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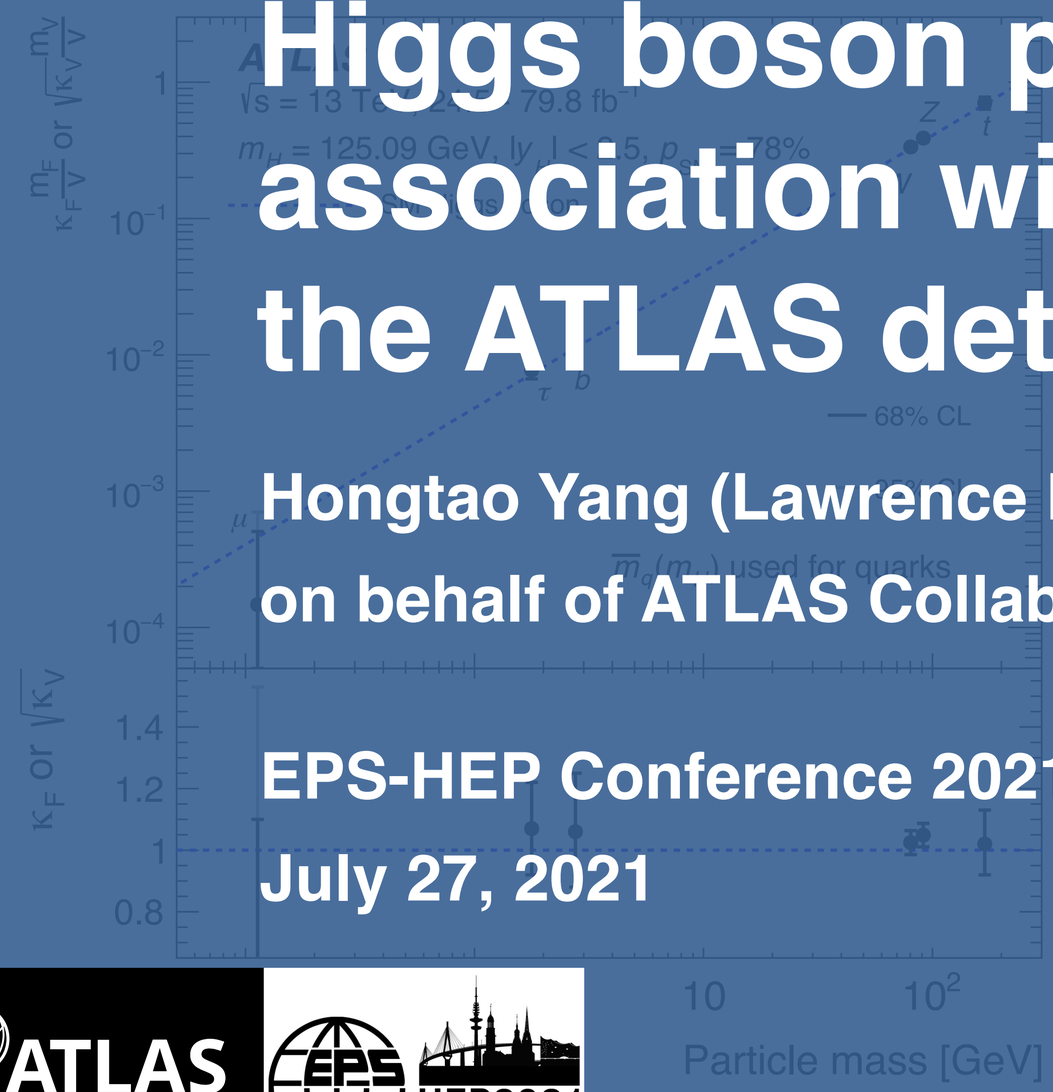
Higgs boson production in association with top quarks with the ATLAS detector

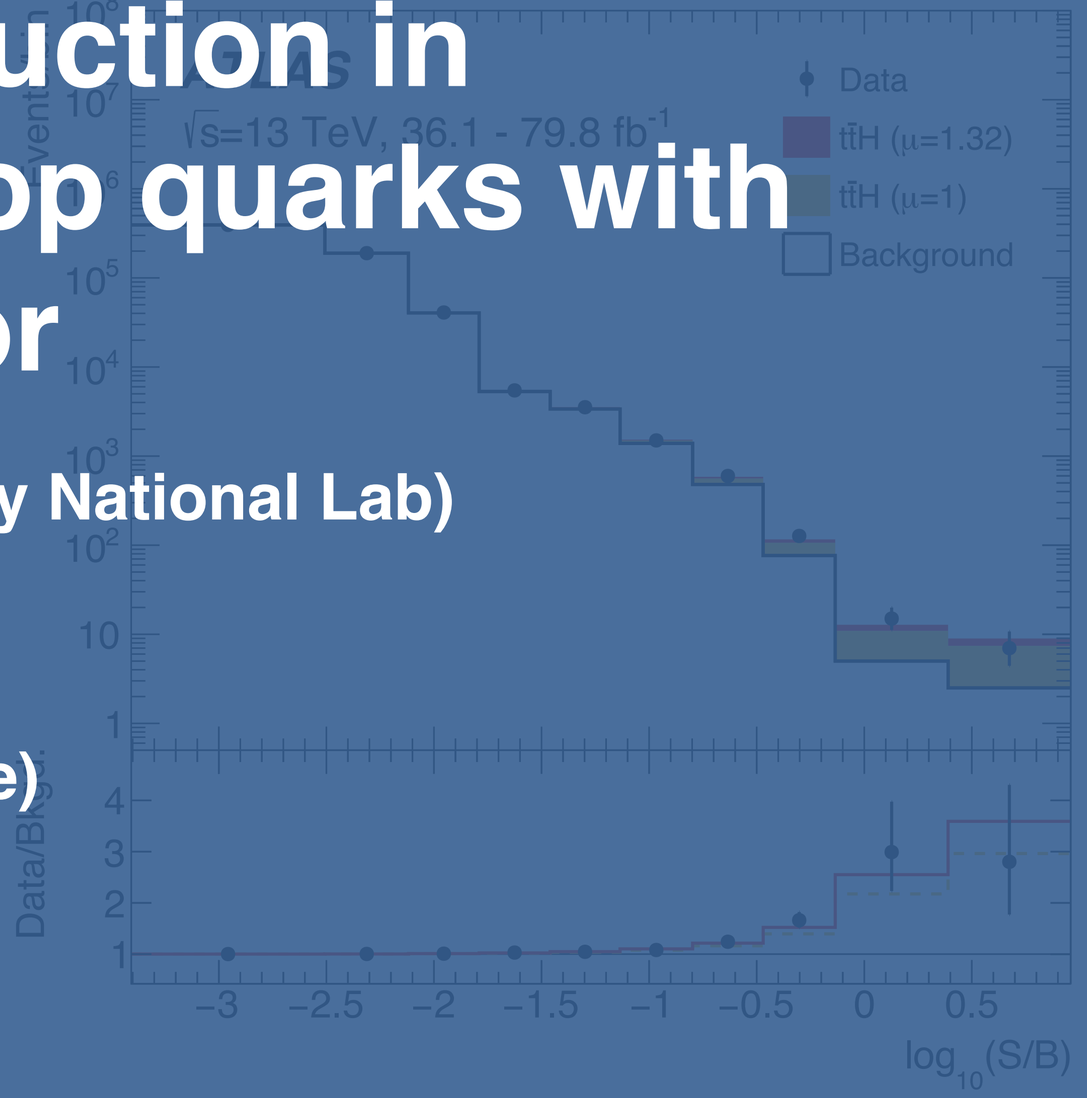
Hongtao Yang (Lawrence Berkeley National Lab)

on behalf of ATLAS Collaboration

EPS-HEP Conference 2021 (online)

July 27, 2021



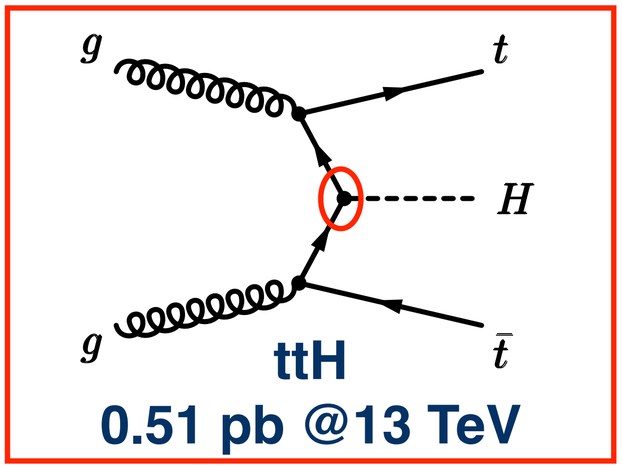


ATLAS EXPERIMENT

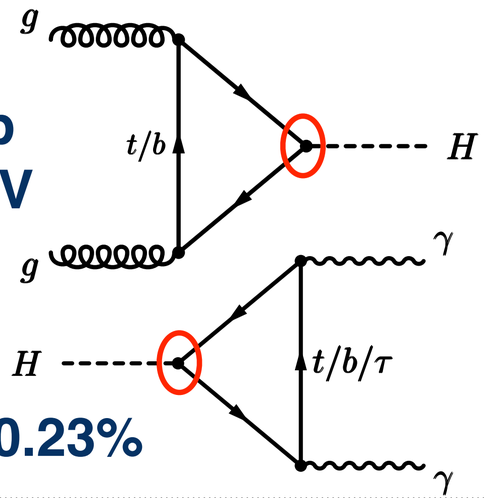
EPS HEP2021 VIRTUAL EDITION

Introduction

- Measurement of **top Yukawa coupling** at LHC is crucial for validating SM and searching for potential new physics
- **ttH/tH production mode** provides a **direct handle** to constrain top Yukawa coupling
  - Indirect constraints from ggF and H→γγ rely on model assumptions

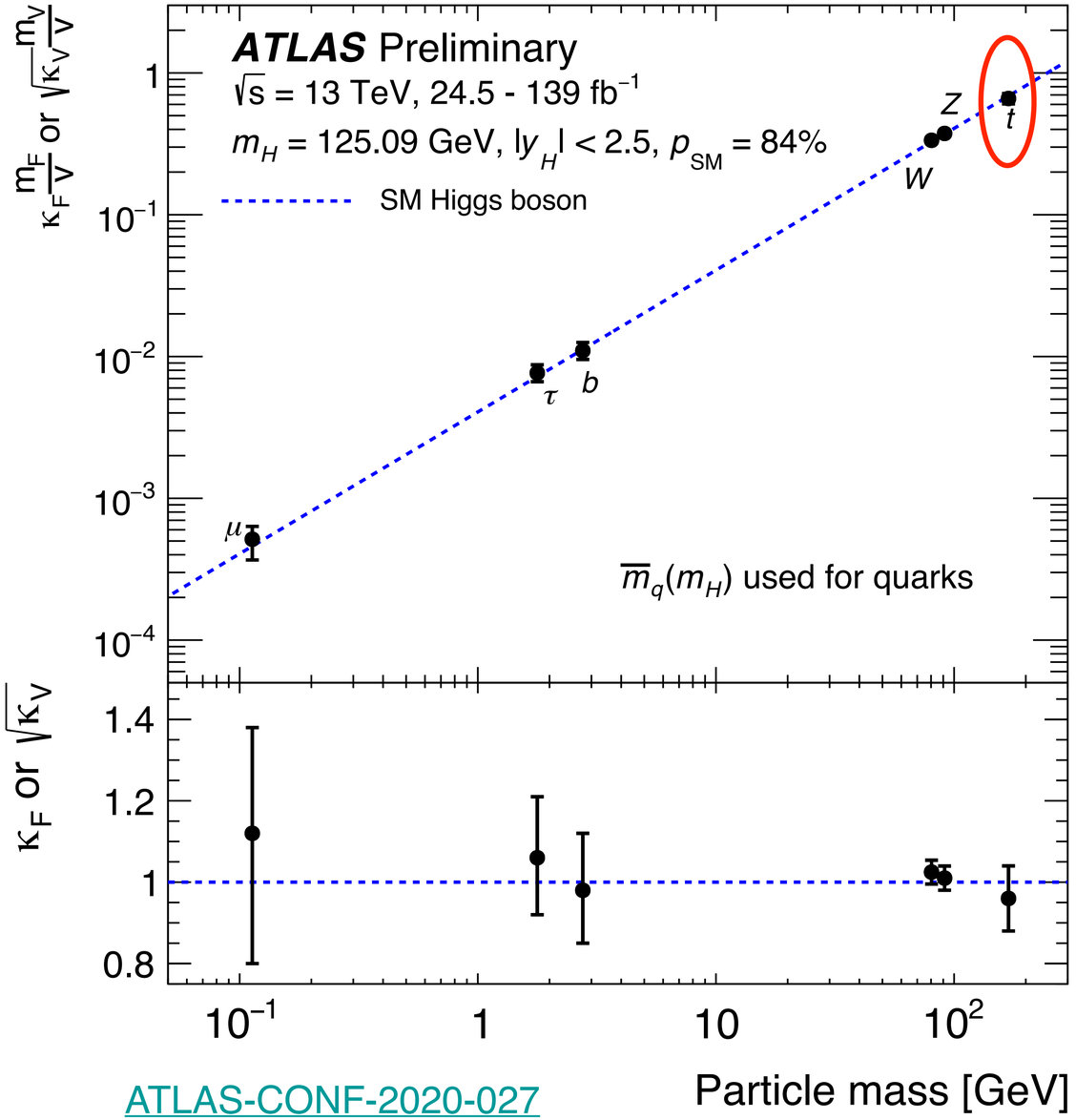


ttH
0.51 pb @13 TeV



ggF
48.5 pb
@13 TeV

H→γγ 0.23%

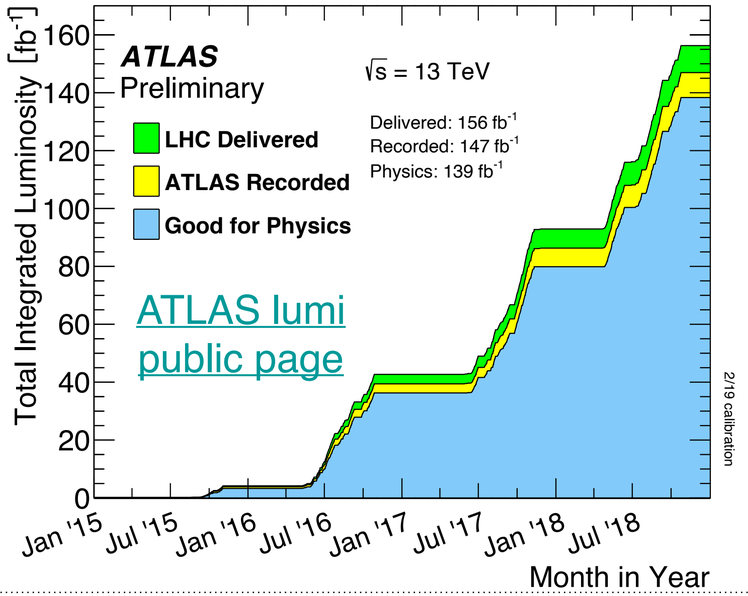


ATLAS-CONF-2020-027

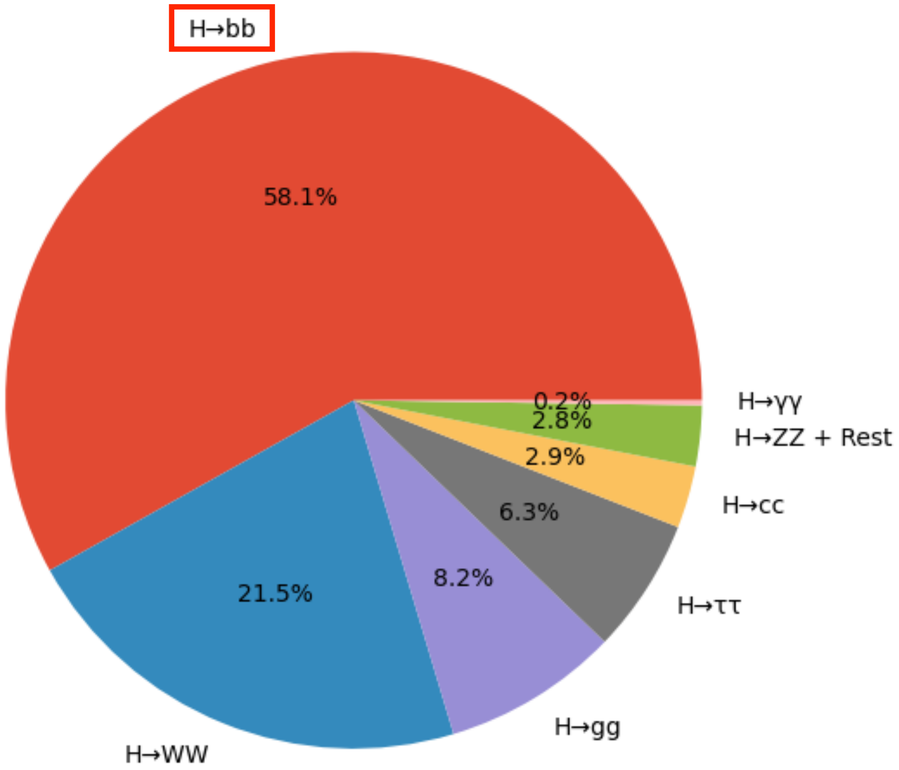
ttH channels

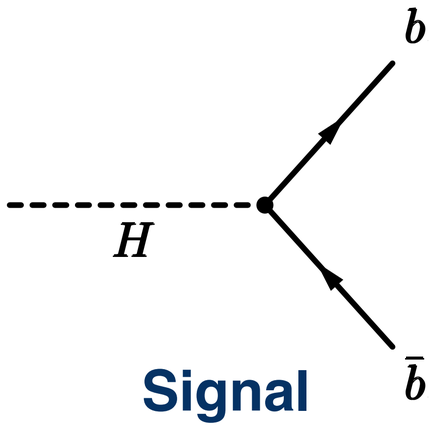
Channel	13 TeV pp dataset	Reference
H→bb	139 fb^{-1} (2015-2018)	ATLAS-CONF-2020-058
H→γγ	139 fb^{-1} (2015-2018)	ATLAS-CONF-2020-026
Combination	Up to 139 fb^{-1}	ATLAS-CONF-2020-027
H→ZZ→4l	139 fb^{-1} (2015-2018)	EPJC 80 (2020) 957
Multi-lepton (H→WW, ZZ, ττ)	80 fb^{-1} (2015-2017)	ATLAS-CONF-2019-045
H→μμ	139 fb^{-1} (2015-2018)	PLB 812 (2021) 135980
H→ττ	139 fb^{-1} (2015-2018)	M. Mlynarikova's talk

