Search for lepton flavor violating decays of Higgs boson into $\mu\tau$ and $e\tau$ final states

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Higgs Hunting

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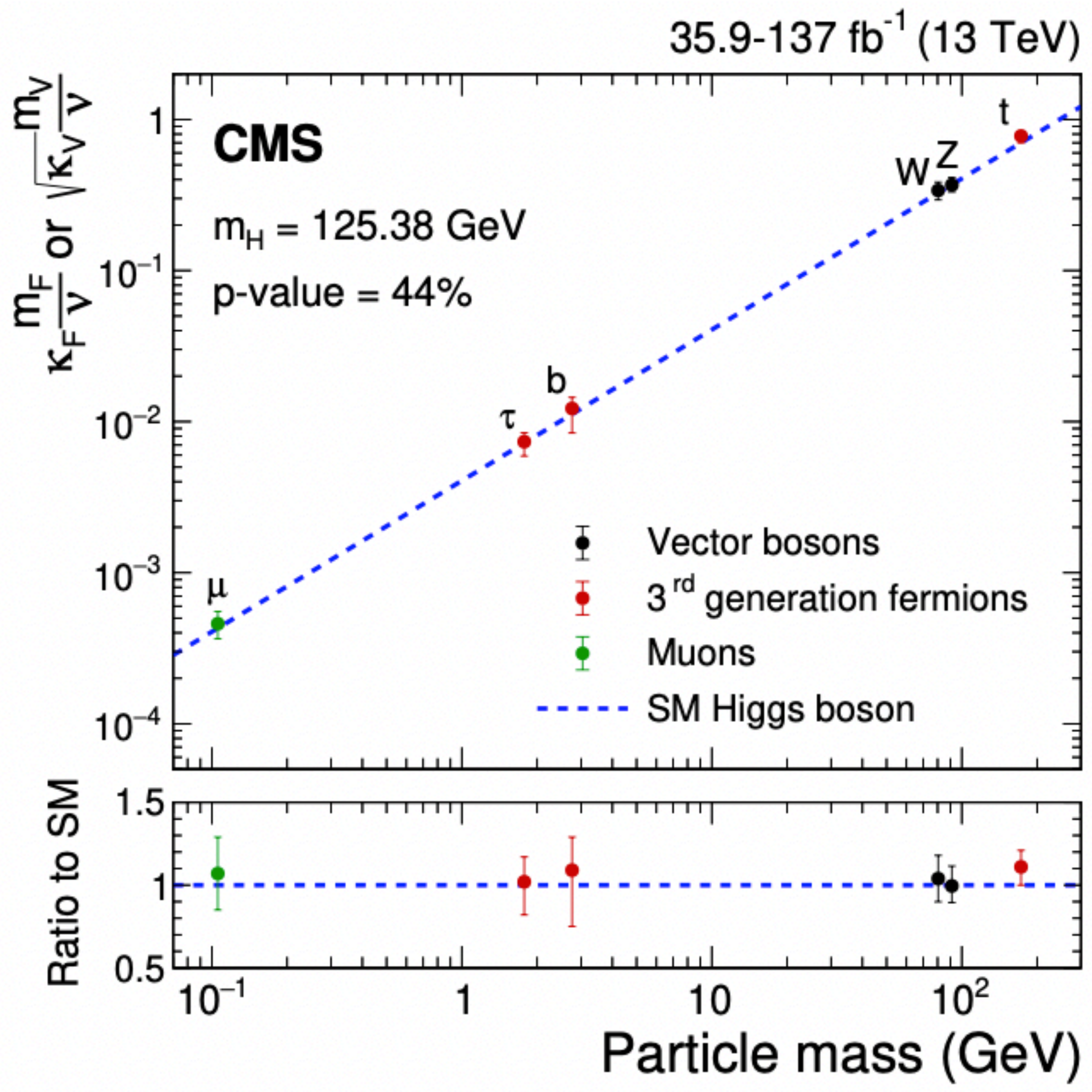
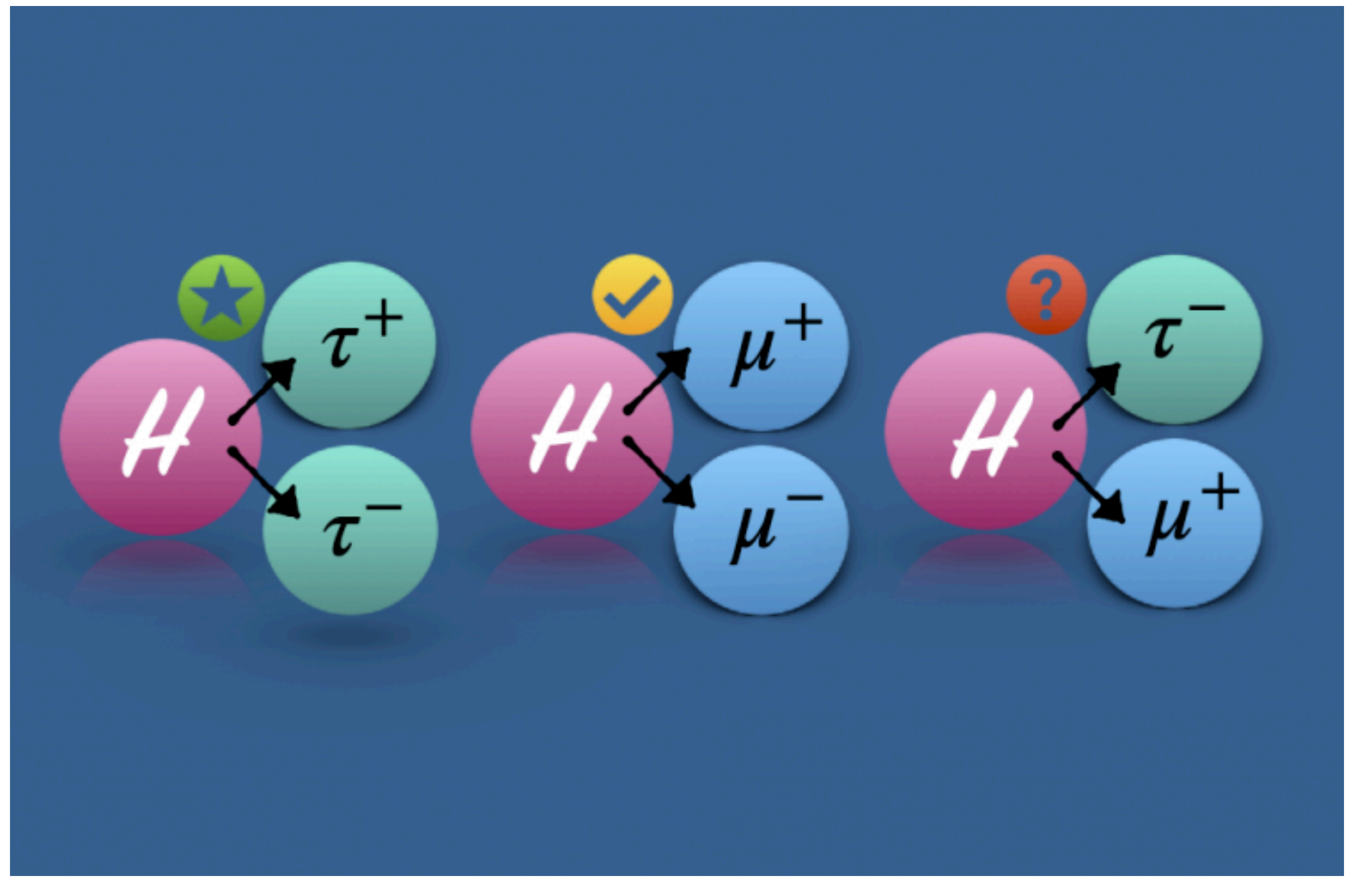
Introduction

- Higgs interactions with fermions gives rise to their mass:

$$\mathscr{L} = \frac{g}{\sqrt{2}}(\bar{\ell}_L \ell_R + \bar{\ell}_R \ell_L)\nu + \frac{g}{\sqrt{2}}(\bar{\ell}_L \ell_R + \bar{\ell}_R \ell_L)h$$

- If mass and the Yukawa matrices are not simultaneously diagonalizable, then the off-diagonal Yukawa couplings can give rise to lepton flavor violating (LFV) Higgs decays
- LFV decays arise in models with more than one Higgs boson doublet, certain supersymmetric models, composite Higgs models, models with flavor symmetries, etc.
- Neutrino oscillations also suggest that lepton flavor is not conserved, however, no charged LFV has been observed to date



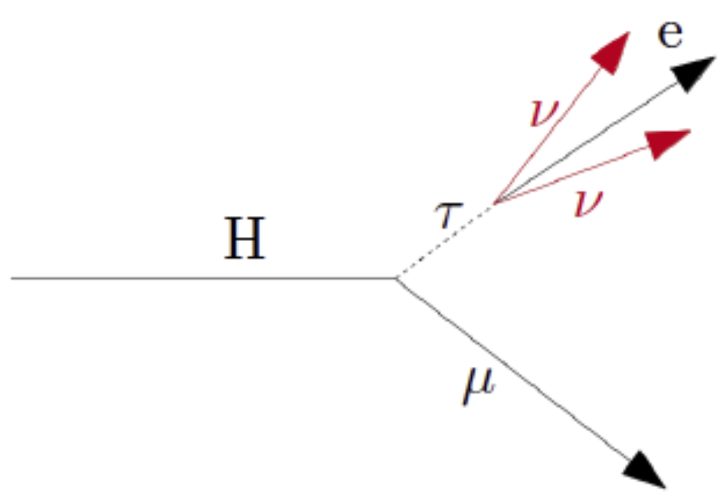


Analysis Overview

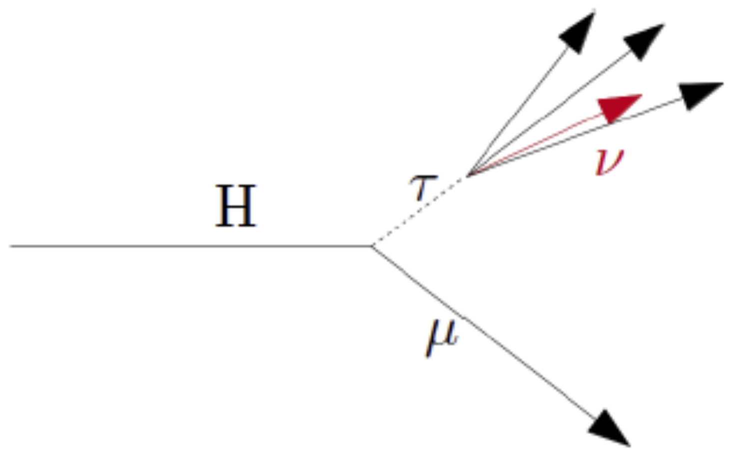
- Channels and final states:
  - $H \to \mu\tau_h$, $H \to \mu\tau_e$, $H \to e\tau_h$, and $H \to e\tau_\mu$
  - $H \to \mu\tau_\mu$ and $H \to e\tau_e$ are not considered because of large Drell-Yan background

- Categories:
  - 0 jet: targeting $gg \to H$
  - 1 jet: targeting $gg \to H$ with Higgs recoiling against a jet (ISR)
  - 2 jets and $m_{jj} < 500/550$ GeV ($e\tau/\mu\tau$): targeting $gg \to H$ with additional jets
  - 2 jets and $m_{jj} \geq 500/550$ GeV ($e\tau/\mu\tau$): targeting $qq \to H$

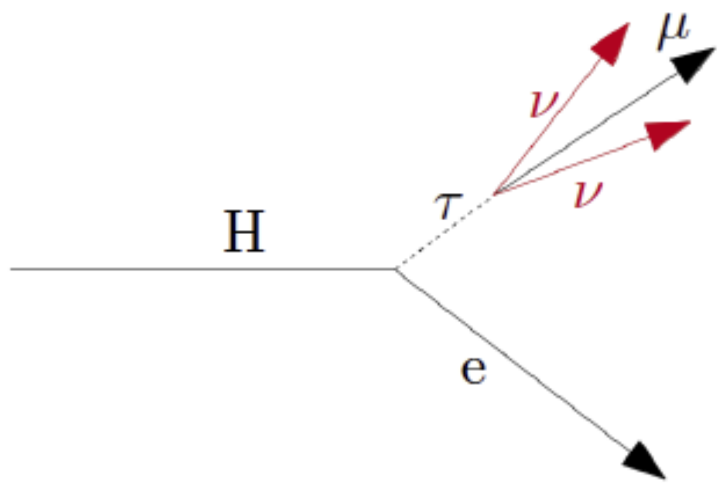
- Signal extraction:
  - BDT trained with adaptive boosting in TMVA to discriminate signal from background
  - Maximum likelihood fit of BDT discriminator distributions



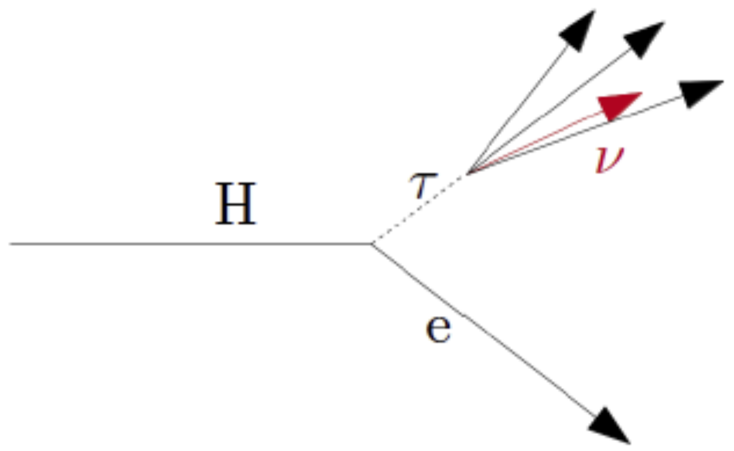
(a) leptonic: $H \to \mu\tau_e$



(b) hadronic: $H \to \mu\tau_h$



(c) leptonic: $H \to e\tau_\mu$

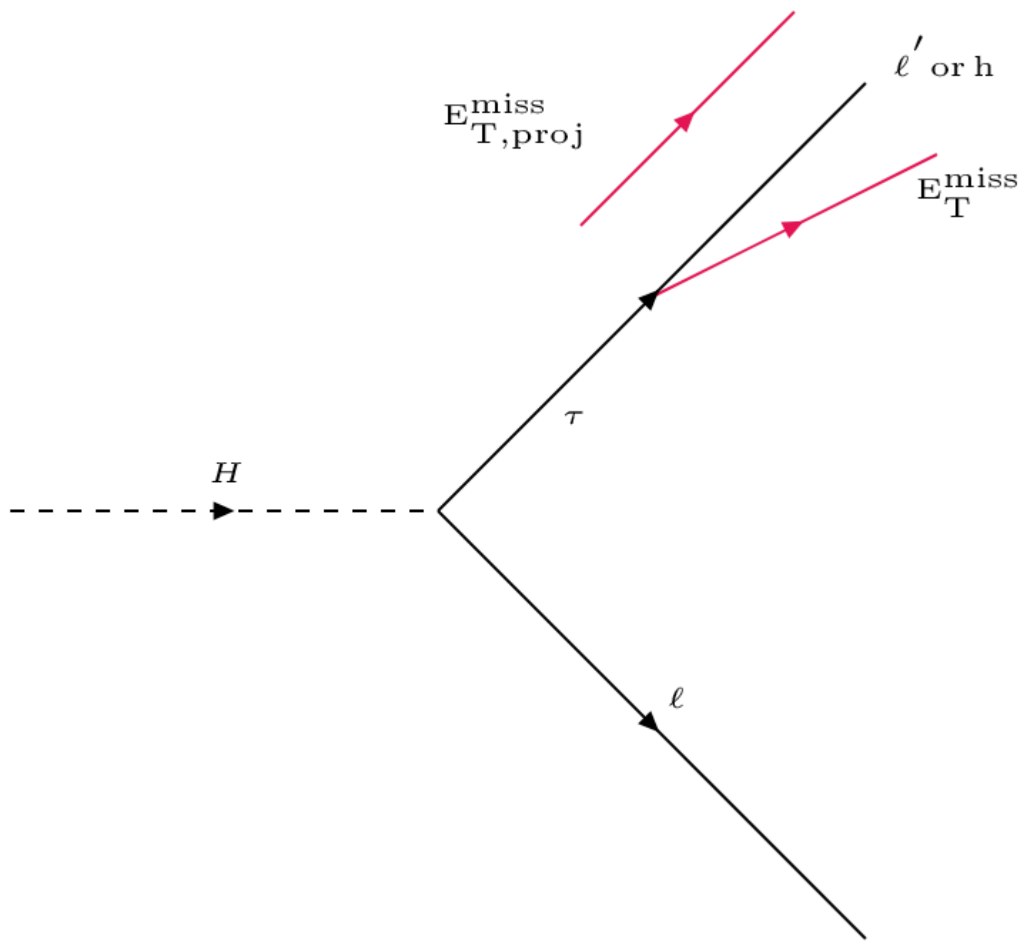


(d) hadronic: $H \to e\tau_h$

Mass Variables

- Transverse mass: $M_T(\ell) = \sqrt{2|\overrightarrow{p_T^{\ell}}||\overrightarrow{p_T^{miss}}|(1 - cos\Delta\phi_{\ell - p_T^{miss}})}$, where $\Delta\phi_{\ell - p_T^{miss}}$ is the angle in the transverse plane between the lepton and the MET

- Collinear mass: τ produced from Higgs decay is Lorentz boosted, so we assume the neutrino(s) produced from the decay of τ is(are) collinear with it's visible decay products

