Search for heavy right-handed Majorana neutrinos in $t\bar{t}$ decays in proton-proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

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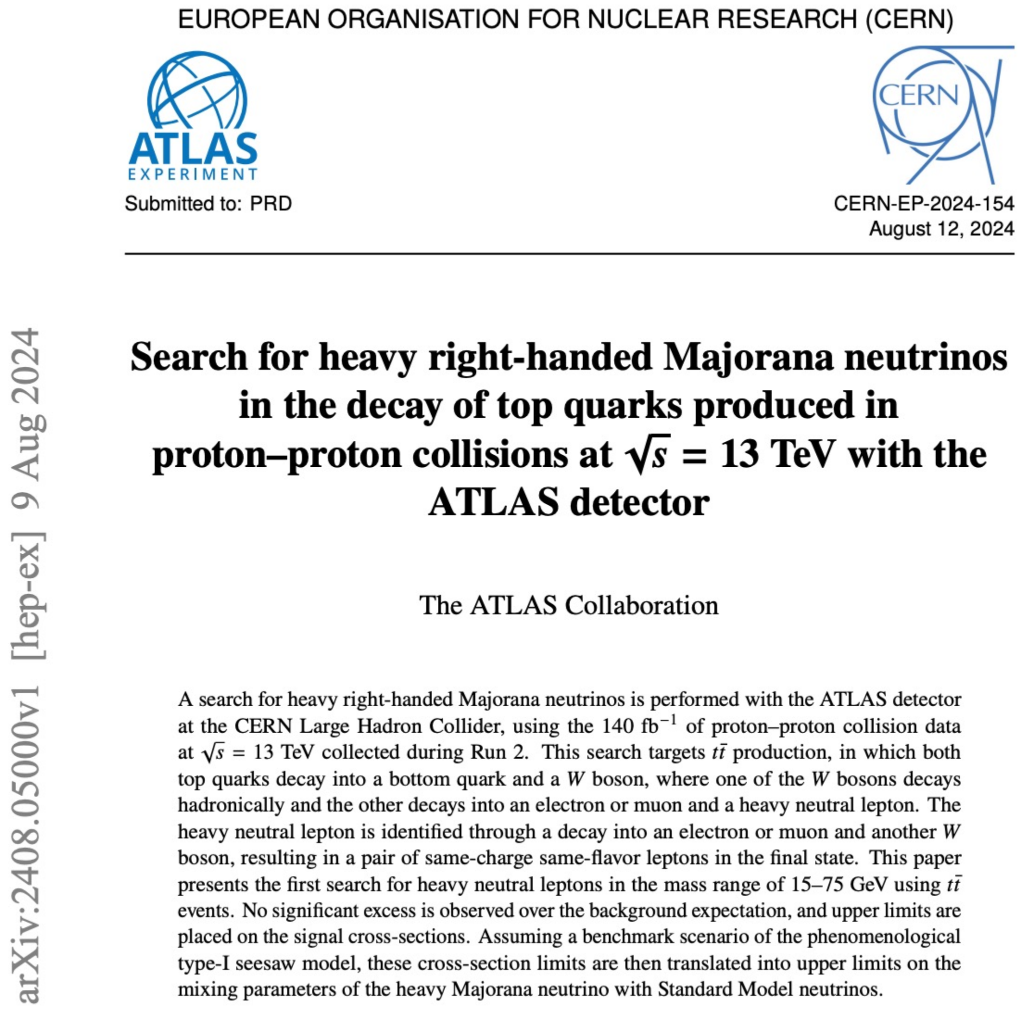
Overview

Search for the HNL in the decay of the top quark

- ✓ Introduction
- ✓ Data/MC samples
- ✓ Object selection
- ✓ Analysis strategy
- ✓ Uncertainties
- ✓ Statistical treatment
- ✓ Results

Paper has been accepted by PRD
arXiv: [2408.05000](https://arxiv.org/abs/2408.05000)



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: PRD

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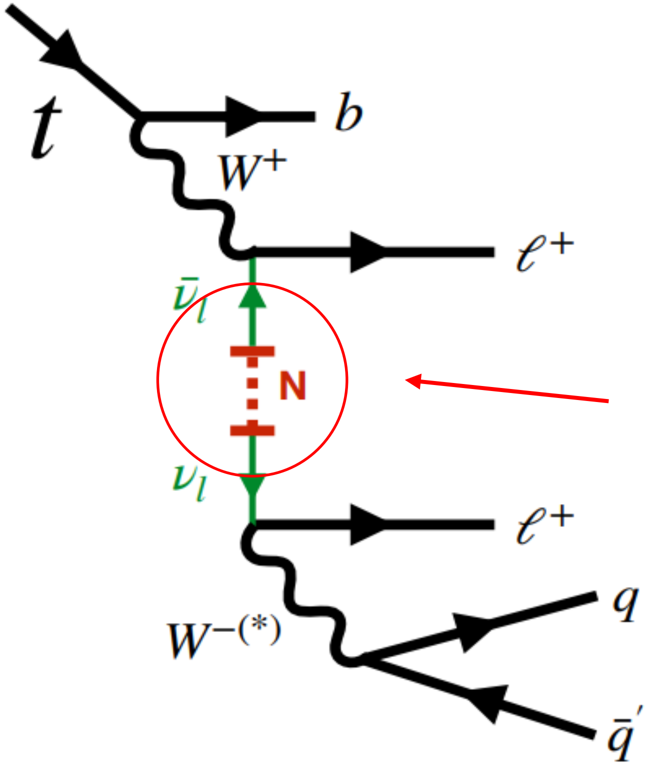
Search for heavy right-handed Majorana neutrinos in the decay of top quarks produced in proton–proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

The ATLAS Collaboration

A search for heavy right-handed Majorana neutrinos is performed with the ATLAS detector at the CERN Large Hadron Collider, using the 140 fb^{-1} of proton–proton collision data at $\sqrt{s}$ = 13 TeV collected during Run 2. This search targets $t\bar{t}$ production, in which both top quarks decay into a bottom quark and a W boson, where one of the W bosons decays hadronically and the other decays into an electron or muon and a heavy neutral lepton. The heavy neutral lepton is identified through a decay into an electron or muon and another W boson, resulting in a pair of same-charge same-flavor leptons in the final state. This paper presents the first search for heavy neutral leptons in the mass range of 15–75 GeV using $t\bar{t}$ events. No significant excess is observed over the background expectation, and upper limits are placed on the signal cross-sections. Assuming a benchmark scenario of the phenomenological type-I seesaw model, these cross-section limits are then translated into upper limits on the mixing parameters of the heavy Majorana neutrino with Standard Model neutrinos.

Introduction

Motivation



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

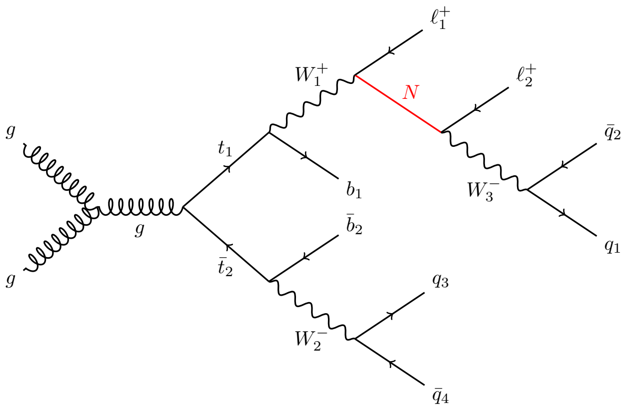
- ✓ Neutrinos are massive and mixing.
- ✓ The seesaw mechanism theory provides an explanation for the small mass of neutrinos.
- ✓ Type-I seesaw is the simplest, adding 3 heavy RH Majorana neutrinos N_1, N_2, N_3.

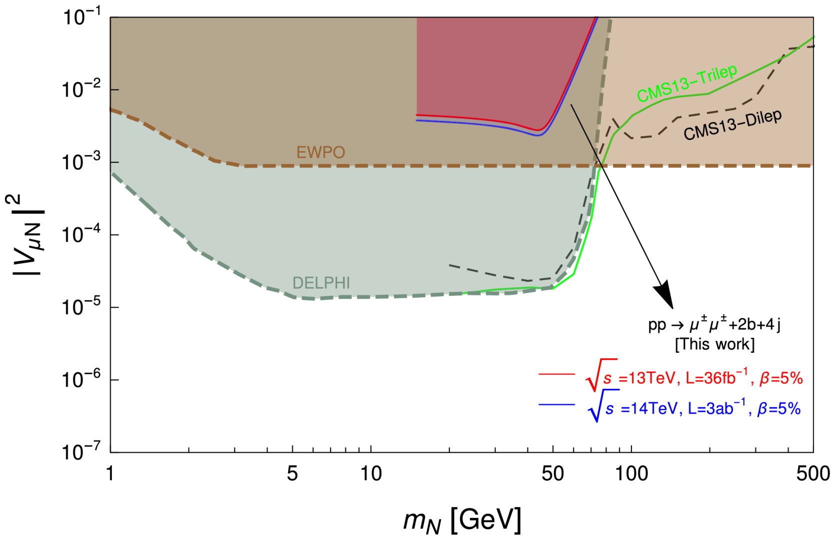
  N_i can couple to SM neutrinos via coupling strength V_{iN}
- ✓ Neutrino-less double-beta decay: a lepton number violation of $|\Delta L| = 2$ along with the process of generating Majorana neutrino.

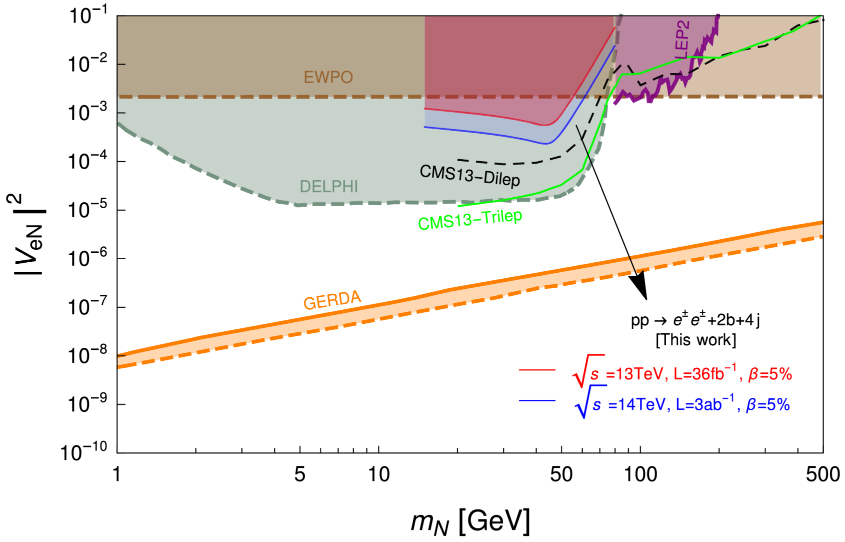
Other analysis:

- ✓ With the Drell-Yan process $q\bar{q} \to W^* \to N\ell$.
- ✓ JHEP10 (2019) 265 (ATLAS) (36.1 fb^{-1}, $[4.5,50]$GeV, $|V_{iN}|^2 > 1.4 * 10^{-5}$)
- ✓ JHEP01 (2019) 122 (CMS) (35.9 fb^{-1}, $[1,1200]$GeV, $|V_{iN}|^2 > 2.3 \times 10^{-5}$)
- ✓ arXiv:2403.00100 (CMS) (138 fb^{-1}, $[10,1500]$GeV, $|V_{iN}|^2 > 4.8 * 10^{-6}$, latest)
- ✓ EPJC 83 (2023) 824 (ATLAS) (140 fb^{-1}, [50, 20000]GeV, $|V_{\mu,N2}|^2 > 0.1$, latest results from same-sign WW scattering process)
- ✓ LHC is a top factory and this analysis searches for heavy neutral leptons in the $t\bar{t}$ process.

Motivation







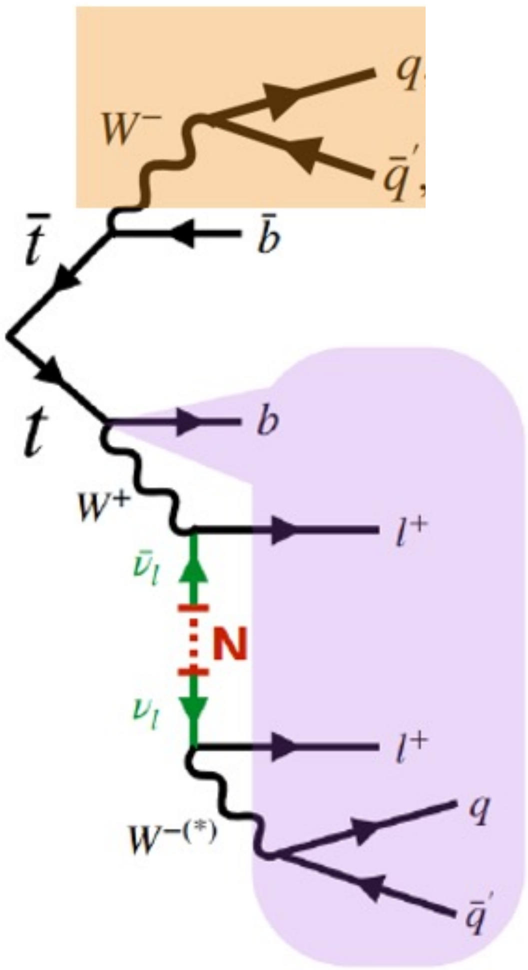
Phys. Rev. D 101, 071701(R) (2020) by Hang Zhou

This analysis:

- ✓ Only the diagonal mixing terms are considered, which means the N1/N2/N3 only couples to e/mu/tau, respectively
- ✓ The first time the heavy-light neutrino mixing parameter value $|V_{\ell,N}|^2$ measured in top quark decay with 140 fb^{-1}

$$v_{mix} = \begin{pmatrix} V_{e,N1} & 0 & 0 \\ 0 & V_{\mu,N2} & 0 \\ 0 & 0 & V_{\tau,N3} \end{pmatrix}$$

Signal process



Signal process -> tt̄ :

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

- ✓ Focus on the 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 (JIRA ticket)
- ✓ 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:

- ✓ $t\bar{t}$ (PhPy8 - 1 nonallhad sample 410470)
- ✓ $t\bar{t}$**W** (Sh2.2.10 - 1 QCD sample 700168 + 1 EW sample 700205)
- ✓ $t\bar{t}$**Z** (aMc@Py8 - 3 sample 504330, 504334, 504343)
- ✓ $t\bar{t}\gamma$ (MadGraph@Py8 - 1 sample 410389)
- ✓ $t\bar{t}H$ (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, t**$\bar{t}$**WW** production (5 samples)
- ✓ **VH, tHW, tHq, t**$\bar{t}$**XX** production (8 samples)

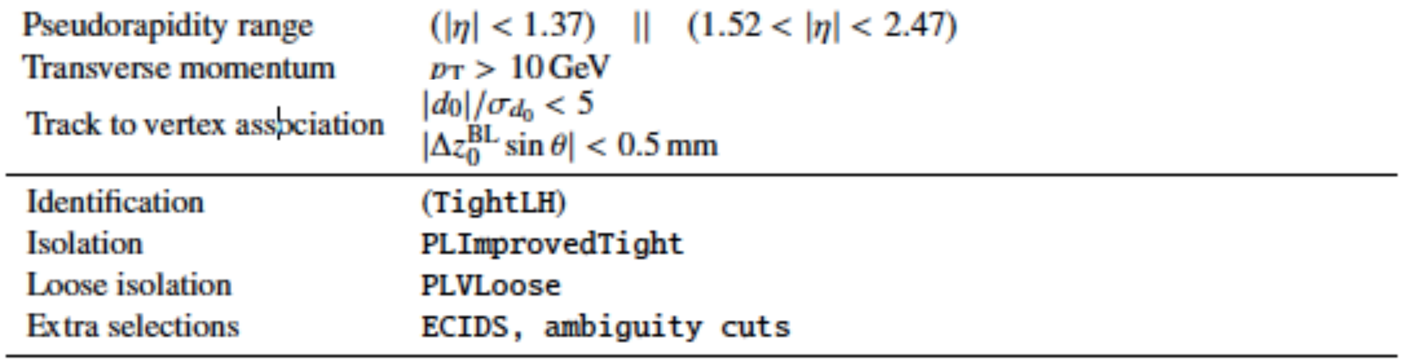
Analysis strategy

Object selection and event selection

Object selection

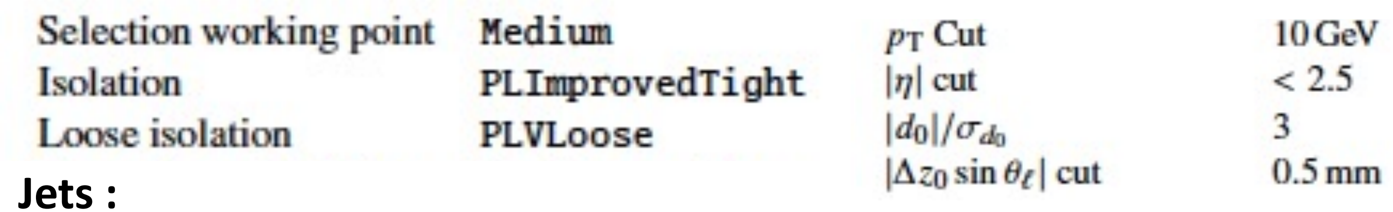
Apply single lepton trigger and overlap Removal

Electrons :



Pseudorapidity range	$(\lvert\eta\rvert < 1.37)$ $\Vert$ $(1.52 < \lvert\eta\rvert < 2.47)$
Transverse momentum	$p_T > 10$ 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	p_T Cut	10 GeV
Isolation	PLImprovedTight	$\lvert\eta\rvert$ cut	< 2.5
Loose isolation	PLVLoose	$\lvert d_0\rvert/\sigma_{d_0}$	3
		$\lvert\Delta z_0 \sin\theta_\ell\rvert$ cut	0.5 mm

Jets :

- ✓ $p_T > 20$ GeV
- ✓ $|\eta| < 4.5$

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 ($|\eta| < 2.5$): $p_T > 20$ GeV
  - ✓ Forward jets ($4.5 > |\eta| > 2.5$): $p_T > 35$ 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 lepton 2 jets	2 lepton 2 jets	1 bjet 2 jets	2 jets

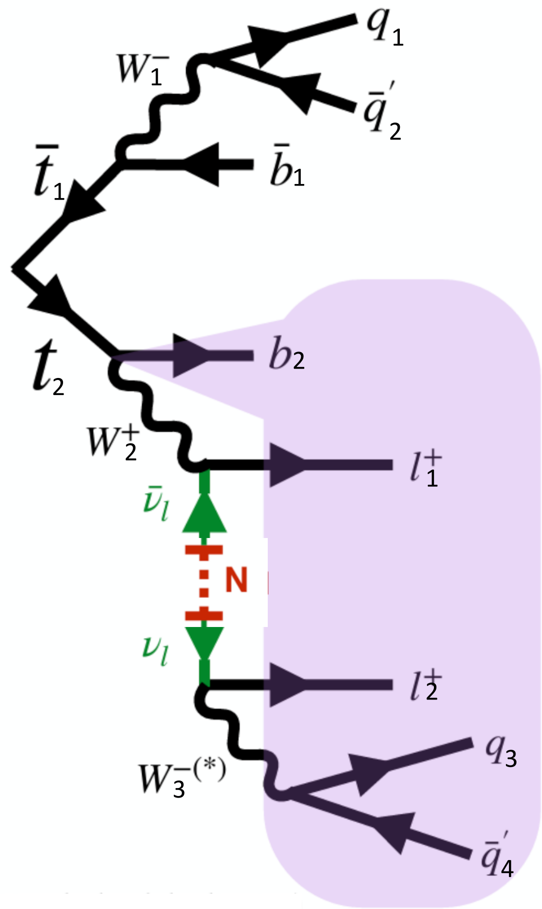
- ✓ $q_i \rightarrow j_i$
- ✓ Top with SM decay:

  $m_{b_1 j_1 j_2}$
- ✓ W with SM decay:

  $m_{j_1 j_2}$
- ✓ Top with BSM decay:

  $m_{b_2 l_1 l_2 j_3 j_4}$
- ✓ W with BSM decay

  $m_{l_1 l_2 j_3 j_4}$



- ✓ 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.

$$\chi^2 = \Sigma_{i=1}^{4} \frac{(m_i \; - M_{t/W})^2}{\sigma_i^2}$$

- ✓ $M_t = 172.76$ GeV
- ✓ $M_W = 80.379$ GeV
- ✓ i = Index of the four reconstructed objects used in the calculation

