Search for $H^{\pm}$ decaying to top and bottom quarks with Single Leptonic Final State at 13 TeV using the CMS Detector

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on behalf of the CMS collaboration

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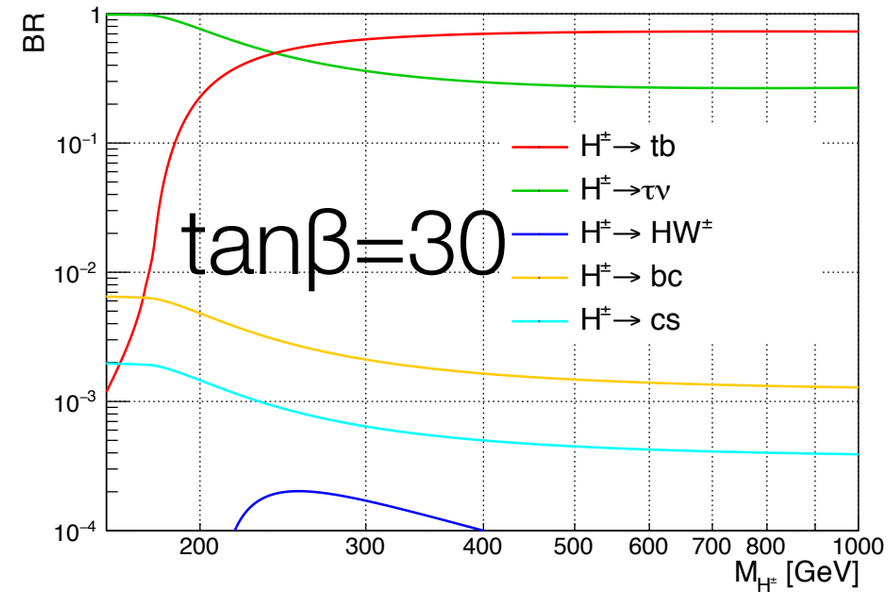
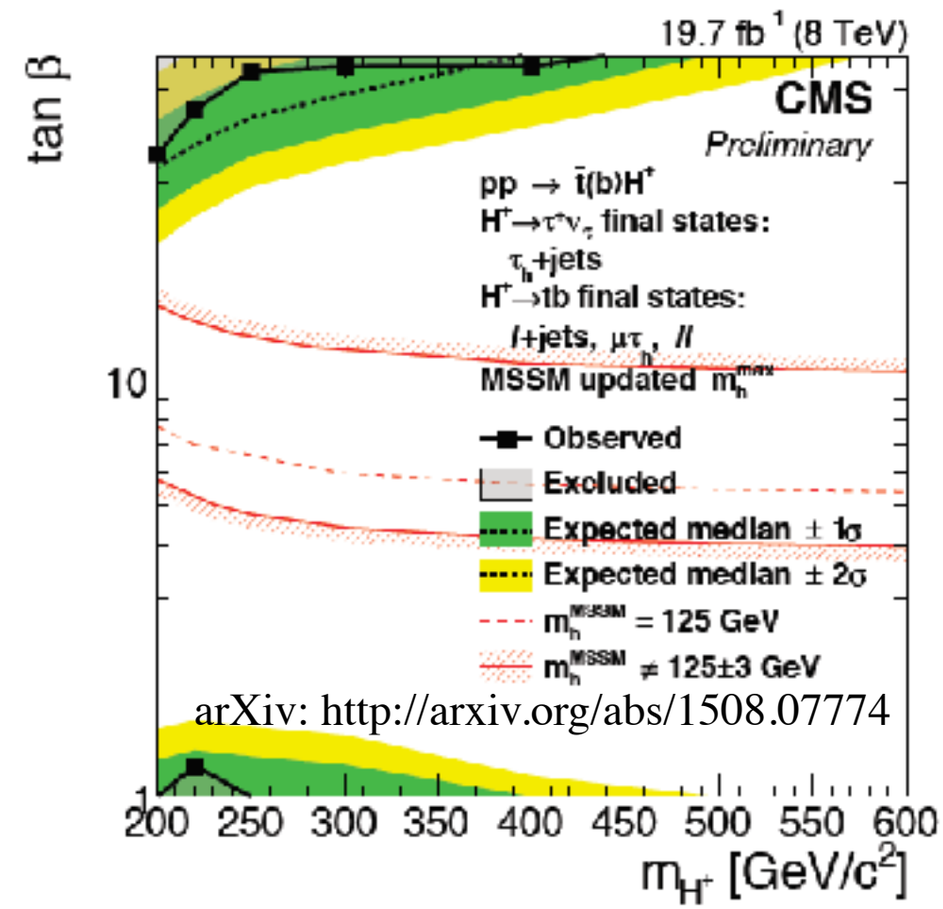
Overview

- Higgs boson discovery provides last piece of the Standard Model
- Further investigations are underway to verify if this is really a SM Higgs
- Two Higgs Doublet Model (2HDM) extends the Standard Model (SM) and expects Charged Higgs
- Largest branching ratio of the charged Higgs in top and bottom quark channel
- Exclusion limit on tanβ results from 8 TeV

