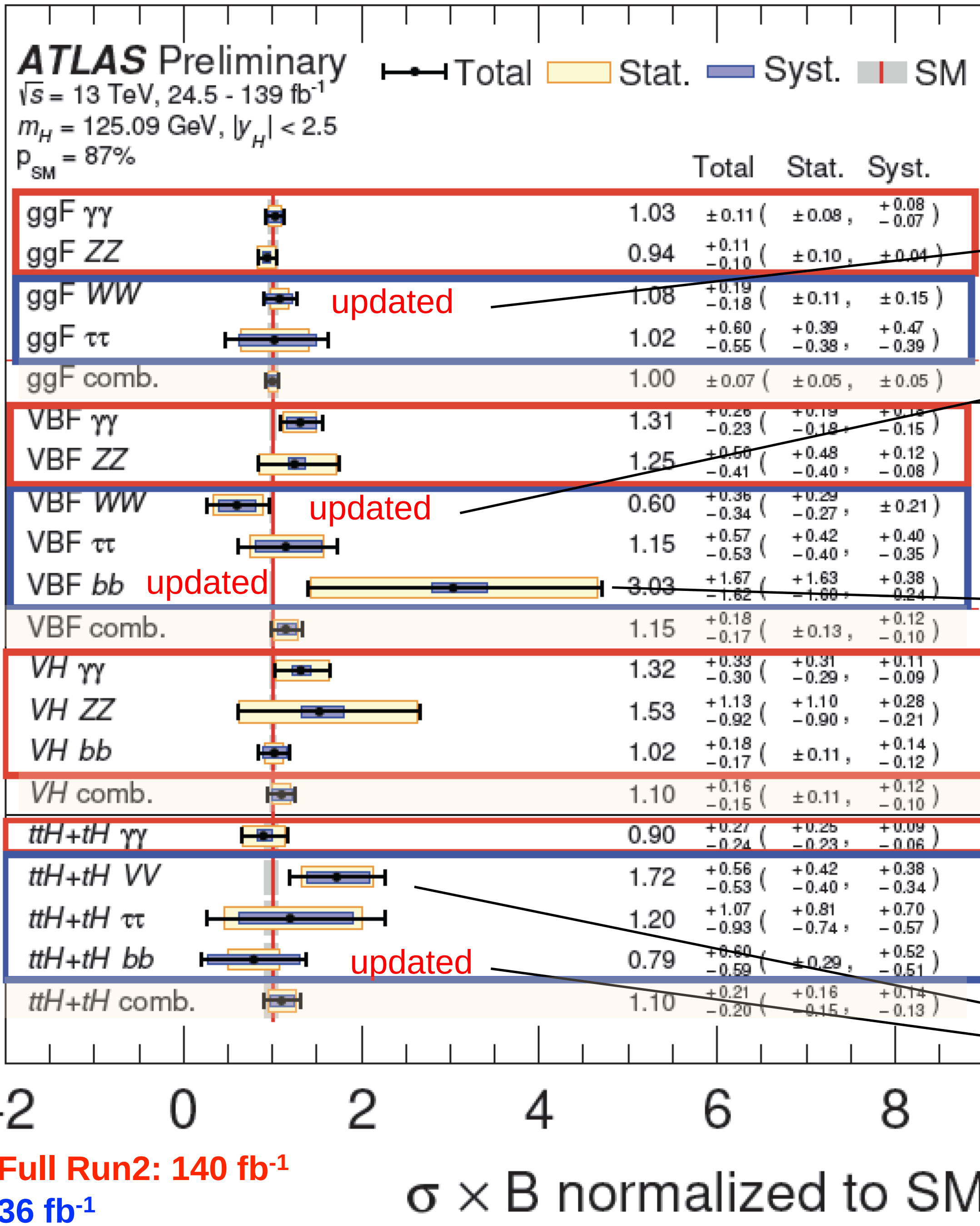
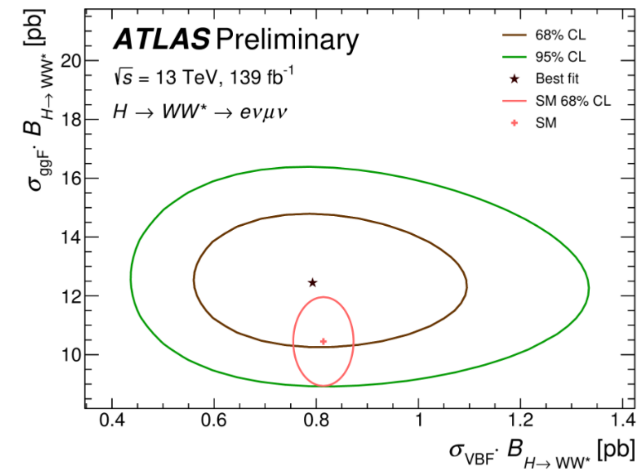
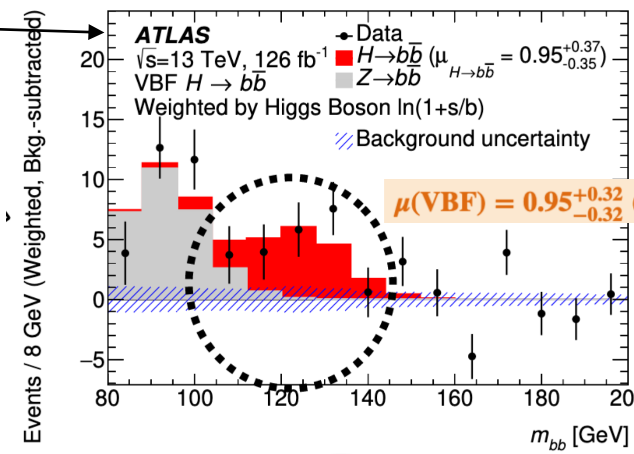


Full Run2: 140 fb^{-1}
36 fb^{-1}



$\mu(ggH) = 1.2^{+0.05}_{-0.05}$ (stat)$^{+0.15}_{-0.14}$ (syst), 1σ deviation from SM

$\mu(VBF) = 0.99^{+0.13}_{-0.12}$ (stat) $^{+0.20}_{-0.16}$ (syst) Most sensitive VBF (limited by signal modelling unc.)



$\mu(VBF) = 0.95^{+0.32}_{-0.32}$ (stat) $^{+0.20}_{-0.17}$ (syst) → *2.6σ*

Modelling of ttW and ttbb backgrounds is a limiting factor for ttH production.

→ It is crucial to improve both signal and background modelling !!!

Evolution of cross-section measurements

Rates by production modes:
- targeting cross-section of main production modes and branching ratios
- assume SM for extrapolation from analysis regions
- powerful to test constant coupling modifiers (kappa-framework)

Simplified template cross-sections (STXS):
- targets kinematic of production modes
- allows to use MVAs
- reduced model dependency
- decay agnostic: suitable for combinations
- good sensitivity to BSM effects

Fiducial / differential cross-sections:
- "fiducial volume" defined close to experimental selection (in order to reduce extrapolation into unmeasured volume)
- simple signal cuts
- most model independent
- include information on decay
- multiple distributions can be measured
- extract signal in each bin of the dist & unfold to truth level

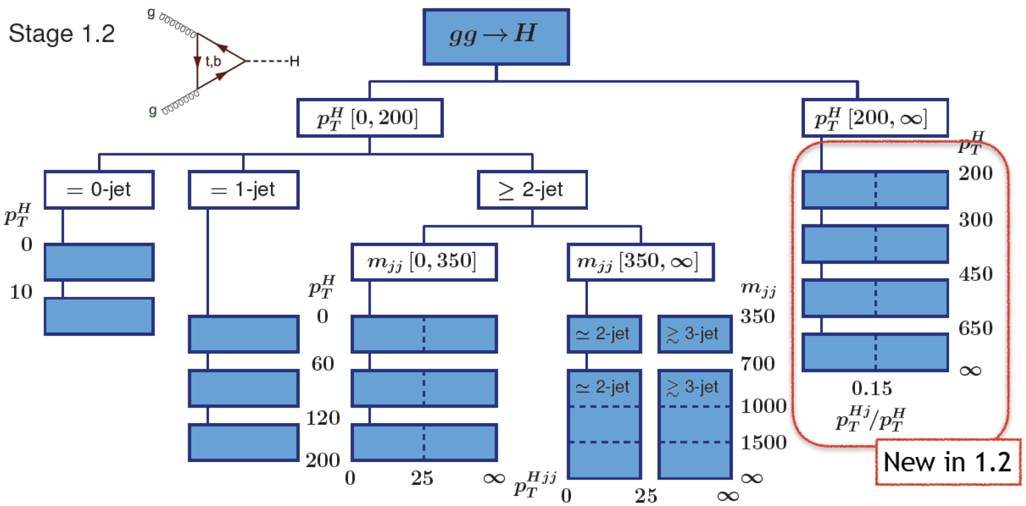
Inspired in V. Dao (Higgs2020)

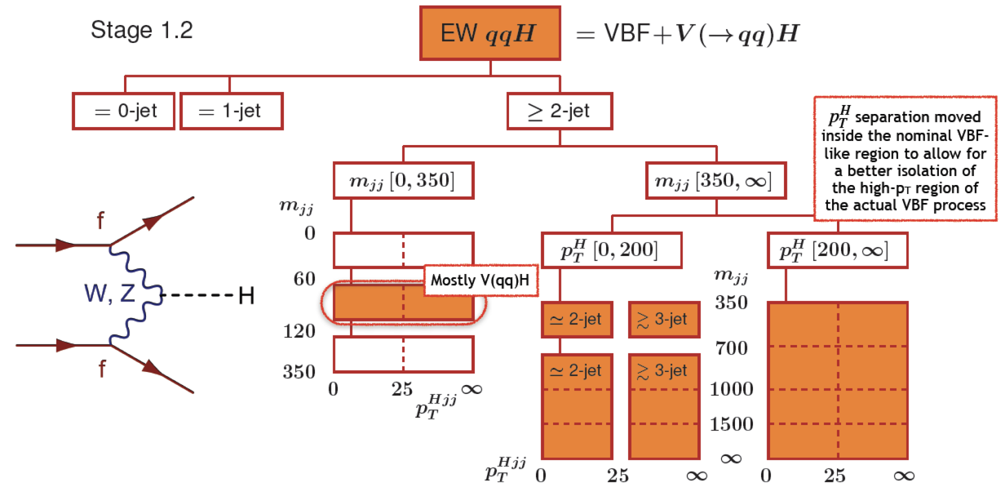
Two complementary approaches, with common issues:

treatment of out-of-acceptance corrections, presentation of results,...

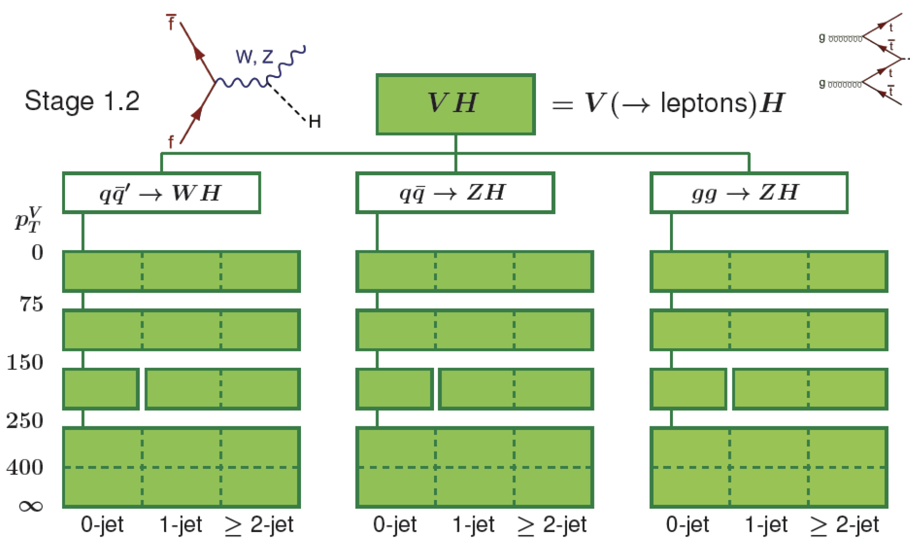
(such that can be compared with latest theory predictions or reinterpreted)

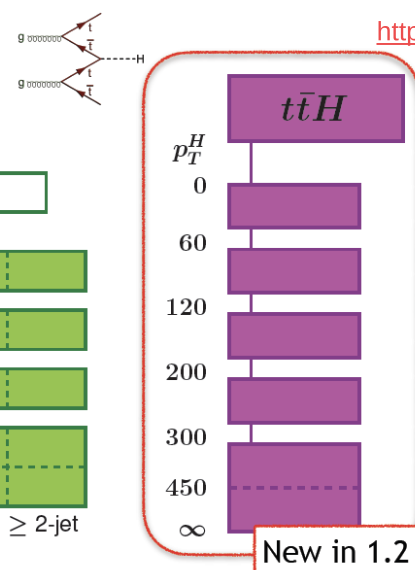
Aim: provide a wealth of information to test our prediction and look for new physics effects





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

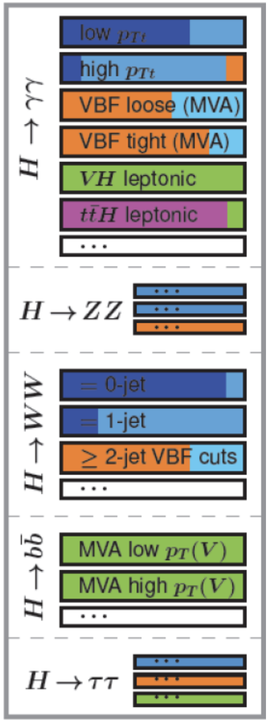




STXS Variables:

- p_T^H: Higgs boson pT
- N_j: Number of jets in the event
- m_{jj}: Invariant mass of dijet system (take leading two for $N_j > 2$)
- p_T^{Hjj}: pT of vector sum of Higgs boson and two leading jets
- p_T^{Hj}/p_T^H: Ratio of pT of vector sum of Higgs boson and leading jet to Higgs boson pT
- p_T^V: Vector boson pT

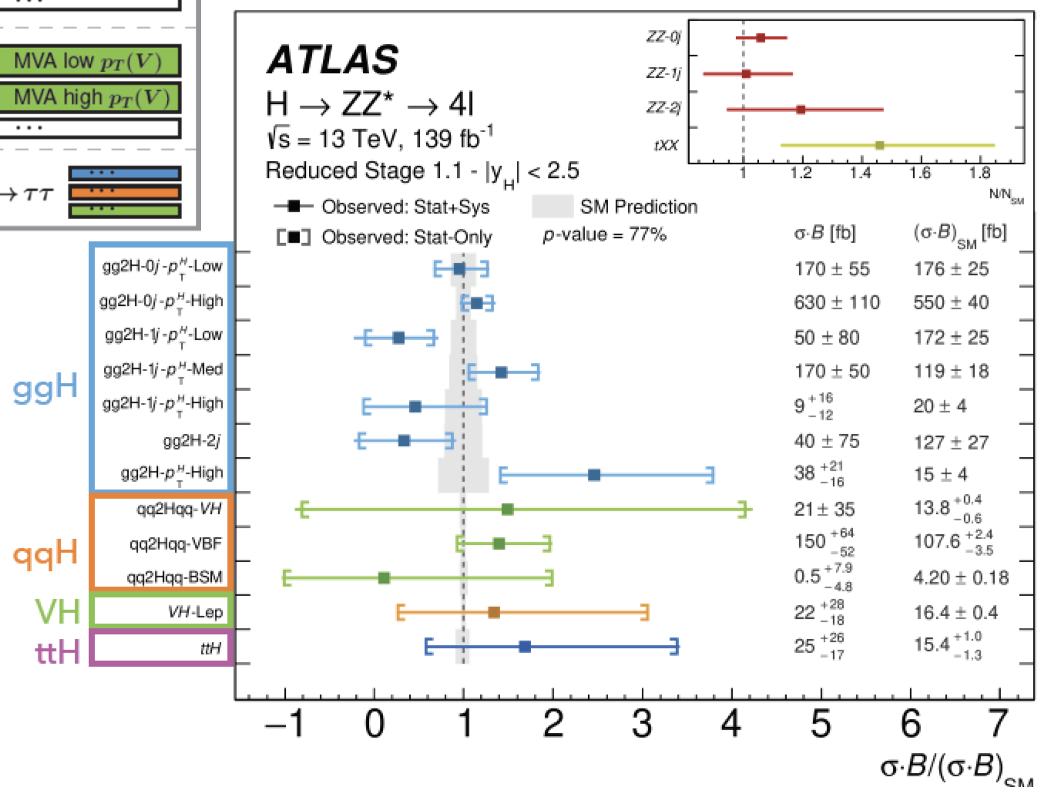
- Categorize each production mode in bins of key (truth) quantities
- Decay agnostic (suitable for combinations)
- Sensitive to deviations from the SM prediction
- Assume SM kinematics within each bin → can use MVAs for signal extraction



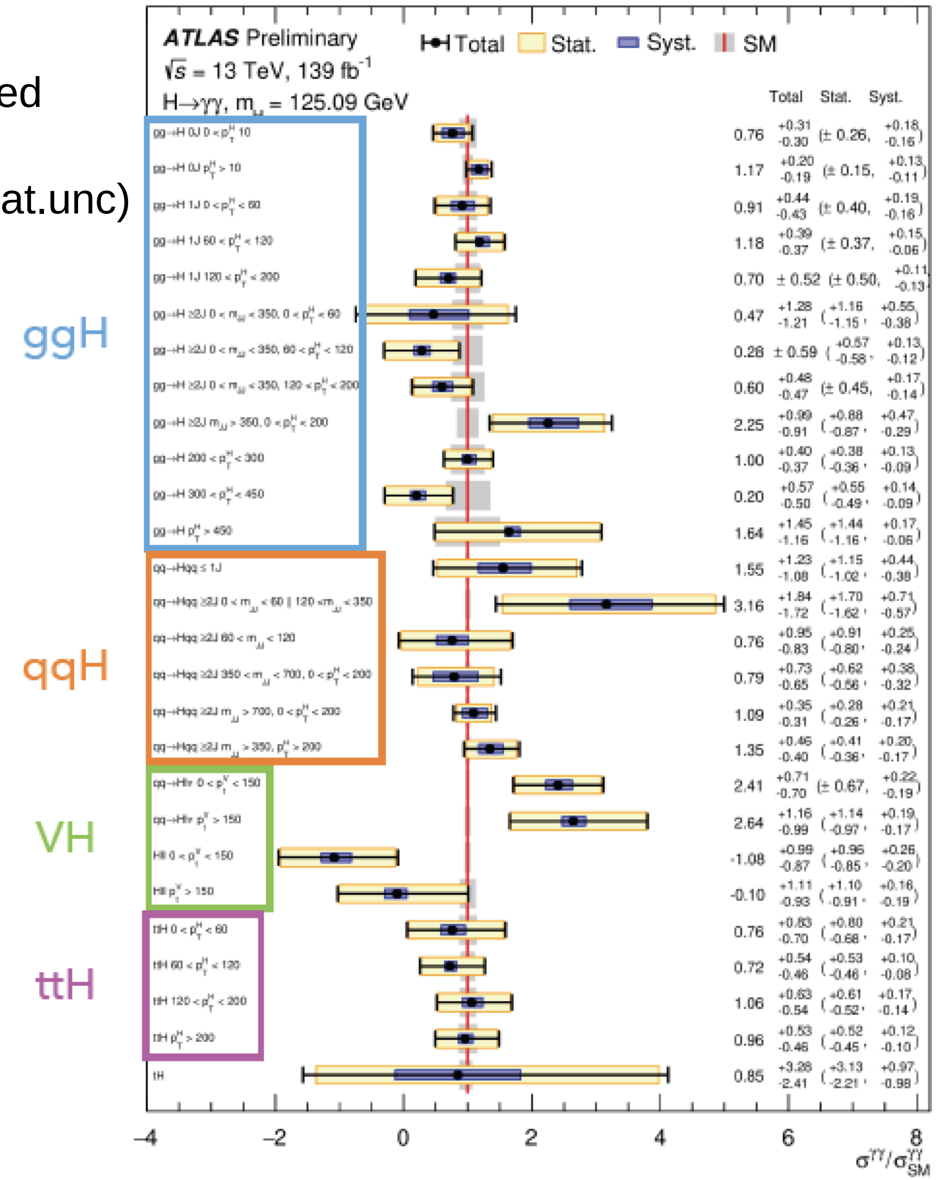
H→4l: several (12) bins measured for ggH & qqH, despite few statistics (low BR)

H→γγ: more stats for allows for finer splitting (including ttH !) with 27 STXS regions measured

Good agreement with SM predictions (large stat.unc)



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



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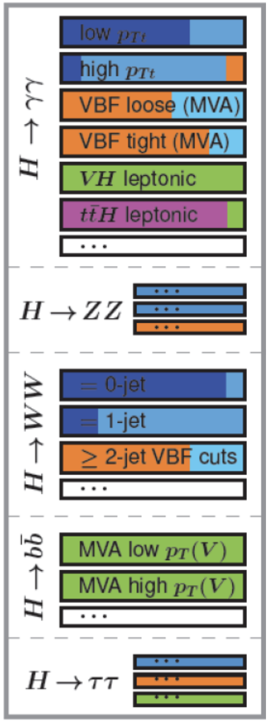
STXS: H→WW*→eνμν and H→bb



H→WW*: targets ggH+qqH STXS bins

H→bb: targets VH (resolved and boosted) and ttH

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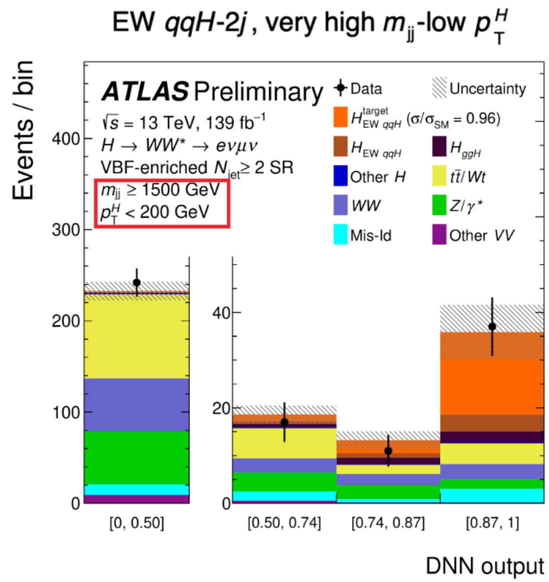
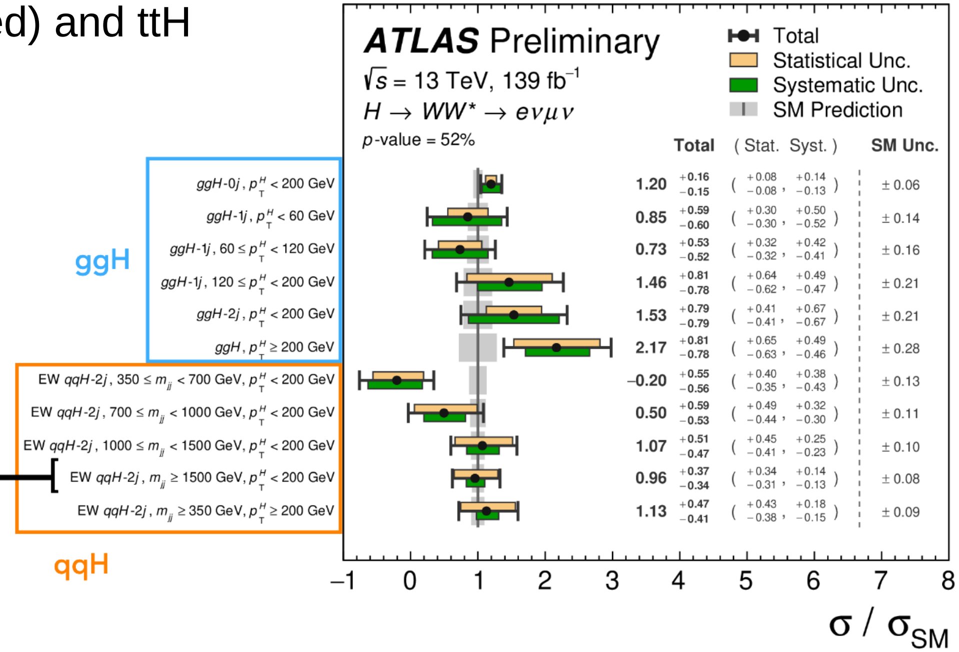
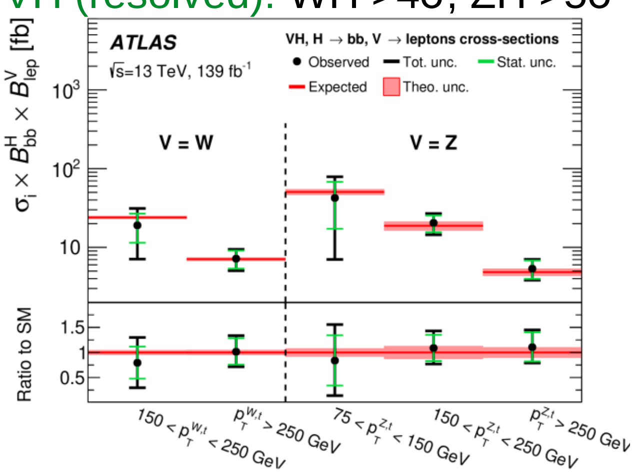


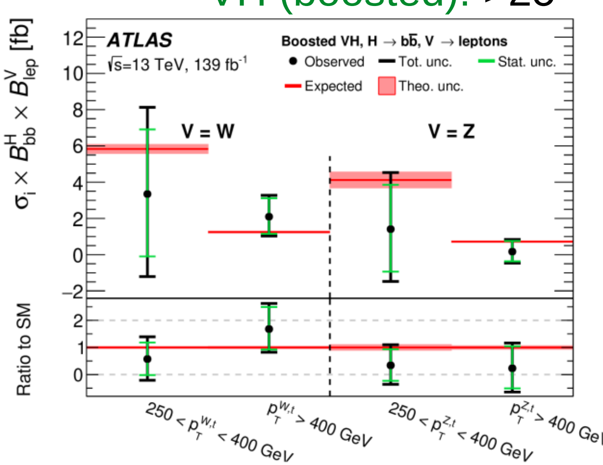


VH (resolved): WH >4σ, ZH >5σ



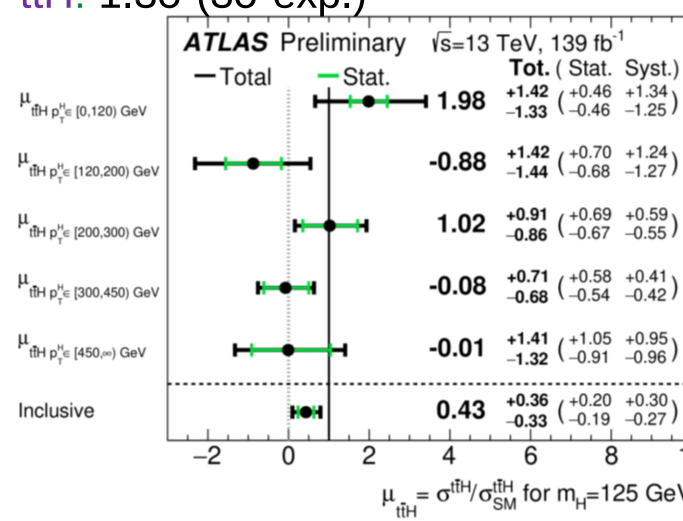
Eur.Phys.J.C81(2021)178

VH (boosted): >2σ



arXiv:2008.02508 (subm. to PLB)

ttH: 1.3σ (3σ exp.)



