Search for production of a Higgs boson and a single top quark in multilepton final states in proton collisions at $\sqrt{s}$ =13 TeV

Approval of HIG-17-005
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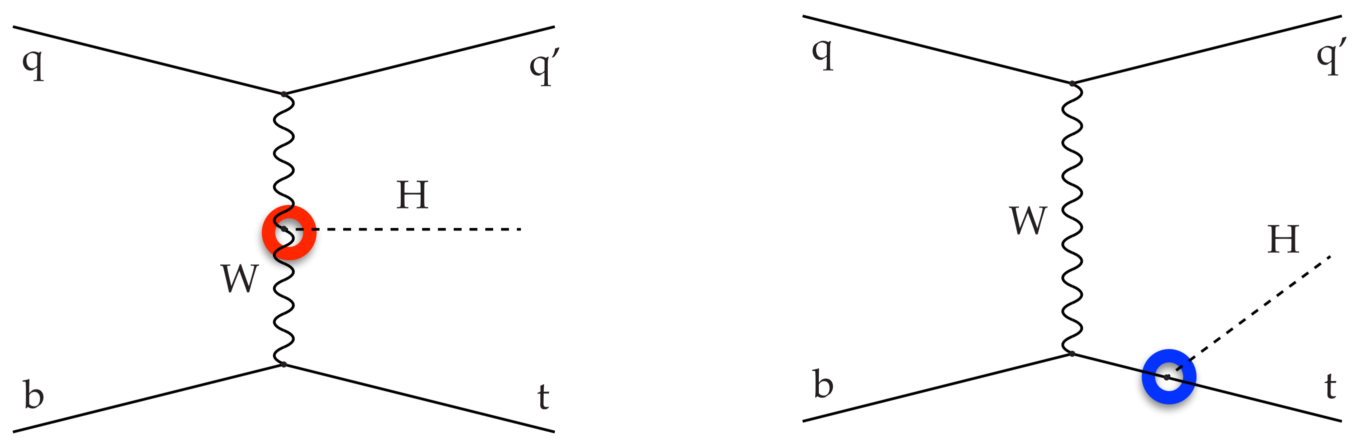
Motivation for tHq search

- Measurement of couplings is essential to establish the nature of the Higgs.
- Most processes are only sensitive to overall coupling strengths.
- Study of tHq process exposes the relative sign of top-Higgs and W-Higgs couplings via interference.

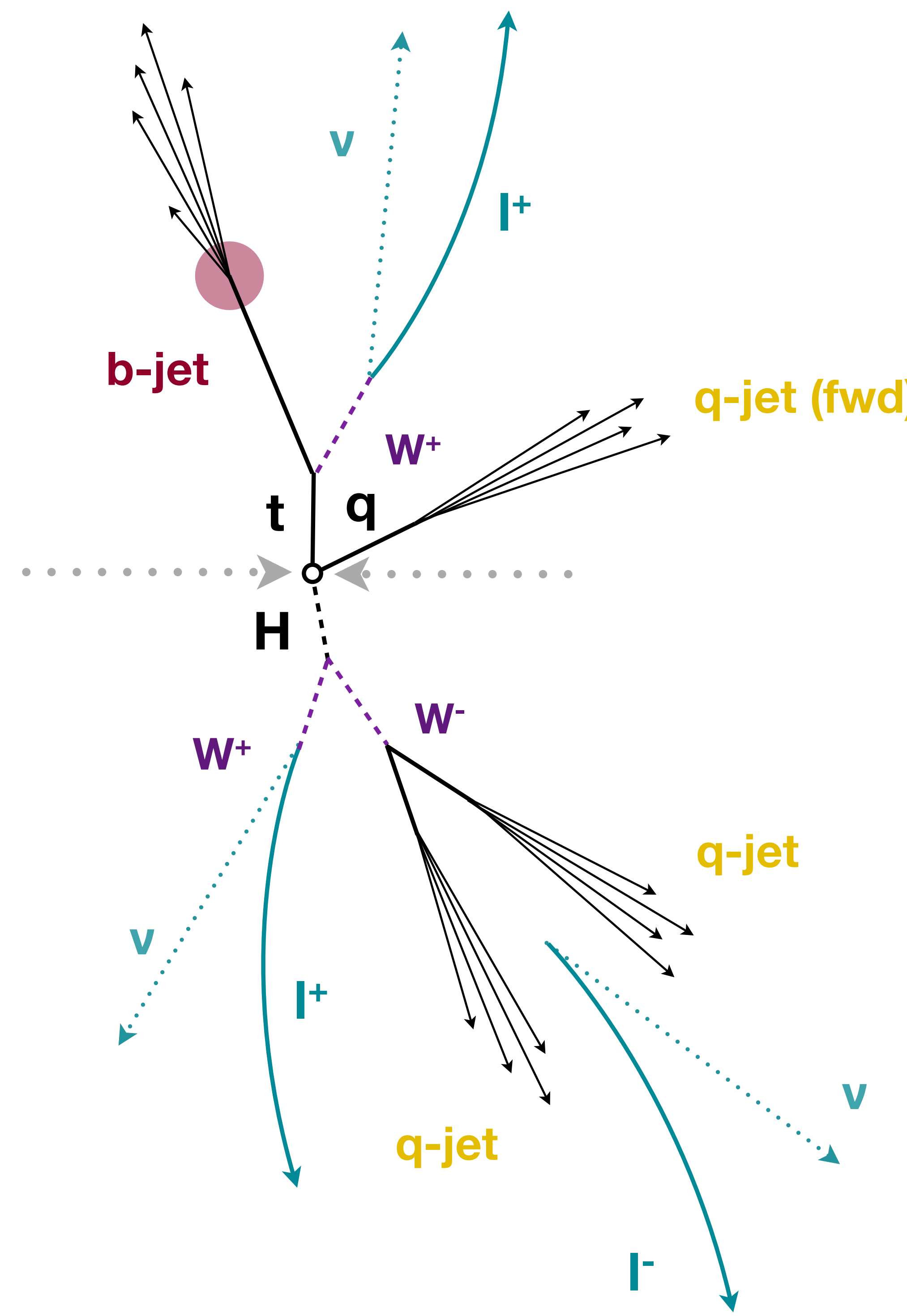


Study the coupling modifiers κ_t and κ_V

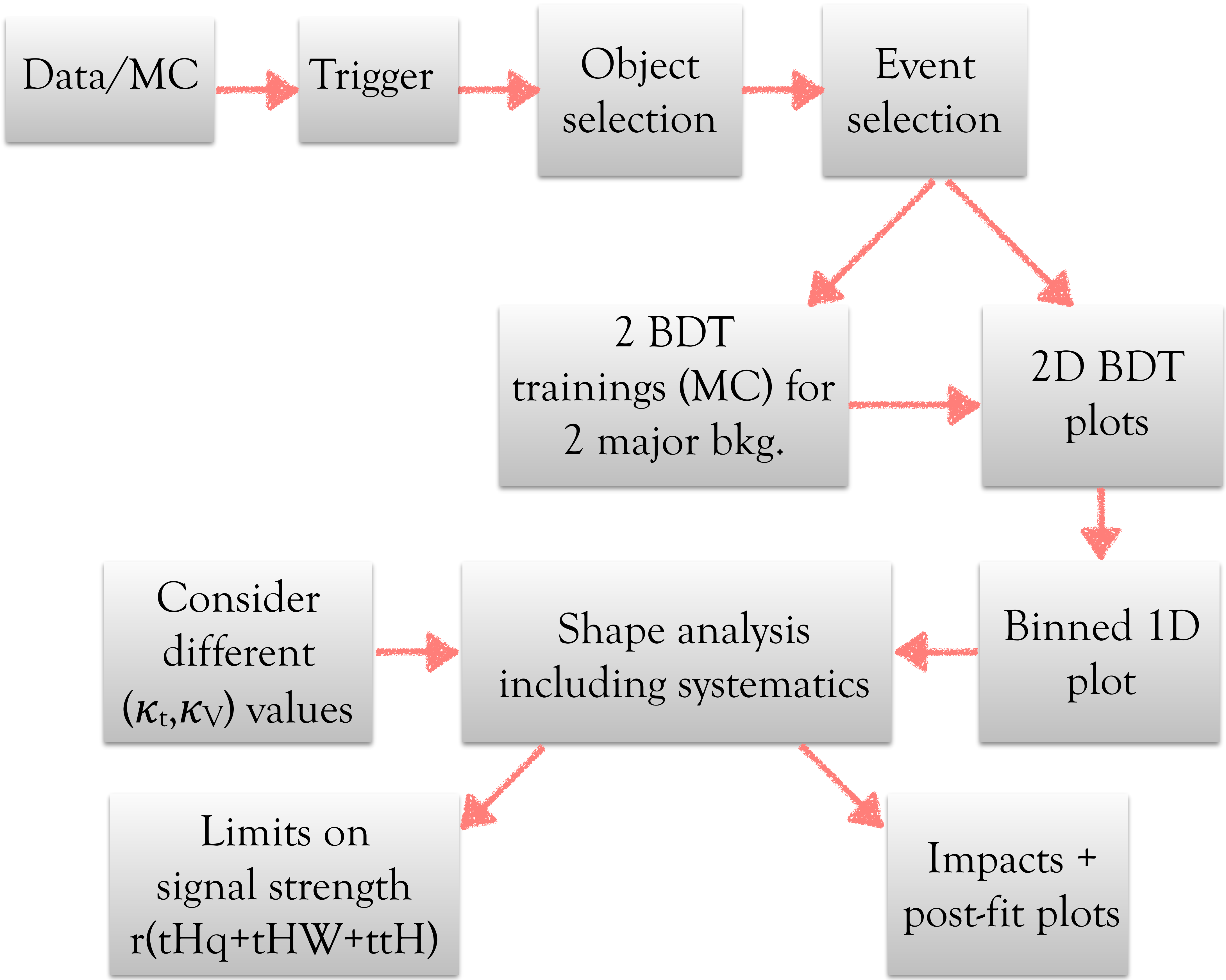
- Destructive interference in SM: $\sigma_{SM}(\kappa_V = \kappa_t = 1)$ = 70.96 fb ($\sqrt{s}$ = 13 TeV).
- Large enhancement for negative relative sign between κ_t and κ_V in tHq production: e.g., $\sigma\,(\kappa_V = -\kappa_t = 1)$ = 792.7 fb.
- Current CMS and ATLAS measurements agree well with SM values.
- Similar interference effect for tHW process is observed: σ_{SM}(tHW) = 15.61 fb.

tHq multilepton signature

- The characteristic feature of the tHq signal:
  - ➡ one light forward jet
  - ➡ one b jet and W boson from top decay, with $W \to l\nu$
  - ➡ one Higgs boson
- Investigate two channels:
  - ➡ Same-sign dilepton (2lss): one W from Higgs decays hadronically, others decay leptonically.
  - ➡ Trilepton (3l): All three Ws decay leptonically.
- Selected sample has contributions from $H \to WW^*$ (~75%), $\tau\tau$(~20%), ZZ^*(~5%) decays.



Analysis workflow



Updates since pre-approval

- Tightened lepton MVA Id: selection cut changed to 0.9 from 0.75, resulting in reduced fake acceptance and ~10% improved limit.
- Increased p_T threshold of trailing leptons to 15 GeV: to obtain better fake rate closure and trigger efficiency.
- Increased p_T threshold to 40 GeV for forward ($|\eta| > 2.4$) light quark jet: better data/MC agreement observed at higher η region.
- Updated physics model (scaling BRs with κ_t, κ_V in addition to cross sections).
- Include ttH to multilepton as signal component (σ_{SM} ~500 fb).

  → sensitivity improved.

Results:

- Limit on σ(tHq+tHW+ttH)xBR(H→WW*, $\tau\tau$, ZZ*) as a function of κ_t/κ_V.
- Added scans of significances, best-fit cross sections and expected limits in presence of SM-like signal.

Checked the overlap between the tHq and ttH selection, in light of possible combination of the two channels in near future.

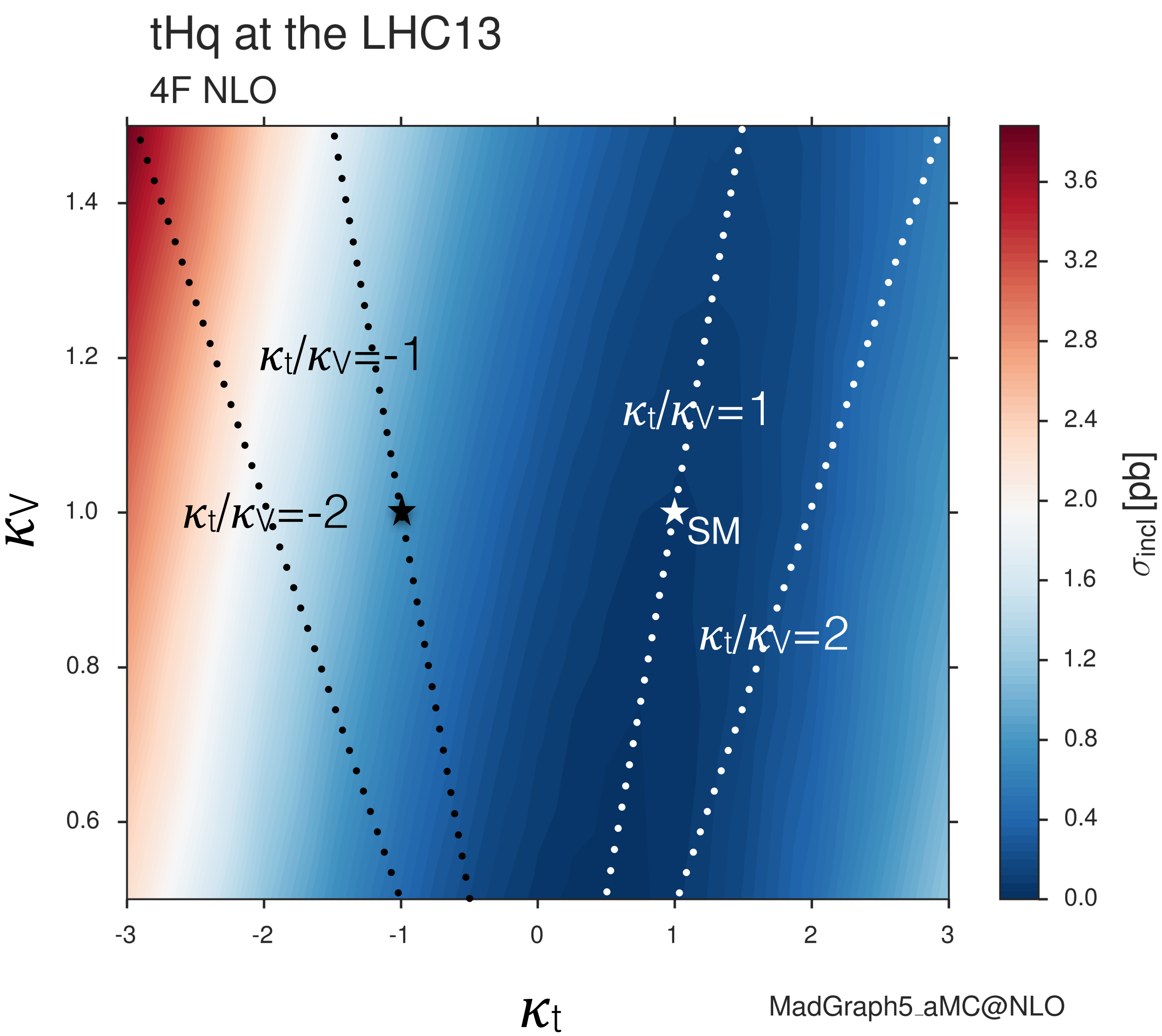
Signal modelling

- MC samples for tHq and tHW modelled with MG5_aMC@NLO at leading order.
  - ➡ Four flavor scheme for tHq
  - ➡ Five flavor scheme for tHW (to avoid overlap with ttH process)
- Forced leptonic decay for top in tHq sample, inclusive decays in tHW sample.
- 51 combinations of (κ_t, κ_V) using LHE weights:

  κ_V = 0.5, 1.0, 1.5

  17 points ranging from -3 to 3 for κ_t,.

  - ➡ 33 unique values of the ratio κ_t/κ_V in the range (-6, 6).



Representative lines corresponding to constant κ_t/κ_V ratio

Data and Monte Carlo samples

- **Data**: Full 2016 dataset with integrated luminosity 35.9 fb^{-1}.
  - ➡ 23 Sep 2016 re-reco(Run B to G), Prompt-reco(Run H).

- **MC**: PU Moriond 17 samples, corrected for efficiency scale factors and pile-up weights. Scaled to NLO or NNLO cross section as applicable.

signal

Sample	σ [pb]	BF
/THQ_Hincl_13TeV-madgraph-pythia8_TuneCUETP8M1/	0.7927	0.324
/THW_Hincl_13TeV-madgraph-pythia8_TuneCUETP8M1/	0.1472	1.0

backgrounds

Sample	σ [pb]	
TTWJetsToLNu_TuneCUETP8M1_13TeV-amcatnloFXFX-madspin-pythia8	0.2043	Prompt leptons
TTZToLLNuNu_M-10_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.2529	
ttHJetToNonbb_M125_13TeV_amcatnloFXFX_madspin_pythia8_mWCutfix	0.2151	
/store/cmst3/group/susy/gpetrucc/13TeV/u/TTLL_m1to10_LO_NoMS_for76X/	0.0283	
WGToLNuG_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	585.8	
ZGTo2LG_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	131.3	
TGJets_TuneCUETP8M1_13TeV_amcatnlo_madspin_pythia8	2.967	
TTGJets_TuneCUETP8M1_13TeV-amcatnloFXFX-madspin-pythia8	3.697	
WpWpJJ_EWK-QCD_TuneCUETP8M1_13TeV-madgraph-pythia8	0.03711	
ZZZ_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.01398	
WWZ_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.1651	
WZZ_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.05565	
WW_DoubleScattering_13TeV-pythia8	1.64	
tZq_ll_4f_13TeV-amcatnlo-pythia8_TuneCUETP8M1	0.0758	
ST_tWll_5f_LO_13TeV-MadGraph-pythia8	0.01123	
TTTT_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.009103	
WZTo3LNu_TuneCUETP8M1_13TeV-powheg-pythia8	4.4296	
ZZTo4L_13TeV_powheg_pythia8	1.256	
TTJets_SingleLeptFromTbar_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	182.1754	Non-prompt leptons
TTJets_SingleLeptFromT_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	182.1754	
TTJets_DiLept_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	87.3	
DYJetsToLL_M-10to50_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	18610	
DYJetsToLL_M-50_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	6024	
WJetsToLNu_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	61526.7	
ST_tW_top_5f_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M1	35.6	
ST_tW_antitop_5f_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M1	35.6	
ST_t-channel_4f_leptonDecays_13TeV-amcatnlo-pythia8_TuneCUETP8M1	70.3144	
ST_t-channel_antitop_4f_leptonDecays_13TeV-powheg-pythia8_TuneCUETP8M1	26.2278	
ST_s-channel_4f_leptonDecays_13TeV-amcatnlo-pythia8_TuneCUETP8M1	3.68064	
WWTo2L2Nu_13TeV-powheg	10.481	

Triggers and efficiencies

- **Same set of single, di- and multi-lepton triggers as ttH analysis**(HIG-17-004)**.**
- **Efficiency:** measured in events collected with MET trigger
  ~1% difference between data and MC (See backup for details).
  accounted for via scale factors.

Same-sign dilepton (==2 muons)
HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_v⋆
HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_DZ_v⋆
HLT_IsoMu22_v⋆
HLT_IsoTkMu22_v⋆
HLT_IsoMu22_eta2p1_v⋆
HLT_IsoTkMu22_eta2p1_v⋆
HLT_IsoMu24_v⋆
HLT_IsoTkMu24_v⋆
Same-sign dilepton (==2 electrons)
HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v⋆
HLT_Ele27_eta2p1_WPLoose_Gsf_v⋆
HLT_Ele27_WPTight_Gsf_v⋆
HLT_Ele25_eta2p1_WPTight_Gsf_v⋆
Same-sign dilepton (==1 muon, ==1 electron)
HLT_Mu23_TrkIsoVVL_Ele8_CaloIdL_TrackIdL_IsoVL_v⋆
HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_v⋆
HLT_Mu23_TrkIsoVVL_Ele8_CaloIdL_TrackIdL_IsoVL_DZ_v⋆
HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ_v⋆
HLT_IsoMu22_v⋆
HLT_IsoTkMu22_v⋆
HLT_IsoMu22_eta2p1_v⋆
HLT_IsoTkMu22_eta2p1_v⋆
HLT_IsoMu24_v⋆
HLT_IsoTkMu24_v⋆
HLT_Ele27_WPTight_Gsf_v⋆
HLT_Ele25_eta2p1_WPTight_Gsf_v⋆
HLT_Ele27_eta2p1_WPLoose_Gsf_v⋆

Three lepton and Four lepton
HLT_DiMu9_Ele9_CaloIdL_TrackIdL_v⋆
HLT_Mu8_DiEle12_CaloIdL_TrackIdL_v⋆
HLT_TripleMu_12_10_5_v⋆
HLT_Ele16_Ele12_Ele8_CaloIdL_TrackIdL_v⋆
HLT_Mu23_TrkIsoVVL_Ele8_CaloIdL_TrackIdL_IsoVL_v⋆
HLT_Mu23_TrkIsoVVL_Ele8_CaloIdL_TrackIdL_IsoVL_DZ_v⋆
HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_v⋆
HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ_v*
HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v⋆
HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_v⋆
HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_DZ_v⋆
HLT_IsoMu22_v⋆
HLT_IsoTkMu22_v⋆
HLT_IsoMu22_eta2p1_v⋆
HLT_IsoTkMu22_eta2p1_v⋆
HLT_IsoMu24_v⋆
HLT_IsoTkMu24_v⋆
HLT_Ele27_WPTight_Gsf_v⋆
HLT_Ele25_eta2p1_WPTight_Gsf_v⋆
HLT_Ele27_eta2p1_WPLoose_Gsf_v⋆

Object selection

- Use **lepton MVA** developed for ttH analysis for optimal selection of prompt leptons and suppression of non-prompt leptons.
- Three levels of lepton selection: loose (low resonance event veto), fakeable object (fake estimation from data), tight (actual signal selection).

Muons

Cut	Loose	Fakeable object	Tight
$\|\eta\| < 2.4$	✓	✓	✓
p_T	$> 5\,\mathrm{GeV}$	$> 15\,\mathrm{GeV}$	$> 15\,\mathrm{GeV}$
$\|d_{xy}\| < 0.05$ (cm)	✓	✓	✓
$\|d_z\| < 0.1$ (cm)	✓	✓	✓
$\mathrm{SIP}_{3D} < 8$	✓	✓	✓
$I_{\mathrm{mini}} < 0.4$	✓	✓	✓
is Loose Muon	✓	✓	✓
jet CSV	–	< 0.8484	< 0.8484
is Medium Muon	–	–	✓
tight-charge	–	–	✓
lepMVA > 0.90	–	–	✓

Electrons

Cut	Loose	Fakeable Object	Tight
$\|\eta\| < 2.5$	✓	✓	✓
p_T	$> 7\,\mathrm{GeV}$	$> 15\,\mathrm{GeV}$	$> 15\,\mathrm{GeV}$
$\|d_{xy}\| < 0.05$ (cm)	✓	✓	✓
$\|d_z\| < 0.1$ (cm)	✓	✓	✓
$\mathrm{SIP}_{3D} < 8$	✓	✓	✓
$I_{\mathrm{mini}} < 0.4$	✓	✓	✓
MVA ID $> (0.0, 0.0, 0.7)$	✓	✓	✓
$\sigma_{i\eta i\eta} < (0.011, 0.011, 0.030)$	–	✓	✓
$H/E < (0.10, 0.10, 0.07)$	–	✓	✓
$\Delta\eta_{in} < (0.01, 0.01, 0.008)$	–	✓	✓
$\Delta\phi_{in} < (0.04, 0.04, 0.07)$	–	✓	✓
$-0.05 < 1/E - 1/p < (0.010, 0.010, 0.005)$	–	✓	✓
p_T^{ratio}	–	$> 0.5\dagger$ / –	–
jet CSV	–	$< 0.3\dagger$ / < 0.8484	< 0.8484
tight-charge	–	–	✓
conversion rejection	–	–	✓
Number of missing hits	< 2	$== 0$	$== 0$
lepMVA > 0.90	–	–	✓

Jets

✓ AK4 CHS PF jets, loose Id
✓ $p_T > 25$ GeV for $|\eta| < 2.4$ and $p_T > 40$ GeV for $|\eta| > 2.4$
✓ Separated from any fakeable lepton candidate by $\Delta R > 0.4$
✓ JEC: Summer16_23Sep2016V3
✓ CSVv2 b-tagging loose and medium working points for identifying b-jets

Event selection

Common selection criteria for all channels:

- Lepton preselection: no loose lepton pair with m_{ll} < 12 GeV.
- b-jets: one or more jets passing CSVv2 medium w.p. ($|\eta| < 2.4$).
- Light quark jet: one or more jets failing the CSVv2 loose w.p.
  central: p_T >25 GeV, $|\eta| < 2.4$
  forward: p_T > 40 GeV, $|\eta| > 2.4$

Selection criteria based on leptons:

2lss

- Exactly two tight leptons with same sign.
- Lepton p_T > 25/15 GeV.
- Electrons are triple-charge consistent.
- Muon p_T resolution: $\Delta p_T/p_T < 0.2$.

3l

- Exactly three tight leptons.
- Lepton p_T > 25/15/15 GeV.
- Z veto: no OSSF pair with $|m_{ll} - m_Z| < 15$ GeV.

Background estimation

Irreducible physics backgrounds: estimated from MC, data/MC scale factors for: b-tagging, lepton efficiency, triggers, PU

- **ttbar+X (X=W/Z/H/γ*)**
- **Photon conversions**
- **Rare SM (tZq, tWZ, tri-bosons, WWqq, tttt)**
- **Di-bosons WZ, ZZ**

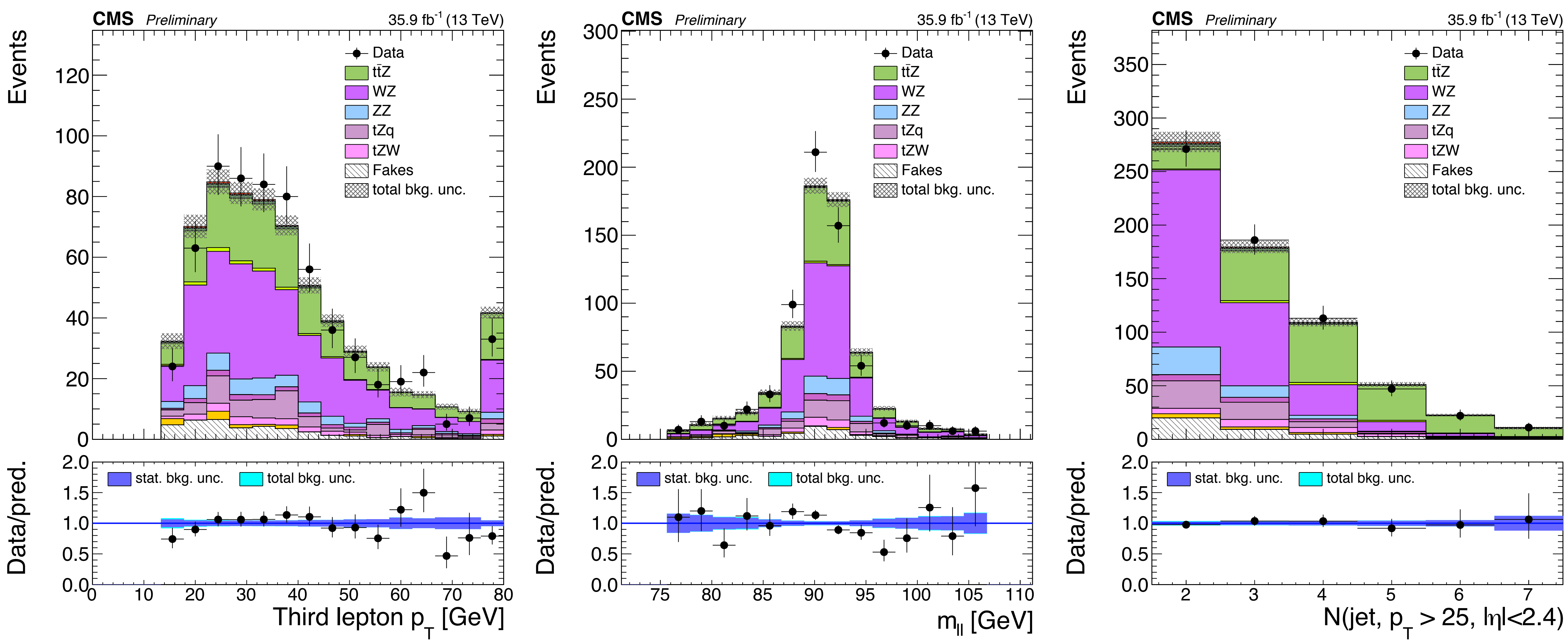
Reducible backgrounds: estimated using a data driven method

- **Fakes:** due to non-prompt leptons and mis-identification of jets, which pass the lepton Id cuts.
- **Charge Flips:** due to mis-assignment of electron charge in opposite sign processes (ttbar, DY), relevant only for the 2lss channel.
  Estimated using mis-id probability measured in control region defined with opposite sign electron pair in Z-resonance region.

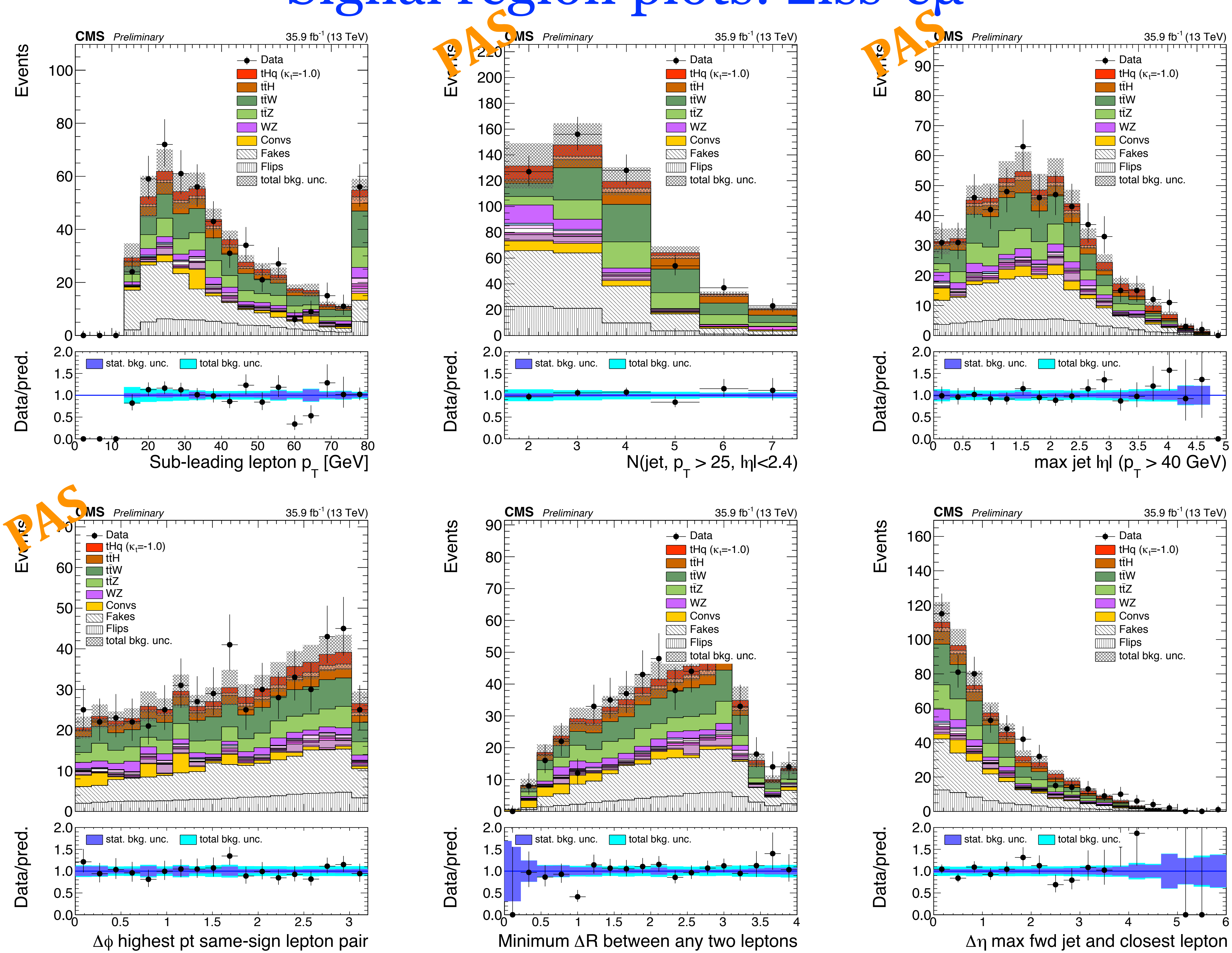
All background contributions are obtained from ttH multilepton analysis.

Control region for background estimation: 3l

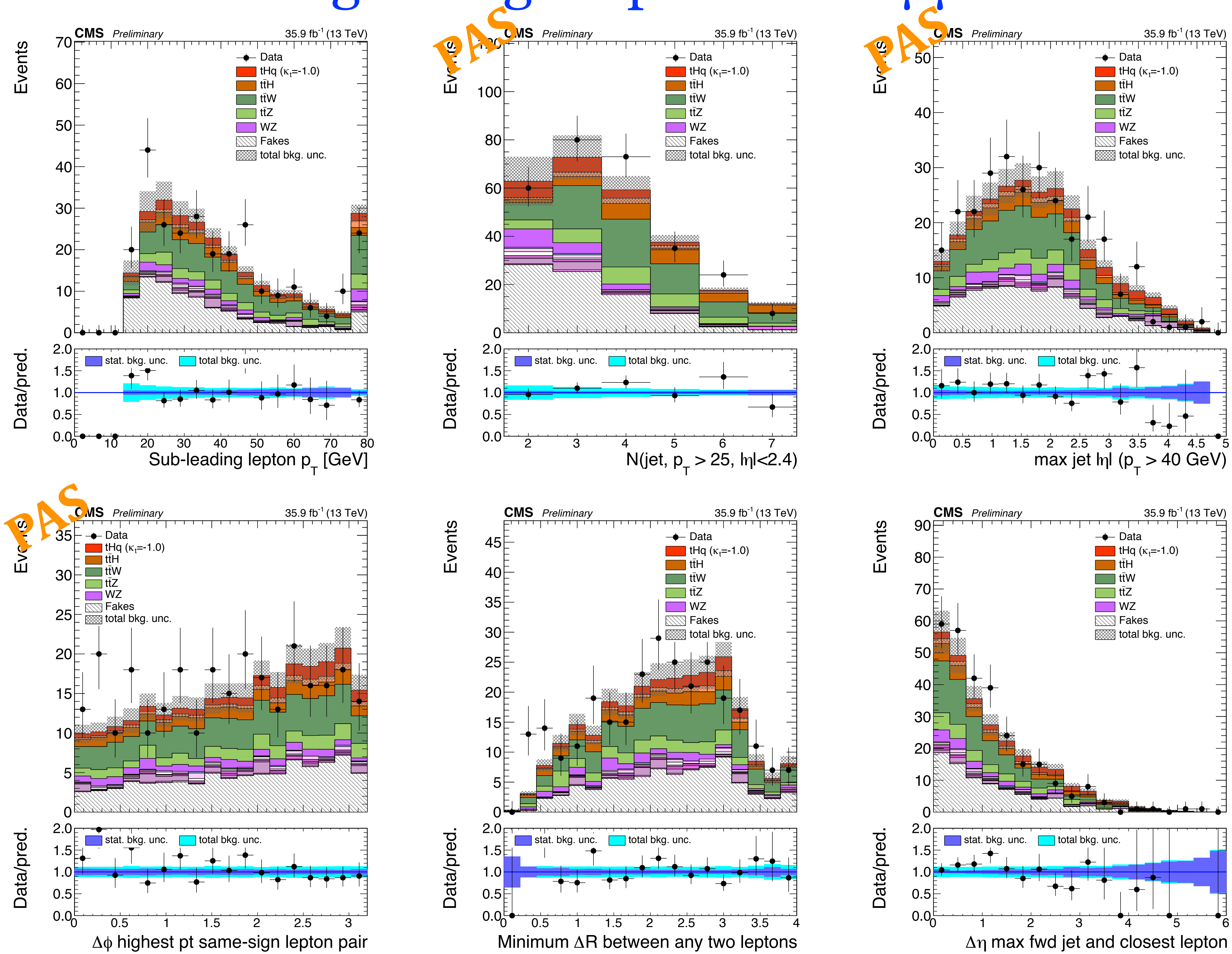
- Selection for Z-enriched CR:
  - ➡ Exactly three tight leptons with p_T > 25/15/15 GeV.
  - ➡ b-jets: one or more jets passing CSVv2 loose w.p. ($|\eta|$ < 2.4).
  - ➡ Number of jets within $|\eta|$ < 2.4 is less than four.
  - ➡ Inverted Z veto: $|m_{ll} - m_Z|$ < 15 GeV (orthogonal to signal region).



