Lepton Number Violation searches in ATLAS

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Theory Motivations

With $M\nu>0$, neutrino oscillations could produce Lepton Number Violation → If the origin of LNV is **only** due to SM neutrinos oscillations, rate of LNV is extremely small at colliders (undetectable)
Lepton Number (and Flavor) is not related to a gauge symmetry=> why conserved?
→ Any observation of LNV at colliders will be a clear signal of physics Beyond Standard Model

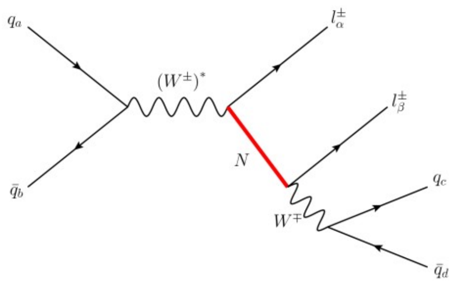
→ Lepton Number Violation **is a portal** to New Physics at colliders

Signatures at LHC

A “natural” way to produce neutrino masses is through SeeSaw mechanism. If neutrino is Majorana → Lepton Number Violation

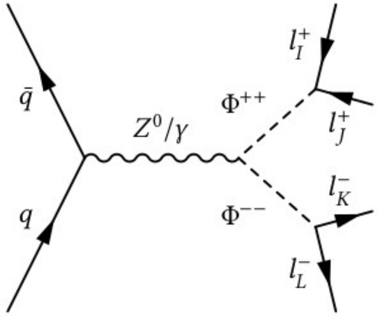
Type-I

Weak fermion singlet (N_R) coupled with W-boson



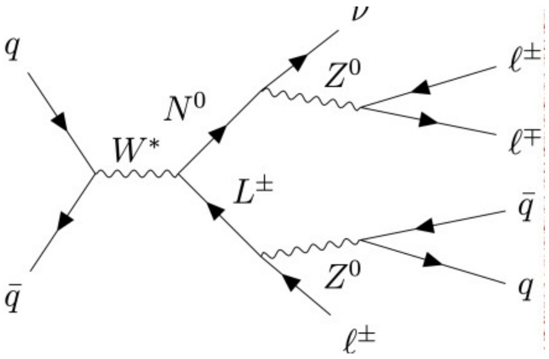
Type-II

Scalar (L and R) triplet



Type-III

Fermionic triplet



ATLAS analysis in 2 slides: 1

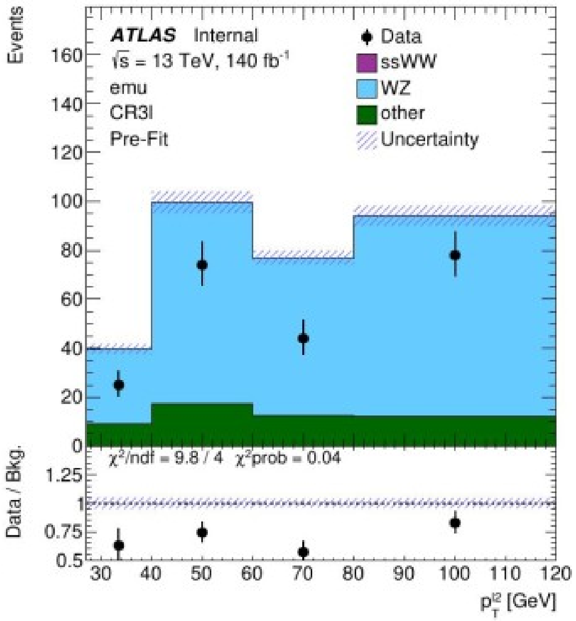
Identify objects, count (number of leptons/jets) and measure (momentum)
Composite or global objects (MET, jet substructure)

Optimize search:
Choose cut & count or advanced stat analysis (MVA), choice of the discriminating variable → Signal Region(s) (**SR**)

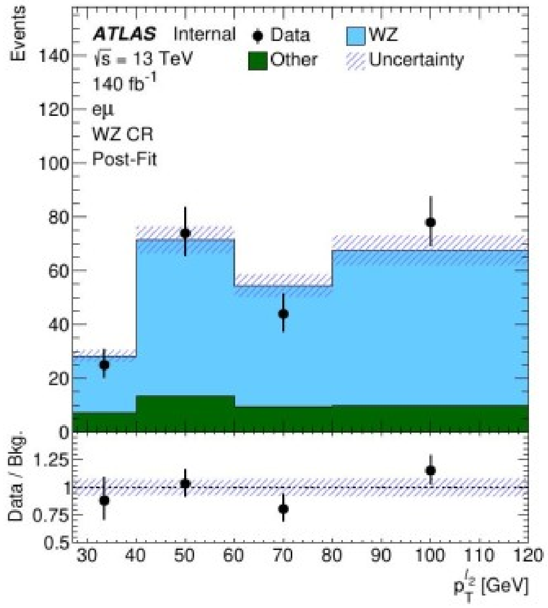
Reducible backgrounds
SM processes with fianl states different from signal
Fake leptons, Fake Etmiss → Data driven estimates
Method validation in Validation Regions (**VR**)

Irreducible Backgrounds
From SM processes that mimic the process
Often in peculiar phase spaces → MC normalized to data in bkg enhanced control regions (**CR**)
Validation in VR → Extrapolation to SR

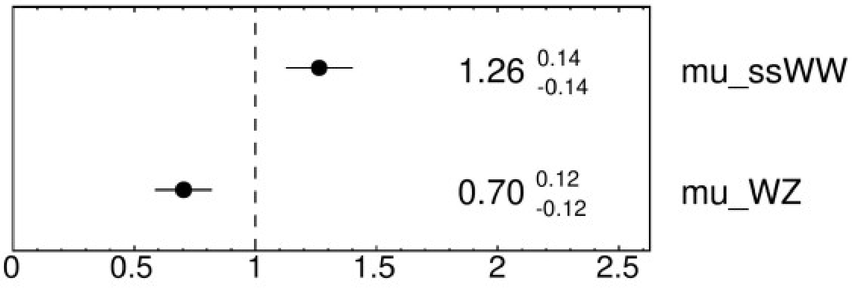
Combined Fit
CR + SR on the discriminating variable to get number of events for the contribution of each process



Pre/Post Fit



For educational purposes only

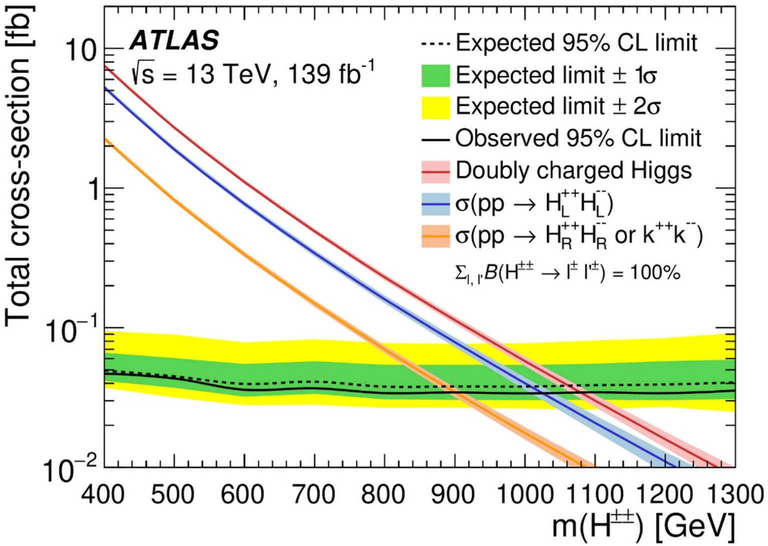


Background normalization

ATLAS analysis in 2 slides: 2

Two possibilities

Significant excess over SM bkg → Evidence

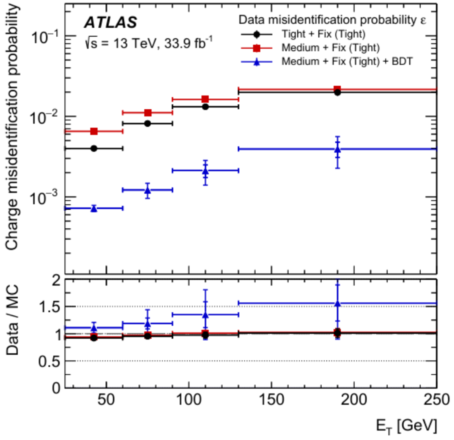


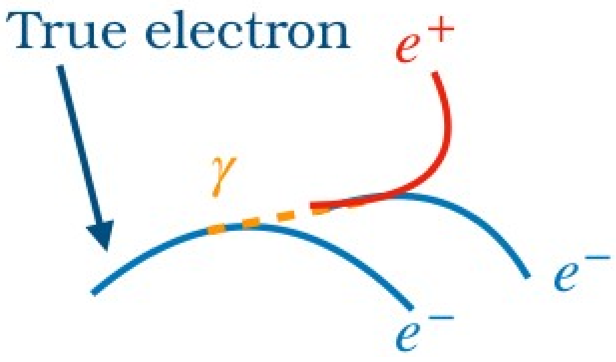
Exclusion limits

One fundamental ingredient in most LNV analysis

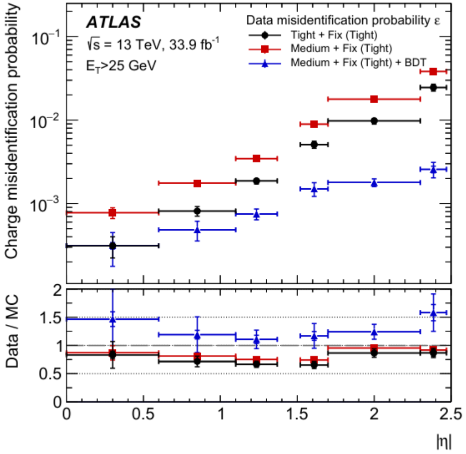
Same sign lepton pairs are generally suppressed in SM processes. However electrons have non negligible probability to be reconstructed with a “wrong” charge.

Not well modeled by simulation → Needs to be data driven





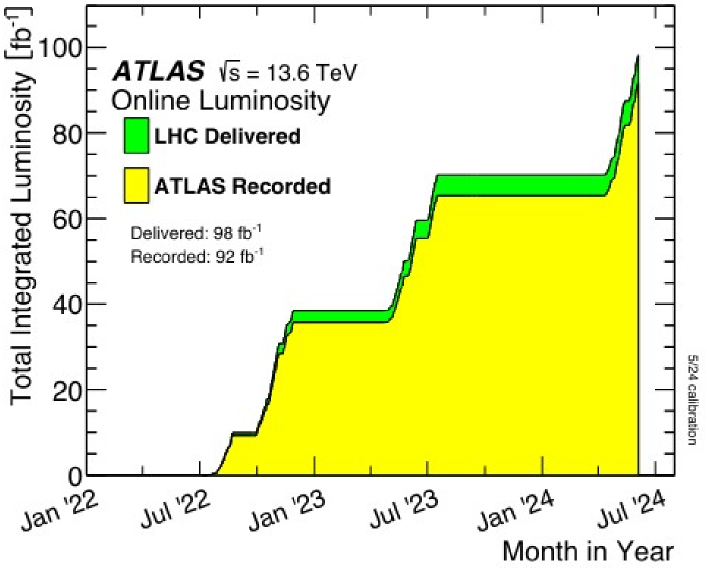
Additional BDT selection to increase “purity” of right sign electron(positron)

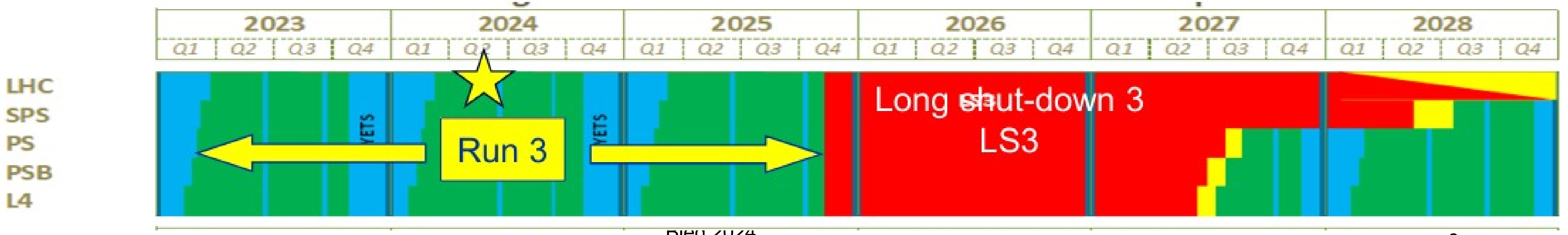


From EPJC 79 (2019) 639

ATLAS Run3

- Third year of Run3 data taking √s=13.6 TeV
- 98 fb^{-1} already collected
- To be added to 140 fb^{-1} of Run2 at √s=13 TeV
- All results presented here are Run2 based





Recent LNV searches in ATLAS

- HNL in VBS scattering → this talk https://arxiv.org/abs/2403.15016
- ~~HNL in tt decays (if approved)~~
- HNL prompt and displaced → this talk JHEP 10 (2019) 265 (Displaced + prompt) PRL 131 (2023) 061803 (Displaced)
- Right Handed Neutrino (and W_R) → this talk EPJC 83 (2023) 1164
- Double Charged Higgs (Type II Seesaw) → cf Blaz talk (Eur. Phys. J. C 83 (2023) 605)
- Type III SeeSaw cf Jernei and Lara talks (Eur. Phys. J C 81 (2021) 218 and Eur. Phys J. C 82 (2022) 988)

Additional BSM sector (Z', W_R, ...)

- HNL in VBS scattering https://arxiv.org/abs/2403.15016
- ~~HNL in tt decays (if approved)~~
- HNL prompt and displaced JHEP 10 (2019) 265 (Displaced + prompt) PRL 131 (2023) 061803 (Displaced)
- Right Handed Neutrino (and W_R) EPJC 83 (2023) 1164

Heavy Neutrino in Vecton Boson Scattering

Vector Boson Scattering Topology.
Outgoing quarks identified as jets with large rapidity gap
M_{jj}>500 GeV and $\Delta(y_i y_j)$>2
ee, μe and μμ final states
→ ee complementary at 0νββ
→ μe and μμ at colliders **only**

Phenomenological type I seesaw model
Mν = 50 GeV - 25 TeV
Introduces right-handed HNL

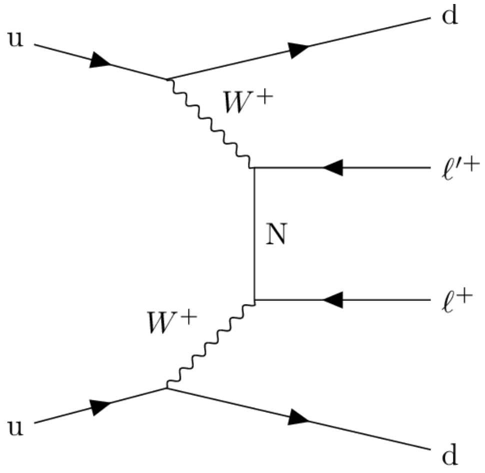
$$\sigma \propto \left|V_{eN}\right|^4$$

ee channel

$$\sigma \propto \left|V_{eN}V^*_{\mu N}\right|^2$$

eμ channel

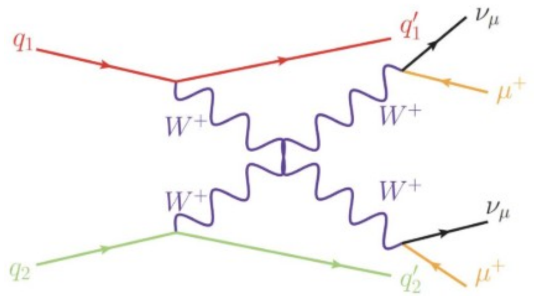
Submitted to Phys Lett B
https://arxiv.org/abs/2403.15016 (ee and eμ)
EPJC 83 (2023) 824 (μμ)



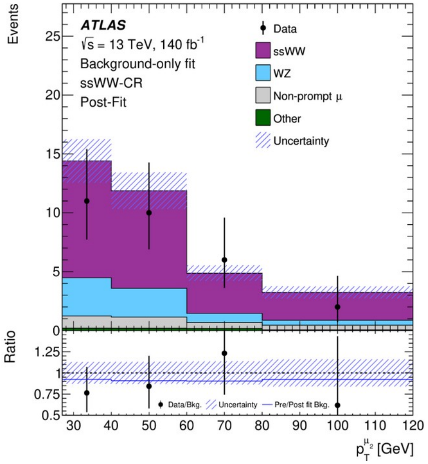
Results interpreted also as limits on 5th order Weimberg operator

$$\mathcal{L}_5 = \frac{C_5^{\ell\ell'}}{\Lambda}\left[\Phi \cdot \bar{L}_\ell^c\right]\left[L_{\ell'} \cdot \Phi\right] + \text{h.c.}$$

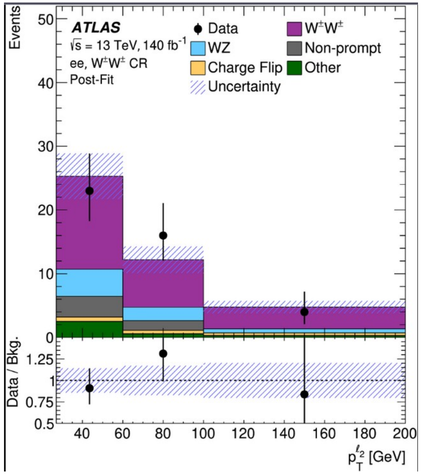
Heavy Neutrino in Vecton Boson Scattering