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

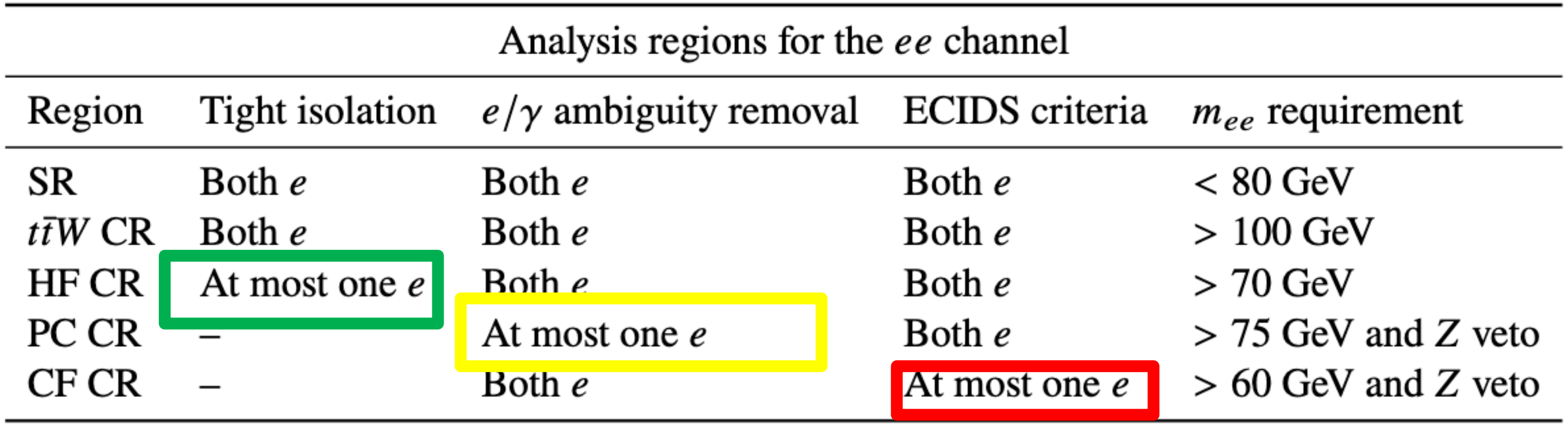
For the electron from the charge misidentification:

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

For the electron coming from the conversion of the photons:

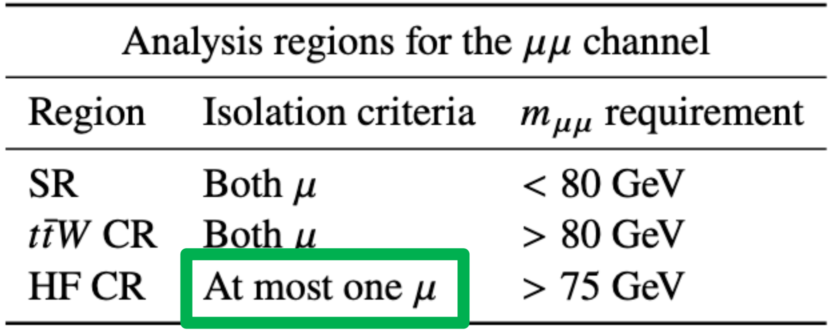
- ✓ Electron Ambiguity Tools are used to suppress the photon conversion contribution

SR/CRs definition



Analysis regions for the ee channel

Region	Tight isolation	e/γ ambiguity removal	ECIDS criteria	m_{ee} requirement
SR	Both e	Both e	Both e	< 80 GeV
$t\bar{t}W$ CR	Both e	Both e	Both e	> 100 GeV
HF CR	At most one e	Both e	Both e	> 70 GeV
PC CR	–	At most one e	Both e	> 75 GeV and Z veto
CF CR	–	Both e	At most one e	> 60 GeV and Z veto



Analysis regions for the $\mu\mu$ channel

Region	Isolation criteria	$m_{\mu\mu}$ requirement
SR	Both μ	< 80 GeV
$t\bar{t}W$ CR	Both μ	> 80 GeV
HF CR	At most one μ	> 75 GeV

- ✓ The signal regions for both the ee and $\mu\mu$ channels are defined by applying the tighter isolation criteria on the same charged leptons and mll < 80 to suppress Z -> ee events.
- ✓ Additionally, in the ee channel, both electrons are required to satisfy the criteria of the ECIDS tool and the e/γ ambiguity removal, which are applied to suppress the charge flip and photon conversion contamination

Multi-variate analysis (BDT)

Performed **Boosted decision tree(Gradient)** for separation of signal and backgrounds using the scikit-learn package

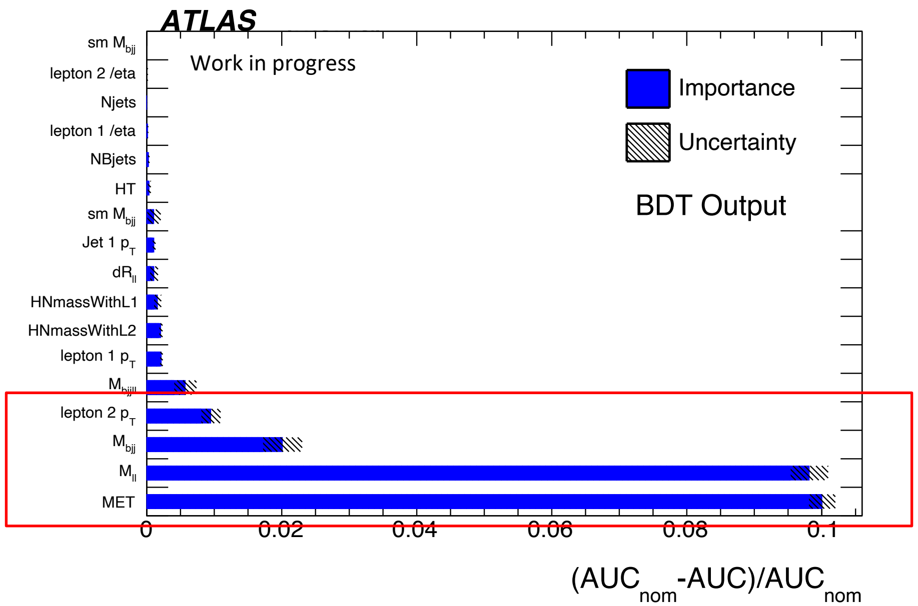
- ✓ Signal: 10 mass points are divided into high and low mass training sets

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

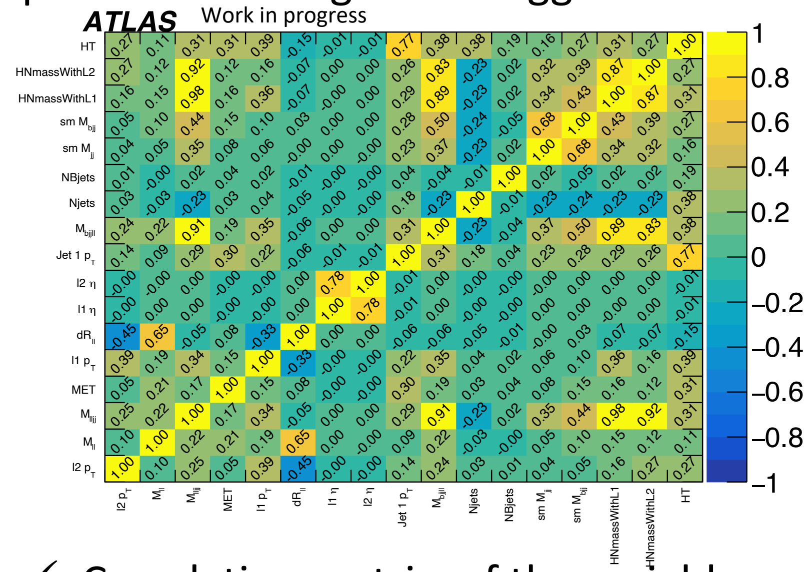
Low mass set: HNL[15, 25, 35, 40] GeV

(Merged 10 different training into 2 training, gain much more sensitivity)

- ✓ Background: all backgrounds considered
- ✓ Perform Cross-Validation Check: 2-fold
- ✓ Negative weights treatment: use absolute value of weights



- ✓ Importance ranking of the biggest ranked variables



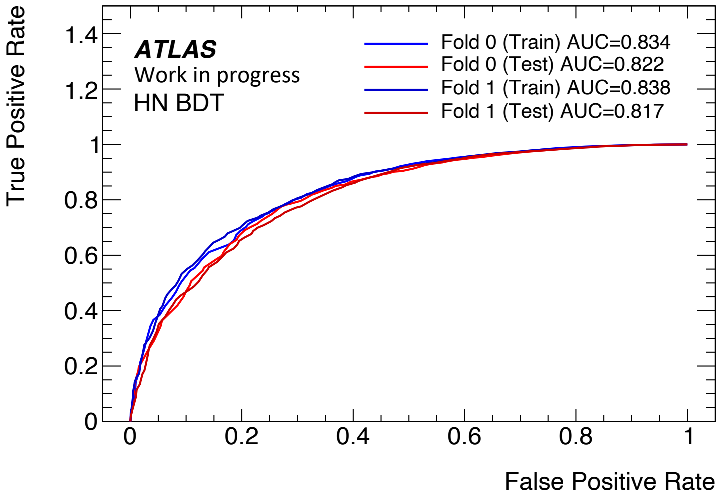
	$l2\ p_T$	M_{ll}	M_{lljj}	MET	$l1\ p_T$	dR_{ll}	$l1\ \eta$	$l2\ \eta$	Jet 1 p_T	M_{bjjll}	Njets	NBjets	sm M_{jj}	sm M_{bjj}	HNmassWithL1	HNmassWithL2	HT
HT	0.27	0.11	0.31	0.31	0.39	-0.15	-0.01	-0.01	0.77	0.38	0.38	0.19	0.16	0.27	0.31	0.27	1.00
HNmassWithL2	0.27	0.12	0.92	0.12	0.16	-0.07	0.00	0.00	0.26	0.83	-0.23	0.02	0.32	0.39	0.87	1.00	0.27
HNmassWithL1	0.16	0.15	0.98	0.16	0.36	-0.07	-0.00	0.00	0.29	0.89	-0.23	0.02	0.34	0.43	1.00	0.87	0.31
sm M_{bjj}	0.05	0.10	0.44	0.15	0.10	0.03	0.00	0.00	0.28	0.50	-0.24	-0.05	0.68	1.00	0.43	0.39	0.27
sm M_{jj}	0.04	0.05	0.35	0.08	0.06	-0.00	0.00	-0.00	0.23	0.37	-0.23	0.02	1.00	0.68	0.34	0.32	0.16
NBjets	0.01	-0.00	0.02	0.04	0.02	-0.01	-0.00	-0.00	0.04	-0.04	-0.01	1.00	0.02	-0.05	0.02	0.02	0.19
Njets	0.03	-0.03	-0.23	0.03	0.04	-0.05	-0.00	-0.00	0.18	-0.23	1.00	-0.01	-0.23	-0.24	-0.23	-0.23	0.38
M_{bjjll}	0.24	0.22	0.91	0.19	0.35	-0.06	0.00	0.00	0.31	1.00	-0.23	-0.04	0.37	0.50	0.89	0.83	0.38
Jet 1 p_T	0.14	0.09	0.29	0.30	0.22	-0.06	-0.01	-0.01	1.00	0.31	0.18	0.04	0.23	0.28	0.29	0.26	0.77
$l2\ \eta$	-0.00	-0.00	0.00	-0.00	-0.00	0.00	0.78	1.00	-0.01	0.00	-0.00	-0.00	-0.00	0.00	0.00	0.00	-0.01
$l1\ \eta$	-0.00	0.00	0.00	-0.00	-0.00	0.00	1.00	0.78	-0.01	0.00	-0.00	-0.00	0.00	0.00	-0.00	0.00	-0.01
dR_{ll}	-0.45	0.65	-0.05	0.08	-0.33	1.00	0.00	0.00	-0.06	-0.06	-0.05	-0.01	-0.00	0.03	-0.07	-0.07	-0.15
$l1\ p_T$	0.39	0.19	0.34	0.15	1.00	-0.33	-0.00	-0.00	0.22	0.35	0.04	0.02	0.06	0.10	0.36	0.16	0.39
MET	0.05	0.21	0.17	1.00	0.15	0.08	-0.00	-0.00	0.30	0.19	0.03	0.04	0.08	0.15	0.16	0.12	0.31
M_{lljj}	0.25	0.22	1.00	0.17	0.34	-0.05	0.00	0.00	0.29	0.91	-0.23	0.02	0.35	0.44	0.98	0.92	0.31
M_{ll}	0.10	1.00	0.22	0.21	0.19	0.65	0.00	-0.00	0.09	0.22	-0.03	-0.00	0.05	0.10	0.15	0.12	0.11
$l2\ p_T$	1.00	0.10	0.25	0.05	0.39	-0.45	-0.00	-0.00	0.14	0.24	0.03	0.01	0.04	0.05	0.16	0.27	0.27

- ✓ Correlation matrix of the variables

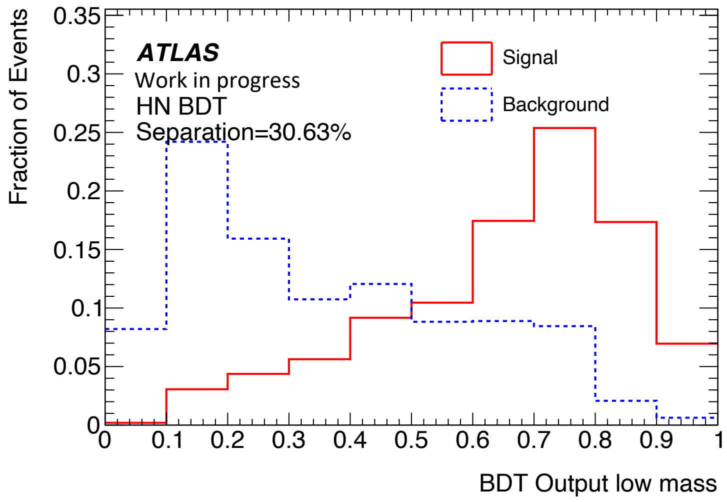
MVA performance

MVA optimization and performance:

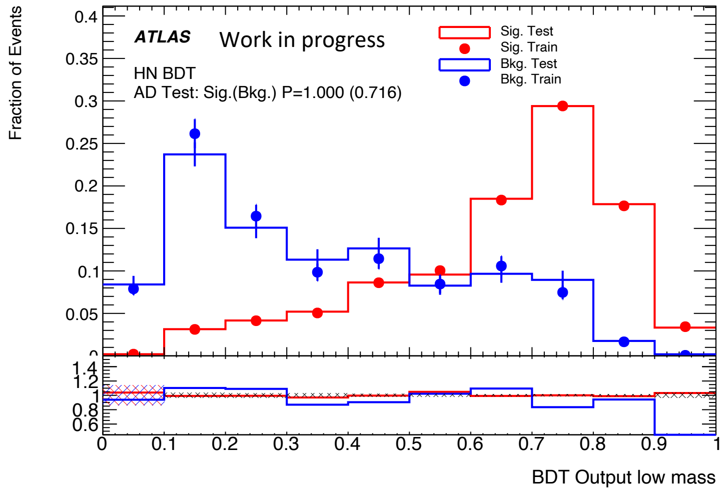
- ✓ Implemented the decorrelation of all variables and reduced low importance variables by gain in AUC values
- ✓ Only use most significant variables as input and four variables were left without significant loss of signal efficiency $(p_t^{lep2}, E_T^{miss},\ m_{ll},\ M_{bsmW})$
- ✓ Training results shows good separation between signal and backgrounds
- ✓ Good agreement between training and testing dataset



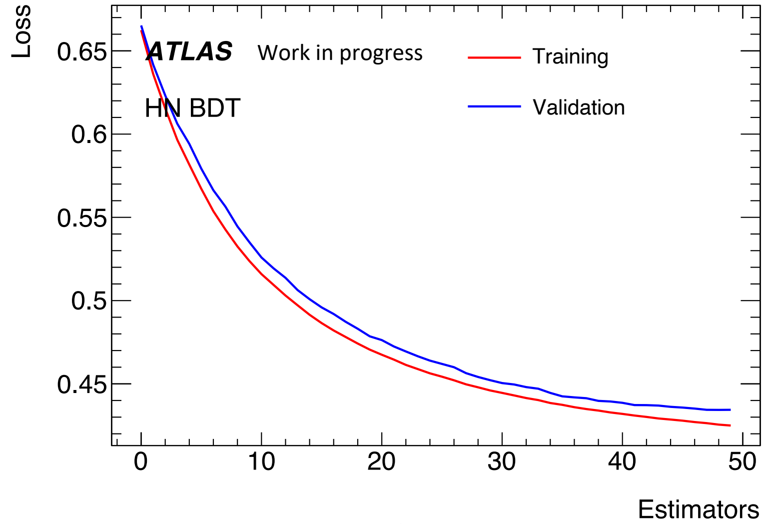
2-fold AUC output



Separation of the signal/backgrounds



Test/training BDT output



Loss function

Uncertainties

Systematics uncertainties

- ✓ **Lepton SFs**:

Electron: efficiencies (Reconstruction, identification, isolation, trigger), energy resolution and energy scale

Muon: efficiencies(Reconstruction and identification, isolation, trigger, Track To Vertex Association), momentum scale and resolution

- ✓ **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$\bar{\text{t}}$ & t$\bar{\text{t}}$H (PhPy8)

- ✓ Alt: Herwig 7
- ✓ Alt: Pythia8 pthard =1
- ✓ Alt: hdamp=3 (only for t$\bar{\text{t}}$)
- ✓ 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$\bar{\text{t}}$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 free-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$\bar{\text{t}}$Z: 12%

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

V EW: 30% (VV/VVV and W/Z+jets)

Top other: 50% (Other minor backgrounds and compositions from t$\bar{\text{t}}$/$t\bar{t}\gamma$)

- ✓ Following the recommendations from the PMG

Statistical treatment

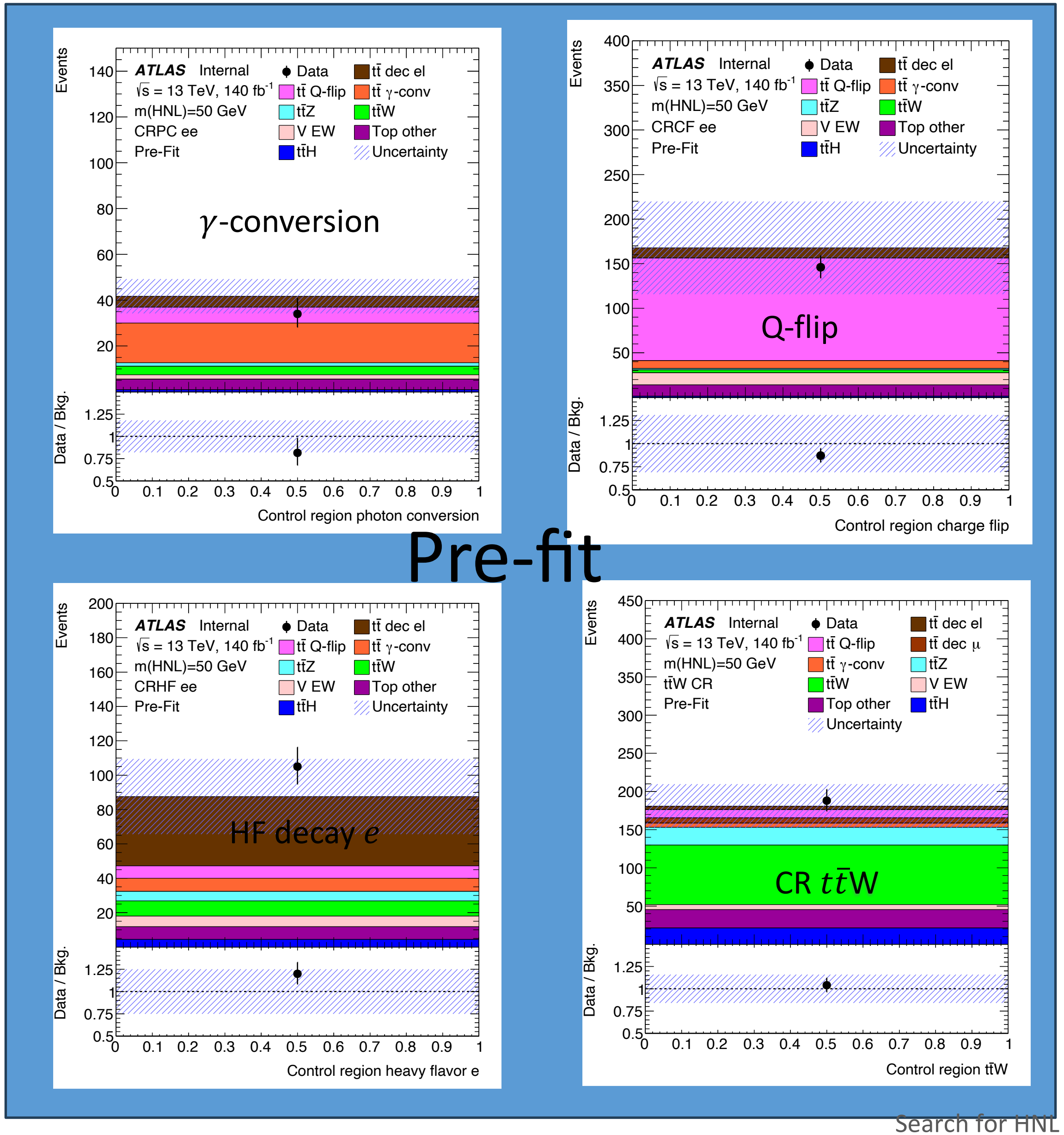
Profile likelihood fits with the S+B hypothesis across SR+CRs

