



9th International Workshop on Top Quark Physics 19 - 23 September 2016

technische universität dortmund

Searches for ttH with $H \rightarrow \gamma \gamma$

Diane Cinca on behalf of the ATLAS and CMS collaborations





Introduction

- Top Yukawa coupling can be extracted at LHC:
 - From m_{top}: good precision, SM hypothesis, computations needed from measurement to pole mass
 - From ggH and γγH vertices through loops: assuming no coupling to New Physics particles
 - From ttH and tH productions: direct measurement of the coupling





ttH (H $\rightarrow\gamma\gamma$)

- BR(H $\rightarrow \gamma \gamma$) = 0.23 %, σ_{ttH} = 507 fb at 13 TeV (NLO)
- Small BR compensated by parametrisable backgrounds and good diphoton mass resolution
 - Higgs boson can be reconstructed as a narrow peak
 - Backgrounds from ttbar+photons, multi-photon/jet final states
- Results from Run 1:
 - ttH (H→γγ) ATLAS (JHEP 05 (2016) 160): μ = 1.3 + 2.6 1.7 (total) observed (expected) limit: 6.7 (4.9)
 - ttH (H→γγ) CMS (CMS-HIG-13-029): μ = 2.7 + 2.5 1.8 (total) observed (expected) limit: 7.4 (4.7)
 - ATLAS + CMS ttH combination, all decay channels: $Z_{obs} = 4.4\sigma (Z_{exp} = 2\sigma)$, above SM value but still compatible







What to expect with Run 2

- From 8 TeV to 13 TeV
 - LHC Run 2 benefits from large increase of the ttH cross section, XS(ttH) x 3.9 from 8 to 13 TeV.
 - Backgrounds increase at a comparable rate, x3.3 for ttbar(NNLO)
- At 13 TeV, ttH corresponds to 1% of the total Higgs production XS
- This presentation focuses on latest results on ttH (H→γγ) from ATLAS (13.3 fb⁻¹, 2015+2016 data) and CMS (12.9 fb⁻¹, 2016 data).
 - For ATLAS and CMS, ttH ($H \rightarrow \gamma \gamma$) is a category of the $H \rightarrow \gamma \gamma$ couplings analysis





$H \rightarrow \gamma \gamma$ candidates

- ATLAS
 - 2 photons (requirements on tracking info and EM deposits)
 - (sub)leading $p_T/m_{\gamma\gamma} > 0.35$ (0.25)
 - $|\eta| < 2.37$ (excluding 1.37 < $|\eta| < 1.52$)
 - $105 < m_{\gamma\gamma} < 160 \text{ GeV}$
- CMS



- 2 photons (requirements on BDTγID and EM deposits)
- (sub)leading $p_T/m_{\gamma\gamma} > 0.5$ (0.25)
- $|\eta| < 2.5$ (excluding 1.44 < $|\eta| < 1.57$)

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- 100 < m_{$\gamma\gamma$} < 180 GeV







Event Selection

On top of the $H \rightarrow \gamma \gamma$ selection,







Event Selection

On top of the $H \rightarrow \gamma \gamma$ selection,

• ttH leptonic category p $>= 1 lepton (e,\mu), p_T > 10 GeV$ $>= 2 jets, p_T > 25 GeV$ >= 1 b-tagged jet Z veto (m_{II} and m_{ey}) MET > 20 GeV (for 1 b-tag events) • ttH hadronic category 0 light lepton (e, μ) $>= 5 jets, p_T > 30 GeV$ >= 1 b-tagged jet

	gg	βH	VE	F		WH	Z	Ή		tīH	bl	БН	tH] jb	tV	VH
Category	$\epsilon(\%)$	<i>f</i> (%)	$\epsilon(\%)$	f(%)	$\epsilon(\%)$	f(%)	$\epsilon(\%)$	f(%)	$\epsilon(\%)$	<i>f</i> (%)	$\epsilon(\%)$	f(%)	$\epsilon(\%)$	f(%)	$\epsilon(\%)$	f(%)
ttH hadronic	0.0	3.8	0.0	0.5	0.0	0.3	0.1	0.8	11.5	88.1	0.0	0.2	2.2	2.5	10.1	3.8
<i>ttH</i> leptonic	0.0	0.3	0.0	0.1	0.0	0.7	0.0	0.4	8.4	89.3	0.0	0.2	3.1	4.8	8.3	4.3
						_					J					
Category		Events	s B) 0	S 90											
tīH hadronic		72	2 8.	1	1.8					÷1						
<i>ttH</i> leptonic		19	2.	3	1.3		Diane (Cinca				А			7	





