Non-Resonant HH

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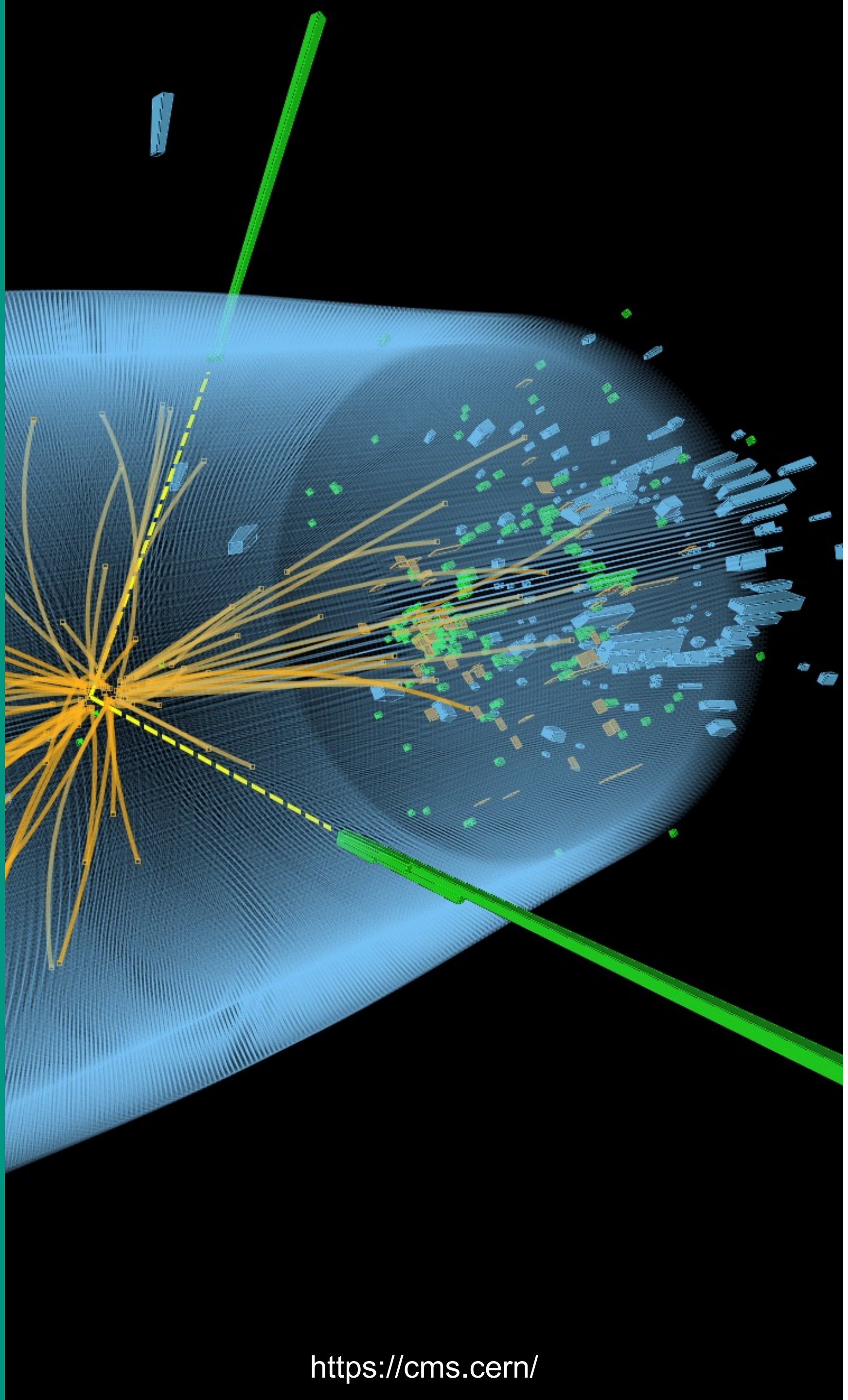

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Motivation for HH

- Probe of the Higgs self-coupling
- Many BSM models predict enhanced non-resonant HH production rates
- Even in the absence of a discovery, setting limits on HH production constrains the parameter space of many BSM theories

- This analysis is based on simulated CMS 2018 UL (Run 2) data

Non-Resonant HH

Processes

- **Processes**
  - Signal Processes
  - Background Processes
- **Object Selection**
  - Cuts & Vetos
  - Control Plots
- **NN Training**
  - Architecture
  - Hyperparameters
  - Confusion Matrices
  - Analysis Shapes
- **Fit**
  - 95 % CL upper limit on signal strength
  - Extrapolation to higher luminosities

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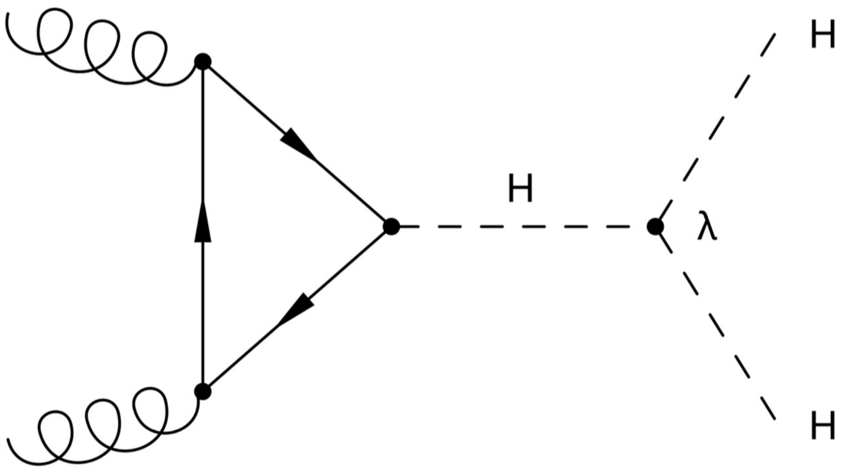
Signal Processes

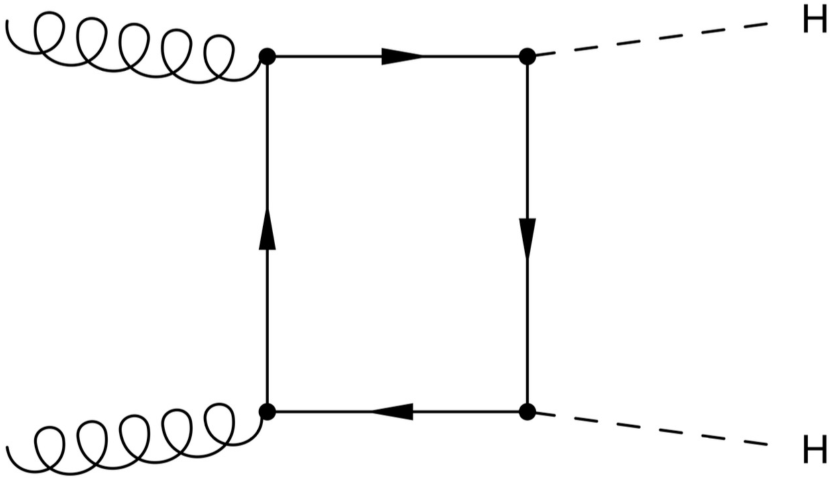
$$\sigma^{SM}(gg \rightarrow H) = 48.5^{+4.6\%}_{-6.7\%} \pm 3.2\% \,(\text{PDF}+\alpha_s)\text{ pb} \quad (\text{N}^3\text{LO})$$

$$\sigma^{SM}(gg \rightarrow HH) = 31.05^{+6\%}_{-23\%} \pm 3\% \,(\text{PDF}+\alpha_s)\text{ fb} \quad (\text{NNLO})$$

→ Difference of a factor ≈ 1500



Destructive interference



Signal Processes

- Search for bb$\tau\tau$ final states
- Branching fraction ≈ 7.3 %
- b quarks reconstructed as b-tagged jets
- $\tau\tau$ final states
  - Full-hadronic final state: $\tau_h\tau_h$
  - Semi-leptonic final states: $e\tau_h$ and $\mu\tau_h$

H boson final states

Decay mode	Branching fraction [%]
$H \to b\bar{b}$	58.2
$H \to WW$	21.5
$H \to gg$	8.2
$H \to \tau^+\tau^-$	6.3
$H \to c\bar{c}$	2.9
$H \to ZZ$	2.6
$H \to \gamma\gamma$	0.23
$H \to Z\gamma$	0.15
$H \to \mu^+\mu^-$	0.022

$\tau\tau$ final states

Final state	Branching fraction [%]
$\tau_h\tau_h$	42.0
$e\tau_h$	23.1
$\mu\tau_h$	22.5
$e\mu$	6.2
ee	3.2
$\mu\mu$	3.0

Background Processes

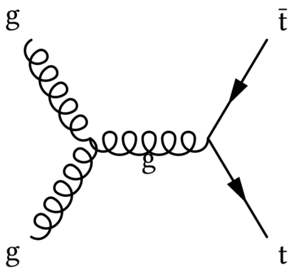
Simulated backgrounds:

- Top quark pair
- Drell-Yan
- Diboson
- Single top quark
- Single Higgs
- Triboson

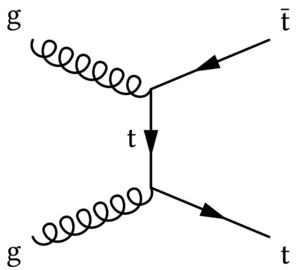
Data driven estimation:

- ABCD method for QCD multijet production

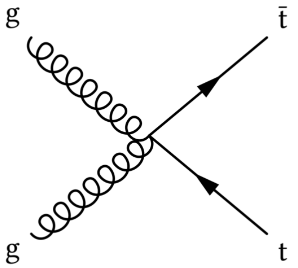
Region	**Charge**	$\tau_{h,1}$ **isolation**	$\tau_{h,2}$ **isolation**
A (target)	OS ($q_1 q_2 < 0$)	Iso	Iso
B (shape)	OS ($q_1 q_2 < 0$)	Iso	Anti-Iso
C (norm)	SS ($q_1 q_2 > 0$)	Iso	Iso
D (norm)	SS ($q_1 q_2 > 0$)	Iso	Anti-Iso



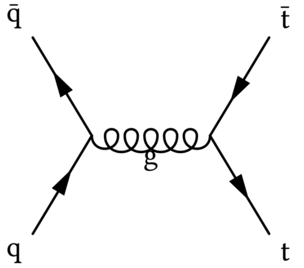
(a) gg $\to$ t$\bar{t}$ (s-channel gluon).



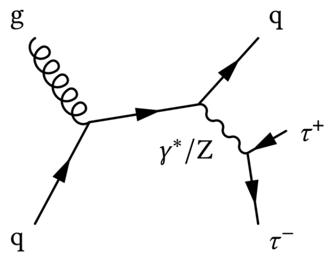
(b) gg $\to$ t$\bar{t}$ (t-channel top exchange).



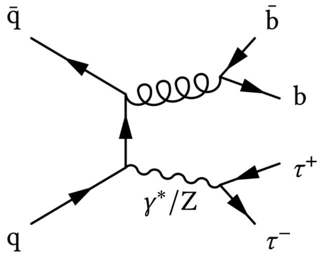
(c) gg $\to$ t$\bar{t}$ (u-channel top exchange).



(d) q$\bar{q}$ $\to$ t$\bar{t}$ (s-channel gluon).



(a) Compton process: qg$\to$ Zq with Z$\to$ $\tau^+\tau^-$.



(b) Z+b$\bar{b}$ from gluon splitting: q$\bar{q}$$\to$ Zg, g$\to$ b$\bar{b}$.

Non-Resonant HH

Object Selection

Processes
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- Cuts
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Fit
- 95 % CL upper limit on signal strength
- Extrapolation to higher luminosities

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Object Selection

- Kinematic cuts
- DeepTau v2.5 for τ_h identification
- DeepJet for identification of b quark-induced jets
  - One b-tagged jet must pass the medium working point
  - The second b-jet is selected as the one with the highest DeepJet score
- Lepton vetos

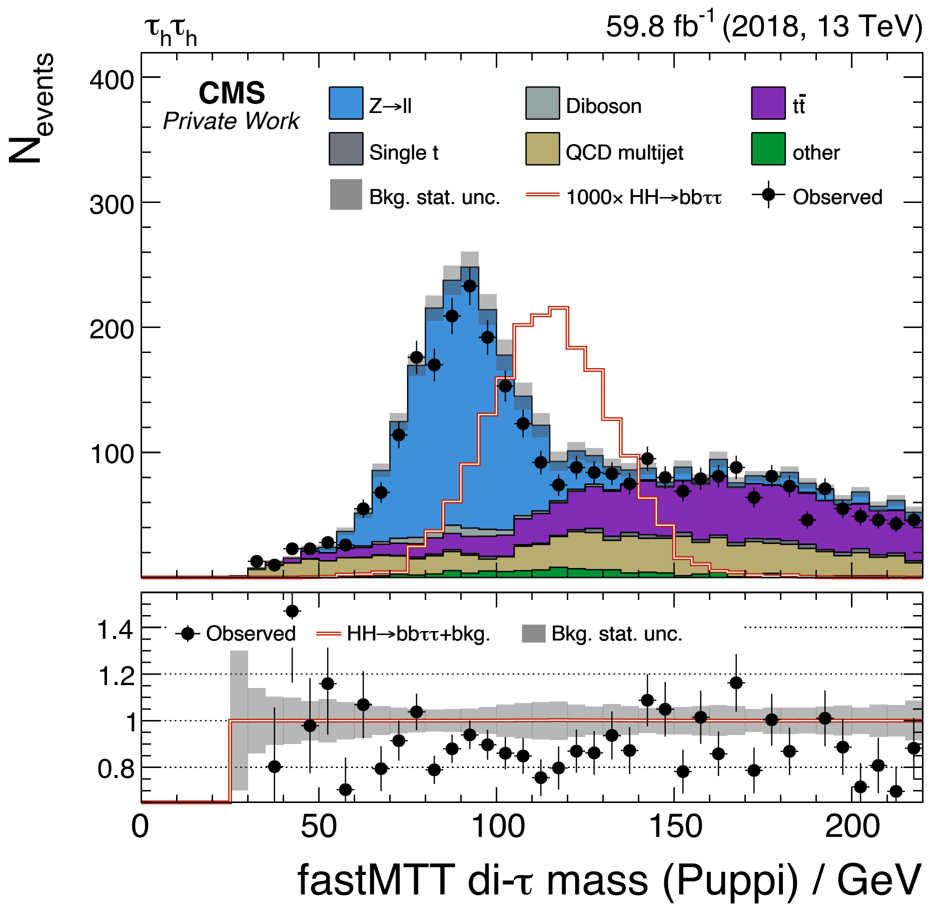
τ_h identification with DeepTau

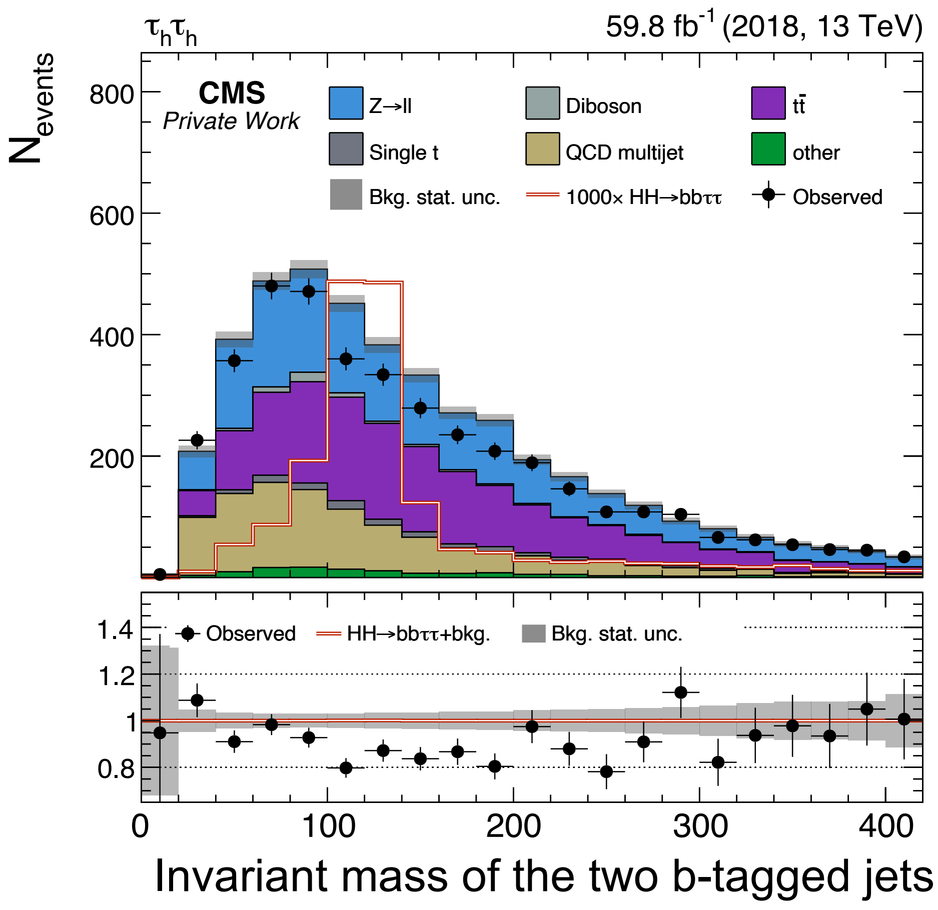
Channel	Object	vsEle	vsMu	vsJet
$e\tau_\mathrm{h}$	τ_h	Tight	VLoose	Medium
$\mu\tau_\mathrm{h}$	τ_h	VVLoose	Tight	Medium
$\tau_\mathrm{h}\tau_\mathrm{h}$	τ_h (each)	VVLoose	VLoose	Medium

Channel	Object	p_T [GeV]	$\lvert\eta\rvert$	$\lvert d_z\rvert$ [cm]	$\lvert d_{xy}\rvert$ [cm]	$I_\mathrm{rel}^{\mathrm{e}/\mu}$	m_T [GeV]
$e\tau_\mathrm{h}$	e	> 33	< 2.1	< 0.2	< 0.045	< 0.15	< 70
	τ_h	> 30	< 2.3	< 0.2			
$\mu\tau_\mathrm{h}$	μ	> 25	< 2.1	< 0.2	< 0.045	< 0.15	< 70
	τ_h	> 30	< 2.3	< 0.2			
$\tau_\mathrm{h}\tau_\mathrm{h}$	τ_h (each)	> 40	< 2.1	< 0.2			