- ttH production mode studied in all the major Higgs boson decay channels at LHC
- Today we will focus on H→bb, γγ, as well as multi-channel combination (including H→ZZ→4l) based on **full Run 2 pp dataset collected at 13 TeV!**



ttH, H→bb





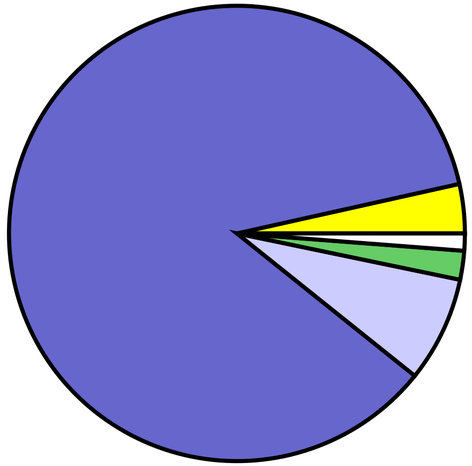
Signal

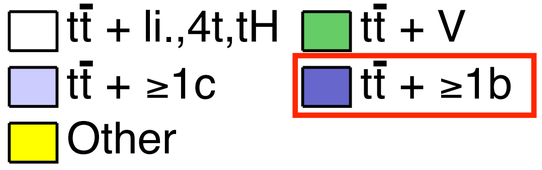
ATLAS Preliminary

$\sqrt{s}$ = 13 TeV

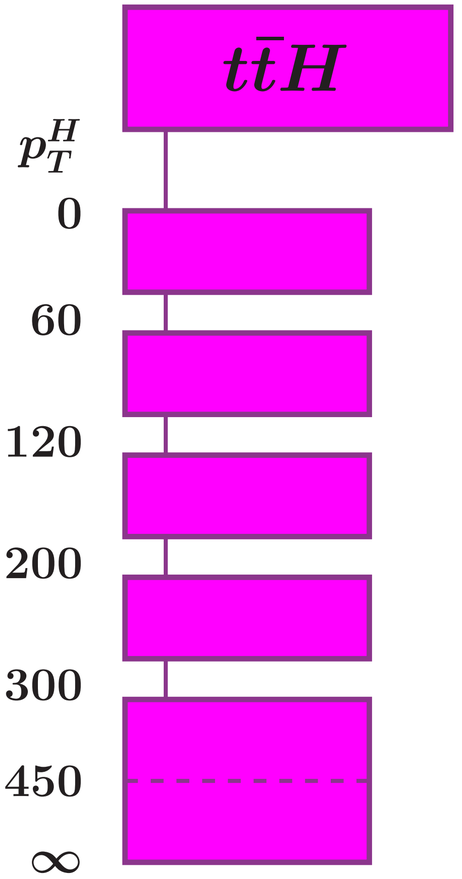
Dilepton ATLAS-CONF-2020-058

$SR^{\geq 4j}_{\geq 4b}$, $p_T^H \in [0,120)$ GeV





Background

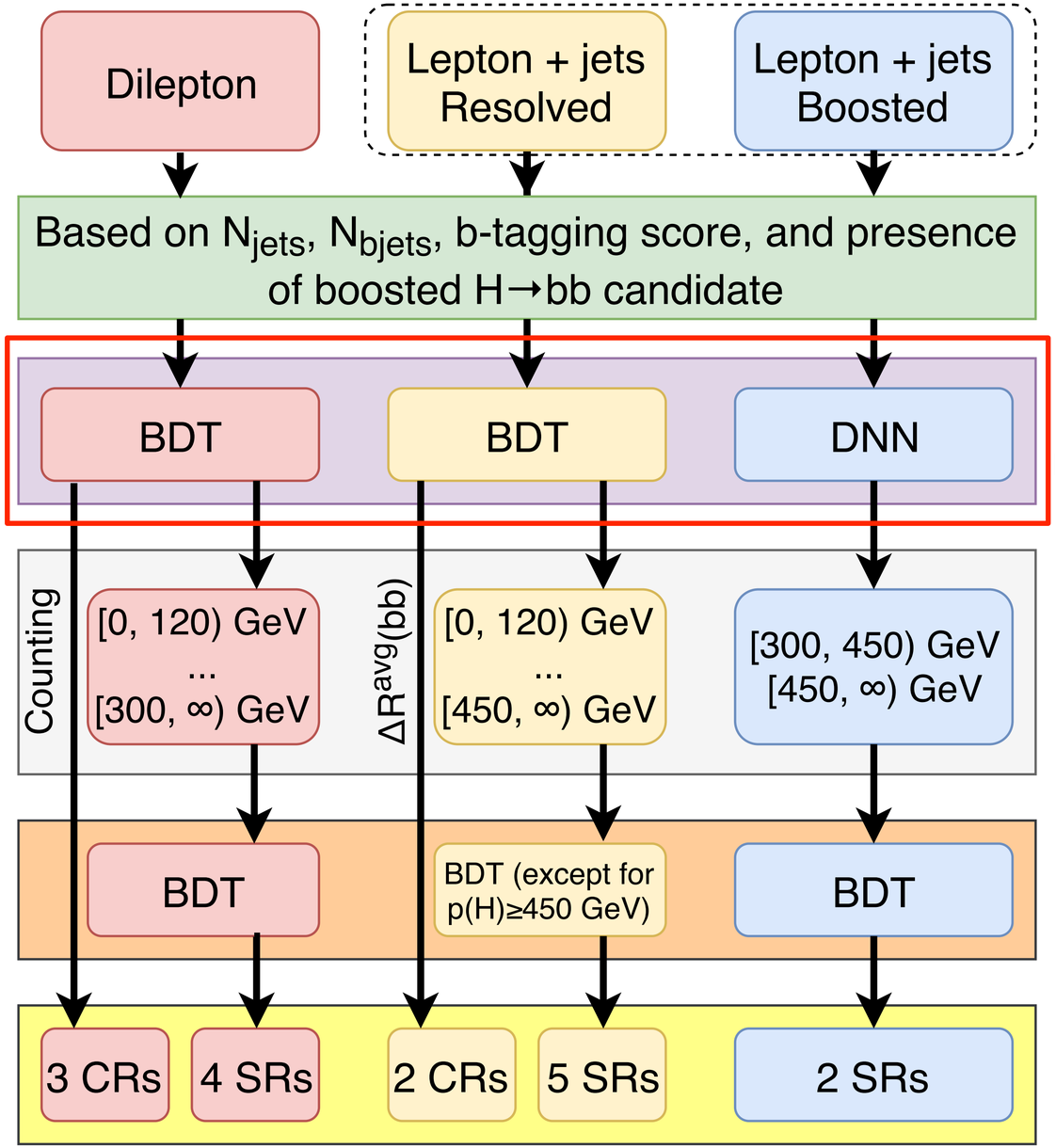


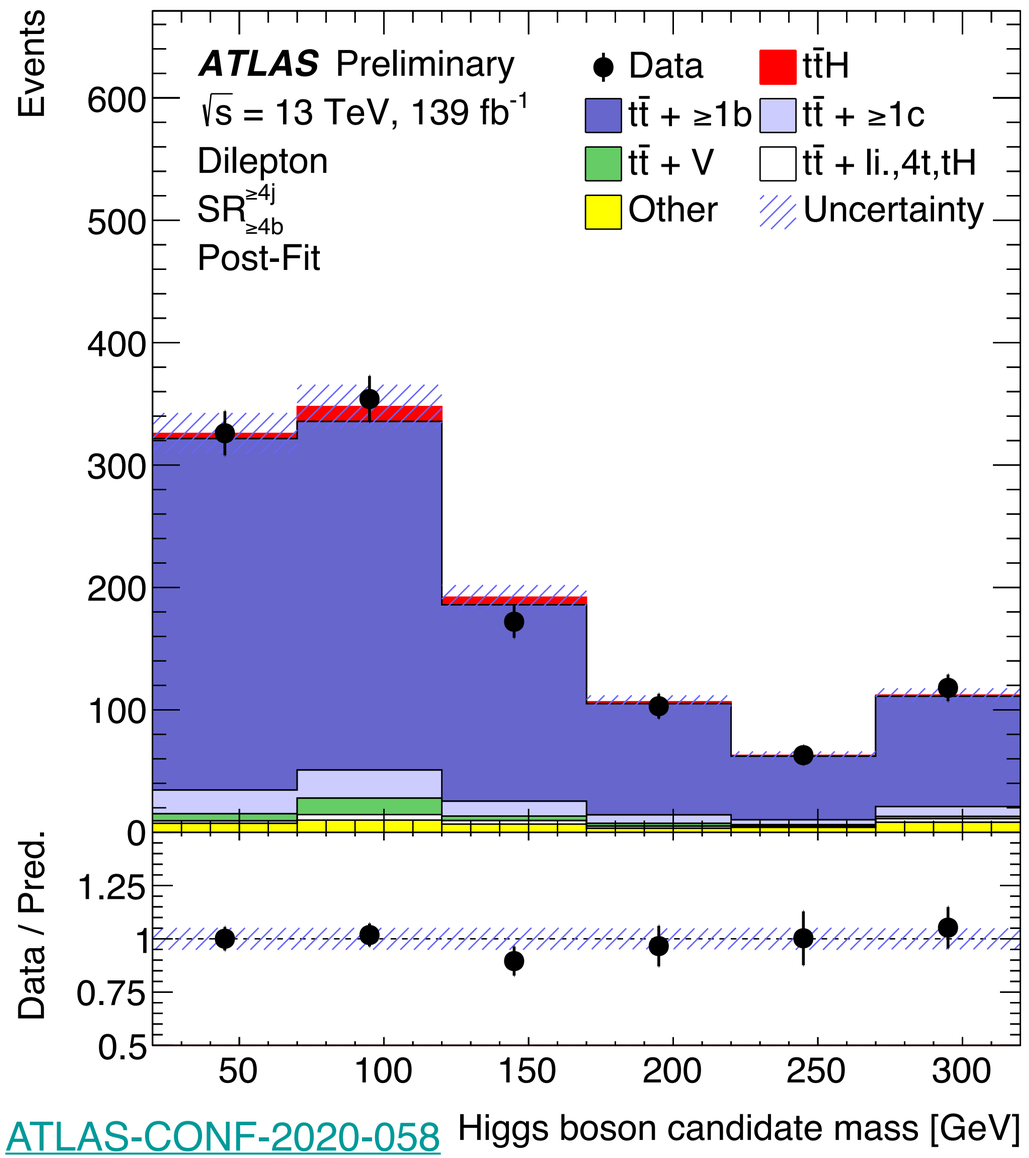
Simplified Template Cross-Section (STXS)

Les Houches 2019

[arXiv:2003.01700 [hep-ph]](arXiv:2003.01700 [hep-ph])

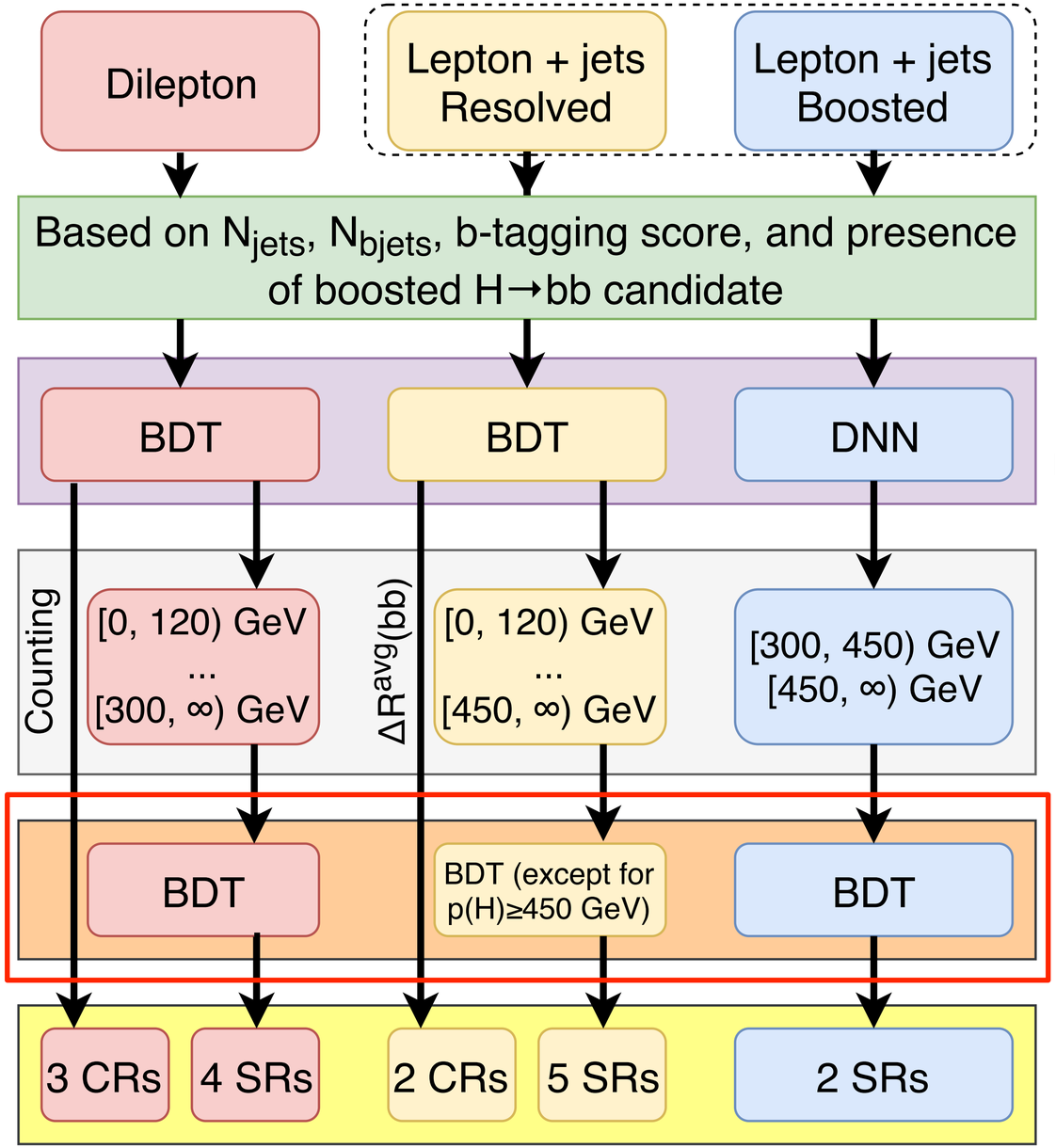
ttH(bb) analysis strategy





ATLAS-CONF-2020-058

ttH(bb) analysis strategy (cont'd)