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

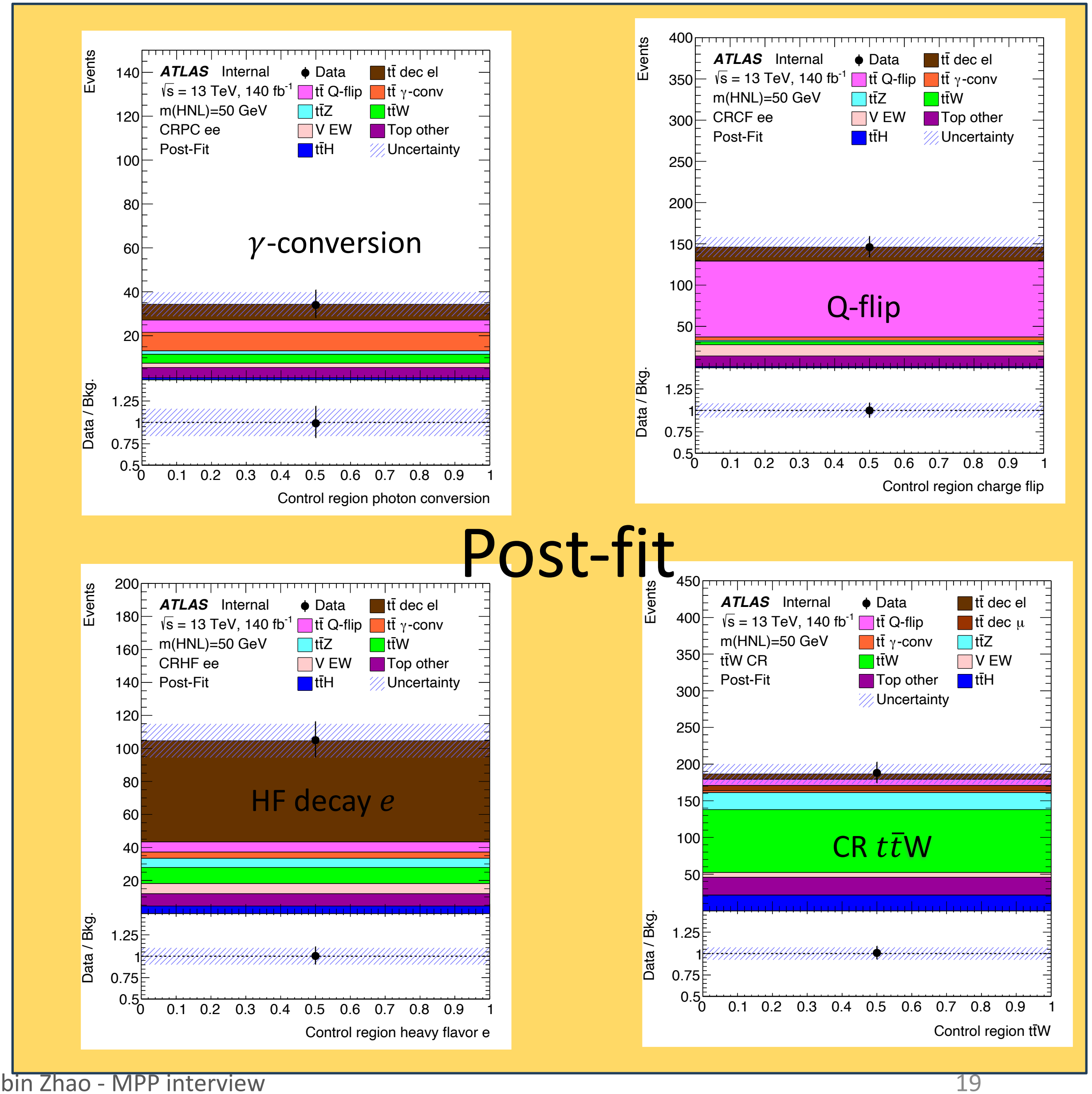
1SR + 4CRs (charge flip, heavy flavor, γ conversion and $t\bar{t}$W) for ee channel

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

Unblinded fit in CR of *ee* channel



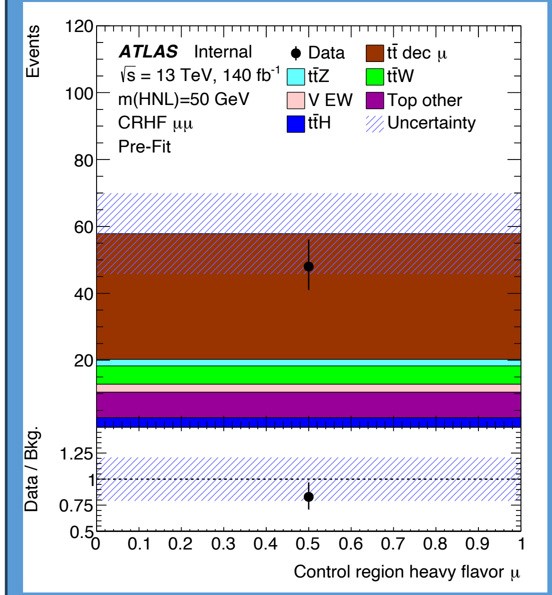
Pre-fit



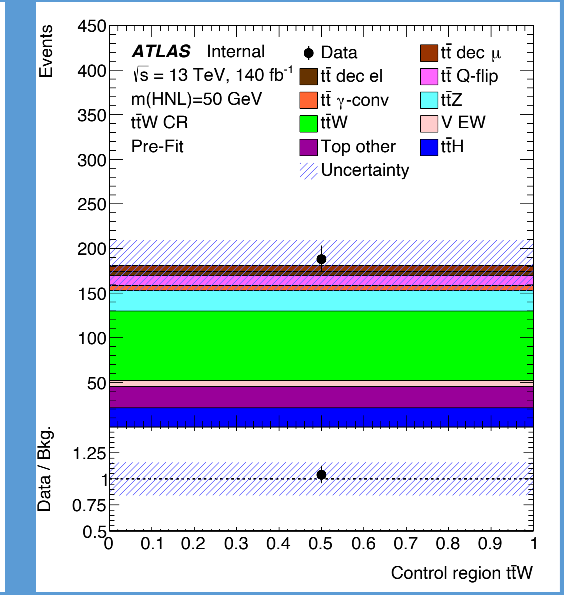
Post-fit

Unblinded fit in CR of $\mu\mu$ channel

HF decay μ

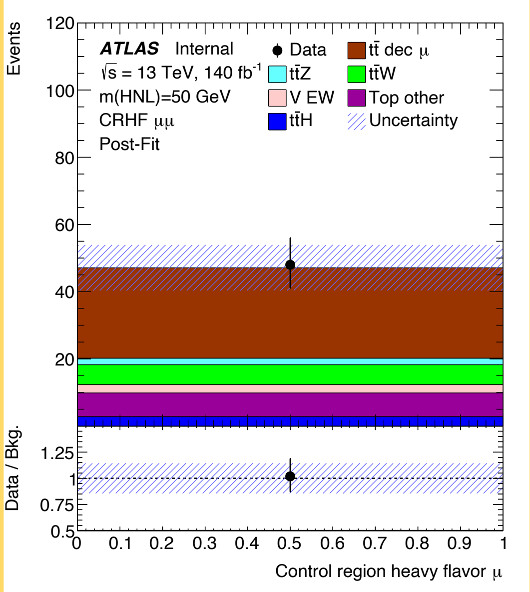


$t\bar{t}$W CR

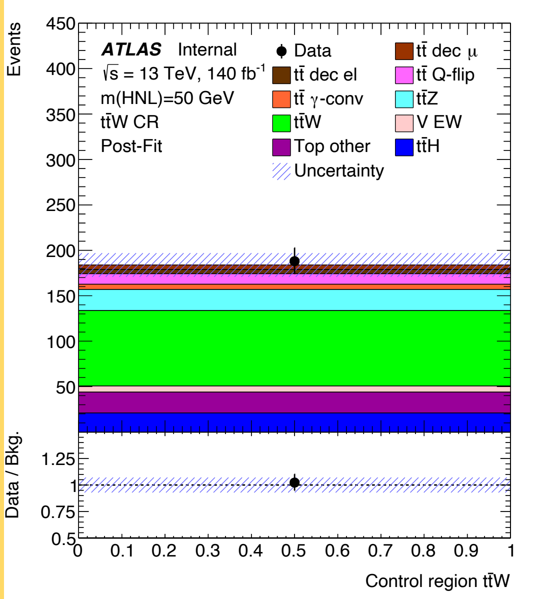


Pre-fit

HF decay μ



$t\bar{t}$W CR

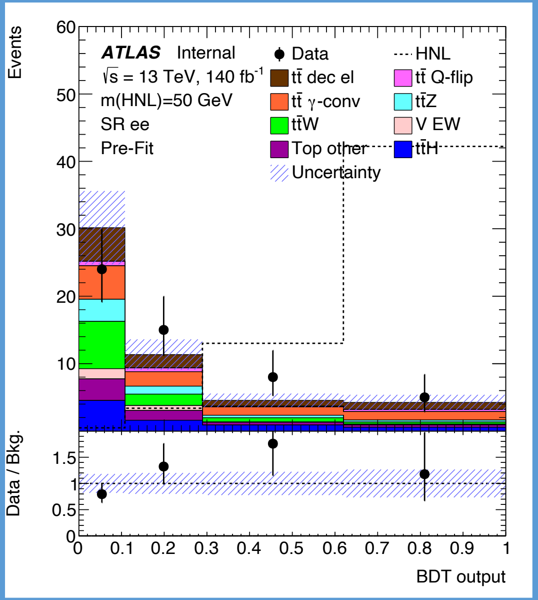


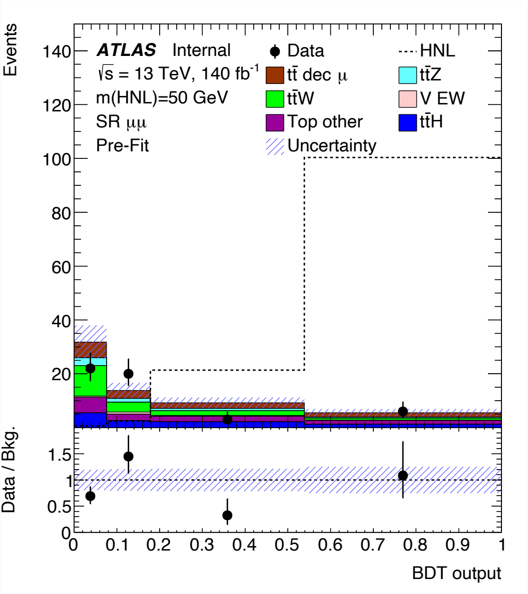
Post-fit

Unblinded fit in SRs

SR ee

SR $\mu\mu$

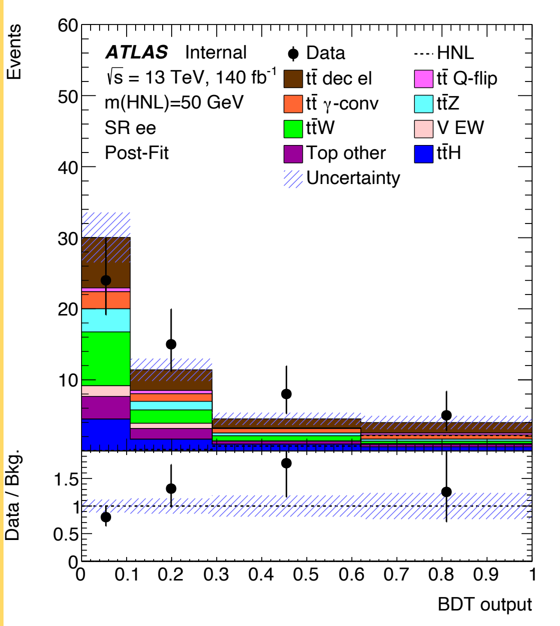


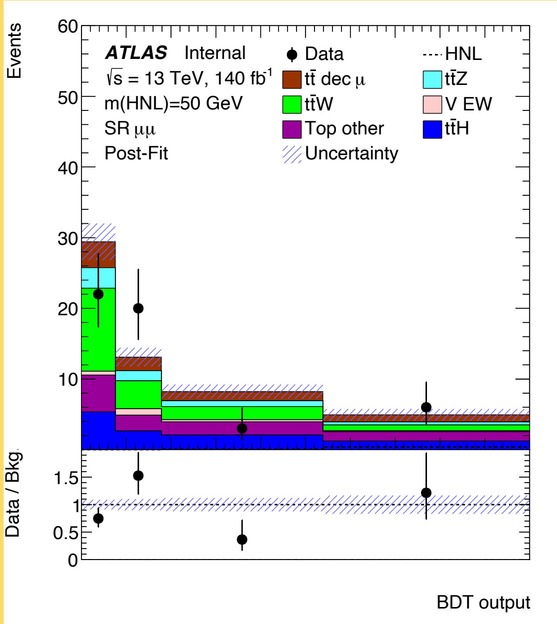


Pre-fit

SR ee

SR $\mu\mu$



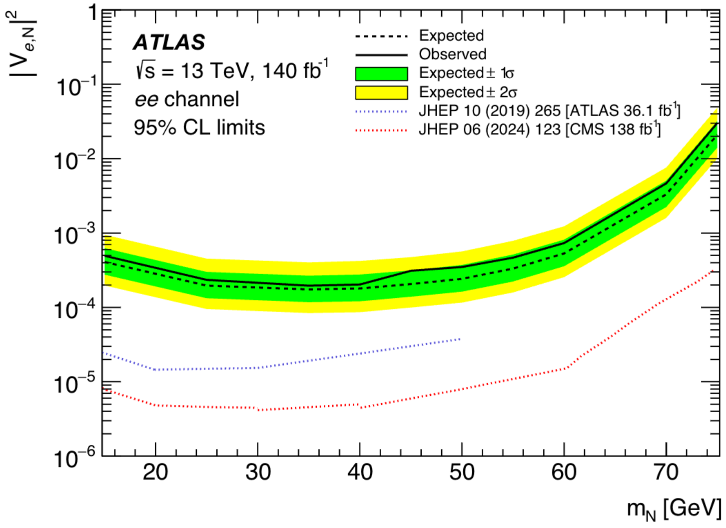


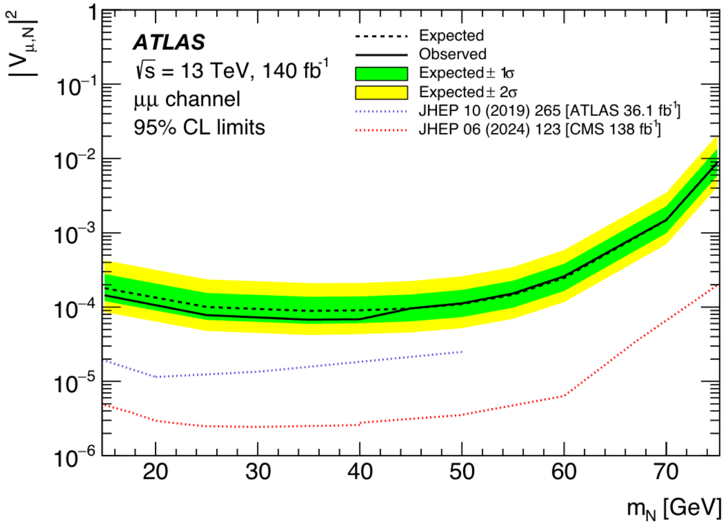
Post-fit

Sensitivity of unblinding results

- ✓ Upper limits on the signal cross-sections at 95% confidence level
- ✓ The limit results from $\tau\tau$ channel are taken from the combined fit

m_N [GeV]	15	25	35	40	45	50	55	60	70	75
Exp. $\sigma_{e,N}$ [fb]	21	9.8	7.3	6.9	6.9	6.7	7.2	8.5	18	36
Obs. $\sigma_{e,N}$ [fb]	26	12	8.2	7.8	10	9.7	10	12	26	52
Exp. $\sigma_{\mu,N}$ [fb]	9.3	5.0	3.7	3.5	3.2	3.1	3.2	4.0	8.2	15
Obs. $\sigma_{\mu,N}$ [fb]	7.5	3.9	2.8	2.6	3.2	3.1	3.3	4.2	8.3	15



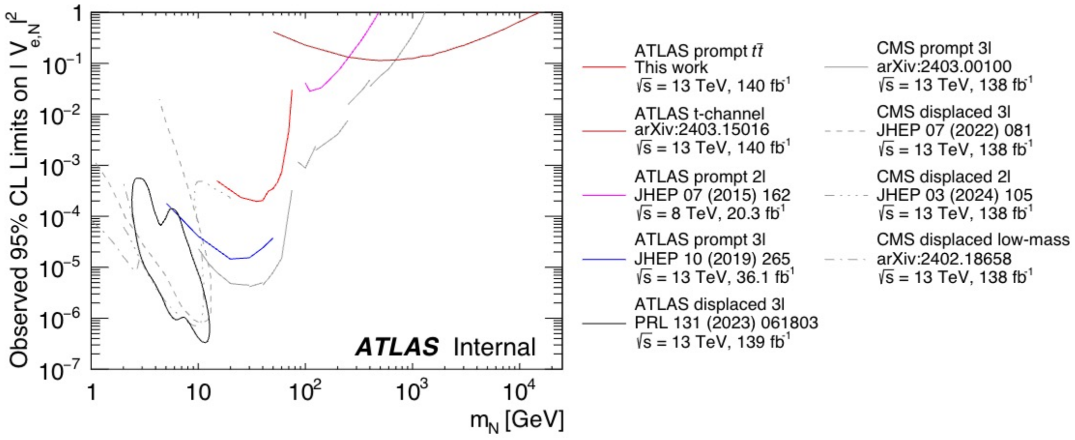


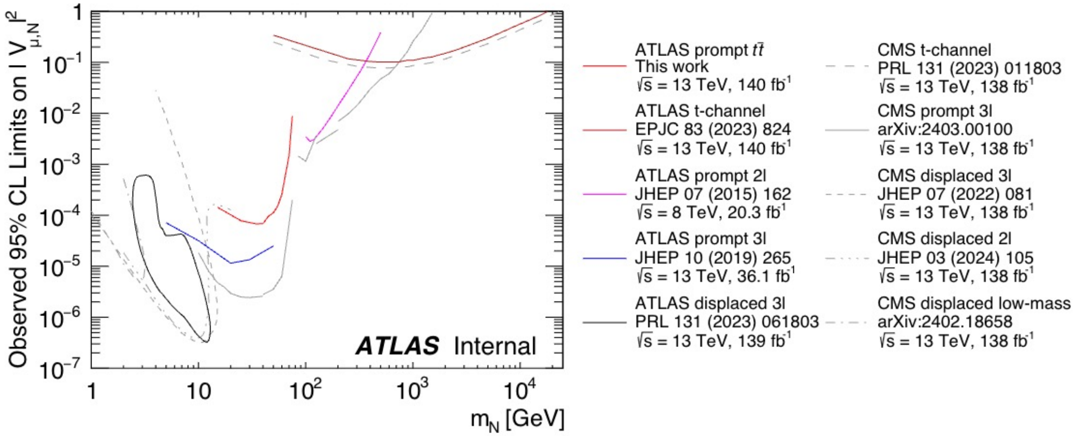
- ✓ The tightest observed upper limit on coupling parameters among [15,75] GeV are $|V_{e,N1}|^2 < 2.0 * 10^{-4}$, $|V_{\mu,N2}|^2 < 6.8 * 10^{-5}$