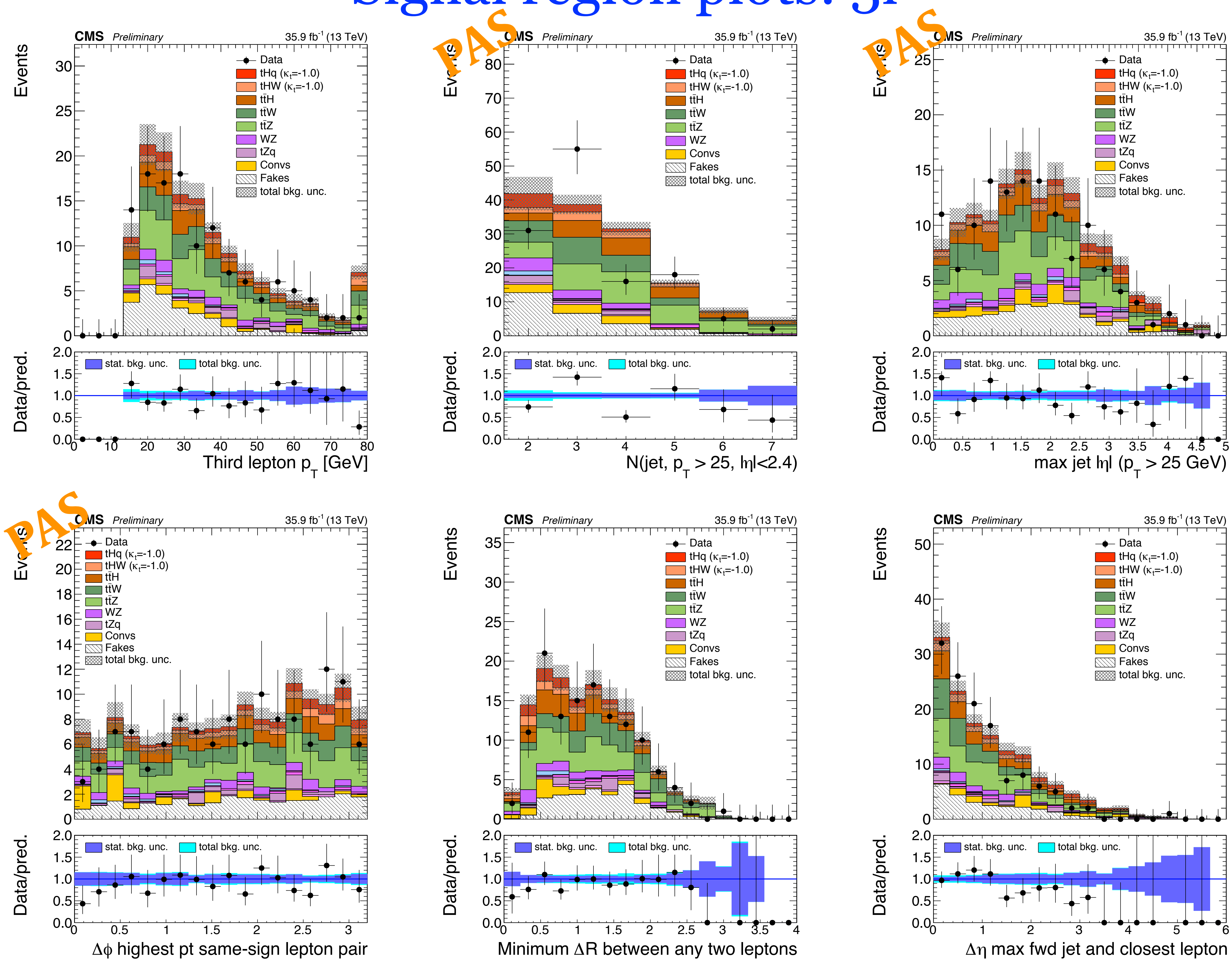
Signal region plots: 2lss-eμ



Signal region plots: 2lss-μμ



Signal region plots: 3l



Data yields and expected background (35.9 fb^{-1})

PAS

Process	$\ell\ell\ell$	$\mu\mu$	$e\mu$
$t\bar{t}W^{\pm}$	22.50 ± 0.35	68.03 ± 0.61	97.00 ± 0.71
$t\bar{t}Z/t\bar{t}\gamma$	32.80 ± 1.79	25.89 ± 1.12	64.82 ± 2.42
WZ	8.22 ± 0.86	15.07 ± 1.19	26.25 ± 1.57
ZZ	1.62 ± 0.33	1.16 ± 0.29	2.86 ± 0.45
$W^{\pm}W^{\pm}qq$	–	3.96 ± 0.52	6.99 ± 0.69
$W^{\pm}W^{\pm}$(DPS)	–	2.48 ± 0.42	4.17 ± 0.54
VVV	0.42 ± 0.16	2.99 ± 0.34	4.85 ± 0.43
tttt	1.84 ± 0.44	2.32 ± 0.45	4.06 ± 0.57
tZq	3.92 ± 1.48	5.77 ± 2.24	10.73 ± 3.03
tZW	1.70 ± 0.12	2.13 ± 0.13	3.91 ± 0.18
γ conversions	7.43 ± 1.94	–	23.81 ± 6.04
Non-prompt	25.61 ± 1.26	80.94 ± 2.02	135.34 ± 2.83
Charge flips	–	–	58.20 ± 0.30
Total Background	106.05 ± 3.45	210.74 ± 3.61	443.30 ± 8.01
tHq ($\kappa_t = -1.0$)	7.48 ± 0.14	18.48 ± 0.22	27.41 ± 0.27
tHW ($\kappa_t = -1.0$)	7.38 ± 0.16	7.72 ± 0.17	11.23 ± 0.20
$t\bar{t}H$	18.29 ± 0.41	24.18 ± 0.48	35.21 ± 0.58
Data	**149**	**280**	**525**

- Uncertainties are statistical only.
- Pre-fit

Signal discrimination using BDT

- Two separate BDT trainings using MC samples for signal and backgrounds:
  - ➡ Signal is only tHq with κ_t = -1.0, κ_V = 1.0. (other variations taken care of via systematic uncertainties)
  - ➡ Against ttbar: non-prompt lepton type background.
  - ➡ Against combined ttZ and ttW: prompt lepton type background.
- Separate trainings for 2lss and 3l channels using the following variables:

Related to lepton kinematics

- ✓ Trailing lepton p_T
- ✓ Total charge of tight leptons
- ✓ min ΔR (lepton pairs)
- ✓ Δϕ between highest p_T lepton pair

Related to jet multiplicities

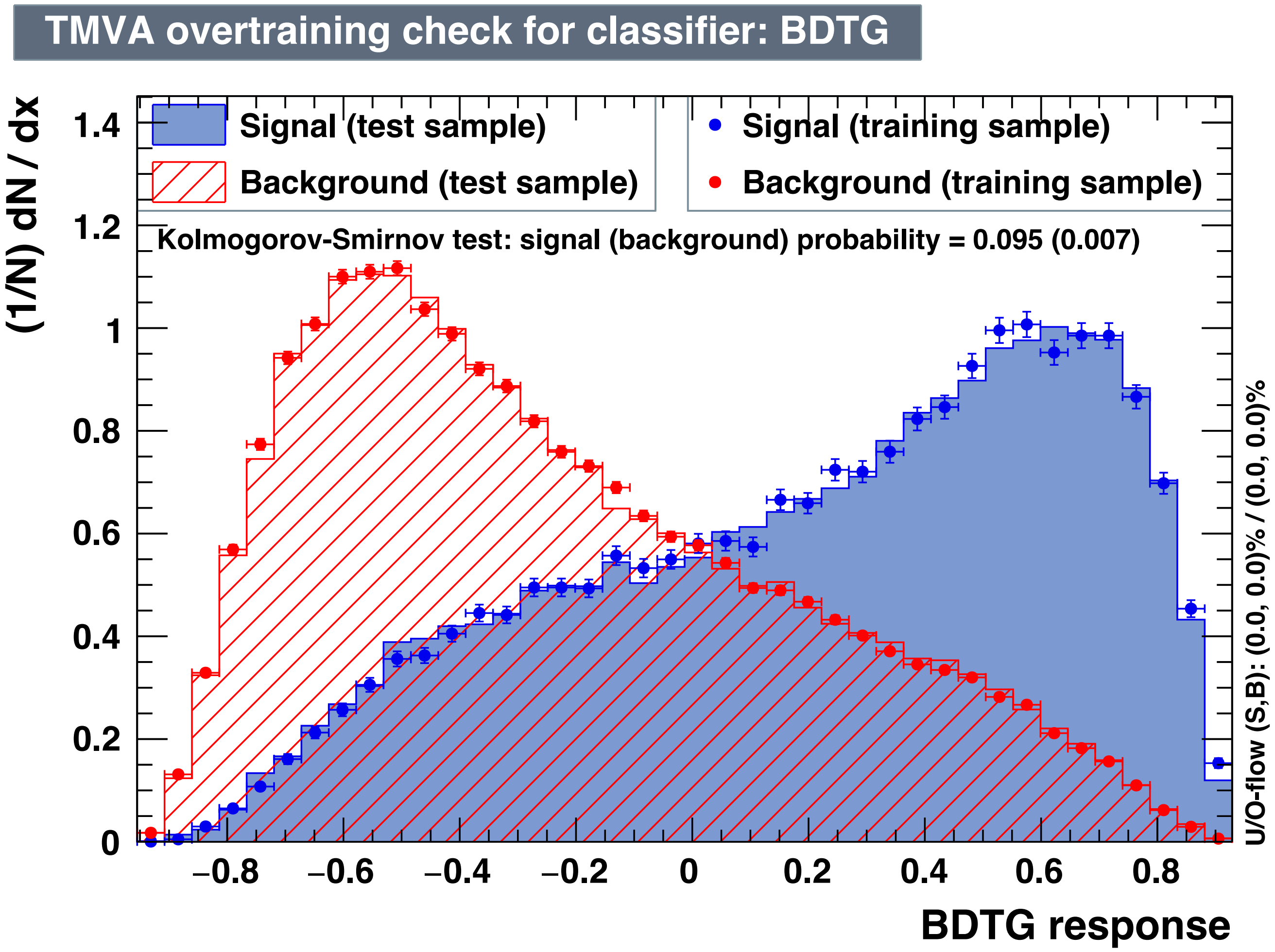
- ✓ Number of jets with $|\eta| < 2.4$
- ✓ Number of non b-tagged jets with $|\eta| > 1.0$

Related to forward jet activity

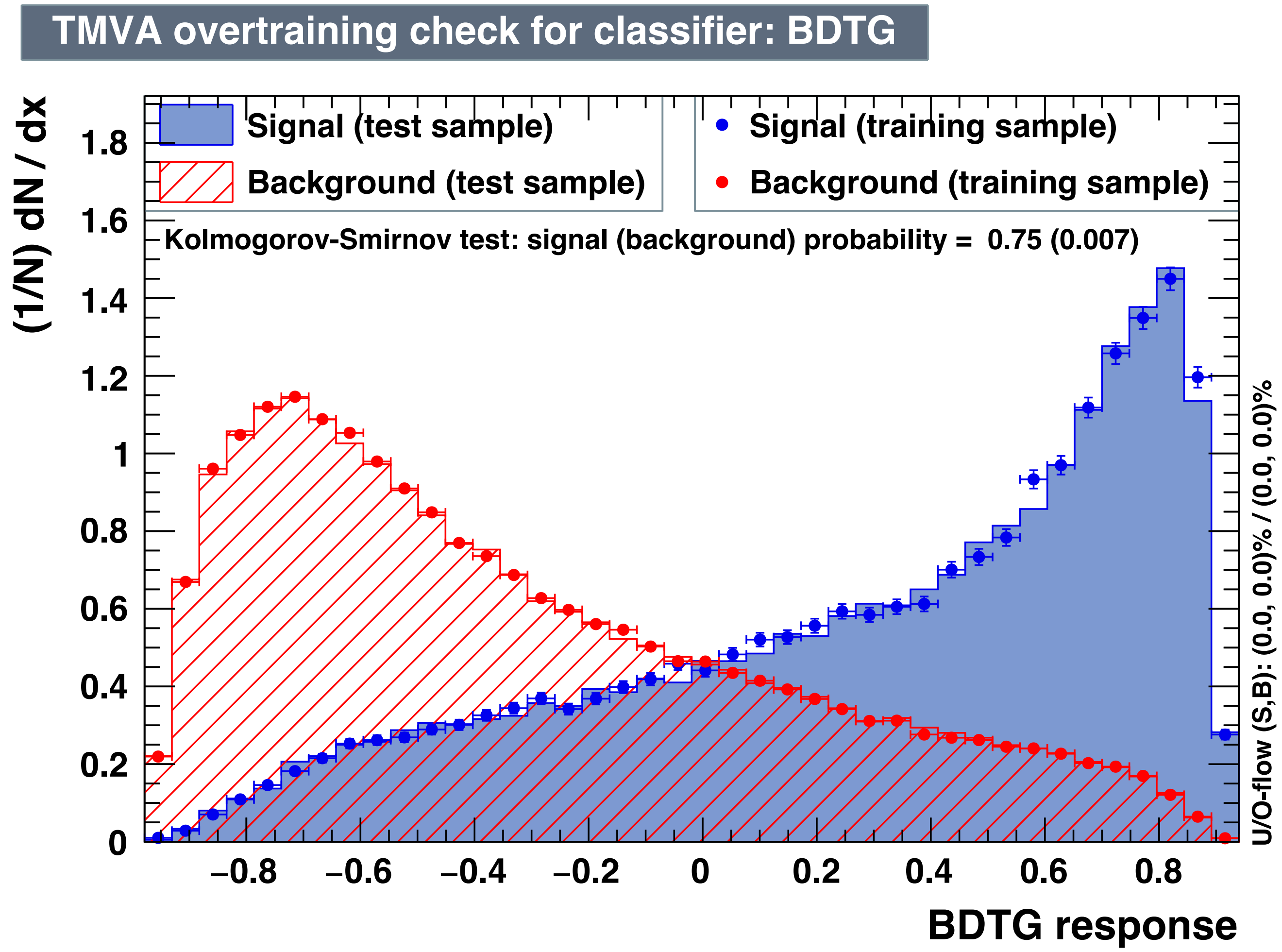
- ✓ Maximum |η| for jets
- ✓ Δη (most forward light jet, closest lepton)
- ✓ Δη (most forward light jet, hardest loosely b-tagged jet)
- ✓ Δη (most forward light jet, 2nd hardest loosely b-tagged jet)

BDT training

- BDT parameters:
  - Gradient boosted (BDTG)
  - No. of trees = 800
  - No. of cuts = 50
  - Maximum depth = 3
- ➡ Found to be most discriminating, minimal overtraining.



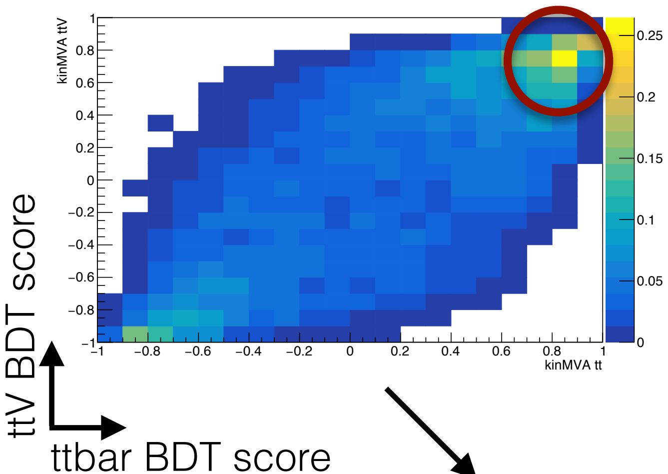
ttbar BDT output (2lss)



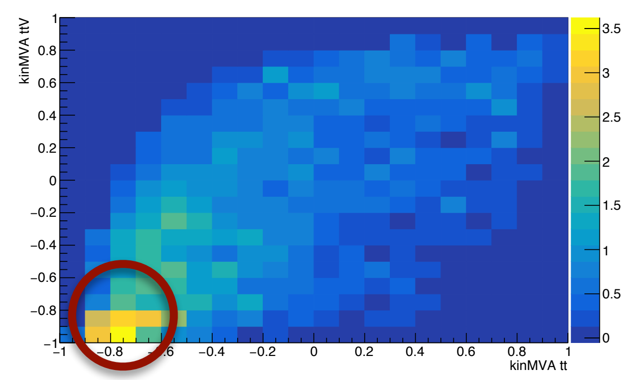
ttV BDT output (2lss)

1D binned distribution for shape analysis

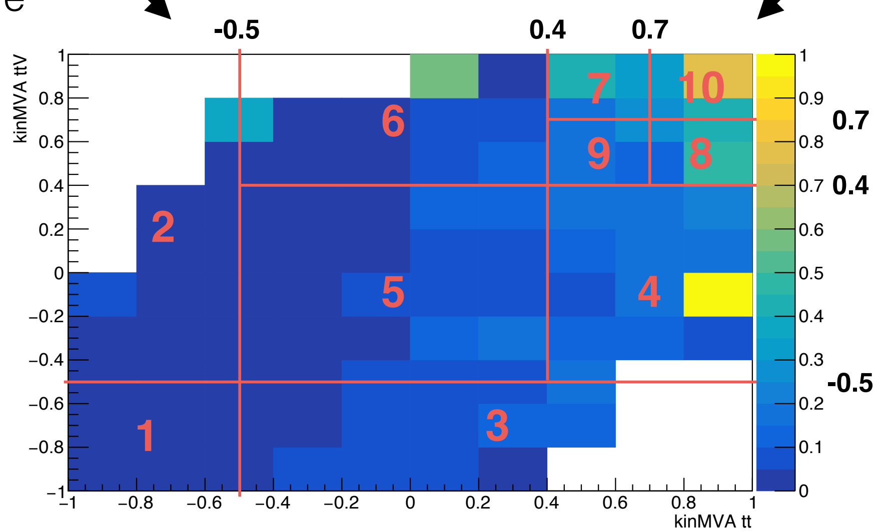
S (tHq+tHW)



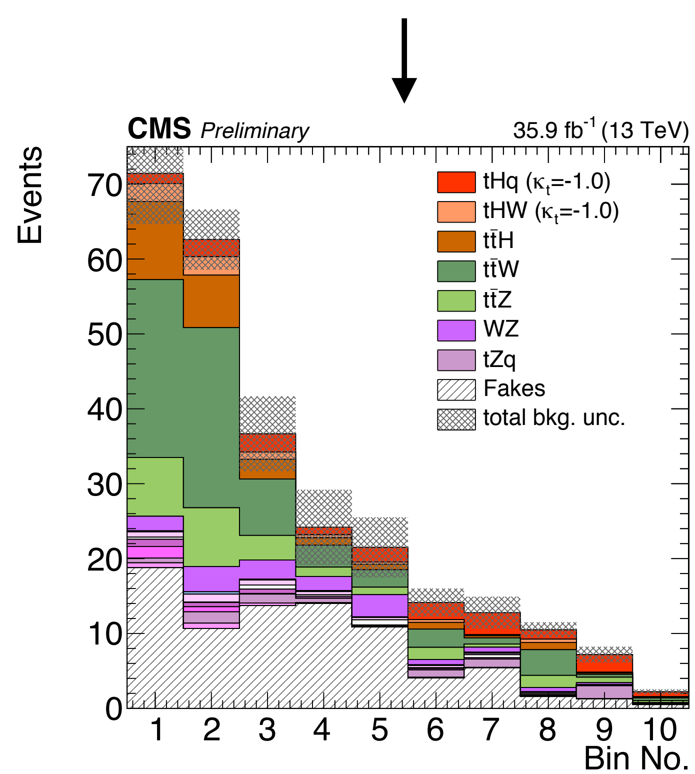
B (all background)



S/B ratio



1D shape



Binning optimization

- Optimization done on the basis of best obtained limit on expected signal strength for each channel.
- Number of bins and bin borders were varied in the 2D plane of the S/B ratio.
- Best limit was obtained for a set of 10 bins.
- Other binning strategies were also tried in terms of expected limit:
  - ➡ S/B clustering: ~20% worse
  - ➡ k-Means clustering: ~10% worse

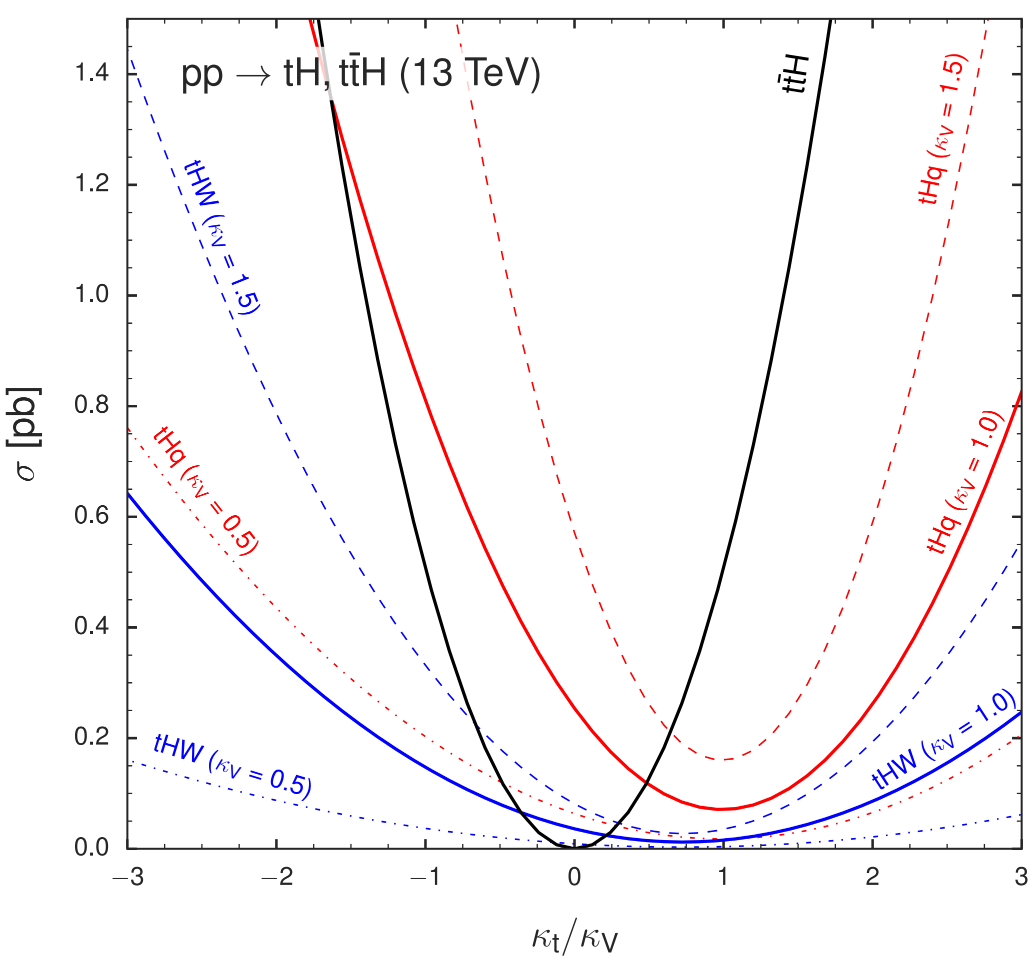
Signal Model

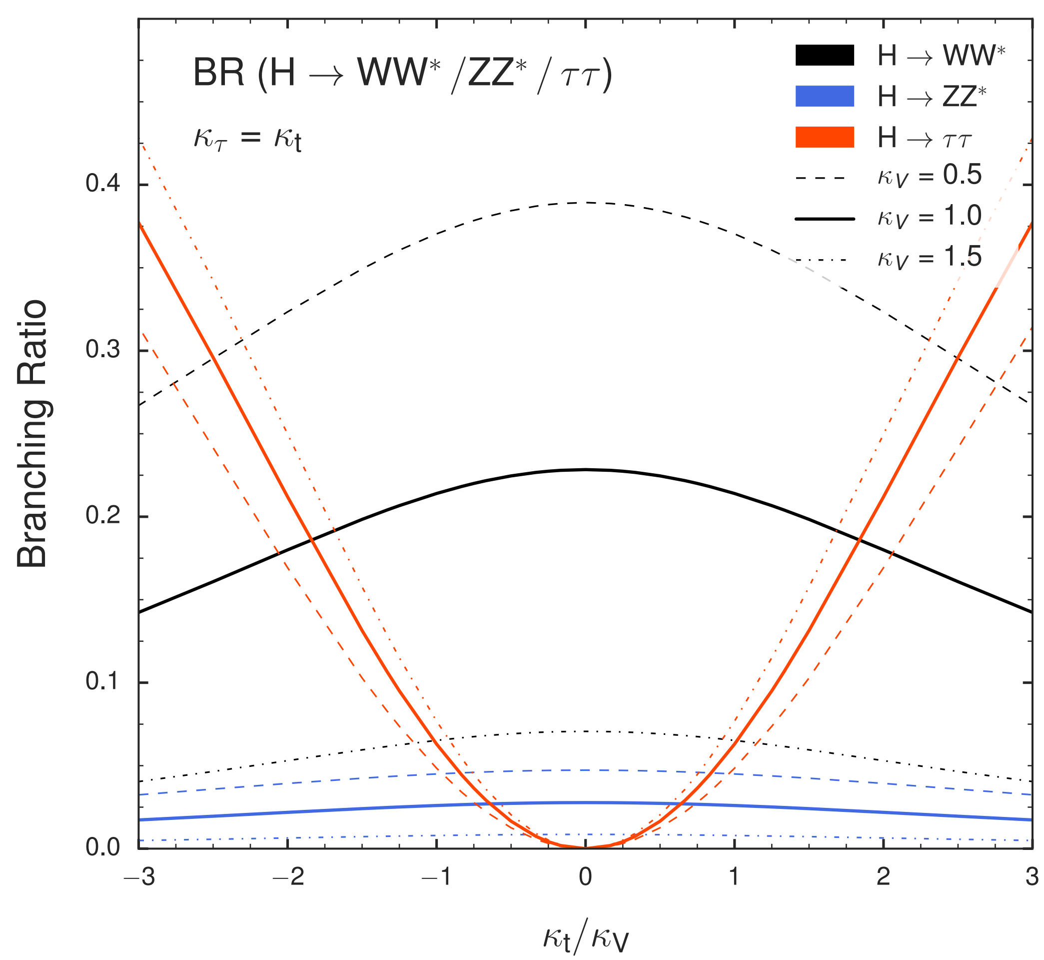
- **Aim:** limit on common signal strength for (tHq+tHW+ttH) as function of κ_t/κ_V. ttH is included as signal since its cross section varies as κ_t^2.
- Signal shape depends on (i) κ_t/κ_V ratio, (ii) relative fractions of tHq/tHW/ttH productions, and (iii) decay fractions of H→WW*/$\tau\tau$/ZZ*.
- For $\kappa_{tau} = \kappa_t$ → κ_t/κ_V uniquely determines the signal shape.

  $\sigma(\mathrm{tHq}) = (2.633\ \kappa_t^2 + 3.578\ \kappa_V^2 - 5.211\ \kappa_t\kappa_V) * \sigma_{SM}(\mathrm{tHq})$

  $\sigma(\mathrm{tHW}) = (2.909\ \kappa_t^2 + 2.310\ \kappa_V^2 - 4.220\ \kappa_t\kappa_V) * \sigma_{SM}(\mathrm{tHW})$

  $\sigma(\mathrm{ttH}) = \kappa_t^2 * \sigma_{SM}(\mathrm{ttH})$





Systematic uncertainties

- **Experimental:**
  - ✓ Luminosity measurement: ~2.6%.
  - ✓ Data/MC scale factors for lepton selection (ID, iso) and trigger efficiencies, ~5% per lepton.
  - ✓ JEC and b-tagging efficiencies: used dedicated shape templates.
  - ✓ Forward jet modelling: shape templates from opposite sign ttbar CR.
- **Theoretical:**
  - ✓ Choice of PDF set: ~3.7% for tHq
    ~4% for tHW, ttW, ttZ, ttH
  - ✓ Scale uncertainties: 12% for ttW, 10% for ttZ, +5.8/-9.2% for ttH.
    The values are coupling dependent in case of tHq/tHW, ~10% for SM.
  - ✓ Modifications in Higgs branching fraction also has uncertainty of order 1%.
- **Backgrounds:**
  - ✓ WZ, ZZ sample modelling and statistics: ~50%.
  - ✓ Rare SM: ~50%, charge flips: ~30%.
- **Fake rate estimation:**
  - ✓ The predicted event yield has a normalization uncertainty of ~30-50%.
    Smaller shape/normalization uncertainties from closure test.