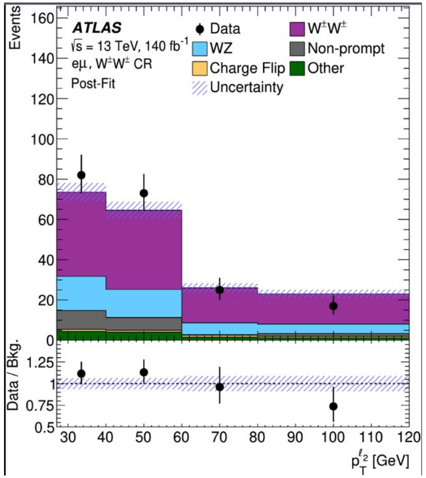


Main background is ssWW

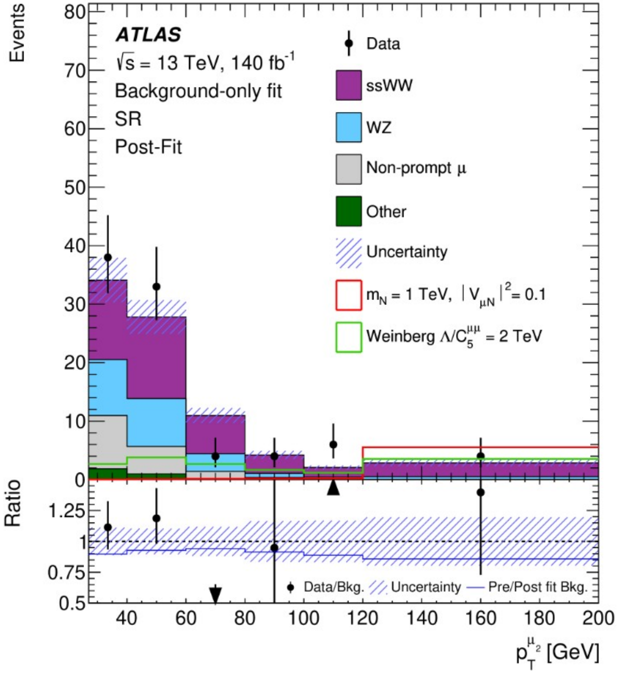


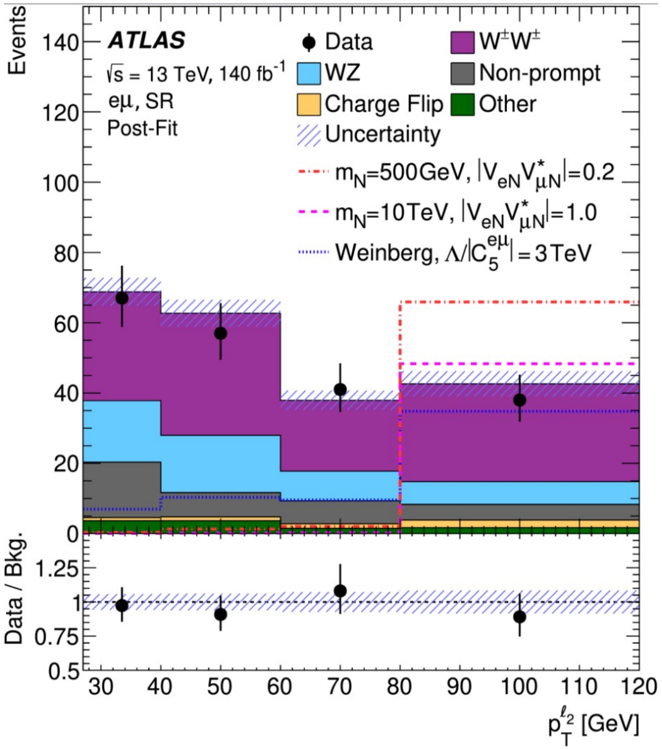
μμ channel

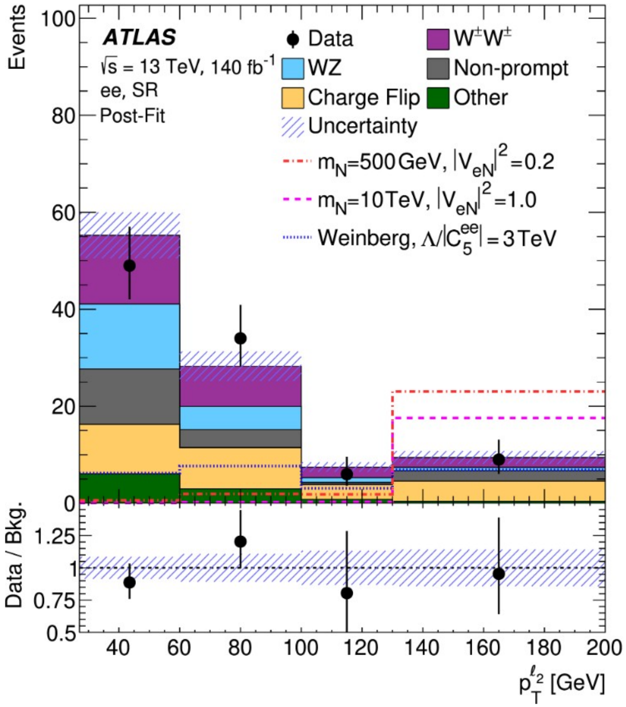


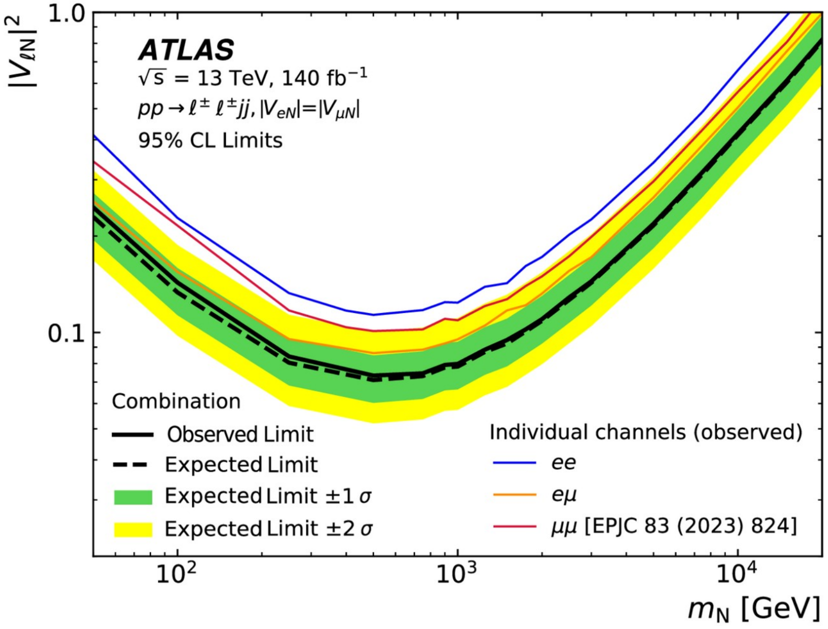


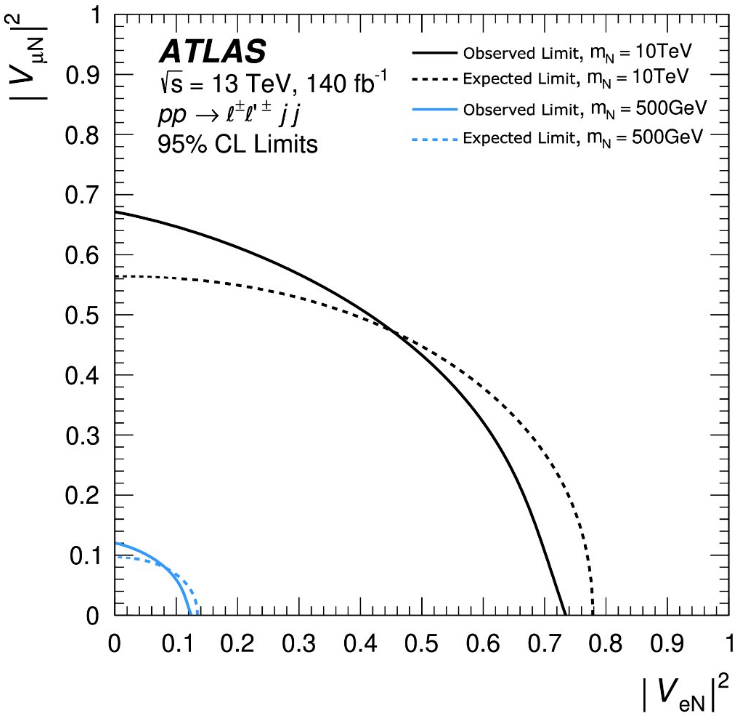
- ee and μμ channel SR based on MET significance (σ(MET)<4.5)
- μe channel (Δφ>2)


ATLAS
√s = 13 TeV, 140 fb-1
Background-only fit
SR
Post-Fit
Data
ssWW
WZ
Non-prompt μ
Other
Uncertainty
m_N = 1 TeV, |V_μN|^2 = 0.1
Weinberg Λ/C_5^μμ = 2 TeV
Events
Ratio
Data/Bkg.
Uncertainty
Pre/Post fit Bkg.
p_T^μ2 [GeV]

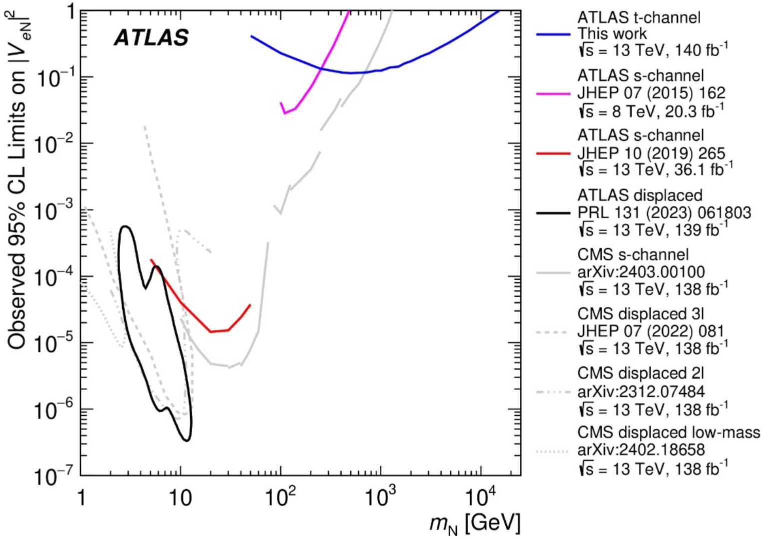

ATLAS
√s = 13 TeV, 140 fb-1
eμ, SR
Post-Fit
Data
W±W±
WZ
Non-prompt
Charge Flip
Other
Uncertainty
m_N=500GeV, |V_eN V*_μN|=0.2
m_N=10TeV, |V_eN V*_μN|=1.0
Weinberg, Λ/|C_5^eμ| = 3TeV
Events
Data / Bkg.
p_T^ℓ2 [GeV]


ATLAS
√s = 13 TeV, 140 fb-1
ee, SR
Post-Fit
Data
W±W±
WZ
Non-prompt
Charge Flip
Other
Uncertainty
m_N=500GeV, |V_eN|^2=0.2
m_N=10TeV, |V_eN|^2=1.0
Weinberg, Λ/|C_5^ee| = 3TeV
Events
Data / Bkg.
p_T^ℓ2 [GeV]

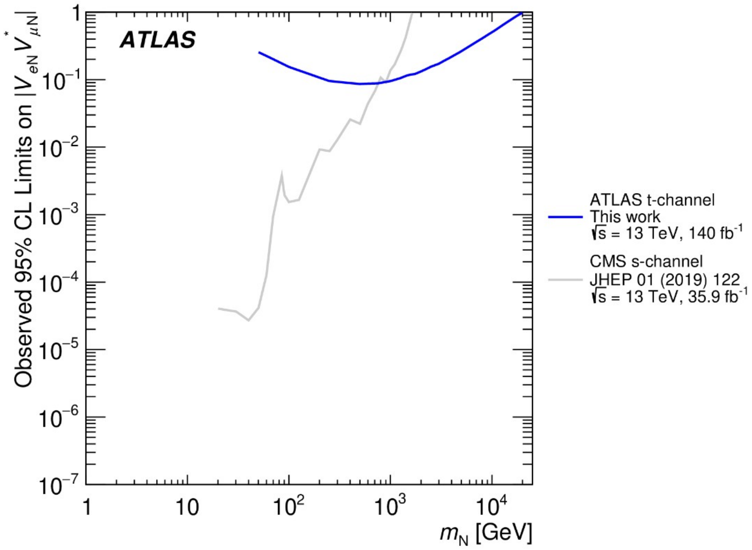

ATLAS
√s = 13 TeV, 140 fb⁻¹
pp → ℓ± ℓ± jj, |V_eN|=|V_μN|
95% CL Limits
Combination
Observed Limit
Expected Limit
Expected Limit ±1 σ
Expected Limit ±2 σ
Individual channels (observed)
ee
eμ
μμ [EPJC 83 (2023) 824]
|V_ℓN|²
m_N [GeV]

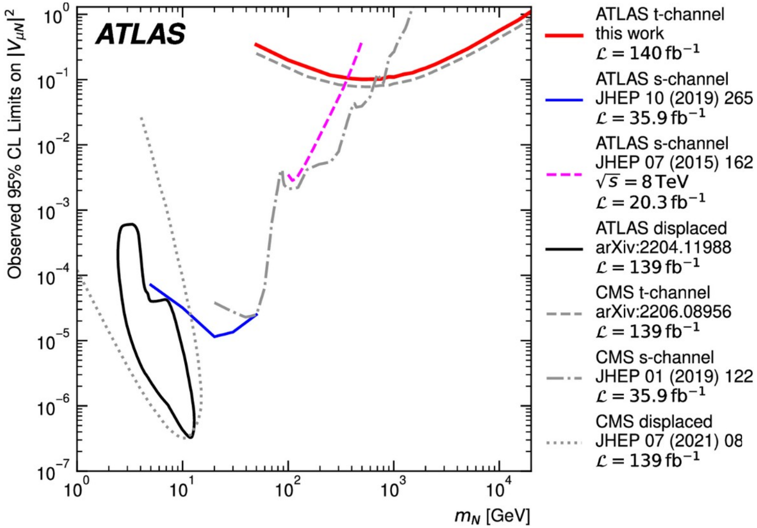

ATLAS
√s = 13 TeV, 140 fb⁻¹
pp → ℓ±ℓ'± j j
95% CL Limits
Observed Limit, m_N = 10TeV
Expected Limit, m_N = 10TeV
Observed Limit, m_N = 500GeV
Expected Limit, m_N = 500GeV
|V_μN|²
|V_eN|²

Limits on $|V_{eN}|^2$ vs M_N



Limits on $|V_{eN}V_{\mu N}|$ vs M_N





Limits on $|V_{\mu N}|^2$ vs M_N

VBS Topology

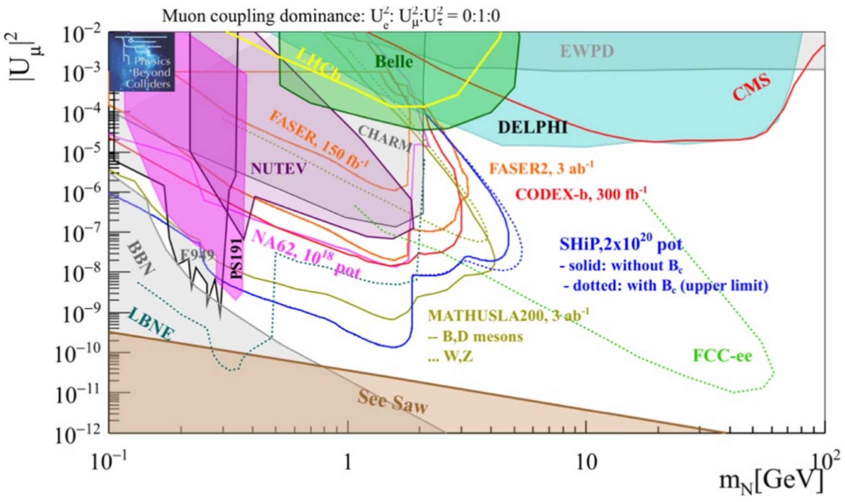
Reaches larger masses

- HNL in VBS scattering https://arxiv.org/abs/2403.15016
- ~~HNL in tt decays (if approved)~~
- HNL prompt and displaced JHEP 10 (2019) 265 (Displaced + prompt) PRL 131 (2023) 061803 (Displaced)
- Right Handed Neutrino (and W_R) EPJC 83 (2023) 1164

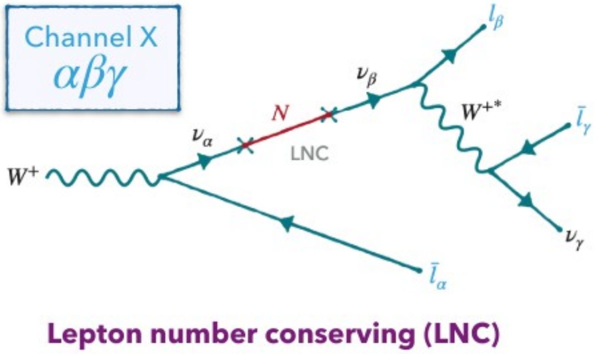
Heavy Neutral Lepton: Prompt and Displaced

JHEP 10 (2019) 265 (Displaced + prompt)
PRL 131 (2023) 061803 (Displaced)

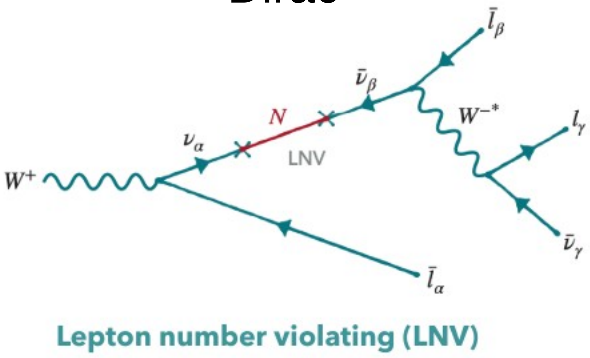
Targeting the region M_N in [3,20] GeV and $|Ua|^2$ in $[10^{-2},10^{-7}]$



