

Measurement of Higgs boson production in association with top quarks by ATLAS and CMS

Lucia Masetti

Johannes Gutenberg University Mainz - PRISMA+ Cluster of Excellence on behalf of the ATLAS and CMS collaboration

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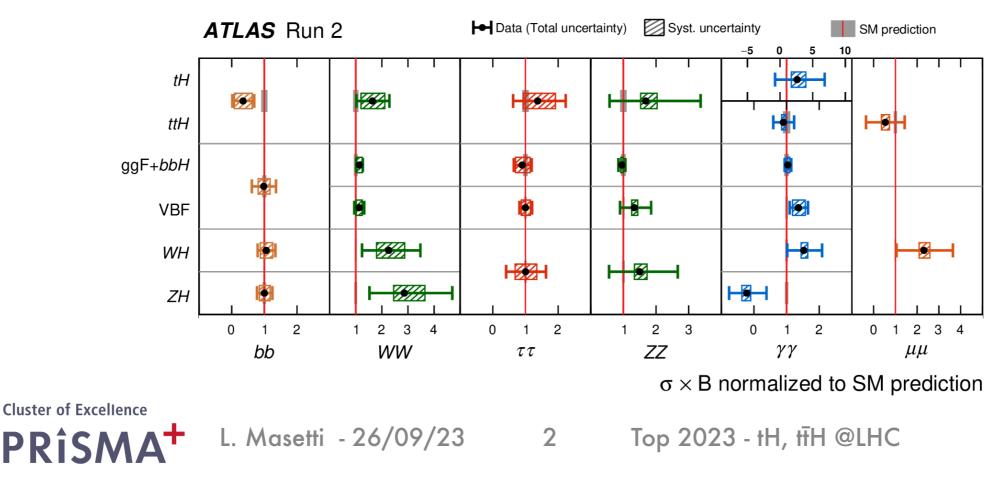
Federal Ministry of Education and Research

FSP ATLAS Erforschung von Universum und Materie



The Higgs boson

- Discovery 2012 by ATLAS and CMS @LHC
 - Observation from combination of 3 decay channels in 1 production process
- 10 years later
 - Single measurements in 7 decay channels and 6 production channels
 - Established spin-parity quantum numbers
 - Extremely precise mass measurement
 - Limits on pair production and self interaction

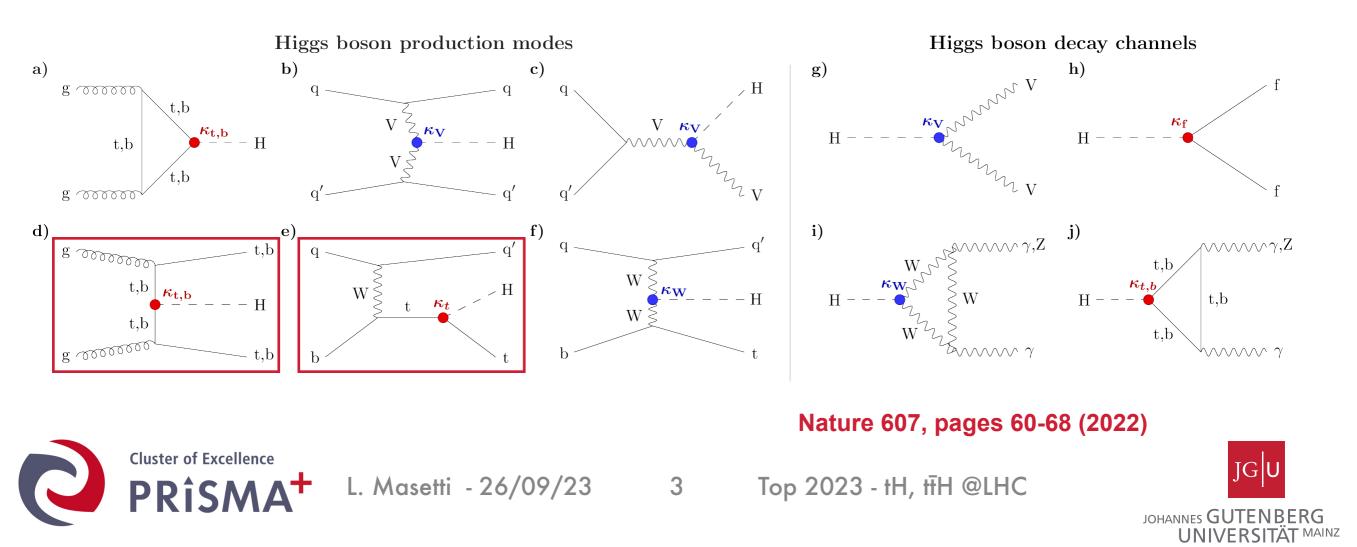


Nature 607, pages 52-59 (2022)



Top Yukawa coupling

- Couplings to fermions (Yukawa couplings) proportional to mass
 - Top Yukawa coupling much larger than all others
 - Dominates fermion loop contributions → model-dependent extraction
- Model-independent measurement
 - via associated production with a top quark pair (tTH) or a single top quark (tH)



Deviations from SM?

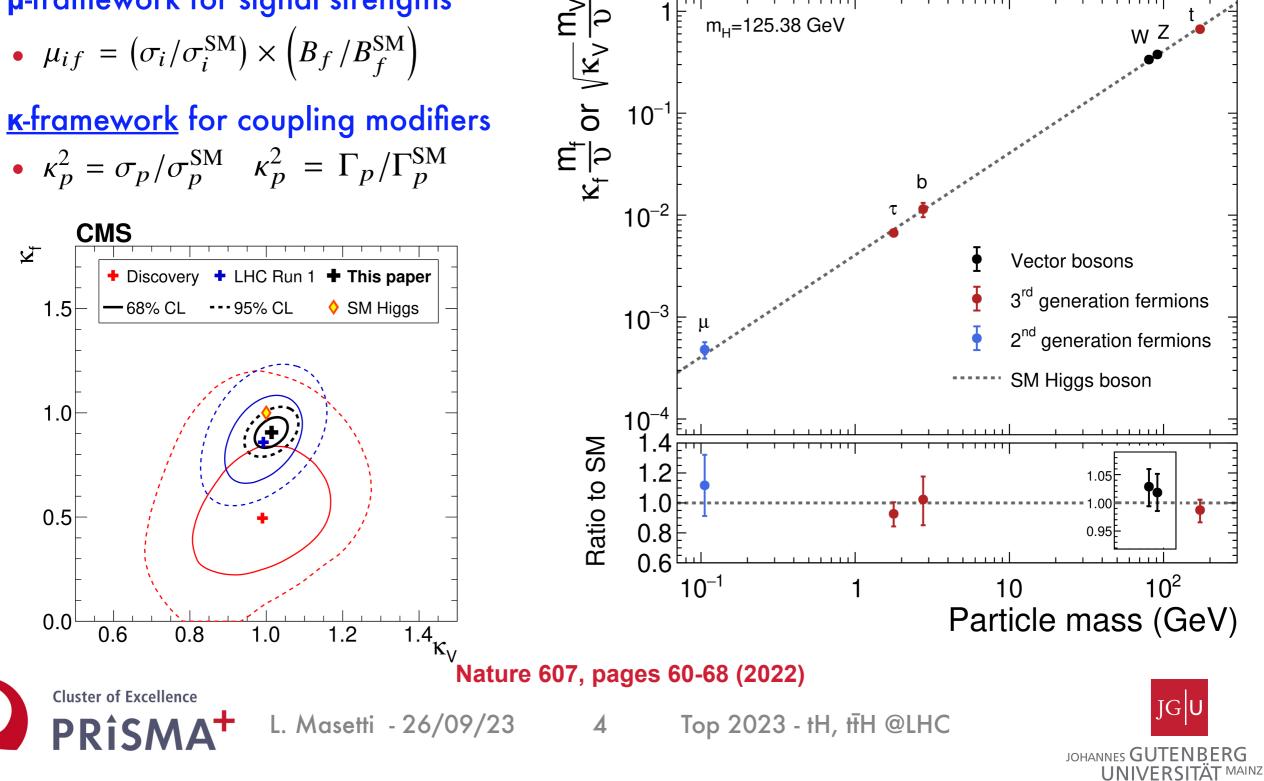
 10^{-1}

CMS

m_H=125.38 GeV

138 fb⁻¹ (13 TeV

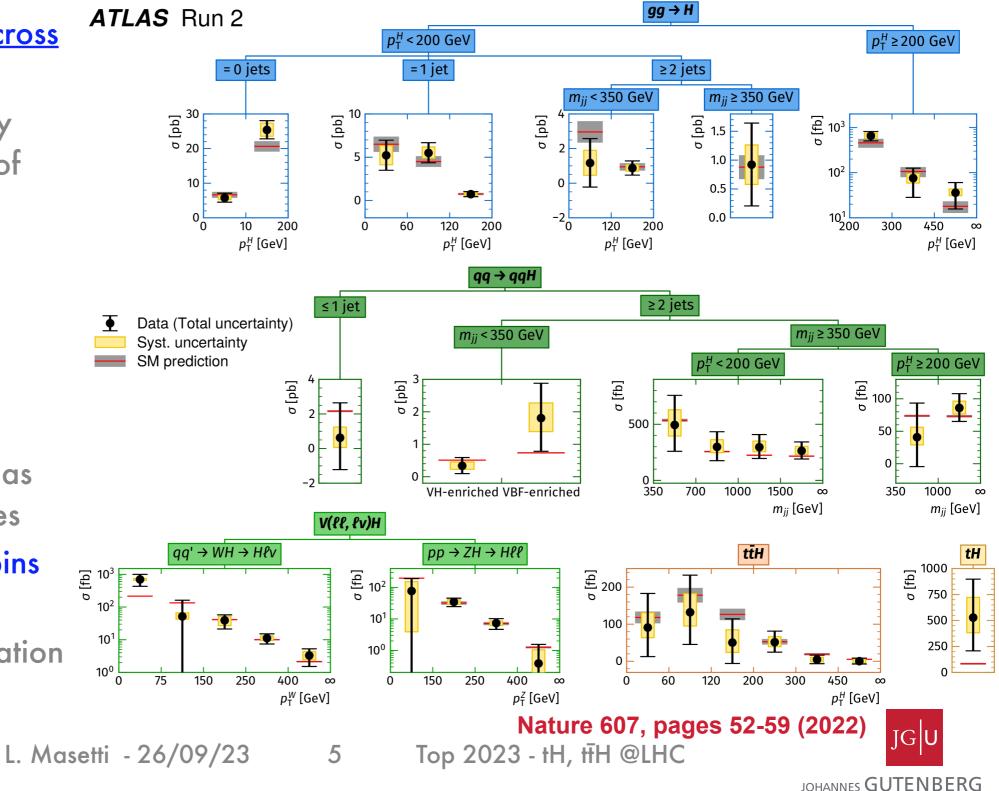
- µ-framework for signal strengths
 - $\mu_{if} = (\sigma_i / \sigma_i^{\text{SM}}) \times (B_f / B_f^{\text{SM}})$
- <u>κ-framework</u> for coupling modifiers



STXS approach

- <u>Simplified template cross</u>
 <u>sections</u>
 - defined in mutually exclusive regions of phase space
 - simplified fiducial volumes
 - inclusive in Higgs boson decay
 - SM production processes serving as kinematic templates
- Common choice of bins for ATLAS and CMS
 - allows for combination



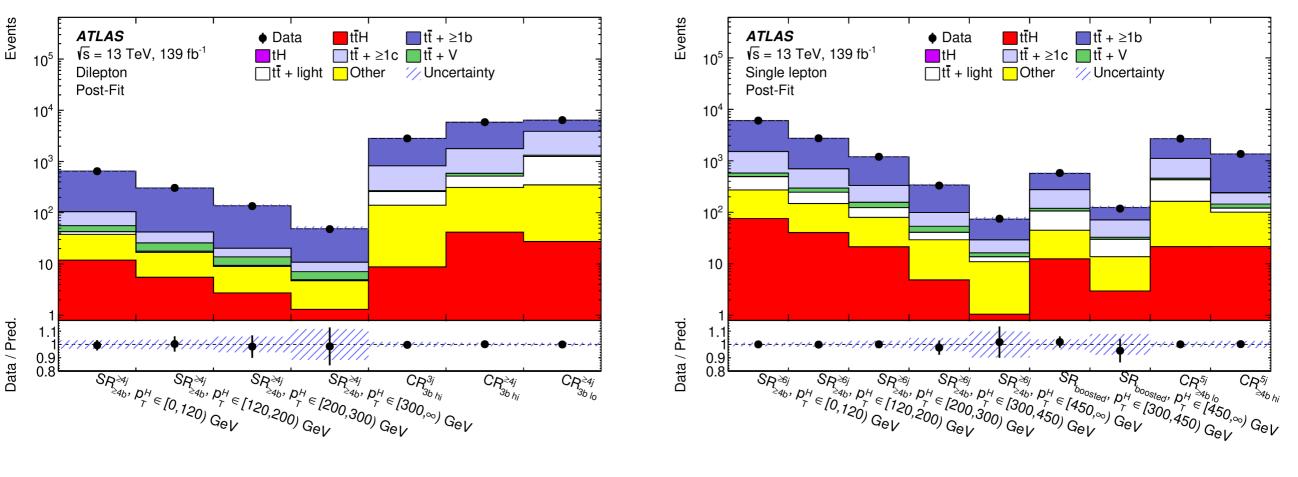


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Single lepton and dilepton regions

Signal and control regions depending on number of jets and b-jets Single lepton boosted for Higgs p_T > 300 GeV Classification BDT for signal regions and yields for control regions in fit



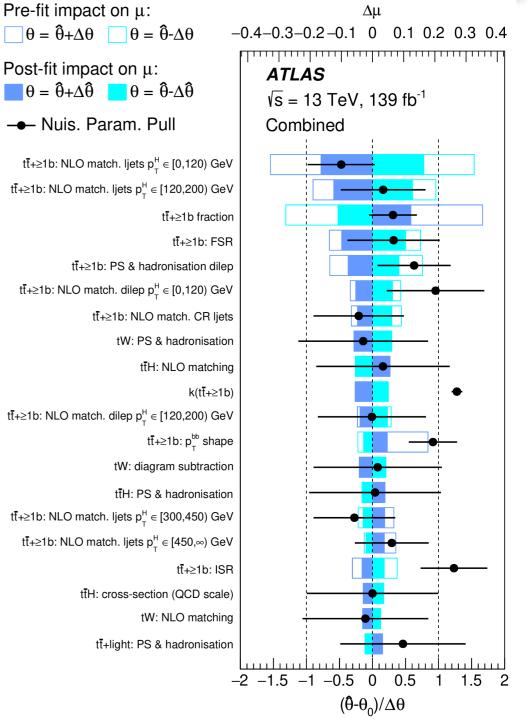
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 Top 2023 - tH, tTH @LHC

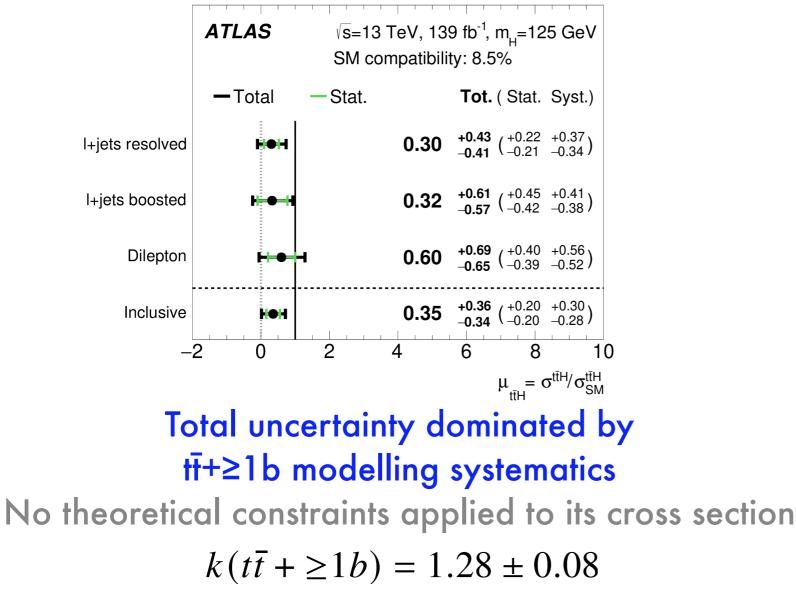


tīH, H→bb





Inclusive measurement



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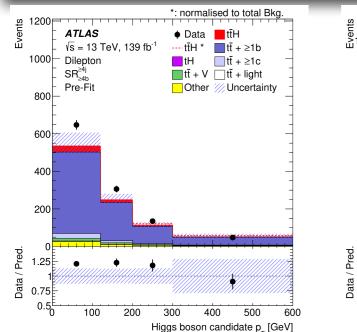
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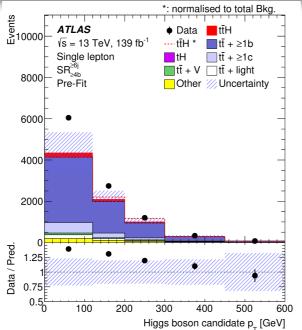
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$\mathsf{TT}\mathsf{F}, \mathsf{F} \to \mathsf{b}\mathsf{b}$