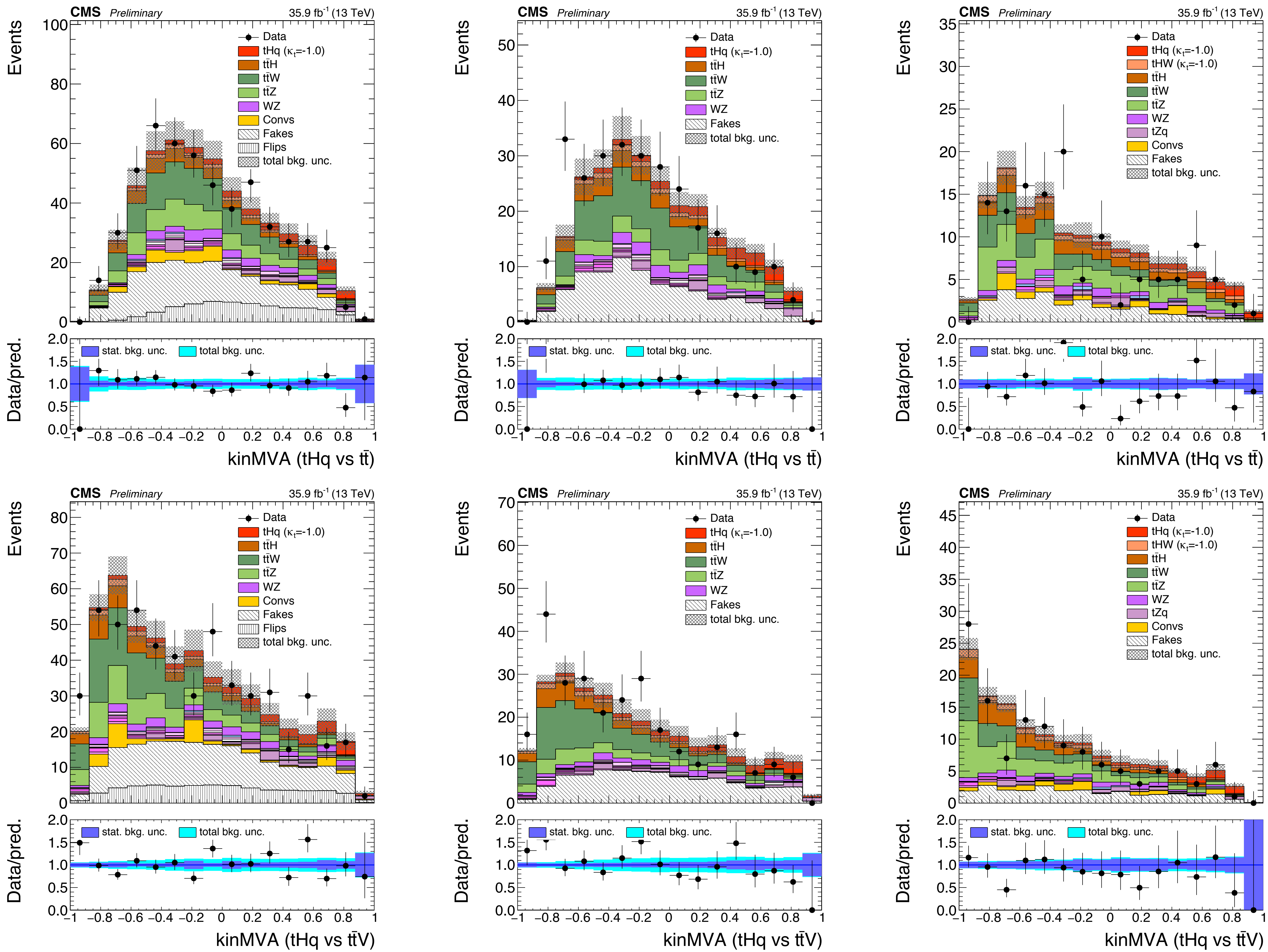
PAS

Pre-fit signal region plots: BDT outputs

2lss-eμ | **2lss-μμ** | **3l**

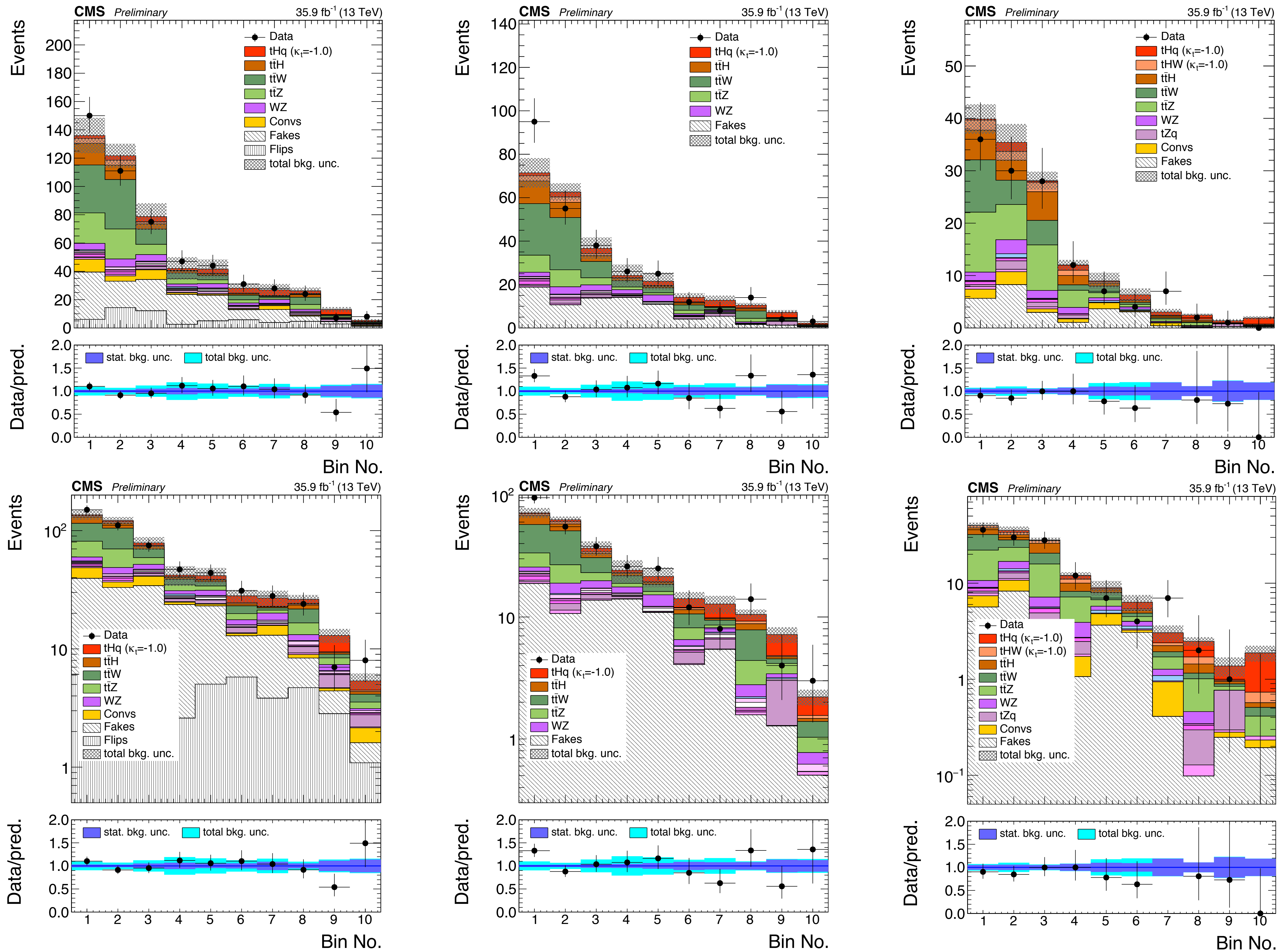
ttbar

ttV

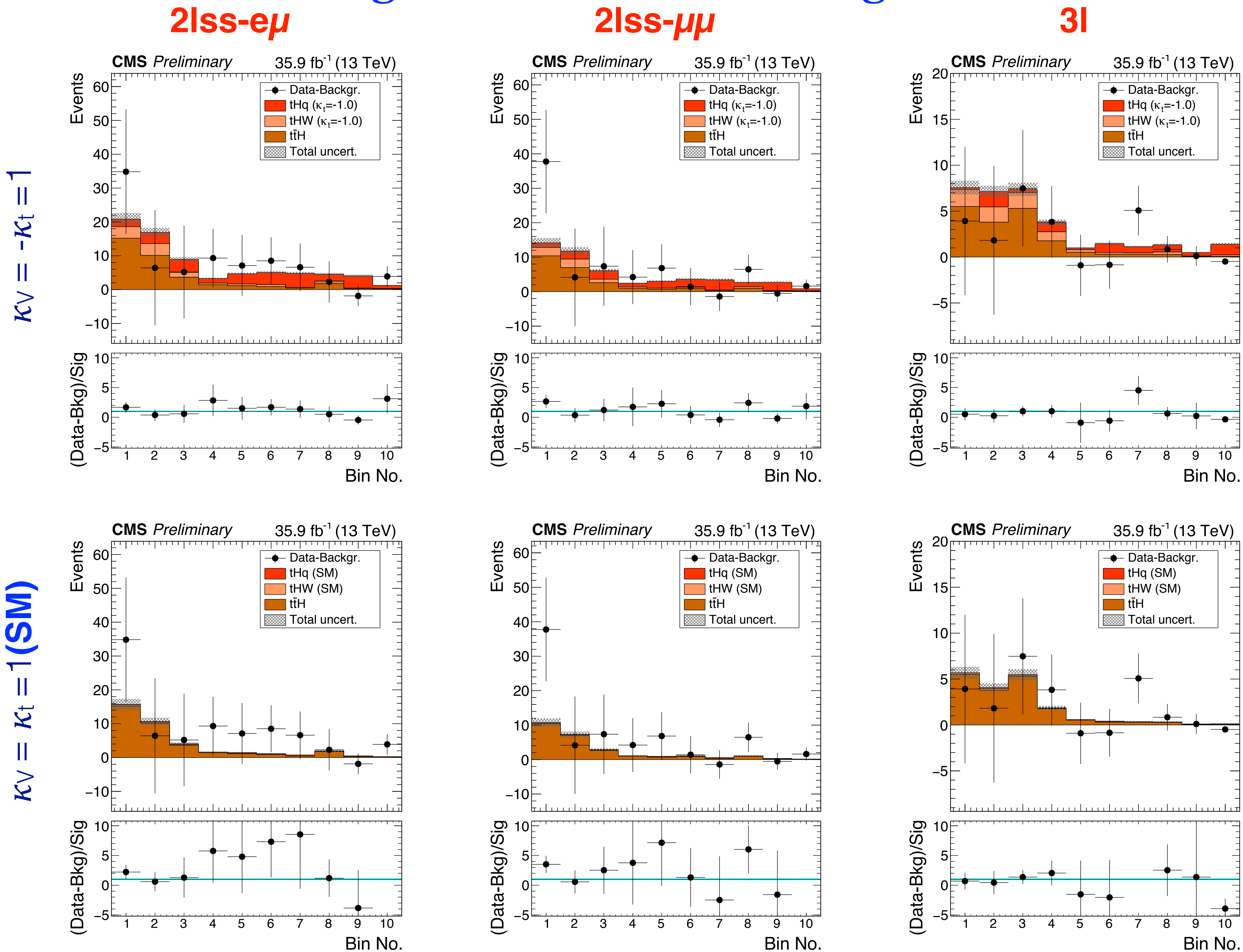


Pre-fit binning distributions

2lss-eμ   2lss-μμ   3l

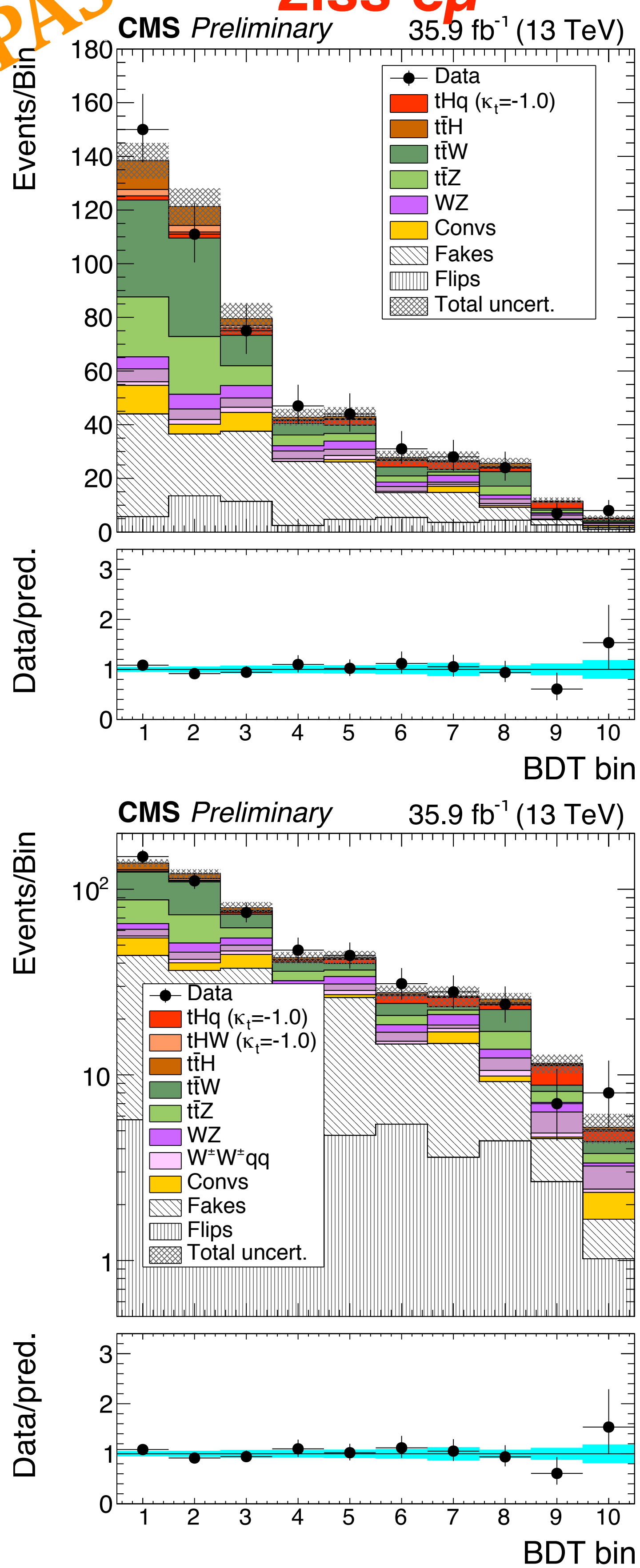


Pre-fit binning distributions of background-subtracted

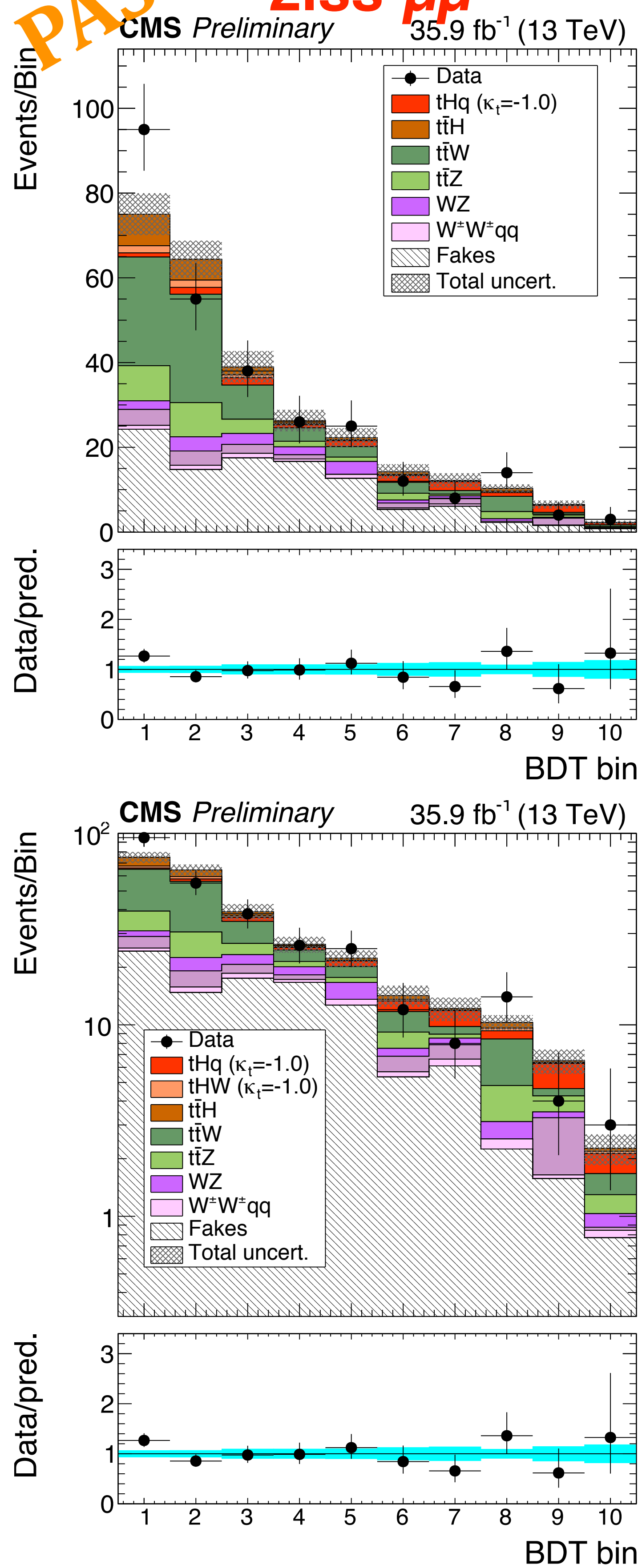


Post-fit binning distributions

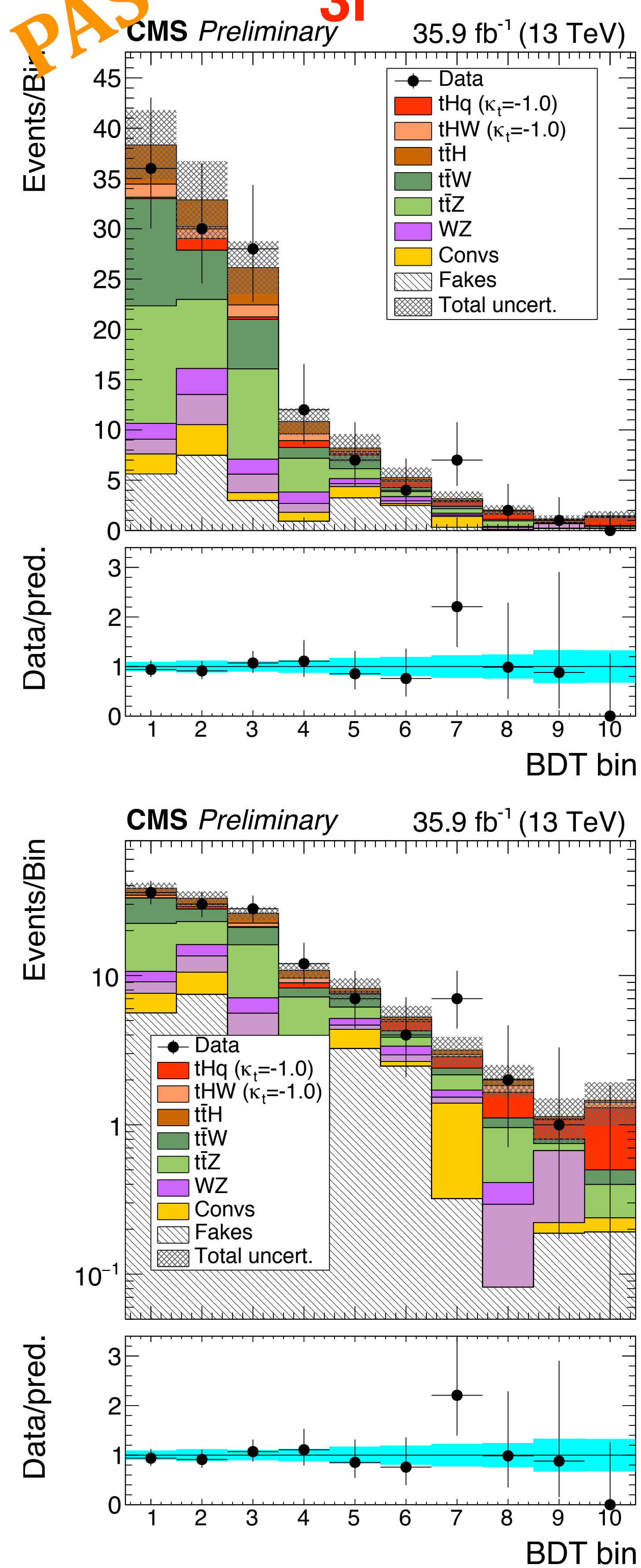
PAS **2lss-eμ**



PAS **2lss-μμ**



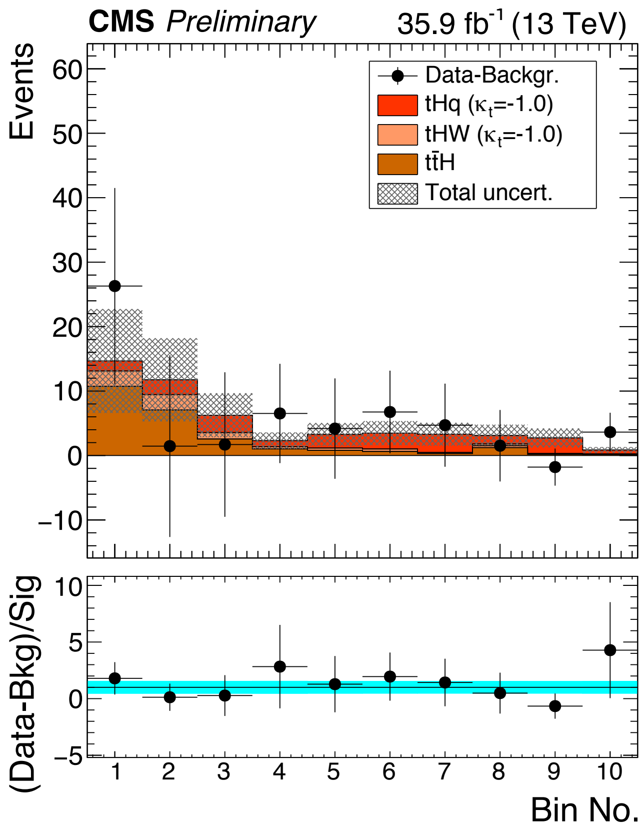
PAS **3l**

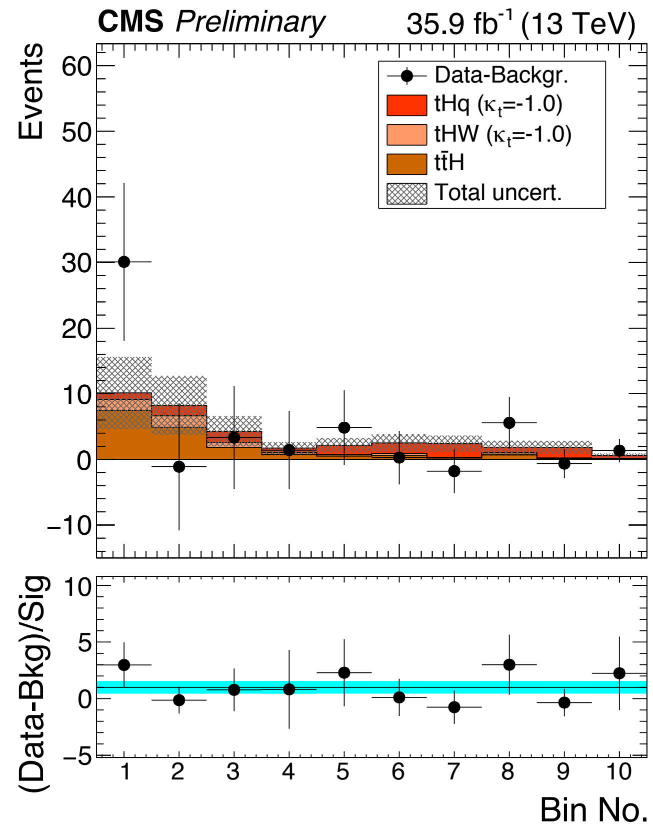


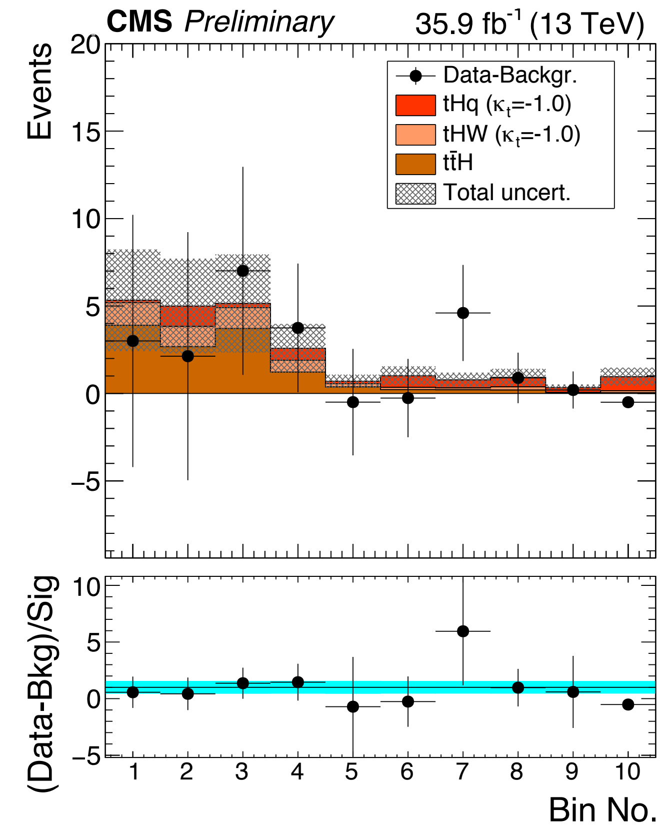
Post-fit binning distributions of background-subtracted

2lss-eμ | **2lss-$\mu\mu$** | **3l**

$\kappa_V = -\kappa_t = 1$

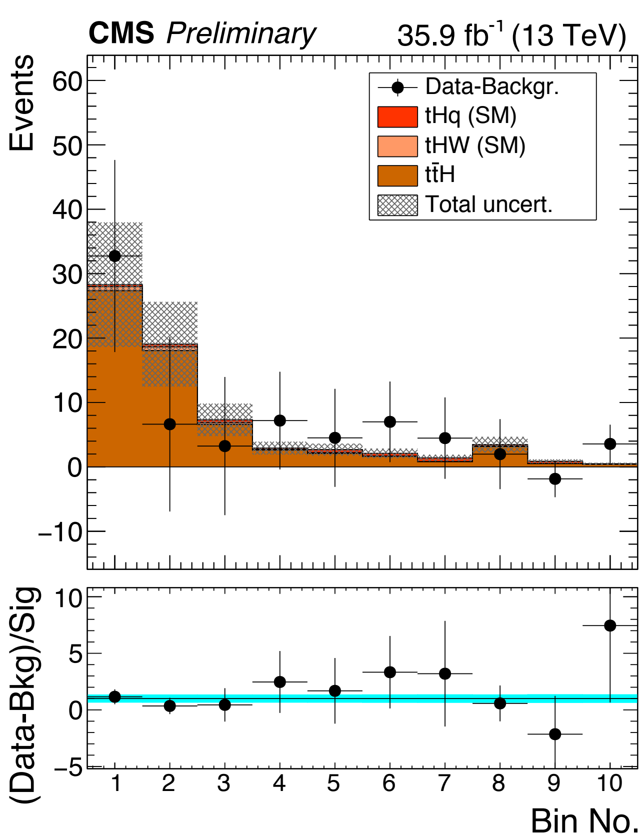


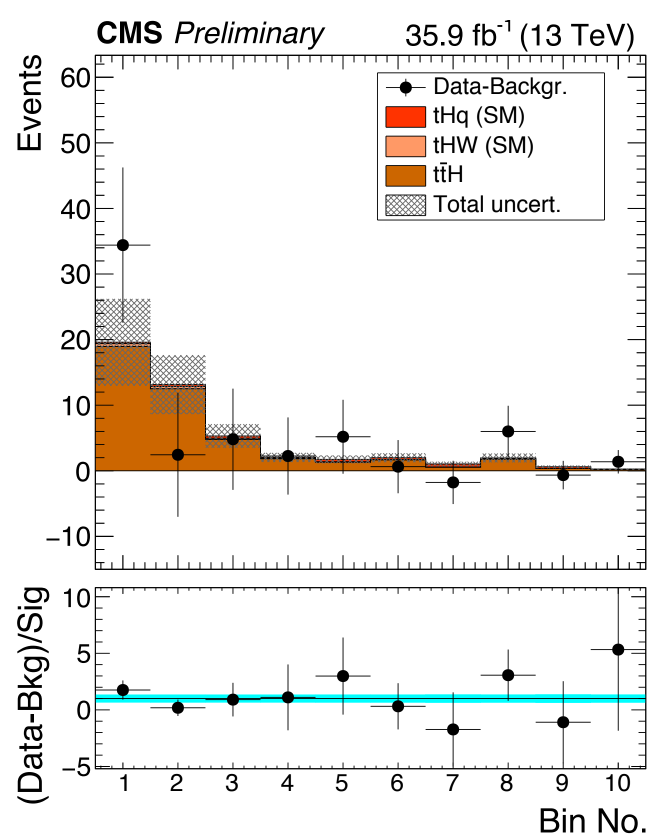


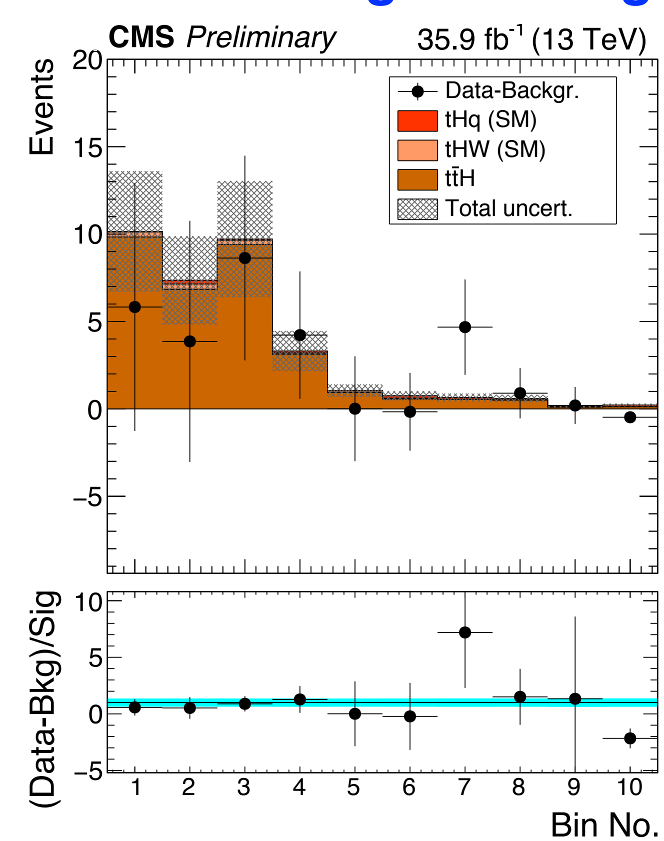


➡ **Best fit signal strength = 0.68**

$\kappa_V = \kappa_t = 1$ **(SM)**







➡ **Best fit signal strength = 1.82**

Fit results

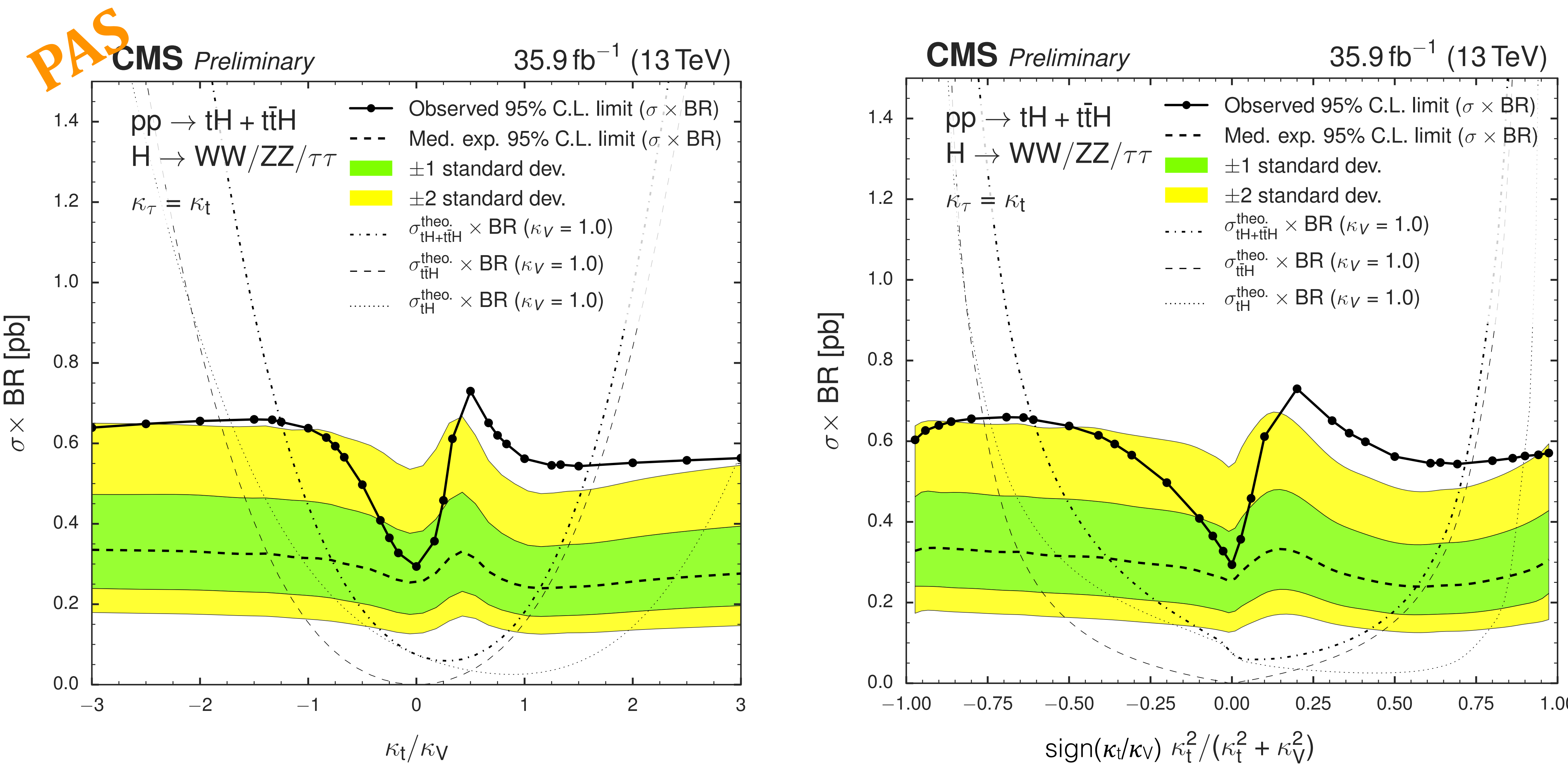
- Excess of about 1 σ of expected SM-like tHq+tHW+ttH signal observed.
- Sensitivity is limited by statistics.
- Best fit signal strength for SM: $r = 1.8 \pm 0.3_{\text{stat.}} \pm 0.6_{\text{syst.}}$

	Best fit signal strength	Best fit σxBR	Significance obs. (exp.)
$\kappa_t/\kappa_V = -1$	0.68 ± 0.40	0.30 ± 0.18 pb	1.70 σ (2.51 σ)
$\kappa_t/\kappa_V = 1$ (SM like)	$1.82^{+0.66}_{-0.67}$	0.33 ± 0.12 pb	2.73 σ (1.50 σ)

PAS

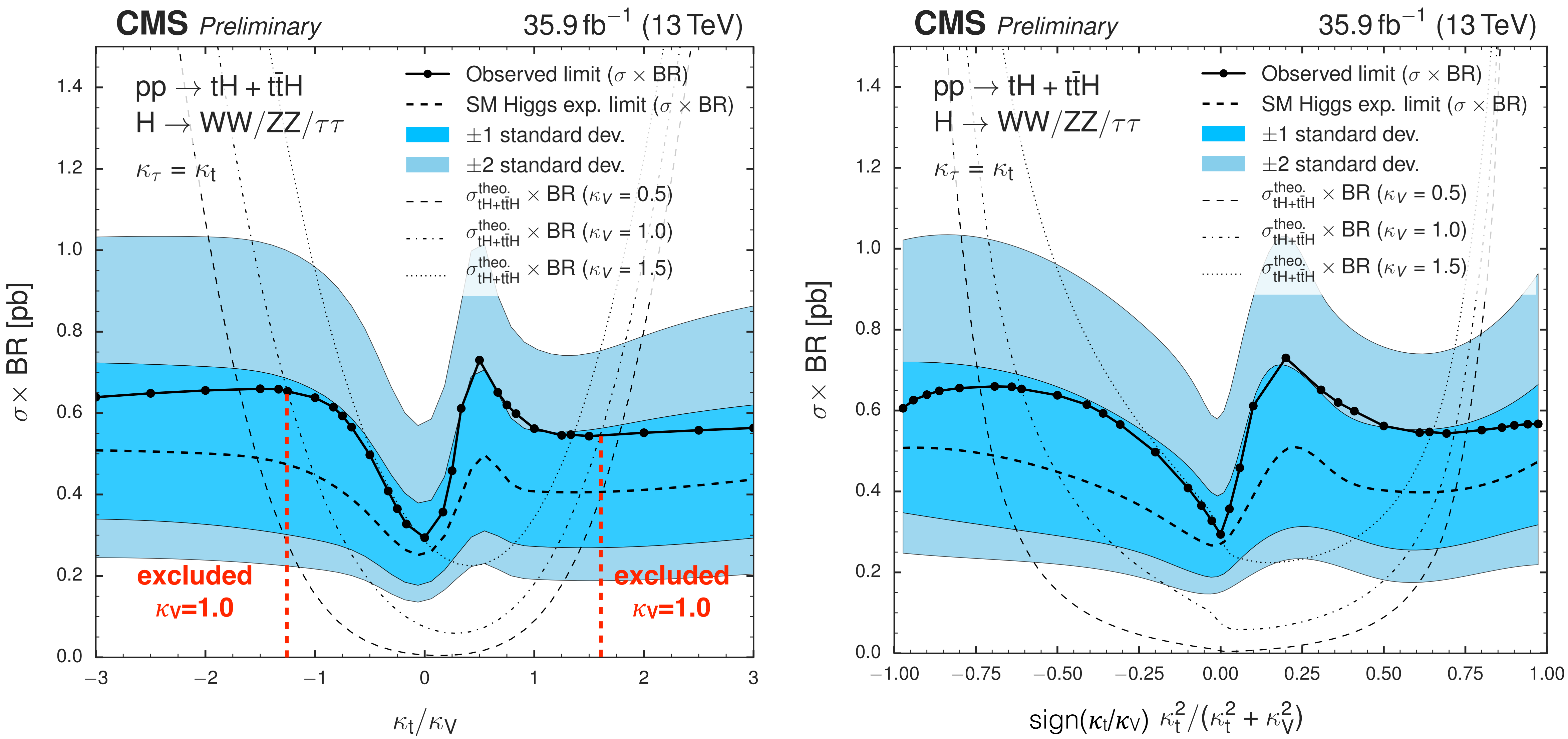
Scenario	Channel	Obs. Limit (pb)	Exp. Limit (pb) Median	±1σ	±2σ
$\kappa_t/\kappa_V = -1$	$\mu\mu$	1.00	0.58	[0.42, 0.83]	[0.31, 1.15]
	$e\mu$	0.84	0.54	[0.39, 0.76]	[0.29, 1.03]
	$\ell\ell\ell$	0.70	0.38	[0.26, 0.56]	[0.19, 0.79]
	Combined	**0.64**	**0.32**	[0.22, 0.46]	[0.16, 0.64]
$\kappa_t/\kappa_V = 1$ (SM-like)	$\mu\mu$	0.87	0.41	[0.29, 0.58]	[0.22, 0.82]
	$e\mu$	0.59	0.37	[0.26, 0.53]	[0.20, 0.73]
	$\ell\ell\ell$	0.54	0.31	[0.22, 0.43]	[0.16, 0.62]
	Combined	**0.56**	**0.24**	[0.17, 0.35]	[0.13, 0.49]

Expected (no Higgs) and observed limit on σ*BR



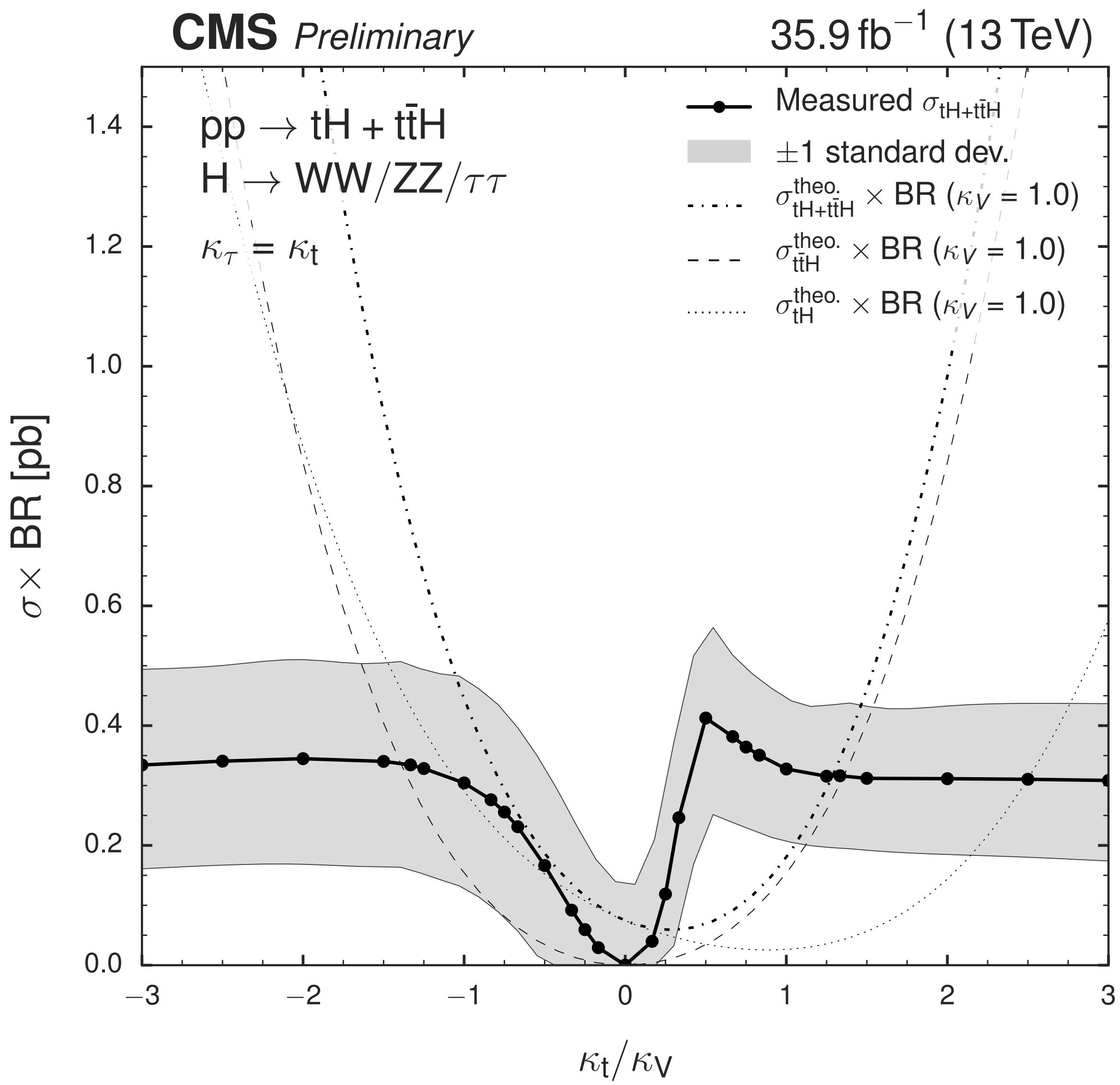
- Expected limit is for a background-only Asimov dataset.
- Right plot: limits as a function of sign(κ_t/κ_V)*$\kappa_t^2/(\kappa_t^2+\kappa_V^2)$
  - ➡ spans the finite range (-1, 1) for all possible values of the coupling modifiers.