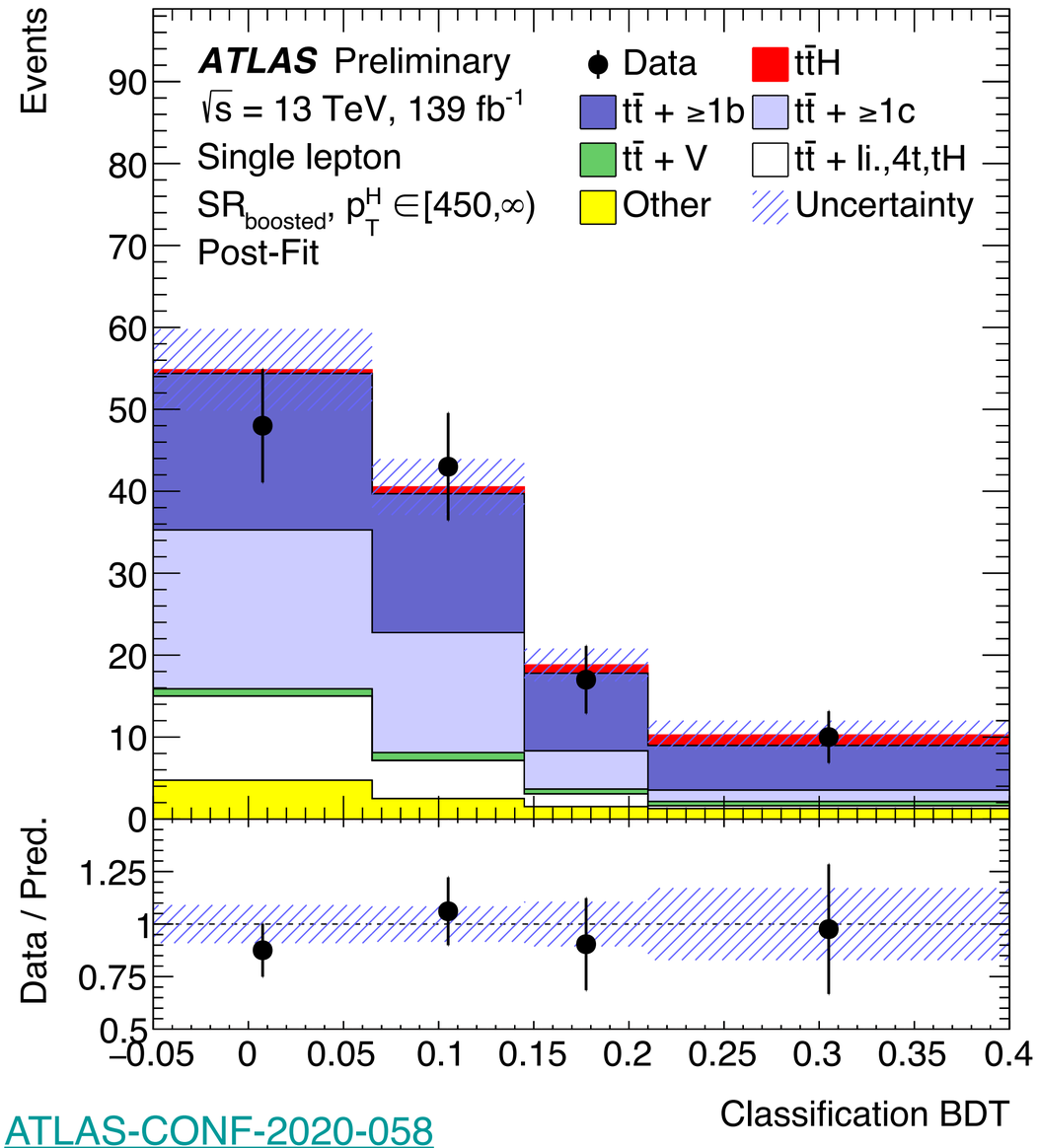
Define signal & control regions

Event reconstruction

Divide in $p_T(H)$ bins according to STXS framework

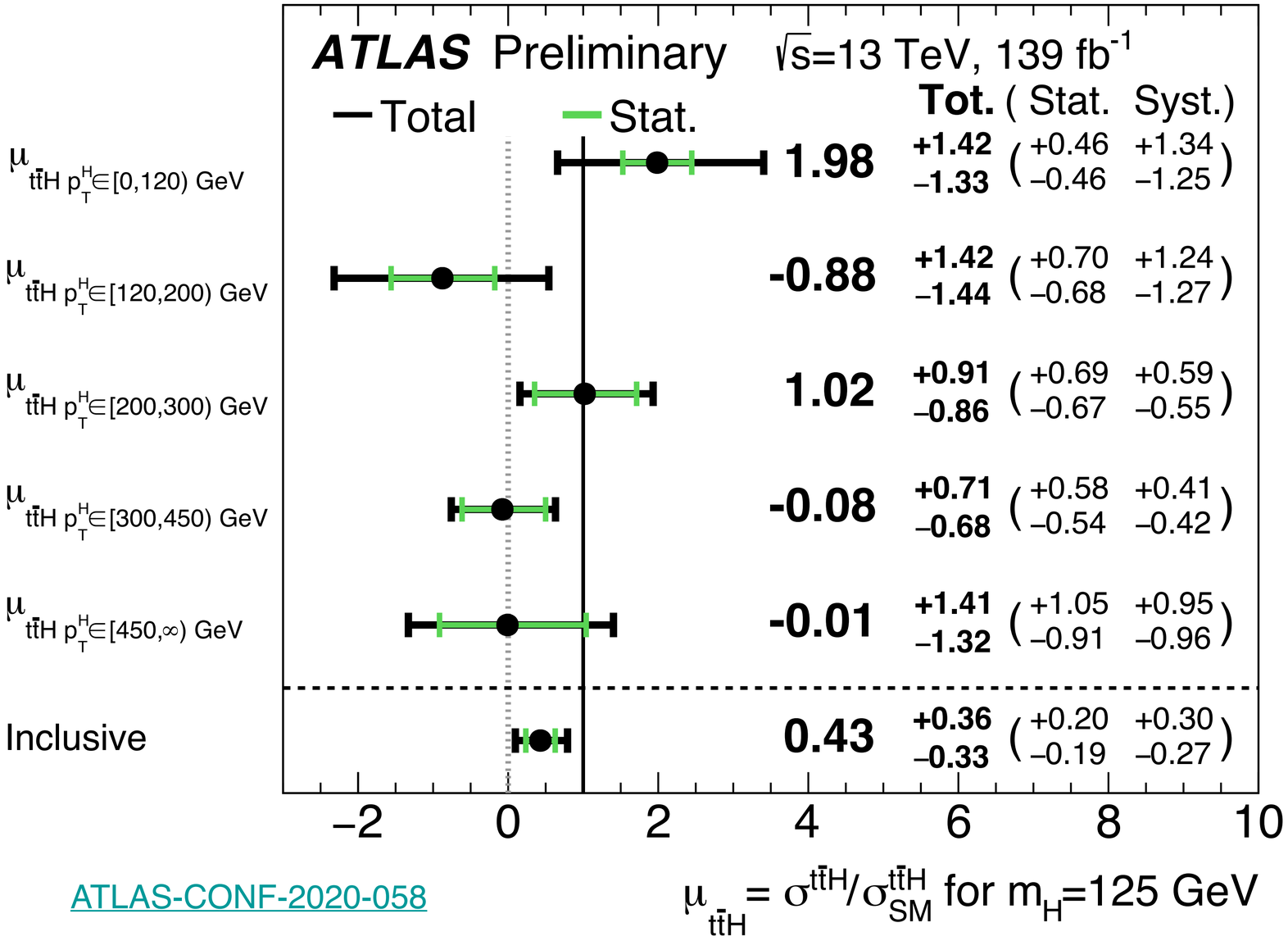
Event classification

Final categories



ATLAS-CONF-2020-058

ttH(bb) results

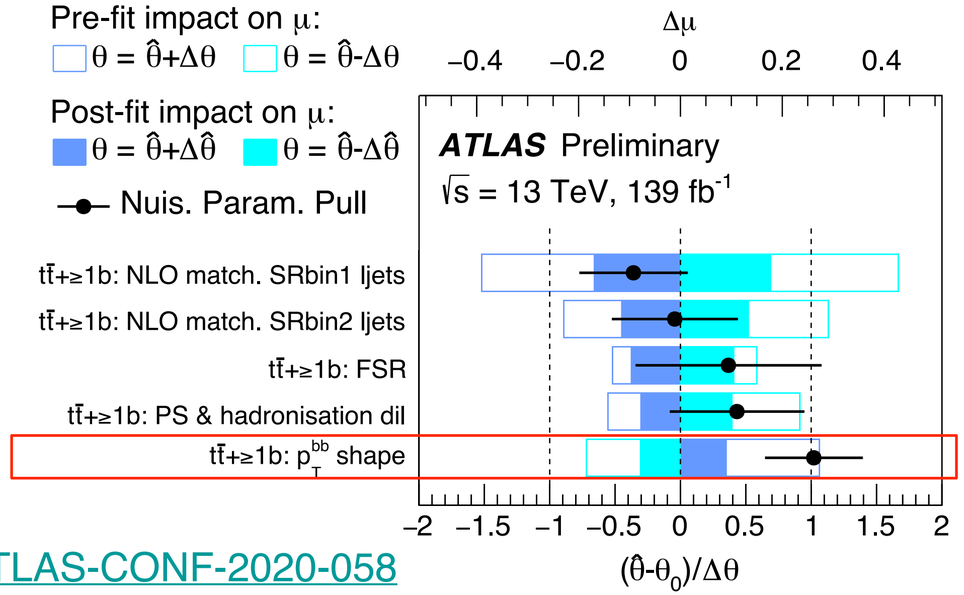


ATLAS-CONF-2020-058

- Observed significance 1.3σ (expected 3.0σ)
- **First STXS measurement in ttH(bb) channel!**
- Inclusive signal strength measurement dominated by systematic uncertainty
  - Uncertainty reduced by almost factor of two compared with analysis based on 36 fb^{-1} partial Run 2 dataset (PRD 97 (2018) 072016)

ttH(bb) systematic uncertainties

Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modelling	+0.25	−0.24
$t\bar{t}H$ modelling	+0.14	−0.06
tW modelling	+0.08	−0.08
b-tagging efficiency and mis-tag rates	+0.05	−0.05
Background-model statistical uncertainty	+0.05	−0.05
Jet energy scale and resolution	+0.03	−0.03
$t\bar{t}+\geq 1c$ modelling	+0.03	−0.03
$t\bar{t}+$ light modelling	+0.02	−0.02
Luminosity	+0.01	−0.00
Other sources	+0.03	−0.03



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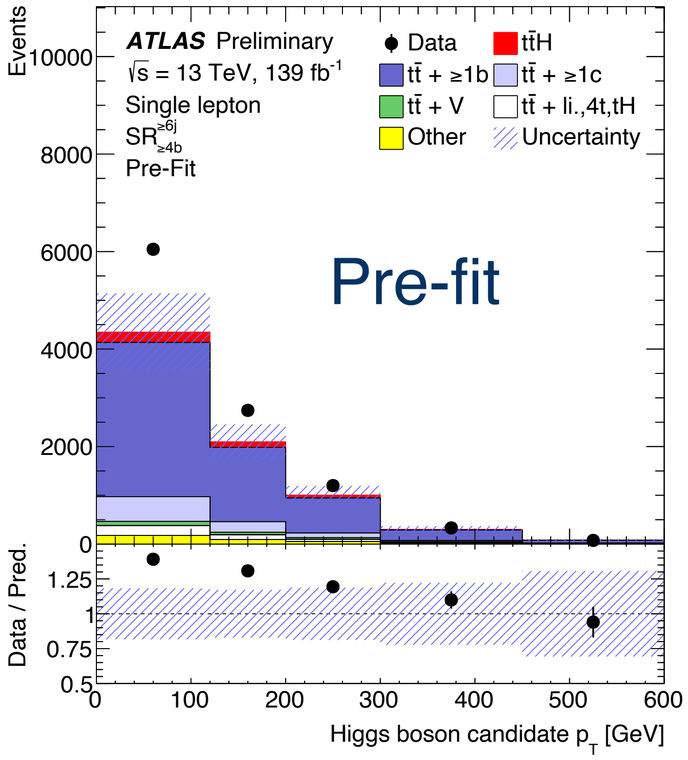
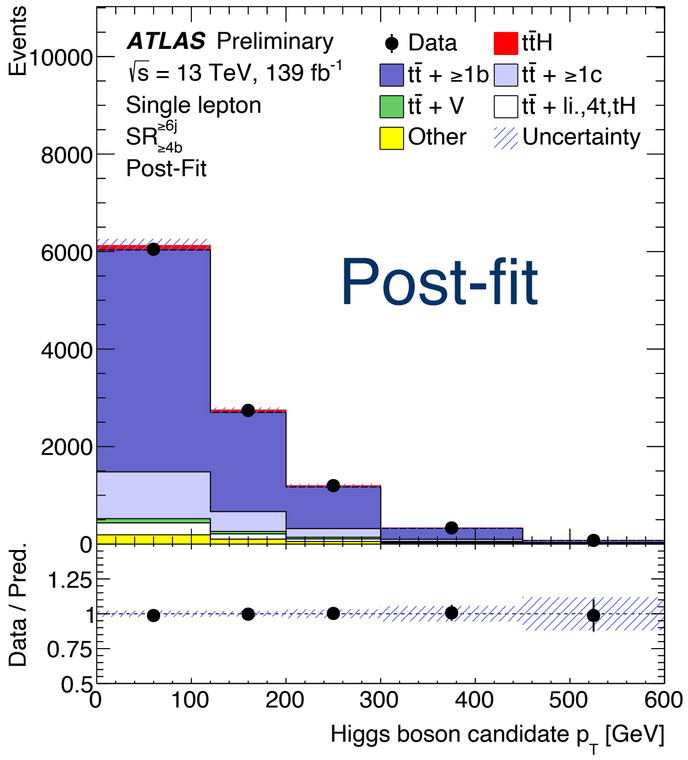
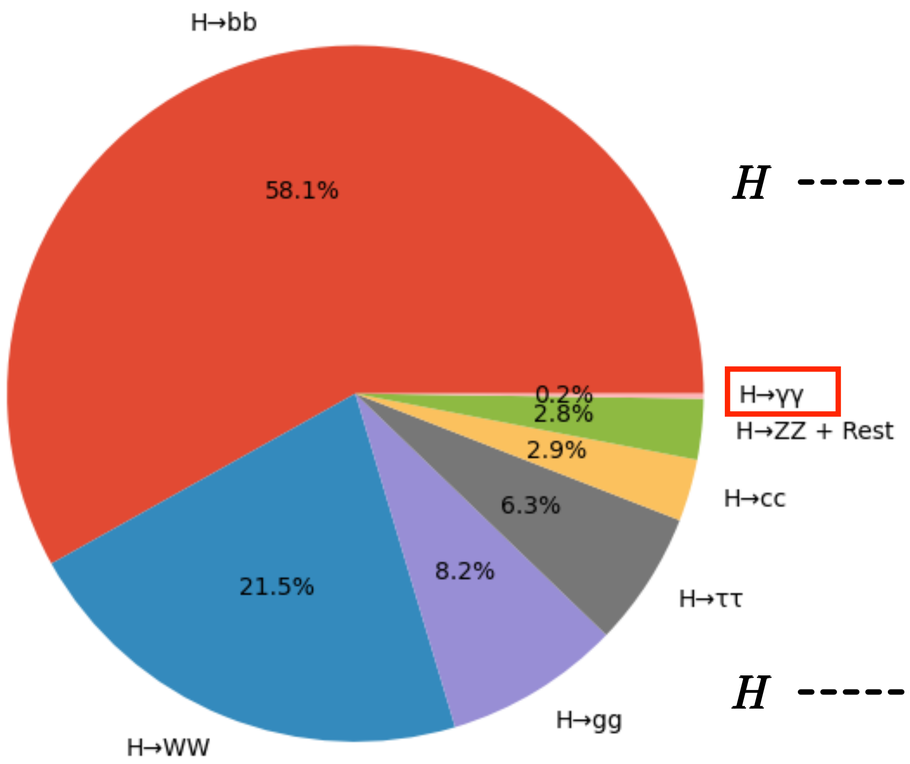
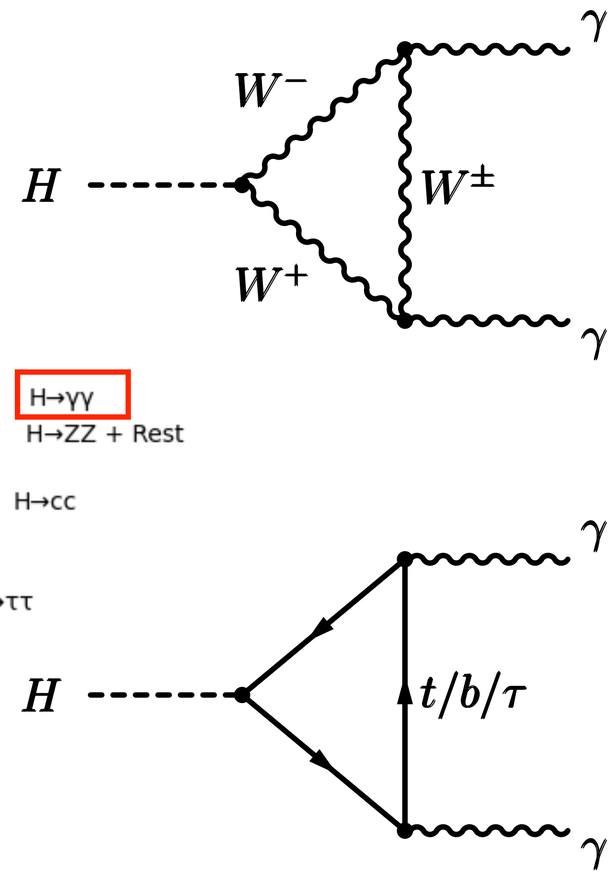