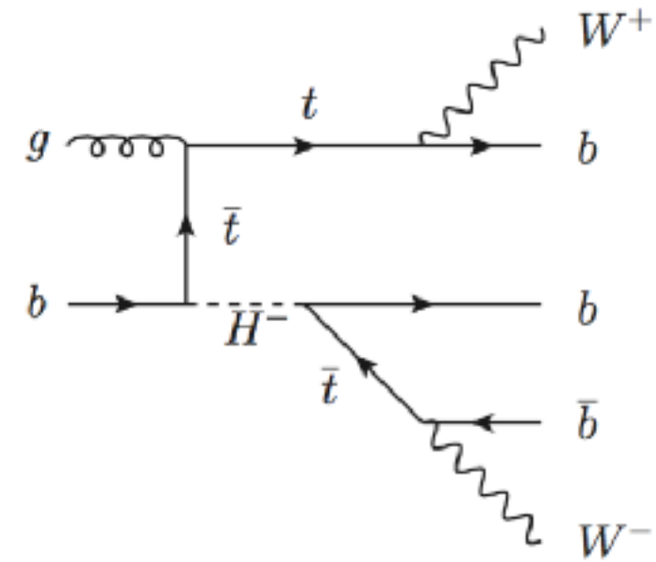


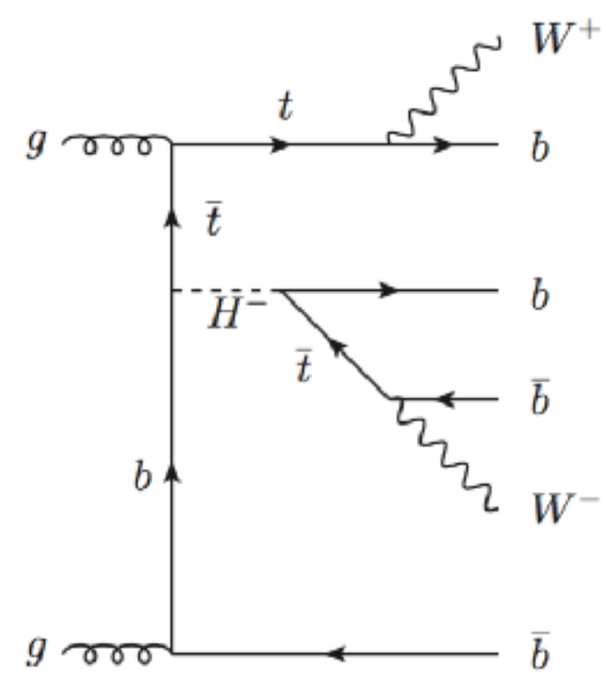


arXiv: http://arxiv.org/abs/1508.07774

Signatures

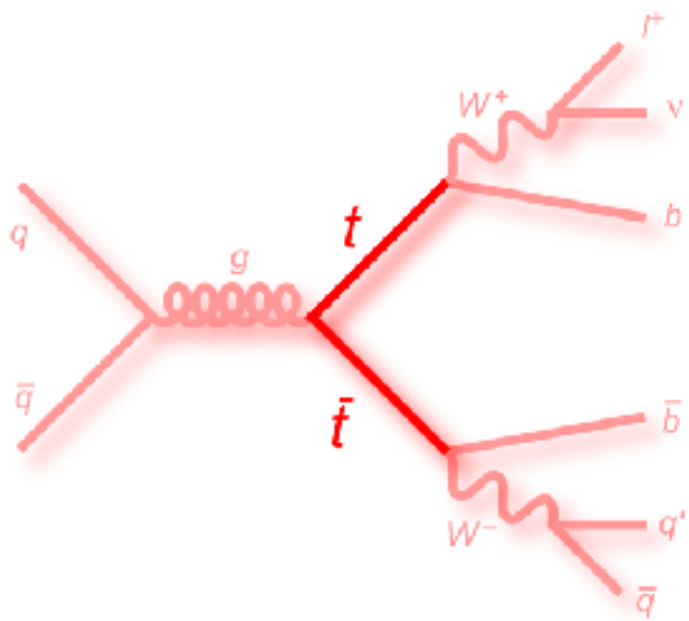
- Charged Higgs decays to top and bottom quarks
- The top quark decays to b quark and W boson
- Extra top quark and b quark from strong interactions
- Two W bosons are produced
  - One decays leptonically and other decays hadronically
- Only one lepton, electron or muon in the final state
- At least 3 b tagged jets, 1 lepton, and 2 other jets in the final state

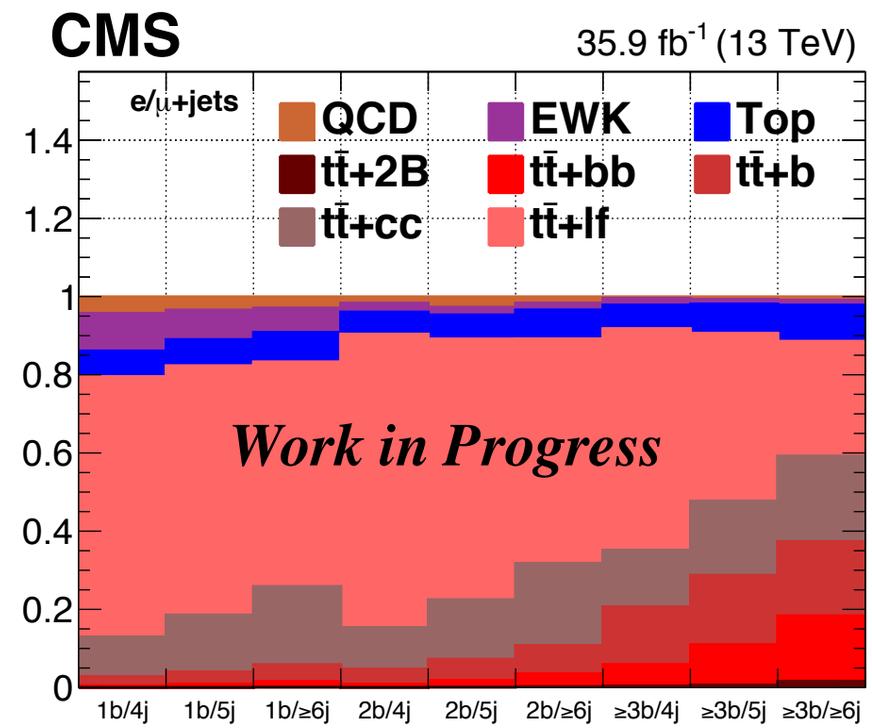




Backgrounds

- Pair produced top quarks (TTbar) decaying single leptonically
  - Dominate background in signal and control regions, over ~80%

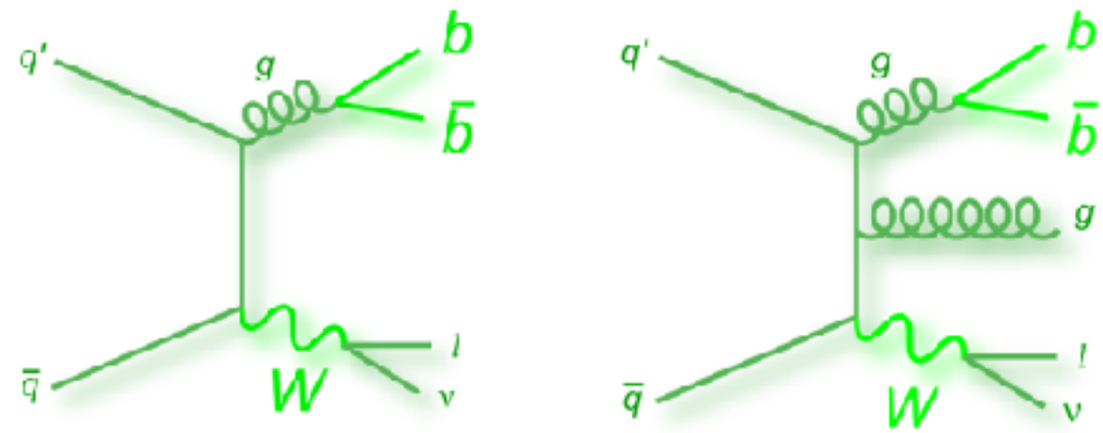




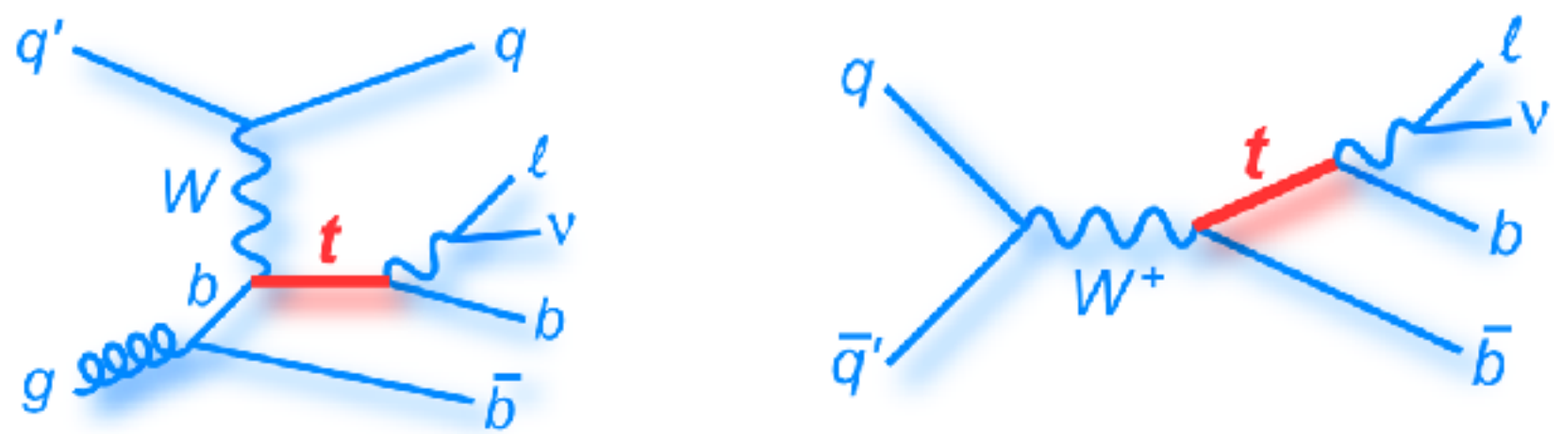
- Categorization by flavor for jets from extra radiation
  - ttbar+2B : one additional b jet containing two b hadrons
  - ttbar+bb : at least two additional b jets, independent of the number of b hadrons in each b jets
  - ttbar+b : one additional b jet containing a single b hadron
  - ttbar+cc : at least one additional c jet, independent of the number of c hadrons in each c jets
  - ttbar + lf : no additional b or c jets