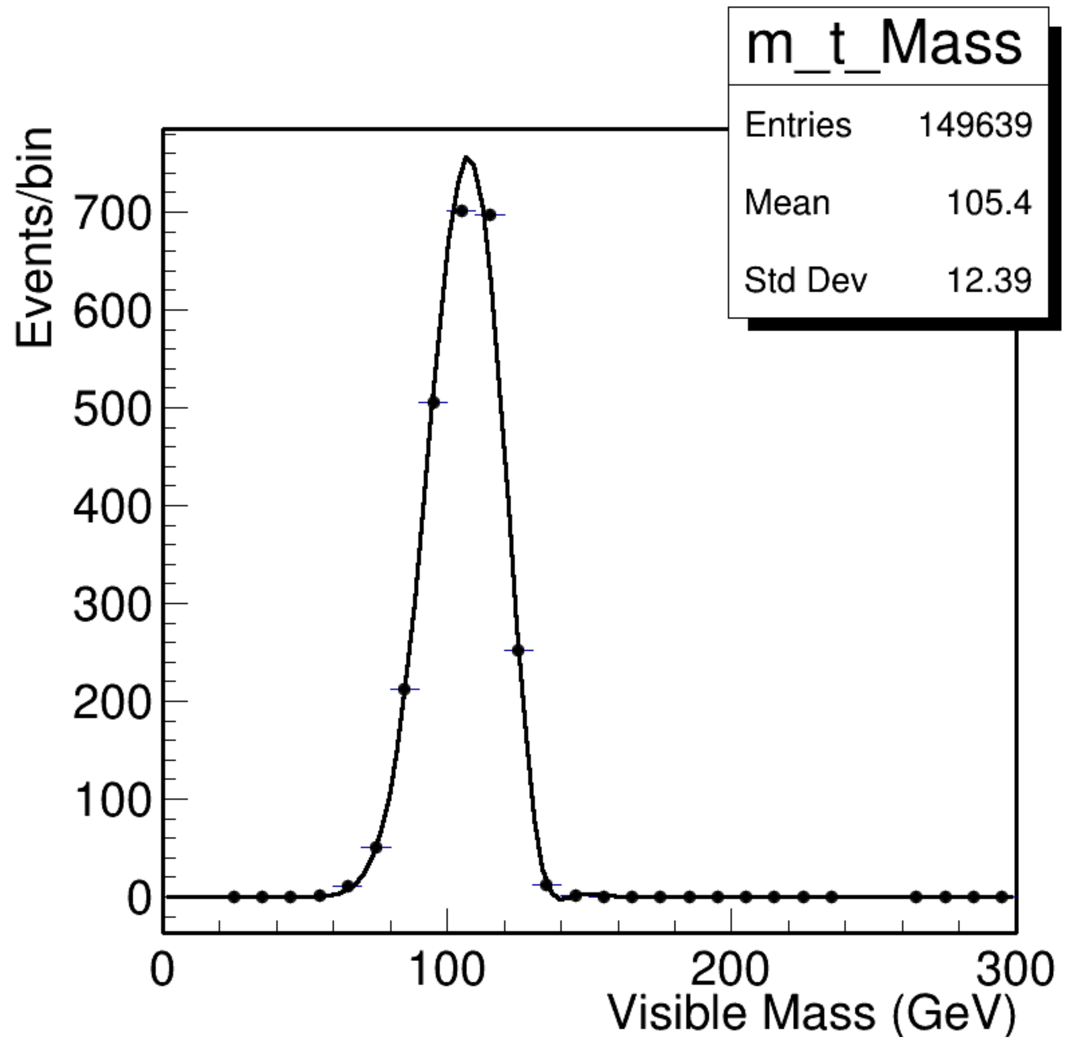


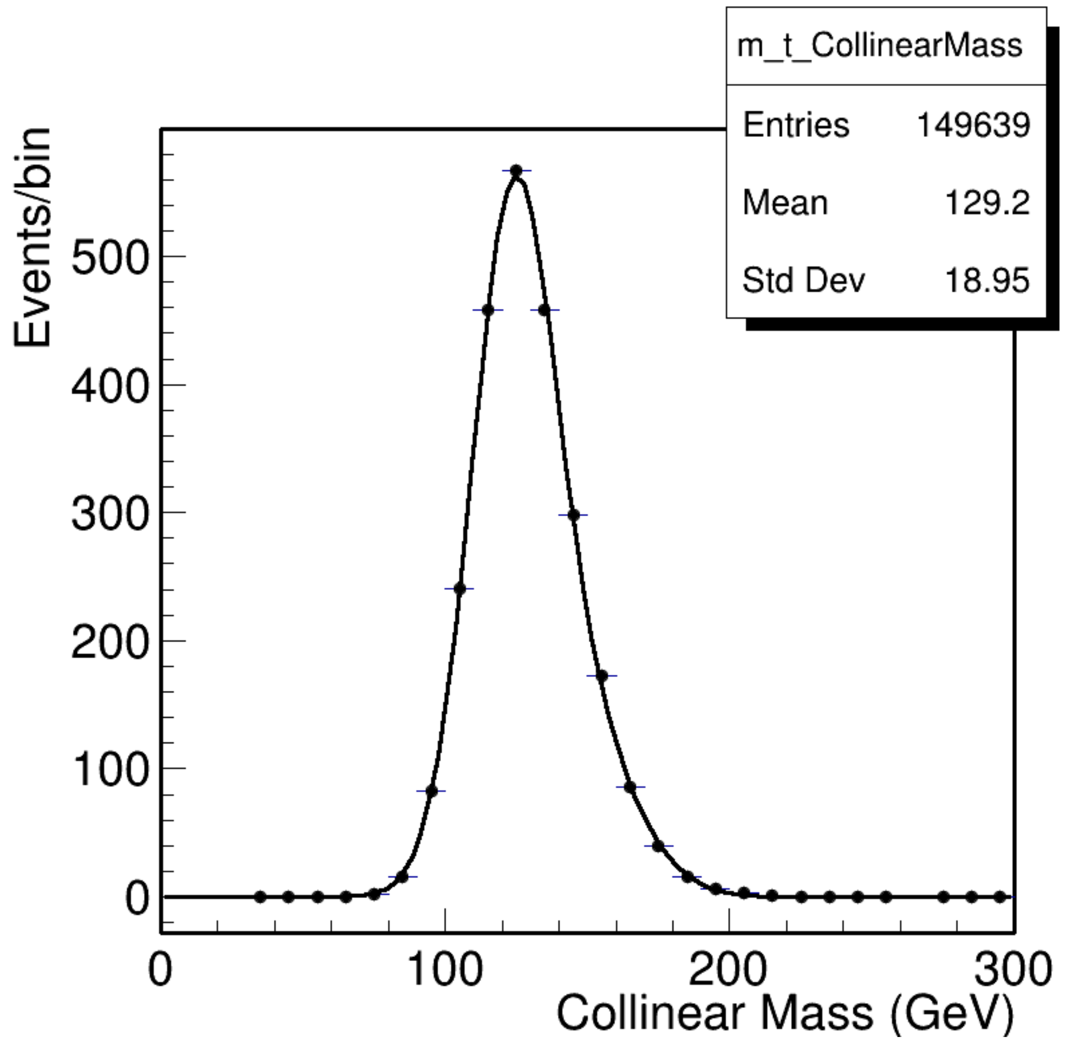
$$|\overrightarrow{p}_T^{\nu}| = \overrightarrow{E}_T^{miss} \cdot \overrightarrow{p}_T^{\tau_{vis}}$$

$$x_{\tau_{vis}} = \frac{|\overrightarrow{p}_T^{\tau_{vis}}|}{|\overrightarrow{p}_T^{\tau_{vis}}| + |\overrightarrow{p}_T^{\nu}|}$$

$$M_{vis} = \sqrt{2p_T^{e/\mu}p_T^{\tau}(1 - cos\Delta\phi)}$$

$$M_H \approx M_{collinear} = \frac{M_{vis}}{\sqrt{x_{\tau_{vis}}}}$$





Event Selection

TABLE I. Event selection criteria for the $H \to \mu\tau$ channels.

Variable	$\mu\tau_h$	$\mu\tau_e$
p_T^e	...	>13 GeV
p_T^μ	>26 GeV	>24 GeV
$p_T^{\tau_h}$	>30 GeV	...
$\|\eta\|^e$	...	<2.5
$\|\eta\|^\mu$	<2.1	<2.4
$\|\eta\|^{\tau_h}$	<2.3	...
I_{rel}^e	...	<0.1
I_{rel}^μ	<0.15	<0.15
Trigger requirement	$p_T^\mu > 24$ GeV (all years) $p_T^\mu > 27$ GeV (2017)	$p_T^e > 12$ GeV $p_T^\mu > 23$ GeV

TABLE II. Event selection criteria for the $H \to e\tau$ channels.

Variable	$e\tau_h$	$e\tau_\mu$
p_T^e	>27 GeV	>24 GeV
p_T^μ	...	>10 GeV
$p_T^{\tau_h}$	>30 GeV	...
$\|\eta\|^e$	<2.1	<2.5
$\|\eta\|^\mu$	...	<2.4
$\|\eta\|^{\tau_h}$	<2.3	...
I_{rel}^e	<0.15	<0.1
I_{rel}^μ	...	<0.15
Trigger requirement	$p_T^e > 25$ GeV (2016) $p_T^e > 27$ GeV (2017) $p_T^e > 32$ GeV (2018) $p_T^e > 24$ GeV and $p_T^{\tau_h} > 30$ GeV (2017, 2018)	$p_T^e > 23$ GeV $p_T^\mu > 8$ GeV

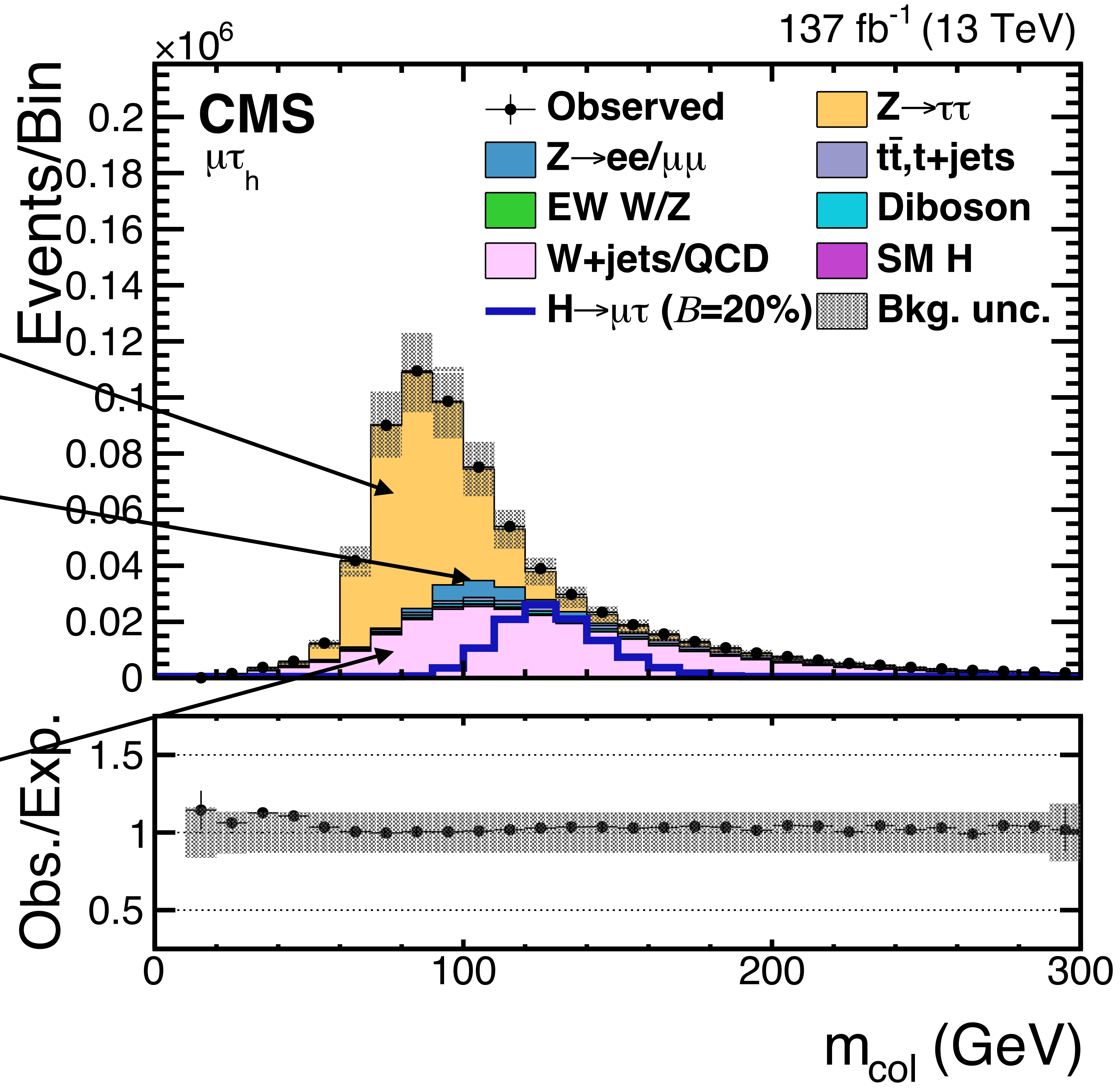
- "DeepTau" is used to distinguish taus decaying hadronically against jets, electrons, and muons with high efficiency and low mis-identification probability

- Events with b-tagged jets ($p_T > 20$ GeV, $|\eta| < 2.4$) identified by the "DeepCSV" discriminator are vetoed

- Events with additional leptons or hadronic taus are vetoed

Background Processes

Hadronic Channels



$\underline{Z \rightarrow \tau\tau}$
From Embedded Technique

$\underline{Z \rightarrow \mu\mu/ee}$
From MC Simulation

Misidentified lepton background
(Fully or Semi-data driven method)

