Search For a Heavy Majorana Neutrino In Top Quark Decays Using Same-Charge Dilepton Final States In pp Collisions @ 13 TeV

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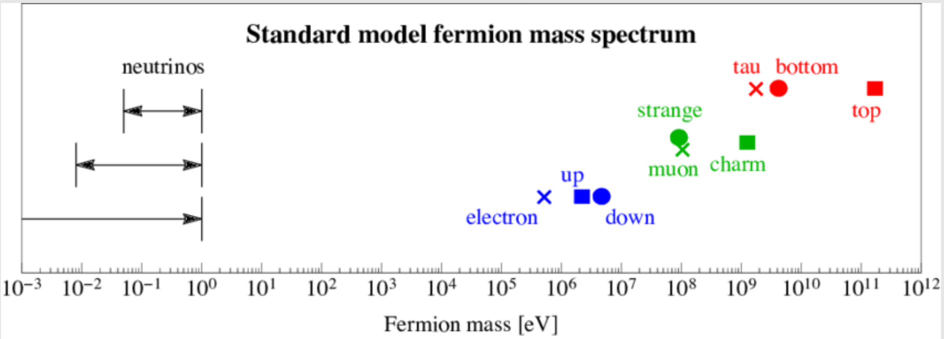
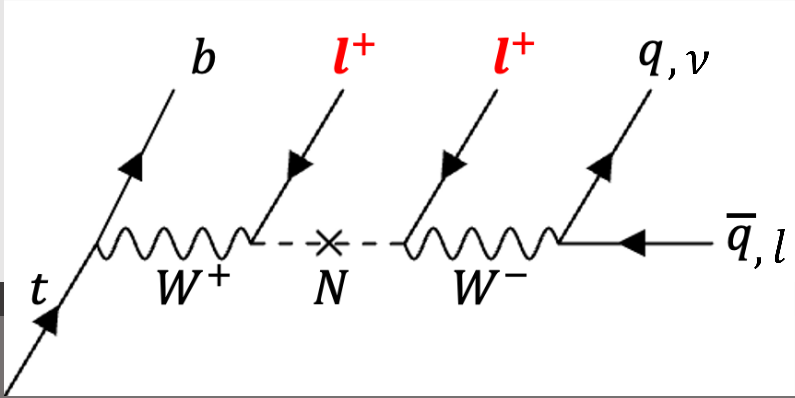
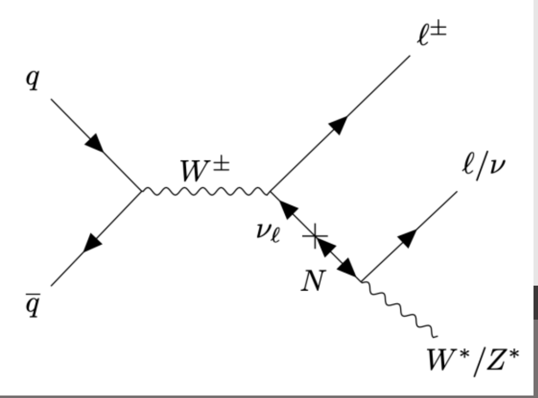


Introduction

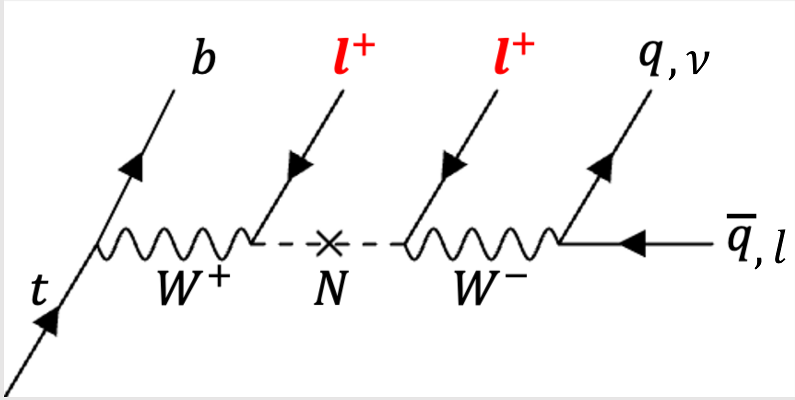
- Type-1 Seesaw Model
  - Heavy Majorana lepton to explain smallness of neutrino mass.
- Direct searches
  - Drell-Yan (DY) W production channel, etc …
- **This is the first search of HNL using top quark decay**
  - **Initiated by Dr. Bhyun, who graduated, and continued by Jihoon Shin**
  - **Less events than DY W, yet still enough**
    - $\sim O(1000)$ in CMS Run2 after selection
  - **Reducible background dominant**

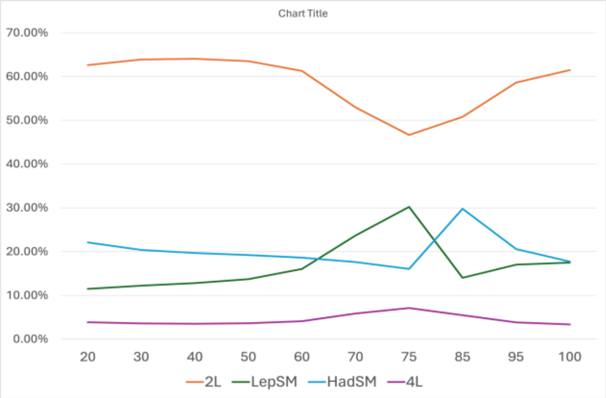




Signal Event

- Generated with 10 m_N scenarios
  - 20,30,40,50,60,70,75,85,95,100 GeV
  - Leading Order Madgraph+pythia8
- Baseline Selection:
  - Same-sign (SS) $2e$ or 2μ
  - $p_T(l^{\pm}) > 20{,}10\ (25{,}15)\text{GeV}$ for $2\mu\ (2e)$
  - $\mathrm{M}(\mu\mu) > 4\ \text{GeV}$
  - $\mathrm{M}(\mathrm{ee}) \notin (81.2, 101.2)\ \text{GeV}$
  - BDT based cut to reduce jets not originated from the primary interaction vertex.
  - $\mathrm{N(jet)} \geq 3$
  - $\mathrm{N(b\text{-}jet)} \geq 1$
  - $\mathrm{N_{untagged}} \geq 1\ (2)$ for $\mathrm{M}_N < 80\text{GeV}\ (> 80\ \text{GeV})$