Backgrounds

- W+jets
  - Leptonically decaying W boson
  - At least two b quarks produced



- Single top
  - At least 1 W boson and 1 b-quark
  - Mistagged Jets + Leptonically decaying W boson could mimic signal-like events



- Diboson, Drell-Yan, and QCD multi-jet backgrounds

Data and MC sets

- 2016 data with integrated luminosity 35.9 fb^{-1} collected by CMS detector
- Monte Carlo (MC) samples were generated with 25ns bunch spacing
- Event generators used for the MC samples
  - MADGRAPH5_aMC@NLO 2.2.2 : Signals, W+Jets, QCD-multijet, TOP DY+Jets, Diboson
  - POWHEG 2.6 : ttbar, TOP, Diboson
  - PYTHIA8.212
- GEANT4 was used for detector simulation
- Background MC samples are grouped into ttbar, TOP, EWK, and QCD multi-jet

Triggers

- Single lepton triggers used for increasing events selection efficiency
- All the triggers were used in logical ‘OR’ operation
- Electron triggers
  - Electron pT > 27 GeV, |η| < 2.1, and Tight ID
  - Electron pT > 35 GeV and Loose ID
  - Electron pT > 105 GeV and Tight ID
  - Photon pT > 165 GeV

Recovering
event selection efficiency
in high pT

- Muon triggers
  - Muon pT > 24 GeV with isolation
  - Muon pT > 24 GeV, reconstructed with hits in tracker
  - Muon pT > 50 GeV

Object Selections

- Electron
  - Multivariate Analysis (MVA) based Tight ID with custom working point, 88% efficiency in ttbar
  - Transverse Momentum (pT) > 35 GeV and $|\eta| < 2.1$
  - Mini-Isolation < 0.1, The cone size depends on pT to increase efficiency at high energy
  - Electron veto : Loose ID where 95% efficiency in ttbar, pT > 10 GeV, $|\eta| < 2.1$, Mini-Isolation < 0.4

- Muon
  - "Medium2016" ID, pT > 30 GeV, $|\eta| < 2.4$, and Mini-Isolation < 0.1
  - Muon veto : Loose ID, pT > 10 GeV, $|\eta| < 2.4$, and Mini-Isolation < 0.4

"Medium ID" used for MC and for data taken later in 2016

- Tau
  - Hadron plus Strip (HPS) algorithm based Tau, pT > 20 GeV, $|\eta| < 2.3$, and ΔR with lepton > 0.4
  - Used for veto in e/μ channels

- Jet
  - Reconstructed Jets with the anti-kT algorithm with a distance parameter of 0.4
  - Loose particle flow jet ID, pT > 40 GeV, $|\eta| < 2.4$, Angular separation (ΔR) with lepton > 0.4

- B-tagging
  - pfCombinedInclusiveSecondaryVertexV2 (CSVv2) > 0.8484 where mistag rate is less ~1%

- Missing Transverse Momentum (MET)
  - Negative vector sum of transverse energy from all particle flow object in an event

Baseline Event Selection

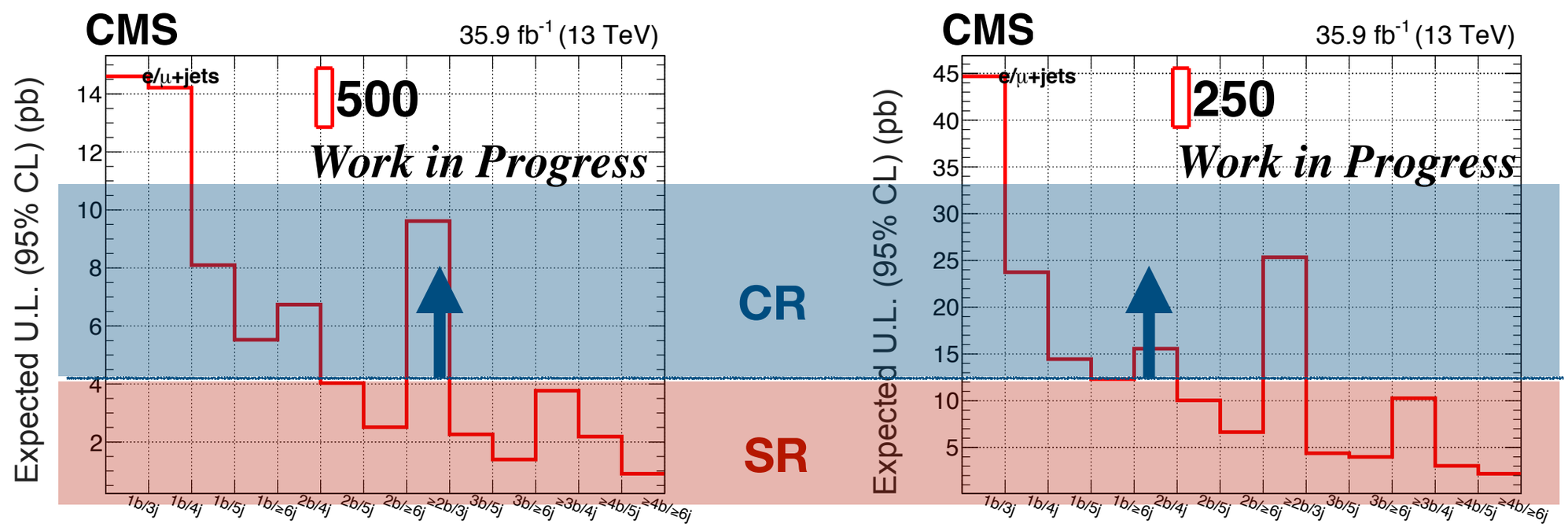
- Select events only passing logical ‘AND’ operation of following conditions
  - Exactly single electron or muon
  - Electron pT > 35 GeV and $|\eta| < 2.1$
  - Muon pT > 30 GeV and $|\eta| < 2.4$
  - Jet pT > 40 GeV
  - MET > 30 GeV
  - Number of jets ≥ 3 and Number of b-tagged jet ≥ 1
  - Minimum $\Delta\phi$ between MET and Jet > 0.05 in control regions of electron channel -> Suppressing QCD events leak
  - No Tau in electron and muon channels

