Search for heavy neutrinos in $t\bar{t}$ decays with the full Run 2 ATLAS dataset

Tongbin Zhao

Supervisor: Lianliang Ma

CLHCP Workshop

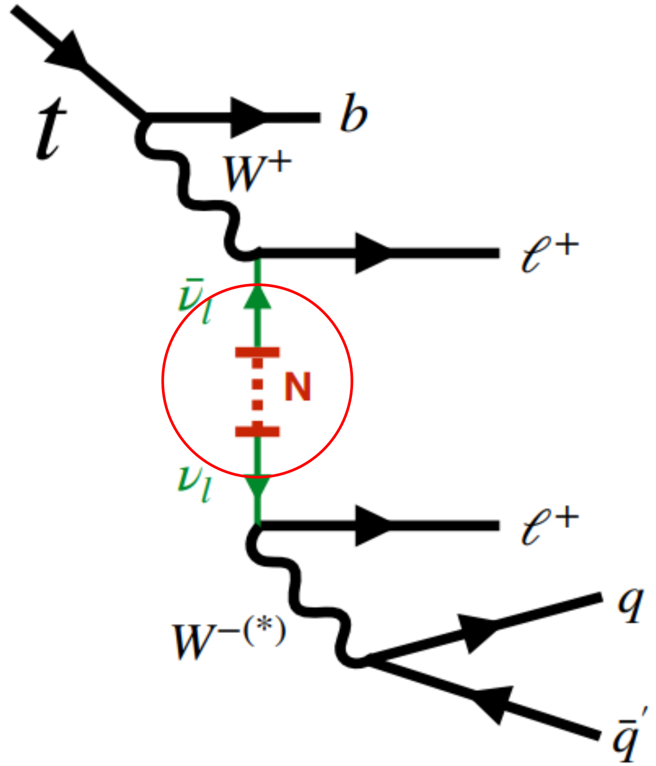
19/11/2023

Outline

- Introduction
- Analysis strategy
- Uncertainties
- Statistical treatment
- Summary
- Backup slides

Introduction

Motivation



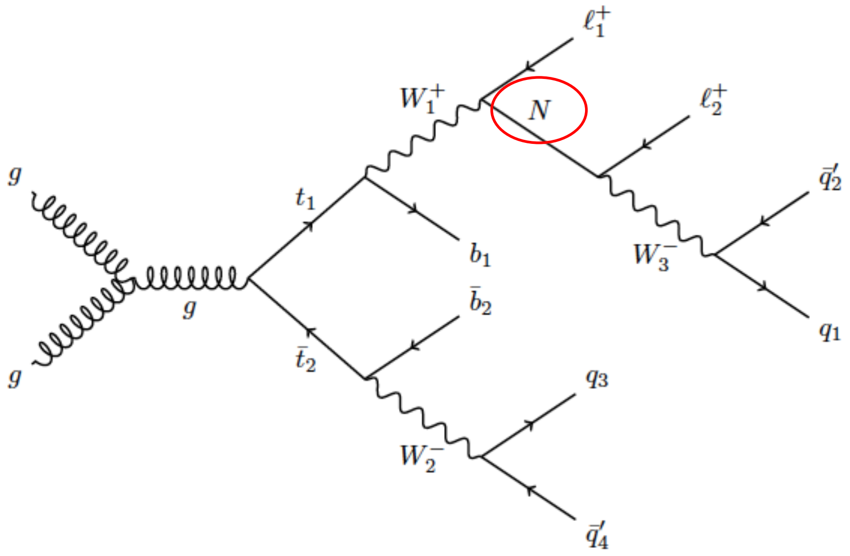
$$V_{\ell,N} = \begin{pmatrix} V_{e,N1} & V_{e,N2} & V_{e,N3} \\ V_{\mu,N1} & V_{\mu,N2} & V_{\mu,N3} \\ V_{\tau,N1} & V_{\tau,N2} & V_{\tau,N3} \end{pmatrix}$$

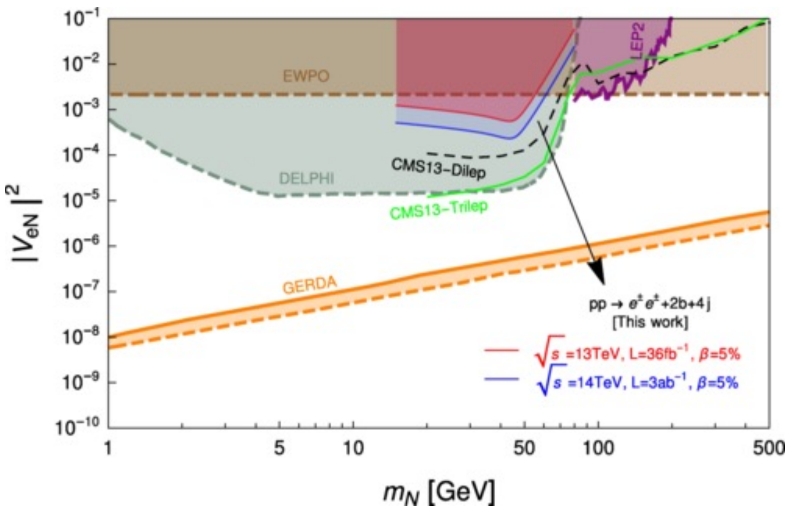
- ✓ Neutrinos are massive and mixing.
- ✓ The seesaw mechanism theory provides an explanation for the small mass of neutrinos.
- ✓ Type-I seesaw is the simplest, adding 3 heavy RH Majorana neutrinos N_1, N_2, N_3.
  N_i can couple to SM neutrinos via coupling strength V_{iN}
- ✓ Neutrino-less double-beta decay: a lepton number violation of $|\Delta L|$ = 2 along with the process of generating Majorana neutrino.

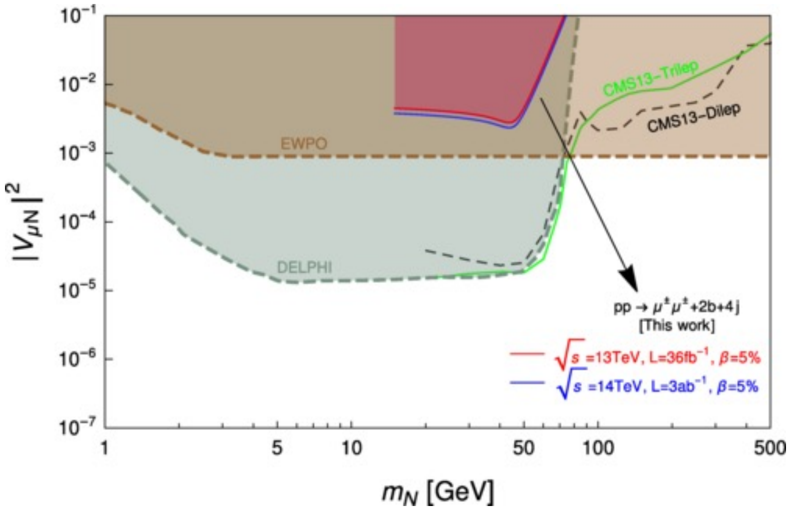
Other analysis:

- ✓ With the Drell-Yan process $q\bar{q} \rightarrow W^* \rightarrow N\ell$.
- ✓ JHEP10 (2019) 265 (ATLAS) ($36.1\ fb^{-1}$, $[5,50]\mathrm{GeV}$, $|V_{iN}|^2 > 1.4 * 10^{-5}$)
- ✓ JHEP01 (2019) 122 (CMS) ($35.9\ fb^{-1}$, $[20,1600]\mathrm{GeV}$, $|V_{iN}|^2 > 2.3 * 10^{-5}$)
- ✓ LHC is a top factory and this analysis searches for heavy neutral leptons in the $t\bar{t}$ process.

Motivation







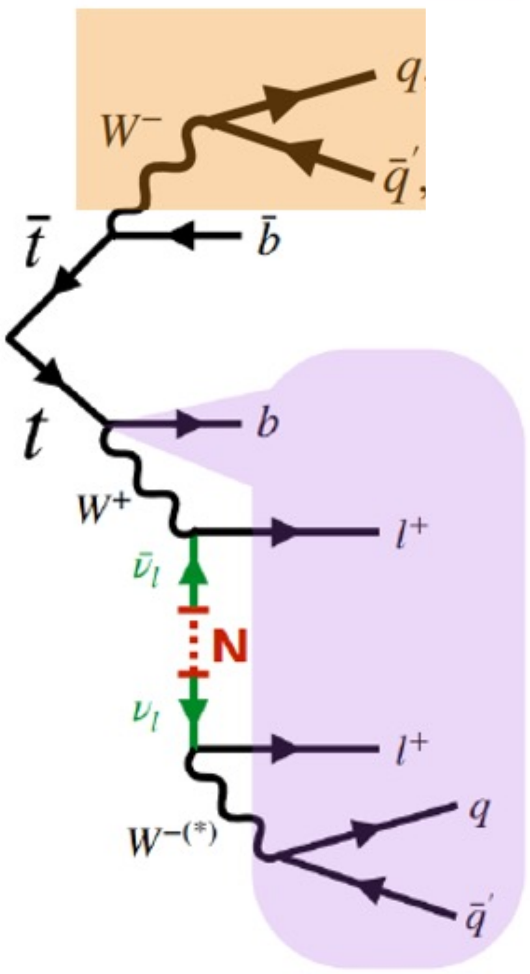
[Phys. Rev. D 101, 071701(R) (2020) by Ning Liu et al]

$$v_{mix} = \begin{pmatrix} V_{eN1} & 0 & 0 \\ 0 & V_{\mu N2} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

This analysis:

- ✓ N_1 only couples to electrons, while N_2 only couples to muons
- ✓ The first time to use the top quark decay to measure the heavy-light neutrino mixing parameters

Signal process



<u>Signal process</u> -> tt̄ :

One top with SM decay and the other top with BSM decay

- ✓ Only consider 2LSS final state: On-shell W from SM top and off-shell W^* both decay hadronically
- ✓ 10 signal mass points for HNL: **15, 25, 35, 40, 45, 50, 55, 60, 70 and 75 GeV**

Signal modelling:

- ✓ BSM signal process with HeavyN UFO Model
- ✓ Athena 21.6.48 setup and AtlFast2 simulation
- ✓ MadGraph5_aMC@NLO 2.7.3 generator
- ✓ PDF: NNPDF3.0NLO
- ✓ Parton shower and hadronization: Pythia 8.244

Backgrounds considered in this analysis

Dominant backgrounds:

- ✓ $\boldsymbol{t\bar{t}}$ (PhPy8 - 1 nonallhad sample 410470)
- ✓ $\boldsymbol{t\bar{t}}$**W** (Sh2.2.10 - 1 QCD sample 700168 + 1 EW sample 700205)
- ✓ $\boldsymbol{t\bar{t}}$**Z** (aMc@Py8 - 3 sample 504330, 504334, 504343)
- ✓ $\boldsymbol{t\bar{t}\gamma}$ (MadGraph@Py8 - 1 sample 410389)
- ✓ $\boldsymbol{t\bar{t}H}$ (PhPy8 - 2 samples 346344,346345)