Event Selection

On top of the $H \rightarrow \gamma \gamma$ selection,

• ttH leptonic category p $>= 1 lepton (e,\mu), p_T > 20 \text{ GeV}$ $>= 2 \text{ jets}, p_T > 25 \text{ GeV}$ >= 1 b-tagged jet $Z \text{ veto } (m_{e\gamma}, \Delta R(I,\gamma) > 0,4)$ Minimal value on BDT $\gamma\gamma$

Event Categories	SM 125	GeV Higgs	s boson ex	pected si	gnal				Bkg
Event Categories	Total	ggh	vbf	wh	zh	tth	σ_{eff}	σ_{HM}	(GeV^{-1})
TTH Hadronic Tag	2.42	16.78 %	1.28 %	2.52 %	2.39 %	77.02 %	1.39	1.21	1.12
TTH Leptonic Tag	1.12	1.09 %	0.08 %	2.43 %	1.06 %	95.34 %	1.61	1.35	0.42

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CMS doesn't consider tH in the backgrounds





Diphoton selection: BDTyy

- BDTγγ aims at discriminating
 H→γγ from diphoton background
- Inputs to BDTγγ are based on diphoton kinematics
 - $p_T \gamma/m_{\gamma\gamma}$, cos(φ1-φ2), $\sigma_m/m_{\gamma\gamma}$, BDTγID...
- The variable is built to be mass independent
- Output is transformed to be flat for H→γγ events.





Signal models

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• ATLAS

- Double-sided Crystal Ball, parameters estimated on simulation for each region
- Peak position and width constrained to expected values within uncertainties

• CMS:

- Sum of gaussians, parameters estimated on simulation
- Physical parameters constrained to expected values within uncertainties



Background models

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- In each category, background model chosen as the one minimising the bias ("spurious signal") observed in the extracted signal yield
- For ttH categories: exponential function



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- Sum of exponentials or power law terms, Laurent series and polynomials
- Best model extracted per category by a discrete profiling



Main systematic uncertainties

- ATLAS:
 - Dominant uncertainties from γ energy resolution/scale, spurious signal
 - Large uncertainties from HF content, photon ID, JES/JER in hadronic category

- CMS:
 - Taking into account γ energy scale/res.
 theor unc., b-tagging, ggH contamination
 in ttH categories...
- For both analyses, total uncertainty is largely dominated by the statistical one.







Results (m_H = 125.09 ± 0.24 GeV)



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• A μ_{ttH} (H $\rightarrow\gamma\gamma$) is measured (μ_{ttH} = 1 corresponds to SM prediction):

 $- \quad \mu_{ttH} = -0.25 + 1.26 - 0.99$

• A ttH ($H \rightarrow \gamma \gamma$) production cross section is measured:

σ_{ttH} x BR(H→γγ) = -0.3 + 1.4 – 1.1 fb

The total uncertainty is dominated by statistics





Results



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A global μ_{ttH} is measured (μ_{ttH} = 1 corresponds to SM prediction):

 μ_{ttH} = 1.91 + 1.5 – 1.2 for a fitted m_H = 126 GeV (maximal observed significance for H \rightarrow $\gamma\gamma$)

• The total uncertainty is dominated by statistics



Conclusion



- A search for ttH (H→γγ) production has been performed as part of the H→γγ production cross section analysis with 13 TeV data (13.3fb⁻¹ for ATLAS, 12.9 fb⁻¹ for CMS).
- Both measurements are in fair agreement with Standard Model expectations.
- Run 2 has just started ! We plan about 100 fb⁻¹ by the end of the Run (end of 2018).
 This will induce a factor 3 reduction of the statistical uncertainty !





Projections currently plan about 35 fb⁻¹ of data for 2016...

See you in Winter for more new results !



