Recent news on SM and BSM Higgs from ATLAS+CMS

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Tsung-Dao Lee Institute &
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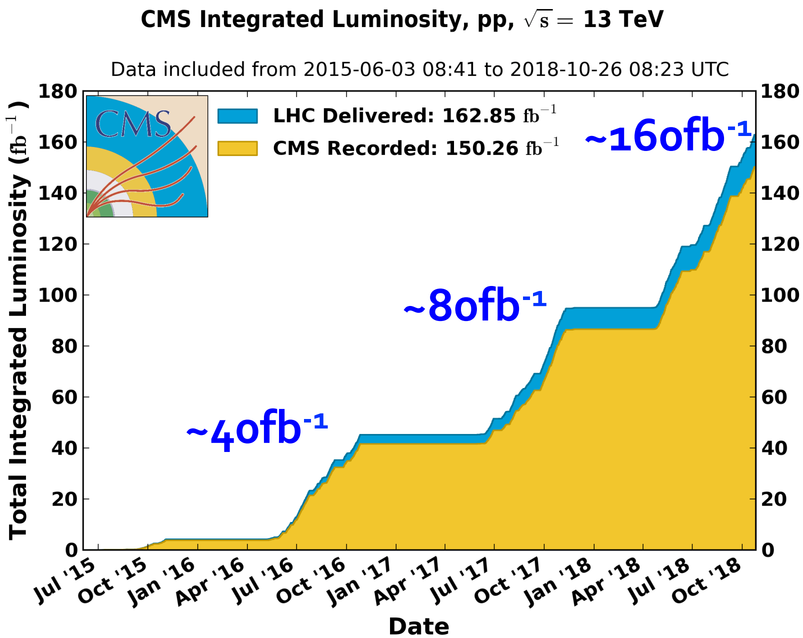
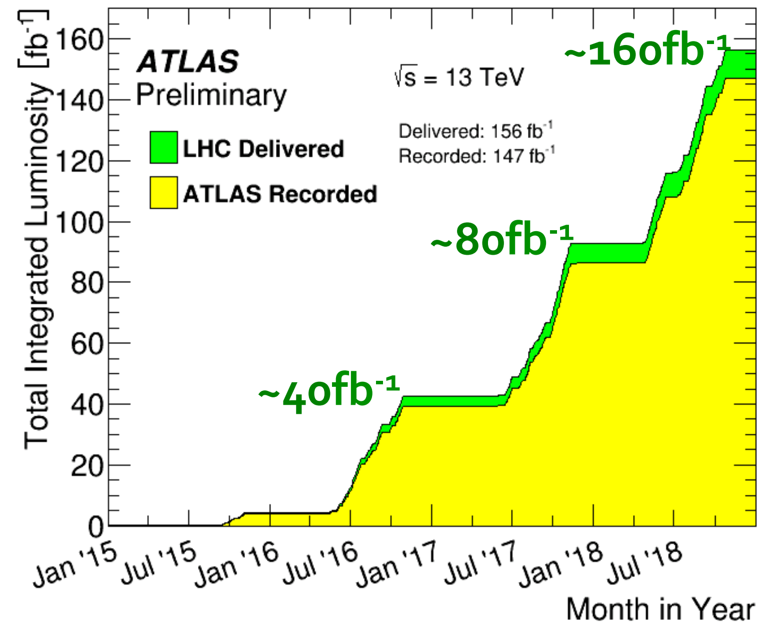
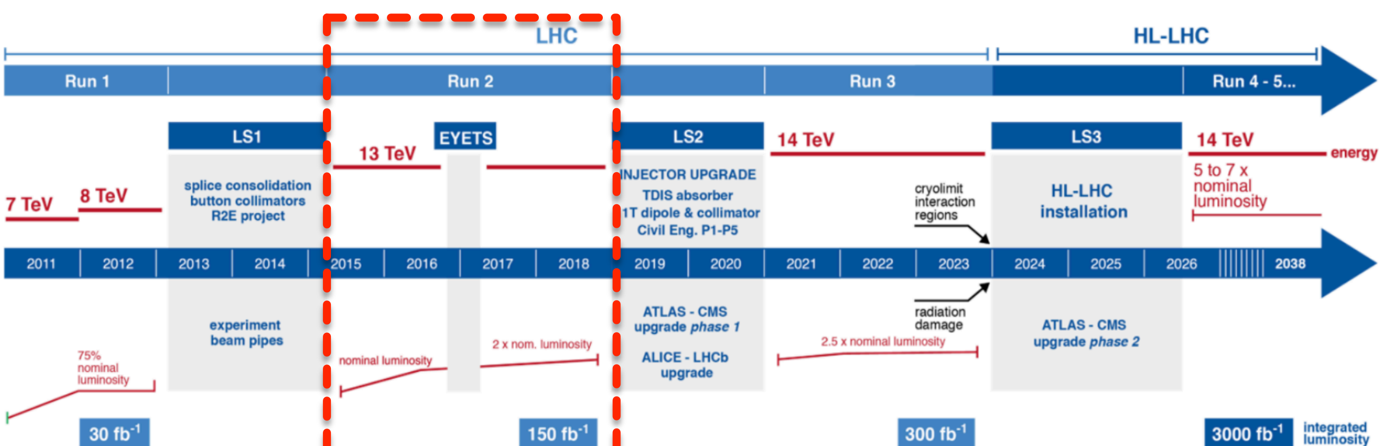
On behalf of ATLAS+CMS Collaborations

LHC data-taking at 13TeV

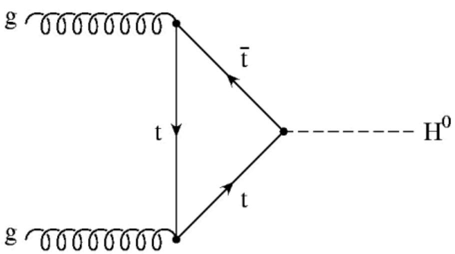




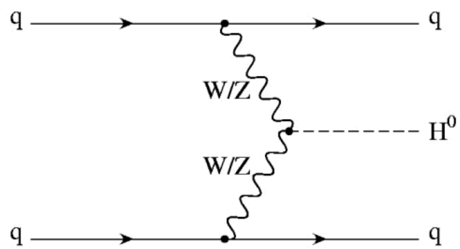


- Run-II provide great opportunity to revisit Run-I Higgs Legacy
  - Observation → measurements!
  - SM → BSM?

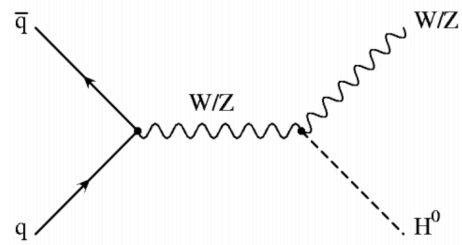
Higgs Physics at the LHC



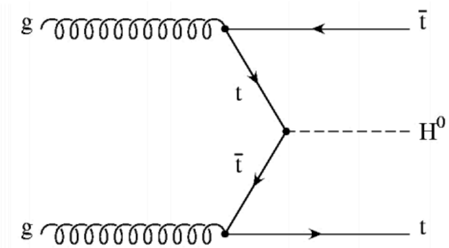
ggF ~87%



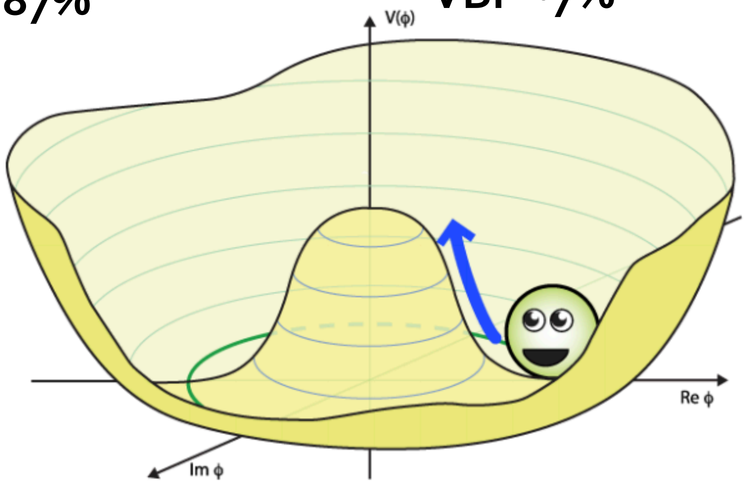
VBF ~7%

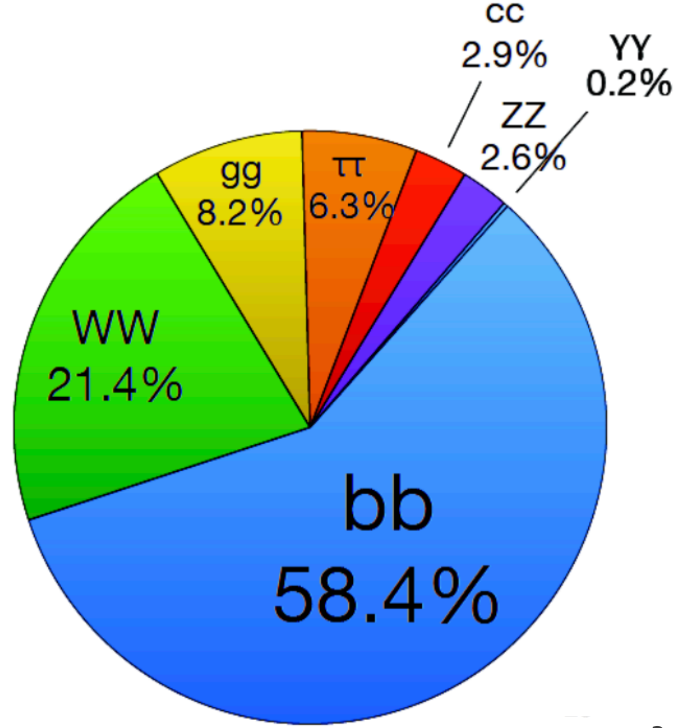


VH ~4%



ttH~1% (+bbH~1%)

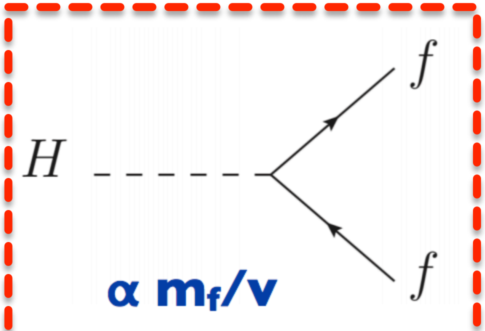




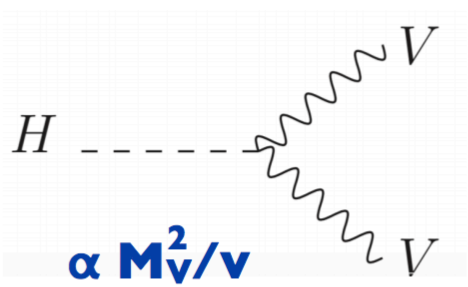
- Major LHC Physics legacy of Run-1
- Many production mechanism and decay channels: Spanning 3 orders of magnitude in x-sec and BR
- Run-2 emphasis: precision (γγ, 4l), new exploration (bb, ττ, ttH,…), combination, kinematics, properties …

Run-II headlines: observations with the 3rd generation fermions!

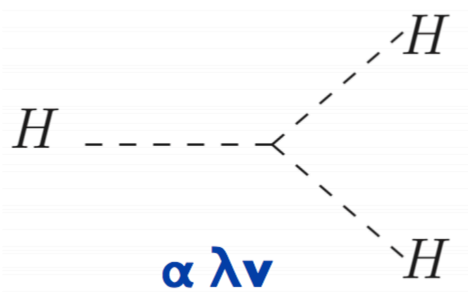
Yukawas at LHC		tau	b	top
ATLAS	Exp. Sig.	5.4σ	5.5σ	5.1σ
	Obs. Sig.	6.4σ	5.4σ	6.3σ
	mu	1.09±0.35	1.01±0.20	1.32±0.27
CMS	Exp. Sig.	5.9σ	5.5σ	4.2σ
	Obs. Sig.	5.9σ	5.6σ	5.2σ
	mu	1.09±0.27	1.04±0.20	1.26±0.26
Paper References		PRD 99 (2019) 072001 PLB 779 (2018) 283	PLB 786 (2018) 59 PRL 121 (2018) 121801	PLB 784 (2018) 173 PRL 120 (2018) 231801



New Observations!