Other backgrounds:

- ✓ **V+jets** production (Sh2.2.1 - 84 samples)
- ✓ **Drell-Yan** production (Sh2.2.1 - 18 samples)
- ✓ **VV/VVV** production (Sh2.2.2 - 23 samples)
- ✓ **Single-t** production (Powheg@Py8 - 6 samples)
- ✓ **tWZ, tZq, 3tops, 4tops,** $\boldsymbol{t\bar{t}}$**WW** production (5 samples)
- ✓ **VH, tHW, tHq,** $\boldsymbol{t\bar{t}}$**XX** production (8 samples)

Analysis strategy

Object selection and event selection

Object selection

Apply single lepton trigger

Electrons :

Pseudorapidity range	$(\lvert\eta\rvert < 1.37) \quad \lVert \quad (1.52 < \lvert\eta\rvert < 2.47)$
Transverse momentum	$p_T > 10\,\text{GeV}$
Track to vertex association	$\lvert d_0\rvert/\sigma_{d_0} < 5$ $\lvert\Delta z_0^{BL} \sin\theta\rvert < 0.5$ mm
Identification	(TightLH)
Isolation	PLImprovedTight
Loose isolation	PLVLoose
Extra selections	ECIDS, ambiguity cuts

Muons :

Selection working point	Medium
Isolation	PLImprovedTight
Loose isolation	PLVLoose

p_T Cut	10 GeV
$\lvert\eta\rvert$ cut	< 2.5
$\lvert d_0\rvert/\sigma_{d_0}$	3
$\lvert\Delta z_0 \sin\theta_\ell\rvert$ cut	0.5 mm

Jets :

- ✓ p_T > 20 GeV
- ✓ |η| < 4.5

B-tagging:

- ✓ CDI: 2020-21-13TeV-MC16-CDI-2021-04-16 v1.root.
- ✓ BTaggingWP: DL1r 85% WPs efficiency

Pre-selection on analysis level:

- ✓ Exactly a pair of same-sign electrons or muons and the leading lepton with p_T > 27 GeV
- ✓ At least 2 b-tagged jets with p_T > 25 GeV
- ✓ At least 4 non-b-tagged jets
  - ✓ Central jets (|η| < 2.5, JVT flag): p_T > 20 GeV
  - ✓ Forward jets (4.5 >|η| > 2.5, fJVT flag): p_T > 35 GeV
- ✓ $m_{\ell\ell}$ > 12 GeV

Event reconstruction

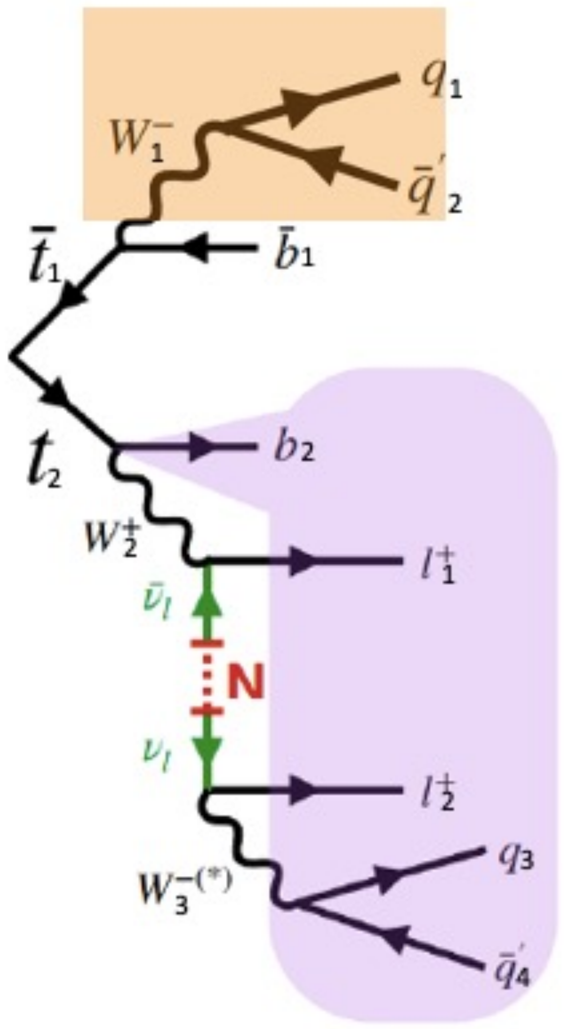
Event selection			
Exactly 2 same-sign same-flavor leptons			
>= 2 b-jets + >= 4 non b-tagged jets			
Top with BSM decay	**W with BSM decay**	**Top with SM decay**	**W with SM decay**
1 bjet 2 leptons 2 jets	2 leptons 2 jets	1 bjet 2 jets	2 jets

- ✓ Reconstruct χ^2 of m_{TopSM}, m_{TopBSM}, m_{WBSM} and m_{WSM}, then minimize the sum of four χ^2 to determine the best combination.
- ✓ These useful kinematic variables are generated and used as the input in MVA.

- ✓ $\boldsymbol{q_i \to j_i}$
- ✓ t_1:Top with SM decay:
  $\boldsymbol{M_{b_1 j_1 j_2}}$
- ✓ W_1: W with SM decay:
  $\boldsymbol{M_{j_1 j_2}}$
- ✓ t_2: Top with BSM decay:
  $\boldsymbol{M_{b_2 l_1 l_2 j_3 j_4}}$
- ✓ W_2: W with BSM decay
  $\boldsymbol{M_{l_1 l_2 j_3 j_4}}$

$$\chi^2 = \Sigma_i^4 \frac{(m_i - M)^2}{\sigma^2} (i = t_1, t_2, W_1, W_2)$$

- ✓ $M_t = 172.69$ GeV
- ✓ $M_W = 80.377$ GeV



Treatment of the non-prompt leptons

Template fit method is used for the non-prompt sources of leptons

- ✓ Assume the shape of the backgrounds in control regions is the same as in signal regions
- ✓ Fit rates of background templates to data in selected control regions

For the fake leptons from heavy flavor decays:

- ✓ Tight isolation (PLIVTight) is performed to reduce the contribution from the fake leptons

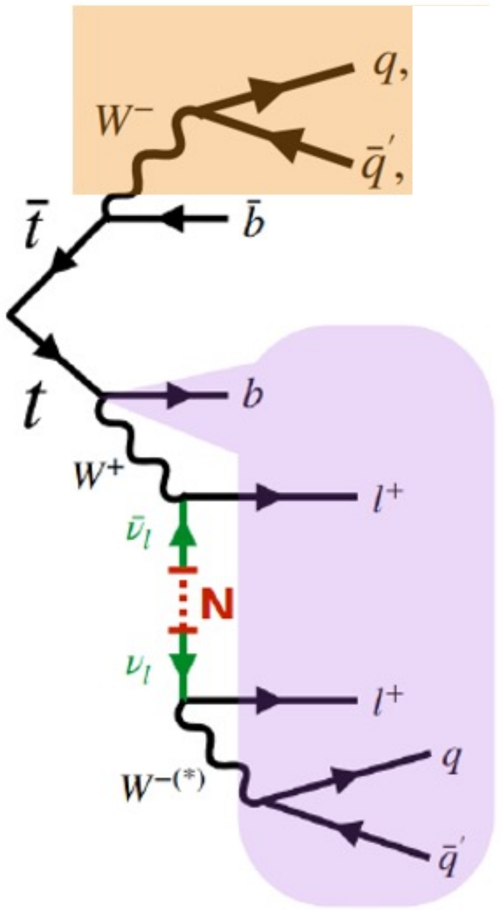
For the electron from the charge misidentification:

- ✓ ECIDS algorithm is used to suppress the Q-flip effects

For the electron coming from the conversion of the photons:

- ✓ Electron Ambiguity Tools are used to suppress the photon conversion contribution

Construction of the templates



One prompt lepton + the other IFF lepton for SS leptons

Split according to the categories provided by the IFF truth classifier

Temples for $t\bar{t}$ samples:

- ✓ Prompt
- ✓ Known-Unknown → $t\bar{t}$ other
- ✓ Tau-decay e/μ / e from μ
- ✓ B(C) hardon decay e/μ
- ✓ LF-decay e/μ

Template 1: HF decay contribution of e/μ

- ✓ Charge-flip e → Template 2: Qflip of e
- ✓ Photon conversion e

For $t\bar{t}\gamma$ samples:

Template 3: Photon conversion of e

- ✓ Contribute to the final states via photon conversion and left floating together with the Photon conversion e from $t\bar{t}$
- ✓ Perform the overlap removal with the inclusive $t\bar{t}$ sample

For $t\bar{t}$W/Z samples:

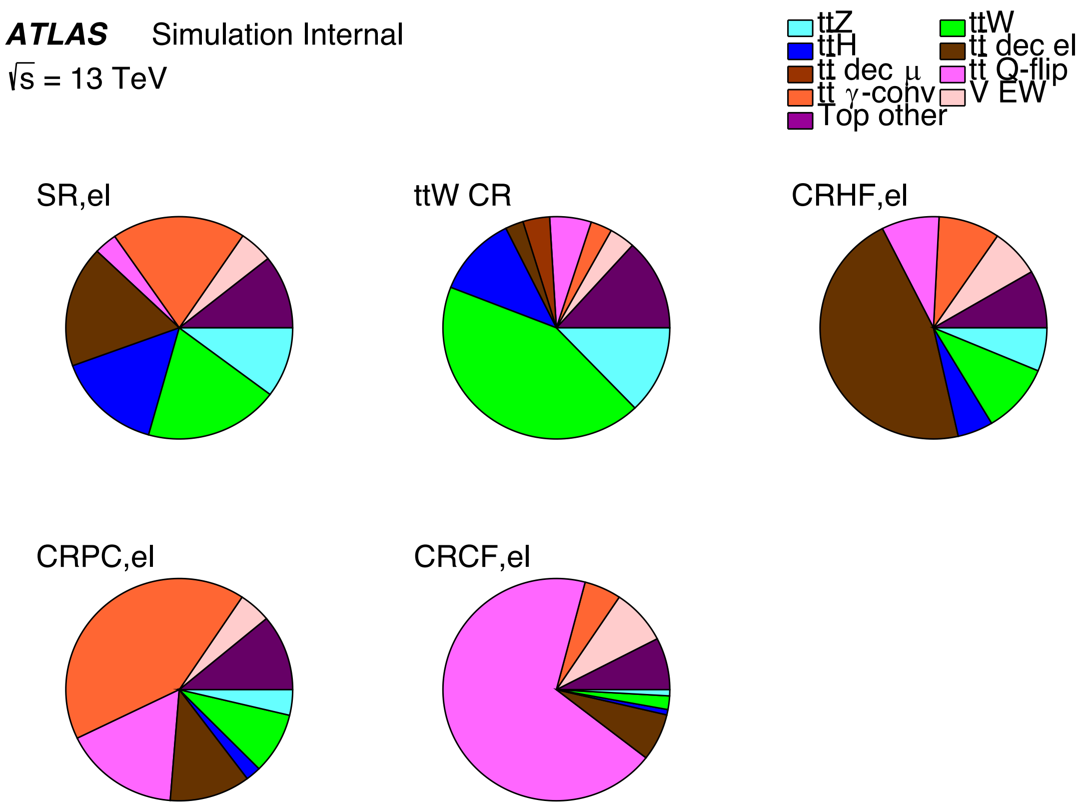
- ✓ They contribute to the final states via prompt leptons classes.
- ✓ Dedicated measurements of the cross sections of $t\bar{t}$Z is deviated from the predictions
- ✓ Template 4: Control region for $t\bar{t}$W is defined and its normalization is left free-floating in the fit.