From J. Phys G: Nucl Part. Phys 47 (2020) 010501



Dirac



Majorana

Heavy Neutral Lepton: Prompt and Displaced

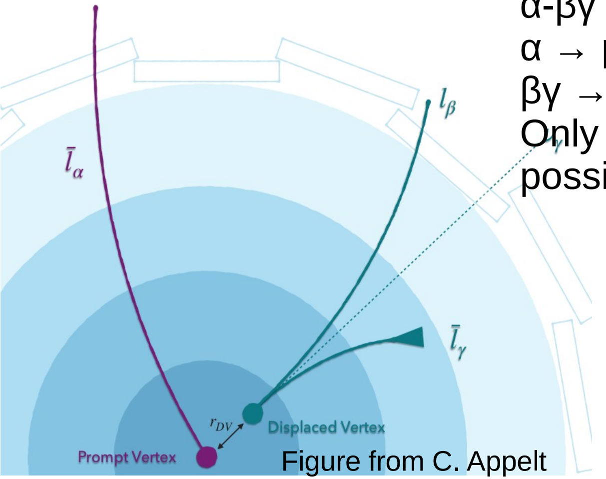
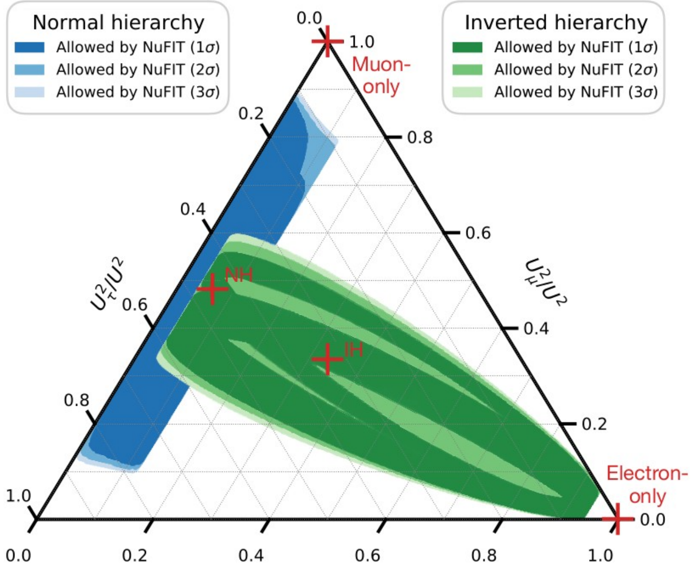


Figure from C. Appelt

α-βγ topologies
α → prompt
βγ → Displaced Vertex
Only e and μ final states → 6 possibilities (+2 if mixing flavor)



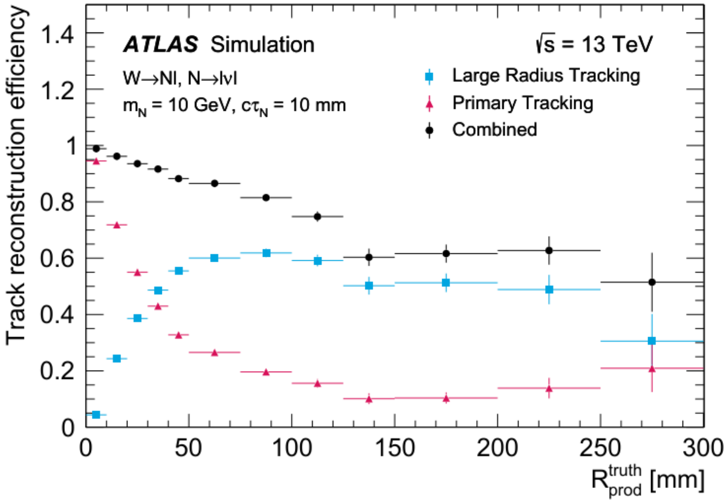
4 benchmark points (2 chosen with more realistic mixing) from Tastet, Ruchayskiy and Timiryasov (arxiv: arXiv:2107.12980)

Main discriminating variable:
HNL mass

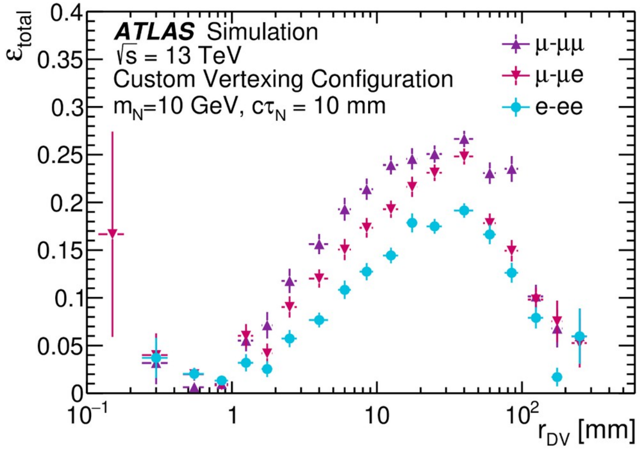
use $p_W = p_{l_\alpha} + p_{l_\beta} + p_{l_\gamma} + p_\nu$ to calculate $m^2_{HNL} = (p_{l_\beta} + p_{l_\gamma} + p_\nu)^2$

Displaced HNL

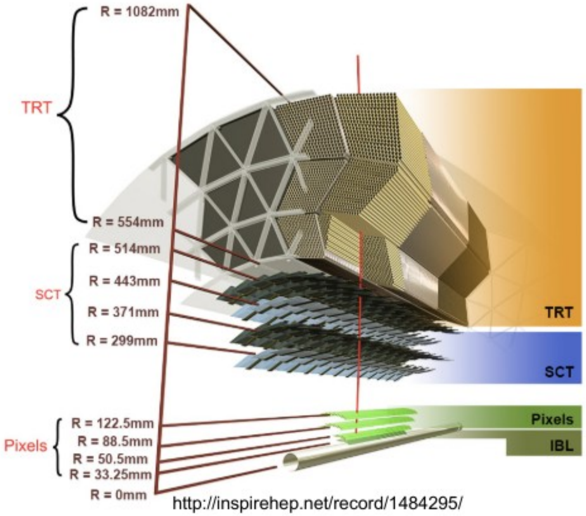
Key ingredients:



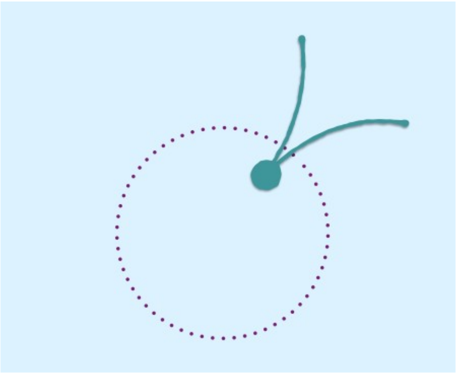
Large Radius Tracking



Displaced Vertex reconstruction



http://inspirehep.net/record/1484295/



Background Sources

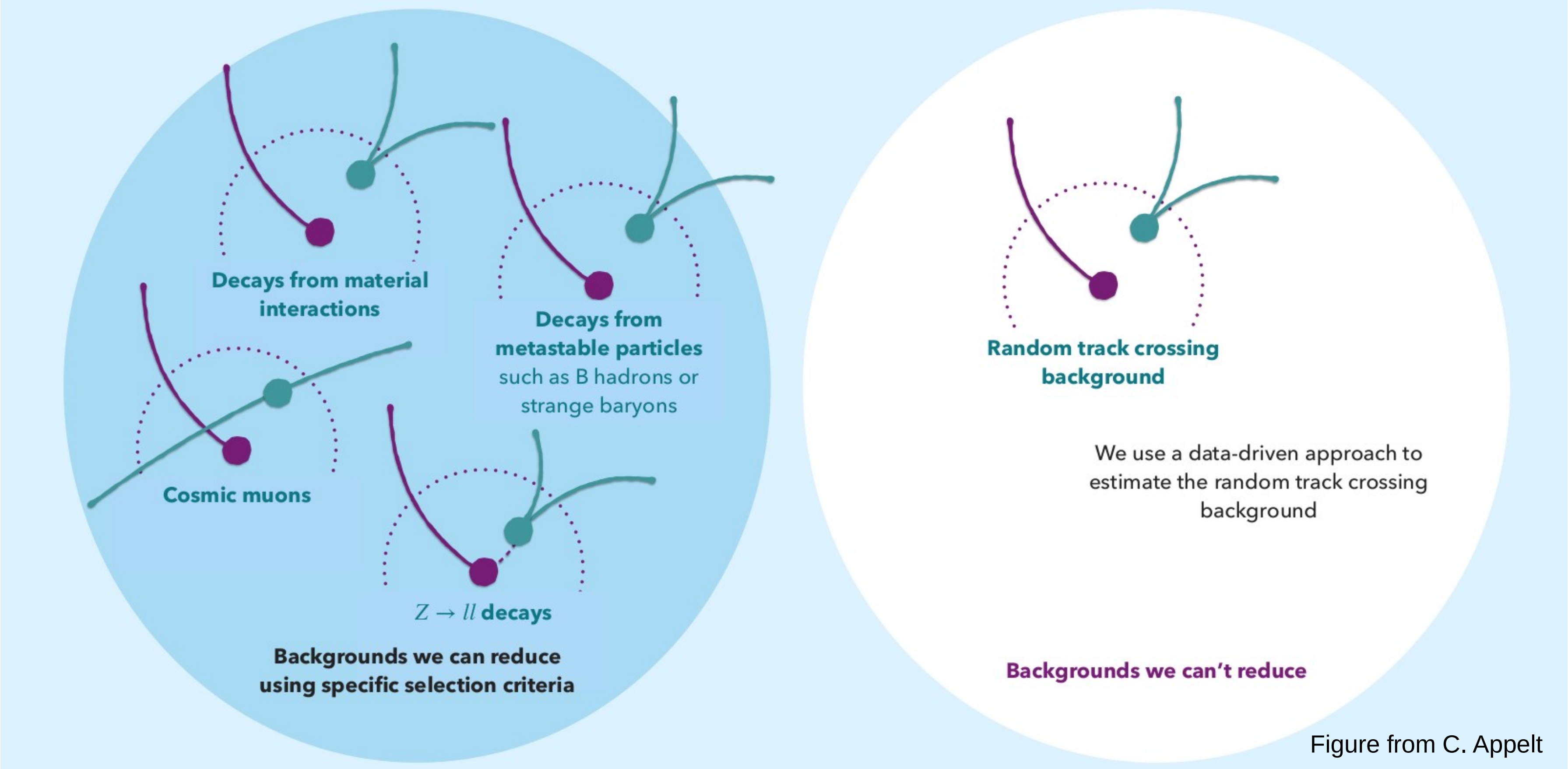
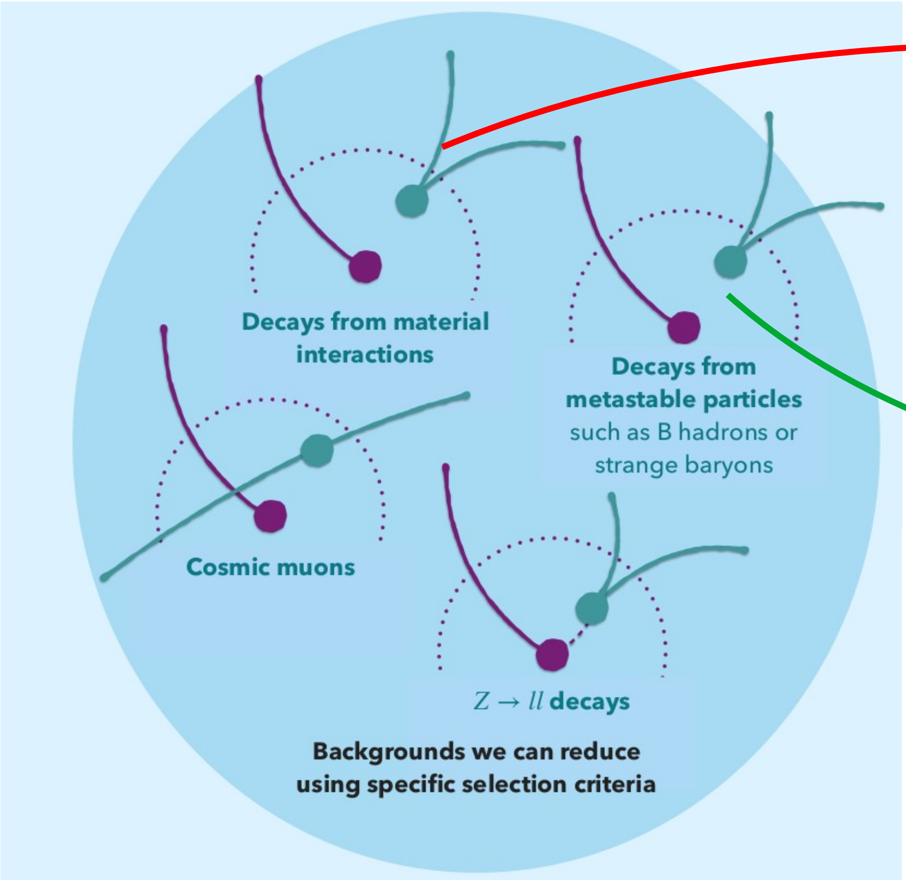
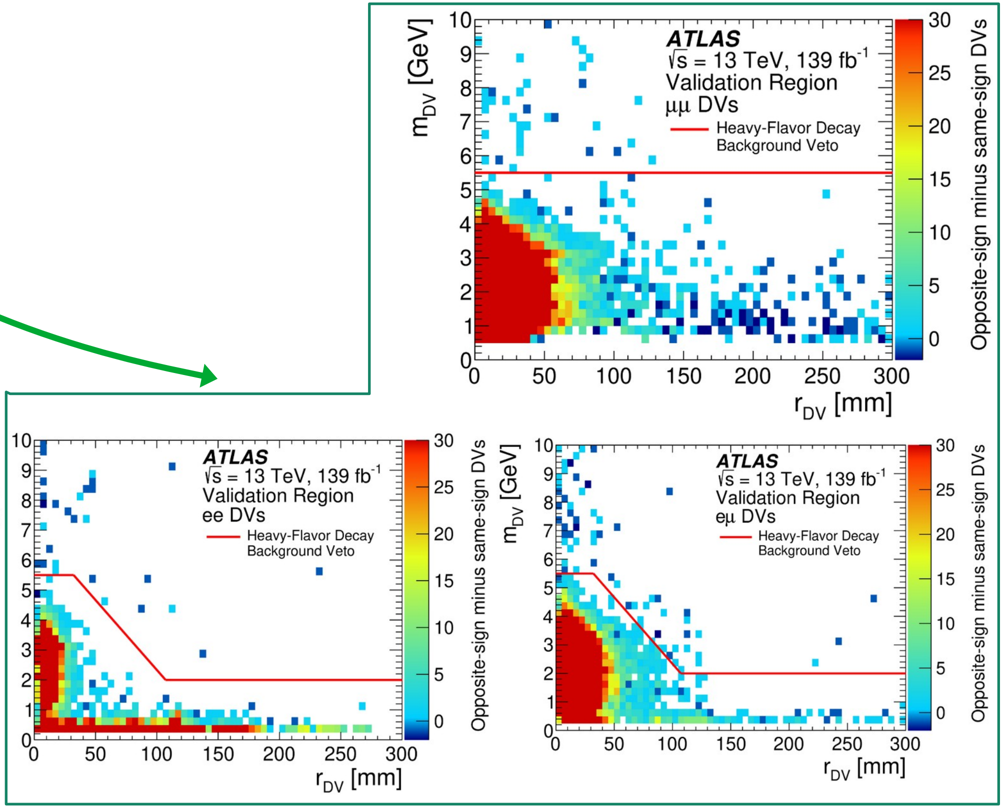


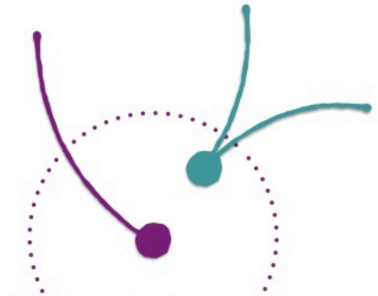
Figure from C. Appelt

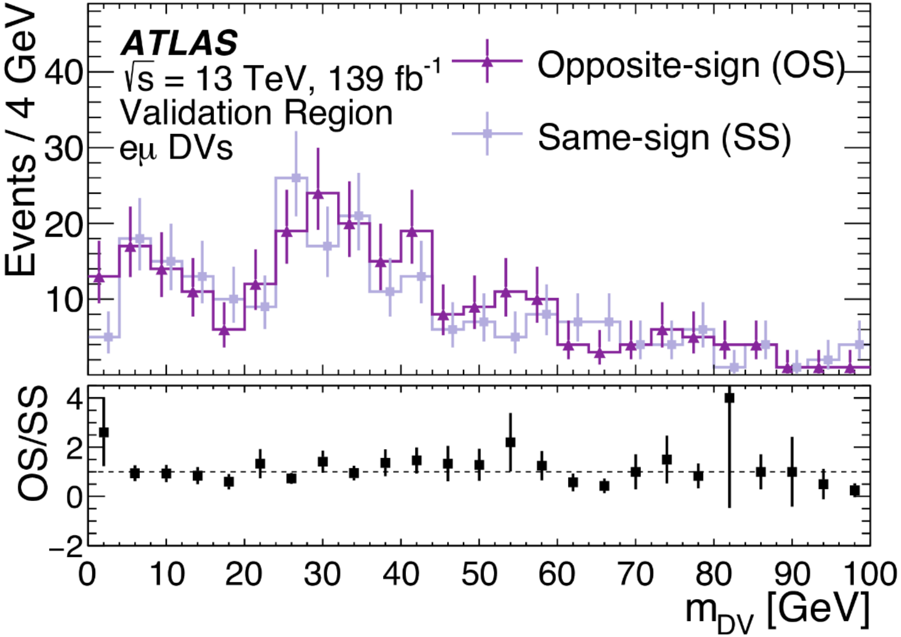
Background Sources

Material Veto (radius of material) and m_{DV}<2GeV



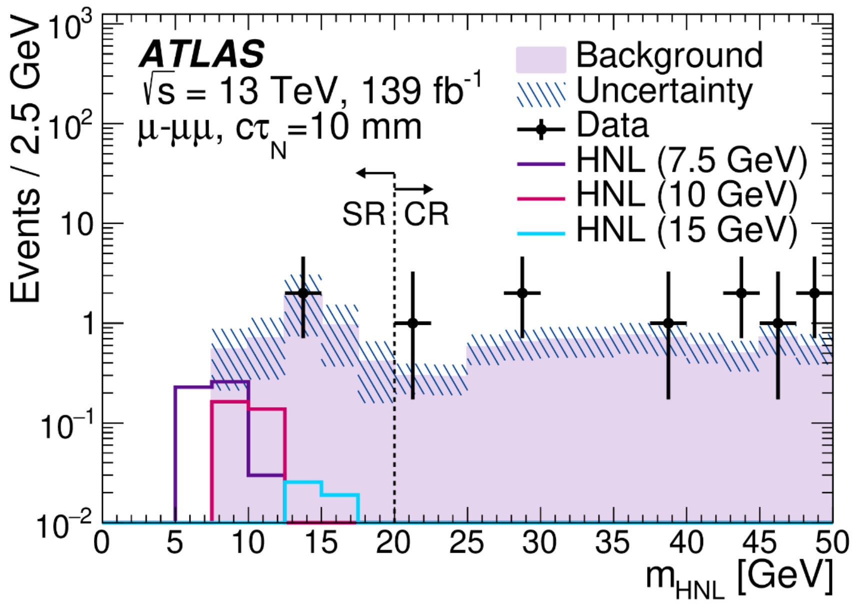


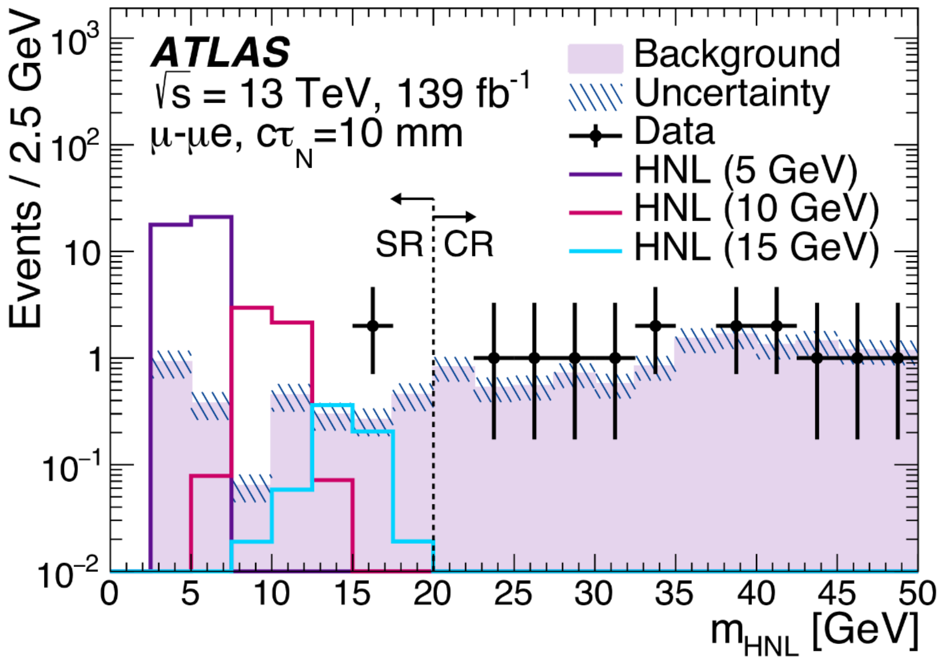




Uses data driven approach to estimate the random track crossing background (SS vs OS)
→ Uses track shuffling (from different events) to increase statistics