Event Categorization

- Define control regions and maximization on signal sensitivity

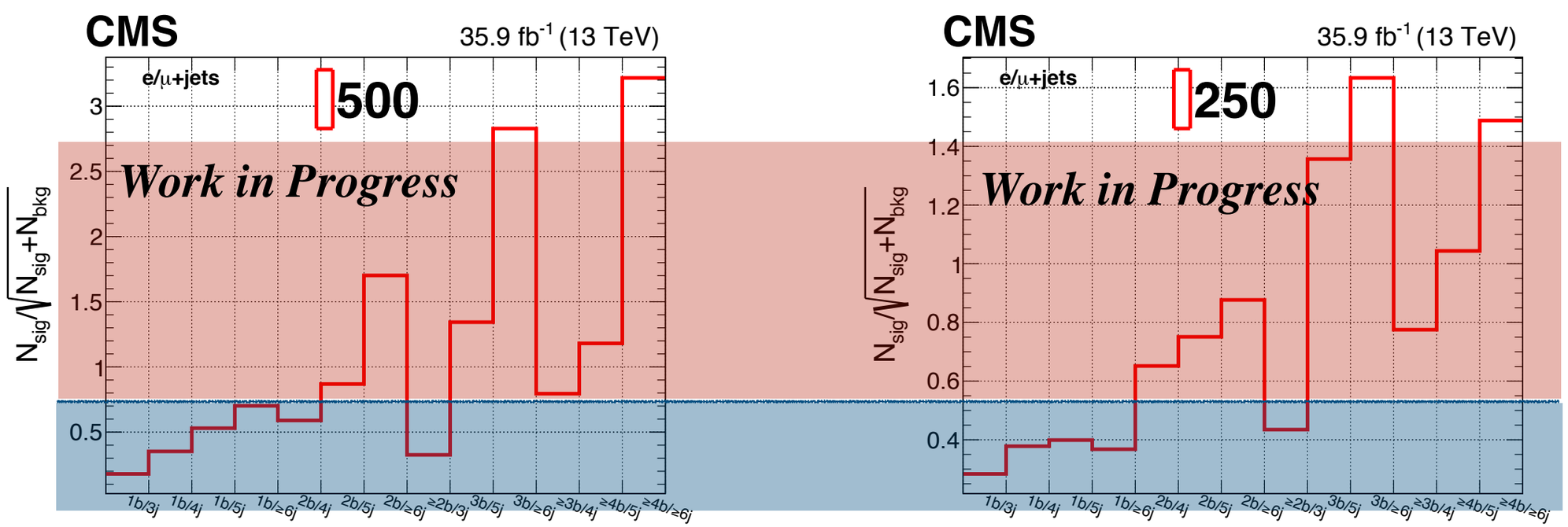
4 Control Regions

1b/4j 1b/5j
1b/≥6j 2b/4j



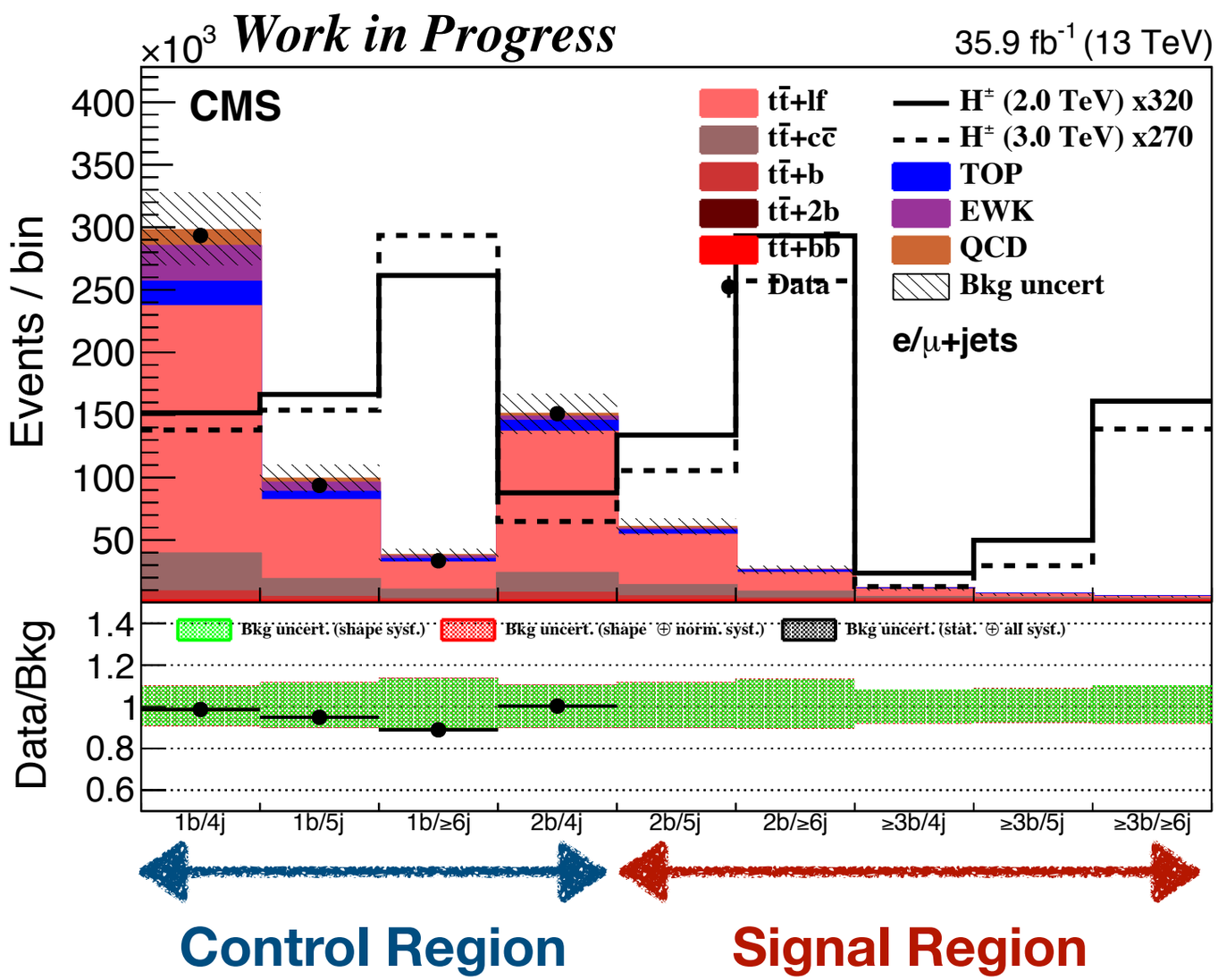
5 Signal Regions

2b/5j 2b/≥6j
≥3b/4j ≥3b/5j
≥3b/≥6j



Data/MC comparison in CR

- Good agreement between Data and MC in control regions within uncertainty



Samples	1b/4j	1b/5j	1b/≥6j	2b/4j
$t\bar{t}$ + lf	200000 ± 22000	63000 ± 8200	22000 ± 3400	110000 ± 12000
$t\bar{t}$ + c(c̄)	30000 ± 3500	14000 ± 1900	7500 ± 1200	16000 ± 1800
tt + 2b	59 ± 9.7	33 ± 6.0	37 ± 8.0	70 ± 12
$t\bar{t}$ + bb̄	1300 ± 160	800 ± 110	530 ± 90	1300 ± 160
$t\bar{t}$ + b	6900 ± 800	3200 ± 430	1600 ± 270	5800 ± 670
TOP	20000 ± 1000	6600 ± 410	2800 ± 220	8400 ± 470
EWK	28000 ± 3400	7400 ± 1000	2300 ± 380	3400 ± 420
QCD	13000 ± 2400	3400 ± 760	1100 ± 310	2600 ± 1300
Total bkg	300000 ± 23000	99000 ± 8800	38000 ± 3800	150000 ± 13000
Data	293365	93676	33440	151011
Data/Bkg	0.99 ± 0.077	0.95 ± 0.081	0.89 ± 0.089	1.0 ± 0.081
Hptb180	350 ± 19	140 ± 12	41 ± 4.7	240 ± 13
Hptb200	350 ± 17	150 ± 12	45 ± 5.3	270 ± 13
Hptb220	370 ± 17	150 ± 9.8	67 ± 7.7	330 ± 15
Hptb250	400 ± 17	180 ± 14	85 ± 8.1	340 ± 17
Hptb300	410 ± 18	230 ± 14	130 ± 11	430 ± 20
Hptb350	430 ± 18	260 ± 15	130 ± 12	440 ± 18
Hptb400	450 ± 19	290 ± 14	160 ± 14	450 ± 19
Hptb500	460 ± 19	340 ± 16	220 ± 15	450 ± 18
Hptb800	480 ± 21	430 ± 19	440 ± 24	420 ± 18
Hptb1000	460 ± 21	460 ± 20	490 ± 26	420 ± 18
Hptb2000	490 ± 21	540 ± 23	840 ± 37	280 ± 17
Hptb3000	480 ± 150	530 ± 160	1000 ± 310	220 ± 71