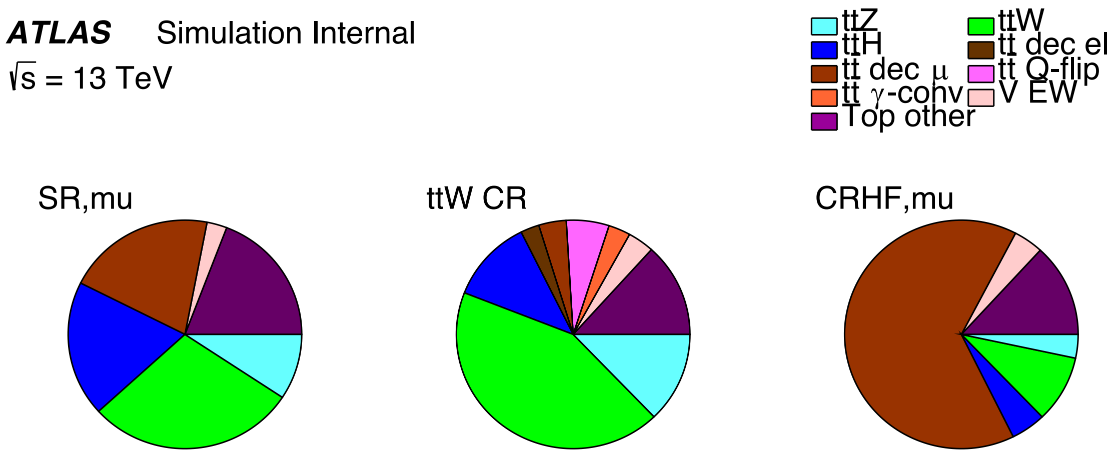
SR/CRs definition

Region	$\ell_1 - \ell_2$ flavour	Isolation cut	Ambiguity cut	ECIDs cut	Other
SR(ee)	e-e	PLIVTight & PLIVTight	Pass & Pass	!Pass & !Pass	$m_{\ell\ell}$ < 80 GeV
CR(e_{ttW})	e-e	PLIVTight & PLIVTight	Pass & Pass	!Pass & !Pass	$m_{\ell\ell}$ > 100 GeV and merged with CR(μ_{ttW})
CR(e_{HF})	e-e	!(PLIVTight & PLIVTight)	Pass & Pass	!Pass & !Pass	$m_{\ell\ell}$ > 75 GeV
CR(e_{PC})	e-e	-	!(Pass & Pass)	!Pass & !Pass	$m_{\ell\ell}$ > 75 GeV and veto Z
CR(e_{CF})	e-e	-	Pass & Pass	Pass | Pass	$m_{\ell\ell}$ > 60 GeV and veto Z
SR($\mu\mu$)	μ-μ	PLIVTight & PLIVTight	-	-	$m_{\ell\ell}$ < 80 GeV
CR(μ_{ttW})	μ-μ	PLIVTight & PLIVTight	-	-	$m_{\ell\ell}$ > 80 GeV and merged with CR(e_{ttW})
CR(μ_{HF})	μ-μ	!(PLIVTight & PLIVTight)	-	-	$m_{\ell\ell}$ > 75 GeV

- If both leptons pass the "Ambiguity cut", it indicates that they both veto the photon conversion candidates.
- Passing the "ECIDS cut" implies that one of the leptons has a misidentified charge, while the reverted situation indicates that none of the leptons have the ECIDS tag.
- The $t\bar{t}$W CRs are merged to improve the statistics and keep the consistency of ee/$\mu\mu$ channels
- Perform the multi-variate analysis on two signal regions

Region composition





- ✓ In each control region, the backgrounds under study are dominant
- ✓ The merged $t\bar{t}$ W CR are included on the separated $ee/\mu\mu$ channel
- ✓ “V EW” contains VV/VVV and V+jets samples and “Top other” contains other minor backgrounds

Multi-variate analysis (BDT)

Performed **Boost decision tree(Gradient)** for separation of signal and backgrounds using the **mva-trainer package** based on scikit-learn

✓ Signal: 10 mass points are divided into high and low mass training sets

High mass set: HNL[45, 50, 55, 60, 70, 75] GeV

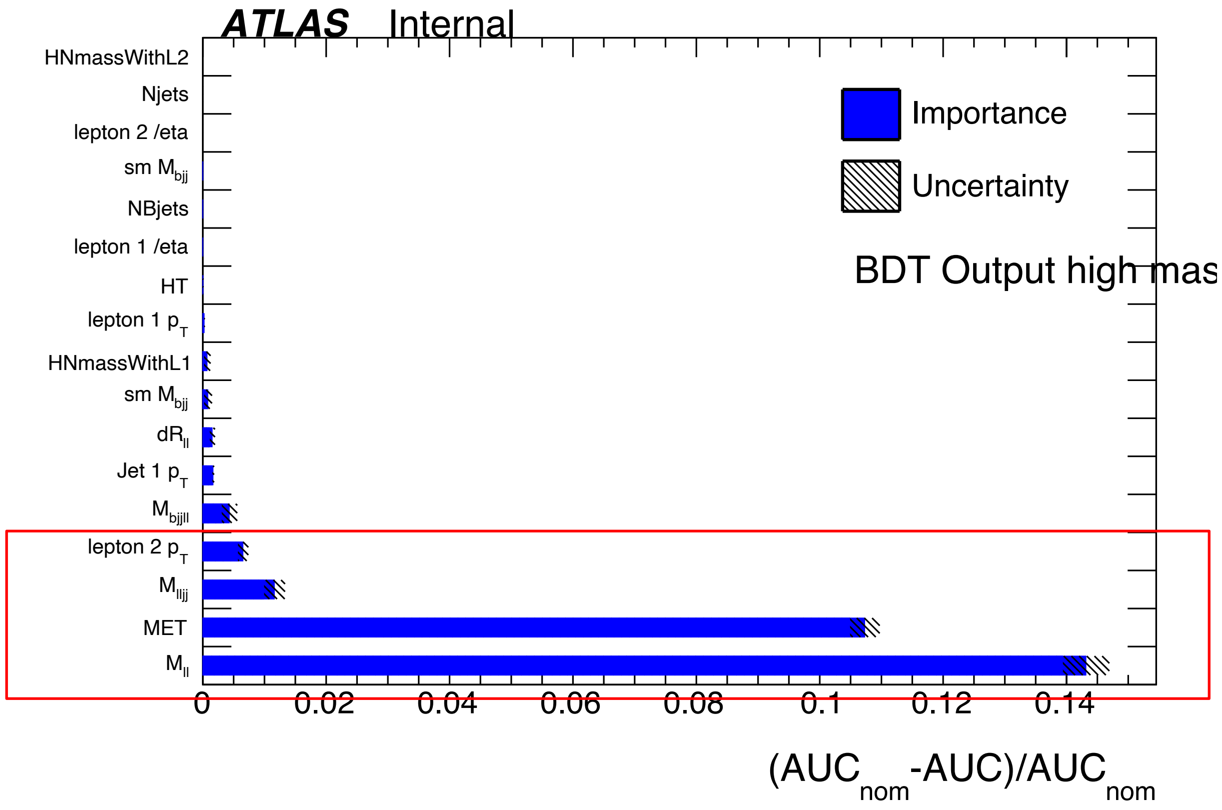
Low mass set: HNL[15, 25, 35, 40] GeV

(for the sake of improving signal statistics)

✓ Background: all backgrounds considered

✓ Perform Cross-Validation Check: 2-fold

✓ Negative weights treatment: use absolute value of weights



✓ Importance ranking of the best ranked variables

Multi-variate analysis (BDT)

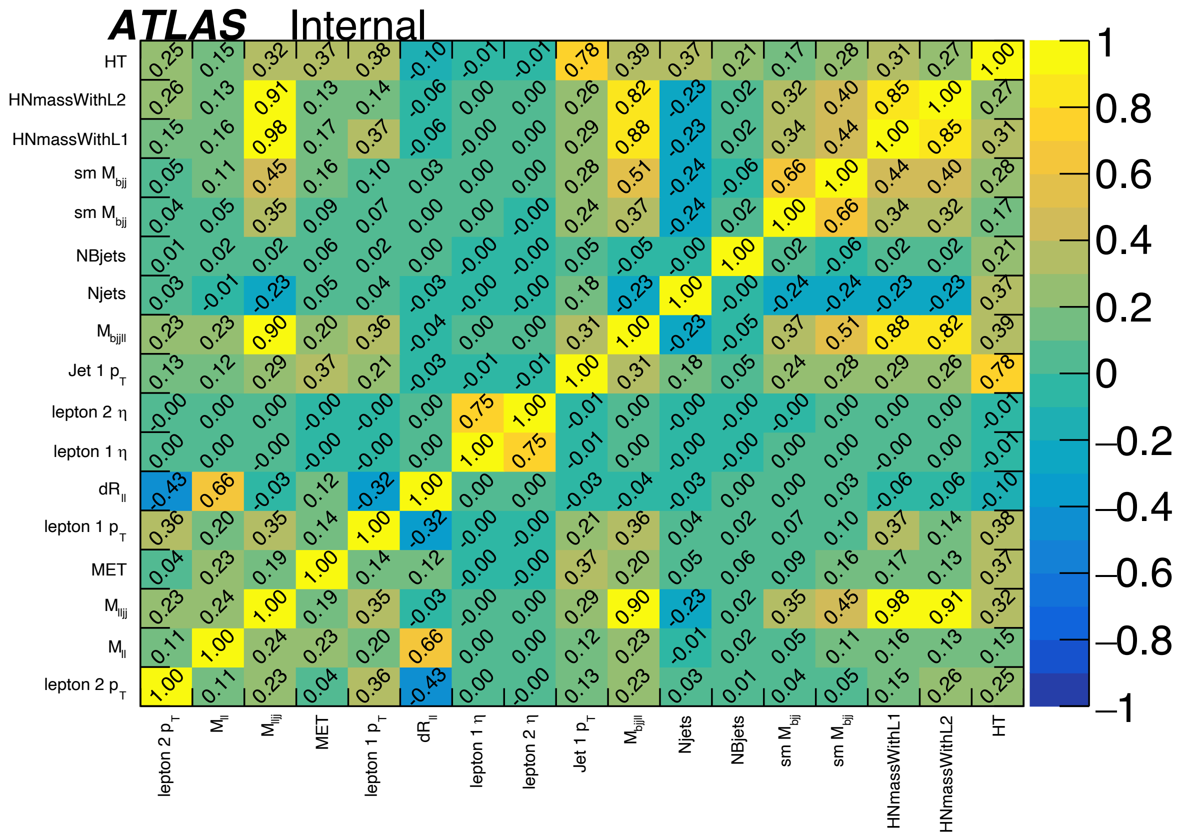
✓ Signal: 10 mass points are divided into high and low mass training sets

High mass set: HNL[45, 50, 55, 60, 70, 75] GeV

Low mass set: HNL[15, 25, 35, 40] GeV

✓ In each set, the combined signal events are trained together with all the background events.