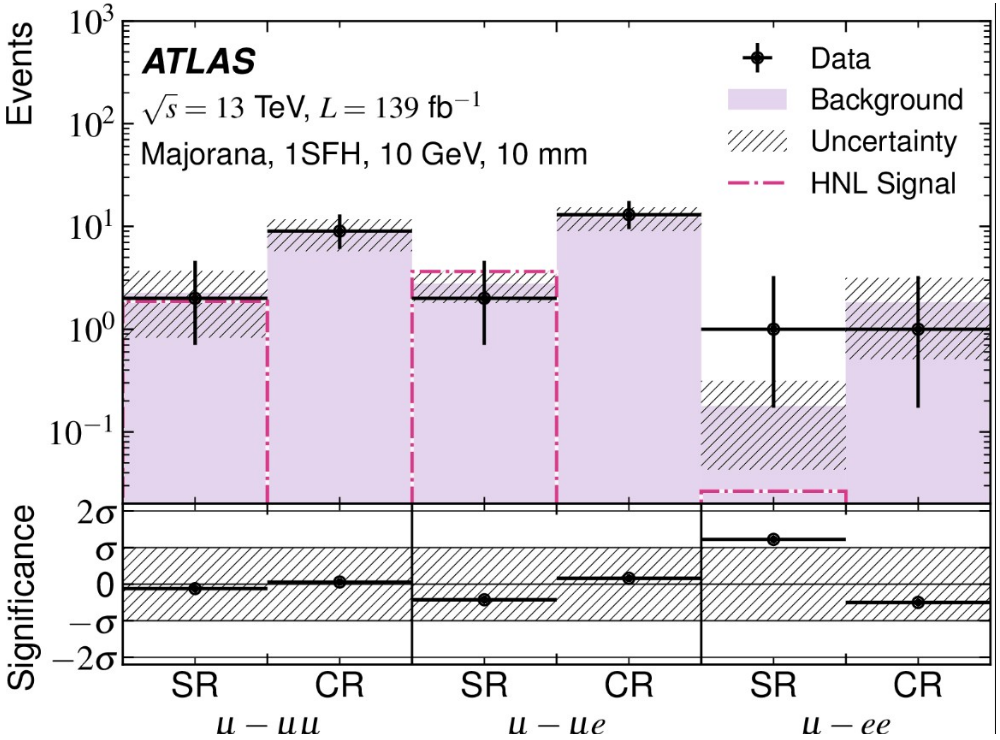
Displaced HNL: Results

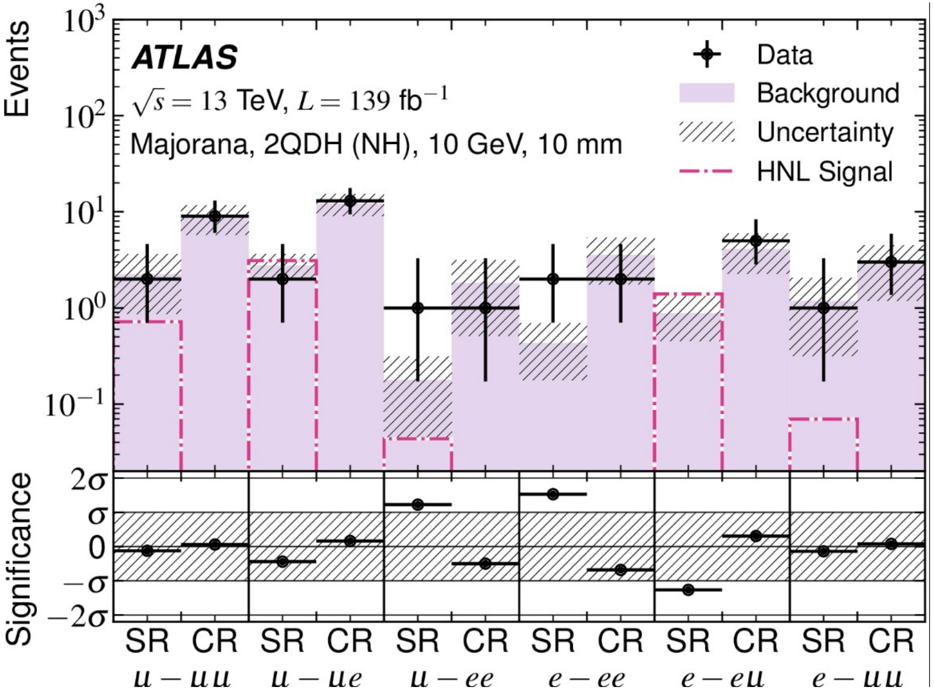




Invariant mass distribution MHNL in two out of 6(+2) channels (Signal Region and Control Region)

Displaced HNL: Results



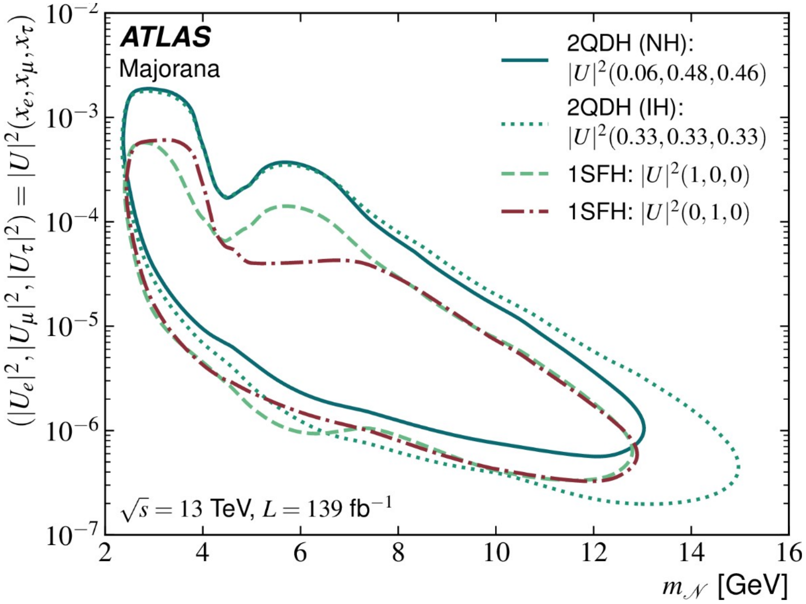


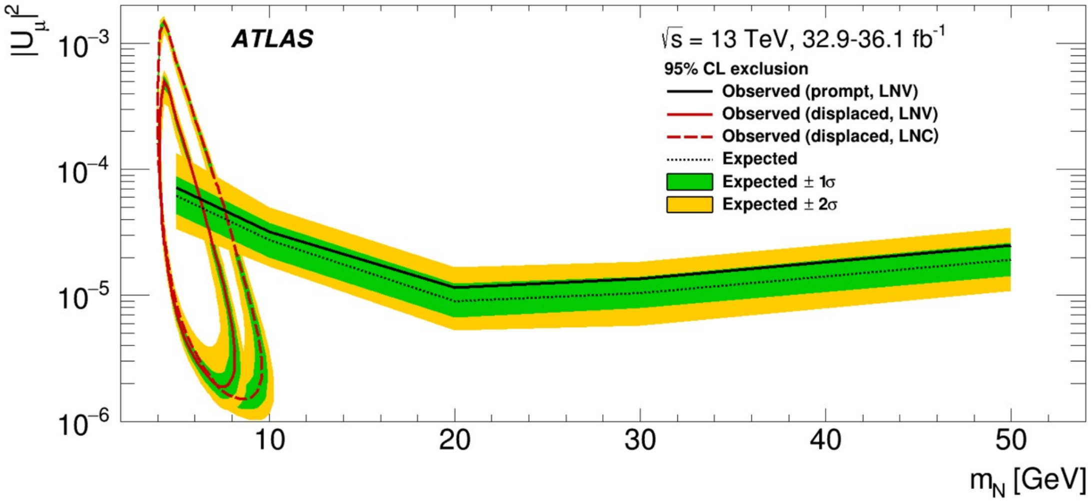
One Single Flavour x_e=0, x_μ=1, x_τ=0

Two quasi-degenerate Normal Mass Hierarchy (NH) x_e=0.06, x_μ=0.48, x_τ=0.46

Yields in the various signal region

Displaced HNL: Results





Former analysis
prompt + Displaced

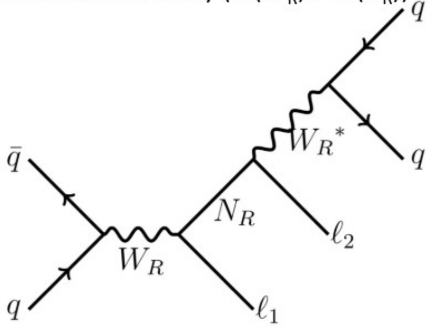
- HNL in VBS scattering https://arxiv.org/abs/2403.15016
- ~~HNL in tt decays (if approved)~~
- HNL prompt and displaced JHEP 10 (2019) 265 (Displaced + prompt) PRL 131 (2023) 061803 (Displaced)
- Right Handed Neutrino (and W_R) EPJC 83 (2023) 1164

EPJC 83 (2023) 1164

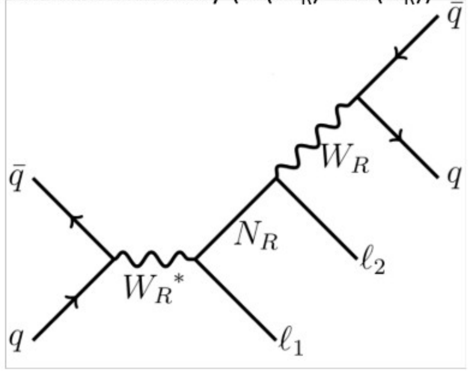
Right Handed Neutrino

Left Right Symmetric Models (LRSM) W_R and N_R: Keung Senjanovic process
Only ee and μμ final states (HN does **not** mix generations)

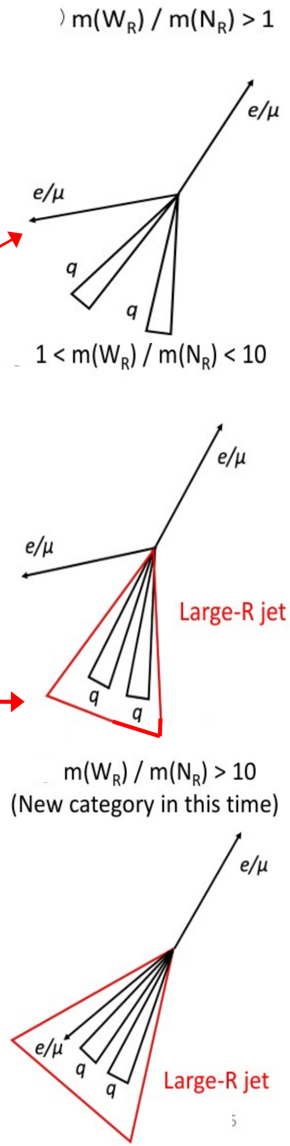
Nominal hierarchy (m(W_R) > m(N_R))



Inverted hierarchy (m(W_R) < m(N_R))

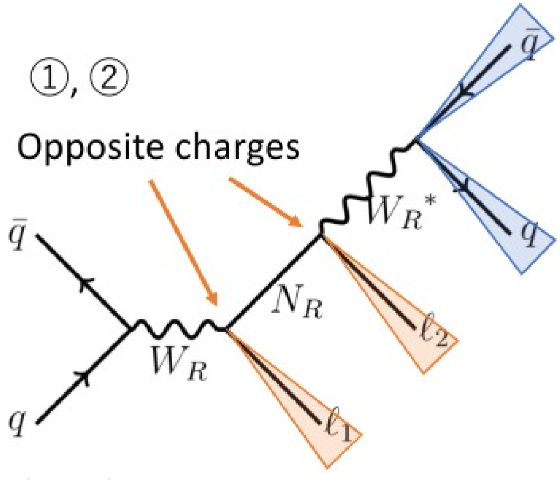


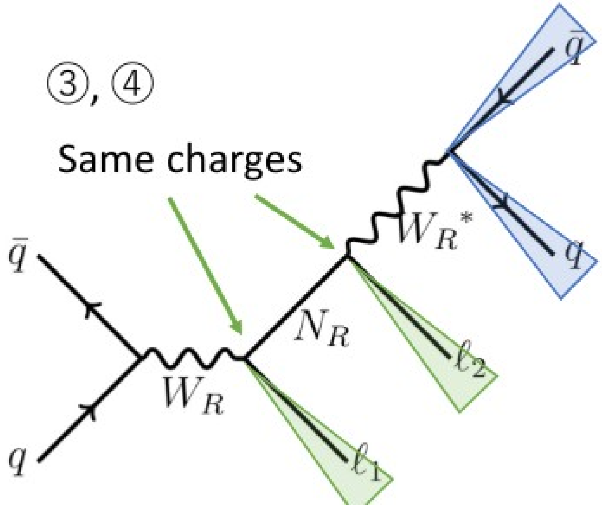
Three topologies to maximize search reach



If N_R is Majorana → 50% OS + 50% SS l_1 l_2 pairs

Resolved Channel



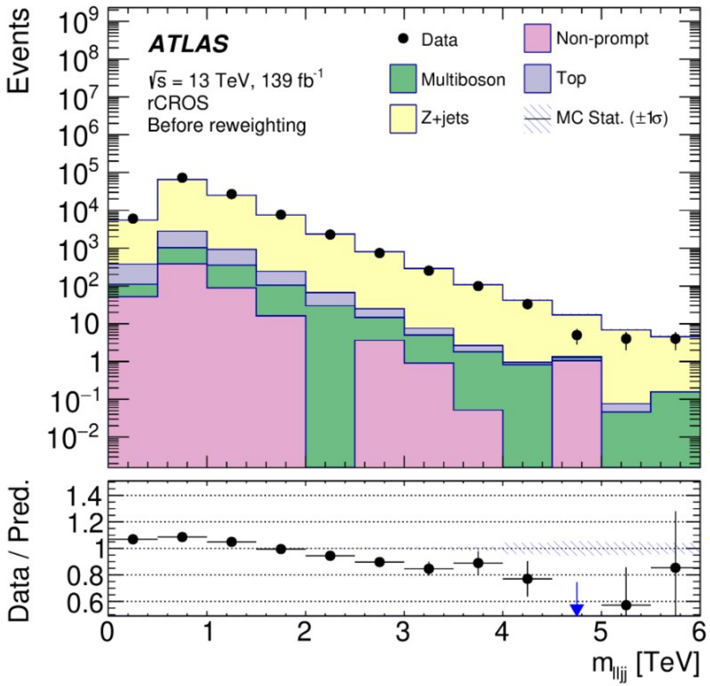


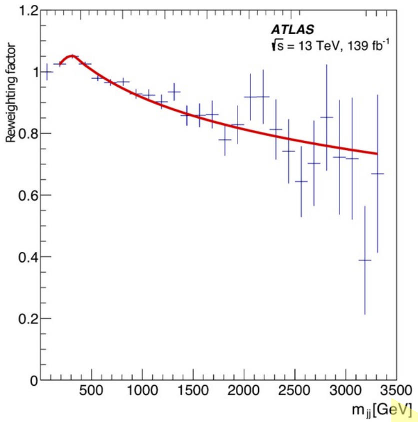
Z+jet and ttbar main background

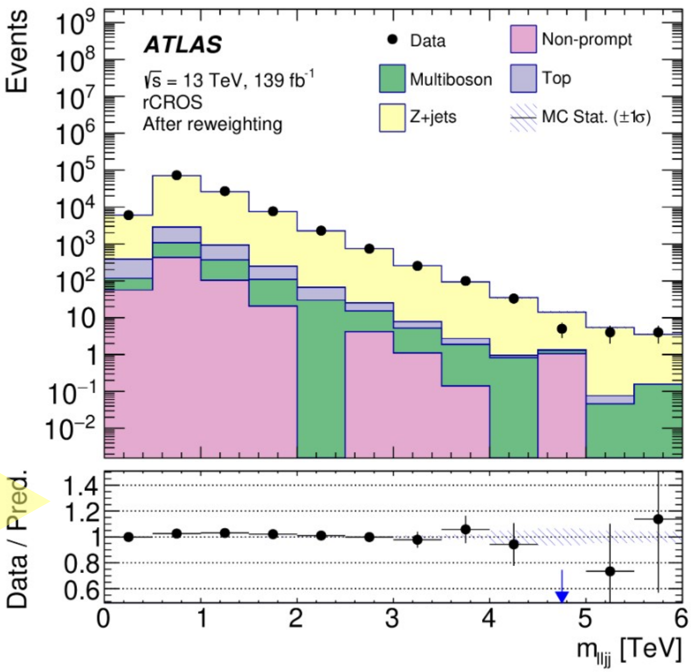
Diboson main background

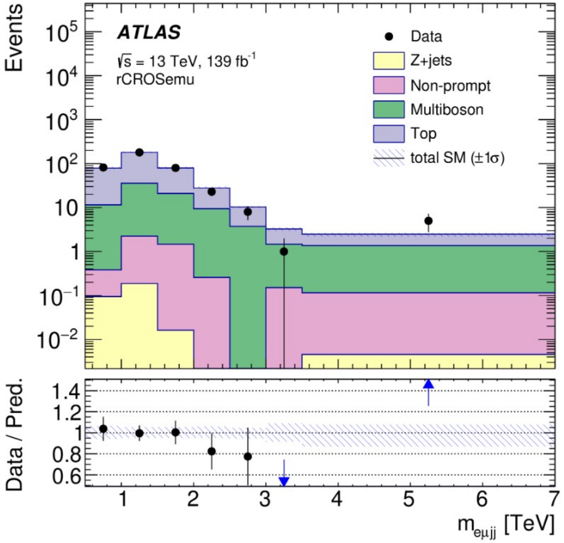
100x more background events in OS wrt SS (10x for em channels)