Summary

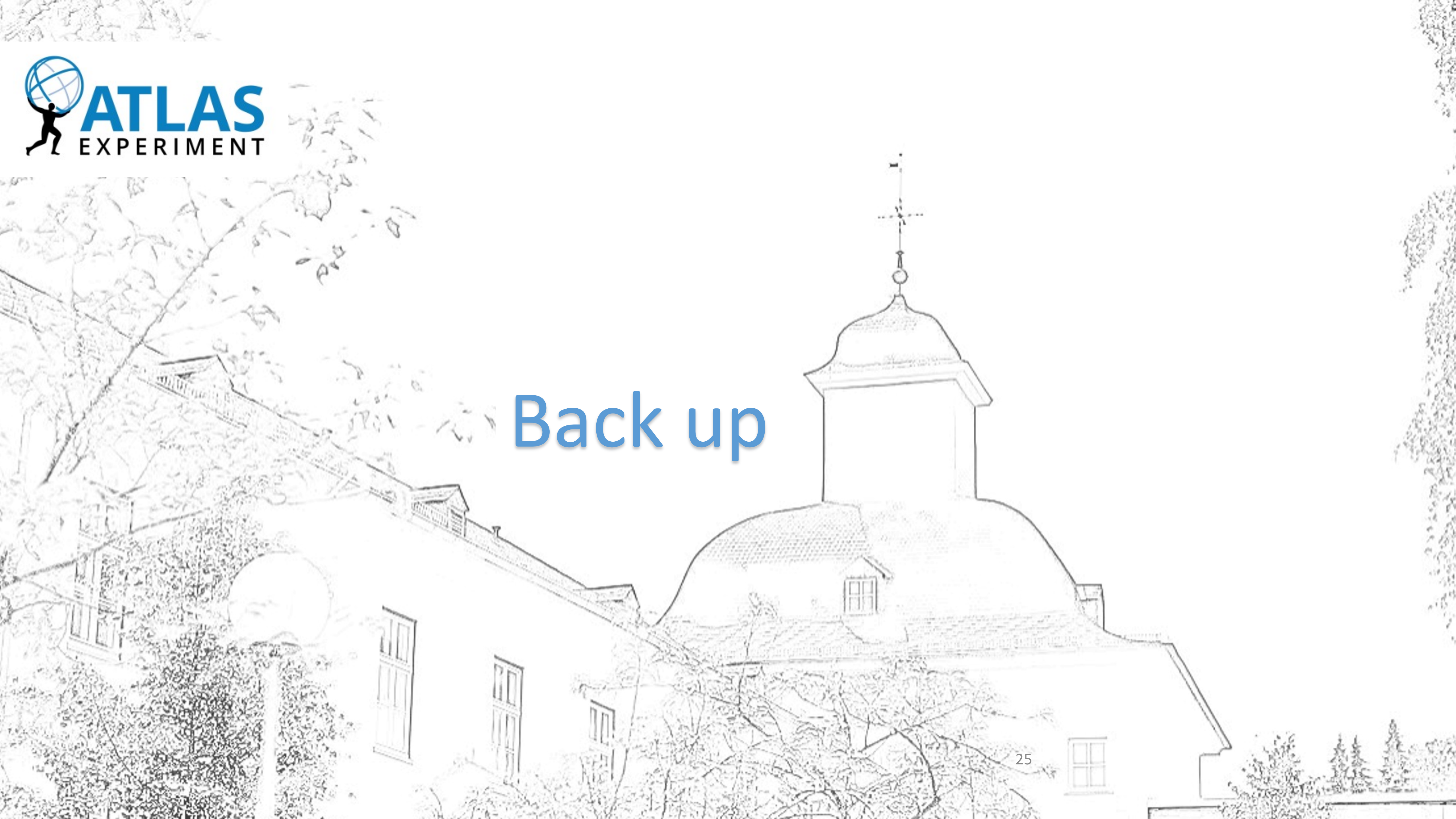
tt̄→ HNL analysis

- ✓ The search is performed on the 2LSS final states based on the full Run-2 data
- ✓ Six control regions based on the selection and two signal regions described with the BDT are applied to our analysis
- ✓ Successfully implement the relative experimental and theoretical uncertainties in the fit.
- ✓ This is the first search for HNL with the $t\bar{t}$ decay and the limit from $\mathrm{ee}/\mu\mu$ extends the ATLAS results beyond 50 GeV to 75 GeV.
- ✓ The paper has been accepted by the PRD



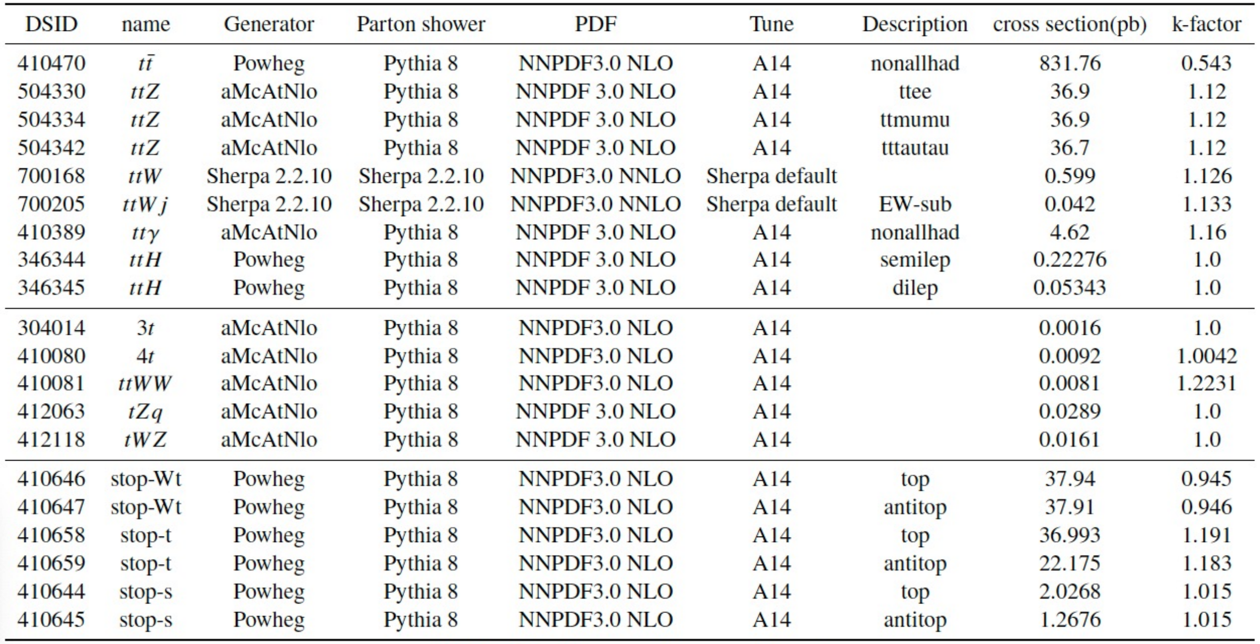


Thanks for your attention!



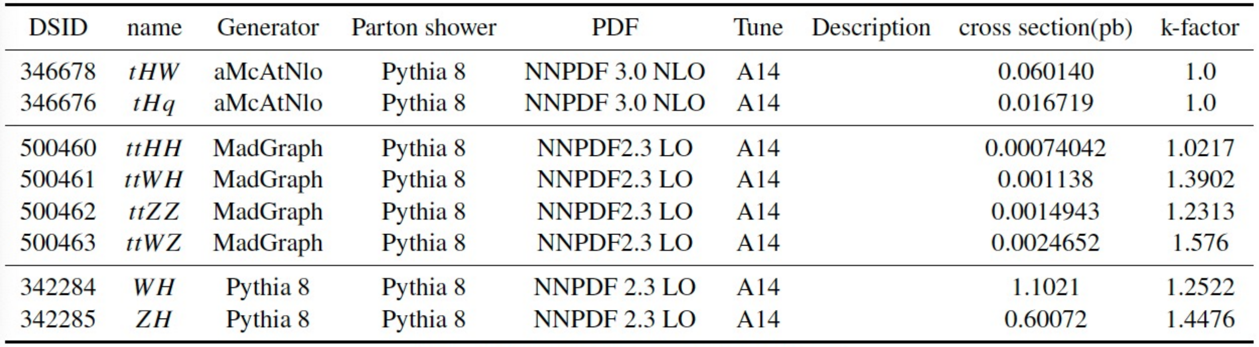
Back up

MC samples



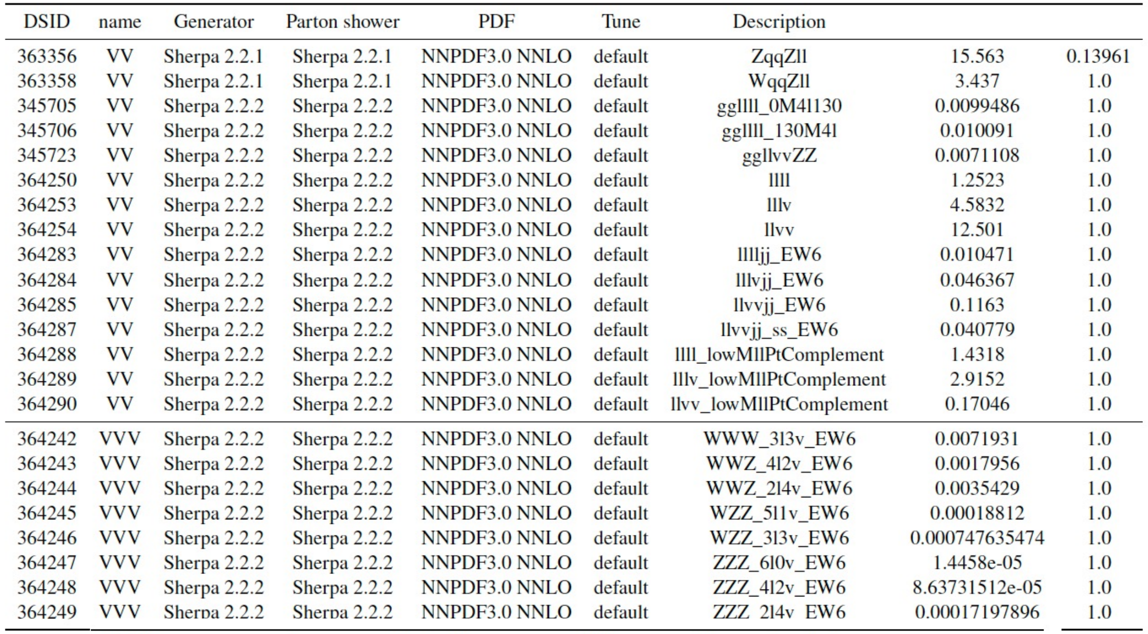
DSID	name	Generator	Parton shower	PDF	Tune	Description	cross section(pb)	k-factor
410470	$t\bar{t}$	Powheg	Pythia 8	NNPDF3.0 NLO	A14	nonallhad	831.76	0.543
504330	ttZ	aMcAtNlo	Pythia 8	NNPDF 3.0 NLO	A14	ttee	36.9	1.12
504334	ttZ	aMcAtNlo	Pythia 8	NNPDF 3.0 NLO	A14	ttmumu	36.9	1.12
504342	ttZ	aMcAtNlo	Pythia 8	NNPDF 3.0 NLO	A14	tttautau	36.7	1.12
700168	ttW	Sherpa 2.2.10	Sherpa 2.2.10	NNPDF3.0 NNLO	Sherpa default		0.599	1.126
700205	$ttWj$	Sherpa 2.2.10	Sherpa 2.2.10	NNPDF3.0 NNLO	Sherpa default	EW-sub	0.042	1.133
410389	$tt\gamma$	aMcAtNlo	Pythia 8	NNPDF 3.0 NLO	A14	nonallhad	4.62	1.16
346344	ttH	Powheg	Pythia 8	NNPDF 3.0 NLO	A14	semilep	0.22276	1.0
346345	ttH	Powheg	Pythia 8	NNPDF 3.0 NLO	A14	dilep	0.05343	1.0
304014	$3t$	aMcAtNlo	Pythia 8	NNPDF3.0 NLO	A14		0.0016	1.0
410080	$4t$	aMcAtNlo	Pythia 8	NNPDF3.0 NLO	A14		0.0092	1.0042
410081	$ttWW$	aMcAtNlo	Pythia 8	NNPDF3.0 NLO	A14		0.0081	1.2231
412063	tZq	aMcAtNlo	Pythia 8	NNPDF 3.0 NLO	A14		0.0289	1.0
412118	tWZ	aMcAtNlo	Pythia 8	NNPDF 3.0 NLO	A14		0.0161	1.0
410646	stop-Wt	Powheg	Pythia 8	NNPDF3.0 NLO	A14	top	37.94	0.945
410647	stop-Wt	Powheg	Pythia 8	NNPDF3.0 NLO	A14	antitop	37.91	0.946
410658	stop-t	Powheg	Pythia 8	NNPDF3.0 NLO	A14	top	36.993	1.191
410659	stop-t	Powheg	Pythia 8	NNPDF3.0 NLO	A14	antitop	22.175	1.183
410644	stop-s	Powheg	Pythia 8	NNPDF3.0 NLO	A14	top	2.0268	1.015
410645	stop-s	Powheg	Pythia 8	NNPDF3.0 NLO	A14	antitop	1.2676	1.015

Table C.1: Top samples considered

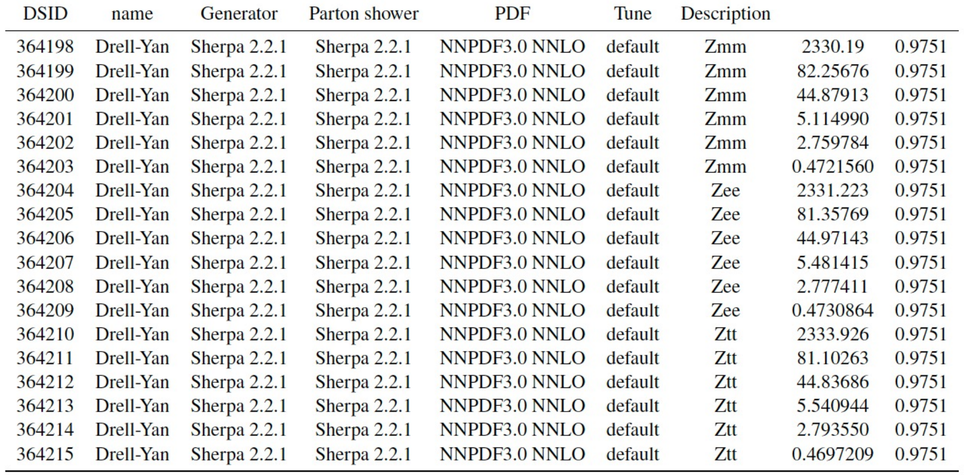


DSID	name	Generator	Parton shower	PDF	Tune	Description	cross section(pb)	k-factor
346678	tHW	aMcAtNlo	Pythia 8	NNPDF 3.0 NLO	A14		0.060140	1.0
346676	tHq	aMcAtNlo	Pythia 8	NNPDF 3.0 NLO	A14		0.016719	1.0
500460	$ttHH$	MadGraph	Pythia 8	NNPDF2.3 LO	A14		0.00074042	1.0217
500461	$ttWH$	MadGraph	Pythia 8	NNPDF2.3 LO	A14		0.001138	1.3902
500462	$ttZZ$	MadGraph	Pythia 8	NNPDF2.3 LO	A14		0.0014943	1.2313
500463	$ttWZ$	MadGraph	Pythia 8	NNPDF2.3 LO	A14		0.0024652	1.576
342284	WH	Pythia 8	Pythia 8	NNPDF 2.3 LO	A14		1.1021	1.2522
342285	ZH	Pythia 8	Pythia 8	NNPDF 2.3 LO	A14		0.60072	1.4476

Table C.2: Rare top samples considered



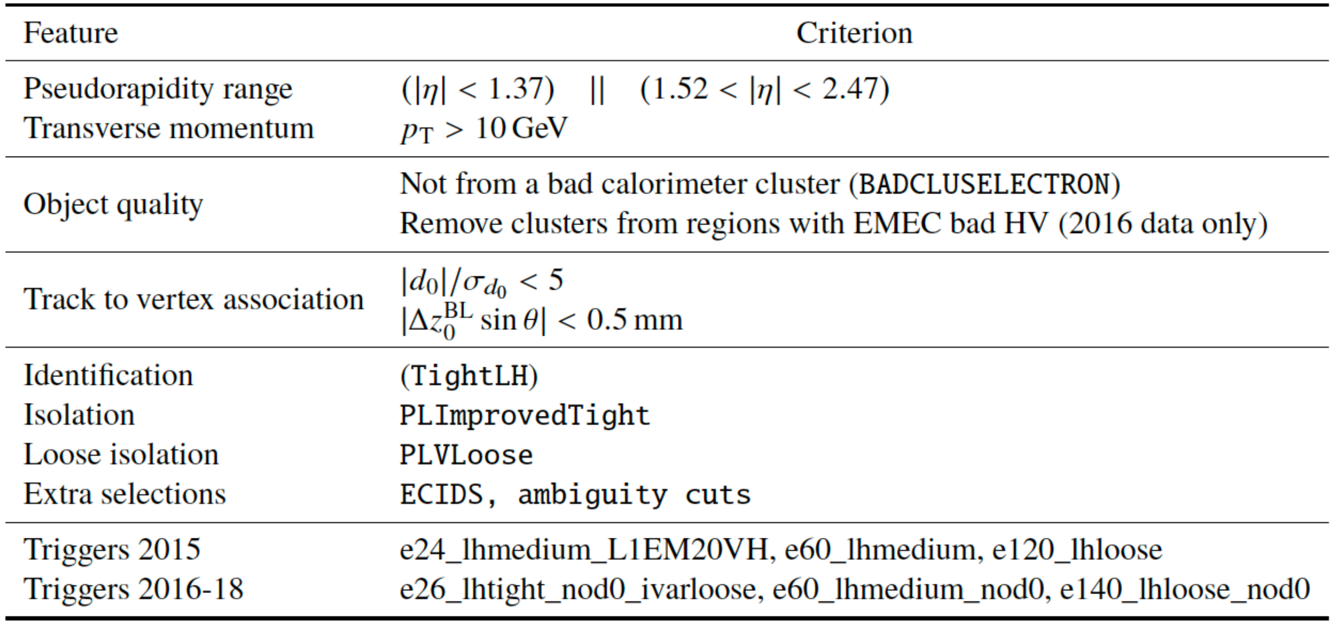
DSID	name	Generator	Parton shower	PDF	Tune	Description		
363356	VV	Sherpa 2.2.1	Sherpa 2.2.1	NNPDF3.0 NNLO	default	ZqqZll	15.563	0.13961
363358	VV	Sherpa 2.2.1	Sherpa 2.2.1	NNPDF3.0 NNLO	default	WqqZll	3.437	1.0
345705	VV	Sherpa 2.2.2	Sherpa 2.2.2	NNPDF3.0 NNLO	default	ggllll_0M4l130	0.0099486	1.0
345706	VV	Sherpa 2.2.2	Sherpa 2.2.2	NNPDF3.0 NNLO	default	ggllll_130M4l	0.010091	1.0
345723	VV	Sherpa 2.2.2	Sherpa 2.2.2	NNPDF3.0 NNLO	default	ggllvvZZ	0.0071108	1.0
364250	VV	Sherpa 2.2.2	Sherpa 2.2.2	NNPDF3.0 NNLO	default	llll	1.2523	1.0
364253	VV	Sherpa 2.2.2	Sherpa 2.2.2	NNPDF3.0 NNLO	default	lllv	4.5832	1.0
364254	VV	Sherpa 2.2.2	Sherpa 2.2.2	NNPDF3.0 NNLO	default	llvv	12.501	1.0
364283	VV	Sherpa 2.2.2	Sherpa 2.2.2	NNPDF3.0 NNLO	default	lllljj_EW6	0.010471	1.0
364284	VV	Sherpa 2.2.2	Sherpa 2.2.2	NNPDF3.0 NNLO	default	lllvjj_EW6	0.046367	1.0
364285	VV	Sherpa 2.2.2	Sherpa 2.2.2	NNPDF3.0 NNLO	default	llvvjj_EW6	0.1163	1.0
364287	VV	Sherpa 2.2.2	Sherpa 2.2.2	NNPDF3.0 NNLO	default	llvvjj_ss_EW6	0.040779	1.0
364288	VV	Sherpa 2.2.2	Sherpa 2.2.2	NNPDF3.0 NNLO	default	llll_lowMllPtComplement	1.4318	1.0
364289	VV	Sherpa 2.2.2	Sherpa 2.2.2	NNPDF3.0 NNLO	default	lllv_lowMllPtComplement	2.9152	1.0
364290	VV	Sherpa 2.2.2	Sherpa 2.2.2	NNPDF3.0 NNLO	default	llvv_lowMllPtComplement	0.17046	1.0
364242	VVV	Sherpa 2.2.2	Sherpa 2.2.2	NNPDF3.0 NNLO	default	WWW_3l3v_EW6	0.0071931	1.0
364243	VVV	Sherpa 2.2.2	Sherpa 2.2.2	NNPDF3.0 NNLO	default	WWZ_4l2v_EW6	0.0017956	1.0
364244	VVV	Sherpa 2.2.2	Sherpa 2.2.2	NNPDF3.0 NNLO	default	WWZ_2l4v_EW6	0.0035429	1.0
364245	VVV	Sherpa 2.2.2	Sherpa 2.2.2	NNPDF3.0 NNLO	default	WZZ_5l1v_EW6	0.00018812	1.0
364246	VVV	Sherpa 2.2.2	Sherpa 2.2.2	NNPDF3.0 NNLO	default	WZZ_3l3v_EW6	0.000747635474	1.0
364247	VVV	Sherpa 2.2.2	Sherpa 2.2.2	NNPDF3.0 NNLO	default	ZZZ_6l0v_EW6	1.4458e-05	1.0
364248	VVV	Sherpa 2.2.2	Sherpa 2.2.2	NNPDF3.0 NNLO	default	ZZZ_4l2v_EW6	8.63731512e-05	1.0
364249	VVV	Sherpa 2.2.2	Sherpa 2.2.2	NNPDF3.0 NNLO	default	ZZZ_2l4v_EW6	0.00017197896	1.0