✓ The assessed BDT outputs are subsequently injected into their respective signal mass points, which is regarded as the kinematic variable in the signal region for the fitting process.



✓ Correlation matrix of the initial 17 variables

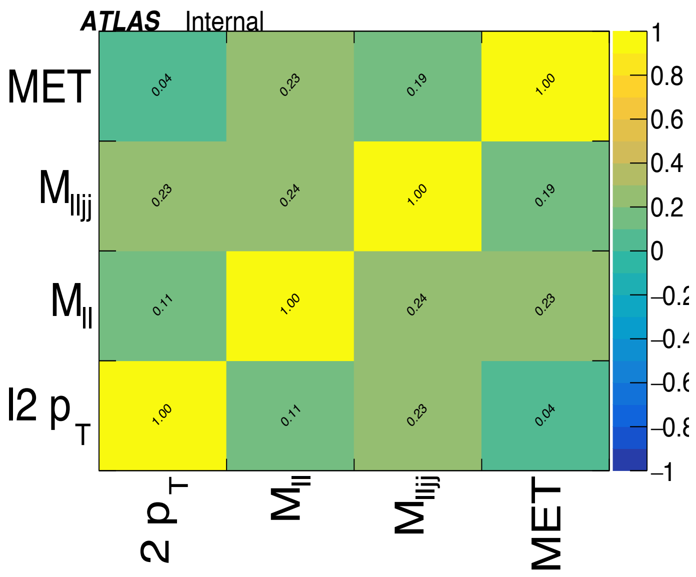
Optimization on the MVA

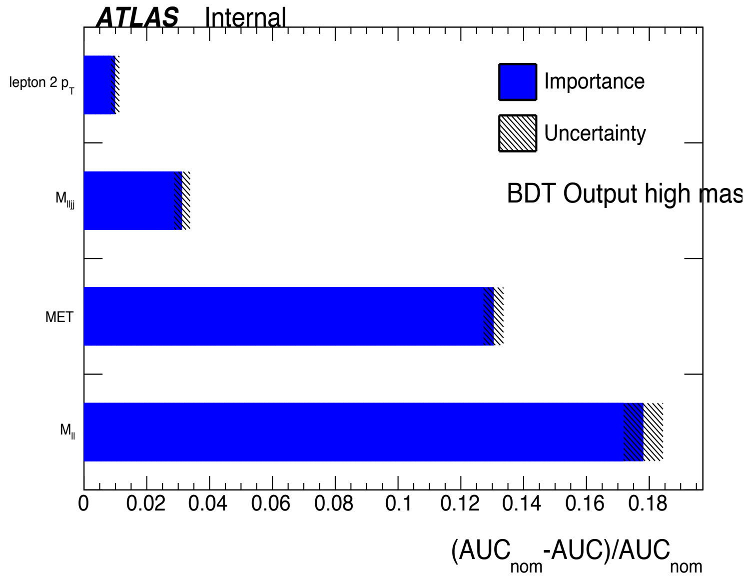
Optimization principle:

- ✓ Decorrelation of all variables
- ✓ Decorrelated and reduced low importance variables by gain in AUC values
- ✓ Only use most significant variables as input and four variables were left without significant loss of signal efficiency $(p_t^{lep2}, MET,\ m_{ll},\ M_{bsmW})$

BDT config:

- ✓ nEstimators=50
- ✓ Loss = deviance
- ✓ LearningRate=0.1
- ✓ MaxDepth=2
- ✓ ValidationSize=0.1
- ✓ Patience=1000
- ✓ MinDelta=0.0001



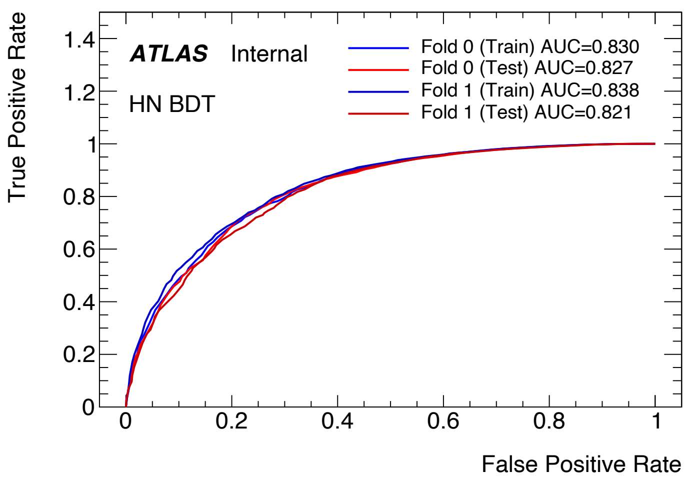


- ✓ Correlation matrix and importance ranking of the final input variables

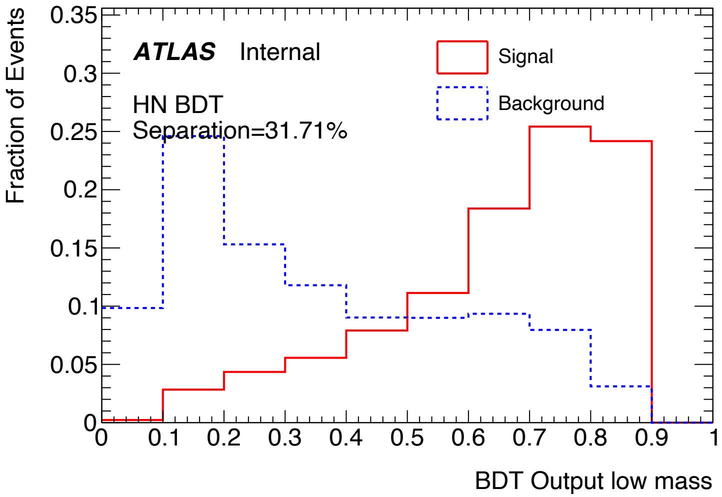
MVA performance

Optimization principle:

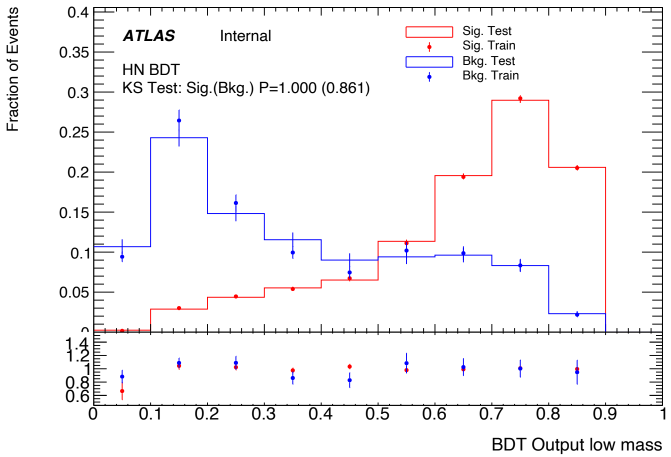
- ✓ Decorrelation of all variables
- ✓ Decorrelated variables ordered by gain in significance
- ✓ Only use most significant variables as input
- ✓ Four variables were left without significant loss of signal efficiency
- ✓ Good agreement between training and testing for different mass sets and different folds



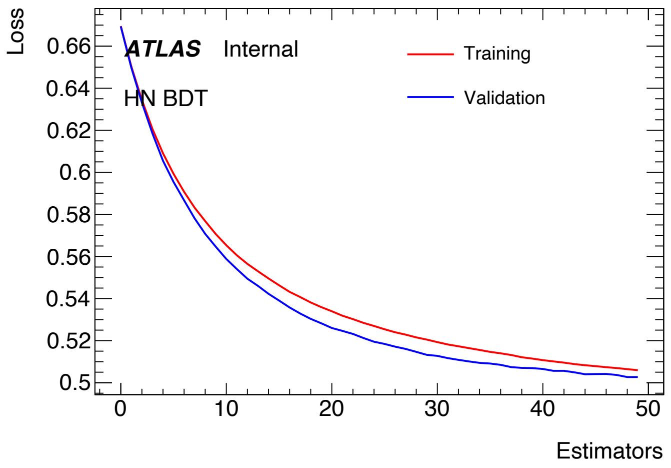
2-fold AUC output



Separation of the signal/backgrounds



Test/training BDT output



Loss function

Uncertainties

Systematics uncertainties

- ✓ **Lepton SFs**:

Electron (Reconstruction, identification, isolation, trigger)

Muon (Reconstruction, identification, isolation, trigger, Track To Vertex Association)

- ✓ **Lepton tree systematics**:

Electron (energy resolution, energy scale),

Muon (momentum resolution, momentum scale, Sagitta Bias)

- ✓ **Jet JES** (CategoryReduction scheme - 30 NPs),
- ✓ **Jet JER** (Full SmearingModel - 13 NPs)
- ✓ **B-tagging scale factor efficiency** (pseudo-continuous B-tag 45NPs, C-tag 20 NPs, L-tag 20 NPs)
- ✓ **MET resolution, scale** (SoftTrk _ResoPerp/ResoPara and SoftTrk_scale)
- ✓ **Others**: Pile-up reweighting, JVT, fJVT

Pruning of shape uncertainty: 1%

Pruning of overall uncertainty: 1%

Other uncertainties

Modelling uncertainties:

$t\bar{t}$ & $t\bar{t}H$ (PhPy8)

- ✓ Alt: Herwig 7
- ✓ Alt: Pythia8 pthard =1
- ✓ Alt: hdamp=3 (only for $t\bar{t}$)
- ✓ PDF set, scale variations μ_R/μ_F, ISR/FSR α_s

$t\bar{t}$W (Sh2.2.10)

- ✓ Alt: aMc@Pythia with FxFx
- ✓ Alt: Powheg@Pythia 8 Vs Powheg@Herwig 7
- ✓ PDF set, scale variations μ_R/μ_F

$t\bar{t}$Z (aMc@Py8)

- ✓ Alt:aMc@Herwig7
- ✓ Alt:aMc@Py8 (A14Var3)
- ✓ Scale variations μ_R/μ_F

Signal(aMc@Py8)

- ✓ PDF set and Scale variations μ_R/μ_F

PDF uncertainties using the PDF4LHC15 prescription

Luminosity: 140 fb^{-1} , 0.83% uncertainties

Processes with tree-floating normalization factors:

- ✓ HF-fake e
- ✓ HF-fake μ
- ✓ Charge flip e
- ✓ Photon conversion e
- ✓ Merged $t\bar{t}$W on ee/$\mu\mu$ channel

Cross section uncertainties:

$t\bar{t}$Z: 12%

$t\bar{t}$H: 10%

V EW: 30% (V EW contains 50% V+jets and 50% VV/VVV events)