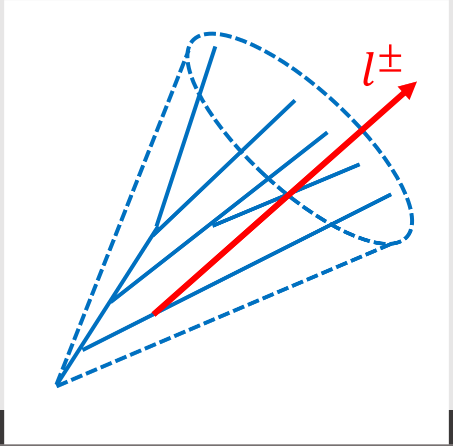
- We included all possible decay combinations of top pair decay

Background

- Non-prompt lepton background (Fake lepton)
- Charge-mismeasurement lepton background (Charge-Flip)
- Conversion lepton background
- Prompt background
  - tt + boson, triboson, etc…

Fake lepton background

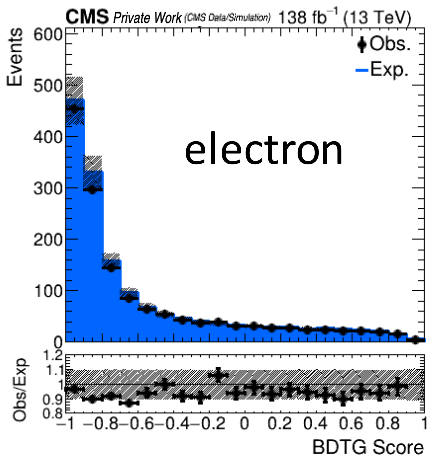
- A parton showers and develops into a jet and can produce a lepton.
- To estimate such event that passes the ID, we use Matrix Method
- $\vec{N}_{obs} = \mathbb{M}\,\vec{N}_{true}$
  - $\vec{N}_{true}$: # prompt/fake combination (pp, pf ,fp, ff)
  - $\vec{N}_{obs}$: # tight/loose ID combination (TT, TL, LT, LL)
- $\mathbb{M}_{ij}(o_1, o_2) = \prod_{n \in passT} \epsilon(o_n) \prod_{m \in failT} (1 - \epsilon(o_m))$
  - $\epsilon(p)/\epsilon(f)$: prompt/fake rate
- Fake rate measured in QCD topology respect to $p_T^{corr^*}$
  - 1 loose ID lepton with $p_T > 20(25)$ GeV for $\mu(e)$
  - 1 jet with $p_T > 40$GeV and $\Delta R(j, l) > 1.0$
  - $p_T^{miss} < 25$ GeV, $M_T(l, p_T^{miss}) < 25$GeV
  - Subtract residual prompt contribution, like W+jets using MC

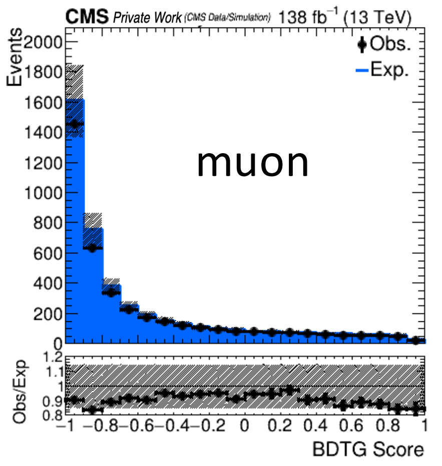


* p_T^{corr}: cone-corrected transverse momentum (p_T) to reduce the dependence on mother jet p_T

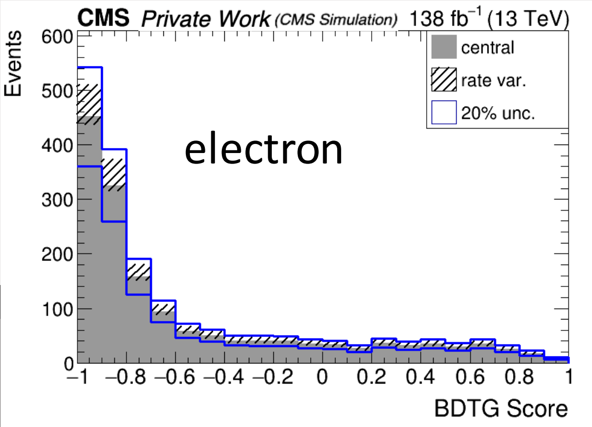
Fake lepton Systematics

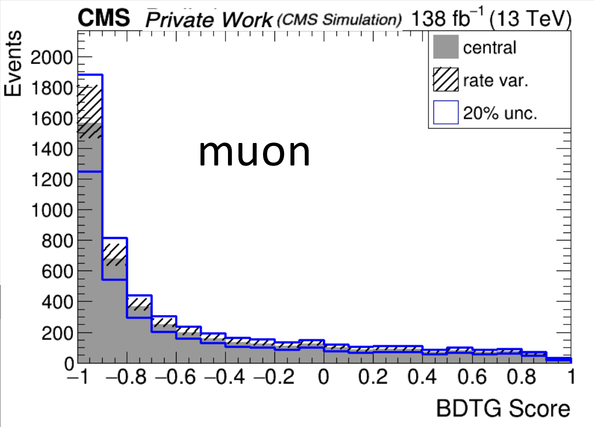
- MC closure test
  - fake rate measured in QCD → apply on TT events → exp/obs
  - Reweight by ratio of exp/obs if a lepton overlaps a b-jet
  - 20% difference → 10%(15%) for e(μ)





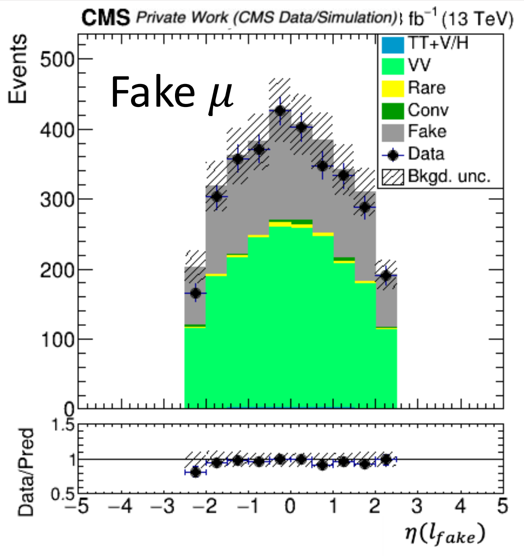
- Fake rate uncertainty
  - Vary prompt subtraction MC normalization by 15%
  - Additional requirement of b-tagging
  - Jet p_T cut: +20(+20) and -10(-20) for e(μ)