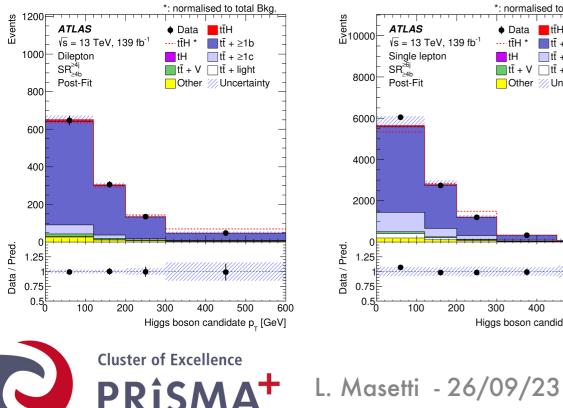
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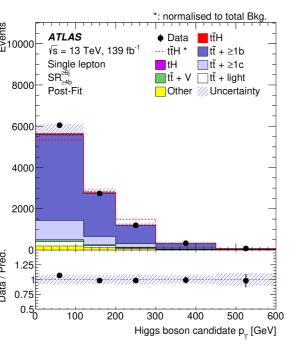




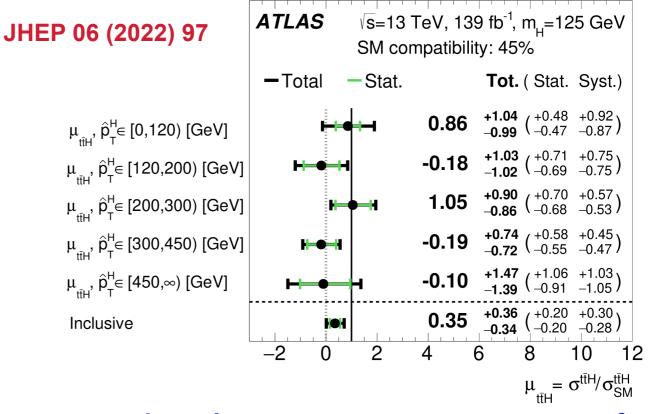


Dedicated systematics in ttb





Differential measurement

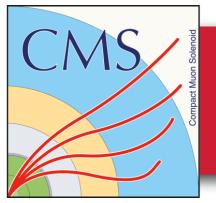


Statistical and systematic uncertainties of similar size in most bins Results compatible with SM predictions within 1-2 σ ,

but several negative fit values

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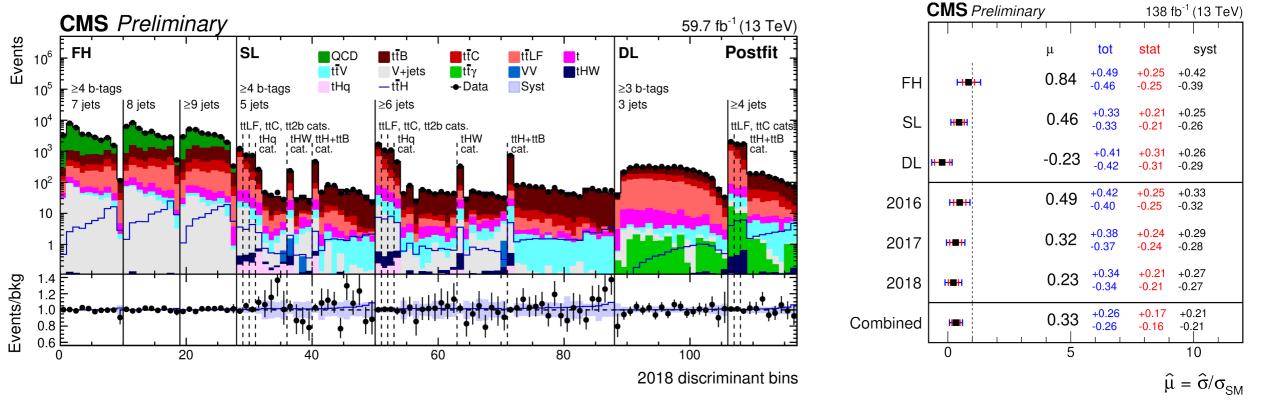


t(F)H, H→bb

CMS-PAS-HIG-19-011

Full hadronic, single lepton and dilepton regions

Signal and control regions depending on number of jets and b-jets Multiclass ANNs separately for each year ANN output and likelihood ratio of outputs used in fit Different treatment of tī+≥1b background wrt ATLAS



Fitted distributions



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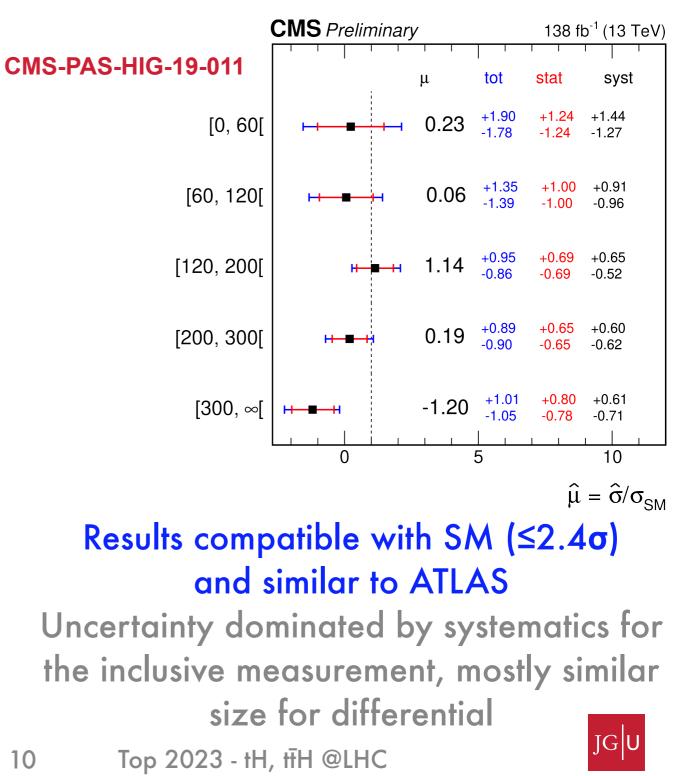
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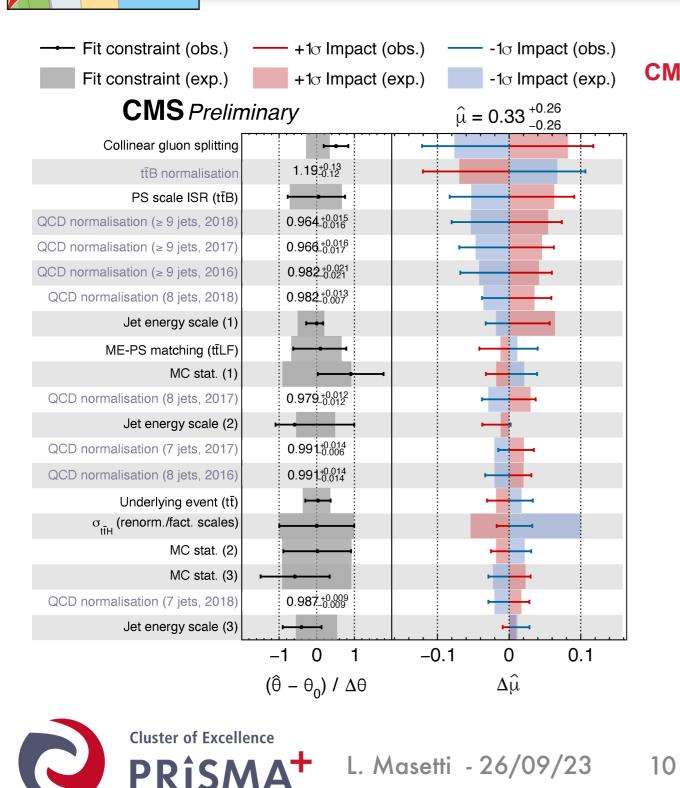
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Inclusive measurement

tīH, H→bb





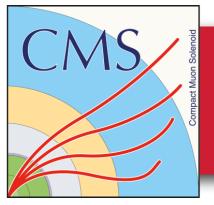
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C Muon Solenoid

tH, H→bb

μ_{tH} < 14.6 @ 95%CL Coupling measurement With μ_{tfH} fixed to 1 and treated as Assuming SM Higgs boson coupling background structure CMS-PAS-HIG-19-011 $\sigma_{\rm tHq} = \left(2.63 \cdot \kappa_{\rm t}^2 + 3.58 \cdot \kappa_{\rm V}^2 - 5.21 \cdot \kappa_{\rm t} \kappa_{\rm V}\right) \sigma_{\rm tHq}^{\rm SM} ,$ Simultaneous fit $\sigma_{\rm tHW} = \left(2.91 \cdot \kappa_{\rm t}^2 + 2.40 \cdot \kappa_{\rm V}^2 - 4.22 \cdot \kappa_{\rm t} \kappa_{\rm V}\right) \sigma_{\rm tHW}^{\rm SM} \ .$ **CMS** *Preliminary* **CMS** Preliminary 138 fb⁻¹ (13 TeV) ≩ ^{10.0}, 138 fb⁻¹ (13 TeV) 3.5 **И** tīН 19.2 (T) 5 ∇log(L) 16.8 2 19.2 000(F) 16.8 Z expected expected 3.0 observed observed 7.5 $\mu_{tH} = -3.83$ $K_t = 0.59$ $K_{V} = 1.40$ $\mu_{t\bar{t}H} = 0.35$ 2.5 68% CL 68% CL 5.0 14.4 14.4 95% CL - 95% CL 2.0 2.5 12.0 12.0 1.5 0.0 9.6 -9.6 1.0 -2.5 7.2 -7.2 0.5 -5.0 4.8 4.8 0.0 2.4 -7.5 2.4 -0.5 -10.0 -2.0 0.0 -1.0^L 0.0 5 10 15 20 -0.5 0 -1.5 0.0 0.5 1.0 1.5 2.0 -1.0 μtH Kt **Cluster of Excellence** JGU L. Masetti - 26/09/23 Top 2023 - tH, tTH @LHC ΡRîSMΔ+ 11

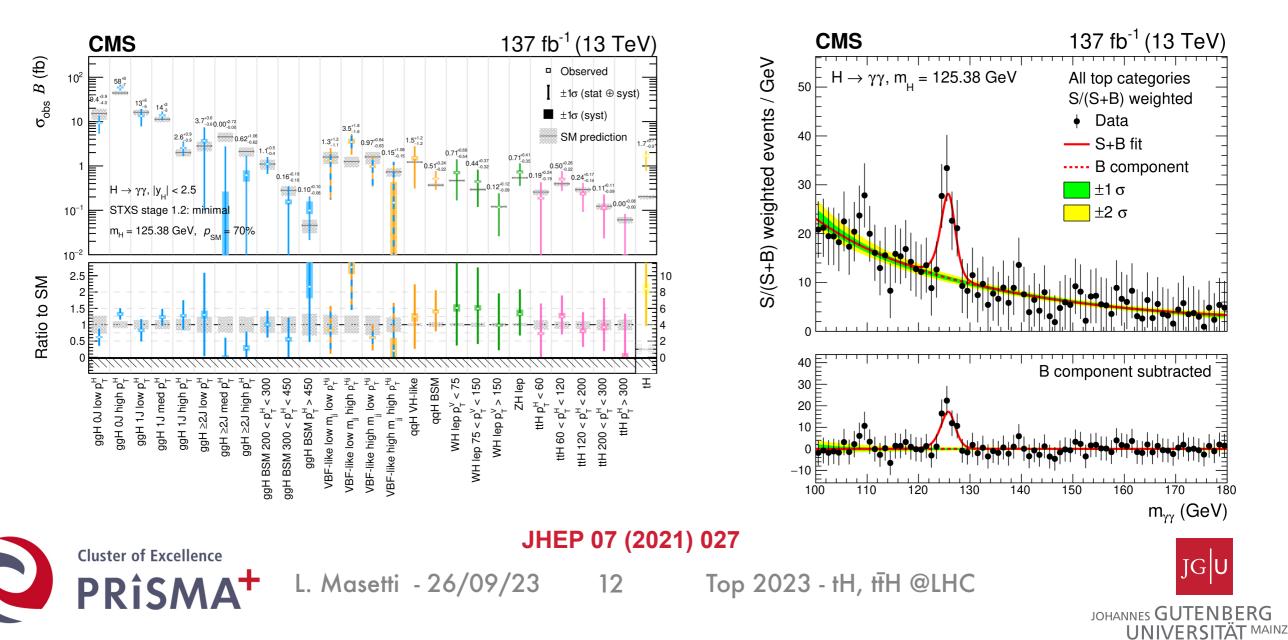
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$H \rightarrow YY$

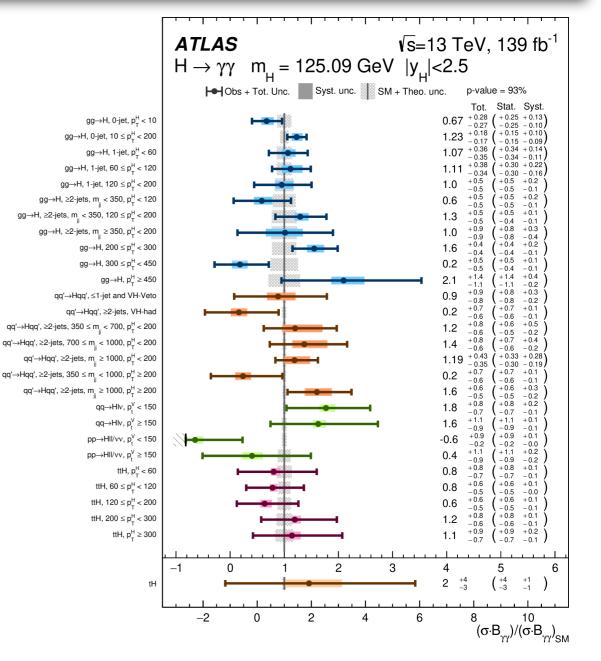
Same decay channel, several production processes

First differential measurement of tFH BDT to distinguish top-associated production from other sources DNN to separate tH from tFH



$H \rightarrow YY$



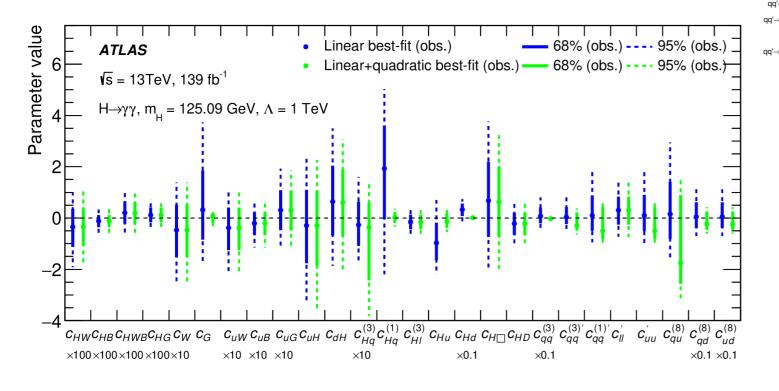


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Multiclass BDT plus binary BDTs within top-associated production categories

SMEFT interpretation additionally to ĸ-framework All results in agreement with SM expectations