BACKUP



Run 2

- XS_{ttH} (13 TeV) = 507 fb (1% of total Higgs production XS)
- Search in many decay modes (BR ~89%)

Higgs decay mode	Branching ratio [%]
H→ bb	58.1
H→ WW	21.5
H→ ττ	6.3
H→ ZZ	2.6
Η→ γγ	0.23



Run 2





Shutdown/Technical stop Protons physics Commissioning Ions

Extended Year End Technical Stop – 20 weeks CMS pixel upgrade; push 2 sectors towards 7 TeV

- Peak luminosity limited to ~1.7e34 by inner triplets
- ~40 fb⁻¹/year in 2017 and 2018
- Prepare for HL-LHC and post-LS2 LIU era
- Prepare for 7 TeV operation

Higgs boson cross section and decay widths as a function of coupling modifiers (*k*)

			Effective	Resolved
Production	Loops	Interference	scaling factor	scaling factor
$\sigma(ggF)$	~	t-b	κ_g^2	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(VBF)$	-	-		$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	-	-		κ_W^2
$\sigma(qq/qg \rightarrow ZH)$	-	-		κ ² _Z
$\sigma(gg \rightarrow ZH)$	~	t-Z		$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	-	1		κ ² _t
$\sigma(gb \rightarrow tHW)$	-	t-W		$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qq/qb \rightarrow tHq)$	-	t-W		$3.40 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
σ(bbH)	-	-		κ_b^2
Partial decay width				9.
Γ ^{ZZ}	-	-		κ ² ₇
Γ^{WW}	-	-		κ_W^2
Γγγ	~	t-W	Ky2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
Γττ	-	-		κ_T^2
Γ^{bb}	-	-		κ_{h}^{2}
$\Gamma^{\mu\mu}$	-	-		κ_{μ}^2
Total width (B _{BSM} =	= 0)			
				$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$
Γ_H	1	-	K ² _H	$0.06 \cdot \kappa_{\tau}^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$
				$0.0023 \cdot \kappa_{\gamma}^2 + 0.0016 \cdot \kappa_{(Z\gamma)}^2 +$
				$0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_u^2$



Analysis chart (focusing on ttH)



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Event preselection



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- $p_T > 30$ (20) GeV, $p_T/m_{yy} > 1/3$ (1/4) for (sub)leading- p_T photon
- $|\eta| < 2.5$, removing 1.44< $|\eta| < 1.57$, electron veto
- either $R_9{>}0.8,$ or charged hadron isolation < 20 GeV, or charged hadron isolation relative to p_T <0.3

	H/E	$\sigma_{\eta\eta}$	R_9	photon iso.	tracker iso.
ECAL barrel; $R_9 > 0.85$	< 0.08	_	>0.5	—	—
ECAL barrel; $R_9 \leq 0.85$	< 0.08	< 0.015	>0.5	< 4.0	< 6.0
ECAL endcaps; $R_9 > 0.90$	< 0.08	_	>0.8	—	_
ECAL endcaps; $R_9 \leq 0.90$	< 0.08	< 0.035	>0.8	< 4.0	< 6.0

BDTyID inputs



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- shower shape observables;
- isolation variables based on the sums of the p_T of photons and of charged hadrons, within regions of R < 0.3 around the candidate. Two such charged hadron isolations are used: one considering hadrons coming from the chosen vertex in the event, and one considering hadrons coming from the vertex with the largest p_T sum among remaining vertices. The latter is effective in rejecting photon candidates originating from mis-identification of jets from a vertex other than the chosen one;
- the median energy density per unit area in the event, ρ , in order for the BDT_{γ ID} to be independent of pileup;
- photon kinematic observables (pseudorapidity and energy), allowing the BDT_{γ ID} to account for the dependence of the shower topology and isolation variables on η and $p_{\rm T}$.

BDTγID



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After preselection For the lowest scoring photon

BDTyy inputs



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- the relative transverse momenta of both photons, $p_T^{1(2)}/m_{\gamma\gamma}$;
- the pseudorapidities of both photons, $\eta^{1(2)}$;
- the cosine of the angle between the two photons in the transverse plane, $\cos(\phi_1 \phi_2)$;
- the relative diphoton mass resolution, under the hypothesis that the mass has been reconstructed using the correct primary vertex, $\sigma_m^{right}/m_{\gamma\gamma}$;
- the relative diphoton mass resolution, under the hypothesis that the mass has been reconstructed using an incorrect primary vertex, $\sigma_m^{wrong}/m_{\gamma\gamma}$;
- the per-event probability estimate that the correct primary vertex has been used to reconstruct the mass, taken from BDT_{VTX PROB};

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• the BDT_{γ ID} score for both photons.