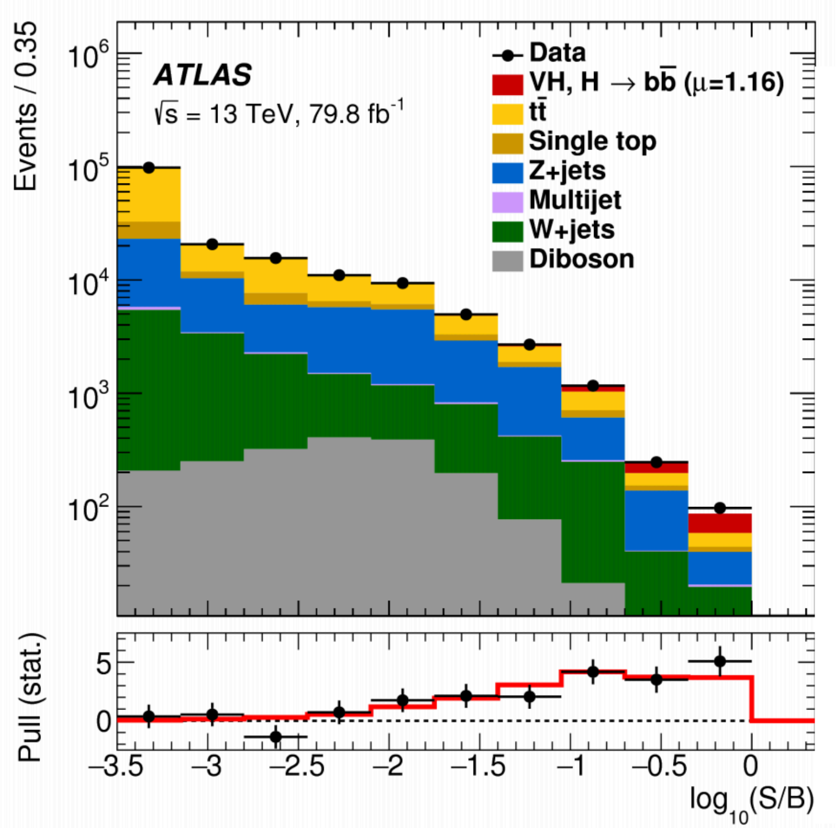
Higgs Discovery 2012

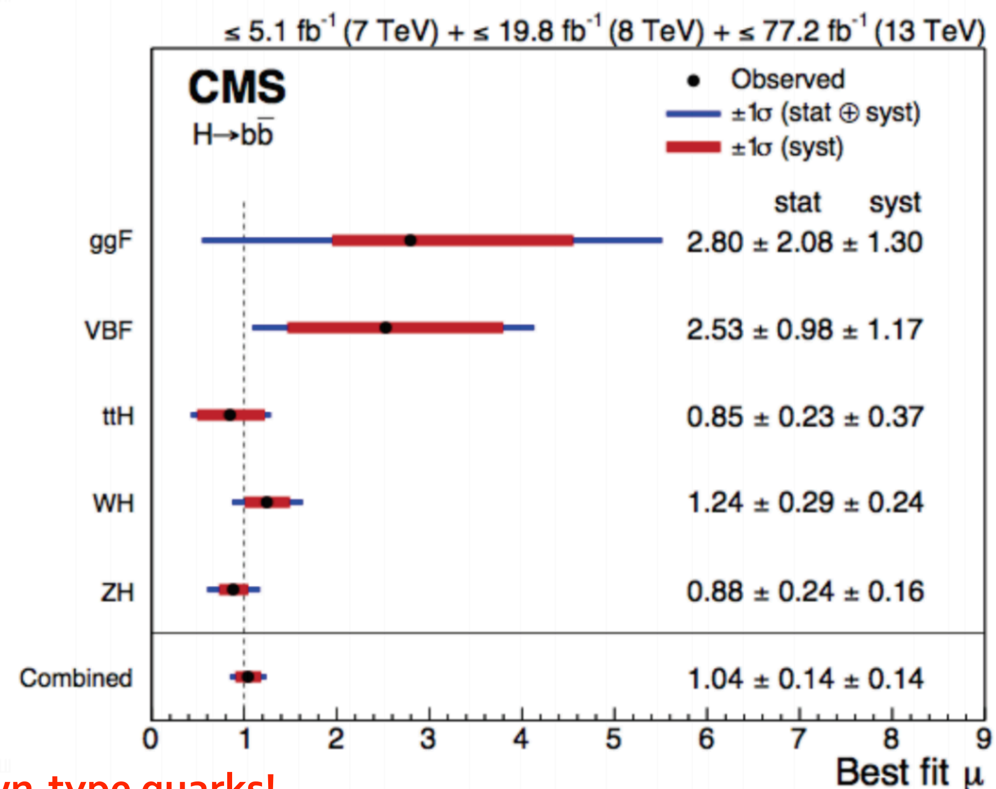


New adventures…

Observation of H(→bb) decays

Phys. Lett. B 786 (2018) 59





First observation of Yukawa couplings to down-type quarks!

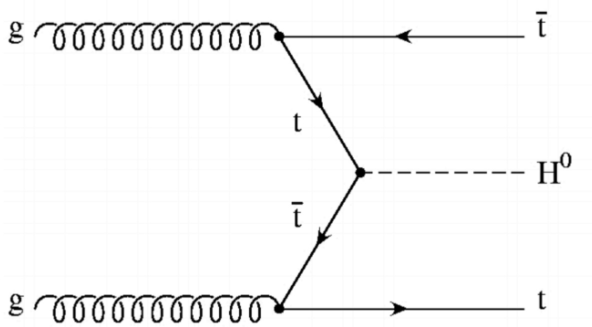
Run-I+Run-II combination of H(→bb)

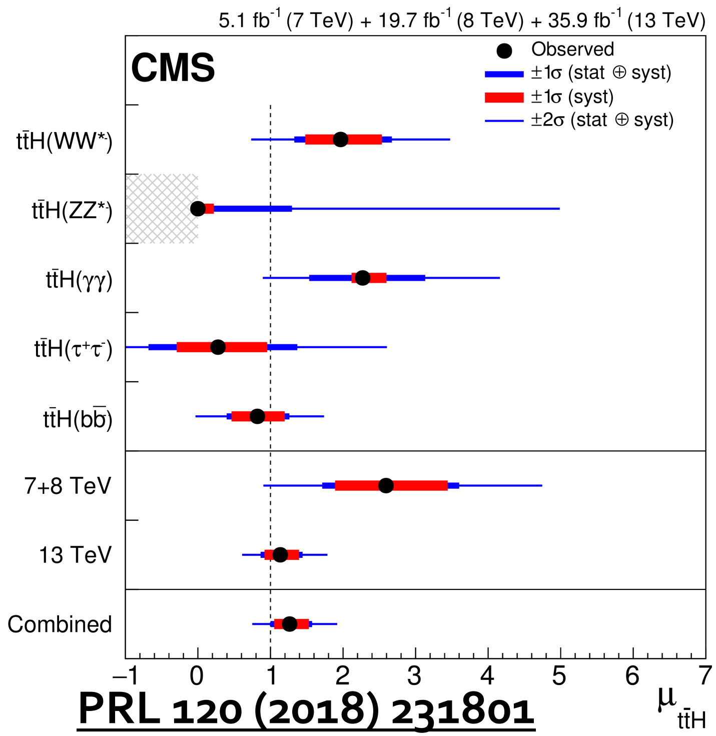
ATLAS 5.5σ (obs), 5.4σ (exp)

CMS 5.6σ (obs), 5.5σ (exp)

Phys. Rev. Lett. 121, 121801 (2018)

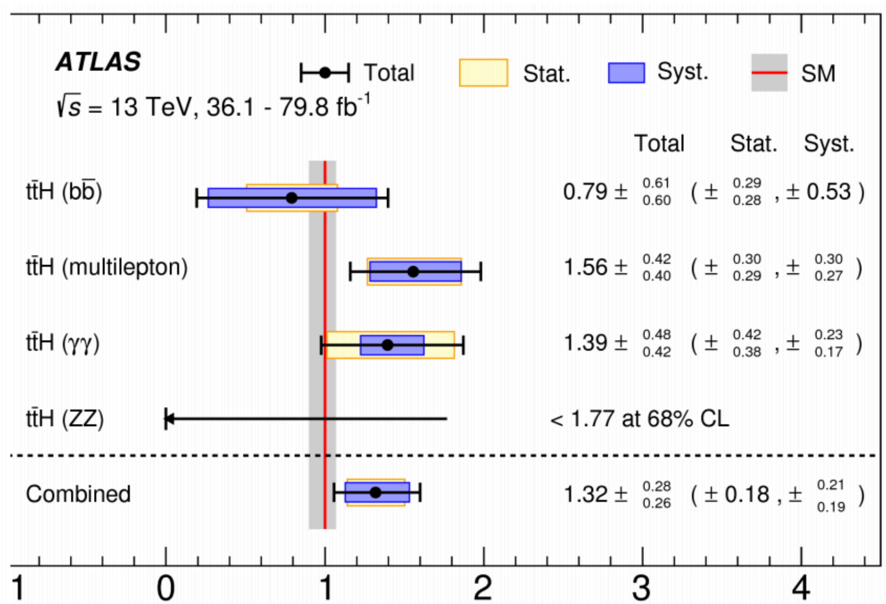
Observation of Higgs Associated Production with Top Quarks





PRL 120 (2018) 231801

- First direct access to top yukawa!
- Experimental challenges
  - Complex final states (decays)
  - Enormous bgd (except γγ) contaminations vs small signal rates~O(0.5)pb@13TeV
- CMS obs.(exp.) 5.2(4.2) σ
- ATLAS obs.(exp.) 6.3(5.1) σ

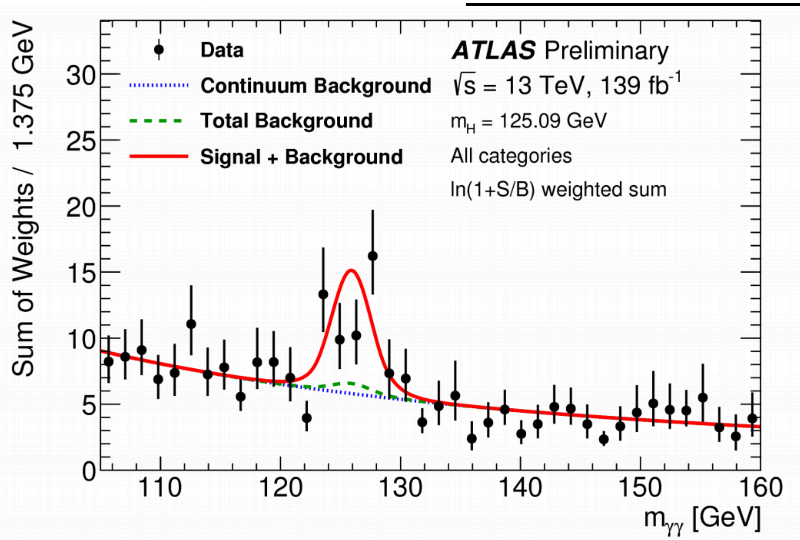


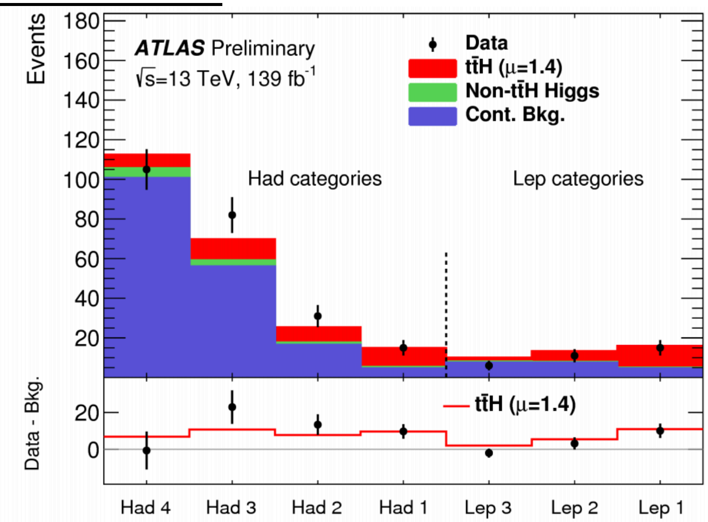
PLB 784 (2018) 173

ttH observation through single channel: ttH, H→γγ

- Observation and measurement of ttH production in the diphoton channel with 139 fb^{-1} of full Run-II data of ATLAS: **obs./exp. 4.9/4.2 σ**
- Events classified in 7 "leptonic"/"hadronic" categories based on multivariate classifier
- Background and signal are modeled with analytic function forms
- Simultaneous fit to the $m_{\gamma\gamma}$ spectrum in these seven regions