$t\bar{t}$_other: 50% (unknown IFF class from $t\bar{t}$ sample)

otherTop: 50%

-> 4tops (dominant one), singleTop, tWZ, tZq, 3tops, $t\bar{t}$WW, t($t\bar{t}$)XX and other IFF classes from $t\bar{t}\gamma$

- ✓ Following the recommendations from the PMG

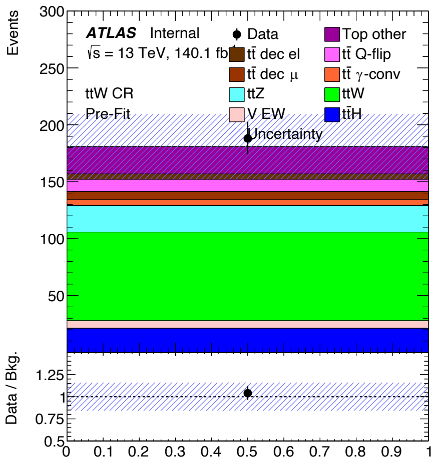
Statistical treatment

$ee/\mu\mu$ channel fitted separately:

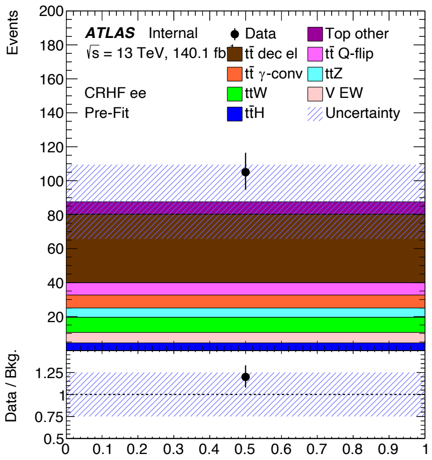
1SR + 4CRs (charge flip, heavy flavor, γ conversion and $t\bar{t}$W) for ee channel