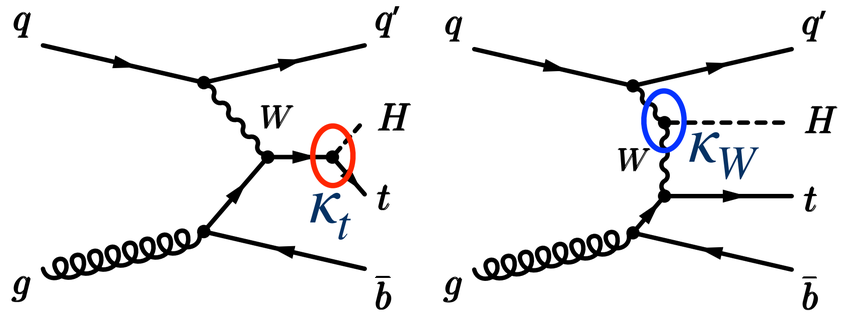
- $t\bar{t}+\geq 1b$ process modeled with **PowhegBoxRes & OpenLoops + Pythia8** in **4-flavor scheme**: $\mu_R = \sqrt[4]{m_T(t)\cdot m_T(\bar{t})\cdot m_T(b)\cdot m_T(\bar{b})}$ and $\mu_F = 0.5\times\sum_{i=t,\bar{t},b,\bar{b},j} m_T(i)$
  - Normalization decided as a free parameter by data: $k(t\bar{t}+\geq 1b) = 1.26\pm 0.09$
- Leading uncertainties from two-point $t\bar{t}+\geq 1b$ PowhegBox + Pythia8 vs. MG5_aMC + Pythia8 NLO matching (uncorrelated between p_T(H) bins)
- Additional uncertainty to cover p_T(H) mis-modeling

ttH/tH, H→γγ

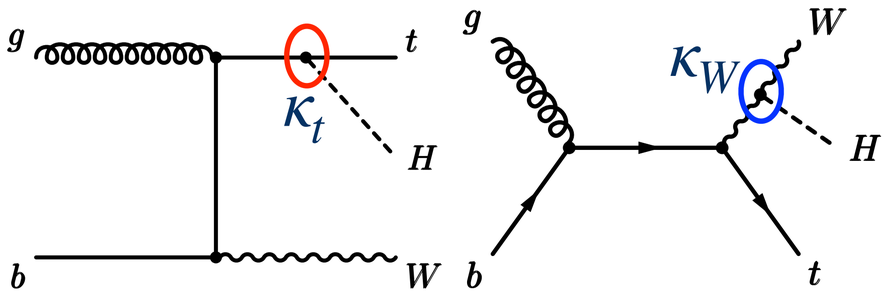




tHqb



tHW



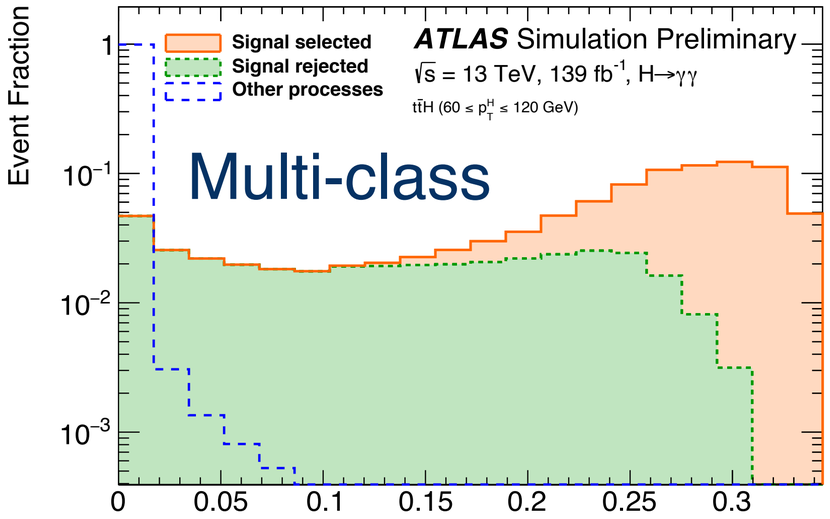
tH

0.09 pb @13 TeV

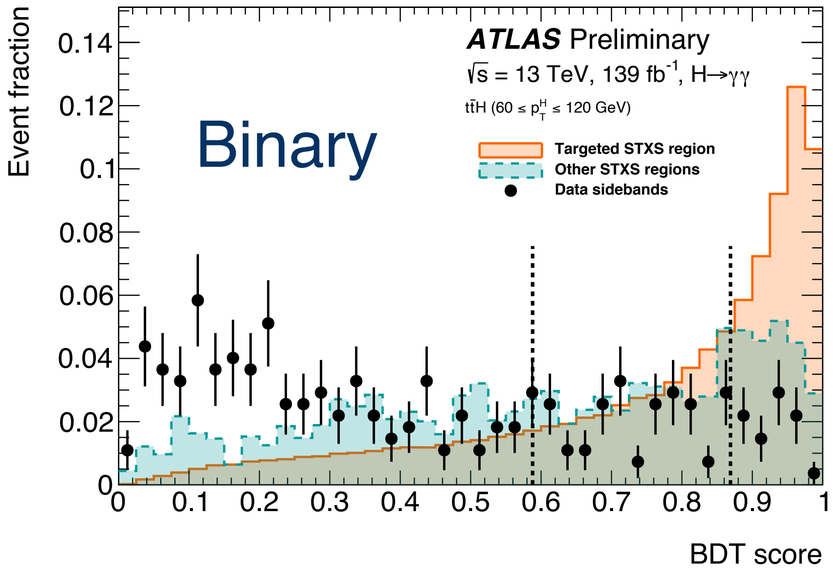
- Excellent sensitivity thanks to good photon energy resolution
- No combinatorics issue in H reconstruction

- Distinguish relative sign of top Yukawa coupling (w.r.t. W-H coupling) using **tH production process**

ttH/tH(γγ) analysis strategy



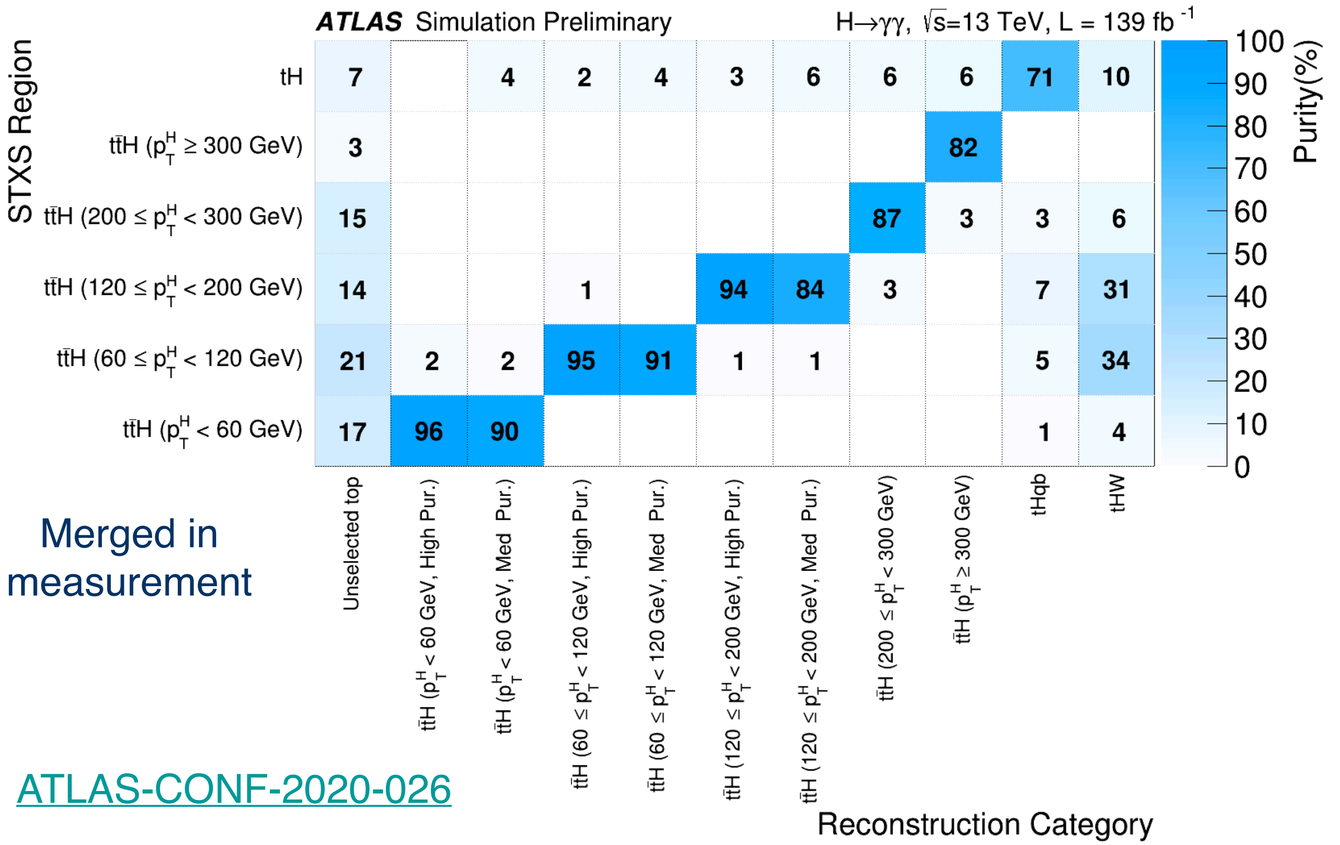
ATLAS-CONF-2020-026



- **Multi-class BDT** trained to divide Higgs boson signal into different STXS bins
  - Use kinematics of diphoton system, N_{jet}, N_{bjet}, N_{lepton}, N_{top}, jet kinematics…
- **Binary BDT** trained to isolate out targeted signal from continuum background
  - Use four-vector of photons/jets/leptons, b-tagging scores of jets, top quark reconstruction BDT etc.
- Define final analysis categories by cutting on Binary BDT. Fit $m_{\gamma\gamma}$ spectrum to extract signal

Categorization

Category	S_{90}	B_{90}	S/(S+B)	Z
$p_T(H) < 60$ GeV High	3.2	5.0	0.39	1.3
$p_T(H) < 60$ GeV Med	3.5	15	0.18	0.8
$60 \le p_T(H) < 120$ GeV High	5.1	4.3	0.54	2.1
$60 \le p_T(H) < 120$ GeV Med	3.7	10	0.26	1.1
$120 \le p_T(H) < 200$ GeV High	6.1	3.8	0.62	2.6
$120 \le p_T(H) < 200$ GeV Med	3.1	8.1	0.28	1.0
$200 \le p_T(H) < 300$ GeV	4.6	1.7	0.73	2.7
$p_T(H) \ge 300$ GeV	3.6	1.0	0.78	2.6
tHW	0.80	2.4	0.25	0.5
tHqb	0.88	2.7	0.24	0.5
Other	11	120	0.08	1.0

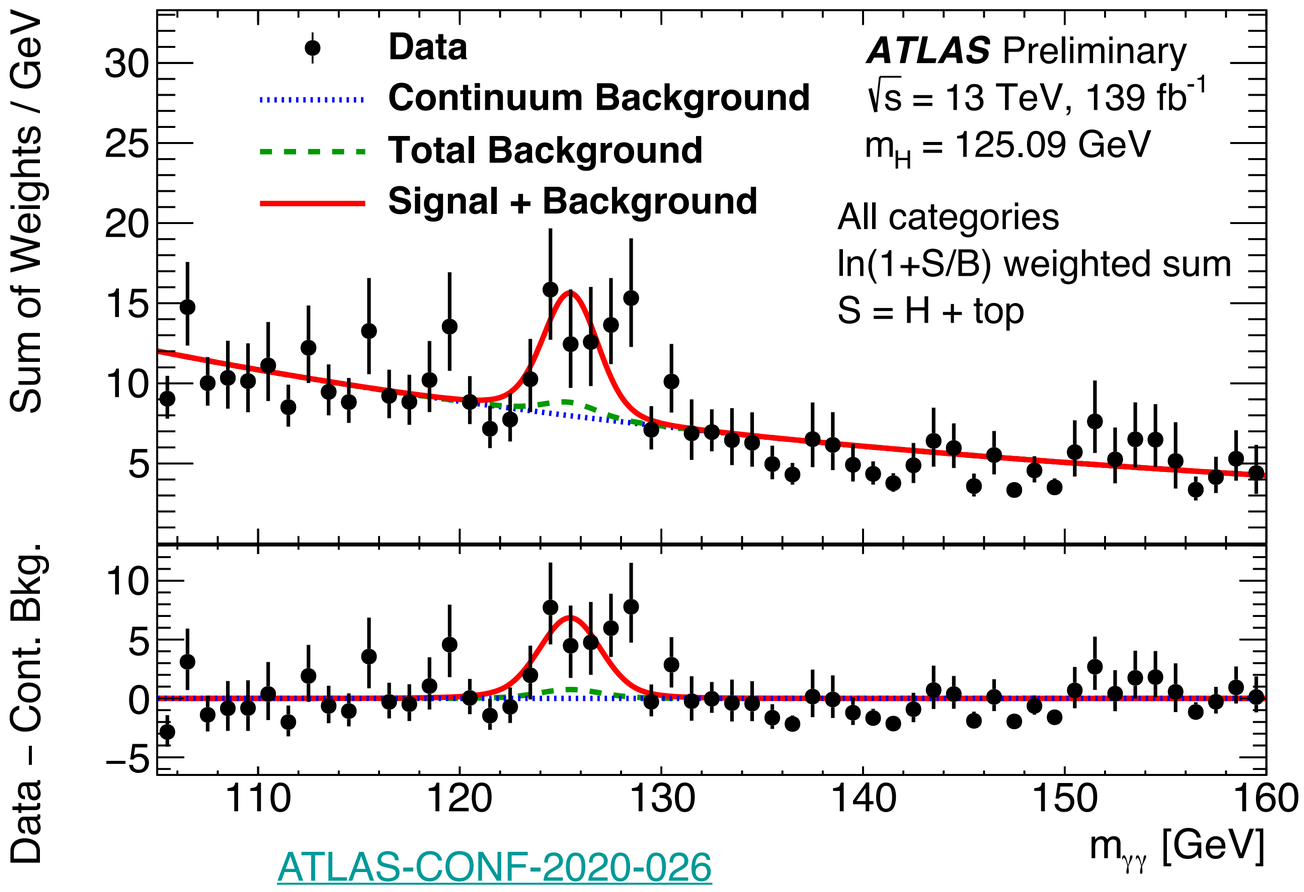


Merged in measurement

ATLAS-CONF-2020-026

- High S/(S+B) and good purity of targeted ttH/tH STXS regions
  - Higgs boson candidate p_T can be reconstructed with high resolution in the diphoton channel
- Sensitivity mostly contributed by high binary BDT categories

ttH/tH(γγ) results



ATLAS-CONF-2020-026

Uncertainty source	Δσ(ttH+tH) [%]
Photon energy resolution	±4.9
Underlying event and parton shower	±3.5
Jet/missing ET	±3.0
Photon efficiency	±2.4
Background modeling	±2.4
Luminosity and trigger	±2.3
Photon energy scale	±2.2
Higgs boson mass	±1.9
Modeling of heavy flavor jets in non-ttH process	±1.3
Pileup	±1.1

- ttH+tH observed significance 4.7σ (exp. 5.0σ)
- $\sigma(ttH+tH)/\sigma_{SM} = 0.92^{+0.25}_{-0.23}\,(\text{Stat.})^{+0.09}_{-0.07}\,(\text{Syst.})$

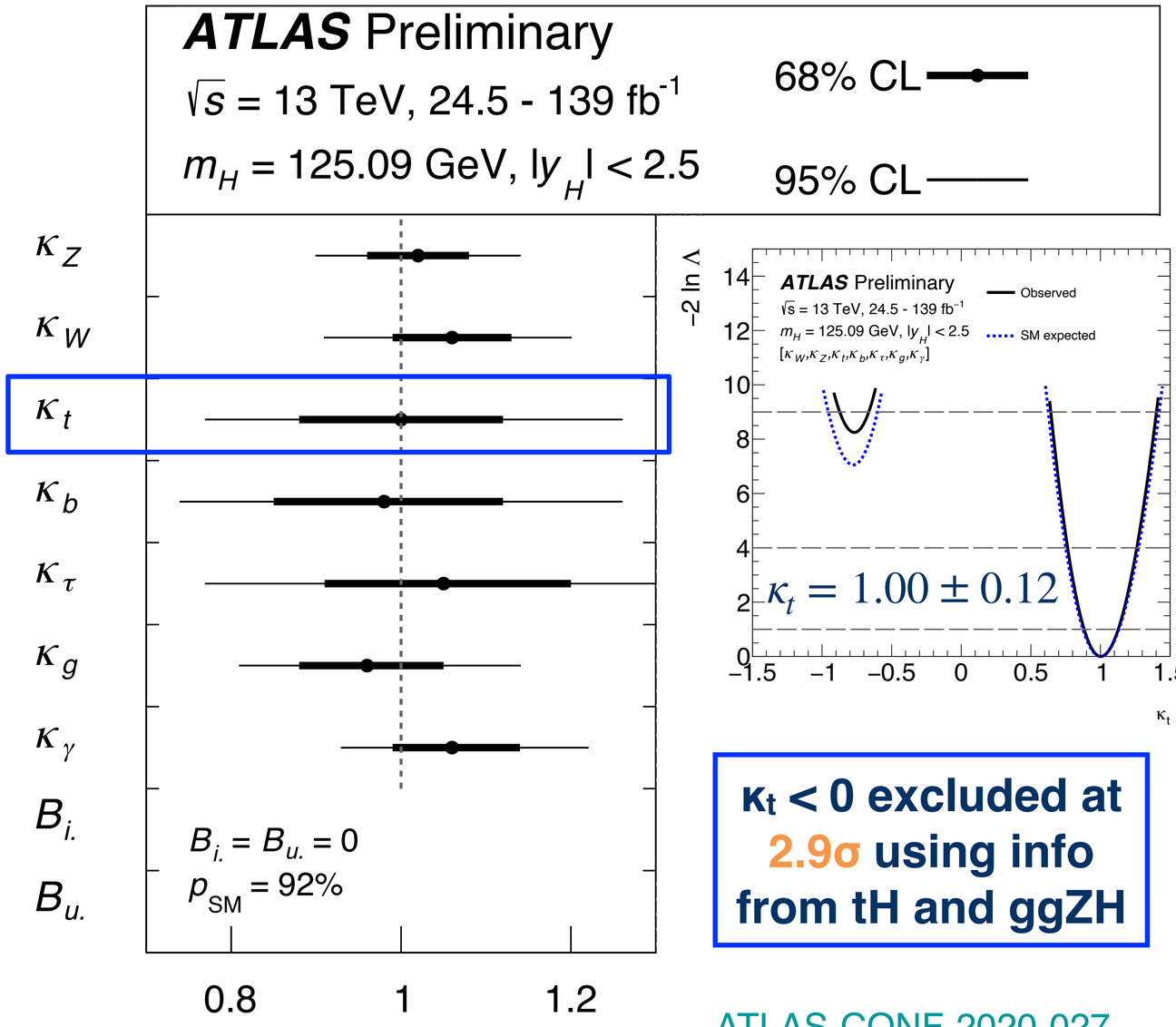
- $\sigma(tH) < 8 \times \sigma_{SM}$ @95% confidence level
- Cross-sections of other production modes decided by data in other analysis categories