M_{jj} reweighting

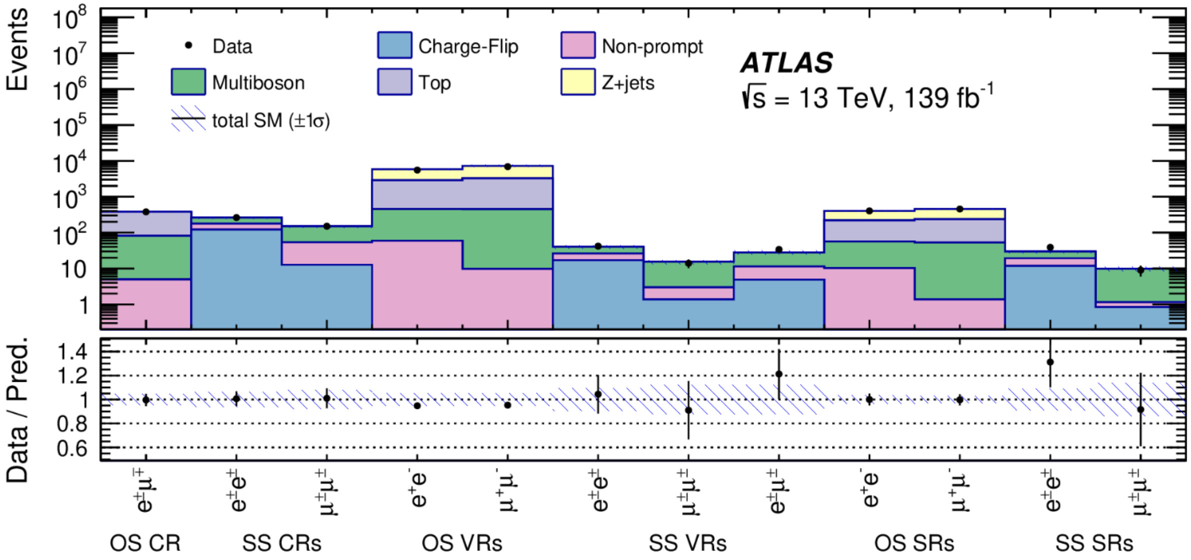


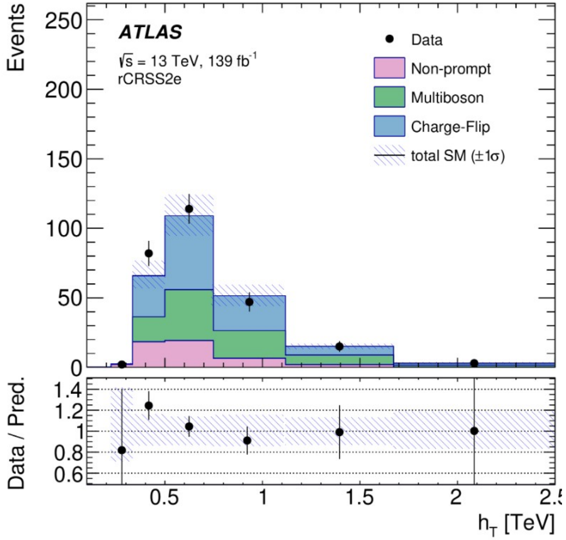




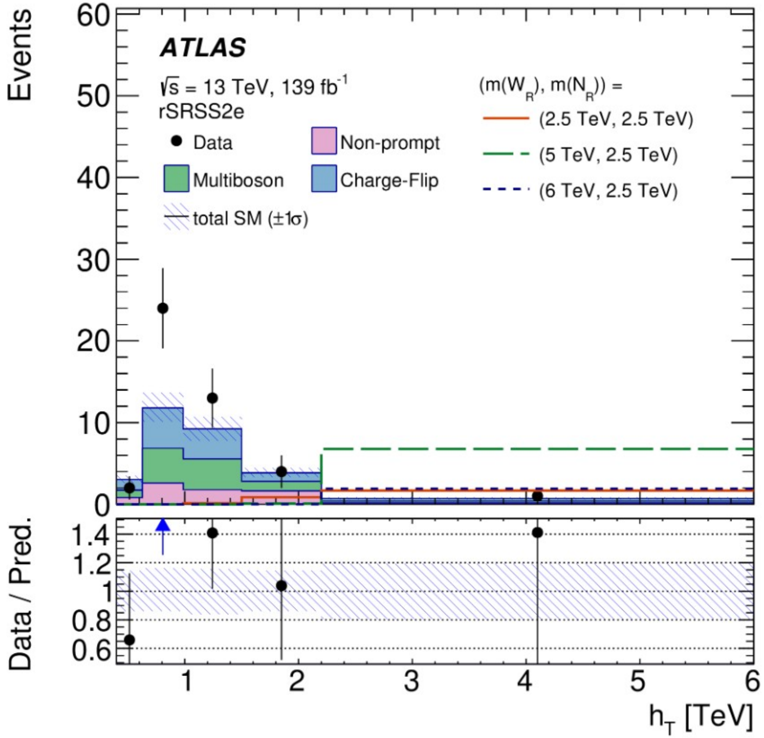


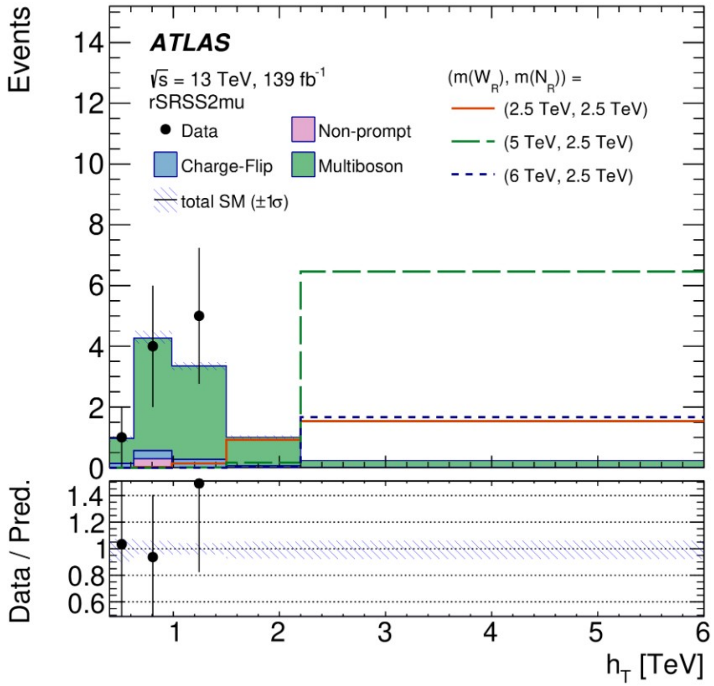
Resolved Channel





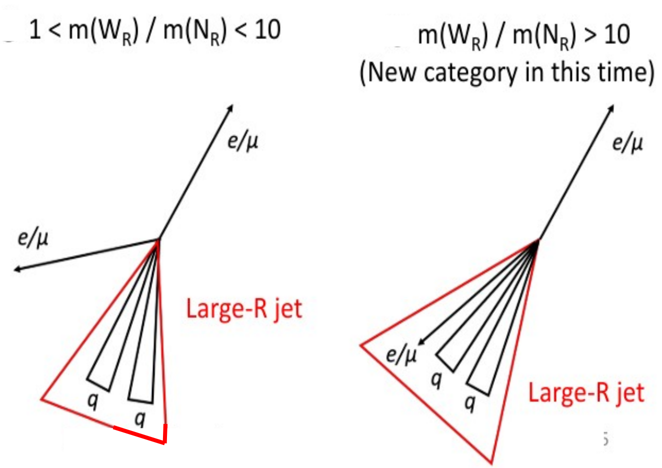
Resolved Channel





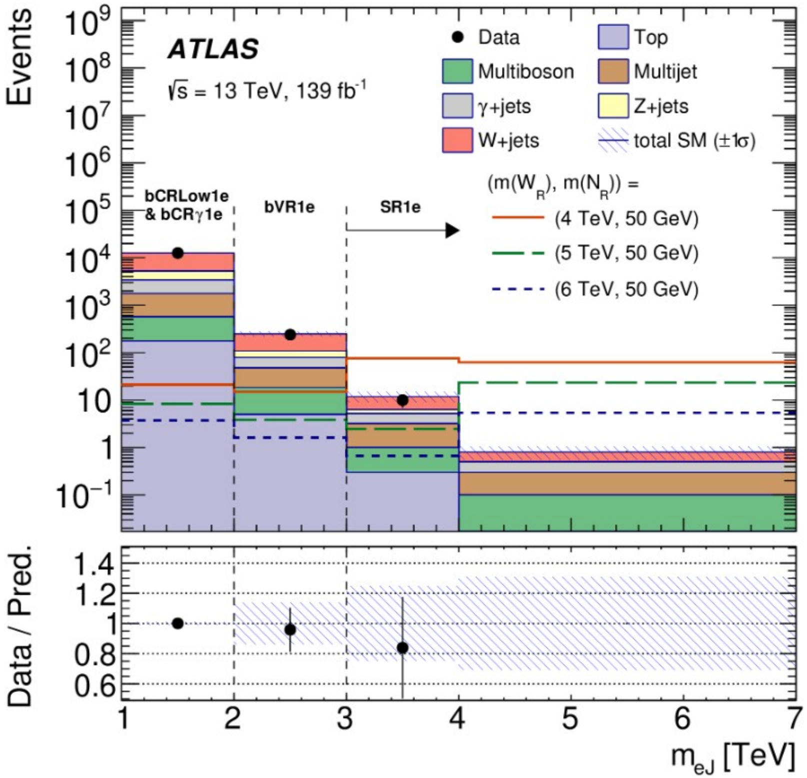
Boosted channel

Two kinematical regions



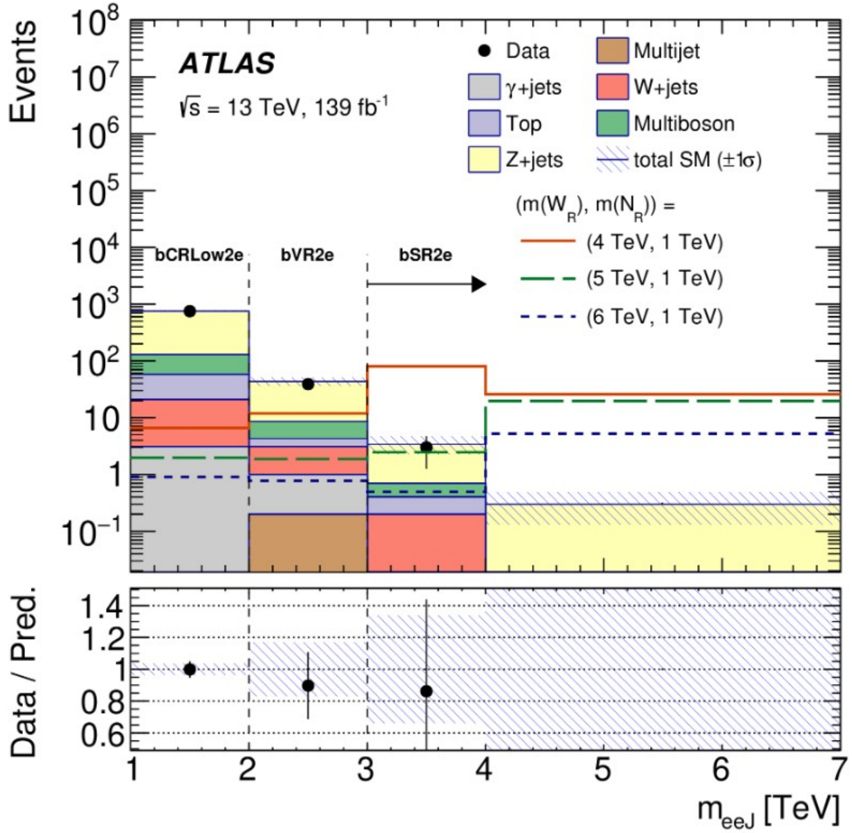
ee boosted channel
μμ boosted channel

Single e boosted channel

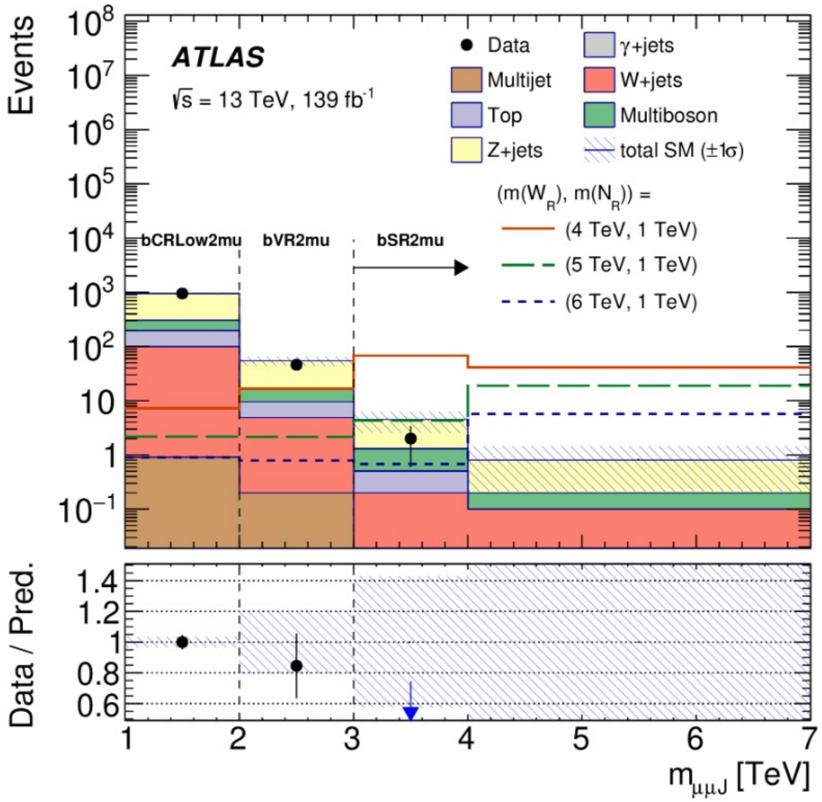


Single e boosted channel

$\Delta(M) = m(W_R) - m(N_R) > 4$ TeV
1 Large-R jet (reclustered Small-R jets)