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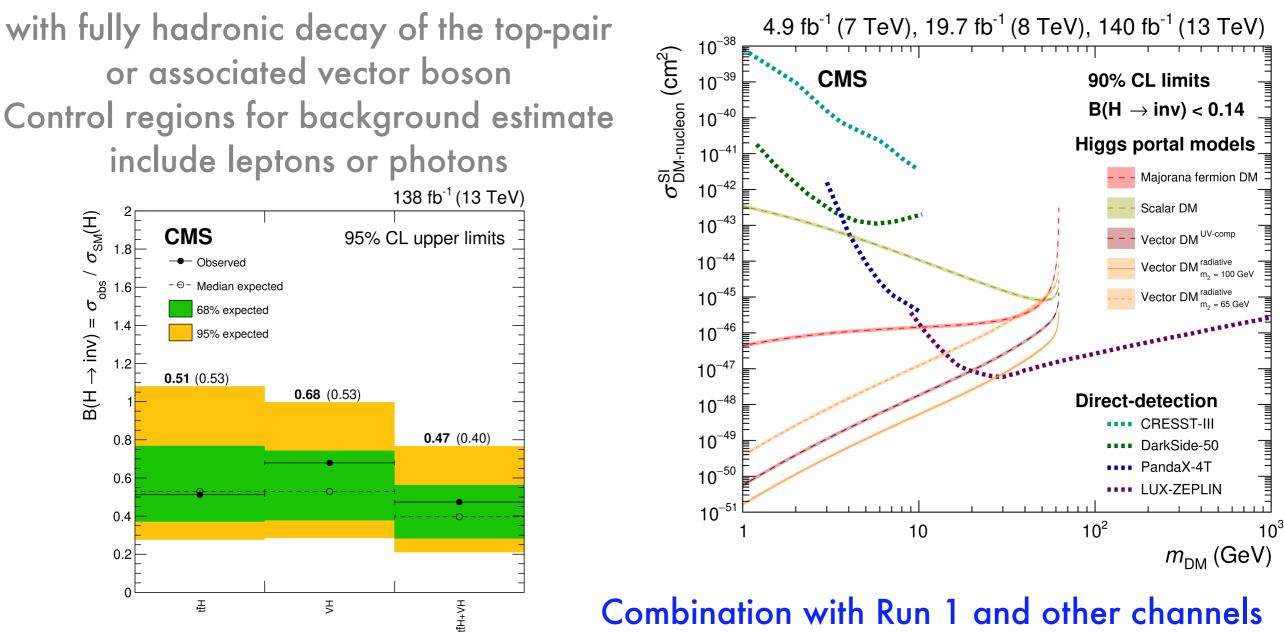
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$H \rightarrow invisible$

arXiv:2303.01214

Search in tTH and VH





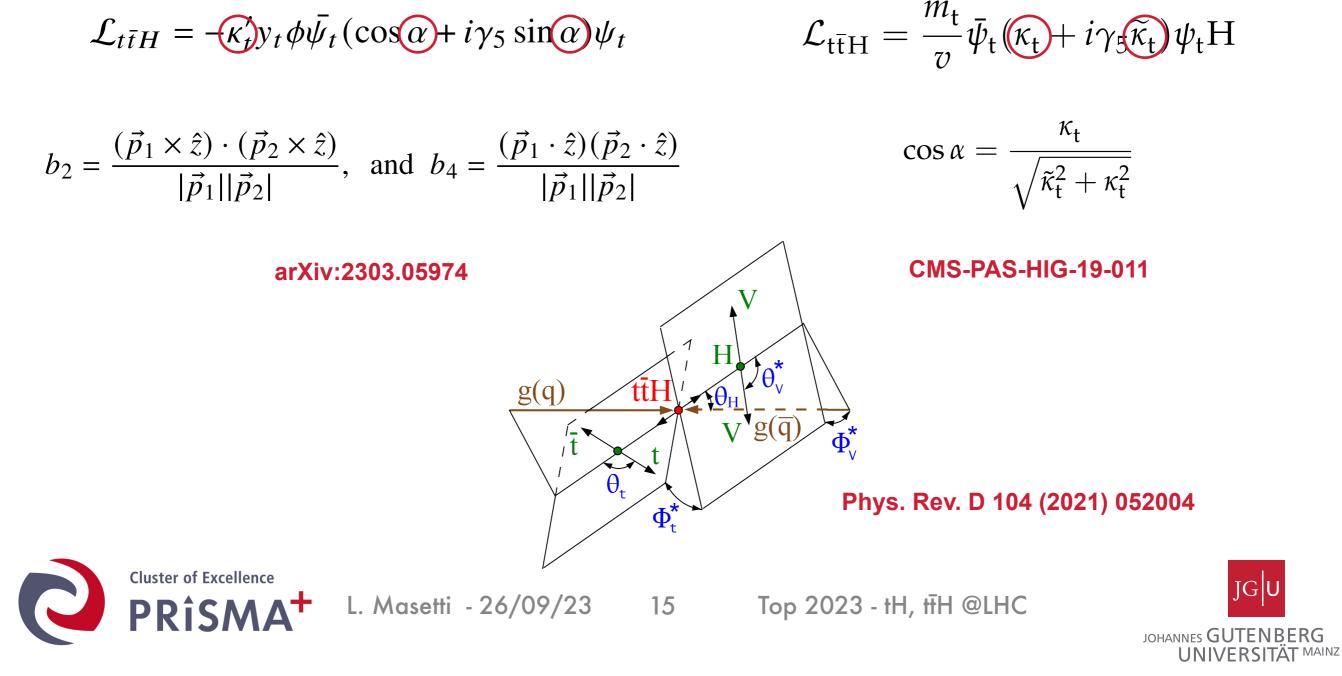
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CP structure

Search for an admixture of a CP-odd component in the top-Higgs coupling Expressed as a coupling modifier κ_t or κ'_t and a mixing angle α Sensitive variables are e.g. relative directions of the top quarks



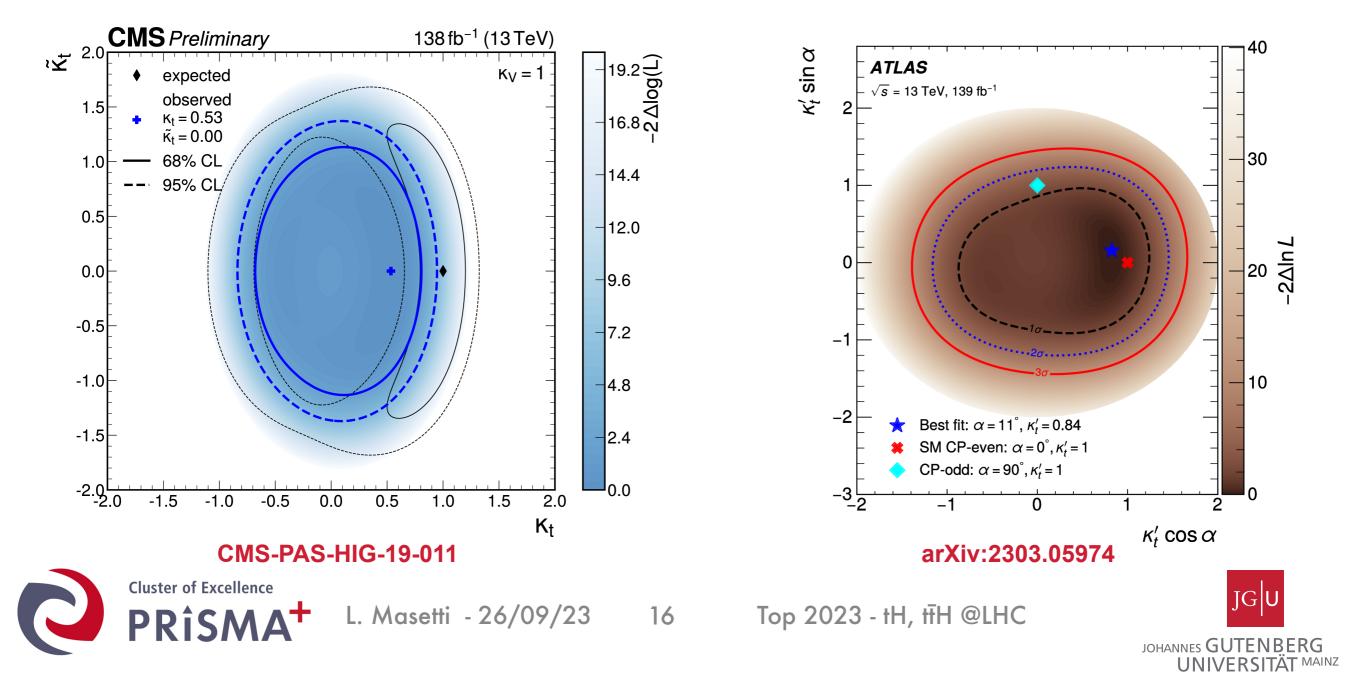


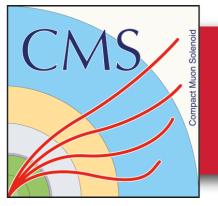
 $H \rightarrow bb$



Dedicated ATLAS result with 1 or 2 leptons

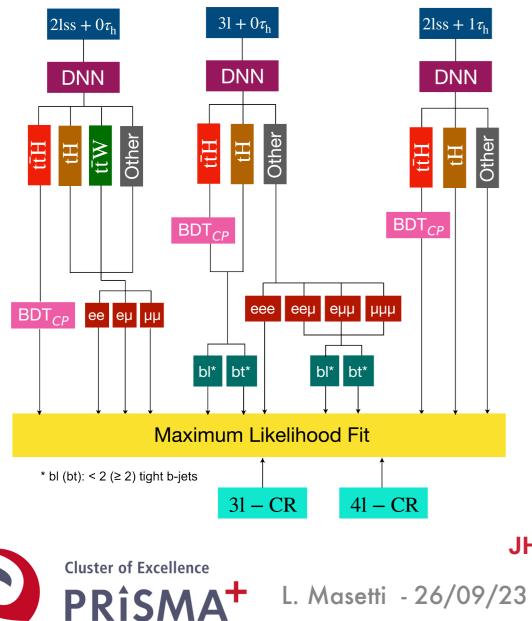
CMS result with same selection as cross section measurement, only leptonic channels Results compatible with pure CP-even coupling structure

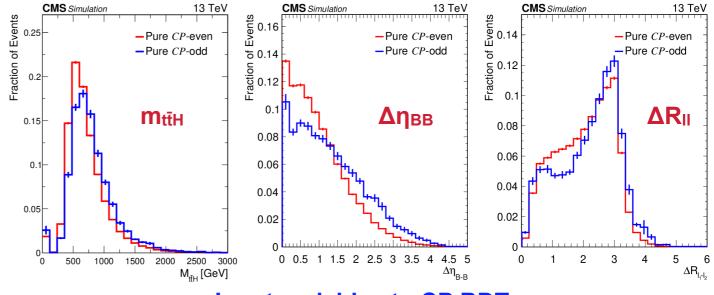




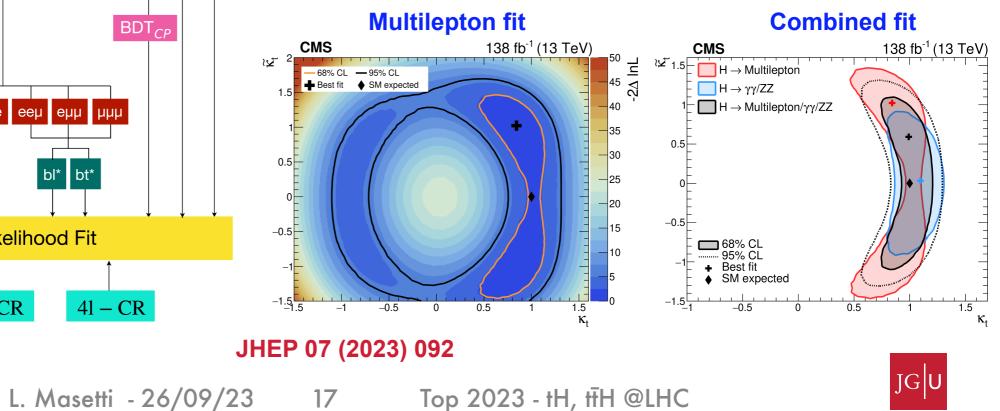
$H \rightarrow \tau \tau \text{ or } H \rightarrow WW$

Dedicated multilepton analysis Results compatible with pure CP-even coupling structure



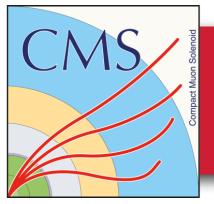


Input variables to CP BDT



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Summary



- tīH and tH
 - Allow for a precise study of the top-Higgs coupling
 - Inclusive and differential cross section measurements compatible with SM predictions
 - In tTH(bb) ATLAS and CMS measure similar $\mu_{\rm tTH},$ <2.40 below SM expectation
 - Heavily using machine learning techniques
 - Better understanding of background necessary to exploit upcoming high statistics datasets

• CP structure of the top-Higgs coupling

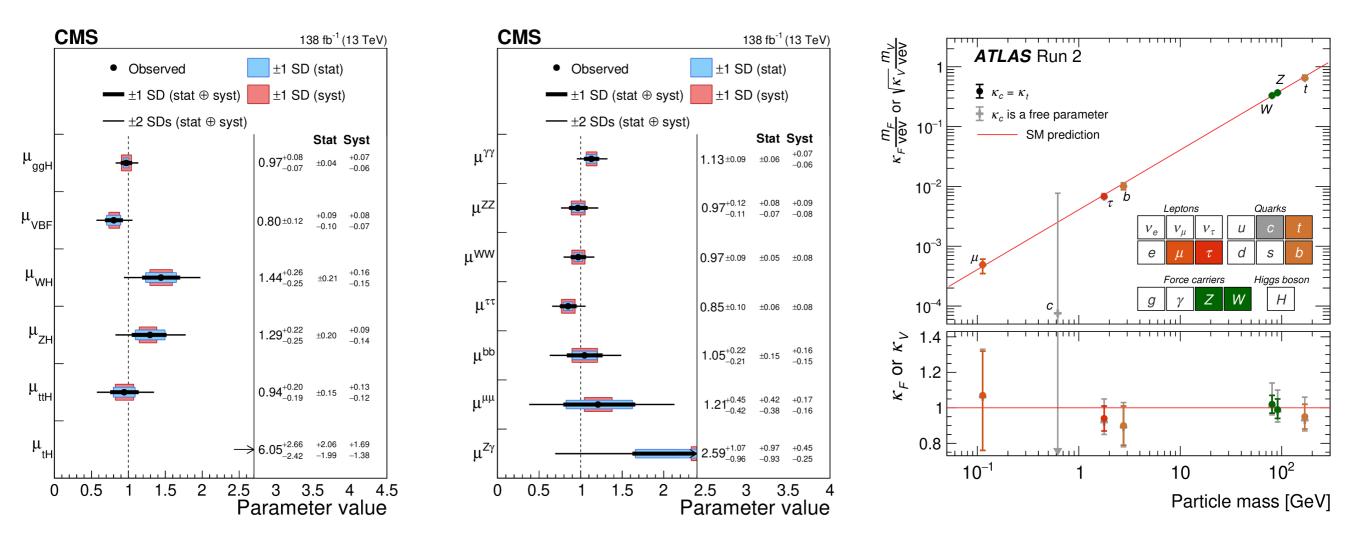
- Has impact on several kinematic distributions
- Searches for admixture of CP-odd component, expressed as mixing angle or fraction
- All results compatible with SM prediction







10 years Higgs boson



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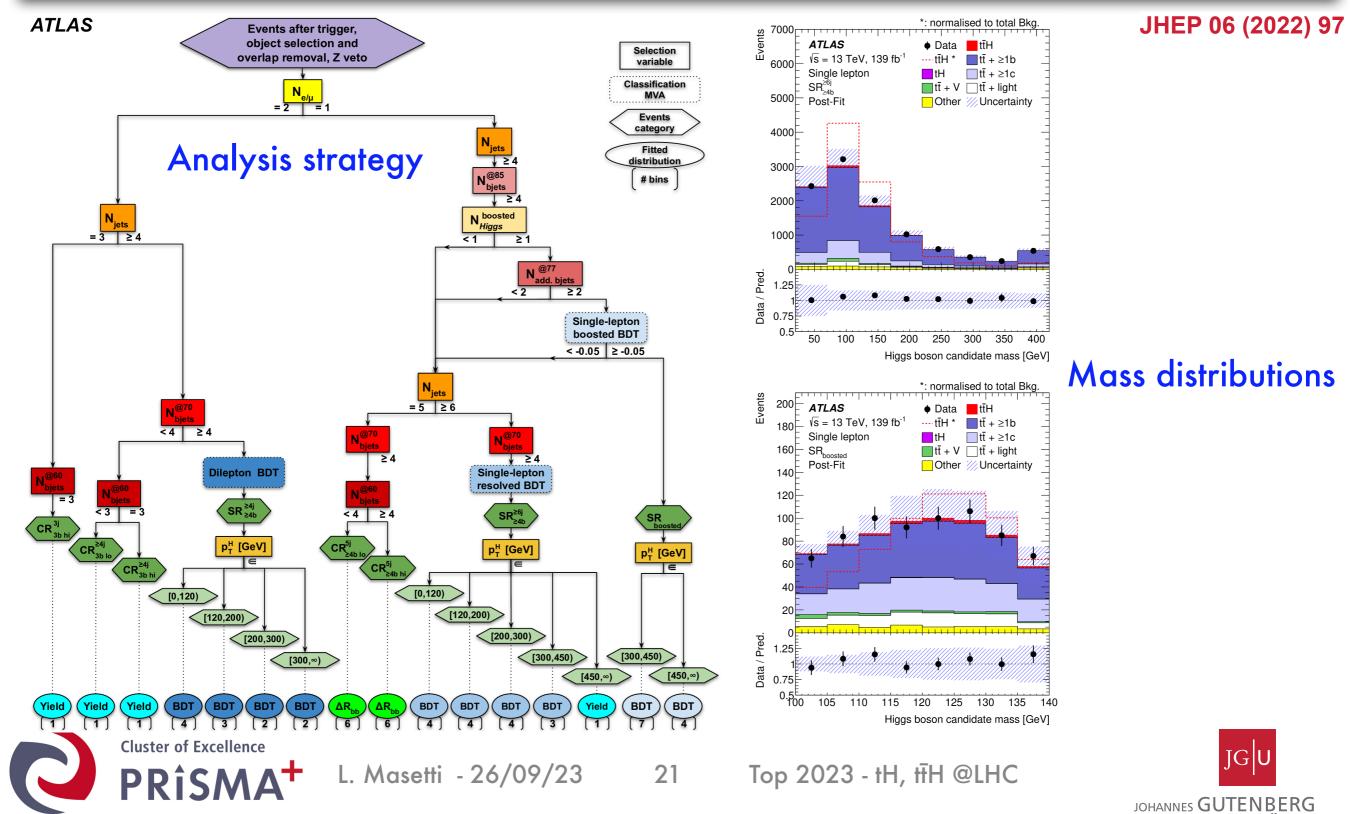