Combination of multiple decay channels

Channel	ggF	VBF	VH	ttH
H→γγ (139 fb^{-1})	✔	✔	✔	✔
H→ZZ (139 fb^{-1})	✔	✔	✔	✔
H→WW (36 fb^{-1})	✔	✔		✔
H→ττ (36 fb^{-1})	✔	✔		✔
H→bb (VH 139 fb^{-1}, others 36 fb^{-1})		✔	✔	✔
H→μμ (139 fb^{-1})	✔	✔	✔	✔
H→inv. (139 fb^{-1})		✔		

- **ttH, H→γγ** (ATLAS-CONF-2020-026) and **H→ZZ→4l** (EPJC 80, 957 (2020)) measurements based on **139 fb^{-1} full Run 2 dataset** and provide **STXS measurements**
- **ttH, H→bb** (PRD 97 (2018) 072016) and **multi-lepton** (PRD 97 (2018) 072003) measurements in this combination use only 36 fb^{-1} partial Run 2 dataset, and provide only inclusive measurements

Test of top Yukawa coupling strength



$\kappa_t < 0$ excluded at 2.9σ using info from tH and ggZH

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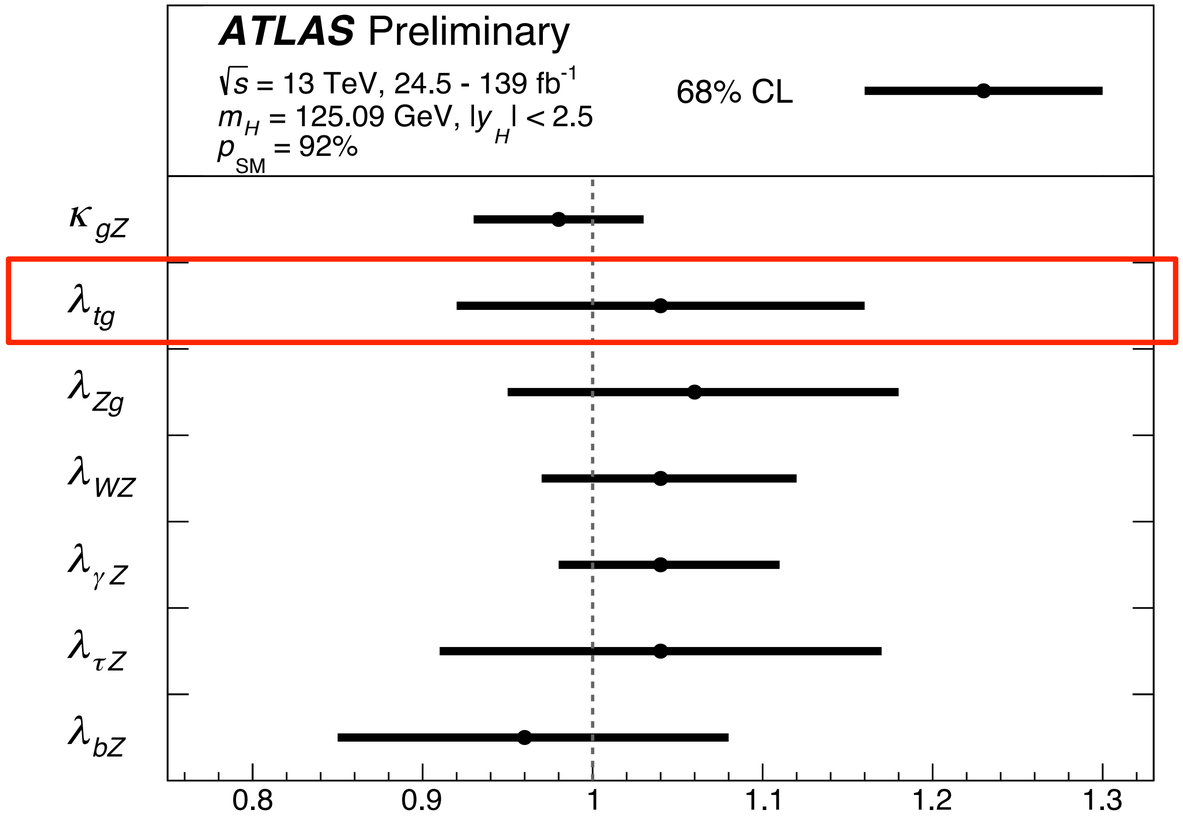
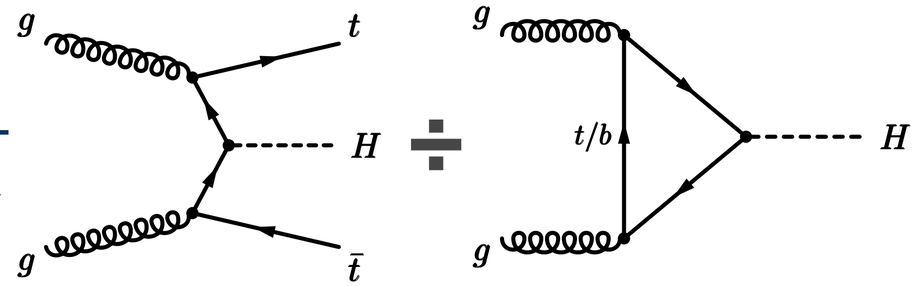
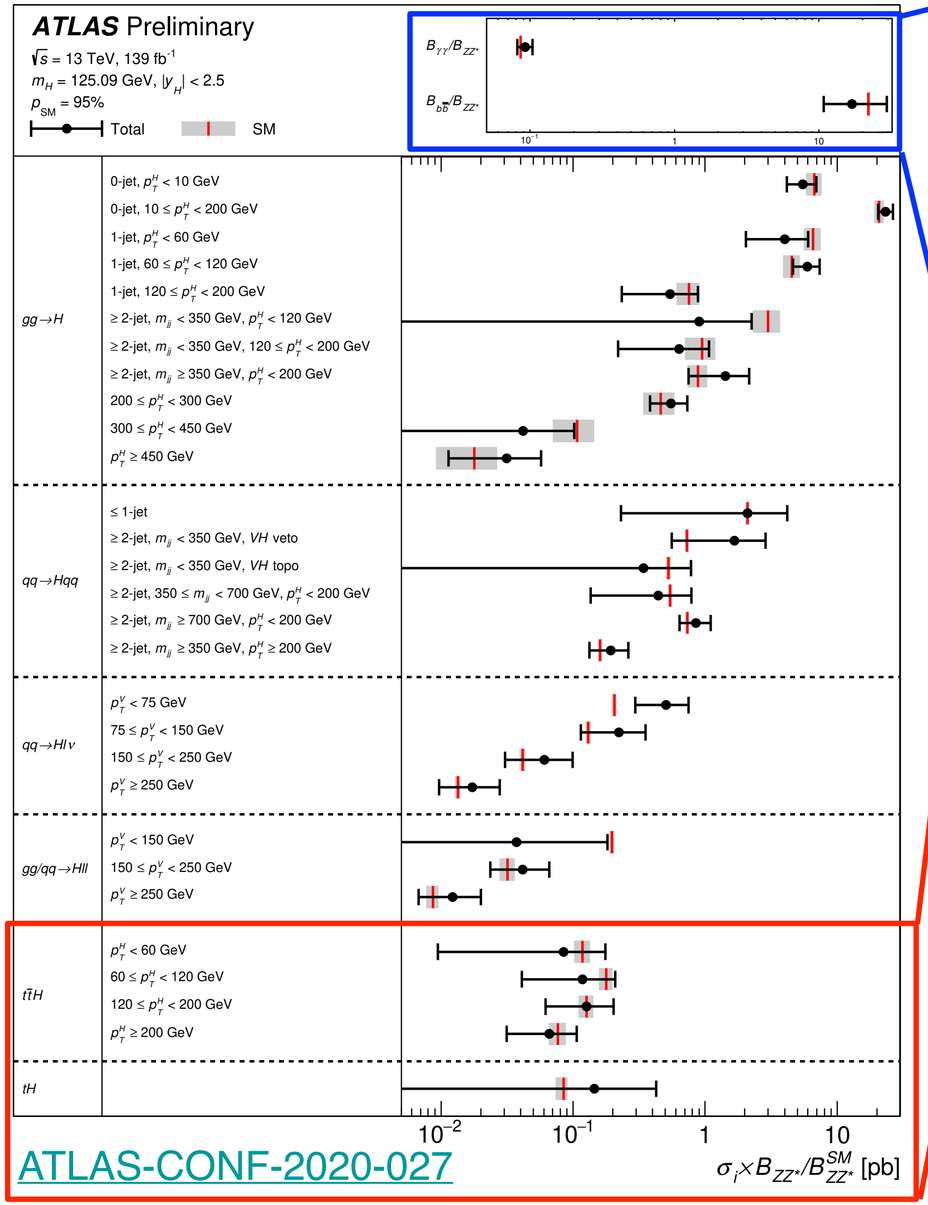


$$\lambda_{tg} = \frac{\kappa_t}{\kappa_g}$$



STXS measurements



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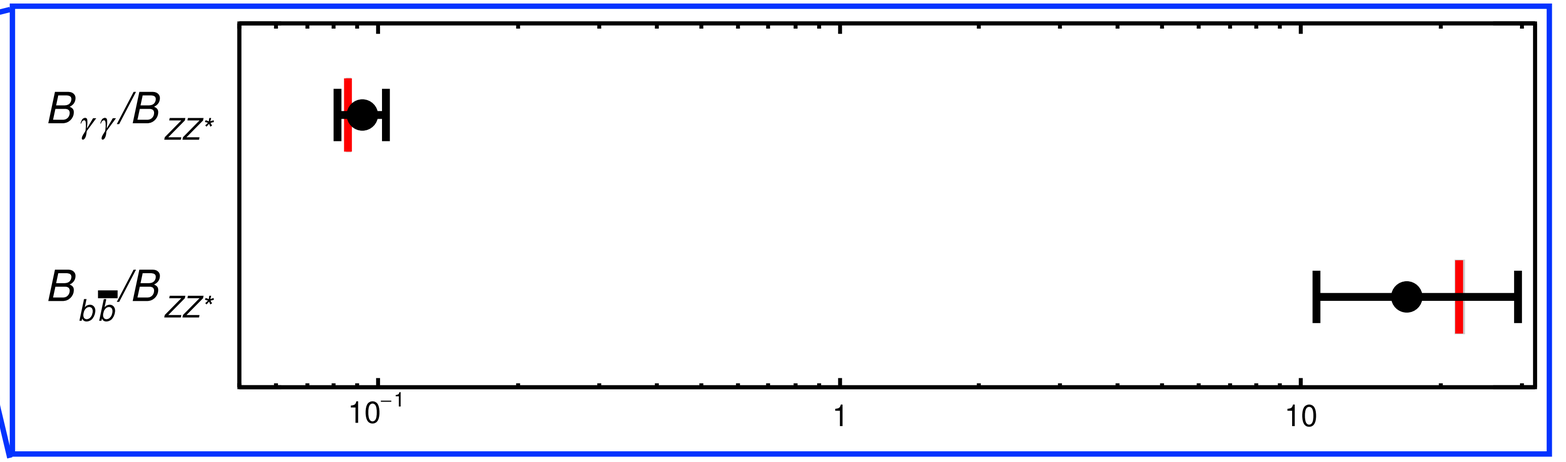
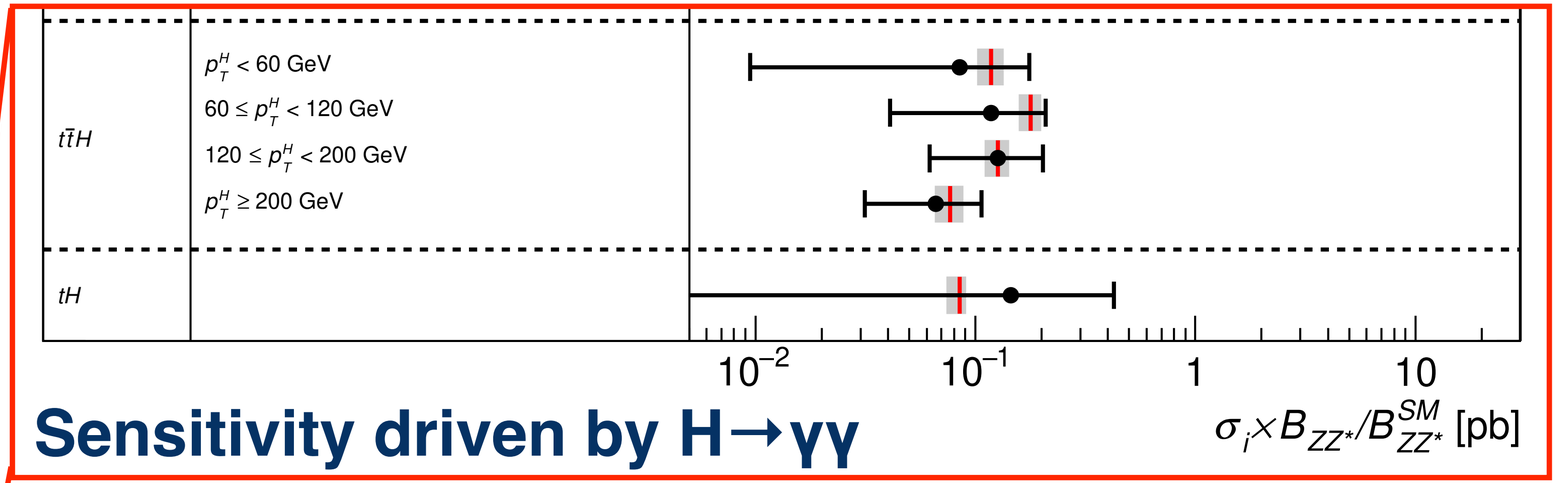


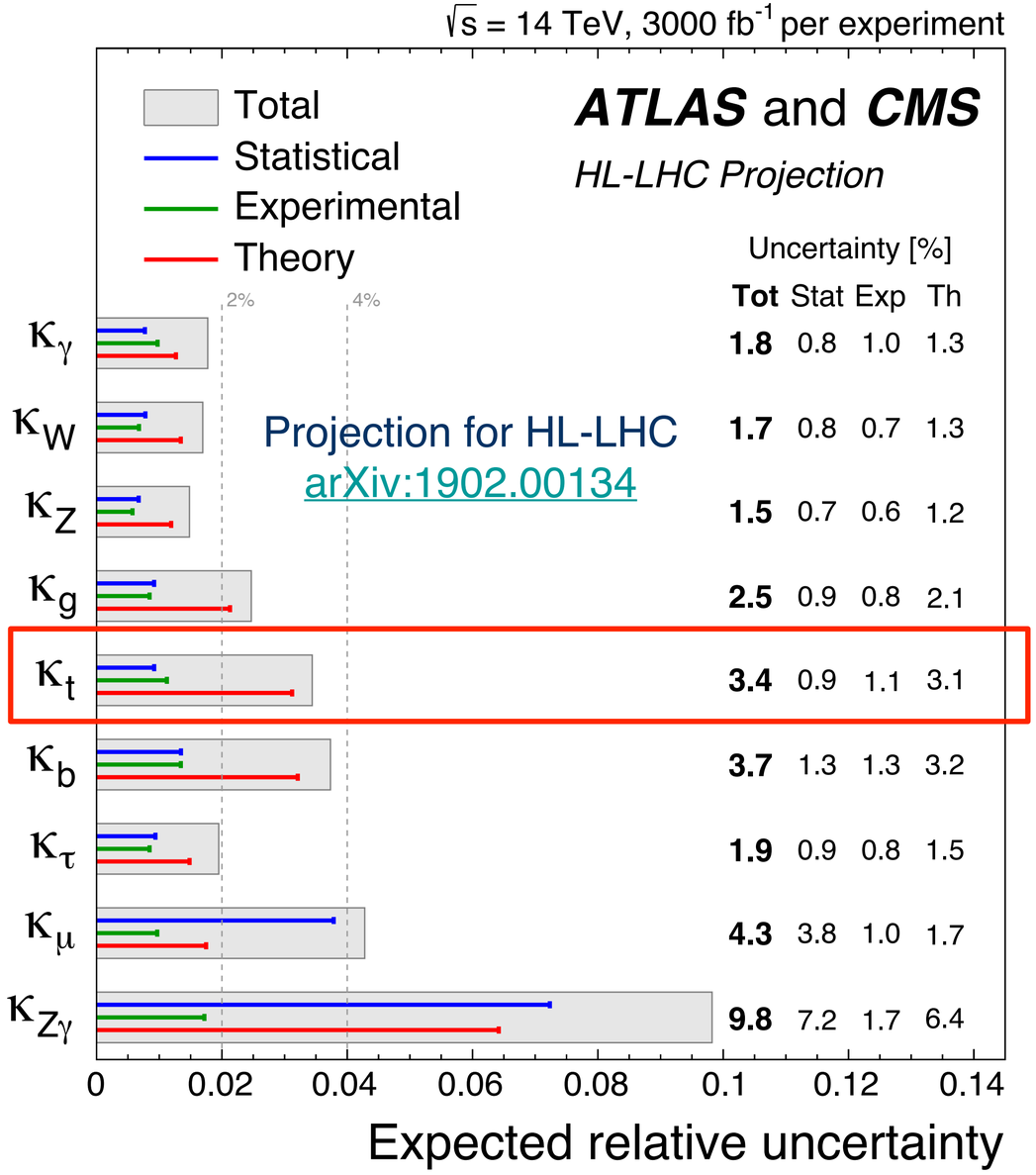


Sensitivity driven by H→γγ

- Combination helps reduce model dependence and improve precision
- Once included, **ttH(bb) will extend p_T(H) measurement to >450 GeV**