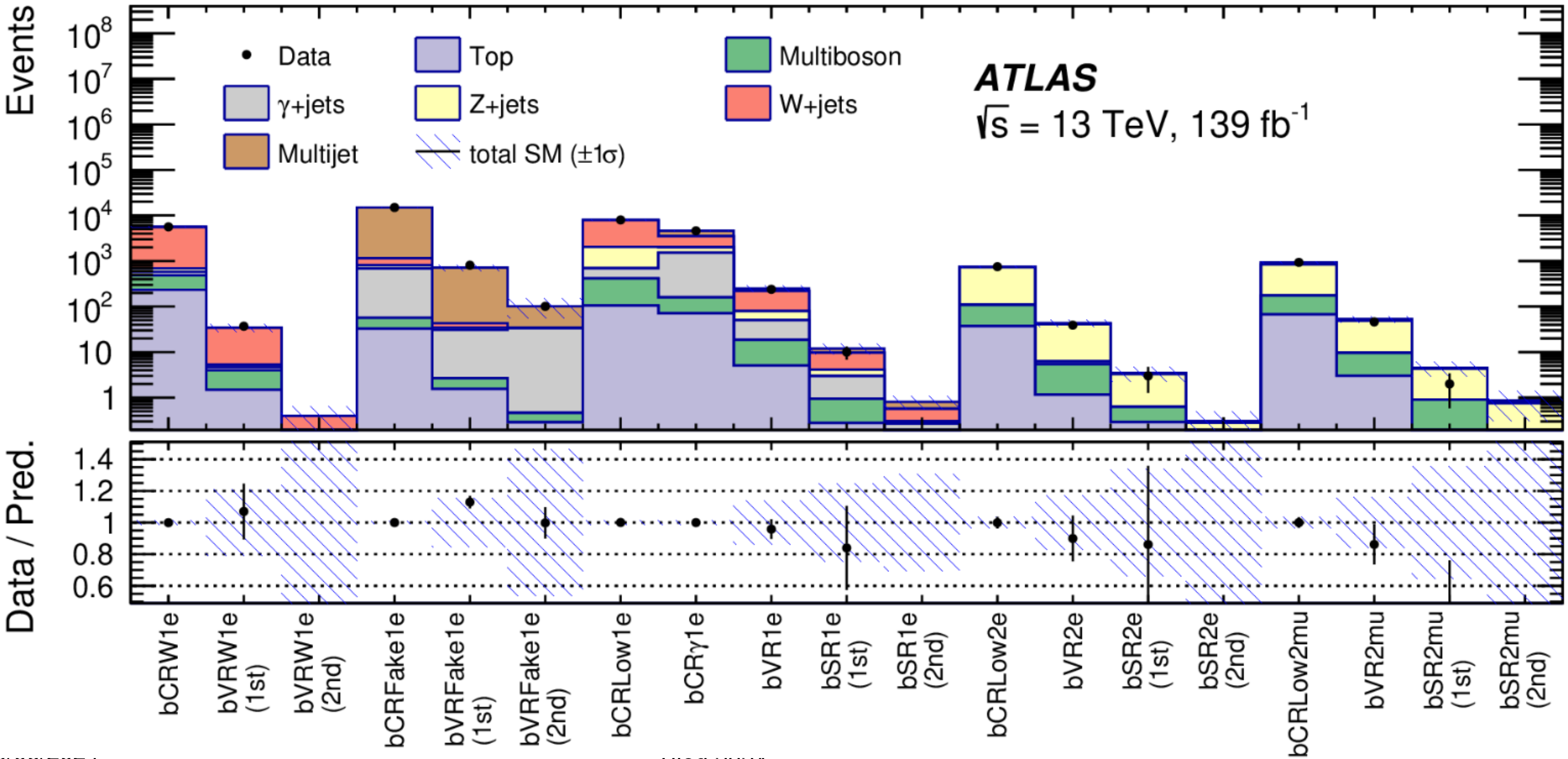


ee boosted channel

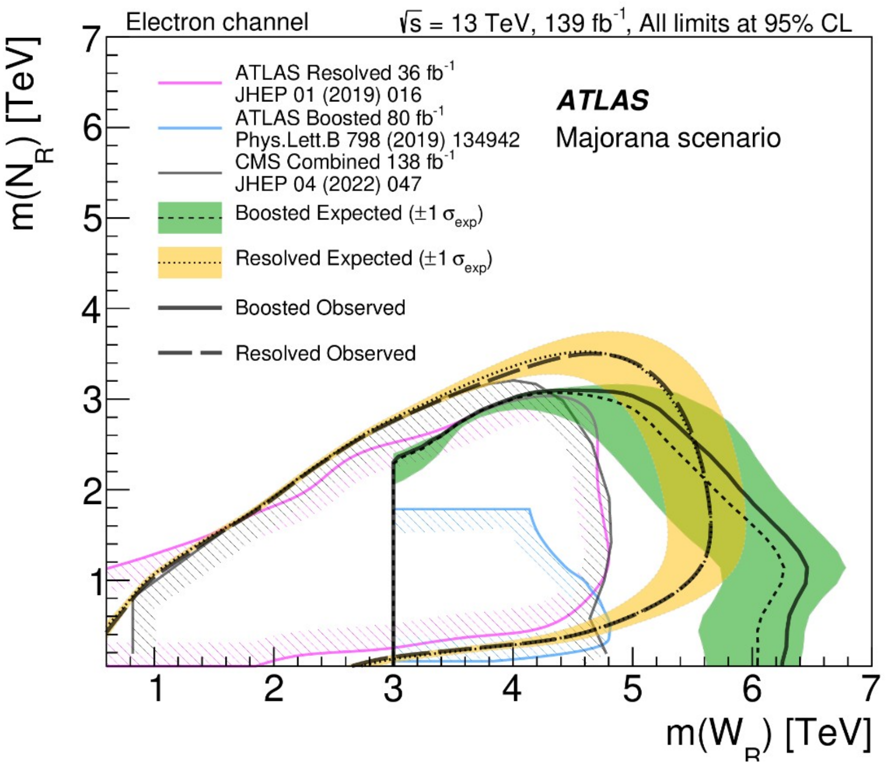


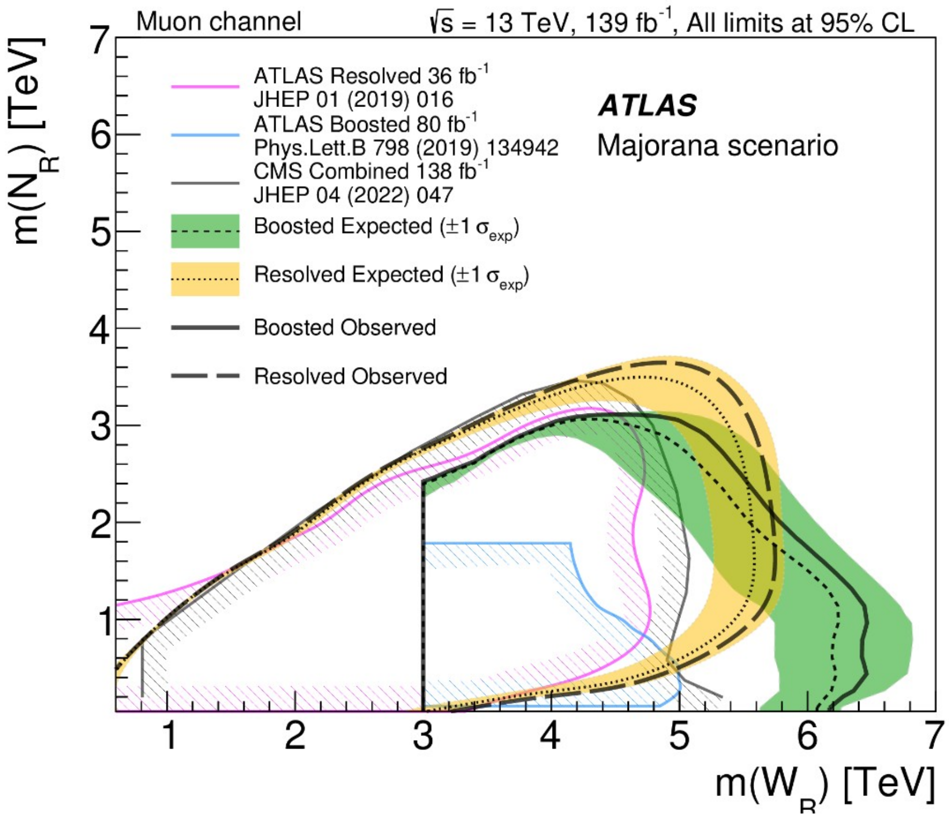
μμ boosted channel

Boosted channel

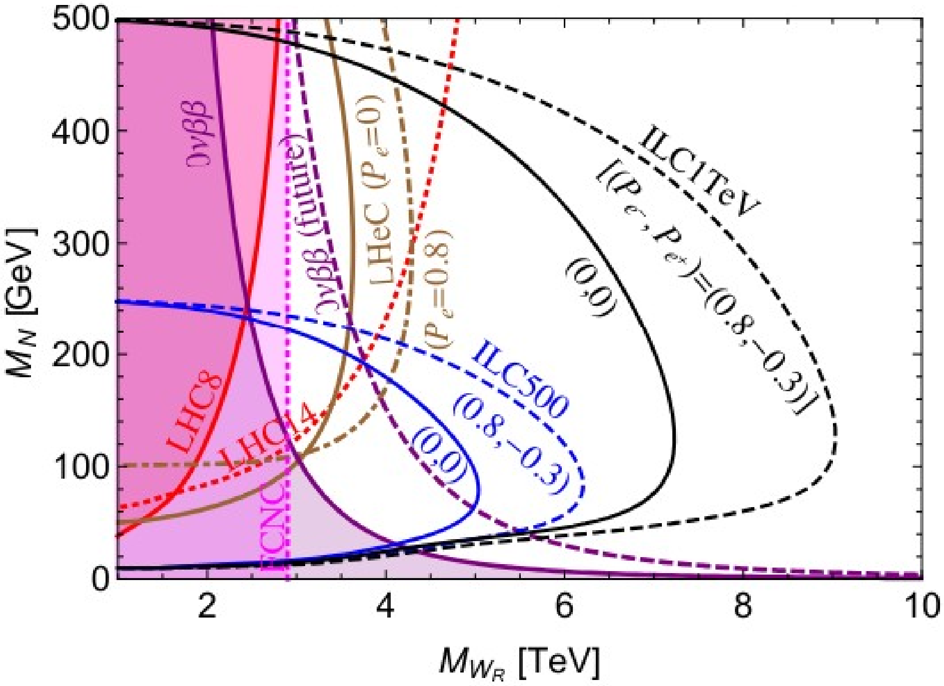


Heavy Majorana: Limits





Heavy Neutrino



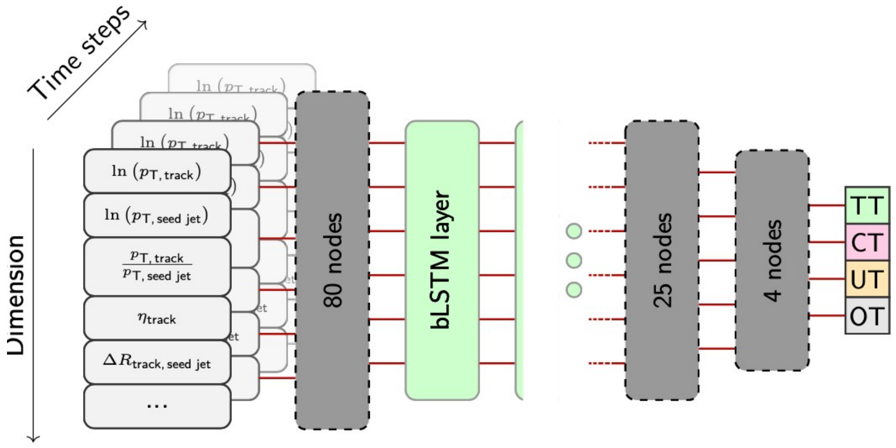
Nice interplay between collider physics and 0νββ (neutrinoless double beta decay searches) (For first generation only)

Biswal, Bhupal Dev Phys Rev D 95 (2017) 115031

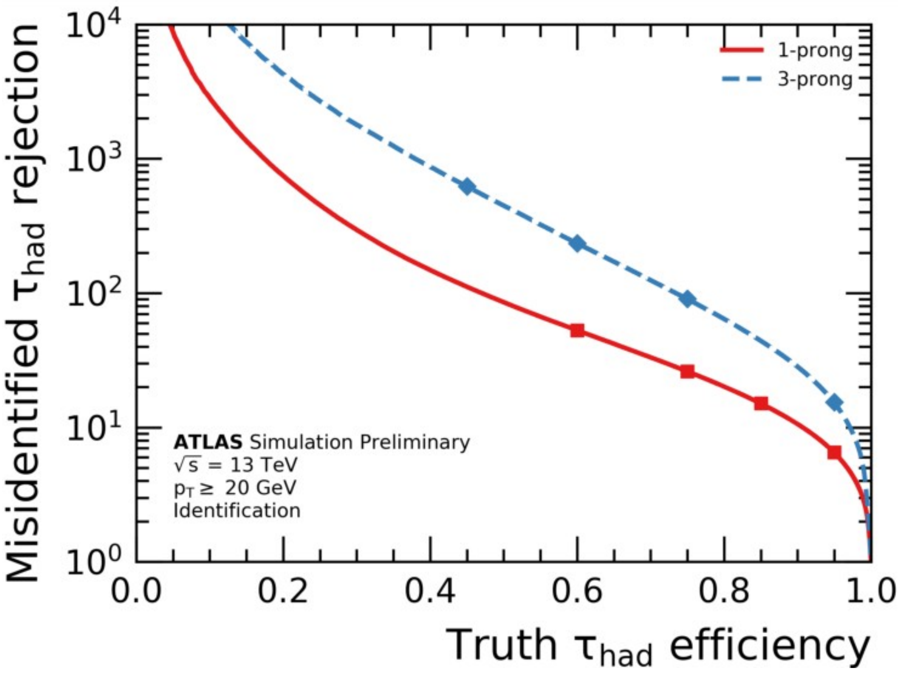
Third Generation

So far explored only couplings with first and second generation. Tau (hadronic) final states are missing

If couplings go with mass, tau should be enhanced



Run3 RNN based tau ID algorithm

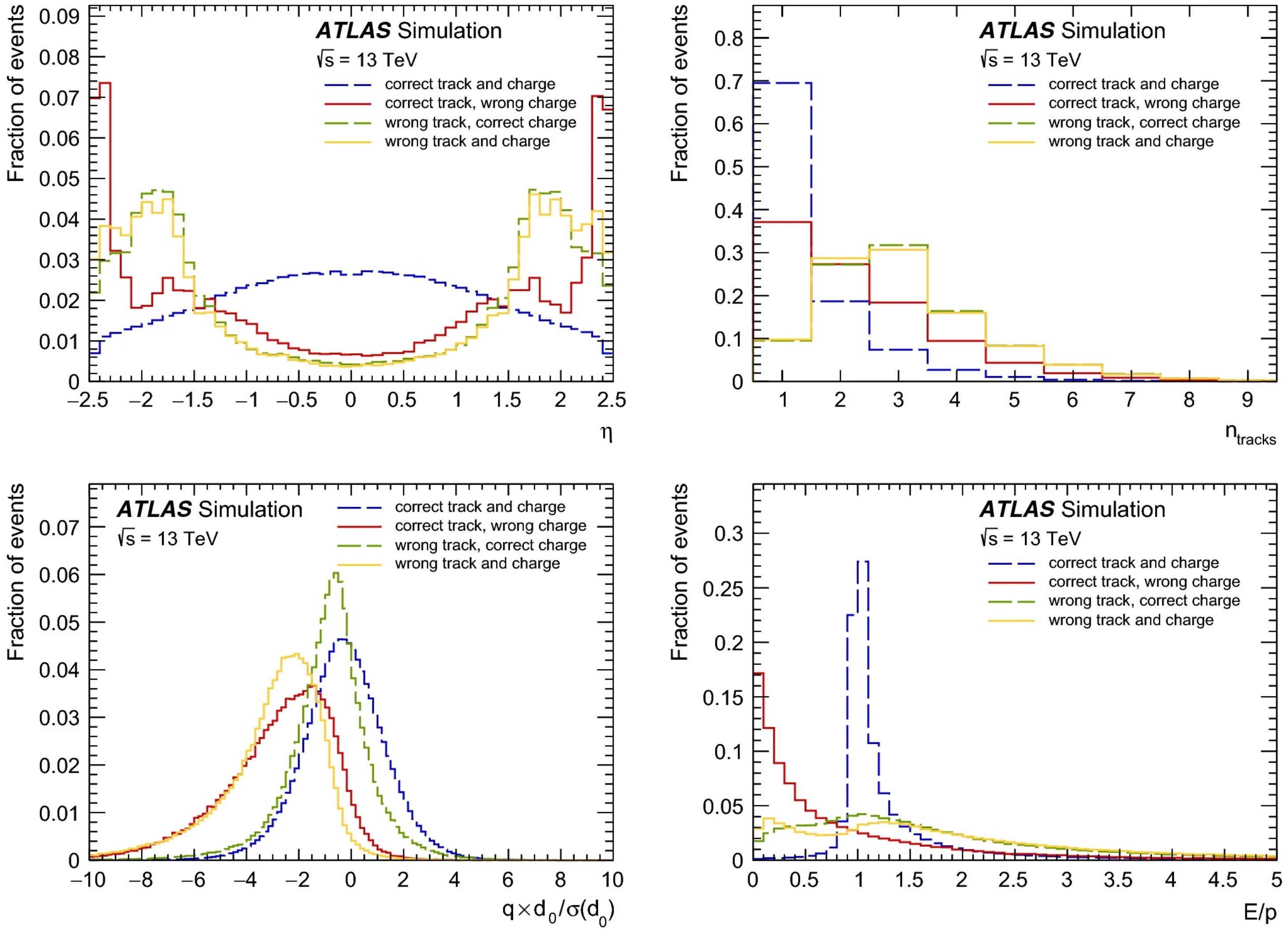


ATLAS-PHYS-PUB-2022-044

Summary

LNV processes are rare ($m_\nu \sim 0$) and require a BSM enhancement and an efficient reconstruction to be observable at the LHC → SeeSaw mechanism and Majorana neutrinos could give sizeable LNV at LHC
Interplay between collider physics, fixed target and neutrino physics experiments
Tau (hadronic) still unexplored in ATLAS → Many improvements in tau id → Investigating couplings with third generation is now possible in Run3

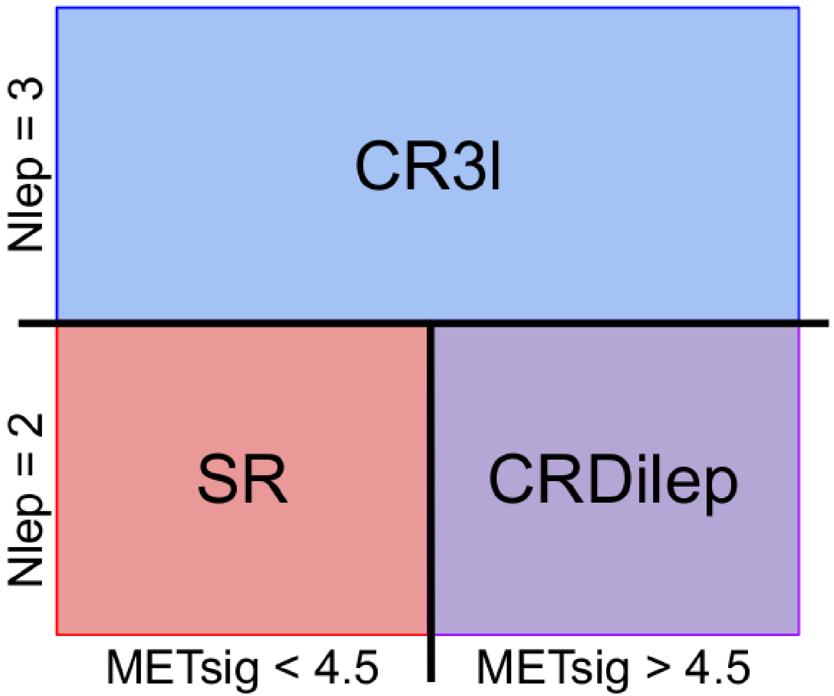

Backup
ctrl
alt


ATLAS Simulation
√s = 13 TeV
correct track and charge
correct track, wrong charge
wrong track, correct charge
wrong track and charge
Fraction of events
η
n_tracks
q×d_0/σ(d_0)
E/p