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tīH, H→bb

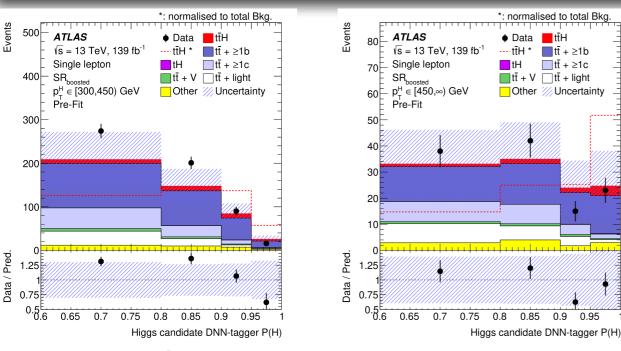


tīH, H→bb

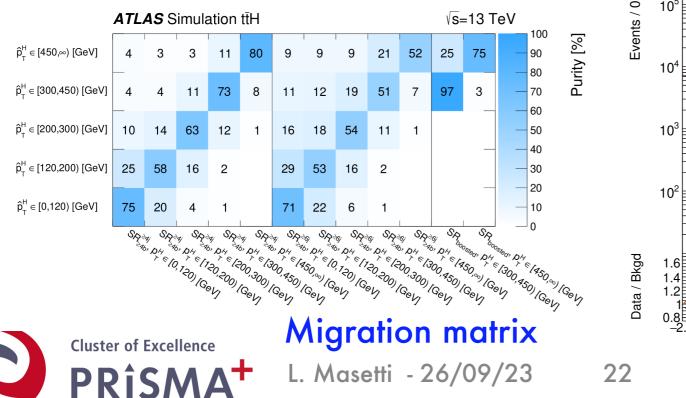


EXPERIME

Uncertainty source	Description		Components
$\begin{array}{l} t\bar{t} \mbox{ cross-section} \\ t\bar{t}+\geq 1b \mbox{ normalisation} \\ t\bar{t}+\geq 1c \mbox{ normalisation} \end{array}$	$\pm 6\%$ Free-floating $\pm 100\%$		$\begin{array}{l} t\bar{t} + \text{light} \\ t\bar{t} + \geq 1b \\ t\bar{t} + \geq 1c \end{array}$
NLO matching PS & hadronisation ISR FSR	MADGRAPH5_AMC@NLO + PYTHI POWHEG BOX + HERWIG 7 vs POWH Varying $\alpha_{\rm s}^{\rm ISR}$ (PS), $\mu_{\rm r} \& \mu_{\rm f}$ (ME) Varying $\alpha_{\rm s}^{\rm FSR}$ (PS)		$ \begin{array}{l} \text{All} \\ \text{All} \\ t\bar{t}+\geq 1b \\ t\bar{t}+\geq 1c, \ t\bar{t}+ \text{light} \\ t\bar{t}+\geq 1b \\ t\bar{t}+\geq 1c, \ t\bar{t}+ \text{light} \end{array} $
$t\bar{t} + \geq 1b$ fractions $p_{\rm T}^{bb}$ shape	Powheg Box + Herwig 7 vs Powh Shape mismodelling measured from	$\begin{array}{l} t\bar{t}+1b,t\bar{t}+\geq\!2b\\ t\bar{t}+\geq\!1b \end{array}$	



Boosted Higgs DNN tagger output



Events / 0.2 10⁵**⊨***ATLAS* Data tτ̄H (μ_{SM}=1.0) $\sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1}$ tīH (μ_{fit}=0.35) Background /// Bkgd Unc. ttH(bb) Combined Single lepton and Dilepton Post-Fit ---- tīH (μ_{SM}=1.0) + Bkgd 1.6⊧ - tīH (μ_=0.35) + Bkgd -1 -0.8 -1.8 -1.6 -1.4 -1.2 -2 $\log_{10}(S/B)$ Top 2023 - tH, tTH @LHC

tī+jets uncertainties

log(S/B) distribution



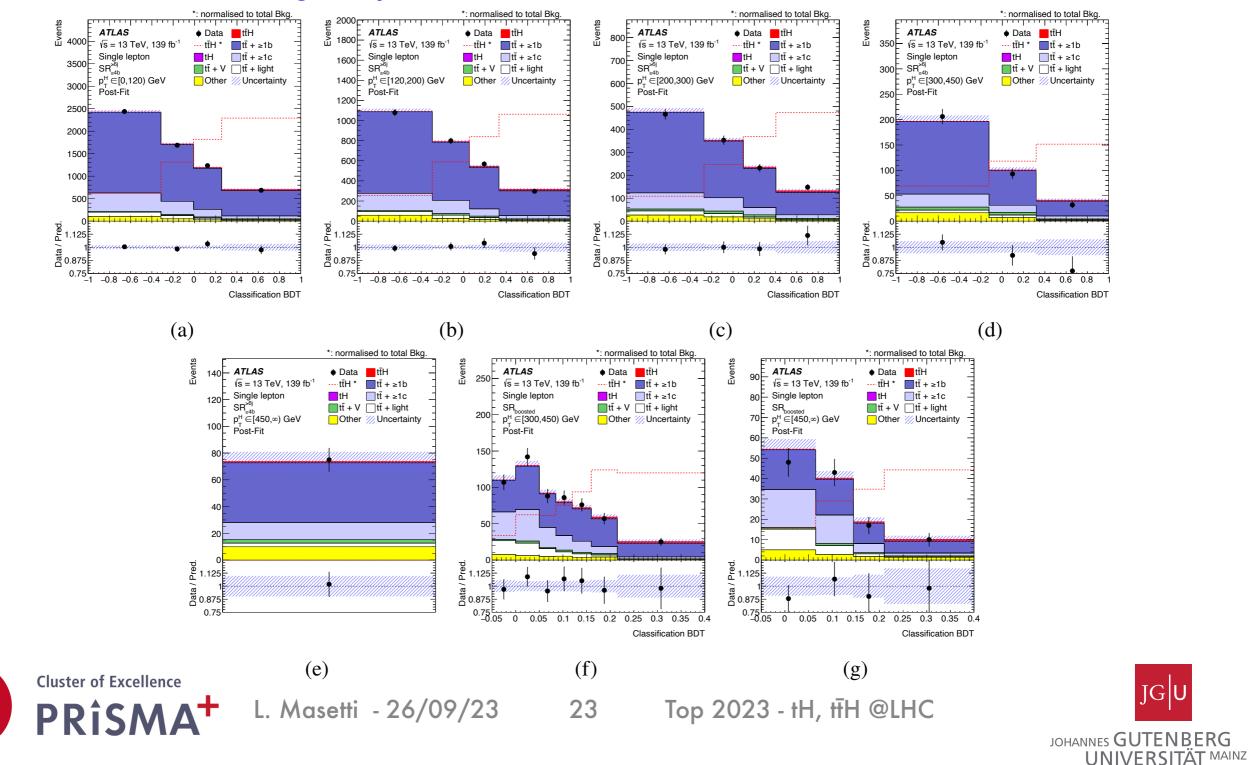
$ttH, H \rightarrow b$

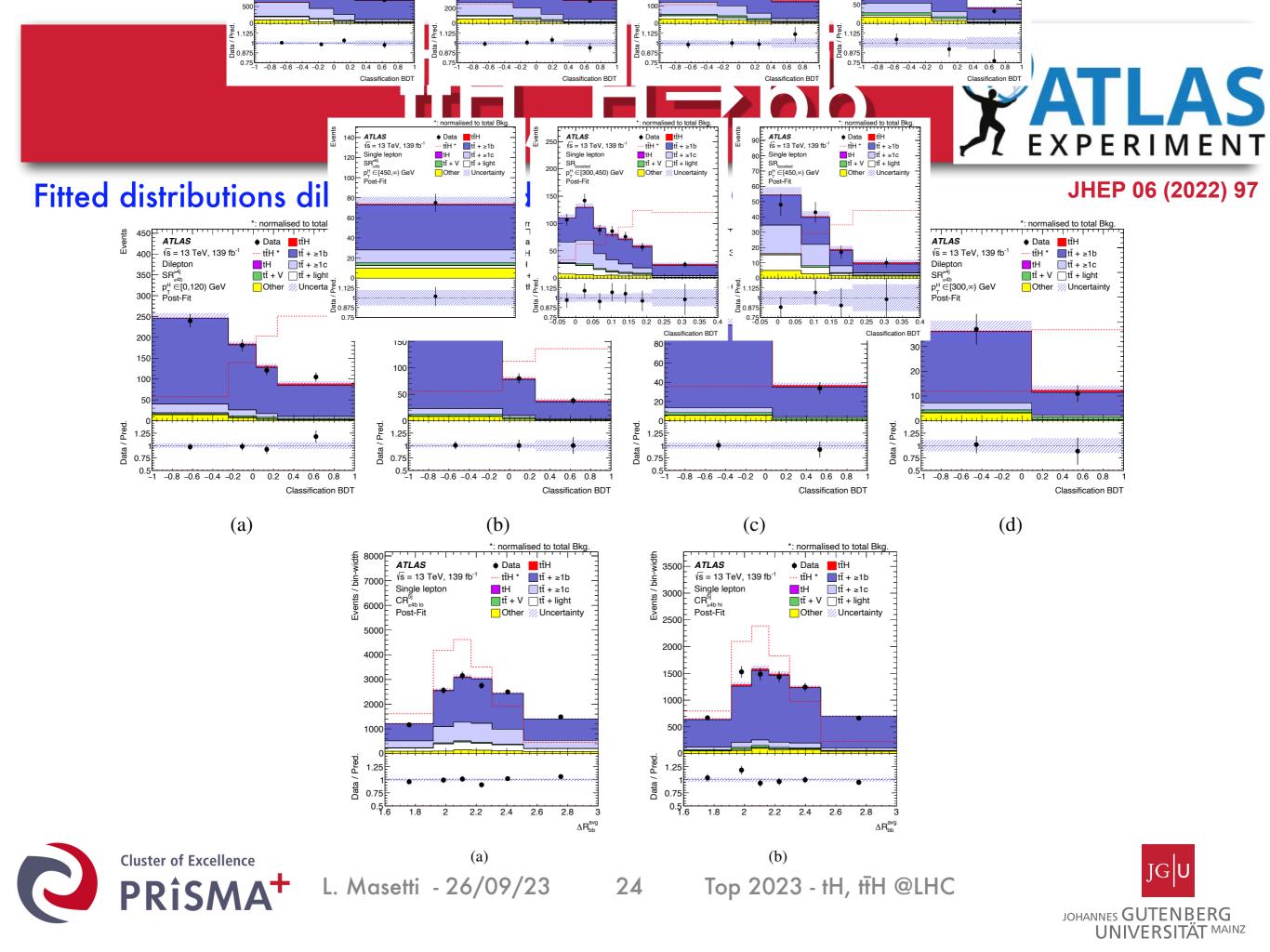


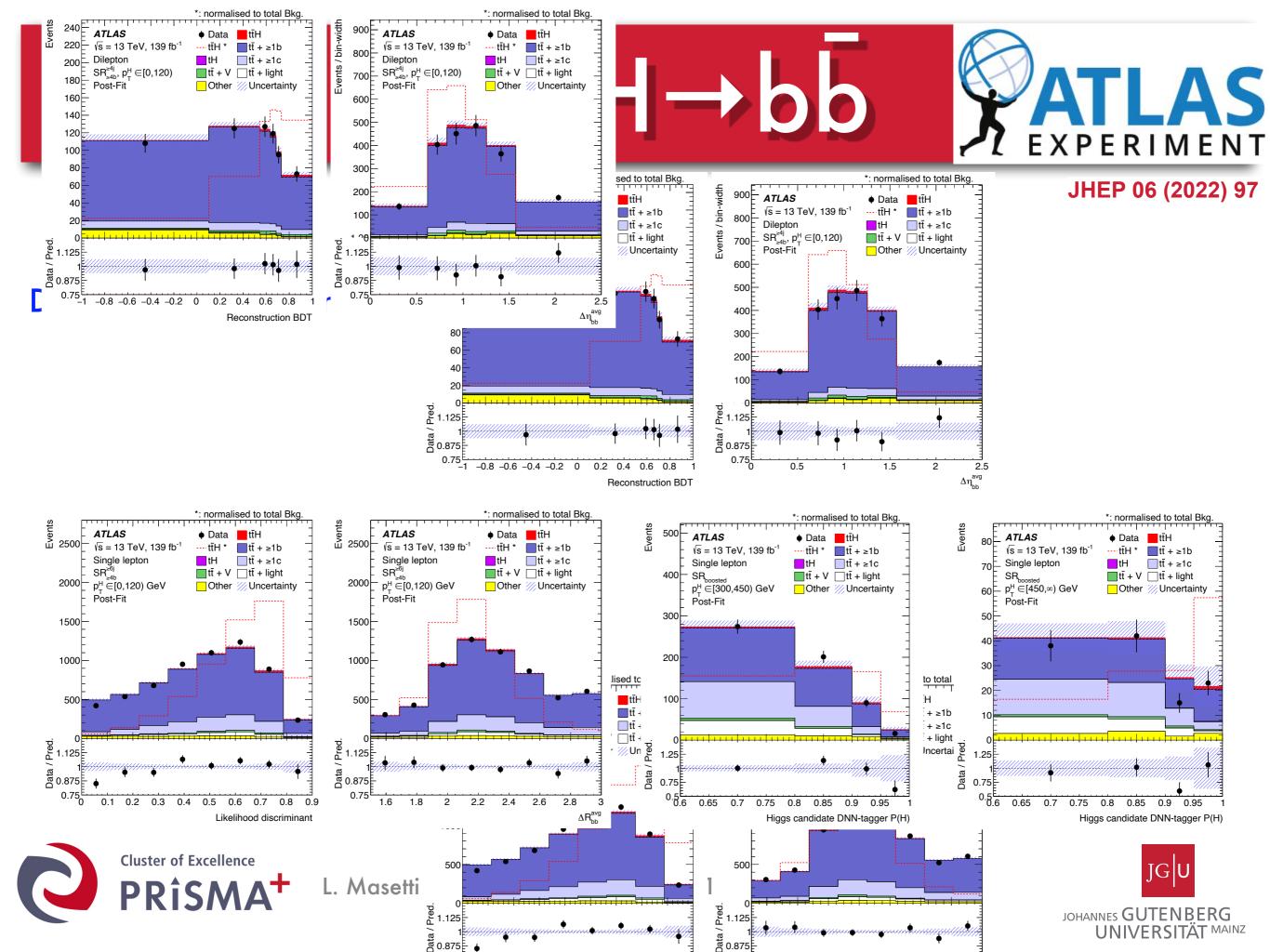
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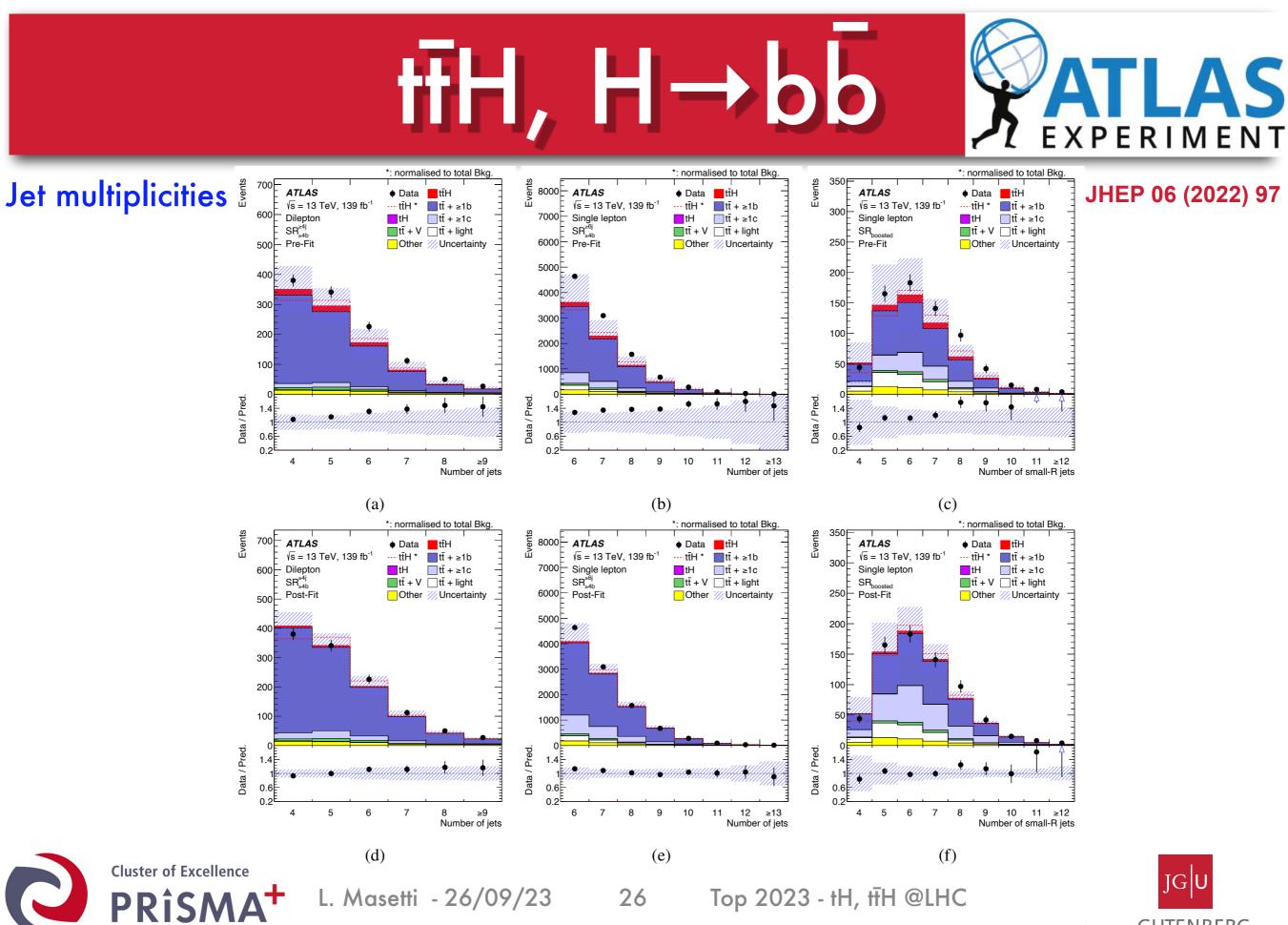
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Fitted distributions single lepton SRs