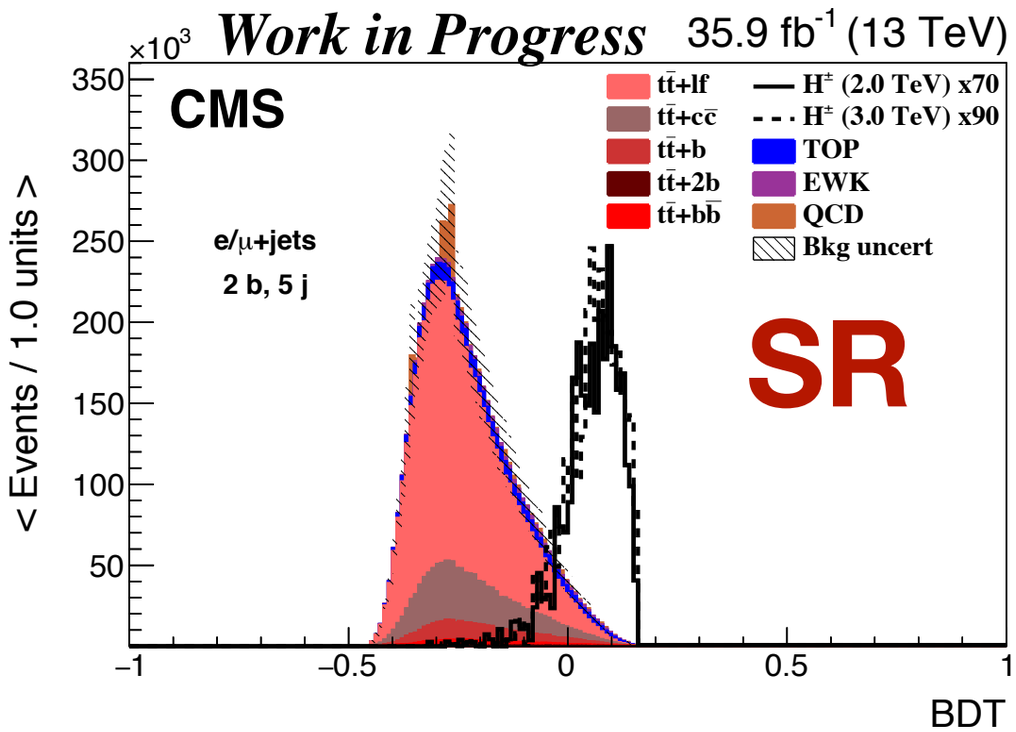
Multivariate Analysis

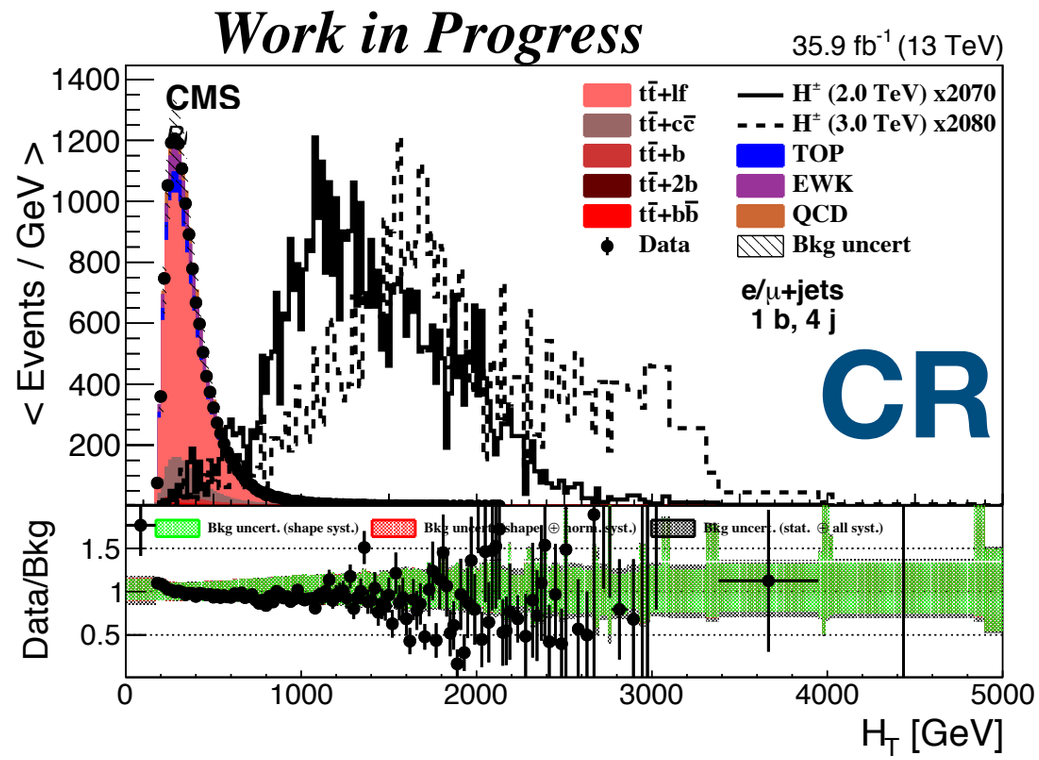
- Boosted Decision Tree with adaptive boost method used
- BDT discriminator is trained to distinguish signal from TTbar background which is main background
- Due to limited statistics in low mass signals two mass region defined
  - Low : 180, 200, 220, 250, and 300 GeV
  - Medium : 350, 400, and 500 GeV
- High mass signals were trained separately, 800, 1000, 2000, and 3000 GeV
- 20 kinematic input variables used for developing BDT discriminators
- Training in inclusive signal regions
- Randomly split signal sample into Train/Test/Application with 25%/25%/50%
- For TTbar background two samples used for Train/Test and Application
- Optimization in depth and number of tree performed to obtain receiver operating characteristics (ROC)