ATLAS–CONF–2019–004



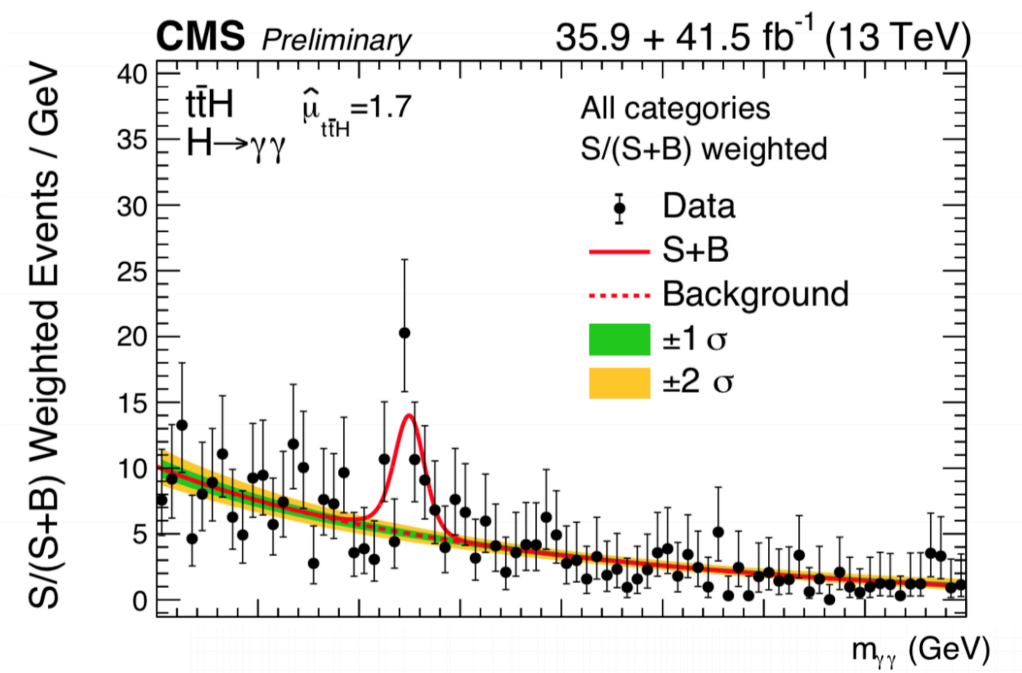


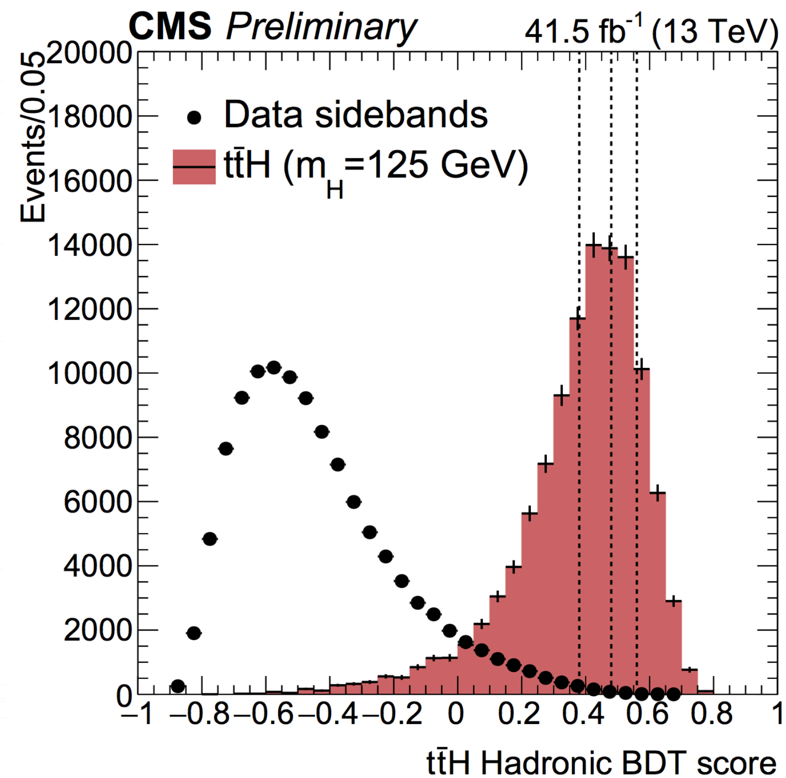
Measured Cross-Section: $\sigma_{ttH} \times B_{\gamma\gamma} = 1.59 \,^{+0.38}_{-0.36}\,(\text{stat.}) \,^{+0.15}_{-0.12}\,(\text{exp.}) \,^{+0.15}_{-0.11}\,(\text{th.})\ \text{fb}$

Comparison w.r.t. SM: $\mu_{ttH} = 1.38 \,^{+0.33}_{-0.31}\,(\text{stat.}) \,^{+0.13}_{-0.11}\,(\text{exp.}) \,^{+0.22}_{-0.14}\,(\text{th.})$

ttH observation through single channel: ttH, H→γγ

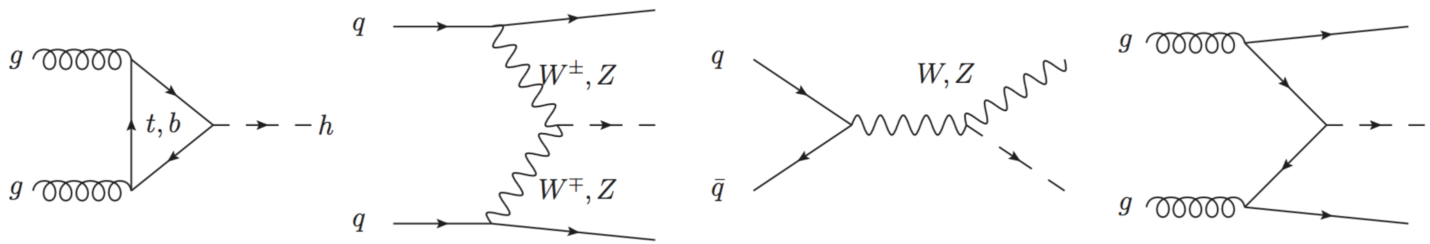
<u>**CMS–PAS–HIG–18–018**</u>





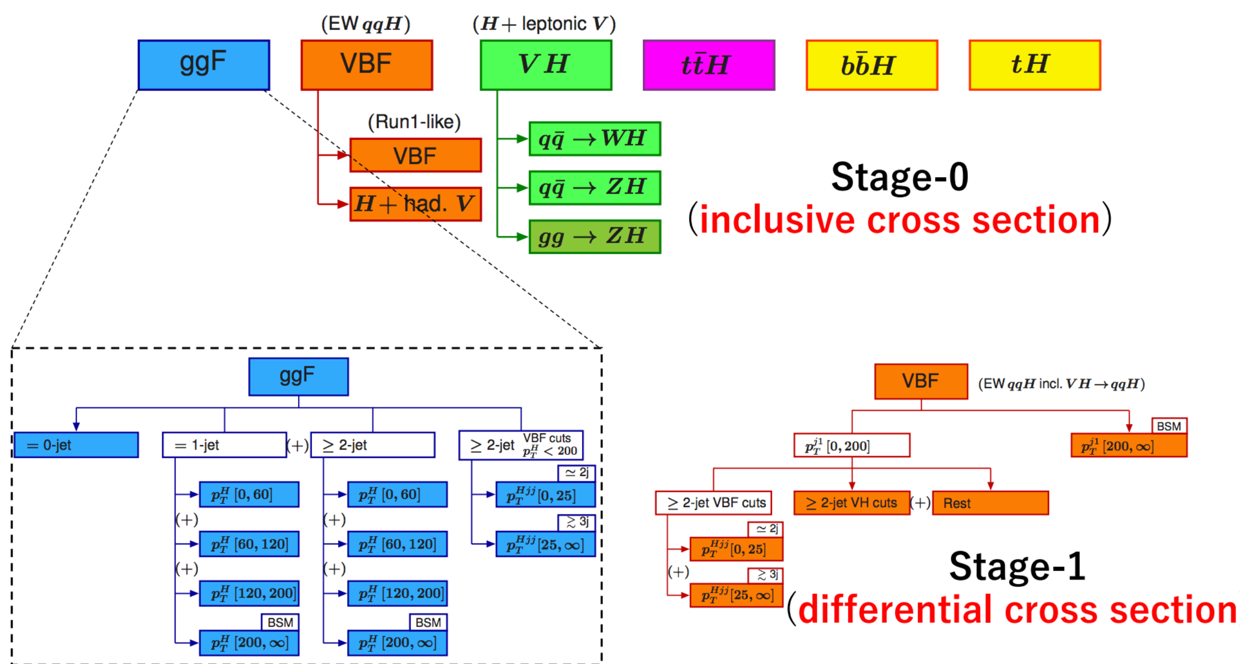
CMS ttH(→γγ) results with partial dataset (NO 2018 inclusion)
Similar analysis with similar performance, difference in sensitivity largely due to incomplete dataset: **obs./exp. 4.1/2.7 σ**

Simplified Template Cross Sections (STXS): Hybrid Fiducial

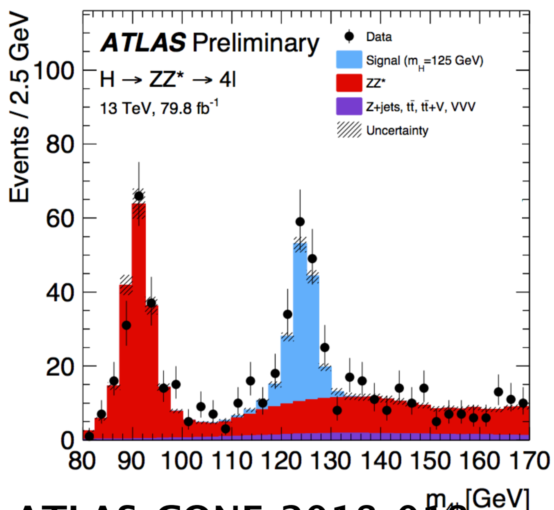


ggF ~87% **VBF ~7%** **VH ~4%** **ttH~1% (+bbH~1%)**

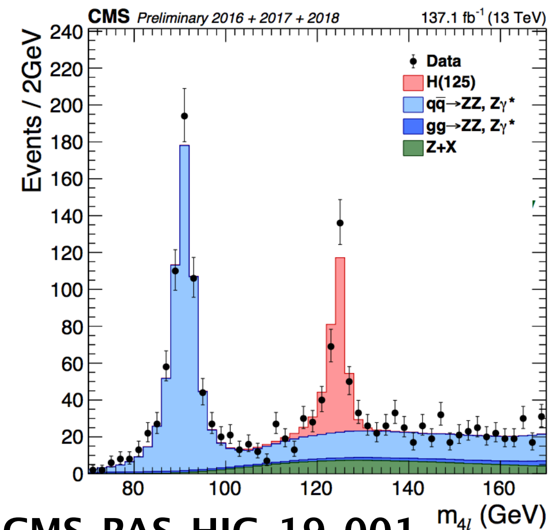
- Defines the cross-sections in exclusive fiducial regions.
- Minimize theory dependence, maximize experimental sensitivity.
- measure as precisely as possible individual production processes (ggF, VBF, V(=W/Z)H and ttH) in different regions of phase space.



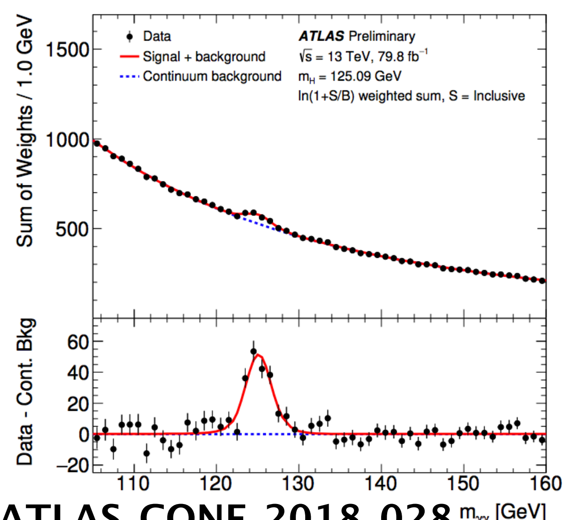
Invariant mass in H(→4l and γγ)