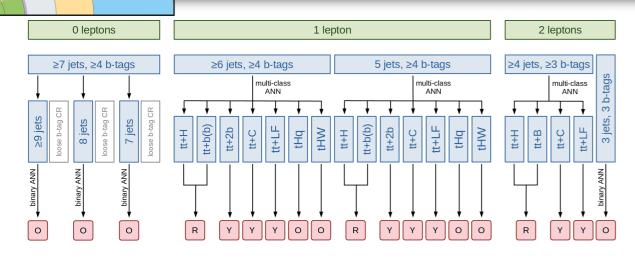






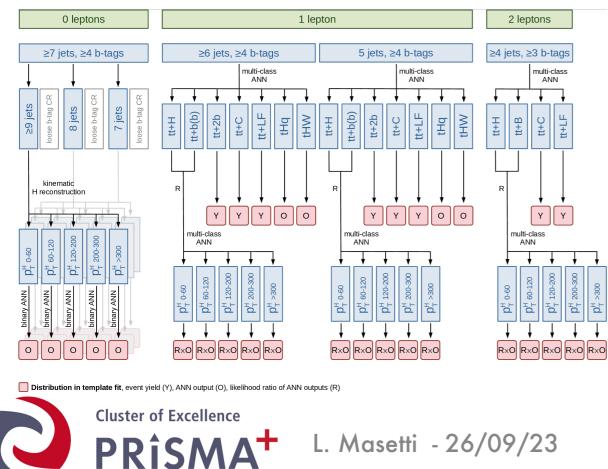
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$f(f)F, F \rightarrow$



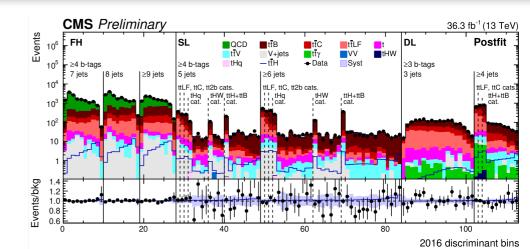
Distribution in template fit, event yield (Y), ANN output (O), likelihood ratio of ANN outputs (R)

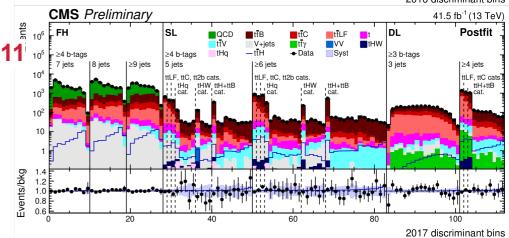
Analysis strategy

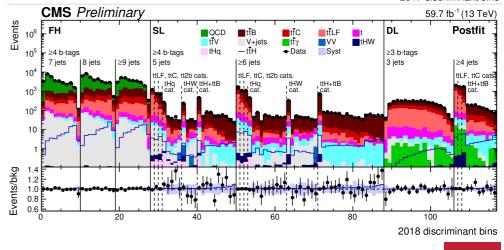


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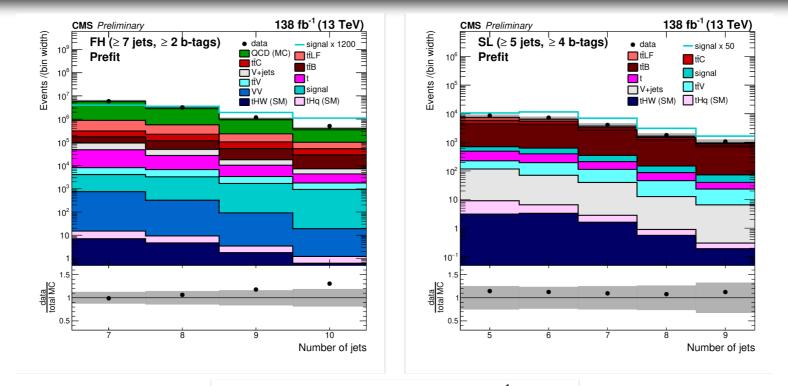


Top 2023 - tH, tTH @LHC

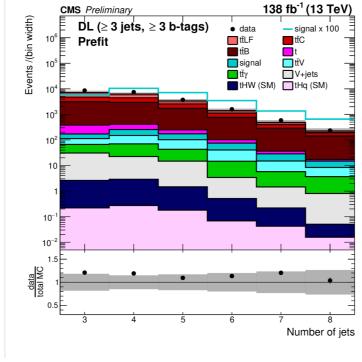


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tīH, H→bb



Jet multiplicities



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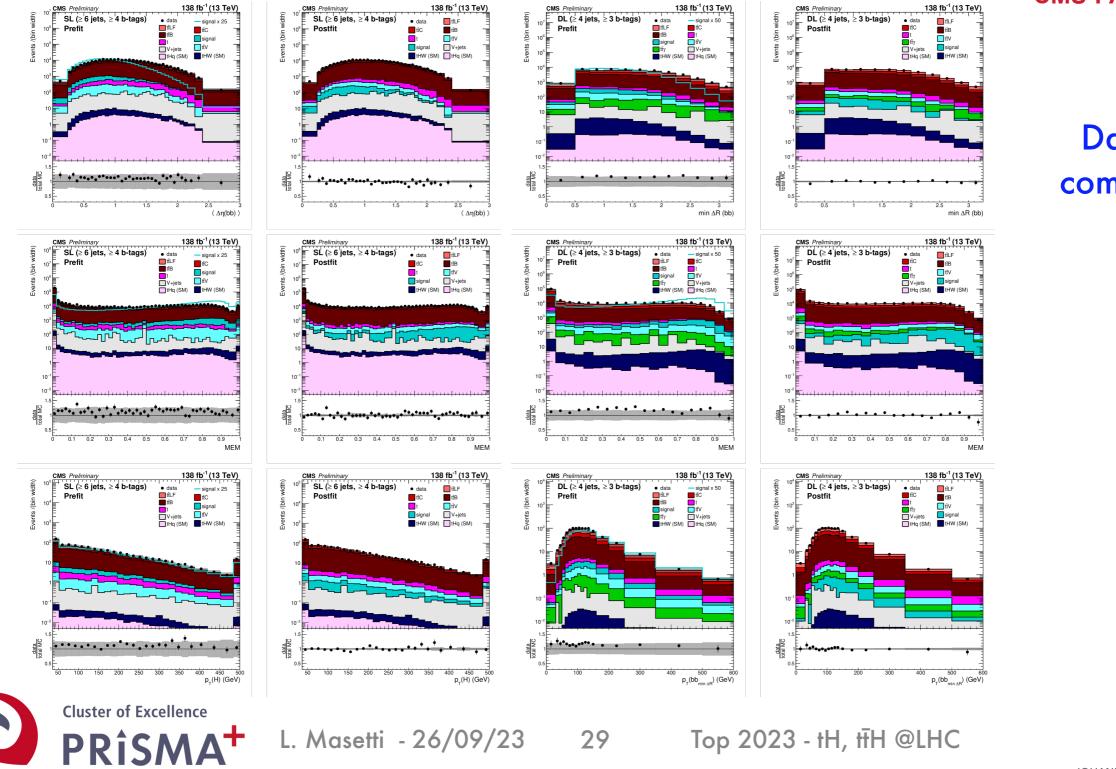
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Top 2023 - tH, tTH @LHC



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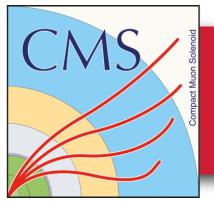
tīH, H→bb



CMS-PAS-HIG-19-011

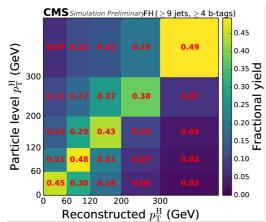
Data/MC comparisons

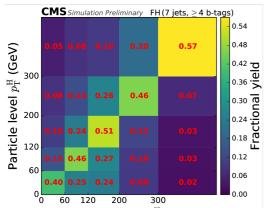
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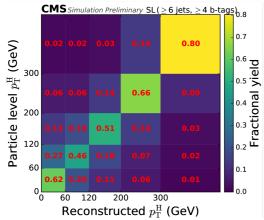
 $H \rightarrow$

Categorisation efficiency

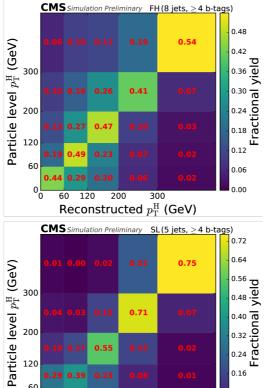




Reconstructed $p_{\rm T}^{\rm H}$ (GeV)



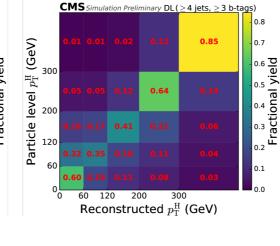
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0.16 0.08 0.00

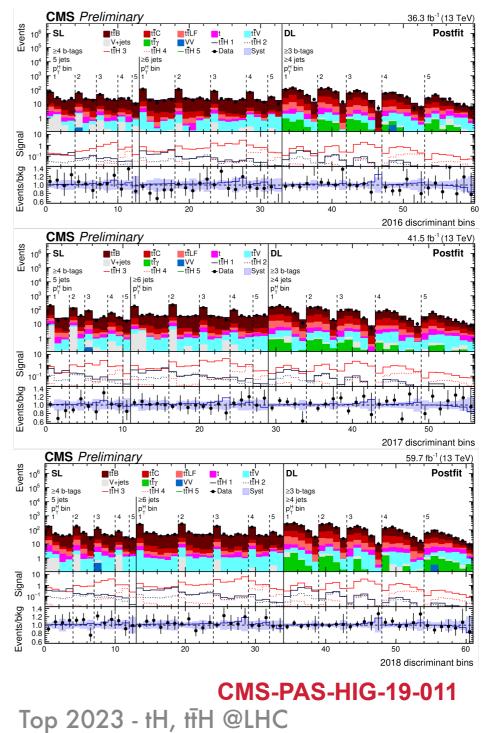
60 120 200 300 Reconstructed $p_{\rm T}^{\rm H}$ (GeV)

60



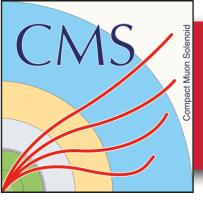
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STXS fit



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 $ttH, H \rightarrow bb$

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Analysis regions

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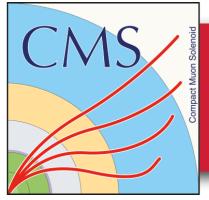
EXPERIMENT

	FH channel	SL channel	DL channel		Dilepton	ΛТ	LAS	Single-lepton	
Number of leptons	0	1	2	Region	$\mathrm{SR}^{\geq 4j}_{\geq 4b}$ $\mathrm{CR}^{\geq 4j}_{3b \mathrm{hi}}$ $\mathrm{CR}^{\geq 4j}_{3b \mathrm{hi}}$	$_{\circ} \operatorname{CR}^{3j}_{3b \operatorname{hi}}$	$\mathrm{SR}^{\geq 6j}_{>4b}$	$CR^{5j}_{>4b \text{ hi}}$ $CR^{5j}_{>4b \text{ lo}}$	$SR_{boosted}$
Sign and flavour of leptons	—	e^{\pm} , μ^{\pm}	$\mathrm{e^+e^-}$, $\mu^\pm\mathrm{e^\mp}$, $\mu^+\mu^-$	//lenteng			_		
Min. $p_{\rm T}$ of leading electron (GeV)	—	29/30/30	25	#leptons	= 2			= 1	
Min. $p_{\rm T}$ of leading muon (GeV)		26/29/26	25	#jets @85%	≥ 4	= 3	≥ 6	=5	≥ 4
Min. $p_{\rm T}$ of additional leptons (GeV)	—		15	@77%			$- \frac{\geq 4}{-} \geq 2^{\dagger}$		$> 2^{\dagger}$
Max. $p_{\rm T}$ of additional leptons (GeV)	15	15	—	#b-tag $@70%$	$ \ge 4 $ $= 3 $			 ≥ 4	
Max. $ \eta $ of leptons	2.4	2.4	2.4	@60%	- = 3 < 3	= 3		≥ 4 ≥ 4	_
Min. $m_{\ell\ell}$ (GeV)	—		20	#boosted cand.				0	≥ 1
$m_{\rm ee/\mu\mu}$ (GeV) CMS		—	< 76 or > 106	Fit input	BDT Yield	[BDT/Yield	$\Delta R_{bb}^{\rm avg}$	BDT
Min. number of jets	7	5	3				/		
Min. $p_{\rm T}$ of jets (GeV)	30	30	30	Leading lepton p _T > 27 GeV					
Min. $p_{\rm T}$ of 6 th jet (GeV)	40		_	Additional lepton p _T > 10 GeV					
Max. $ \eta $ of jets	2.4	2.4	2.4						
Min. number of b-tagged jets	2	4	3	Lepton η < 2.47 (e), 2.5 (μ)					
$m_{\rm qq}~({\rm GeV})$	> 30 and < 250			m∥ > 15 (GeV, m _{ee} /μμ <	< 83 (GeV or	> 99 GeV	7
Min. <i>H</i> _T (GeV)	500		_	Jet p _T > 25 GeV					
Min. $p_{\rm T}^{\rm miss}$ (GeV)	—	20	40	- Jet n < 2.5					
					× 2.J				



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 $H \rightarrow bb$



 $m_{\mathrm{T}}(\bar{t}) \cdot m_{\mathrm{T}}(b) \cdot m_{\mathrm{T}}(\bar{b})$

Top 2023 - tH, tTH @LHC

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Background simulation

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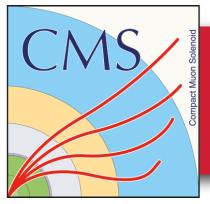
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Process	ME generator	ME PDF	PS	Normalisation
$tar{t}$	Powheg Box v2 Powheg Box v2	NNPDF3.0nlo NNPDF3.0nlo	Pythia 8.230 Herwig 7.04	NNLO+NNLL [45,46,47,48,49,50,51] NNLO+NNLL [45,46,47,48,49,50,51]
$tar{t}+bar{b}$	MADGRAPH5_AMC@NLO 2.6.0 Powheg Box Res	NNPDF3.0nlo NNPDF3.0nlo nf4	Рутніа 8.230 Рутніа 8.230	NNLO+NNLL [45,46,47,48,49,50,51]
	SHERPA 2.2.1	NNPDF3.0NNLO nf4	Sherpa	_ ATLAS

	t ī sample	$t\bar{t}b\bar{b}$ sample	
POWHEG version	Powheg v2	Powheg-Box-Res	
PYTHIA version	8.230	8.230	
Flavour scheme	5	CMS 4	
PDF set	NNPDF3.1	NNPDF3.1	
m _t	172.5 GeV	172.5 GeV	
m _b	0	4.75 GeV	
$\mu_{ m R}$	$\sqrt{\frac{1}{2}\left(m_{\mathrm{T,t}}^2+m_{\mathrm{T,\bar{t}}}^2\right)}$	$\frac{1}{2}\sqrt[4]{m_{\mathrm{T,t}}\cdot m_{\mathrm{T,\bar{t}}}\cdot m_{\mathrm{T,b}}\cdot m_{\mathrm{T,\bar{b}}}}$	$0.5 \times \Sigma_{i=t,\bar{t},b}$
$\mu_{ m F}$	$\mu_{ m R}$	$\frac{\frac{1}{2}\sqrt[4]{m_{\mathrm{T,t}} \cdot m_{\mathrm{T,\bar{t}}} \cdot m_{\mathrm{T,b}} \cdot m_{\mathrm{T,\bar{b}}}}}{\frac{1}{4}\left[m_{\mathrm{T,t}} + m_{\mathrm{T,\bar{t}}} + m_{\mathrm{T,b}} + m_{\mathrm{T,\bar{b}}} + m_{\mathrm{T,g}}\right]}$	$\sqrt[4]{m_{\mathrm{T}}(t)\cdot m_{\mathrm{T}}(\overline{t})\cdot m_{\mathrm{T}}(\overline$
h _{damp}	$1.379 \cdot m_{\rm t}$	$1.379 \cdot m_{\rm t}$	$0.5 \times \Sigma_{i=t,\bar{t},k}$
Tune	CP5	CP5	A14