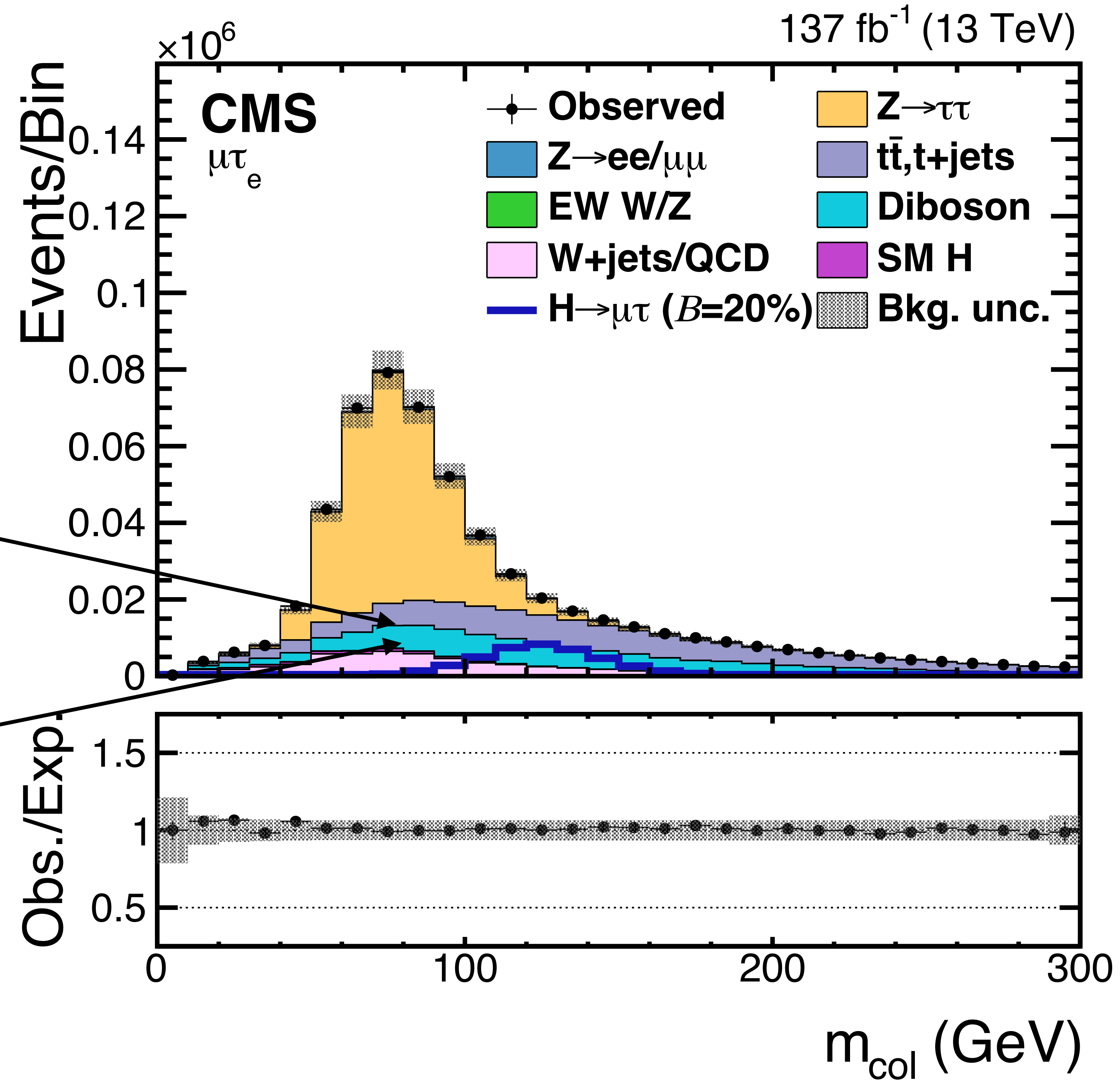
Leptonic Channels

SM Higgs
From MC Simulation

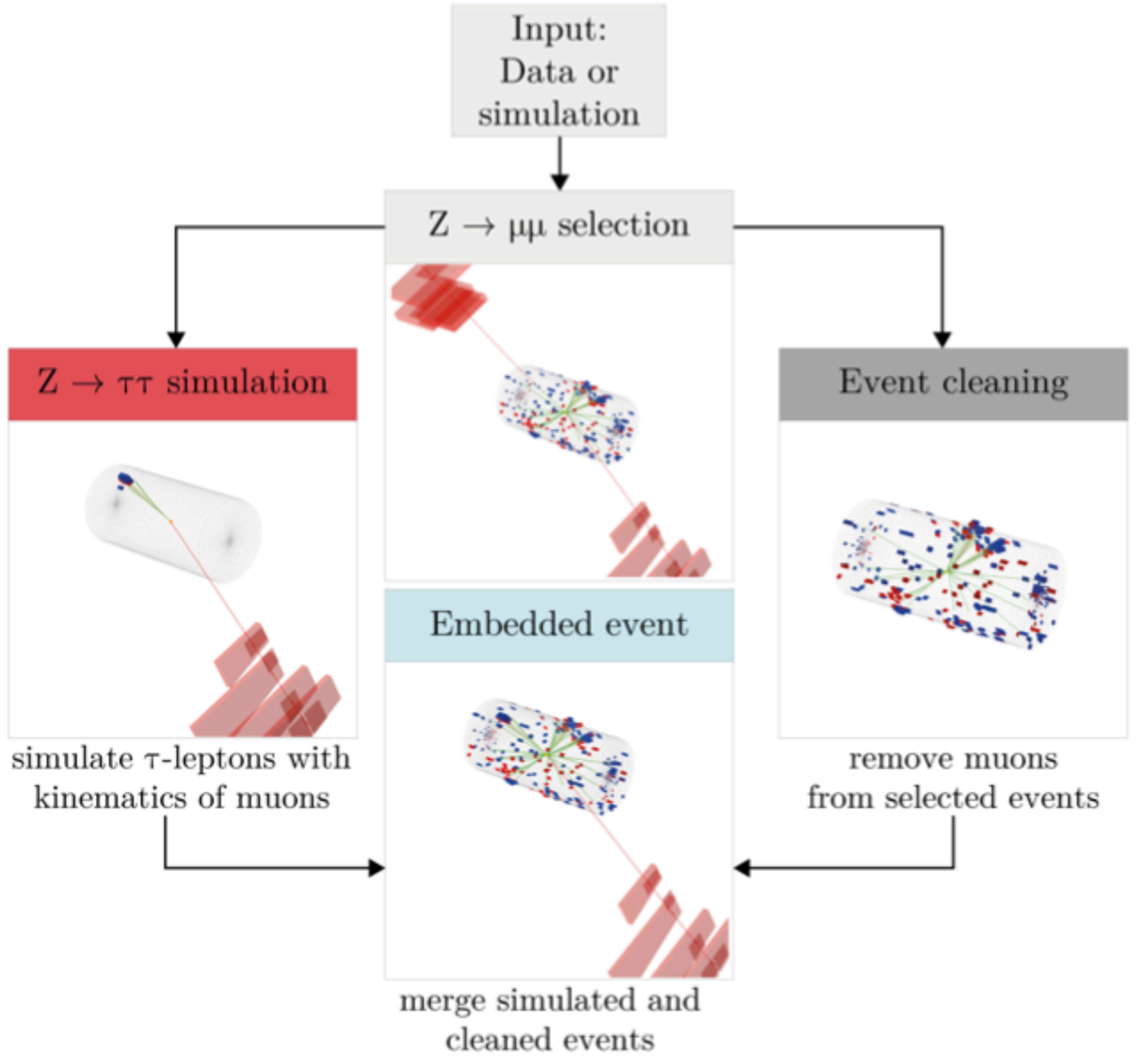
tt̄/Single Top
From MC Simulation

Diboson
From MC Simulation

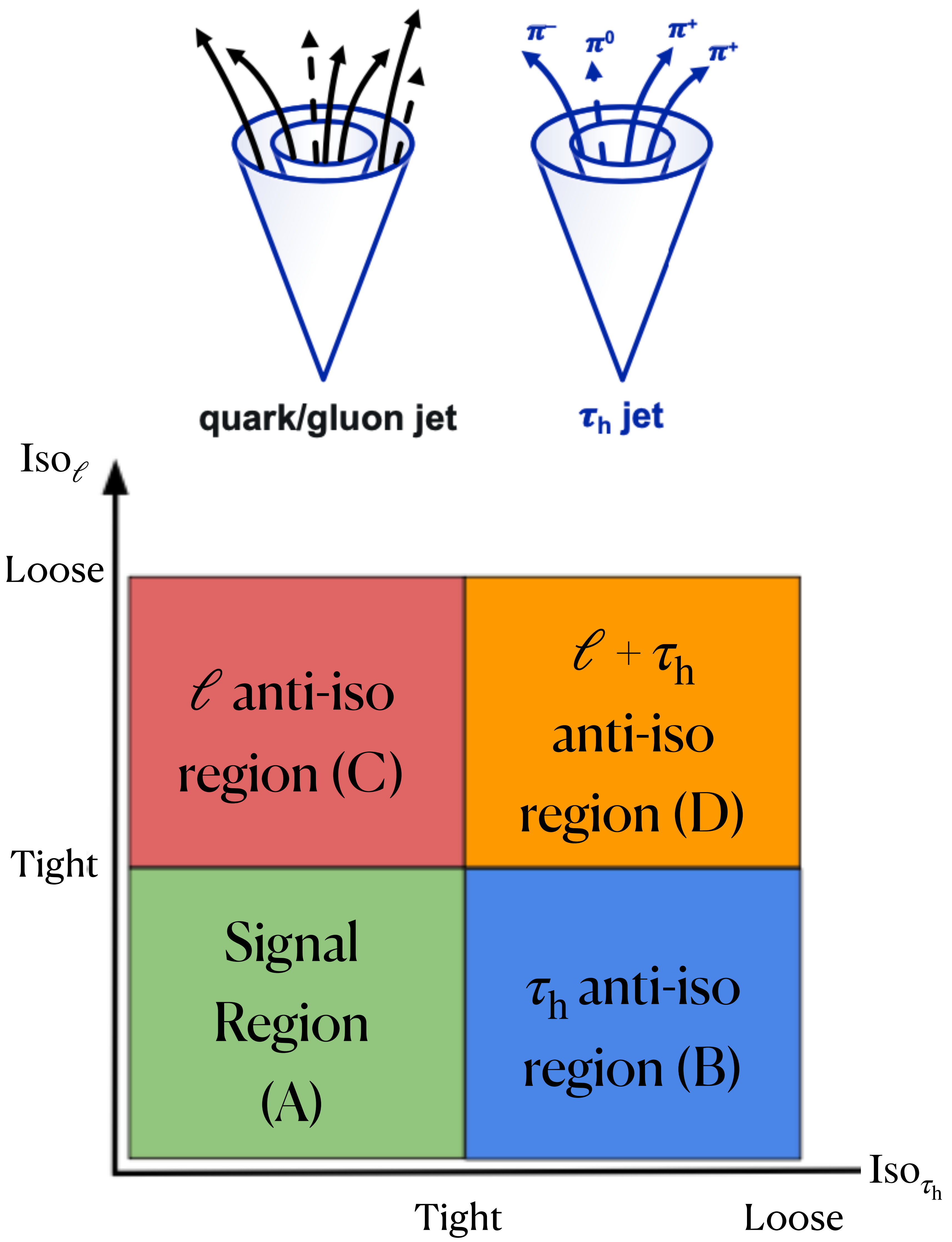
EWKW/Z
From MC Simulation



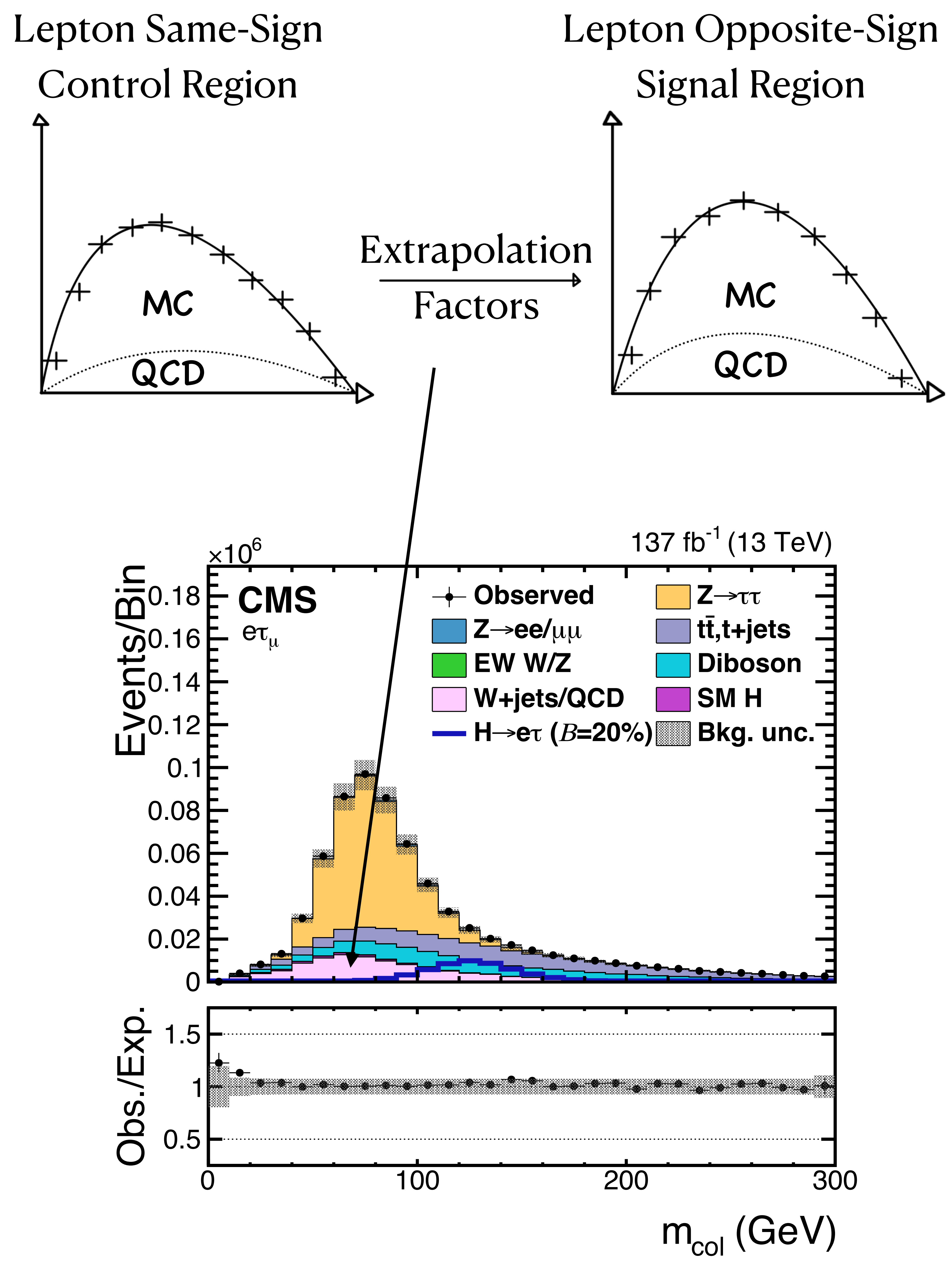
Background Estimation



Embedding Technique



Misidentified lepton background in hadronic channels



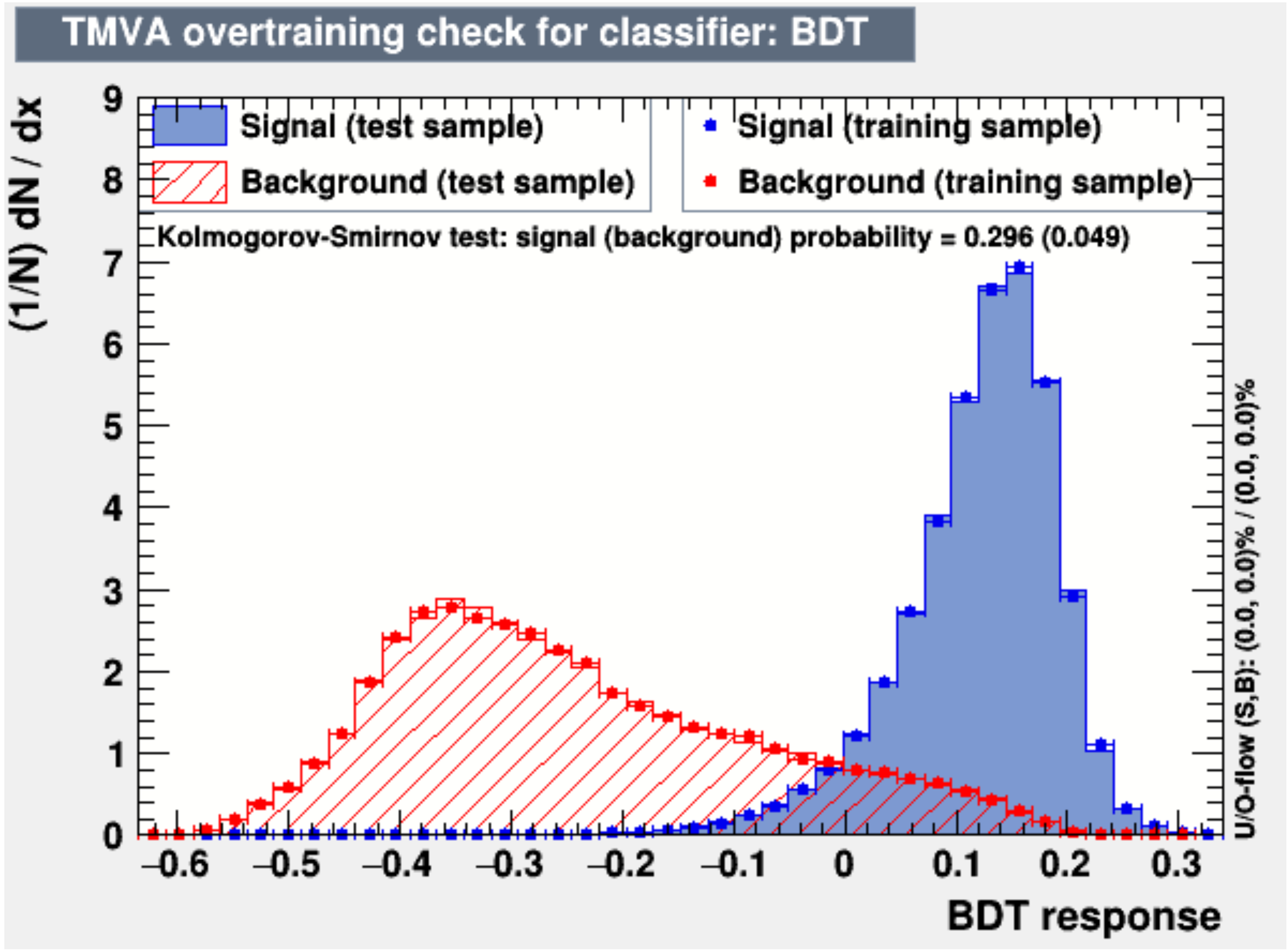
Misidentified lepton background in leptonic channels

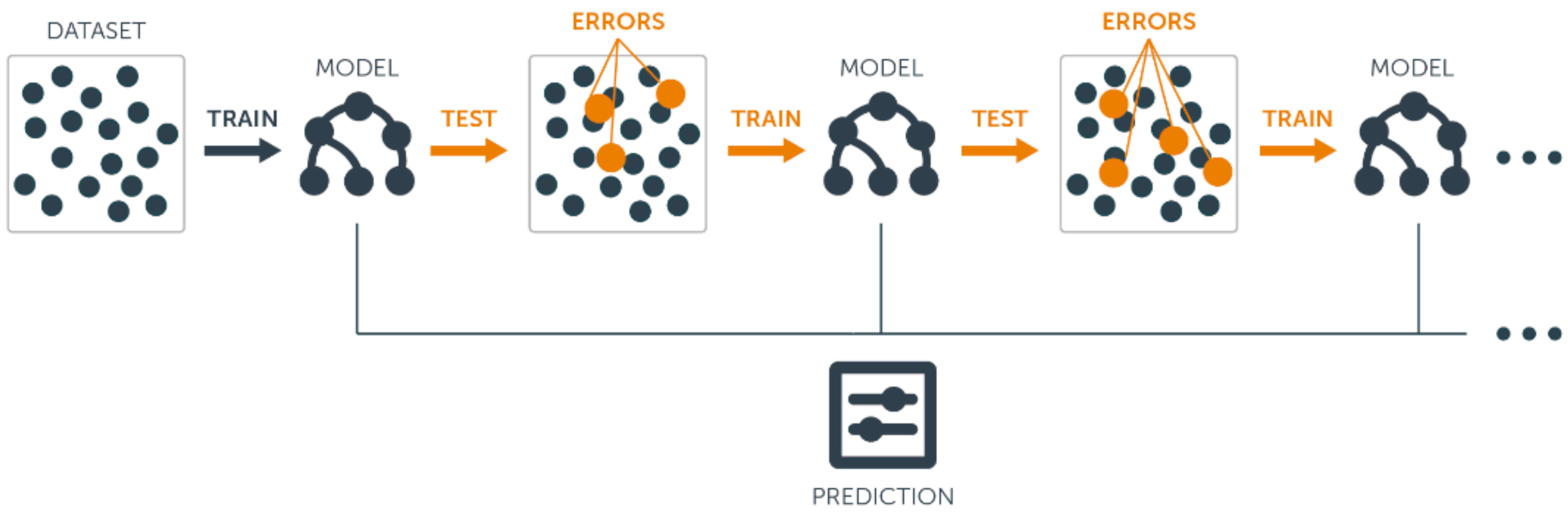
Classification

- Classification is done using the BDT adaptive boosting technique for discriminating the signal from background

- Training is done with the signal as GluGlu/VBF samples weighted according to their production cross-section

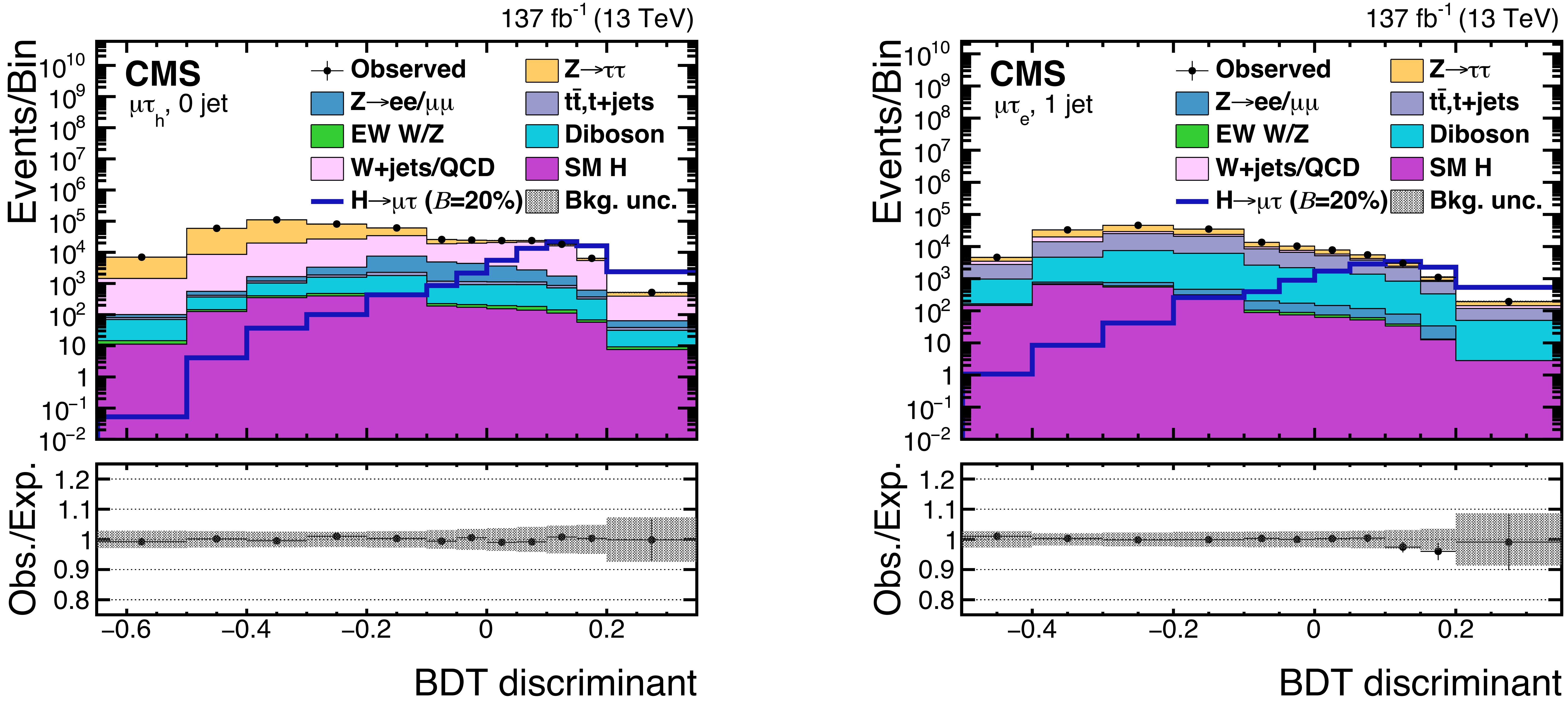
- Background used for training is a representative subset of the background samples