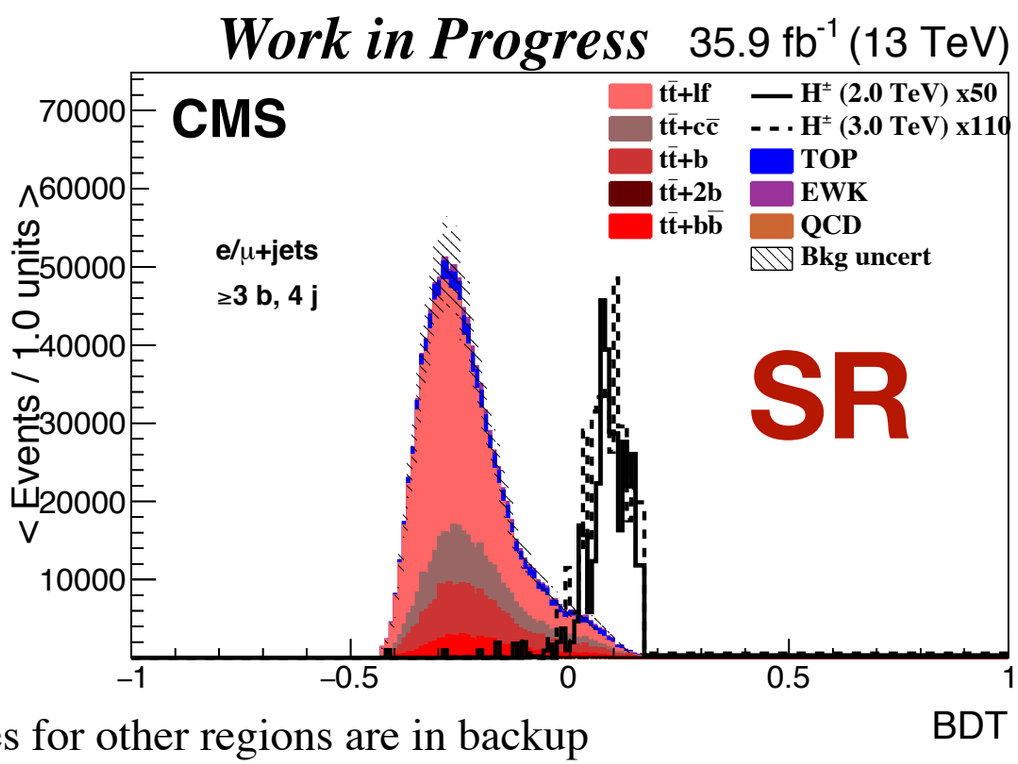
Multivariate Analysis

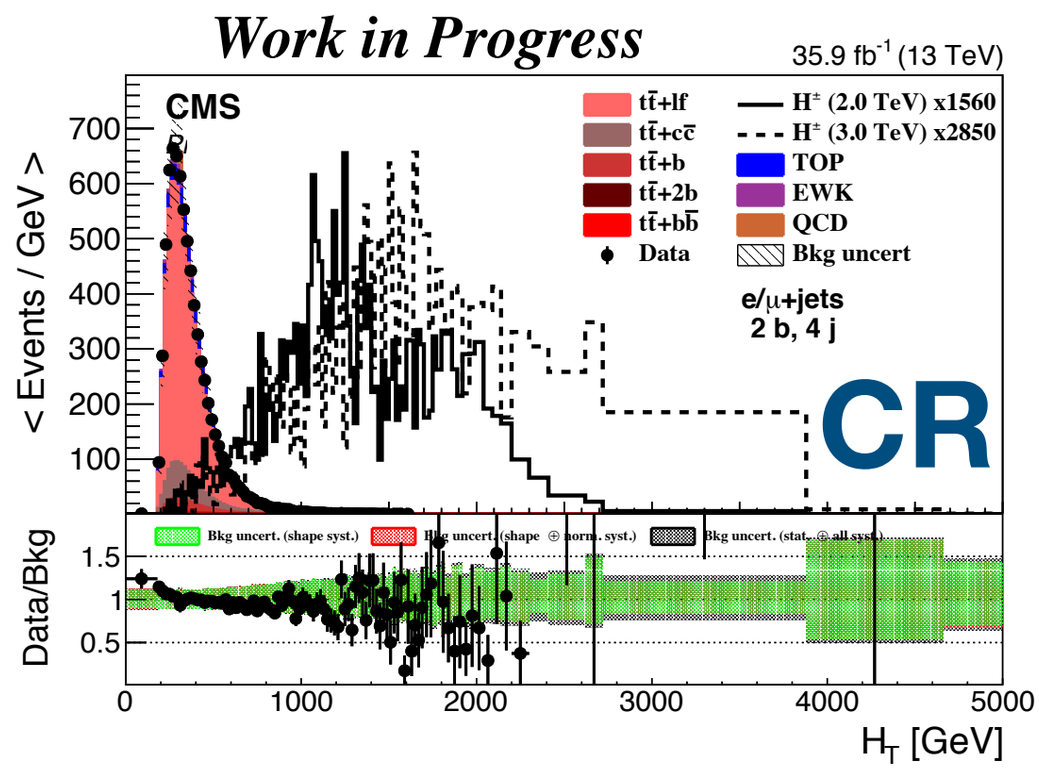
- the scalar sum of the all jet transverse momenta, H_T
- minimum mass of lepton and b-jet, min[M(ℓ, b)]
- the mass of the b-jet pair with minimum separation, M(b, b) with min[$\Delta R(b, b)$]
- the separation between the lepton and b-jet with maximum p_T, $\Delta R(\ell, b)$ with max[p_T ℓ, b]
- the separation between the lepton and leading jet, $\Delta R(\ell, j_1)$
- the separation between the lepton and sub-leading jet, $\Delta R(\ell, j_2)$
- the separation between the lepton and third leading jet, $\Delta R(\ell, j_3)$
- the separation between the lepton and leading b-jet, $\Delta R(\ell, b_1)$
- the separation between the lepton and b-jet pair where the separation between b-jet pair is minimum, $\Delta R(\ell, bb)$ with min[$\Delta R(b, b)$]
- Centrality, the ratio of the sum of the transverse momentum and total energy of all jets
- the separation in η between furthest b-jet pair, max[$\Delta\eta(b, b)$]
- *averageCSV*: this is p_T weighted average discriminator of the non b-tagged jets.
- average separation between b-jet pairs, ave[ΔR(b,b)]
- The second Fox-Wolfram moment where all jets are included in the calculation, 2nd FW moment
- the mass of the three jet system with maximum p_T, M(jjj) with max[p_T (jjj)]
- the transverse momentum of leading b-jet, p_T (b_1)
- minimum separation between b-jet pairs, min[$\Delta R(b, b)$]
- minimum separation between the lepton and b-jet, min[$\Delta R(\ell, b)$]
- the transverse mass of the leading lepton and the missing transvers energy, $M_T(\ell, E_T^{miss})$
- missing transverse energy, E_T^{miss}

Templates in SR/CR









Templates for other regions are in backup

Templates binning and Statistical Uncertainty

- Template binning choice
  - BDT template for Signal regions
    - Start from 200 uniform bins and rebin to have < 30% statistical uncertainty
  - HT template for Control regions
    - Start from 500 uniform bins and rebin to have < 30% statistical uncertainty

- Statistical Uncertainties in MC
  - Balow-Beeston lite methods used
  - Add additional nuisances on each bin if statistical uncertainty > 10%
  - Calculate uncertainty of the total background and assign to the dominant process
  - Advantage in reducing number of nuisances

Systematic Uncertainties

- Rate and Shape uncertainties are considered

- Renormalization and Factorization, Top pT, and b-tagging are most impact uncertainties

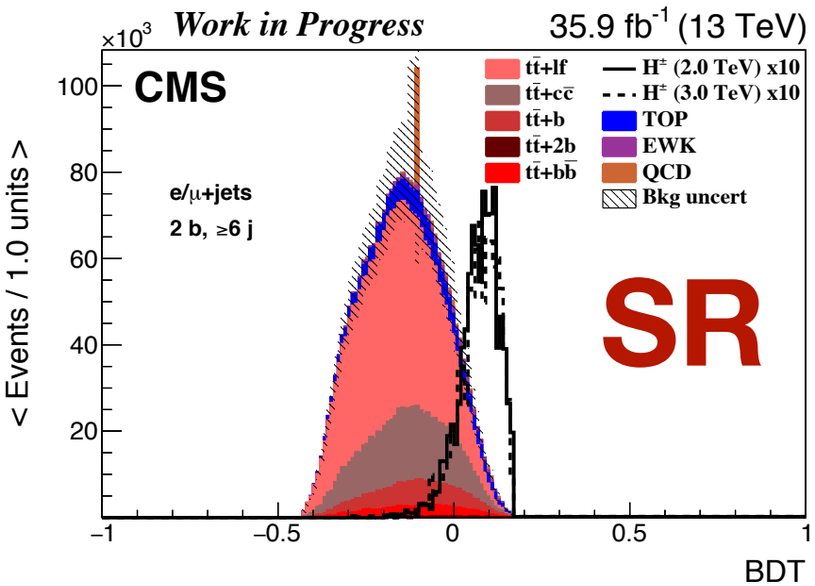
Source	Uncertainty	Signal	Background	Shape
Luminosity	2.5%	Yes	All	No
Electron Efficiency	3%	Yes	All	No
Muon Efficiency	4%	Yes	All	No
Tau Veto	3%	Yes	All	No
$t\bar{t}+lf$ rate	50%	No	$t\bar{t}+lf$	No
$t\bar{t}+cc$ rate	50%	No	$t\bar{t}+cc$	No
$t\bar{t}+2b$ rate	50%	No	$t\bar{t}+2b$	No
$t\bar{t}+bb$ rate	50%	No	$t\bar{t}+bb$	No
$t\bar{t}+b$ rate	50%	No	$t\bar{t}+b$	No
PDF	4.2%	No	$t\bar{t}$	No
PDF	4.0%	No	EWK	No
PDF	3.0%	No	TOP	No
Renorm./Fact. Energy Scale	+2.4/-3.5%	No	$t\bar{t}$	Yes
Renorm./Fact. Energy Scale	2%	No	EWK	Yes
Renorm./Fact. Energy Scale	10%	No	TOP	Yes
Jet Energy Scale	$\pm\sigma(p_T,\eta)$	Yes	All	Yes
Jet Energy Resolution	$\pm\sigma(\eta)$	Yes	All	Yes
b/c tagging	$\pm\sigma(p_T)$	Yes	All	Yes
udsg mistagging	$\pm\sigma$	Yes	All	Yes
Pileup	$\sigma_{\text{inel.}} \pm 4.6\%$	Yes	All	Yes
Top p_T	$\pm\Delta$(weighted, unweighted)	No	$t\bar{t}$	Yes
HT	env(upper fit, lower fit)	No	EWK	Yes