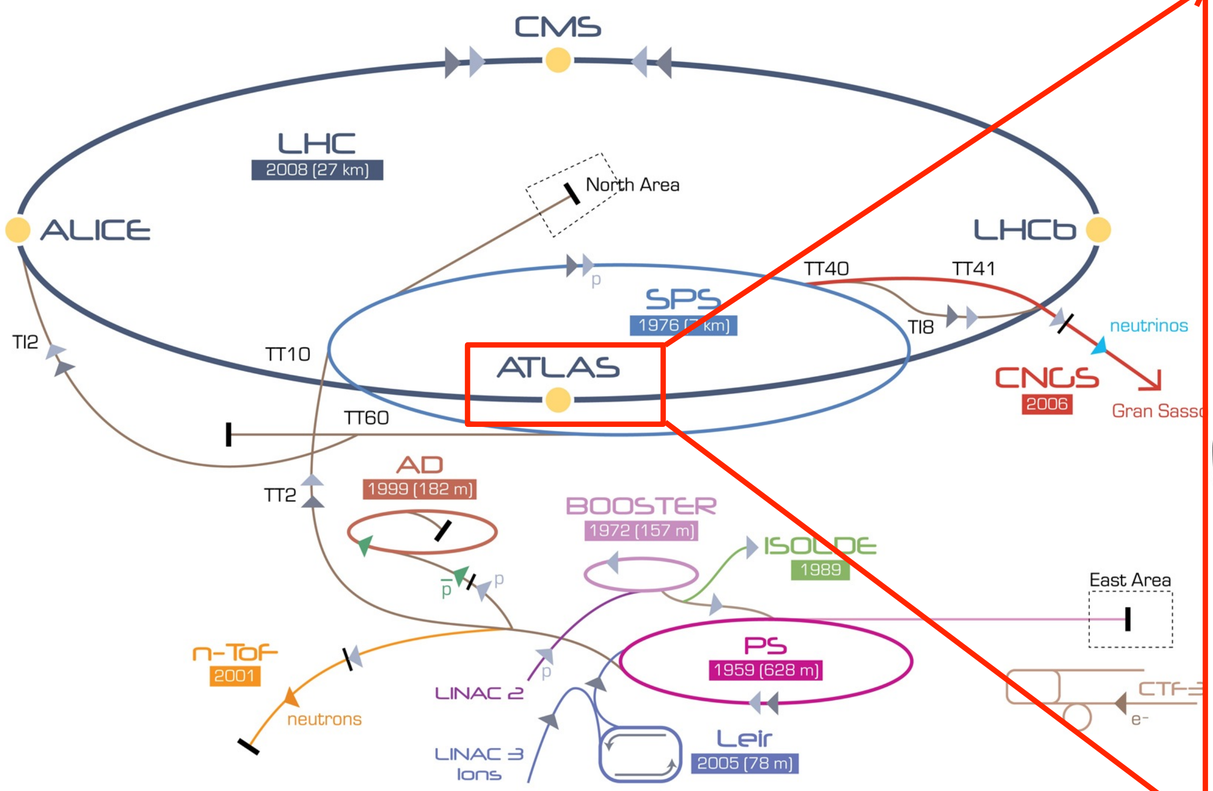
Conclusions

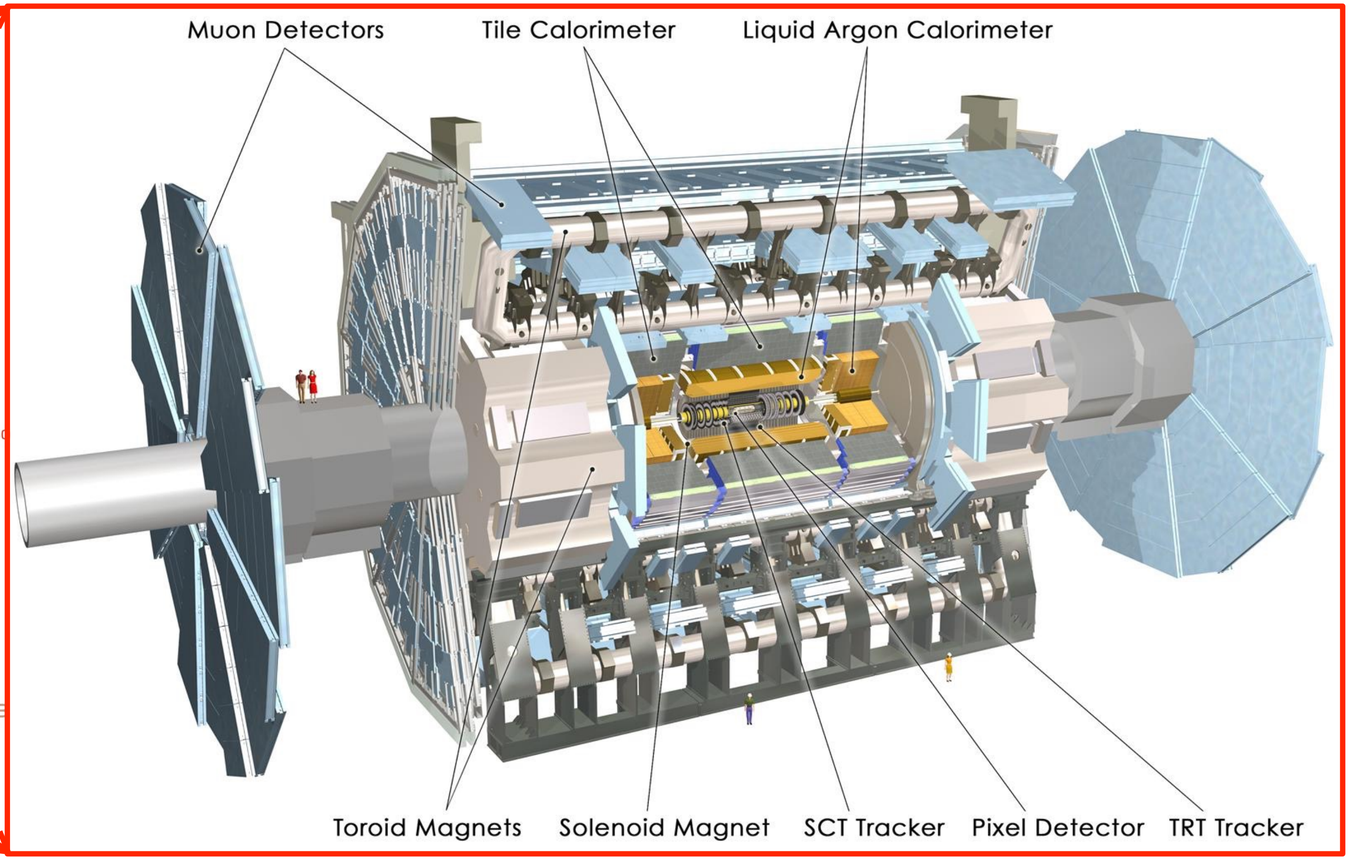
- ttH/tH remains a hot topic in LHC Higgs physics
  - Run 2 analyses being finalized, highlighting ttH differential measurements in $p_T(H)$ bins based on STXS framework
  - ATLAS standalone as well as ATLAS + CMS combinations will follow
- Factor of ~3 improvement in precision expected at High-Luminosity LHC
  - While waiting, work hard to resolve bkg. modeling challenges (e.g. $t\bar{t} + \geq 1b$ for ttH(bb)) & brainstorm new ideas to explore rich physics in ttH/tH using Run 2 & Run 3 data!



Backup

LHC and ATLAS detector





- Successful Run 2 data-taking at $\sqrt{s}$ = **13 TeV**. **139 fb^{-1}** proton-proton collision data for physics thanks to the excellent LHC performance!

Efficiency of Higgs boson reconstruction in ttH(bb)

p_{T}^{H} [GeV]	Dilepton $\mathrm{SR}^{\geq 4j}_{\geq 4b}$	Single-lepton $\mathrm{SR}^{\geq 6j}_{\geq 4b}$	Single-lepton $\mathrm{SR}_{\mathrm{boosted}}$
Inclusive	51%	43%	91%
$[0, 120)$	43%	35%	—
$[120, 200)$	50%	45%	—
$[200, 300)$	64%	57%	—
$[300, 450)$	78%	59%	90%
$[450, \infty)$			93%

ATLAS-CONF-2020-058

Systematic sources for $t\bar{t}$ + jets modeling in ttH(bb)

Uncertainty source	Description		Components
$t\bar{t}$ cross-section	$\pm 6\%$		$t\bar{t}+$ light
$t\bar{t}+\geq 1b$ normalisation	Free-floating		$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1c$ normalisation	$\pm 100\%$		$t\bar{t}+\geq 1c$
NLO matching	MadGraph5_aMC@NLO+Pythia8 vs. PowhegBox+Pythia8		All
PS & hadronisation	PowhegBox+Herwig7 vs. PowhegBox+Pythia8		All
ISR	Varying α_S^{ISR} (PS), μ_{R}&μ_{F} (ME)	in PowhegBoxRes+Pythia8	$t\bar{t}+\geq 1b$
		in PowhegBox+Pythia8	$t\bar{t}+\geq 1c$, $t\bar{t}+$ light
FSR	Varying α_S^{FSR} (PS)	in PowhegBoxRes+Pythia8	$t\bar{t}+\geq 1b$
		in PowhegBox+Pythia8	$t\bar{t}+\geq 1c$, $t\bar{t}+$ light
$t\bar{t}+\geq 1b$ fractions	PowhegBox+Herwig7 vs. PowhegBox+Pythia8		$t\bar{t}+1b/1B$, $t\bar{t}+\geq 2b$
p_{T}^{bb} shape	Shape mismodelling measured from data		$t\bar{t}+\geq 1b$

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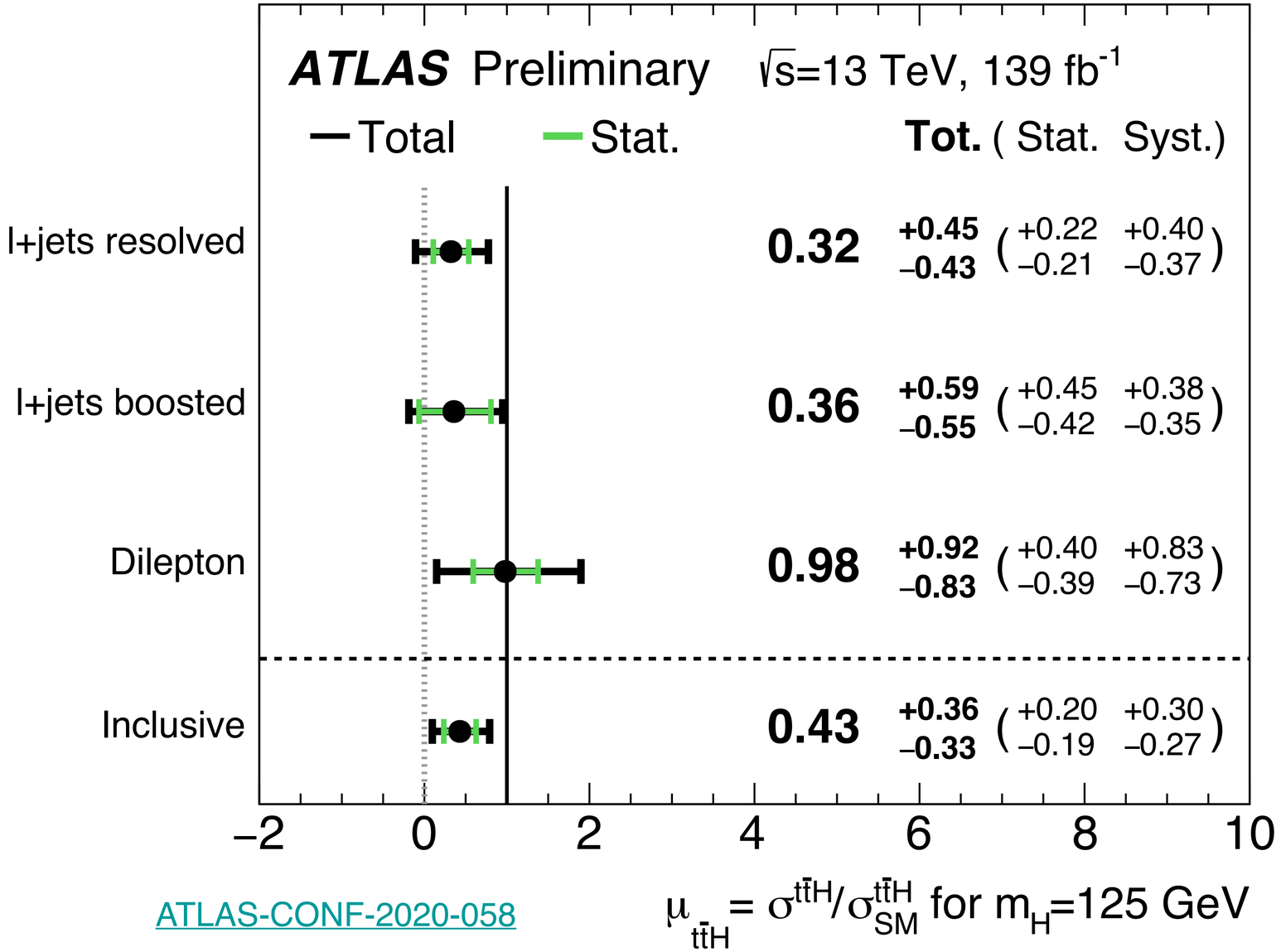
ttH(bb) signal strength in different regions