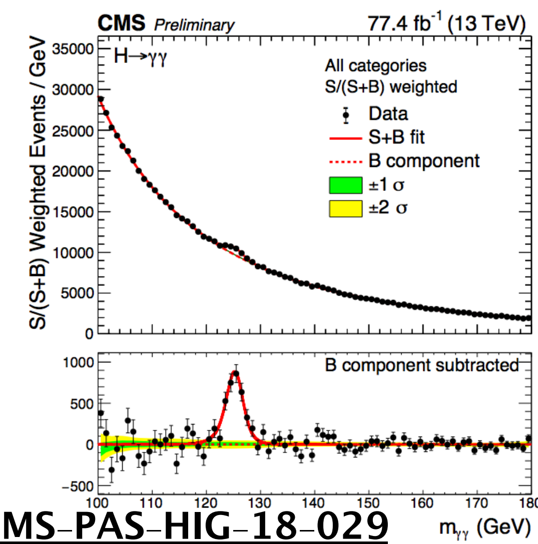
ATLAS-CONF-2018-018



CMS-PAS-HIG-19-001



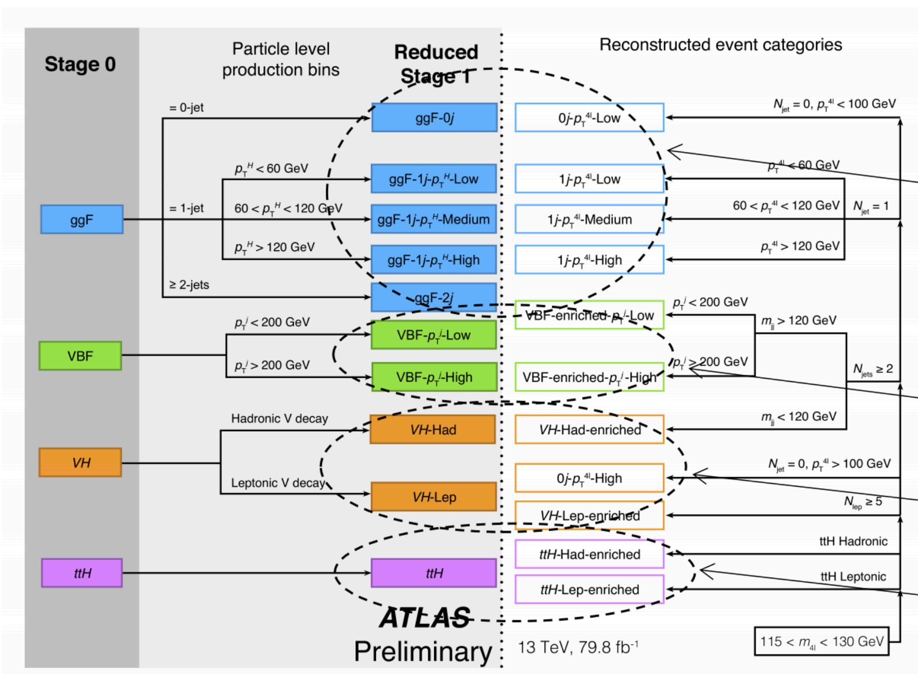
ATLAS-CONF-2018-028



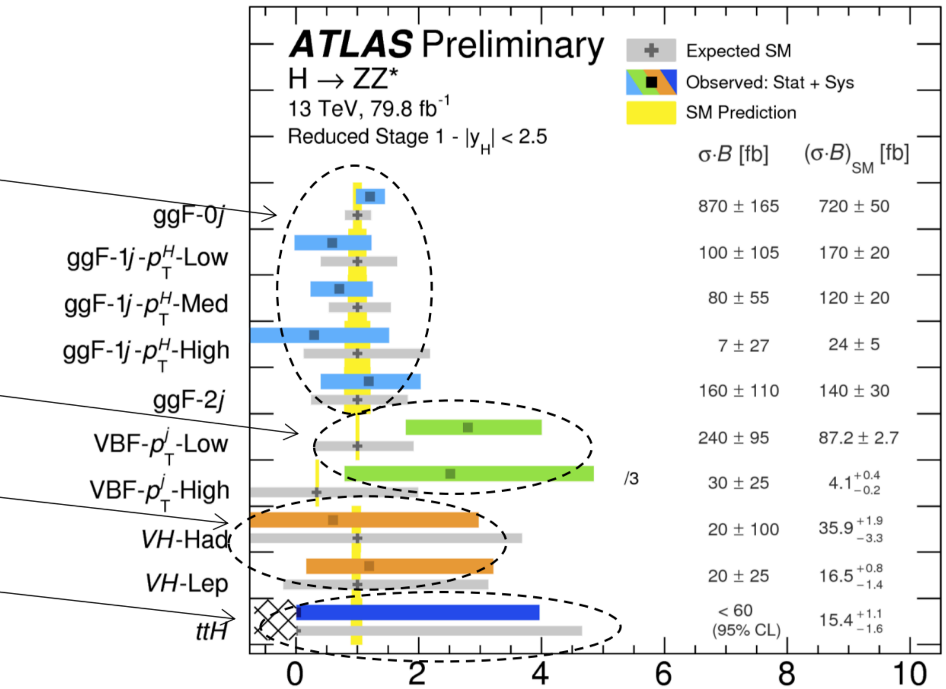
CMS-PAS-HIG-18-029

- High purity and clean final state channels for precision studies of Higgs properties
- 4l: Small branching fraction (0.0124% at mH = 125 GeV), final states are fully reconstructable, S/B better than 2
- Diphoton: Small branching fraction (0.23% at mH = 125.09 GeV), final states are fully reconstructable, look for a narrow peak on a smooth background

STXS example in H→ZZ→4l

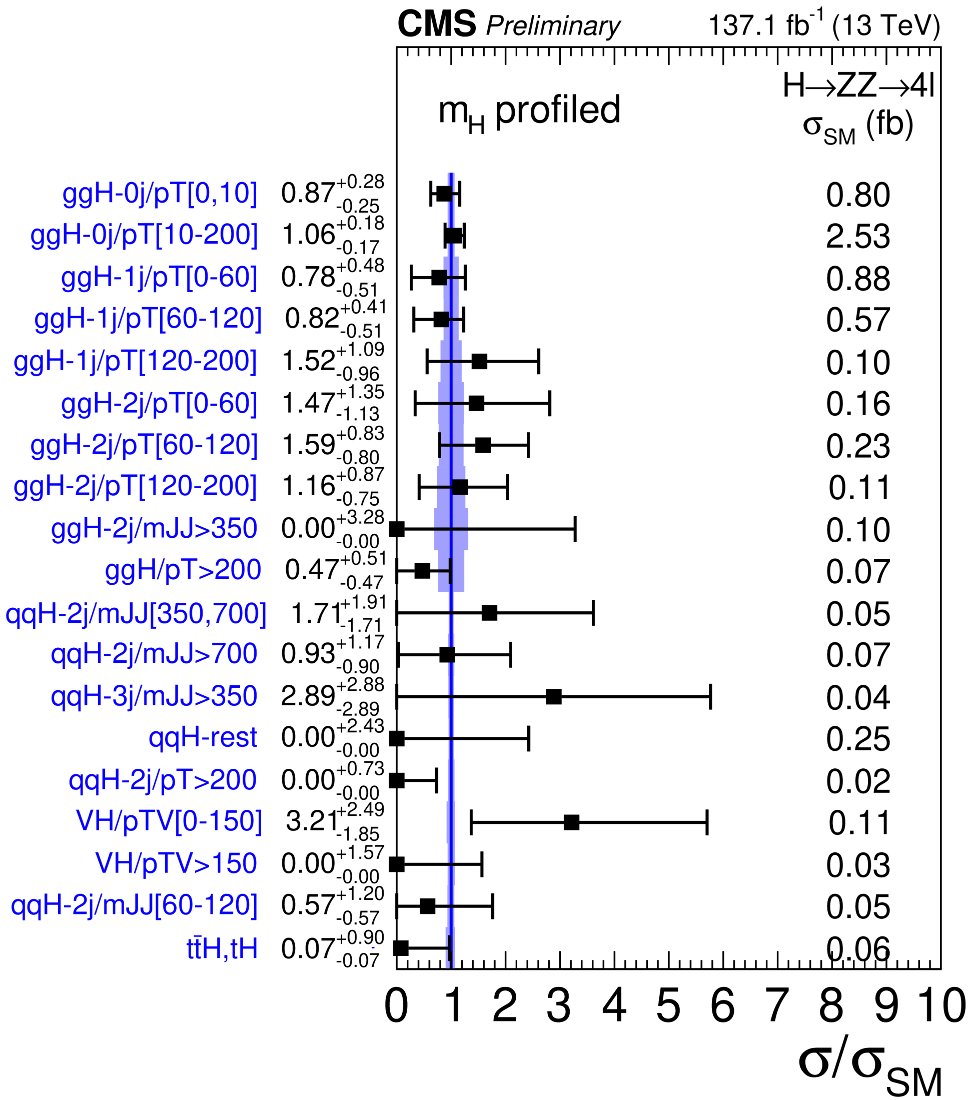


ATLAS-CONF-2018-018



Example measurement summary plot here: Cross Section * BR(H→ZZ*→4l)
More similar STXS (*BR(yy)) are measured in H->yy, see: ATLAS-CONF-2018-028

CMS STXS exploration in H→ZZ→4l



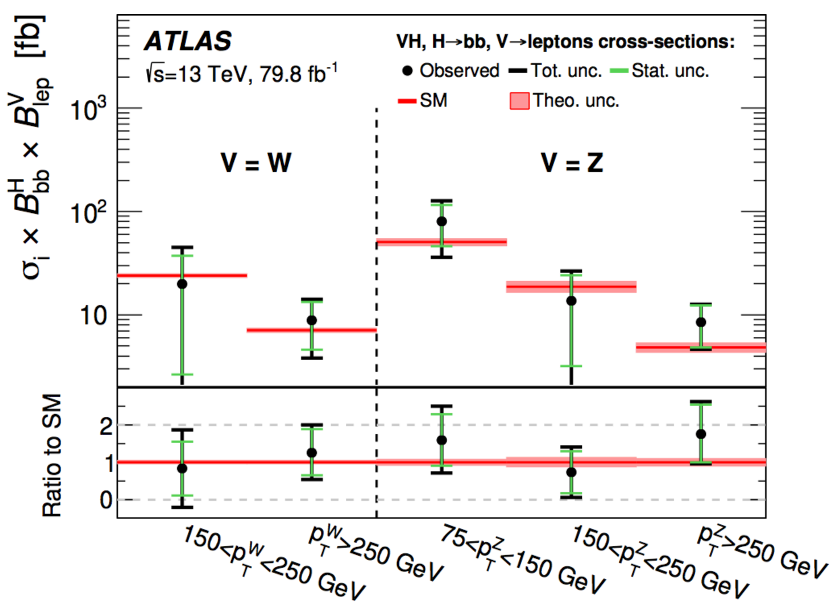
CMS-PAS-HIG-19-001

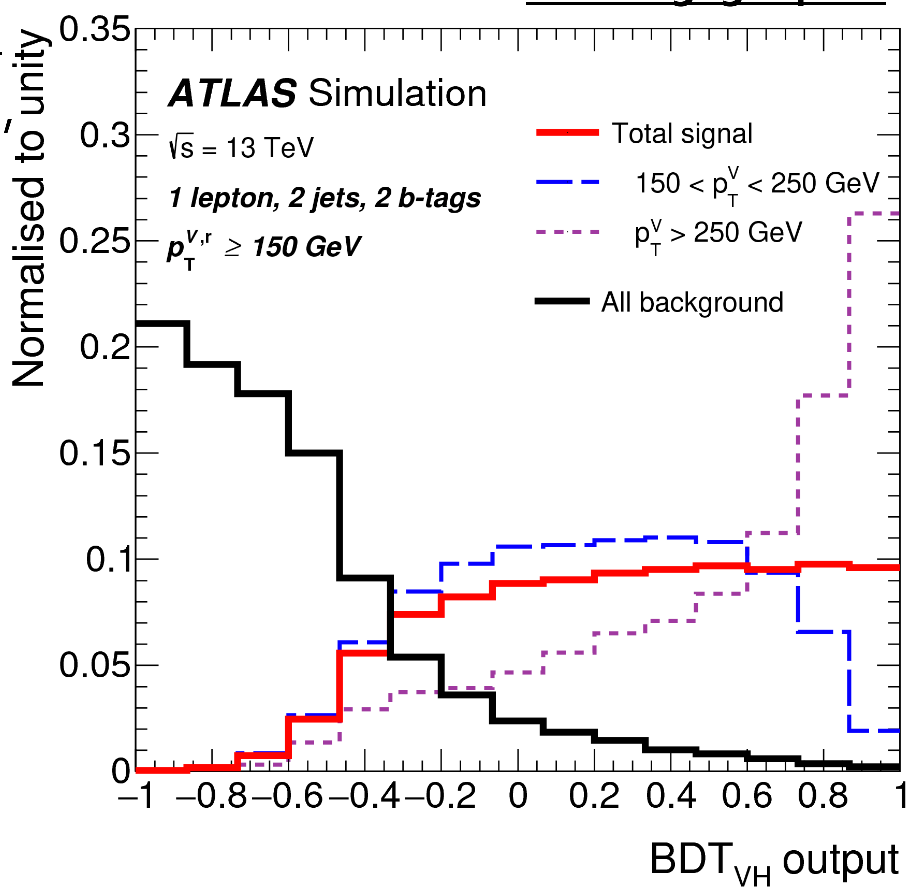
CMS full Run2 H→ZZ→4l analysis already exploiting STXS stage 1.1

STXS in H(→bb)

- Cross section measurements of WH and ZH in different $p_T(V)$ regions in the STXS framework
- Further categorized in 0/1/2-L W/Z decays
- Main background is V+jets (in particular b-jets) and ttbar, relies on a good simulation, but is controlled in the mass side-bands and control regions!
- To be Combined with other channels in STXS framework