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tfH, H→bb



CMS-PAS-HIG-19-011

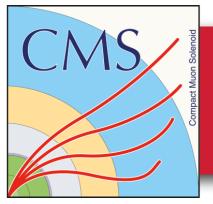
Systematic uncertainties on tī+≥1b

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Source	Туре	Correlation	Remarks				
Renorm./fact. scales	R	correlated	Scale uncertainty of (N)NLO prediction, indepen- dent for tīH, tHq, tHW, tī, t, V+jets, VV				
Collinear gluon splitting [†]	S	correlated	Additional 100% rate uncertainty on $t\bar{t} + 2b$ component of $t\bar{t}B$ background	Uncertainty source	Description		Components
$\mu_{\rm R}$ scale	S	correlated	Renormalisation scale uncertainty of the ME gen- erator, independent for $t\bar{t}H$, tHq , tHW , $t\bar{t}B$ ($t\bar{t}b\bar{b}$ sample), other $t\bar{t}$ ($t\bar{t}$ sample)	$t\bar{t}$ cross-section $t\bar{t} + \geq 1b$ normalisation	±6% ATL	AS	$t\bar{t} + ext{light}$ $t\bar{t} + \ge 1b$ $t\bar{t} + \ge 1$
$\mu_{\rm F}$ scale	S	correlated	Factorisation scale uncertainty of the ME gener- ator, independent for $t\bar{t}H$, tHq , tHW , $t\bar{t}B$ ($t\bar{t}b\bar{b}$	$t\bar{t} + \geq 1c$ normalisation	±100%		$t\bar{t} + \ge 1c$
0140			sample), other tī (tī sample) From NNPDF variations, independent for tHq,	NLO matchingMADGRAPH5_AMC@NLO + PYTHIA 8 vs POWHEG BOX + PPS & hadronisationPOWHEG BOX + HERWIG 7 vs POWHEG BOX + PYTHIA 8			All All
tHW, $t\bar{t}B$ ($t\bar{t}b\bar{b}$ sample), other	S	correlated		PS & hadronisation		in Powheg Box Res + Pythia 8	$t\bar{t} + \geq 1b$
	tHW, tt B (tt b b sample), other tt (tt sample) and tt H	ISR	Varying $\alpha_{\rm s}^{\rm ISR}$ (PS), $\mu_{\rm r} \& \mu_{\rm f}$ (ME)	in Powheg Box + Pythia 8	$t\bar{t} + \geq 1b$ $t\bar{t} + \geq 1c, t\bar{t} + \text{light}$		
PS scale ISR [†]	S	correlated	Initial state radiation uncertainty of the PS (PYTHIA), independent for $t\bar{t}H$, $t\bar{t}B$ ($t\bar{t}b\bar{b}$ sam-	FSR	Varying $\alpha_{\rm s}^{\rm FSR}$ (PS)	in Powheg Box Res + Pythia 8 in Powheg Box + Pythia 8	$ \begin{aligned} t\bar{t} + \geq & 1b \\ t\bar{t} + \geq & 1c, \ t\bar{t} + \text{light} \end{aligned} $
PS scale FSR [†]	S	correlated	ple), other tt̄ (tt̄ sample) Final state radiation uncertainty of the PS	$t\bar{t} + \geq 1b$ fractions	Powheg Box + Herwig 7 vs Powheg Box + Pythia 8		$t\bar{t}+1b, t\bar{t}+\geq 2b$
	5	correlated	(PYTHIA), independent for $t\bar{t}H$, $t\bar{t}B$ ($t\bar{t}b\bar{b}$ sam-	p_{T}^{bb} shape	Shape mismodelling measured from	m data	$t\bar{t} + \ge 1b$
ME-PS matching $(t\bar{t})^{\dagger}$	R	correlated	ple), other tt (tt sample) NLO ME-PS matching (for tt + jets events), inde- pendent for tt B, tt C, tt LF				
Underlying event $(t\bar{t})$	R	correlated	Underlying event (for all $t\bar{t}$ + jets events)				







tīH, H→bb



CMS-PAS-HIG-19-011

Impact of systematic uncertainties

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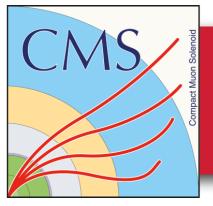
Uncertainty source	$\Delta \mu_{t\bar{t}H}$ (observed)	$\Delta \mu_{t\bar{t}H}$ (expected)
Total experimental	+0.10/-0.10	+0.11/-0.10
jet energy scale and resolution	+0.08/-0.07	+0.09/-0.09
b tagging	+0.07/-0.06	+0.06/-0.02
luminosity	+0.02/-0.02	+0.01/-0.01
Total theory	+0.1(/-0.1(
Total theory	+0.16/-0.16	+0.18/-0.14
t \overline{t} + jets background	+0.15/-0.16	+0.12/-0.11
signal modelling	+0.06/-0.01	+0.13 / -0.06
Size of the simulated event samples	+0.13/-0.12	+0.10/-0.10
Total systematic	+0.20/-0.21	+0.23/-0.19
Statistical	+0.17/-0.16	+0.17/-0.17
background normalisation	+0.13/-0.13	+0.13 / -0.13
$t\bar{t}B$ and $t\bar{t}C$ normalisation	+0.12/-0.12	+0.12/-0.12
QCD normalisation	+0.01/-0.01	+0.01/-0.01
Total	+0.26/-0.26	+0.28/-0.25

Uncertainty source	$\Delta \mu$		
Process modelling			
$t\bar{t}H$ modelling	+0.13	-0.05	
$t\bar{t} + \geq 1b \mod ling$			
$t\bar{t} + \geq 1b$ NLO matching	+0.21	-0.20	
$t\bar{t} + \geq 1b$ fractions	+0.12	-0.12	
$t\bar{t} + \geq 1b \; \mathrm{FSR}$	+0.10	-0.11	
$t\bar{t} + \geq 1b \text{ PS }\&$ hadronisation	+0.09	-0.08	
$t\bar{t} + \geq 1b \ p_{\rm T}^{bb}$ shape	+0.04	-0.04	
$t\bar{t} + \geq 1b$ ISR	+0.04	-0.04	
$t\bar{t} + \geq 1c \mod ATLAS$	+0.03	-0.04	
$t\bar{t} + \text{light modelling}$	+0.03	-0.03	
tW modelling	+0.08	-0.07	
Background-model statistical uncertainty	+0.04	-0.05	
b-tagging efficiency and mis-tag rates			
b-tagging efficiency	+0.03	-0.02	
c-mis-tag rates	+0.03	-0.03	
<i>l</i> -mis-tag rates	+0.02	-0.02	
Jet energy scale and resolution			
<i>b</i> -jet energy scale	+0.00	-0.01	
Jet energy scale (flavour)	+0.01	-0.01	
Jet energy scale (pile-up)	+0.00	-0.01	
Jet energy scale (remaining)	+0.01	-0.01	
Jet energy resolution	+0.02	-0.02	
Luminosity	+0.01	-0.00	
Other sources	+0.03	-0.03	
Total systematic uncertainty	+0.30	-0.28	
$t\bar{t} + \geq 1b$ normalisation	+0.04	-0.07	
Total statistical uncertainty	+0.20	-0.20	
Total uncertainty	+0.36	-0.34	



Top 2023 - tH, tTH @LHC







STXS bins

ggH $= ggH + gg \rightarrow Z(q\bar{q})H + b\bar{b}H$ $= VBF + q\bar{q} \rightarrow V(q\bar{q})H$ qqH $p_{\mathrm{T}}^{\mathrm{H}}$ [0, 200] $p_{\mathrm{T}}^{\mathrm{H}}\left[\mathbf{200},\mathbf{\infty}
ight]$ \geq 2-jet = 0-jet = 1-jet \geq 2-jet 200= 0-jet = 1-jet $p_{\mathrm{T}}^{\mathrm{H}}$ $m_{
m jj}$ [350, ∞] $m_{
m jj}$ [0, 350] 300 0 m_{jj} $m_{
m jj}$ [0,350] $m_{
m jj}$ [350, ∞] 0 $p_{\rm T}^{\rm H}$ [0, 200] $p_{\mathrm{T}}^{\mathrm{H}}\left[\mathbf{200},\mathbf{\infty}
ight]$ $m_{\rm jj}$ 450 $p_{\mathrm{T}}^{\mathrm{H}}$ 10 $m_{
m jj}$ 350 60 650 qqHrest35060 700120 ∞ 700 $p_{\mathrm{T}}^{\mathrm{H}}$ ∞ 120350250 ∞ ∞ $p_{\mathrm{T}}^{\mathrm{Hjj}}$ $\begin{array}{c} \mathbf{25} \\ p_{\mathrm{T}}^{\mathrm{Hjj}} \end{array}$ 0 ∞ 200 tīH VH = V(leptons)H0 $p_{\rm T}^{\rm V}$ $q\bar{q} \to ZH$ $\mathrm{gg} \to \mathrm{ZH}$ $q\bar{q}' \to WH$ tH 60 0 120tHq $p_{\rm T}^{\rm H}$ $\mathbf{75}$ 200tHW 150 \geq 1-jet 0-jet \geq 1-jet 0-jet \geq 1-jet 0-jet 300 $\mathbf{250}$ ∞ ∞ **Cluster of Excellence**

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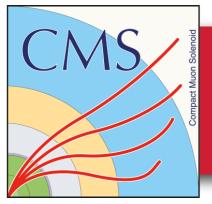
Top 2023 - tH, tTH @LHC

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PR^îSMA⁺



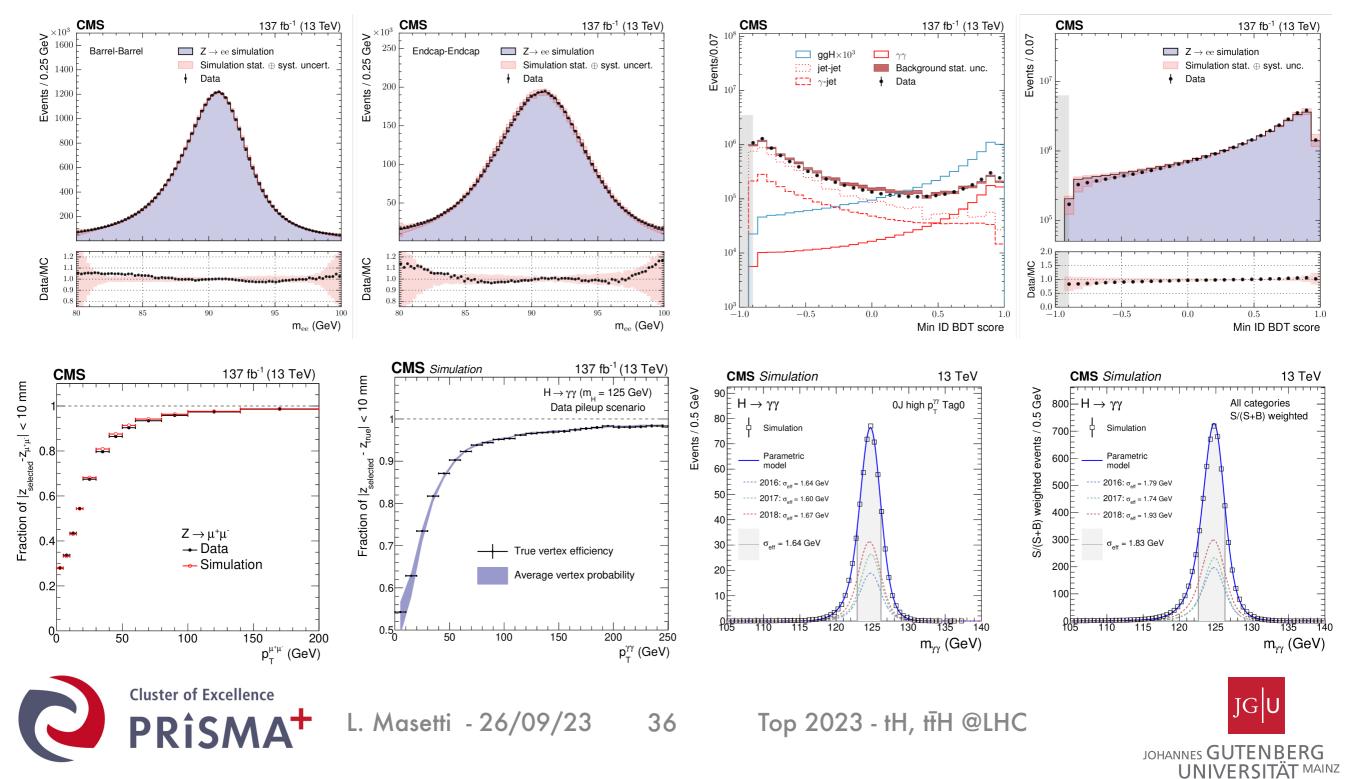
JHEP 07 (2021) 027

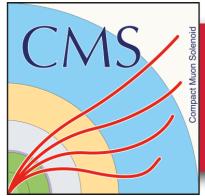


$H \rightarrow YY$

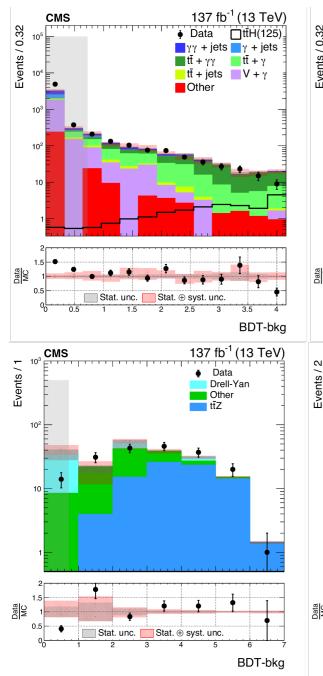
Photons, vertices and mass

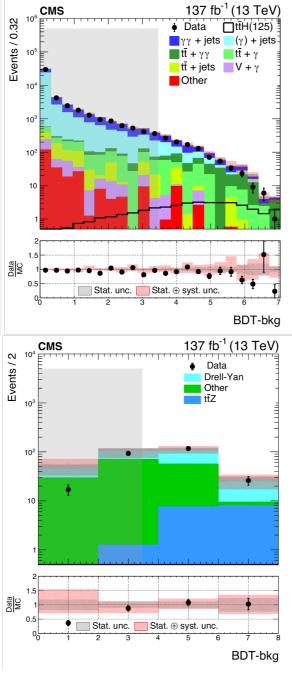
JHEP 07 (2021) 027





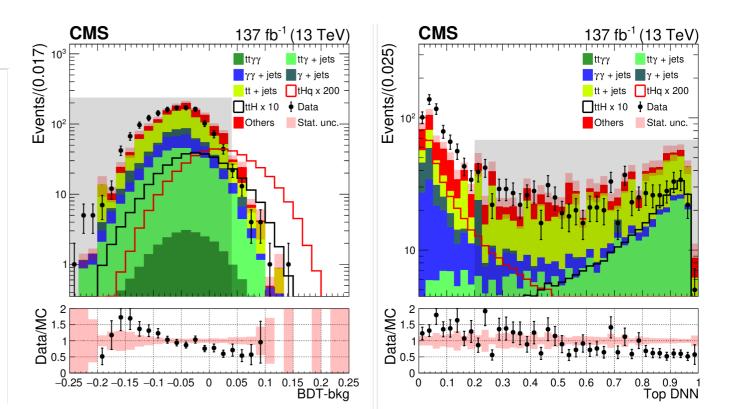
$H \rightarrow YY$





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37 Top 2

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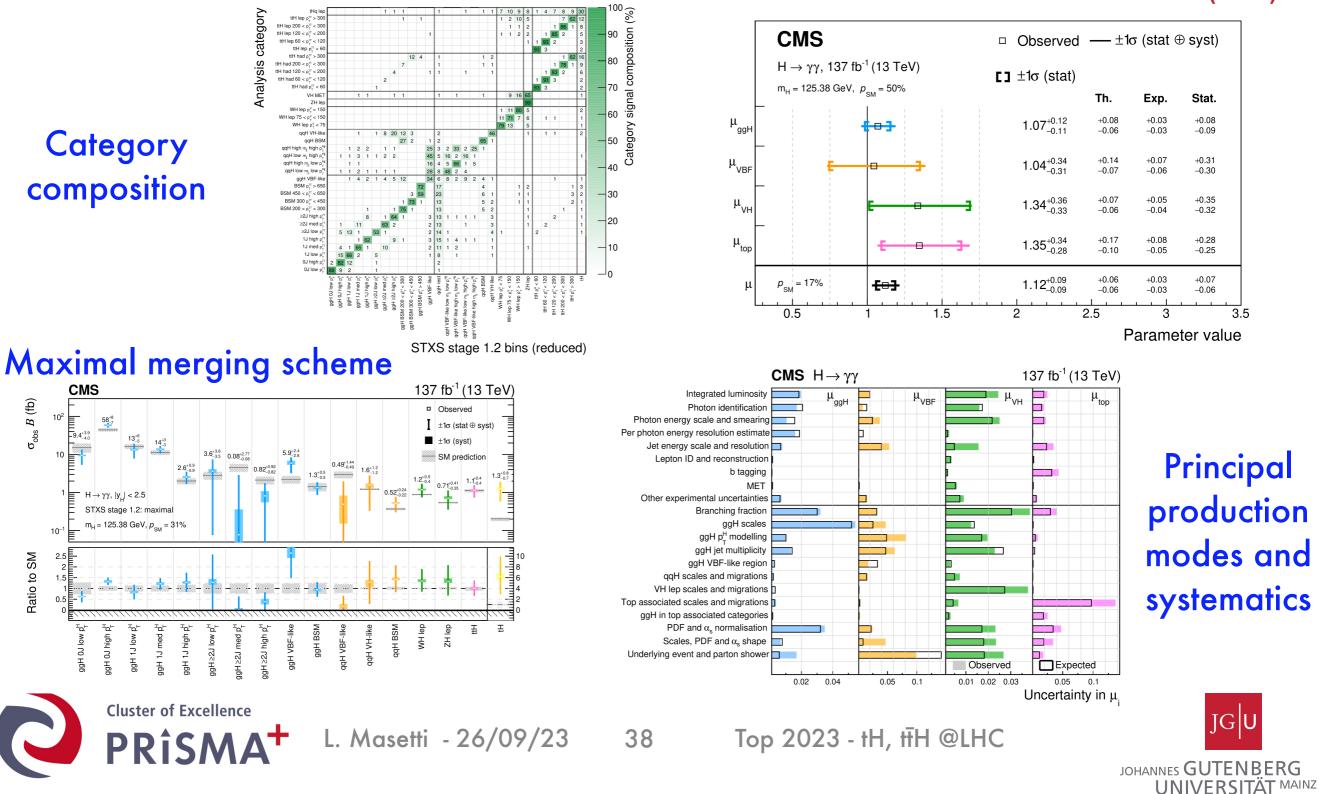