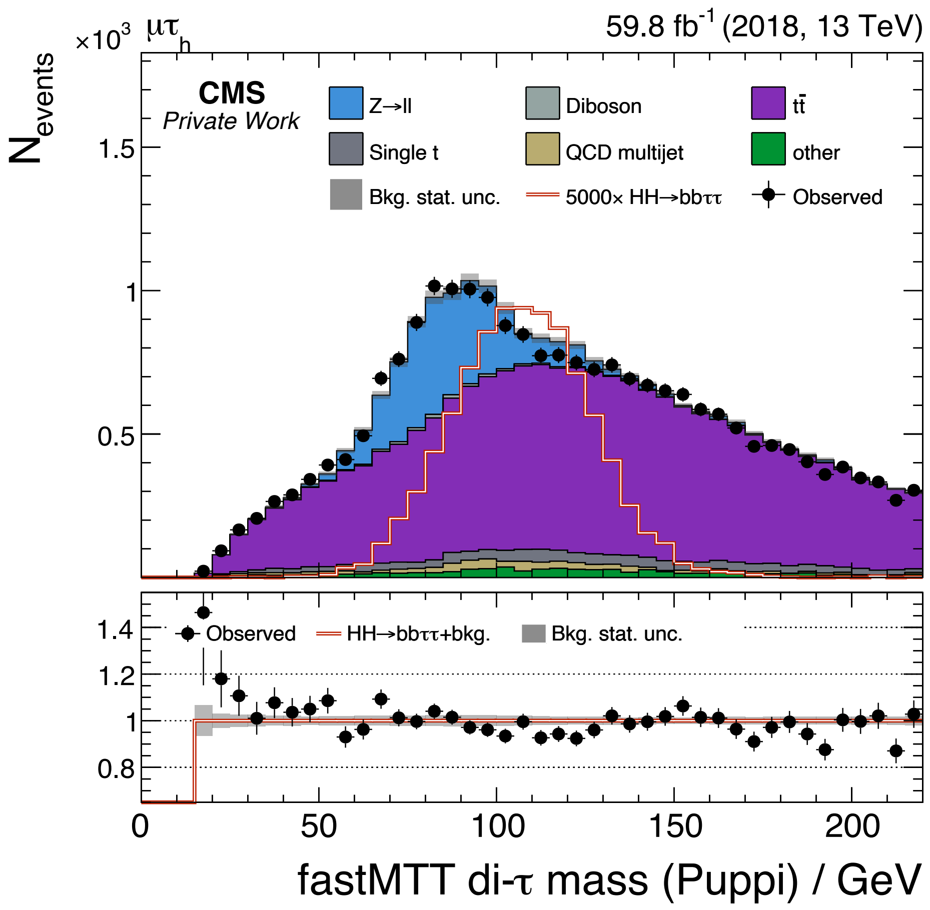
p_T	transverse momentum
$\lvert\eta\rvert$	pseudo rapidity
d	impact parameter
I_{rel}	relative isolation
m_T	transverse mass

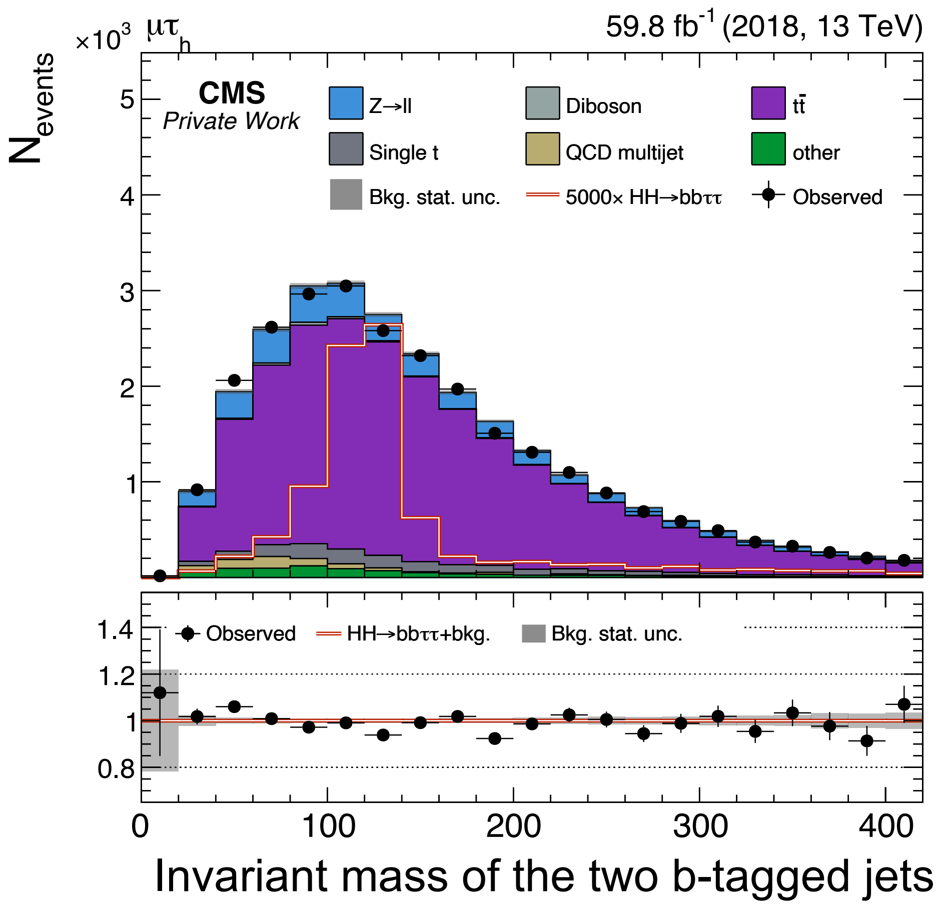
Control Plots - $\tau_h\tau_h$



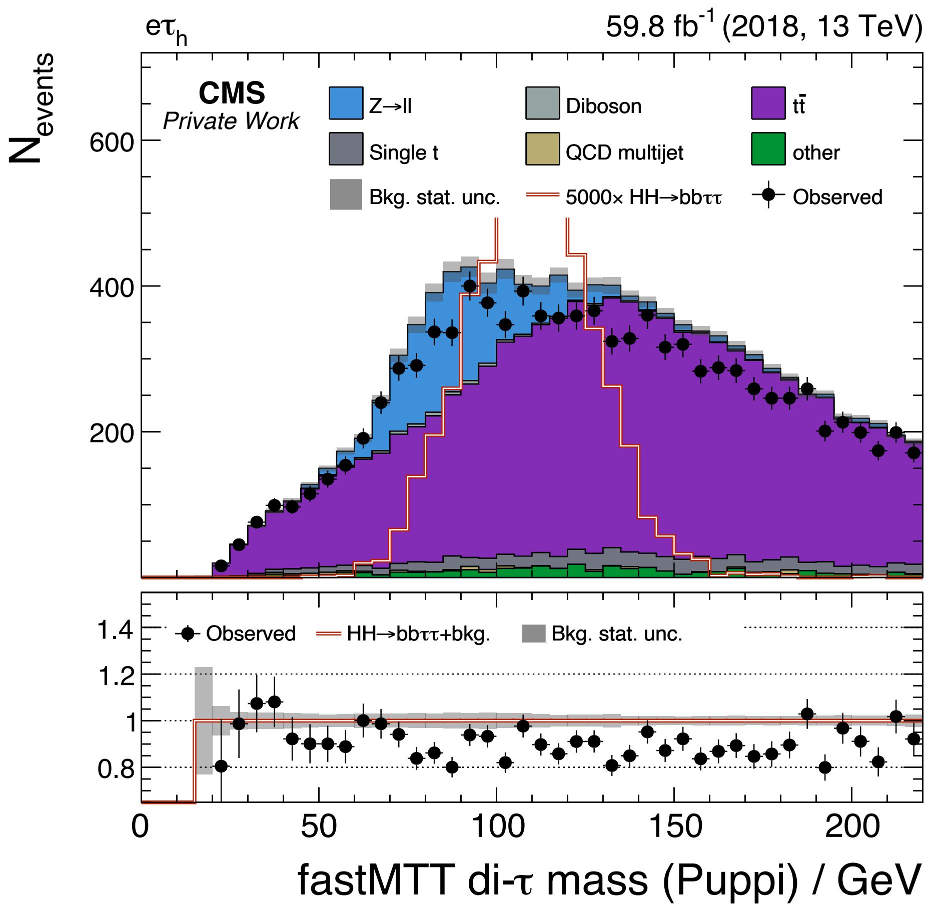


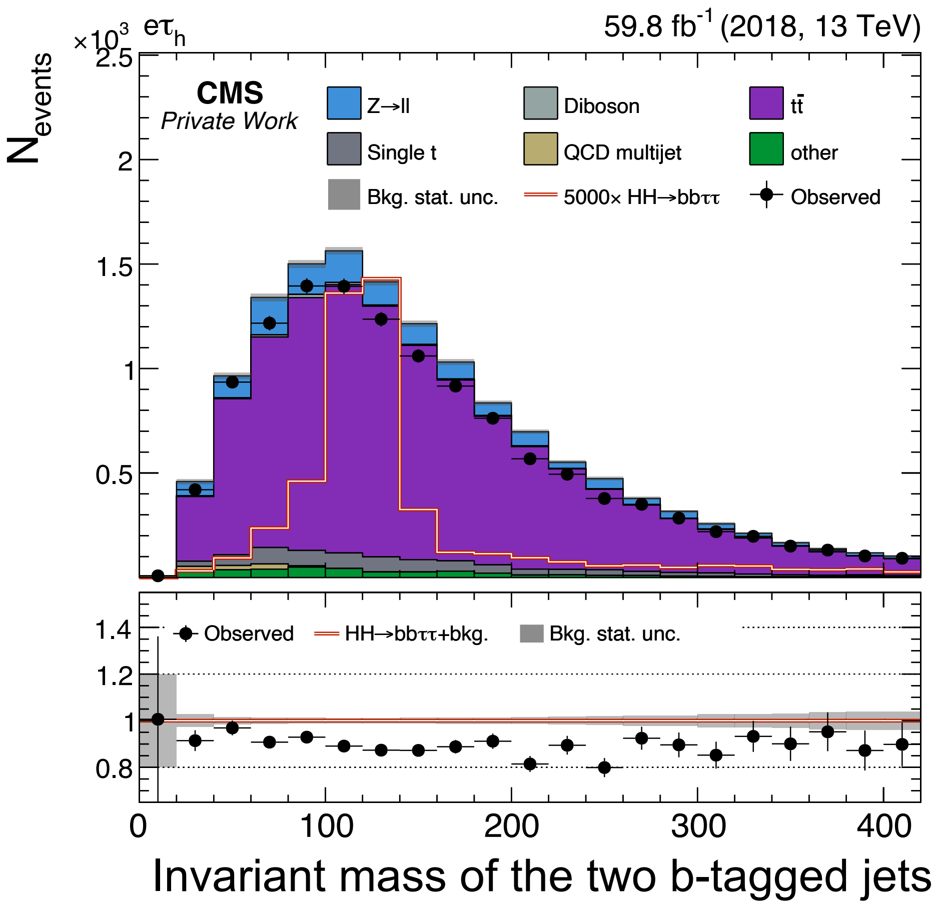
Control Plots - $\mu\tau_h$





Control Plots - $e\tau_h$





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Classes – $\tau_h\tau_h$ final state

Simulated events: 244 726

Physical events: 3606

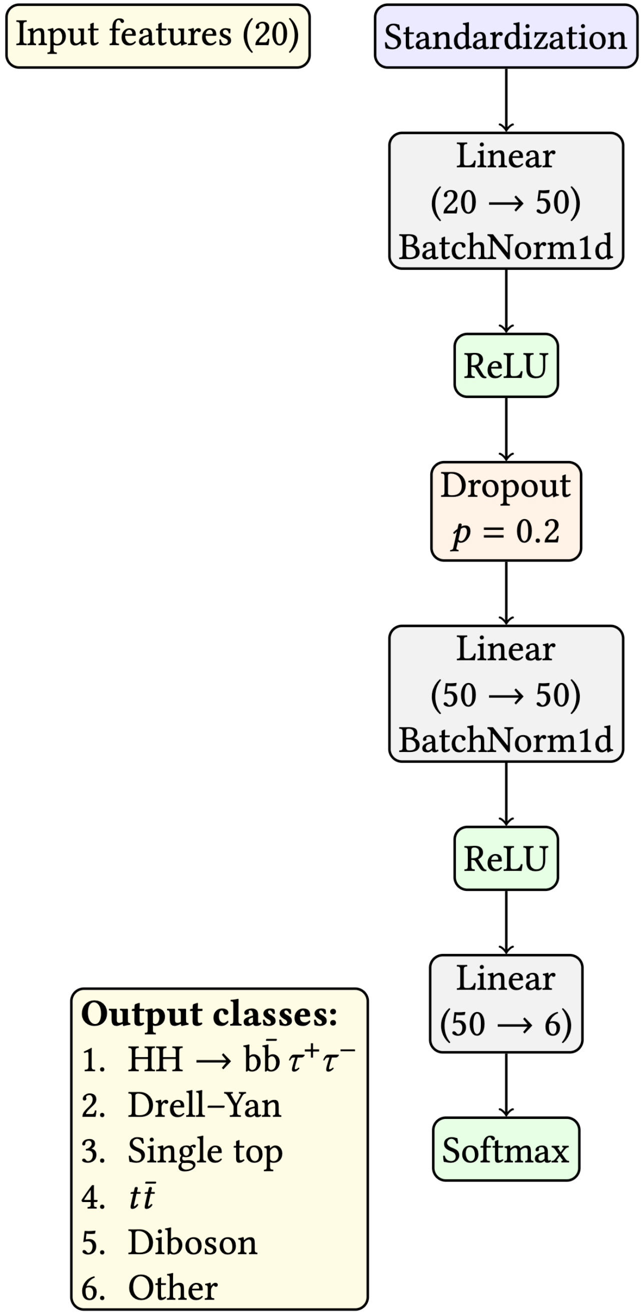
Class	MC Events (in 10^3)	MC Event fraction	Physical events	Physical fraction
HH2B2Tau	5.8	2.4%	1.87	0.05%
Drell-Yan	42.0	17.2%	1700.0	47.1%
Single top	0.6	0.3%	120	3.3%
tt	45.3	18.5%	1587	44.0%
Di-Boson	7.6	3.1%	67.7	1.9%
other	143.4	58.6%	129.1	3.6%

Other: remaining tt (ttW, ttZ, …), Tri-Boson, W, EWK, ggH, ttH, qqH, VH

NN Training

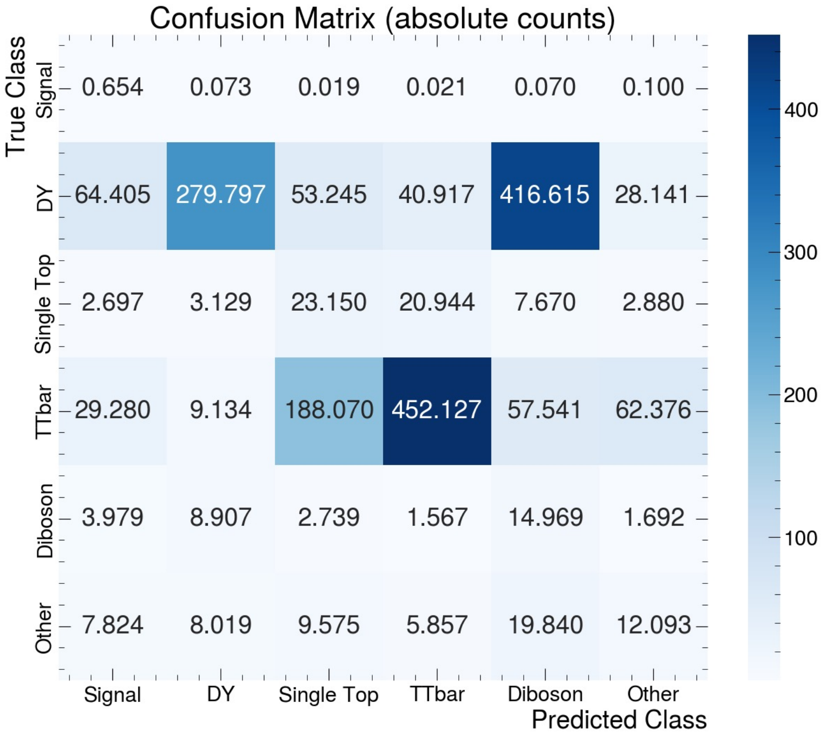
- Cross Entropy Loss function
- Single parameter update per epoch
- Adam Optimizer with L2 regularization
  - Learning rate 10^{-4}
  - Weight decay 10^{-3}
- Early stopping

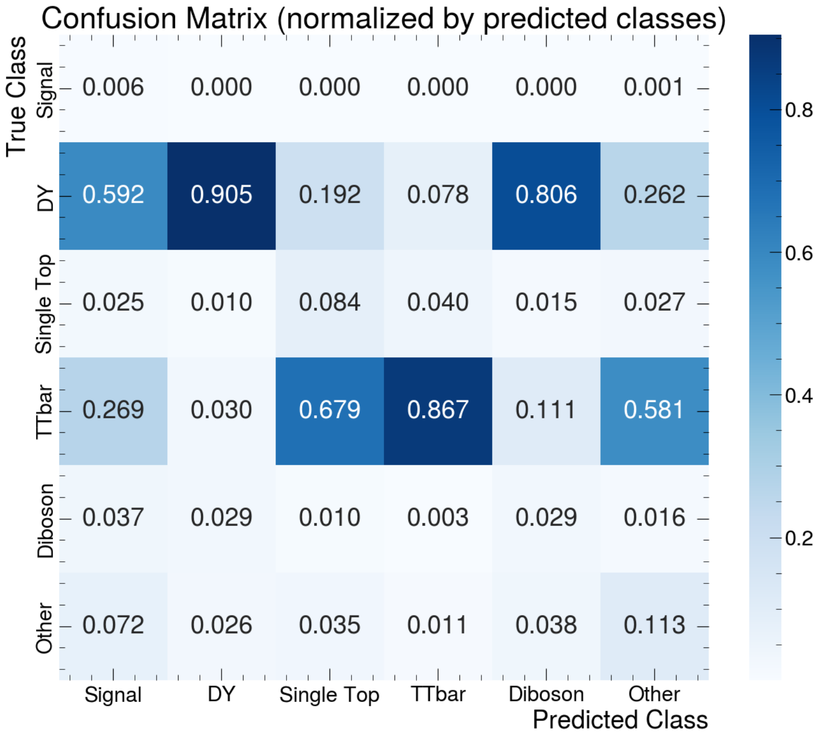
- Balancing weights
  - by simulated events
  - by physical events