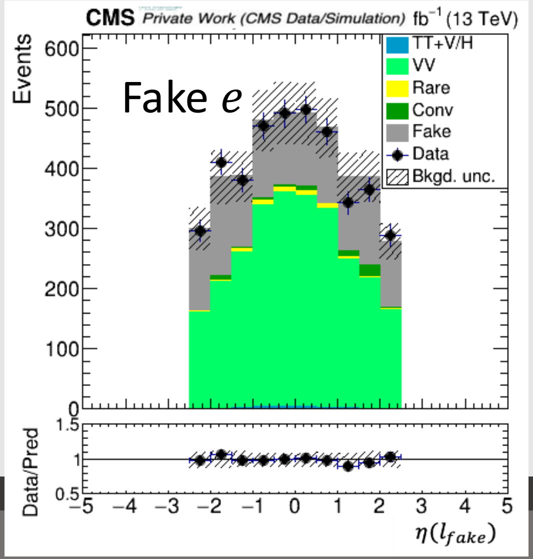




Fake Validation

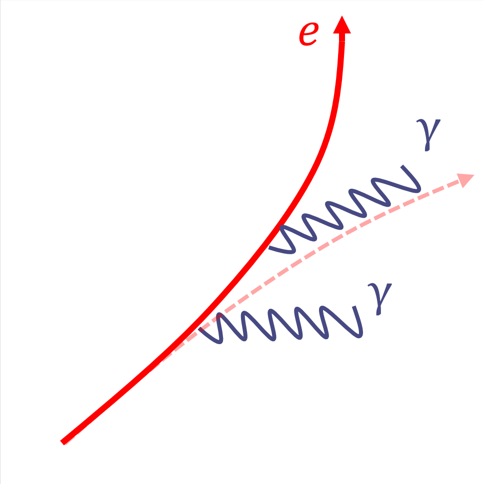
- Z+jet topology
  - $ee\mu$ or $\mu\mu e$
    - Dimuon: muons $\mathrm{p}_T > 20\ GeV$ and $> 10\ GeV$
    - Dielectron: electrons $\mathrm{p}_T > 25\ GeV$ and $> 15\ GeV$
  - Opposite-sign same-flavour lepton pair mass $\in [81.2, 102.2]$
  - No b jet

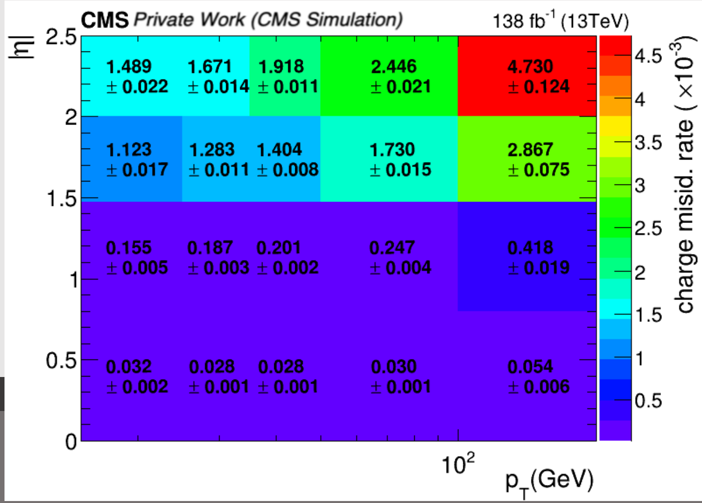


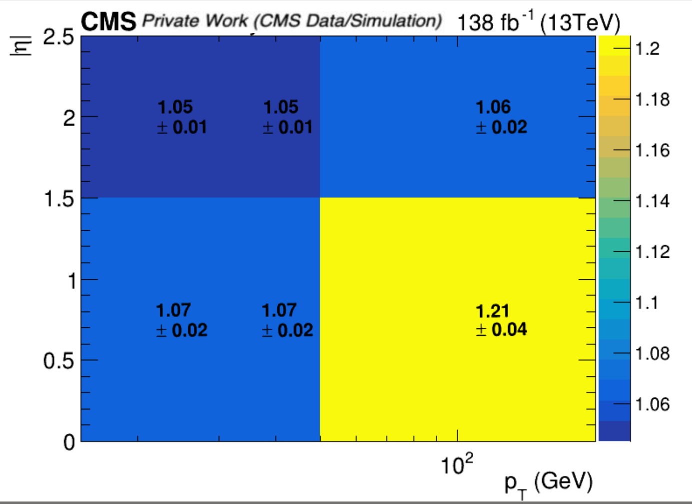


Charge measurement lepton background

- Bremsstrahlung radiation deflects the lepton's path
  - Mismeasured charge (or charge flip) if deflected enough.
    - e: $\sim 10^{-3}$, μ: $\sim 10^{-5}$(negligible)
- Measure charge-flip rate (CFR) in MC and data DY
  - MC: track the generated info
  - Data: opposite (OS) vs same (SS) sign dielectron events
    - M(ee) $\in [60,120], p_T(e_1) > 25GeV,\ p_T(e_2) > 15GeV$
    - Extract number using fitting model

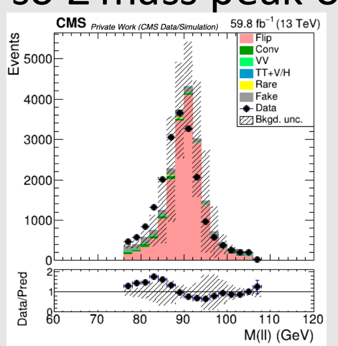






Charge-Flip systematics

- Charge-flip rate extraction 2-7% depending on era, pt, and eta
  - Fitting model variation: (Gaussian, ROOCMS) → (Crystalball, exponential)
- Electron p_T scale: 0.8-2.7% depending on era and η
  - Extreme Bremsstrahlung radiation escapes reconstruction cone
  - Shift electron p_T so Z mass peak of two electrons in OS and SS in DY MC agree.
  - 0.5~1.5% syst



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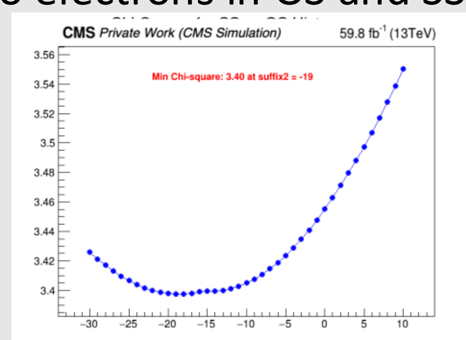