BDT*γγ* systematics

- Studied on Zee events with electrons reconstructed as photons
- Impact on BDTγγ of uncertainties from:
 - Relative energy resolution (5% relative shift)
 - BDTγID (0.03 shift + linearly increasing term)



Systematic uncertainties



Theory uncertainties (PDFs, α_s , QCD scale, underlying event and parton shower, $H \rightarrow \gamma \gamma$ branching fraction)

ggH contamination in VBF and ttH tagged categories

Trigger efficiency, integrated luminosity, vertex efficiency, preselection

Non-unformity of light collection, non-linearity, detector simulation, modeling of the material budget, shower shape corrections

Photon energy scale and resolution

 $BDT_{\boldsymbol{\gamma}\,\text{ID}}$ and per-photon energy resolution

Jet energy scale and smearings

b-tagging efficiency, **gluon-splitting** fraction, **parton shower**, ID efficiency for **e and** μ

Composition





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	gg	βH	V	BF	W	Ή	Z	H	tī	H	bł	ЪH	tH	jb	tV	/H
Category	$\epsilon(\%)$	f(%)														
Central low- p_{Tt}	12.7	92.7	6.9	3.9	6.3	1.3	6.0	0.8	3.5	0.3	14.2	1.0	4.6	0.1	3.8	0.0
Central high- p_{Tt}	1.2	78.2	2.4	12.8	2.1	4.0	1.8	2.2	2.9	2.0	0.4	0.3	3.7	0.4	5.1	0.2
Forward low- p_{Tt}	22.0	92.1	12.5	4.1	13.0	1.5	12.7	1.0	5.1	0.2	24.9	1.0	9.5	0.1	4.8	0.0
Forward high- p_{Tt}	1.9	76.8	4.1	13.4	3.9	4.6	3.7	2.8	3.6	1.5	0.8	0.3	6.6	0.4	4.8	0.1
VBF loose	0.5	46.3	7.3	51.6	0.2	0.6	0.2	0.4	0.3	0.3	0.4	0.3	3.4	0.5	0.6	0.0
VBF tight	0.1	23.8	5.4	75.5	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.0	1.2	0.3	0.1	0.0
VH hadronic loose	0.4	64.6	0.4	4.3	3.9	16.5	4.1	11.0	1.7	2.6	0.5	0.6	1.0	0.2	2.2	0.2
VH hadronic tight	0.1	48.9	0.1	2.5	1.8	28.1	1.6	16.9	0.5	3.1	0.0	0.1	0.3	0.2	0.7	0.2
$VH E_{\rm T}^{ m miss}$	0.0	2.4	0.0	0.6	0.6	28.5	1.9	55.8	0.6	10.9	0.0	0.0	0.3	0.7	1.2	1.0
VH one-lepton	0.0	0.2	0.0	0.0	1.3	83.7	0.1	3.0	0.4	10.4	0.0	0.0	0.4	1.3	1.1	1.3
VH dilepton	0.0	0.0	0.0	0.0	0.0	0.0	1.2	95.1	0.1	4.5	0.0	0.0	0.0	0.0	0.2	0.4
ttH hadronic	0.0	3.8	0.0	0.5	0.0	0.3	0.1	0.8	11.5	88.1	0.0	0.2	2.2	2.5	10.1	3.8
ttH leptonic	0.0	0.3	0.0	0.1	0.0	0.7	0.0	0.4	8.4	89.3	0.0	0.2	3.1	4.8	8.3	4.3
Total efficiency (%)	38.9	-	39.2	-	33.2	-	33.5	-	38.6	-	41.2	-	36.2	-	43.1	-
Events	56	8.8	44	1.6	13	3.7	8	.9	5	.9	5	.6	0	.8	0	.3