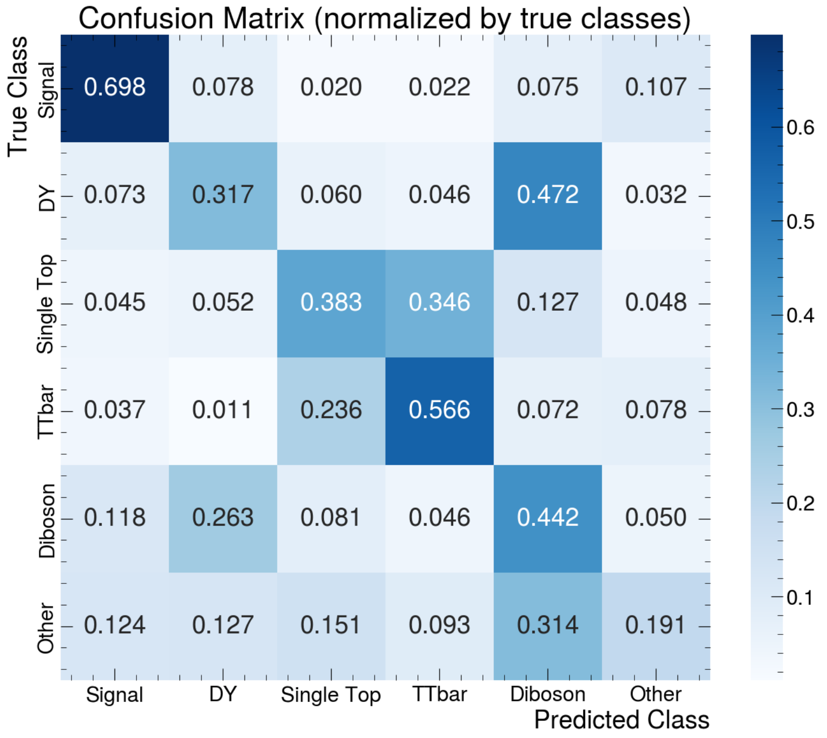


$\tau_h \tau_h$ final state

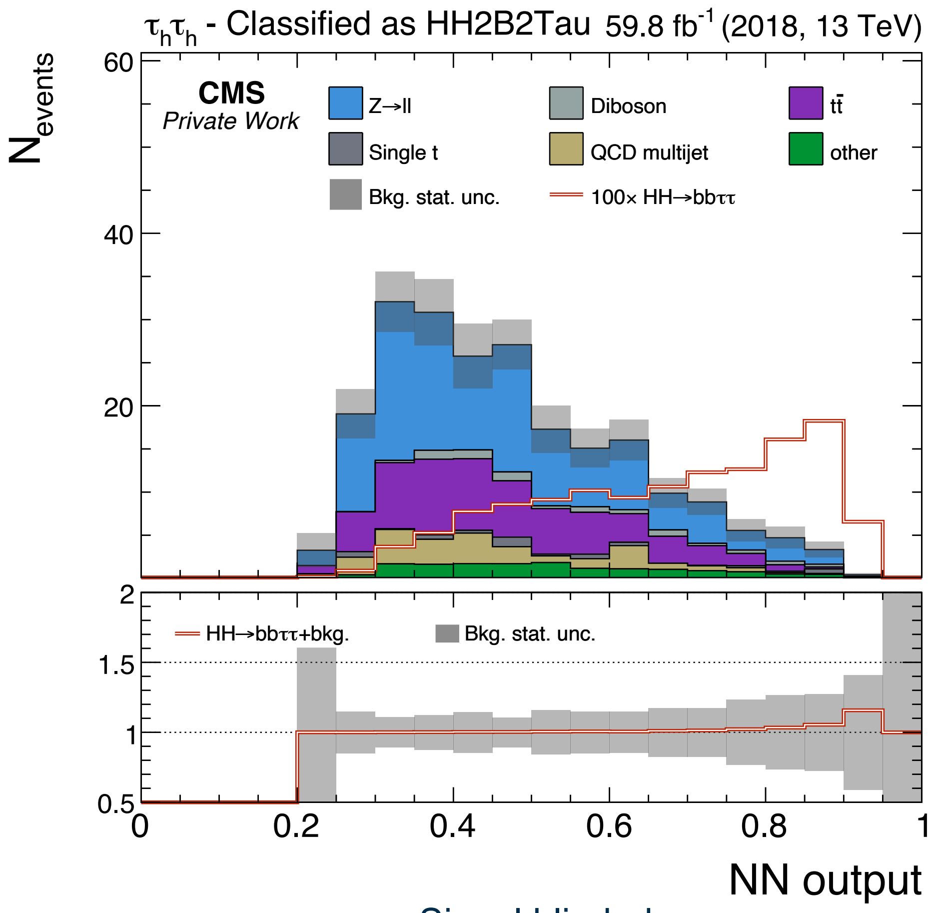
Equal balancing by simulated events



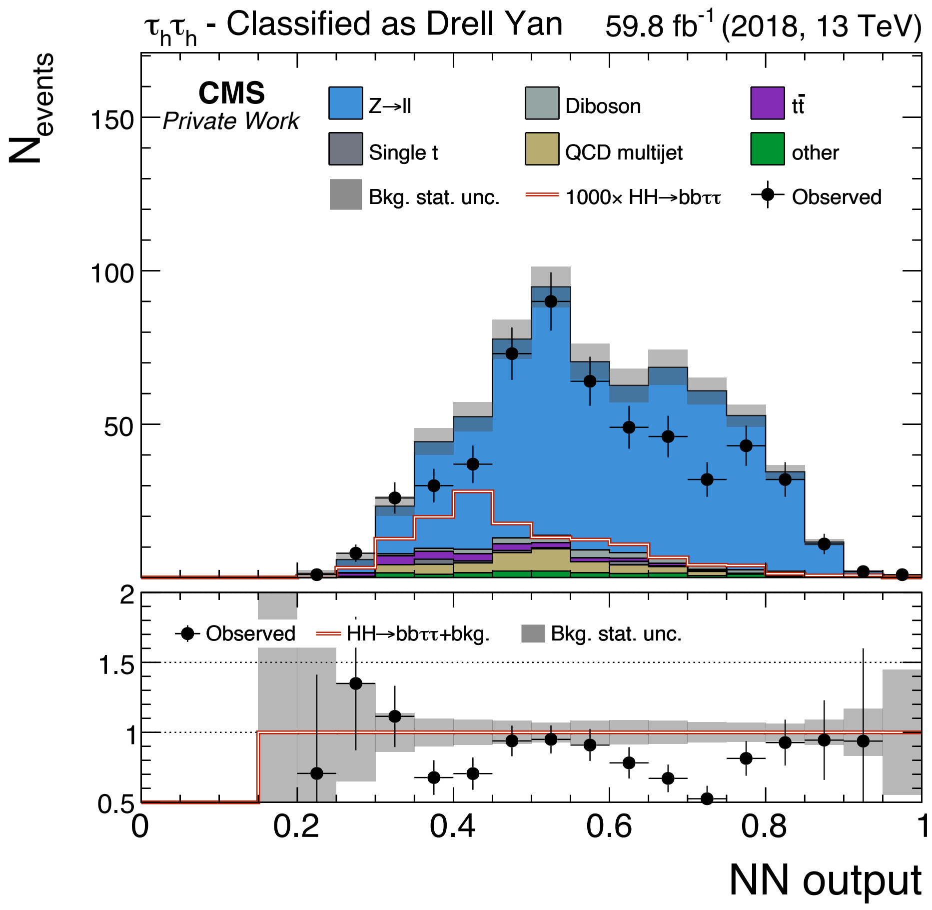




Analysis categories - Examples



Signal blinded



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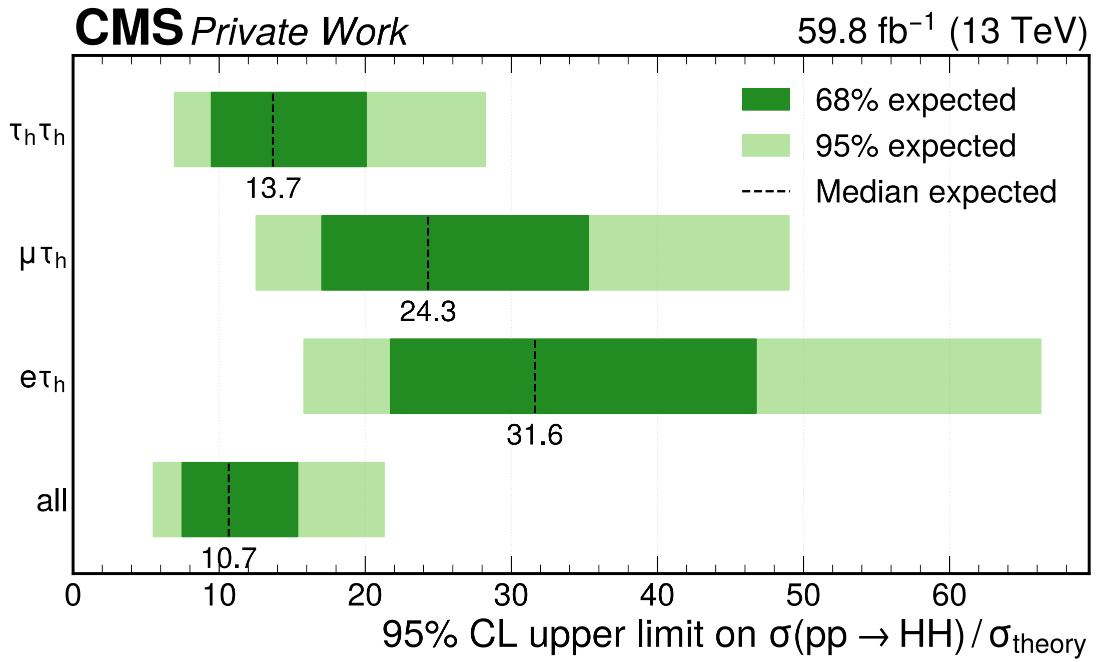
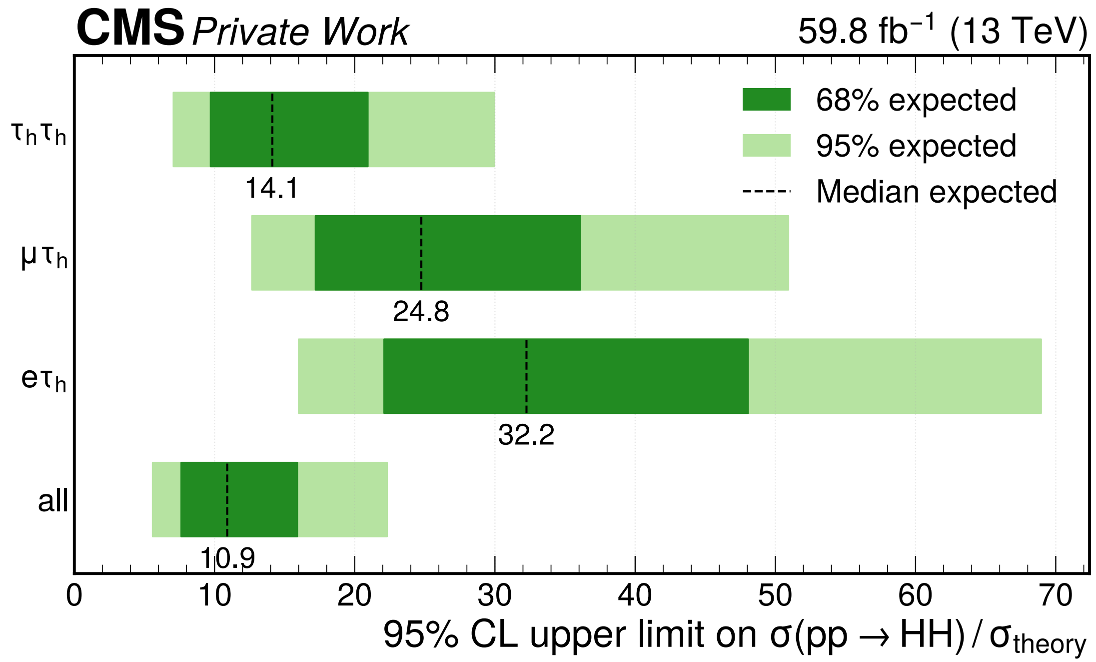
Fit

Only statistic uncertainties



With systematic uncertainties

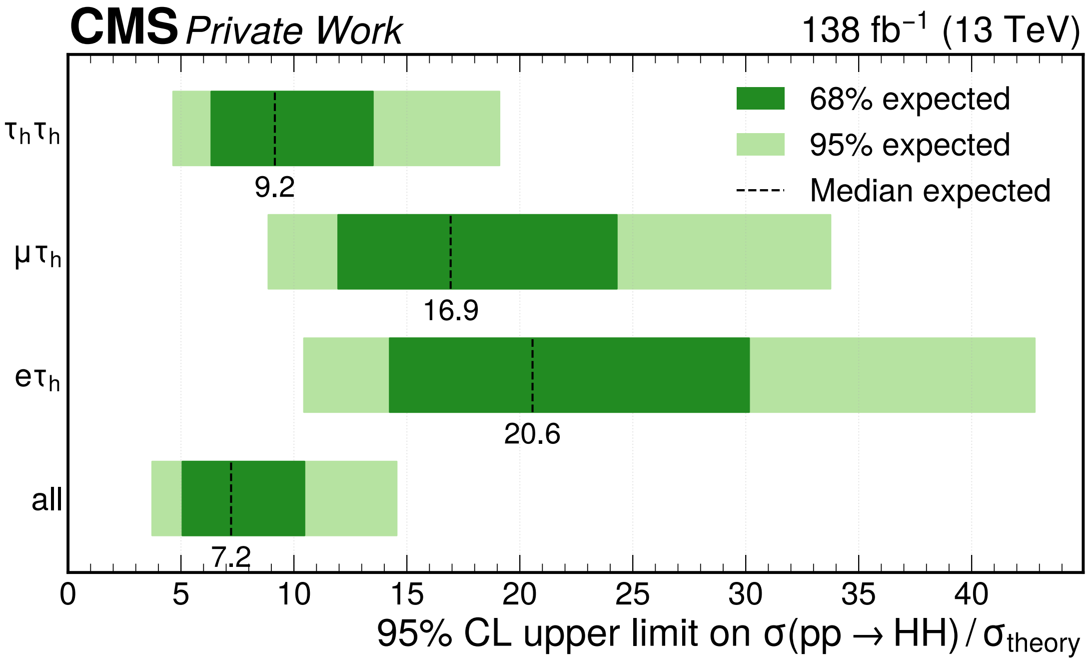


Results from CMS-HIG-20-010:

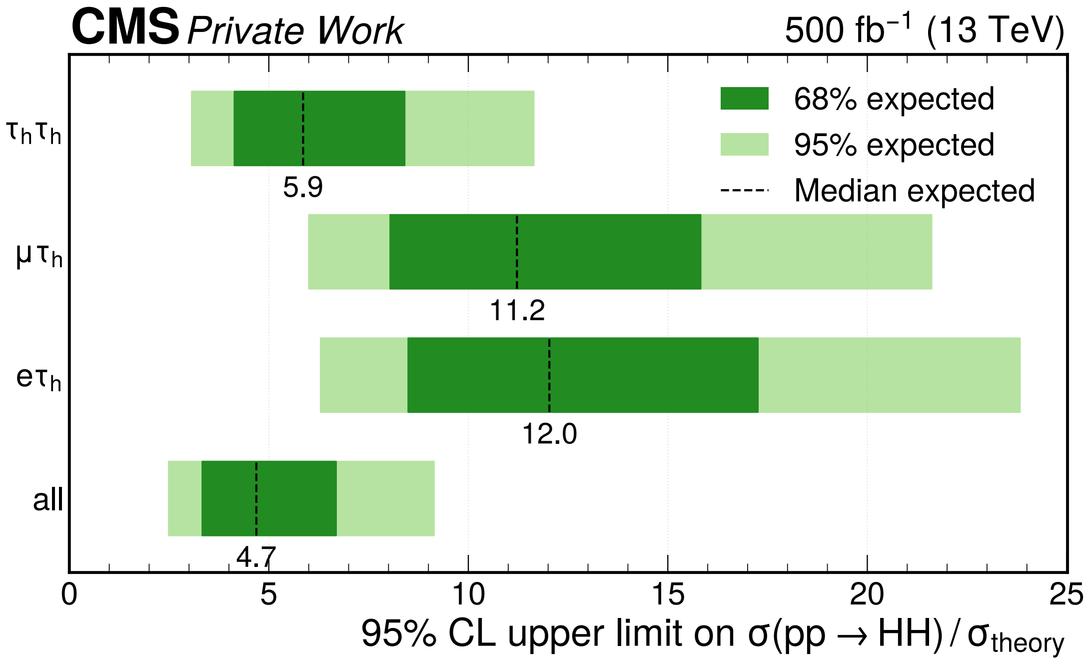
Expected limit	2016	2017	2018	Combined
$\sigma_{ggF+VBF}(pp \to HH)/\sigma^{SM}_{ggF+VBF}$	10.6	11.7	$\boxed{8.2}$	5.2
$\sigma_{ggF+VBF}(pp \to HH)$ [fb]	324	356	249	159
$\sigma_{ggF+VBF}(pp \to HH \to bb\tau\tau)$ [fb]	23.6	26.0	18.2	11.6

Extrapolation to Higher Luminosities

Scaled to luminosity of full Run 2



Scaled to luminosity of Run 2 + 3



Outlook

- Move from an expected-only study to a full unblinded analysis
- Expand to full Run 2 and upcoming Run 3 data
- Include VBF production
- Improve modelling of backgrounds
- Explore more advanced machine learning architectures and training strategies
- Optimize binning of final fit

Datasets

Classes - tt

Nominal events

MC events: 244 726

Physical events: 3606

Class	MC Events (in 10^3)	MC Event fraction	Physical events	Physical fraction
HH2B2Tau	5.8	2.4%	1.87	0.05%
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Di-Boson	7.6	3.1%	67.7	1.9%
other	143.4	58.6%	129.1	3.6%

Other: remaining tt (ttW, ttZ, …), Tri-Boson, W, EWK, ggH, ttH, qqH, VH

Classes - mt

Nominal events

MC events: 1 088 740

Physical events: 27 243

Class	MC Events (in 10^3)	MC Event fraction	Physical events	Physical fraction
HH2B2Tau	6.4	0.6%	1.87	0.0069%
Drell-Yan	59.4	5.5%	3288	12.1%
Single top	7.7	0.7%	1384	5.1%
tt	654.0	60.1%	21 582	79.2%
Di-Boson	13.6	1.2%	172	0.6%
other	347.7	31.9%	816	3.0%

Other: remaining tt (ttW, ttZ, …), Tri-Boson, W, EWK, ggH, ttH, qqH, VH

Classes - et

Nominal events

MC events: 566 562

Physical events: 14 288

Class	MC Events (in 10^3)	MC Event fraction	Physical events	Physical fraction
HH2B2Tau	3.3	0.6%	1.02	0.0071%
Drell-Yan	30.7	5.4%	1407	9.8%
Single top	3.9	0.7%	746	5.2%
tt	338.2	59.7%	11 644	81.5%
Di-Boson	6.5	1.1%	88	0.6%
other	184.1	32.5%	401	2.8%

Other: remaining tt (ttW, ttZ, …), Tri-Boson, W, EWK, ggH, ttH, qqH, VH

NN Training and Architecture

NN Architecture

- CrossEntropyLoss
- Adam optimizer
- Full-Batch training
- Balancing class weights
- Learning rate 1e-4
- No L2 regularization
- Expanded input features

Batch Norm, Dropout

Layers	False, False	False, True	True, False	True, True
50, 50	6.648 +- 0.061	6.545 +- 0.041	6.698 +- 0.046	6.452 +- 0.031
100, 100	6.657 +- 0.027	6.557 +- 0.011	6.720 +- 0.041	6.495 +- 0.034
200, 200	6.679 +- 0.032	6.581 +- 0.019	6.755 +- 0.030	6.543 +- 0.015
400, 400	6.703 +- 0.018	6.602 +- 0.017	6.959 +- 0.036	6.637 +- 0.017
200, 200, 50	6.732 +- 0.025	6.576 +- 0.026	7.294 +- 0.097	6.508 +- 0.020
400, 400, 100	6.948 +- 0.043	6.607 +- 0.014	7.499 +- 0.070	6.634 +- 0.019

