A Search for Invisible Decays of the Higgs Boson produced in ttH(had)+V(jj)H Channels

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Status of Invisible Decays of the Higgs at CMS

SM predicts BR($H \to ZZ \to 4\nu$) < 0.1%

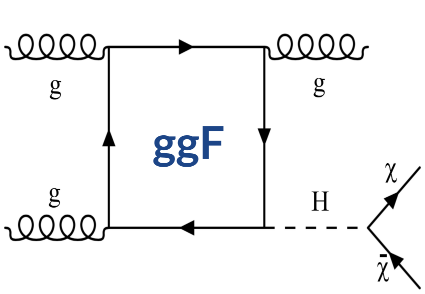
Several production modes can be explored at colliders

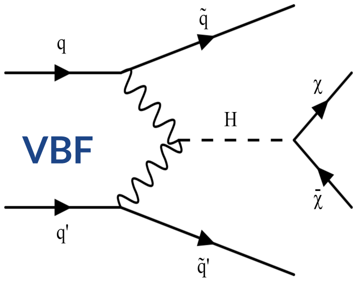
Most recent fully combined observed limit from CMS is 19 % at 95 % C.L.

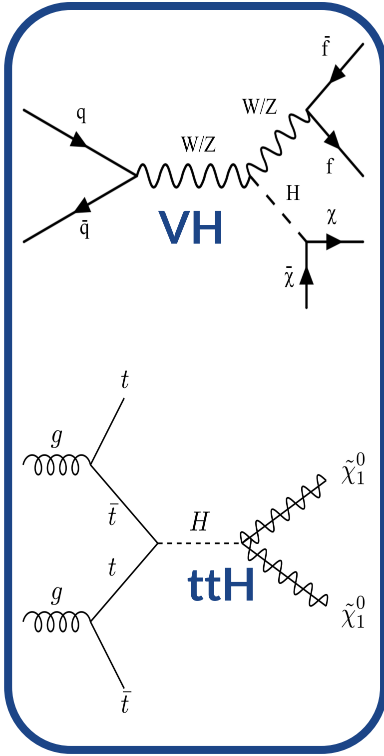
VBF full Run-2 analysis observed (expected) limit of **0.176** (0.108).

Other full Run-2 results have also been published, with observed (expected) as follows:

- MonoJet/Mono-V: **0.283** (0.266)
- Mono-Z: **0.295** (0.248)
- ttH (1l/2l): **0.318** (0.381)



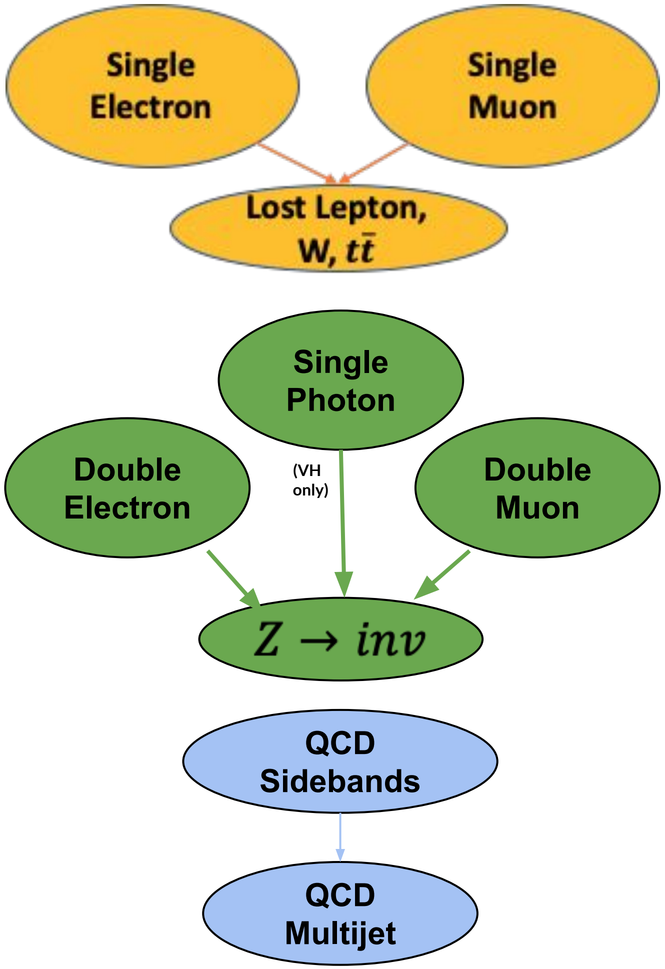




ttH (had) + V(jj)H

Analysis strategy

- Search for invisibly decaying Higgs Bosons in fully hadronic final state **ttH** and **V(->jj)H** channels
- Common selection contains
  - Kinematic selection for SR and CRs
  - Cuts mitigate overlap with **VBF** and **MonoJ/V**
- Dedicated leptonic control regions used to estimate background in fully hadronic signal region
  - VH categories also use photon CR
  - Hadronic sidebands estimate QCD multijet in SR
- SR event selection furthered
  - Signal enhancement cuts
  - QCD suppression cuts in SR (enhancing sidebands)
- SR and CRs then categorised based on event topologies of interest



Analysis Strategy: search in hadronic final state categorisation for ttH and VH production modes