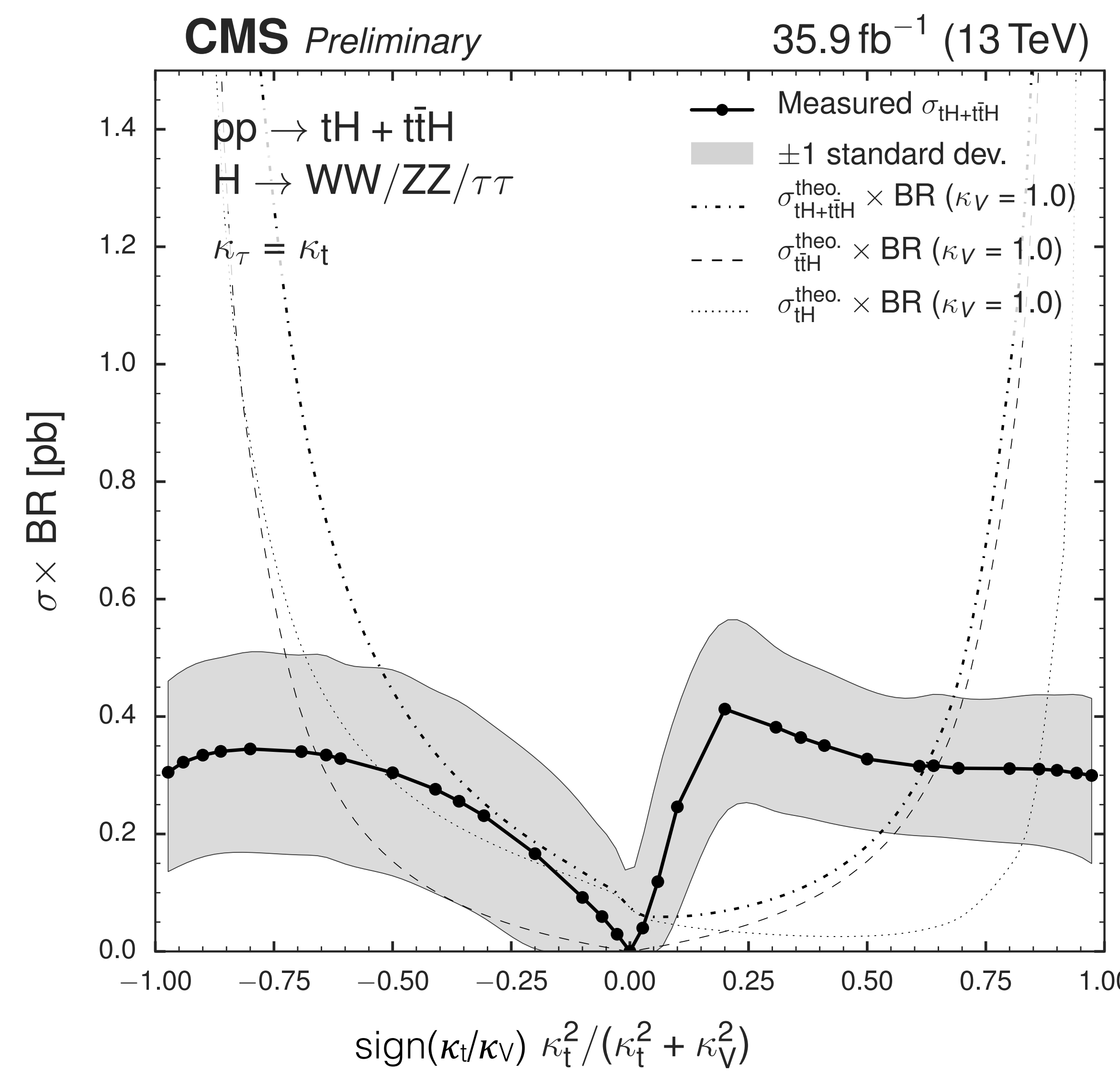
Expected (including SM Higgs) and observed limit on σ*BR



- Adding SM-like tHq+tHW+ttH to the Asimov data.
- “Non-resolved” model for theoretical cross sections, i.e. H→gg/γγ/Zγ branching ratios (affecting the overall Higgs width) not scaled with κ_t, κ_V

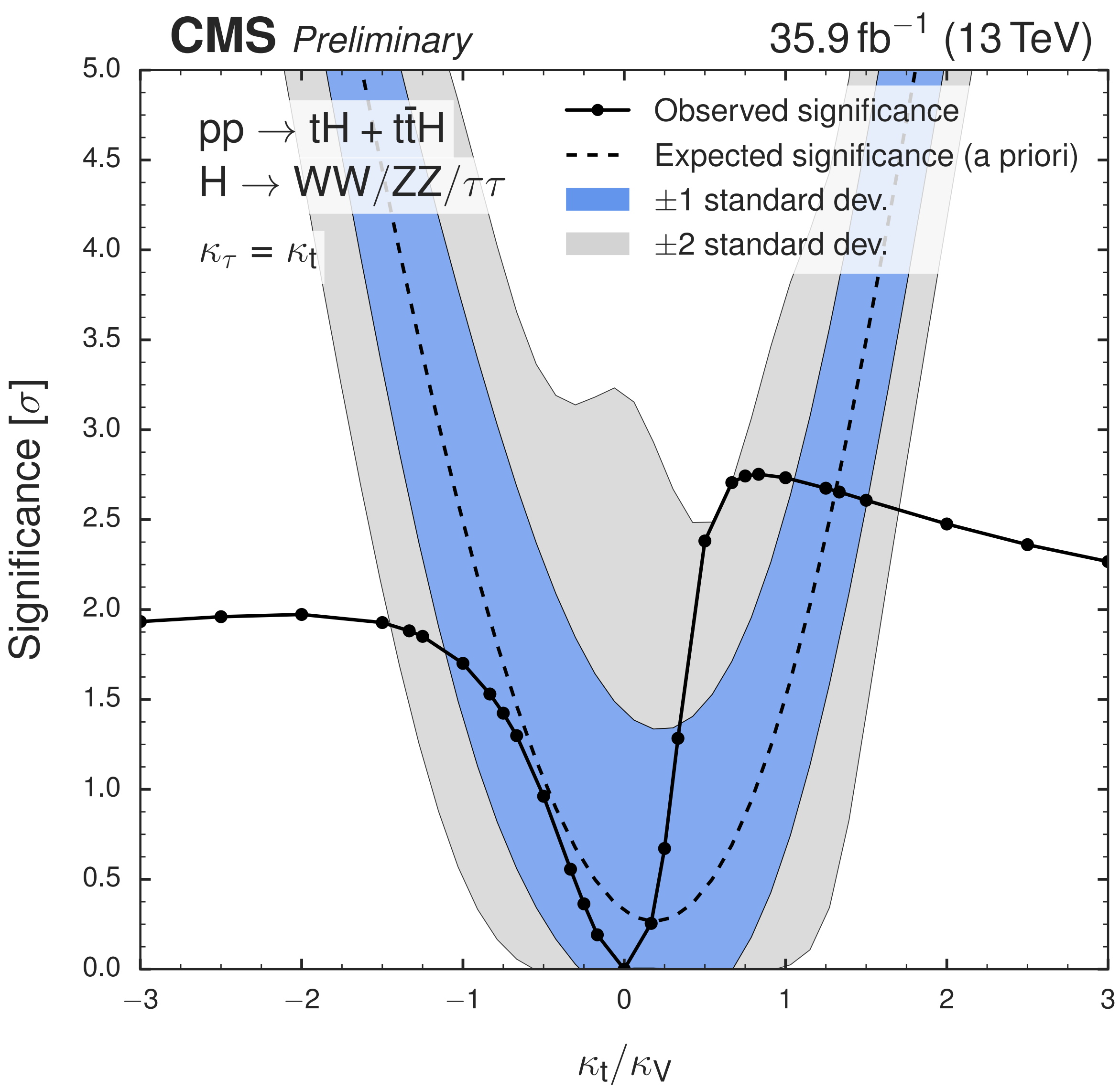
Scan of best fit σ*BR

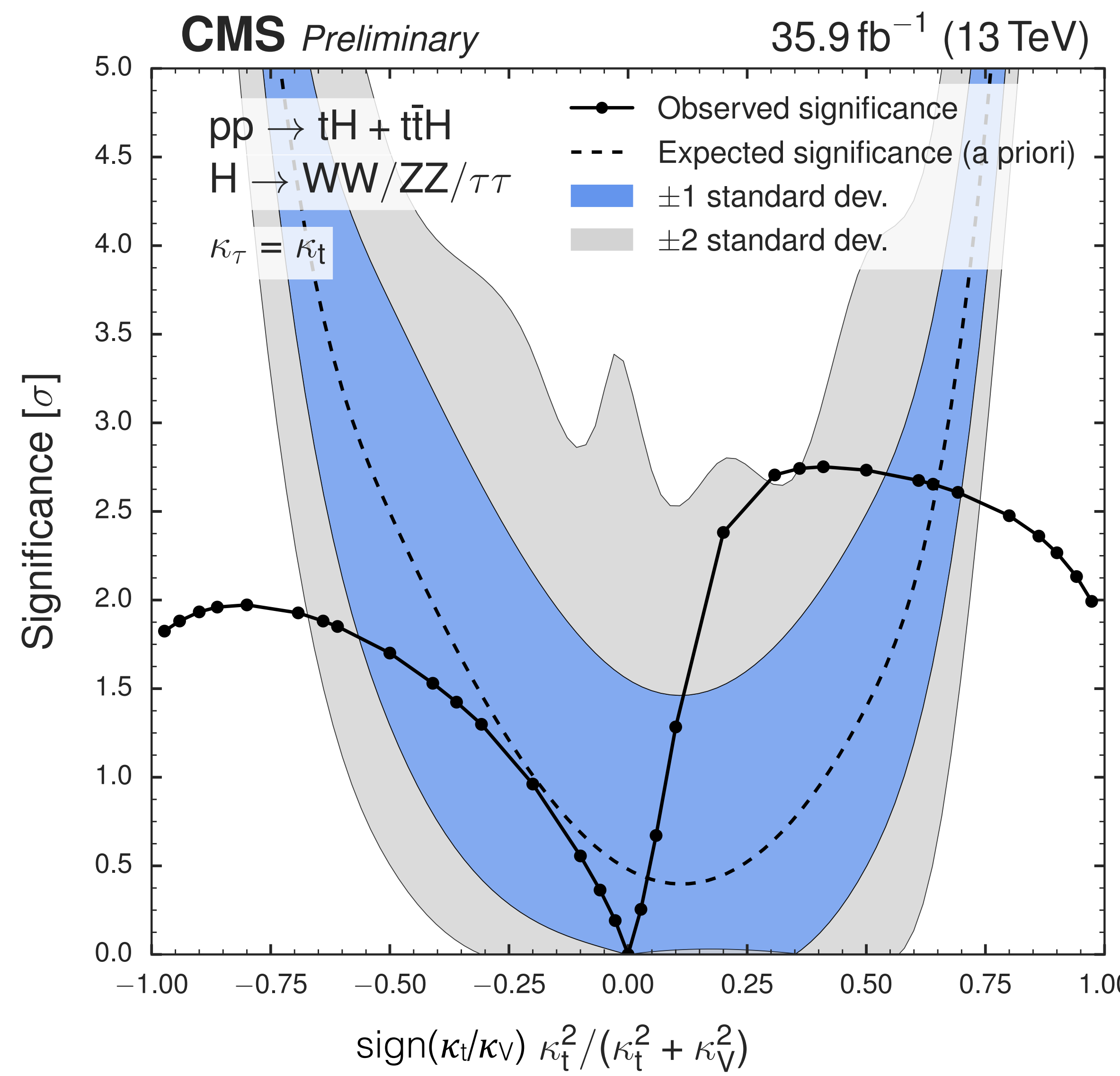




- Best fit signal strength of 0 in $\kappa_t/\kappa_V = 0$ (where ttH=0)
  - ➡ excess is not due to (tHq+tHW).

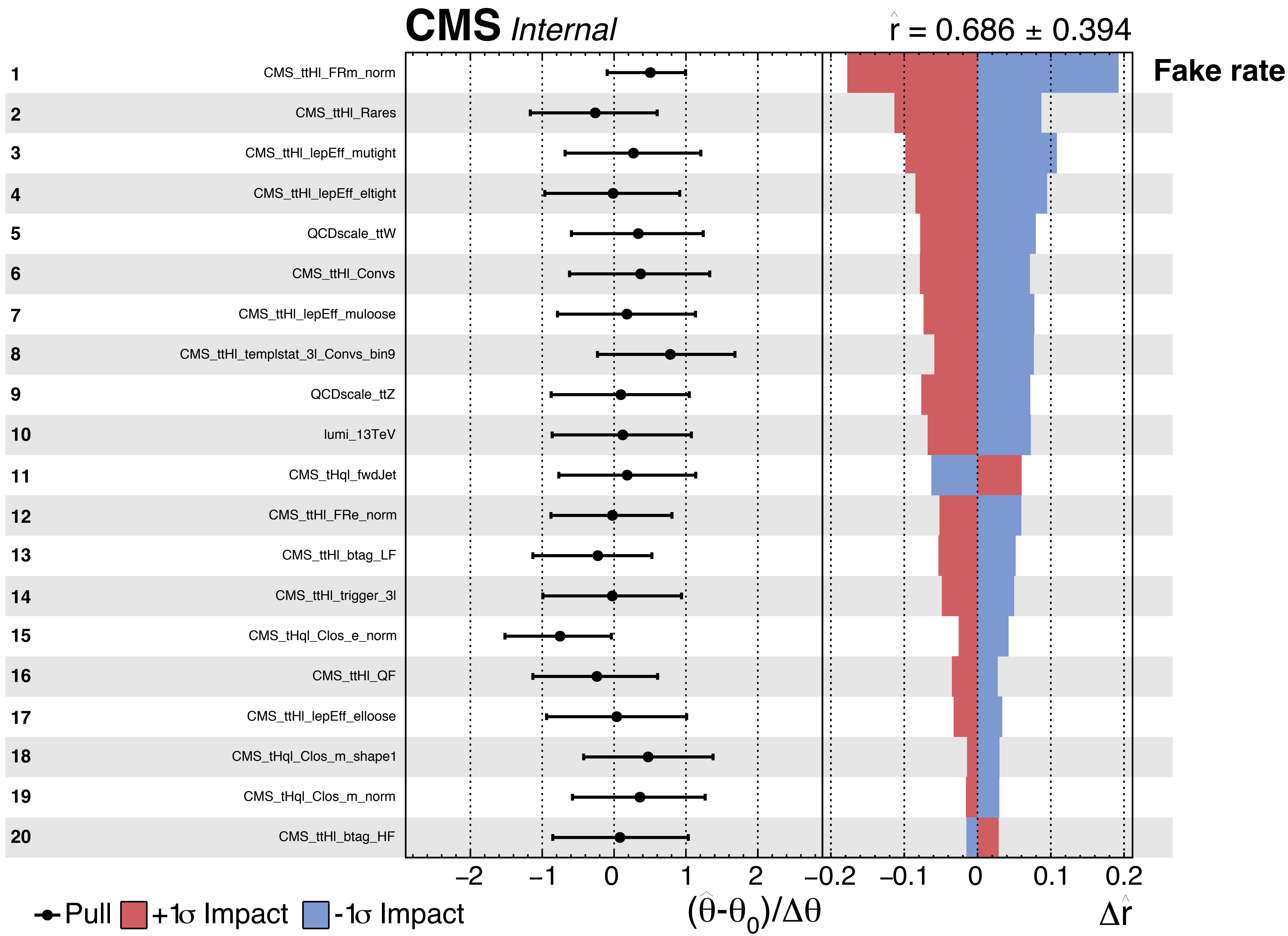
Scan of observed & expected (no Higgs) significance





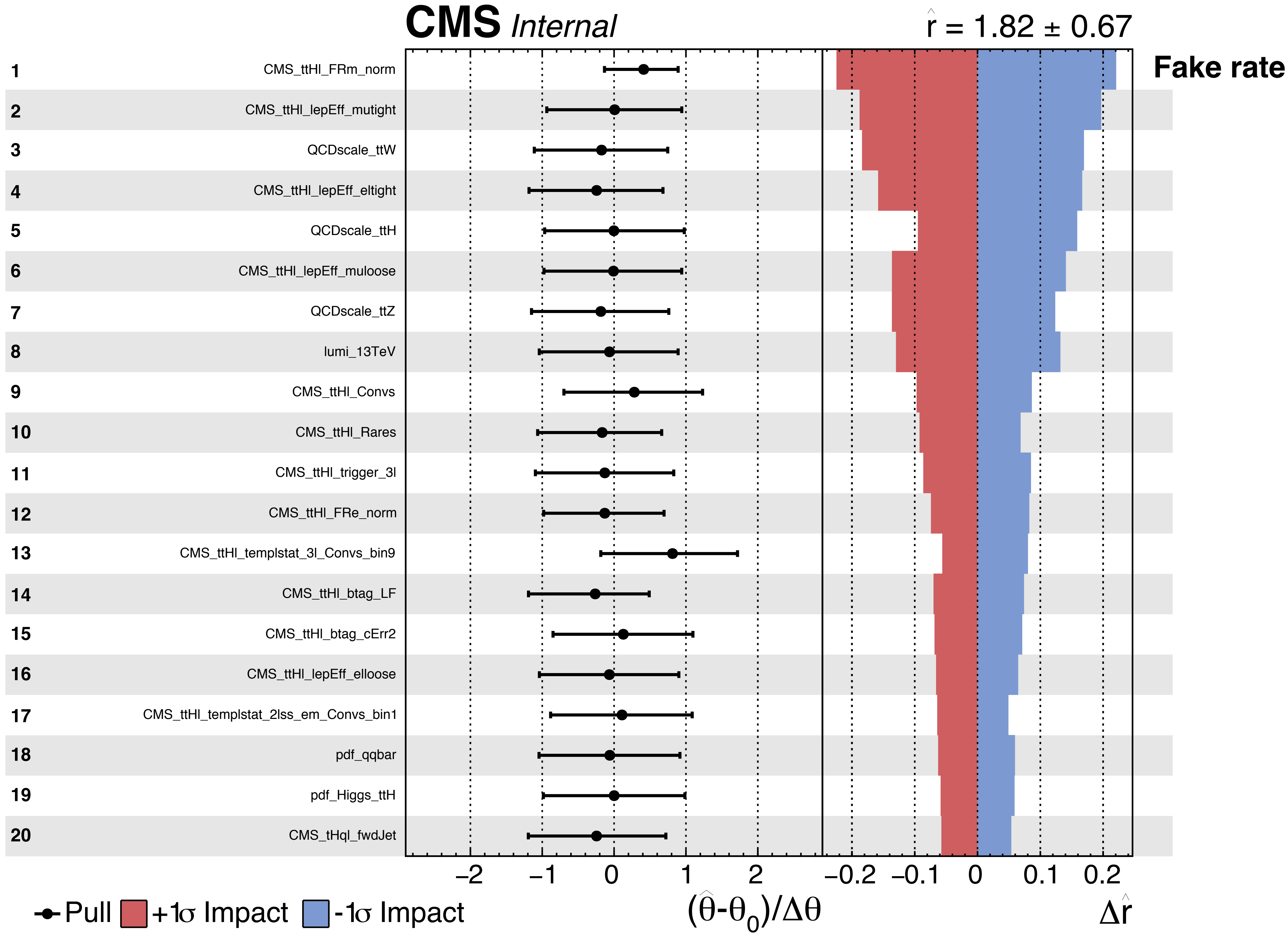
- Expected from background only Asimov dataset.

Effect of nuisances (κ_t/κ_V=-1)



Post-fit pulls and impacts of the 20 most important nuisance parameters.

Effect of nuisances (κ_t/κ_V=1)



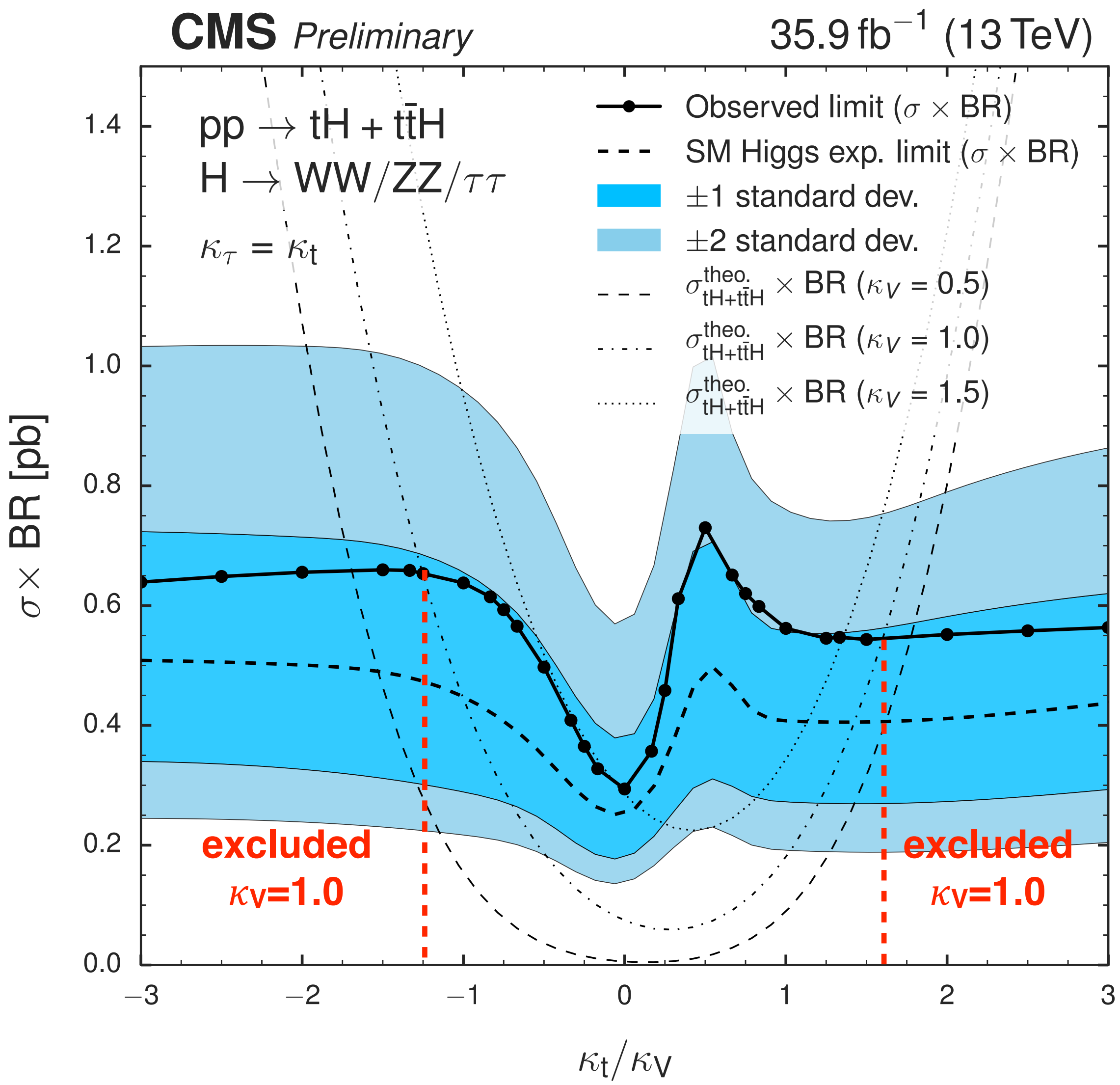
Post-fit pulls and impacts of the 20 most important nuisance parameters.

Conclusions

- Results of tHq to multilepton final state analysis at $\sqrt{s}$ = 13 TeV presented for the first time, using 2016 data.
- Sensitivity improved significantly compared to 8 TeV result (r = 6.7 for $\kappa_V = -\kappa_t = 1$).
- No longer statistically limited.
- Limit on σ(tHq+tHW+ttH)xBR(H$\rightarrow$WW*, $\tau\tau$, ZZ*) is presented as a function of the ratio of the Higgs coupling modifiers κ_t/κ_V.
- κ_t values outside (-1.25, 1.6) are excluded at 95% C.L. for κ_V = 1.0.

We thank the ARC and the Higgs conveners for guidance.

Today we seek approval for this analysis.


CMS Preliminary
35.9 fb^{-1} (13 TeV)
pp → tH + tt̄H
H → WW/ZZ/ττ
$\kappa_\tau = \kappa_t$
Observed limit ($\sigma \times$ BR)
SM Higgs exp. limit ($\sigma \times$ BR)
±1 standard dev.
±2 standard dev.
$\sigma^{theo.}_{tH+t\bar{t}H} \times$ BR (κ_V = 0.5)
$\sigma^{theo.}_{tH+t\bar{t}H} \times$ BR (κ_V = 1.0)
$\sigma^{theo.}_{tH+t\bar{t}H} \times$ BR (κ_V = 1.5)
excluded
κ_V=1.0
excluded
κ_V=1.0
$\sigma \times$ BR [pb]
κ_t/κ_V

Back Up

Documentation

AN-16-378

Available on the CMS information server — **CMS AN-16-378**

The Compact Muon Solenoid Experiment

CMS Draft Note

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

2017/04/19
Head Id: 398231
Archive Id: 398498:399531
Archive Date: 2017/04/07
Archive Tag: trunk

Search for tHq production in multilepton final states at 13 TeV

Jose Monroy[1], Pallabi Das[2], Benjamin Stieger[1], Sandhya Jain[2], Ken Bloom[1], and Kajari Mazumdar[2]

[1] University of Nebraska-Lincoln
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HIG-17-005

CMS PAS HIG-17-005

DRAFT
CMS Physics Analysis Summary

The content of this note is intended for CMS internal use and distribution only

2017/04/19
Head Id: 399703
Archive Id: 399703P
Archive Date: 2017/04/19
Archive Tag: trunk

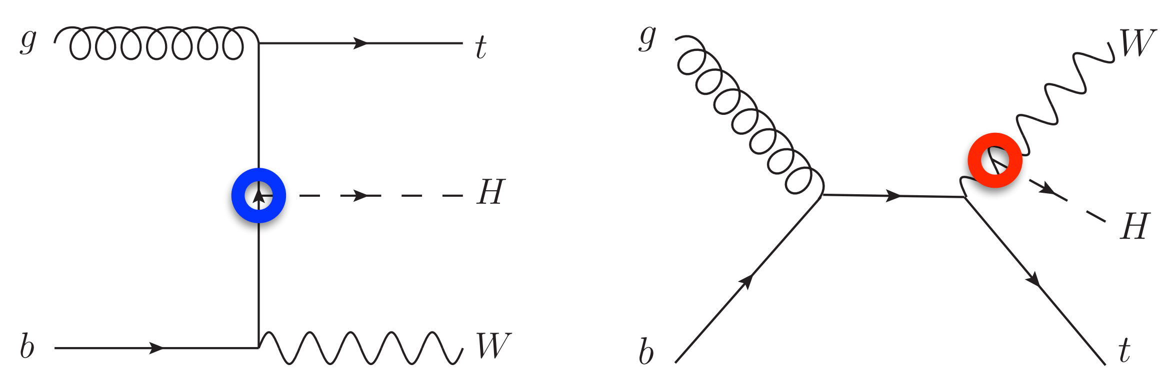
Search for production of a Higgs boson and a single top quark in multilepton final states in proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

- ttH multilepton, 13 TeV (Moriond 2017): HIG-17-004, AN-17-029
- tHq(Hbb), 13 TeV (ICHEP 2016): HIG-16-019, AN-16-065
- 8 TeV analysis: HIG-14-026, AN-14-140
- tHq paper: arXiv:1509.08159

The tH signal process

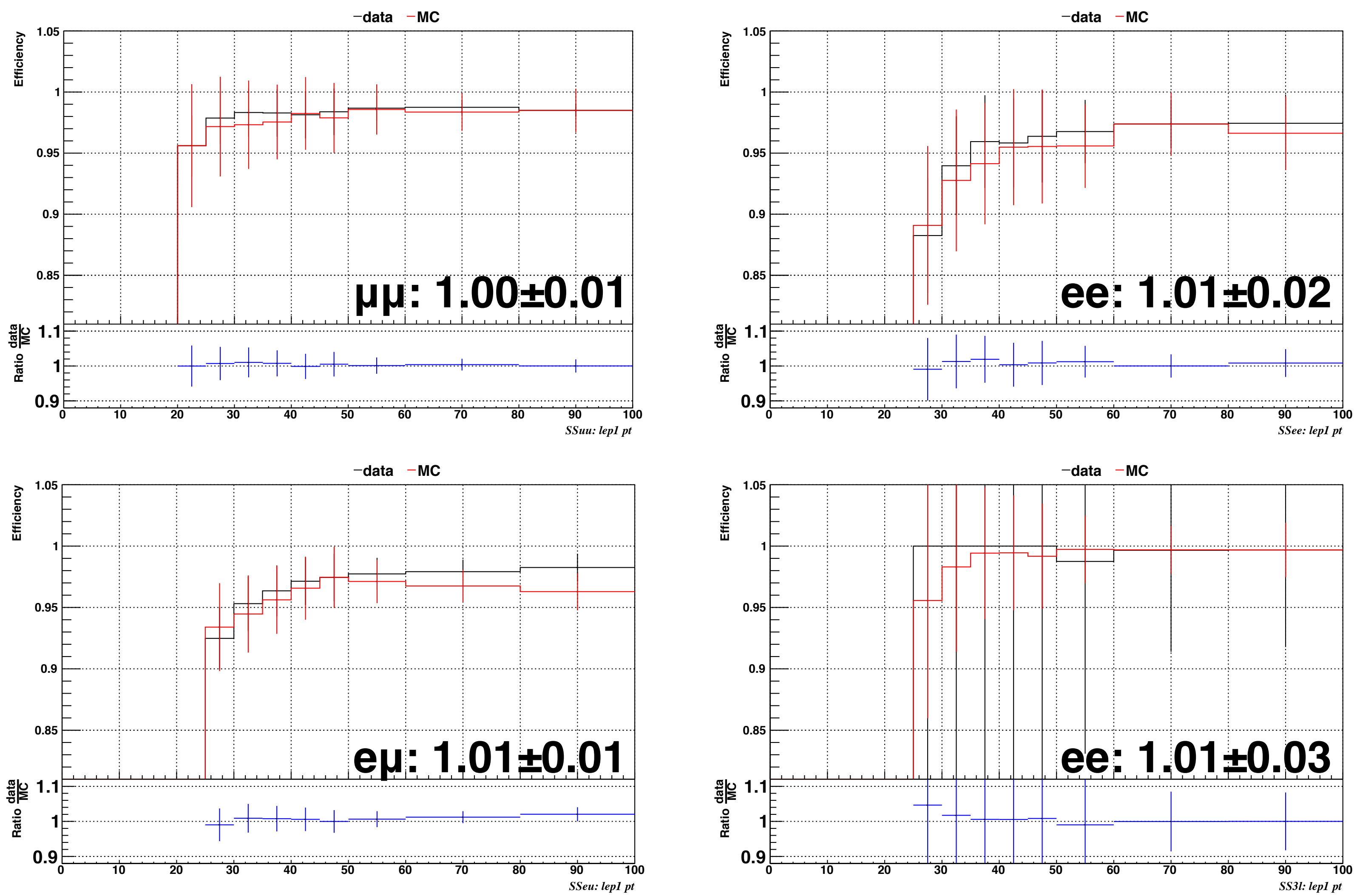
- A cross section modification similar to tHq can also be observed in case of the tHW production, which also has contribution from both ttH and WWH couplings.
- SM(κ_t = 1, κ_V = 1) cross section at 13 TeV is σ_{SM} = 15.61 fb.
- For κ_t = -1, κ_V = 1, it becomes σ_{ITC} = 147.2 fb.



- In the present study tHq and tHW are denoted together as the tH signal process.
- The BDT training is optimized on the tHq process as signal for κ_t = -1, κ_V = 1.