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STXS combination

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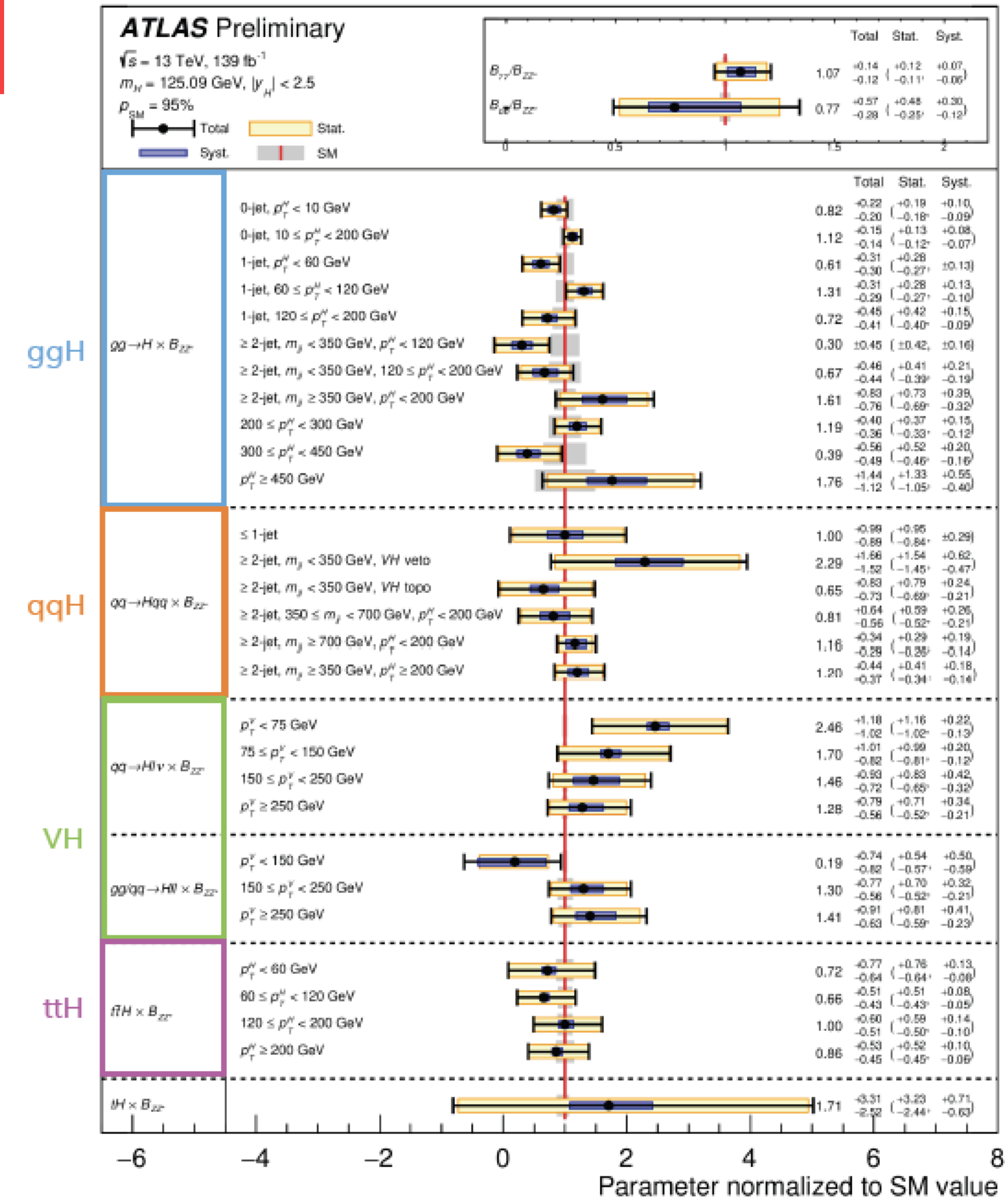


Includes full Run 2 results from H→ZZ*, H→γγ, VH(bb)

Not included: single channel results that have become available more recently (H→WW*, ttH→bb, H→Zγ)

H→ZZ channel as reference

12% unc. on $BR_{\gamma\gamma}/BR_{ZZ}$

larger unc. on BR_{bb}/BR_{ZZ}: dominated by large VH H→ZZ stat. unc.

29 STXS bins measured

Uncertainties btw. 15-100% for most bins

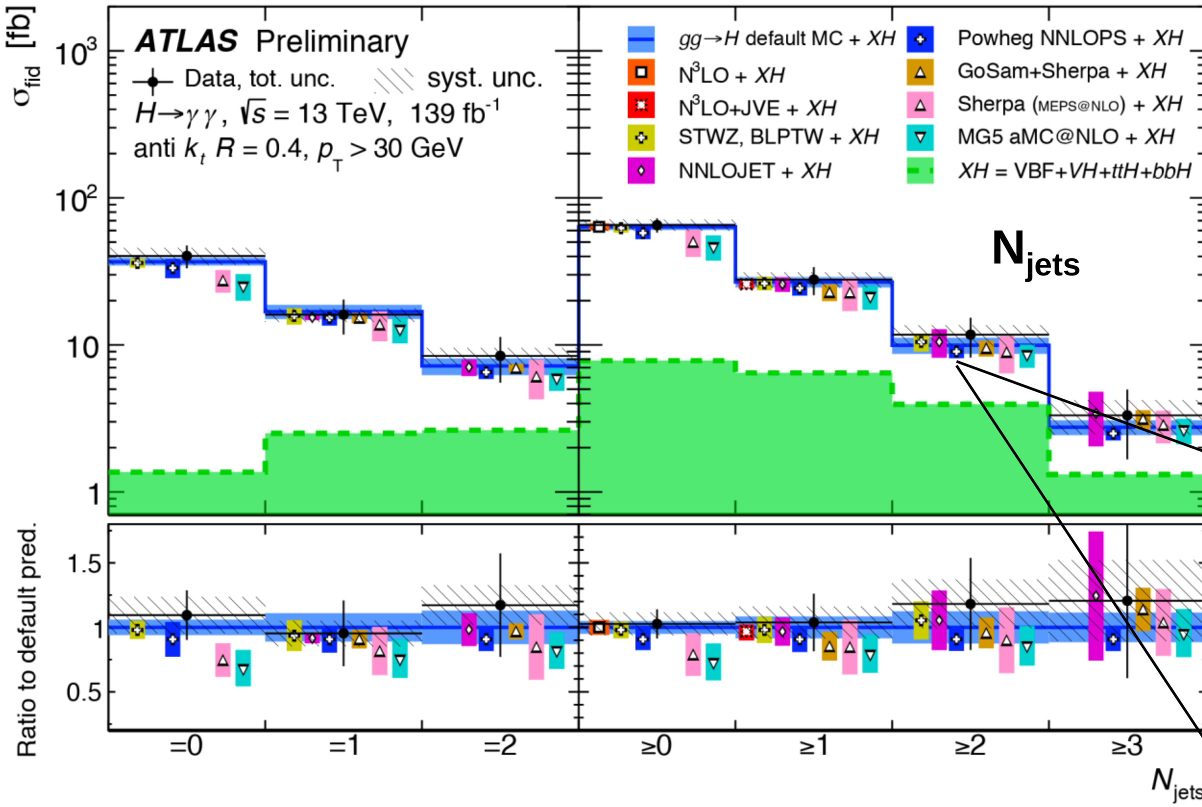
Statistical uncertainties dominate

Good agreement (p=95%) with SM pred.

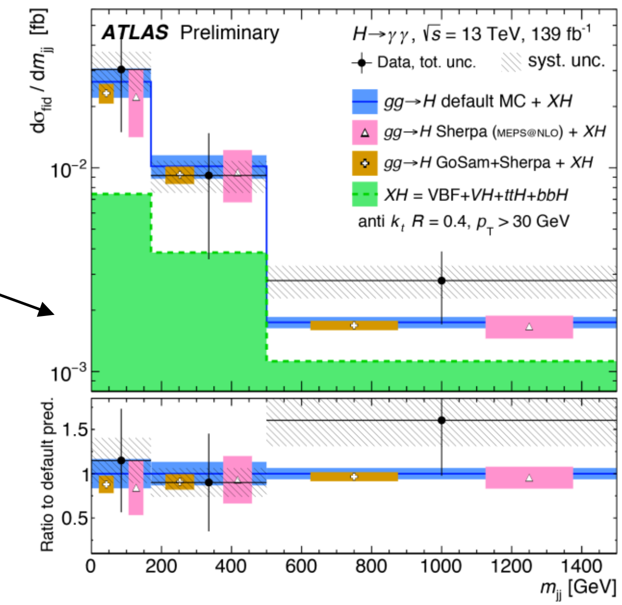
tH XS upper limit: <8.2 x σ_{SM} @95% CL

Fiducial and differential cross-sections: H→$\gamma\gamma$

ATLAS-CONF-2019-029



Fiducial XS:
65.2±4.5(stat.)±5.6(exp.)±0.3(th.) fb (11%)
[SM prediction: 63.6 ± 3.3 fb]

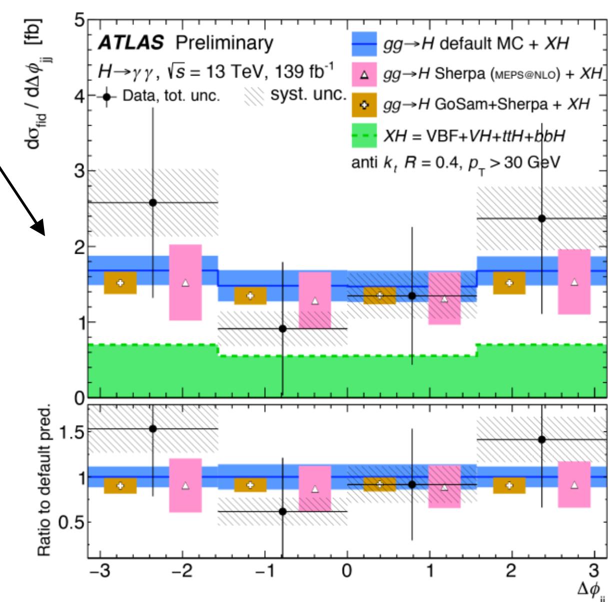


* Excellent resolution
* Six dist. measured:
  - Higgs kinematics: p_T, y
  - jets: N_{jets}, jet p_T
  - H+2j system: m_{jj}, $\Delta\phi_{jj}$

sensitive to production modes and higher order QCD effects: 20-40% unc. up to 2 jets

sensitive to anomalous operators including CP-odd ones

Unc. dominated by data stat.
Good agreement with theory predictions



Fiducial and differential cross-sections: H→ZZ*→4l

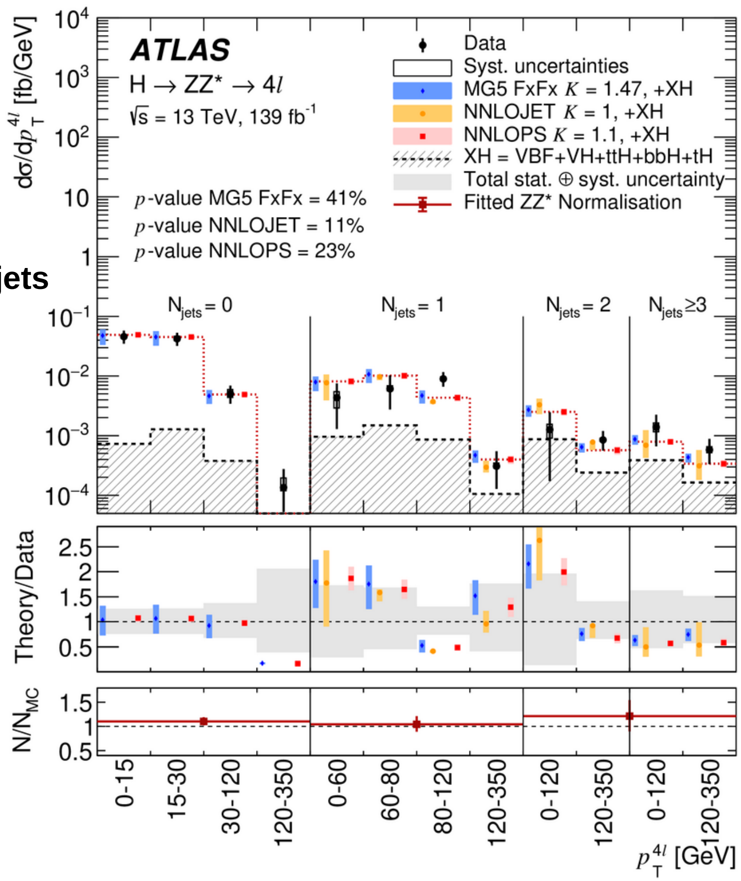
Eur.Phys.J.C80(2020)942

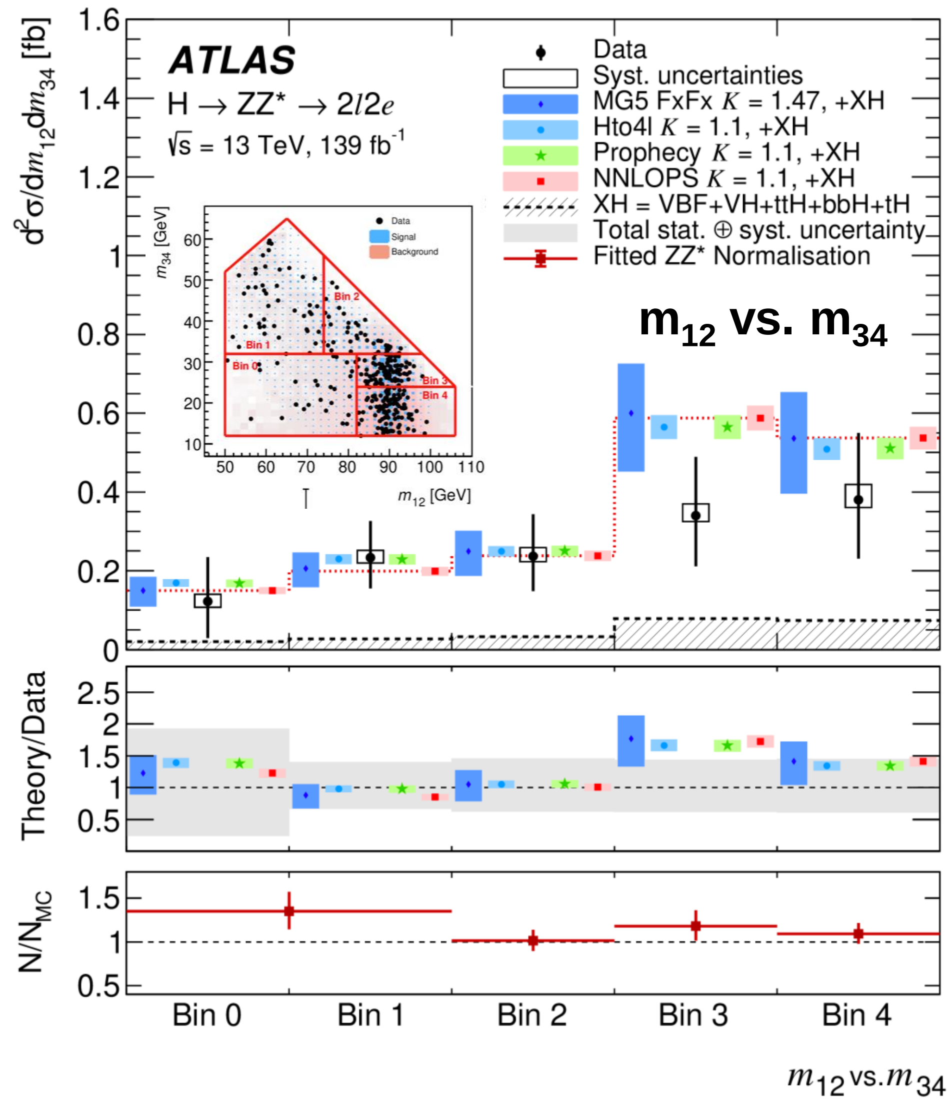
* Also excellent resolution and very good S/B ratio
* Many dist. measured, including:
  - Higgs kinematics: $\mathbf{p_T}$, **y**
  - jets: $\mathbf{N_{jets}}$, $N_{b\text{-jets}}$, jets p_T
  - H+2j system: m_{jj}, $\Delta\phi_{jj}$, $\Delta\eta_{jj}$
  - Higgs decay information: $\mathbf{m_{12}}$, $\mathbf{m_{34}}$, angular variables [sensitive to anomalous H→ZZ couplings]
  - **several double-diff. dist.**

Fiducial XS: 3.28 ±0.30(stat) ±0.11(syst) fb (prec.~10%)
[SM prediction: 3.41± 0.18 fb]

Unc. dominated by data stat.

2D:
p_T & N_{jets}





Global fit of couplings modifiers using kappa framework

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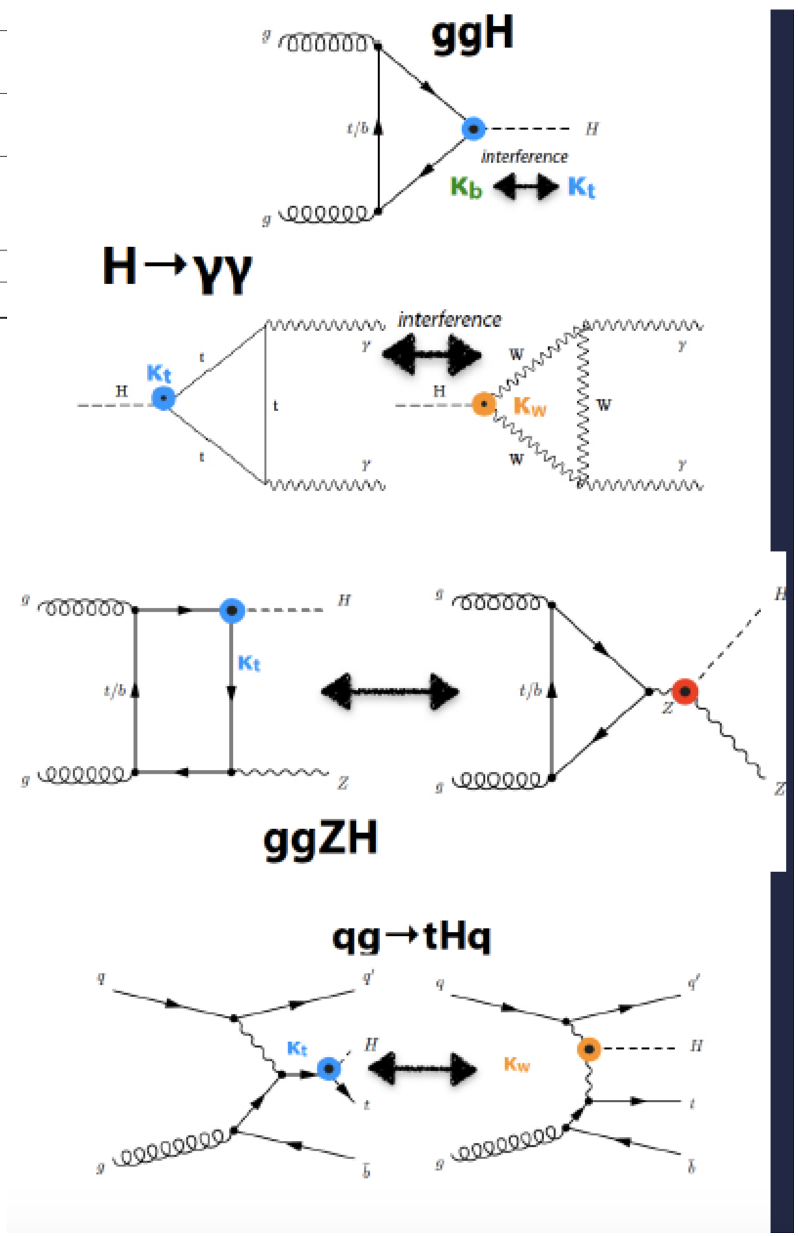
Using all production & decay modes

$$(\sigma \times \mathrm{B})_{if} = \kappa_i^2 \sigma_i^{\mathrm{SM}} \frac{\kappa_f^2 \Gamma_f^{\mathrm{SM}}}{\kappa_H^2 \Gamma_H^{\mathrm{SM}}}$$

Analysis decay channel	Target Prod. Modes	$\mathcal{L}$ [fb^{-1}]
$H \to \gamma\gamma$	ggF, VBF, WH, ZH, $t\bar{t}H$, tH	139
$H \to ZZ^*$	ggF, VBF, WH, ZH, $t\bar{t}H(4\ell)$	139
	$t\bar{t}H$ excl. $H \to ZZ^* \to 4\ell$	36.1
$H \to WW^*$	ggF, VBF	36.1
	$t\bar{t}H$	
$H \to \tau\tau$	ggF, VBF	36.1
	$t\bar{t}H$	
$H \to b\bar{b}$	VBF	24.5 – 30.6
	WH, ZH	139
	$t\bar{t}H$	36.1
$H \to \mu\mu$	ggF, VBF, VH, $t\bar{t}H$	139
$H \to inv$	VBF	139

Production	Loops	Effective modifier	Resolved modifier
$\sigma(\mathrm{ggF})$	✓	κ_g^2	$1.040\,\kappa_t^2 + 0.002\,\kappa_b^2 - 0.038\,\kappa_t\kappa_b - 0.005\,\kappa_t\kappa_c$
$\sigma(\mathrm{VBF})$	-	-	$0.733\,\kappa_W^2 + 0.267\,\kappa_Z^2$
$\sigma(qq/qg \to ZH)$	-	-	κ_Z^2
$\sigma(gg \to ZH)$	✓	$\kappa_{(ggZH)}$	$2.456\,\kappa_Z^2 + 0.456\,\kappa_t^2 - 1.903\,\kappa_Z\kappa_t$ $-0.011\,\kappa_Z\kappa_b + 0.003\,\kappa_t\kappa_b$
$\sigma(WH)$	-	-	κ_W^2
$\sigma(t\bar{t}H)$	-	-	κ_t^2
$\sigma(tHW)$	-	-	$2.909\,\kappa_t^2 + 2.310\,\kappa_W^2 - 4.220\,\kappa_t\kappa_W$
$\sigma(tHq)$	-	-	$2.633\,\kappa_t^2 + 3.578\,\kappa_W^2 - 5.211\,\kappa_t\kappa_W$
$\sigma(b\bar{b}H)$	-	-	κ_b^2
Partial decay width			
Γ^{bb}	-	-	κ_b^2
Γ^{WW}	-	-	κ_W^2
Γ^{gg}	✓	κ_g^2	$1.111\,\kappa_t^2 + 0.012\,\kappa_b^2 - 0.123\,\kappa_t\kappa_b$
$\Gamma^{\tau\tau}$	-	-	κ_τ^2
Γ^{ZZ}	-	-	κ_Z^2
Γ^{cc}	-	-	$\kappa_c^2\ (=\kappa_t^2)$
$\Gamma^{\gamma\gamma}$	✓	κ_γ^2	$1.589\,\kappa_W^2 + 0.072\,\kappa_t^2 - 0.674\,\kappa_W\kappa_t$ $+0.009\,\kappa_W\kappa_\tau + 0.008\,\kappa_W\kappa_b$ $-0.002\,\kappa_t\kappa_b - 0.002\,\kappa_t\kappa_\tau$
$\Gamma^{Z\gamma}$	✓	$\kappa_{(Z\gamma)}^2$	$1.118\,\kappa_W^2 - 0.125\,\kappa_W\kappa_t + 0.004\,\kappa_t^2 + 0.003\,\kappa_W\kappa_b$
Γ^{ss}	-	-	$\kappa_s^2\ (=\kappa_b^2)$
$\Gamma^{\mu\mu}$	-	-	κ_μ^2
Total width ($B_{i.} = B_{u.} = 0$)			
Γ_H	✓	κ_H^2	$0.581\,\kappa_b^2 + 0.215\,\kappa_W^2 + 0.082\,\kappa_g^2$ $+0.063\,\kappa_\tau^2 + 0.026\,\kappa_Z^2 + 0.029\,\kappa_c^2$ $+0.0023\,\kappa_\gamma^2 + 0.0015\,\kappa_{(Z\gamma)}^2$ $+0.0004\,\kappa_s^2 + 0.00022\,\kappa_\mu^2$



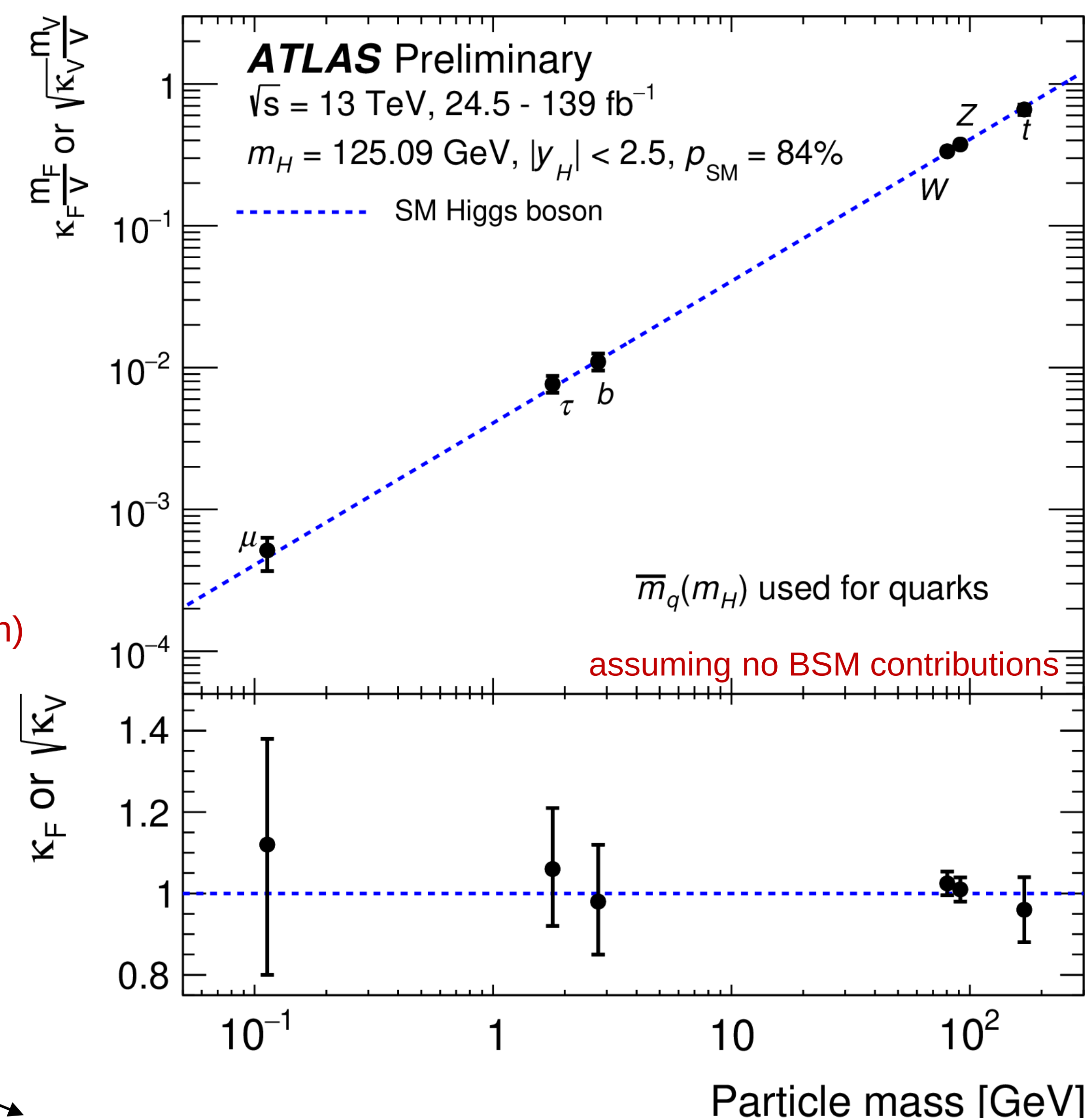
Couplings combination: kappa framework

ATLAS-CONF-2020-027

- assuming only modification of couplings' strength
- agreement with SM predictions: 84%
- unc. on Higgs couplings:
  - ~6% to vector bosons
  - ~10-15% to 3rd gen. fermions
  - <30% for muons

Resolved

κ_Z	1.02 ± 0.06
κ_W	1.05 ± 0.06
κ_b	$0.98\ ^{+0.14}_{-0.13}$
κ_t	$0.96\ \pm 0.08$
κ_τ	$1.06\ ^{+0.15}_{-0.14}$
κ_μ	$1.12\ ^{+0.26}_{-0.32}$



Effective loops (wo./w. BSM contributions to total width)

Parameter	(a) $B_{i.} = B_{u.} = 0$	(b) $B_{i.}$ free, $B_{u.} \geq 0$, $\kappa_{W,Z} \leq 1$
κ_Z	1.02 ± 0.06	> 0.88 at 95% CL
κ_W	1.06 ± 0.07	> 0.89 at 95% CL
κ_b	$0.98\ ^{+0.14}_{-0.13}$	$0.92\ \pm 0.10$
κ_t	1.00 ± 0.12	$0.97\ \pm 0.12$
κ_τ	$1.05\ ^{+0.15}_{-0.14}$	$1.02\ ^{+0.13}_{-0.14}$
κ_γ	$1.06\ ^{+0.08}_{-0.07}$	$1.04\ ^{+0.06}_{-0.07}$
κ_g	$0.96\ ^{+0.09}_{-0.08}$	$0.93\ ^{+0.08}_{-0.07}$
$B_{i.}$	-	< 0.09 at 95% CL
$B_{u.}$	-	< 0.19 at 95% CL