- Best model loss out of **five trainings**

NN Architecture

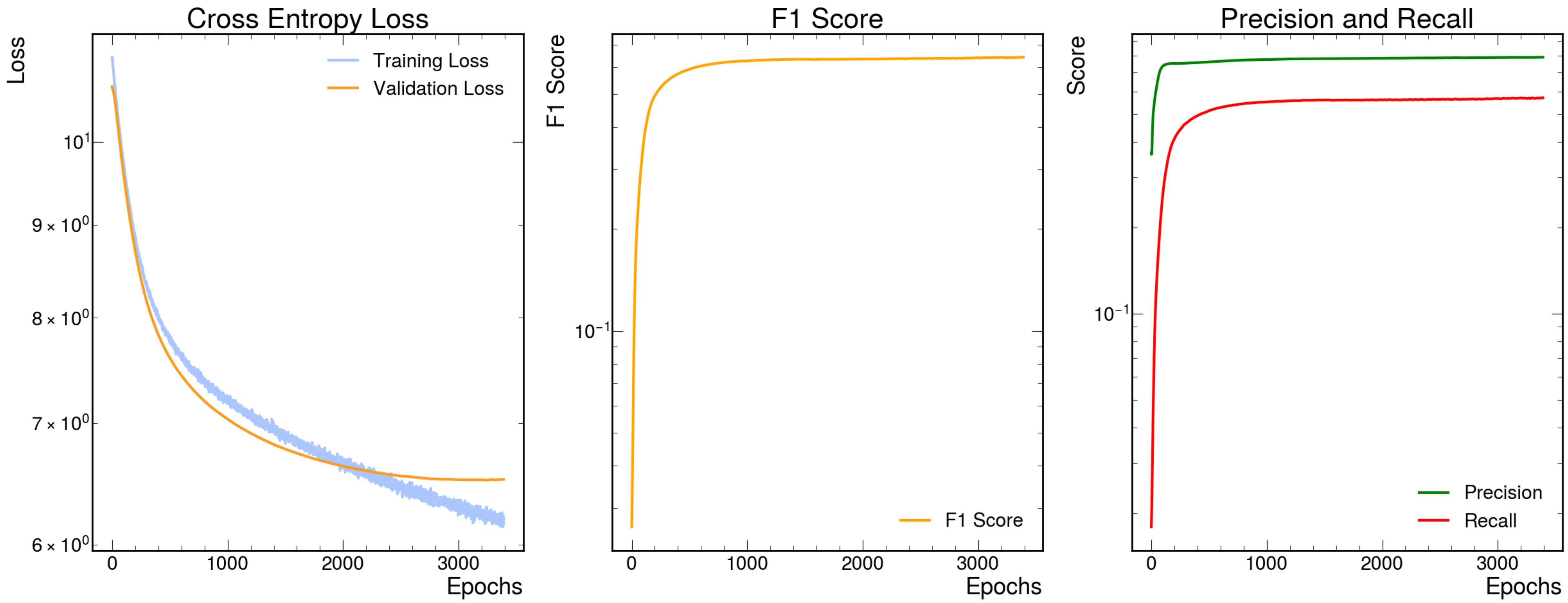
tt_20250821_141751

With dropout

With batch normalization

Lr = 1e-4

Layers: 50, 50



NN Architecture

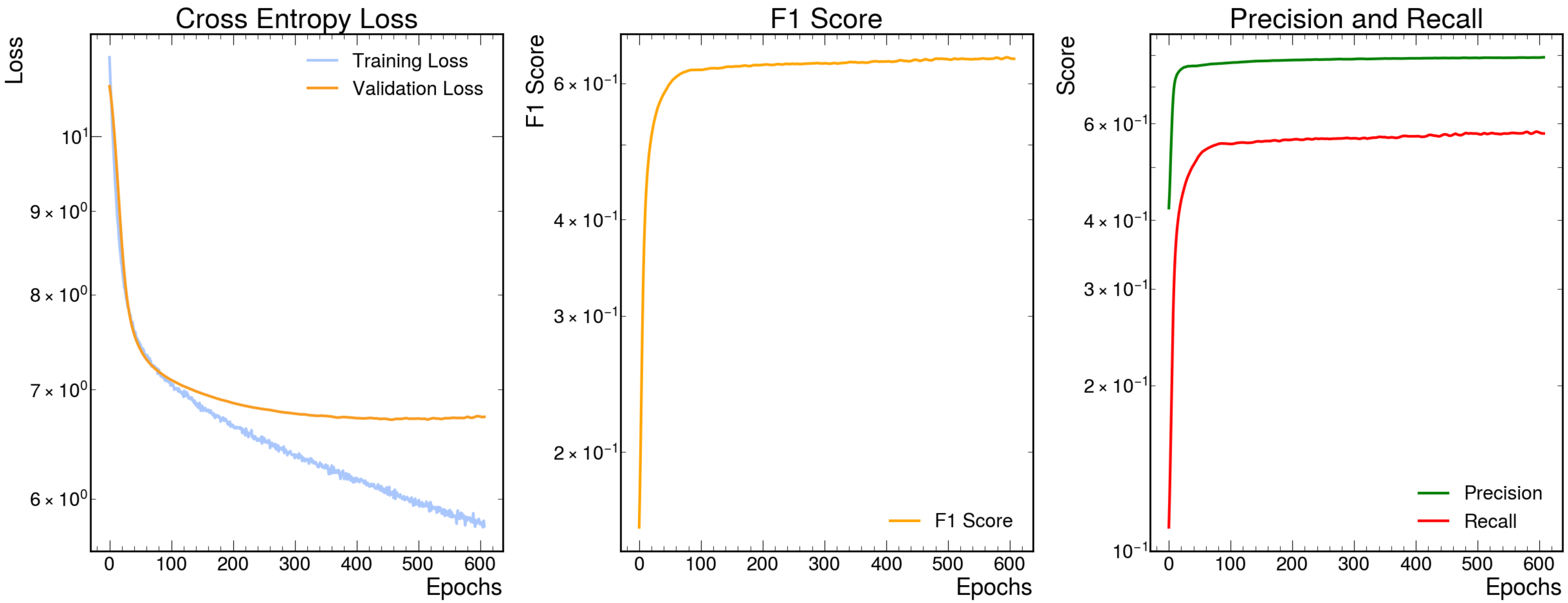
tt_20250821_153055

With dropout

With batch normalization

Lr = 1e-4

Layers: 400, 400



Training – Learning Rate

Layers	Lr = 1e-4	Lr = 4e-4
50, 50	6.554 +- 0.025	6.558 +- 0.028
100, 100	6.560 +- 0.015	6.576 +- 0.013
200, 200	6.608 +- 0.013	6.728 +- 0.038
400, 400	6.669 +- 0.016	6.929 +- 0.068

- With batch normalization
- With dropout

→ Learning rate: small impact on small NNs, large impact on large NNs

Training – L2 Regularization

Layers	W_decay = 0	W_decay = 1e-4	W_decay = 1e-3
50, 50		6.554 +- 0.025	6.527 +- 0.025
100, 100		6.560 +- 0.015	6.565 +- 0.035
200, 200		6.608 +- 0.013	6.608 +- 0.019
400, 400		6.669 +- 0.016	6.675 +- 0.025

- Learning rate 1e-4
- With batch normalization
- With dropout

→ L2 regularization doesn‘t have an impact

Training Weights

- Equal class balancing
  - Each class has the same share
- Custom class balancing
  - Signal class 50%
  - Background classes equally balanced
- With physical weights
  - Physical weights are balanced
- Without physical weights
  - Number of events are balanced

- Equal balancing by physical weights
- Equal balancing by events
- Custom balancing by physical weights
- Custom balancing by events

Input Features

- Standard (13)
- Extended (20)
- All (53)

```
columns_standard = [
    "bpair_btag_value_1",
    "bpair_btag_value_2",
    "bpair_deltaR",
    "bpair_m_inv",
    "bpair_pt_1",
    "bpair_pt_dijet",
    "deltaR_ditaupair",
    "jpt_1",
    "m_fastmtt",
    "mjj",
    "nbtag",
    "njets",
    "pt_fastmtt",
]

columns_extended = columns_standard + [
    "mtt_coll_approx",
    "m_vis",
    "mt_tot",
    "jpt_2",
    "pt_1",
    "pt_dijet",
    "pt_vis",
]
```

```
columns_all = [
    "iso_1",
    "iso_2",
    "mass_1",
    "mass_2",
    "pt_1",
    "pt_2",
    "eta_1",
    "eta_2",
    "phi_1",
    "phi_2",
    "tau_decaymode_1",
    "tau_decaymode_2",
    "m_vis",
    "mt_1",
    "mt_2",
    "mt_1_pf",
    "mt_2_pf",
    "pfmet",
    "met",
    "pzetamissvis",
    "metphi",
    "deltaR_ditaupair",
    "pt_vis",
    "mtt_coll_approx",
    "jpt_1",
    "jpt_2",
    "jeta_1",
    "jeta_2",
    "jphi_1",
    "jphi_2",
    "mjj",
    "njets",
    "pt_dijet",
    "jet_hemisphere",
    "nbtag",
    "bpair_pt_1",
    "bpair_pt_2",
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    "bpair_eta_2",
    "bpair_phi_1",
    "bpair_phi_2",
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    "mass_tautaubb",
    "m_fastmtt",
    "pt_fastmtt",
    "eta_fastmtt",
    "phi_fastmtt",
]
```

Input Features & Training Weights

Lr = 1e-4

W_decay = 1e-3

Layers: 50, 50

	Standard	Extended	All
Equal balancing by events	6.5274 +- 0.0252	6.4885 +- 0.0228	6.9359 +- 0.0578
Equal balancing by physical weights	0.1151 +- 0.0005	0.1171 +- 0.0009	0.1256 +- 0.0008
Custom balancing by events	8.4839 +- 0.0339	8.4042 +- 0.0468	8.7794 +- 0.0714
Custom balancing by physical weights	0.1429 +- 0.0003	0.1440 +- 0.0007	0.1541 +- 0.0014

Layers: 100, 100

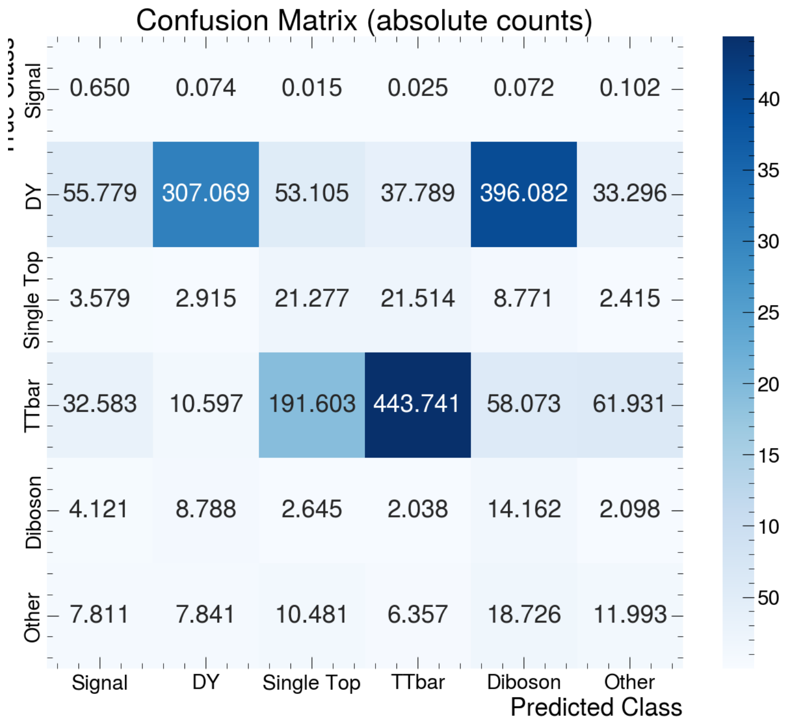
	Standard	Extended	All
Equal balancing by events	6.5655 +- 0.0348	6.4947 +- 0.0154	7.1006 +- 0.0354
Equal balancing by physical weights	0.1167 +- 0.0003	0.1197 +- 0.0009	0.1254 +- 0.0007
Custom balancing by events	8.4816 +- 0.0169	8.4004 +- 0.0225	9.0965 +- 0.0515
Custom balancing by physical weights	0.1446 +- 0.0003	0.1466 +- 0.0005	0.1578 +- 0.0016

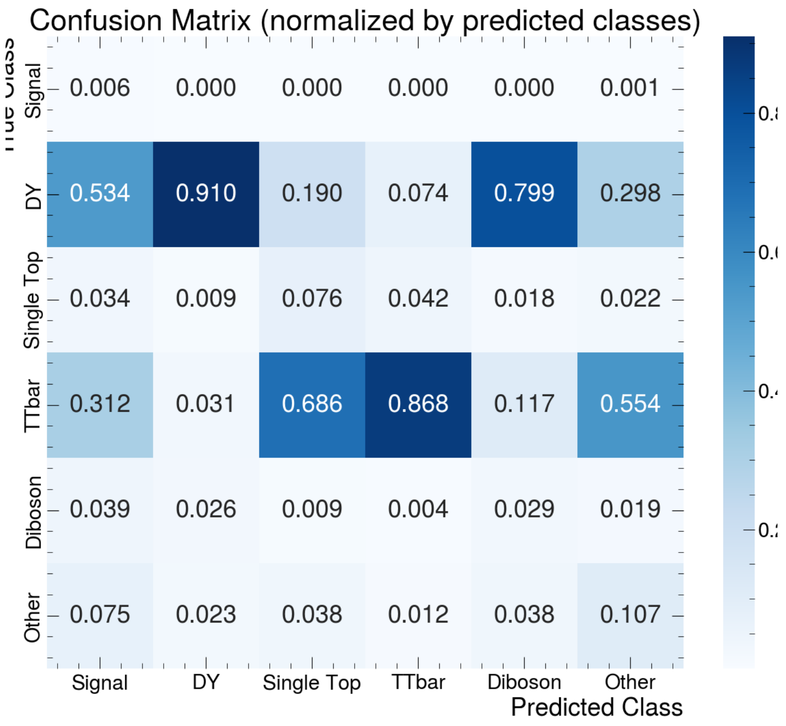
Losses of different weight systems are not comparable

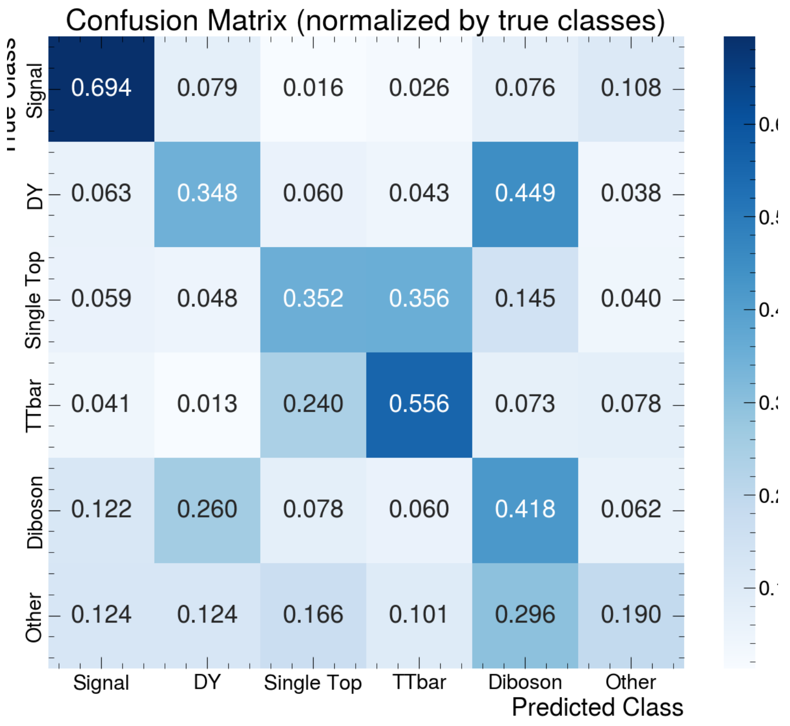
Confusion Matrices

tt final state

Equal balancing by events







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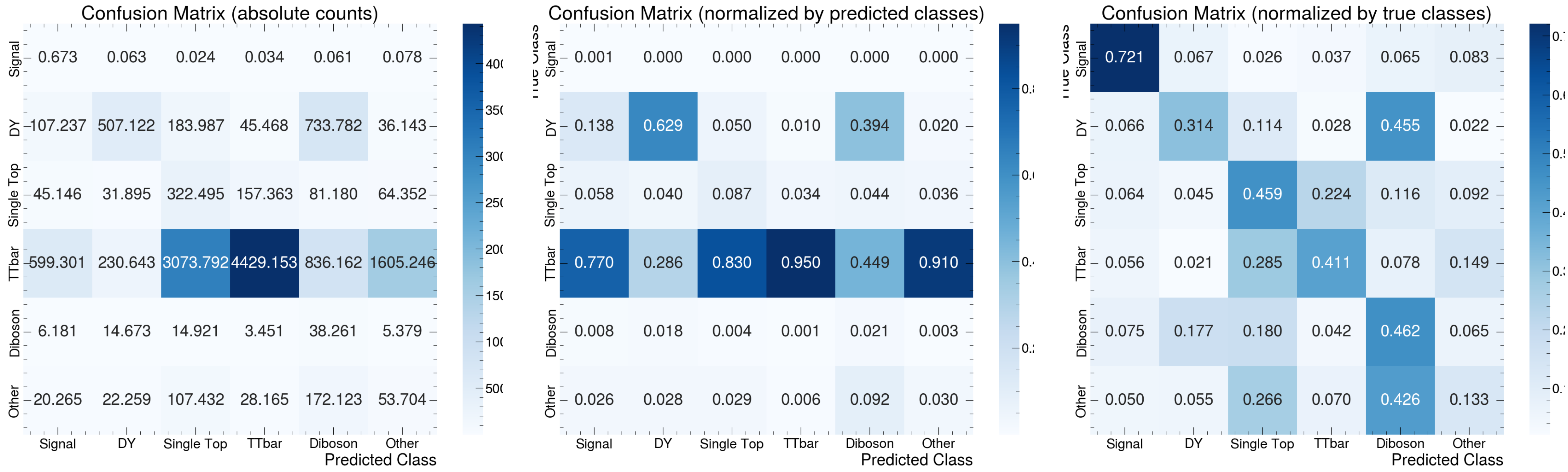
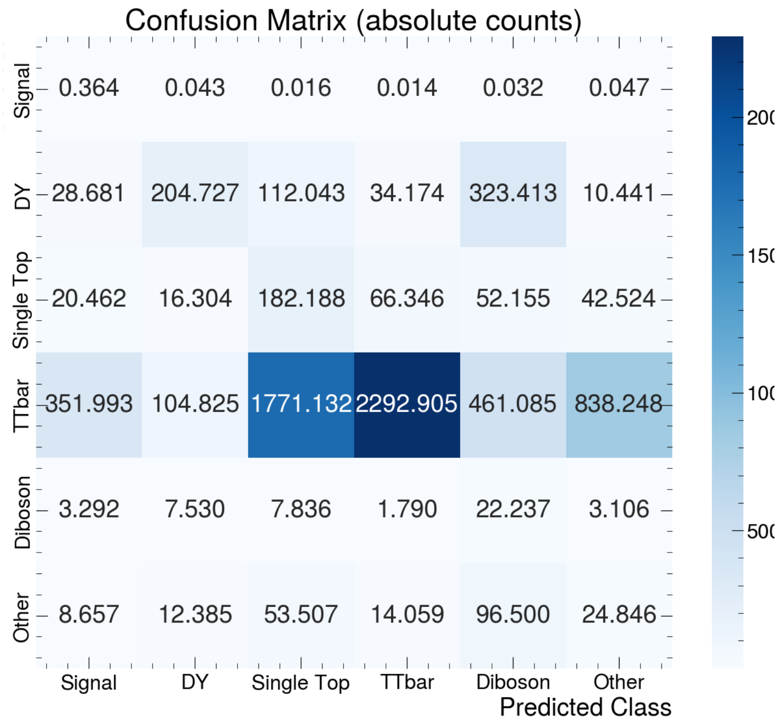
mt final state