Expected number of events

Event Categories	Event Categories SM 125GeV Higgs boson expected signal								
Liveni Calegones	Total	ggh	vbf	wh	zh	tth	σ_{eff}	σ_{HM}	$ (GeV^{-1}) $
Untagged Tag 0	11.92	79.10 %	7.60 %	7.11 %	3.59 %	2.60 %	1.18	1.03	4.98
Untagged Tag 1	128.78	85.98 %	7.38 %	3.70 %	2.12 %	0.82 %	1.35	1.20	199.14
Untagged Tag 2	220.12	91.11 %	5.01 %	2.18 %	1.23 %	0.47 %	1.70	1.47	670.44
Untagged Tag 3	258.50	92.35 %	4.23 %	1.89 %	1.06 %	0.47 %	2.44	2.17	1861.23
VBF Tag 0	9.35	29.47 %	69.97 %	0.29 %	0.07 %	0.20 %	1.60	1.33	3.09
VBF Tag 1	15.55	44.91 %	53.50 %	0.86 %	0.38 %	0.35 %	1.71	1.40	22.22
TTH Hadronic Tag	2.42	16.78 %	1.28 %	2.52 %	2.39 %	77.02 %	1.39	1.21	1.12
TTH Leptonic Tag	1.12	1.09 %	0.08 %	2.43 %	1.06 %	95.34 %	1.61	1.35	0.42
Total	647.77	87.93 %	7.29 %	2.40 %	1.35 %	1.03 %	1.88	1.52	2762.65

Selection of diphoton candidate events

<u>Η -> γγ candidates</u>

Two reconstructed photons with:

- $p_{T,1} > 0.35 m_{\gamma\gamma}$ and $p_{T,2} > 0.25 m_{\gamma\gamma}$
- |η|< 2.37 (excuding 1.37<|η|<1.52)
- 105 < m_{vv} < 160 GeV
- Isolated in tracker and calorimeter

In total 124137 diphoton events selected

Additional object selection

Jets (anti- k_T , R=0.4):

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- $p_T > 25 \text{ GeV for } |\eta| < 2.4$
- p_T > 30 GeV for 2.4<|η|< 4.4
- Jet vertex tagger used to reject pile-up
- b-jet tagger to identify heavy-flavour

Muons: $p_T > 10$ GeV and $|\eta| < 2.7$ Electrons: $p_T > 10$ GeV and $|\eta| < 2.47$ (excluding 1.37< $|\eta| < 1.52$)

Missing transverse momentum reconstructed from photons, jets, leptons and tracks





Main uncertainties

All $H \rightarrow \gamma \gamma$ inclusive, not showing much about ttH



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All systematics are included as nuisance

parameters in the fit.



Higgs production XS

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Higgs production cross section ($|\gamma_{H}| < 2.5$) $\sigma_{ggH} \times \mathcal{B}(H \to \gamma \gamma) = 63 {}^{+30}_{-29}$ fb $\sigma_{VBF} \times \mathcal{B}(H \to \gamma \gamma) = 17.8 {}^{+6.3}_{-5.7}$ fb $\sigma_{VHlep} \times \mathcal{B}(H \to \gamma \gamma) = 0.96 {}^{+2.52}_{-1.90}$ fb $\sigma_{VHhad} \times \mathcal{B}(H \to \gamma \gamma) = -2.3 {}^{+6.8}_{-5.8}$ fb $\sigma_{t\bar{t}H} \times \mathcal{B}(H \to \gamma \gamma) = -0.28 {}^{+1.43}_{-1.12}$ fb

Total Higgs production cross section

 $\sigma_{ggH} \times \mathcal{B}(H \to \gamma \gamma) = 65 ^{+32}_{-31} \text{ fb}$ $\sigma_{\text{VBF}} \times \mathcal{B}(H \to \gamma \gamma) = 19.2 ^{+6.8}_{-6.1} \text{ fb}$ $\sigma_{\text{VH}} \times \mathcal{B}(H \to \gamma \gamma) = 1.2 ^{+6.5}_{-5.4} \text{ fb}$ $\sigma_{t\bar{t}H} \times \mathcal{B}(H \to \gamma \gamma) = -0.28 ^{+1.44}_{-1.12} \text{ fb}$



ttH combination: Log-likelihood scores





Expected signal strength



Figure 4: Expected $\mu_{t\bar{t}H}$ measurements (left) and expected negative logarithm of the likelihood ratio as a function of the signal strength for the individual analyses and for their combination (right), assuming $m_H = 125$ GeV.



Limits for ttH combination





ttH combination results



Channel	Significance					
	Observed $[\sigma]$	Expected $[\sigma]$				
$t\bar{t}H, H \to \gamma\gamma$	-0.2	0.9				
$t\bar{t}H, H \to (WW, \tau\tau, ZZ)$	2.2	1.0				
$t\bar{t}H, H \rightarrow b\bar{b}$	2.4	1.2				
$t\bar{t}H$ combination	2.8	1.8				

From ttH combination paper, slightly different result as contributions other than ttH are fixed to SM expectations.

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