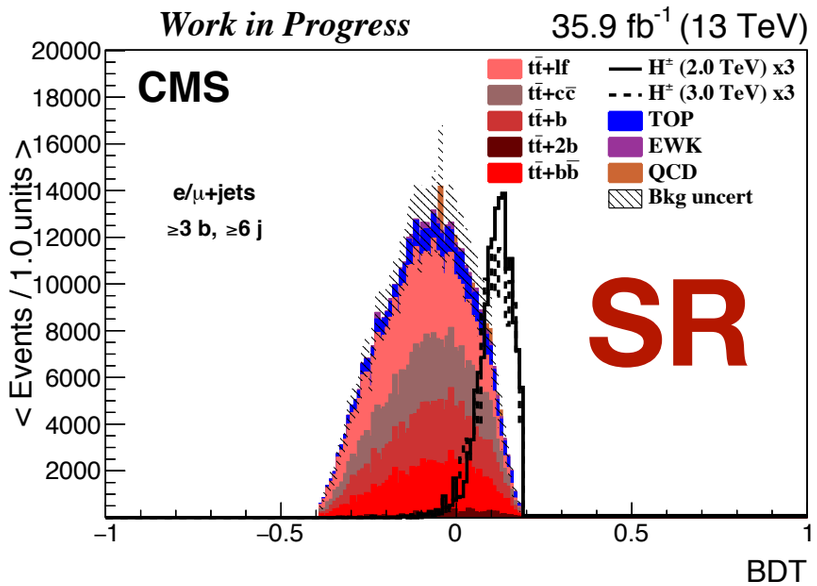
Expected Results

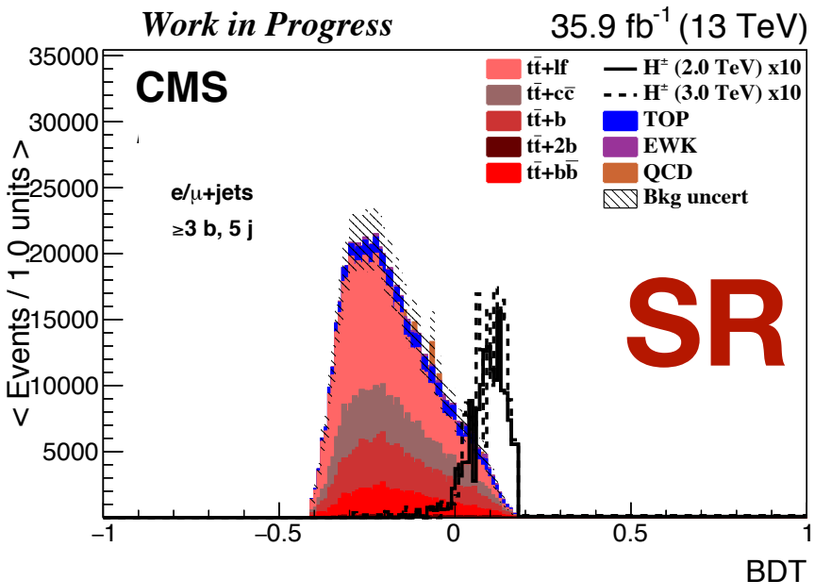
- 95% CL expected upper limits on cross section of a charged Higgs boson production
  - Asymptotic approximation used for limits
  - BDT (HT) discriminant for SR (CR)
  - QCD multi-jet excluded since its yield less than 5%
  - The expected limit varies between 2 pb and 0.01 pb for Charged Higgs mass between 180 and 3000 GeV