- Input variables to the BDT are:
  - Collinear mass
  - Visible mass
  - Transverse mass
  - Missing transverse momentum (MET)
  - Spatial separation between leptons and MET
  - Lepton transverse momentum

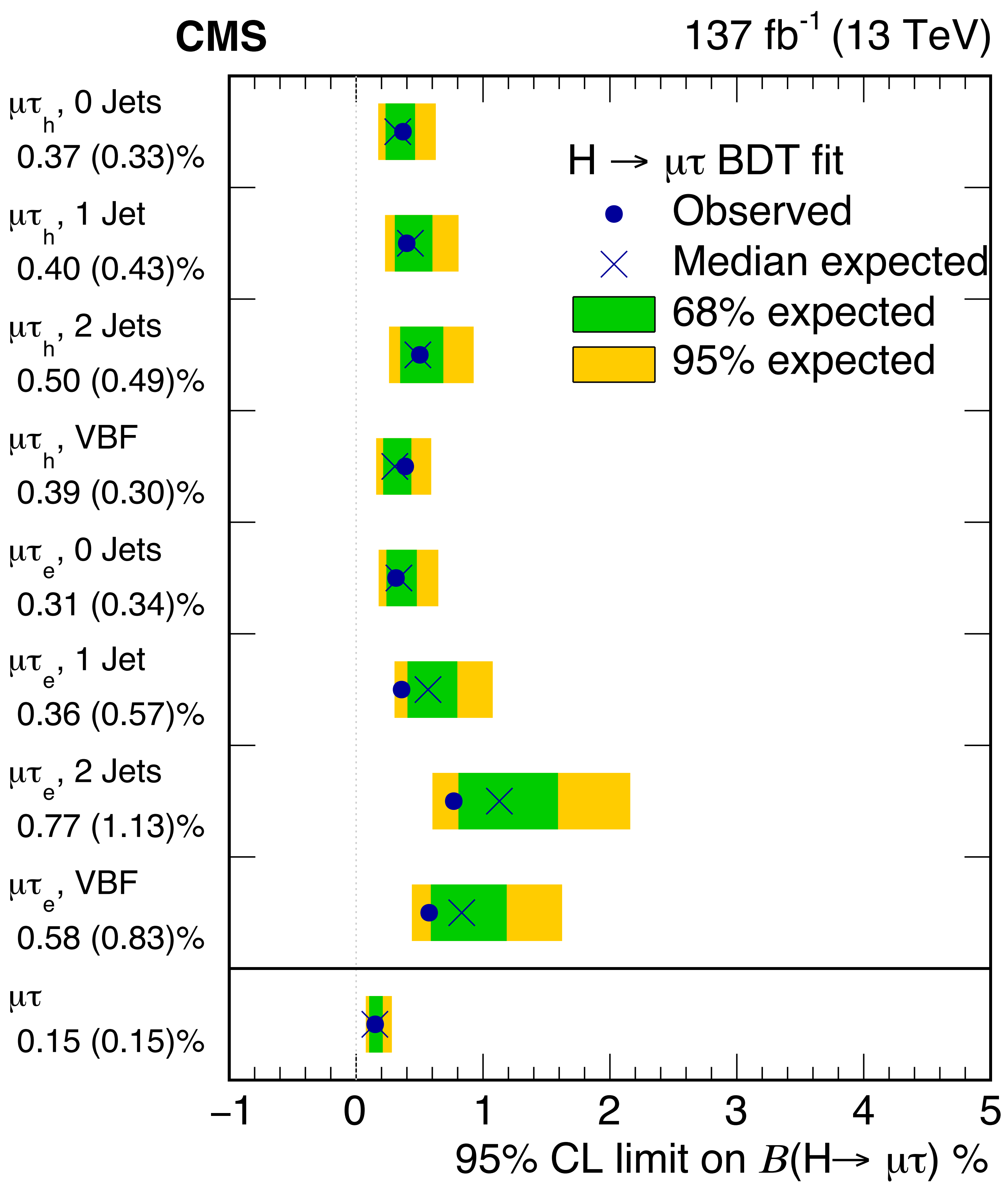
BDT Discriminator Distributions

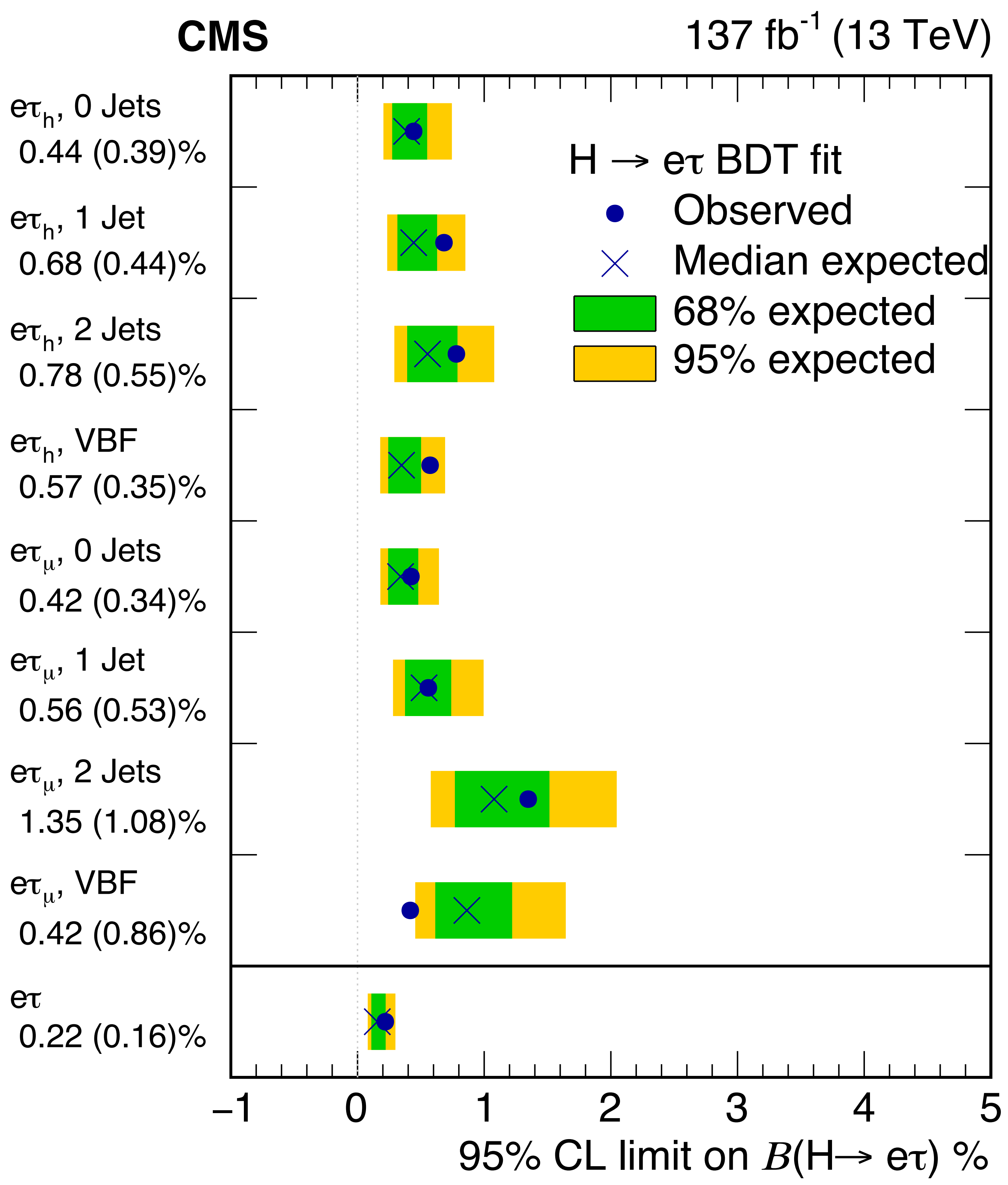


- Systematic uncertainties are incorporated into a likelihood function which is fit to obtain the best-fit and upper limits on the branching fractions

- Post-fit BDT discriminant distributions of two categories of the $H \rightarrow \mu\tau$ channel are shown above

$H \rightarrow \mu\tau/e\tau$ Limits on Branching Fraction



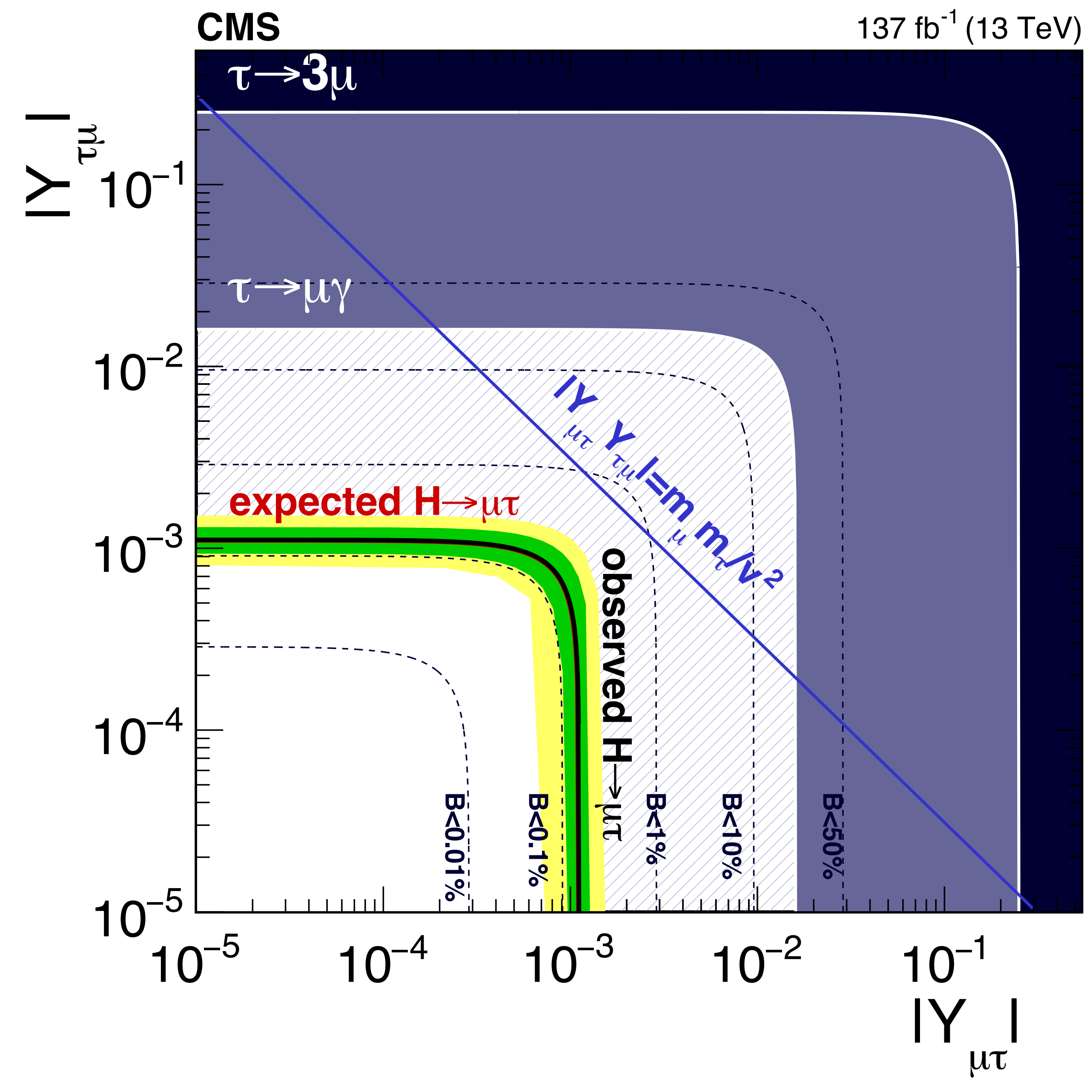


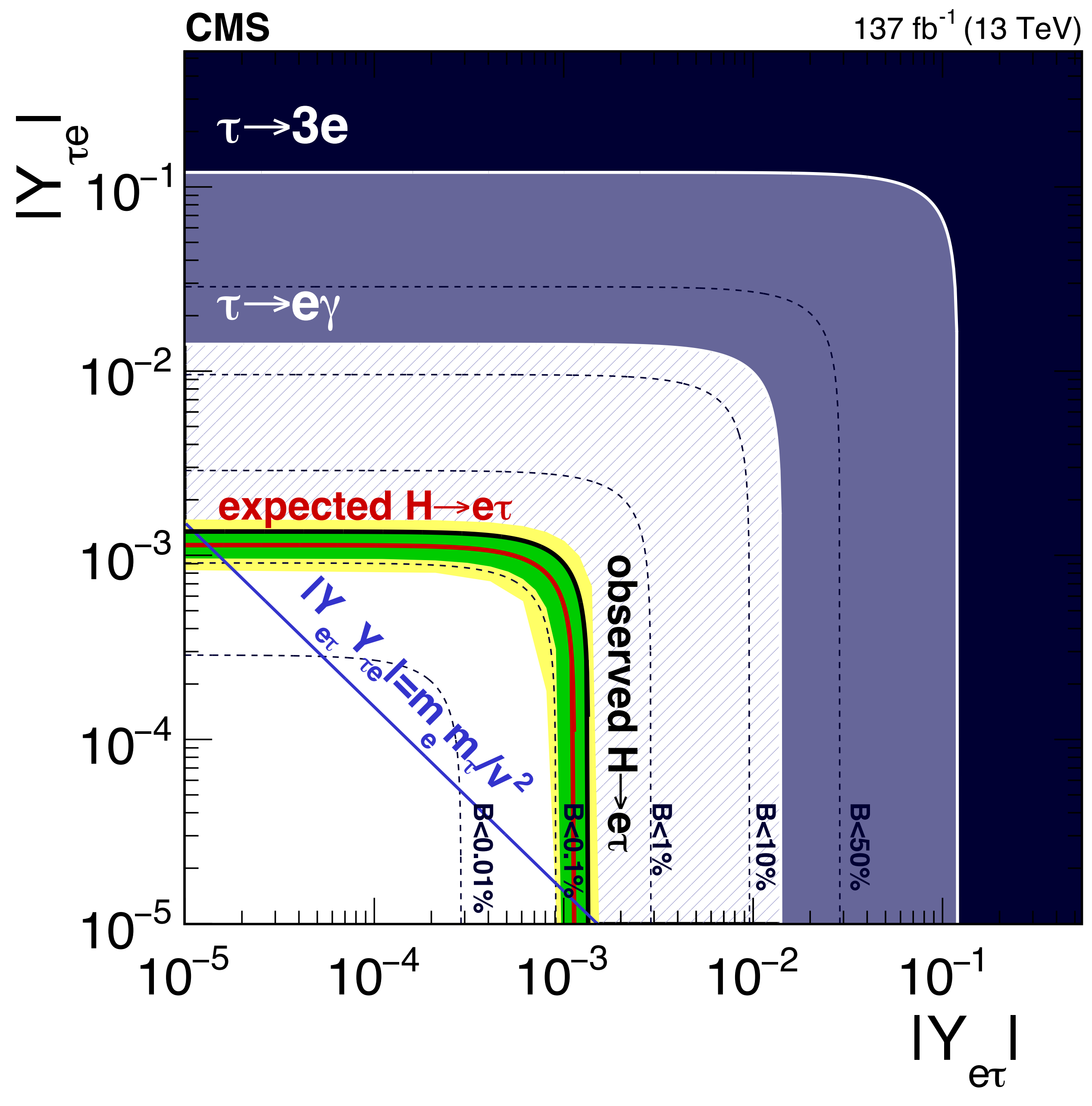
Results	$\mathscr{B}(H \rightarrow \mu\tau)$	$\mathscr{B}(H \rightarrow e\tau)$
Previous 2016 analysis	$<0.25\%$ (0.25%)	$<0.61\%$ (0.37%)
Full Run2 analysis	$<0.15\%$ (0.15%)	$<0.22\%$ (0.16%)

Yukawa Limits

- Decay width of LFV Higgs boson decays is $\Gamma\left(H \to \ell_i \ell_j\right) = \frac{m_H}{8\pi}\left(\left|Y_{ji}\right|^2 + \left|Y_{ij}\right|^2\right)$

- Branching fraction is related to the decay width: $\mathscr{B}\left(H \to \ell_i \ell_j\right) = \frac{\Gamma\left(H \to \ell_i \ell_j\right)}{\Gamma\left(H \to \ell_i \ell_j\right) + \Gamma_{SM}}$





- Observed Yukawa limits

$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 0.00111$$

$$\sqrt{|Y_{e\tau}|^2 + |Y_{\tau e}|^2} < 0.00135$$

Summary

PhysRevD.104.032013

- Search for experimental evidence of physics beyond the SM is of significant interest, and LFV decays of the Higgs boson provides one such signal

- Expected limits obtained are an improvement compared to the previous analysis not just because of the increased statistics but also attributable to the improved object identification, background estimation, and BDT classification techniques

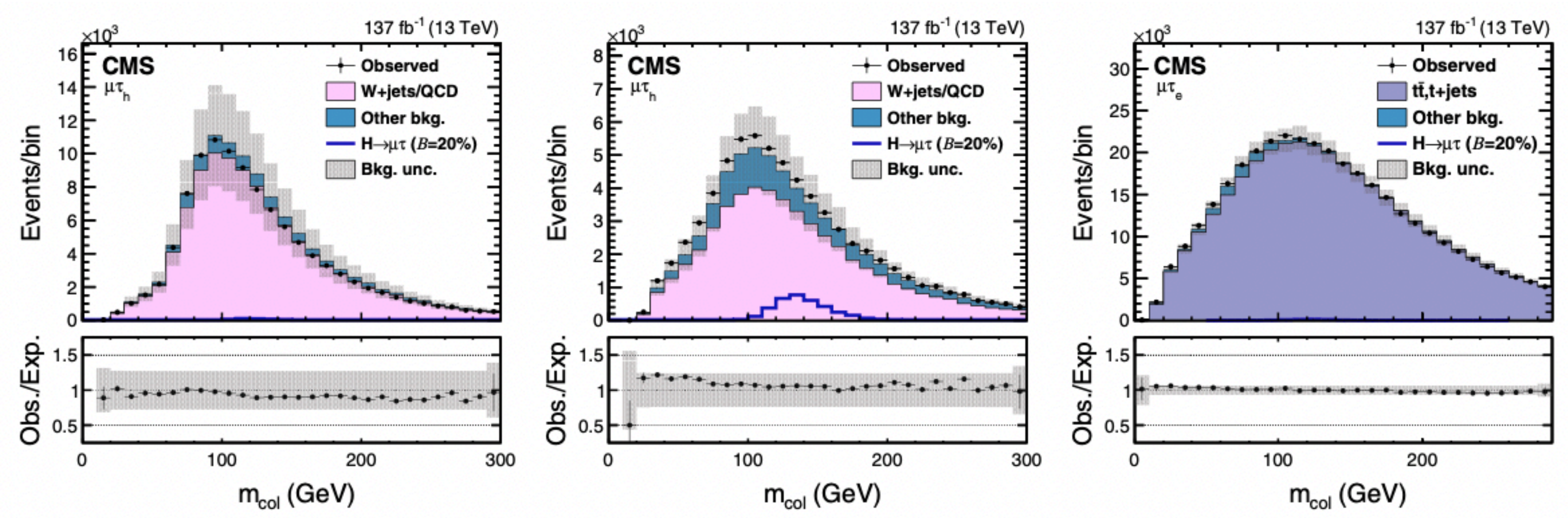
- No excess is observed, and the most stringent upper limits on these branching fractions have been set

TABLE VI. Summary of observed and expected upper limits at 95% C.L., best fit branching fractions and corresponding constraints on Yukawa couplings for the $H \to \mu\tau$ and $H \to e\tau$ channels.