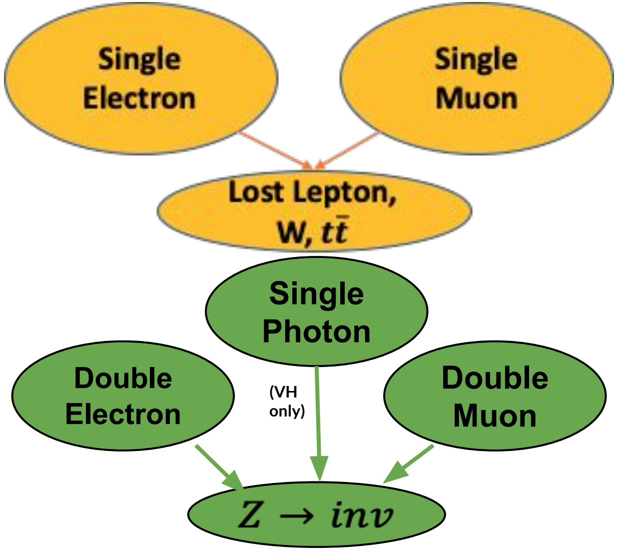
- **ttH** analysis split in events with boosted Ws or tops (“ttH boosted”) and with resolved top jets (“ttH resolved”)
- **VH** category requires exactly 2 resolved light jets
- Bin on recoil (“MET-no leptons and no photons”) within each category

Category	Subcategory	n_{jet}	n_b	n_t	n_V	p_{T,j_2}	Other	Recoil bin edges
ttH Boosted	2Boosted1b	≥ 5	1	2		≥ 80	-	$[200, 300, +\infty]$
	2Boosted2b	≥ 5	≥ 2	2				
	1t1b	≥ 5	1	1	0			$[200, 300, 400, 500, +\infty]$
	1t2b	≥ 5	≥ 2	1	0			
	1W1b	≥ 5	1	0	1			
	1W2b	≥ 5	≥ 2	0	1			
ttH Resolved	5j1b	5	1	0	0	≥ 80	$\Delta\phi(b_1, \vec{p}_T^{miss}) > 1.0$ & $\Delta\phi(j_1, \vec{p}_T^{miss}) > \pi/2$	$[200, 300, 400, 500, +\infty]$
	6j1b	≥ 6	1	0	0			
	5j2b	5	≥ 2	0	0		$\Delta\phi(b_1, \vec{p}_T^{miss}) > 1.0$ & $\Delta\phi(b_2, \vec{p}_T^{miss}) > \pi/2$	
	6j2b	≥ 6	≥ 2	0	0			
VH	2j0b	2	0	0	0	≥ 30	$m_{jj} \in [65, 120)$	$[200, 300, 400, 500, +\infty]$
	2j1b	2	1	0	0			$[200, 300, 400, +\infty]$
	2j2b	2	2	0	0			$[200, 300, +\infty]$

Fit Strategy

MET-binned maximum likelihood fit performed across SR and CRs together, for individual years and categories

- Statistics in 2e/2mu CRs is smaller than in signal region
  - Combine bins in CRs to increase statistics and be able to have BG prediction for MET > 500 GeV
- Combine subcategories in boosted and resolved but keep MET dependence (MET is our main search variable)
  - Boosted ttH: combined 2e and 2mu into 2l CR
  - Resolved ttH: keep separate 2e and 2mu CRs



	ttH Categories										VH Categories		
$W \to e\nu$	2Boost1b	2Boost2b	1W1b	1W2b	1t1b	1t2b	5j1b	6j1b	5j2b	6j2b	2j0b	2j1b	2j2b
$W \to \mu\nu$	2Boost1b	2Boost2b	1W1b	1W2b	1t1b	1t2b	5j1b	6j1b	5j2b	6j2b	2j0b	2j1b	2j2b
$Z \to ee$	Boosted						Resolved				2j0b	2j1b	2j2b
$Z \to \mu\mu$							Resolved				2j0b	2j1b	2j2b

2boosted categories only use 2 MET bins

[200, 300)	[300, 400) [300, inf)	[400, 500)	[500, inf)