DSID	name	Generator	Parton shower	PDF	Tune	Description		
364198	Drell-Yan	Sherpa 2.2.1	Sherpa 2.2.1	NNPDF3.0 NNLO	default	Zmm	2330.19	0.9751
364199	Drell-Yan	Sherpa 2.2.1	Sherpa 2.2.1	NNPDF3.0 NNLO	default	Zmm	82.25676	0.9751
364200	Drell-Yan	Sherpa 2.2.1	Sherpa 2.2.1	NNPDF3.0 NNLO	default	Zmm	44.87913	0.9751
364201	Drell-Yan	Sherpa 2.2.1	Sherpa 2.2.1	NNPDF3.0 NNLO	default	Zmm	5.114990	0.9751
364202	Drell-Yan	Sherpa 2.2.1	Sherpa 2.2.1	NNPDF3.0 NNLO	default	Zmm	2.759784	0.9751
364203	Drell-Yan	Sherpa 2.2.1	Sherpa 2.2.1	NNPDF3.0 NNLO	default	Zmm	0.4721560	0.9751
364204	Drell-Yan	Sherpa 2.2.1	Sherpa 2.2.1	NNPDF3.0 NNLO	default	Zee	2331.223	0.9751
364205	Drell-Yan	Sherpa 2.2.1	Sherpa 2.2.1	NNPDF3.0 NNLO	default	Zee	81.35769	0.9751
364206	Drell-Yan	Sherpa 2.2.1	Sherpa 2.2.1	NNPDF3.0 NNLO	default	Zee	44.97143	0.9751
364207	Drell-Yan	Sherpa 2.2.1	Sherpa 2.2.1	NNPDF3.0 NNLO	default	Zee	5.481415	0.9751
364208	Drell-Yan	Sherpa 2.2.1	Sherpa 2.2.1	NNPDF3.0 NNLO	default	Zee	2.777411	0.9751
364209	Drell-Yan	Sherpa 2.2.1	Sherpa 2.2.1	NNPDF3.0 NNLO	default	Zee	0.4730864	0.9751
364210	Drell-Yan	Sherpa 2.2.1	Sherpa 2.2.1	NNPDF3.0 NNLO	default	Ztt	2333.926	0.9751
364211	Drell-Yan	Sherpa 2.2.1	Sherpa 2.2.1	NNPDF3.0 NNLO	default	Ztt	81.10263	0.9751
364212	Drell-Yan	Sherpa 2.2.1	Sherpa 2.2.1	NNPDF3.0 NNLO	default	Ztt	44.83686	0.9751
364213	Drell-Yan	Sherpa 2.2.1	Sherpa 2.2.1	NNPDF3.0 NNLO	default	Ztt	5.540944	0.9751
364214	Drell-Yan	Sherpa 2.2.1	Sherpa 2.2.1	NNPDF3.0 NNLO	default	Ztt	2.793550	0.9751
364215	Drell-Yan	Sherpa 2.2.1	Sherpa 2.2.1	NNPDF3.0 NNLO	default	Ztt	0.4697209	0.9751

Table C.4: Drell-Yan samples considered

Object selection / single lepton trigger information

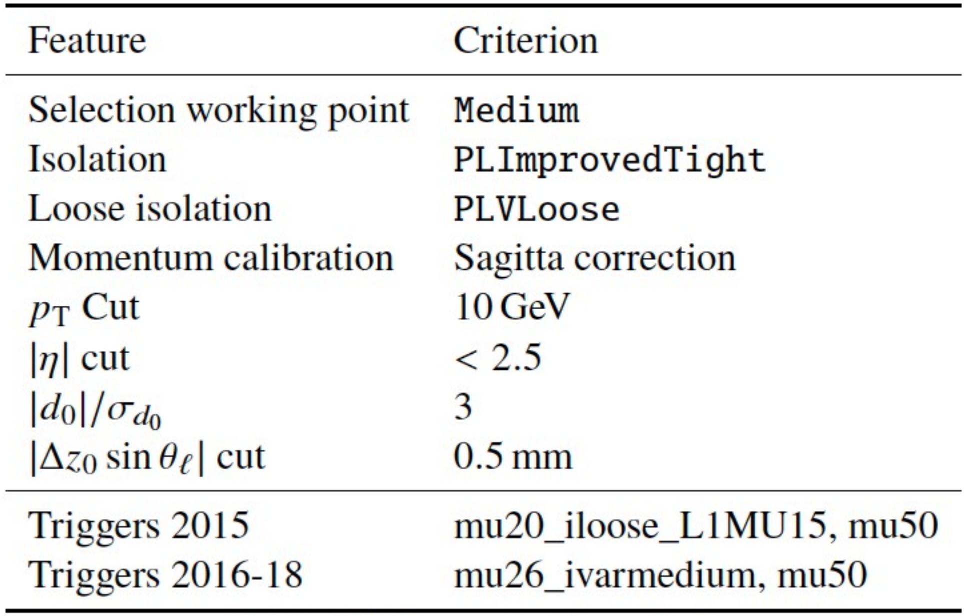


Feature	Criterion
Pseudorapidity range Transverse momentum	$(\lvert\eta\rvert < 1.37) \quad \Vert \quad (1.52 < \lvert\eta\rvert < 2.47)$ $p_T > 10\,\mathrm{GeV}$
Object quality	Not from a bad calorimeter cluster (`BADCLUSELECTRON`) Remove clusters from regions with EMEC bad HV (2016 data only)
Track to vertex association	$\lvert d_0\rvert/\sigma_{d_0} < 5$ $\lvert\Delta z_0^{\mathrm{BL}} \sin\theta\rvert < 0.5\,\mathrm{mm}$

Identification
Isolation
Loose isolation
Extra selections
	(`TightLH`)
	`PLImprovedTight`
	`PLVLoose`
	`ECIDS, ambiguity cuts`

Triggers 2015 Triggers 2016-18	e24_lhmedium_L1EM20VH, e60_lhmedium, e120_lhloose e26_lhtight_nod0_ivarloose, e60_lhmedium_nod0, e140_lhloose_nod0

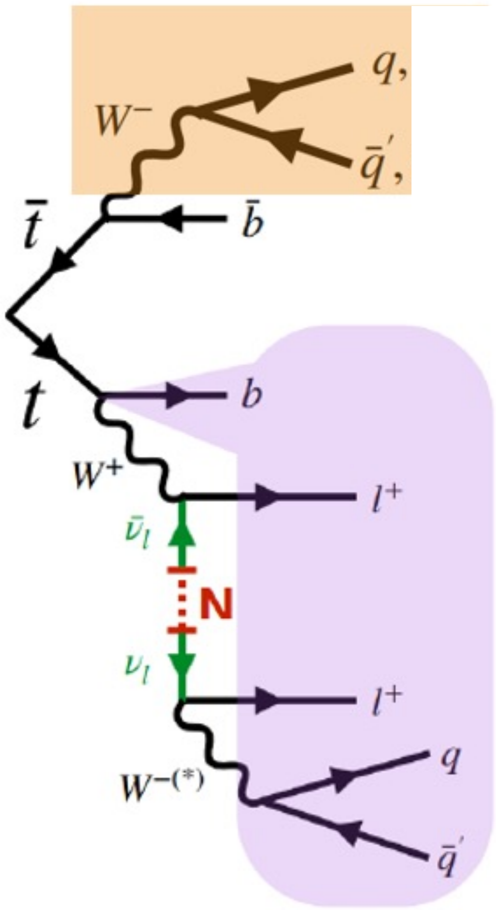
Table 4.1: Electron selection criteria.



Feature	Criterion
Selection working point	`Medium`
Isolation	`PLImprovedTight`
Loose isolation	`PLVLoose`
Momentum calibration	Sagitta correction
p_T Cut	$10\,\mathrm{GeV}$
$\lvert\eta\rvert$ 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.

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

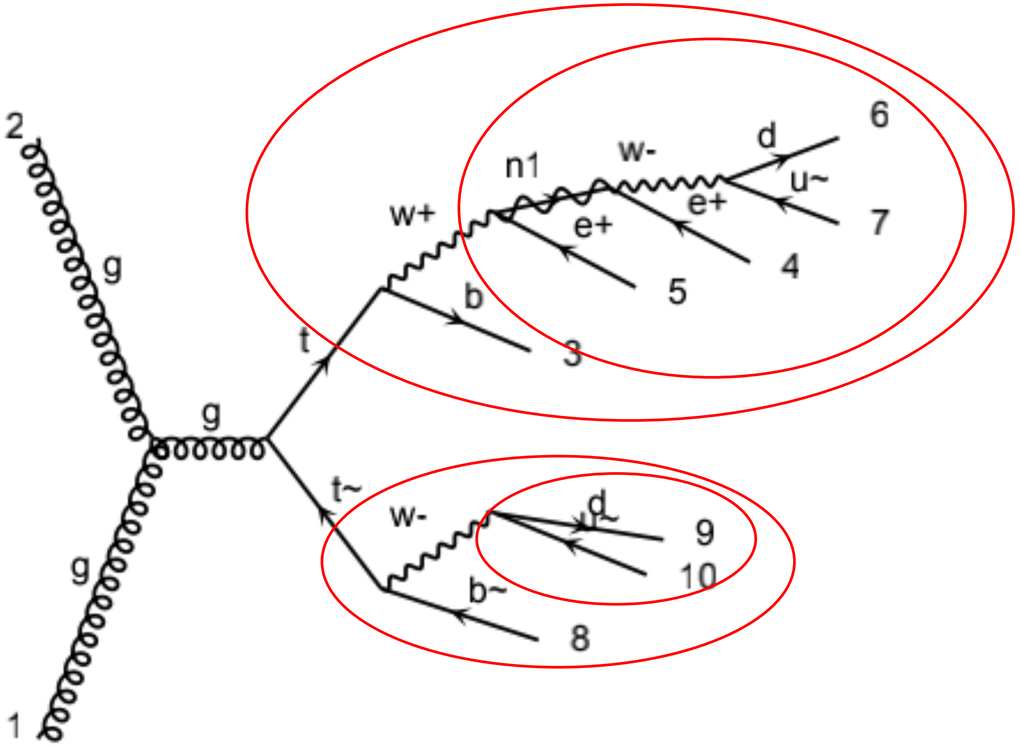
- ✓ Contribute to the final states via photon conversion and left floating together with the Photon conversion e from $t\bar{t}$
- ✓ Perform the overlap removal with the inclusive $t\bar{t}$ sample

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

- ✓ They contribute to the final states via prompt leptons classes.
- ✓ Dedicated measurements of the cross sections of $t\bar{t}$Z/ $t\bar{t}$H 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.

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}
- $\Delta R_{ll},$
- $M_{bsmTreso}$
- $M_{bsmWreso}$
- $M_{bsmN1reso}$
- $M_{bsmN2reso}$
- $M_{smTreso}$
- $M_{smWreso}$
- 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

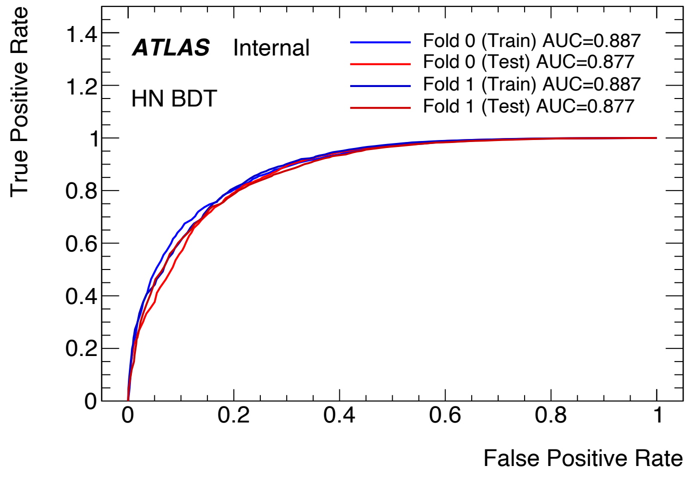
High mass set: HNL[45, 50, 55, 60, 70, 75] GeV

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

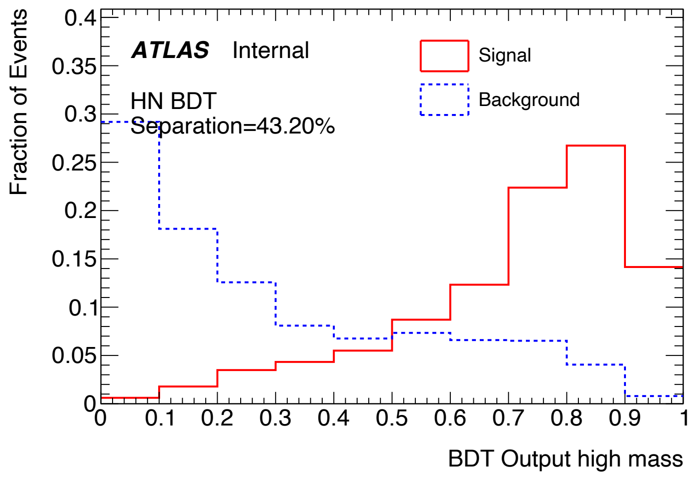
MVA performance (high mass)

MVA performance:

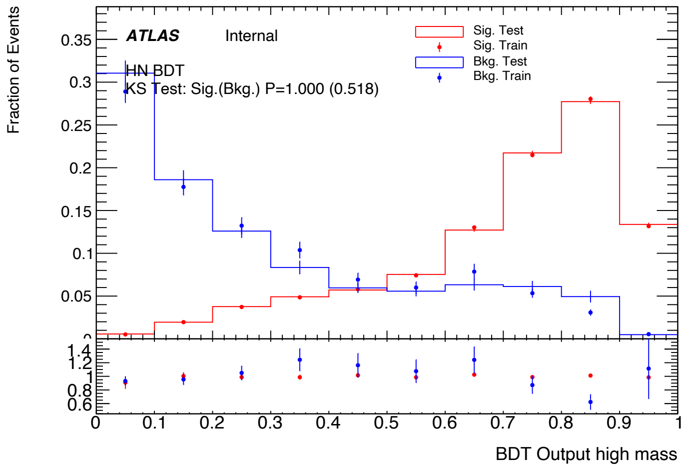
- ✓ Training results shows good separation between signal and backgrounds
- ✓ No overfit issues observed when comparing the loss function(training and validation)
- ✓ Good agreement between training and testing dataset (only one fold results showed)



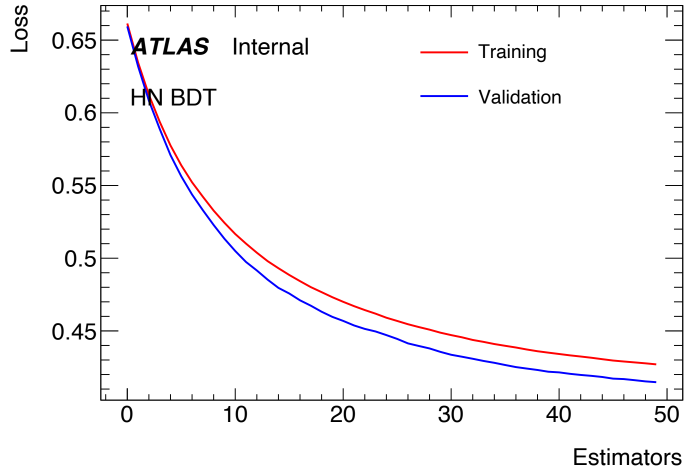
2-fold AUC output



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.

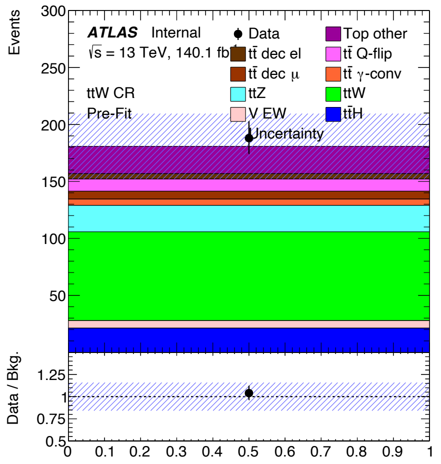
8/9.HadronDecay:

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).

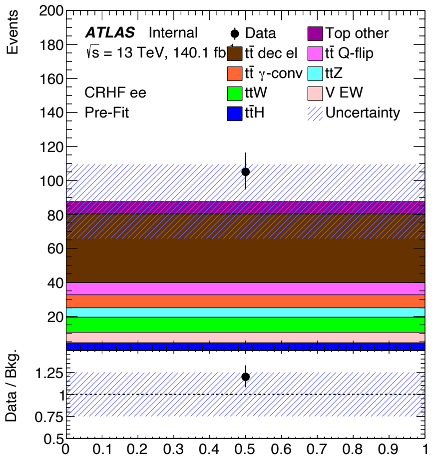
10.LightFlavourDecay:

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.