	Observed (expected) upper limits (%)	Best fit branching fractions (%)	Yukawa coupling constraints
$H \to \mu\tau$	<0.15 (0.15)	0.00 ± 0.07	$<1.11(1.10) \times 10^{-3}$
$H \to e\tau$	<0.22 (0.16)	0.08 ± 0.08	$<1.35(1.14) \times 10^{-3}$

Backup

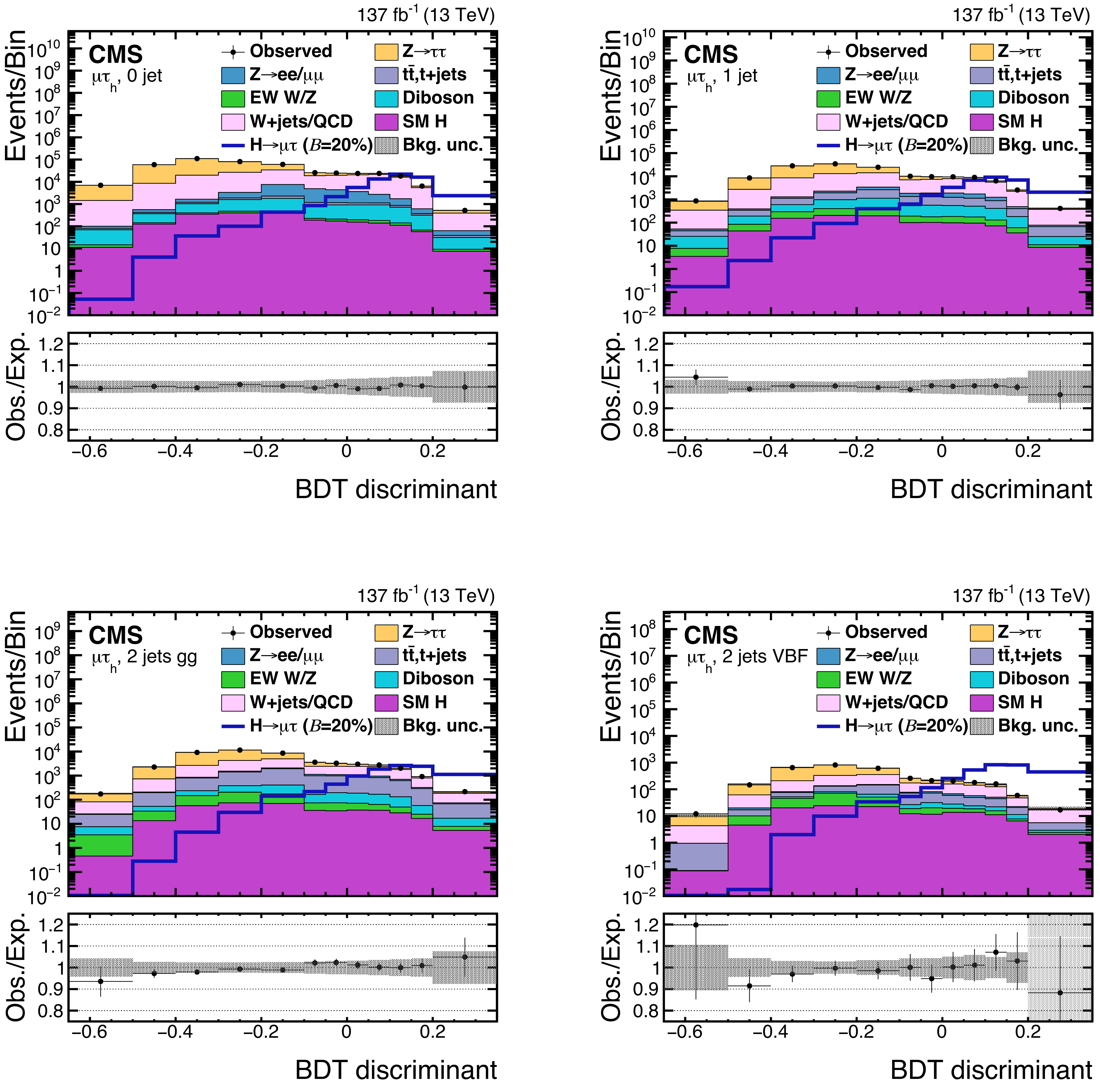
Background Validation



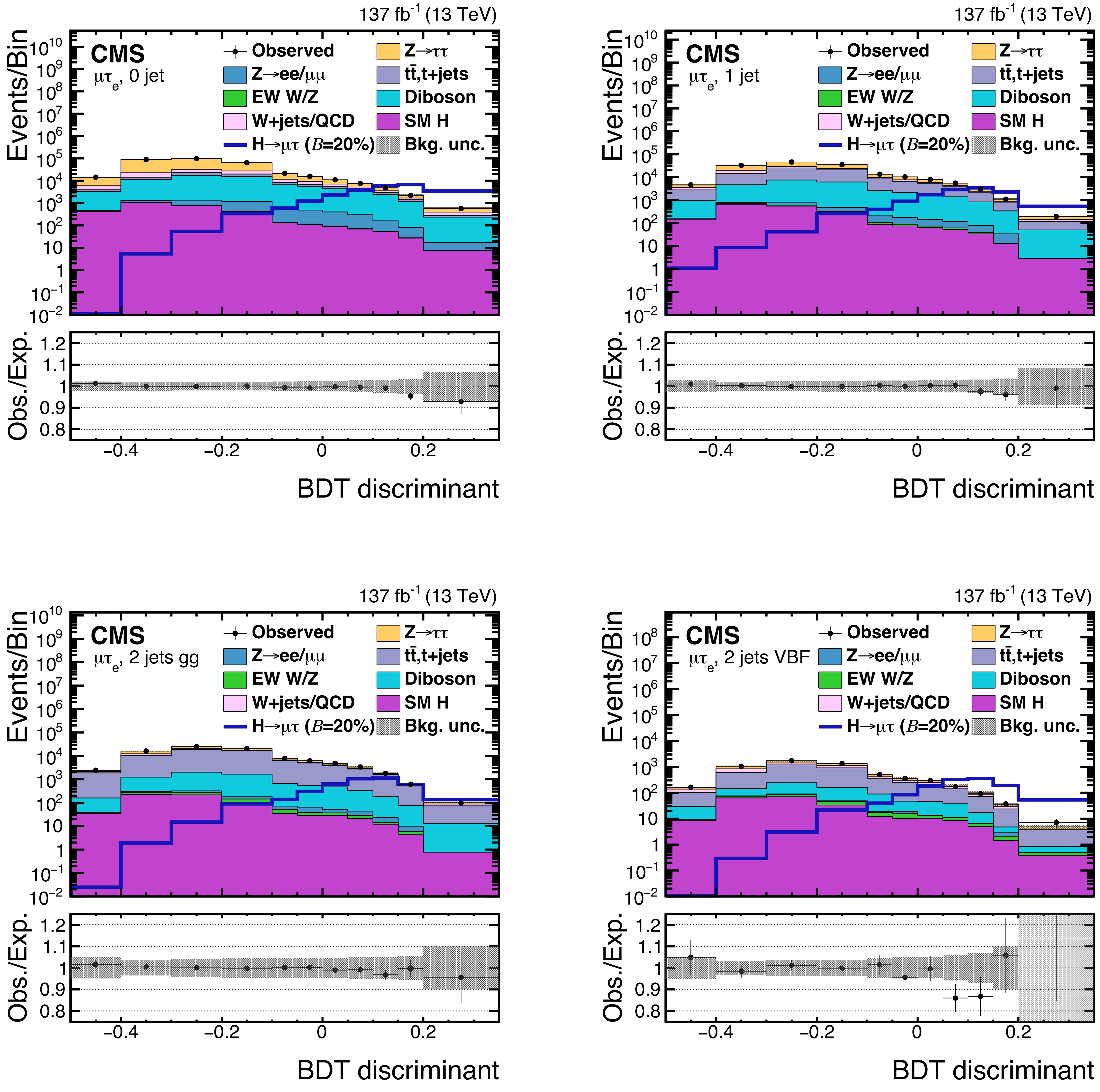
- Same-Sign control region: Selection is the presence of same sign leptons instead of opposite sign leptons
- W+Jet control region: $M_T(\tau, \text{MET}) > 80$ GeV $M_T(\mu, \text{MET}) > 60$ GeV
- $t\bar{t}$ control region: At least one b-tagged jet in the event