Data control regions for background estimation

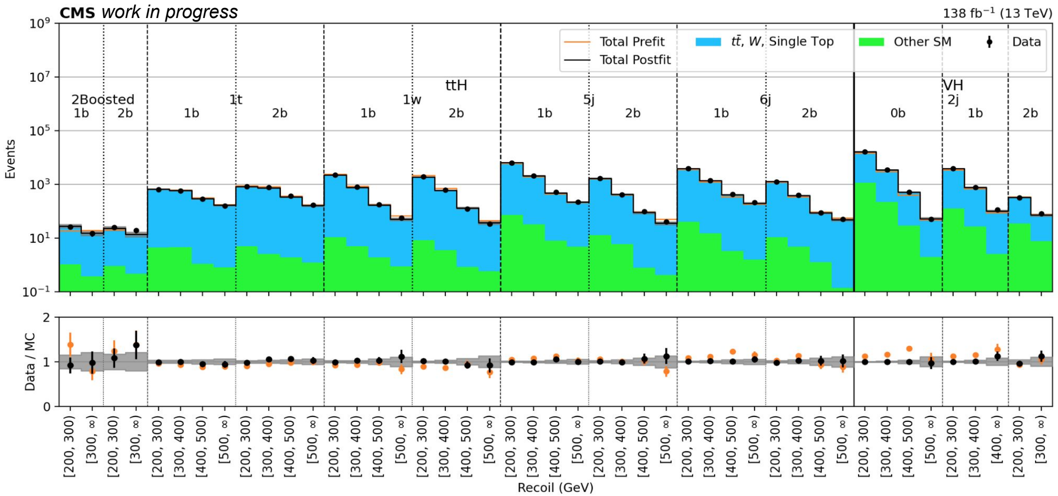
Lost lepton background CRs

Lost lepton bkg
- W->$\ell\nu$ with charged lepton failing reconstruction

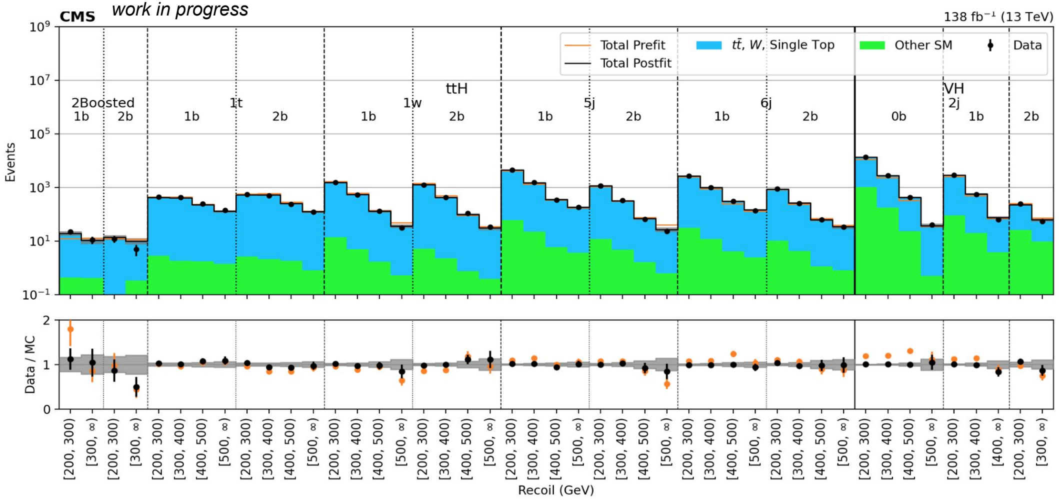
Processes include:
- ttbar
- single top
- W+Jets
- EWK W

Note that for all Run-2 plots, years are summed together for convenience, but the fit takes separate years as input

Single Electron CR Run 2



Single Muon CR Run 2



Z invisible background CRs

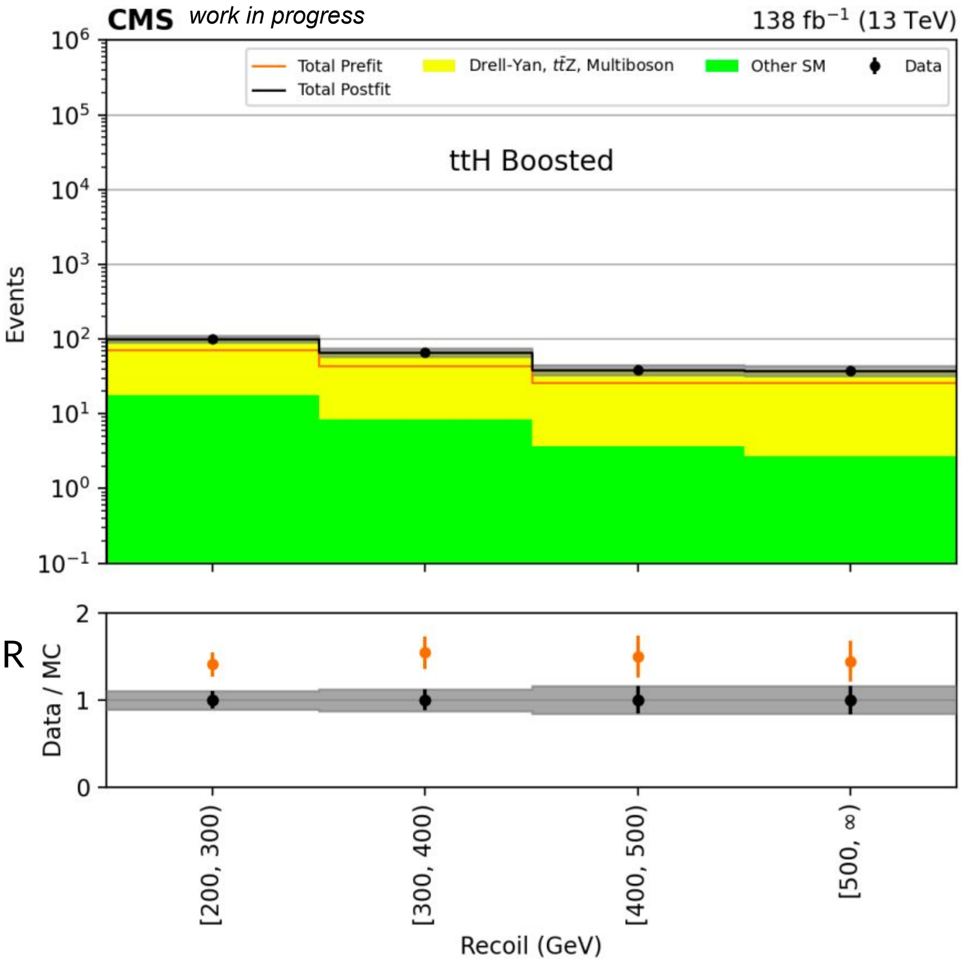
Zinv bkg ($Z\nu\nu$)

- Zll bkg in dilepton CRs (kinematically similar)
- γ+jets bkg in photon CR (mapped with photon theory uncertainty)

Processes include:

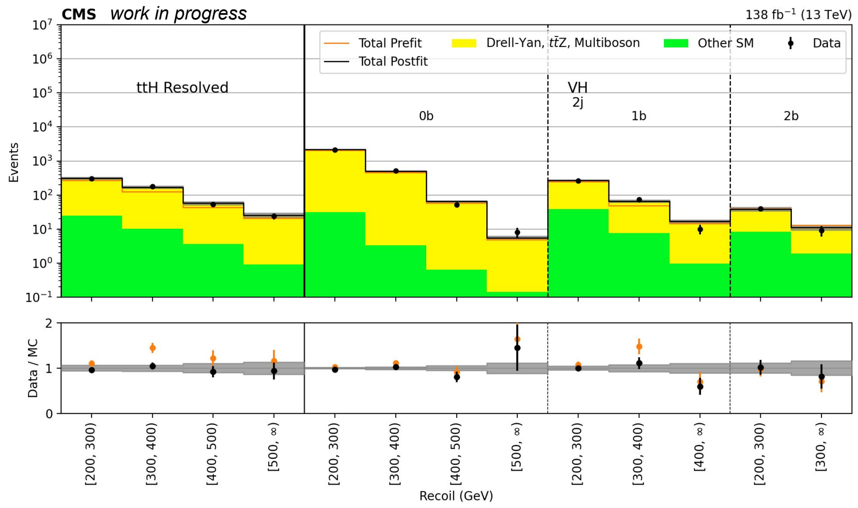
- Drell-Yan
- EWK Zll
- ttZ
- VV, VVV

Double Lepton CR
Run 2

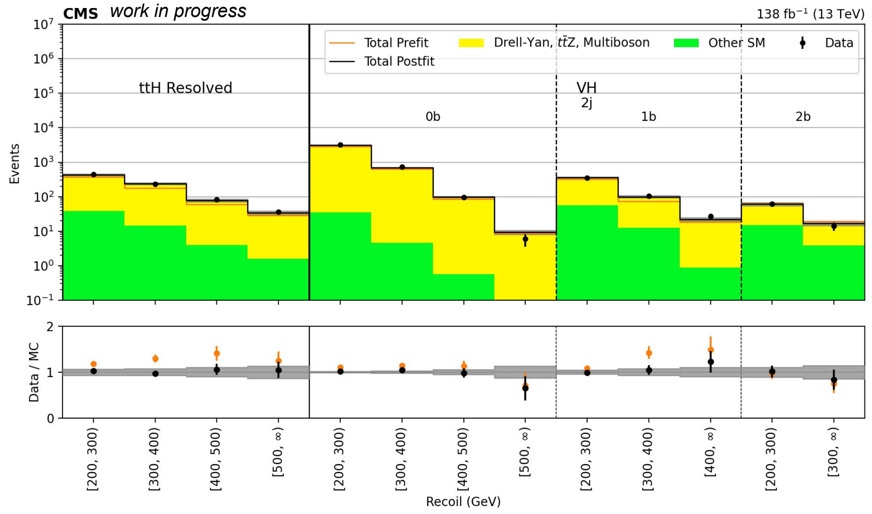


Z invisible backgrounds CRs

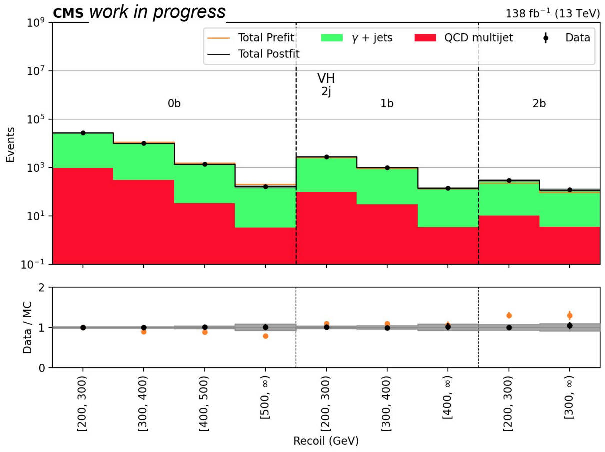
Double Electron CR Run 2



Double Muon CR Run 2



Single photon CR Run 2



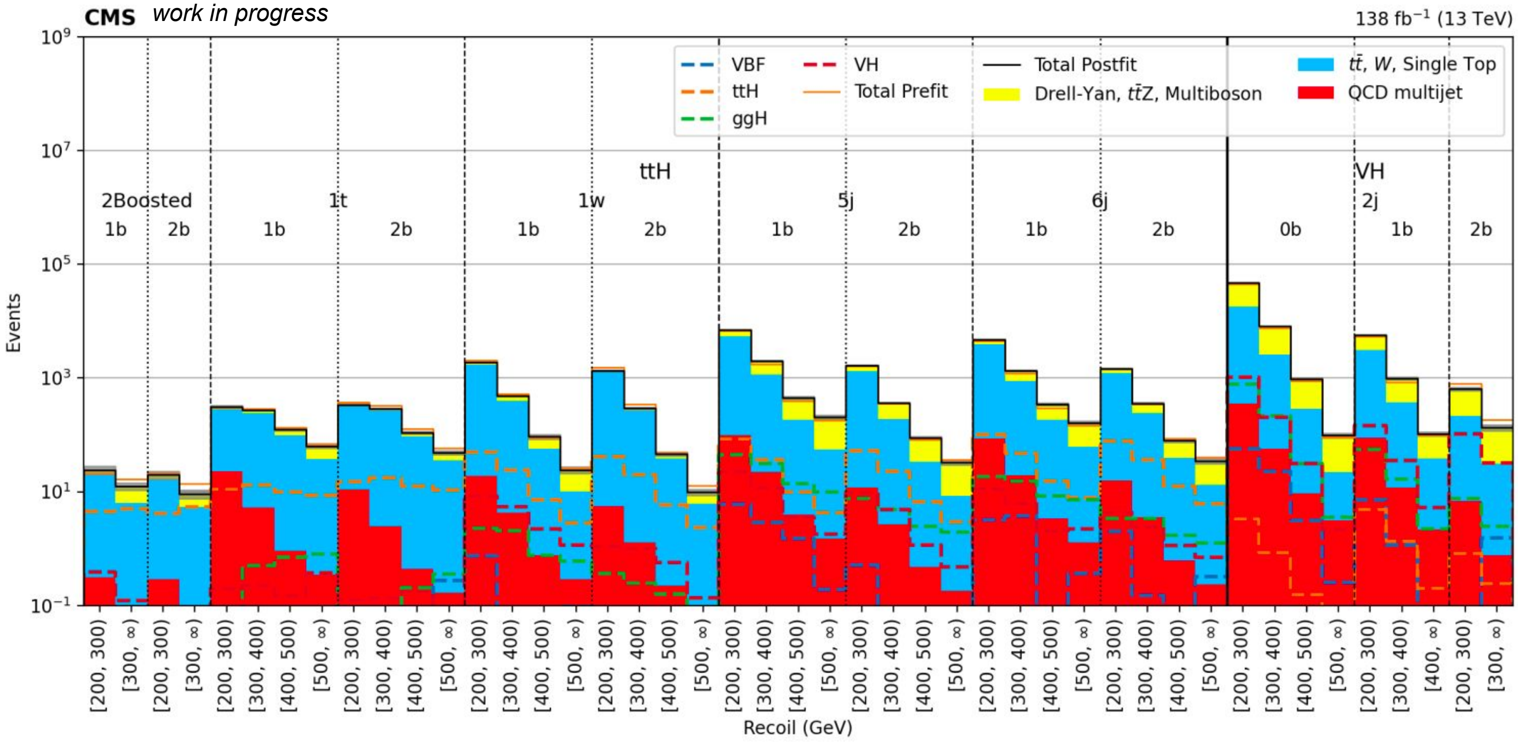
Overview of considered systematics

- Jet Energy Uncertainties:
  - Split into individual components based on detector topology
- V+ Jets LO-to-NLO reweighting uncertainties:
  - One of the larger sources of uncertainty
- Boosted object tagging:
  - Following central CMS recommendations
- b-tagging efficiency uncertainty
  - How often a b-jet is tagged that is truly a b-jet
- Electron/Muon ID/Isolation/Reconstruction uncertainties

Systematic Uncertainty	SR	γ + jets	e + jets	μ + jets	ee + jets	$\mu\mu$ + jets
Theoretical uncertainties						
Fact. scale V+jets (QCD)	18-23 %	0.1-0.2 %	8.6-10 %	9.4-11 %	21-26 %	21-26 %
PDF V+jets (QCD)	21-28 %	0.1 %	10-13 %	12-15 %	20-25 %	20-26 %
Ren. scale V+jets (QCD)	19-27 %	0.1-0.3 %	13-16 %	13-19 %	22-34 %	21-34 %
Ren. and Fact. scale ttH (QCD)	0.1-1.8	0.0 %	0.1-1.1 %	0.1-1.4 %	0.1-0.3 %	0.1-0.4 %
Ren. and Fact. scale $t\bar{t}$ (QCD)	7.6-14	0.1-0.4 %	8.7-17 %	7.4-13 %	1.2-2.8 %	1.4-5.8 %
Cross-section scale ttH	6.0-9.0 %	-	-	-	-	-
Cross-section PDF ttH	3.5 %	-	-	-	-	-
Experimental uncertainties						
Luminosity	1.5-2.6 %	1.5-2.6 %	1.5-2.6 %	1.5-2.6 %	1.5-2.6 %	1.5-2.6 %
Top tagging	3.5-6.5 %	-	3.7-5.6 %	3.7-5.6 %	-	-
W tagging	11-18 %	-	10-18 %	9.3-16 %	-	-