$\kappa_t<0$ excluded at 2.9σ

EFT interpretation: effect of operators in XSs and BRs

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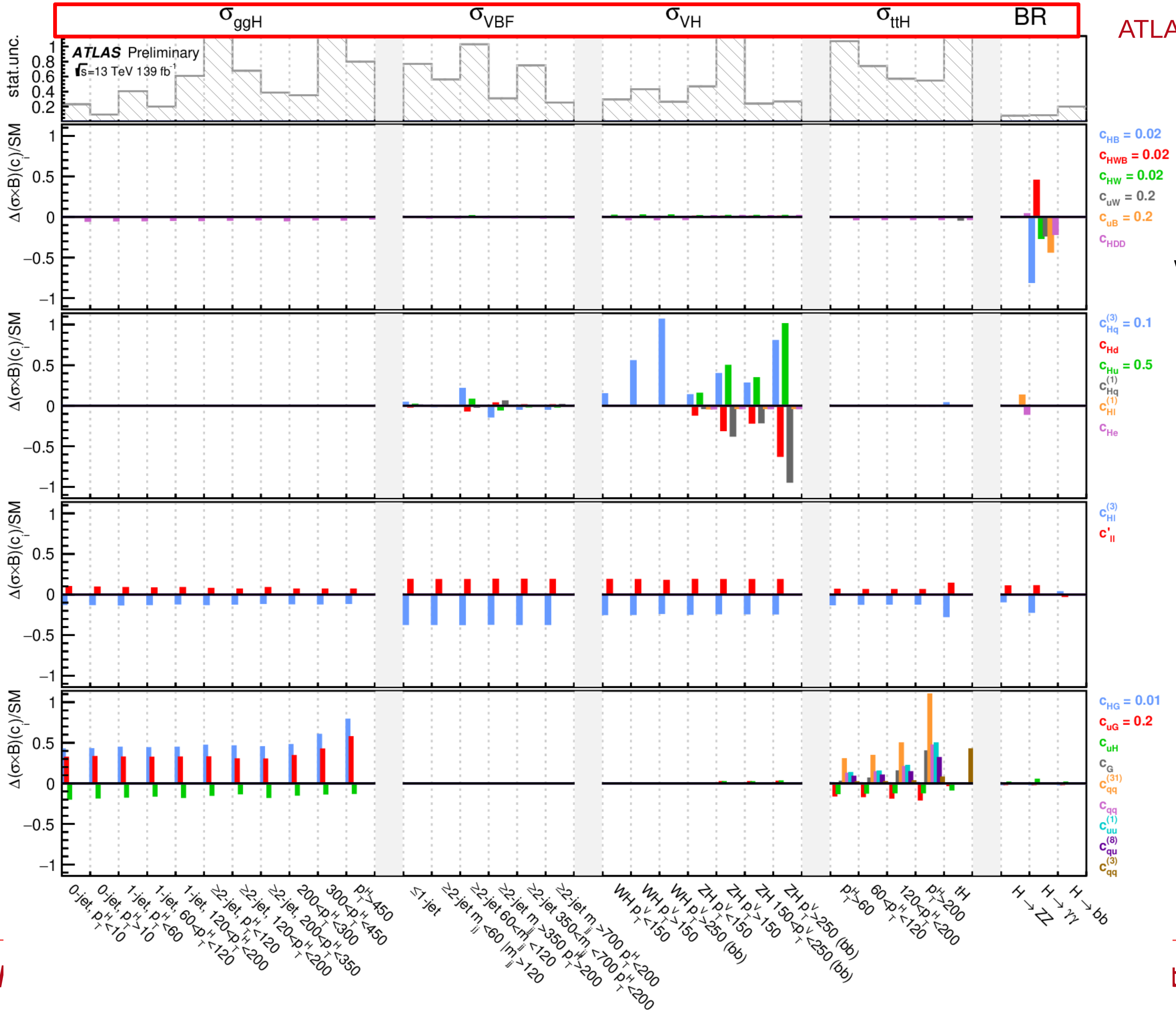

Warsaw basis

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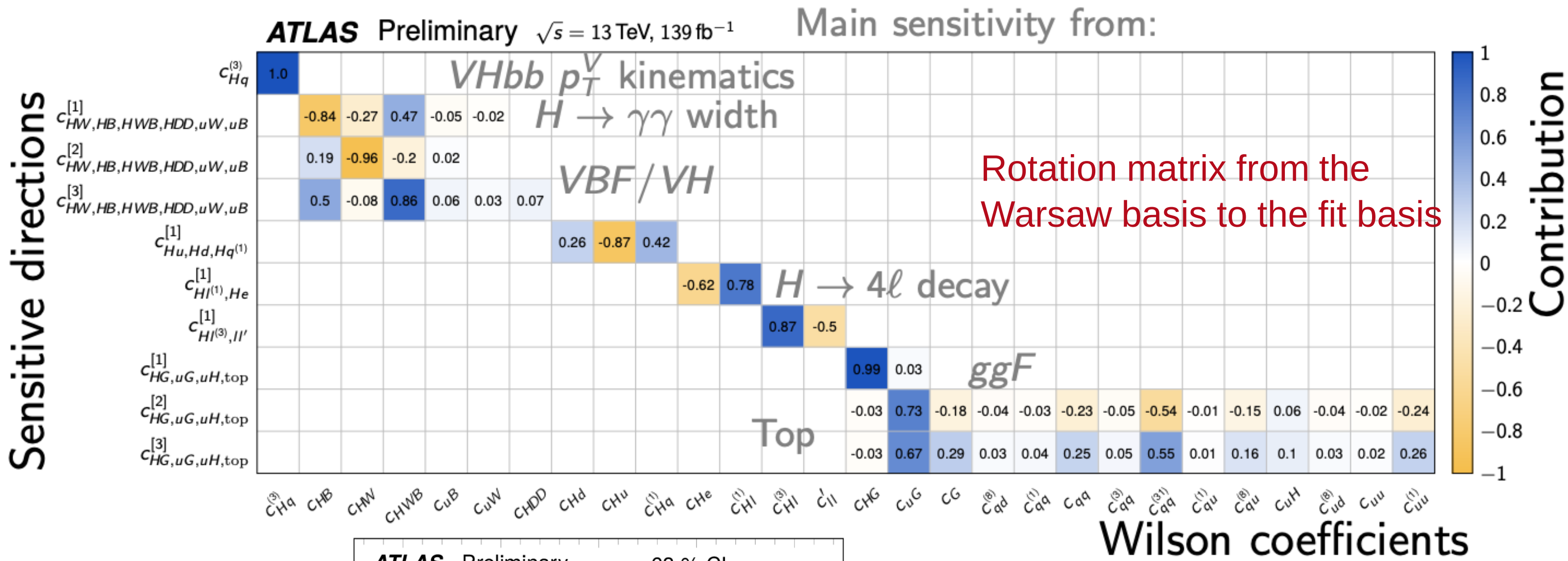
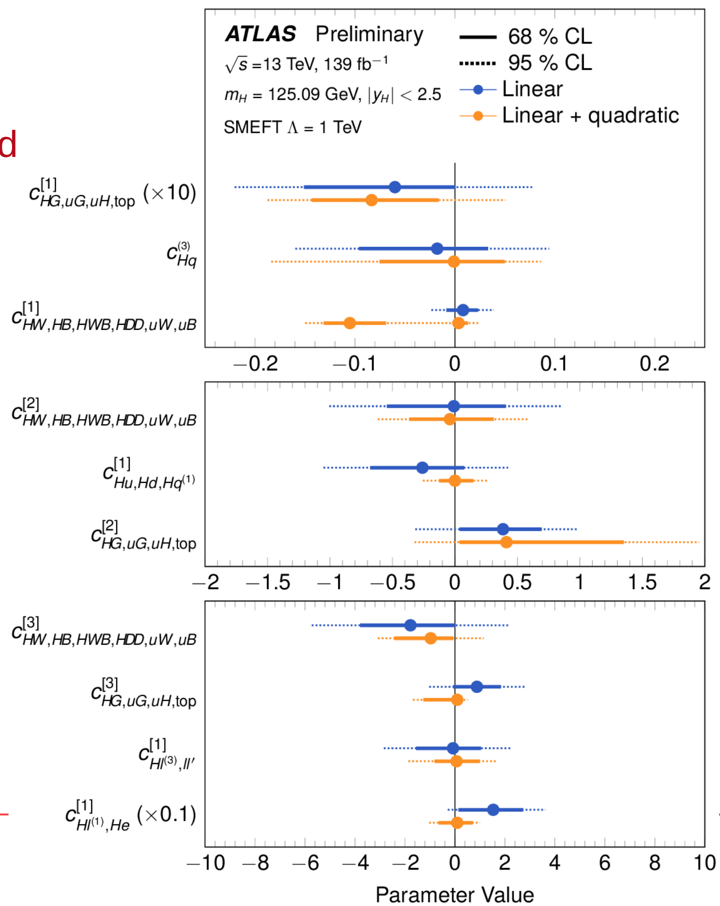


Obtained limits



Simultaneous fit of 10 Wilson coefficients/groups

(groups of operators with similar impact on physics processes identified; eigenvector decomposition)

Is the top-Higgs coupling a pure scalar interaction ?

$J^{CP} = 0^{++}$? Phys.Rev.Lett.125(2020)061802

No deviations found in CP properties of the Higgs couplings to gauge bosons (studied in Run 1)

Caveat: in those, CP-odd contributions enter only via higher-order operators

NEW: pseudoscalar admixture directly tested in top-Higgs interaction using ttH/tH events with H→γγ

$$\mathcal{L}_t = -\frac{m_t}{v}(\kappa_t \bar{t}t + i\tilde{\kappa}_t \bar{t}\gamma_5 t)H$$

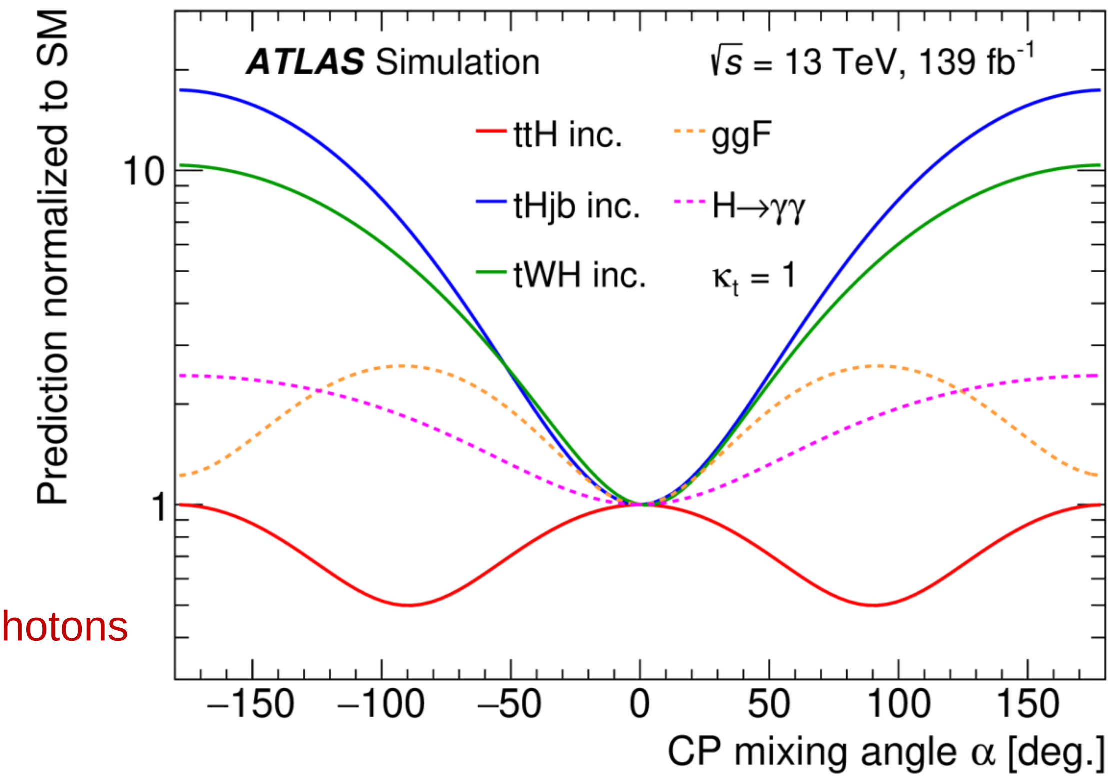
↑ CP (crossed out)

SM: $(\kappa_t, \tilde{\kappa}_t) = (1, 0)$

$$\kappa_t = k_t \cos\alpha$$
$$\tilde{\kappa}_t = k_t \sin\alpha$$

CP mixing angle: α

Rate variation vs. CP mixing angle α

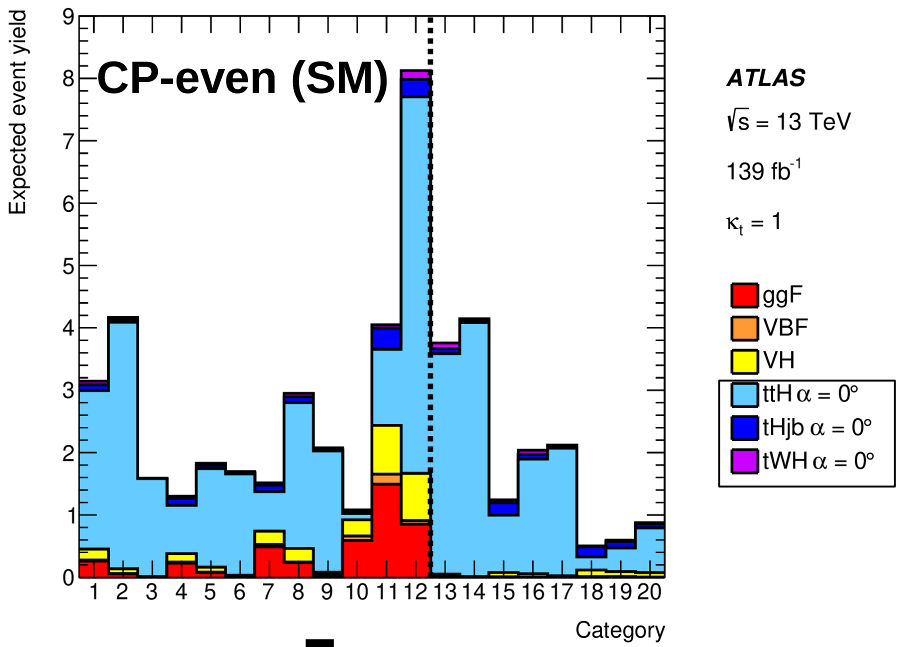


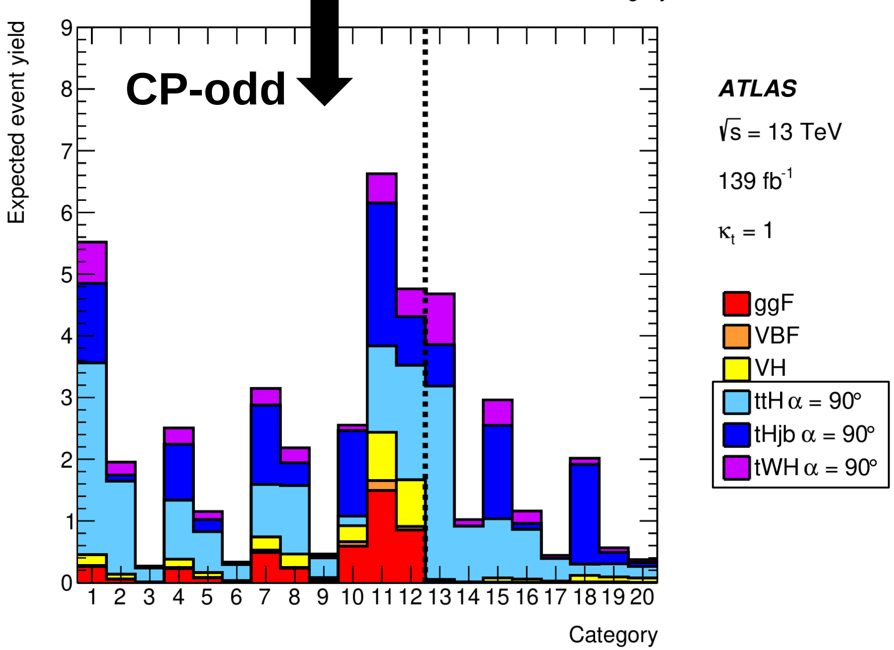
CP-odd contributions would alter:

- rates and kinematics of *ttH* and *tH* processes
  - *tH* also sensitive to the sign of y_t
- loop-induced Higgs couplings to gluons and photons

CP properties of the top-Higgs Yukawa coupling (ttH/tH, H→γγ)

Phys.Rev.Lett.125(2020)061802





Several MVAs for object reconstruction (also top quark)

Two event-level MVAs used → define several regions

1: ttH vs. continuum bkg.

2: ttH+tH CP-odd vs. CP-even

Signal extraction: fit $m_{\gamma\gamma}$ in all categories

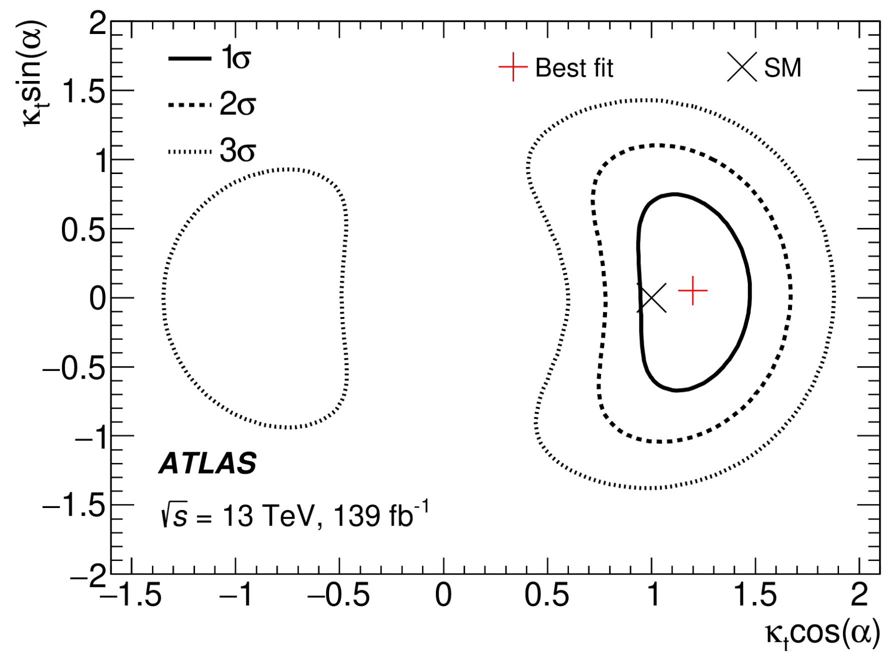
A pure CP-odd coupling excluded at 3.9σ

CP mixing angle **|α|< 43º at 95% CL**

y_t <0 disfavoured

tH rate < 12 x σ_{SM} at 95% CL

Result limited by data statistics



Hadronic boosted H→bb: reaching 1 TeV !

ATLAS-CONF-2021-010

Probing Higgs production at **high $p_T(H)$** (and $|\eta_H|<2$) using final states with 2 jets: at least one large-radius jet with **p_T > 450 GeV** and just one that contains two b-hadrons

Inclusive, fiducial and differential cross-sections measured:

Region	Jet p_T [GeV] SRL	Jet p_T [GeV] SRS	p_T^H [GeV] SRL	p_T^H [GeV] SRS
Inclusive	>450	>250	–	–
Fiducial	>450 >1000	>450 –	>450 >1000	>450 –
Differential	450–650, 650–1000	250–450, 450–650, 650–1000	450–650, 650–1000	300–450, 450–650, 650–1000

SRL (SRS): leading (subleading) jet tagged as H(bb) candidate

Fractional contribution of each prod mode to SRs within [105,140] GeV

Process	p_T Range [GeV] 250–450	450–650	650–1000	> 1000
SRL				
ggF	–	0.56	0.50	0.39
VBF	–	0.17	0.16	0.17
VH	–	0.14	0.18	0.25
$t\bar{t}H$	–	0.13	0.16	0.19
SRS				
ggF	0.28	0.46	0.43	–
VBF	0.07	0.19	0.21	–
VH	0.26	0.24	0.26	–
$t\bar{t}H$	0.39	0.11	0.10	–

Inclusive

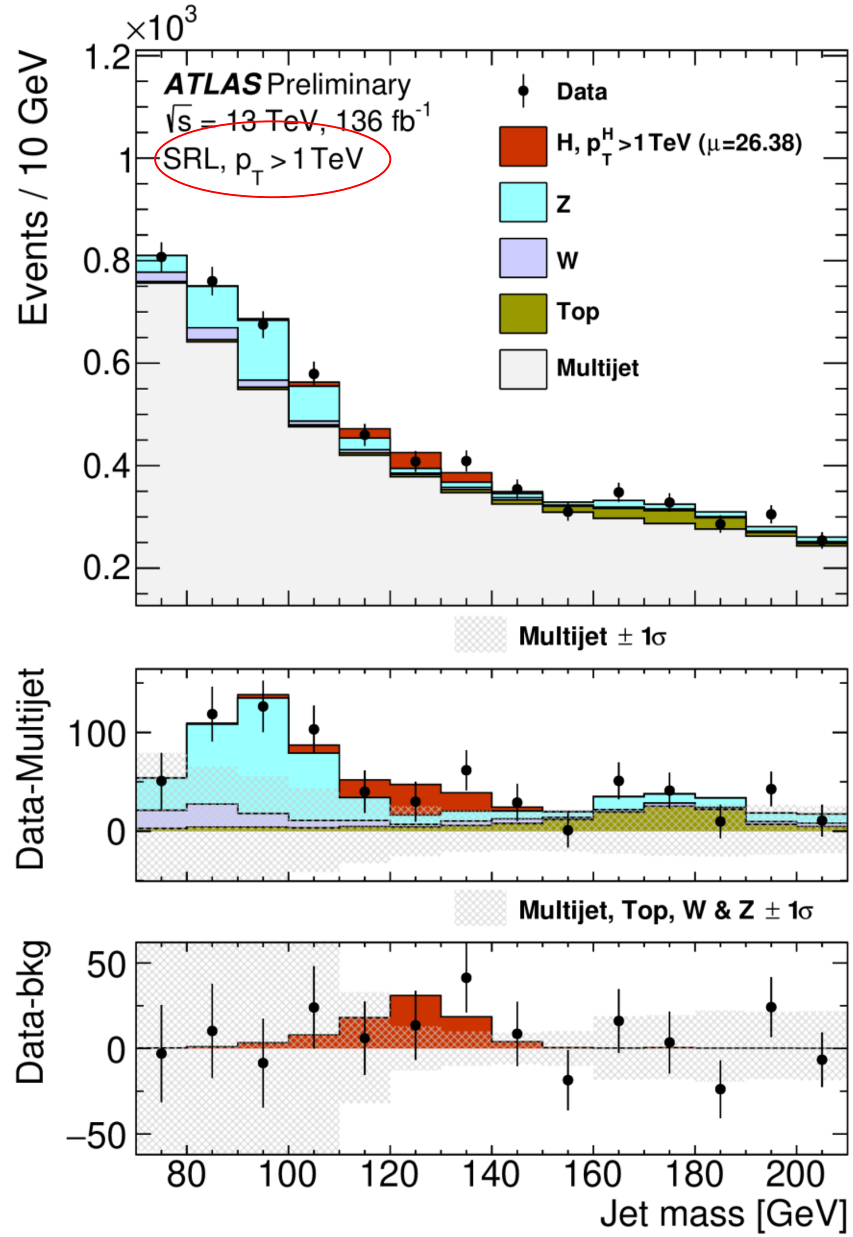
$$\mu_H = 1.1 \pm 3.6$$

Limited by stat. unc.
Leading systematics are jet-mass resolution and scale

Fiducial

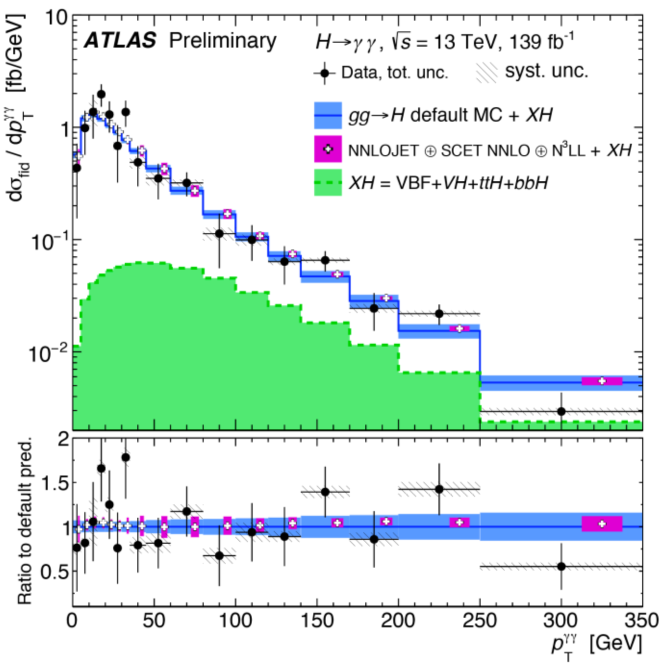
p_T^H/Jet p_T	μ_H Exp.	μ_H Obs.
> 450 GeV	1.0 ± 3.3	0.7 ± 3.3
> 1 TeV	1.0 ± 29.0	26 ± 31

$$\sigma_H(p_T^H > 450\text{ GeV}) < 144\text{ fb} \quad (\sim 8 \times \sigma_{SM})$$
$$\sigma_H(p_T^H > 1\text{ TeV}) < 10.3\text{ fb.} \quad (\sim 80 \times \sigma_{SM})$$



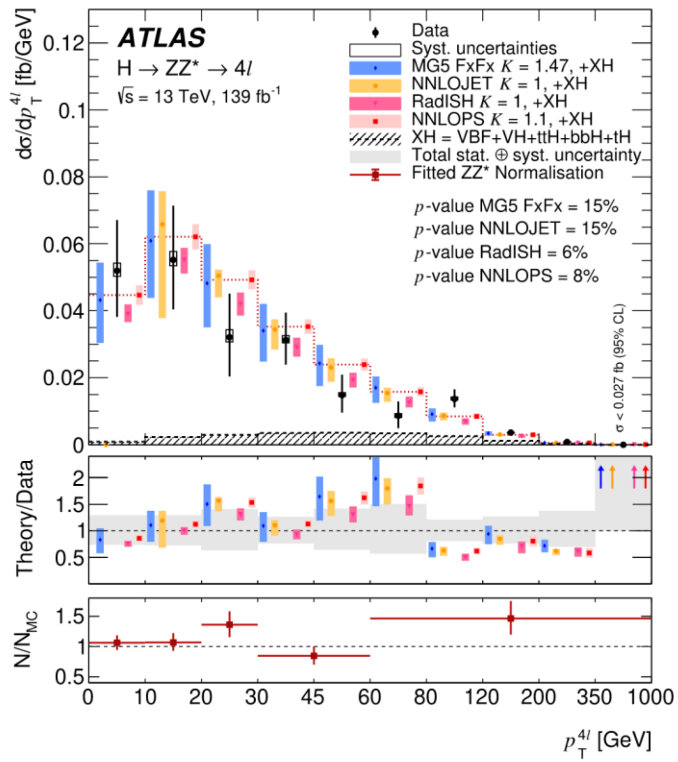
Measured Higgs p_T spectrum: reaching 1 TeV !