VBS μμ analysis

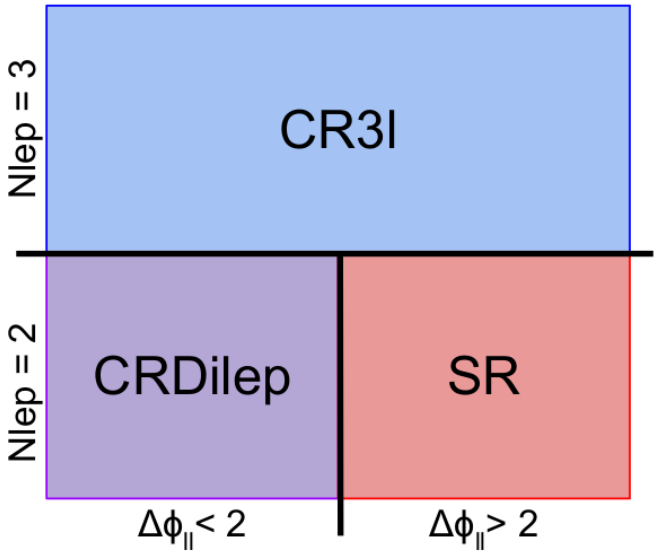
Observable	SR	ssWW VR	ssWW CR (highpT VR)	WZ CR
b-jet veto	✓	✓	✓	✓
m_{jj}	> 300 GeV	> 300 GeV	> 300 GeV (—)	> 300 GeV
ΔY_{jj}	> 4	> 4	> 4 (—)	> 4
third lepton	$= 0$ (baseline)	$= 0$ (baseline)	$= 0$ (baseline)	$= 1$ (signal)
Z cand. (OSSF only)	—	—	—	✓
$E_{\mathrm{T}}^{\mathrm{miss}}$ sign.	< 4.5	$\in [4.5, 5.8]$	> 5.8	< 4.5
m_{lll}	—	—	—	> 100 GeV
$p_{\mathrm{T}}^{\mu_2}$	—	< 120	< 120 (> 120) GeV	—

VBS ee



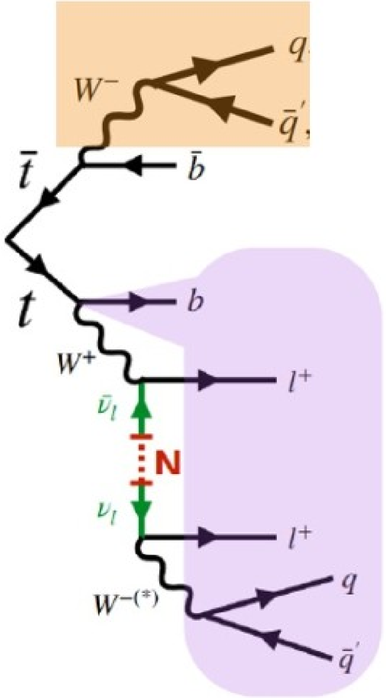
Observable	SR	CRDilep	CR3l
N b-jets	0 b-jets	0 b-jets	0 b-jets
N leptons	2	2	3
$\|M_{ll} - M_Z\|$	> 15 GeV	> 15 GeV	-
METsig	< 4.5	> 4.5	-
M_{jj}	> 500 GeV	> 500 GeV	> 500 GeV
ΔY_{jj}	> 2	> 2	> 2
$\|\eta_l\|$	< 2	< 2	< 2
pT_{l1}	-	< 250 GeV	-
pT_{j0} (pT_{j1})	> 30 (25) GeV	> 45 (30) GeV	> 30 (25) GeV
Z Candidate	-	-	1
M_{lll}	-	-	> 106 GeV

VBS eμ



Observable	SR	CRDilep	CR3l
N b-jets	0	0	0
N leptons	2	2	3
ΔPhi ll	> 2	< 2	-
M_{jj}	> 500 GeV	> 500 GeV	> 500 GeV
ΔY_{jj}	> 2	> 2	> 2
pT_{j0} (pT_{j1})	> 30 (25) GeV	> 45 (30) GeV	> 45 (30) GeV
M_{lll}	-	-	> 106 GeV

Heavy Neutrino in $t\bar{t}$ decays



Final states analyzed: ee, μμ
Focus on SS final states
$\tau_{lep}\tau_{had}$ also analyzed with lt leptonic decays
In ee channel 1SR + 4 CR
In μμ channel 1 SR + 2 CR
$t\bar{t}$ and ttW dominant backgrounds

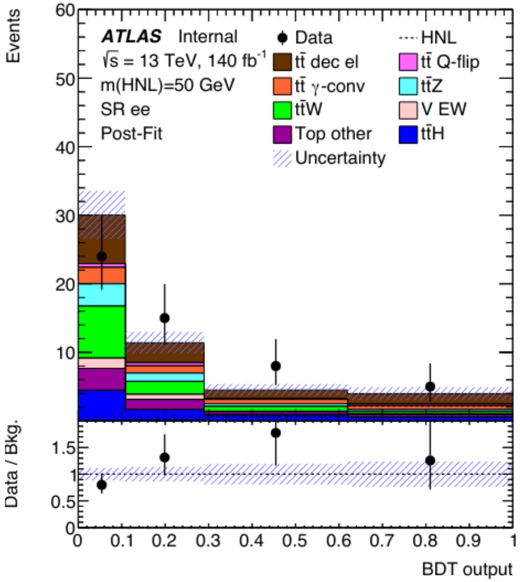
Only diagonal terms investigated

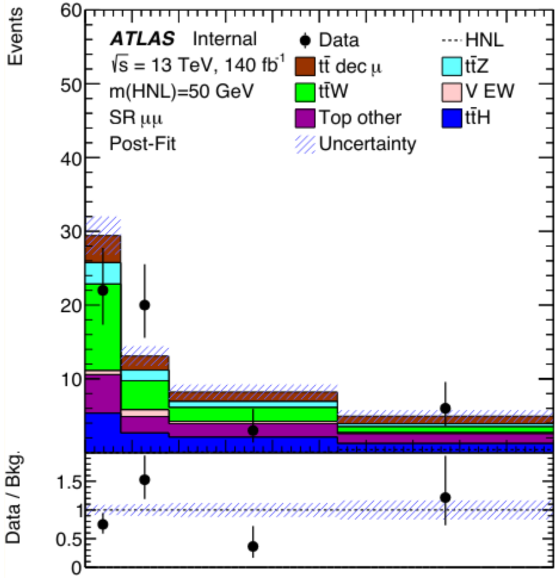
$$v_{mix} = \begin{pmatrix} V_{e,N1} & 0 & 0 \\ 0 & V_{\mu,N2} & 0 \\ 0 & 0 & V_{\tau,N3} \end{pmatrix}$$

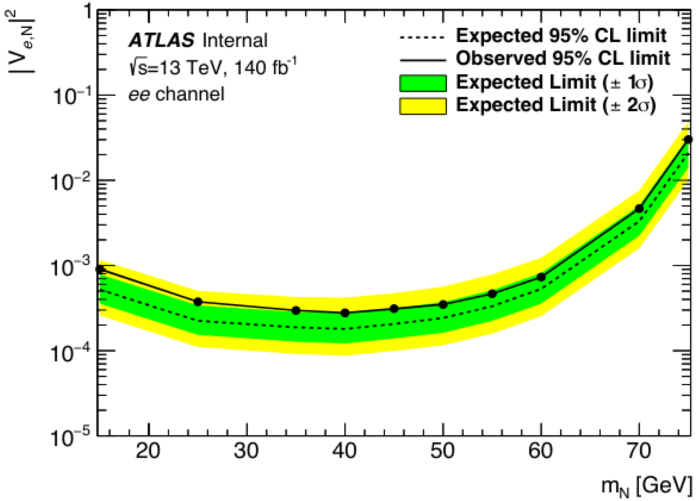
Analysis uses BDT selection

Still not public
To be removed if not public by the time of the talk

Heavy Neutrino in $t\bar{t}$ decays





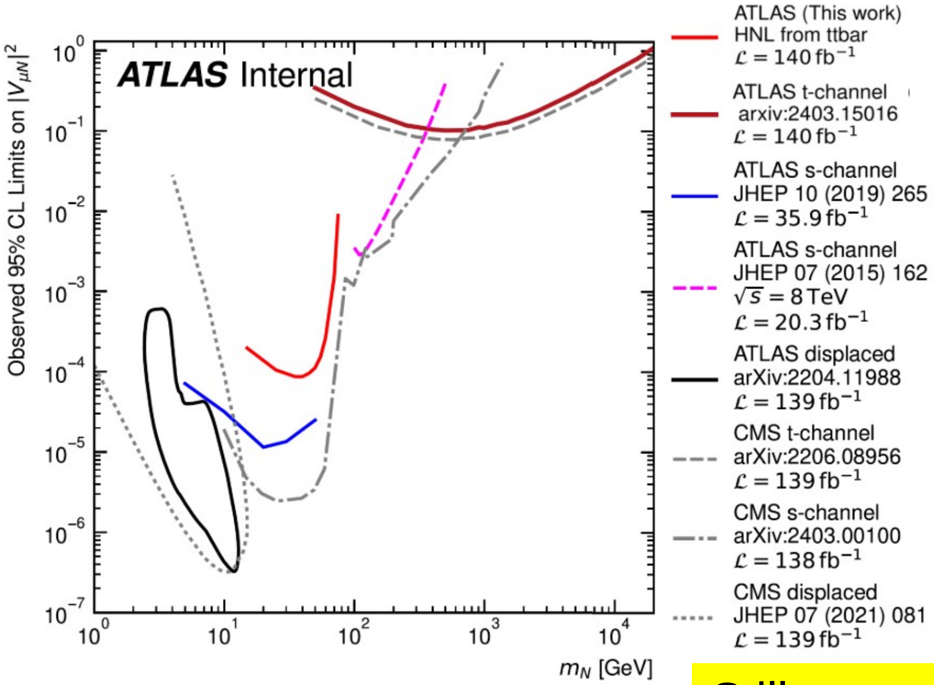


Discriminating variable is P_T of sub-leading lepton

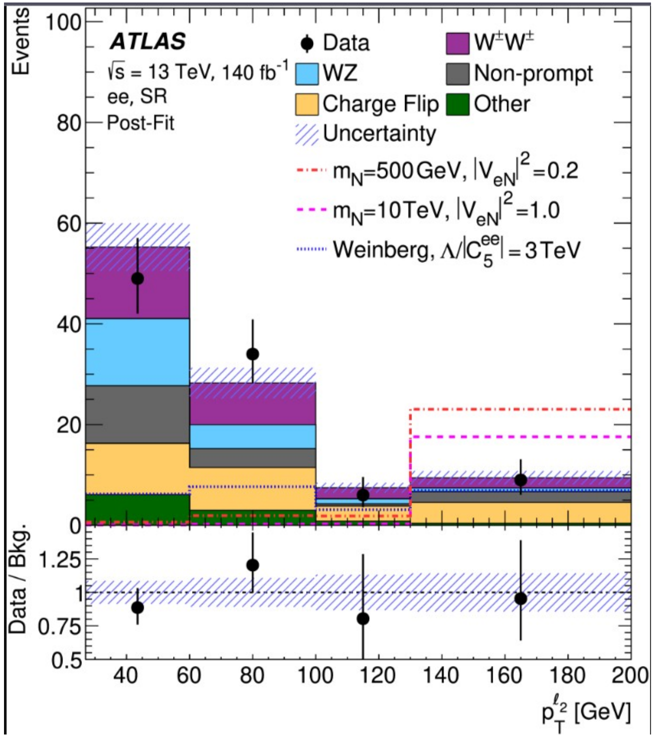
The tightest observed upper limit on coupling parameters among [15,75] GeV are $|V_{eN}|^2 < 2.8\ 10^{-4}$, $|V_{\mu N}|^2 < 9\ 10^{-5}$ and $|V_{\tau N}|^2 < 5.9\ 10^{-2}$

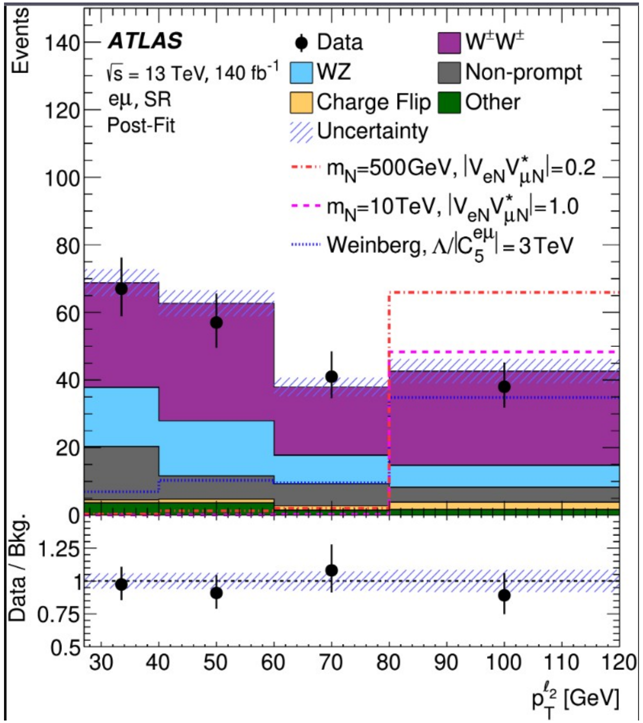
Still not public
To be removed if not public by the time of the talk

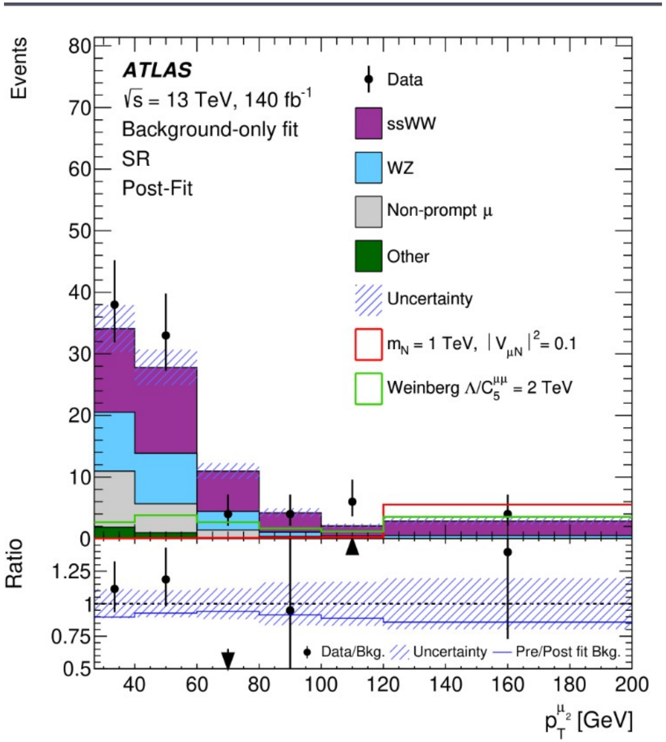
Heavy Neutrino in $t\bar{t}$ decays



Still not public
To be removed if not public by the time of the talk


ATLAS
√s = 13 TeV, 140 fb⁻¹
ee, SR
Post-Fit
Data
W±W±
WZ
Non-prompt
Charge Flip
Other
Uncertainty
m_N=500GeV, |V_eN|²=0.2
m_N=10TeV, |V_eN|²=1.0
Weinberg, Λ/|C_5^ee|=3TeV
Events
Data / Bkg.
p_T^ℓ2 [GeV]

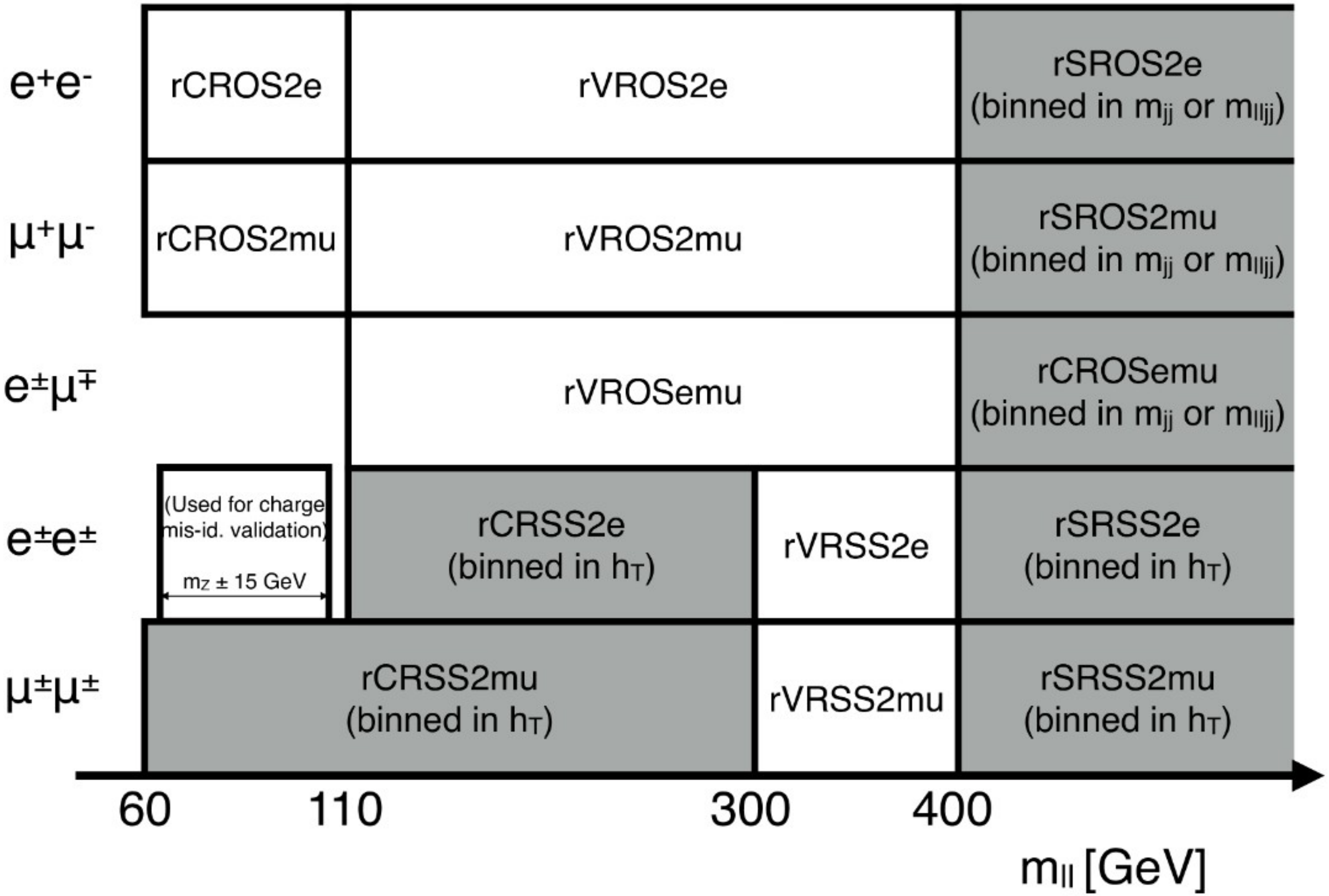

ATLAS
√s = 13 TeV, 140 fb⁻¹
eμ, SR
Post-Fit
Data
W±W±
WZ
Non-prompt
Charge Flip
Other
Uncertainty
m_N=500GeV, |V_eN V*_μN|=0.2
m_N=10TeV, |V_eN V*_μN|=1.0
Weinberg, Λ/|C_5^eμ|=3TeV
Events
Data / Bkg.
p_T^ℓ2 [GeV]