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ttH(bb) ranking results

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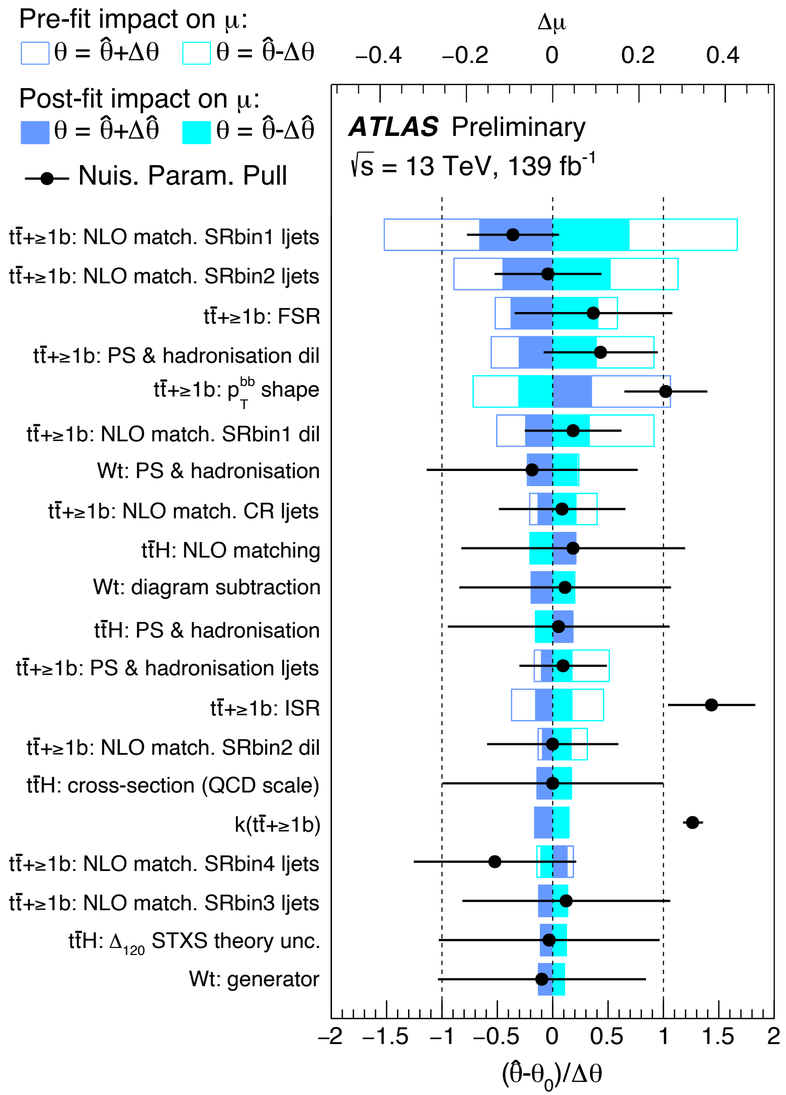
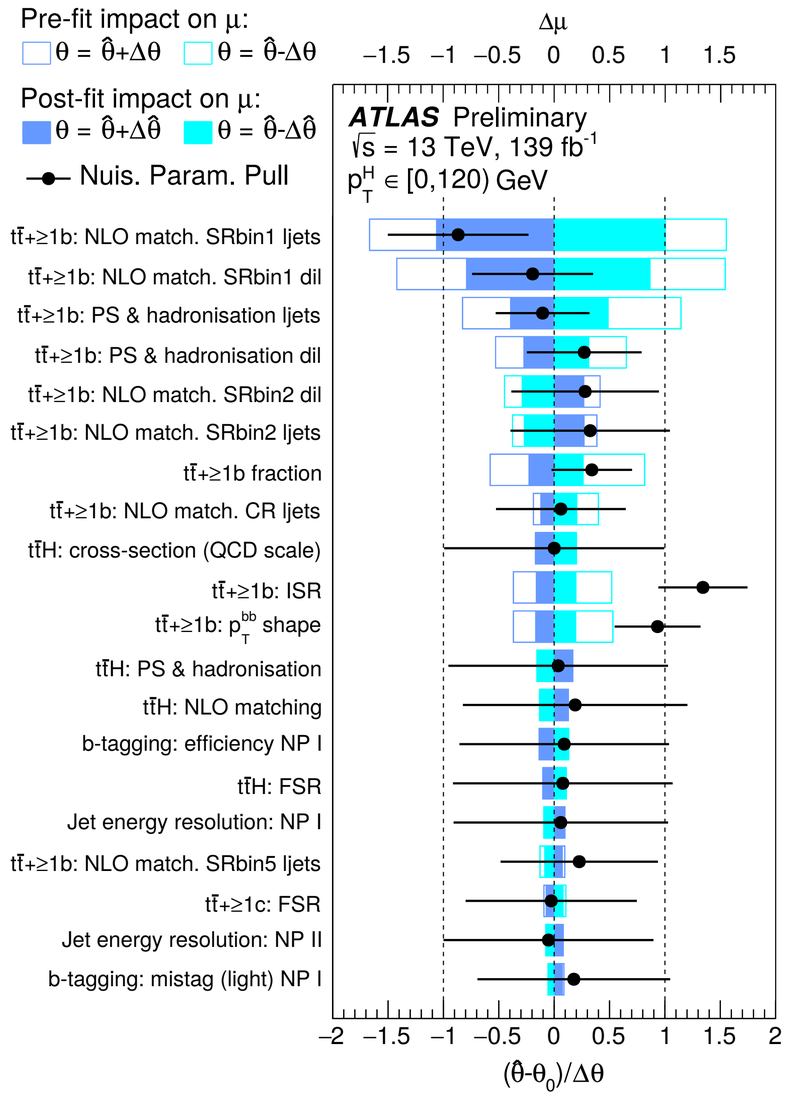
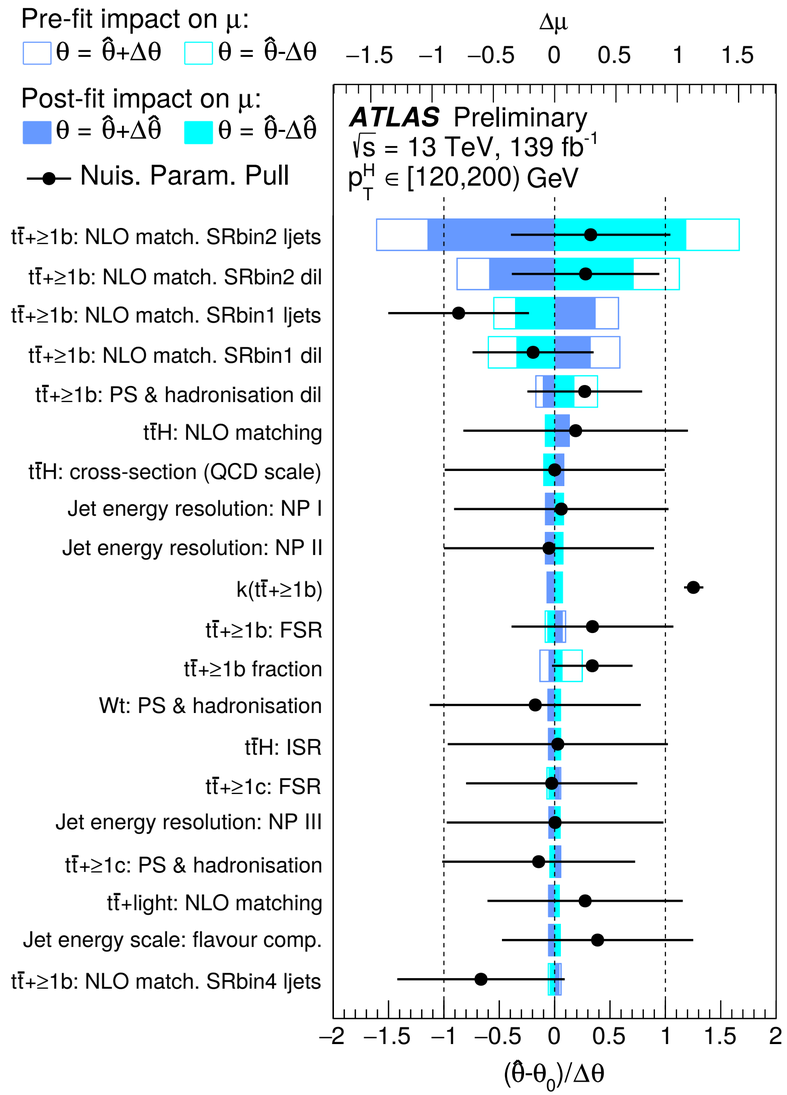


Inclusive



$p_T(H) < 120$ GeV



$120 \leq p_T(H) < 200$ GeV

ttH(bb) ranking results

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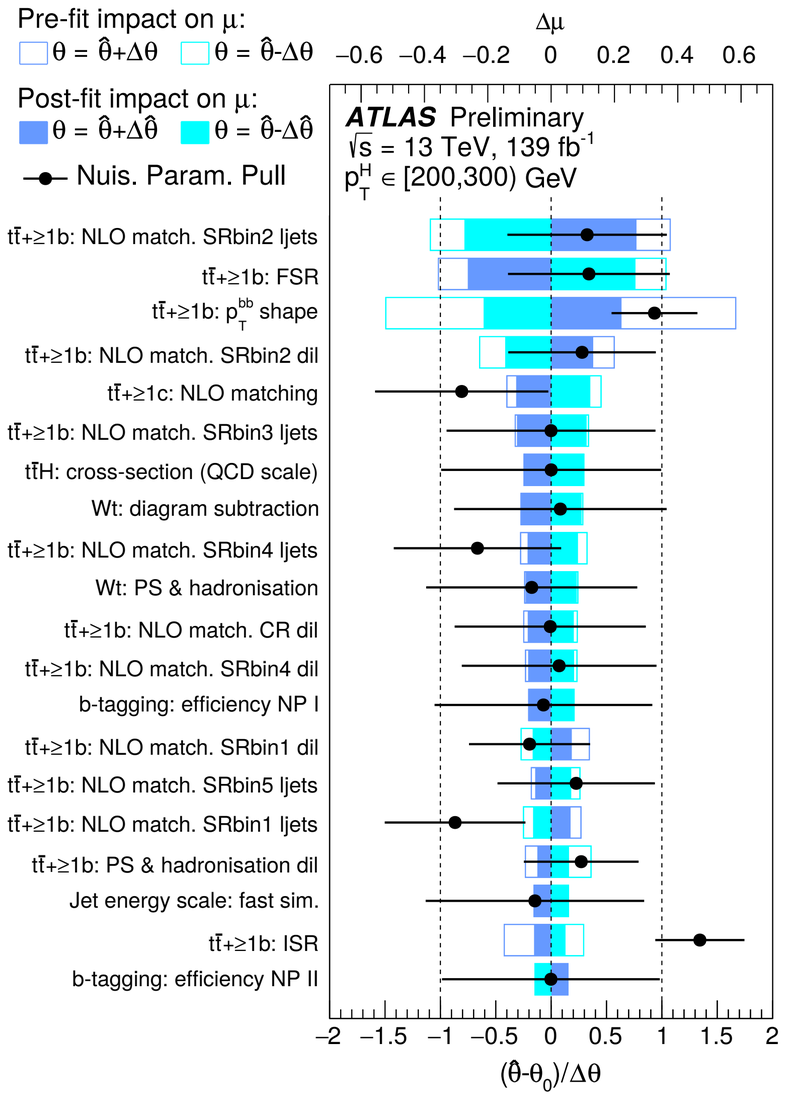

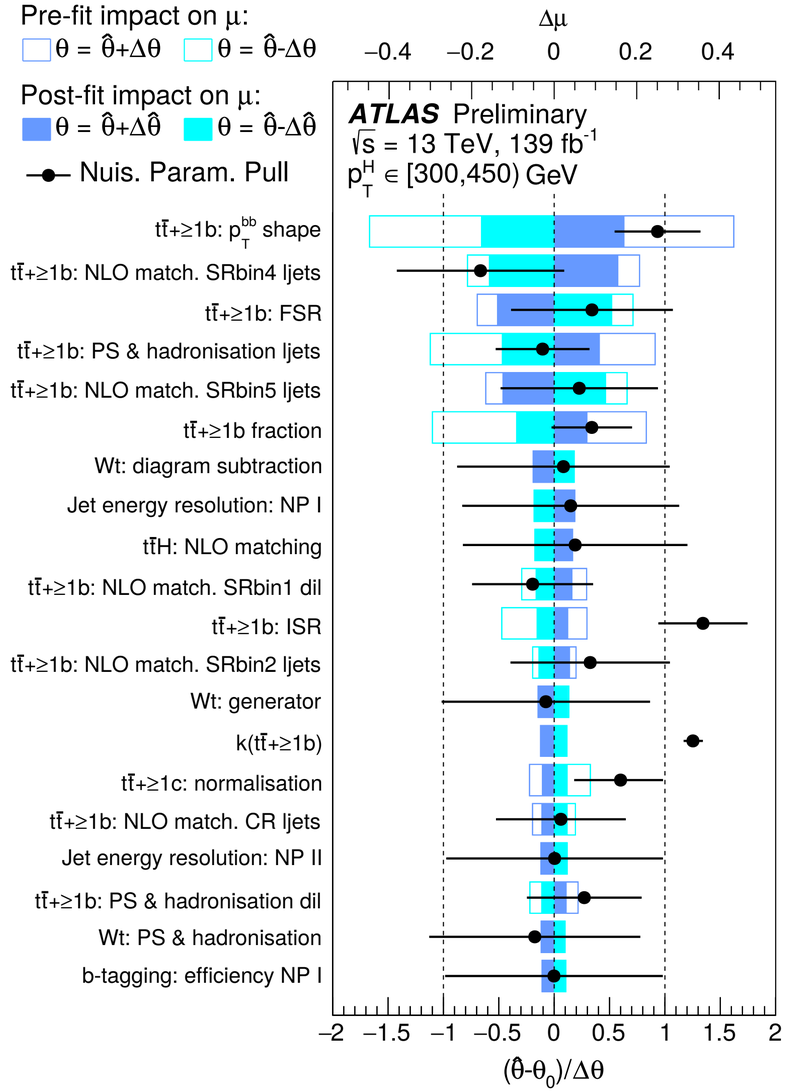

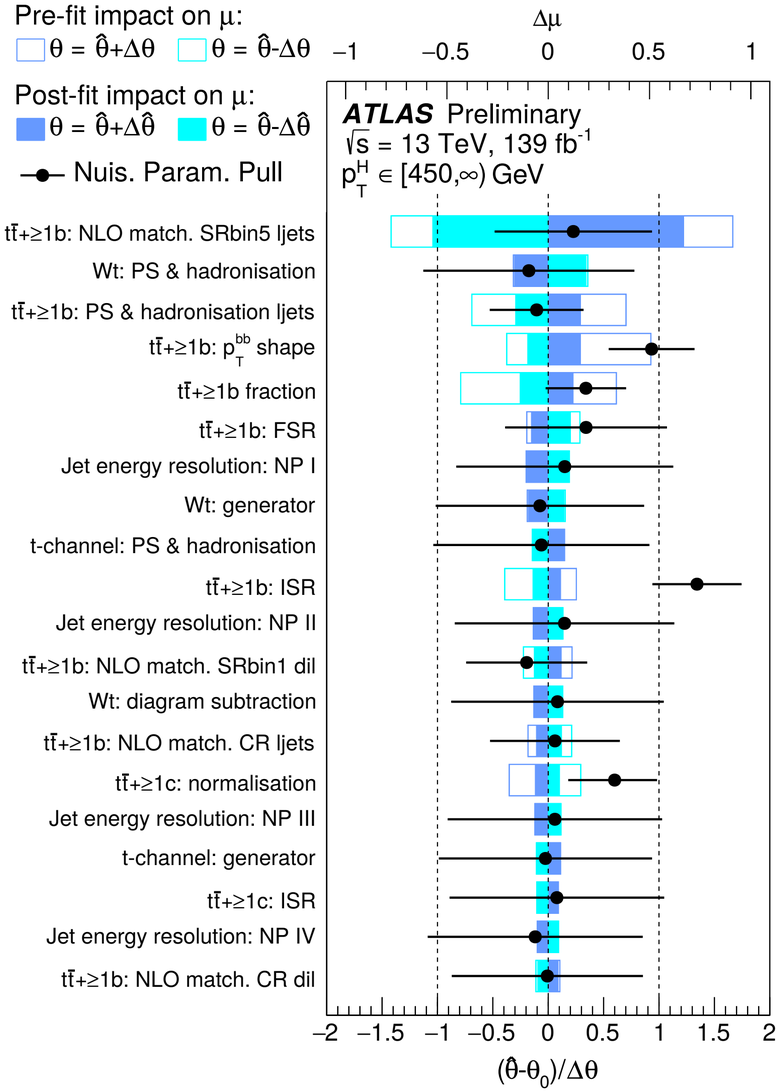

200 ≤ p_T(H) < 300 GeV

300 ≤ p_T(H) < 450 GeV

p_T(H) ≥ 450 GeV

Post-fit event yields in ttH(bb) di-lepton channel

	$\mathrm{SR}^{\geq 4j}_{\geq 4b}$				$\mathrm{CR}^{3j}_{3b\ \mathrm{hi}}$	$\mathrm{CR}^{\geq 4j}_{3b\ \mathrm{hi}}$	$\mathrm{CR}^{\geq 4j}_{3b\ \mathrm{lo}}$
p_{T}^{H} range [GeV]	[0,120)	[120,200)	[200,300)	[300,∞)			
$t\bar{t}H$	14 ± 12	6.7 ± 5.3	3.3 ± 2.6	1.6 ± 1.2	10.5 ± 8.4	51 ± 41	33 ± 27
$t\bar{t} + \geq 1b$	557 ± 28	265 ± 17	117.6 ± 9.6	37.4 ± 5.6	2030 ± 130	4080 ± 210	2540 ± 170
$t\bar{t} + \geq 1c$	48.7 ± 9.5	14.4 ± 4.4	6.2 ± 1.4	3.9 ± 1.0	523 ± 130	1190 ± 260	2550 ± 500
$t\bar{t}$ + light, $4t$, tH	7.9 ± 5.8	4.2 ± 2.8	2.1 ± 1.5	1.4 ± 1.3	123 ± 66	221 ± 120	923 ± 360
$t\bar{t} + Z$	12.5 ± 2.0	7.6 ± 1.6	4.15 ± 0.71	2.03 ± 0.44	10.7 ± 1.7	57.4 ± 7.3	52.5 ± 6.8
$t\bar{t} + W$	0.75 ± 0.31	0.41 ± 0.12	0.27 ± 0.11	0.128 ± 0.069	1.83 ± 0.55	10.9 ± 1.6	22.0 ± 3.5
Other top sources	19.0 ± 6.7	7.7 ± 4.2	4.4 ± 4.0	2.0 ± 1.5	126 ± 34	208 ± 60	254 ± 71
Fakes	3.6 ± 1.1	1.32 ± 0.51	0.40 ± 0.23	0.57 ± 0.30	6.31 ± 1.8	46.3 ± 12	55.7 ± 14
Total	664 ± 24	307 ± 16	138.5 ± 8.9	48.9 ± 5.1	2830 ± 54	5860 ± 79	6430 ± 82
Data	647	306	135	48	2827	5865	6429

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Post-fit event yields in ttH(bb) lepton+jet channel

	$\mathrm{SR}^{\geq 6j}_{\geq 4b}$					$\mathrm{SR}_{\mathrm{boosted}}$		$\mathrm{CR}^{5j}_{\geq 4b\ \mathrm{lo}}$	$\mathrm{CR}^{5j}_{\geq 4b\ \mathrm{hi}}$
p_{T}^{H} range [GeV]	[0,120)	[120,200)	[200,300)	[300,450)	[450,∞)	[300,450)	[450,∞)		
$t\bar{t}H$	93 ± 74	49 ± 39	26 ± 21	5.9 ± 4.6	1.26 ± 1.00	15 ± 12	3.6 ± 2.8	26 ± 20	26 ± 21
$t\bar{t} + \geq 1b$	4450 ± 160	2040 ± 85	855 ± 43	234 ± 20	43.4 ± 8.2	297 ± 27	51.0 ± 9.8	1595 ± 80	1102 ± 51
$t\bar{t} + \geq 1c$	960 ± 210	404 ± 87	179 ± 38	46 ± 11	12.9 ± 3.3	157 ± 37	40 ± 11	630 ± 140	90 ± 23
$t\bar{t}$ + light, $4t$, tH	250 ± 140	105 ± 57	52 ± 26	15.4 ± 8.8	3.5 ± 2.2	62 ± 25	16.9 ± 7.6	270 ± 100	26 ± 16
$t\bar{t} + W$	7.3 ± 1.1	4.46 ± 0.87	2.54 ± 0.48	1.09 ± 0.31	0.48 ± 0.14	1.89 ± 0.36	0.57 ± 0.17	2.62 ± 0.46	0.53 ± 0.12
$t\bar{t} + Z$	79 ± 10	46.0 ± 6.4	31.1 ± 4.9	11.8 ± 2.3	2.12 ± 0.64	11.0 ± 2.1	2.34 ± 0.60	25.9 ± 3.5	22.8 ± 3.1
Single top Wt	80 ± 43	44 ± 27	18.7 ± 7.8	9.5 ± 9.0	6.1 ± 5.4	14.0 ± 8.3	4.9 ± 4.3	60 ± 32	28 ± 20
Other top sources	48 ± 25	24 ± 16	14 ± 10	4.5 ± 2.7	1.09 ± 0.54	4.4 ± 3.0	0.88 ± 0.78	41 ± 16	28 ± 11
V & VV + jets	63 ± 24	30 ± 11	20.6 ± 8.2	8.1 ± 3.4	1.92 ± 0.84	13.1 ± 5.6	4.2 ± 2.0	43 ± 15	24.9 ± 8.8
Total	6026 ± 84	2747 ± 52	1198 ± 31	336 ± 15	72.8 ± 7.0	575 ± 23	124.4 ± 9.7	2700 ± 52	1348 ± 38
Data	6047	2742	1199	331	75	581	118	2696	1362