b tagging	8.9-12 %	7.0-8.9 %	8.6-11 %	8.2-10 %	9.9-14 %	9.9-16 %
Electron identification and isolation	-	-	5.6-12 %	-	11-20 %	-
Electron reconstruction	-	-	0.6-0.9 %	-	1.1-1.5 %	-
Muon identification	-	-	-	0.2-1.0 %	-	0.4-1.9 %
Muon isolation	-	-	-	0.1-0.2 %	-	0.2-0.3 %
Photon identification and isolation	-	2.4-12 %	-	-	-	-
Photon reconstruction	-	0.4-0.7 %	-	-	-	-
Pile-up	3.6-10.0 %	1.6-3.3 %	2.9-4.9 %	2.7-4.9 %	3.0-8.5 %	2.6-5.6 %
Pre-firing	1.0-1.2 %	0.7-0.9 %	1.2 %	1.0-1.2 %	0.9-1.6 %	0.7-1.3 %
Top pT reweighting	3.3-3.4	0.0 %	3.6-3.9 %	3.6-4.0 %	0.3-0.6 %	0.3-0.5 %
Trigger	2.0 %	2.0 %	2.0 %	2.0 %	2.0 %	2.0 %
Tau veto	0.0 %	0.0 %	0.1-0.2 %	0.2 %	0.1 %	0.1 %
Jet Energy Uncertainties						
Absolute	3.1-3.9 %	0.1-3.1 %	2.6-3.3 %	2.9-3.6 %	3.0-4.9 %	2.4-4.1 %
Absolute (dec)	1.0-3.0 %	0.1-2.0 %	0.8-2.5 %	0.9-2.6 %	1.2-2.9 %	1.2-2.7 %
BBEC1	0.5-2.1 %	0.2-1.0 %	0.5-1.8 %	0.5-1.8 %	0.7-2.5 %	0.7-2.7 %
BBEC1 (dec)	0.2-1.1 %	0.0-0.8 %	0.3-1.3 %	0.2-1.4 %	0.6-3.9 %	0.4-3.6 %
EC2	0.4-1.0 %	0.1-0.3 %	0.3-0.9 %	0.6-1.9 %	1.2-4.0 %	1.4-4.4 %
EC2 (dec)	0.3-0.9 %	0.0-0.4 %	0.2-0.9 %	0.1-1.0 %	1.0-4.2 %	1.4-4.4 %
FlavorQCD	0.4-5.8 %	0.4-3.8 %	4.2-4.8 %	4.4-4.8 %	4.3-6.6 %	4.0-5.2 %
HF	0.6-2.6 %	0.1-2.1 %	0.2-2.3 %	0.3-1.0 %	1.2-3.8 %	0.7-4.3 %
HF (dec)	0.4-0.8 %	0.0-0.2 %	0.2-0.9 %	0.2-0.9 %	1.6-3.9 %	1.2-4.2 %
Jet Energy Resolution	2.4-3.6 %	0.9-2.9 %	1.7-2.8 %	1.7-3.0 %	1.0-3.5 %	1.1-3.2 %
Relative Bal	0.6-2.6 %	0.2-2.1 %	0.4-2.3 %	0.5-2.1 %	0.3-2.6 %	0.3-3.4 %
Relative Sample (dec)	0.3-6.3 %	0.1-2.7 %	0.2-5.0 %	0.3-5.1 %	0.1-6.7 %	0.8-5.7 %