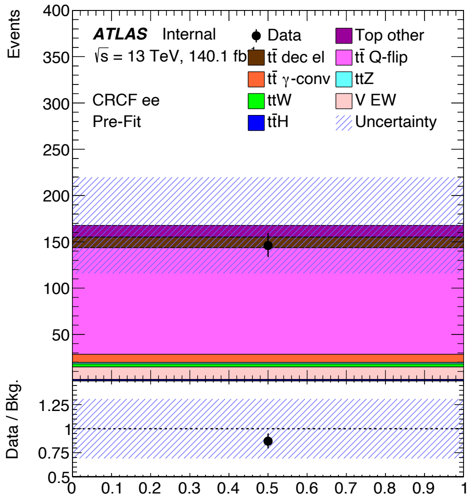
Pre-fit of CR-only fit



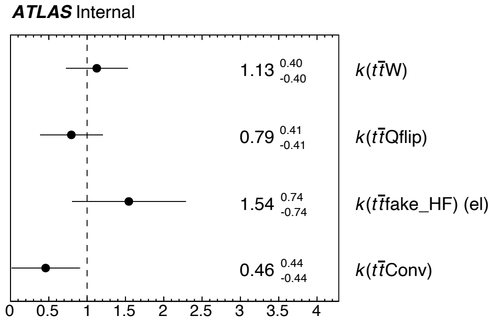
CR $t\bar{t}W$ ee



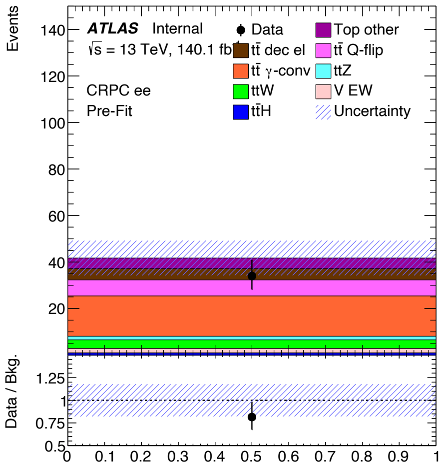
CR HF ee



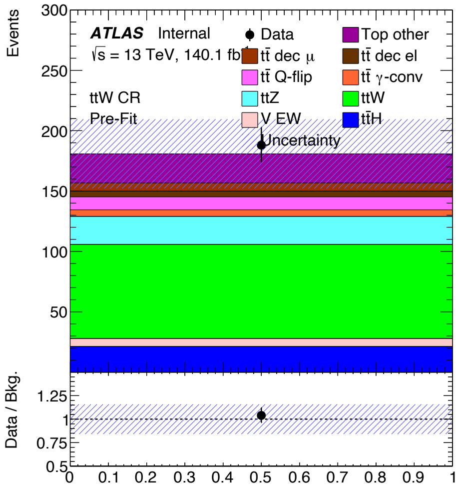
CR Qflip ee



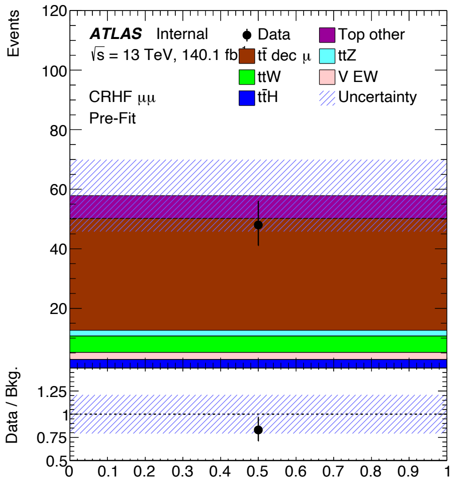
✓ SFs of the ee channel



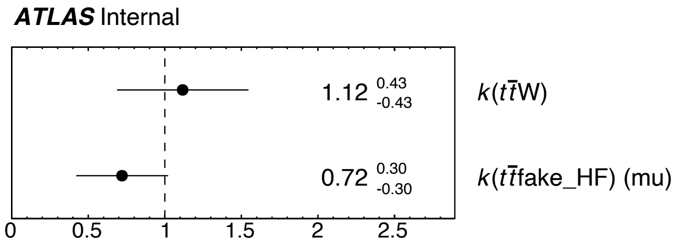
CR γ-conv ee



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

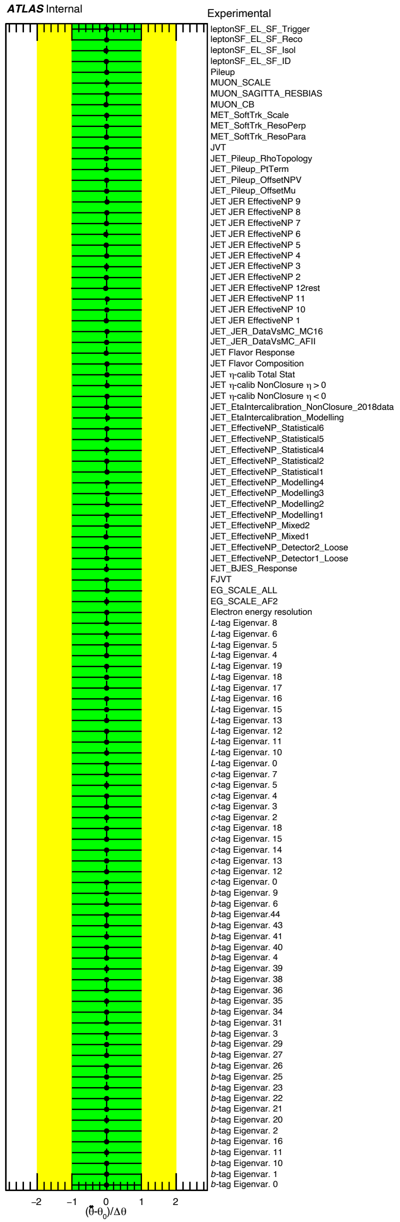


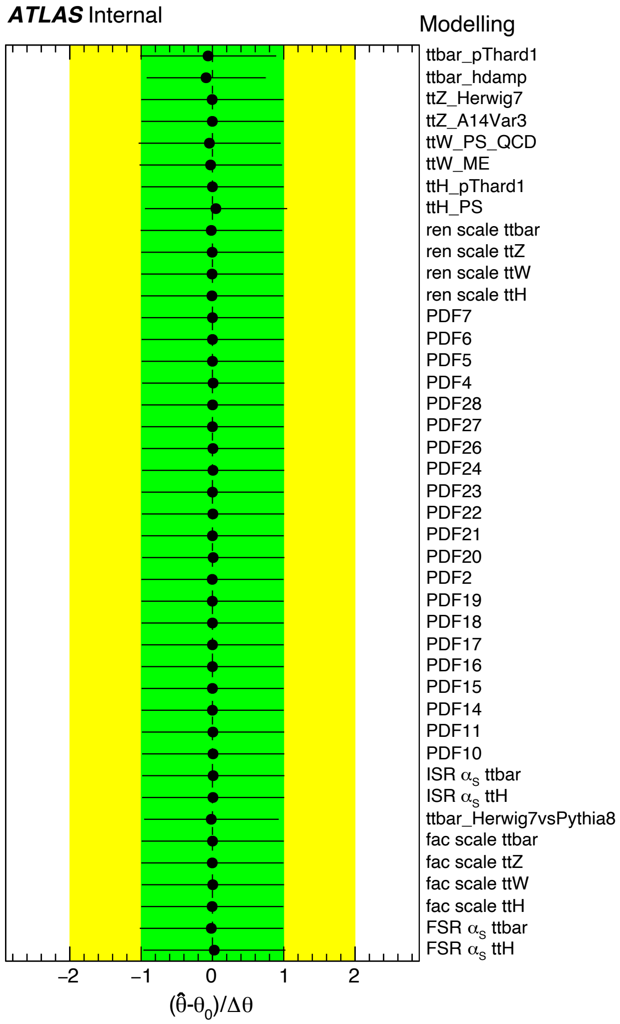
CR HF $\mu\mu$



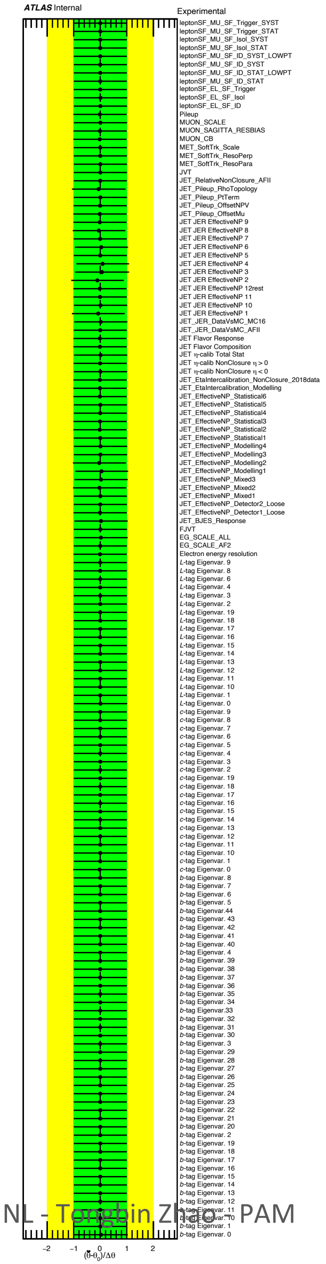
✓ SFs of the $\mu\mu$ channel

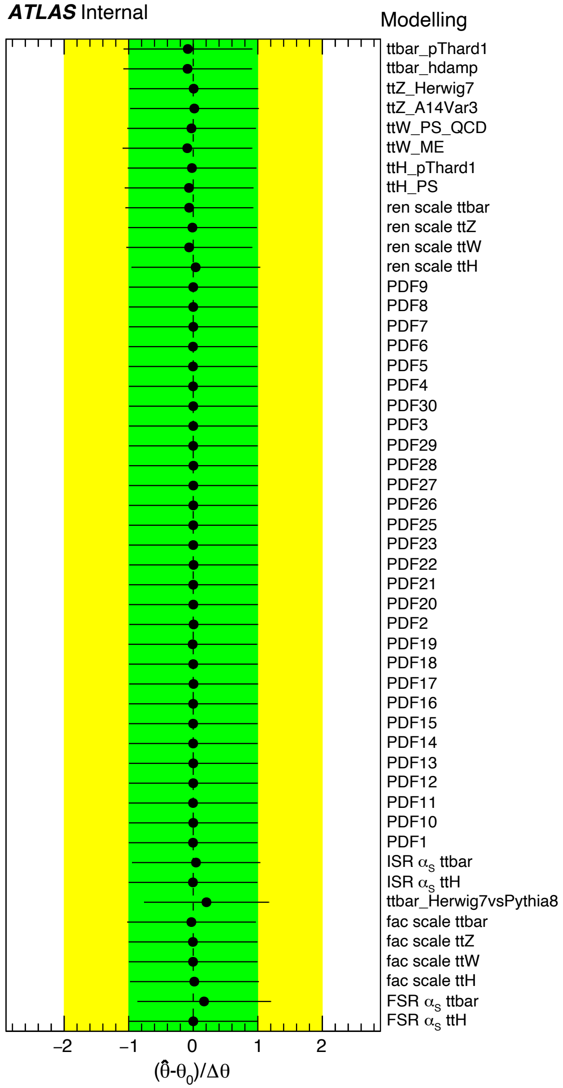
NPs (Experimental and modeling)





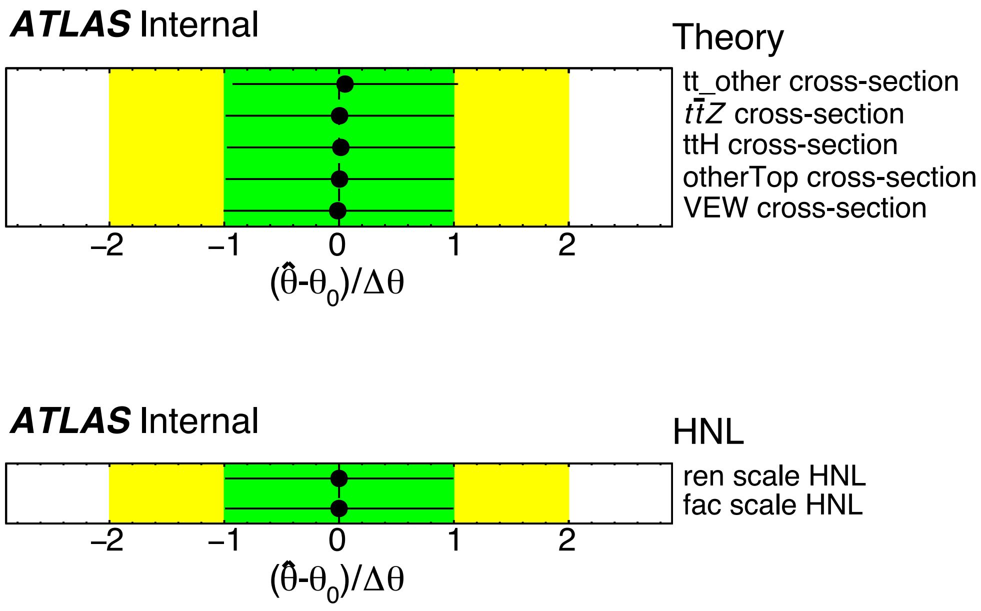
Data fit *ee* channel



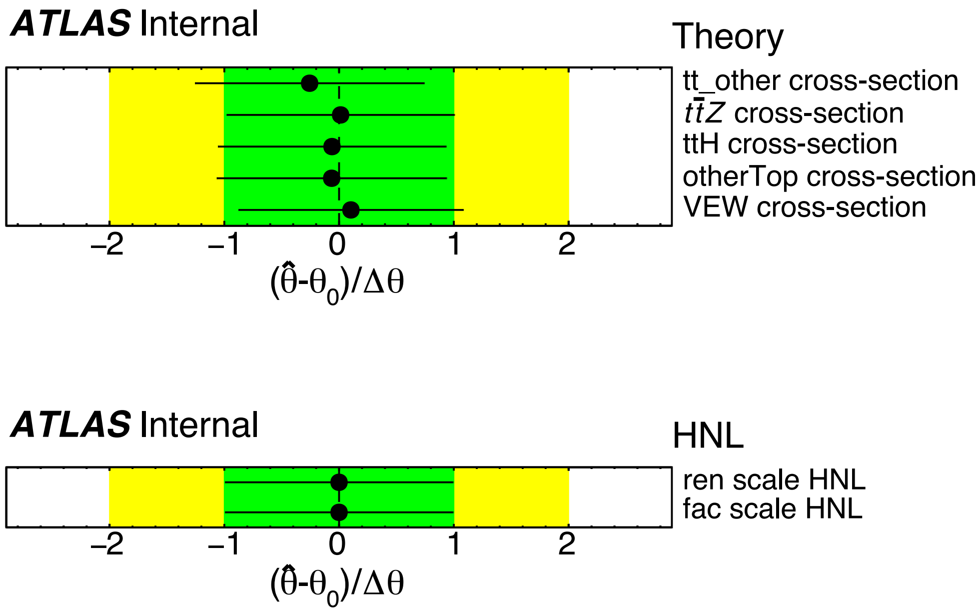


Data fit $\mu\mu$ channel

NPs (Theory and HNL related)



Data fit ee channel

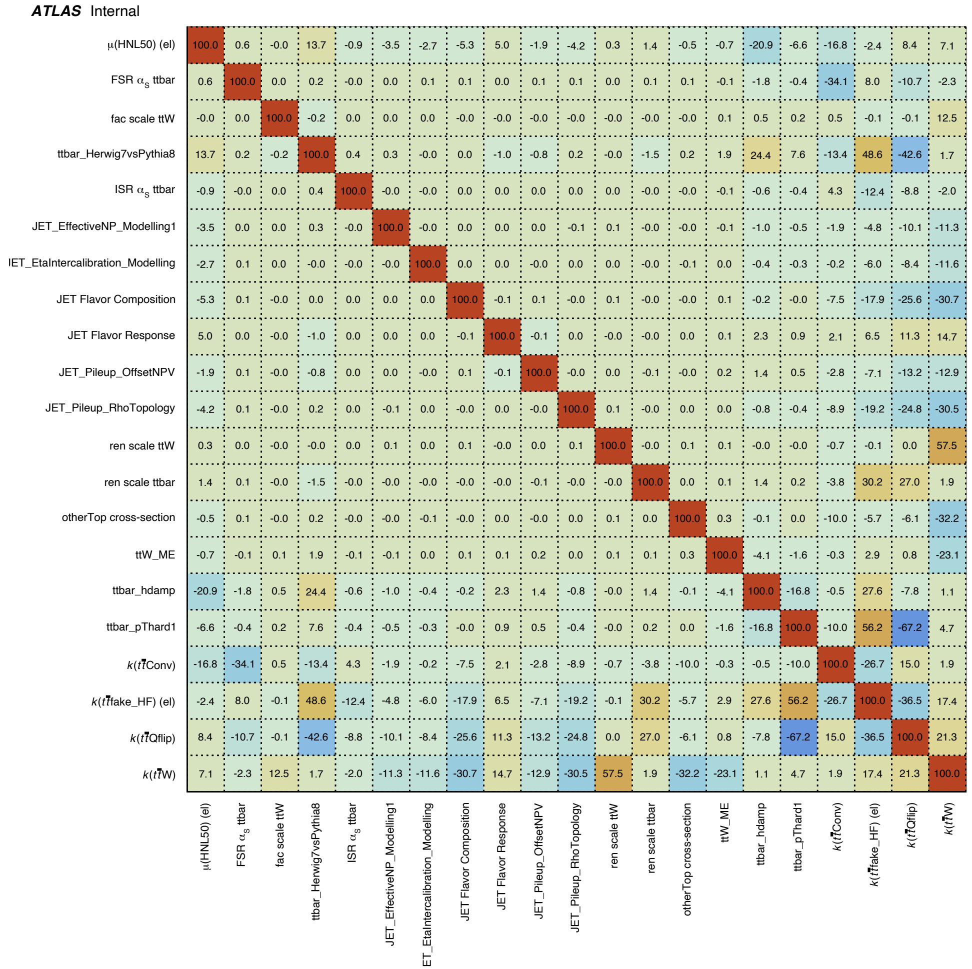


Data fit $\mu\mu$ channel

✓ Small pulls from the $t\bar{t}$ related modeling uncertainties and $t\bar{t}$_other cross section uncertainties

Data fit results (Correlation)