$H \rightarrow \mu\tau$ BDT Discriminator Distributions

$H \rightarrow \mu\tau_h$

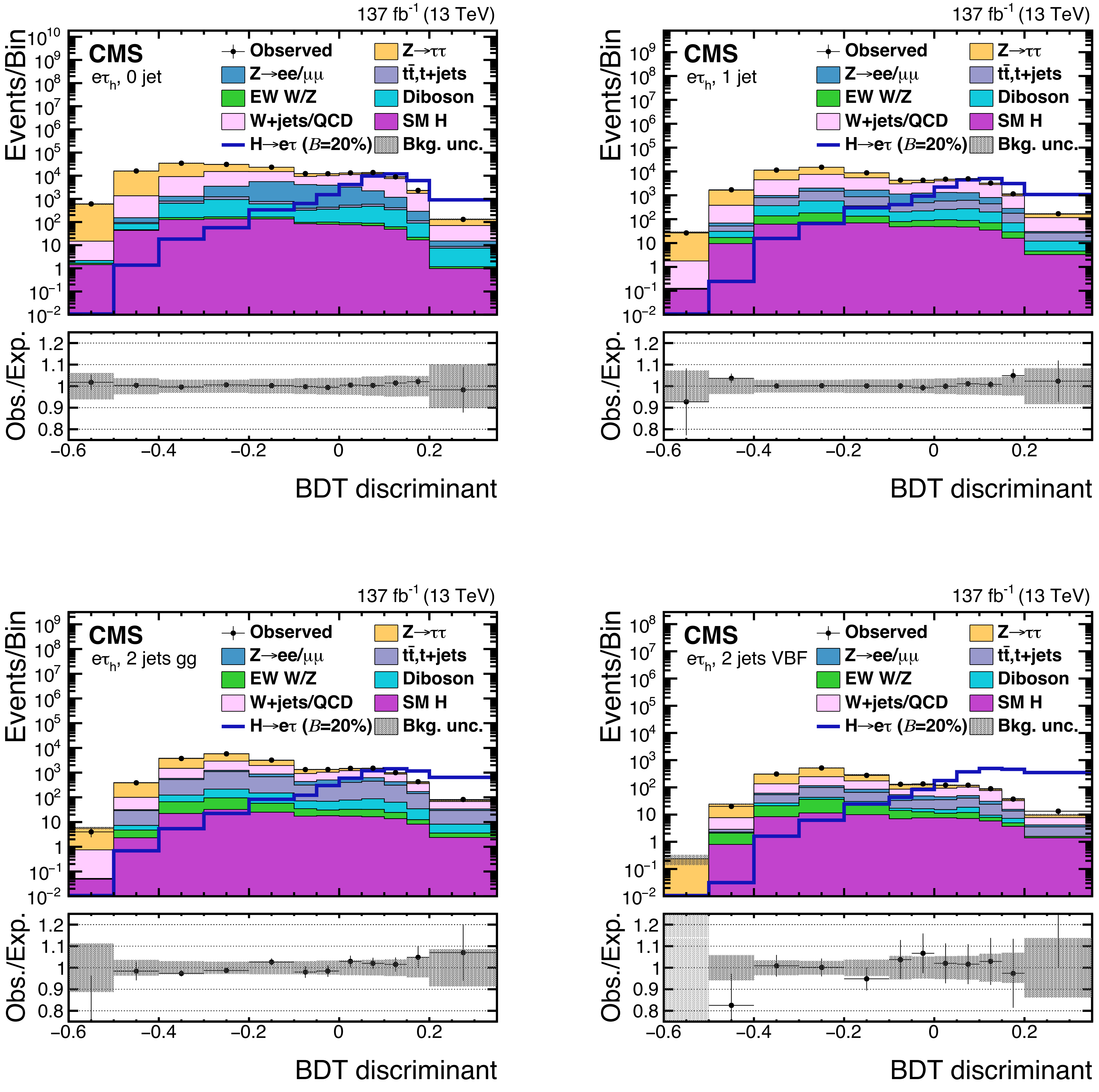


$H \rightarrow \mu\tau_e$

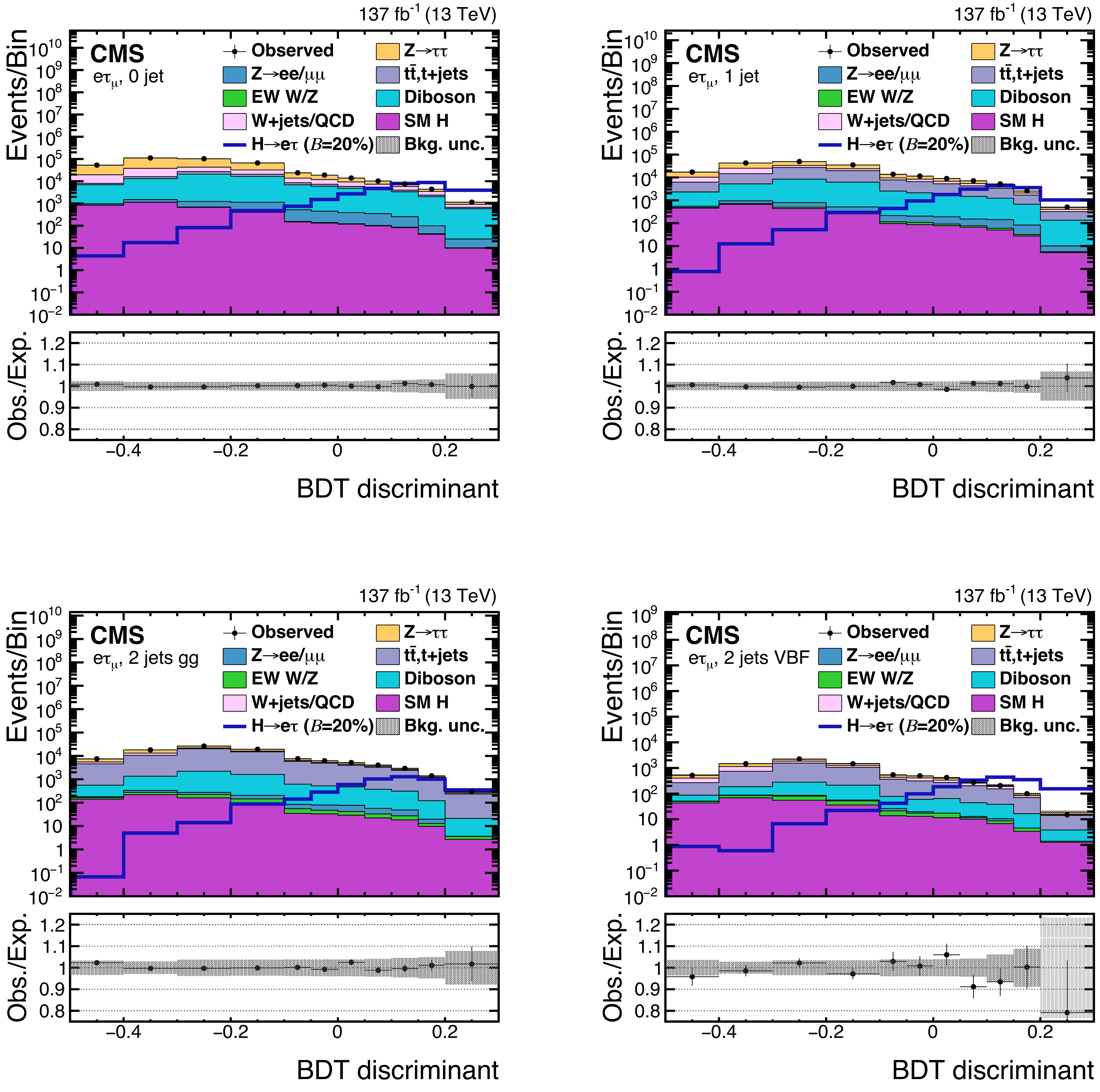


H → eτ BDT Discriminator Distributions

H → $e\tau_h$



H → $e\tau_\mu$



Systematic Uncertainties

Lepton ID/Iso./Trigger uncertainty

Cross-section or normalization uncertainty

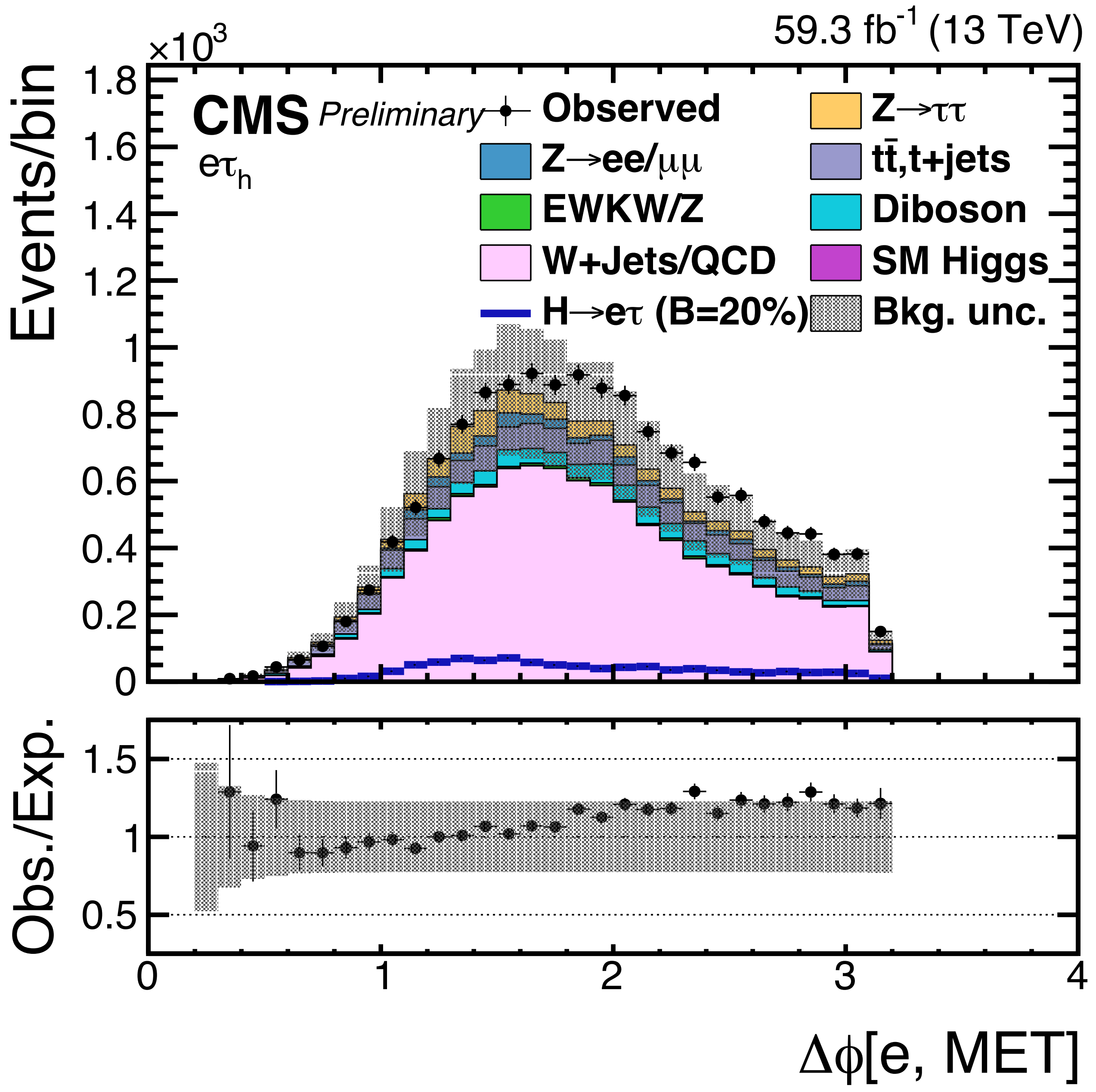
Energy scale uncertainty

Theoretical uncertainty

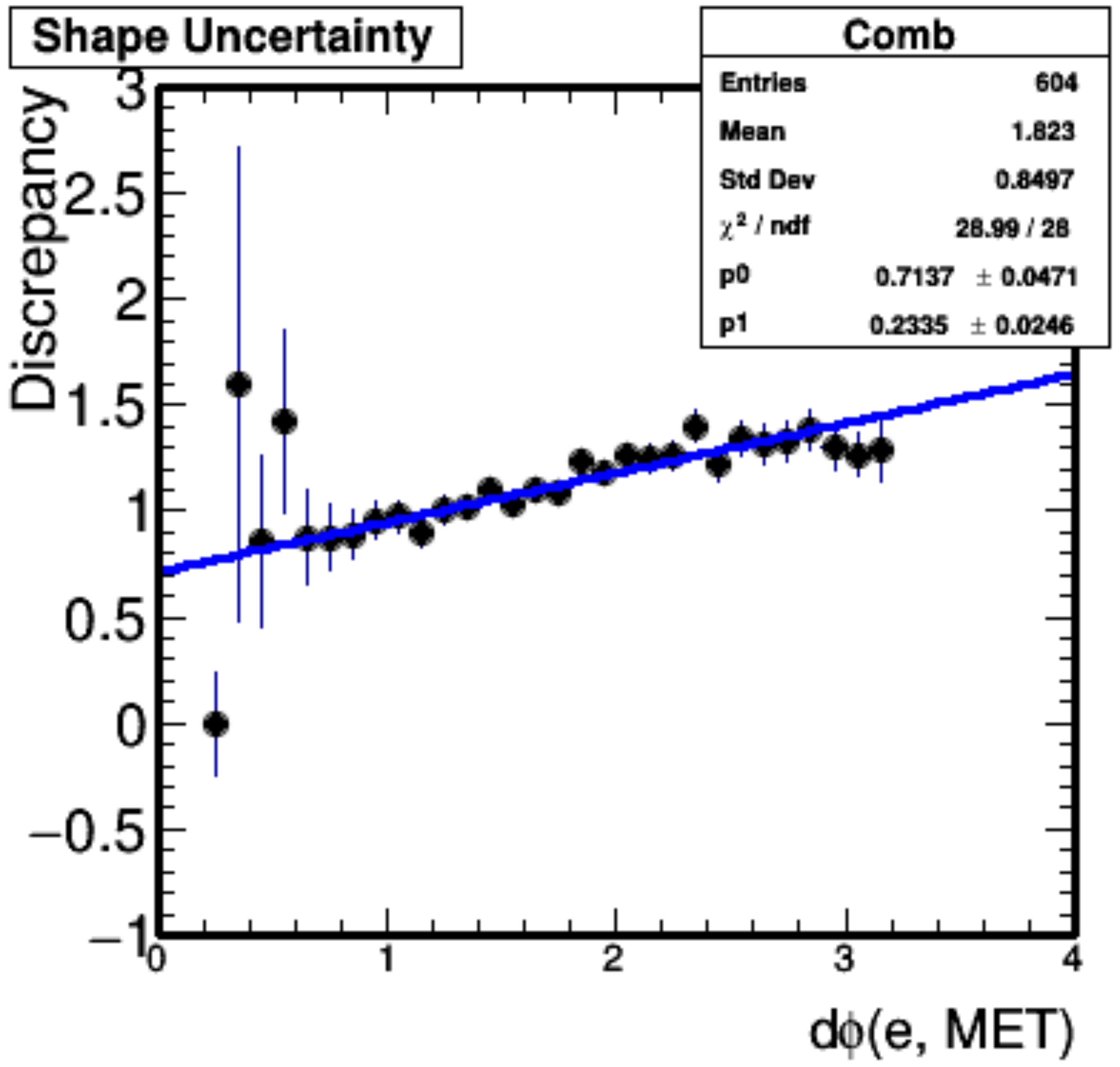
TABLE III. Systematic uncertainties in the expected event yields. All uncertainties are treated as correlated among categories, except those with two values separated by the ⊕ sign. In this case, the first value is the correlated uncertainty and the second value is the uncorrelated uncertainty for each category.

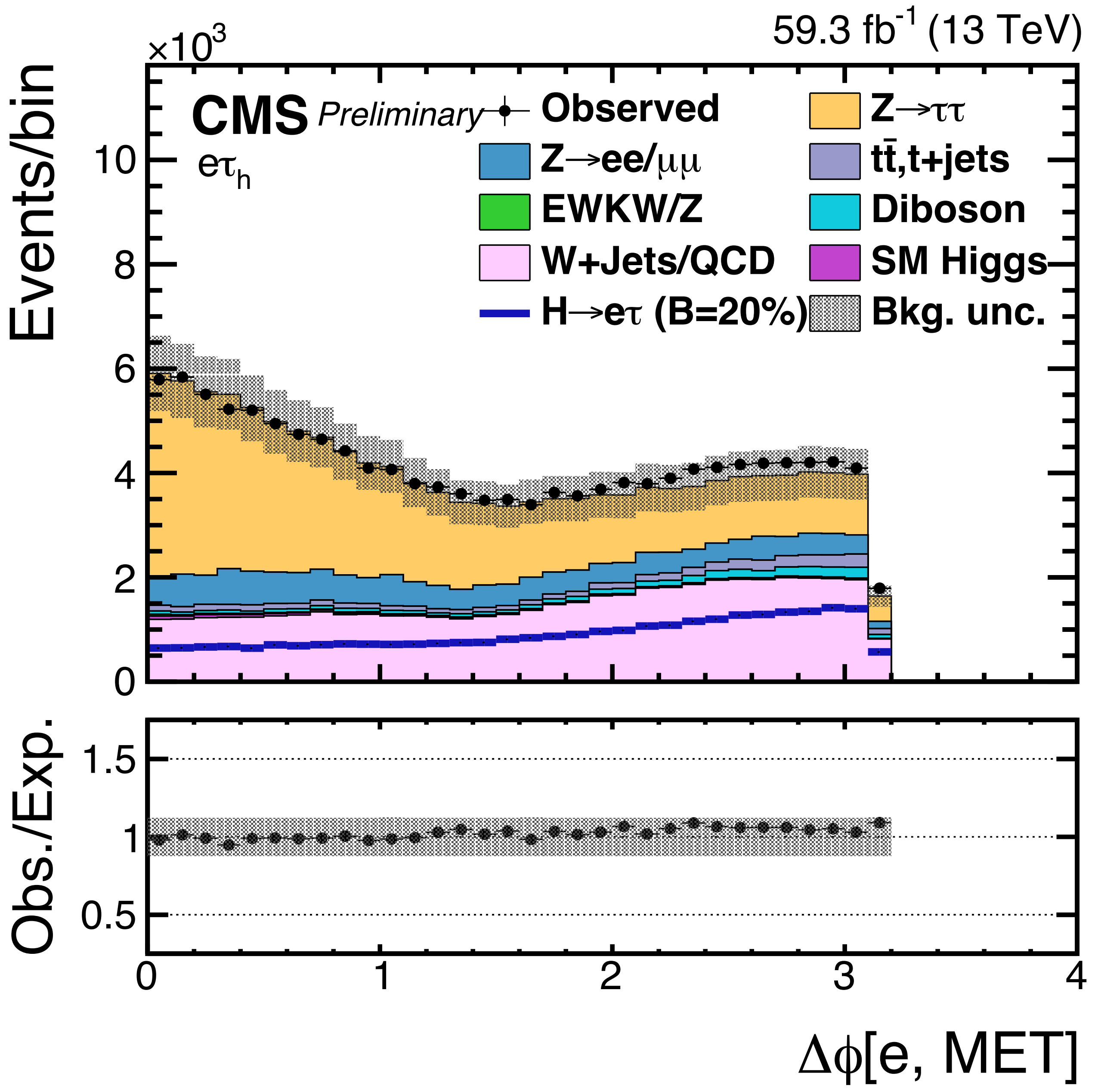
Systematic uncertainty	$\mu\tau_h$	$\mu\tau_e$	$e\tau_h$	$e\tau_\mu$
Muon ident. and iso.	2%	2%	···	2%
Electron ident. and iso.	···	2%	2%	2%
Trigger	2%	2%	2%	2%
τ_h ident.	p_T dep. (2%–3%)	···	p_T dep. (2%–15%)	···
$\mu \to \tau_h$ misid.	10%–70%	···	···	···
$e \to \tau_h$ misid.	···	···	40%	···
b tagging efficiency	<6.5%	<6.5%	<6.5%	<6.5%
Embedded bkg.	4%	4%	4%	4%
$Z \to \mu\mu, ee$ bkg.	4% ⊕ 5%	4% ⊕ 5%	4% ⊕ 5%	4% ⊕ 5%
EW bkg.	4% ⊕ 5%	4% ⊕ 5%	4% ⊕ 5%	4% ⊕ 5%
$W+$jets bkg.	···	10%	···	10%
Diboson bkg.	5% ⊕ 5%	5% ⊕ 5%	5% ⊕ 5%	5% ⊕ 5%
$t\bar{t}$ bkg.	6% ⊕ 5%	6% ⊕ 5%	6% ⊕ 5%	6% ⊕ 5%
Single top quark bkg.	5% ⊕ 5%	5% ⊕ 5%	5% ⊕ 5%	5% ⊕ 5%
Jet $\to \tau_h$ bkg.	30% ⊕ 10%	···	30% ⊕ 10%	···
Jet energy scale	3%–20%	3%–20%	3%–20%	3%–20%
τ_h energy scale	0.7%–1.2%	···	0.7%–1.2%	···
$e \to \tau_h$ energy scale	1%–7%	···	1%–7%	···
$\mu \to \tau_h$ energy scale	1%	···	1%	···
Electron energy scale	···	1%–2.5%	1%–2.5%	1%–2.5%
Muon energy scale	0.4%–2.7%	0.4%–2.7%	···	0.4%–2.7%
Trigger timing inefficiency	0.2%–1.3%	0.2%–1.3%	0.2%–1.3%	0.2%–1.3%
Integrated luminosity	1.8%	1.8%	1.8%	1.8%
QCD scales (ggH)	3.9%			
QCD scales (VBF)	0.5%			
PDF $+ \alpha_S$ (ggH)	3.2%			
PDF $+ \alpha_S$ (VBF)	2.1%			
QCD acceptance (ggH)	−10.3% to +5.9%			
QCD acceptance (VBF)	−2.7% to +2.3%			
PDF $+ \alpha_S$ acceptance (ggH)	−0.8% to +2.8%			
PDF $+ \alpha_S$ acceptance (VBF)	−1.7% to +2.3%			

Misidentified Lepton Background Uncertainties



W+Jet control region (CR)