Current Fit Results

SR Background Composition



Overall background yields for Run 2 in the SR

- Dominant lost lepton, Zinv and QCD contributions shown
- MC contributions only while blinded

Run 2 | SR-blinded Expected Limits

Expected limits on *BR(H->inv)* calculated with SR data blinded

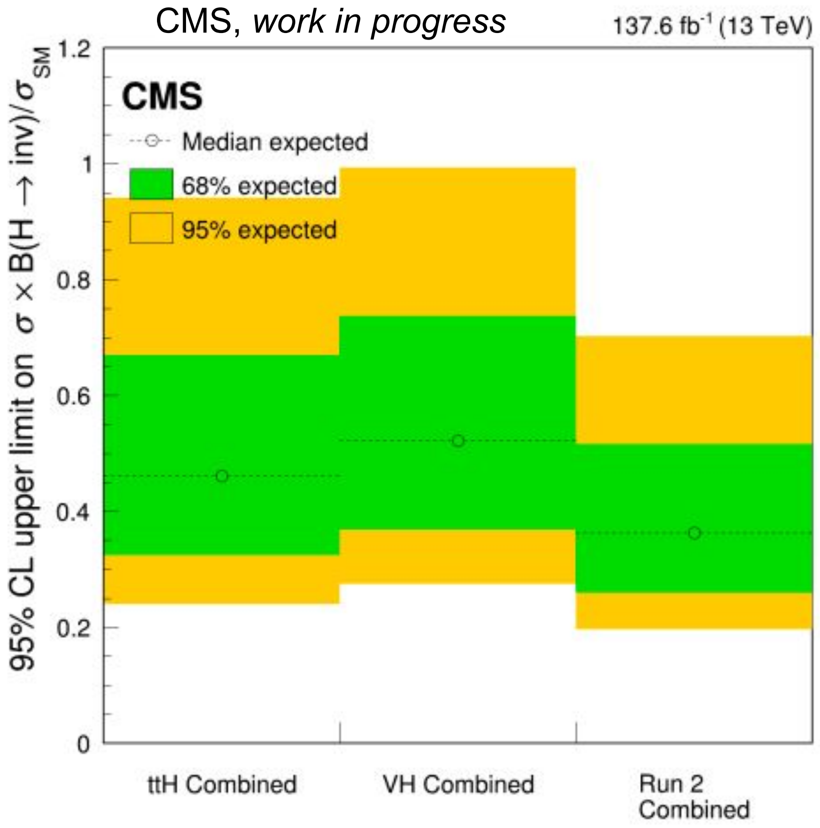
- CR data-MC fit performed
- Asimov data for SR generated from this
- Comparison fit between SR Asimov and MC

ttH+VH	ttH	VH
X.XX (0.36)	**X.XX** (0.46)	**X.XX** (0.52)

ttH(had) competitive with similar analyses

- ATLAS CONF-2020-052 report ttH(had) 0.64^{+29}_{-19} (exp), 0.94 (obs)

Will contribute to a combined limit with e.g. **VBF**, **MonoJ/V**, **MonoZ** and **ttH(lep)** signal channels



Summary

Performed a search for Hinv in **ttH(had)** and **V(jj)H** final state to measure *BR(H->inv)* at 95% CL

- Events categorised by jet multiplicity, b-jet multiplicity and boosted objects
- Studied comprehensive list of systematics and their relevant correlations
- For comparison, ATLAS CONF-2020-052 report **ttH(had):** 0.64^{+29}_{-19} (exp), 0.94 (obs)