Trigger efficiencies

- **Triggers** (full list in back-up)
  - *2lss* : OR of non prescaled single lepton + dilepton HLT
  - *3l, 4l* : OR of non prescaled single lepton + dilepton + trilepton HLT
- **Method** : Measure data/MC scale factors using mET primary dataset



Lepton identification MVA

Kin

- p_T, η

Iso

- PF miniRelIso, charged had. (R=0.3)
- PF miniRelIso, neutral had. & photon (R=0.3, scaled EA)

IP

- 3D IP significance (SIP_{3D})
- 2D IP $|d_{xy}|$ and $|d_z|$

Lep-Jet

- Lepton's closest jet (JEC applied only to hadronic activity)
    - $p_T(\ell)/p_T(\text{jet})$: « p_T ratio »
    - Lepton's p_T^{rel} wrt jet
    - jet CSV b-tag
    - #charged tracks in jet

ID

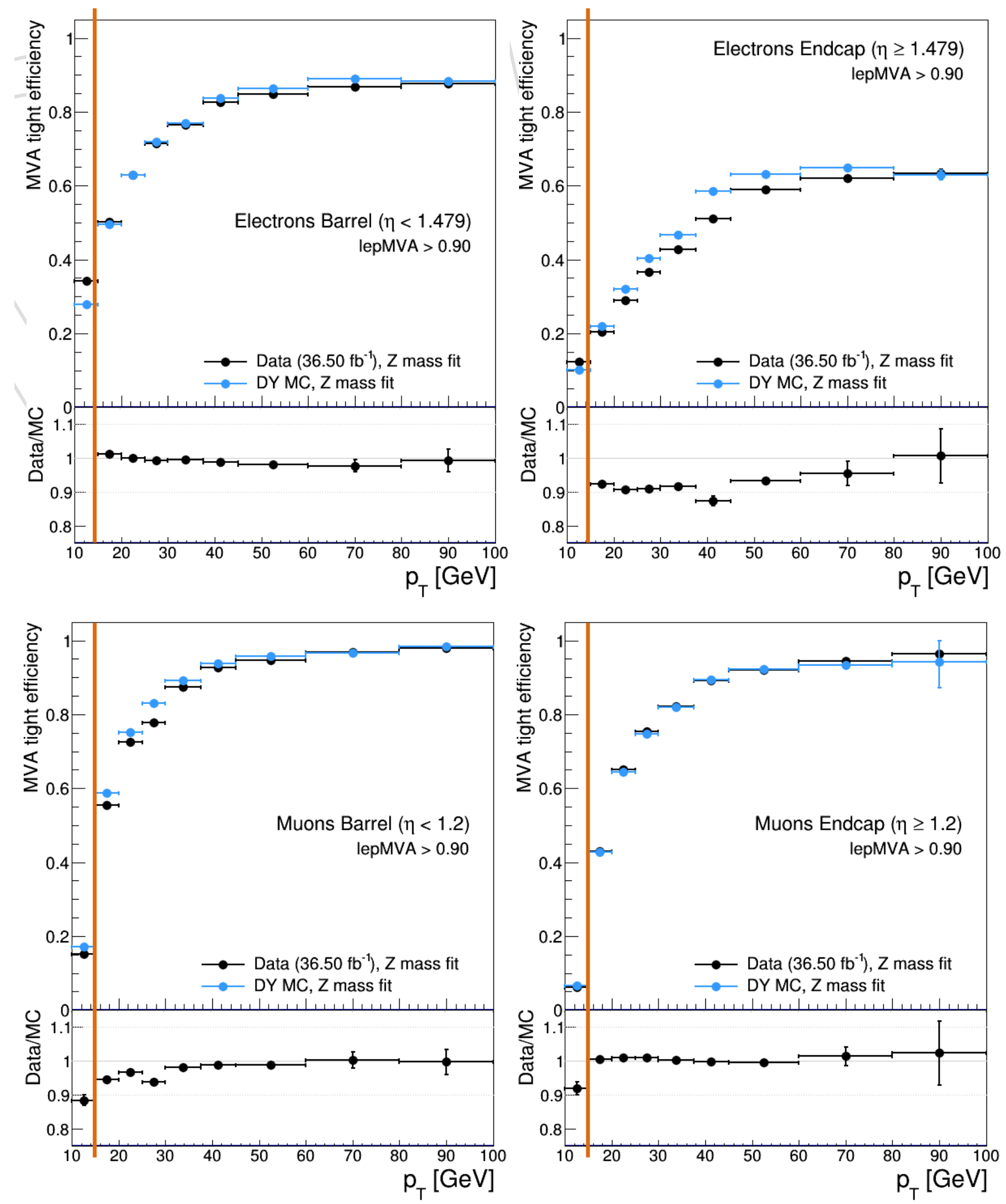
- (μ) Segment compatibility
- (e) Electron ID MVA (EGM POG)

Lepton identification efficiencies (2lss)

- **Remeasured lepton efficiencies and scale factors with updated lepMVA cut**
- Measure tight to loose efficiencies
- Use Tag and probe method from Z(ll) events data and MC
- Loose selection scale factors taken from SUSY lepton SF group

2lss

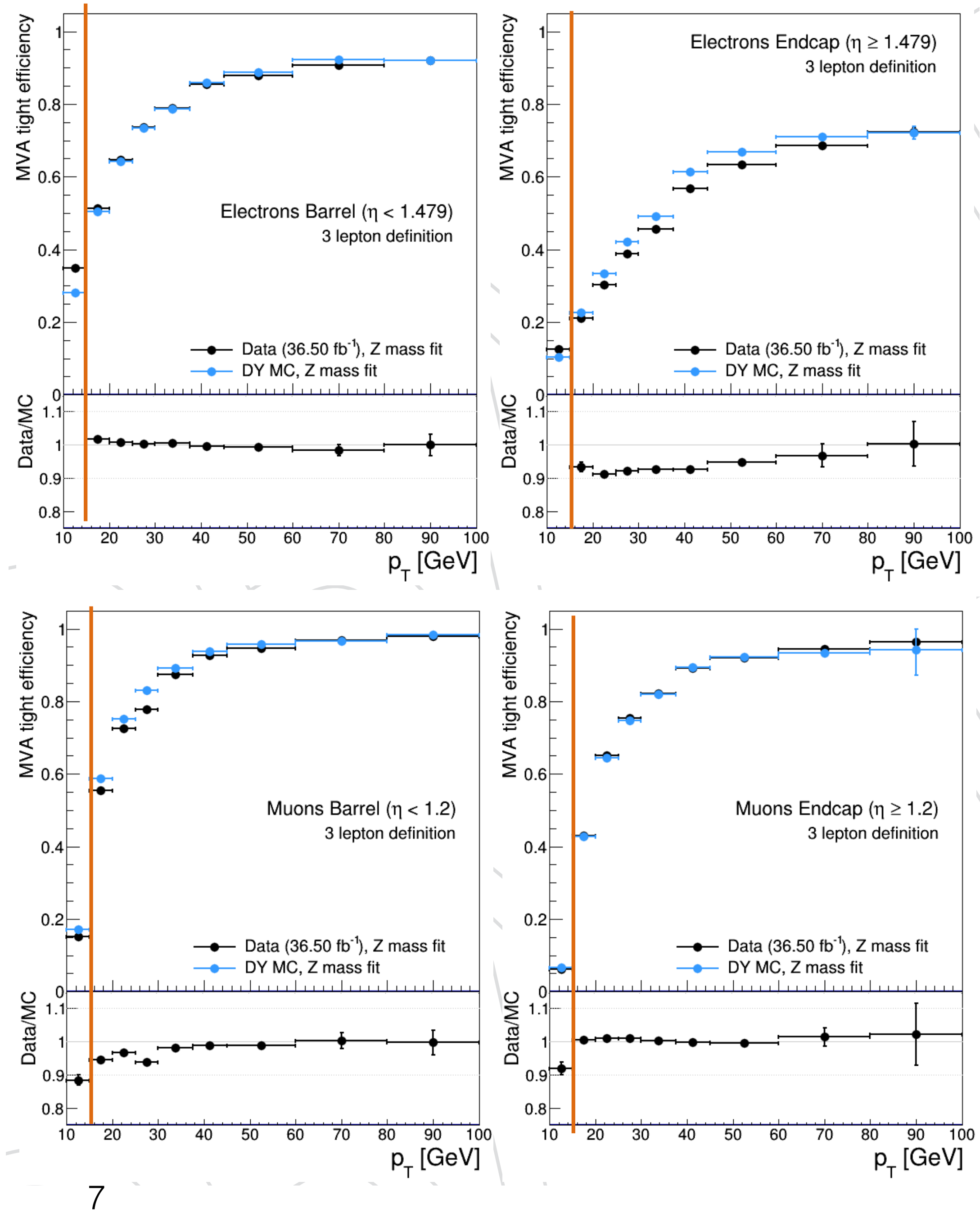
- 2lss : include the **tight charge** requirement (suppress OS events)
  - muon : ΔpT/pT < 0.2
  - electron : consistency of charge measurement with KF, gsf track and ECAL



Lepton identification efficiencies (3l)

- **Remeasured lepton efficiencies and scale factors with updated lepMVA cut**
- Measure tight to loose efficiencies
- Use Tag and probe method from Z(ll) events data and MC
- Loose selection scale factors taken from SUSY lepton SF group

3l



Fake rate method

- Used to estimate the non-prompt lepton backgrounds such as ttbar, DY, W+jets etc.
- Fakes: real leptons from quark decays or mis-reconstructed jets.
- Based on a loose and tight cut on a single variable, for our case: lepton MVA
- Fake rate: probability of the fakeable objects to pass the tight selection in the fake dominated CR (QCD di-jet sample).
- For example, in case of the 2lss channel, the fake prediction is:

$$\boxed{N_{pp}^{\mathrm{bkg}} = \frac{f_1}{1-f_1} N_{pf} + \frac{f_2}{1-f_2} N_{pf} - \frac{f_1 f_2}{(1-f_1)(1-f_2)} N_{ff}}$$

Lepton fake rate measurement

Fake rate is measured in an independent sample:

- **QCD sample**, require 1 fakeable lepton + ΔR>0.7 jet

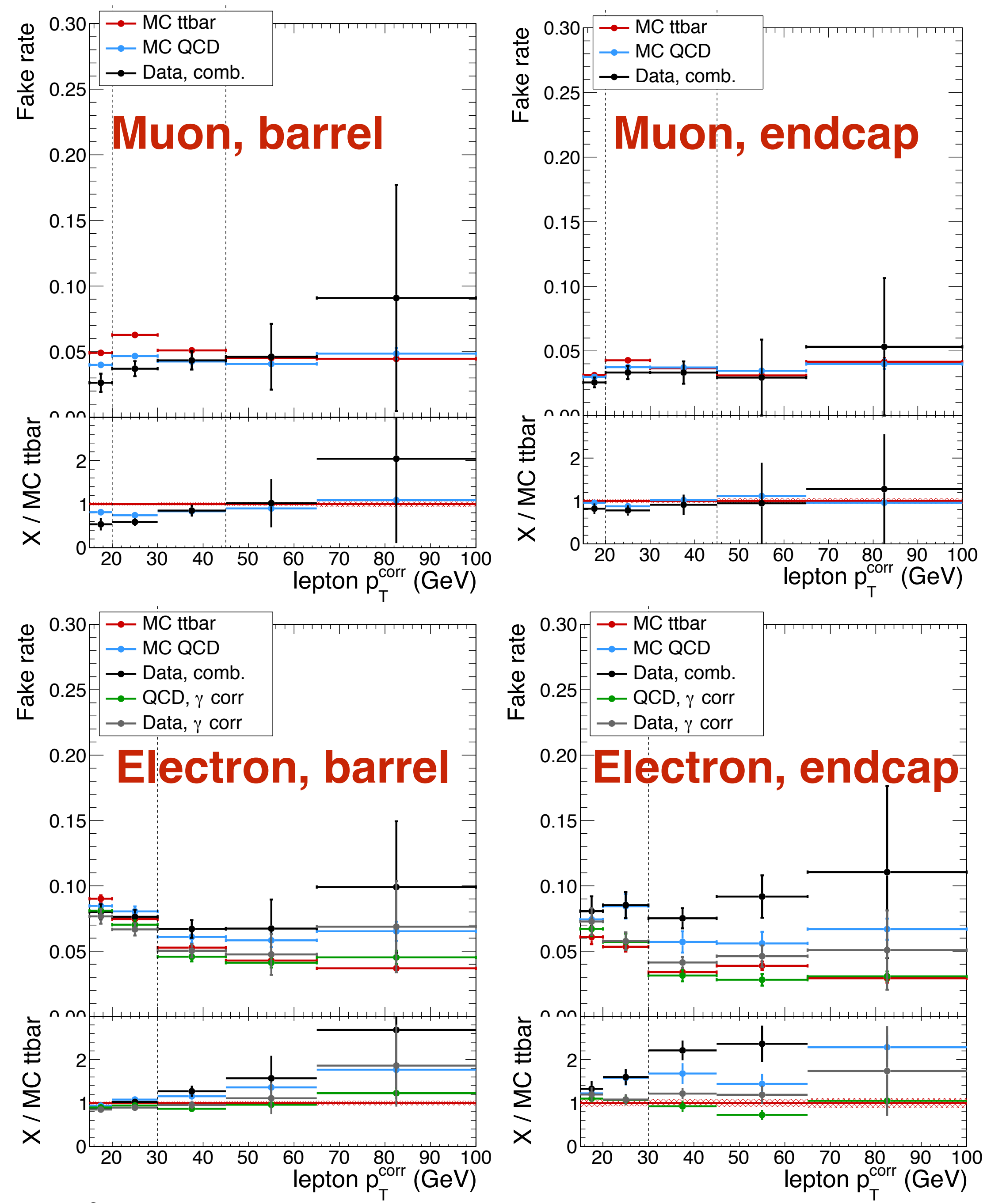
Muon :

- 10 < pT < 20: HLT_Mu3_PFJet40
- 20 < pT < 45: HLT_Mu8
- pT>45 : HLT_Mu17

Electron :

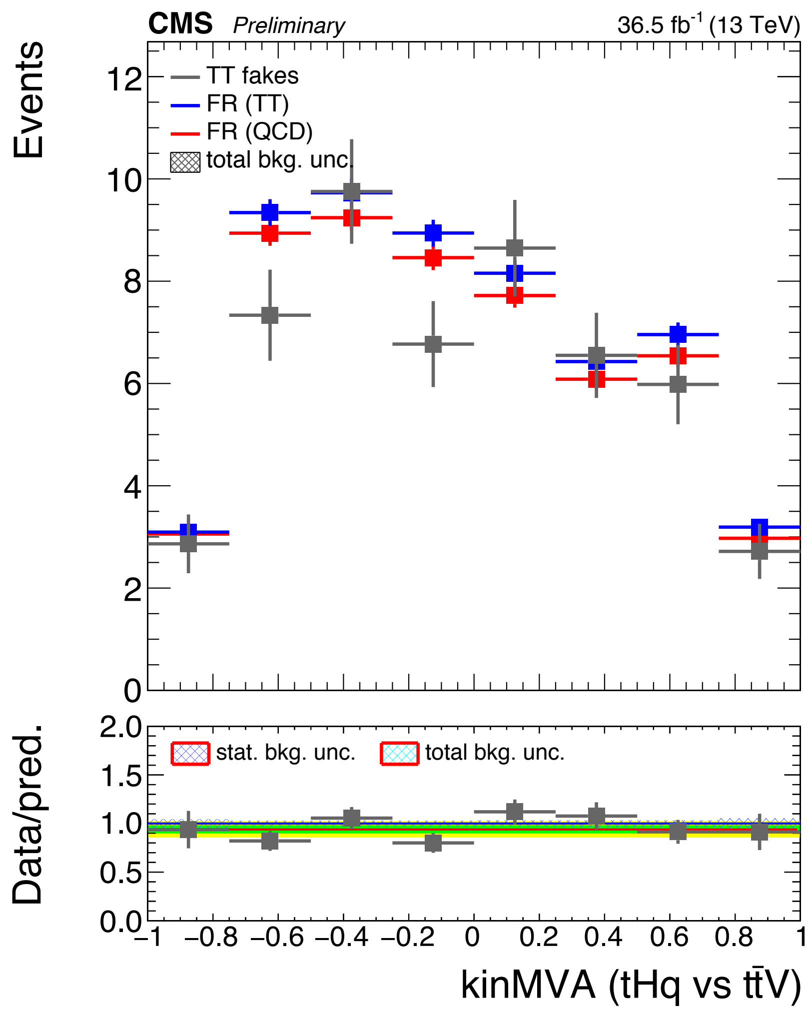
- pT > 15 : electron+jet trigger with 8, 12 GeV

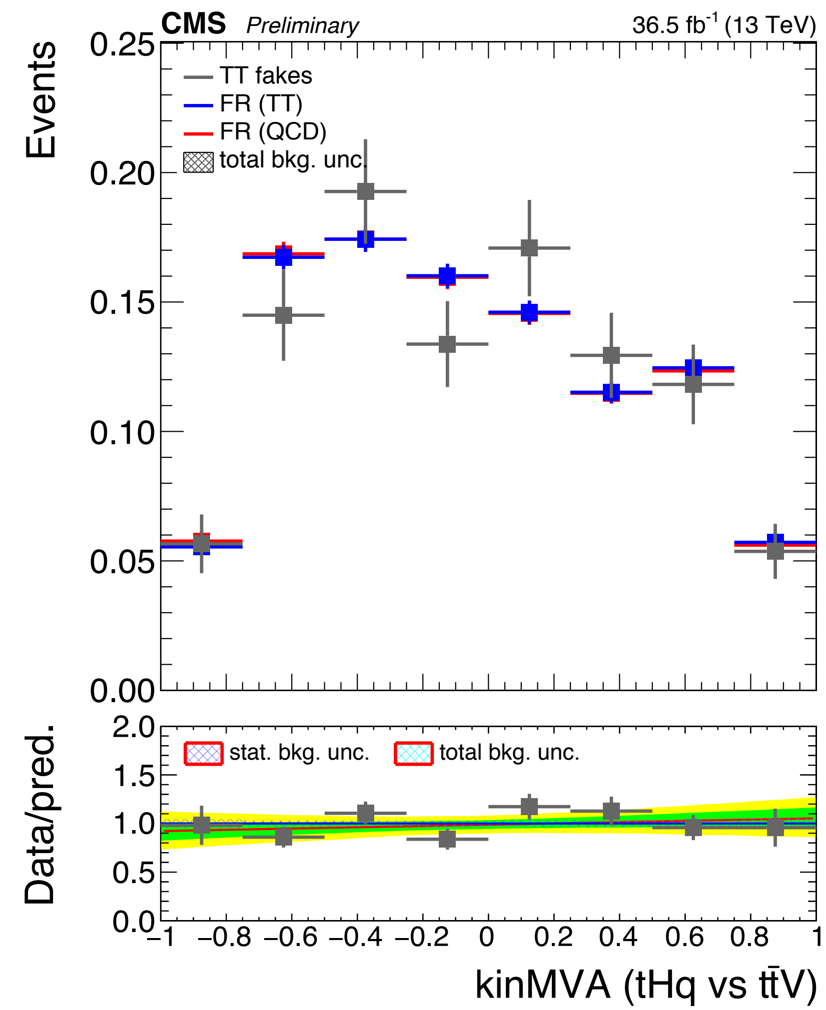
- Correct lepton pT for hadronic energy
- Corrected for prompt-lepton contribution.



Fake rate closure

- Compare events with leptons passing tight selection in ttbar MC with (i) fake prediction on ttbar MC using FR measured in QCD sample FR(QCD), (ii) fake prediction on ttbar MC using FR measured in ttbar sample FR(TT)



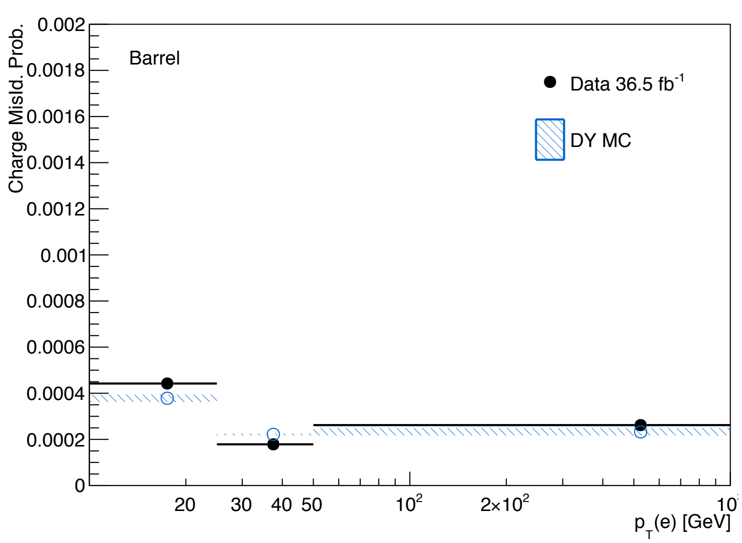


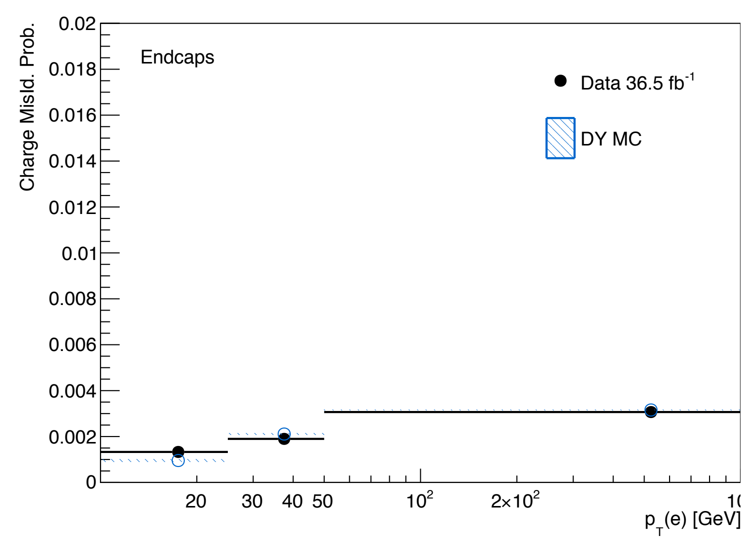
- Normalization (left) and shape (right) prediction, for BDT score against ttV in the 2lss eμ channel.

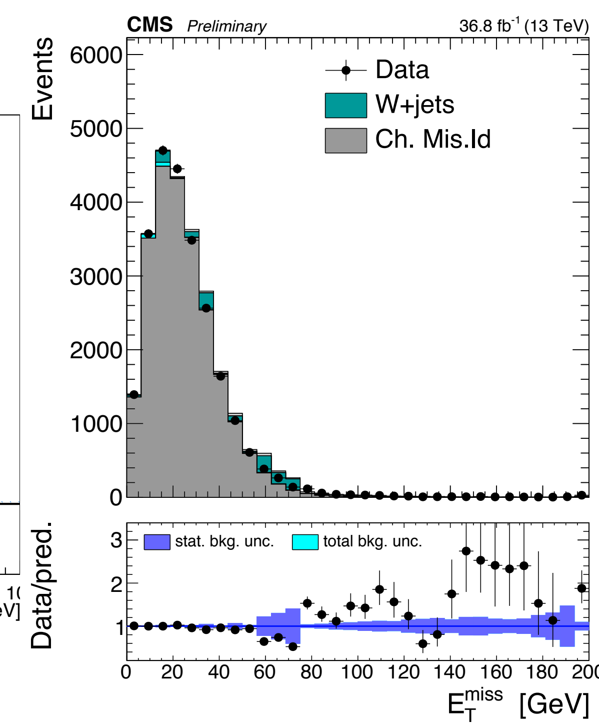
Charge mis-identification background

Measurement of charge flips :

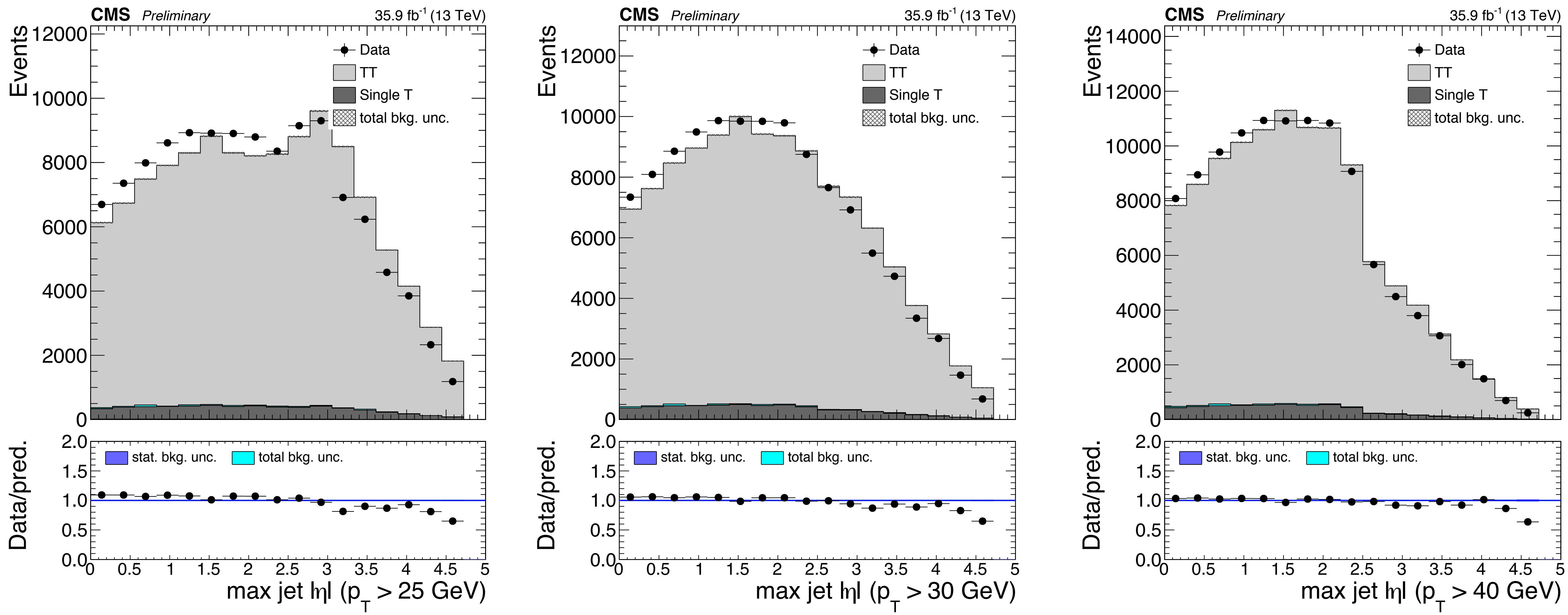
- Especially relevant for electrons (negligible background for muons)
- Use **Zee events with same sign electrons** in data
- Measure the ratio of same sign to opposite sign events, per lepton
- As a function of pT and eta
- **Application region**: opposite sign events in data
- Apply 30% systematics from closure on DY and ttbar events







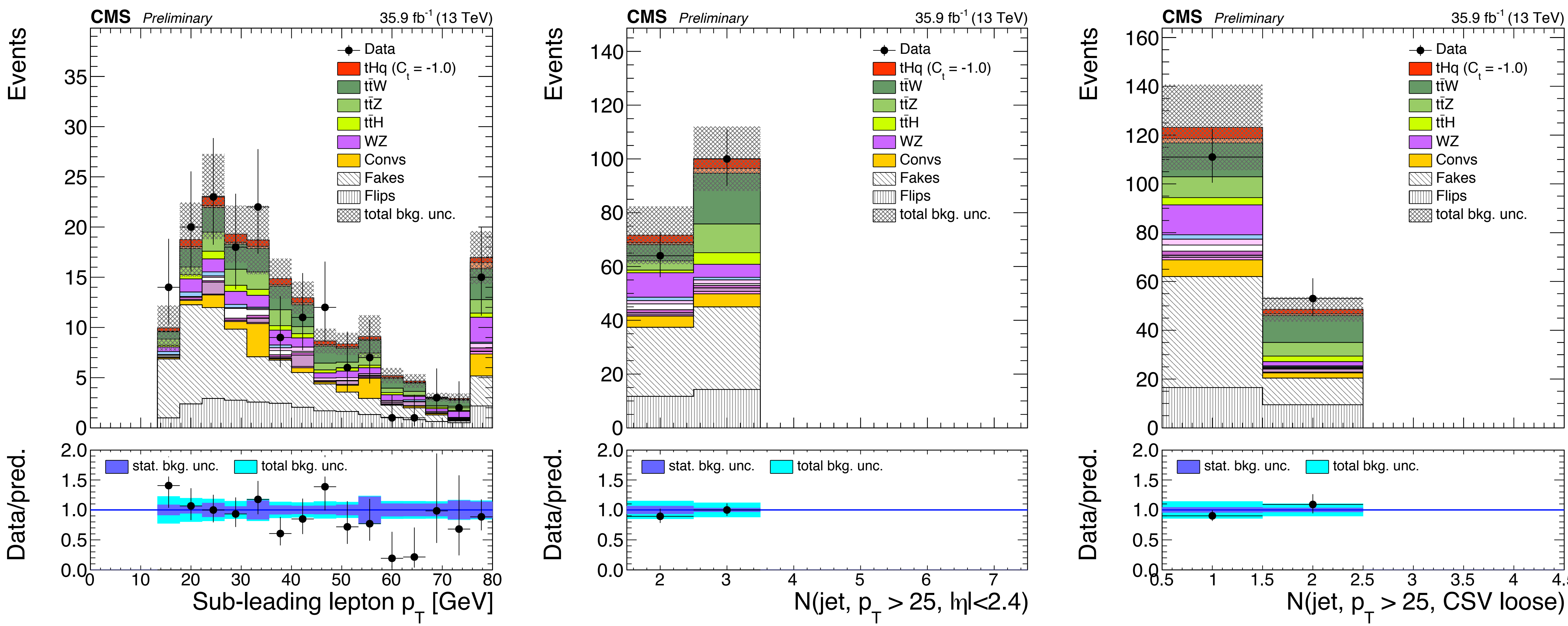
Data/MC scale factor modelling for forward jet



- $|\eta|$ distributions of the most forward non-tagged jet in the tt-enriched opposite signed eμ selection for different p_T cut values

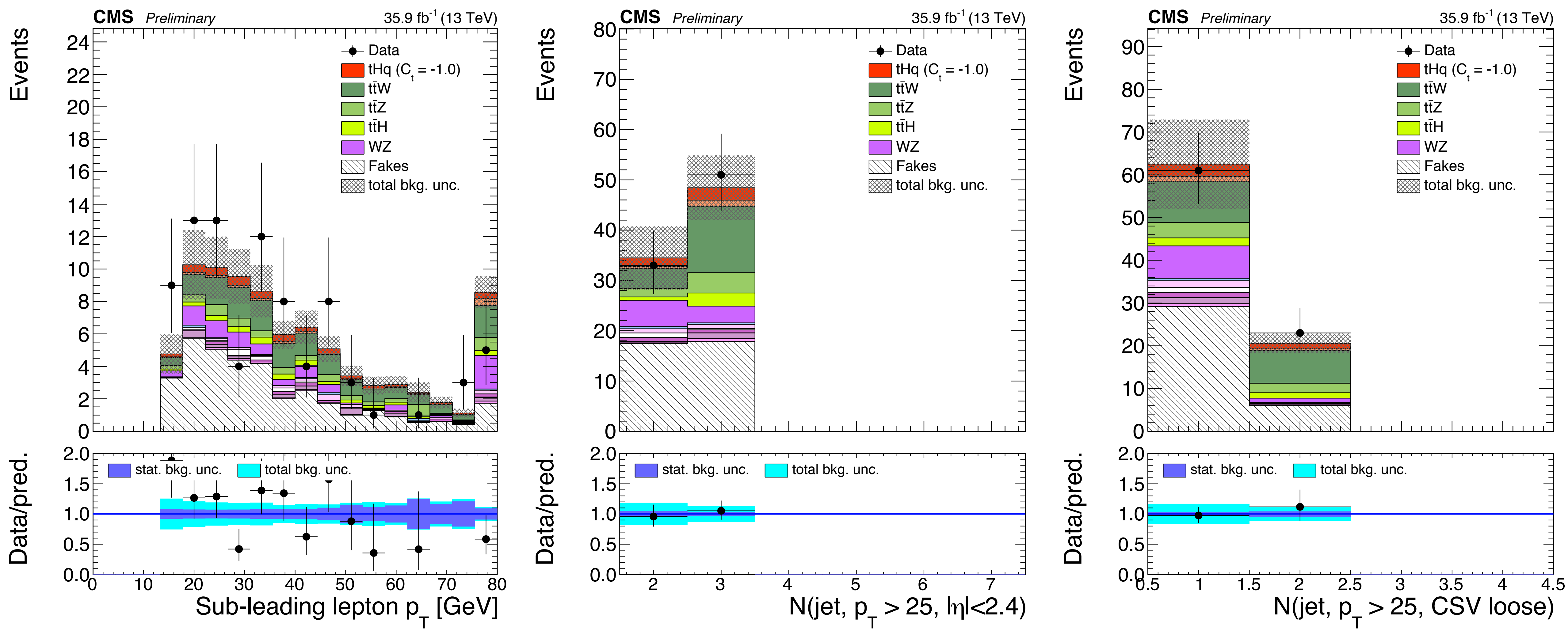
Control regions for background estimation: 2lss-eμ

- Selection for ttbar enriched CR:
  - ➡ Exactly two same sign tight leptons (eμ) with $p_T > 25/15$ GeV.
  - ➡ b-jets: one or more jets passing CSVv2 medium w.p. ($|\eta| < 2.4$).
  - ➡ Number of jets within $|\eta| < 2.4$ is less than four.
  - ➡ Maximum (un-tagged) jet $|\eta| < 2$ (to suppress signal region)

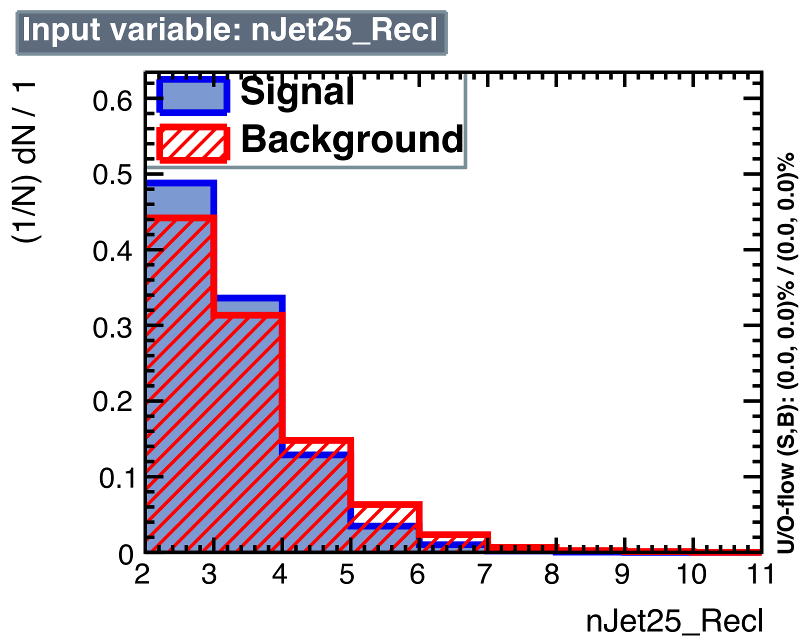


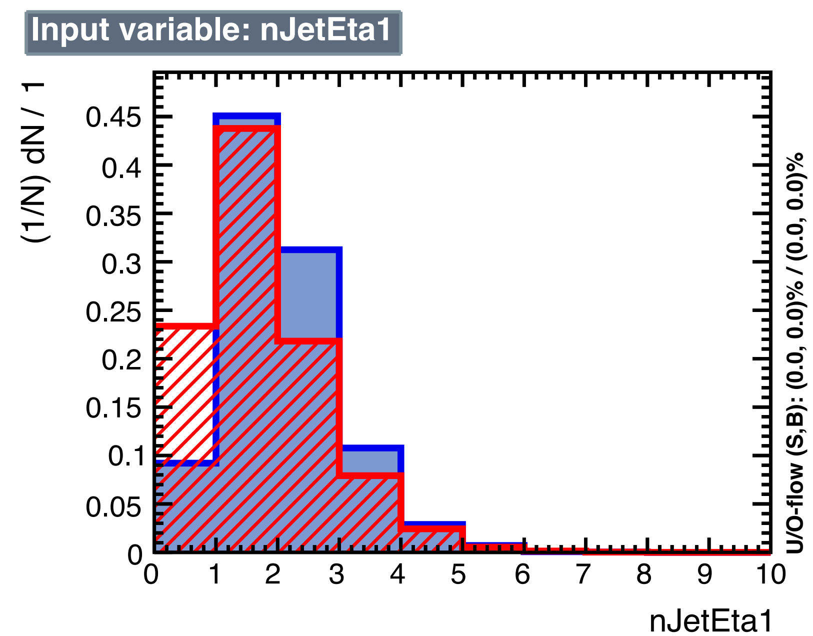
Control regions for background estimation: 2lss-μμ

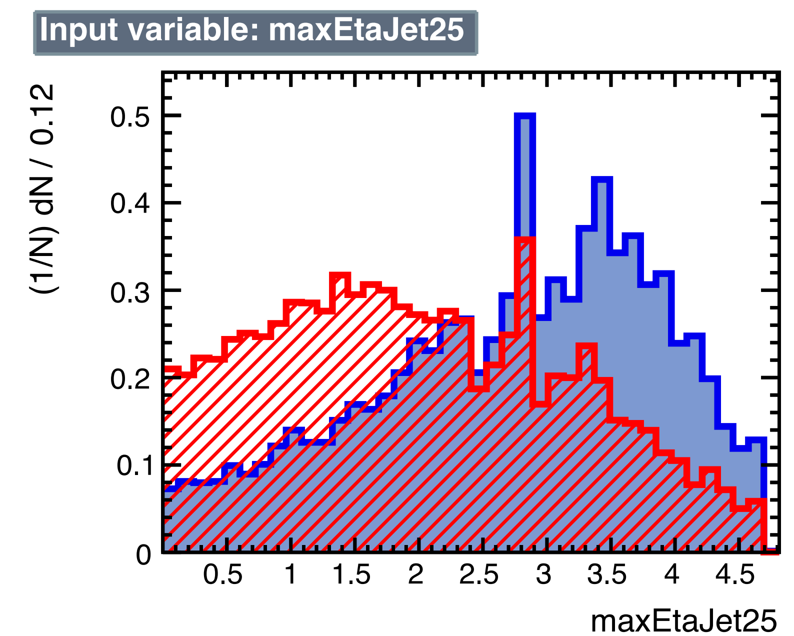
- Selection for ttbar enriched CR:
  - ➡ Exactly two same sign tight leptons (μμ) with $p_T > 25/15$ GeV.
  - ➡ b-jets: one or more jets passing CSVv2 medium w.p. ($|\eta| < 2.4$).
  - ➡ Number of jets within $|\eta| < 2.4$ is less than four.
  - ➡ Maximum (un-tagged) jet $|\eta| < 2$ (to suppress signal region)