H→γγ



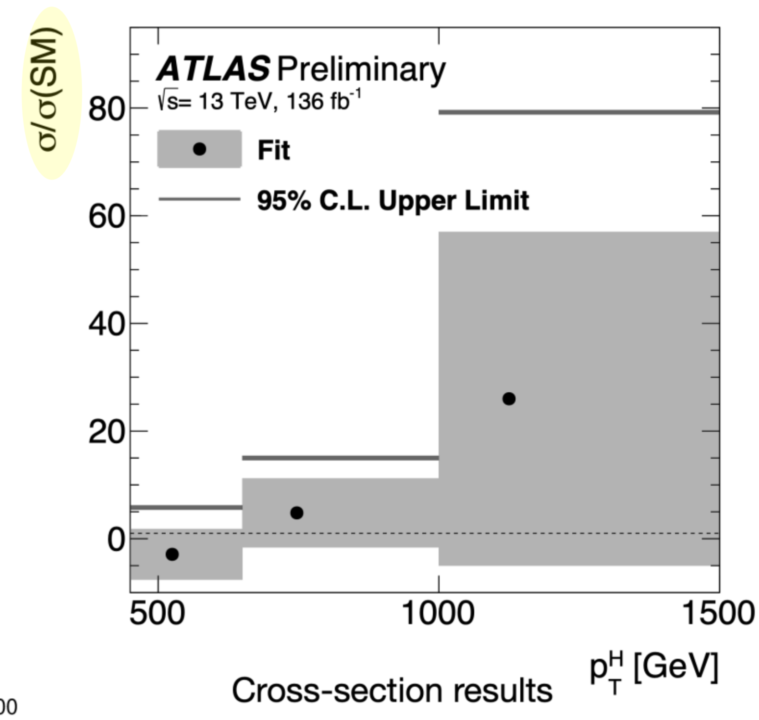
ATLAS-CONF-2019-029

H→ZZ*→4l



Eur.Phys.J.C80(2020)942

H→bb



ATLAS-CONF-2021-010

Direct search for interaction of Higgs with 2nd gen. fermion ☺
Rare decay channel (BR~0.022%) with a large (Drell-Yan) background ☹
S/B ~O(0.1%) within [120, 130] GeV
Clean and sharp Higgs peak: $\sigma(m_{\mu\mu})$ ~2.5-3.0 GeV

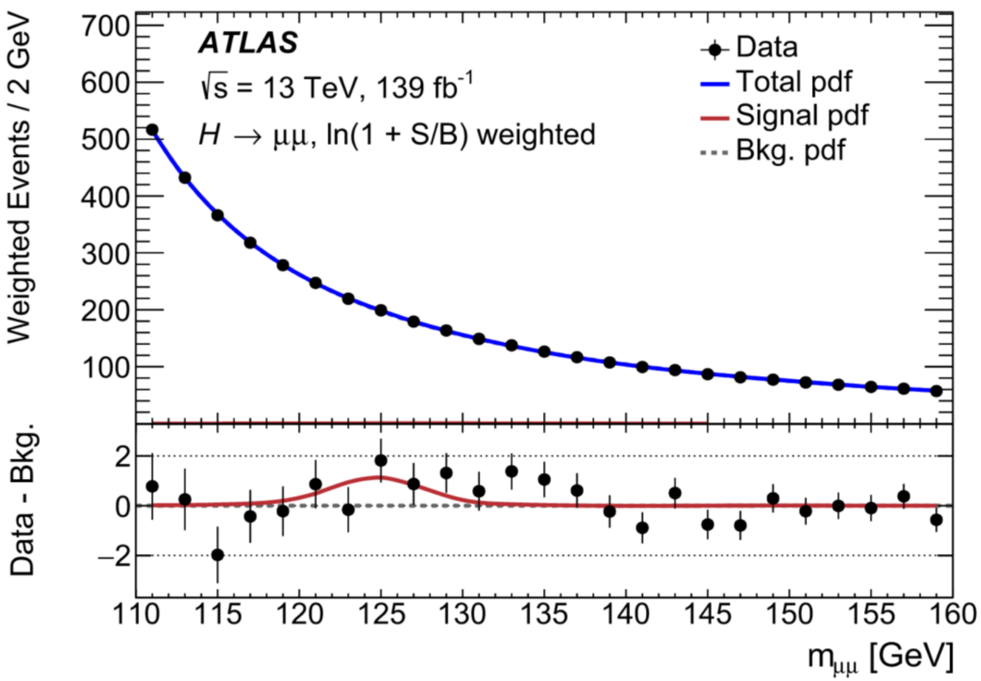
Phys.Lett.B 812 (2021) 135980

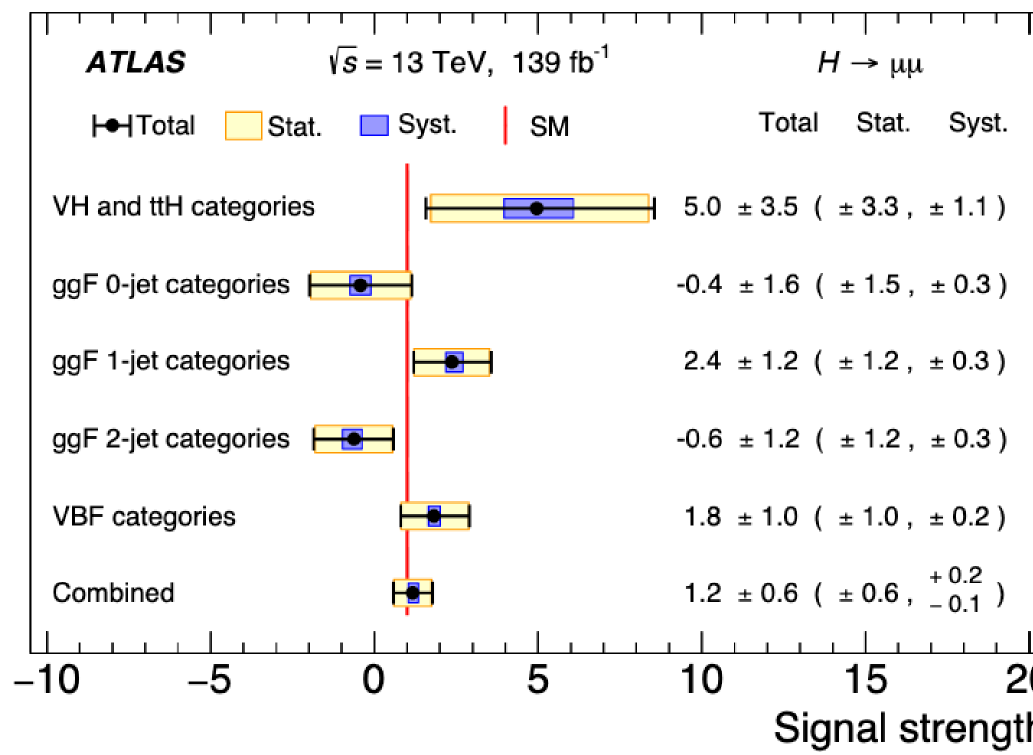
Measured μ = 1.2±0.6

Close to evidence for H→μμ decay: 2.0σ (1.7σ) obs.(exp.)

$\kappa_\mu = 1.12^{+0.26}_{-0.32}$ @68% CL

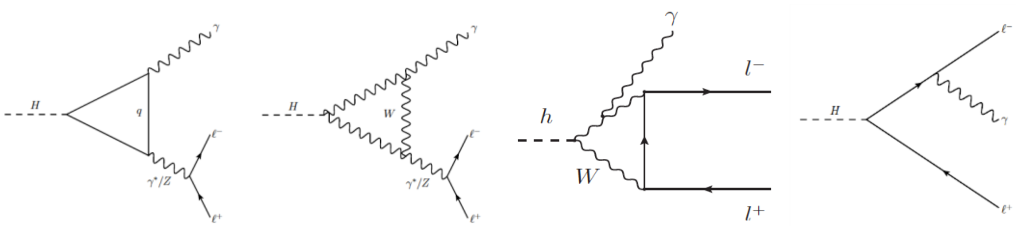
Statistical uncertainty dominates !

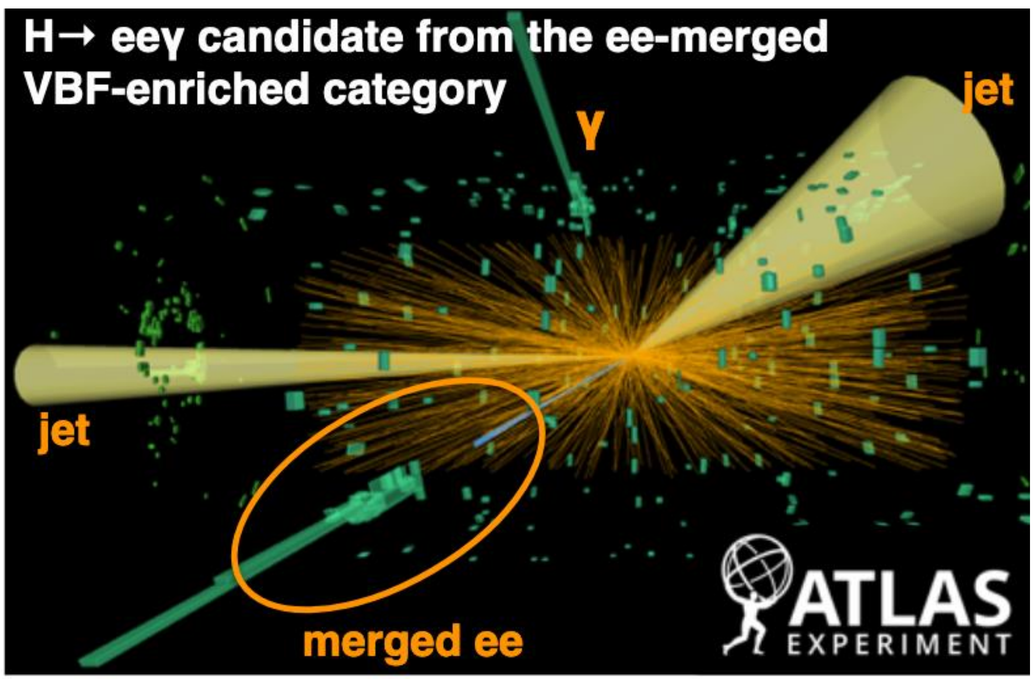


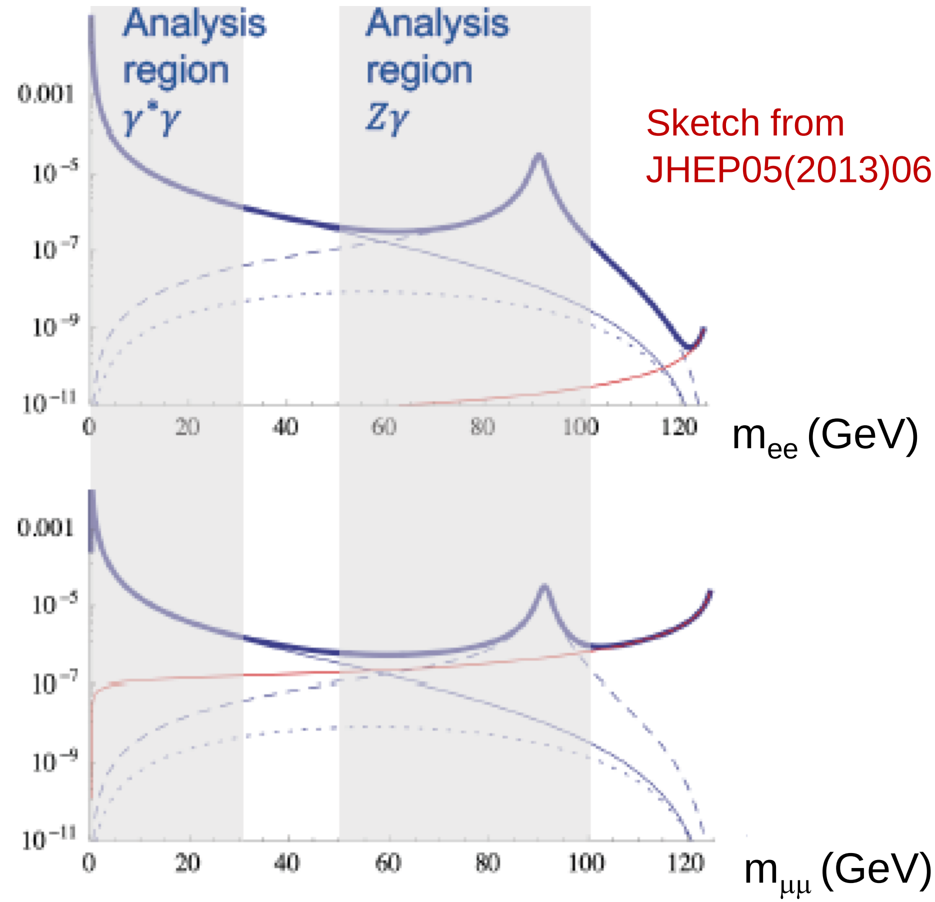


Processes that contribute to H→llγ final state:

- loop-induced H→Zγ with Z→ll (dash line)
- loop-induced H→$\gamma^*\gamma$ with $\gamma* \rightarrow ll$ (thin solid line)
- 4-vertex box diagram (dot line)
- H→ll + FSR (thin red line)





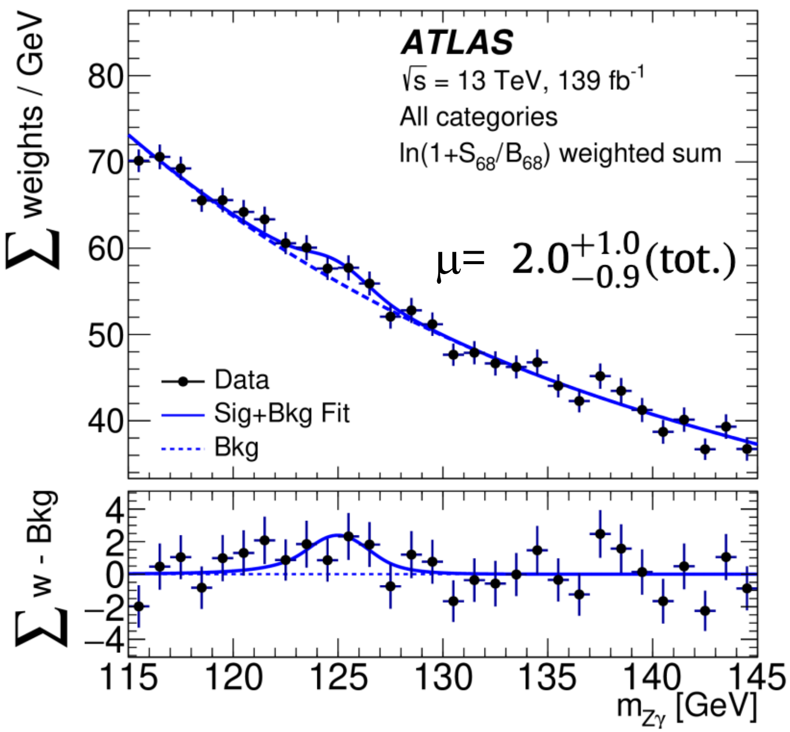


Sketch from JHEP05(2013)061

Both H→Zγ and H →$\gamma^*\gamma$ with $ll\gamma$ final state have SM BR ~0.01% (~5% of H→$\gamma\gamma$ BR)

Phys.Lett.B809(2020)135754
arXiv: 2103.10322 (s ubmitted to PLB)

H→Zγ



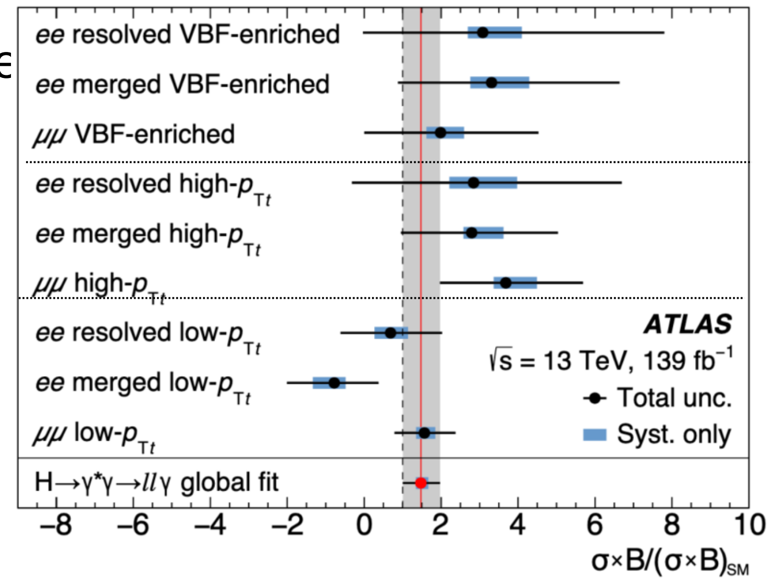
Obs. (exp.) sign.: 2.2σ (1.2σ)

Upper limit at 95%CL: 3.6 x σ_{SM}

New opportunity to probe CP structure of Higgs couplings in 3-body decays

H→γ*γ

- Probing ggH (high & low p_T) and VBF production modes
- Decay categories: μμ and ee (resolved and merged)
- Stat. limited

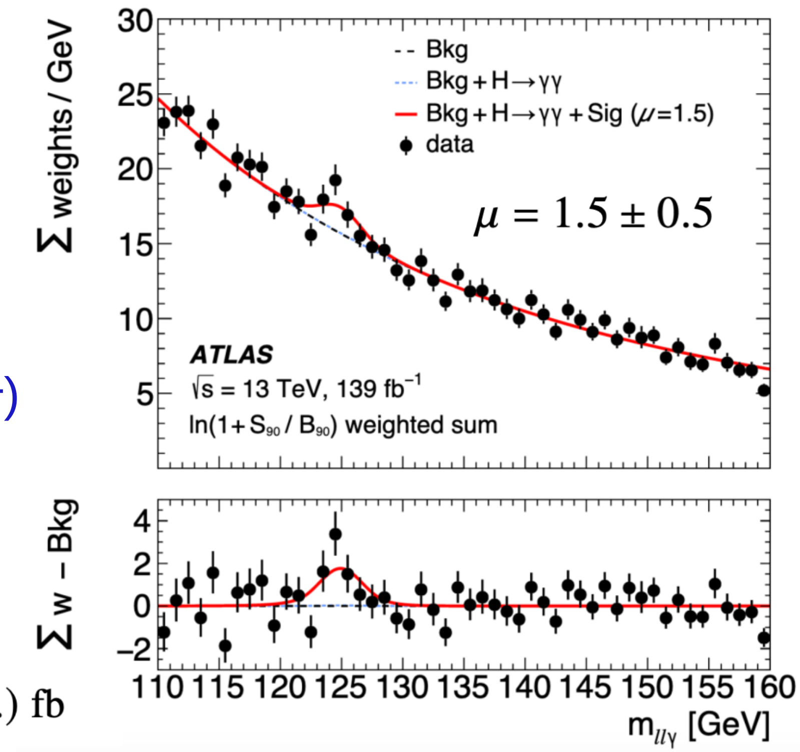


Obs. (exp.) sign: 3.2σ (2.1σ)

→ evidence H→*llγ*

$\sigma \times BR(\ell\ell\gamma)|_{m_{\ell\ell}<30\ \mathrm{GeV}}$:

$$8.7\,^{+2.8}_{-2.7}\ \mathrm{fb} = 8.7\,^{+2.7}_{-2.7}\ (\mathrm{stat.})\ ^{+0.7}_{-0.6}\ (\mathrm{syst.})\ \mathrm{fb}$$



ATLAS-CONF-2020-052

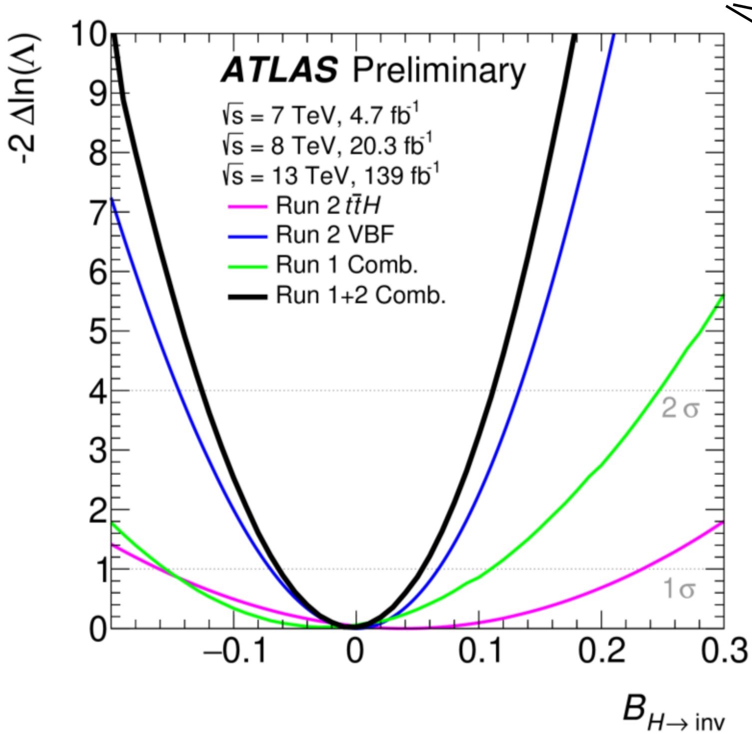
Searches for invisible Higgs decays: a portal to dark matter and invisible BSM particles

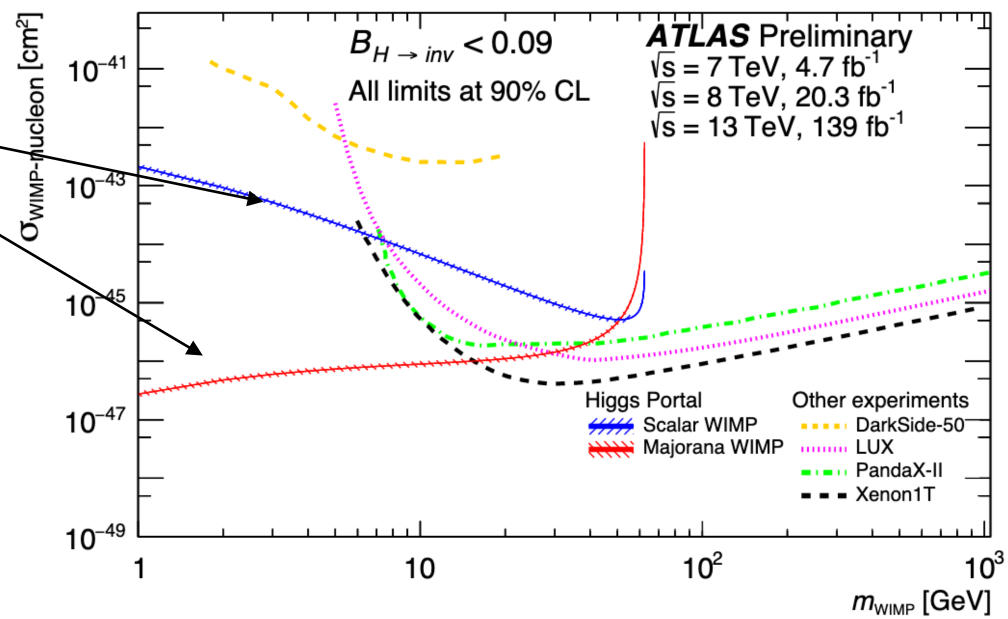
SM prediction: BR(H→invisible)~0.1% from H→ZZ*→4ν

Signature: just $E_{T,miss}$ (not good resolution in high pile-up environments)

→ need to rely on associated production modes as tags (VBF, and ttH with 0 or 2l)

Observed upper limit BR<11% @95CL





Within Higgs portal model, constrain dark matter interactions in terms of weakly int. massive particle (WIMP):

- complementary to direct detection experiments
- model dependent

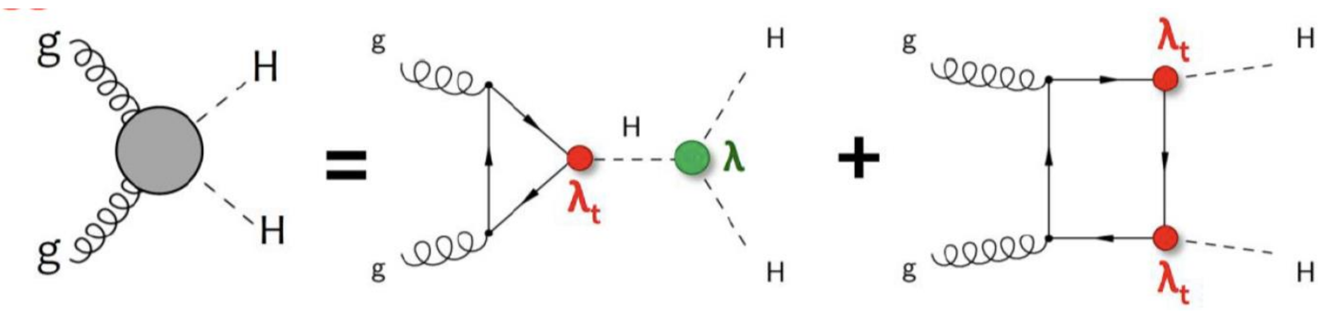
ALSO a broad program in BSM Higgs searches: additional Higgses (charged Higgses, 2HDM+scalar models with h→aa, ...), lepton-flavour-violating decay, etc.