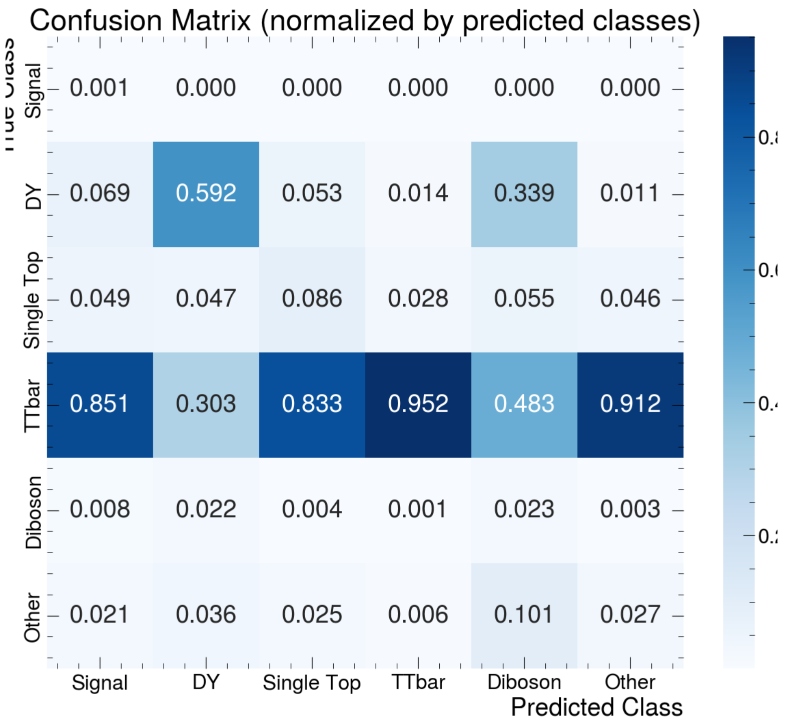
Equal balancing by events

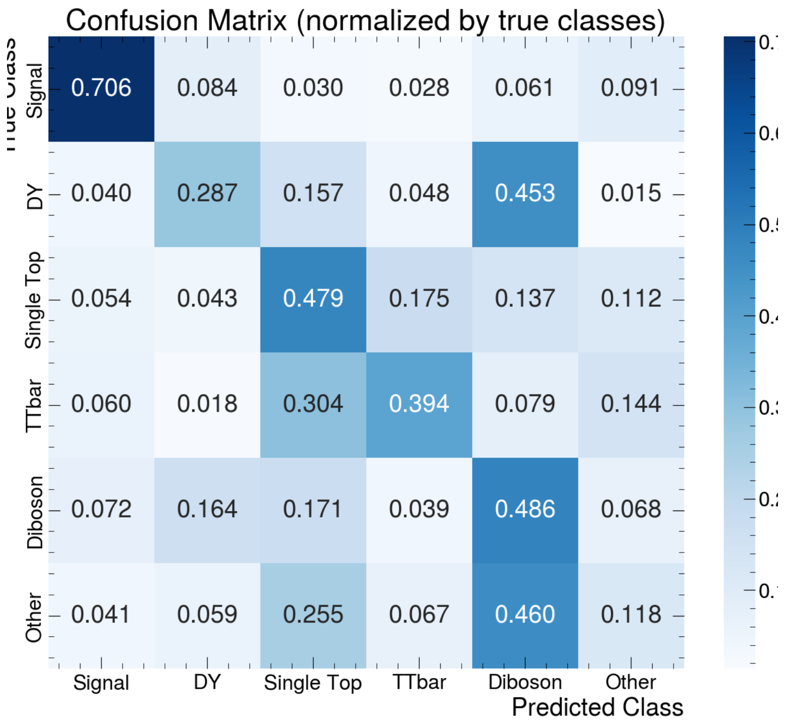


et final state

Equal balancing by events

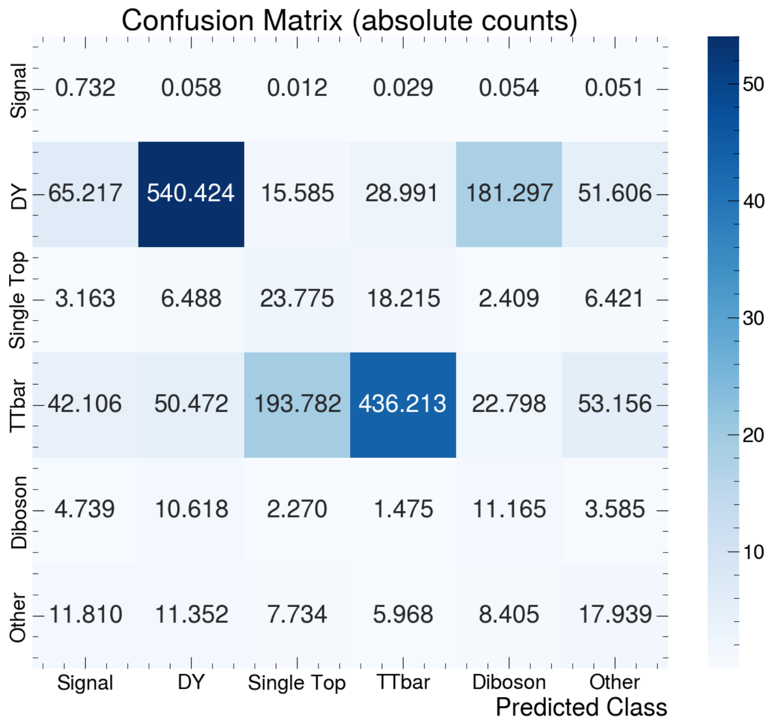


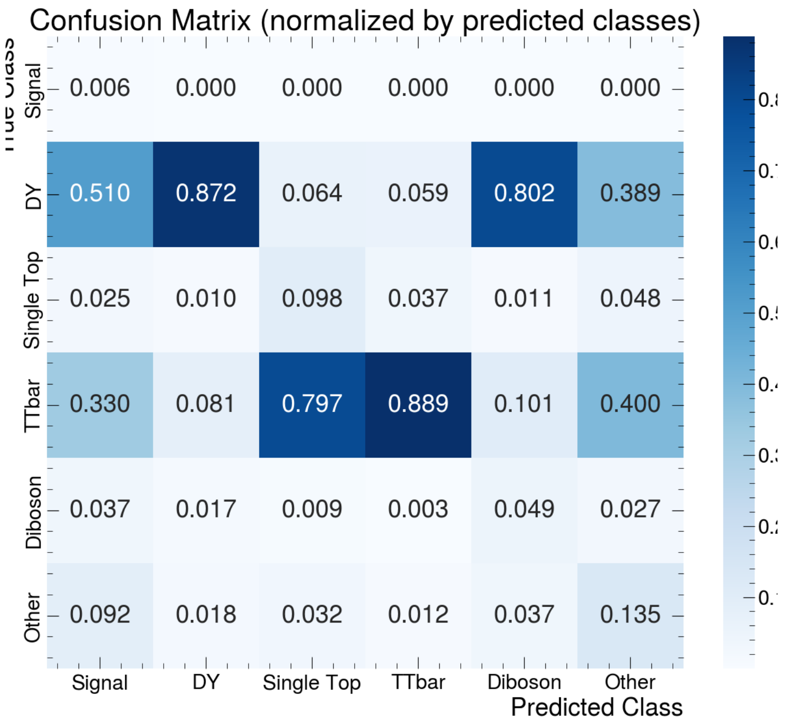


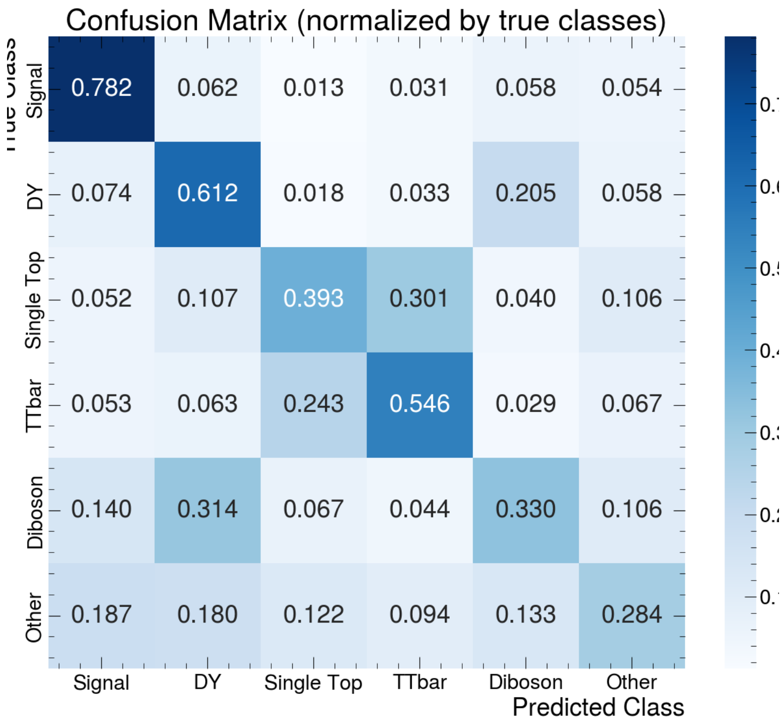


tt final state

Equal balancing by physical weights



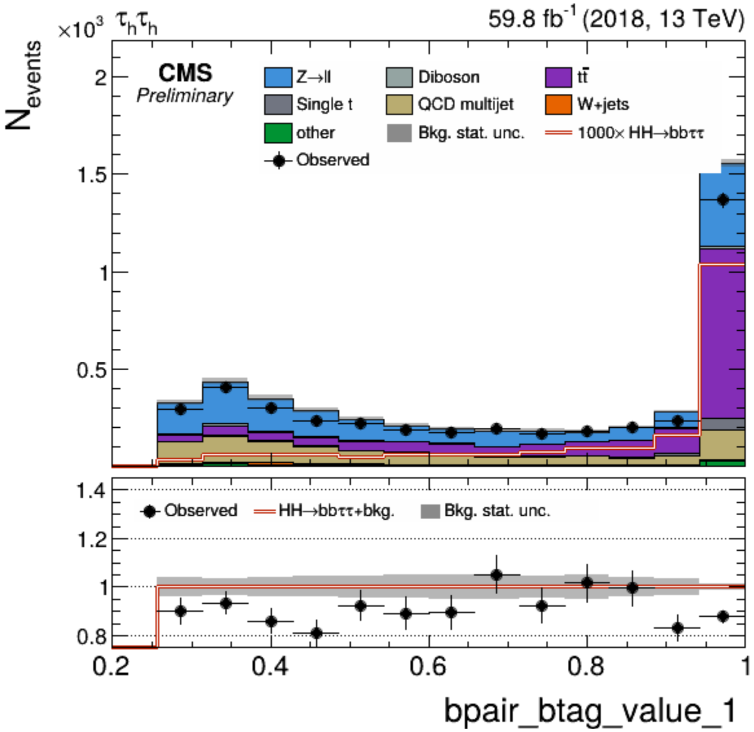


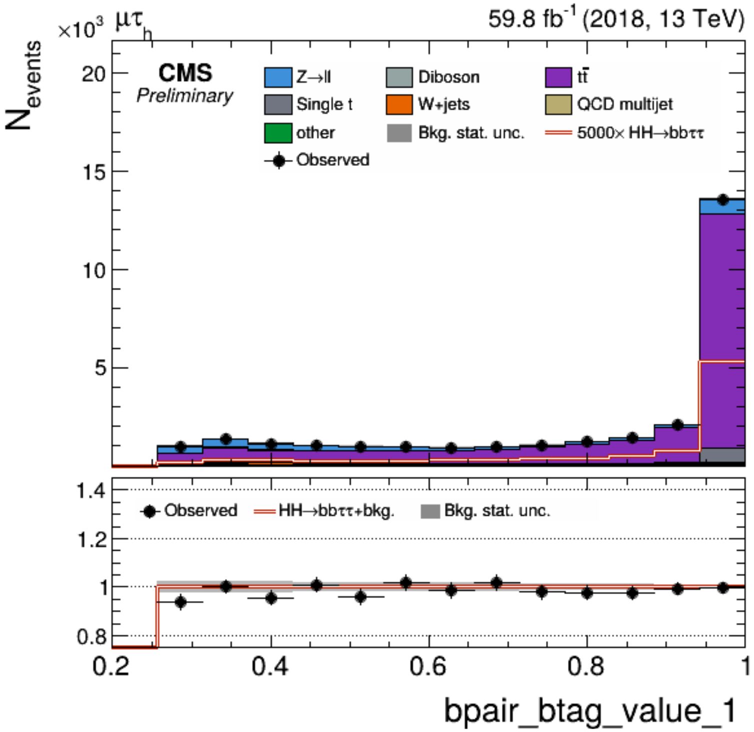


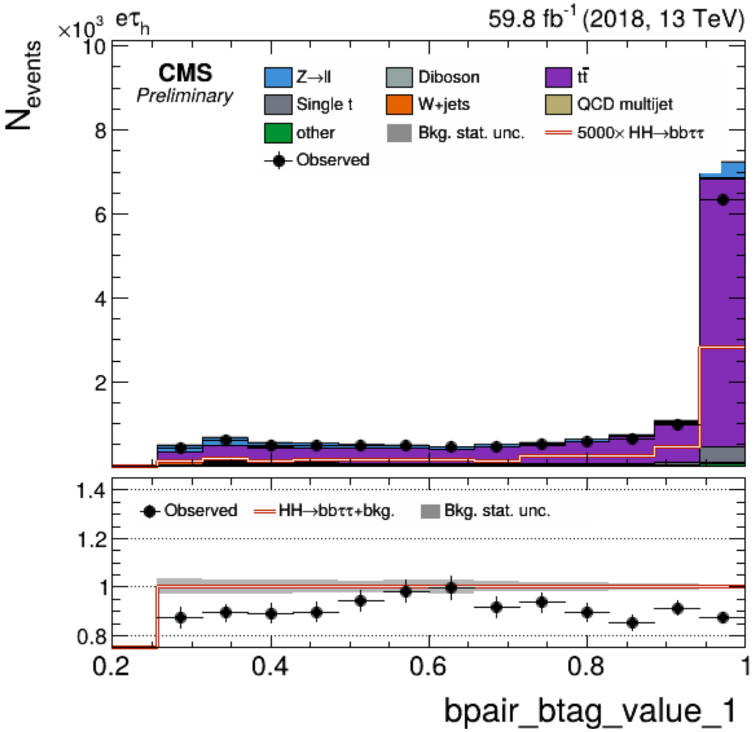
tt_20250822_162914

Control Plots

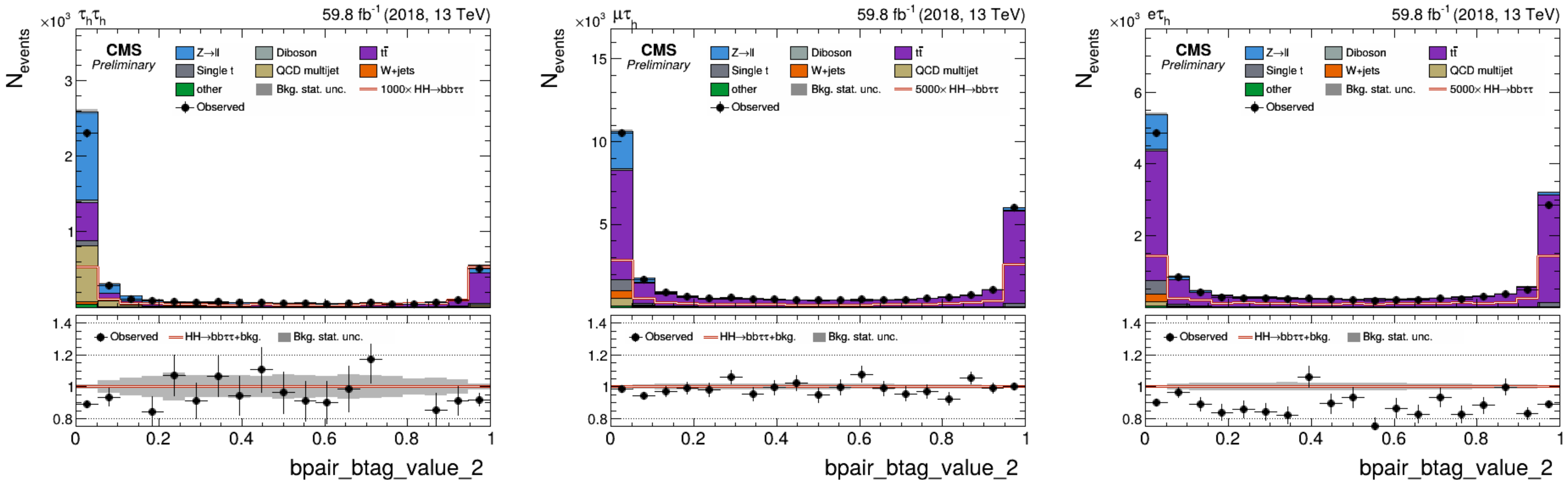
Control plots
Standard features







Control plots
Standard features



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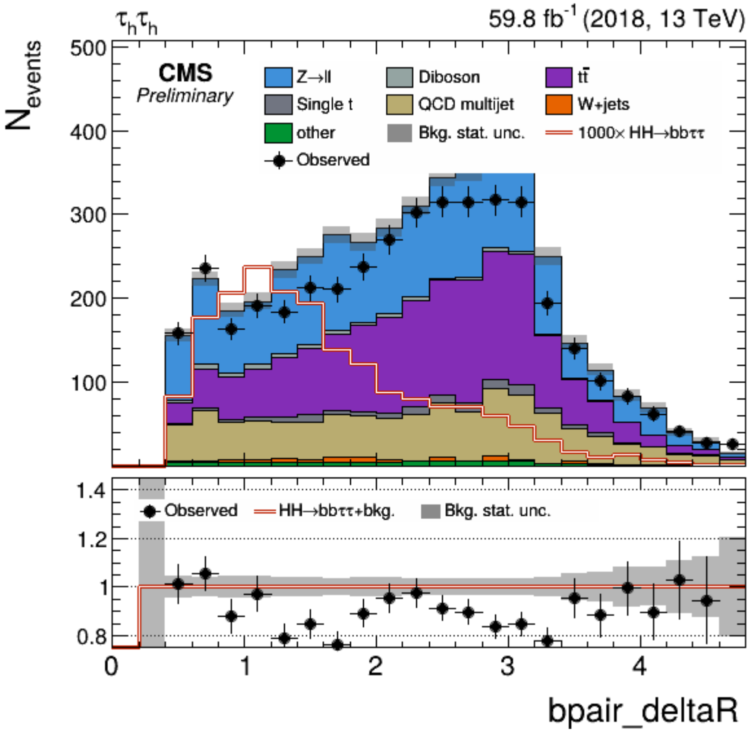