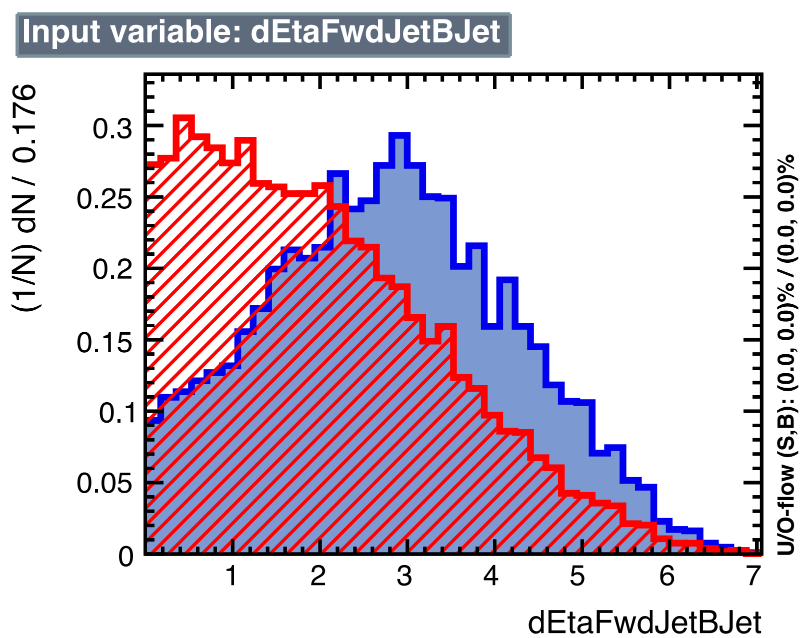


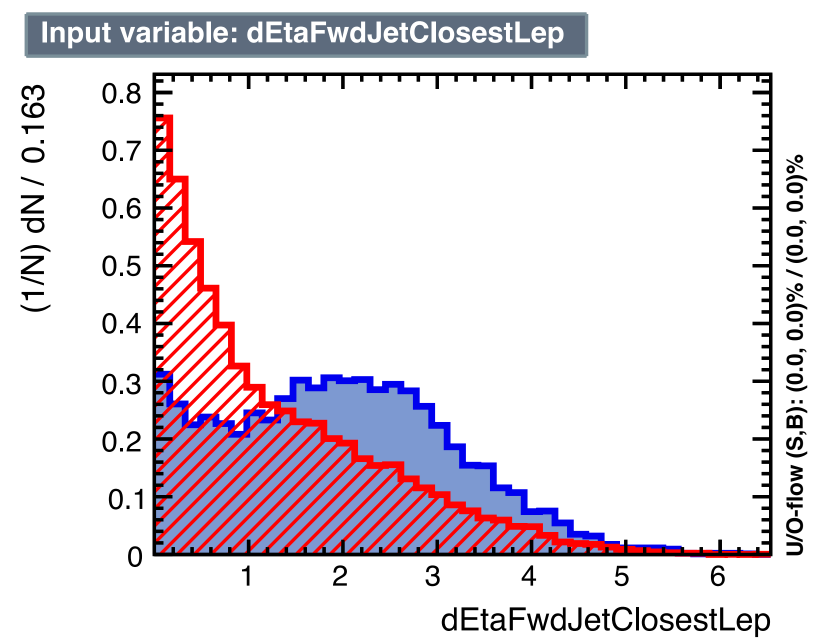
Input variables for ttbar BDT: 3l

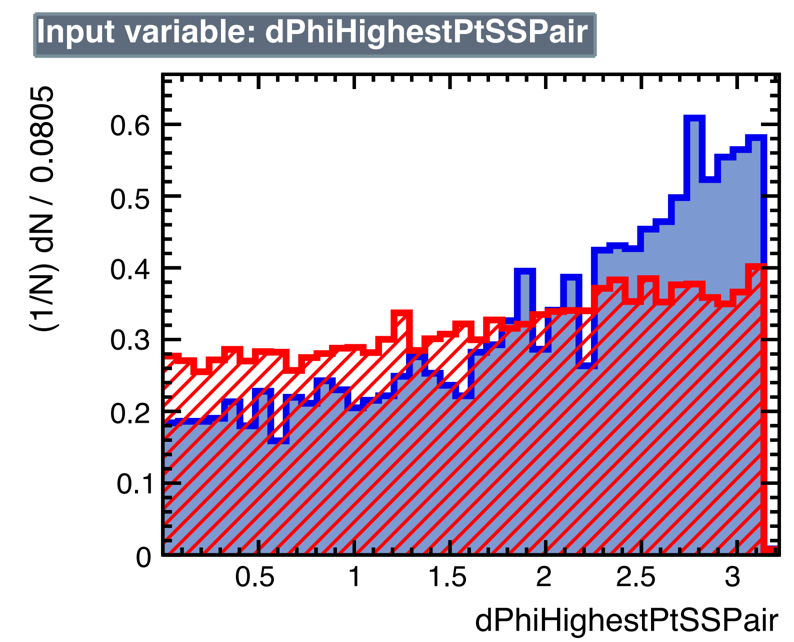




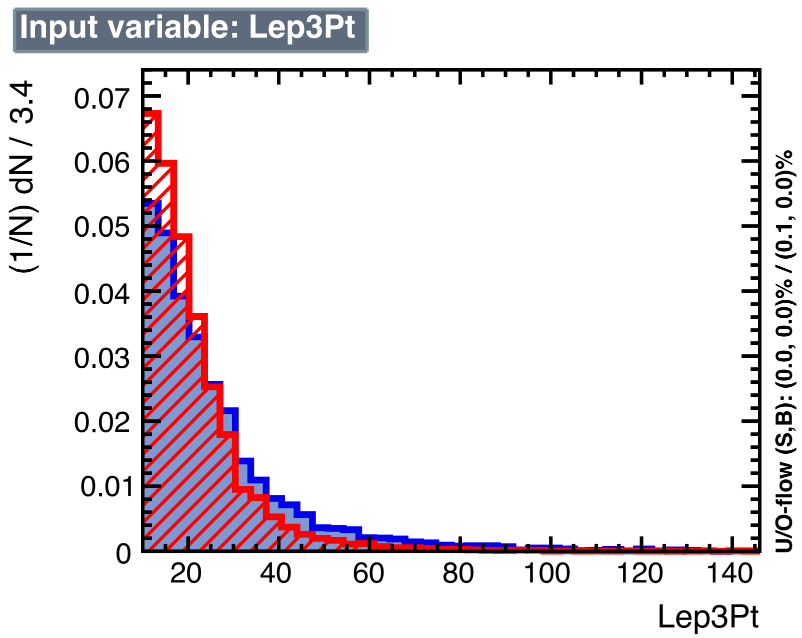


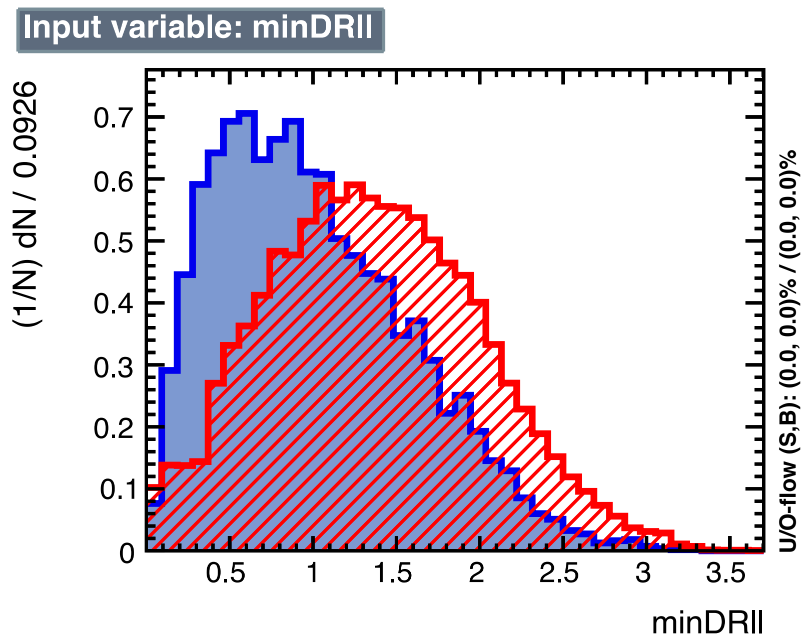


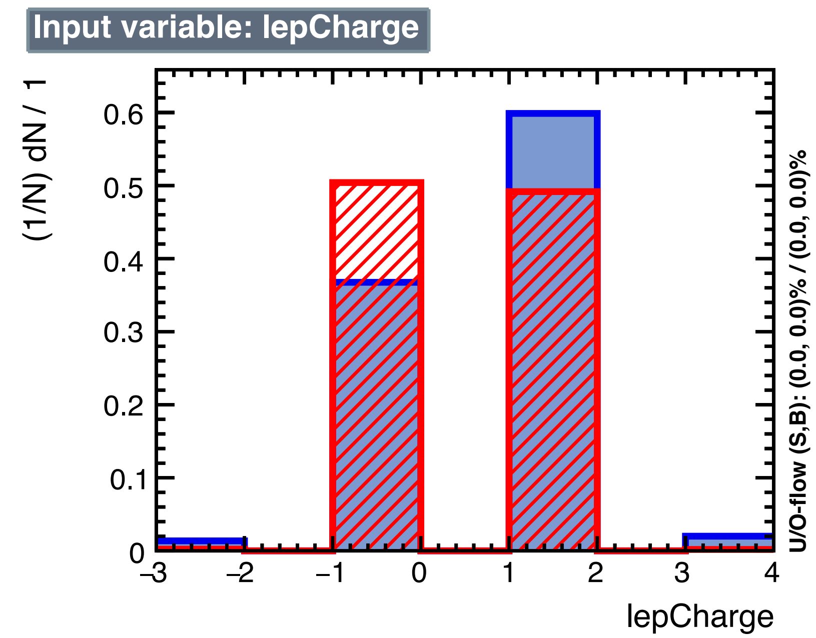


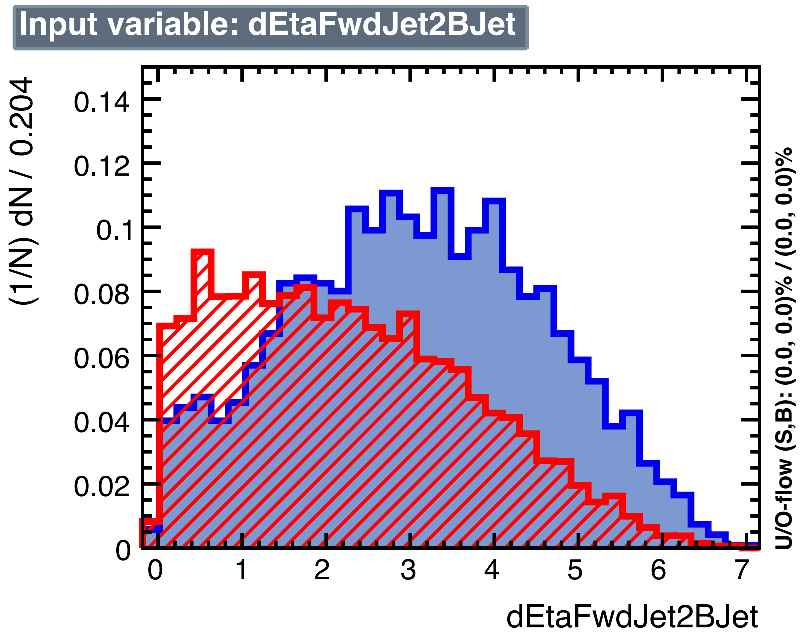


Input variables for ttbar BDT: 3l

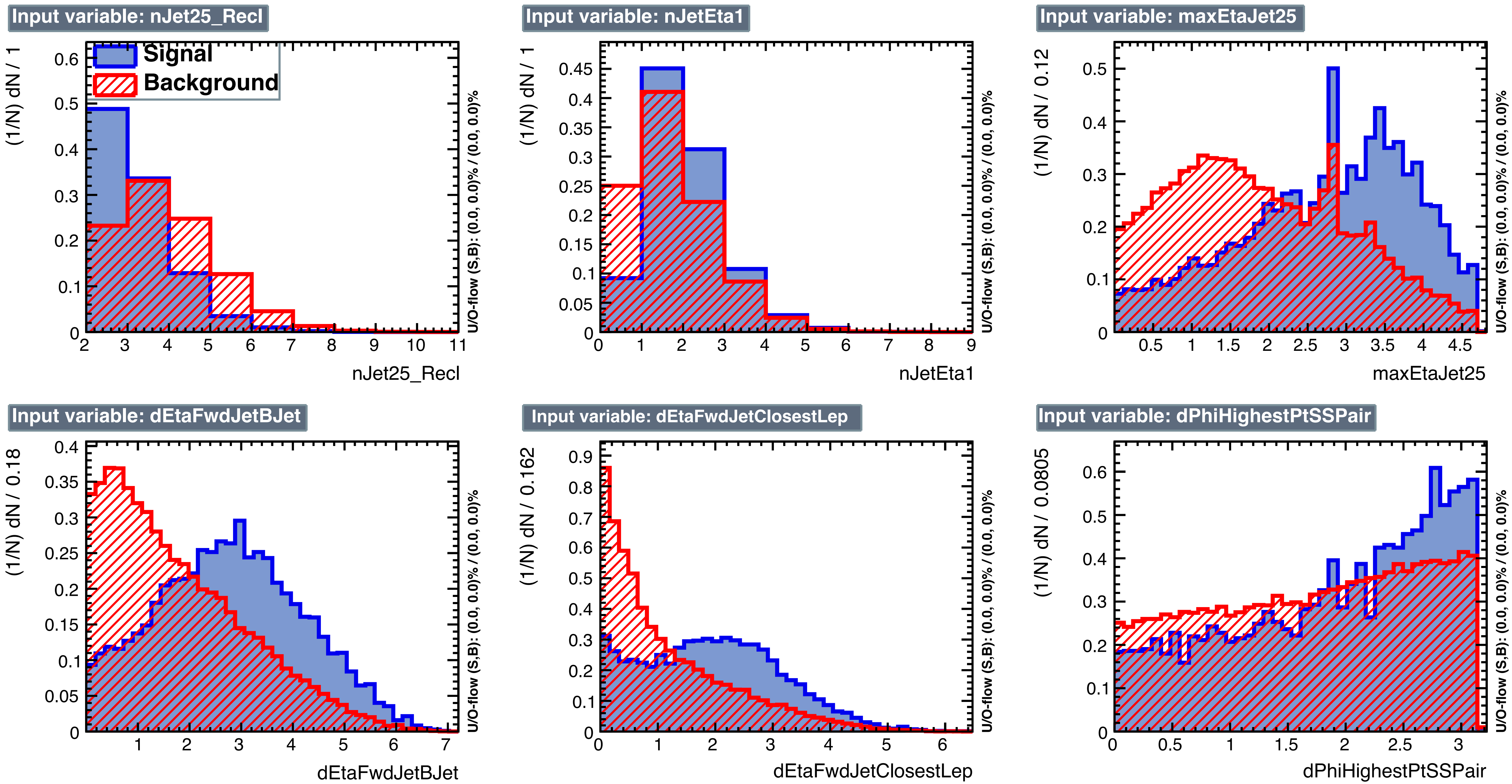




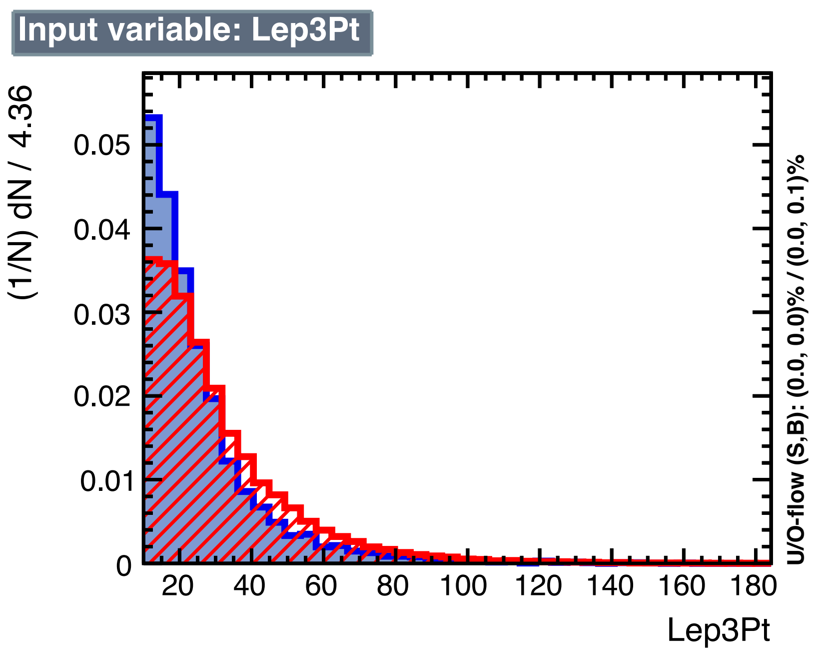


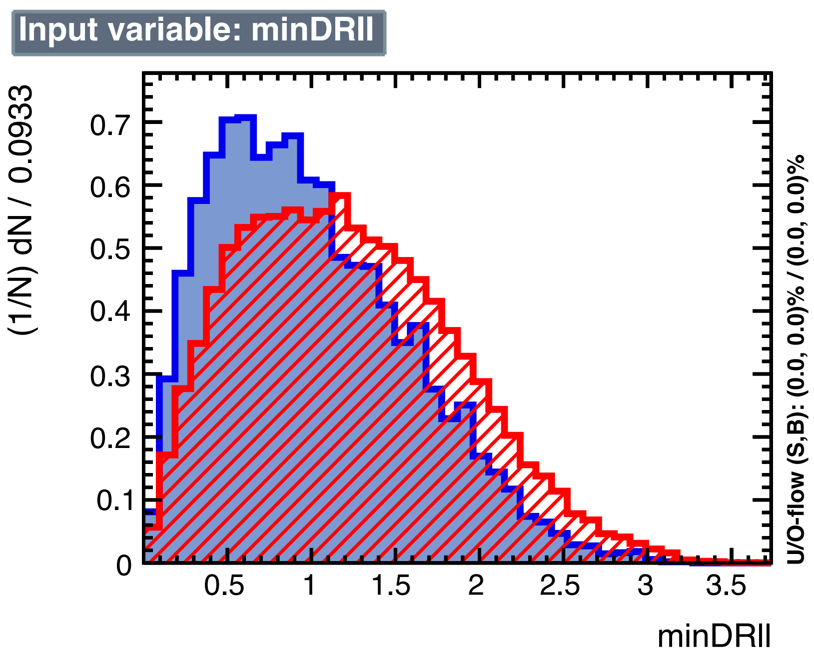


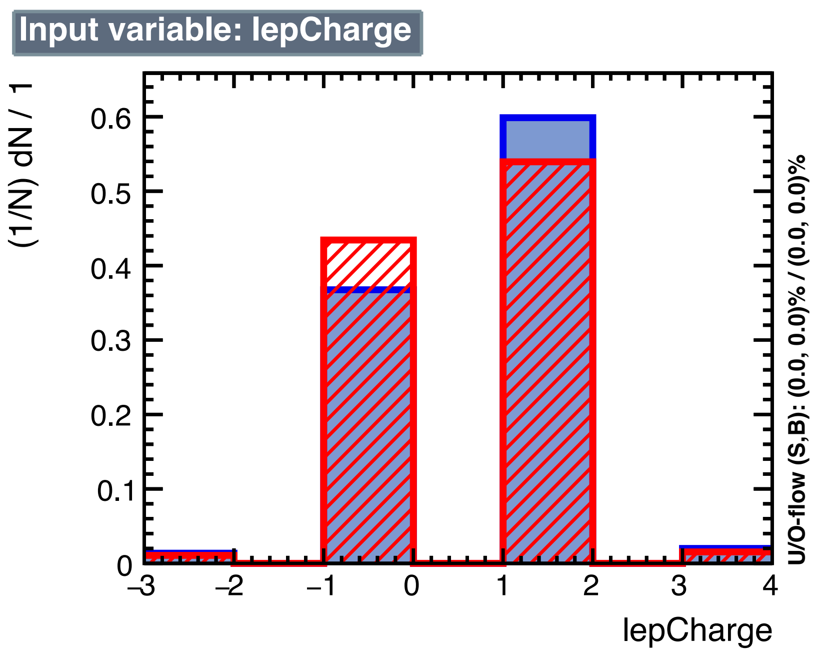
Input variables for ttV BDT: 3l

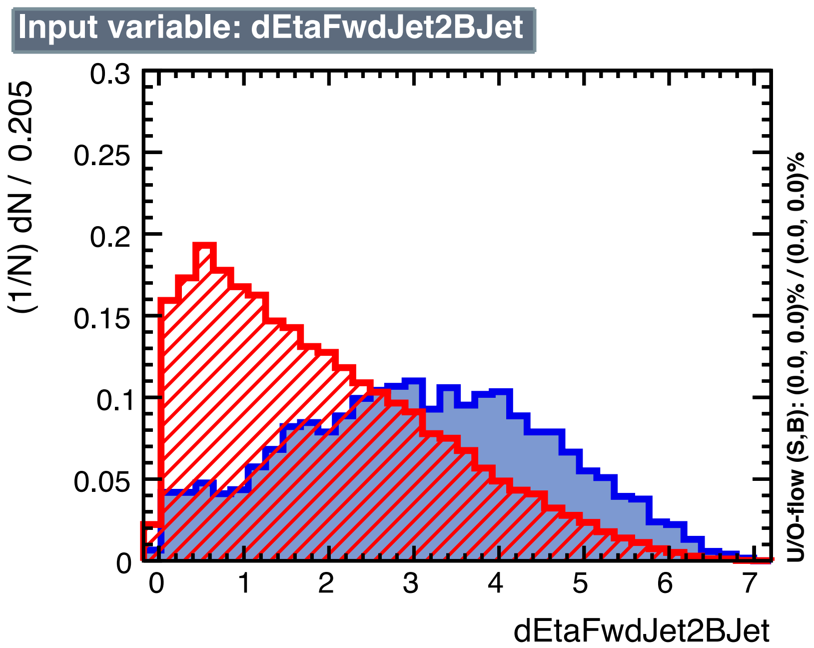


Input variables for ttV BDT: 3l

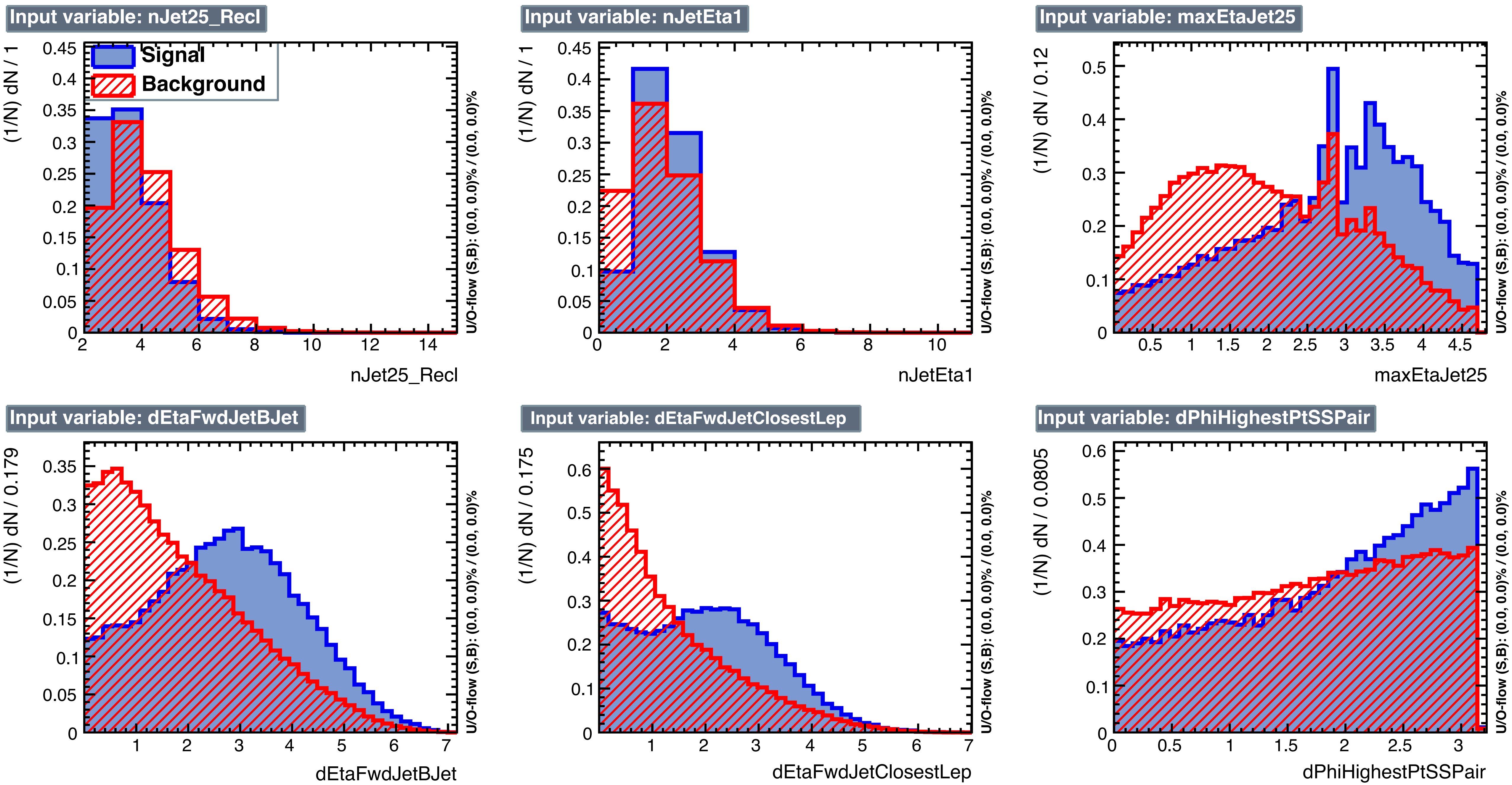




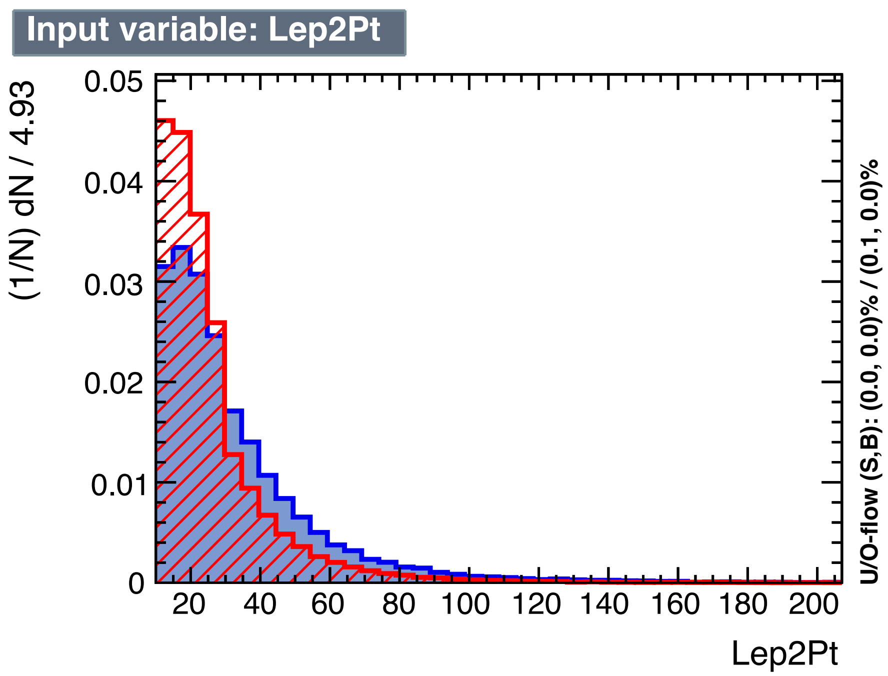


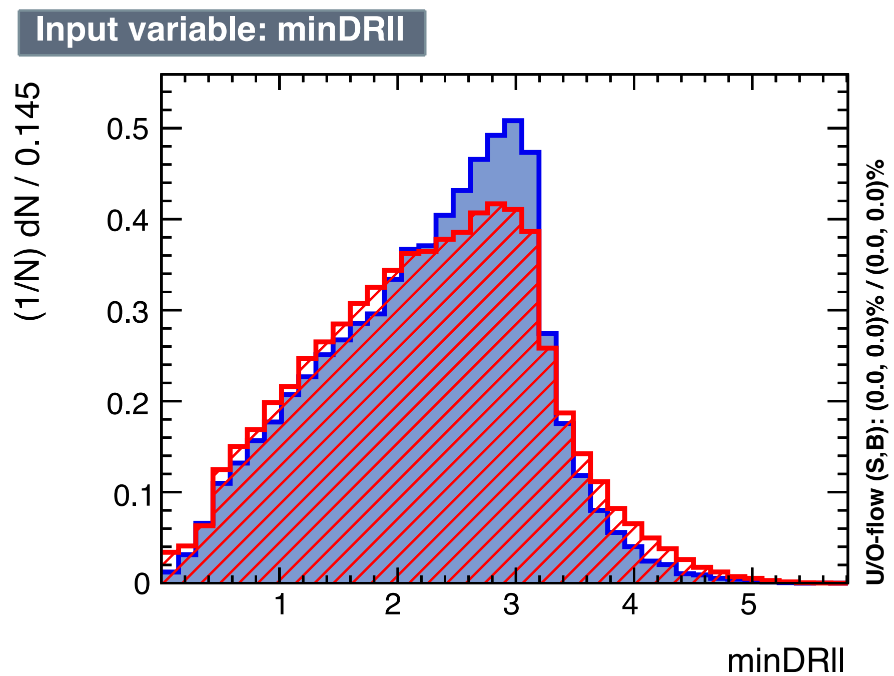


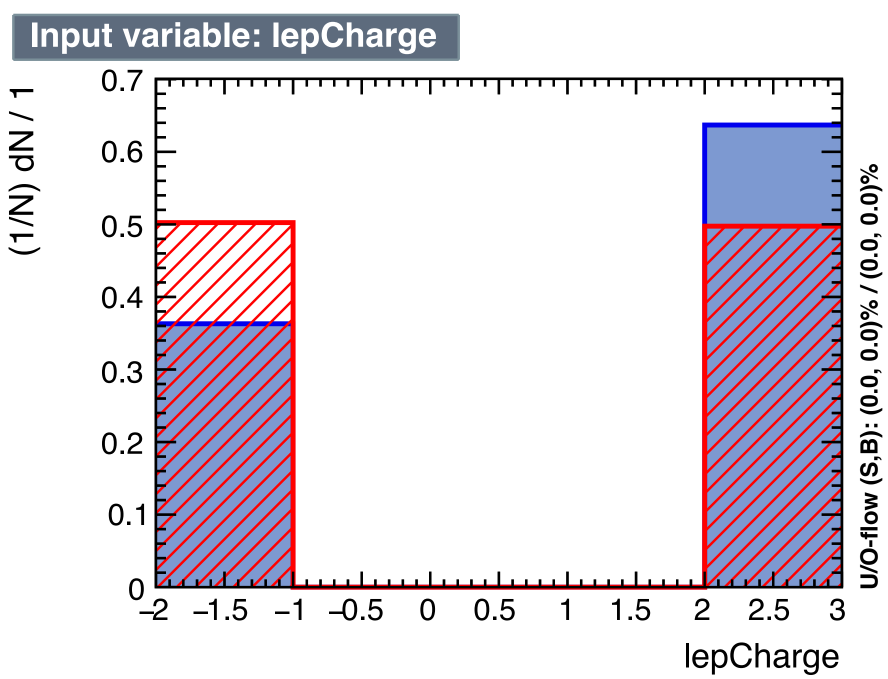
Input variables for ttbar BDT: 2lss

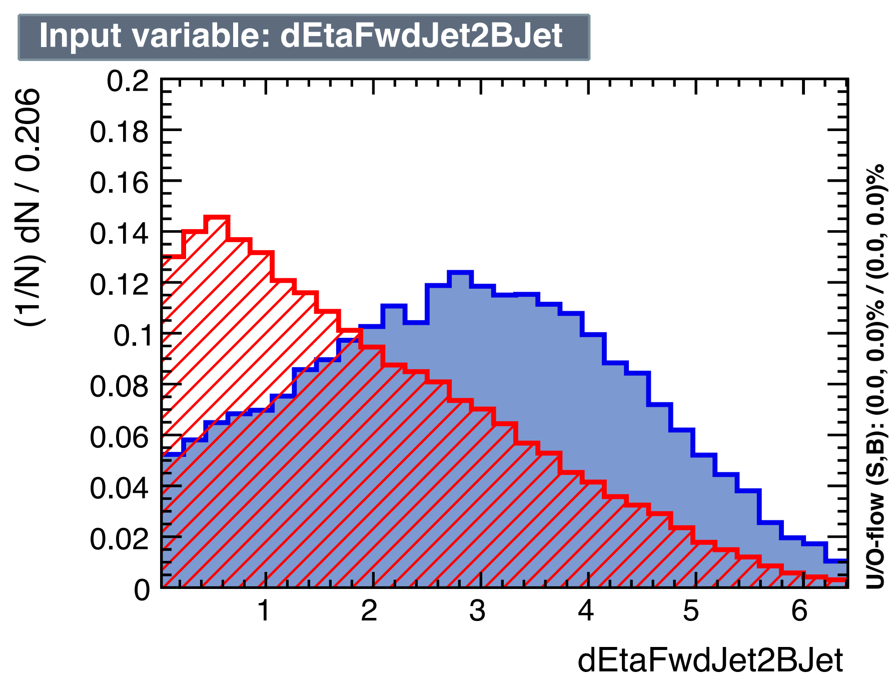


Input variables for ttbar BDT: 2lss

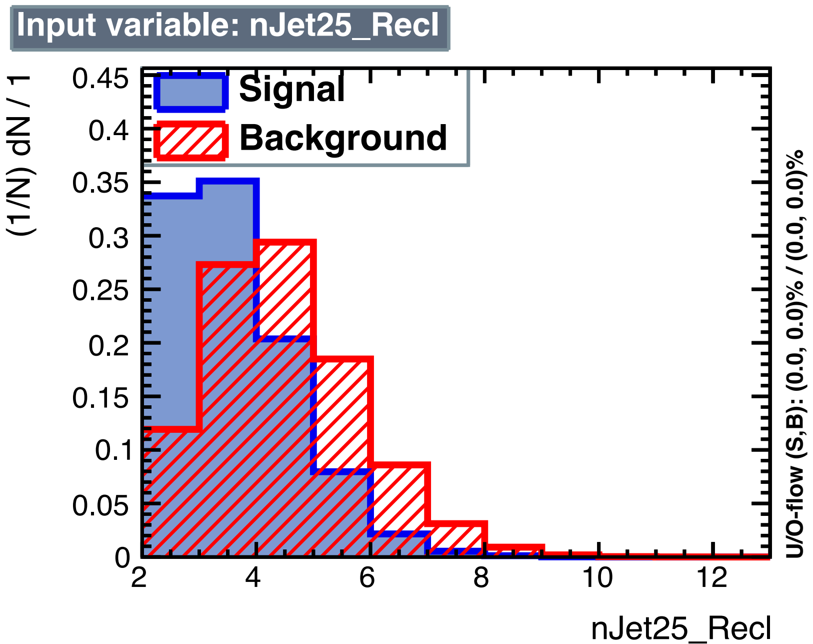


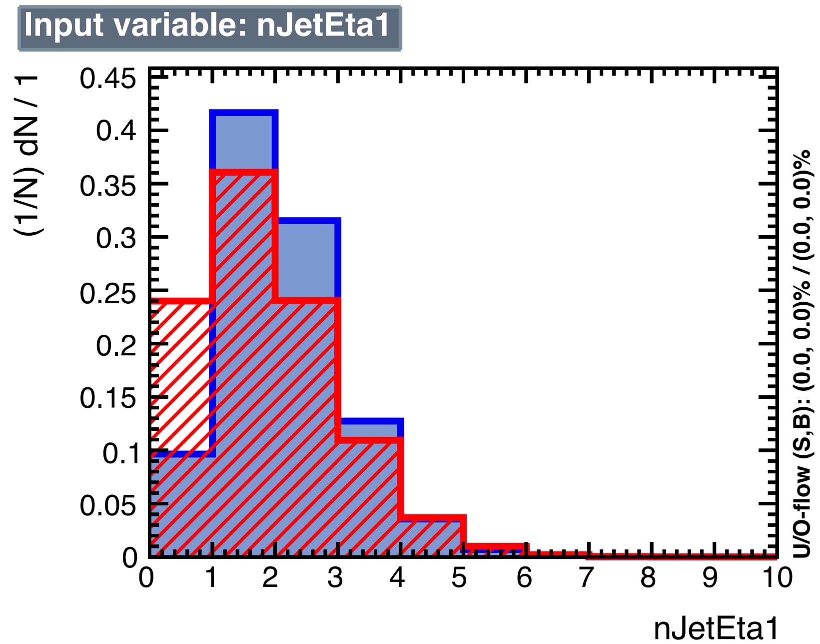