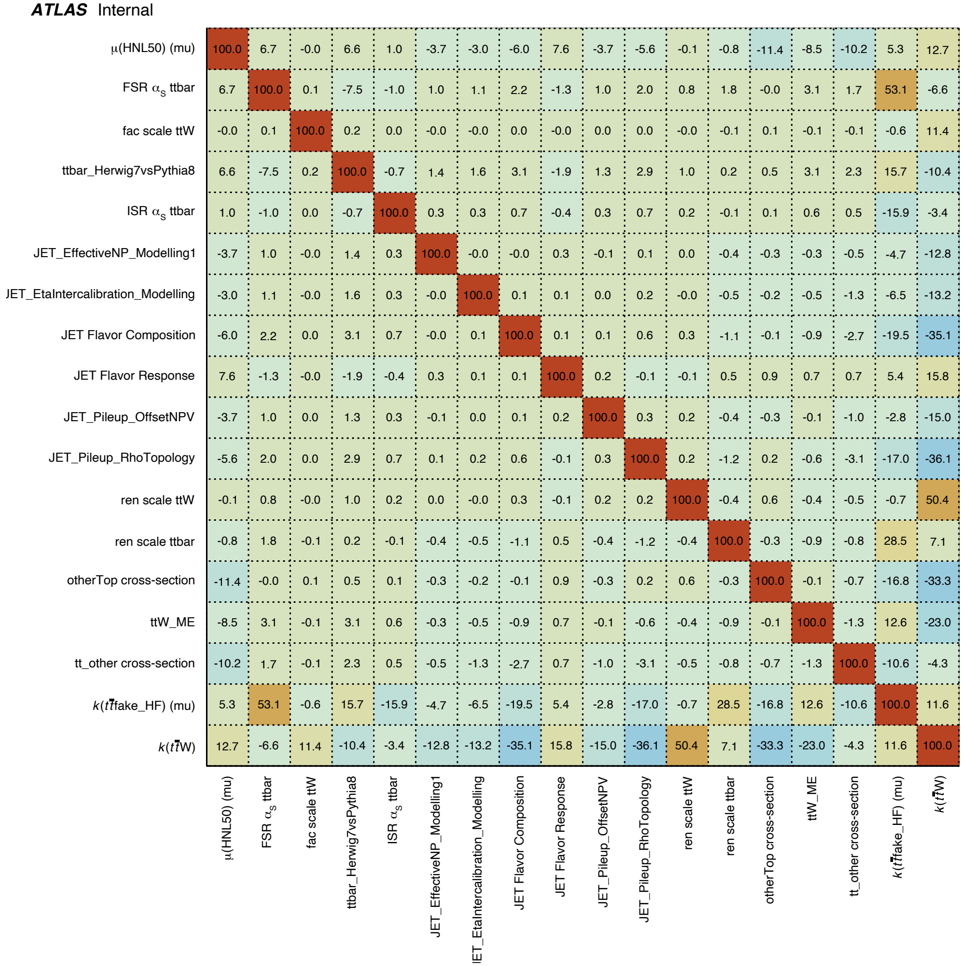
Data fit ee channel



ATLAS Internal

	μ(HNL50) (el)	FSR α_S ttbar	fac scale ttW	ttbar_Herwig7vsPythia8	ISR α_S ttbar	JET_EffectiveNP_Modelling1	JET_EtaIntercalibration_Modelling	JET Flavor Composition	JET Flavor Response	JET_Pileup_OffsetNPV	JET_Pileup_RhoTopology	ren scale ttW	ren scale ttbar	otherTop cross-section	ttW_ME	ttbar_hdamp	ttbar_pThard1	$k(t\bar{t}$Conv)	$k(t\bar{t}$fake_HF) (el)	$k(t\bar{t}$Qflip)	$k(t\bar{t}$W)
μ(HNL50) (el)	100.0	0.6	-0.0	13.7	-0.9	-3.5	-2.7	-5.3	5.0	-1.9	-4.2	0.3	1.4	-0.5	-0.7	-20.9	-6.6	-16.8	-2.4	8.4	7.1
FSR α_S ttbar	0.6	100.0	0.0	0.2	-0.0	0.0	0.1	0.1	0.0	0.1	0.1	0.0	0.1	0.1	-0.1	-1.8	-0.4	-34.1	8.0	-10.7	-2.3
fac scale ttW	-0.0	0.0	100.0	-0.2	0.0	0.0	0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	0.1	0.5	0.2	0.5	-0.1	-0.1	12.5
ttbar_Herwig7vsPythia8	13.7	0.2	-0.2	100.0	0.4	0.3	-0.0	0.0	-1.0	-0.8	0.2	-0.0	-1.5	0.2	1.9	24.4	7.6	-13.4	48.6	-42.6	1.7
ISR α_S ttbar	-0.9	-0.0	0.0	0.4	100.0	-0.0	-0.0	0.0	0.0	0.0	0.0	0.0	-0.0	-0.0	-0.1	-0.6	-0.4	4.3	-12.4	-8.8	-2.0
JET_EffectiveNP_Modelling1	-3.5	0.0	0.0	0.3	-0.0	100.0	-0.0	0.0	0.0	0.0	-0.1	0.1	-0.0	-0.0	-0.1	-1.0	-0.5	-1.9	-4.8	-10.1	-11.3
JET_EtaIntercalibration_Modelling	-2.7	0.1	0.0	-0.0	-0.0	-0.0	100.0	0.0	0.0	-0.0	0.0	0.0	-0.0	-0.1	0.0	-0.4	-0.3	-0.2	-6.0	-8.4	-11.6
JET Flavor Composition	-5.3	0.1	-0.0	0.0	0.0	0.0	0.0	100.0	-0.1	0.1	-0.0	0.1	-0.0	-0.0	0.1	-0.2	-0.0	-7.5	-17.9	-25.6	-30.7
JET Flavor Response	5.0	0.0	-0.0	-1.0	0.0	0.0	0.0	-0.1	100.0	-0.1	0.0	-0.0	-0.0	0.0	0.1	2.3	0.9	2.1	6.5	11.3	14.7
JET_Pileup_OffsetNPV	-1.9	0.1	-0.0	-0.8	0.0	0.0	-0.0	0.1	-0.1	100.0	-0.0	0.0	-0.1	-0.0	0.2	1.4	0.5	-2.8	-7.1	-13.2	-12.9
JET_Pileup_RhoTopology	-4.2	0.1	-0.0	0.2	0.0	-0.1	0.0	-0.0	0.0	-0.0	100.0	0.1	-0.0	0.0	0.0	-0.8	-0.4	-8.9	-19.2	-24.8	-30.5
ren scale ttW	0.3	0.0	-0.0	-0.0	0.0	0.1	0.0	0.1	-0.0	0.0	0.1	100.0	-0.0	0.1	0.1	-0.0	-0.0	-0.7	-0.1	0.0	57.5
ren scale ttbar	1.4	0.1	-0.0	-1.5	-0.0	-0.0	-0.0	-0.0	-0.0	-0.1	-0.0	-0.0	100.0	0.0	0.1	1.4	0.2	-3.8	30.2	27.0	1.9
otherTop cross-section	-0.5	0.1	-0.0	0.2	-0.0	-0.0	-0.1	-0.0	0.0	-0.0	0.0	0.1	0.0	100.0	0.3	-0.1	0.0	-10.0	-5.7	-6.1	-32.2
ttW_ME	-0.7	-0.1	0.1	1.9	-0.1	-0.1	0.0	0.1	0.1	0.2	0.0	0.1	0.1	0.3	100.0	-4.1	-1.6	-0.3	2.9	0.8	-23.1
ttbar_hdamp	-20.9	-1.8	0.5	24.4	-0.6	-1.0	-0.4	-0.2	2.3	1.4	-0.8	-0.0	1.4	-0.1	-4.1	100.0	-16.8	-0.5	27.6	-7.8	1.1
ttbar_pThard1	-6.6	-0.4	0.2	7.6	-0.4	-0.5	-0.3	-0.0	0.9	0.5	-0.4	-0.0	0.2	0.0	-1.6	-16.8	100.0	-10.0	56.2	-67.2	4.7
$k(t\bar{t}$Conv)	-16.8	-34.1	0.5	-13.4	4.3	-1.9	-0.2	-7.5	2.1	-2.8	-8.9	-0.7	-3.8	-10.0	-0.3	-0.5	-10.0	100.0	-26.7	15.0	1.9
$k(t\bar{t}$fake_HF) (el)	-2.4	8.0	-0.1	48.6	-12.4	-4.8	-6.0	-17.9	6.5	-7.1	-19.2	-0.1	30.2	-5.7	2.9	27.6	56.2	-26.7	100.0	-36.5	17.4
$k(t\bar{t}$Qflip)	8.4	-10.7	-0.1	-42.6	-8.8	-10.1	-8.4	-25.6	11.3	-13.2	-24.8	0.0	27.0	-6.1	0.8	-7.8	-67.2	15.0	-36.5	100.0	21.3
$k(t\bar{t}$W)	7.1	-2.3	12.5	1.7	-2.0	-11.3	-11.6	-30.7	14.7	-12.9	-30.5	57.5	1.9	-32.2	-23.1	1.1	4.7	1.9	17.4	21.3	100.0

Data fit $\mu\mu$ channel



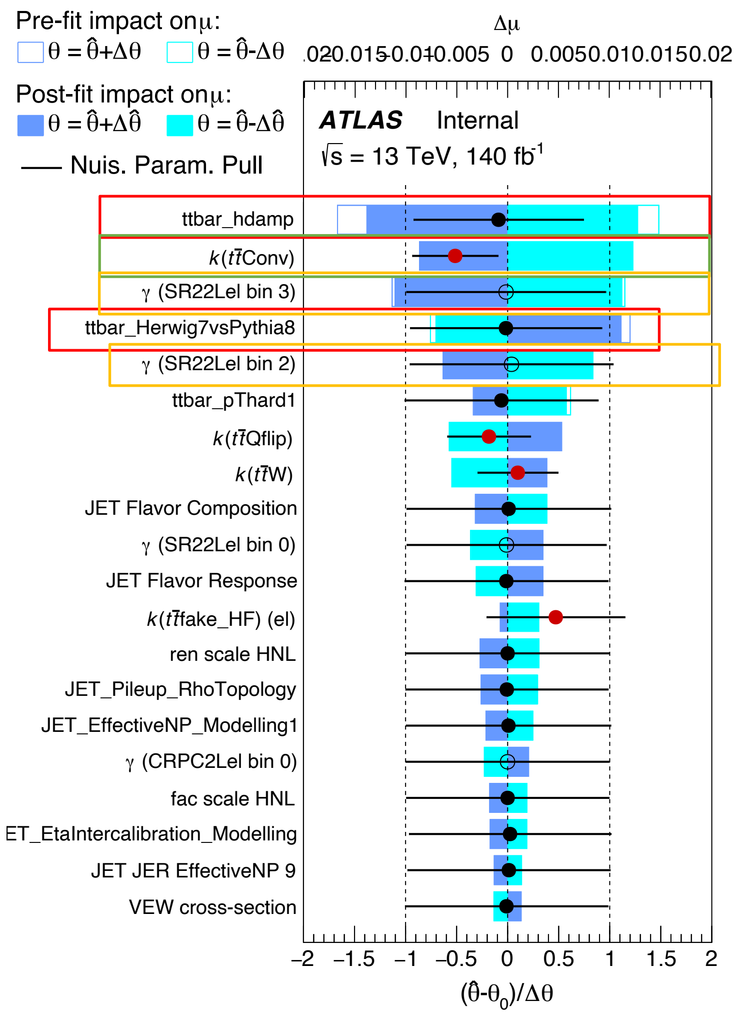
ATLAS Internal

	μ(HNL50) (mu)	FSR α_S ttbar	fac scale ttW	ttbar_Herwig7vsPythia8	ISR α_S ttbar	JET_EffectiveNP_Modelling1	JET_EtaIntercalibration_Modelling	JET Flavor Composition	JET Flavor Response	JET_Pileup_OffsetNPV	JET_Pileup_RhoTopology	ren scale ttW	ren scale ttbar	otherTop cross-section	ttW_ME	tt_other cross-section	$k(t\bar{t}$fake_HF) (mu)	$k(t\bar{t}$W)
μ(HNL50) (mu)	100.0	6.7	-0.0	6.6	1.0	-3.7	-3.0	-6.0	7.6	-3.7	-5.6	-0.1	-0.8	-11.4	-8.5	-10.2	5.3	12.7
FSR α_S ttbar	6.7	100.0	0.1	-7.5	-1.0	1.0	1.1	2.2	-1.3	1.0	2.0	0.8	1.8	-0.0	3.1	1.7	53.1	-6.6
fac scale ttW	-0.0	0.1	100.0	0.2	0.0	-0.0	-0.0	0.0	-0.0	0.0	0.0	-0.0	-0.1	0.1	-0.1	-0.1	-0.6	11.4
ttbar_Herwig7vsPythia8	6.6	-7.5	0.2	100.0	-0.7	1.4	1.6	3.1	-1.9	1.3	2.9	1.0	0.2	0.5	3.1	2.3	15.7	-10.4
ISR α_S ttbar	1.0	-1.0	0.0	-0.7	100.0	0.3	0.3	0.7	-0.4	0.3	0.7	0.2	-0.1	0.1	0.6	0.5	-15.9	-3.4
JET_EffectiveNP_Modelling1	-3.7	1.0	-0.0	1.4	0.3	100.0	-0.0	-0.0	0.3	-0.1	0.1	0.0	-0.4	-0.3	-0.3	-0.5	-4.7	-12.8
JET_EtaIntercalibration_Modelling	-3.0	1.1	-0.0	1.6	0.3	-0.0	100.0	0.1	0.1	0.0	0.2	-0.0	-0.5	-0.2	-0.5	-1.3	-6.5	-13.2
JET Flavor Composition	-6.0	2.2	0.0	3.1	0.7	-0.0	0.1	100.0	0.1	0.1	0.6	0.3	-1.1	-0.1	-0.9	-2.7	-19.5	-35.1
JET Flavor Response	7.6	-1.3	-0.0	-1.9	-0.4	0.3	0.1	0.1	100.0	0.2	-0.1	-0.1	0.5	0.9	0.7	0.7	5.4	15.8
JET_Pileup_OffsetNPV	-3.7	1.0	0.0	1.3	0.3	-0.1	0.0	0.1	0.2	100.0	0.3	0.2	-0.4	-0.3	-0.1	-1.0	-2.8	-15.0
JET_Pileup_RhoTopology	-5.6	2.0	0.0	2.9	0.7	0.1	0.2	0.6	-0.1	0.3	100.0	0.2	-1.2	0.2	-0.6	-3.1	-17.0	-36.1
ren scale ttW	-0.1	0.8	-0.0	1.0	0.2	0.0	-0.0	0.3	-0.1	0.2	0.2	100.0	-0.4	0.6	-0.4	-0.5	-0.7	50.4
ren scale ttbar	-0.8	1.8	-0.1	0.2	-0.1	-0.4	-0.5	-1.1	0.5	-0.4	-1.2	-0.4	100.0	-0.3	-0.9	-0.8	28.5	7.1
otherTop cross-section	-11.4	-0.0	0.1	0.5	0.1	-0.3	-0.2	-0.1	0.9	-0.3	0.2	0.6	-0.3	100.0	-0.1	-0.7	-16.8	-33.3
ttW_ME	-8.5	3.1	-0.1	3.1	0.6	-0.3	-0.5	-0.9	0.7	-0.1	-0.6	-0.4	-0.9	-0.1	100.0	-1.3	12.6	-23.0
tt_other cross-section	-10.2	1.7	-0.1	2.3	0.5	-0.5	-1.3	-2.7	0.7	-1.0	-3.1	-0.5	-0.8	-0.7	-1.3	100.0	-10.6	-4.3
$k(t\bar{t}$fake_HF) (mu)	5.3	53.1	-0.6	15.7	-15.9	-4.7	-6.5	-19.5	5.4	-2.8	-17.0	-0.7	28.5	-16.8	12.6	-10.6	100.0	11.6
$k(t\bar{t}$W)	12.7	-6.6	11.4	-10.4	-3.4	-12.8	-13.2	-35.1	15.8	-15.0	-36.1	50.4	7.1	-33.3	-23.0	-4.3	11.6	100.0

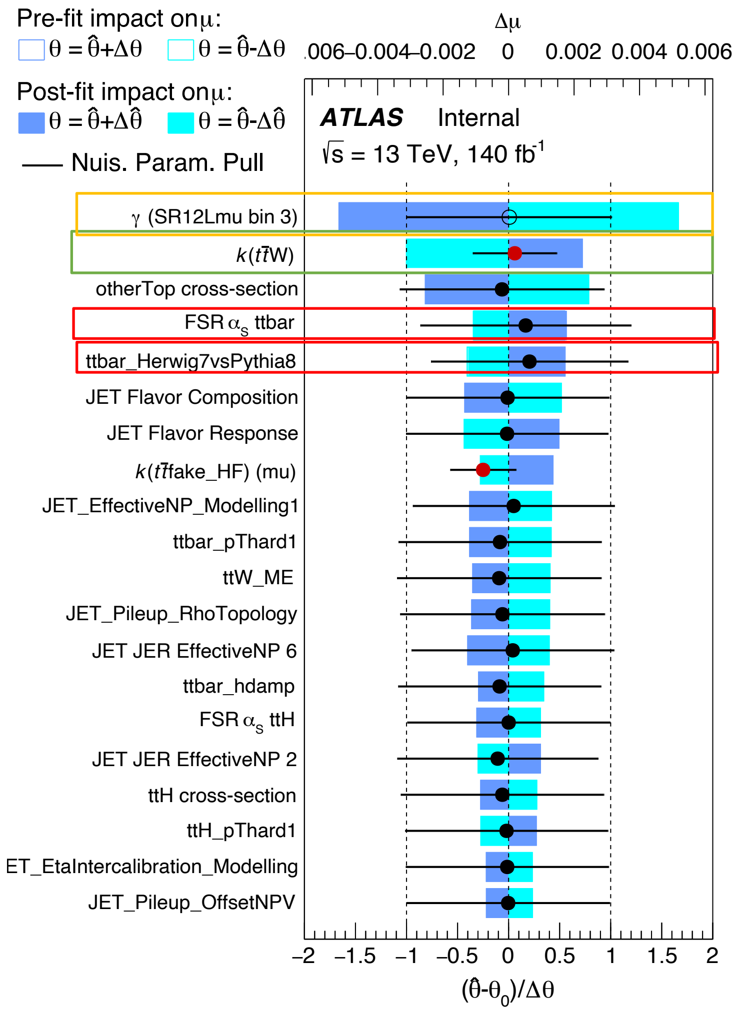
✓ The $t\bar{t}$ related modeling uncertainties and NFs contribute significantly to high correlation.

Data fit results (Ranking)

Data fit ee channel



Data fit $\mu\mu$ channel



- ✓ The dominant NPs come from the $t\bar{t}$ related modeling uncertainties, NFs and Gammas.
- ✓ These NPs consistently contribute significantly to high correlation.
- ✓ The ranking results also exhibit consistency between the Realistic and data fits.

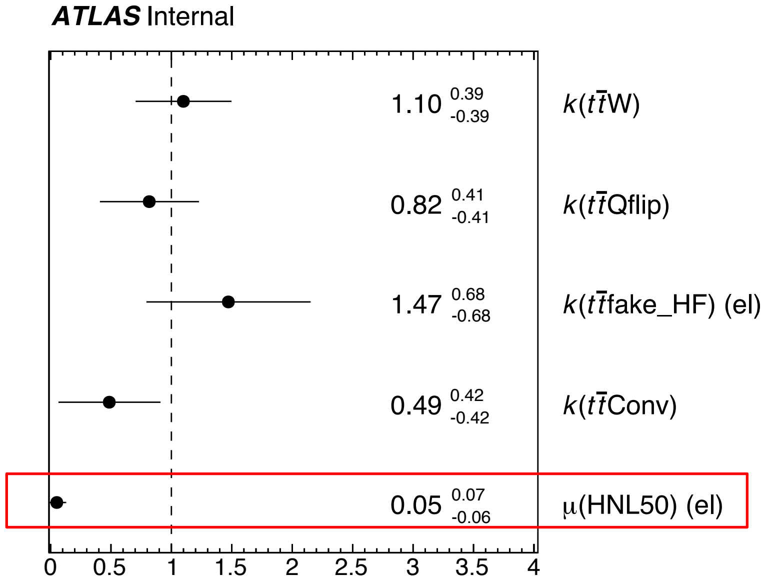
Conclusion from the unblinded fit

Overall:

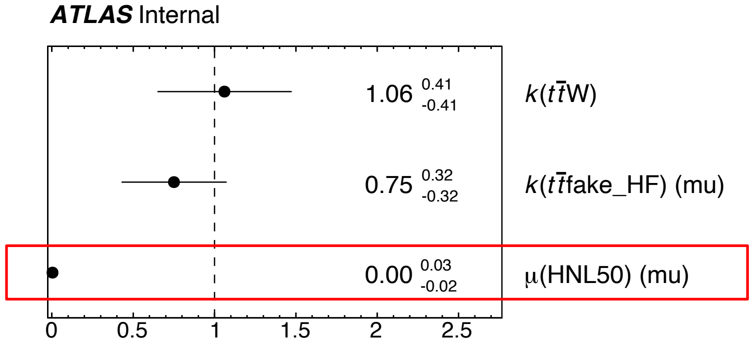
✓No pulls/constraints issues are observed

✓The data fit results (Correlation matrix, pulls, ranking, NFs) are consistent with the blinded fit