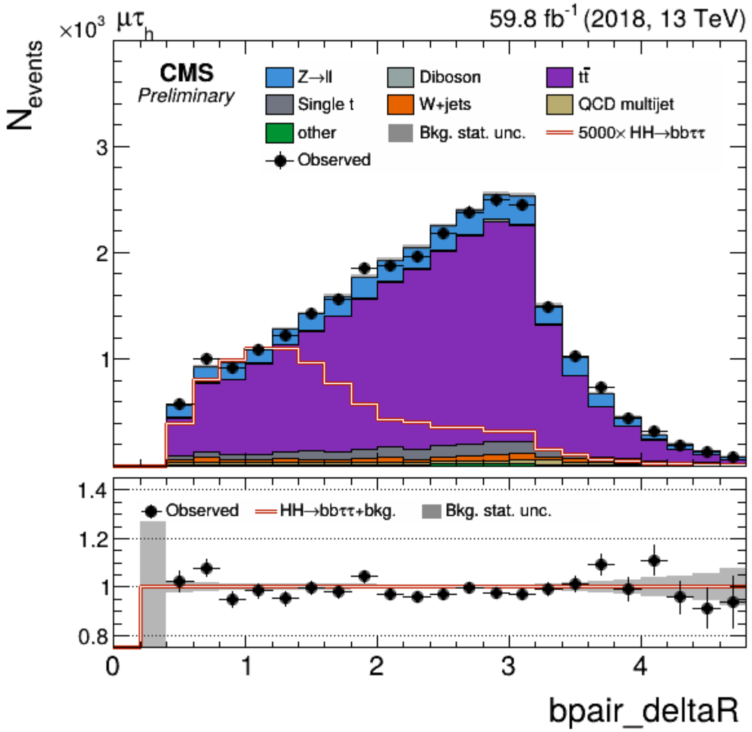

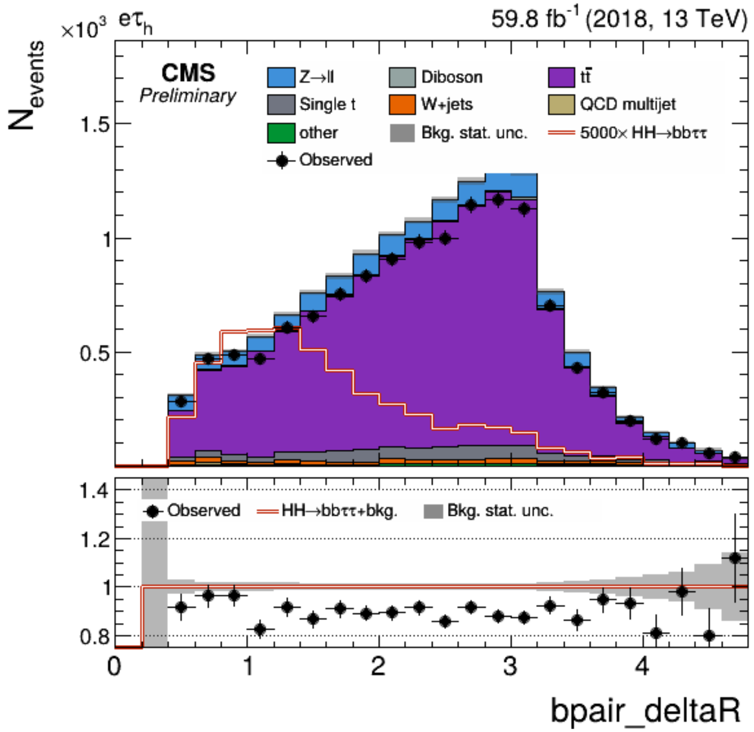

Control plots
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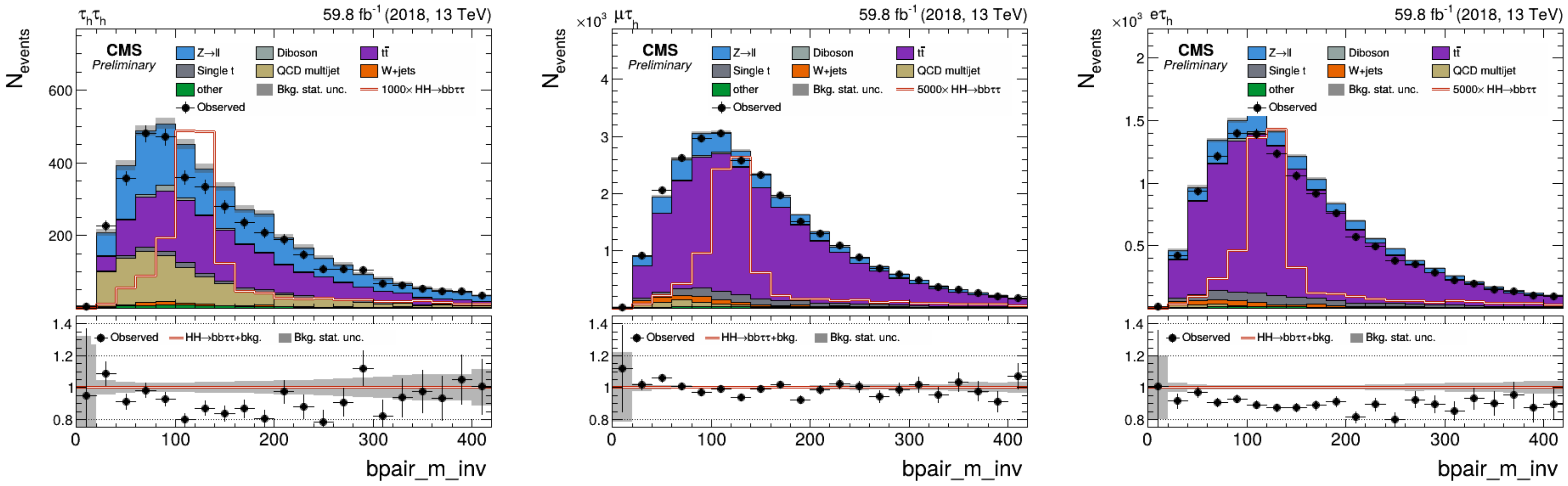

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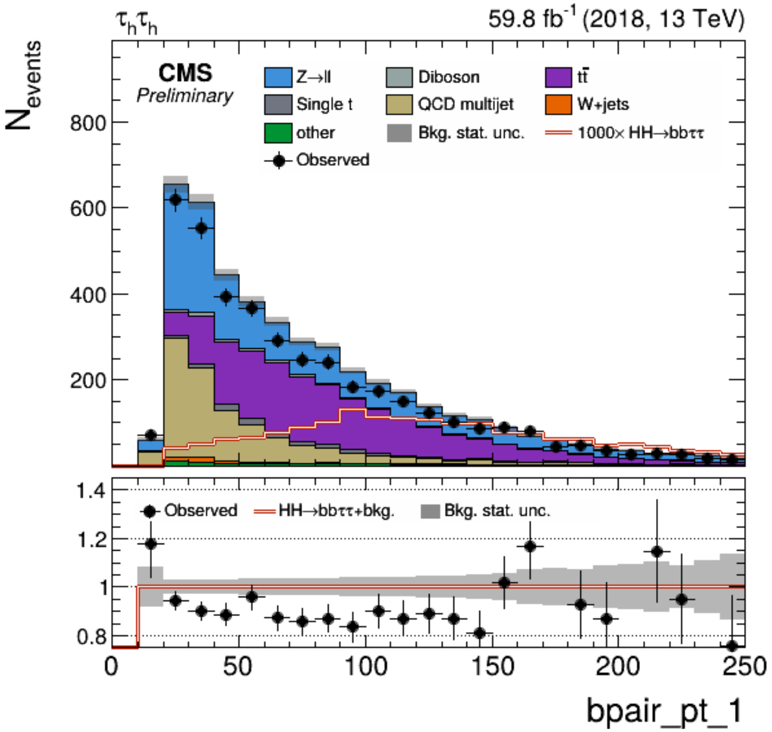

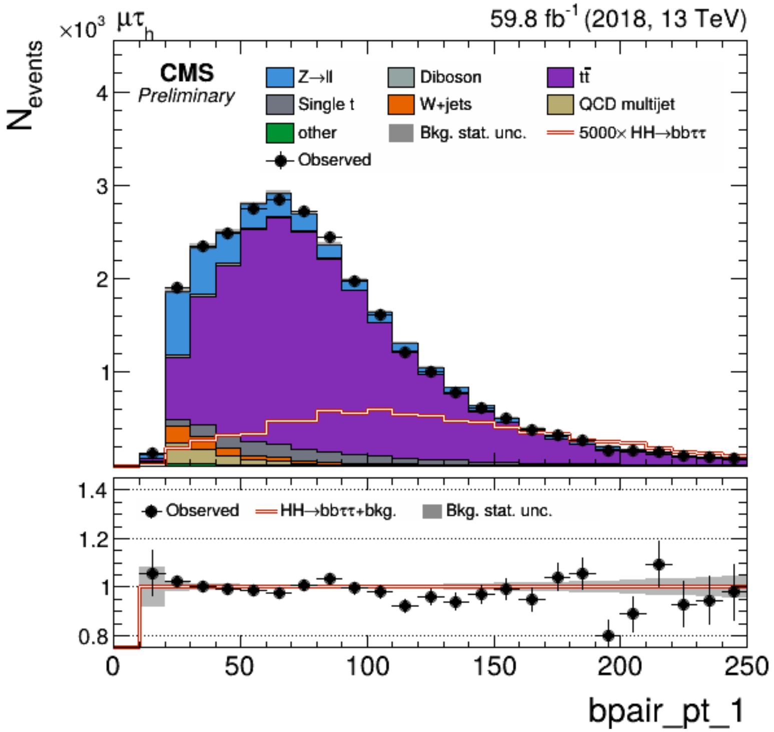

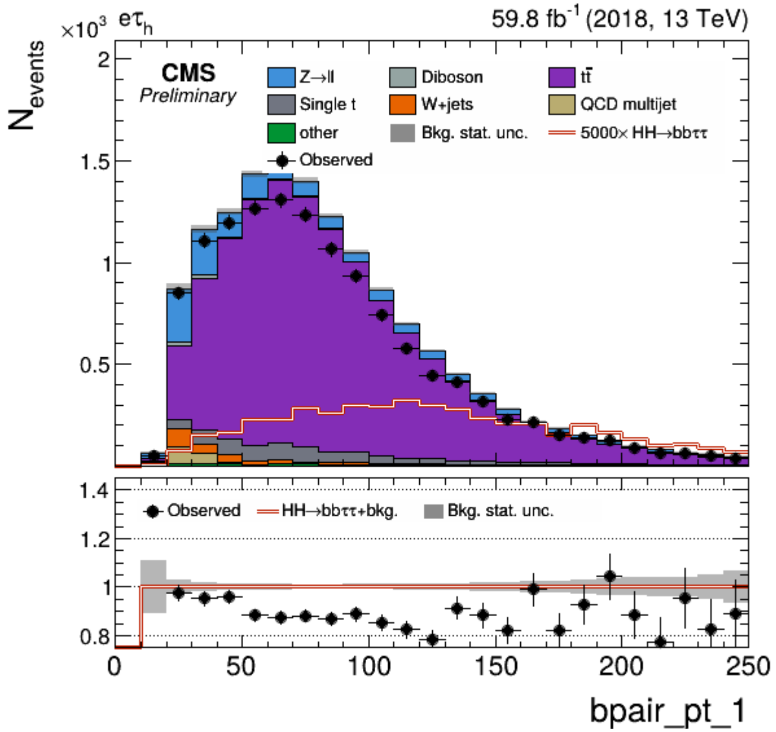

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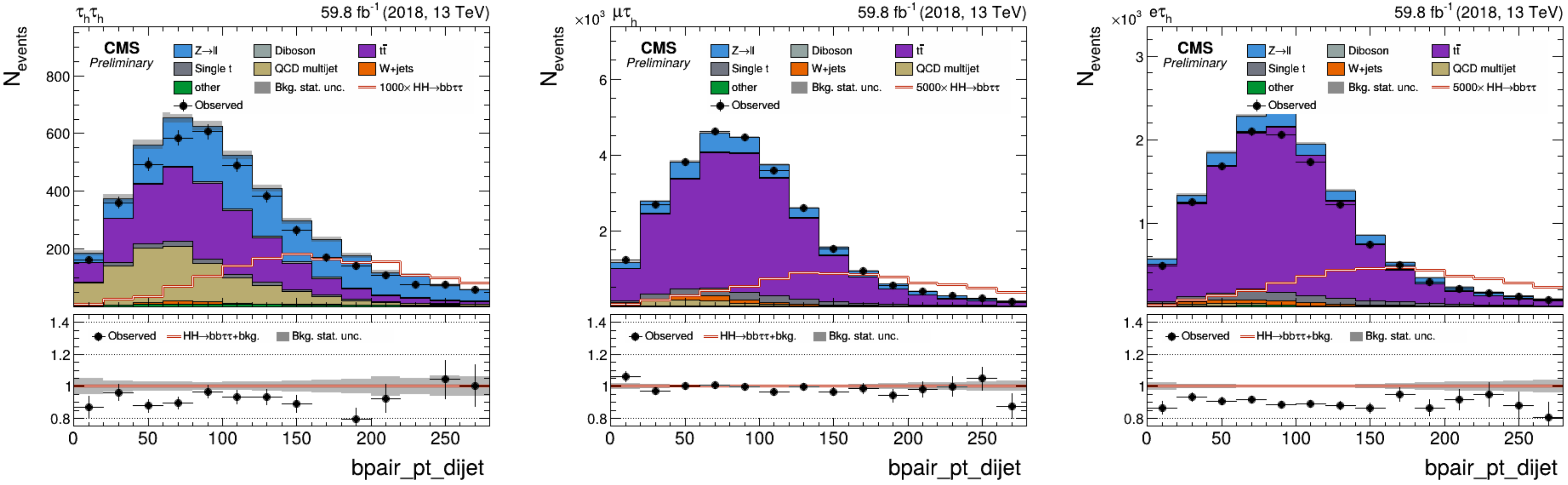

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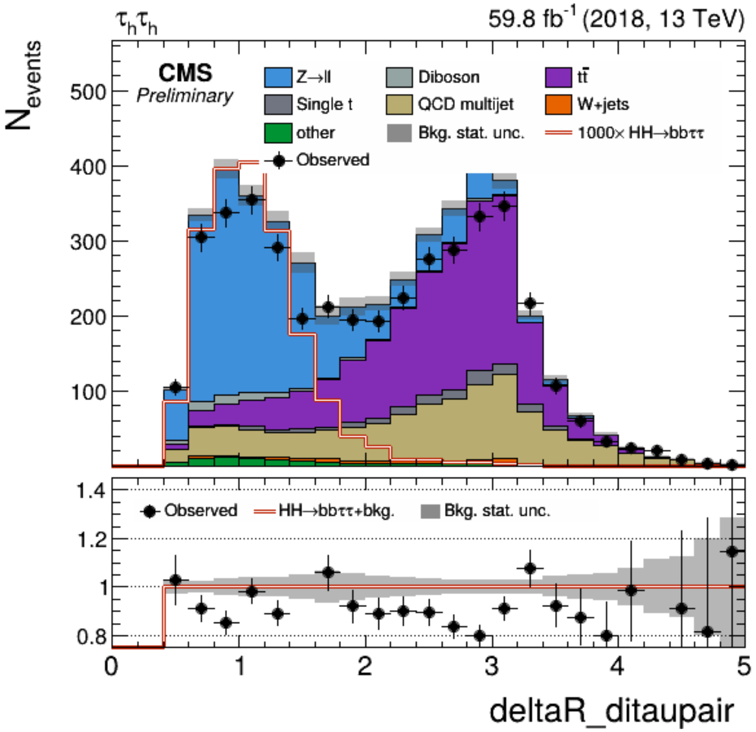
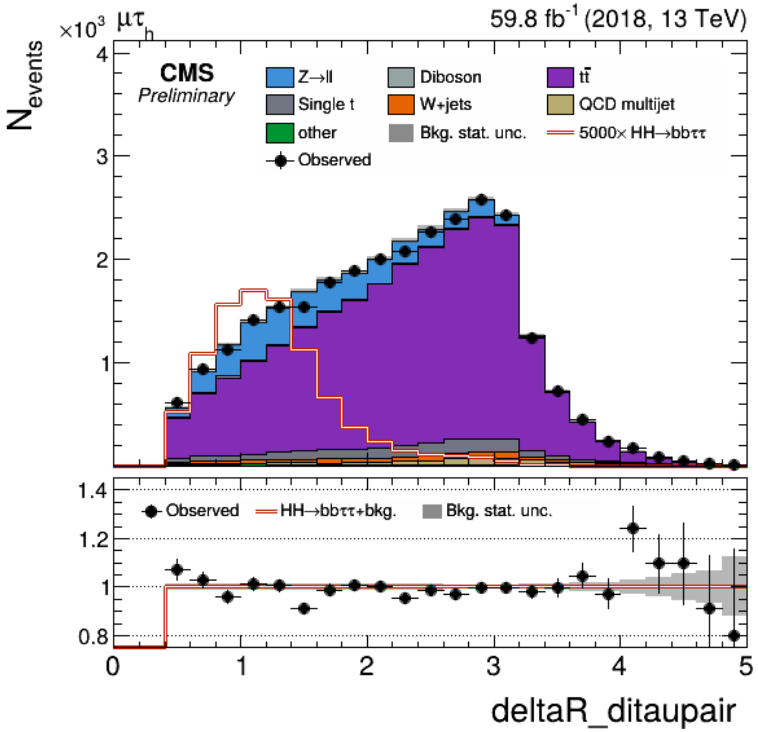
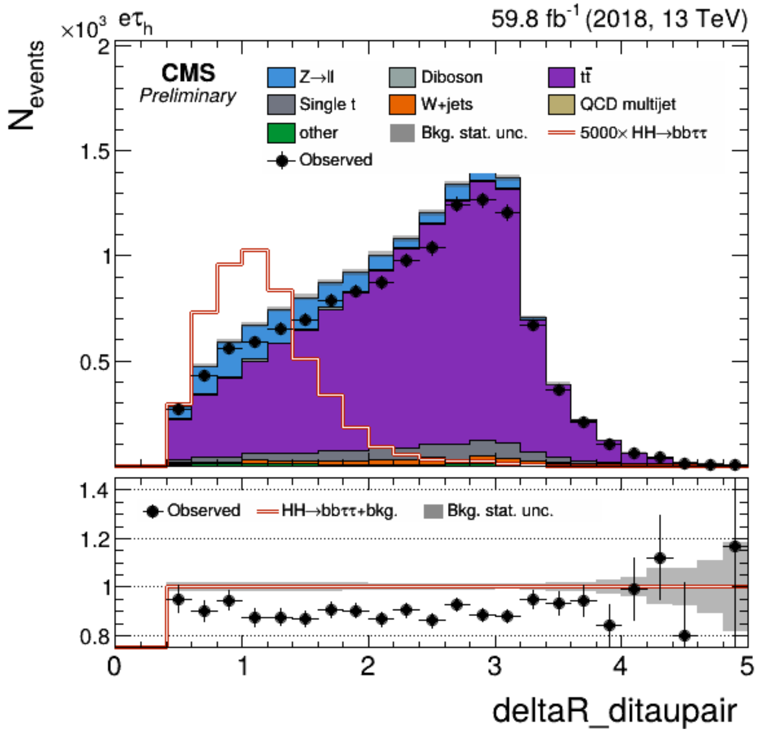
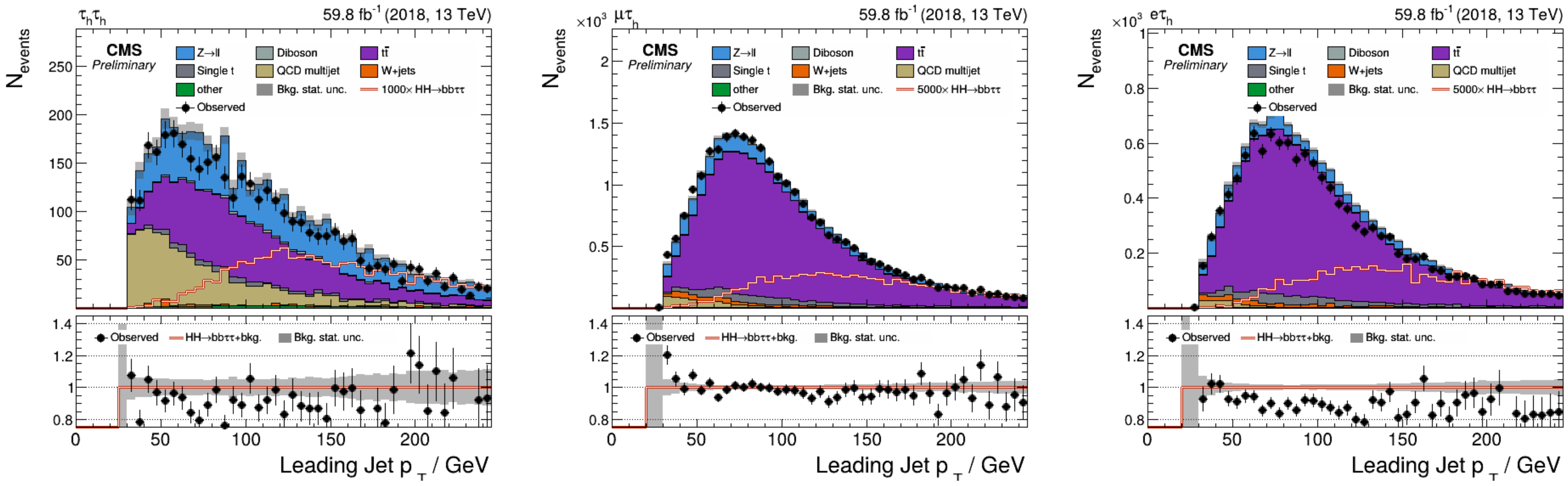