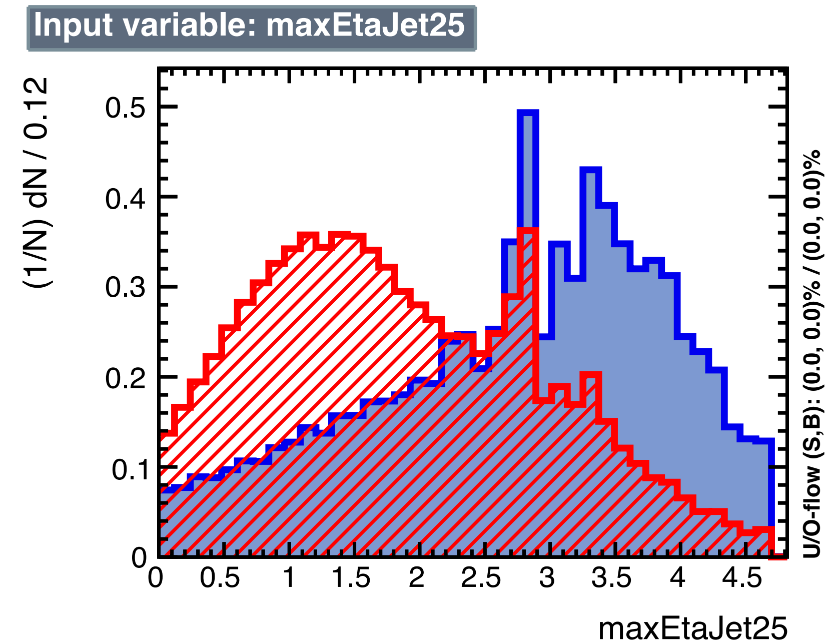


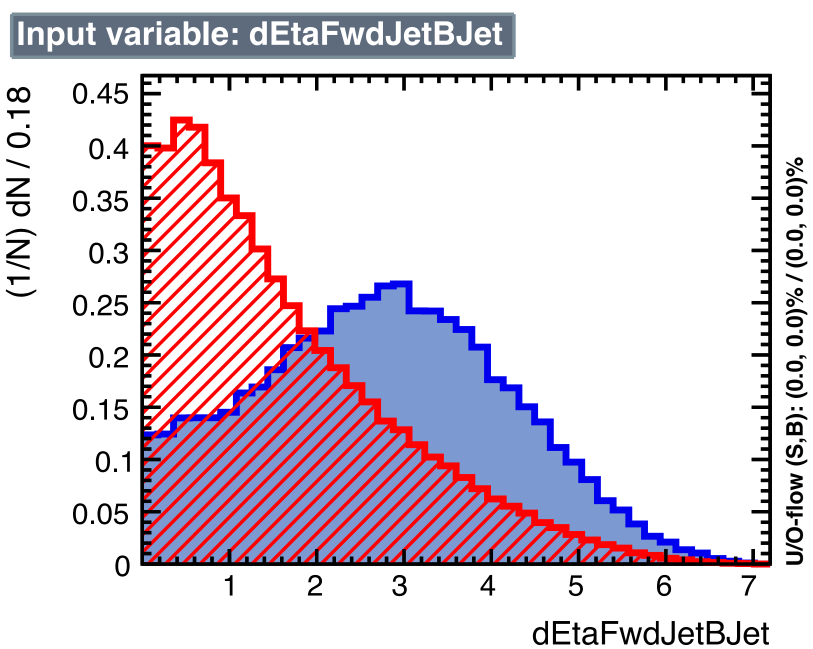


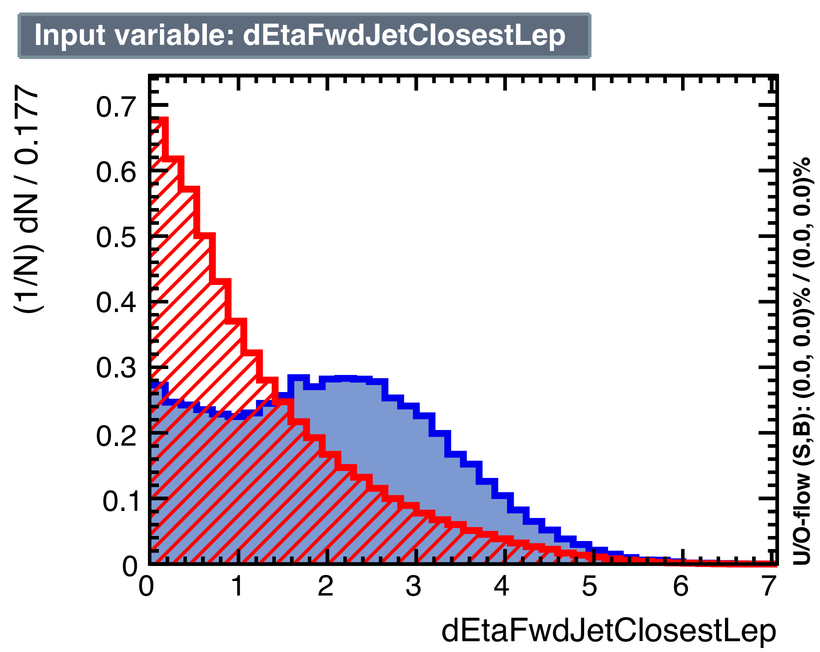
Input variables for ttV BDT: 2lss

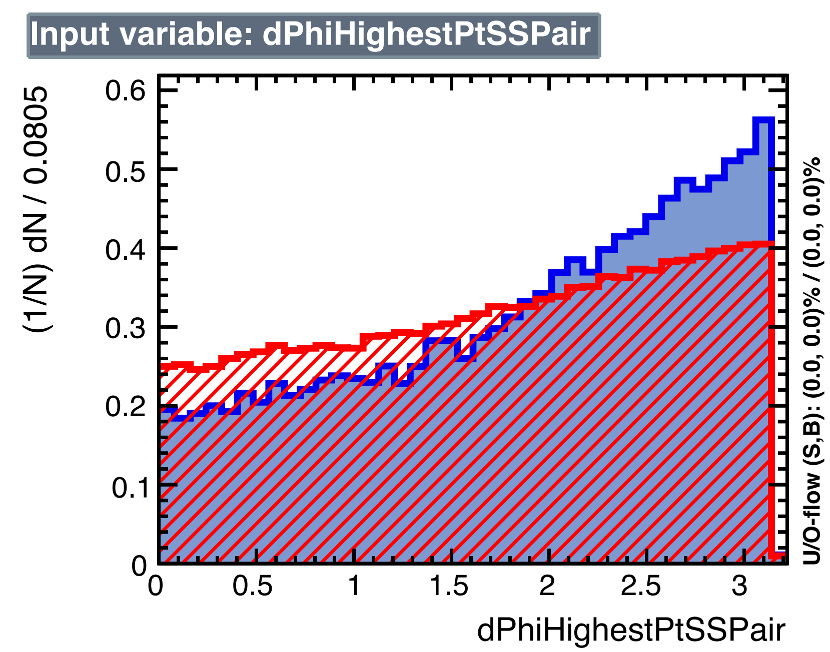




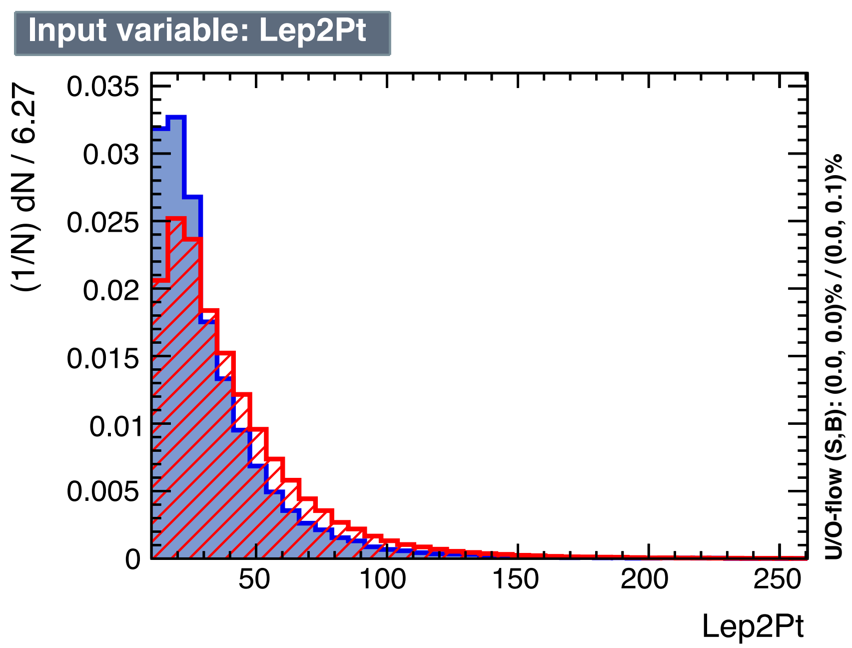


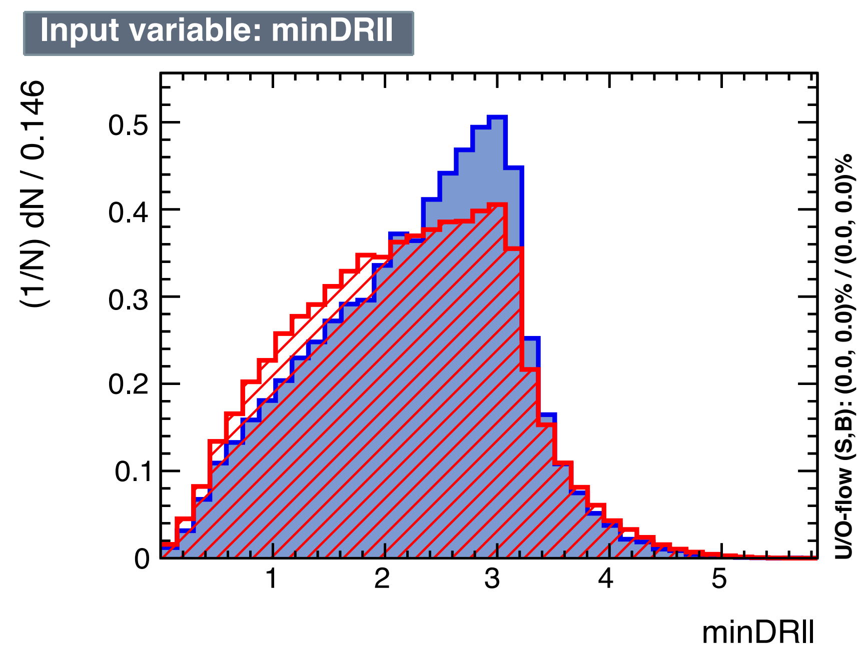


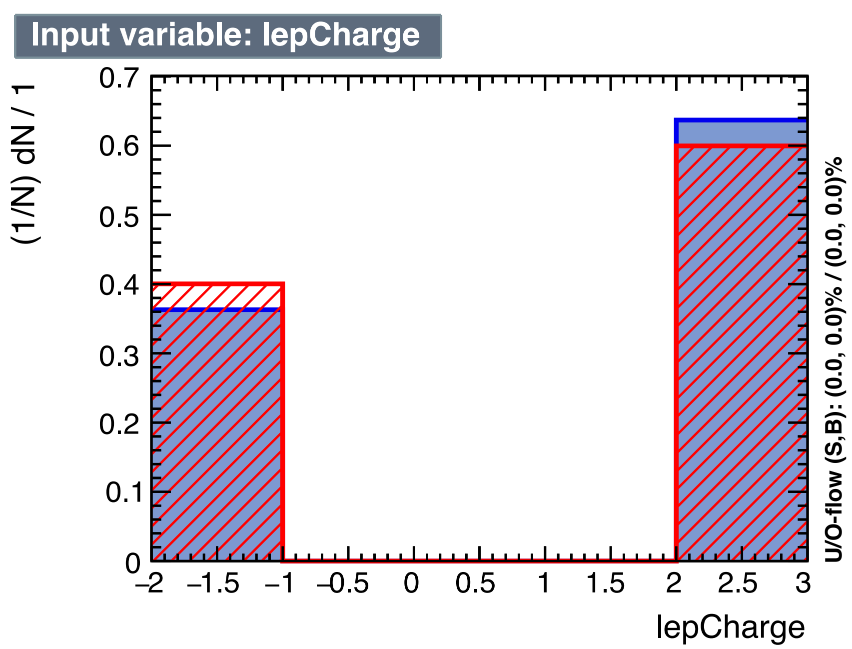


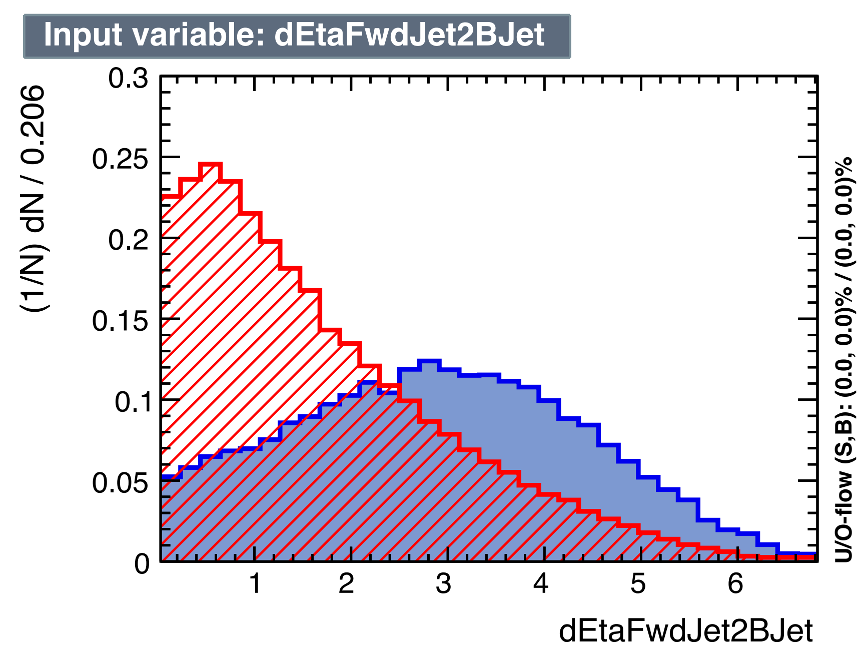


Input variables for ttV BDT: 2lss

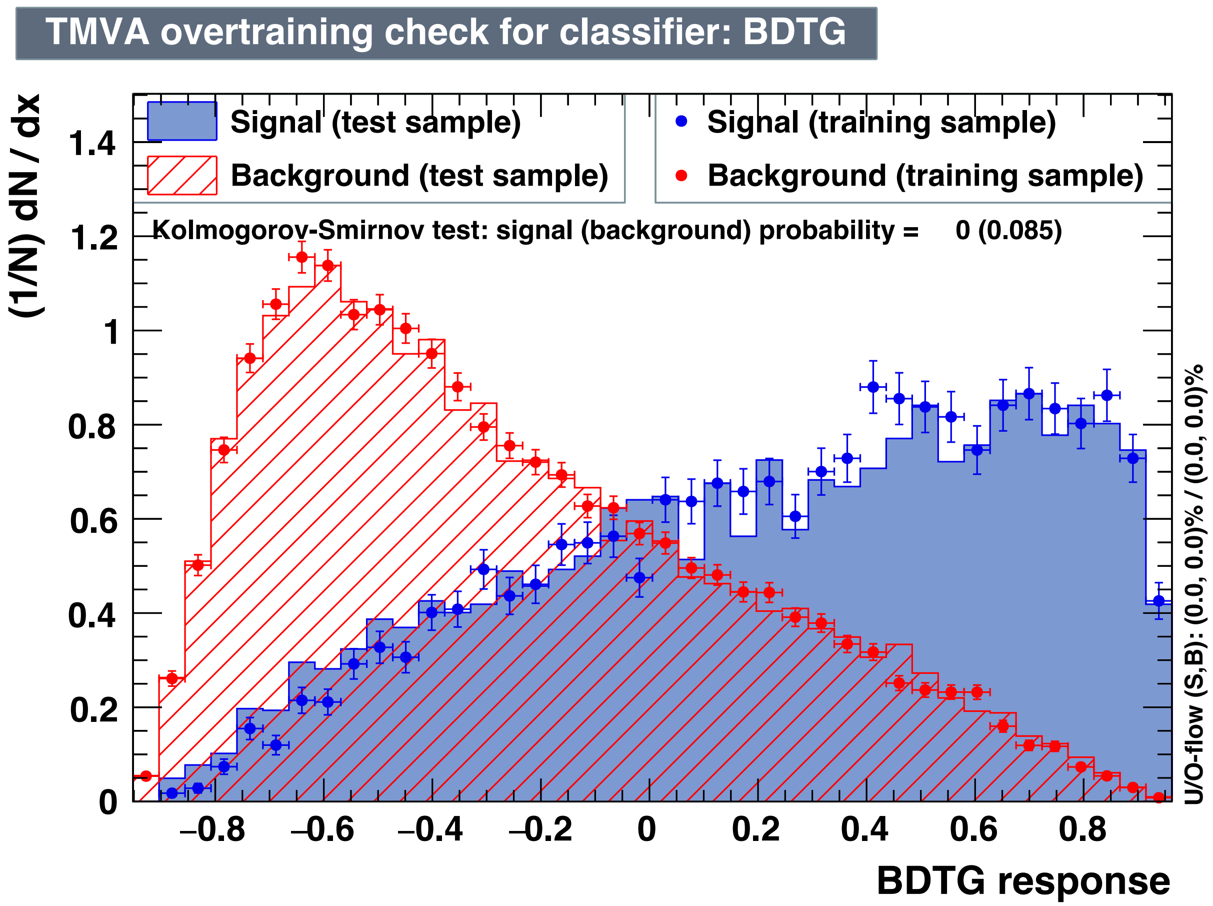


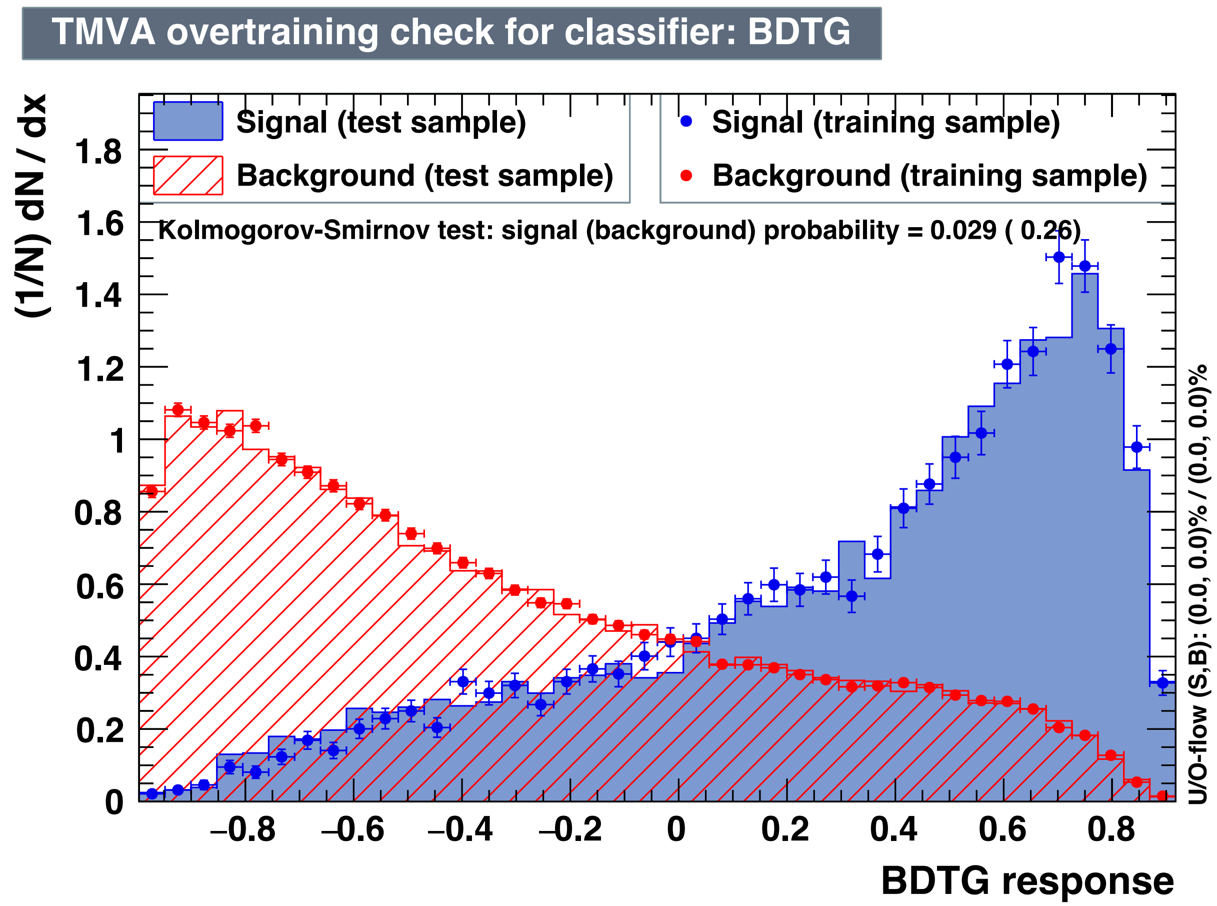




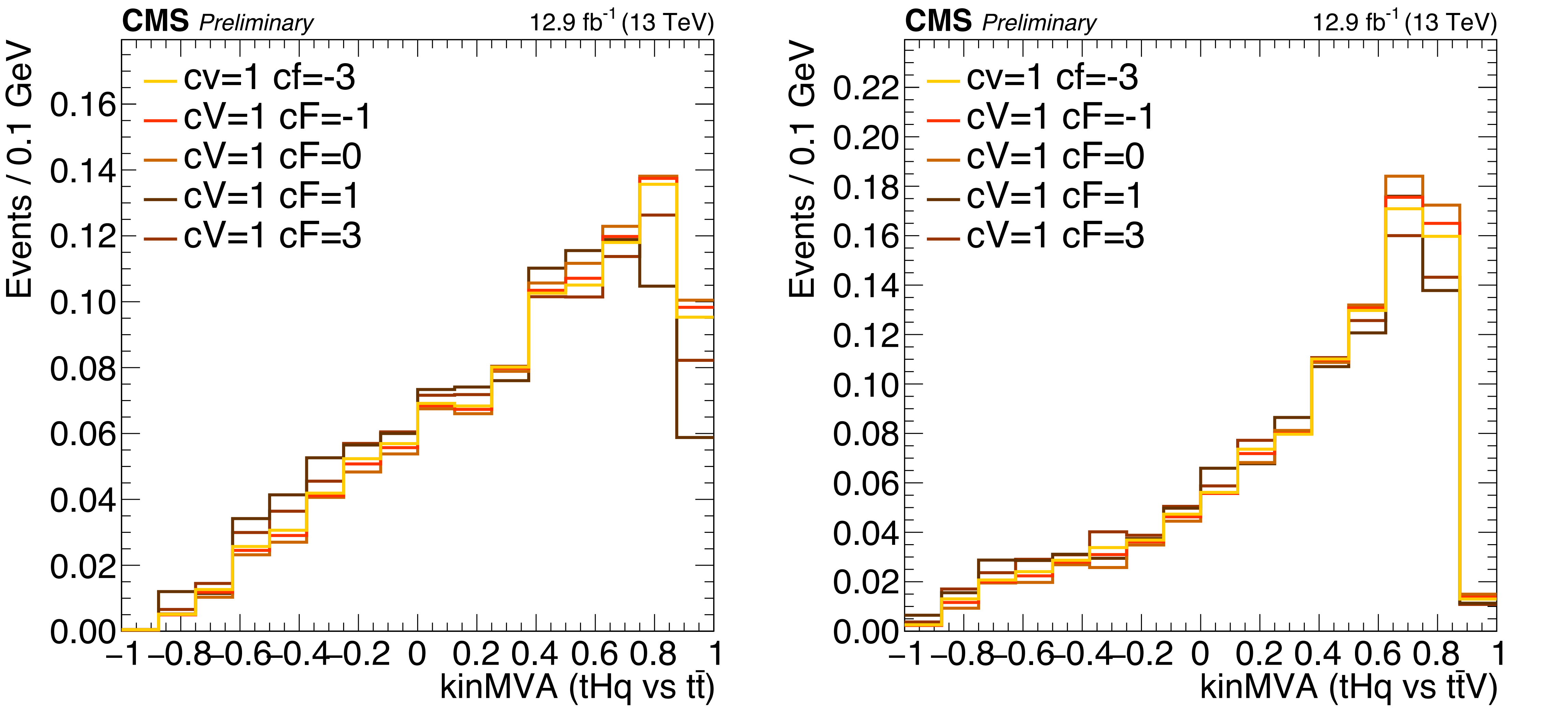


BDT training: 3l





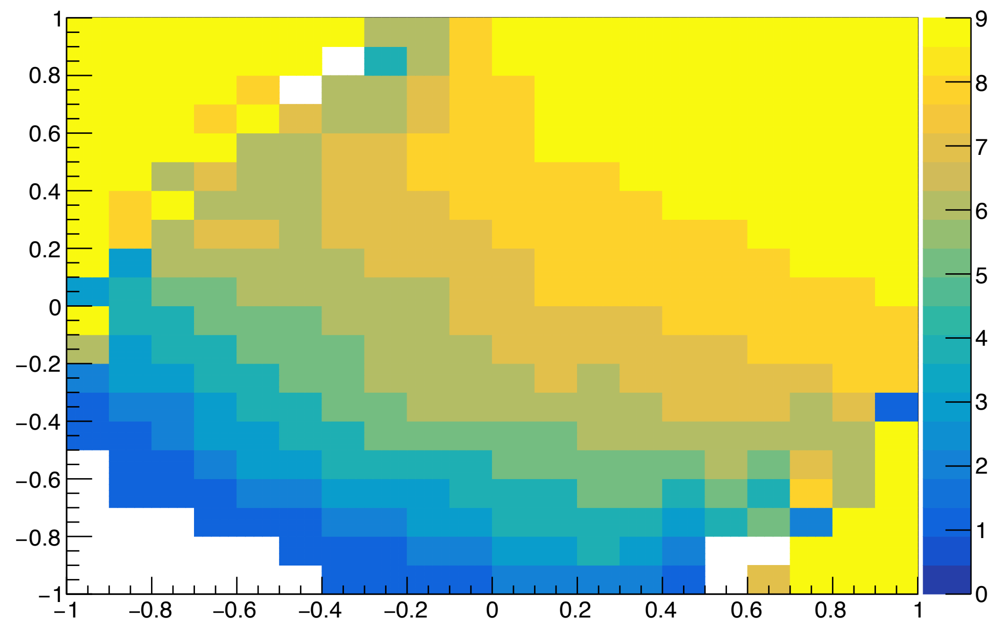
kinMVA variations with coupling



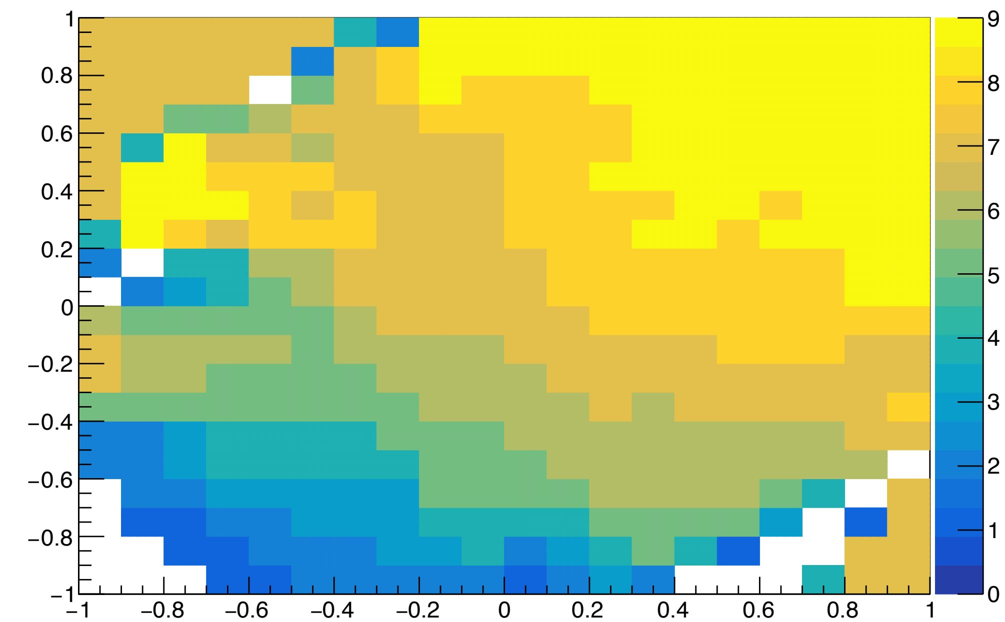
- Change in the BDT output (3l) when varying the coupling. There is variation in shape.

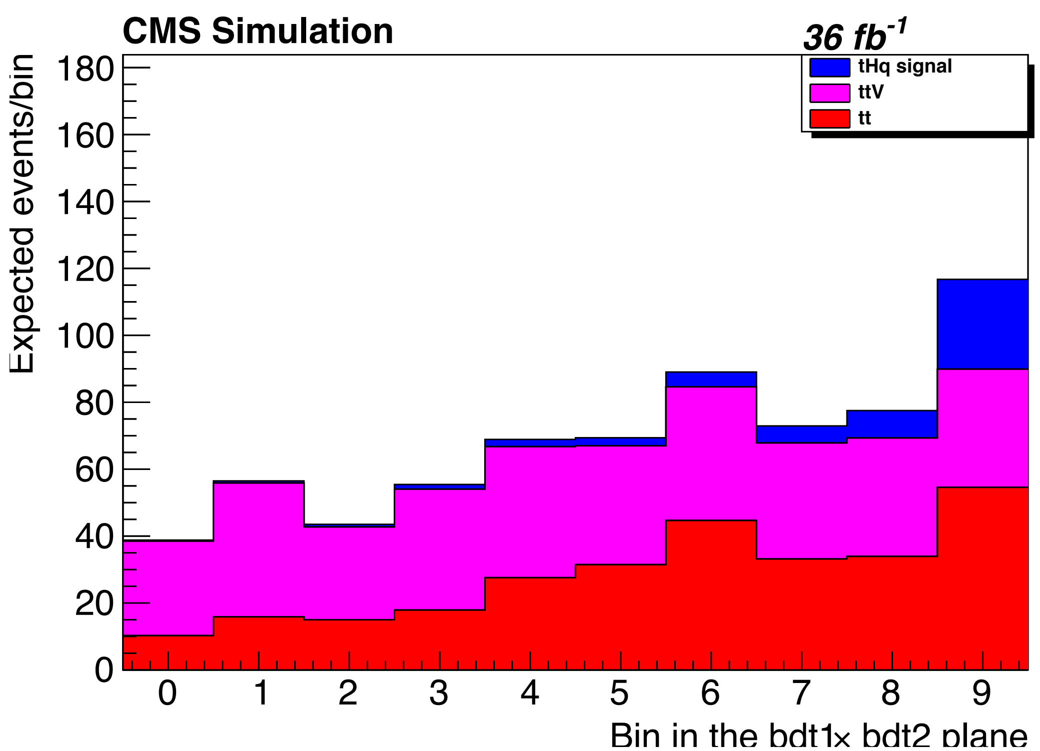
Other binning strategies

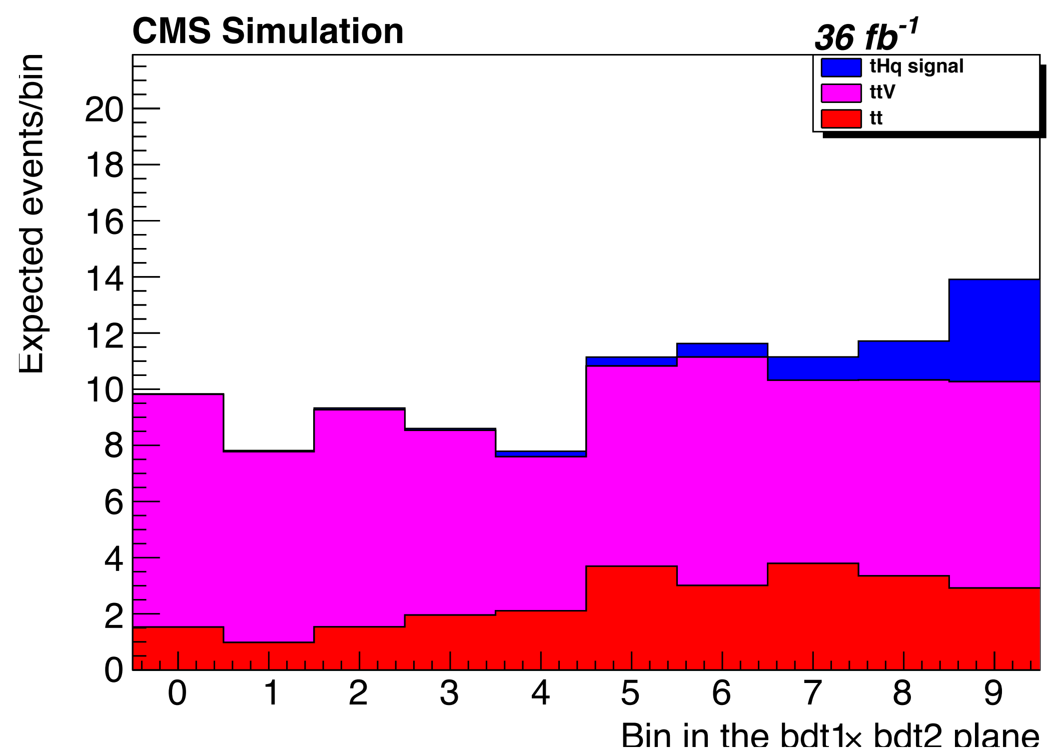
2lss



3l

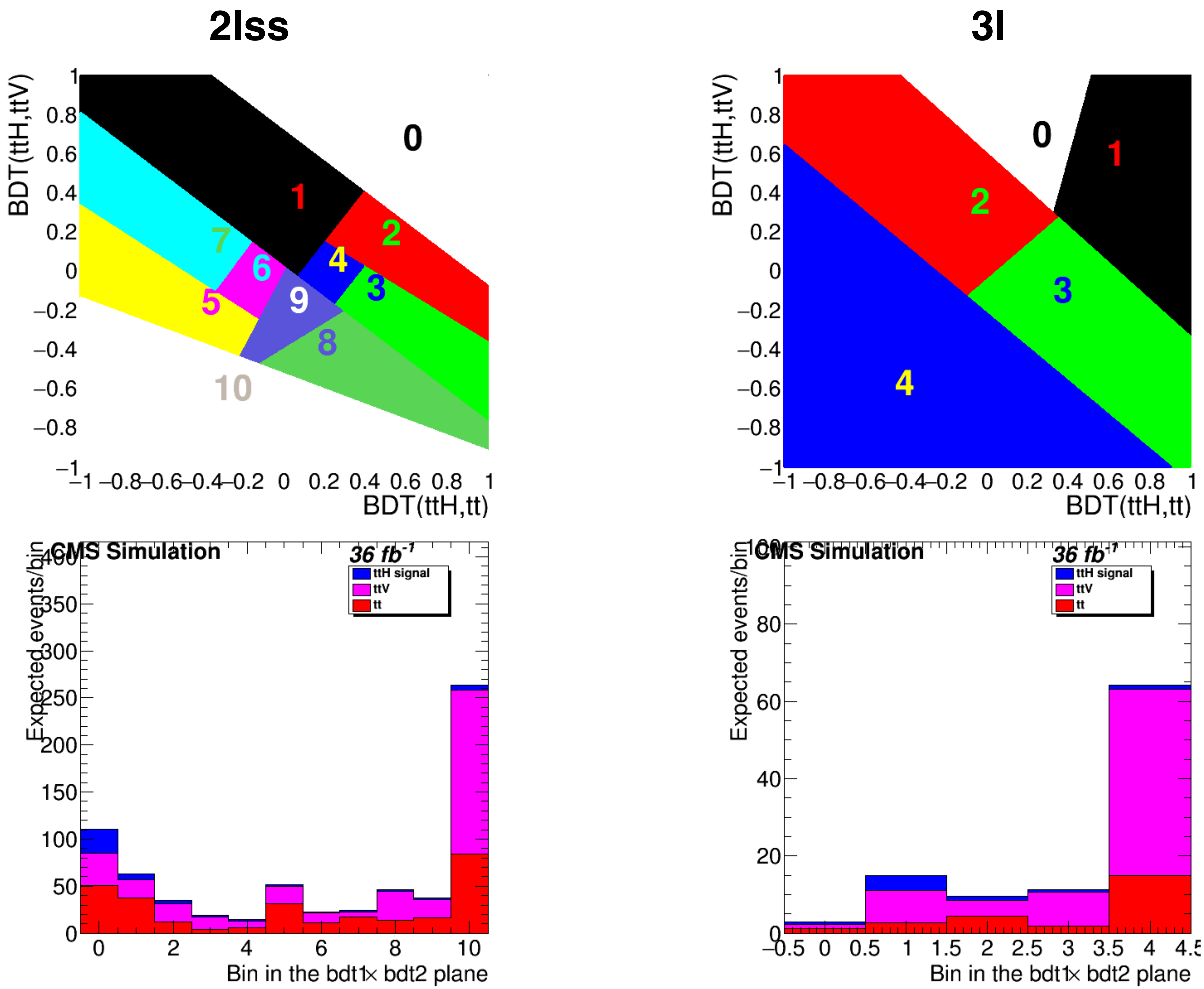






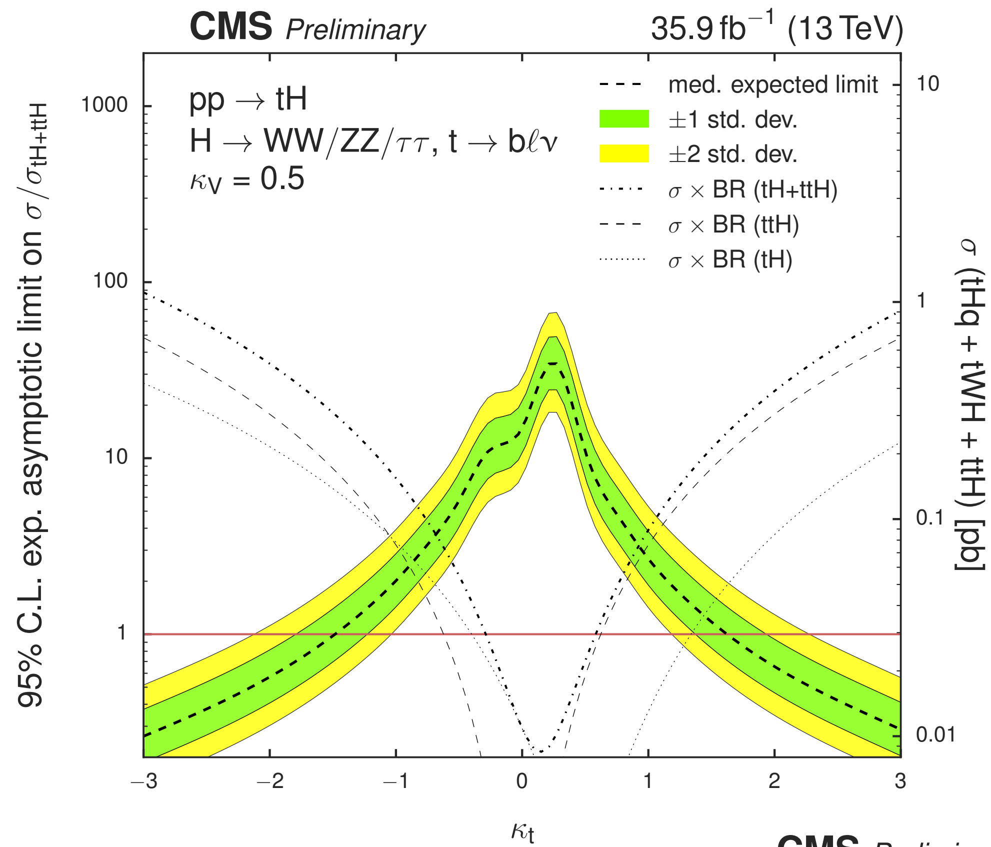
- S/B clustering: binning corresponding to regions where S/B is within a certain range