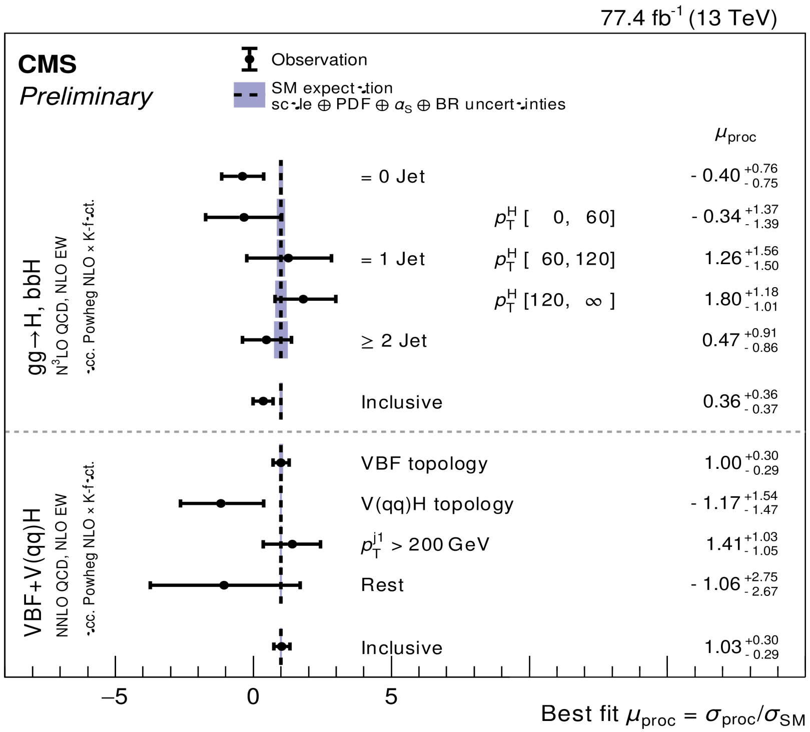
arXiv:1903.04618

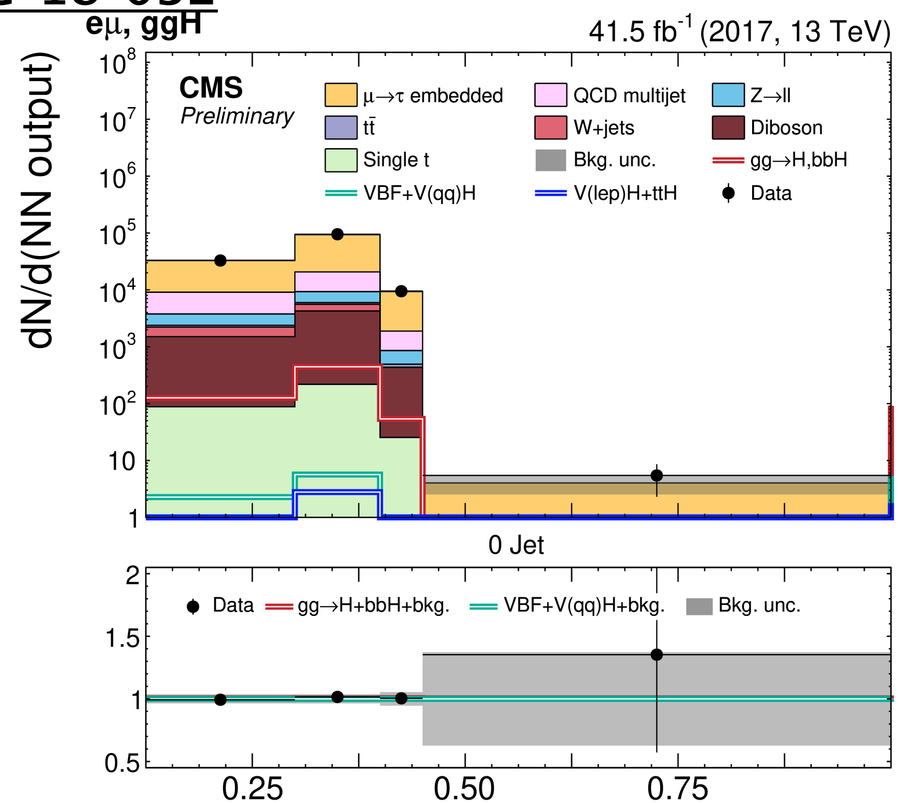




Measurement H→ττ decays post observations

CMS-PAS-HIG-18-032





- Targetting ggF/VBF production modes.
- Improved background modeling for genuine taus (embedding) and reducible background. Classification using a Multi-Class NN technique with 8 categories.
- Split the ggH, bbH and VBF production modes: σ(gg→H,bbH)BR(H→ττ)= 1.11 ± 0.81 (stat) ± 0.78 (syst) pb and σ(VBF+VHqq)BR(H→ττ)= 0.34 ± 0.08 (stat) ± 0.09 (syst) pb.

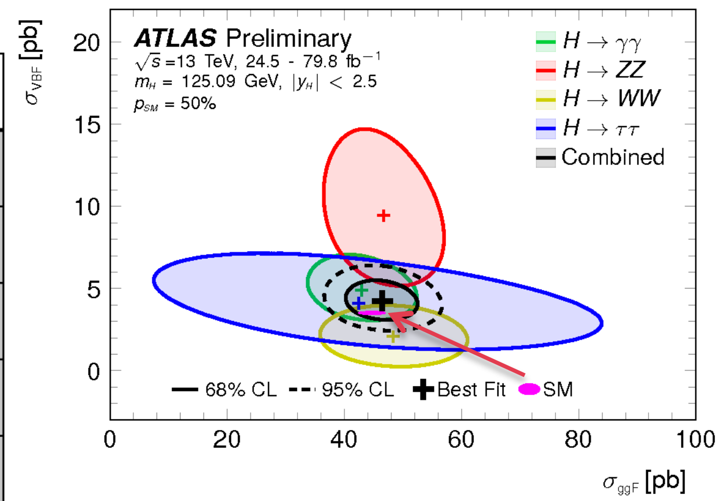
STXS combination

ATLAS-CONF-2019-005

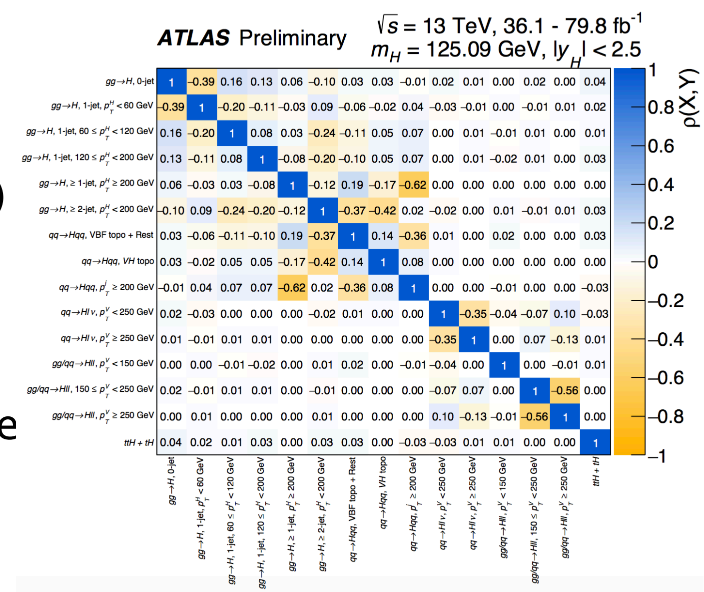
	ggF	VBF	VH	ttH+tH
H→γγ	✔	✔	✔	✔
H→ZZ	✔	✔	✔	✔
H→WW	✔	✔	✓	✔
H→ττ	✔	✔		✔
H→bb	✓	✓	✔	✔

✔: channel included in the combination

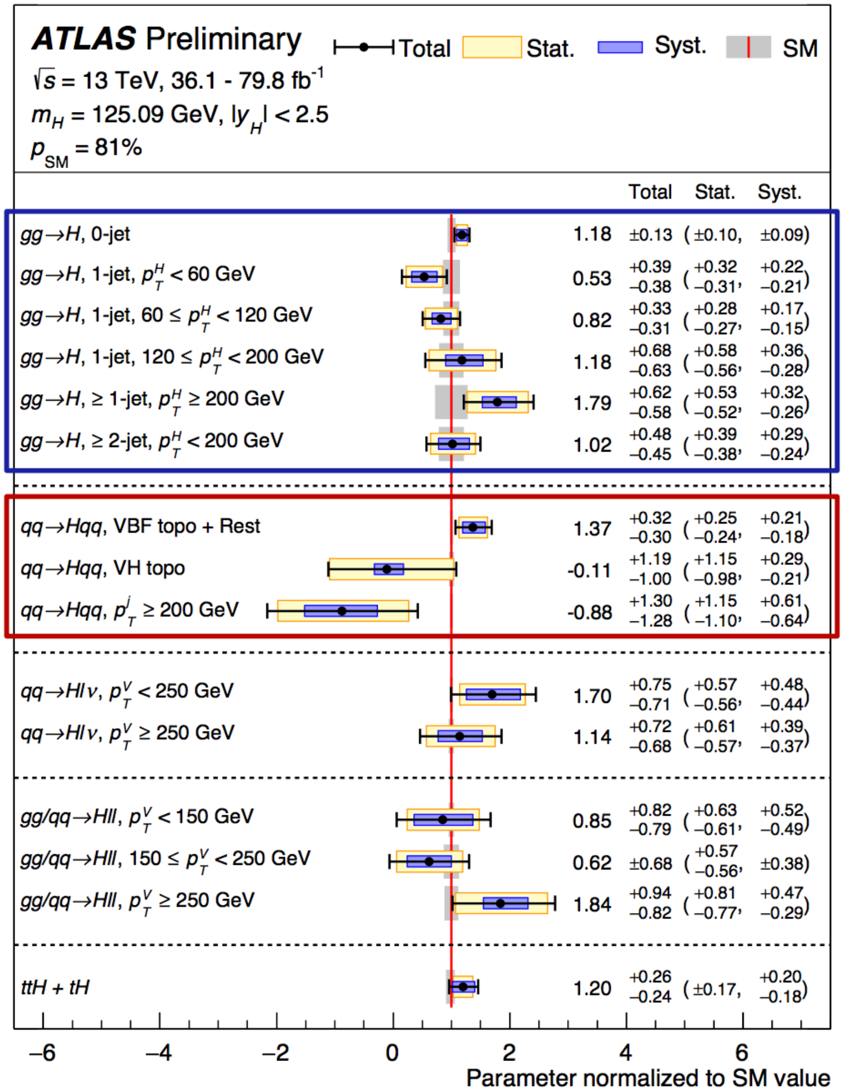
✓: channel available but not included in combination

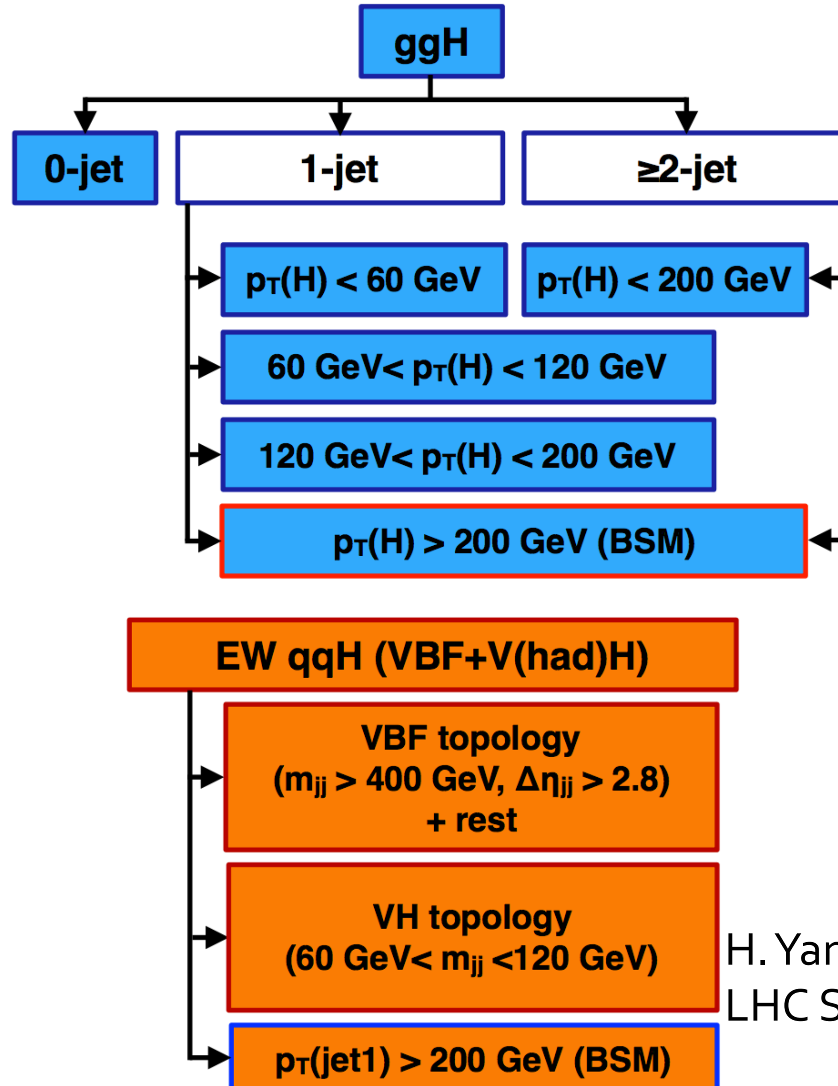


- Combination of all channels including STXSs (ATLAS)
- All main channels entering the combination (diphoton, ZZ*, WW*, bb, tautau, ttH)
- Correlation matrix indicating the level of degeneracy of different STXSs and the resolution effects from one bin to the other. Fixed branching fraction for simplicity



STXS results assuming the SM BRs



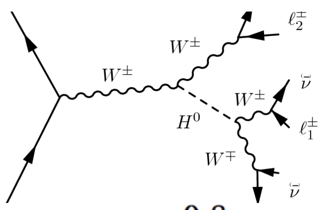


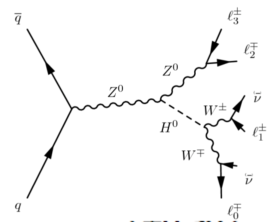
H. Yang
LHC Seminar

VH, H(→WW) at 13TeV

Measurement of the Higgs boson production cross sections via associated WH and ZH production using $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decays.