$H \rightarrow YY$

(13 TeV)

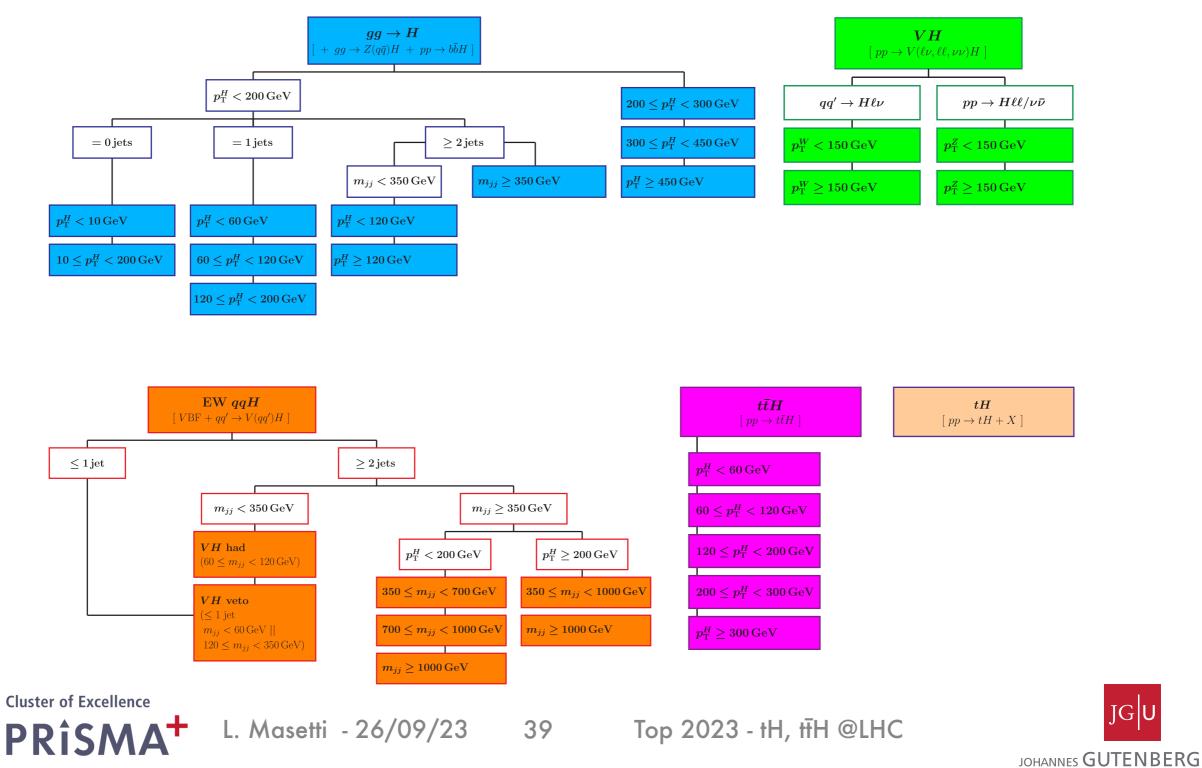
CMS Simulation $H \rightarrow \gamma \gamma$

JHEP 07 (2021) 027





STXS bins



JHEP 07 (2023) 088

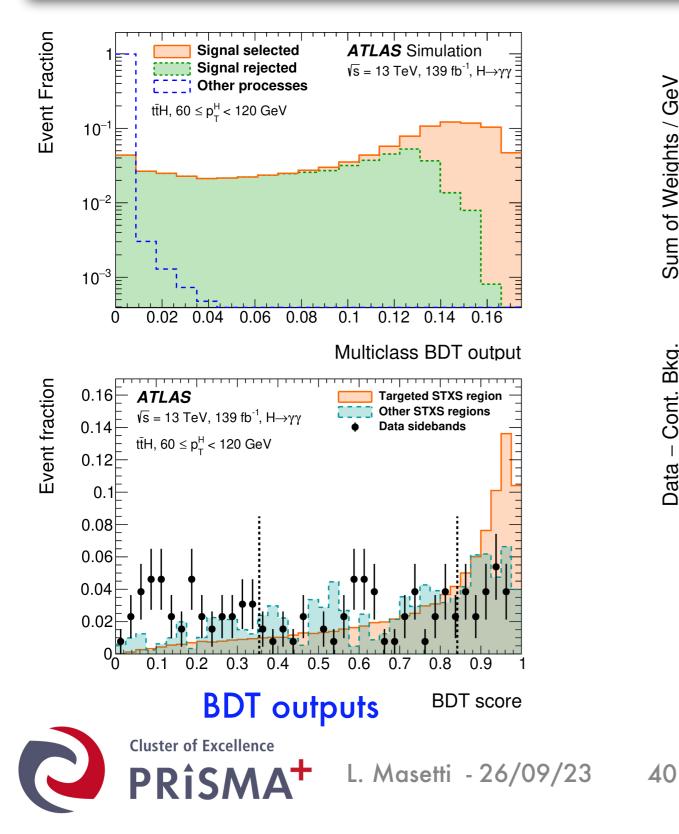
JGU

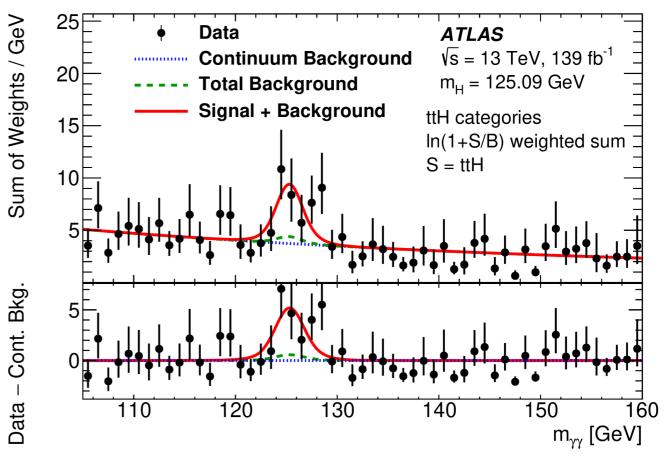
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JHEP 07 (2023) 088





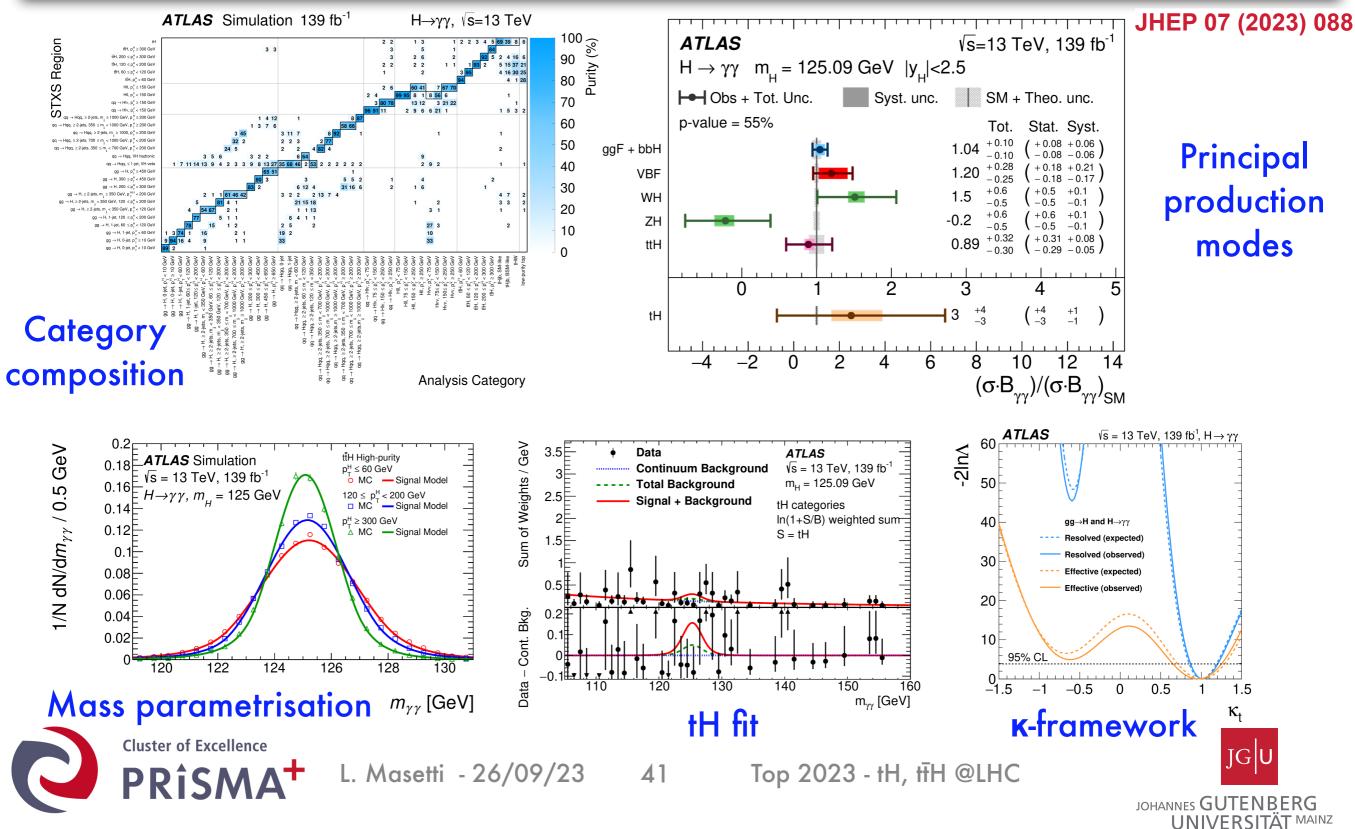
Fit to data including background estimate

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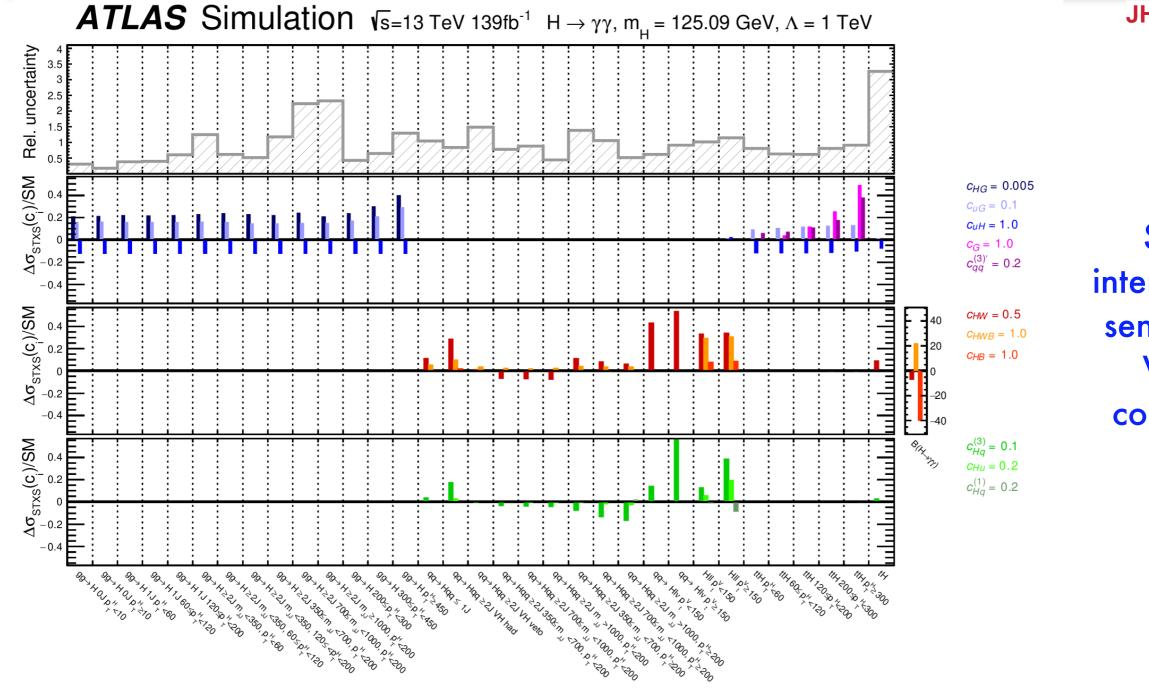


 $H \rightarrow YY$









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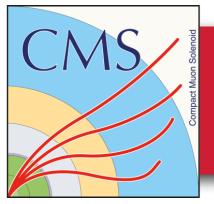
SMEFT interpretaion: sensitivity to Wilson coefficients



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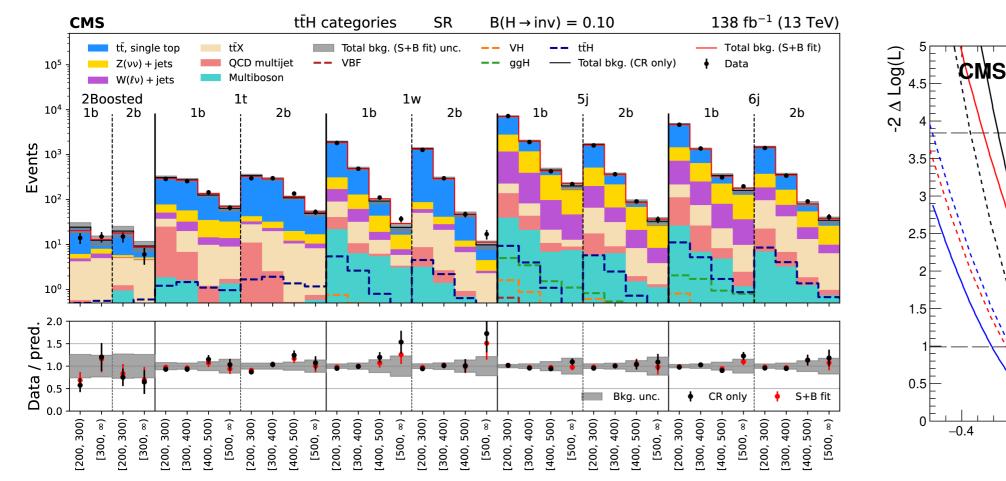




H→invisible

arXiv:2303.01214

138 fb⁻¹ (13 TeV)



Hadronic recoil (GeV)