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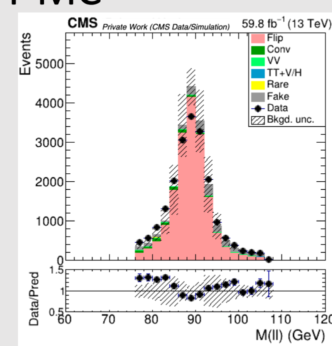
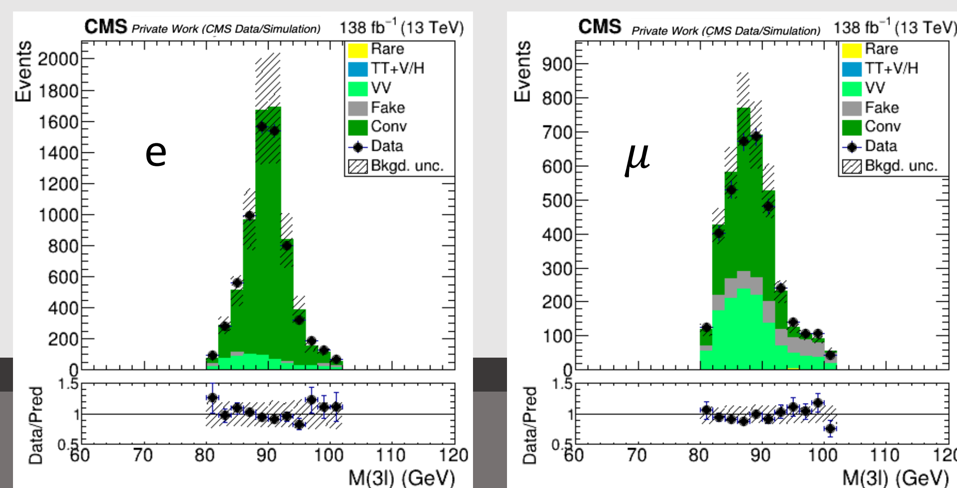


- MC Closure: 6%
  - TTbar MC closure of expected using OS + CFR vs observed SS

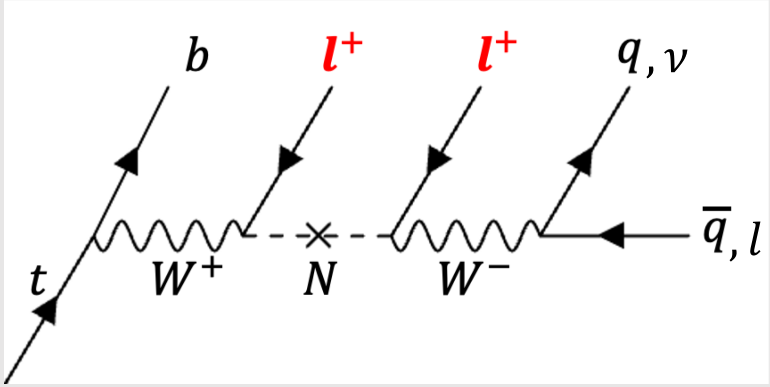
	2016preVFP	2016postVFP	2017	2018
obs./exp. (DY)	0.995±0.006	0.994±0.006	0.984±0.006	0.987±0.005
obs./exp. ($t\bar{t}$)	1.05±0.02	1.04±0.02	1.03±0.02	1.06±0.02

Conversion background

- Internal ($\gamma^* \to l^+ l^-$) before reaching the detector ~ $\ln\big(M(l)\big)$
- External ($\gamma \to l^+ l^-$) inside the detector ~ $M(l)^{-1}$
- One of the leptons does not get reconstructed and pass SS lepton selection
- The modeling of conversion in MC validated using $Z + \gamma$
  - 3 leptons, no b-jet
  - OS same flavour $|M(ll) - 91.2| > 10GeV$ & $M(ll) > 12GeV$
  - Leading electron(muon) $p_T > 25(20)GeV$ for dielectron (dimuon)
  - $|M(lll) - 91.2| < 10GeV$
- Flat 20% systematic



Search Strategy



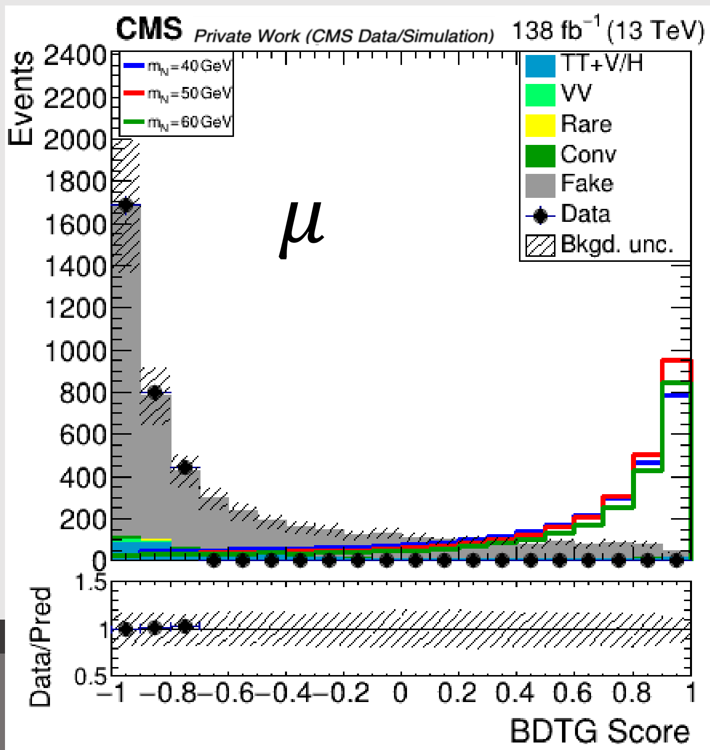
- Full reconstruction of signal event is between 0.02 ~ 4 %
  - Use Multivariate Gradient Boosted Decision Tree technique
  - 5 models trained using 5 m_N hypothesis: **20,50,75,85,100** GeV
- Total 17 variables from 4 categories.
  - Particles and energy scale
  - Angular distribution
  - Signal decay mass
  - Background decay mass