1SR + 2CRs (heavy flavor and $t\bar{t}$W) for $\mu\mu$ channel

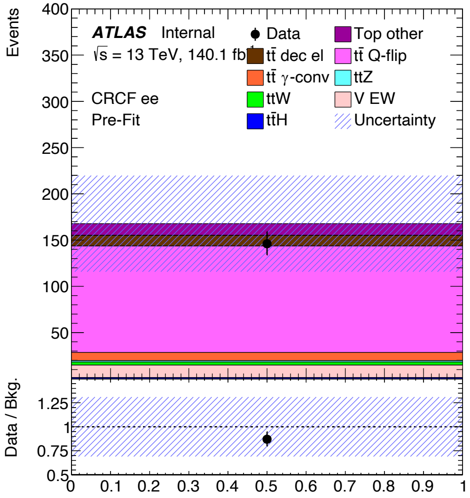
Pre-fit plots of the CR-only fit



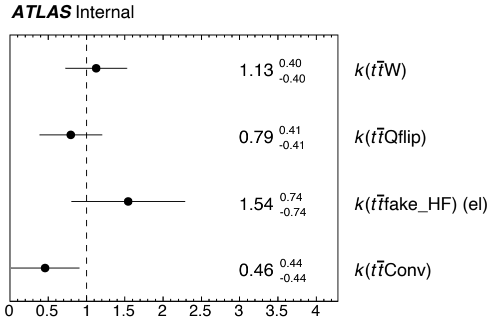
CR $t\bar{t}W$ ee



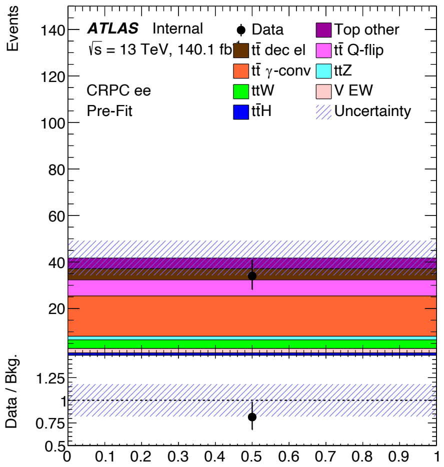
CR HF ee



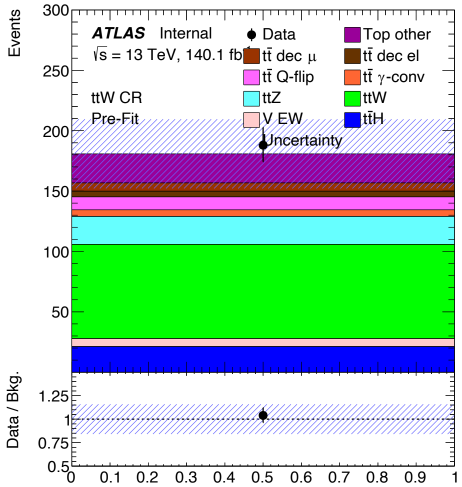
CR Qflip ee



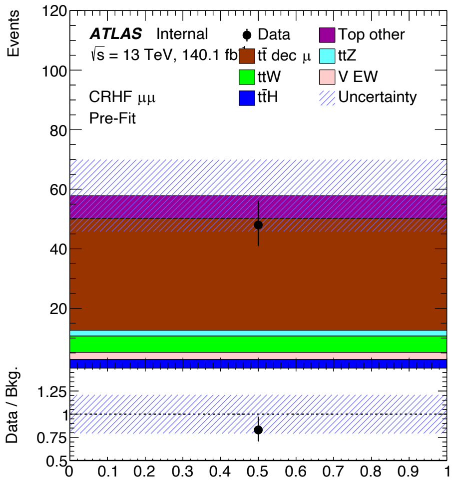
✓ SFs of the ee channel



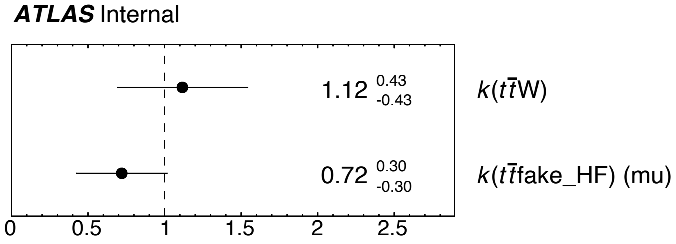
CR γ-conv ee



CR $t\bar{t}W$ $\mu\mu$

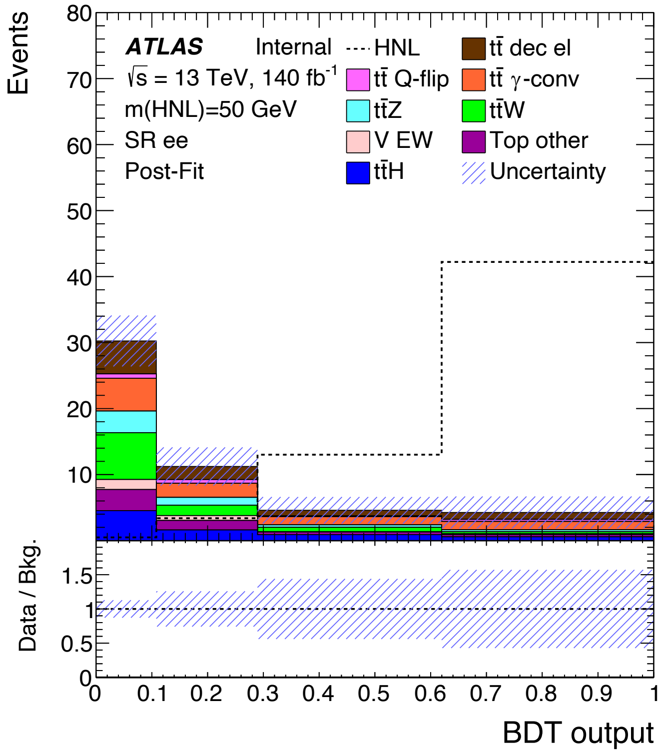


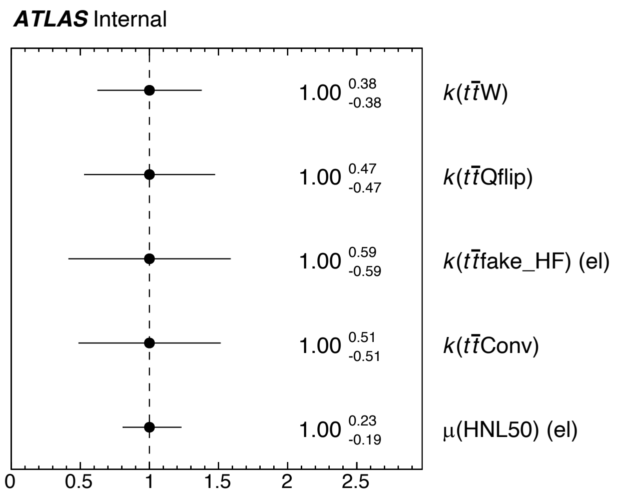
CR HF $\mu\mu$

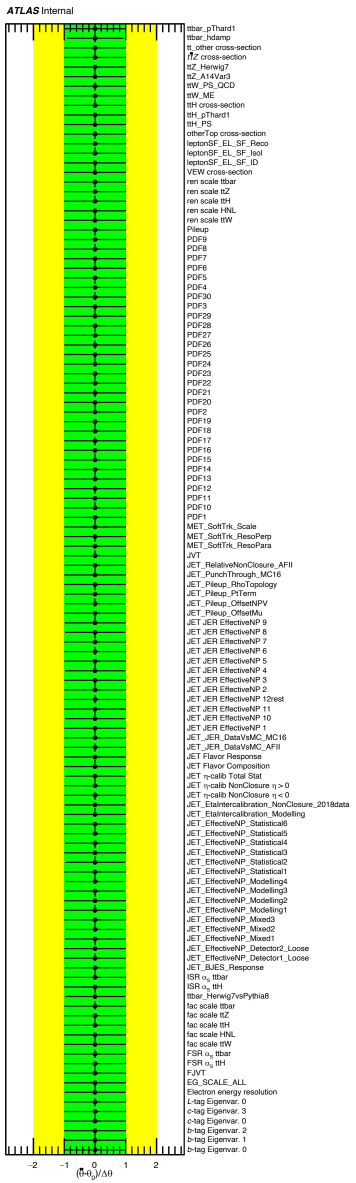


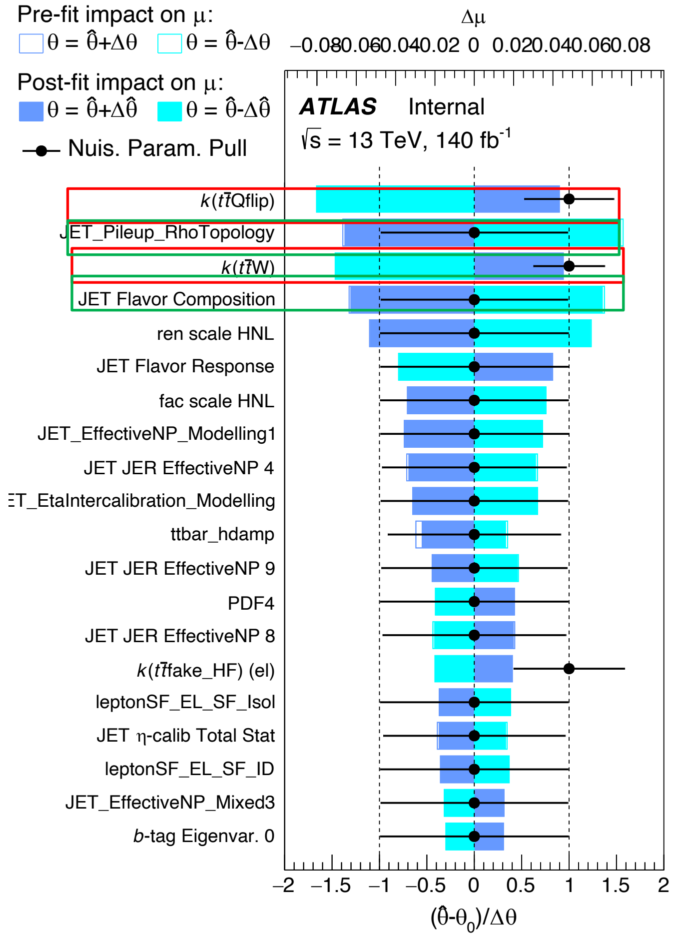
✓ SFs of the $\mu\mu$ channel

Asimov fit results



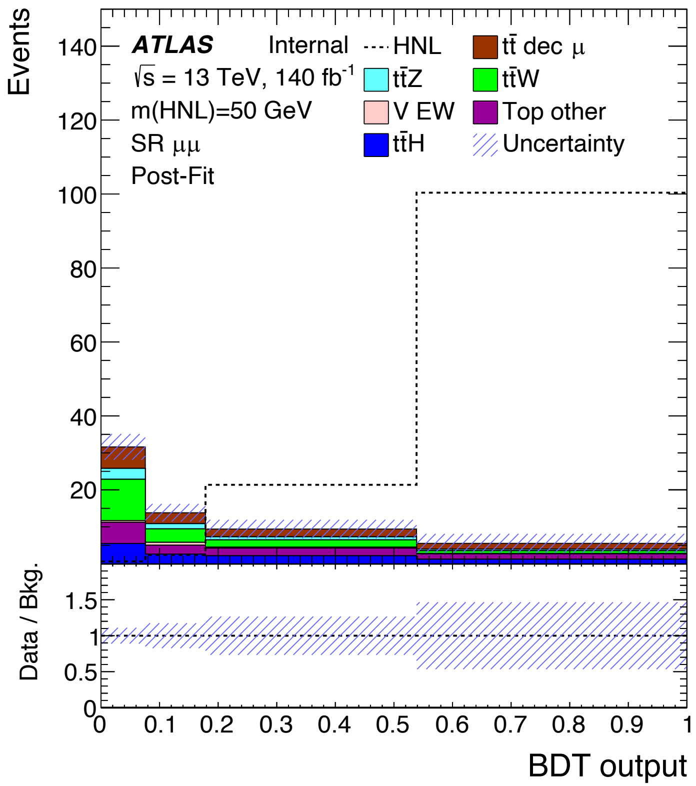


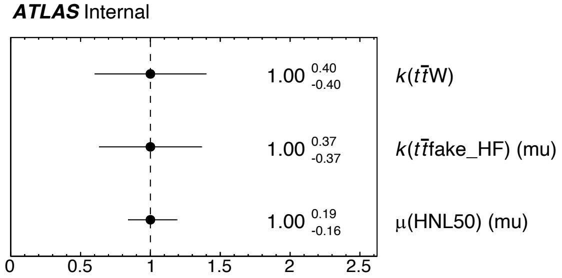


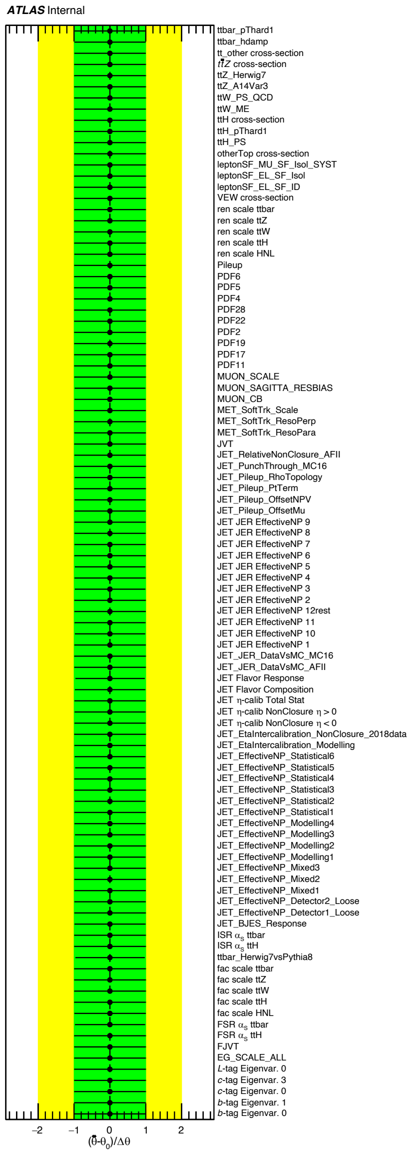


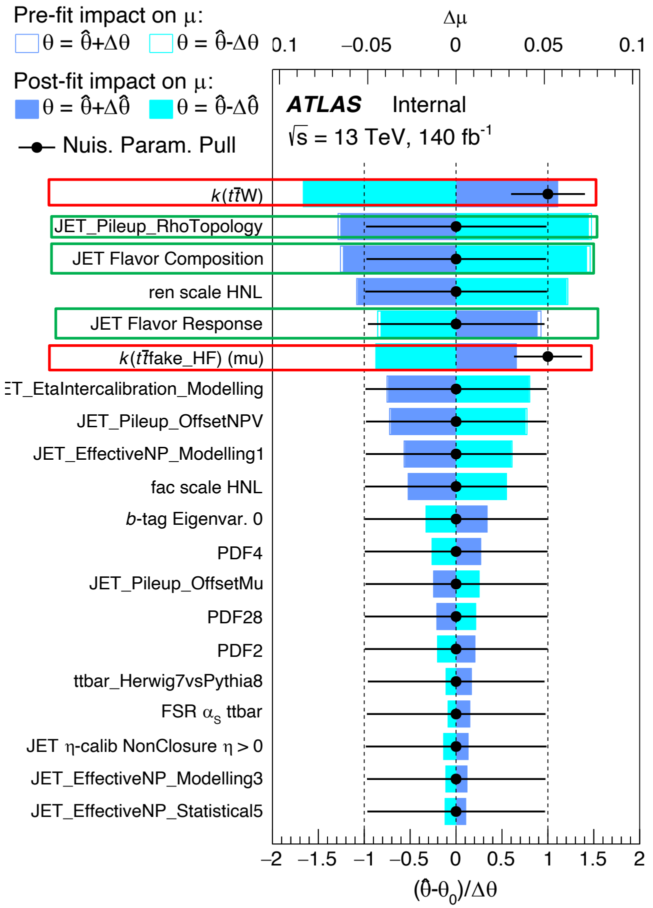
- ✓ The signal cross section is normalized to 0.1 pb for visual purpose
- ✓ No pull/constraint issues were observed
- ✓ The dominant NPs come from the JES and NFs
- ✓ The signal and ttbar modelling uncertainties are rankly high because of their high contribution of the event yields

Asimov fit results (updated mm channel)





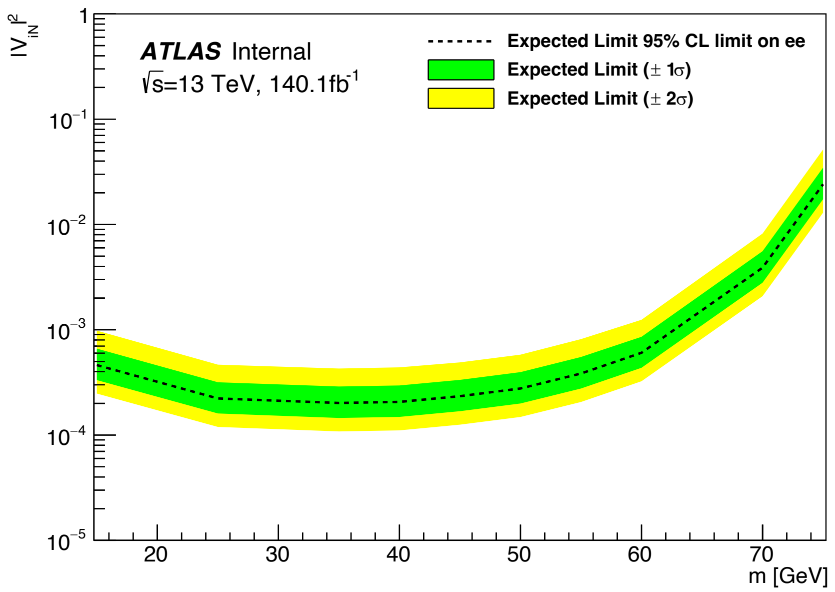




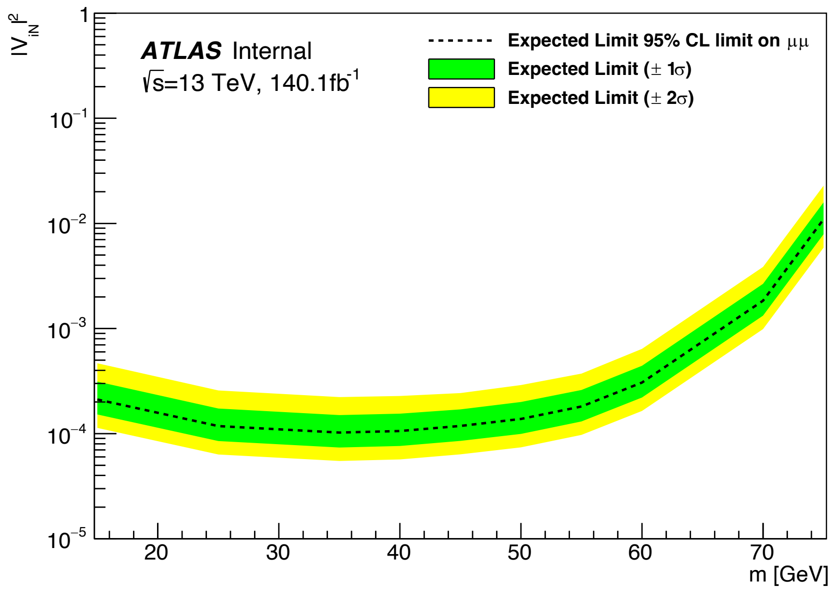
- ✓ The signal cross-section is normalized to 0.1pb
- ✓ No pull/constraint issues were observed
- ✓ The dominant NPs come from the JES and NFs
- ✓ The signal and ttbar modelling uncertainties are rankly high because of their high contribution of the event yields