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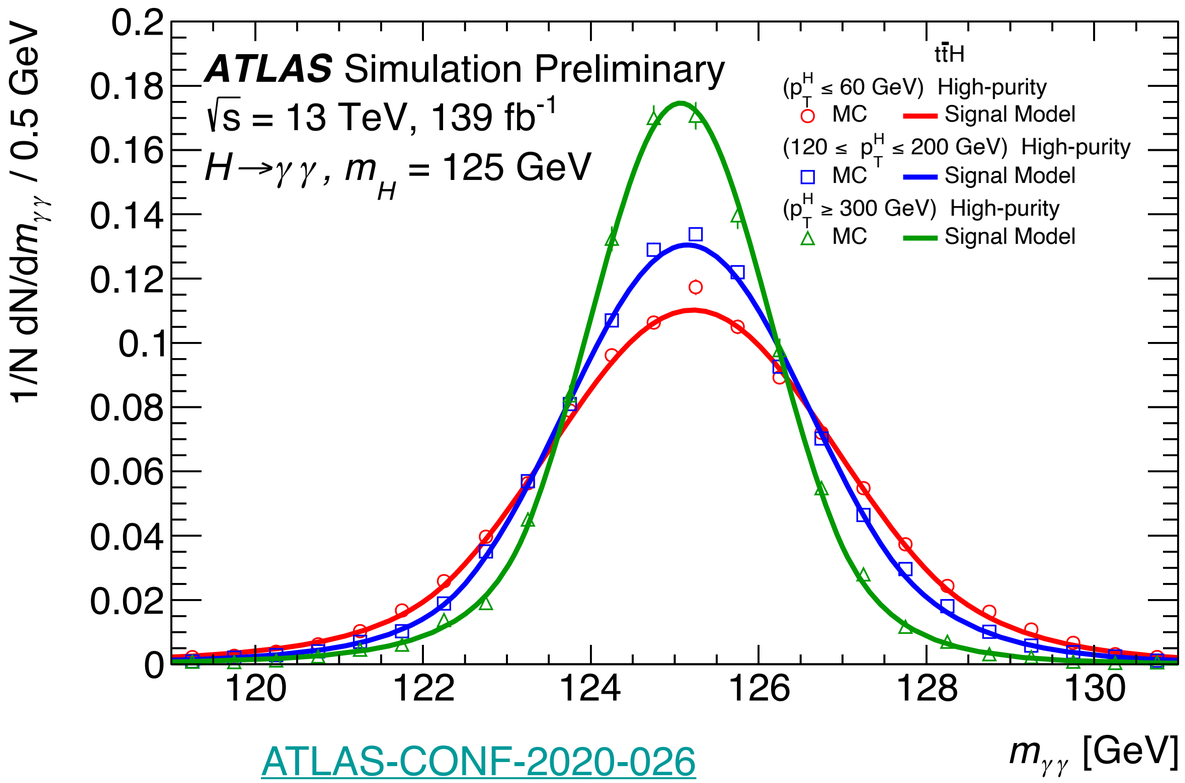
Summary of training variables in H→γγ

STXS regions	Multi-class BDT	STXS regions	Binary BDT
$gg \to H$	di-photon p_{T} and absolute rapidity; di-jet p_{T}, mass, Δy, $\Delta\phi$, $\Delta\eta$ between the 2 jets; p_{T}, mass of $\gamma\gamma + j$ and $\gamma\gamma + jj$, Δy, $\Delta\phi$ between $\gamma\gamma$ and jj, minimum ΔR between jets and photons, mass of the sum of all jets; di-lepton p_{T}, di-e or di-μ mass, E_{T}^{miss}, p_{T} of lepton + E_{T}^{miss}; p_T, η, ϕ, mass of top candidates; Number of jets, barrel jets ($\lvert\eta\rvert < 2.5$), b-jets and leptons; leading jet p_T, sum p_{T} of all jets $\sum E^{\mathrm{T}}$, E_{T}^{miss} significance; Average interaction per crossing, number of primary vertices	individual STXS regions from $gg \to H$ or $qq' \to Hqq'$	Multi-class BDT variables, and $\Delta\phi$, $\Delta\eta$ between the 2 photons ($\Delta\phi_{\gamma\gamma}$, $\Delta\eta_{\gamma\gamma}$); Number of electrons and muons; E_{T}^{miss}, $\sum E^{\mathrm{T}}$, E_{T}^{miss} significance, and E_{T}^{miss} azimuthal angle computed from hardest vertex; $\gamma\gamma$ $\vec{p}_{\mathrm{T}}$ projected to its thrust axis ($p_{\mathrm{Tt}}^{\gamma\gamma}$); Half difference between di-photon η and sum η of leading 2 jets (η^{Zepp}); $\phi^*_{\gamma\gamma} = \tan(\frac{\pi - \lvert\Delta\phi_{\gamma\gamma}\rvert}{2})\sqrt{1-\tanh^2(\frac{\Delta\eta_{\gamma\gamma}}{2})}$ $\cos\theta^*_{\gamma\gamma} = \lvert\frac{(E^{\gamma_1}+p_z^{\gamma_1})\cdot(E^{\gamma_2}-p_z^{\gamma_2}) - (E^{\gamma_1}-p_z^{\gamma_1})\cdot(E^{\gamma_2}+p_z^{\gamma_2})}{m_{\gamma\gamma}+\sqrt{(m_{\gamma\gamma}^2+(p_{\mathrm{T}}^{\gamma\gamma})^2)}}\rvert$
$qq' \to Hqq'$			
$qq \to H\ell\nu$		WH STXS regions combined	$p_{\mathrm{T}}/m_{\gamma\gamma}$, η, ϕ of 2 leading photons; p_{T}, η, ϕ of 2 leading leptons; E_{T}^{miss}, E_{T}^{miss} significance, E_{T}^{miss} azimuthal angle; Whether or not the E_{T}^{miss} built from di-photon vertex is larger than that built from the hardest vertex by more than 30 GeV; di-lepton mass, and transverse mass of lepton + E_{T}^{miss}
$qq \to H\ell\ell$		ZH STXS regions combined	
$t\bar{t}H$	ATLAS-CONF-2020-026	$t\bar{t}H$ STXS regions combined	p_{T}, η, ϕ of 2 leading photons; p_{T}, η, ϕ and B-tagging scores of 6 leading jets; E_{T}^{miss}, E_{T}^{miss} significance, E_{T}^{miss} azimuthal angle; Top reconstruction BDT scores
tH		tWH, $tHqb$	

H→γγ Signal and background modeling



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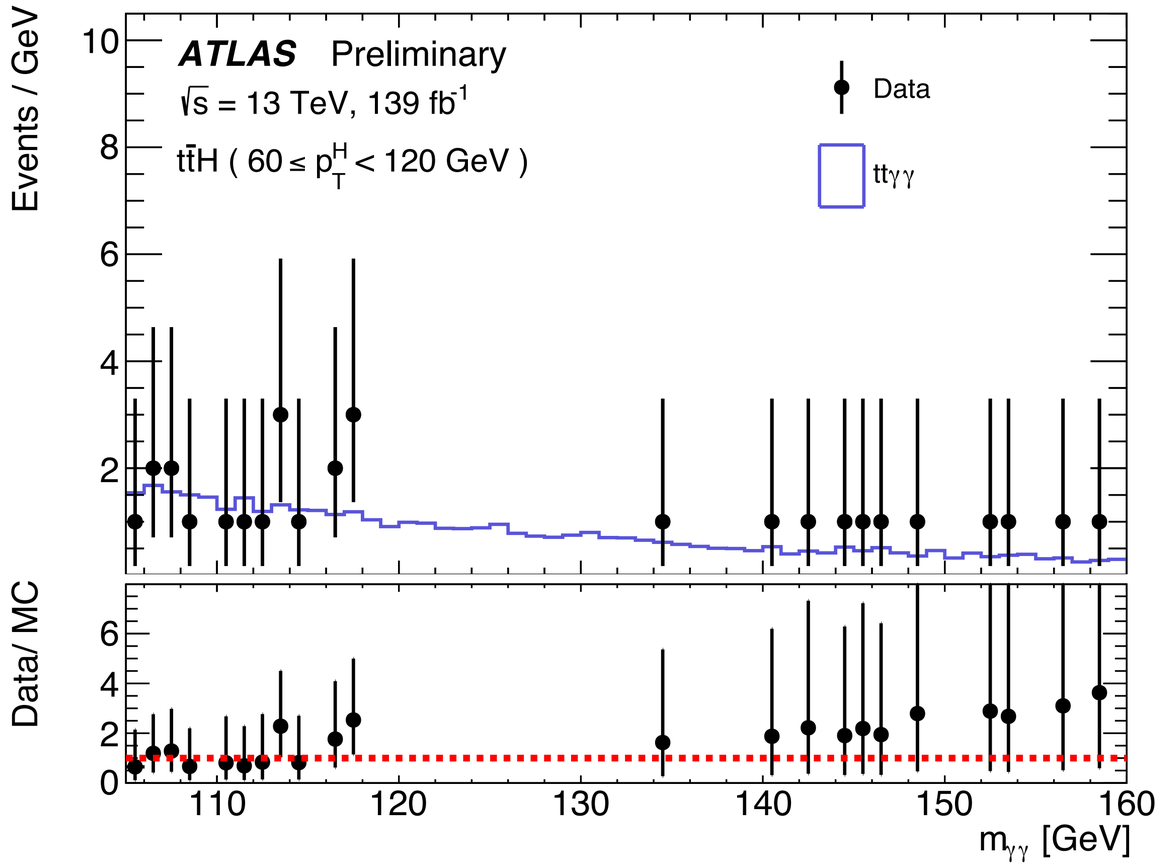
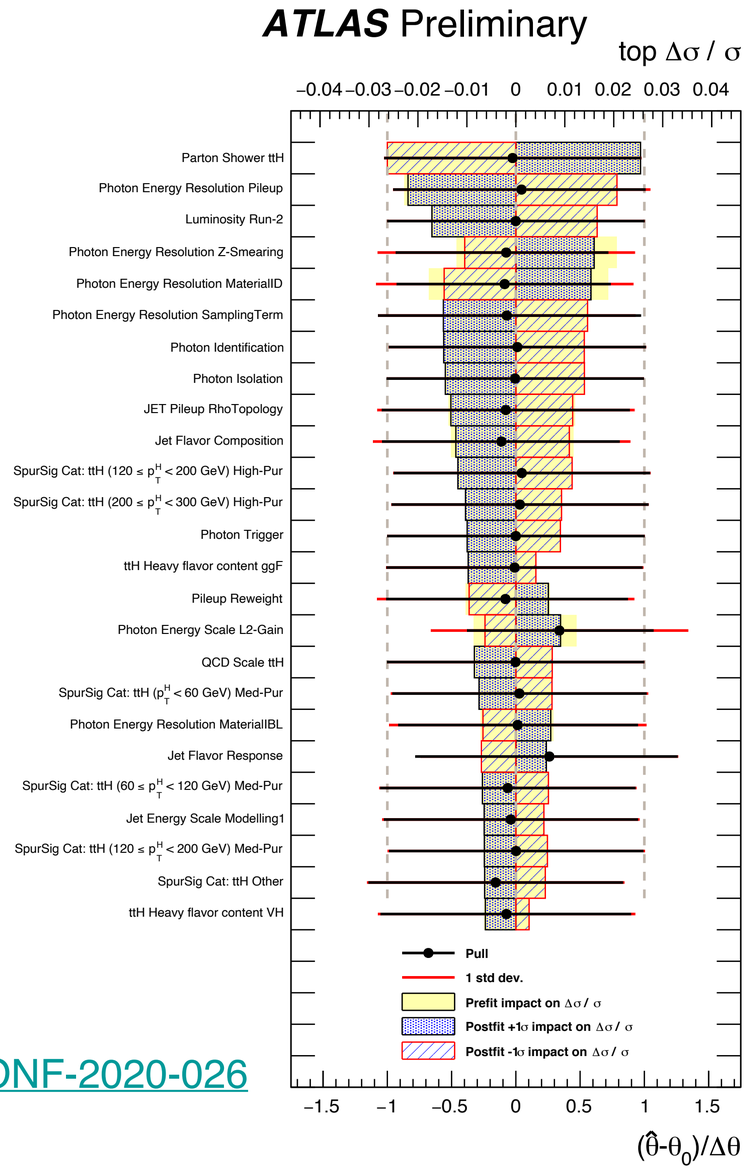


- Parameterize signal with double-sided crystal ball function
- Select background model on MC template using spurious signal procedure.
  Exponential function chosen for all ttH/tH categories

Nuisance parameter ranking from H→γγ



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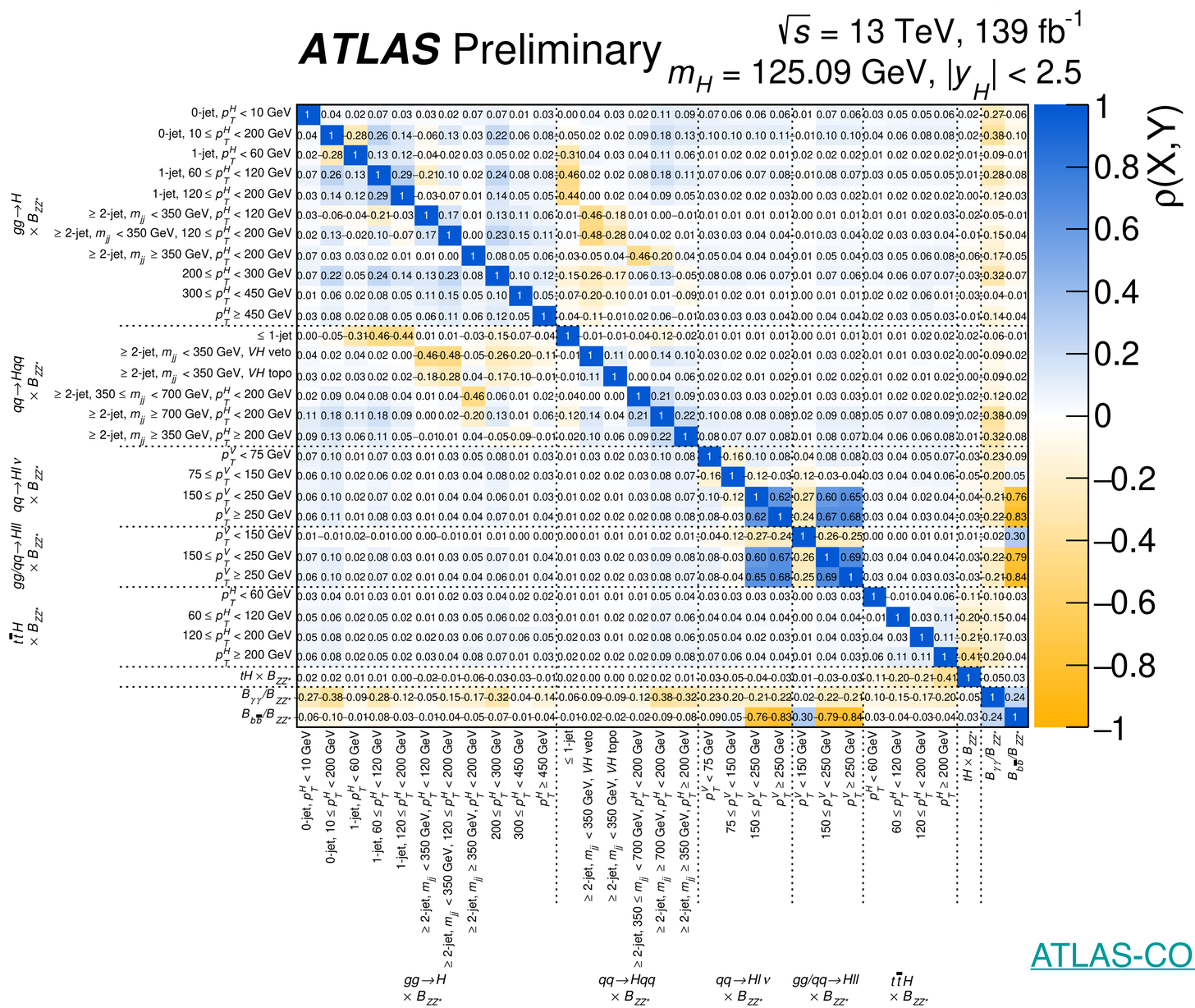
- No significant pull or over-constraint of nuisance parameter for systematic uncertainties

STXS correlation matrix



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