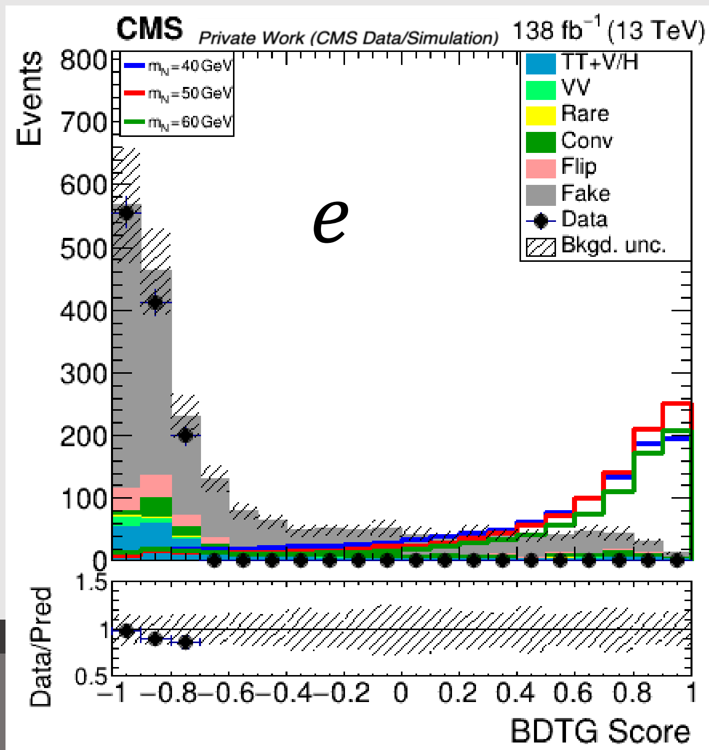
Energy Difference	Angular Difference	Signal Decay Mass	Background Decay Mass
N(j)	$\Delta R(ll)$	m(ll)	$m_T(l_1 p_T^{miss})$
N(b)	$\Delta R(l_a j_b)$	$m(l_a j_{N,1})$	$m_T(b_1 l_1 p_T^{miss})$
$p_T(l_a)$		$m(bllj_{N,1})$	$m_T(l_2 j_{L,1})$
p_T^{miss}		$m(llj_{N,1})$	$m_T(l_2 j_W j_W)$
H_T		$m(laj_N j_N)$	
		$m(bllj_N j_N)$	

Described in the backup slide Variable examples in the backup slide

BDTG Score Distribution

- BDTG Distributions of signal and background for 50 GeV m_N hypothesis
- This distribution is used to extract signal cross section pp$\rightarrow t\bar{t} \rightarrow \mathrm{tblN}$





Extract Limit

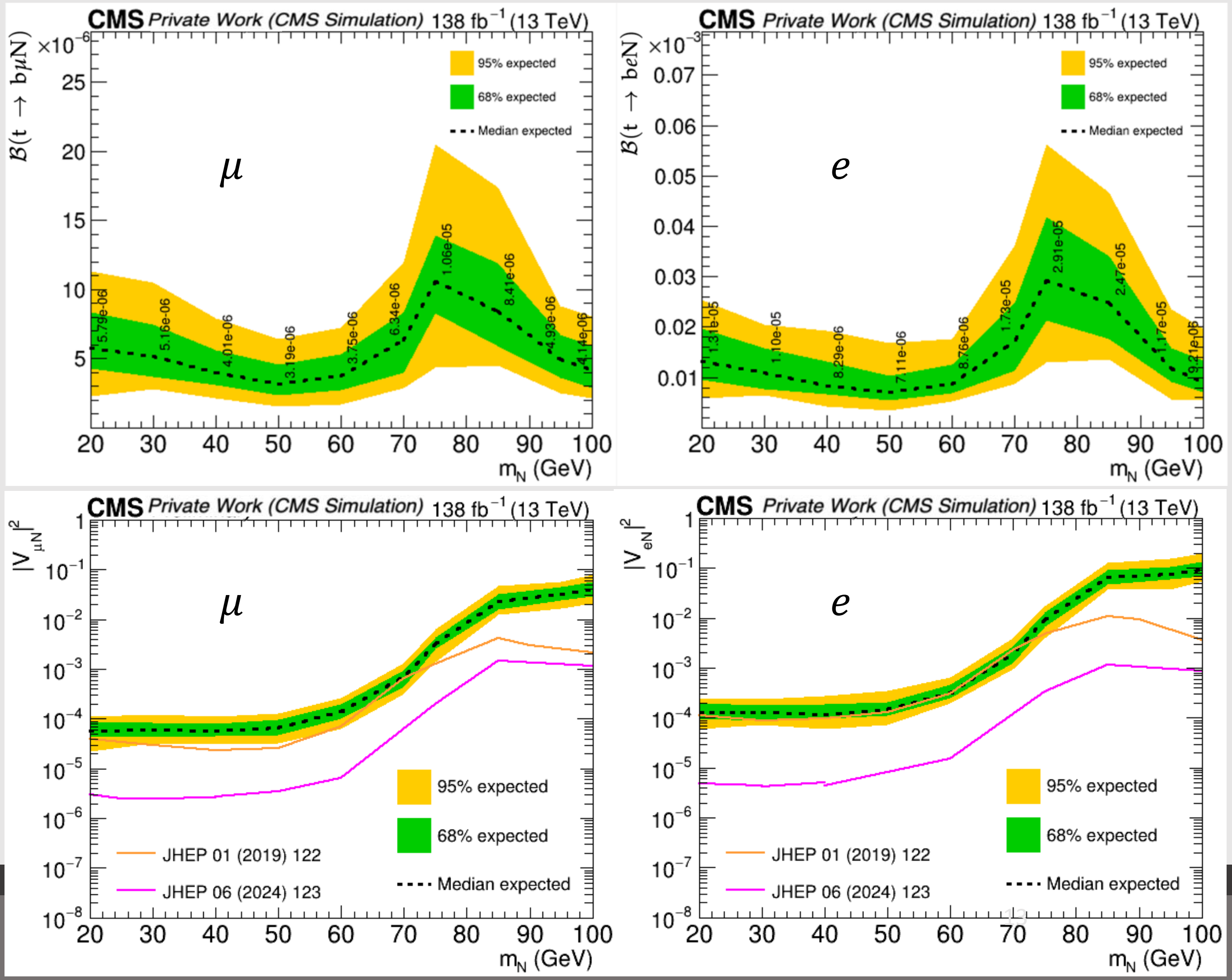
- Optimize the BDTG Score binning for good sensitivity to signal in reasonable computing time
- Finer binning where signal is dominant
- Small number of events require fully frequentist method to extract the limit
  - Make 1000~5000 toy data and run the fit for corresponding expected limit quantile.
- Extracted cross section is inclusive top pair production decaying to N, which can be written as:

$$\sigma(\mathrm{pp} \rightarrow t\bar{t} \rightarrow blN\bar{t})_{obs} = \sigma(pp \rightarrow t\bar{t})_{incl} \times Br(t \rightarrow blN)_{obs}$$

- Comparing observed $Br(t \rightarrow blN)$ to expected $Br(t \rightarrow blN)$ from matrix element calculation allow translation to mixing angles

$$\frac{|V_{lN}|^2_{exp}}{|V_{lN}|^2_{obs}} = \frac{Br(t \rightarrow blN)_{exp}}{Br(t \rightarrow blN)_{obs}}$$