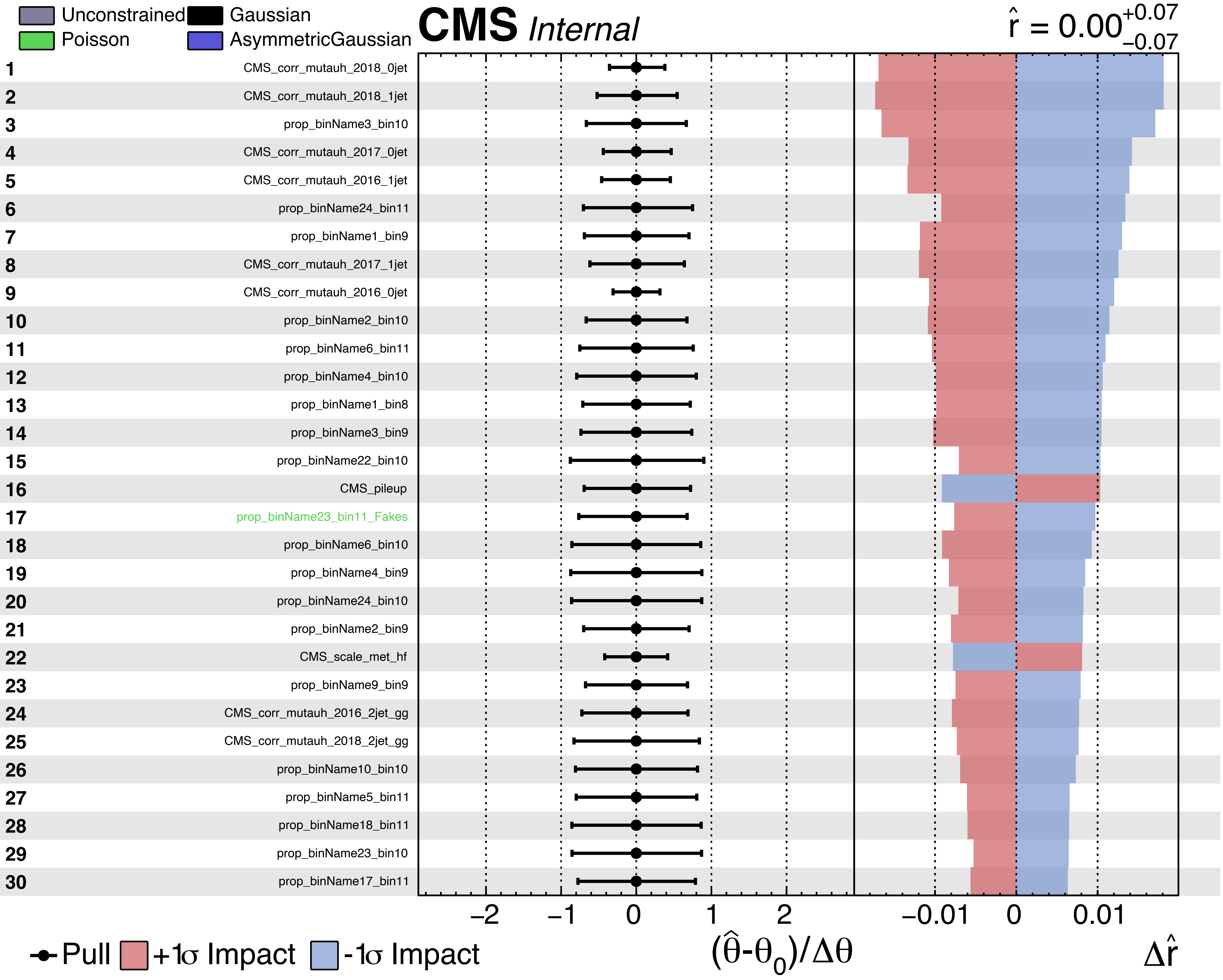


Signal region

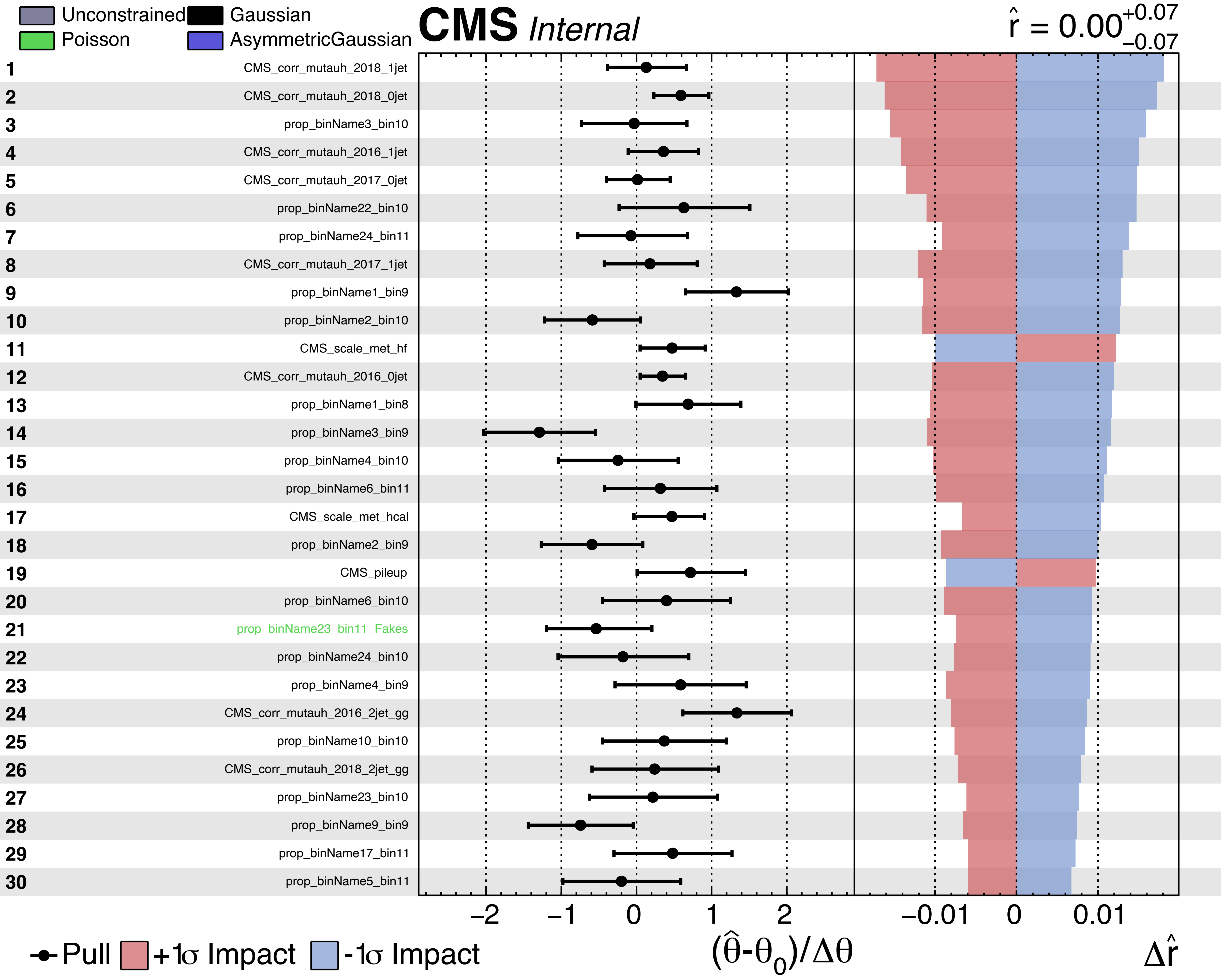
- Shape uncertainty is estimated in the W+Jet CR, where we observed dependence on the variable $d\phi(\mu/e, \text{MET})$
- This is applied in the signal region, which is defined orthogonally to the W+Jet CR

$H \rightarrow \mu\tau$ Impacts

Expected Impacts



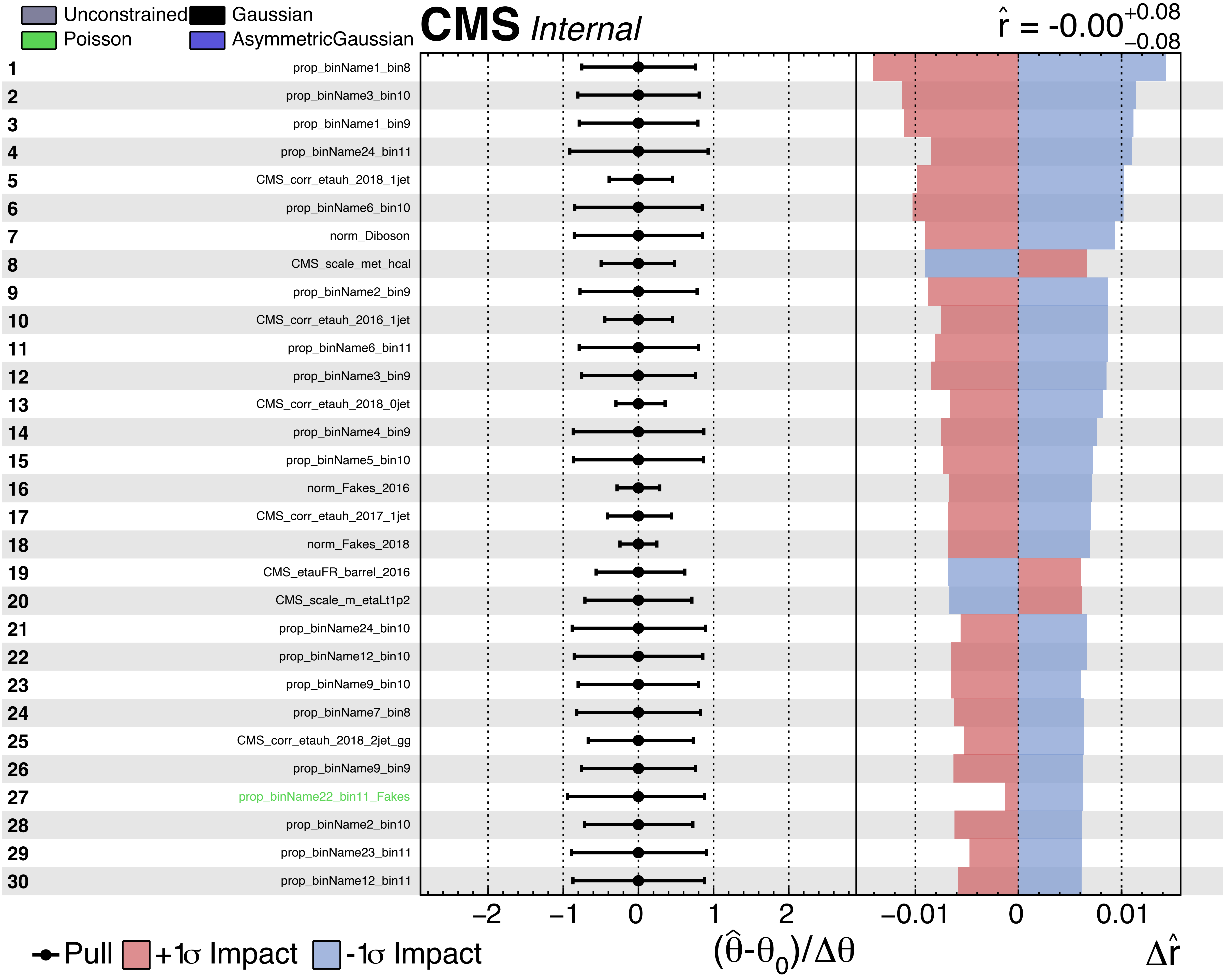
Observed Impacts



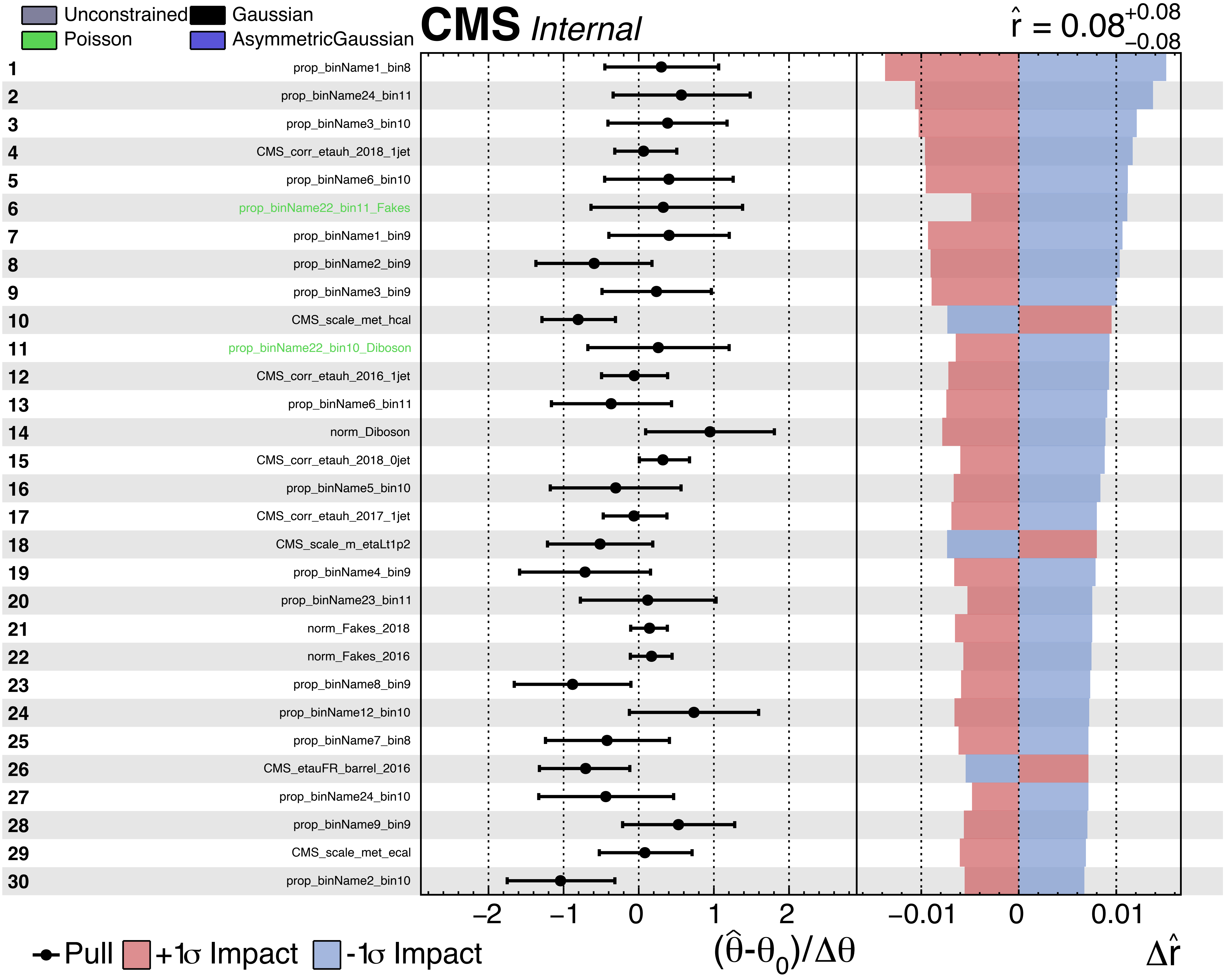
- As can be seen most uncertainty pulls are within 1σ
- "norm_Fakes", Shape uncertainty for Fakes are constrained but is expected as we use conservative uncertainties

$H \to e\tau$ Impacts

Expected Impacts



Observed Impacts



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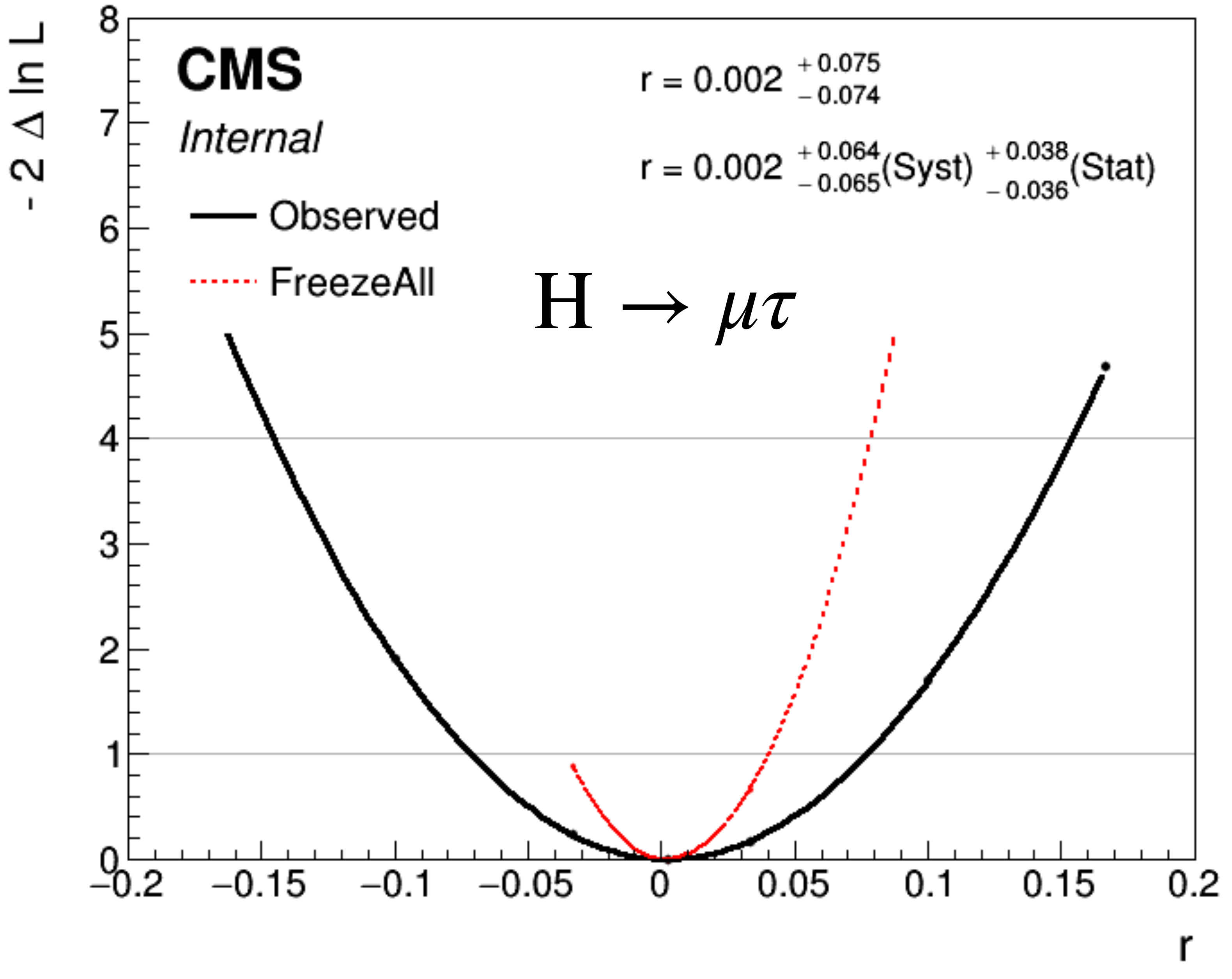
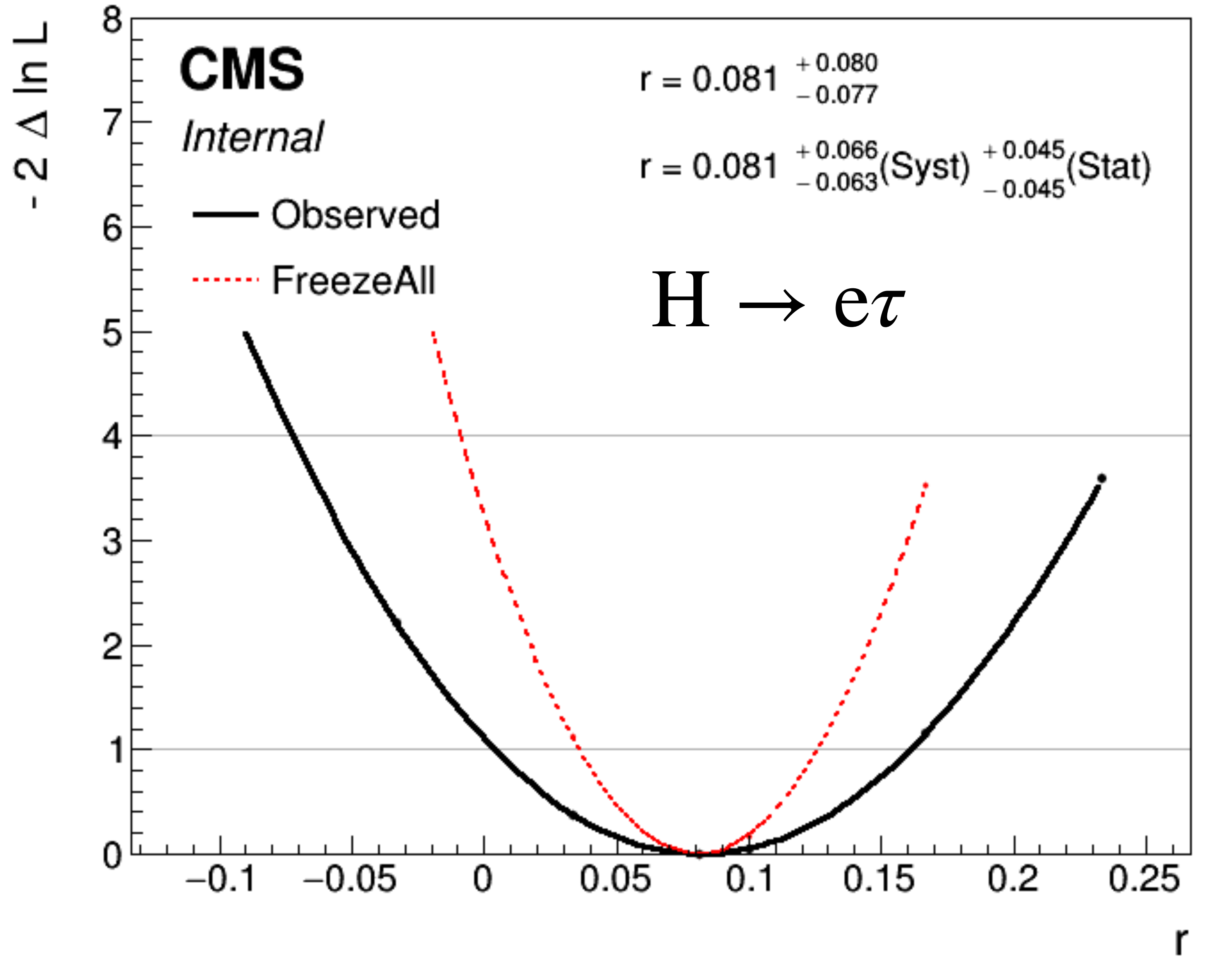
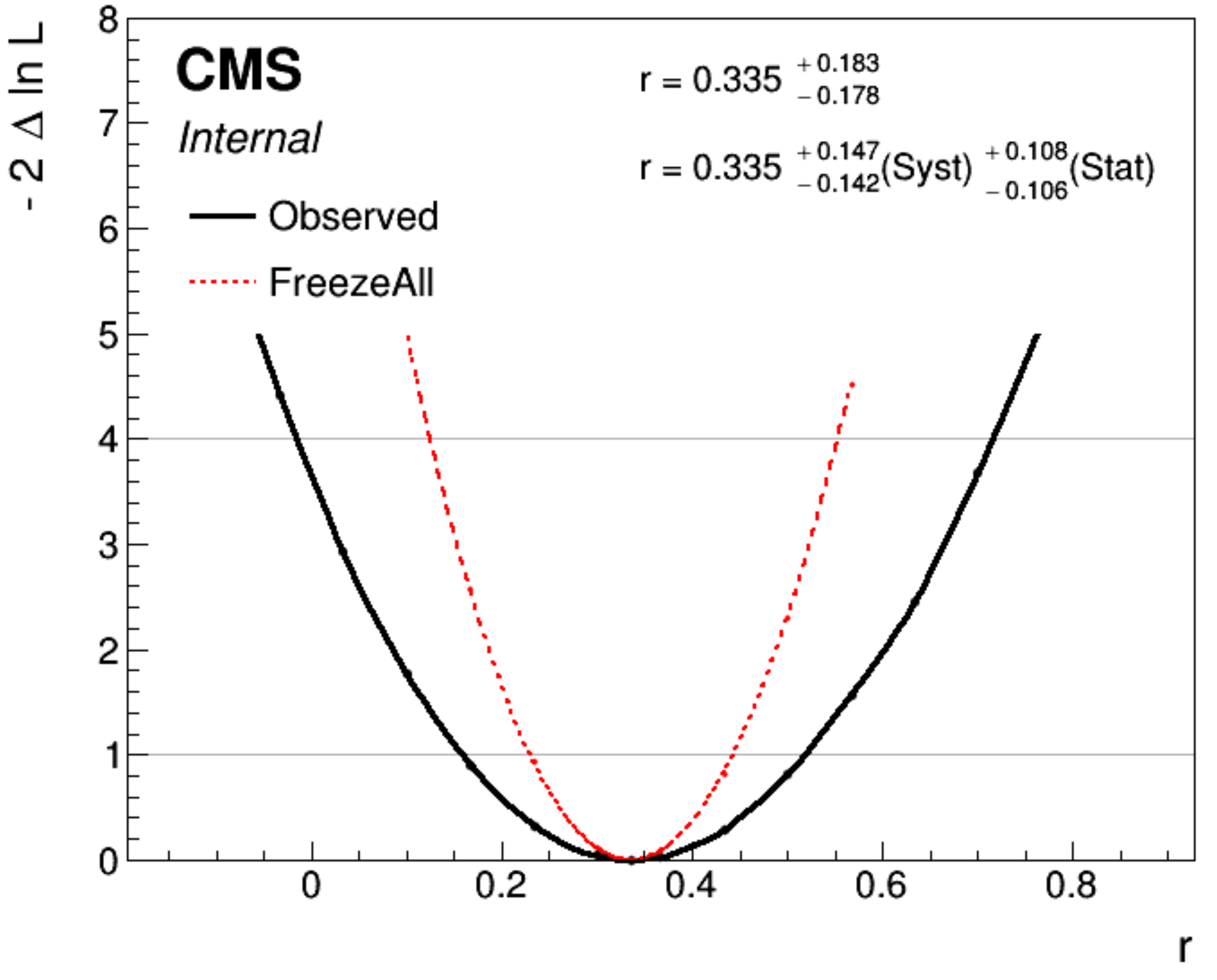
NLL distribution