Combination with limits from other Hinv analyses

- Limits within range of those of similar analyses
  - VBF: **0.176** (0.108).
  - MonoJet/Mono-V: **0.283** (0.266)
  - Mono-Z: **0.295** (0.248)
  - ttH (1l/2l): **0.318** (0.381)
- Differences in analysis approach, i.e. fit model and systematics treatment
- Sync efforts underway i.e. handling overlap in V(jj)H and Mono-V channels

BACK-UP

Object definitions

- Primary AK4 Jets:
  - pT > 30 GeV for jets in barrel (|eta| < 2.4)
  - 30 < pT < 50 GeV for forward jets (|eta| > 2.4)
- Leptons and photons:
  - Muons: Select for Tight/Loose, veto against Loose collection
  - Electrons: Select for Tight/Veto, veto against Veto collection
  - Photons: Select for Tight, veto against Loose collection
- B-tagging from DeepCSV medium WP
  - Same pt threshold as AK4s (30 GeV)
- Boosted objects defined using nominal DeepAK8 algorithm
  - Boosted V:
    - pT >200 GeV
    - $65 < m_{softdrop} < 120$ GeV (to be in sync with EXO-20-004)
    - 1% mistag rate WP
  - Boosted Top
    - pT > 400 GeV
    - $120 < m_{softdrop} < 210$ GeV
    - 1% mistag rate WP

Event selection:

Common selection for SR and CRs

- HT > 200 GeV
- MHT > 200 GeV
- Recoil > 200 GeV

  Recoil = MET + P_T of leptons and photons in CRs
- Lead and sublead jet pt > 80 GeV
- MHT / Recoil < 1.2
- dPhi(Recoil, MHT) < 0.5
- VBF orthogonality:
  - |lead jet η| < 2.4
  - |subleading jet η| < 2.4
  - NOT of VBF kinematic selection

Signal region: ttH and VH

- Lepton and photon vetoes
- $\Delta\Phi$(Recoil, TrkMet) < 1

  TrkMet_pt > 60 GeV
- **QCD suppression cuts:**
  - min$\Delta\Phi$4j > 0.5
  - min$\tilde{\omega}$ > 0.3 (ttH, VH)

Event Cleaning:

- MET Filters,
- JetID, pileup ID
- bad jet filters (EE noise in 2017)
- EE prefiring fix (2017)
- HEM treatment (2018)
  - Veto events where MET points into affected phi region

Event selection: Control Regions

Common selection

Single electron / muon CRs

1 tight lepton

Transverse mass mT(lν) = [50, 110] GeV

Double electron / muon CRs

1 tight lepton & 1 loose or tight lepton

Photon CR

1 tight photon

Lepton veto

ttH categories

No QCD angular suppression cuts

Di-lepton mass = [75,105]GeV

$\Delta\Phi$(Recoil, TrkMet) > 1.5

VH categories

QCD angular suppression cuts

Di-lepton mass = [60,120]GeV

QCD-enriched Multijet sideband

Invert min$\Delta\Phi$_4j and minω~ cut

Lepton and photon vetoes

$\Delta\Phi$(Recoil, TrkMet) < 1 & TrkMet_pt > 60

Datasets

Monte-Carlo datasets

Generator	Processes
MadGraph (inc. Madspin and amcatnlo)	single top, ttW, ttZ, VV, VVV
Pythia	Znunu, Zll
Powheg	ttbar, ttH (H->SM), Hinv: ttH, VH, ggH, VBF

Data Datasets

Year	Muon CRs and Hadronic region PD	Electron CRs PD	Photon CR PD
2016	MET	Single Electron	Single Photon
2017	MET	Single Electron	Single Photon
2018	MET	EGamma	EGamma

- All samples are end-of-year
- Skimmed using nanoAOD v7 CMSSW 10_2_15
- Pythia CP5 tune (some 2016 samples with CUETP8M1)
- 2016, 2017 and 2018 use campaigns Run2Summer16, Run2Fall17, Run2Autumn18 respectively