Higgs boson self-coupling: search for di-Higgs production

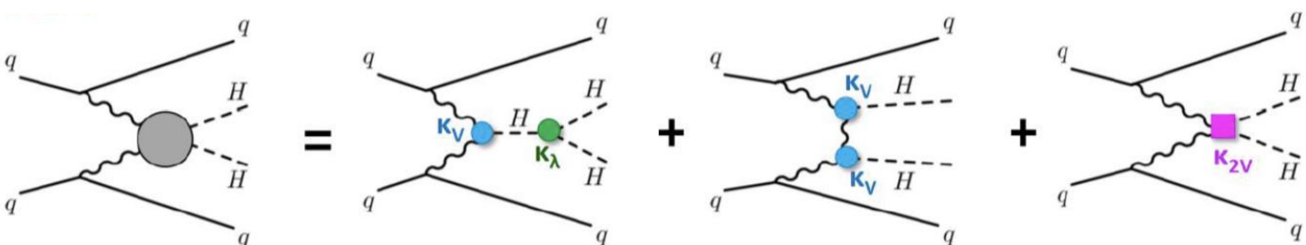
SM expects Higgs to couple to itself (κ_λ)
Diverse HH production modes, all with small cross section at 13 TeV (1/1000 than single Higgs)

Diagrams from G. Petrucciani @LHCP2020

ggF HH ~ 31.1 fb

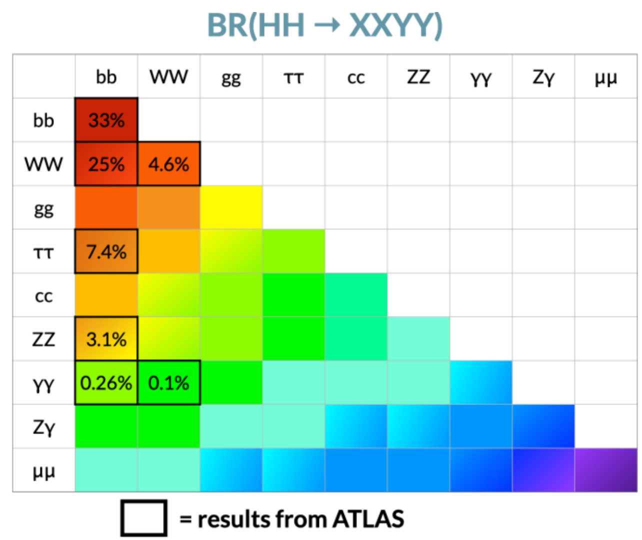


VBF HH ~ 1.72 fb

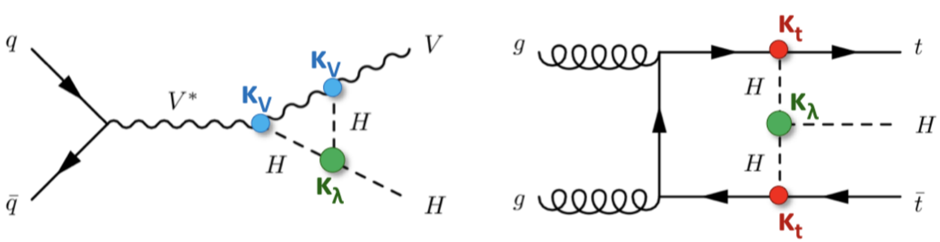


VBF offers access to HHVV quartic coupling

Several channels explored:



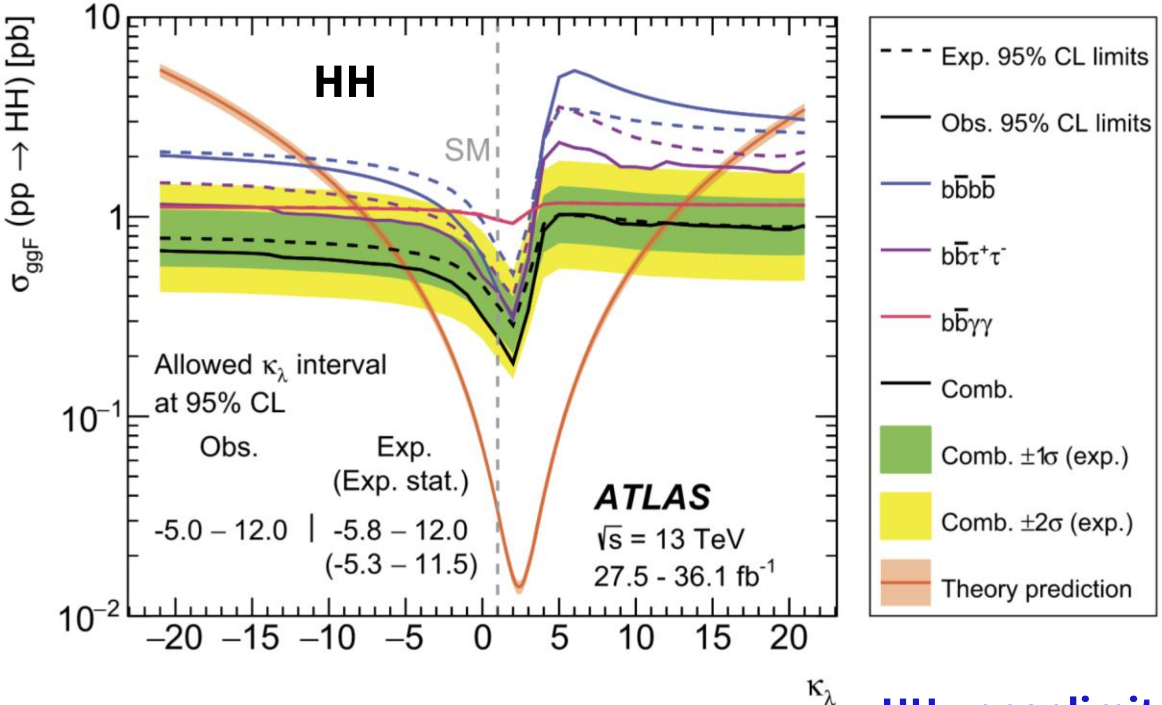
Single Higgs (mainly ttH and VH) also sensitive to κ_λ

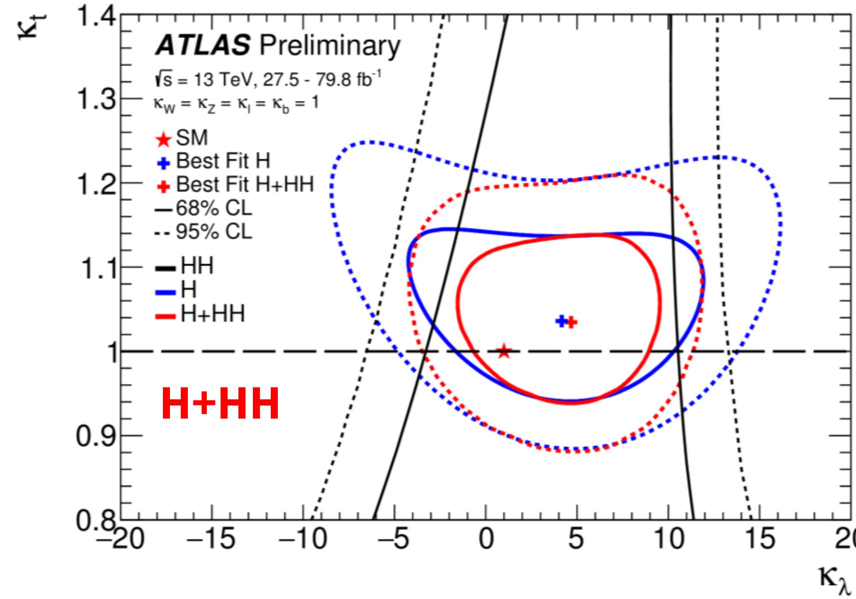


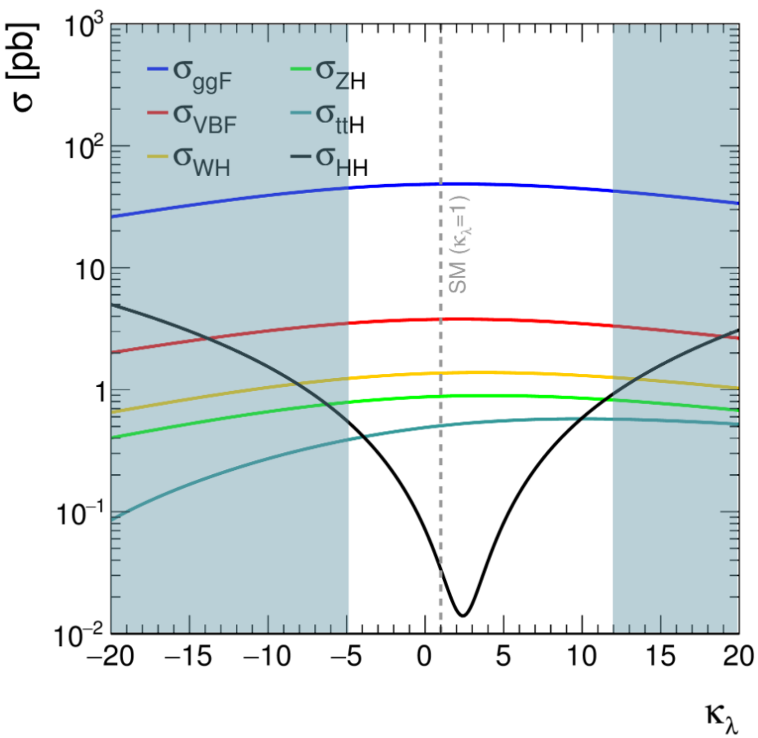
Run 1 + partial Run 2 data
HH: Phys. Lett. B 800 (2020) 135103
Single Higgs: ATLAS-CONF-2019-049

Also few updates with full Run 2

Higgs boson self-coupling: search for di-Higgs production







HH upper limit at 95%CL: 6.9 x σ_{SM}

κ_λ:(-5.0, 12.1) → **very similar limits using single Higgs, but with assumptions**

Few analyses updated with the full Run 2 data (new ch. and improved strategies):

HH→ bbWW (Phys.Lett.B801(2020)135145)

boosted HH→bbττ (JHEP11(2020)163)

and VBF HH→4b (JHEP07(2020)108)

First constraint on κ_{2V} : -0.43 < κ_{2V} < 2.56

Summary: What have we learnt about Higgs properties ?

Extensive studies within the Higgs sector:

- ✓ Higgs mass: reaching 0.15%
- ✓ Spin = 0
- ✓ Higgs production: all major production modes observed
- ✓ Higgs decays: - most major decays observed
  - now tackling rare decays like $H\rightarrow\mu\mu$, $H\rightarrow ll\gamma$
  - $H\rightarrow$invisible constrained to 11% (@95CL)
  - next target: $H\rightarrow cc$ (c-tagging is crucial)
- ✓ Higgs couplings
  - assuming SM: tested fermion and boson coupling strengths
  - pure CP odd couplings to bosons excluded $>5\sigma$
  - pure CP odd couplings to fermions excluded $>3\sigma$

➔ No disagreements from the SM predictions (so far)

Outstanding level of precision reached and continue pushing the limit.

- Full Run 2 still being analyzed (and it is just 4% of expected LHC data)
- Systematic uncertainties are becoming a more dominant for many results
- Need to reduce systematics (theory, modelling of signal and bkgs.)

Learn from the limitations and improve to reach the ultimate precision.

Collaboration with theorists is crucial and makes all of us smarter ☺ !!!

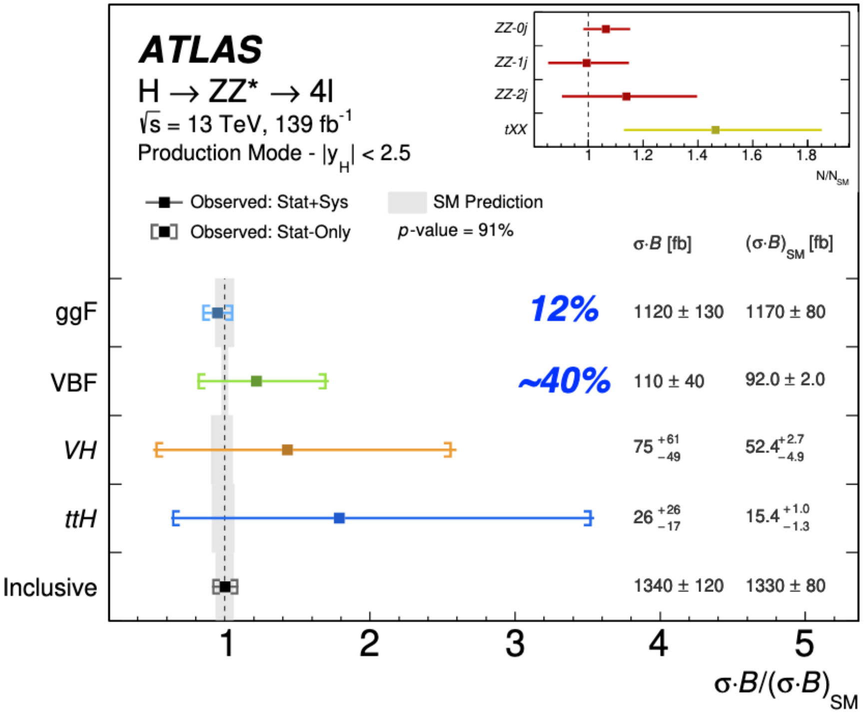
THANKS FOR YOUR ATTENTION

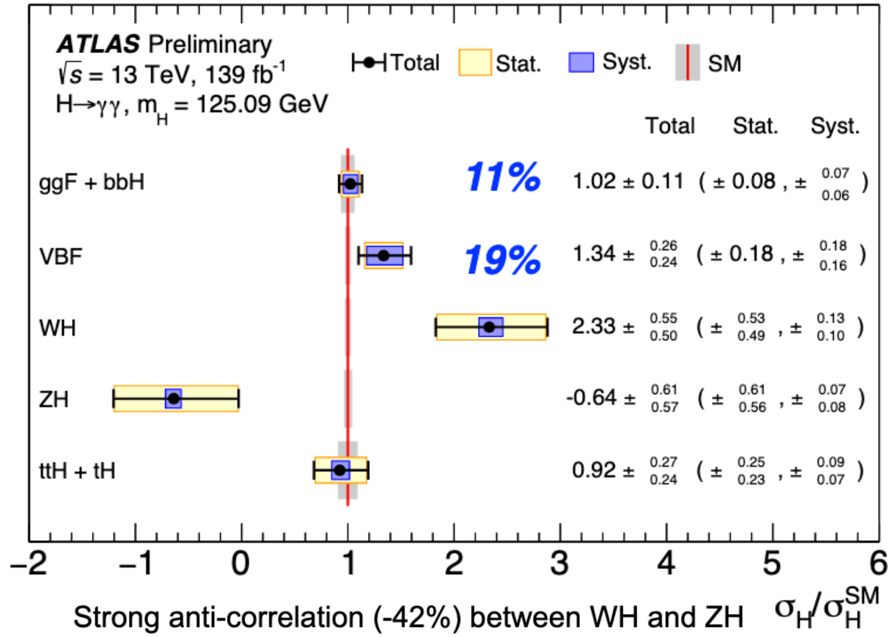
Inclusive cross-sections: main limitations

ATLAS-CONF-2020-027

Process ($\|y_H\| < 2.5$)	Value [pb]	Uncertainty [pb] Total	Stat.	Syst.	Exp.	Sig. Th.	Bkg. Th.	SM pred. [pb]
ggF	44.7	± 3.1	± 2.2	± 2.2	$^{+1.8}_{-1.7}$	$^{+1.0}_{-0.9}$	$^{+0.9}_{-0.7}$	44.7 ± 2.2
VBF	4.0	± 0.6	± 0.5	± 0.4	$^{+0.3}_{-0.2}$	± 0.3	± 0.1	$3.51 ^{+0.08}_{-0.07}$
WH	1.45	$^{+0.28}_{-0.25}$	$^{+0.20}_{-0.19}$	$^{+0.18}_{-0.17}$	$^{+0.13}_{-0.12}$	$^{+0.08}_{-0.06}$	$^{+0.10}_{-0.09}$	1.204 ± 0.024
ZH	0.78	$^{+0.18}_{-0.17}$	± 0.13	$^{+0.12}_{-0.10}$	$^{+0.08}_{-0.07}$	$^{+0.07}_{-0.05}$	± 0.06	$0.797 ^{+0.033}_{-0.026}$
$t\bar{t}H + tH$	0.64	± 0.12	± 0.09	± 0.08	$^{+0.06}_{-0.05}$	$^{+0.03}_{-0.02}$	± 0.05	$0.59 ^{+0.03}_{-0.05}$

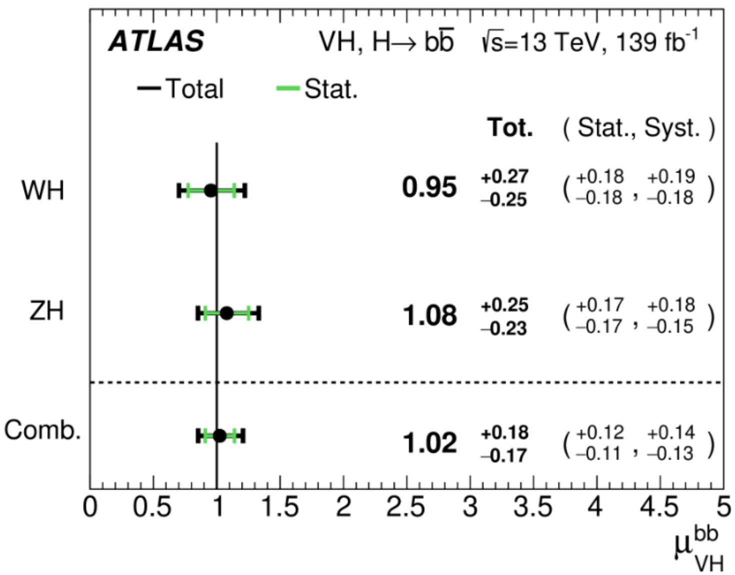
Inclusive cross-sections

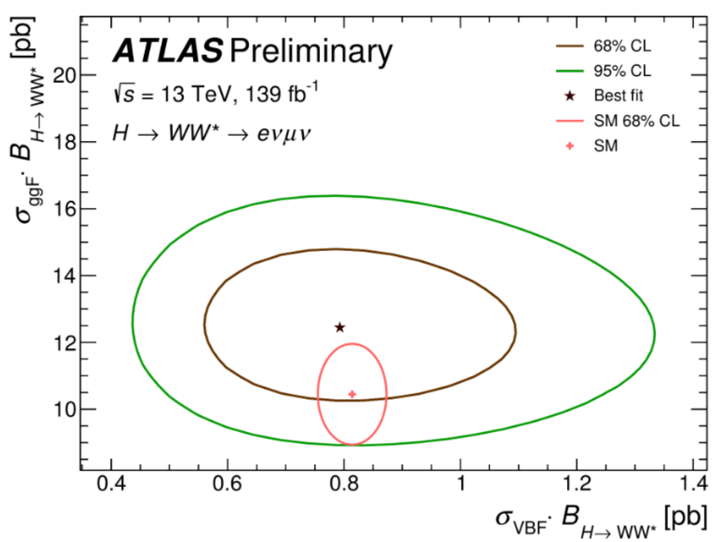




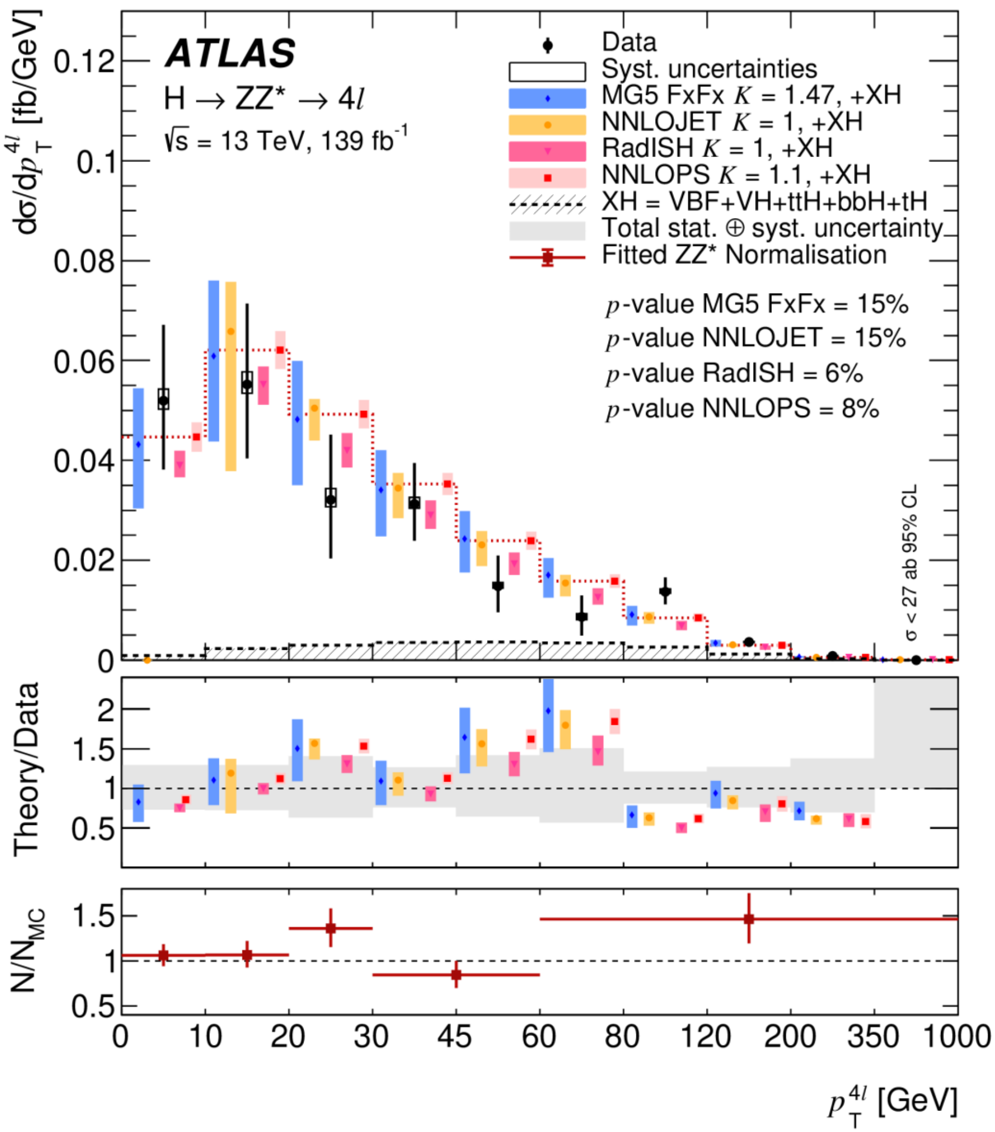
Strong anti-correlation (-42%) between WH and ZH due to process cross-contamination:

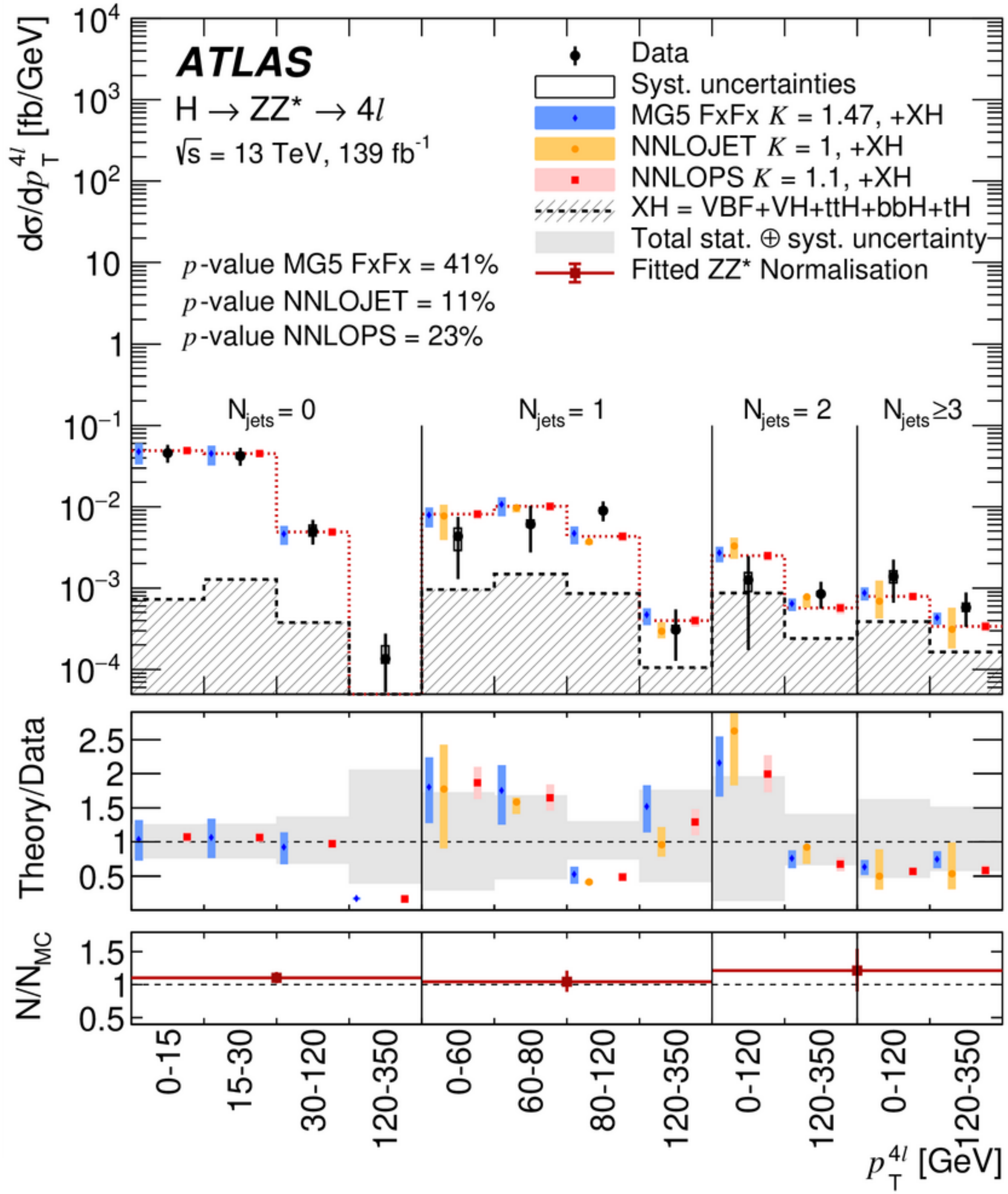
- 5 POI: p_{SM}= 3%
- merging WH and ZH: p_{SM}= 50%





Eur.Phys.J.C80(2020)942



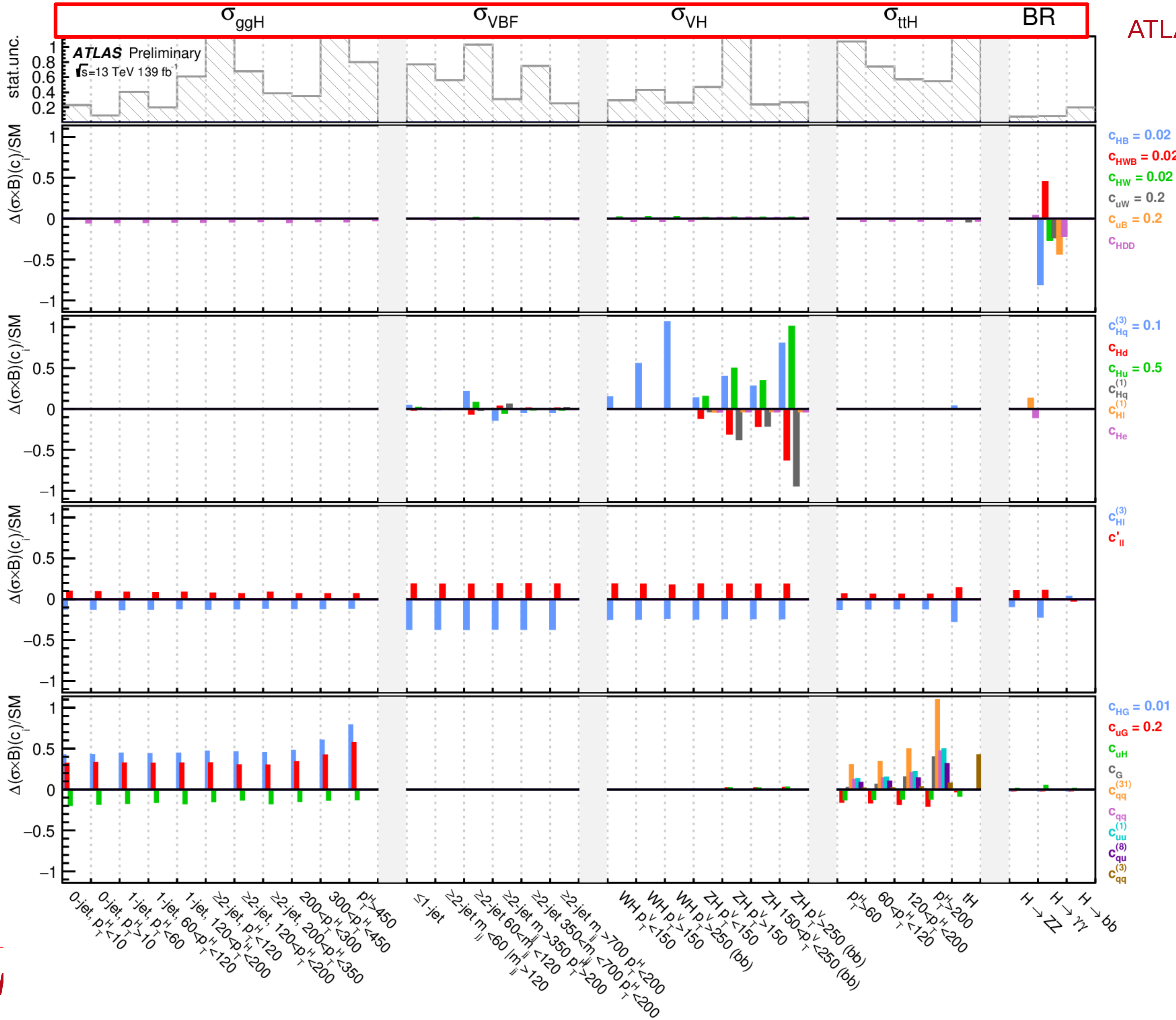


Eur.Phys.J.C80(2020)942

Higgs boson kinematic-related variables	
$p_T^{4\ell}$, $\lvert y_{4\ell}\rvert$	Transverse momentum and rapidity of the four-lepton system
m_{12}, m_{34}	Invariant mass of the leading and subleading lepton pair
$\lvert\cos\theta^*\rvert$	Magnitude of the cosine of the decay angle of the leading lepton pair in the four-lepton rest frame relative to the beam axis
$\cos\theta_1$, $\cos\theta_2$	Production angles of the anti-leptons from the two Z bosons, where the angle is relative to the Z vector.
ϕ, ϕ_1	Two azimuthal angles between the three planes constructed from the Z bosons and leptons in the Higgs boson rest frame.
Jet-related variables	
N_{jets}, $N_{b\text{-jets}}$	Jet and b-jet multiplicity
$p_T^{\text{lead. jet}}$, $p_T^{\text{sublead. jet}}$	Transverse momentum of the leading and subleading jet, for events with at least one and two jets, respectively. Here, the leading jet refers to the jet with the highest p_T in the event, while subleading refers to the jet with the second-highest p_T.
m_{jj}, $\lvert\Delta\eta_{jj}\rvert$, $\Delta\phi_{jj}$	Invariant mass, difference in pseudorapidity, and signed difference in ϕ of the leading and subleading jets for events with at least two jets
Higgs boson and jet-related variables	
$p_T^{4\ell j}$, $m_{4\ell j}$	Transverse momentum and invariant mass of the four-lepton system and leading jet, for events with at least one jet
$p_T^{4\ell jj}$, $m_{4\ell jj}$	Transverse momentum and invariant mass of the four-lepton system and leading and subleading jets, for events with at least two jets