Control plots
Standard features



Control plots
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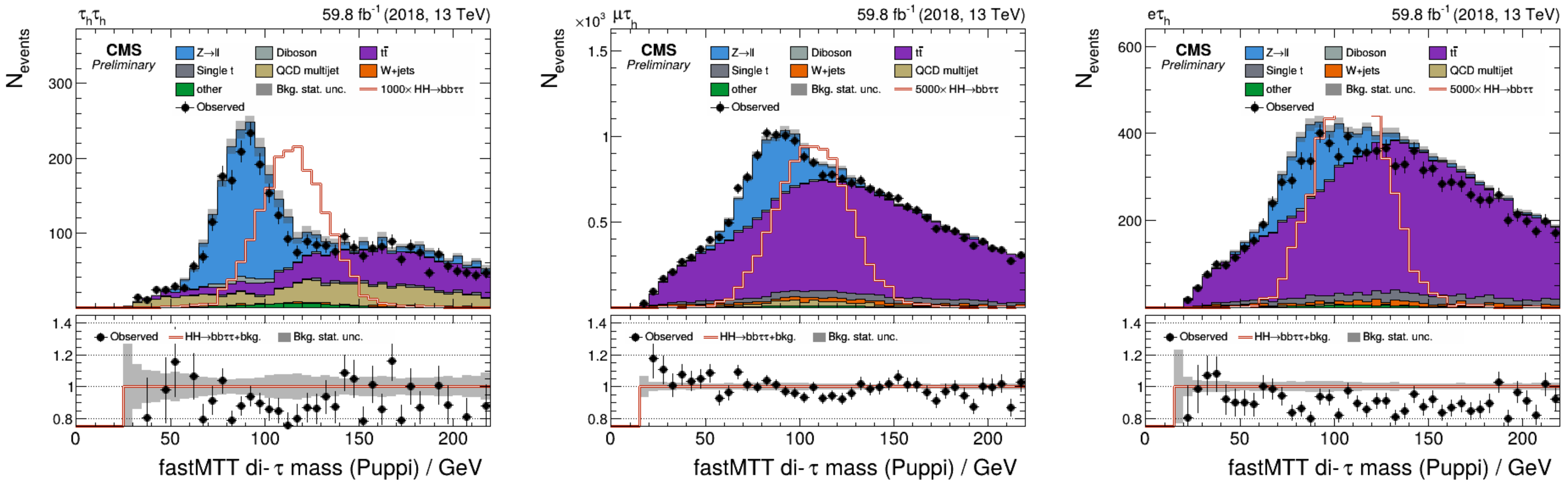
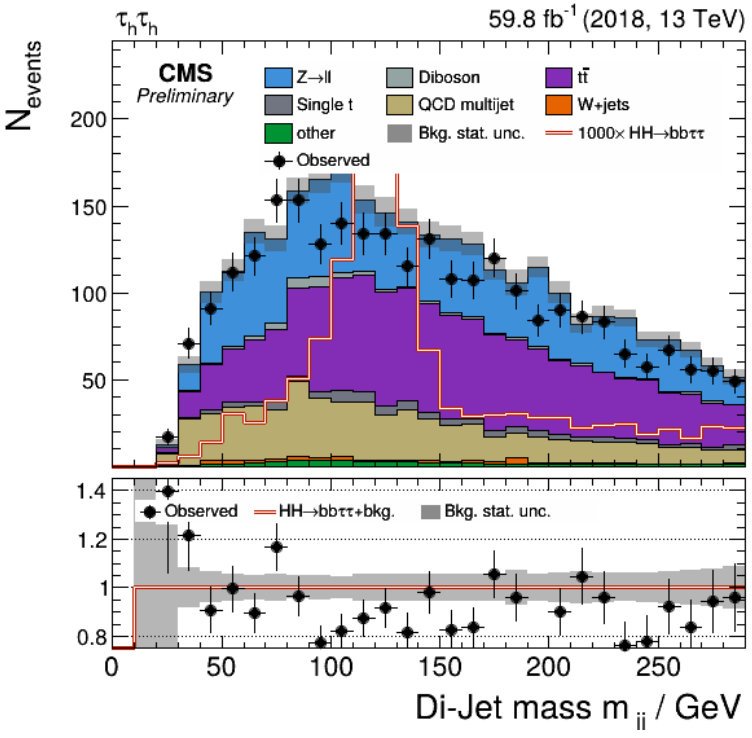
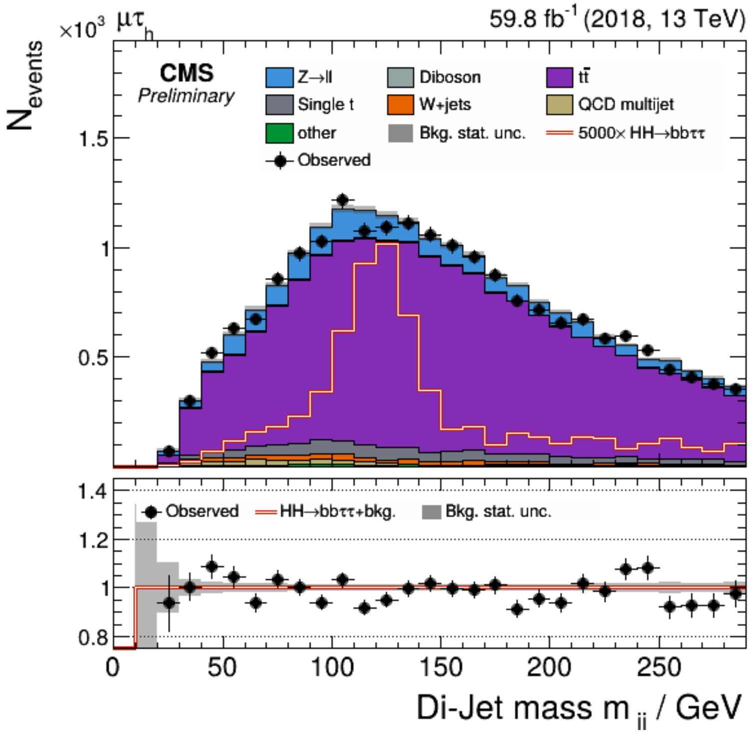
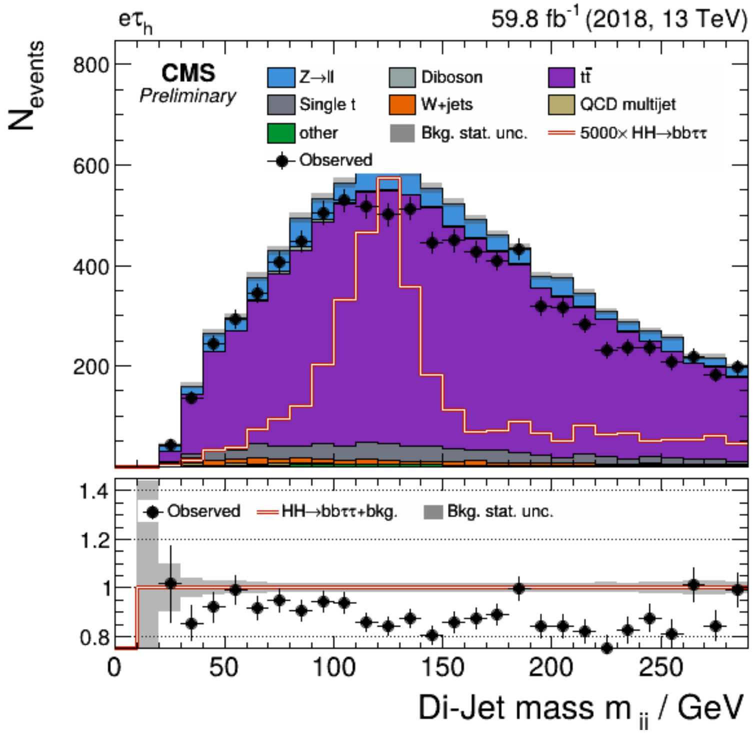


Control plots
Standard features







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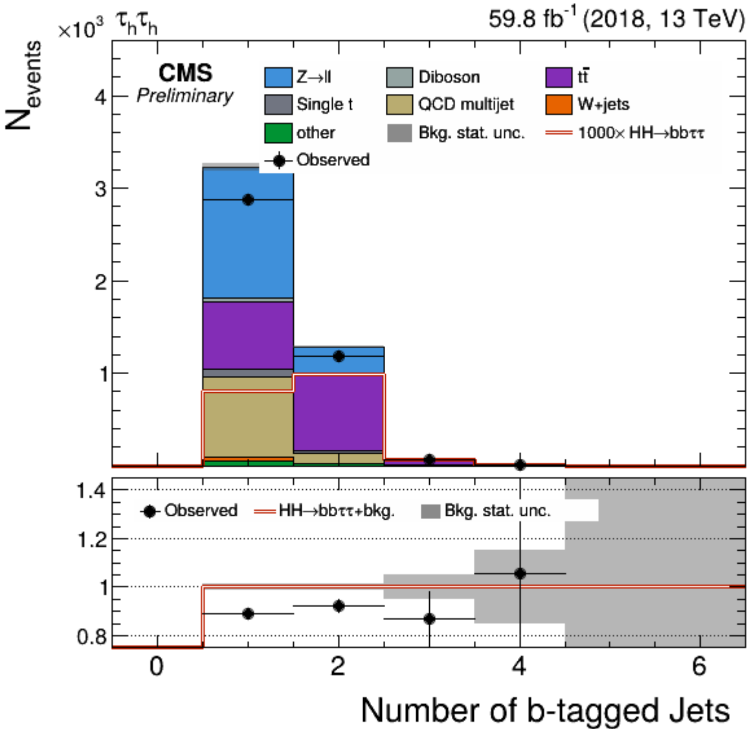

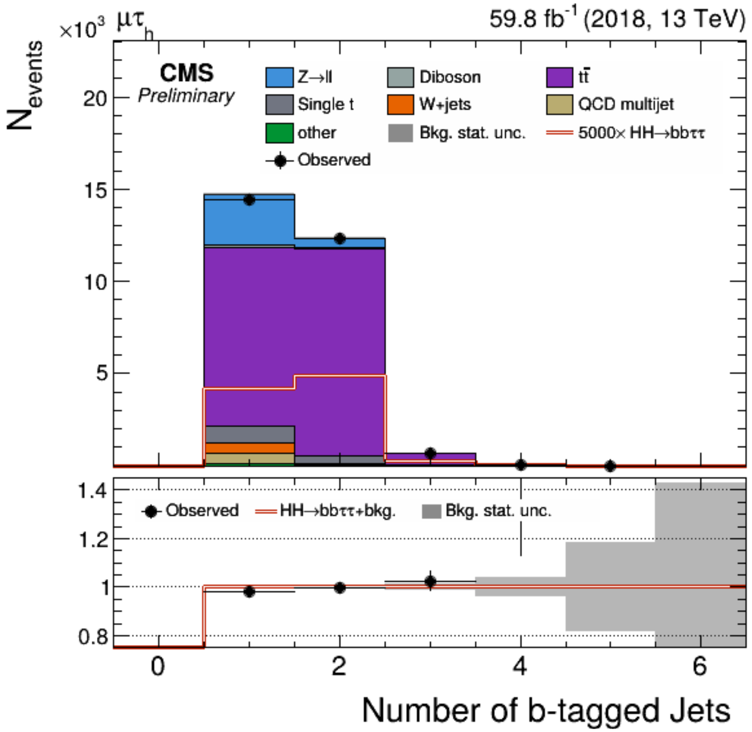

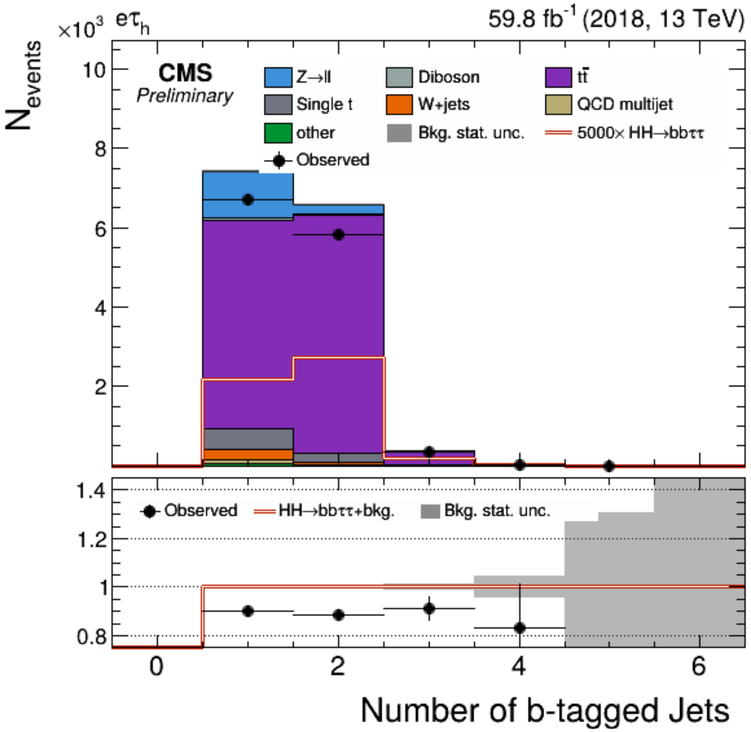

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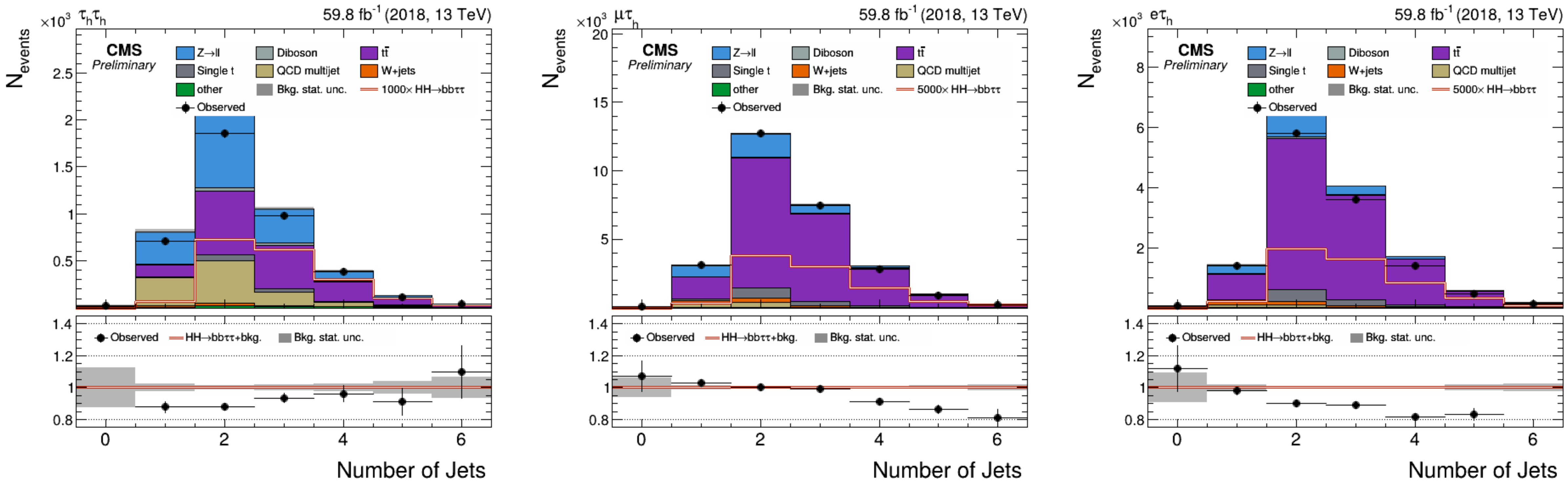

Control plots
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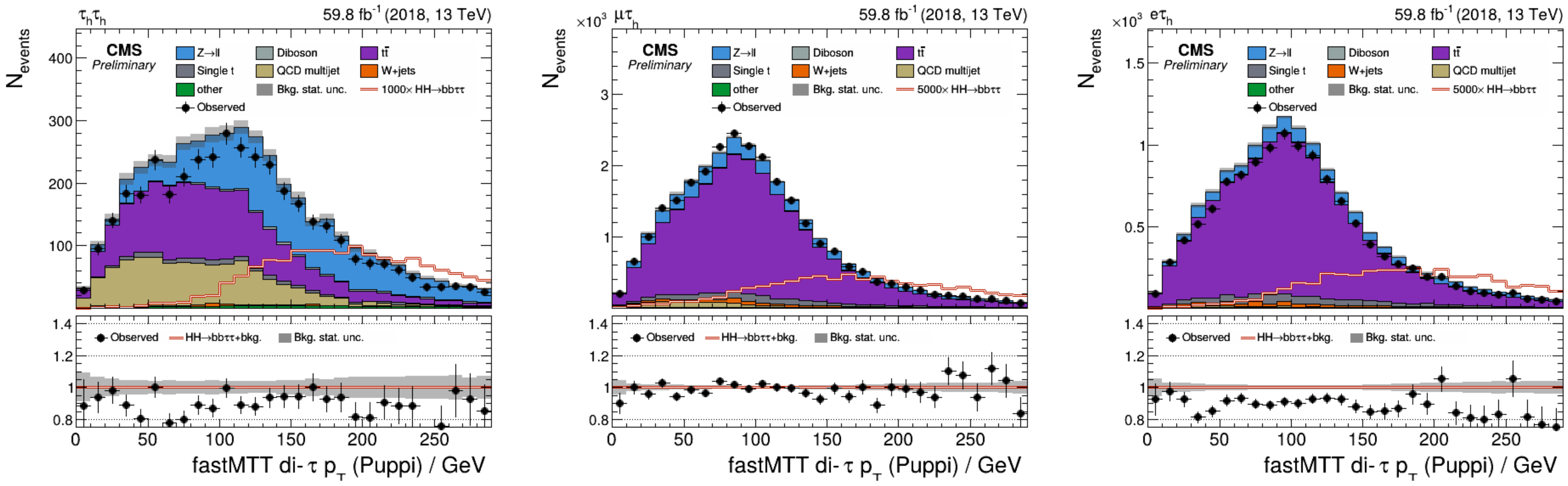
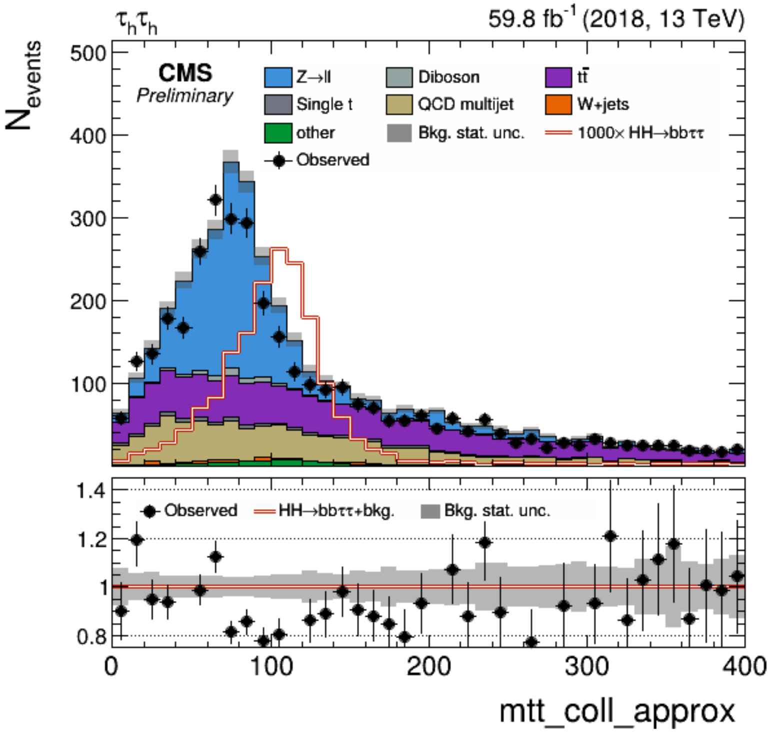
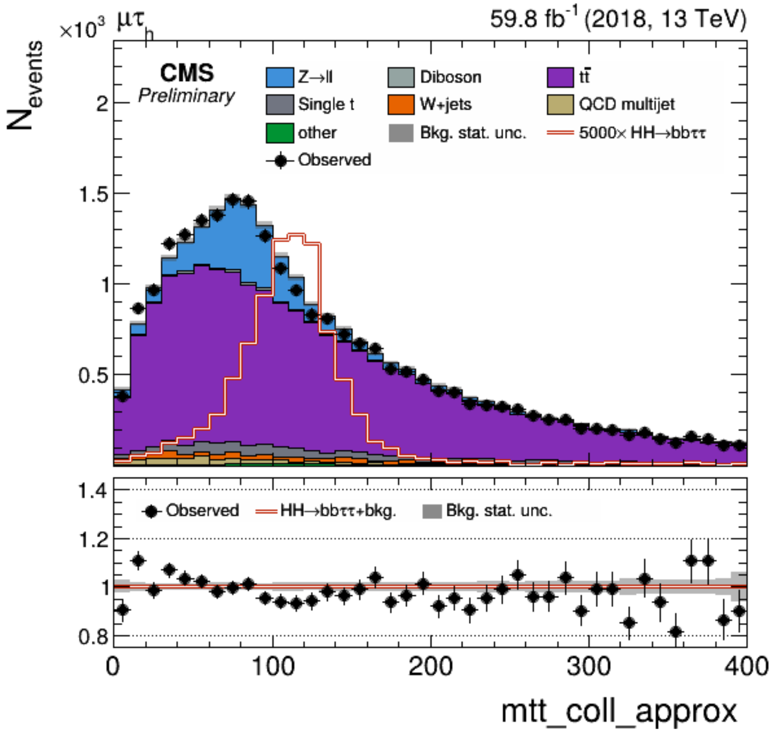
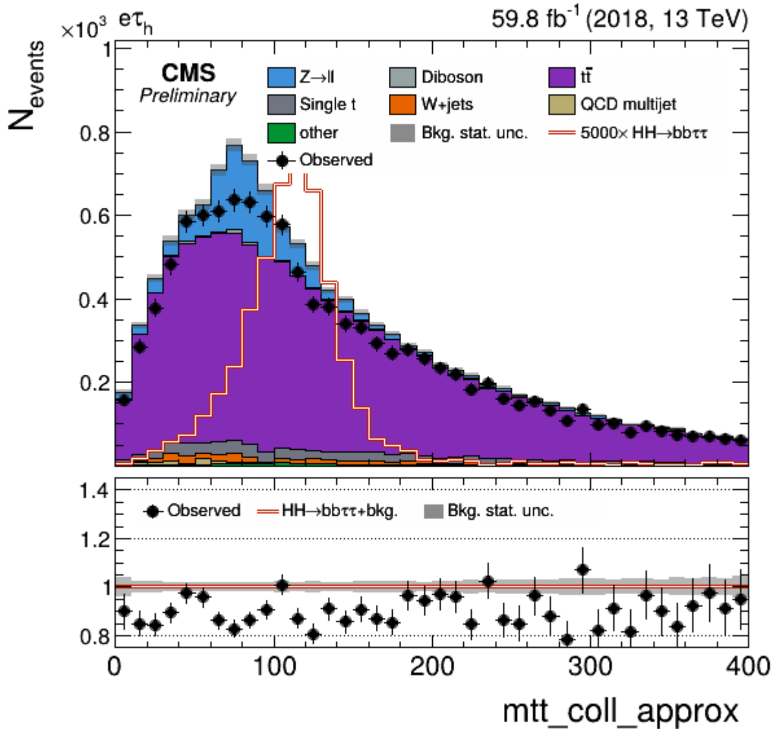