Result

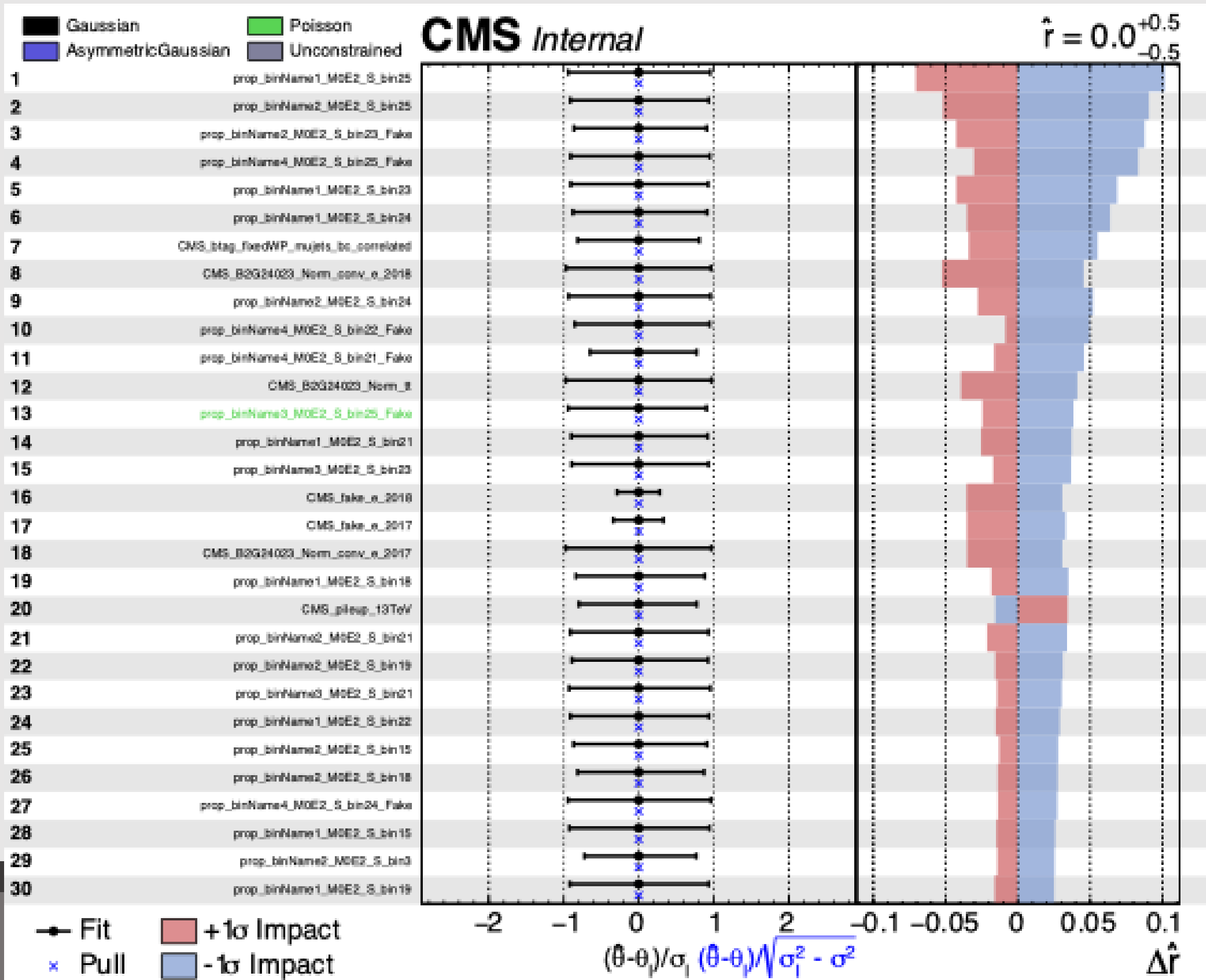

CMS Private Work (CMS Simulation) 138 fb^{-1} (13 TeV)
$\mathcal{B}(t \to b\mu N)$
$\times 10^{-6}$
95% expected
68% expected
Median expected
μ
5.79e-06
5.16e-06
4.01e-06
3.19e-06
3.75e-06
6.34e-06
1.06e-05
8.41e-06
4.93e-06
4.14e-06
m_N (GeV)
CMS Private Work (CMS Simulation) 138 fb^{-1} (13 TeV)
$\mathcal{B}(t \to beN)$
$\times 10^{-3}$
95% expected
68% expected
Median expected
e
1.31e-05
1.10e-05
8.29e-06
7.11e-06
8.76e-06
1.73e-05
2.91e-05
2.47e-05
1.17e-05
9.21e-06
m_N (GeV)
CMS Private Work (CMS Simulation) 138 fb^{-1} (13 TeV)
$|V_{\mu N}|^2$
μ
95% expected
68% expected
Median expected
JHEP 01 (2019) 122
JHEP 06 (2024) 123
m_N (GeV)
CMS Private Work (CMS Simulation) 138 fb^{-1} (13 TeV)
$|V_{eN}|^2$
e
95% expected
68% expected
Median expected
JHEP 01 (2019) 122
JHEP 06 (2024) 123
m_N (GeV)