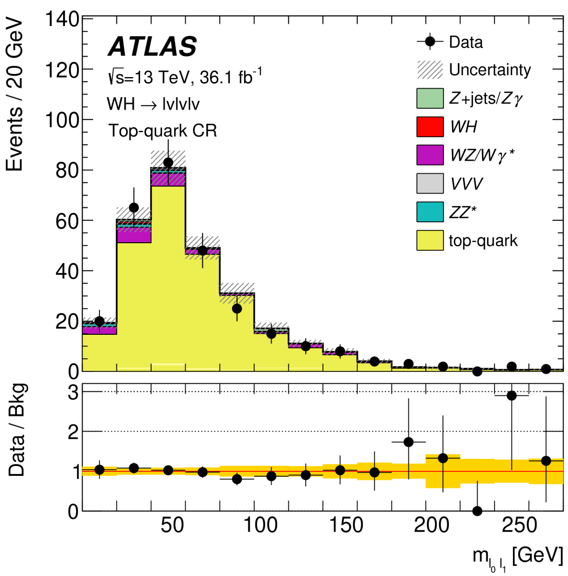
arXiv:1903.10052

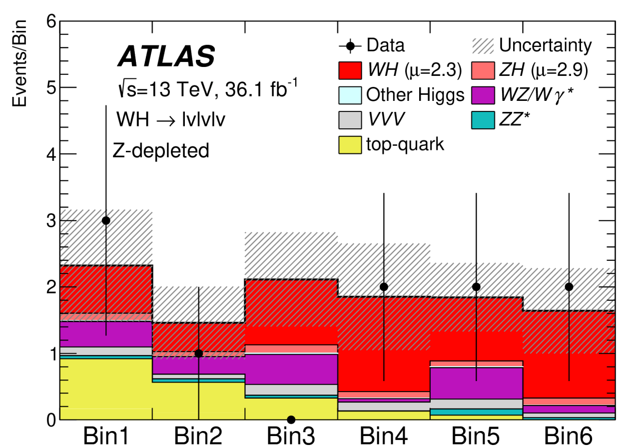


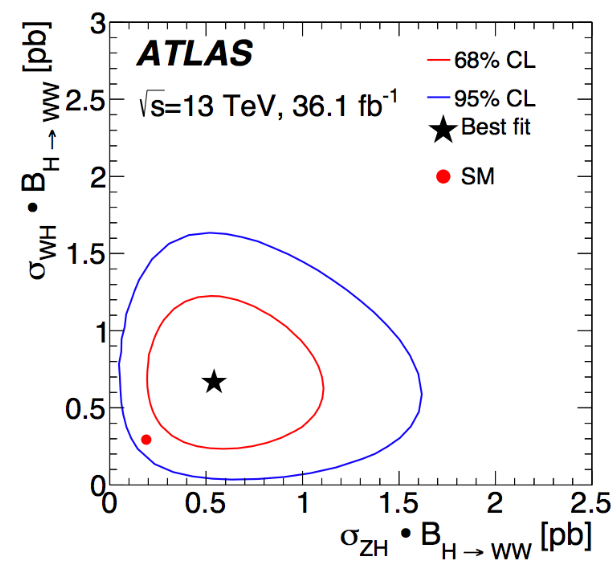


$$\mu_{VH} = 2.5^{+0.8}_{-0.7}(\text{stat.})^{+0.37}_{-0.26}(\text{theo syst.})^{+0.30}_{-0.23}(\text{exp syst.}) = 2.5^{+0.9}_{-0.8}$$

- Compatible with SM
  - Within 1.3(1.5)σ of SM for WH(ZH)
- Observed (expected) VH significance: 4.1σ (1.9σ)





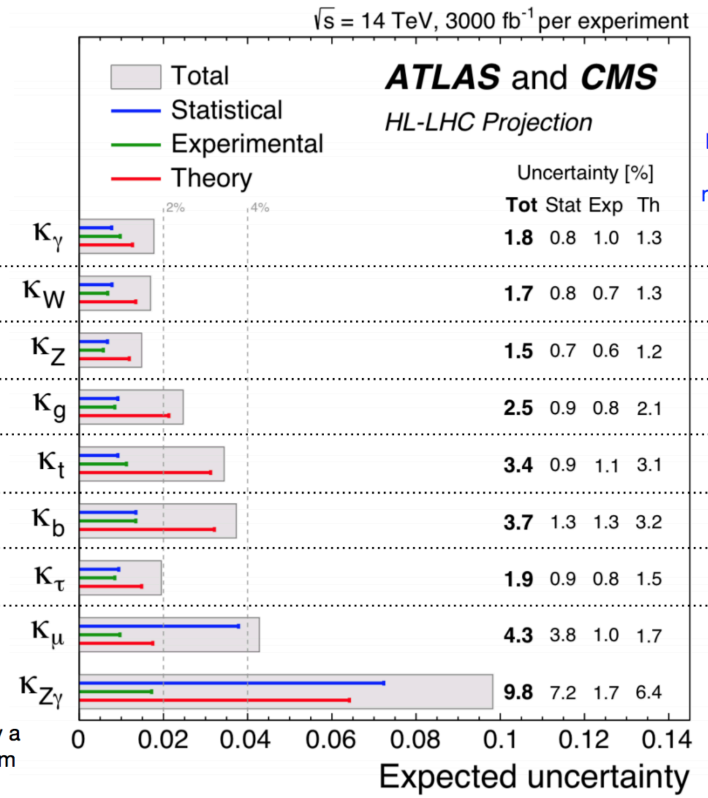


High purity CR for Top and ZZ backgrounds

Combination of Main Decay and Production Channels Towards HL-LHC

M. Kato
Aspen2019

	ATLAS+CMS Run1	ATLAS Run2	ATLAS+CMS HL-LHC
κ_γ	13%	9%	1.8%
κ_W	11%	8.6%	1.7%
κ_Z	11%	7.2%	1.5%
κ_g	14%	11%	2.5%
κ_t	30%	14%	3.4%
κ_b	26%	18%	3.7%
κ_τ	15%	14%	1.9%
	JHEP 08 (2016) 045	ATLAS-CONF-2019-04	HL-LHC YR 1902.00134



Experimental systematics non negligible

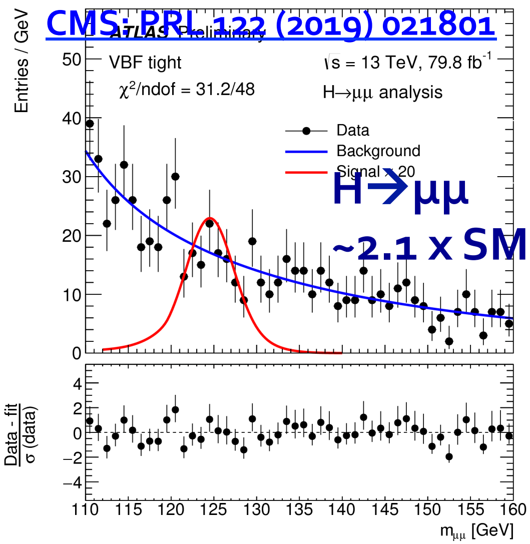
Improved TH and PDF uncertainties by a factor of 2 w.r.t. current (motivated from current PDF studies and current TH uncertainties assumptions)

HL-LHC: high-luminosity LHC (~2026-2038), 3000/fb per experiment at $\sqrt{s}$ = 14 TeV
In need of theorists' efforts for those with theo. unc. dominance ☺