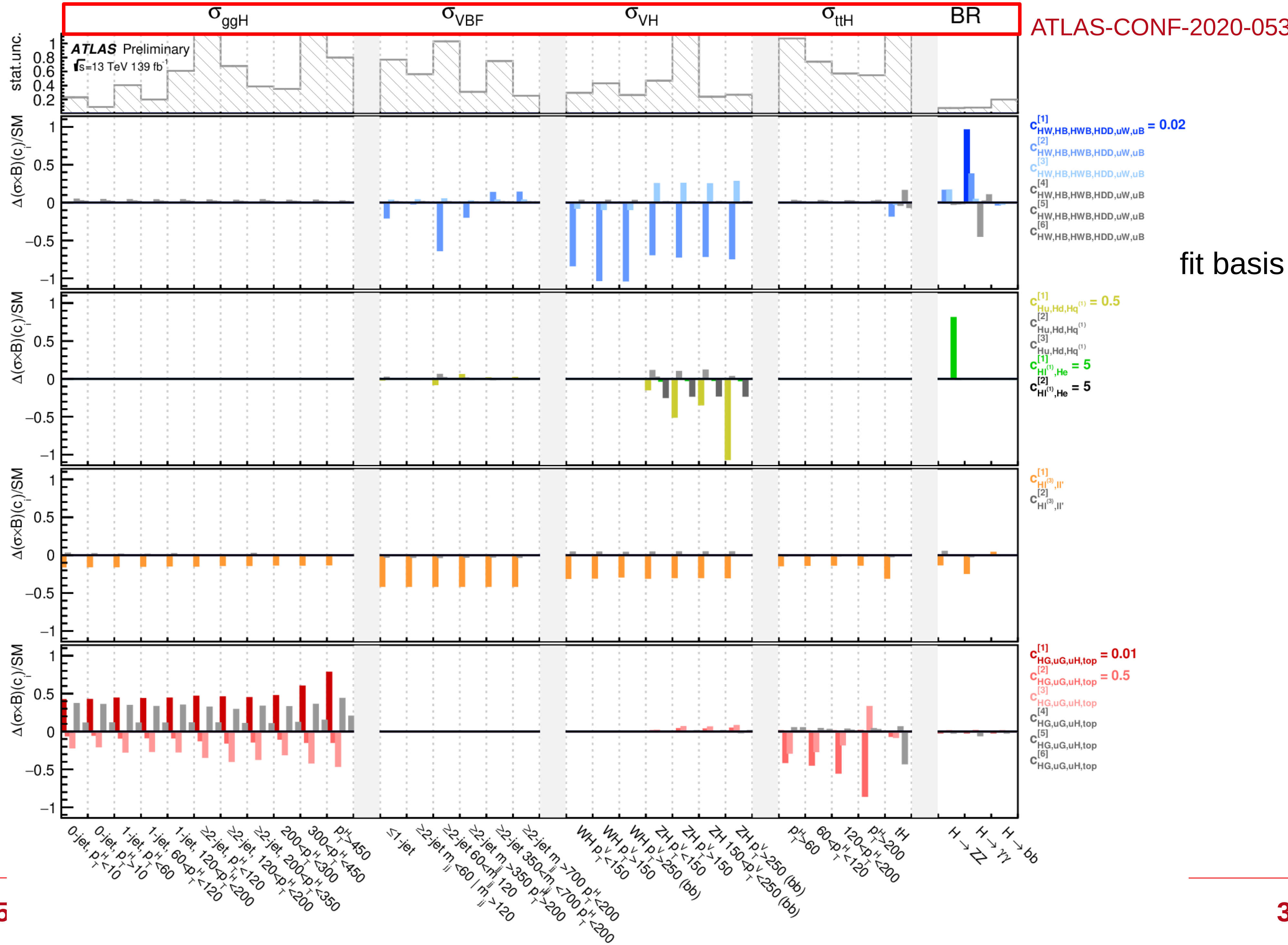
EFT interpretation: effect of operators in XSs and BRs

ATLAS-CONF-2020-053



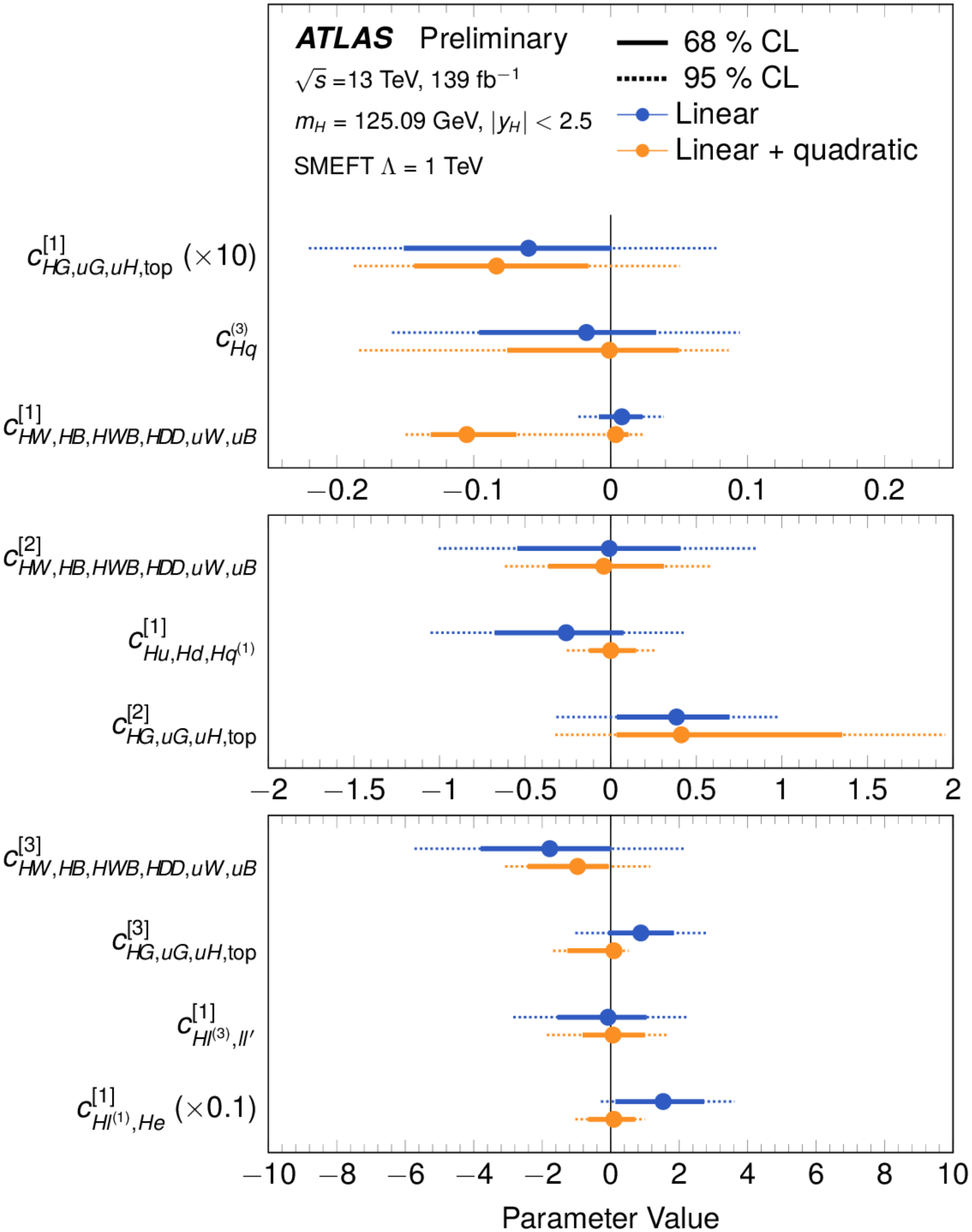
Warsaw basis

EFT interpretation: effect of operators in XSs and BRs



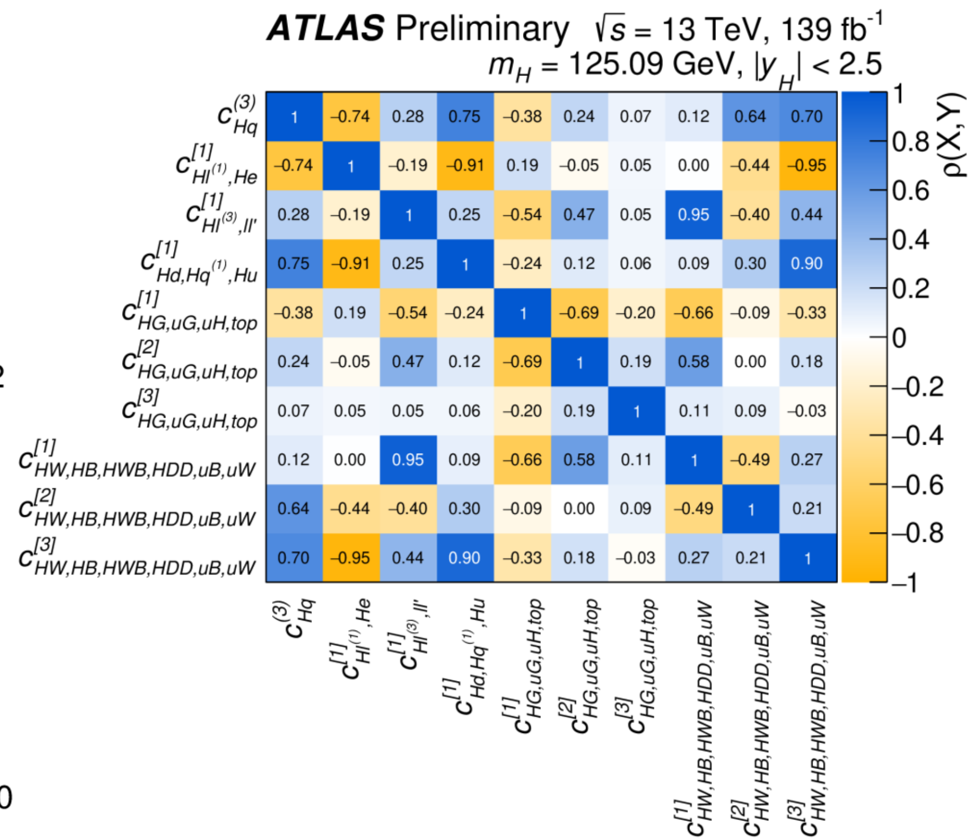
EFT interpretation: limits on 10 Wilson coefficients

ATLAS-CONF-2020-053



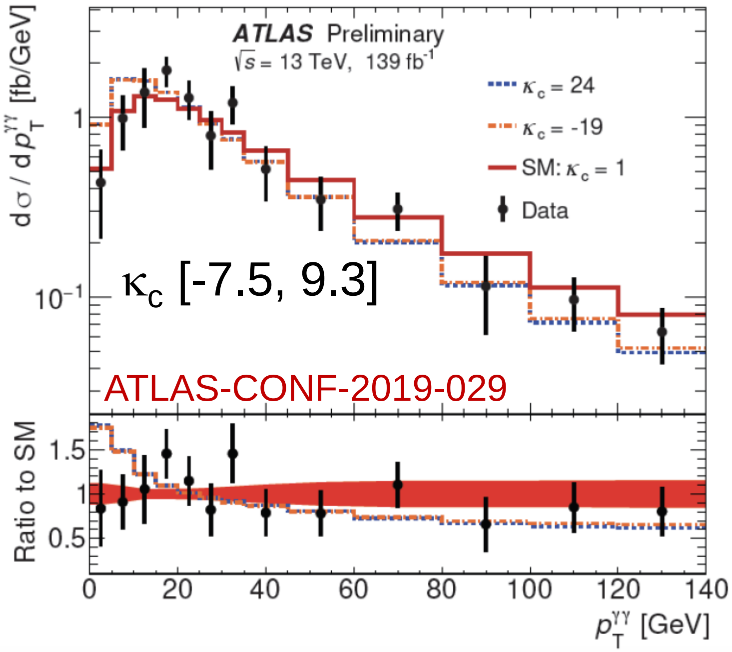
Simultaneous fit of 10 Wilson coefficients/groups

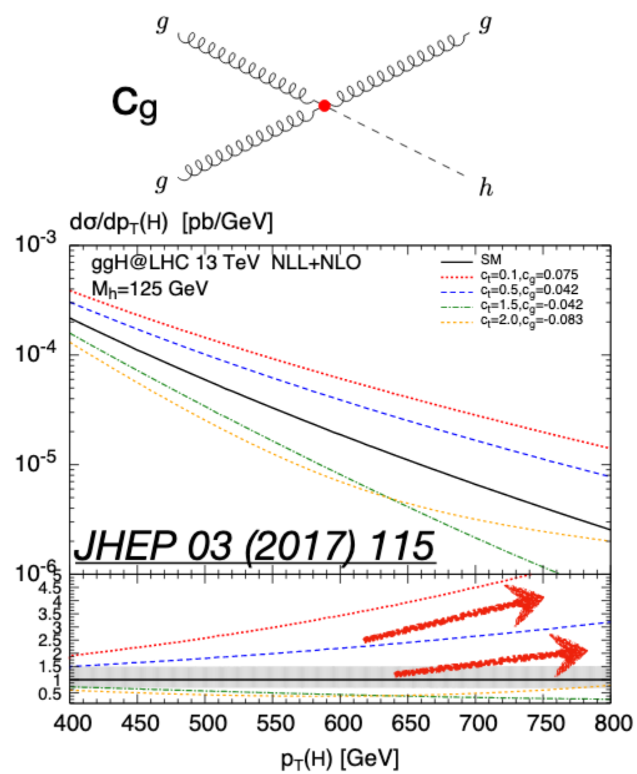
(groups of operators with similar impact on physics processes identified; eigenvector decomposition)

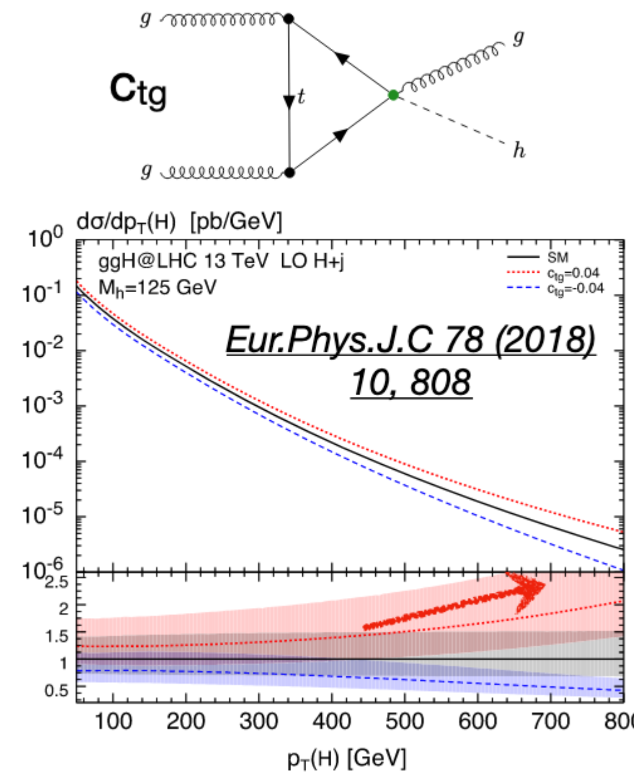


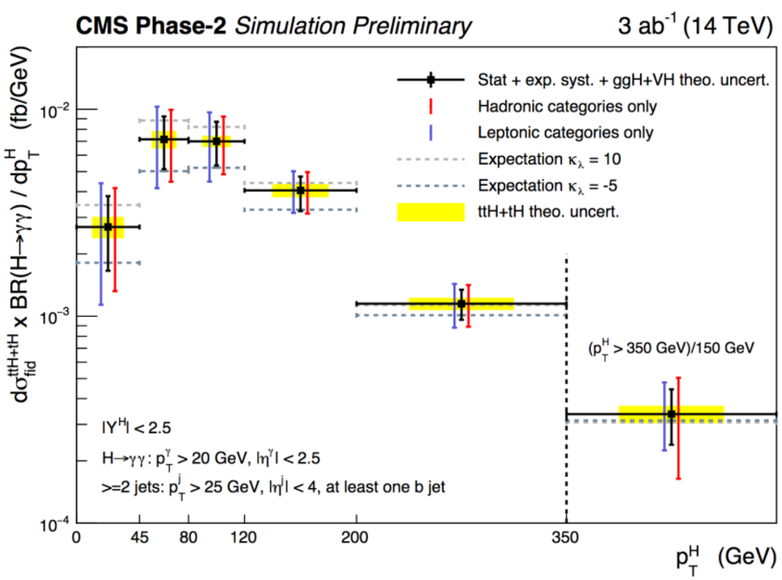
Higgs p_T: sensible to different couplings

Low p_T regime: sensitive to charm-quark contribution from loop modification and ccH → limit on kc
and to Higgs self-coupling...
High p_T regime: sensitive to top Yukawa coupling and possible new particles in the loop.









VBF $H \to b\bar{b}$

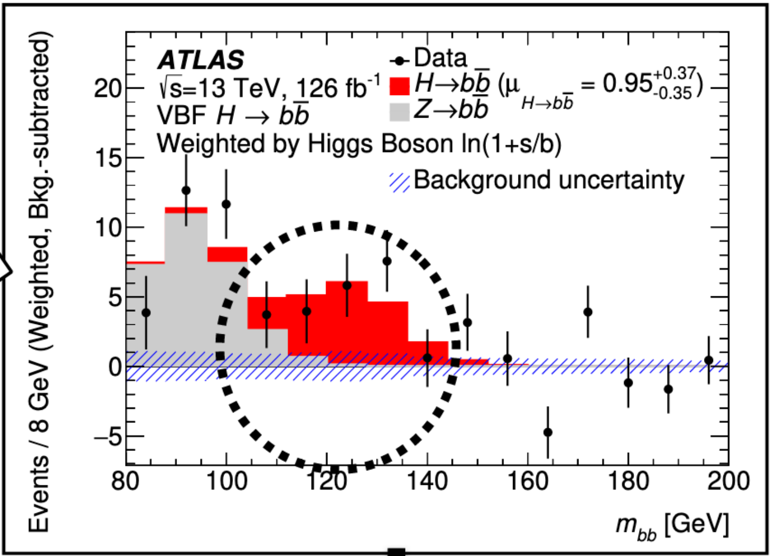
arXiv:2011.08280

Link to backup

- Events considered have $p_T(bb) > 150$ GeV because of trigger limitations

- Probing *VBF* production categorising events:
  - ***Forward (FW):*** jet with $p_T > 60$ GeV in $|\eta| > 3.2$
  - ***Central (CN):*** jet with $p_T > 160$ GeV in $|\eta| < 3.2$

required also by the trigger



- ***Adversarial NNs*** used to enhance S vs B separation ***without learning m(bb)***
  - ***4 DNN-score categories*** for FW & CN events

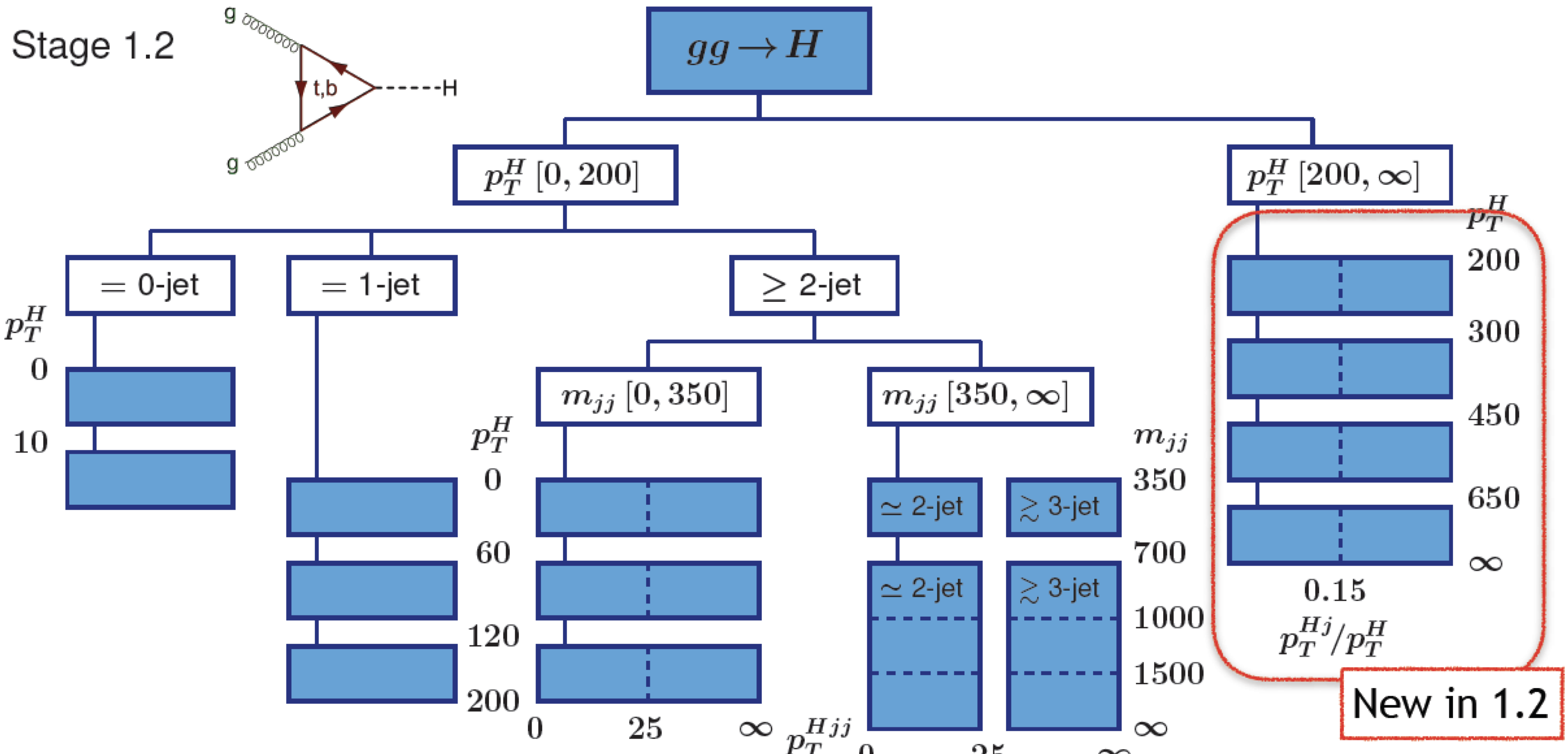
- ***Signal extraction:*** binned fits to the m(bb)
  - ***Non-resonant Bkg*** from data m(bb) sidebands

- $\mu(\mathrm{VBF}) = 0.95^{+0.32}_{-0.32}\,(\mathrm{stat})\ ^{+0.20}_{-0.17}\,(\mathrm{syst})$ → ***2.6σ significance***
- Good compatibility with SM expectation

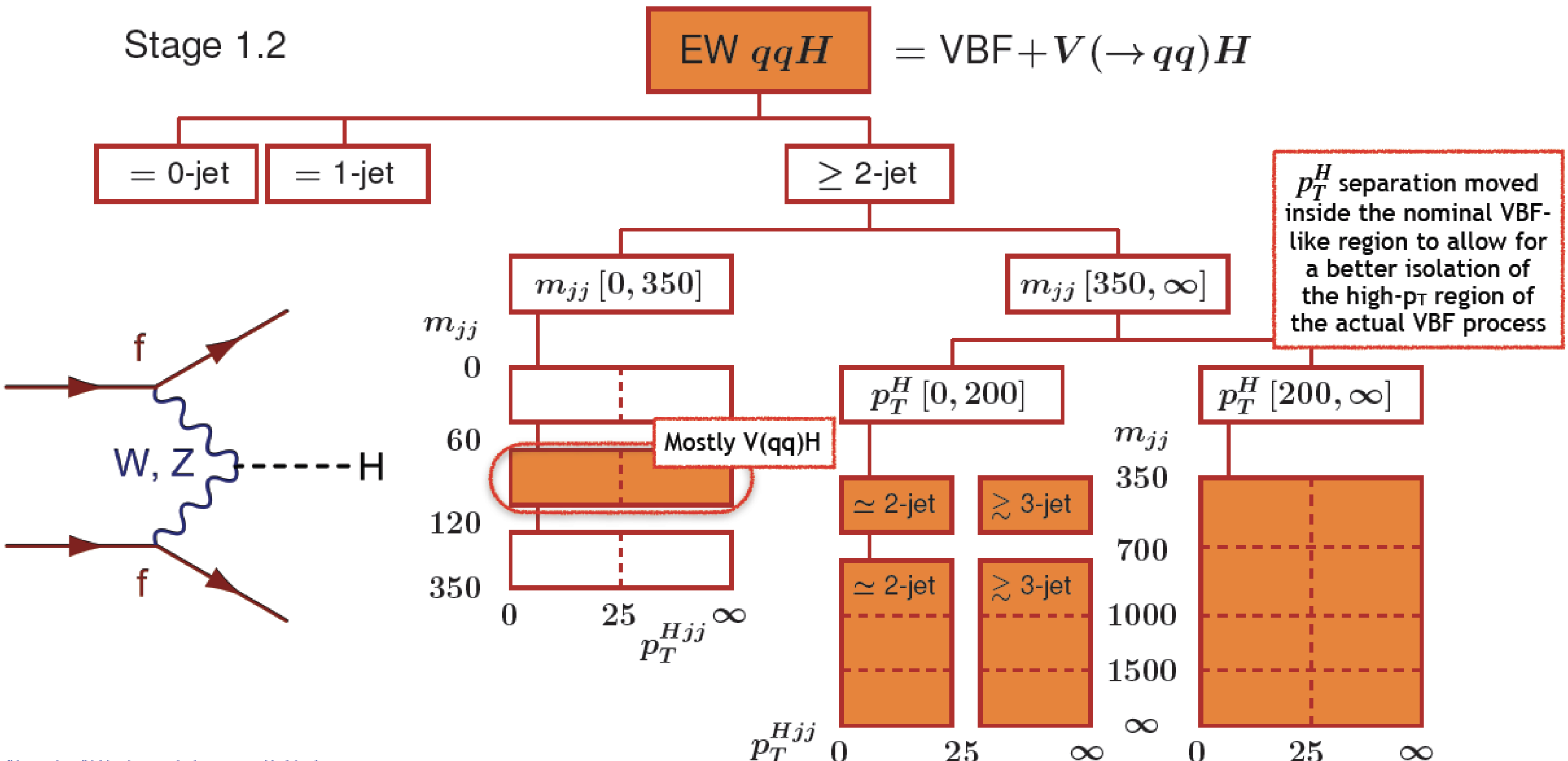
Combination with **VBF+γ [aXiv:2010.13651]** → $\mu(\mathrm{VBF}) = 0.99^{+0.30}_{-0.30}\,(\mathrm{stat})\ ^{+0.18}_{-0.16}\,(\mathrm{syst})$ → ***2.9σ significance***

Process	Generator	Showering	PDF set	Order of σ calculation
ggF	NNLOPS	Pythia 8	PDF4LHC15	N^3LO(QCD)+NLO(EW)
VBF	Powheg-Box	Pythia 8	PDF4LHC15	approximate-NNLO(QCD)+NLO(EW)
WH	Powheg-Box	Pythia 8	PDF4LHC15	NNLO(QCD)+NLO(EW)
$qq/qg \rightarrow ZH$	Powheg-Box	Pythia 8	PDF4LHC15	NNLO(QCD)+NLO(EW)
$gg \rightarrow ZH$	Powheg-Box	Pythia 8	PDF4LHC15	NLO(QCD)
$t\bar{t}H$	Powheg-Box	Pythia 8	PDF4LHC15	NLO(QCD)+NLO(EW)
$b\bar{b}H$	Powheg-Box	Pythia 8	PDF4LHC15	NNLO(QCD)
$tHqb$	MG5_aMC@NLO	Pythia 8	NNPDF3.0nnlo	NLO(QCD)
tWH	MG5_aMC@NLO	Pythia 8	NNPDF3.0nnlo	NLO(QCD)

Stage 1.2



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



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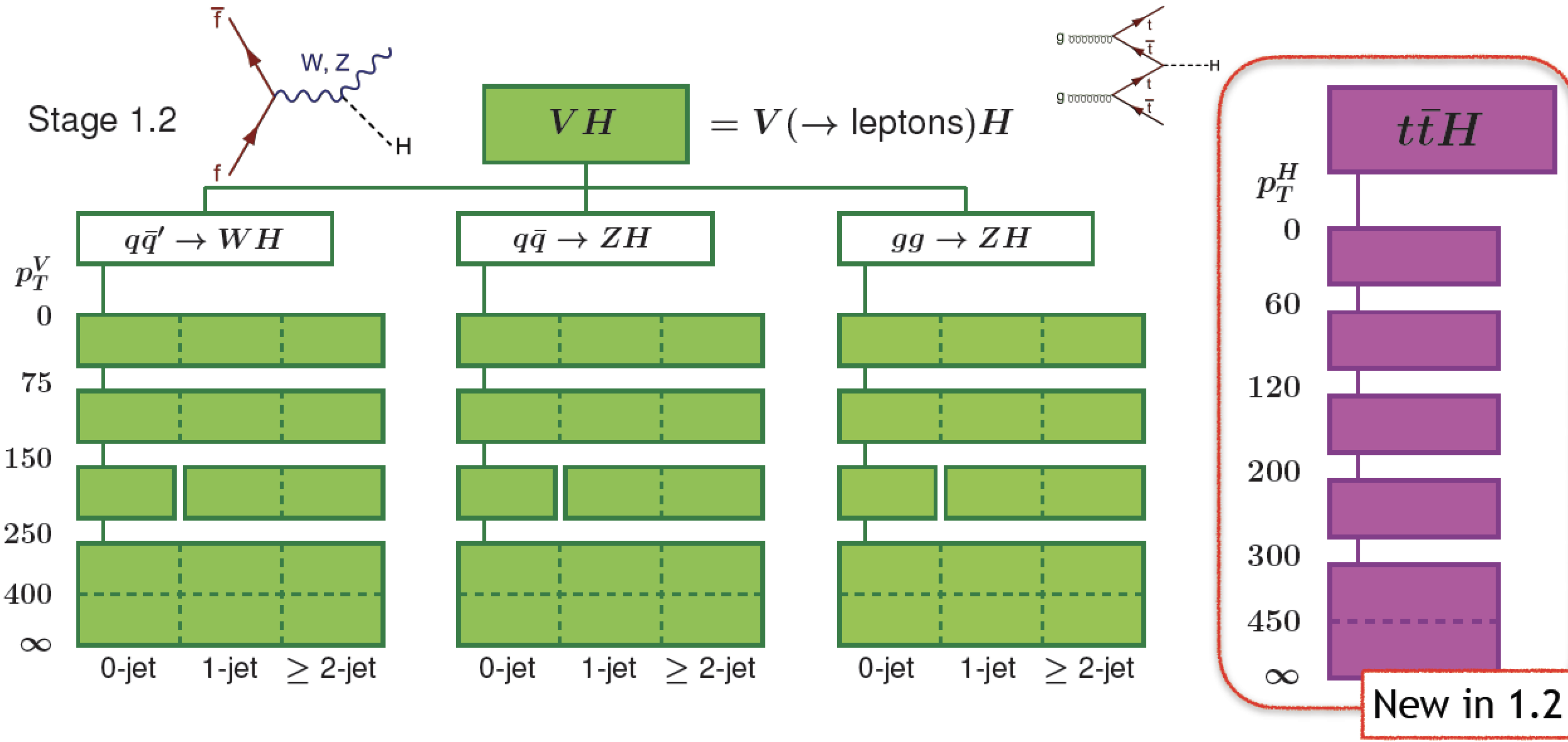


https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWGFiducialAndSTXS

Is the top-Higgs coupling a pure scalar interaction ?