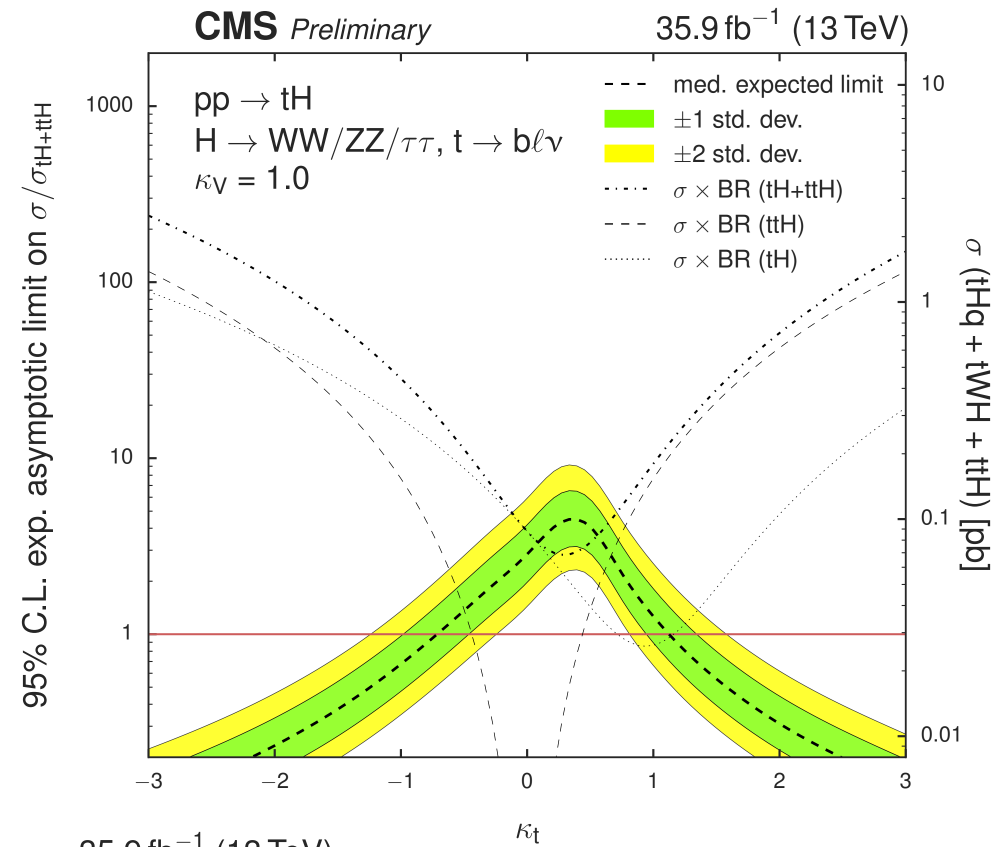
Other binning strategies

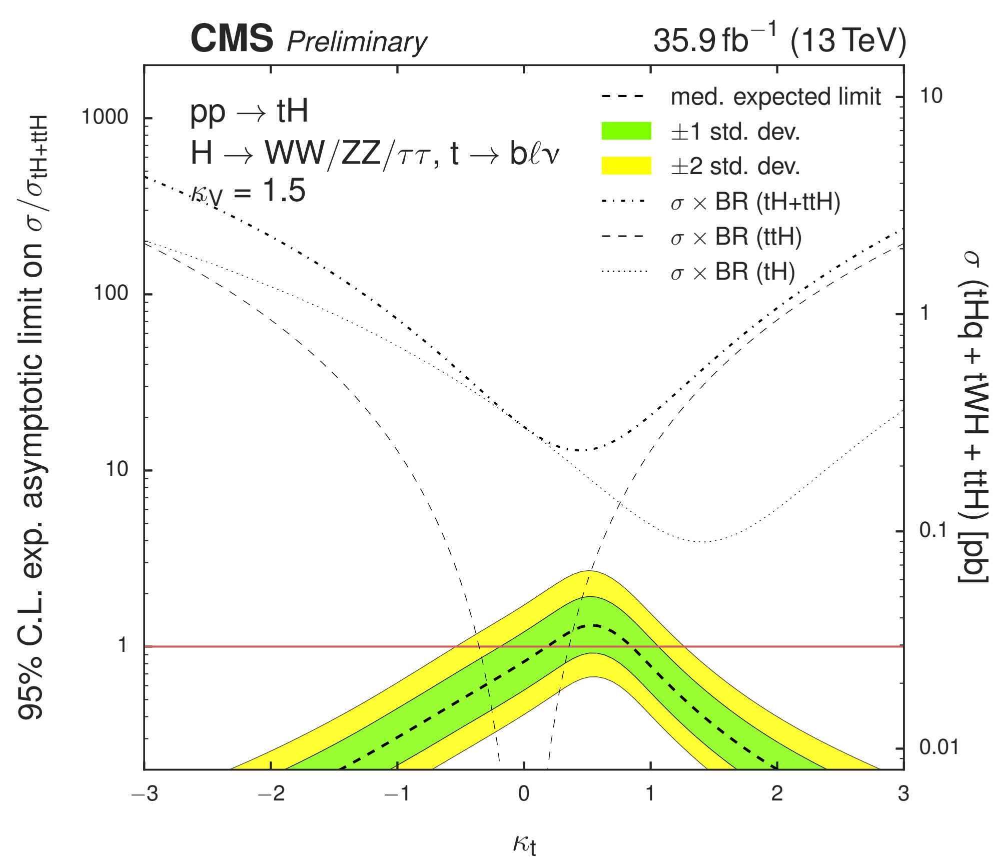


- k-Means clustering: k-Means algorithm to separate the 2D plane into geometric regions

Expected (no Higgs) limit on signal strength r as a function of κ_t







Signal yields split by decay channels

	3ℓ		$\mu\mu$	
tHq(Inclusive)	**6.57**	100.0%	**17.38**	100.0%
tHq($H \to WW$)	4.84	73.9%	13.33	76.9%
tHq($H \to \tau\tau$)	1.04	15.9%	3.62	20.6%
tHq($H \to ZZ$)	0.48	7.2%	0.37	2.2%
tHq($H \to \mu\mu$)	0.21	3.0%	0.04	0.2%
tHq($H \to \gamma\gamma$)	< 0.01	0.1%	0.02	0.1%
tHq($H \to bb$)	< 0.01	$< 0.1\%$	0.01	$< 0.1\%$
tHW(Inclusive)	**7.32**	100.0%	**7.62**	100.0%
tHW($H \to WW$)	5.50	76.9%	5.60	74.1%
tHW($H \to \tau\tau$)	1.40	20.6%	1.81	23.1%
tHW($H \to ZZ$)	0.31	2.2%	0.21	2.7%
tHW($H \to \mu\mu$)	0.12	0.2%	0.01	0.1%
tHW($H \to \gamma\gamma$)	< 0.01	$< 0.1\%$	< 0.01	$< 0.1\%$
tHW($H \to bb$)	< 0.01	$< 0.1\%$	< 0.01	$< 0.1\%$

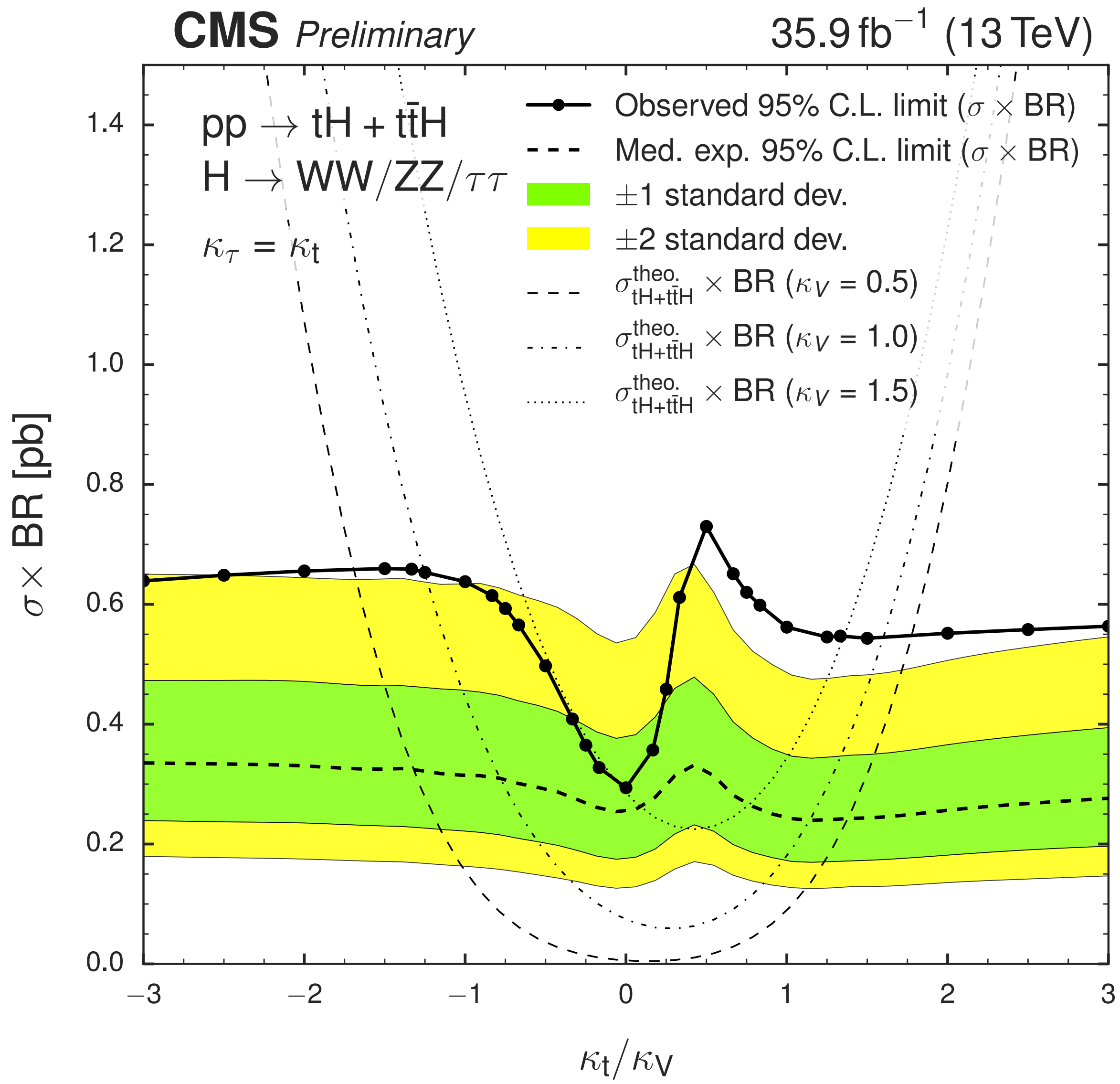
Scaling of cross section times BR

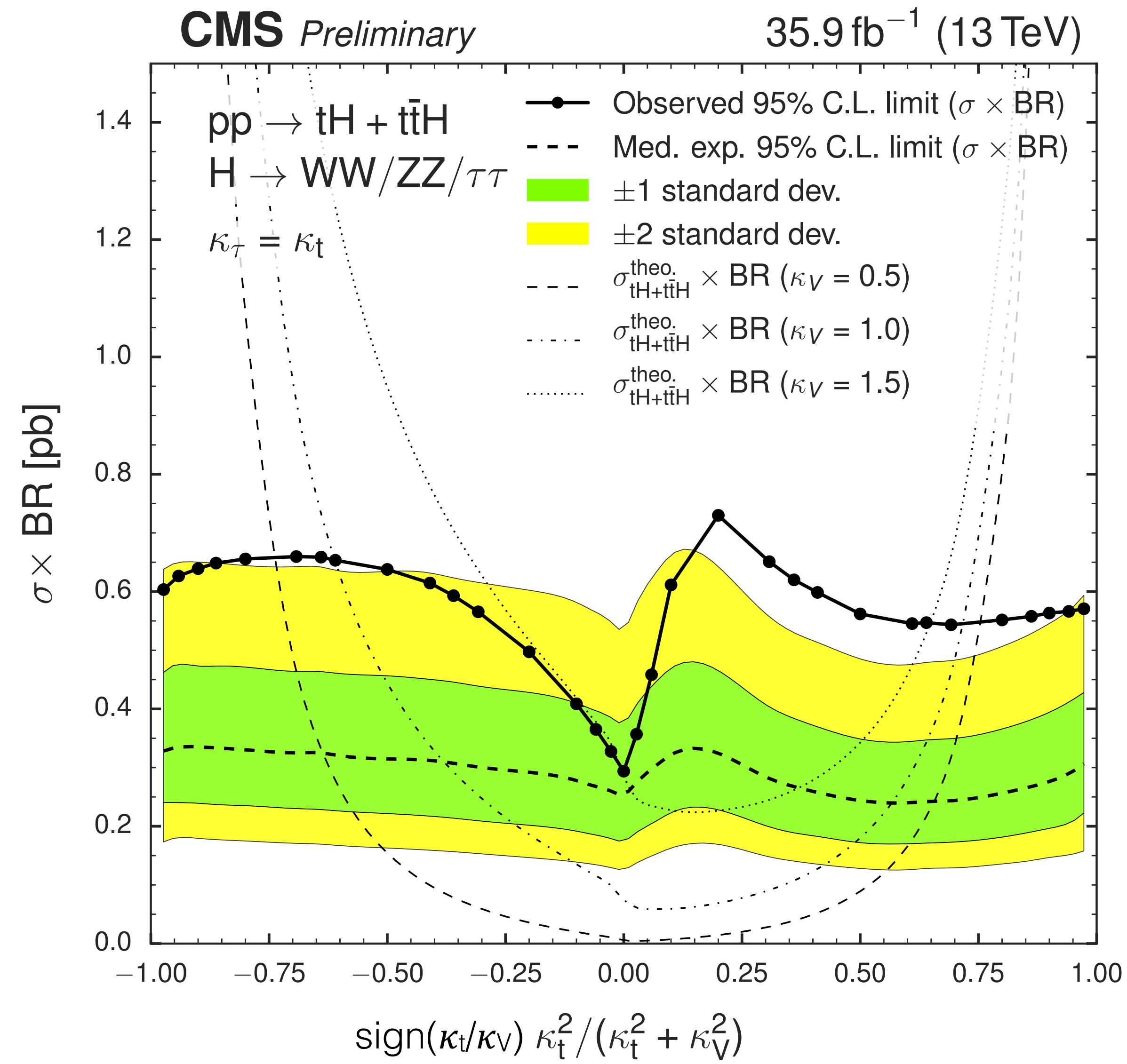
κ_V	κ_t	ttHWW	ttHZZ	ttH$\tau\tau$	tHqWW	tHqZZ	tHq$\tau\tau$	tHWWW	tHWZZ	tHW$\tau\tau$
1.0	-6.0	11.2408	11.2408	404.6686	40.4768	40.4768	1457.1666	41.3681	41.3681	1489.2533
1.0	-4.0	8.2305	8.2305	131.6886	34.2339	34.2339	547.7422	33.8480	33.8480	541.5676
1.0	-3.0	5.9862	5.9862	53.8759	28.5396	28.5396	256.8562	27.3983	27.3983	246.5850
1.0	-2.5	4.6979	4.6979	29.3616	24.8511	24.8511	155.3195	23.3557	23.3557	145.9734
1.0	-2.0	3.3647	3.3647	13.4590	20.6360	20.6360	82.5440	18.8497	18.8497	75.3987
1.0	-1.5	2.0859	2.0859	4.6933	16.0557	16.0557	36.1254	14.0919	14.0919	31.7068
1.0	-1.333	1.6941	1.6941	3.0102	14.4942	14.4942	25.7545	12.5059	12.5059	22.2216
1.0	-1.25	1.5091	1.5091	2.3579	13.7201	13.7201	21.4377	11.7273	11.7273	18.3239
1.0	-1.0	1.0000	1.0000	1.0000	11.4220	11.4220	11.4220	9.4484	9.4484	9.4484
1.0	-0.833	0.7075	0.7075	0.4909	9.9372	9.9372	6.8953	8.0059	8.0059	5.5552
1.0	-0.75	0.5784	0.5784	0.3254	9.2212	9.2212	5.1869	7.3200	7.3200	4.1175
1.0	-0.667	0.4610	0.4610	0.2051	8.5229	8.5229	3.7917	6.6579	6.6579	2.9620
1.0	-0.5	0.2624	0.2624	0.0656	7.1807	7.1807	1.7952	5.4076	5.4076	1.3519
1.0	-0.333	0.1175	0.1175	0.0130	5.9375	5.9375	0.6584	4.2814	4.2814	0.4748
1.0	-0.25	0.0664	0.0664	0.0042	5.3616	5.3616	0.3351	3.7730	3.7730	0.2358
1.0	-0.167	0.0297	0.0297	0.0008	4.8163	4.8163	0.1343	3.3009	3.3009	0.0921
1.0	0.0	0.0000	0.0000	0.0000	3.8183	3.8183	0.0000	2.4676	2.4676	0.0000
1.0	0.167	0.0297	0.0297	0.0008	2.9624	2.9624	0.0826	1.7981	1.7981	0.0501
1.0	0.25	0.0664	0.0664	0.0042	2.5928	2.5928	0.1620	1.5284	1.5284	0.0955
1.0	0.333	0.1175	0.1175	0.0130	2.2612	2.2612	0.2507	1.3014	1.3014	0.1443
1.0	0.5	0.2624	0.2624	0.0656	1.7115	1.7115	0.4279	0.9742	0.9742	0.2435
1.0	0.667	0.4610	0.4610	0.2051	1.3198	1.3198	0.5871	0.8188	0.8188	0.3643
1.0	0.75	0.5784	0.5784	0.3254	1.1834	1.1834	0.6657	0.8042	0.8042	0.4524
1.0	0.833	0.7075	0.7075	0.4909	1.0852	1.0852	0.7530	0.8301	0.8301	0.5760
1.0	1.0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
1.0	1.25	1.5091	1.5091	2.3579	1.1380	1.1380	1.7782	1.5278	1.5278	2.3872
1.0	1.333	1.6941	1.6941	3.0102	1.2492	1.2492	2.2197	1.7691	1.7691	3.1434
1.0	1.5	2.0859	2.0859	4.6933	1.5628	1.5628	3.5163	2.3434	2.3434	5.2727
1.0	2.0	3.3647	3.3647	13.4590	3.1023	3.1023	12.4092	4.6362	4.6362	18.5449
1.0	2.5	4.6979	4.6979	29.3616	5.2667	5.2667	32.9167	7.4799	7.4799	46.7493
1.0	3.0	5.9862	5.9862	53.8759	7.7435	7.7435	69.6914	10.5403	10.5403	94.8625
1.0	4.0	8.2305	8.2305	131.6886	12.7892	12.7892	204.6276	16.4642	16.4642	263.4266
1.0	6.0	11.2408	11.2408	404.6686	20.9516	20.9516	754.2573	25.5403	25.5403	919.4497

Best fit signal strength

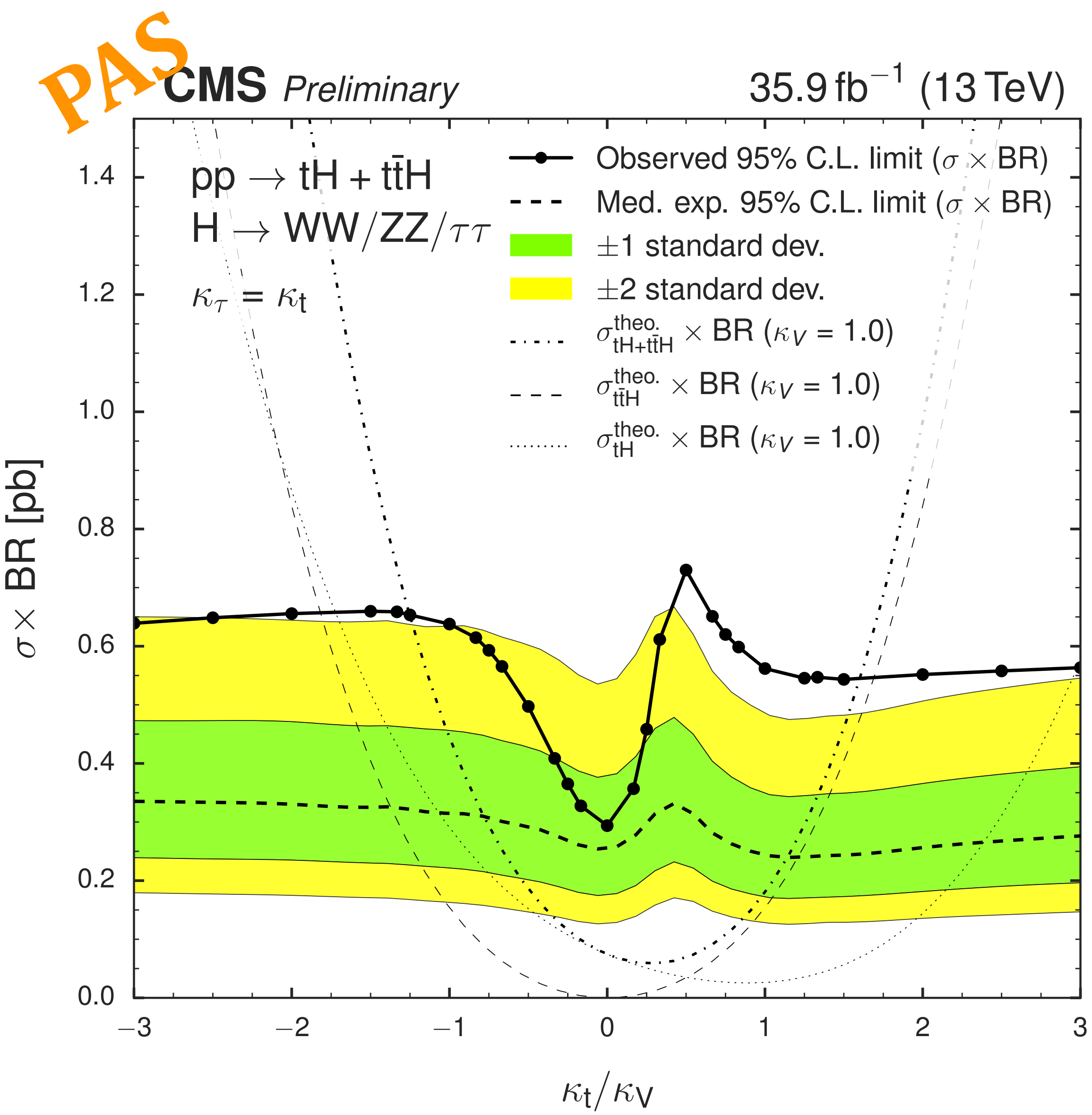
f_t	κ_t/κ_V	Exp. lim.	SM exp.	Obs. lim.	Best fit σ [pb]	Best fit r
-0.973	-6.000	$0.328^{+0.136}_{-0.090}$	$0.507^{+0.206}_{-0.158}$	0.603	$0.305^{+0.155}_{-0.169}$	$0.013^{+0.007}_{-0.007}$
-0.941	-4.000	$0.335^{+0.137}_{-0.098}$	$0.509^{+0.215}_{-0.166}$	0.627	$0.322^{+0.157}_{-0.174}$	$0.036^{+0.018}_{-0.020}$
-0.900	-3.000	$0.335^{+0.138}_{-0.096}$	$0.510^{+0.215}_{-0.172}$	0.639	$0.334^{+0.160}_{-0.173}$	$0.075^{+0.036}_{-0.039}$
-0.862	-2.500	$0.334^{+0.139}_{-0.097}$	$0.505^{+0.217}_{-0.173}$	0.649	$0.341^{+0.160}_{-0.174}$	$0.119^{+0.056}_{-0.061}$
-0.800	-2.000	$0.330^{+0.141}_{-0.095}$	$0.500^{+0.212}_{-0.176}$	0.656	$0.345^{+0.165}_{-0.176}$	$0.202^{+0.097}_{-0.103}$
-0.692	-1.500	$0.325^{+0.139}_{-0.095}$	$0.485^{+0.209}_{-0.172}$	0.660	$0.340^{+0.164}_{-0.176}$	$0.369^{+0.178}_{-0.191}$
-0.640	-1.333	$0.325^{+0.139}_{-0.097}$	$0.482^{+0.210}_{-0.173}$	0.659	$0.334^{+0.169}_{-0.174}$	$0.456^{+0.231}_{-0.238}$
-0.610	-1.250	$0.321^{+0.140}_{-0.095}$	$0.474^{+0.210}_{-0.169}$	0.653	$0.328^{+0.164}_{-0.177}$	$0.505^{+0.252}_{-0.272}$
-0.500	-1.000	$0.315^{+0.142}_{-0.093}$	$0.450^{+0.213}_{-0.160}$	0.638	$0.304^{+0.175}_{-0.176}$	$0.685^{+0.395}_{-0.396}$
-0.410	-0.833	$0.312^{+0.138}_{-0.095}$	$0.424^{+0.210}_{-0.147}$	0.615	$0.276^{+0.168}_{-0.177}$	$0.819^{+0.498}_{-0.526}$
-0.360	-0.750	$0.307^{+0.138}_{-0.093}$	$0.409^{+0.200}_{-0.136}$	0.593	$0.256^{+0.170}_{-0.176}$	$0.874^{+0.581}_{-0.601}$
-0.308	-0.667	$0.301^{+0.138}_{-0.092}$	$0.384^{+0.198}_{-0.124}$	0.566	$0.231^{+0.165}_{-0.174}$	$0.915^{+0.655}_{-0.689}$
-0.200	-0.500	$0.292^{+0.136}_{-0.090}$	$0.345^{+0.181}_{-0.109}$	0.497	$0.166^{+0.163}_{-0.162}$	$0.895^{+0.879}_{-0.871}$
-0.100	-0.333	$0.278^{+0.132}_{-0.086}$	$0.303^{+0.156}_{-0.092}$	0.409	$0.092^{+0.157}_{-0.092}$	$0.679^{+1.159}_{-0.679}$
-0.059	-0.250	$0.268^{+0.129}_{-0.083}$	$0.283^{+0.152}_{-0.085}$	0.365	$0.059^{+0.148}_{-0.059}$	$0.515^{+1.285}_{-0.515}$
-0.027	-0.167	$0.260^{+0.125}_{-0.081}$	$0.266^{+0.135}_{-0.077}$	0.328	$0.029^{+0.142}_{-0.029}$	$0.297^{+1.434}_{-0.297}$
0.000	0.000	$0.254^{+0.123}_{-0.079}$	$0.252^{+0.123}_{-0.073}$	0.294	$0.000^{+0.132}_{-0.000}$	$0.002^{+1.776}_{-0.002}$
0.027	0.167	$0.275^{+0.132}_{-0.086}$	$0.284^{+0.148}_{-0.084}$	0.357	$0.040^{+0.154}_{-0.040}$	$0.650^{+2.514}_{-0.650}$
0.059	0.250	$0.297^{+0.141}_{-0.093}$	$0.329^{+0.171}_{-0.099}$	0.458	$0.119^{+0.183}_{-0.119}$	$2.015^{+3.098}_{-2.015}$
0.100	0.333	$0.322^{+0.148}_{-0.099}$	$0.405^{+0.220}_{-0.135}$	0.611	$0.246^{+0.166}_{-0.184}$	$4.147^{+2.802}_{-3.103}$
0.200	0.500	$0.324^{+0.141}_{-0.096}$	$0.505^{+0.212}_{-0.181}$	0.730	$0.413^{+0.150}_{-0.177}$	$5.982^{+2.174}_{-2.559}$
0.308	0.667	$0.281^{+0.122}_{-0.082}$	$0.462^{+0.172}_{-0.159}$	0.651	$0.382^{+0.136}_{-0.144}$	$4.186^{+1.492}_{-1.574}$
0.360	0.750	$0.268^{+0.116}_{-0.079}$	$0.442^{+0.160}_{-0.154}$	0.620	$0.364^{+0.130}_{-0.135}$	$3.392^{+1.214}_{-1.253}$
0.410	0.833	$0.258^{+0.112}_{-0.075}$	$0.427^{+0.162}_{-0.147}$	0.599	$0.351^{+0.127}_{-0.130}$	$2.754^{+0.999}_{-1.022}$
0.500	1.000	$0.244^{+0.105}_{-0.072}$	$0.401^{+0.154}_{-0.137}$	0.562	$0.328^{+0.118}_{-0.121}$	$1.821^{+0.657}_{-0.671}$
0.610	1.250	$0.240^{+0.104}_{-0.070}$	$0.394^{+0.154}_{-0.133}$	0.545	$0.315^{+0.118}_{-0.119}$	$1.072^{+0.399}_{-0.403}$
0.640	1.333	$0.242^{+0.105}_{-0.071}$	$0.398^{+0.156}_{-0.136}$	0.547	$0.316^{+0.122}_{-0.121}$	$0.921^{+0.354}_{-0.352}$
0.692	1.500	$0.244^{+0.106}_{-0.071}$	$0.401^{+0.159}_{-0.136}$	0.543	$0.312^{+0.120}_{-0.120}$	$0.678^{+0.262}_{-0.261}$
0.800	2.000	$0.256^{+0.109}_{-0.075}$	$0.416^{+0.169}_{-0.138}$	0.552	$0.311^{+0.121}_{-0.127}$	$0.317^{+0.123}_{-0.129}$
0.862	2.500	$0.268^{+0.114}_{-0.078}$	$0.433^{+0.169}_{-0.142}$	0.558	$0.310^{+0.127}_{-0.130}$	$0.170^{+0.070}_{-0.072}$
0.900	3.000	$0.276^{+0.118}_{-0.080}$	$0.442^{+0.177}_{-0.144}$	0.563	$0.308^{+0.128}_{-0.134}$	$0.102^{+0.042}_{-0.044}$
0.941	4.000	$0.290^{+0.122}_{-0.084}$	$0.459^{+0.184}_{-0.149}$	0.566	$0.304^{+0.134}_{-0.140}$	$0.046^{+0.020}_{-0.021}$
0.973	6.000	$0.306^{+0.122}_{-0.081}$	$0.474^{+0.192}_{-0.150}$	0.571	$0.300^{+0.131}_{-0.150}$	$0.016^{+0.007}_{-0.008}$

Expected (no Higgs) and observed limit on cross section times branching ratio

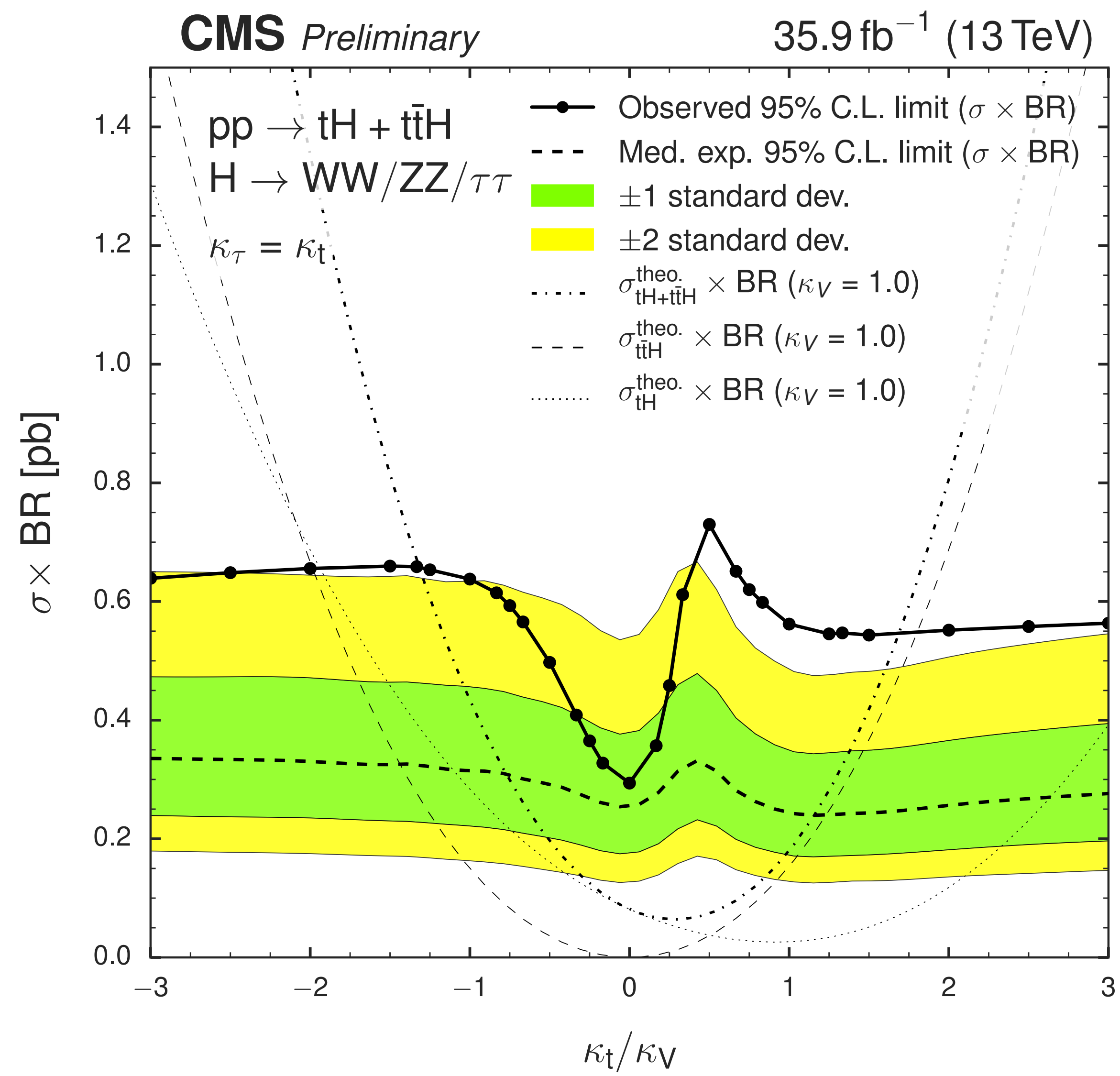




Expected (no Higgs) and observed limit on cross section times branching ratio



H→gg/γγ/Zγ not resolved



H→gg/γγ/Zγ resolved

Overlap of ttH and (tHq+tHW)

Channel	tHq	$t\bar{t}$H
3l	Z veto, 15 GeV	Z veto, 10 GeV
	$N_{\text{jets}}^{\text{b, med.}} \geq 1$	$N_{\text{jets}}^{\text{b, med.}} \geq 1$ OR $N_{\text{jets}}^{\text{b, loose}} \geq 2$
	≥ 1 un-tagged jet	$E_{\text{T}}^{\text{miss}}{}_{\text{LD}} > 0.2$ OR $N_{\text{jets}}^{\text{centrl.}} \geq 4$
2lss	$N_{\text{jets}}^{\text{b, med.}} \geq 1$	$N_{\text{jets}}^{\text{b, med.}} \geq 1$ OR $N_{\text{jets}}^{\text{b, loose}} \geq 2$
	≥ 1 un-tagged jet	$N_{\text{jets}}^{\text{central}} \geq 4$

tHq **sample**	tHq	$t\bar{t}$H	Common	(% tHq)	(% $t\bar{t}$H)
$\mu^\pm\mu^\pm$	7400	2353	2166	29.3	92.1
$e^\pm\mu^\pm$	11158	3600	3321	29.8	92.2
$e^\pm e^\pm$	3550	1106	1025	28.9	92.7
$\ell\ell\ell$	3115	2923	2347	75.3	80.3

$t\bar{t}$H **sample**	tHq	$t\bar{t}$H	Common	(% tHq)	(% $t\bar{t}$H)
$\mu^\pm\mu^\pm$	32612	28703	26547	81.4	92.5
$e^\pm\mu^\pm$	48088	42521	39164	81.4	92.1
$e^\pm e^\pm$	15476	12869	11896	76.9	92.4
$\ell\ell\ell$	26627	30598	25288	95.0	82.6

Data	tHq	$t\bar{t}$H	Common	(% tHq)	(% $t\bar{t}$H)
$\mu^\pm\mu^\pm$	280	160	140	50.0	87.5
$e^\pm\mu^\pm$	525	280	242	46.1	86.4
$e^\pm e^\pm$	208	90	79	38.0	87.8
$\ell\ell\ell$	126	154	104	82.5	67.5