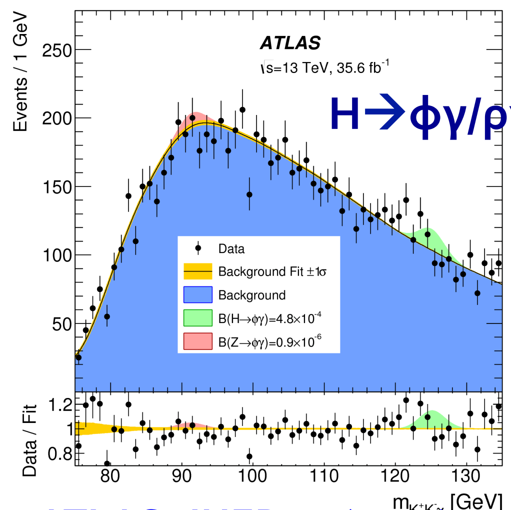
Quick glimpse of the rare decays

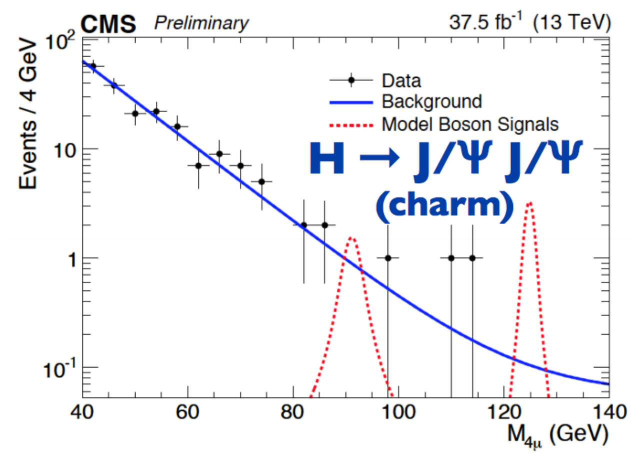
ATLAS-CONF-2018-026

CMS: PRL 122 (2019) 021801

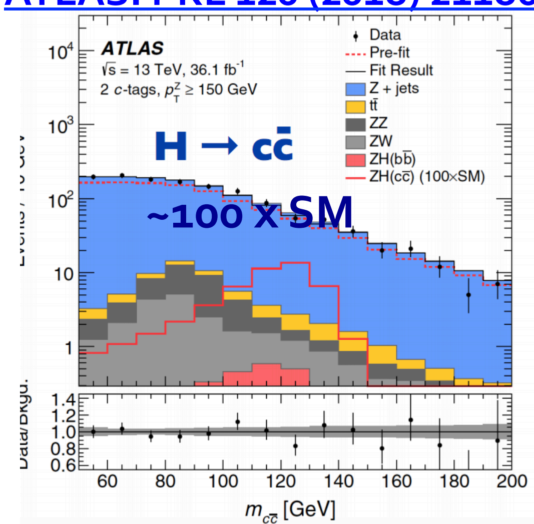


ATLAS: JHEP 07 (2018) 127



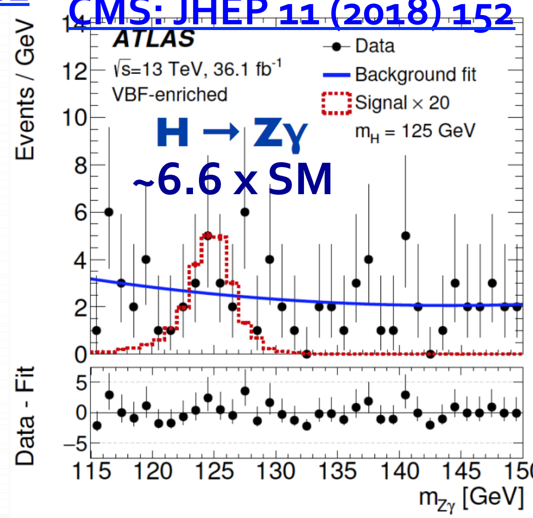


ATLAS: PRL 120 (2018) 211802

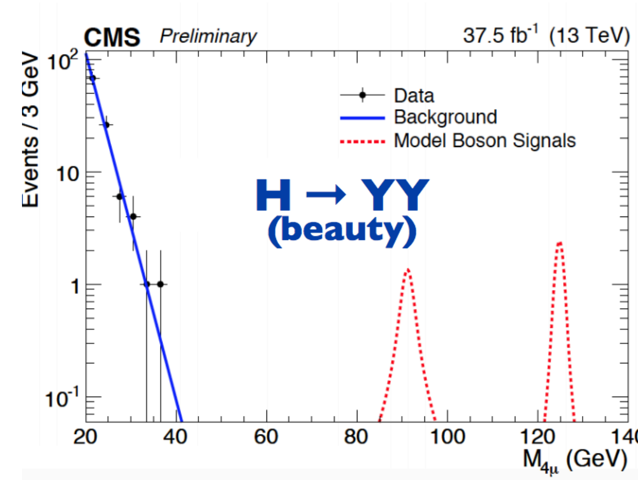


ATLAS: JHEP 10 (2017) 112

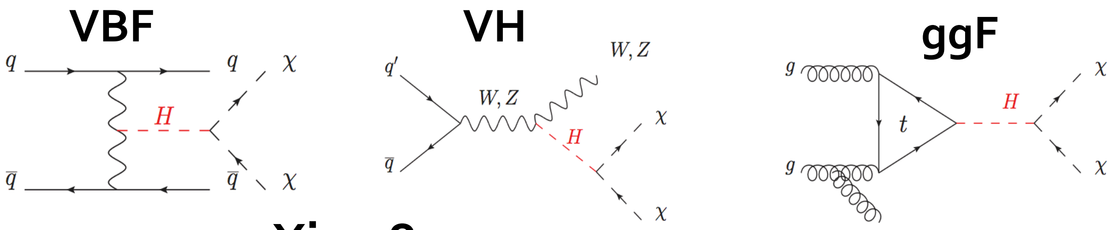
CMS: JHEP 11 (2018) 152



CMS-PAS-HIG-18-025

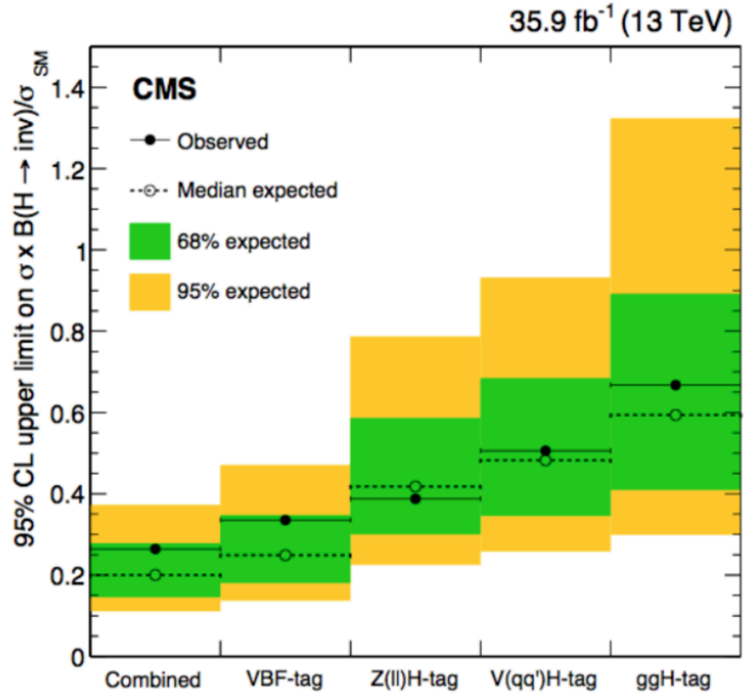


Invisible decays of the Higgs (NEW!)

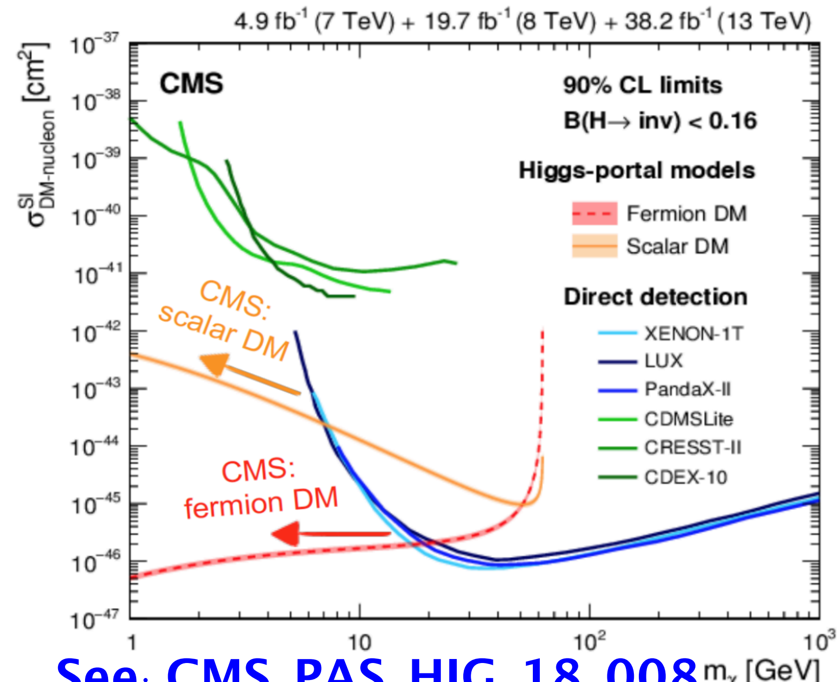


- Comprehensive analysis of many channels
- VBF most sensitive
- Includes a mono-jet and mono-V hadronic boosted mode

arXiv:1809.05937

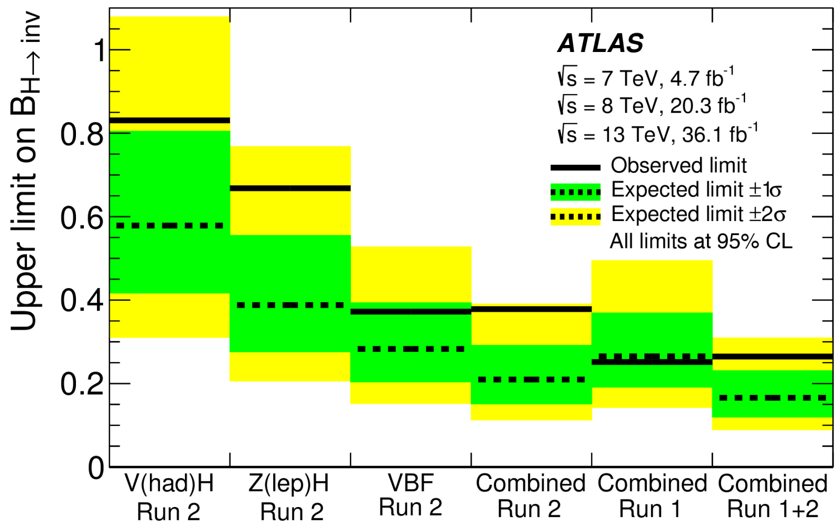


Br(H → inv) <0.19 (0.15) 95% C.L. with Run1+Run2 combination

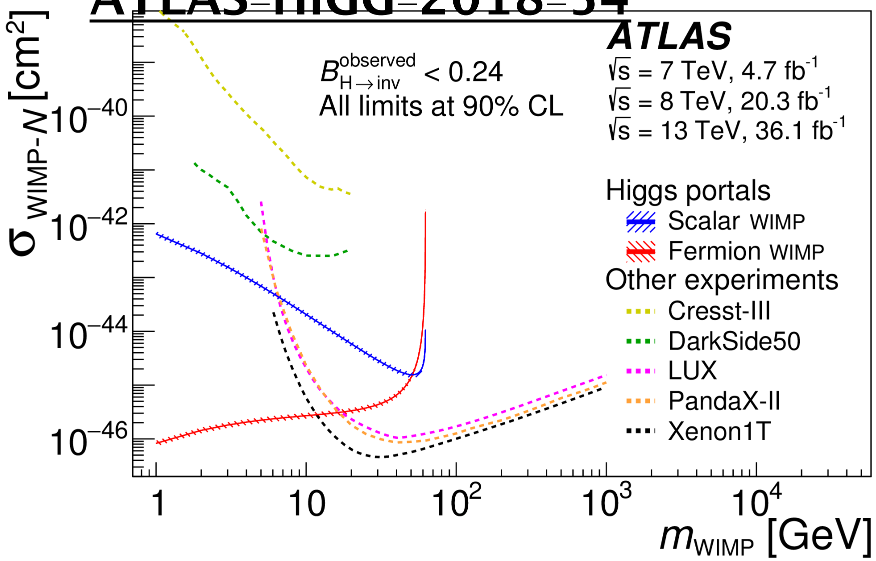


See: CMS-PAS-HIG-18-008 for latest ttH->invis

H→inv. Combination (NEW!)



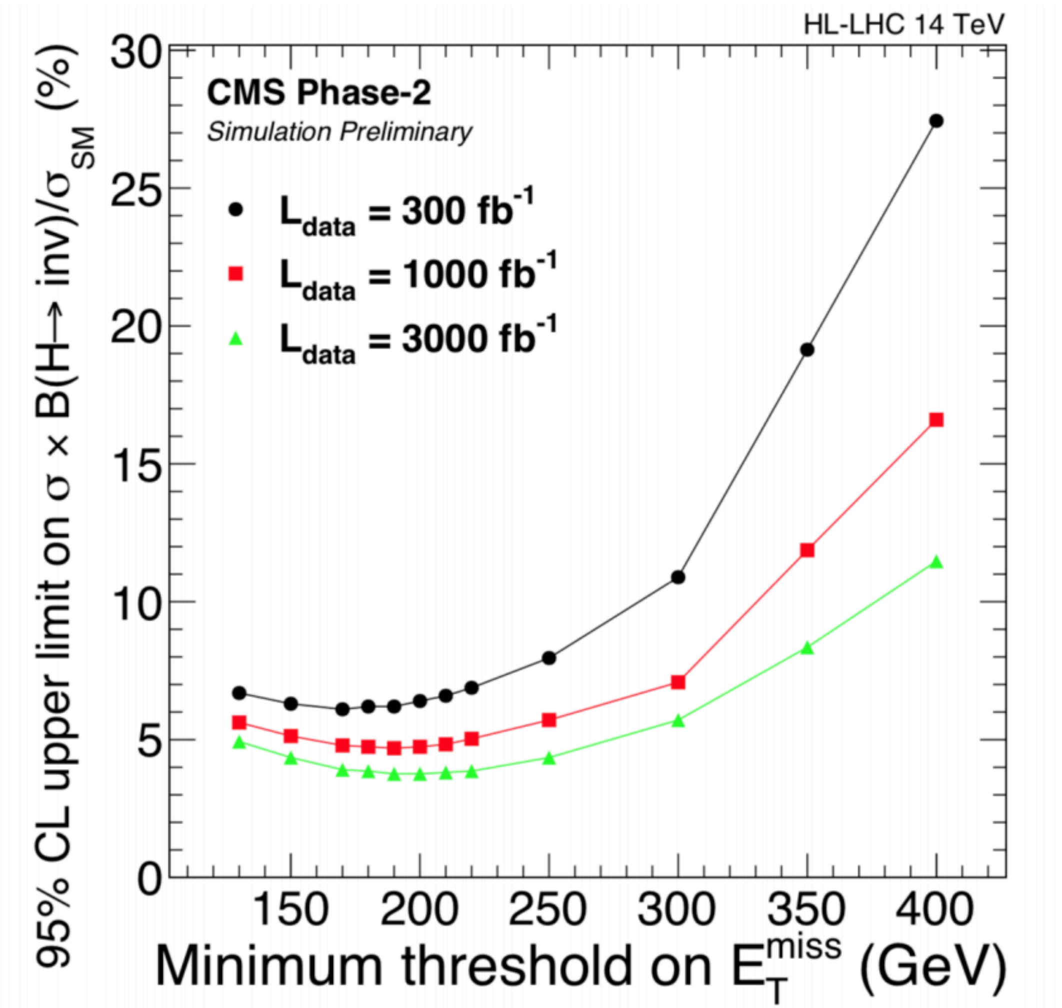
ATLAS-HIGG-2018-54



The observed and expected upper limits on BR(H→inv) at 95% CL from direct searches for invisible decays of the 125 GeV Higgs boson and their statistical combinations in Run 1 and 2.

Comparison of the upper limits at 90% CL from DD experiments on the spin-independent WIMP-nucleon scattering cross section to the observed exclusion limits from this analysis, assuming Higgs portal scenarios where the 125 GeV Higgs boson decays to a pair of DM particles.