Conclusion

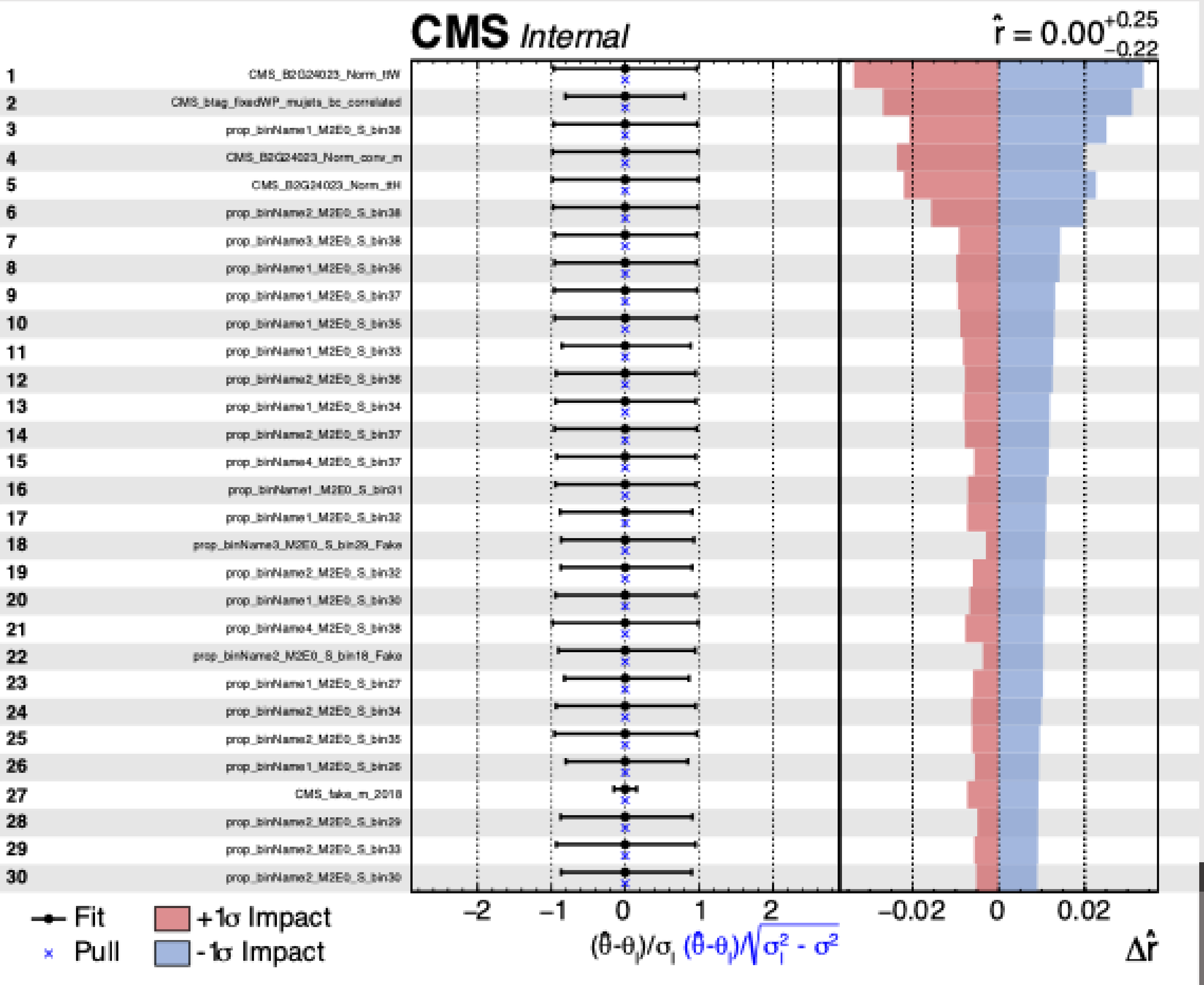
- **This is the first indirect search for Heavy Majorana Neutrino using top decay.**
- Main backgrounds are non-prompt lepton, charge-mismeasured lepton, and conversion lepton.
  - The systematics and validation has been analyzed
  - Main update on fake MC Closure correction, charge-flip electron momentum correction, and limit extraction using the shape of score distribution
- Used BDTG training due to low event reconstruction efficiency
- Comparable performance to CMS DY W direct search
- This channel opens a new CP-violation in seesaw-model search for the future

Backup

Nuisance Parameter (El)



Nuisance Parameter (Mu)