✓Post-fit signal normalizations are compatible with Zero

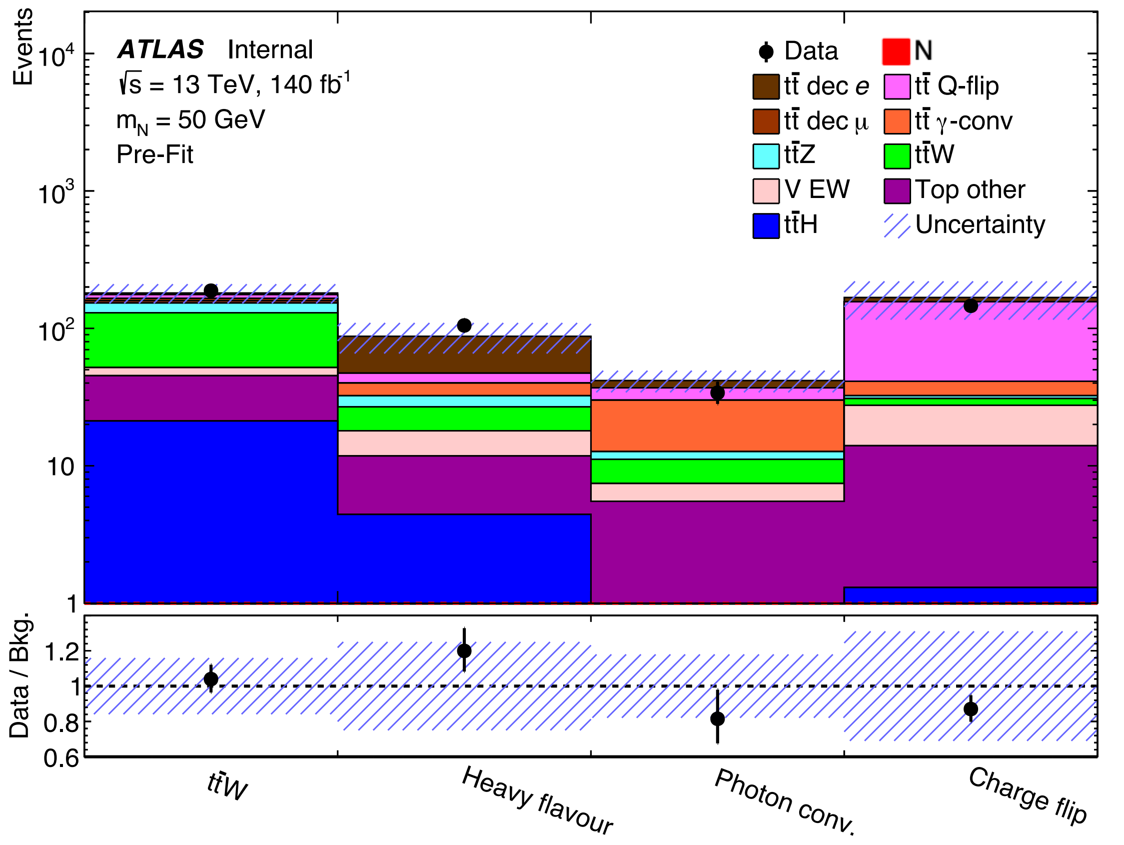


Data fit ee channel

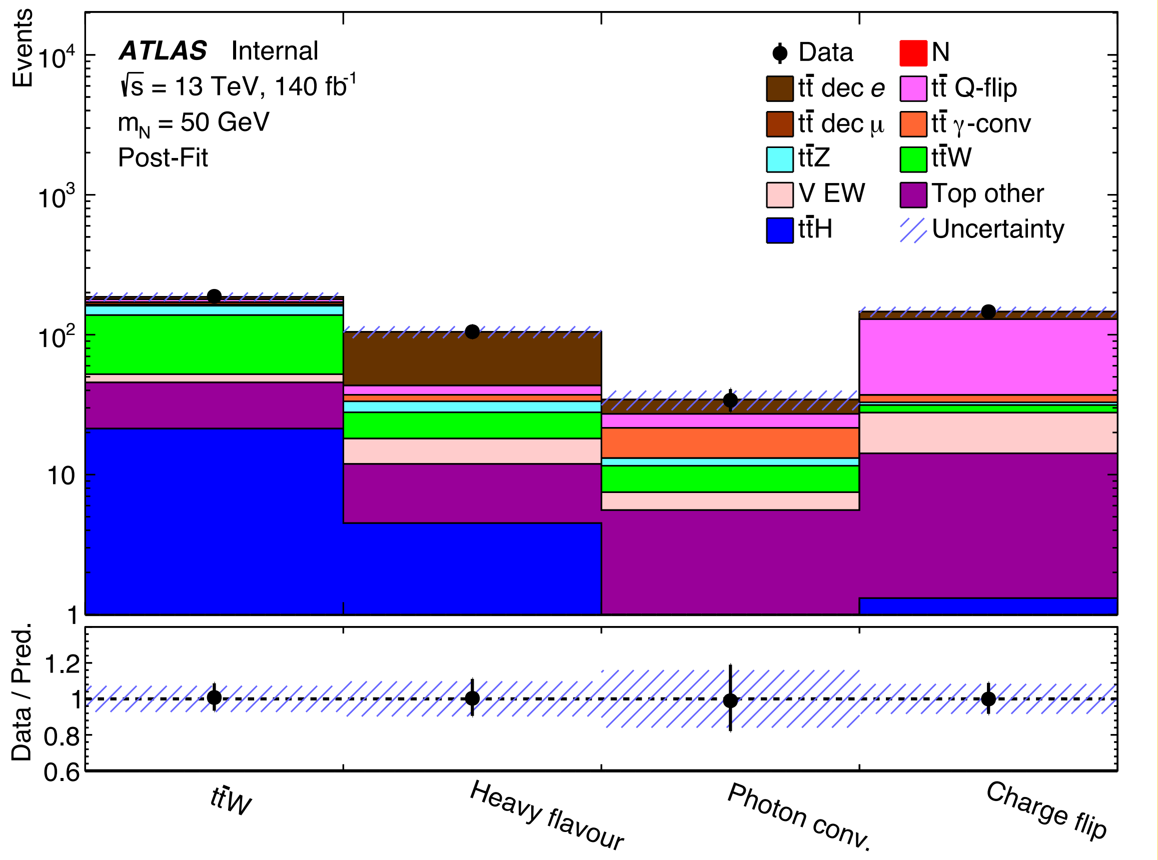


Data fit $\mu\mu$ channel

Unblinded fit in CRs of *ee* channel

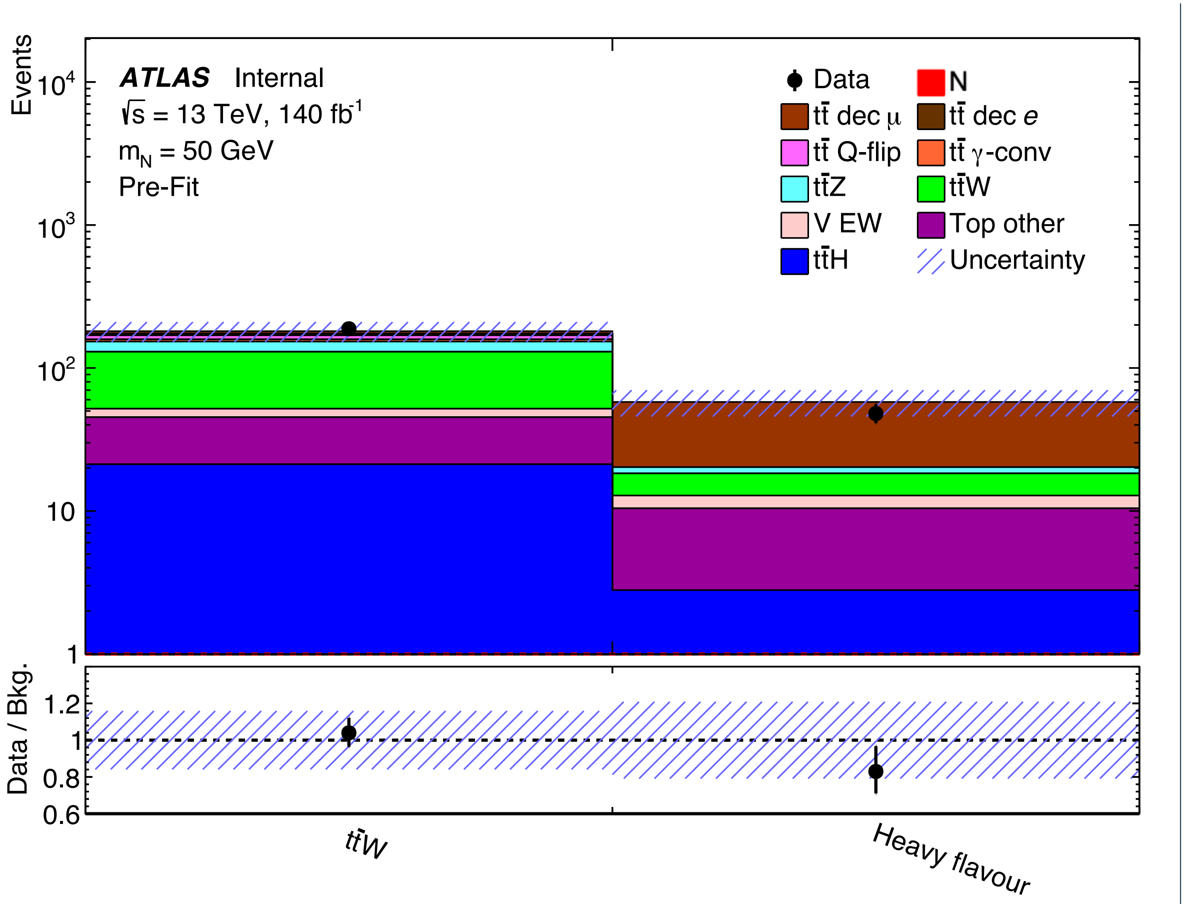


Pre-fit

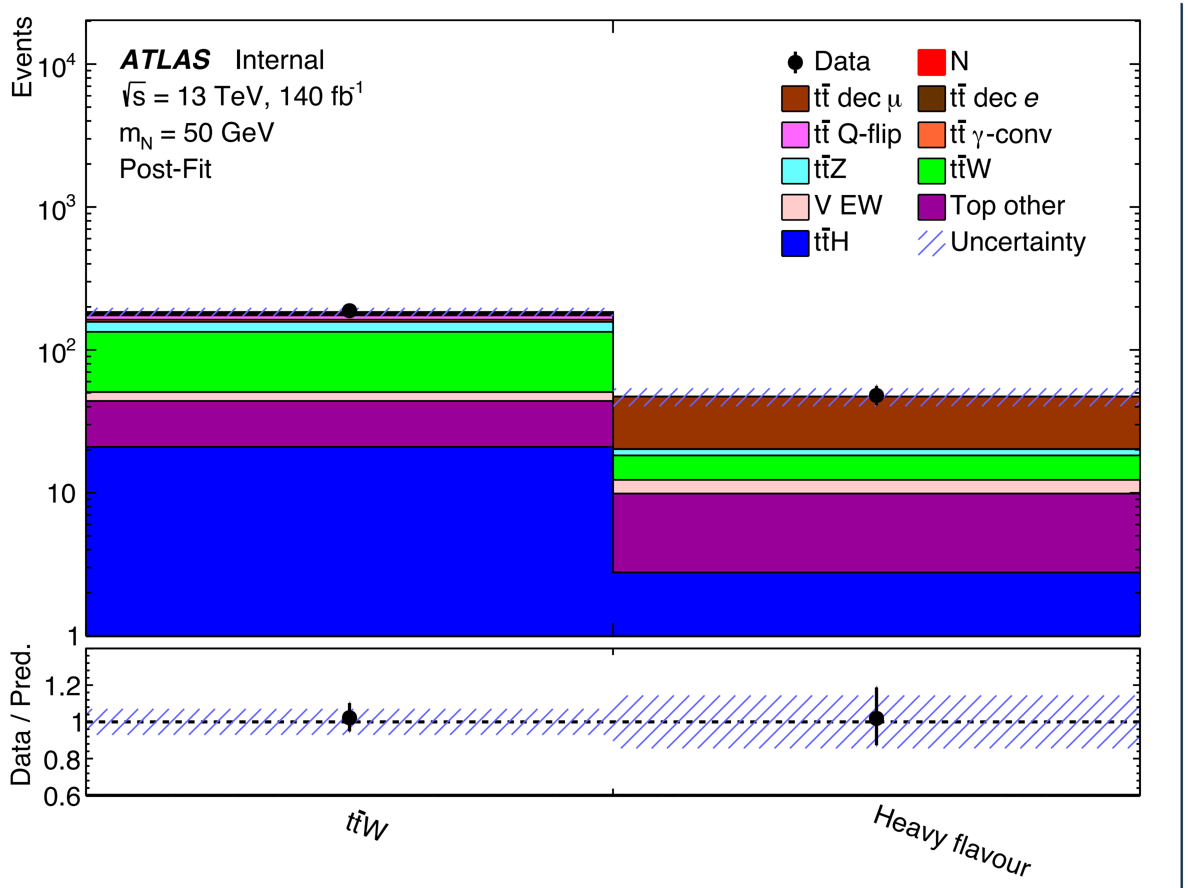


Post-fit

Unblinded fit in CRs of $\mu\mu$ channel



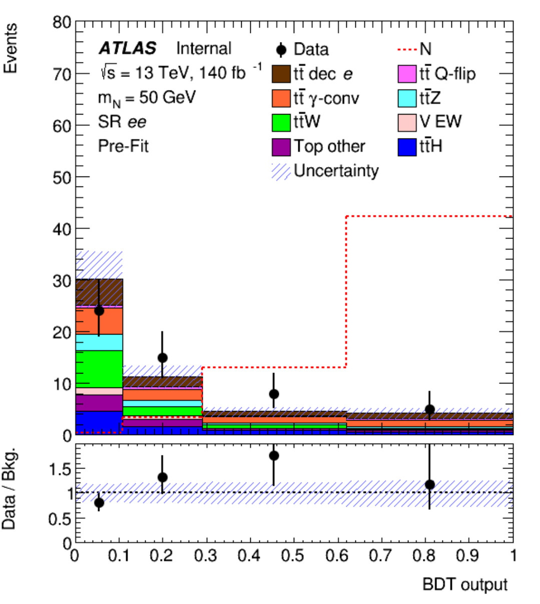
Pre-fit



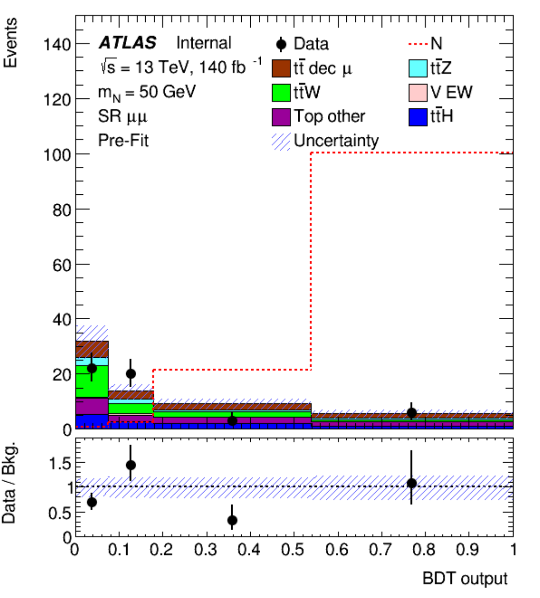
Post-fit

Unblinded fit in SRs (50 GeV)

SR ee



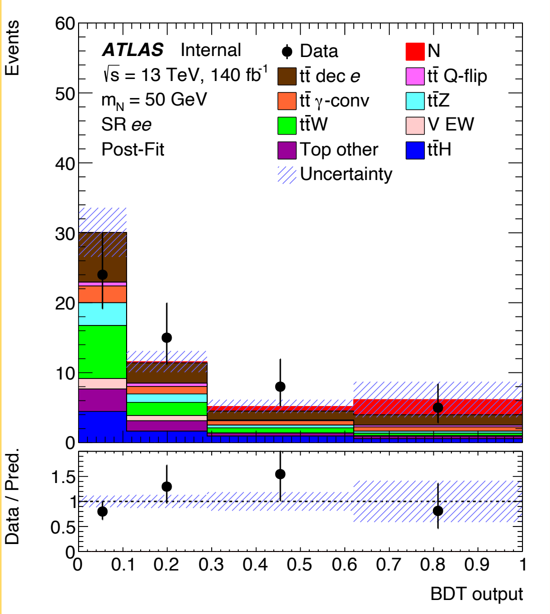
SR $\mu\mu$



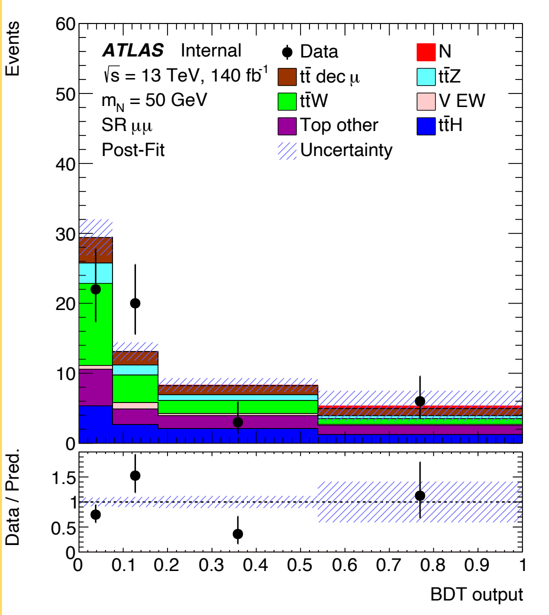
Pre-fit

Signal cross sections are normalized to 0.05 pb for visual purposes

SR ee



SR $\mu\mu$



Post-fit

Tau channel reinterpretation

Results in ee/$\mu\mu$ are reinterpreted to search for N3, assuming same-flavour decay of both tau leptons

Tau channel reinterpretation

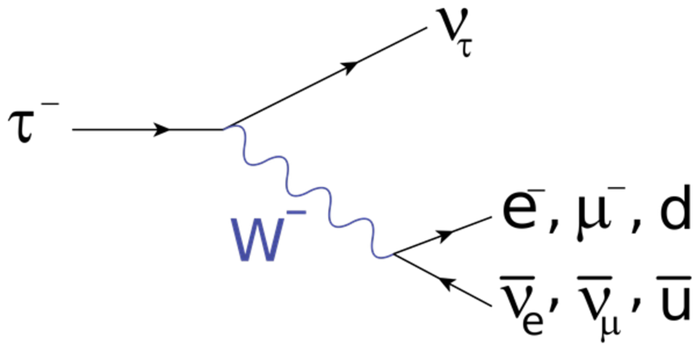
Motivation

- ✓ $\tau_{lep}\tau_{lep}$ presents the opportunity to reinterpret main analysis for $V_{\tau,N3}$ mixing
- ✓ Branching ratio is ~ 6%, signal introduces MET from tau decay

$$v_{mix} = \begin{pmatrix} V_{e,N1} & 0 & 0 \\ 0 & V_{\mu,N2} & 0 \\ 0 & 0 & \boxed{V_{\tau,N3}} \end{pmatrix}$$

$\boldsymbol{\tau_{lep}\tau_{lep}}$ reinterpretation strategy:

- ✓ Same signal model but with $\tau\tau$ final state
- ✓ Same analysis regions
- ✓ Reutilized ee/mm BDTs

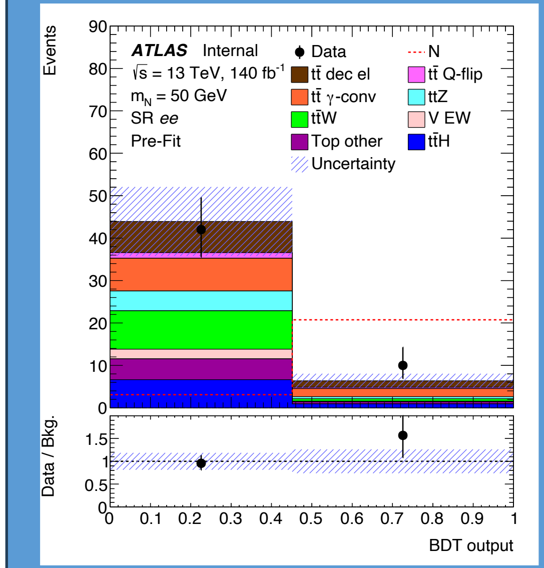


Statistical treatment

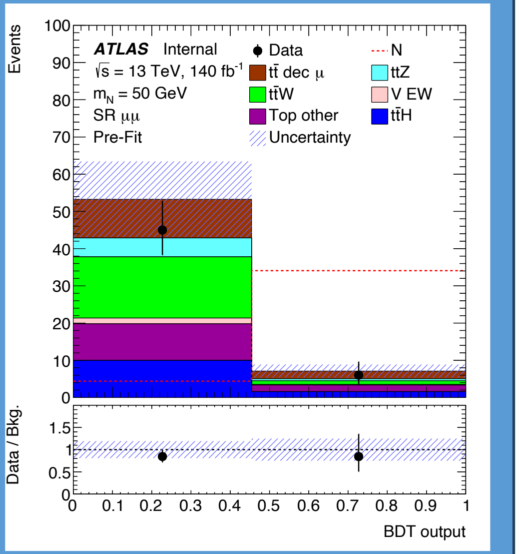
- ✓ Combined fit performed in ee and mm analysis regions

Unblinded fit for tau reinterpretation

SR $\tau\tau \rightarrow ee$

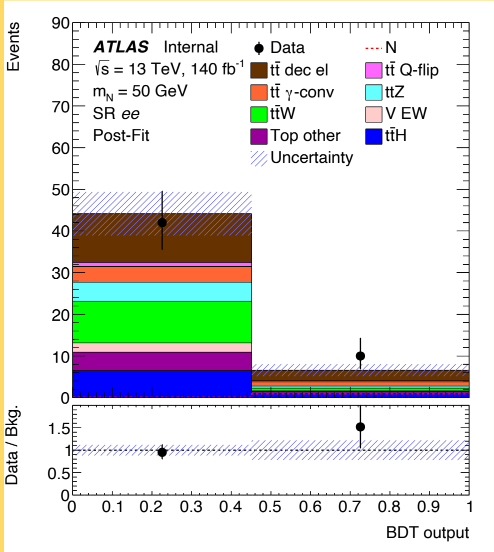


SR $\tau\tau \rightarrow \mu\mu$

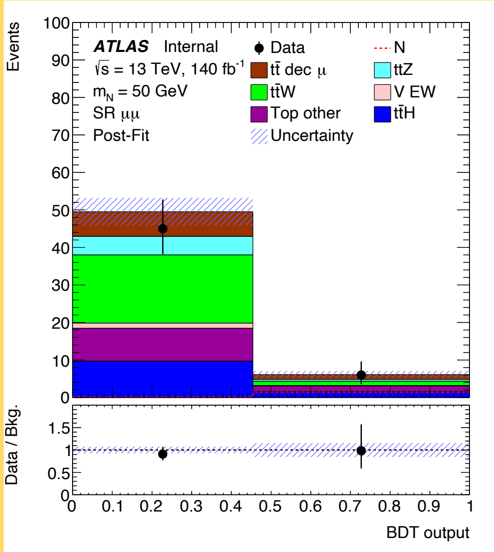


Pre-fit

SR $\tau\tau \rightarrow ee$



SR $\tau\tau \rightarrow \mu\mu$



Post-fit