Inv. Higgs at HL-LHC



CMS FTR 18-016

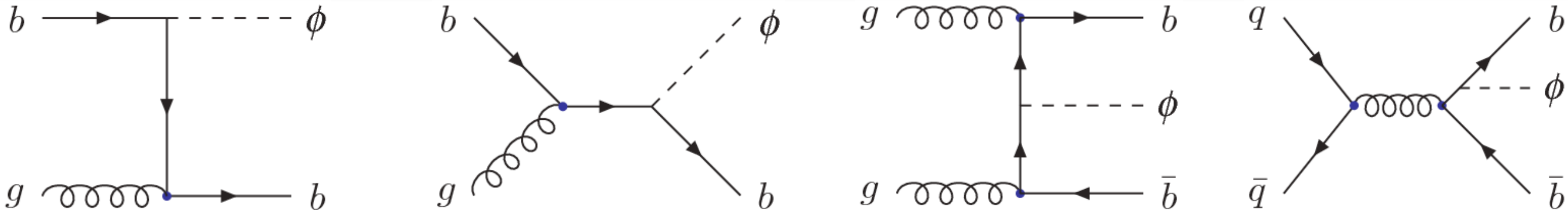
CMS projection for VBF: BR(H→inv)<3.8%

ATLAS projection for VH: BR(H→inv)<8%

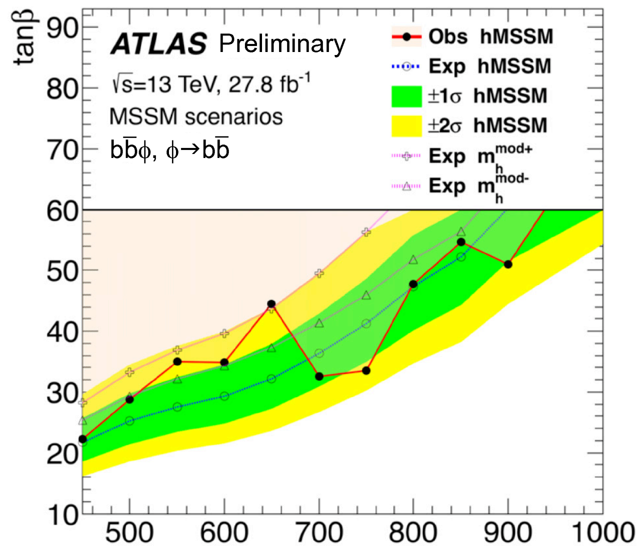
Combination VH and VBF and consider ATLAS ~ CMS Br(H→inv) < 2.5%

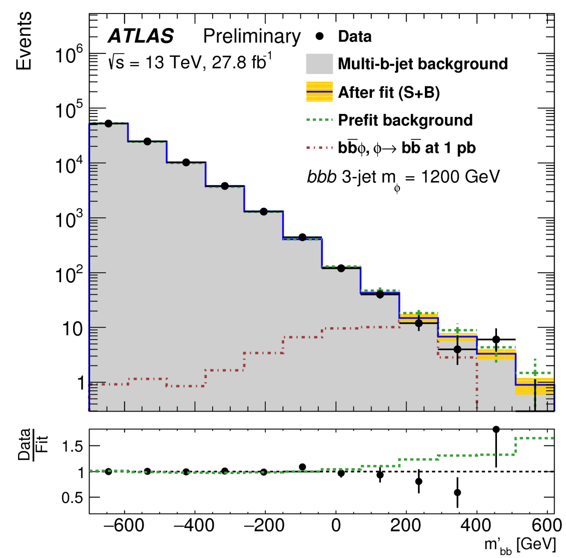
More can be found: HL-LHC YR 1902.00134

BSM Higgs searches: heavy bH(→bb)



Search for heavy neutral Higgs bosons produced in association with b-quarks and decaying to b-quarks with the results interpreted within Two Higgs Doublet Model and the Minimal Supersymmetric SM. (more channels explored: check out arXiv:1901.08144 for bH(→μμ))





More on MSSM Higgs results:

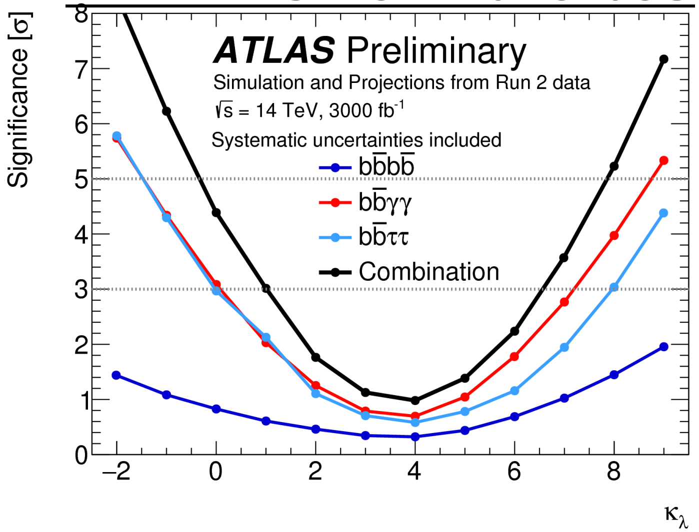
Hττ : JHEP 09 (2018)007 Hμμ: CMS_PAS_HIG_18_010

ATLAS_CONF_2019_010

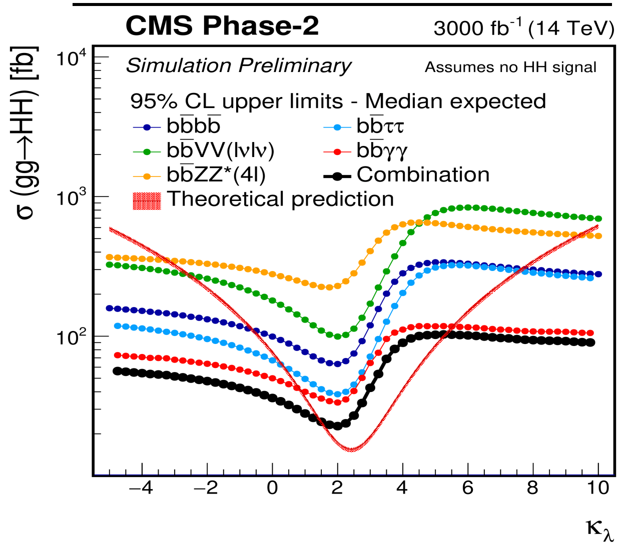
CMS: JHEP 08 (2018) 113

Di-Higgs Prospects at HL-LHC

ATL–PHYS–PUB–2018–053



CMS–PAS–FTR–18–019



- Combine 4b, bbγγ and bbττ (+bbVV from CMS) final states, 3000 fb^{-1} at 14 TeV.
- When neglecting(including) syst.
  - exp. significance 3.5 (3.0) σ
  - the signal strength w.r.t. SM prediction to be measured with an accuracy of 31(40)%. Self-coupling constrained to $-0.1(-0.4) \leq \lambda_{HHH}/\lambda^{SM}_{HHH} \leq 2.7 \cup 5.5 \leq \lambda_{HHH}/\lambda^{SM}_{HHH} \leq 6.9(7.3)$, at 95% CL, and the measured value of $\lambda_{HHH}/\lambda^{SM}_{HHH}$ is expected to be $1.0^{+0.7(+0.9)}_{-0.6(-0.8)}$

Summary

- When there is yet NO lepton collider, (HL-)LHC will remains the only Higgs factory. In the event of a lepton collider, the role still remains despite the new collider would have cleanness ☺

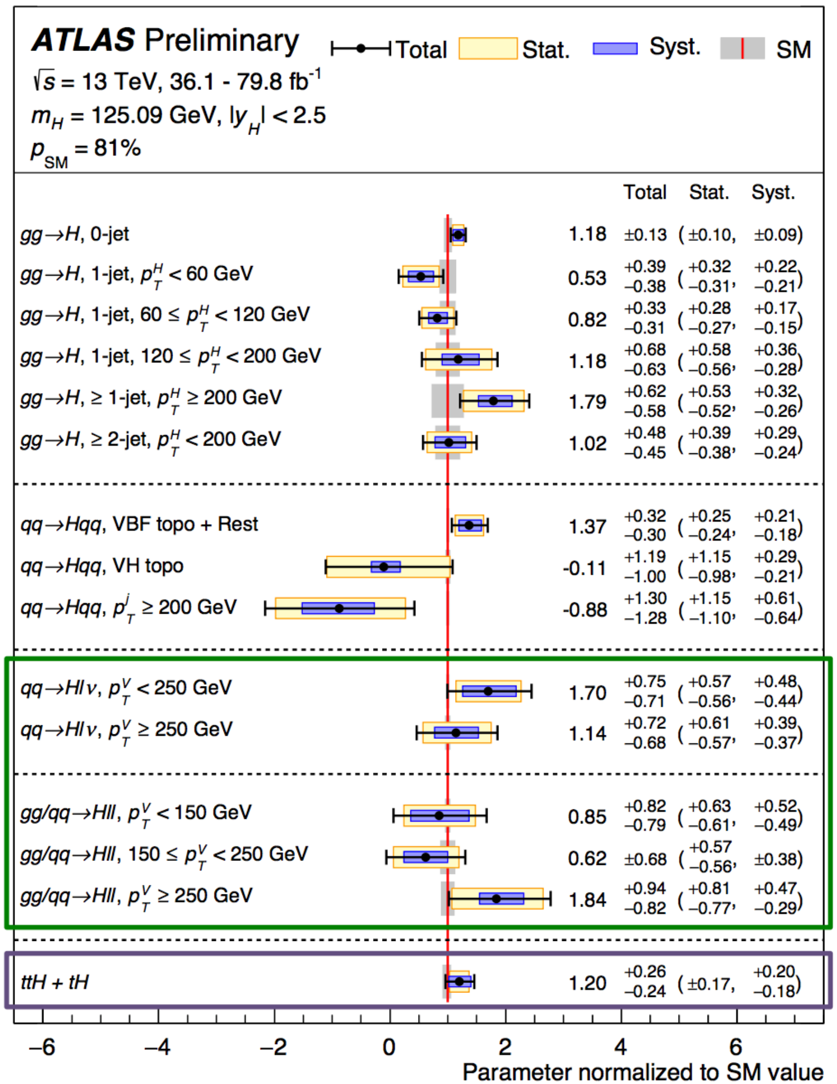
- All SM Higgs measurements perform consistent results w.r.t. predictions within current accuracy (in need of higher precision!), third Generation Yukawa is established and to be continued

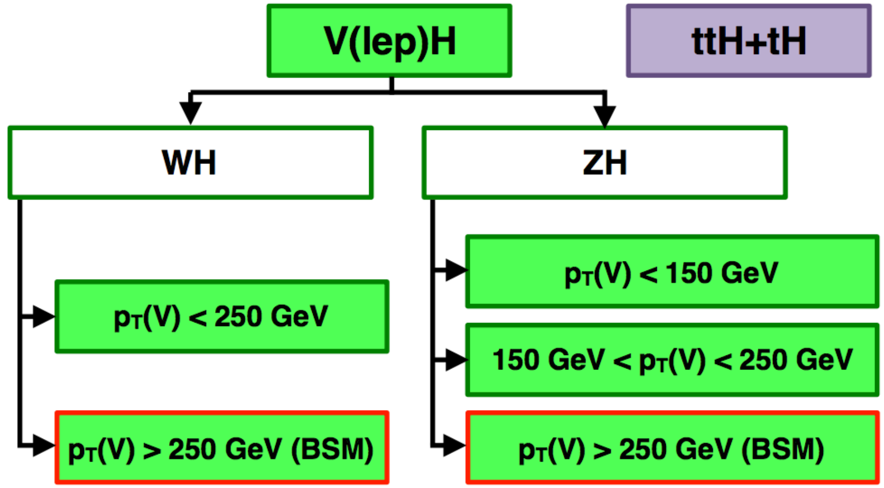
- Active program in both ATLAS and CMS and in between, to improve the measured precisions on cross-sections, couplings, properties and explore the extended BSM scalar sectors

- A lot to cover… tend to be selective to the most recent and general topics latest results (seeing parallel talks for more)

backup

STXS results assuming the SM BRs





- Overall good compatibility with SM (p-value 81%)
- Statistical precision, in particular in most BSM-sensitive regions is still limited: more data will help!

H. Yang
LHC Seminar

H→inv. Combination (NEW!)

Analysis	$\sqrt{s}$	Int. luminosity	Observed	Expected	p_{SM}-value	Reference
Run 2 VBF	13 TeV	36.1 fb^{-1}	0.37	$0.28^{+0.11}_{-0.08}$	0.19	[36]
Run 2 $Z(\mathrm{lep})H$	13 TeV	36.1 fb^{-1}	0.67	$0.39^{+0.17}_{-0.11}$	0.06	[37]
Run 2 $V(\mathrm{had})H$	13 TeV	36.1 fb^{-1}	0.83	$0.58^{+0.23}_{-0.16}$	0.12	[38]
Run 2 Comb.	13 TeV	36.1 fb^{-1}	0.38	$0.21^{+0.08}_{-0.06}$	0.03	this Letter
Run 1 Comb.	$7, 8$ TeV	4.7, 20.3 fb^{-1}	0.25	$0.27^{+0.10}_{-0.08}$	—	[35]
Run 1+2 Comb.	$7, 8, 13$ TeV	$4.7, 20.3, 36.1$ fb^{-1}	0.26	$0.17^{+0.07}_{-0.05}$	0.10	this Letter