Trigger selection

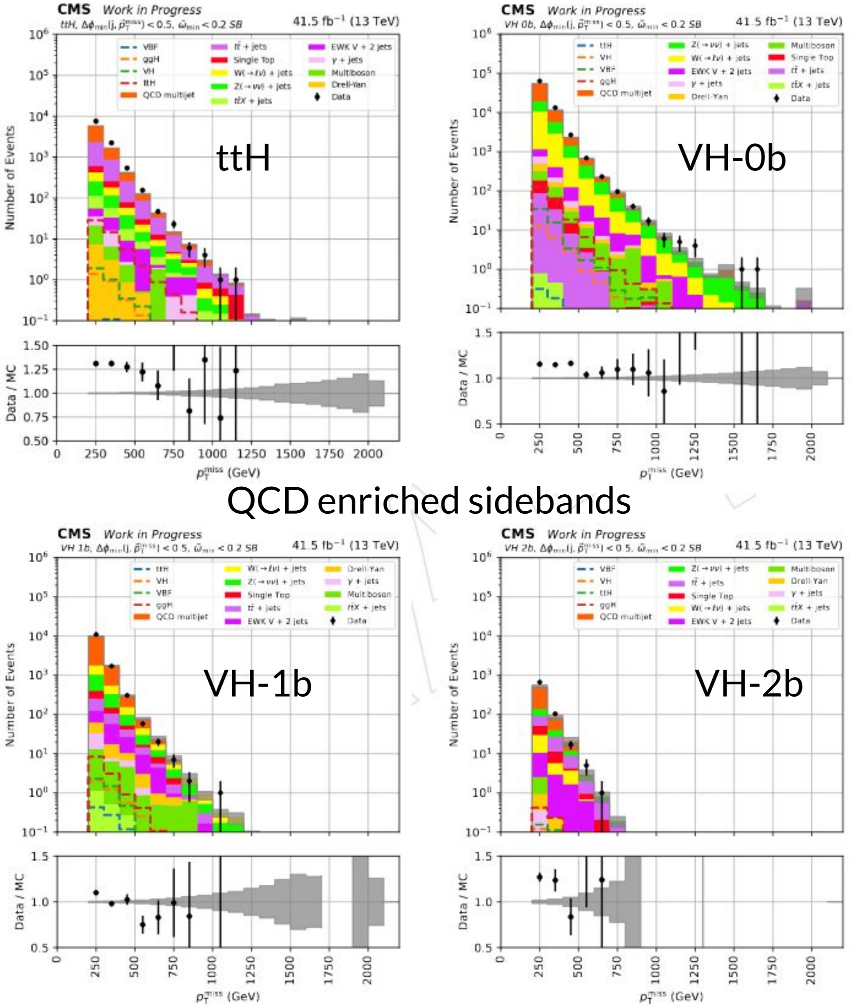
	2016	2017	2018
Signal region, muon control regions, QCD sidebands	**MET PD** HLT_PFMET*_PFMHT*_IDTight * = NoMu{90, 100, 110, 120}	**MET PD** HLT_PFMET*_PFMHT*_IDTight HLT_PFMET*_PFMHT*_IDTight_PFHT60 * = NoMu120	**MET PD** HLT_PFMET*_PFMHT*_IDTight * = NoMu120
Electron CR Data	**SingleElectron PD** HLT_Ele27_WPTight_Gsf HLT_Ele105_CaloIdVT_GsfTrkIdT	**SingleElectron PD** HLT_Ele35_WPTight_Gsf HLT_Ele115_CaloIdVT_GsfTrkIdT	**EGamma PD** HLT_Ele32_WPTight_Gsf HLT_Ele115_CaloIdVT_GsfTrkIdT HLT_Photon200
	SinglePhoton PD HLT_Photon165_HE10 HLT_Photon175 *NOT of above electron triggers*	**SinglePhoton PD** HLT_Photon200 *NOT of above electron triggers*	
Electron CR MC	Any of electron and photon triggers	Any of electron and photon triggers	
Photon CR	**SinglePhoton PD** HLT_Photon165_HE10 HLT_Photon175	**SinglePhoton PD** HLT_Photon200	**EGamma PD** HLT_Photon200

QCD prediction

- QCD strongly suppressed by event selection
- Residual QCD prediction from sidebands by inverting/tightening min$\Delta\Phi_{4j}$ & min$\tilde{\omega}$ cuts
- Use MC transfer factor method for QCD prediction (non-QCD BG subtracted)

$$N^{QCDpred} = (N^{data,CR} - N^{EWKMC,CR})*(N^{QCD,SR}/N^{QCD,CR})$$

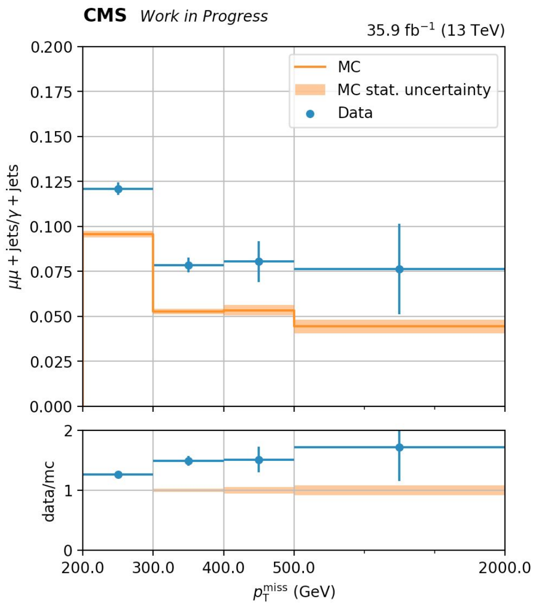
- As QCD MC stats in SR are poor, we determine overall QCD MC scale factor for each category (ttH, VH0b, VH1b, VH2b)
- Use MC fractions to break down by MET bin and in case of ttH also by sub-category



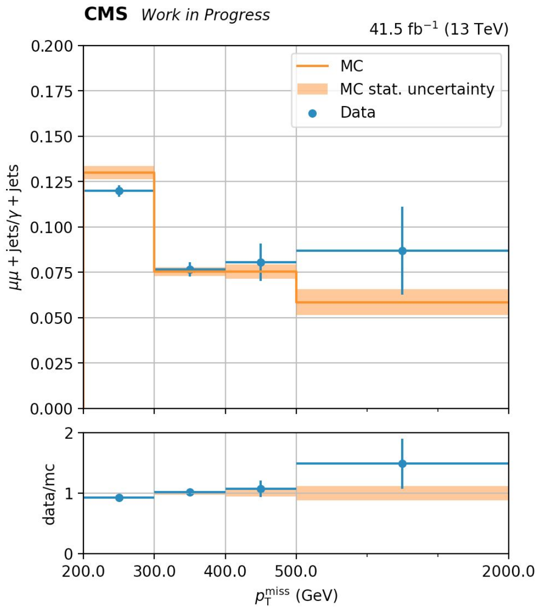
Additional systematic on Photon normalization

dimuon/photon in data and MC

2016



2017



2018