$J^{CP} = 0^{++}$?

No deviations found in CP properties of the Higgs couplings to gauge bosons

Caveat: in those, CP-odd contributions enter only via higher-order operators

NEW: pseudoscalar admixture directly tested in top-Higgs interaction using ttH/tH events with H→γγ

$$\mathcal{L}_t = -\frac{m_t}{v}(\kappa_t \bar{t}t + i\tilde{\kappa}_t \bar{t}\gamma_5 t)H \qquad \text{SM: } (\kappa_t, \tilde{\kappa}_t) = (1,0) \qquad \kappa_t = k_t \cos\alpha, \quad \tilde{\kappa}_t = k_t \sin\alpha$$

ATLAS: 1D fit: CP mixing angle α

2D fit: $k_t \cos\alpha$ vs $k_t \sin\alpha$

CMS: 1D fit: $f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2} \text{sign}(\tilde{\kappa}_t/\kappa_t)$

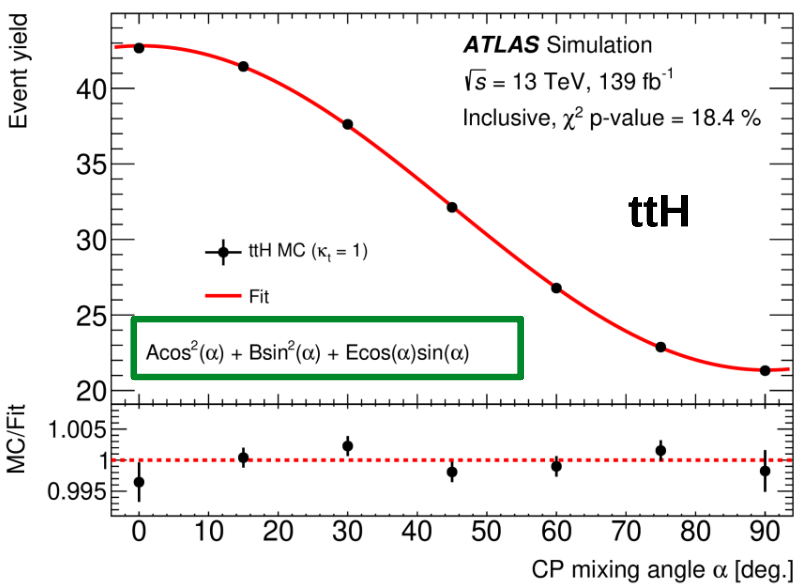
Signal parametrisation

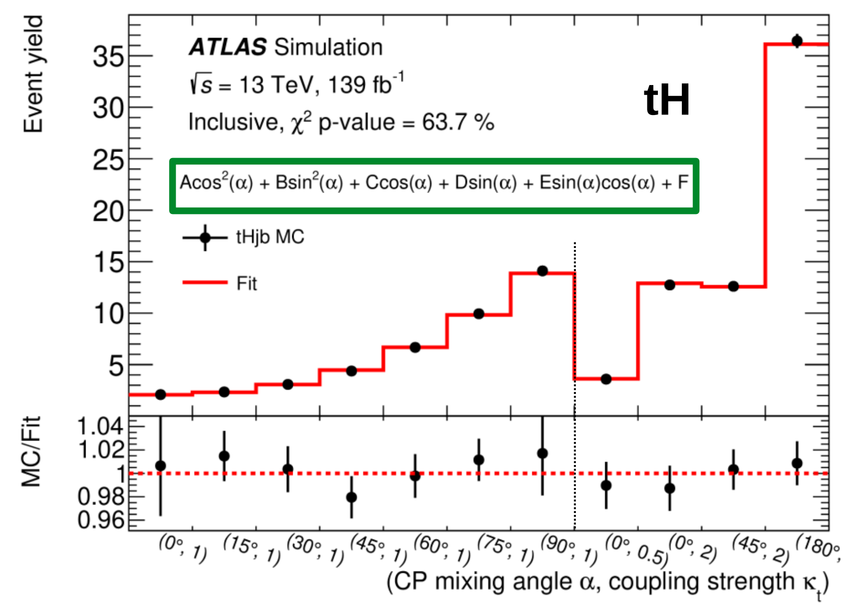
signal yields parametrised as function of (k_t, α) or (μ_{ttH}, f_{CP}^{Htt}) CP parameters

Models used

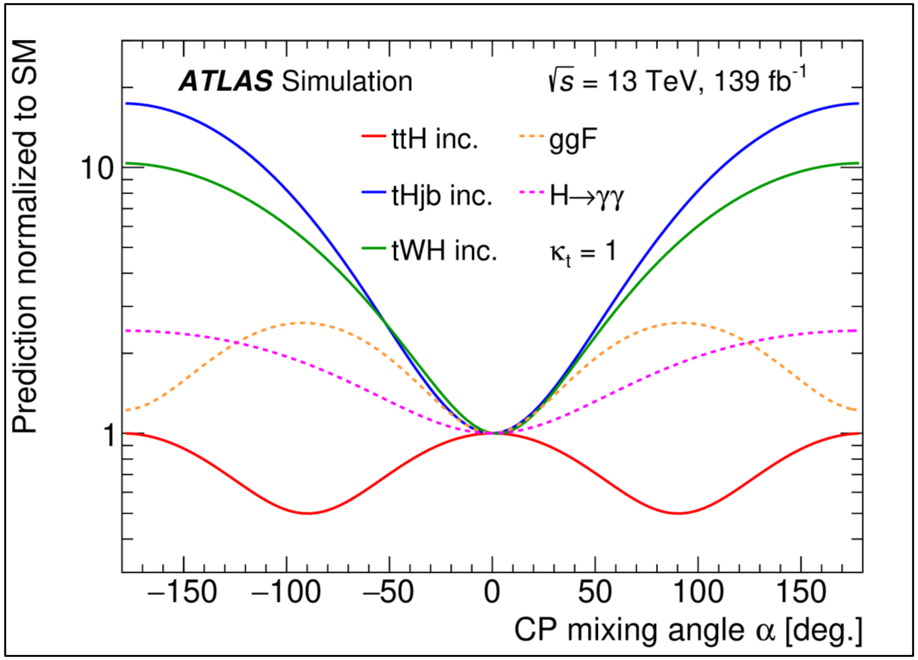
ATLAS:
ttH, tHjb & tWH @NLO
Higgs Characterisation

CMS:
ttH @LO
JHUGEN with MELA

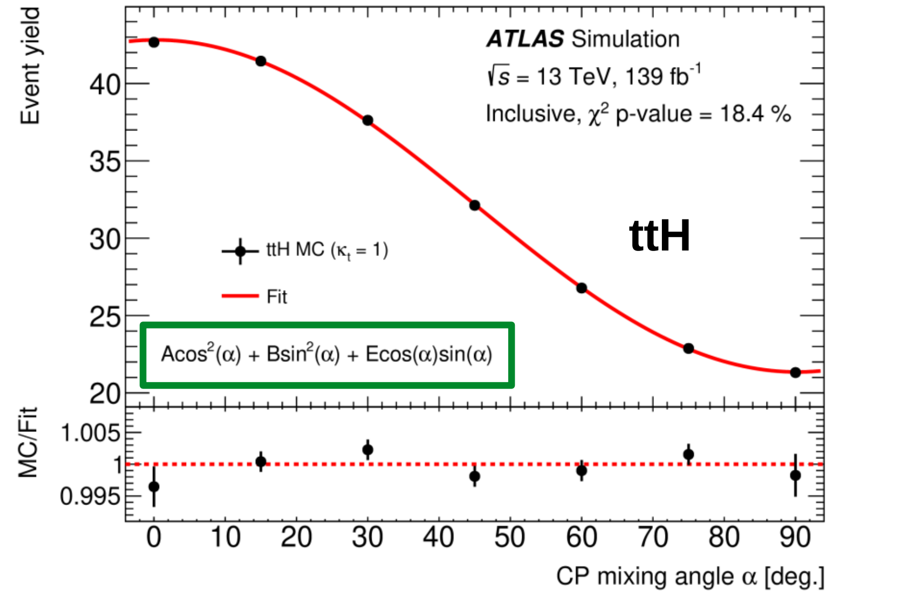


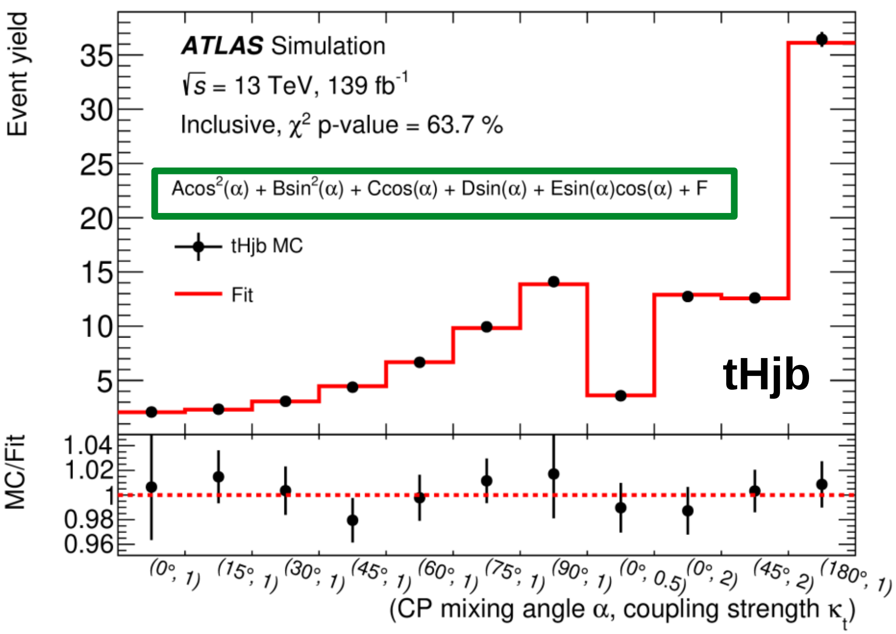


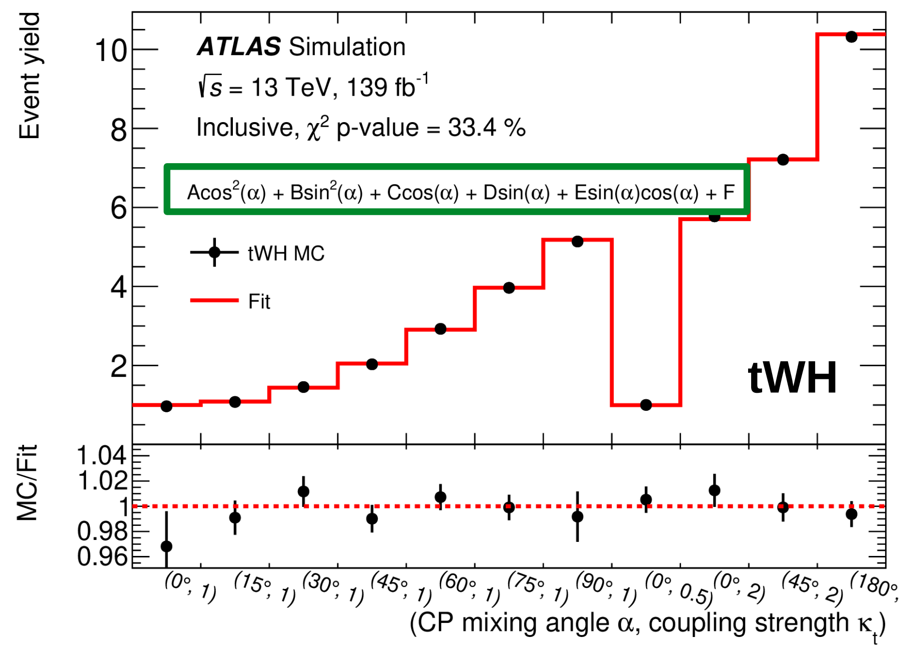
CP properties of the top-Higgs Yukawa coupling (ttH/tH, H→γγ)



Used in ATLAS



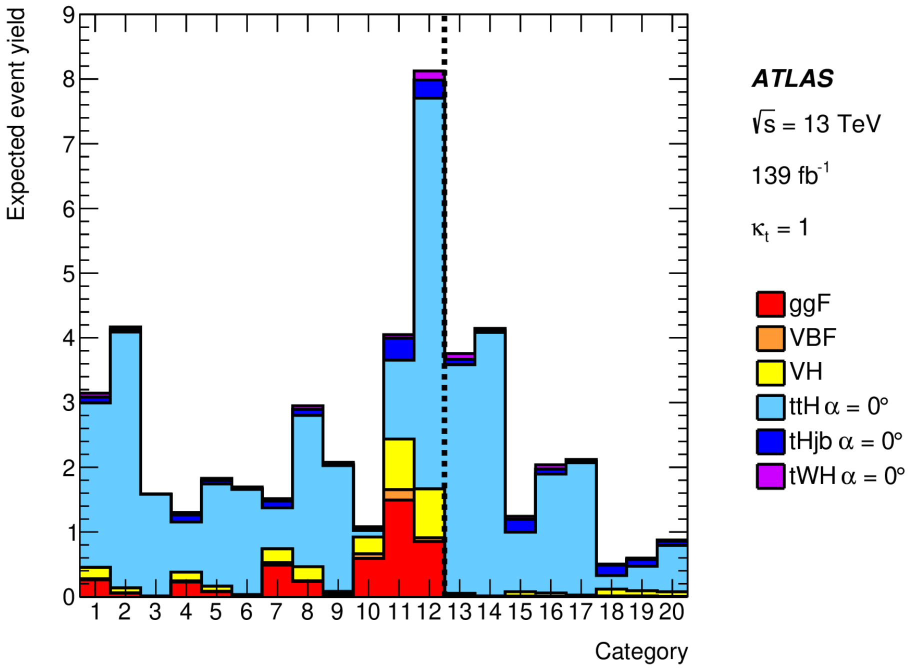


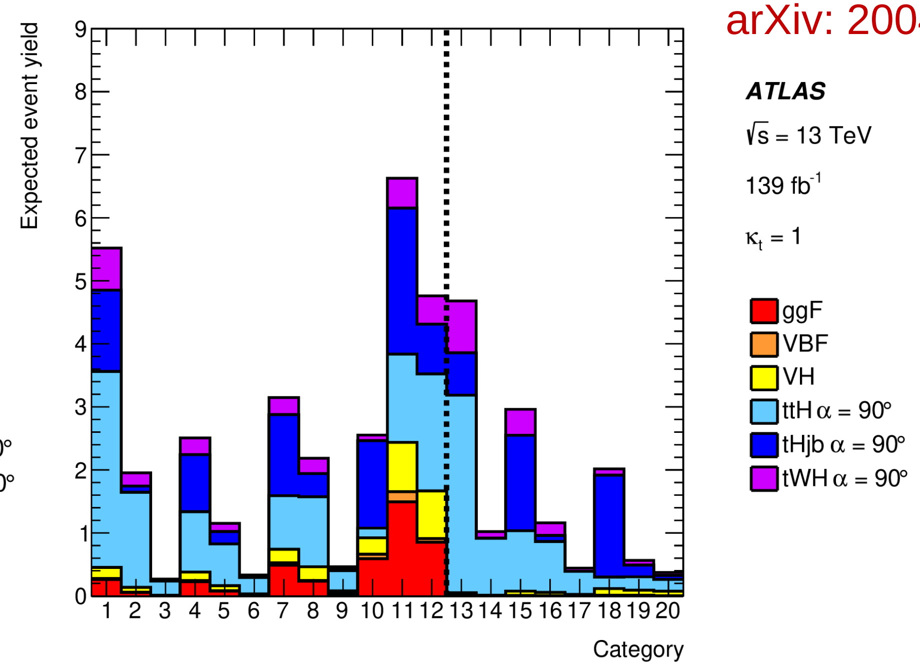


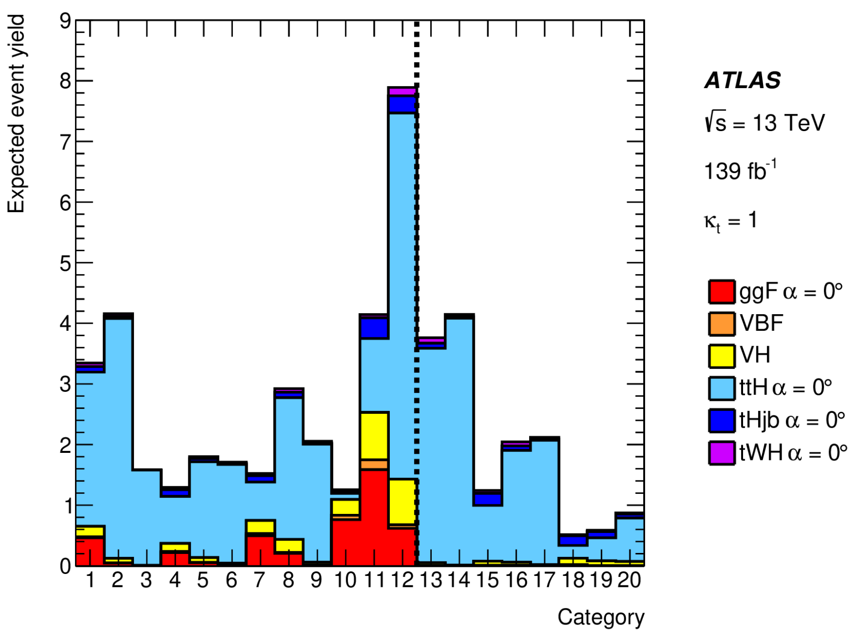
CP properties of the top-Higgs Yukawa coupling (ttH/tH, H→γγ)

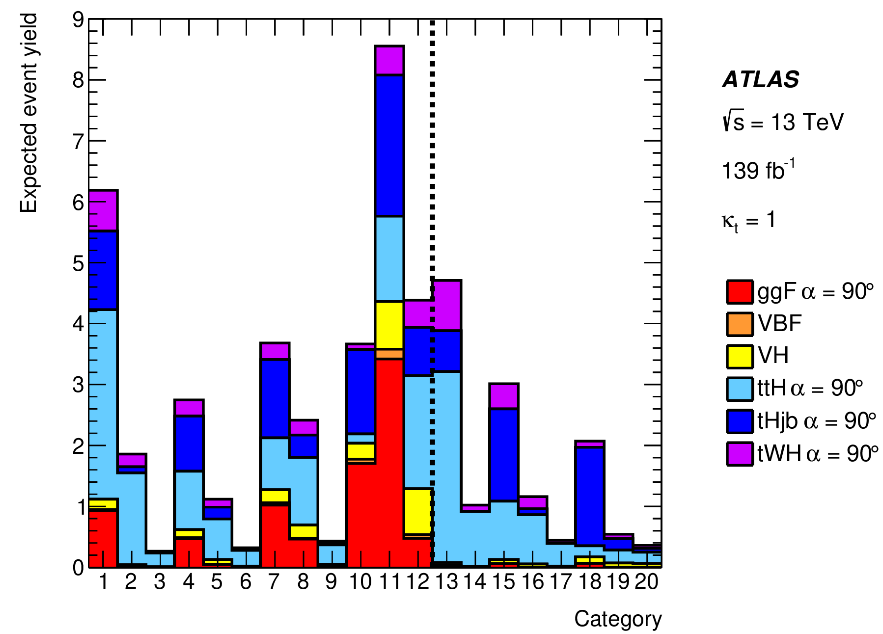
arXiv: 2004.04545

Yields parametrised (κ_t, α) based on Higgs Characterisation model









ttH/tH (H→γγ) CP analysis: comparison of CP parameters

CMS	ATLAS
$\mathcal{A}(\mathrm{Htt}) = -\frac{m_\mathrm{t}}{v}\overline{\psi}_\mathrm{t}\left(\kappa_\mathrm{t} + \mathrm{i}\tilde{\kappa}_\mathrm{t}\gamma_5\right)\psi_\mathrm{t}$	$\mathcal{L} = -\frac{\sqrt{2}m_t}{v}(\bar{\psi}_t\kappa_t\,(\cos(\alpha) + \mathrm{i}\sin(\alpha)\gamma_5)\psi_t)H$

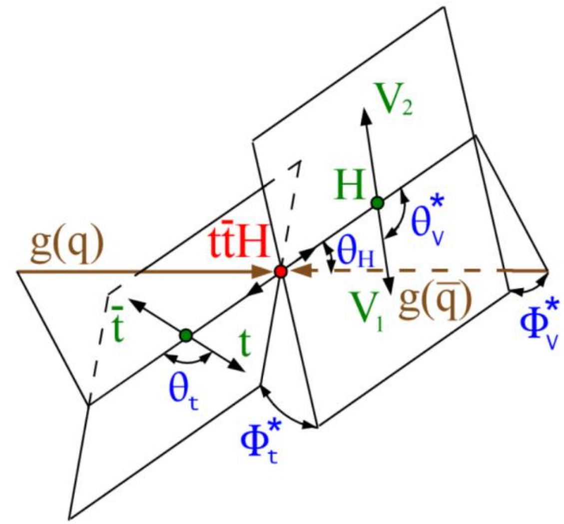
CMS		ATLAS
κ_t	$\Leftrightarrow$	$\kappa_t\cos\alpha$
$\tilde{\kappa}_t$	$\Leftrightarrow$	$\kappa_t\sin\alpha$
$\kappa_t > 0$	$\Rightarrow$	$-90^\circ < \alpha < 90^\circ$
$\lvert f_{\mathrm{CP}}^{\mathrm{Htt}}\rvert = \frac{\lvert\tilde{\kappa}_t\rvert^2}{\lvert\tilde{\kappa}_t\rvert^2+\lvert\kappa_t\rvert^2}$	$\Leftrightarrow$	$\sin^2\alpha$
μ_{ttH}	$\Leftrightarrow$	κ_t^2

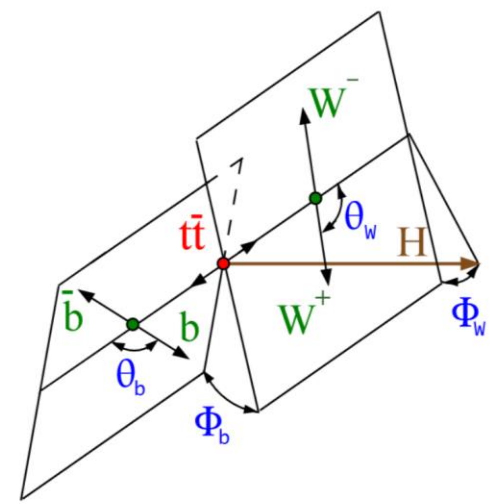
What is the impact of restricting $\kappa_t\cos\alpha > 0$?

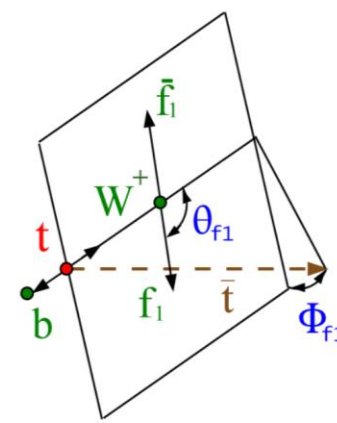
CP properties of the top-Higgs Yukawa coupling (ttH/tH, H→γγ)

Pheno paper PRD94,055023 (2016)

(i) $m_{t\bar{t}H}$: invariant mass of the $t\bar{t}H$ system;
(ii) θ_H: angle between the H boson direction and the incoming partons in the $t\bar{t}H$ frame;
(iii) θ_V^*: angle of the $H \to VV(f\bar{f})$ decay with respect to the opposite $t\bar{t}$ direction in the H frame;
(iv) Φ_V^*: angle between the production plane, defined by incoming partons and H, and $H \to VV(f\bar{f})$ decay plane;
(v) θ_t: angle between the top-quark direction and the opposite Higgs direction in the $t\bar{t}$ frame;
(vi) Φ_t^*: angle between the decay planes of the $t\bar{t}$ system and $H \to VV(f\bar{f})$ in the $t\bar{t}H$ frame;
(vii) m_{tt}: invariant mass of the $t\bar{t}$ system;
(viii) θ_W: angle between W^+ and opposite of the $b\bar{b}$ system in the W^+W^- frame;
(ix) Φ_W: angle between the production $(b\bar{b})(W^+W^-)H$ plane and the plane of the W^+W^- system in the $t\bar{t}$ frame;
(x) θ_b: angle between the b quark and opposite of the W^+W^- system in the $b\bar{b}$ frame;
(xi) Φ_b: angle between the planes of the $b\bar{b}$ and W^+W^- systems in the $t\bar{t}$ frame;
(xii) m_{Wb1} or m_{Wb2}: invariant mass of the W^+b or $W^-\bar{b}$ system;
(xiii) θ_{f1} or θ_{f2}: angles between fermion direction and opposite of the b or $\bar{b}$ quark in the W^+ or W^- frame;
(xiv) Φ_{f1} or Φ_{f2}: angle between the W^+ or W^- decay plane and the $\bar{t}W^+b$ or $tW^-\bar{b}$ plane in the t or $\bar{t}$-quark frame;
(xv) $m_{f1\bar{f}1}$ or $m_{f2\bar{f}2}$: invariant mass of the $f_1\bar{f}_1$ or $f_2\bar{f}_2$ system.