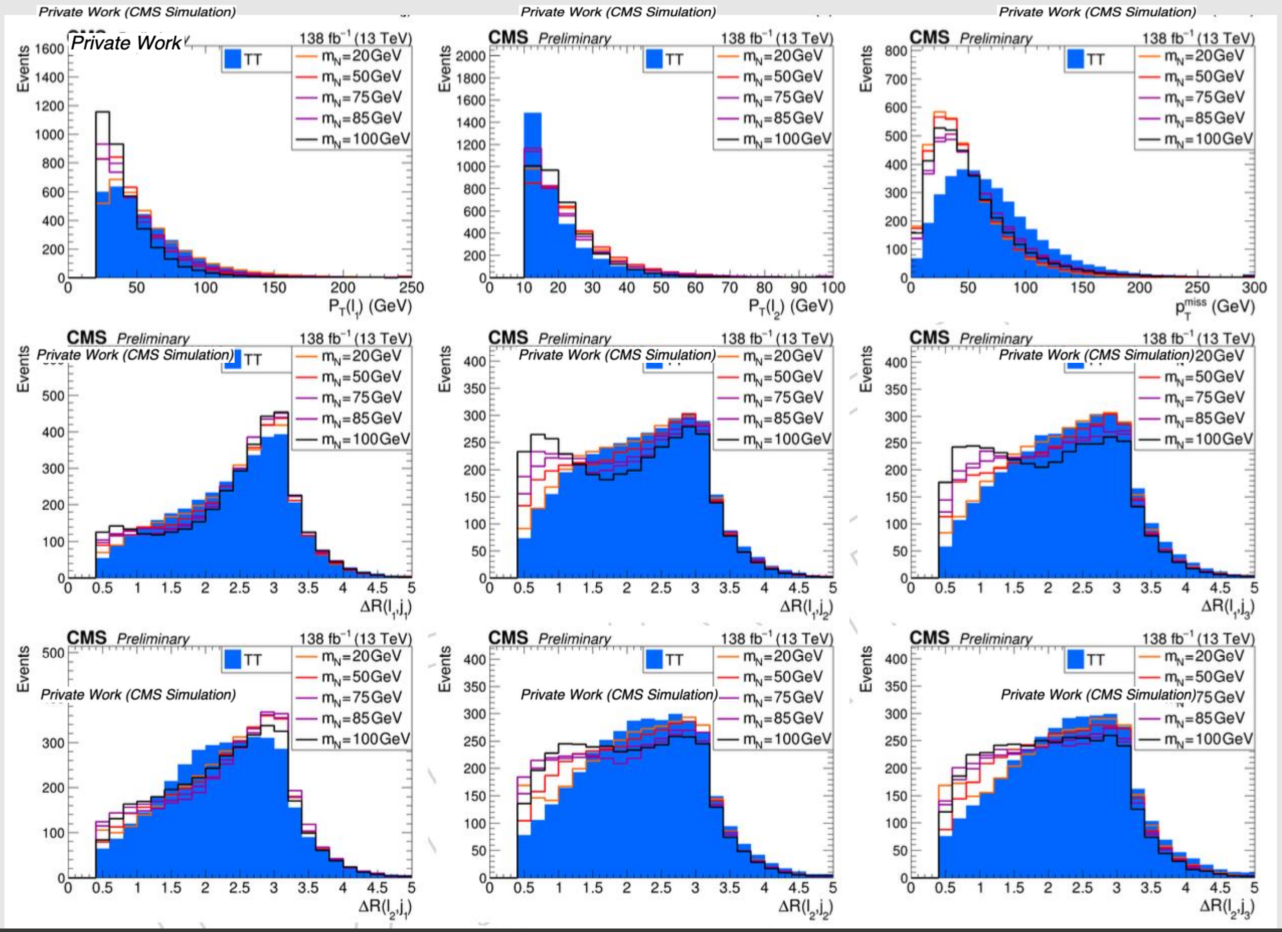
BDTG Input Variables

variable	low mass	high mass	description
N(j)	✓	✓	jet multiplicity
N(b)	✓	✓	b-tag multiplicity
$p_{\mathrm{T}}(\ell_a)$	✓	✓	a-th lepton p_{T} (a:1–2)
$p_{\mathrm{T}}^{\mathrm{miss}}$	✓	✓	missing transverse energy
HT	✓	✓	scalar sum of jet p_{T}
$\Delta R(\ell\ell)$	✓	✓	ΔR between two leptons
$\Delta R(\ell_a \mathrm{j}_b)$	✓	✓	ΔR between a-th lepton and b-th jet (a:1–2, b:1–3)
$\mathrm{m}_{\ell\ell}$	✓	✓	dilepton invariant mass
$m(\ell_a \mathrm{j}_{\mathrm{N},1})$	✓	✓	invariant mass of a-th lepton and leading N-jet candidate (a:1–2)
$m(\ell_1 \ell_2 \mathrm{j}_{\mathrm{N},1})$	✓		invariant mass of two lepton and leading N-jet candidate
$m(\mathrm{b}\ell_1 \ell_2 \mathrm{j}_{\mathrm{N},1})$	✓	✓	invariant mass of two lepton, b-tagged jet, and leading N-jet candidate
$m(\ell_a \mathrm{j}_{\mathrm{N},1} \mathrm{j}_{\mathrm{N},2})$		✓	invariant mass of a-th lepton and two N-jet candidates (a:1–2)
$m(\mathrm{b}\ell\ell \mathrm{j}_{\mathrm{N},1} \mathrm{j}_{\mathrm{N},2})$		✓	invariant mass of two leptons, b-tagged jet, and two N-jet candidates
$m_{\mathrm{T}}(\ell_1, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$	✓	✓	transverse mass of leading lepton and $p_{\mathrm{T}}^{\mathrm{miss}}$
$m_{\mathrm{T}}(\mathrm{b}_1 \ell_1, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$	✓	✓	transverse mass of leading lepton +leading b-tagged jet, and $p_{\mathrm{T}}^{\mathrm{miss}}$
$m(\ell_2 \mathrm{j}_{L,1})$	✓	✓	invariant mass of subleading lepton and leading untagged jet
$m(\ell_2 \mathrm{j}_{\mathrm{W},1} \mathrm{j}_{\mathrm{W},2})$		✓	invariant mass of subleading lepton and two W-jet candidates

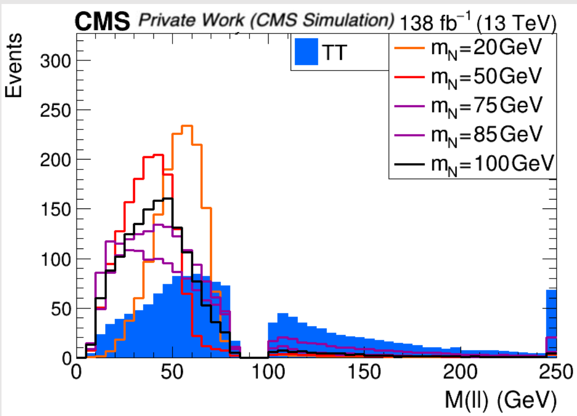
List of Systematic Uncertainty sources

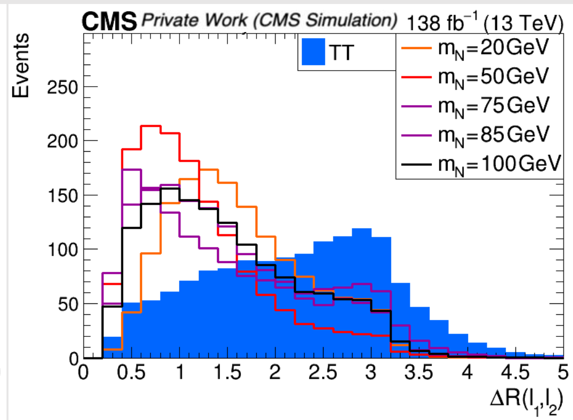
Source	Correlation in data-taking eras	Process
luminosity	yes/no	prompt (OS, SS), signal, conversion
Pileup Reweight	yes	prompt (OS, SS), signal, conversion
L1-prefiring rate	no	prompt (OS, SS), signal, conversion
trigger efficiency	yes	prompt (OS, SS), signal, conversion
electron reco. efficiency	yes	prompt (OS, SS), signal, conversion
electron energy scale	yes	prompt (OS, SS), signal, conversion
electron energy resolution	yes	prompt (OS, SS), signal, conversion
electron ID efficiency	yes	prompt (OS, SS), signal, conversion
muon p_T scale, resolution	yes	prompt (OS, SS), signal, conversion
muon ID efficiency	yes	prompt (OS, SS), signal, conversion
jet energy scale	yes	prompt (OS, SS), signal, conversion
jet energy resolution	no	prompt (OS, SS), signal, conversion
unclustered energy scale	no	prompt (OS, SS), signal, conversion
Pileup Jet ID	no	prompt (OS, SS), signal, conversion
HEM Region Jet Scale	no (2018 only)	prompt (OS, SS), signal, conversion
b-tagging efficiency (b,c)	yes/no	prompt (OS, SS), signal, conversion
b-tagging efficiency (u,d,s,g)	yes/no	prompt (OS, SS), signal, conversion
CFR measurement	no	prompt (OS)
CFR parameterization	yes	prompt (OS)
electron energy scale (charge-mismeasured)	yes	prompt (OS)
fake rate	no	fake lepton (jet)
conversion rate (e)	no	conversion (electron-only)
conversion rate (μ)	yes	conversion (muon-only)
limited sample size	no	prompt (OS, SS), signal, conversion, fake lepton (jet)
cross section	yes	prompt (OS, SS)
QCD scales (ME, acceptance)	yes	signal
PDF (acceptance)	yes	signal
parton shower modeling	yes	signal

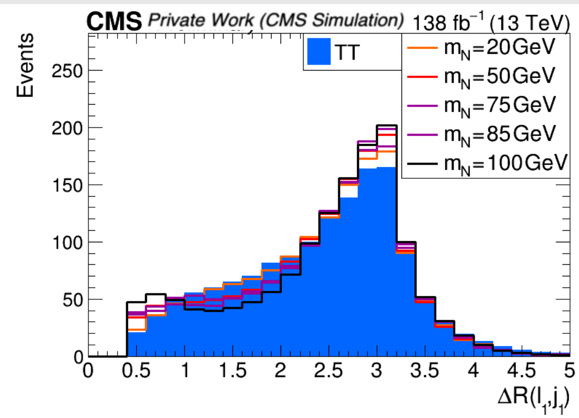
BDTG Input distribution



BDTG Important Input distribution







MSSSF $\Delta R(l_1 l_2)$ $\Delta R(l_1 j_1)$