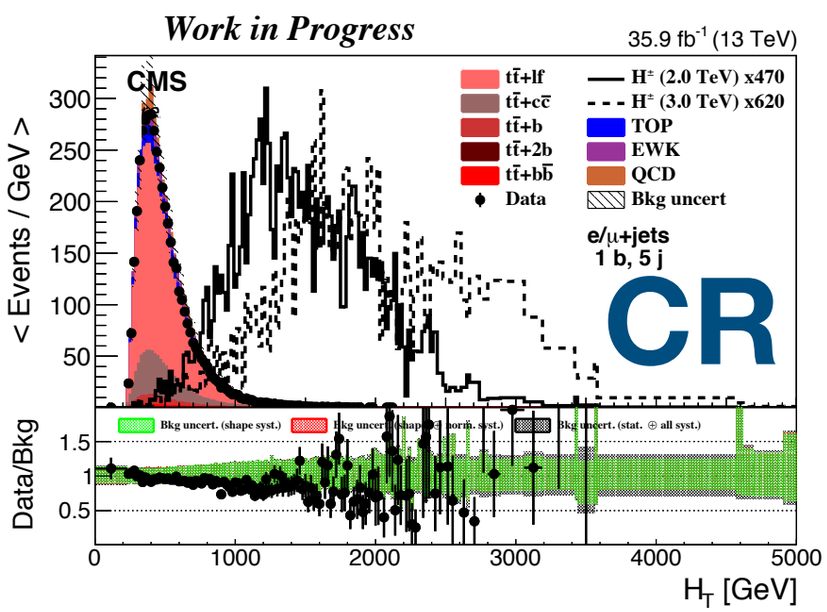
Backup

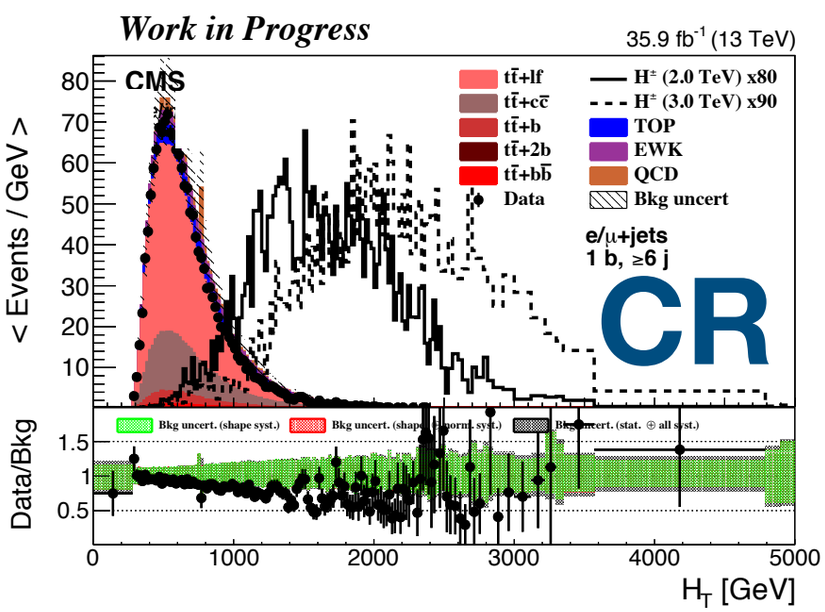
Templates in SR/CR











Data and MC samples

Primary Dataset	Reconstruction Group
SingleMuon	Run2016B-03Feb2017_ver2-v2
SingleMuon	Run2016C-03Feb2017-v1
SingleMuon	Run2016D-03Feb2017-v1
SingleMuon	Run2016E-03Feb2017-v1
SingleMuon	Run2016F-03Feb2017-v1
SingleMuon	Run2016G-03Feb2017-v1
SingleMuon	Run2016H-03Feb2017_ver2-v1
SingleMuon	Run2016H-03Feb2017_ver3-v1
SingleElectron	Run2016B-03Feb2017_ver2-v2
SingleElectron	Run2016C-03Feb2017-v1
SingleElectron	Run2016D-03Feb2017-v1
SingleElectron	Run2016E-03Feb2017-v1
SingleElectron	Run2016F-03Feb2017-v1
SingleElectron	Run2016G-03Feb2017-v1
SingleElectron	Run2016H-03Feb2017_ver2-v1
SingleElectron	Run2016H-03Feb2017_ver3-v1
Int. Lumi [fb^{-1}]	35.867

	QCD	
QCD_HT-100to200	madgraphMLM-pythia8	27990000 ± 4100 [15]
QCD_HT-200to300	madgraphMLM-pythia8	1712000 ± 380 [15]
QCD_HT-300to500	madgraphMLM-pythia8	347700 ± 75 [15]
QCD_HT-500to700	madgraphMLM-pythia8	32100 ± 7 [15]
QCD_HT-700to1000	madgraphMLM-pythia8	6831 ± 1.7 [15]
QCD_HT-1000to1500	madgraphMLM-pythia8	1207 ± 0.5 [15]
QCD_HT-1500to2000	madgraphMLM-pythia8	119.9 ± 0.06 [15]
QCD_HT-2000toInf	madgraphMLM-pythia8	25.24 ± 0.02 [15]

Signal	Generators	Cross Section [fb] [14, 17]	N_{gen}	N_{pos} - N_{neg}
HplusToTB_M-180	amcatnlo-pythia8	994.54	1499270	404688
HplusToTB_M-200	amcatnlo-pythia8	824.53	1473805	400501
HplusToTB_M-220	amcatnlo-pythia8	683.58	1499361	402569
HplusToTB_M-250	amcatnlo-pythia8	524.25	1491475	395891
HplusToTB_M-300	amcatnlo-pythia8	343.80	1497522	390646
HplusToTB_M-350	amcatnlo-pythia8	231.22	1496373	390221
HplusToTB_M-400	amcatnlo-pythia8	158.14	1496088	387746
HplusToTB_M-500	amcatnlo-pythia8	78.557	1500000	400004
HplusToTB_M-800	amcatnlo-pythia8	13.065	1494646	376326
HplusToTB_M-1000	amcatnlo-pythia8	4.7456	1491600	376708
HplusToTB_M-2000	amcatnlo-pythia8	0.0871	1500000	373174
HplusToTB_M-3000	amcatnlo-pythia8	0.0016	1497017	377717

Background	Generators	Cross Section [pb]
	$t\bar{t}$	
TT	powheg-pythia8	832^{+40}_{-46} [15]
TTTo2L2Nu	powheg-pythia8	832 ($\times(3*0.108)^2$)
TT_Mtt-700to1000	powheg-pythia8	832^{+40}_{-46} ($\times$0.092) [15]
TT_Mtt-1000toInf	powheg-pythia8	832^{+40}_{-46} ($\times$0.025) [15]
TT_Semilepton	powheg-pythia8	364.4 [15]
	TOP	
ST_t-channel_top_4f_inclusiveDecays	powhegV2-madspin-pythia8	$136.0^{+5.5}_{-4.7}$ [16]
ST_t-channel_antitop_4f_inclusiveDecays	powhegV2-madspin-pythia8	$80.9^{+4.1}_{-3.7}$ [16]
ST_s-channel_4f_leptonDecays	amcatnlo-pythia8	$11.36^{+0.44}_{-0.48}$ ($\times$1/3) [16]
ST_tW_top_5f_inclusiveDecays	powheg-pythia8	35.8 ± 1.9 [16]
ST_tW_antitop_5f_inclusiveDecays	powheg-pythia8	35.8 ± 1.9 [16]
TTWJetsToLNu	amcatnloFXFX-madspin-pythia8	0.204 ± 0.002 [15]
TTWJetsToQQ	amcatnloFXFX-madspin-pythia8	0.406 ± 0.002 [15]
TTZToQQ	amcatnlo-pythia8	0.530 ± 0.001 [15]
TTZToLLNuNu_M-10	amcatnlo-pythia8	0.253 ± 0.001 [15]
TTGJets	amcatnloFXFX-madspin-pythia8	3.697 ± 0.0013 [15]
TTTT	amcatnlo-pythia8	0.009103 [15]
tZq_ll_4f	amcatnlo-pythia8	0.0758 [15]
ttHJetTobb_M125	amcatnloFXFX_madspin_pythia8	0.2934045 [15]
ttHToNonbb_M125	powheg-pythia8	0.215 [15]
	EWK	
DYJetsToLL_M-50	madgraphMLM-pythia8	1921.8 ± 33.2 ($\times$3) [15]
DYJetsToLL_M-10to50	madgraphMLM-pythia8	18610.
WJetsToLNu_HT-100to200	madgraphMLM-pythia8	1345.0 ± 1.2 ($\times$1.21) [15]
WJetsToLNu_HT-200to400	madgraphMLM-pythia8	359.7 ± 0.2 ($\times$1.21) [15]
WJetsToLNu_HT-400to600	madgraphMLM-pythia8	48.910 ± 0.072 ($\times$1.21) [15]
WJetsToLNu_HT-600to800	madgraphMLM-pythia8	12.050 ± 0.007 ($\times$1.21) [15]
WJetsToLNu_HT-800to1200	madgraphMLM-pythia8	5.501 ± 0.017 ($\times$1.21) [15]
WJetsToLNu_HT-1200to2500	madgraphMLM-pythia8	1.329 ± 0.002 ($\times$1.21) [15]
WJetsToLNu_HT-2500toInf	madgraphMLM-pythia8	0.0322 ± 0.0001 ($\times$1.21) [15]
WWW_4F	amcatnlo-pythia8	0.2086 [15]
WWZ	amcatnlo-pythia8	0.1651 [15]
WZZ	amcatnlo-pythia8	0.05565 [15]
ZZZ	amcatnlo-pythia8	0.01398 [15]
WWTo2L2Nu	powheg	12.178 [15]
WWToLNuQQ	powheg	49.997 [15]
WZTo1L1Nu2Q	amcatnloFXFX_madspin_pythia8	10.71 [15]
WZTo1L3Nu	amcatnloFXFX_madspin_pythia8	3.033 [15]
WZTo2L2Q	amcatnloFXFX_madspin_pythia8	5.595 [15]
WZTo3LNu	powheg-pythia8	4.42965 [15]
ZZTo2L2Nu	powheg_pythia8	0.564 [15]
ZZTo2L2Q	amcatnloFXFX_madspin_pythia8	3.22 [15]
ZZTo4L	powheg_pythia8	1.256 [15]
WH_HToBB_WToLNu_M125	amcatnloFXFX_madspin_pythia8	0.419 [15]
VHToNonbb_M125	amcatnloFXFX_madspin_pythia8	0.952 [15]