Pheno paper PRD94,055023 (2016)

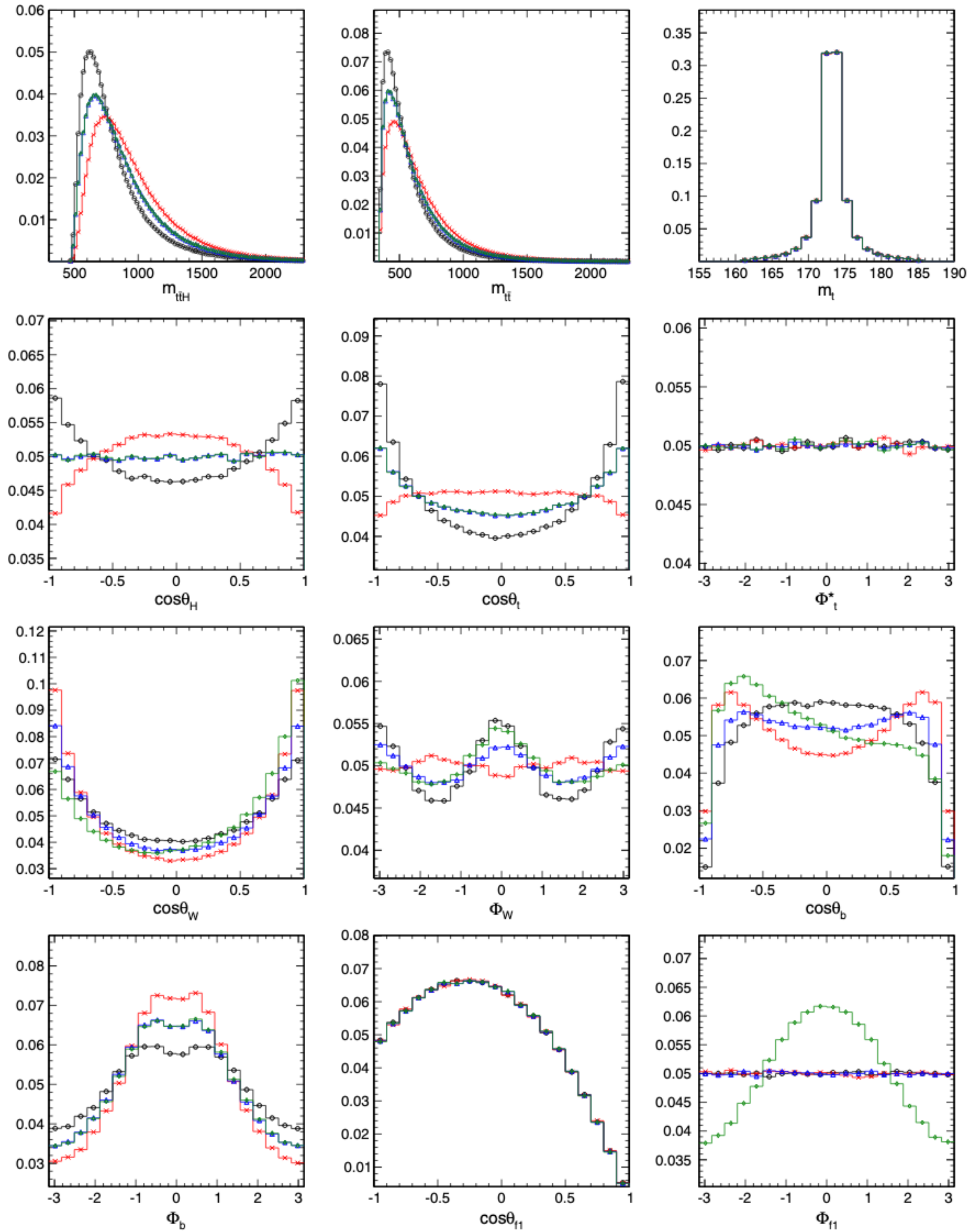


FIG. 5. The normalized angular and mass distributions in the process $pp \to t\bar{t}H$ corresponding to four scenarios of anomalous $t\bar{t}H$ couplings: $f_{CP} = 0$ (SM 0^+, red crosses), $f_{CP} = 1$ (pseudoscalar 0^-, black circles), $f_{CP} = 0.28$ with $\phi_{CP} = 0$ (blue triangles), and $\phi_{CP} = \pi/2$ (green diamonds). The LHC pp energy of 13 TeV and H boson mass of 125 GeV are used in simulation. See the text for the definition of all observables.

CP-even
CP-odd
Mixture with ϕ_{CP}=0
Mixture with ϕ_{CP}=90 degrees

Pheno paper PRD94,055023 (2016)

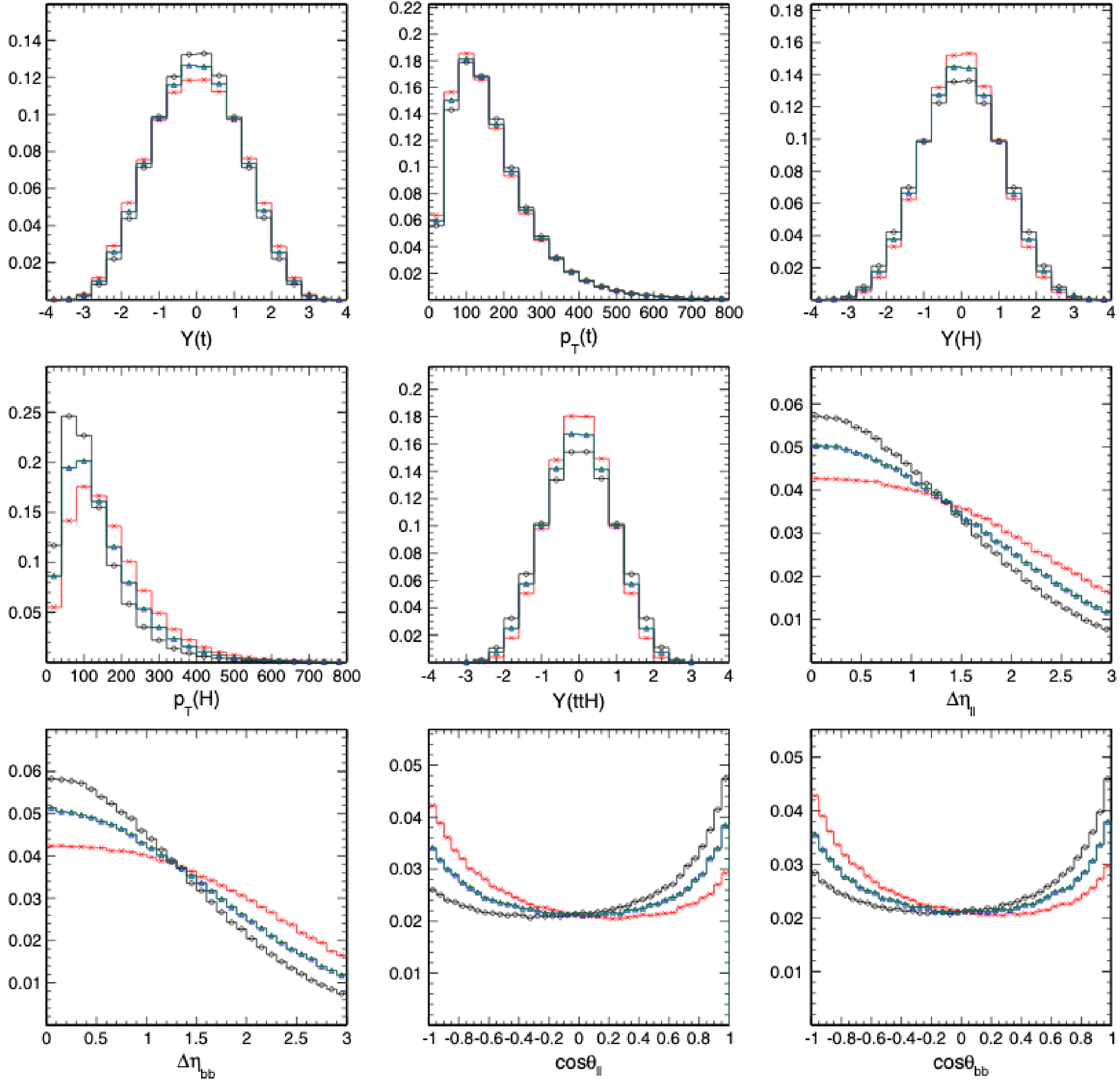
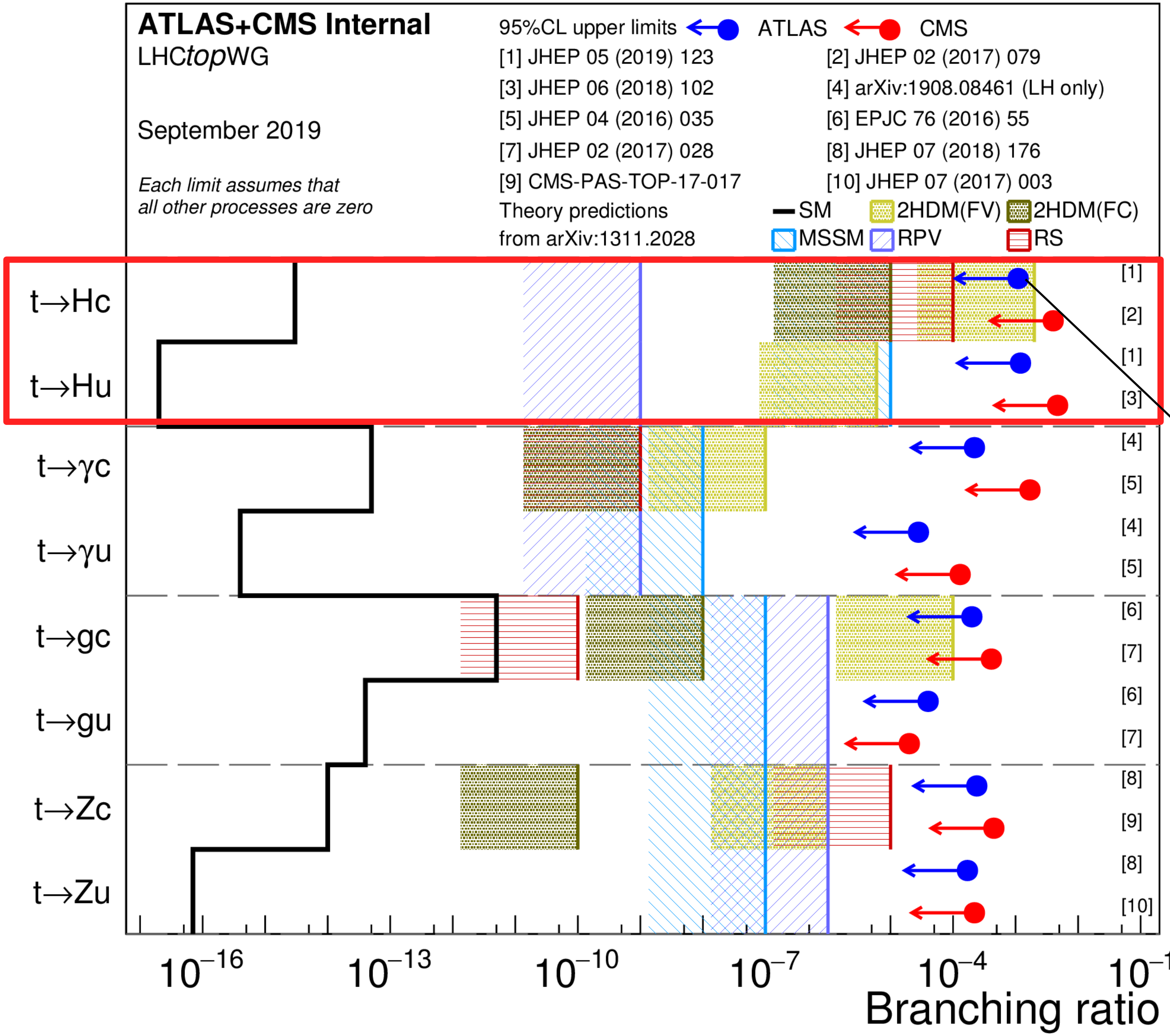
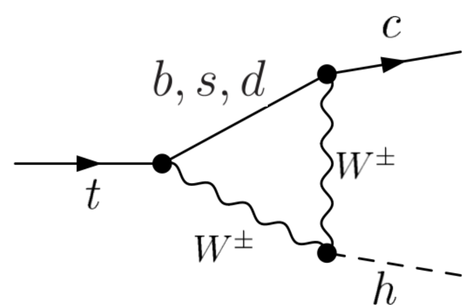


FIG. 14. The kinematic distributions in the process gg and $q\bar{q} \to t\bar{t}H$ defined in the laboratory frame: top-quark rapidity $[Y(t)]$, transverse momentum of the top quark $[p_T(t)]$, H boson rapidity $[Y(t)]$, transverse momentum of the H boson $[p_H(t)]$, $t\bar{t}H$ system rapidity $[Y(t\bar{t}H)]$, pseudorapidity difference between the two down-type fermions decayed from top and antitop ($\Delta\eta_{ll}$) and between two bottom quarks ($\Delta\eta_{bb}$), $\cos\theta_{ll}$ between the two down-type fermions, and $\cos\theta_{bb}$ between the two bottom quarks. Four scenarios of anomalous $t\bar{t}H$ couplings are shown: $f_{CP} = 0$ (SM 0^+, black circles), $f_{CP} = 1$ (pseudoscalar 0^-, red crosses), $f_{CP} = 0.28$ with $\phi_{CP} = 0$ (blue triangles), and $\phi_{CP} = \pi/2$ (green diamonds). The LHC pp energy of 13 TeV and H boson mass of 125 GeV are used in simulation.

CP-even
CP-odd
Mixture with ϕ_{CP}=0
Mixture with ϕ_{CP}=90 degrees





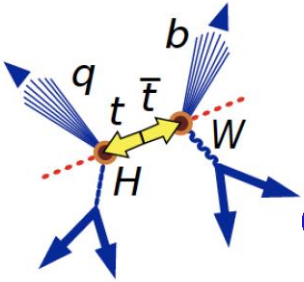
Flavour changing top-Higgs interactions?

starting to exclude some 2HDM models without flavour symmetry imposed…

Using 36 fb^{-1}:

BR(t→Hq)< 10^{-3}

HL-LHC projections: < 10^{-4}



decay FCNC

H→γγ: [JHEP 10 (2017) 129]
H→WW*,ττ,ZZ*: [PRD 98 (2018) 032002]
H→bb,ττ & full combination: [arXiv: 1812.11568] (subm. JHEP)

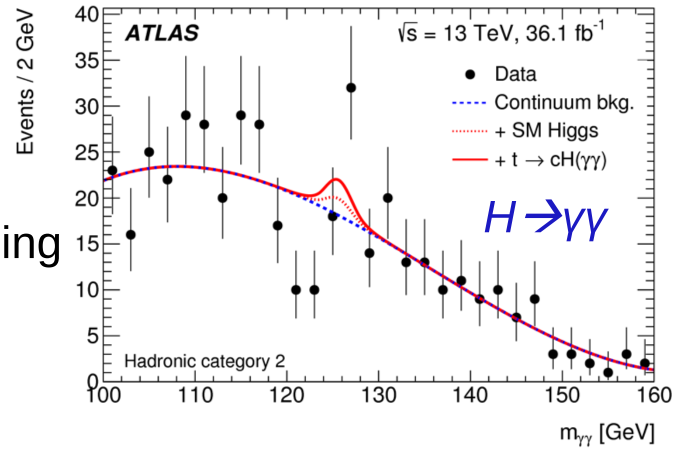
H→γγ
- limited by data statistics
- main syst. unc.: JES, theory modelling

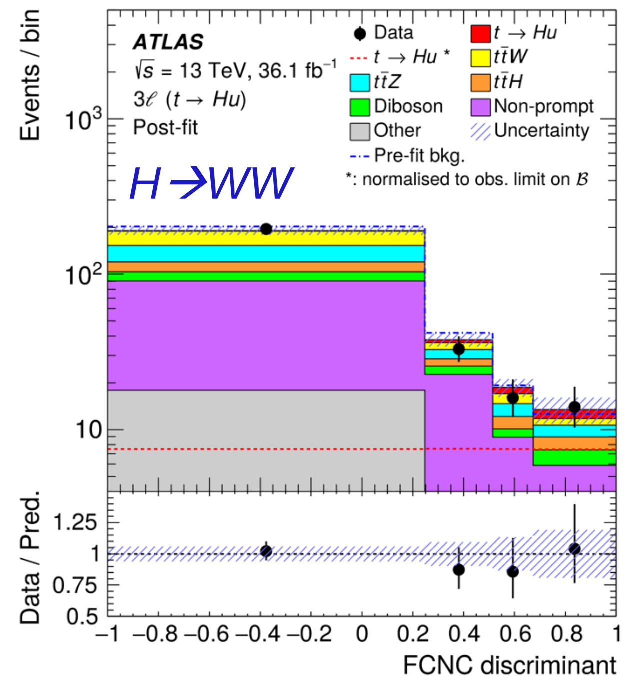
H→WW*,(ττ,ZZ*)
- SS and 3l (e or μ) final states
- reinterpretation of *ttH(ML)* analysis
- MVA technique (inputs: m_{eff}, m_{ll})

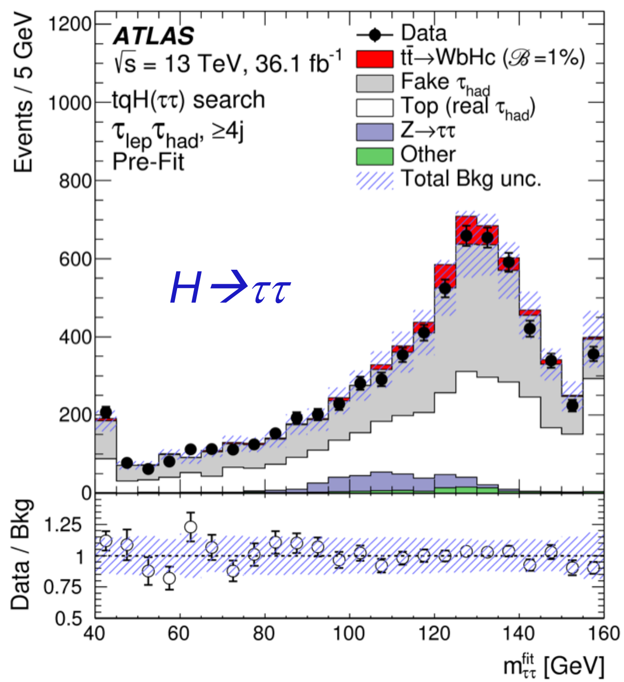
H→ττ ($\tau_{had}\tau_{had}$, $\tau_{lep}\tau_{had}$)
- 4 SRs based on # τ_{had}, τ_{lep}, jets
- event reco. (χ^2 minimisation)
- MVA technique (inputs: $m_{\tau\tau}$, $p_{T,\tau}$)

H→bb
- several regions (N_{jets} , $N_{b\text{-}tags}$)
- likelihood discriminant

→ *Combination of the 4 channels*







BR(t→uH)< 12x10^{-4} (8.3 x10^{-4})
BR(t→cH)< 11x10^{-4} (8.3 x10^{-4})

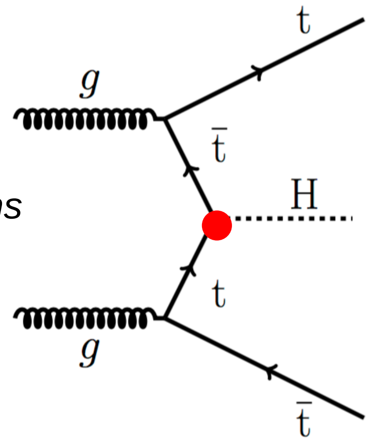
$|\lambda_{tuH}|$ < 0.066 (0.055)
$|\lambda_{tcH}|$ < 0.064 (0.055)

How to access the top quark Yukawa?

Directly

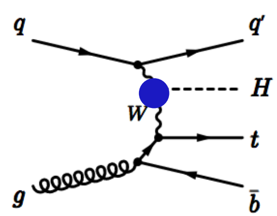
ttH ~500 fb (1% Higgs)

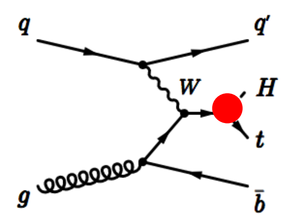
Cross-sections at 13 TeV pp collisions



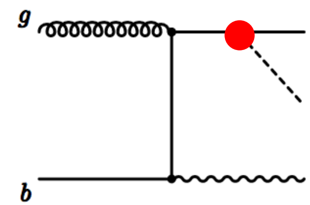
tH ~100 fb (0.2% Higgs)

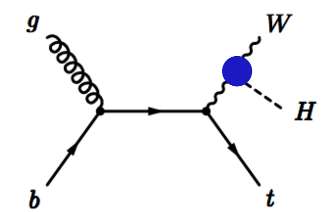
tHqb ~70 fb





tHW ~20 fb

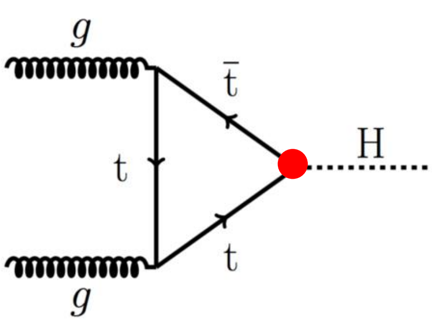




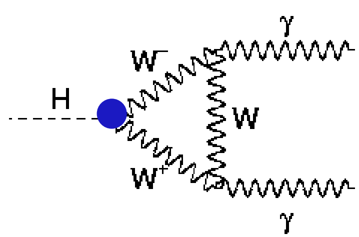
- **sensitive to the sign of κ_t**
- suppressed in SM by destructive interference $\kappa_t\kappa_V<0$

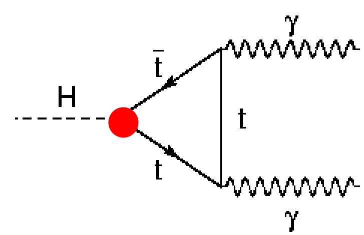
Indirectly

ggH

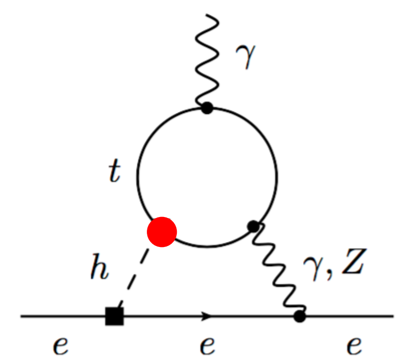


H→χχ





Electron EDM CP



Caveat: new particles could contribute to the loops !

Also other processes like *HZ* in gluon fusion, *HH*, *4-tops* and *ttbar*.
Even flavour violating couplings (*t→Hq* FCNC)…

Several connections between the top and the Higgs

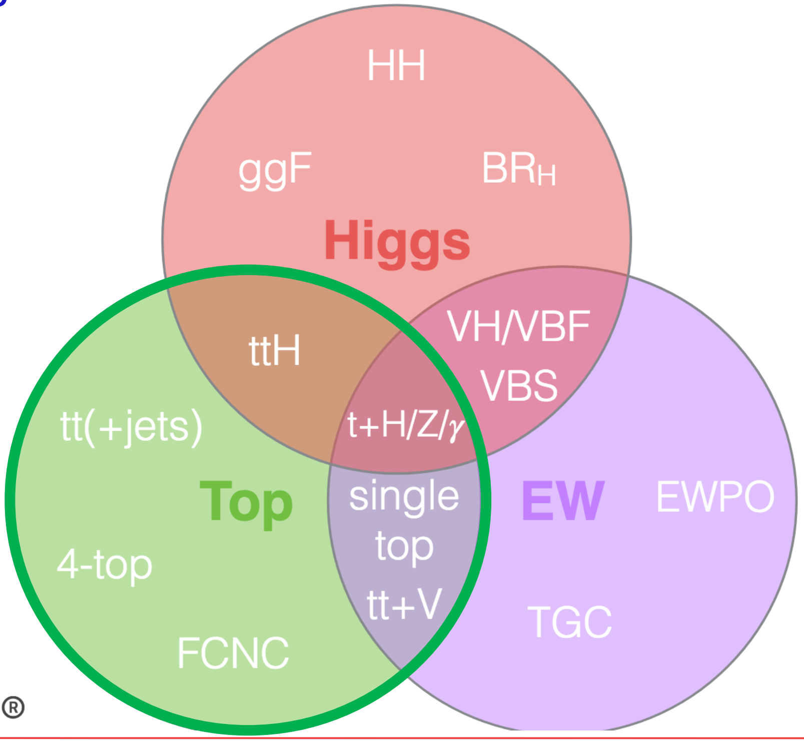
→ Improve SM measurements:

- Effect of top coupling on rates of associated production of Higgs with top(s)
- Various ways top processes (without Higgs bosons) affect Higgs physics
- Effect of top loops on Higgs couplings
- Effect of top loops on m_Z, m_W, m_H
- Effect of top loops on production rates of multi-Higgs

→ BSM searches for new particles or interactions:

- Probing extensions of the Higgs sector ($H^{\pm}$, A, etc.) with top quarks in their decays
- Flavour changing neutral currents (FCNC) in top-Higgs sector
- CP violation in Higgs-top interactions

→ Completely new (unknown) physics…



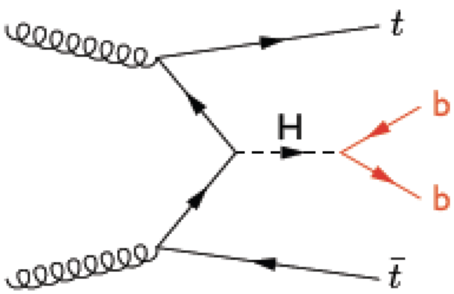
Ken Mimasu®

Challenging and overwhelming backgrounds

ttH(bb) | ttH multi-leptons | ttH(γγ) | ttH(ZZ*→4l)

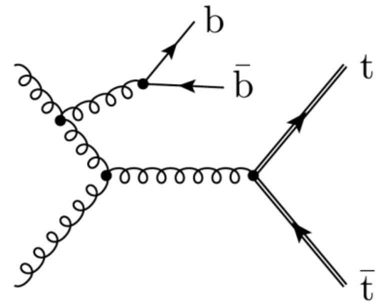
← Low S/B (need MVAs) ... Clear peak (bump hunt)

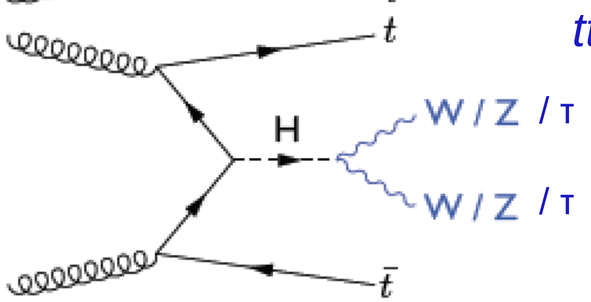
High Higgs Branching Ratios ... Low Higgs Branching Ratios →



tt+H(bb) vs. tt+jets(bb)

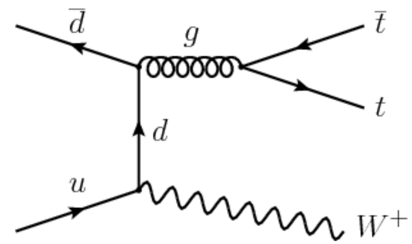
BR~58%

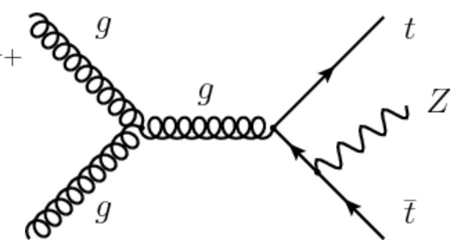




tt+H(WW,ττ,ZZ*) vs. tt+W/Z*

BR~30%





Difficult to distinguish individual tt+X processes …

*Jet (b-jet) multiplicity for final states with **1ℓ***

<u>tt+bb</u>: 6j (4b)
<u>ttH(bb)</u>: 6j (4b)
<u>tttt</u>: 10j (4b)

exploit matrix elements, m_{bb}, $dR_{bb,...}$ [$g \rightarrow bb$]

with 2ℓSS

<u>ttW</u>: 4j (2b)
<u>ttH(WW)</u>: 6j (2b)
<u>tttt</u>: 8j (4b)

N_{jets}, leptons charge,…