Expected sensitivity comparison of separately ee/$\mu\mu$ channel

	m_N/GeV	15	25	35	40	45	**50**	55	60	70	75
ee channel.	Upper limit on μ	0.48	0.22	0.17	0.16	0.16	0.15	0.17	0.20	0.43	0.83
$\mu\mu$ channel	Upper limit on μ	0.22	0.12	0.09	0.08	0.08	0.08	0.08	0.10	0.20	0.38



Upper limit on coupling parameter on ee channel



Upper limit on coupling parameter on $\mu\mu$ channel

✓ The expected upper limit on mixing parameters among [15,75] GeV is $|V_{eN}|^2 < 2 * 10^{-4}$ and $|V_{\mu N}|^2 < 1 * 10^{-4}$

Summary

tt̄→ HNL analysis

- The first search for HNL with the $t\bar{t}$ decay
- ✓ Six control regions based on the selection and two signal regions described with the BDT are applied on our analysis
- ✓ Successfully implement the relative experimental and theoretical uncertainties in the fit.
- ✓ Set the expected sensitivity on coupling parameters of $ee/\mu\mu$ channel, which extends the ATLAS results beyond 50 GeV

Outlook

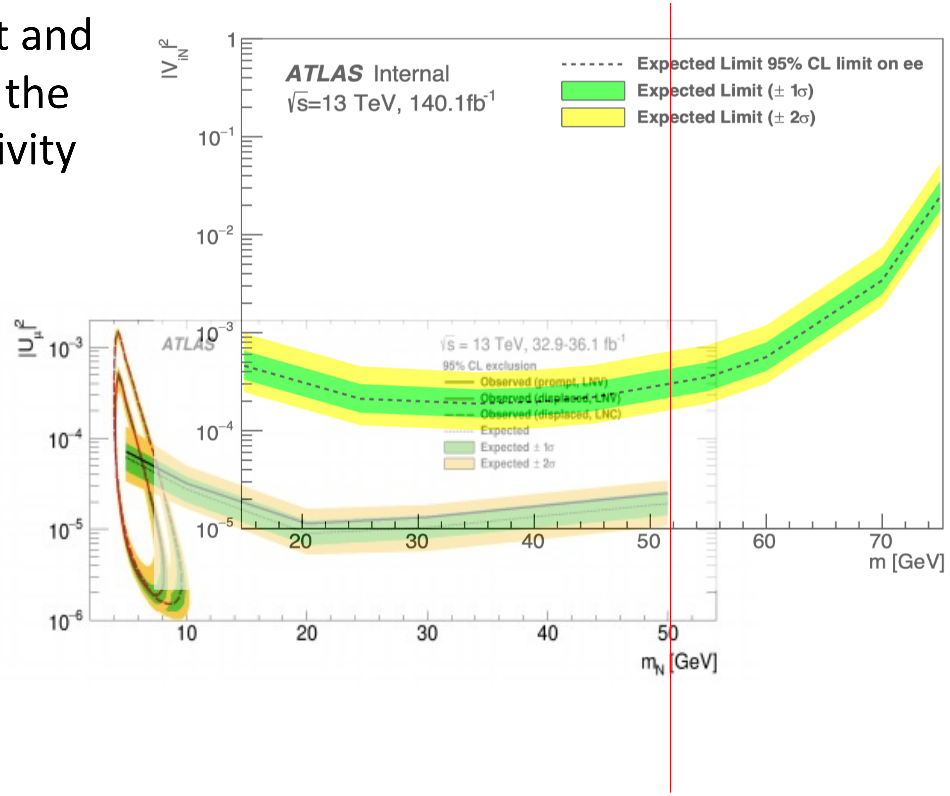
- ✓ The analysis is in good shape and ready for unblinding

Thanks for your attention!

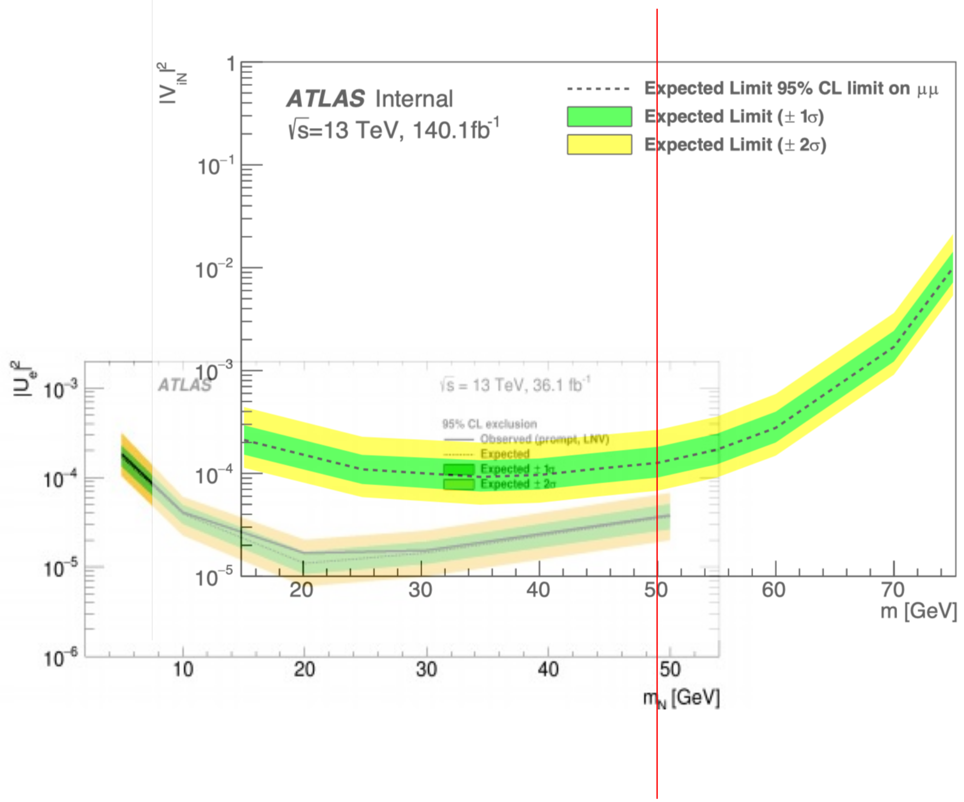
Back up

Comparison with the existing experiments

- ✓ Currently only [0,50] GeV results of ATLAS exist and we extended the results sensitivity to 75 GeV.



Published ee result



Published $\mu\mu$ result

[JHEP 10 (2019) 265](#)

Object selection / single lepton trigger information

Feature	Criterion
Pseudorapidity range	$(\lvert\eta\rvert < 1.37) \quad \lvert\lvert \quad (1.52 < \lvert\eta\rvert < 2.47)$
Transverse momentum	$p_T > 10\,\text{GeV}$
Object quality	Not from a bad calorimeter cluster (`BADCLUSELECTRON`) Remove clusters from regions with EMEC bad HV (2016 data only)
Track to vertex association	$\lvert d_0\rvert/\sigma_{d_0} < 5$ $\lvert\Delta z_0^{BL} \sin\theta\rvert < 0.5\,\text{mm}$
Identification	(`TightLH`)
Isolation	`PLImprovedTight`
Loose isolation	`PLVLoose`
Extra selections	`ECIDS, ambiguity cuts`
Triggers 2015	e24_lhmedium_L1EM20VH, e60_lhmedium, e120_lhloose
Triggers 2016-18	e26_lhtight_nod0_ivarloose, e60_lhmedium_nod0, e140_lhloose_nod0

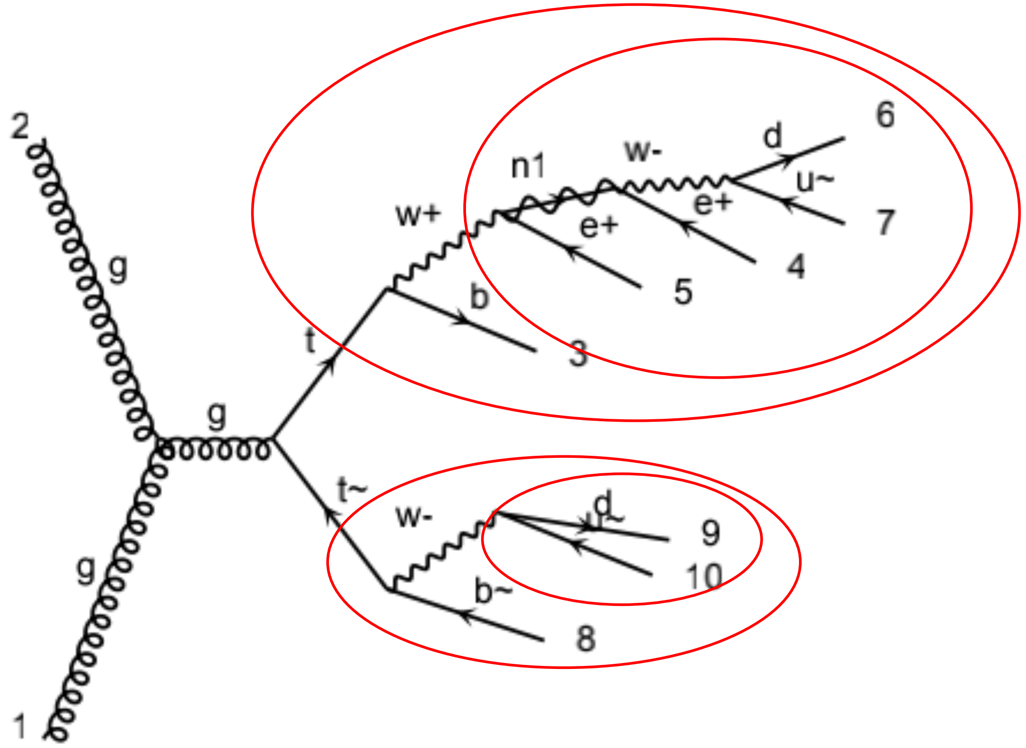
Table 4.1: Electron selection criteria.

Feature	Criterion
Selection working point	`Medium`
Isolation	`PLImprovedTight`
Loose isolation	`PLVLoose`
Momentum calibration	Sagitta correction
p_T Cut	10 GeV
$\lvert\eta\rvert$ cut	< 2.5
$\lvert d_0\rvert/\sigma_{d_0}$	3
$\lvert\Delta z_0 \sin\theta_\ell\rvert$ cut	0.5 mm
Triggers 2015	mu20_iloose_L1MU15, mu50
Triggers 2016-18	mu26_ivarmedium, mu50

Table 4.2: Muon selection criteria.