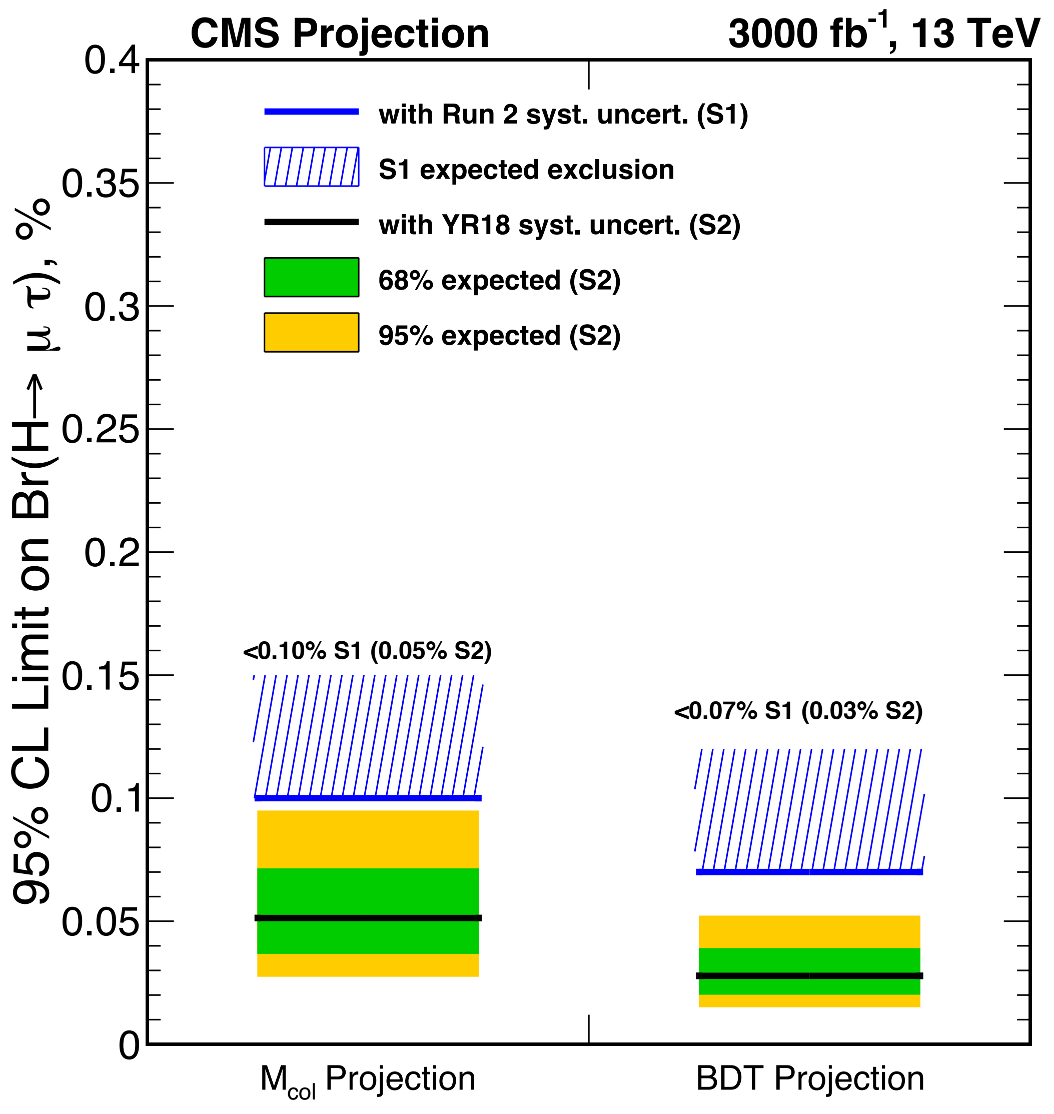
H → eτ from previous analysis

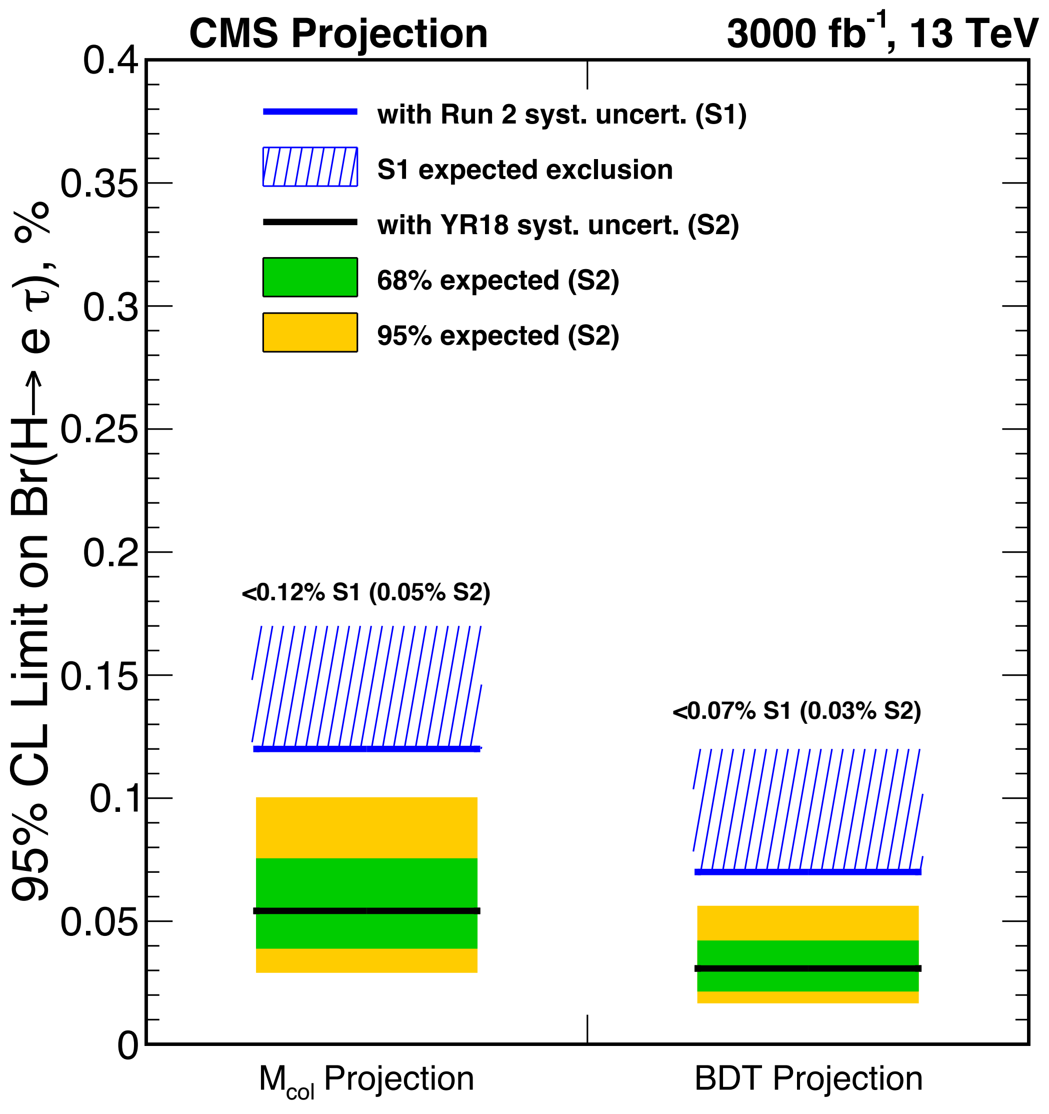


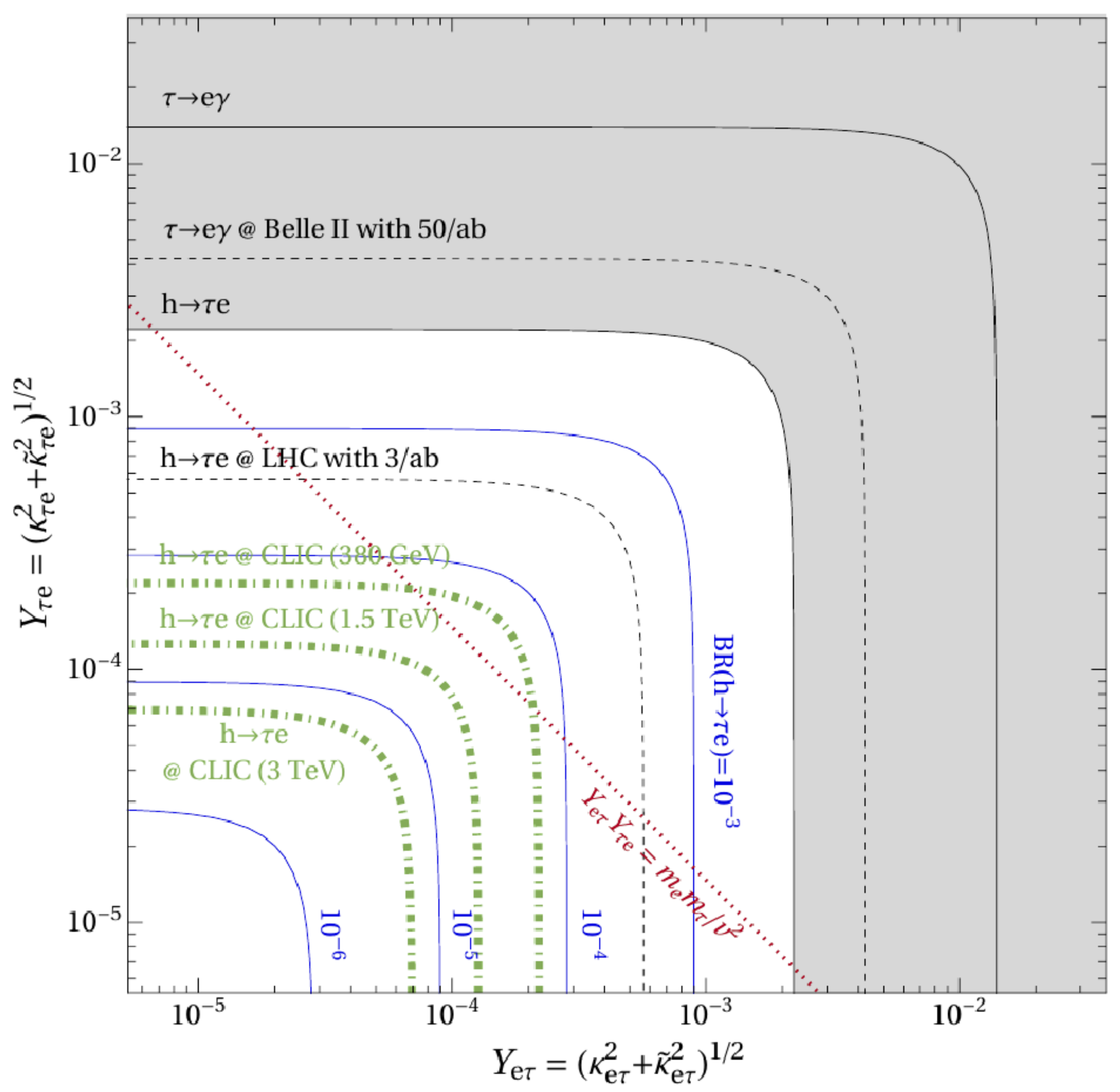
- Best-fit branching fraction can be seen in the distribution of the negative log-likelihood distribution
- Uncertainties are split into systematics and statistical contribution and as can be seen the analysis is systematically limited

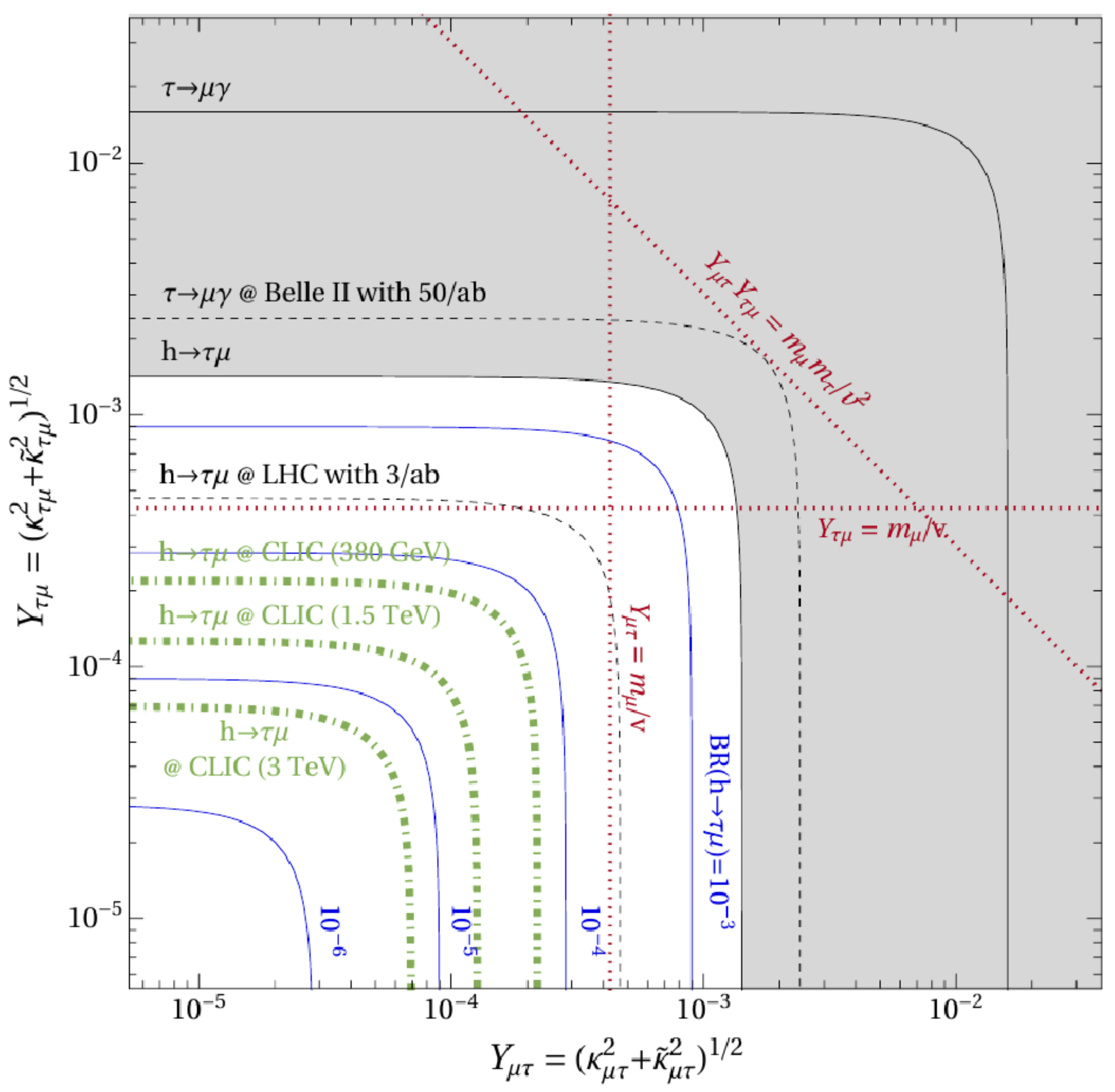
Future Projections

Higgs Physics at the HL-LHC - arXiv:1902.00134









- Naively, assuming that both systematics and statistical error scale with square root of the luminosity, one can expect that the sensitivity of the HL-LHC with 3000 fb^{-1} will be around half per-mil level for the branching ratio of H $\rightarrow \mu\tau$ or H $\rightarrow e\tau$