SR distributions

Likelihood curves

0.2

0.4

∙tī̇H+VH obs

• tīH obs • VH obs

ttH+VH exp
ttH exp

VH exp

0

-0.2



43

Top 2023 - tH, tTH @LHC

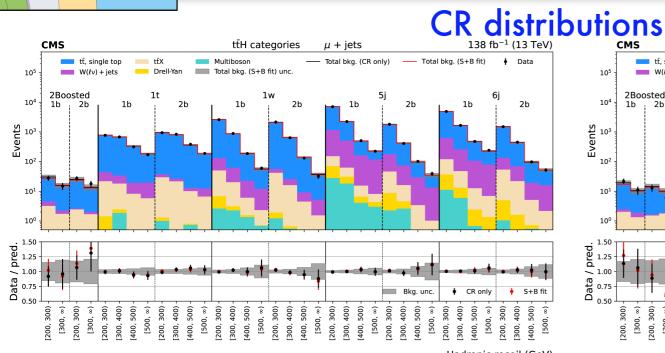


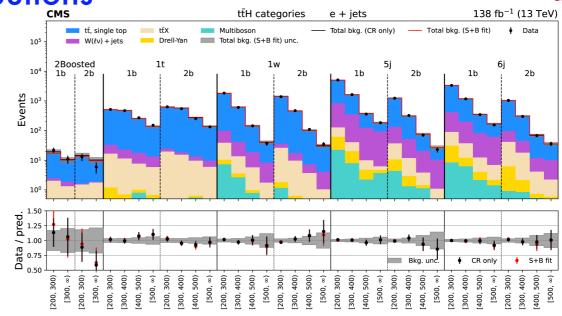
0.6

 $B(H \rightarrow inv)$

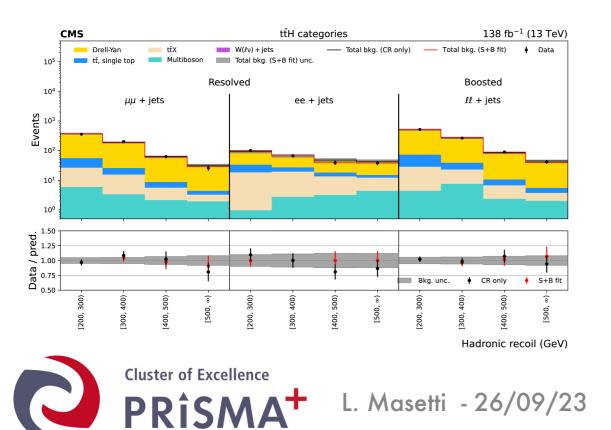
H→invisible

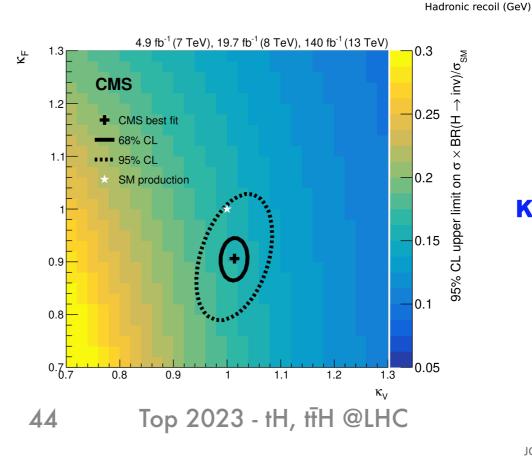
arXiv:2303.01214





Hadronic recoil (GeV)





к-framework



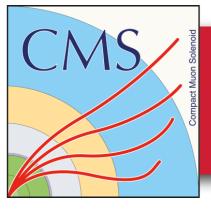




CMS-PAS-HIG-19-011] D log(L) CMS Preliminary 138 fb⁻¹ (13 TeV) SR and CR yields -2 ∆log(L) κ'_t profiled observed expected Dilepton /+jets Events ATLAS Bkgd+[$t\bar{t}H$ + tH] (κ'_t = 0.84, α = 11°) Other *t*t̄ + ≥ 1*b* \sqrt{s} = 13 TeV, 139 fb⁻¹ ////// Unc. tt + light $--- [t\bar{t}H + tH]^{\dagger}(\alpha = 0^{\circ})$ 10⁵ Data *t̄t* + ≥ 1*c* $[t\bar{t}H + tH]^{\dagger}(\alpha = 90^{\circ})$ [†] normalised to total data yield 10⁴ 10³ -1.00 -0.75 -0.50 -0.25 0.00 0.25 0.50 0.75 1 00 f_{CP} 10² **CMS** *Preliminary* 138 fb⁻¹ (13 TeV) (1) 10 14 14 14 14 κ't profiled 4σ observed expected 10¹ Ratio to Bkgd 12 1.2 Bkgd+[$t\bar{t}H$ + tH] (κ'_t = 0.84, α = 11°) 10 1.0 0.2 $t\bar{t}H(\kappa_t'=1, \alpha=0^\circ)$ $H(\kappa'_t = 1, \alpha = 0^\circ)$ 8 0.1 $H(\kappa_t'=1, \alpha=90^\circ)$ $t\bar{t}H(\kappa_t'=1, \alpha=90^\circ)$ 0.0 $CR_{bi}^{\geq 4j, 3b}$ $CR_{no-reco}^{\geq 4j, \geq 4b}$ $CR^{\geq 4j, \geq 4b}$ $SR_{1}^{\geq 4j, \geq 4b}$ $SR_{2}^{\geq 4j, \geq 4b}$ $CR_{bo}^{\leq j, \geq 4b}$ $CR_{bi}^{5j, \ 24b}$ $CR_{1}^{\ 26j, \ 24b}$ $CR_{2}^{\ 26j, \ 24b}$ $SR^{\ 26j, \ 24b}$ $SR_{boosted}$ $CR_{hi}^{3j, 3b}$ CR^{≥4j,3b} -1.00 -0.75 -0.50 -0.25 0.00 0.25 0.50 0.75 1.00 cosα **Cluster of Excellence** JGU PR^îSMA⁺ L. Masetti - 26/09/23 45 Top 2023 - tH, tTH @LHC

arXiv:2303.05974

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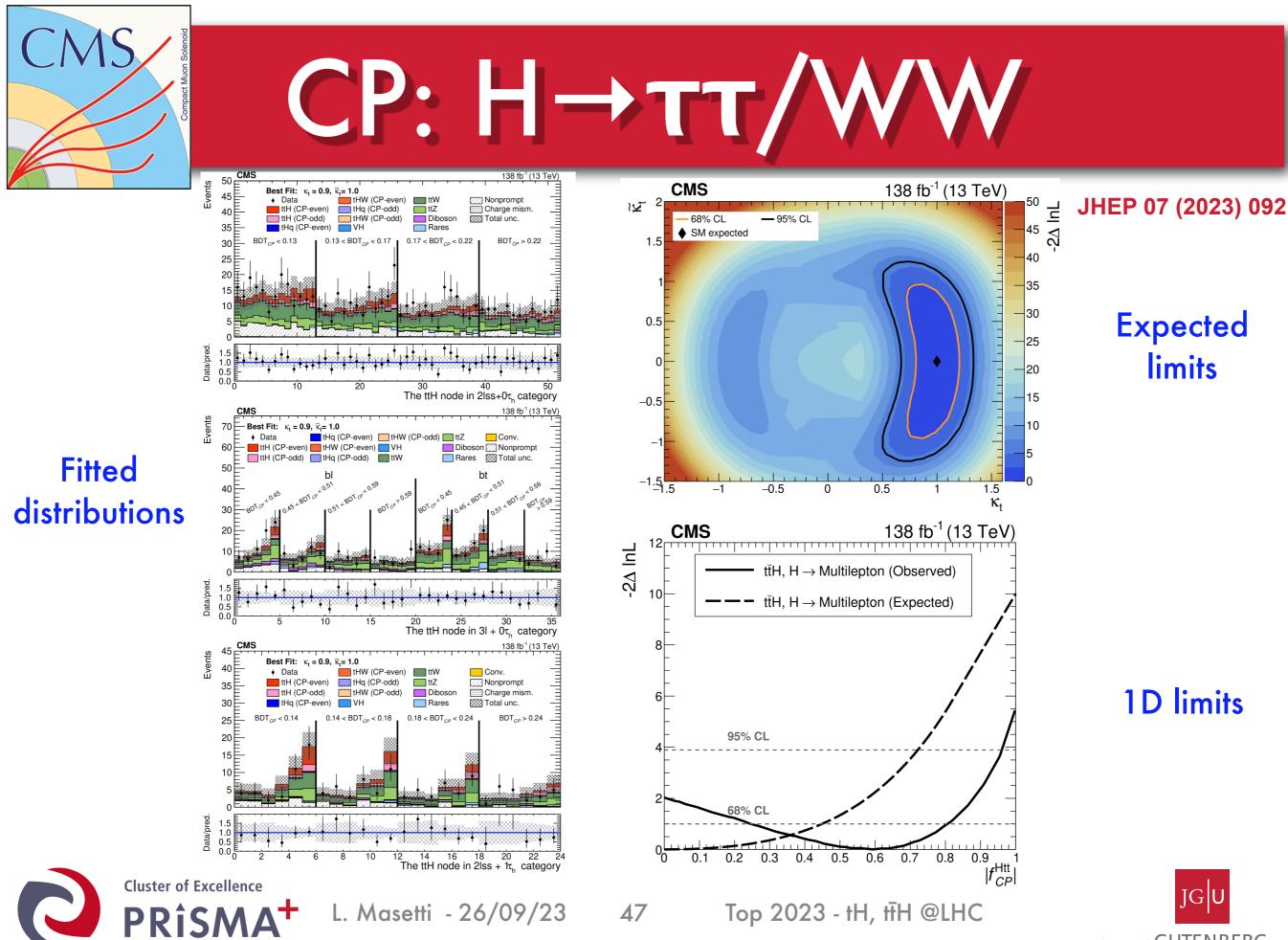
$\mathsf{CP}: \mathsf{H} \to \mathsf{TT}/\mathsf{W}\mathsf{W}$

Data/MC comparisons in validation regions

500 **CMS** 138 fb⁻¹ (13 TeV) 138 fb⁻¹ (13 TeV) 138 fb⁻¹ (13 TeV) CMS CMS Events 120 120 Events Events Data tHW (CP-odd) Rares ttW Rares ttW Rares 🔶 Data • Data 400[†] 450E Conv. ttH (CP-even) ttH (CP-even) ttZ Conv. ttH (CP-even) ttZ Conv. Nonprompt ttH (CP-odd) 350 ttH (CP-odd) WZ ttH (CP-odd) WZ Nonprompt 400⊢ Nonprompt tHq (CP-even) ttW Charge mism tHW (CP-even) Total unc. ZZ Total unc. VH ZZ Total unc. 350 300 Dib 80 300E 250 250È 60 200 200È 150<u></u>-40 150E 100 100⊨ 20 **50** 50È Data/pred Data/pred Data/pred 0.8 0.6 0.8 0.6 1500 2000 M_{ttH} [GeV] 1500 2000 M_{ttH} [GeV] 500 1000 500 1000 400 600 800 1000 1200 200 M_{ttH} [GeV] 138 fb⁻¹ (1<u>3 TeV)</u> 138 fb⁻¹ (13 TeV) 138 fb⁻¹ (13 TeV) CMS CMS CMS 200 350 vents vents Events Data Rares 🛉 Data ttW Rares 🛉 Data ttW Rares tHW (CP-odd) 500 180 ttH (CP-even) Conv. ttH (CP-even) ttH (CP-even) Conv. Conv. 300 ш ttH (CP-odd) Nonprompt aaH 160 ttH (CP-odd) ttH (CP-odd) WZ Nonprompt WZ Nonprompt tHq (CP-even) ttW Charge mism tHW (CP-even) ttZ Total unc. 400 ZZ Total unc. VH ZZ Total unc. 250H 140È tHa (CP-odd) Dibos 120 200 300 100 150 80 200 60 100 40 100 50 20 0 Λ Data/pred. 1.4 Data/pred. Data/pred 1.2 1.8 0.8 0.6 0 0.8 0.8 0 1.5 2 2.5 2 0.5 1 0.5 1.5 2.5 0 0.5 1.5 2 2.5 1 $\Delta\eta_{_{BB}}$ $\Delta \eta_{BB}$ $\Delta \eta_{BB}$ **Cluster of Excel** PRiSMA⁺ L. Masetti - 26/09/23 46 Top 2023 - tH, tTH @LHC

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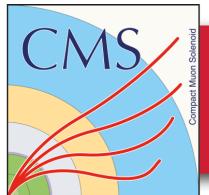




Expected limits

1D limits

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$\rightarrow 4$

ttH

10

9

8

6

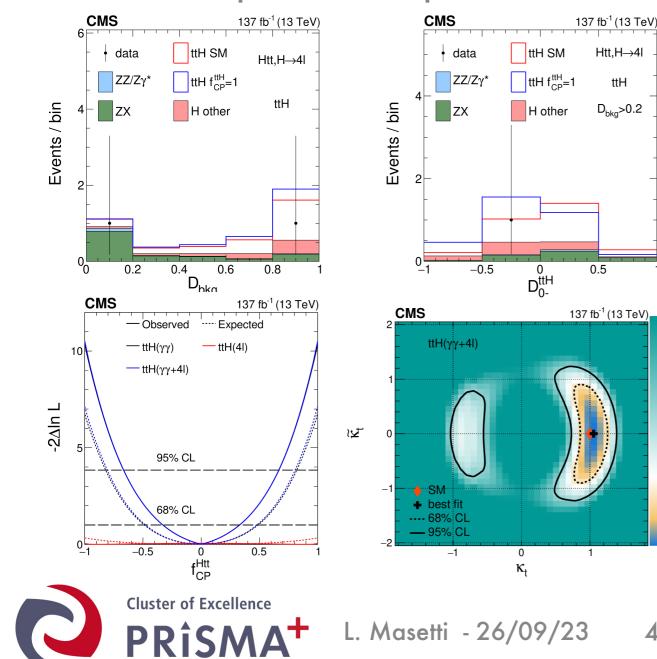
5

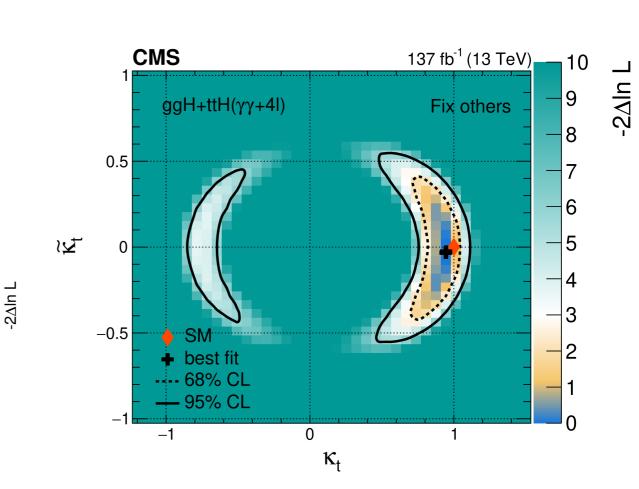
2

48

Dedicated analysis in several production channels

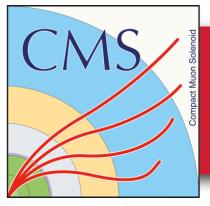
Combination with $H \rightarrow \gamma \gamma$ and ggH Results compatible with pure CP-even coupling structure Phys. Rev. D 104 (2021) 052004





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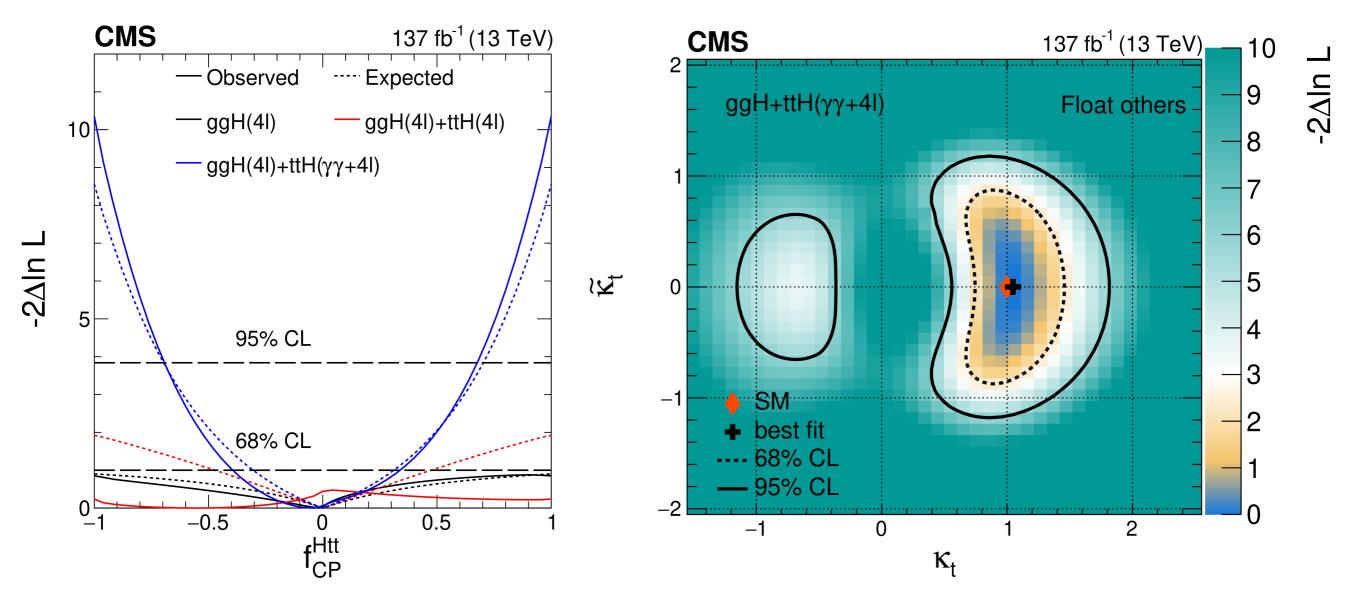


$\mathsf{CP:} H \to 4$

Phys. Rev. D 104 (2021) 052004

1D limits







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CP summary

EXPERIMENT