Reconstruction for the MVA input

- p_T^{lep1}
- p_T^{lep2}
- MET
- H_T
- η_{lep1}
- η_{lep2}
- $\mathrm{m}_{\ell\ell}$
- p_T^{jet1}
- ΔR_{ll},
- $M_{bsmTreso}$
- $M_{bsmWreso}$
- $M_{bsmN1reso}$
- $M_{bsmN2reso}$
- $M_{smTreso}$
- $M_{smWreso}$
- N_{jets}
- N_{bjets}



✓ H_T : Scalar sum of all leptons and jets transverse momentum
✓ $M_{bsmTreso}$: Invariant mass of BSM Top (3+4+5+6+7)
✓ $M_{bsmWreso}$:Invariant mass of BSM W (4+5+6+7)
✓ $M_{bsmN1reso}$: candidate invariant mass HN with L1 (leading)+6+7
✓ $M_{bsmN2reso}$: candidate invariant mass HN with L2 (sub-leading)+6+7

Significance comparison

	channel	HN75	HN60	HN55	HN50	HN45	HN40	HN35	HN25	HN15
• Book signal with their own weights	ee	3.3	9.7	10.9	11.7	11.8	12.1	11.3	8.8	5.5
	mm	6.8	16.6	19.1	20.0	18.8	19.2	18.1	14.0	9.7
• Book signal with HNL50 weights	ee	3.1(-6%)	9.6	11.0	11.7	11.9	11.9	11.0	7.8	4.6
	mm	6.4	16.2	19.1	20.0	19.0	18.5	17.5	12.6	8.4
• Book signal with HNL25 weights	ee						11.9	11.4	8.8	5.6
	mm						18.5	18.4	14.0	10.3(+6%)
• Book signal with high mass set weights	ee	3.3	9.9	11.4 (-4.6%)	11.7	11.8				
	mm	6.7	16.9	19.4	20.5	19.4				
• Book signal with low mass set weights	ee						11.5	11.1	9.2	5.3
	mm						18.1 (-5.7%)	17.9	14.6	9.5

- The largest difference is about 6% (with HNL50) , 6% (with HNL25), 4.6% (with high mass set) and 5.7% (with low mass set)

✓ Signal: 10 mass points are divided into high and low mass training sets

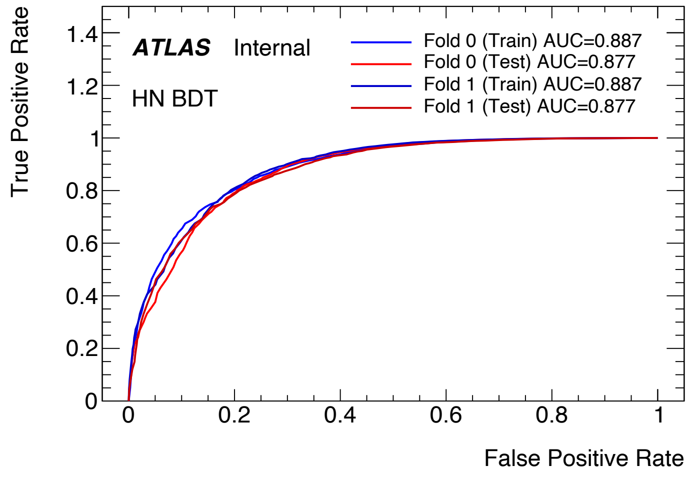
High mass set: HNL[45, 50, 55, 60, 70, 75] GeV

Low mass set: HNL[15, 25, 35, 40] GeV

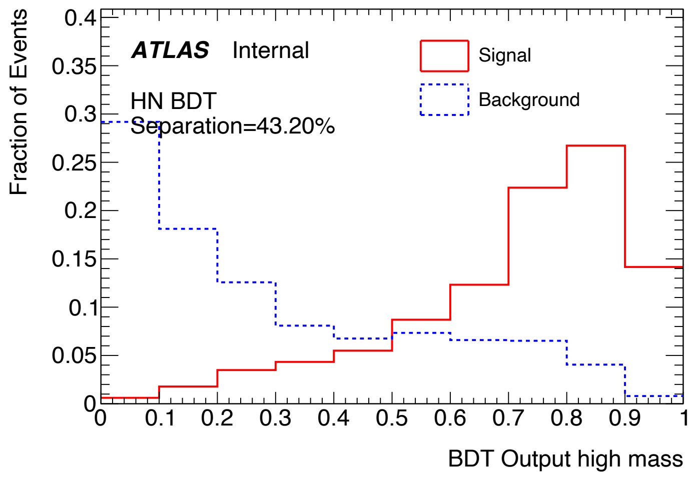
MVA performance (high mass)

MVA performance:

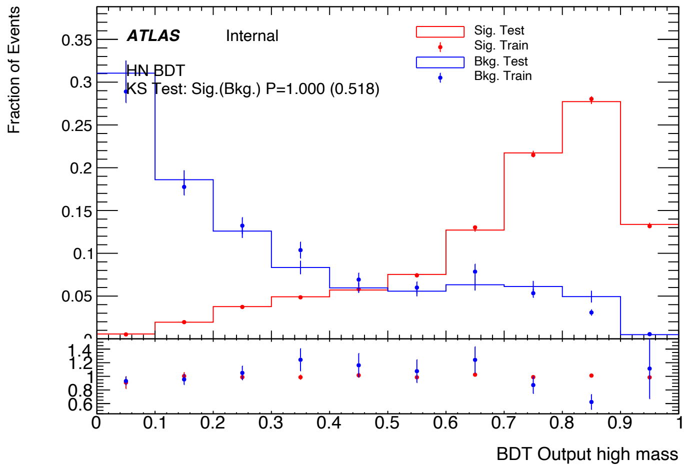
- ✓ Training results shows good separation between signal and backgrounds
- ✓ No overfit issues observed when comparing the loss function(training and validation)
- ✓ Good agreement between training and testing dataset (only one fold results showed)



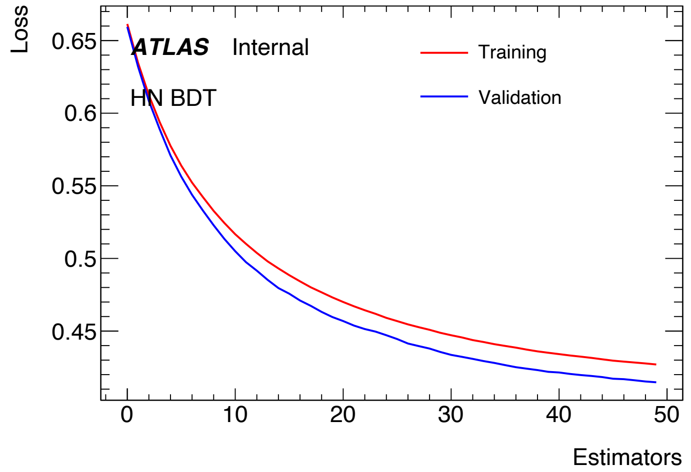
2-fold AUC output



Separation of the signal/backgrounds



Test/training BDT output



Loss function

IFF classification

0.Unknown

Leptons are entering the category Unknown (IFF class 0), if they cannot be attributed to any or the classes described bellow.

1.KnownUnknown:

The KnownUnknown category (IFF class 1) refers to leptons which can (in principle) be classified, but the tool fails with the classification due to missing information.

2.IsoElectron

An electron is classified as prompt (or isolated) electron (IFF class 2), if its truth-type (or the type of its EG mother-particle) is corresponding to an

3.ChargeFlipIsoElectrons:

The distinction between electrons with correctly-assigned and mis-identified charge (charge-flip), is not relevant for all analyses.

4.PromptMuon:

An muon is classified as prompt (IFF class 4), if its truth-type is corresponding to an isolated muon (== 6), and it originates from a prompt source (e.g. W/Z, top, Higgs).

5.PromptPhotonConversion:

Electrons originating from the conversion of prompt photons (IFF class 5) are identified if the truth-type corresponds to a background electron (== 4) and it originates from a photon conversion or an electromagnetic

6.ElectronFromMuon:

An electron is classified as a muon being reconstructed as electron (IFF class 6) if the truth-type of the electron corresponds to a non-isolated electron or photon (== 3/15) and its truth-origin is a muon. This category gathers also the electrons from muon bremstraulung.

7.TauDecay:

Non-isolated electrons and muons from hadronic tau-decays (IFF class 7), are identified if the truth-type of the leptons corresponds to a non-isolated muon (== 7 for the muon case) or to a non-isolated electron/photon (== 3/15 for the electron case) and its truth-origin is a tau lepton.

8/9.HadronDecay:

Electrons and muons originating from heavy-flavor decays can come from two types: b-hadrons (IFF class 8) and c-hadrons (IFF class 9) which are distinguished in the tool. It is checked if the truth-origin of an electron or muon corresponds to a bottom-meson or baryon (b-type) or to a charm-meson/baryon (c-type). For electrons, the check is also done for the origin of the first EG mother-particle (with the origin required to be b/c-type for either the EG mother- or the final-state particle).

10.LightFlavourDecay:

Leptons produced by light-flavor jets (IFF class 10) are identified by checking if the truth-type of the lepton corresponds to a hadron type (== 17). Also, if the truth-type corresponds to a background electron, muon or photon (== 4/8/16) and it originates from a light-meson, a strange-meson or light/strange-baryons, it is considered for the light-flavour category.

Formula for converting limit on σ to limit on $|V_{iN}|^2$

HNL Mass	$\mathcal{B}(W_+)$	ID1	ID2
50	3.031044e-01	4	-3
50	3.031044e-01	2	-1
50	1.010348e-01	16	-15
50	1.010348e-01	14	-11
50	1.010348e-01	12	-11
50	4.534337e-02	9900014	-13
50	4.534337e-02	9900012	-11

HNL Mass	$\mathcal{B}(W_+)$	ID1	ID2
15	8.698991e-02	9900014	-13
15	8.698991e-02	9900012	-11
25	7.986472e-02	9900014	-13
25	7.986472e-02	9900012	-11
35	6.889419e-02	9900014	-13
35	6.889419e-02	9900012	-11
40	6.194110e-02	9900014	-13
40	6.194110e-02	9900012	-11
45	5.405472e-02	9900014	-13
45	5.405472e-02	9900012	-11
50	4.534337e-02	9900014	-13
50	4.534337e-02	9900012	-11
55	3.601351e-02	9900014	-13
55	3.601351e-02	9900012	-11
60	2.641310e-02	9900014	-13
60	2.641310e-02	9900012	-11
70	8.812049e-03	9900014	-13
70	8.812049e-03	9900012	-11
70	2.671983e-03	9900014	-13
70	2.671983e-03	9900012	-11

Decay channel Mass	Mother particle Mode	Branch Ratio Branch ratio $N-W\ell$
HNL15	N1	0.3576
HNL15	N2	0.3574
HNL25	N1	0.3586
HNL25	N2	0.3583
HNL35	N1	0.3603
HNL35	N2	0.3600
HNL40	N1	0.3614
HNL40	N2	0.3610
HNL45	N1	0.3628
HNL45	N2	0.3624
HNL50	N1	0.3645
HNL50	N2	0.3641
HNL55	N1	0.3667
HNL55	N2	0.3663
HNL60	N1	0.3699
HNL60	N2	0.3693
HNL70	N1	0.3793
HNL70	N2	0.3789
HNL75	N1	0.3893
HNL75	N2	0.3879

HNL mass (GeV)	15	25	35	40	45	50	55	60	70	75
Factor	9.7*e-4	1.0e-3	1.2e-3	1.3e-3	1.5e-3	1.3e-3	1.3e-3	3.1e-3	9.0e-3	2.9e-2

$$\sigma_{signal} = \sigma_{t\bar{t}} * |V_{eN}|^2 * \mathcal{B}(W^- \to N_1 e^-) * \mathcal{B}(N_1 \to e^- W^+)$$