Control plots

Extended features







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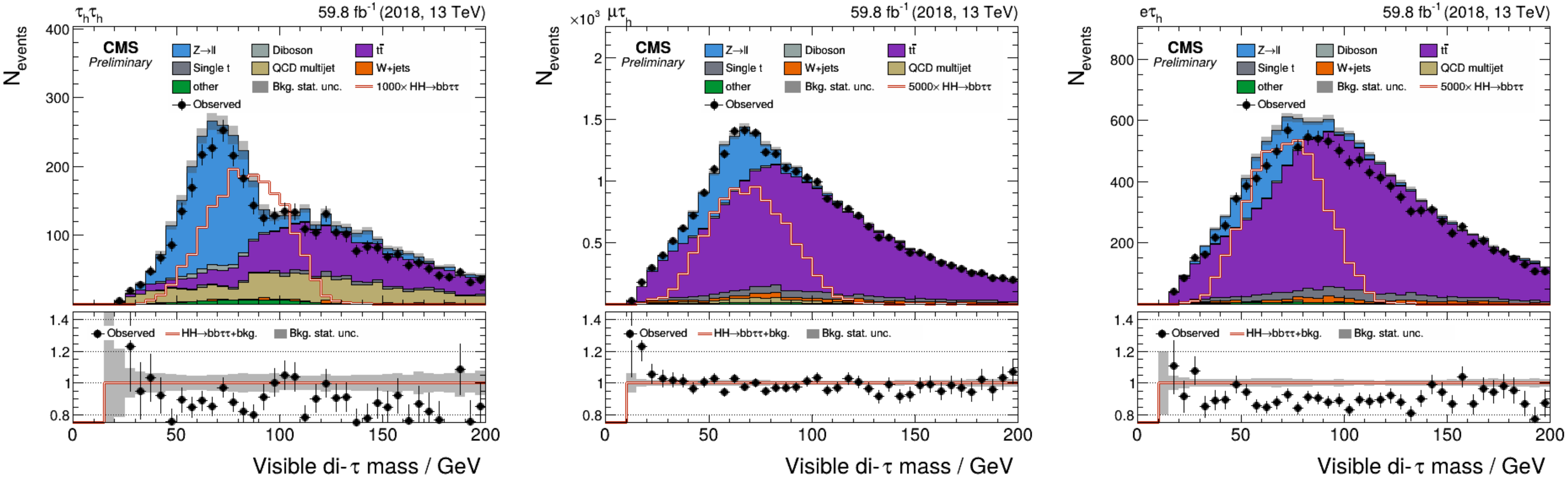

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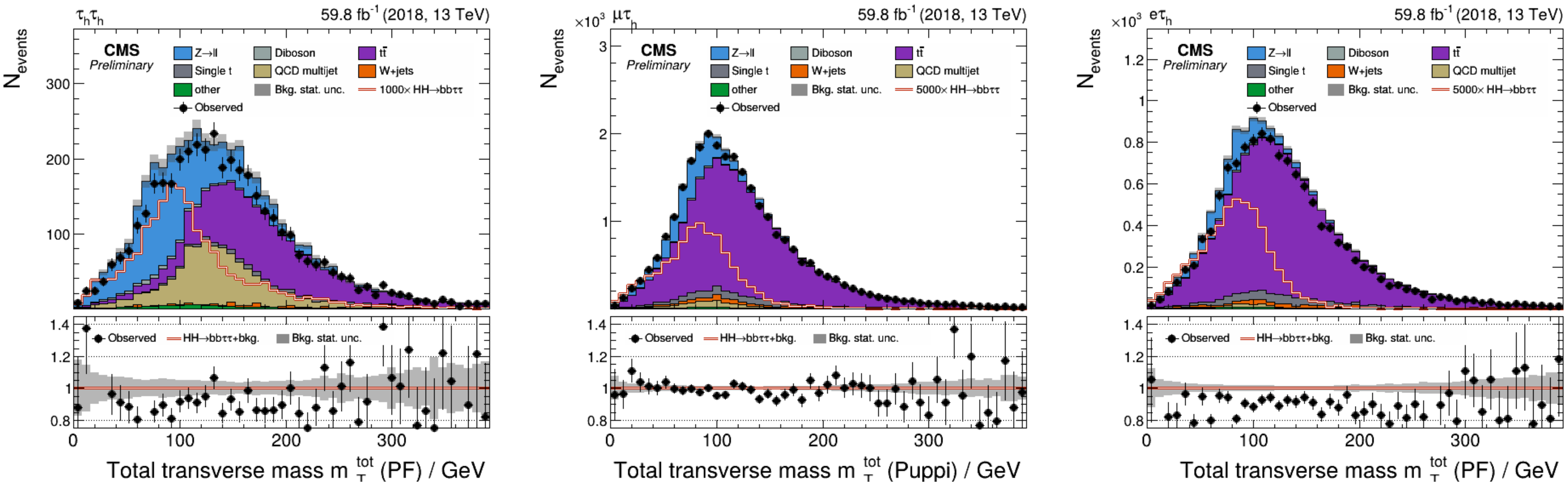
Extended features



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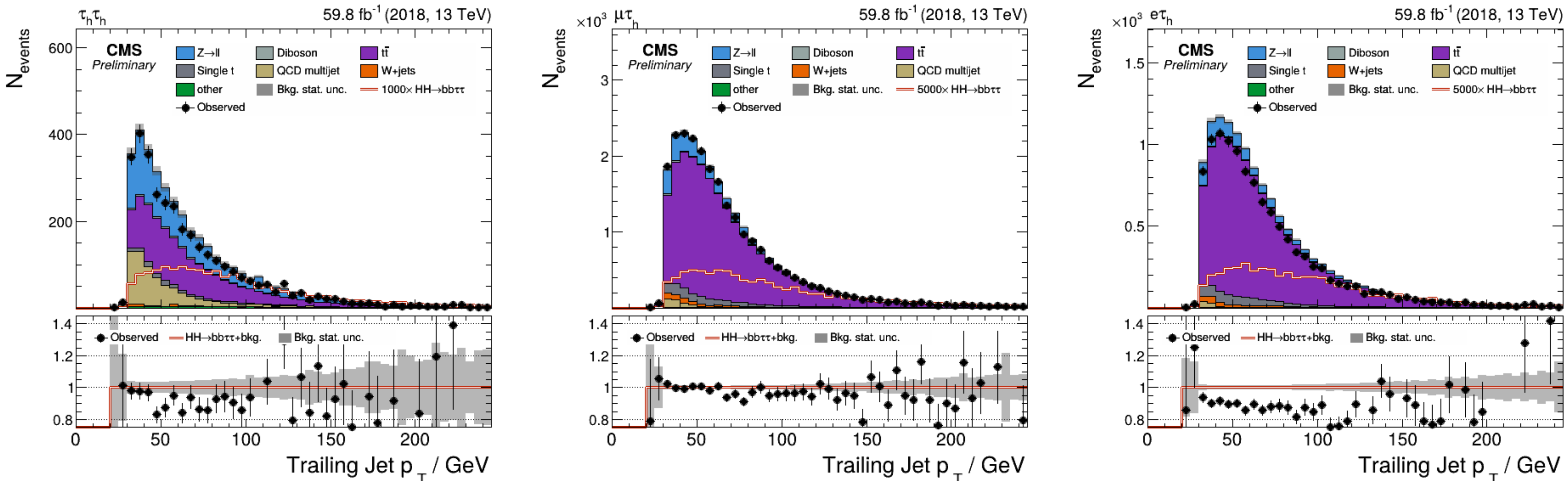

Control plots

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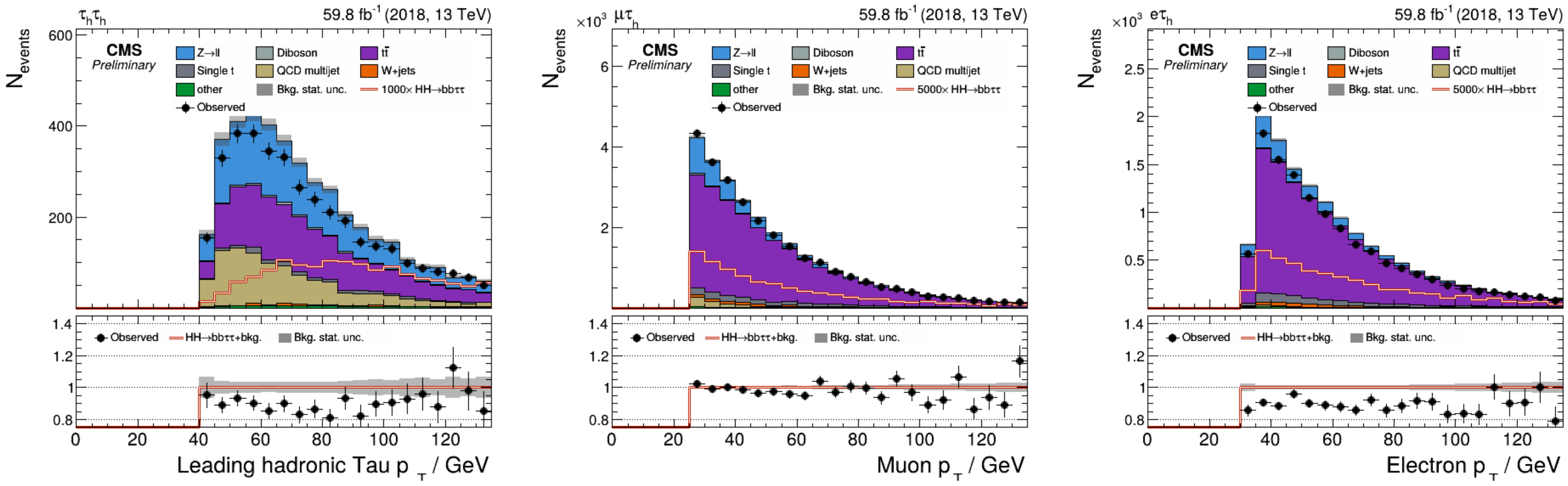
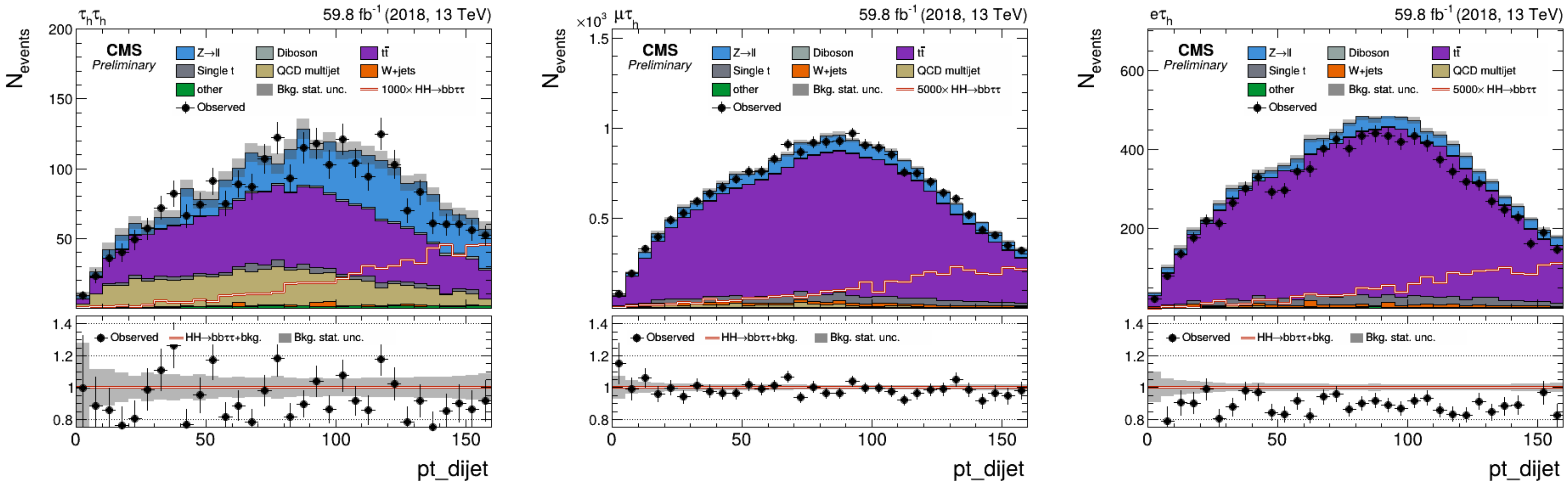


Control plots
Extended features



Control plots

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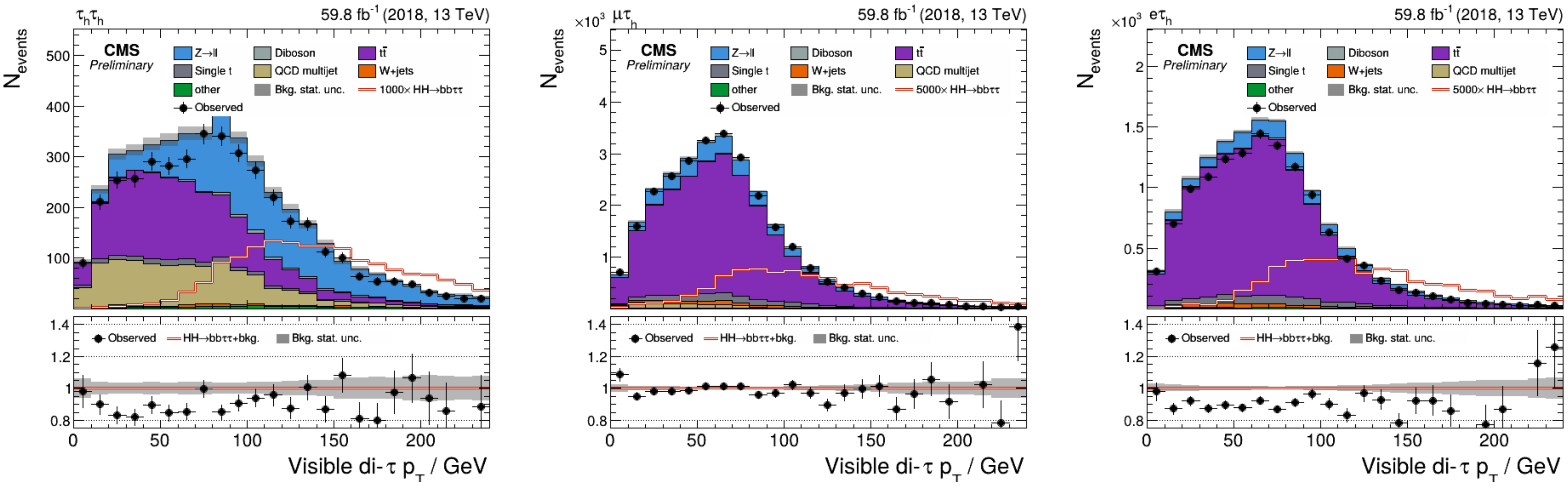

Systematic uncertainties

Systematic uncertainties

Nuisance	Processes	Channels	Size (up/down)
eff_e	all	et	1.02
eff_m	all	mt	1.02
eff_t_vsLep	all	et,mt	1.01
eff_t_vsLep	all	tt	1.02
eff_t_vsJet†	all	et,mt	1.02
eff_t_vsJet†	all	tt	1.04
lumi_13TeV	all	all	1.025
htt_vvXsec	diboson	all	1.05
htt_stXsec	single t	all	1.05
htt_tjXsec	$t\bar{t}$	all	1.06
htt_wjXsec	W	all	1.04
htt_zjXsec	DY	all	1.02
QCDNorm	QCD	et, mt	1.108
QCDNorm	QCD	tt	1.216
QCDscale_ttH, pdf_ttH, alphaS_ttH	ttH	all	(1.058/0.908), 1.030, 1.020
QCDscale_ggH, pdf_ggH, alphaS_ggH	ggH	all	1.039, 1.019, 1.026
QCDscale_qqH, pdf_qqH, alphaS_qqH	qqH	all	(1.004/0.997), 1.021, 1.005
QCDscale_VH, pdf_VH, alphaS_VH	VH(WH+ZH)	all	(1.038/0.970), 1.017, 1.009
QCDscale_HH	signal	all	(1.022/0.950)
PDF_alphas_HH	signal	all	1.030
mtop_HH	signal	all	1.026
BR_h_bb	signal	all	(1.0125/0.9873)
BR_h_tautau	signal	all	1.0165