ATLAS
√s = 13 TeV, 140 fb⁻¹
Background-only fit
SR
Post-Fit
Data
ssWW
WZ
Non-prompt μ
Other
Uncertainty
m_N = 1 TeV, |V_μN|² = 0.1
Weinberg Λ/C_5^μμ = 2 TeV
Data/Bkg.
Uncertainty
Pre/Post fit Bkg.
Events
Ratio
p_T^μ2 [GeV]

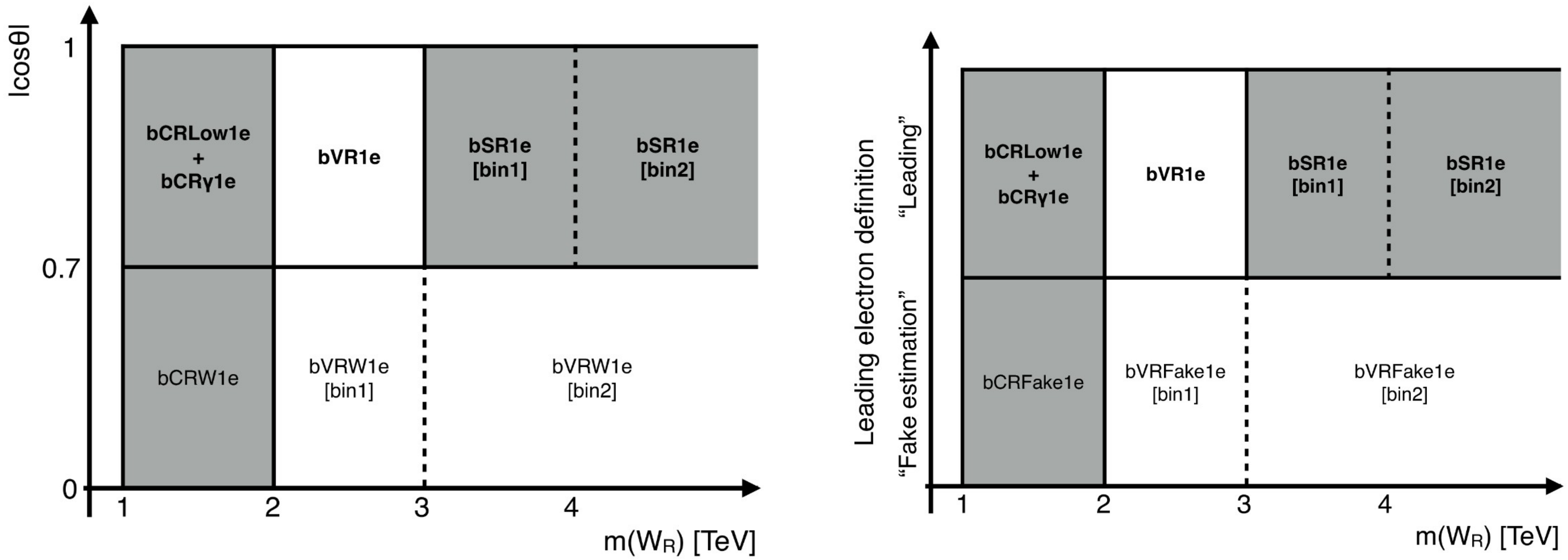
Level	Selection	Value
Pre-selection	Event cleaning	Standard ATLAS event cleaning
	Trigger	Pass at least one single muon or electron trigger
	Trigger matched lepton	At least one lepton with *Medium* (or *LHMedium*) quality
	Primary Vertex	At least one (standard ATLAS selection)
	DRAW Filter	Pass any HNL filter
	Prompt lepton quality	*Medium* (muons) or *LHMedium* (electrons)
	Prompt lepton impact parameters	$d_0 < 3$ mm and $\|z_0 \sin\theta\| < 0.5$ mm
	Trigger matched lepton	At least one
	Cosmic veto	$\sqrt{(\Sigma\eta)^2 + (\pi - \Delta\phi)^2} > 0.05$
	Displaced lepton-only vertex	At least one
	Number of tracks in DV	2
	Fiducial volume	$4 < L_{xy} < 300$ mm
SR selection	DV charge	Opposite-sign tracks
	Prompt+ disp. l charge	Opposite-sign leptons (one Dirac HNL single-flavour mixing model only)
	DV type	ee, $e\mu$ or $\mu\mu$ vertex
	Displaced lepton quality	*Medium* (muons), *VeryVeryLoose* (electrons)
	Material veto	Applied for ee DVs only
	B-hadron veto	$m_{DV} > 5.5$ GeV ($\mu\mu$ DVs) or Diagonal m_{DV}-L_{xy} cut (ee or $e\mu$ DVs)
	Z mass veto	$m_{prompt+disp.lep.} < 80$ or $m_{prompt+disp.lep.} > 100$ GeV if prompt and displaced leptons have same flavour and OS
	Tri-lepton mass	$40 < m_{lll} < 90$ GeV
	HNL mass	$m_{\text{HNL}} < 20$ GeV

		Resolved		Boosted		
Electrons		Baseline	Fake estimation	Baseline	Leading	Fake estimation
	p_T (GeV)	> 25		> 26	> 200	
	$\lvert\eta\rvert$	$(0, 1.37]$ or $[1.52, 2.47]$				
	Quality	Tight	Loose	Medium	Tight	
	Isolation	Loose	Fail Loose or Tight	Loose	HighPtCaloOnly	Loose but fail FCHighPtCaloOnly
Muons		Baseline	Fake estimation	Baseline	Leading	
	p_T (GeV)	> 25		> 28	> 200	-
	$\lvert\eta\rvert$	< 2.5				-
	Quality	High-p_T if pT $>$ 300 GeV else Medium		Medium	Tight	-
	Isolation	FixedCutTightTrackOnly	fail FixedCutTightTrackOnly	-	Tight	-
Small-R jet	p_T (GeV)	> 20				
	$\lvert\eta\rvert$	< 2.5				
Large-R jet	p_T (GeV)	-		> 200		
	$\lvert\eta\rvert$	-		< 2		

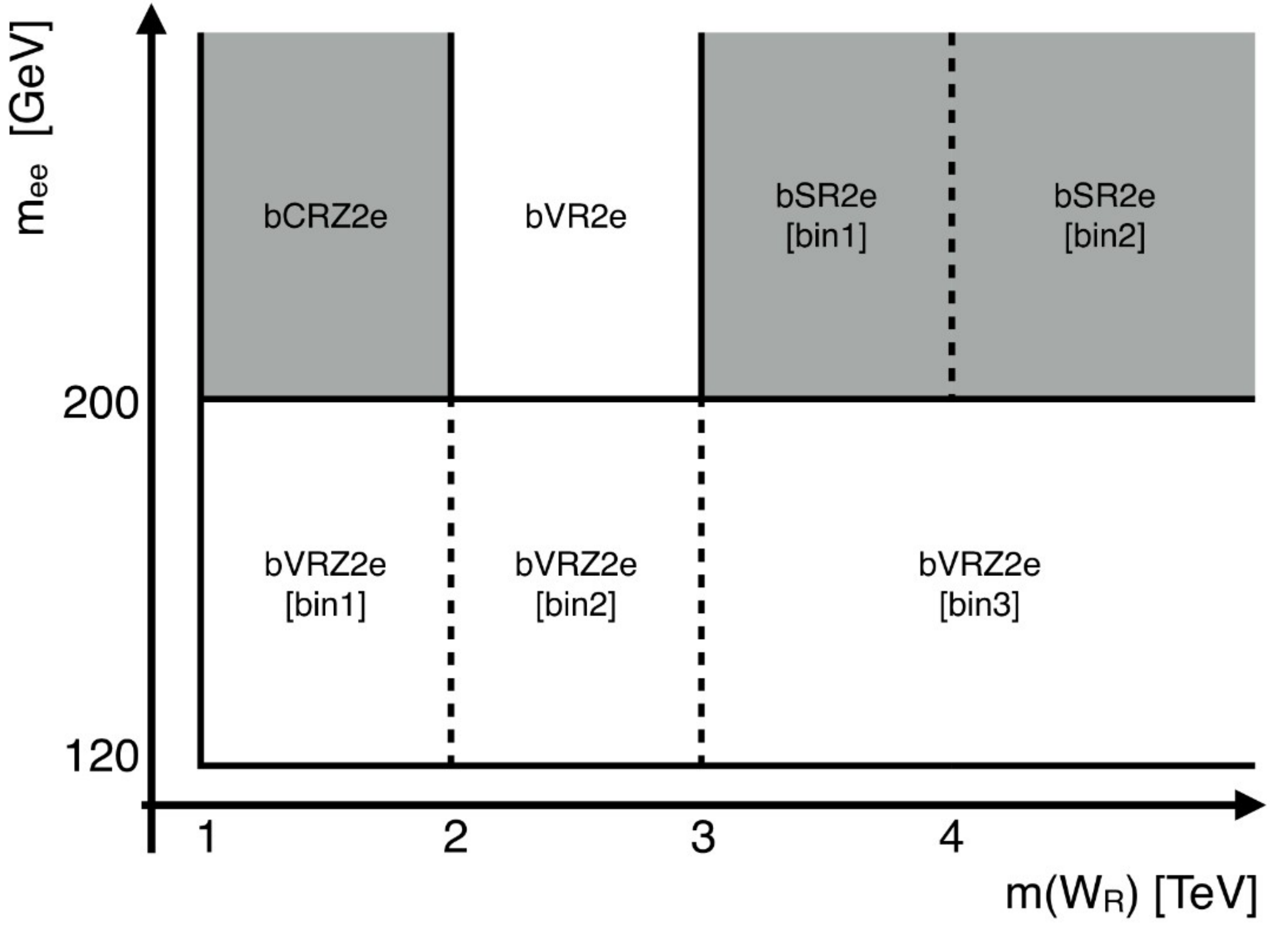
Heavy Neutrino and WR (resolved)



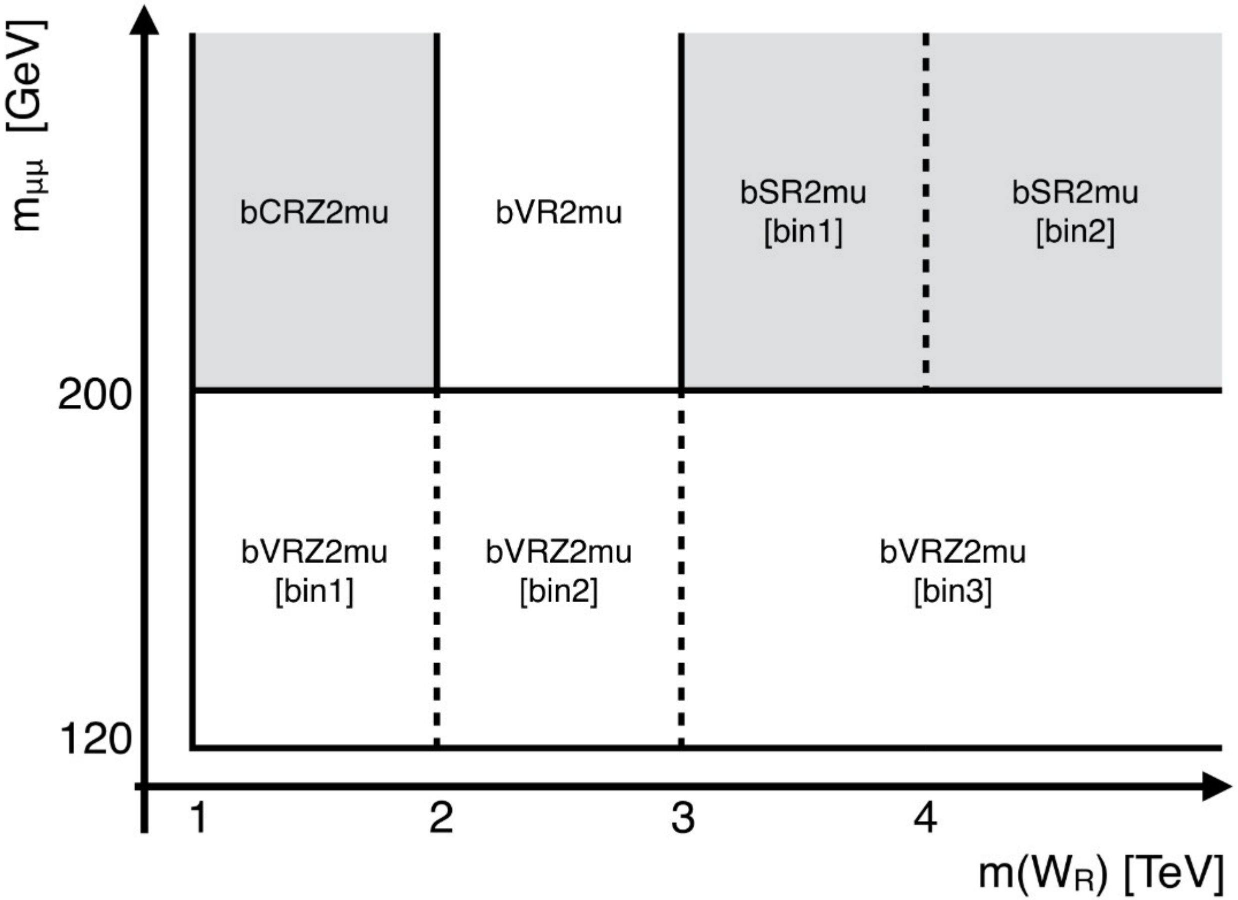
1-electron boosted



ee boosted

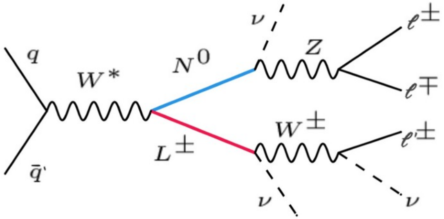

m_{ee} [GeV]
200
120
bCRZ2e
bVR2e
bSR2e [bin1]
bSR2e [bin2]
bVRZ2e [bin1]
bVRZ2e [bin2]
bVRZ2e [bin3]
1
2
3
4
$m(W_R)$ [TeV]

μμ boosted

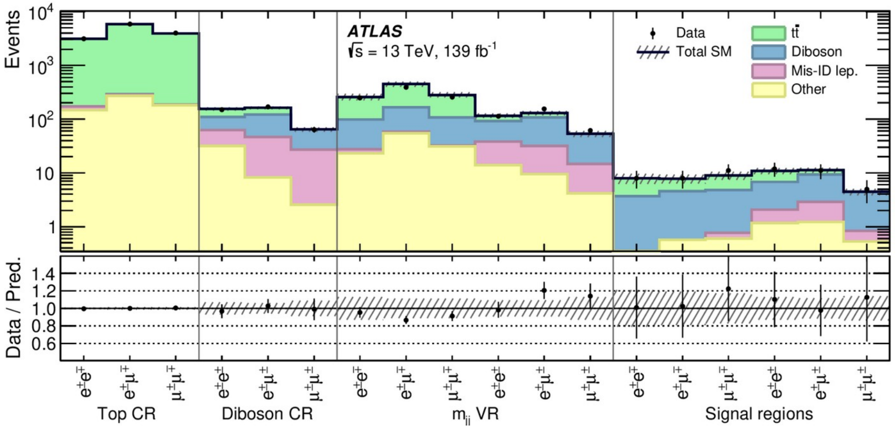


$m_{\mu\mu}$ [GeV]
200
120
bCRZ2mu
bVR2mu
bSR2mu
[bin1]
bSR2mu
[bin2]
bVRZ2mu
[bin1]
bVRZ2mu
[bin2]
bVRZ2mu
[bin3]
1
2
3
4
$m(W_R)$ [TeV]

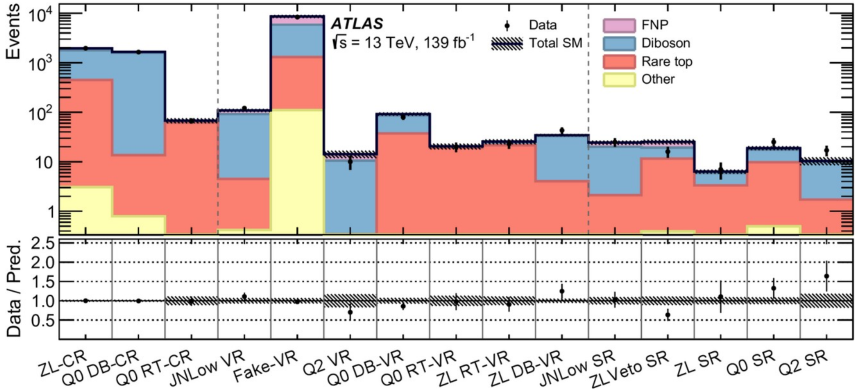
Type III SeeSaw (Heavy Leptons)



Only e and m in 2, 3 and 4 leptonic final states
2 lep final states uses Same Sign in SR

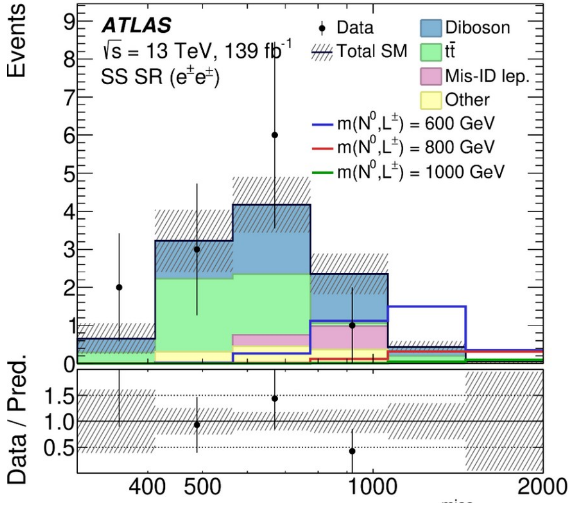


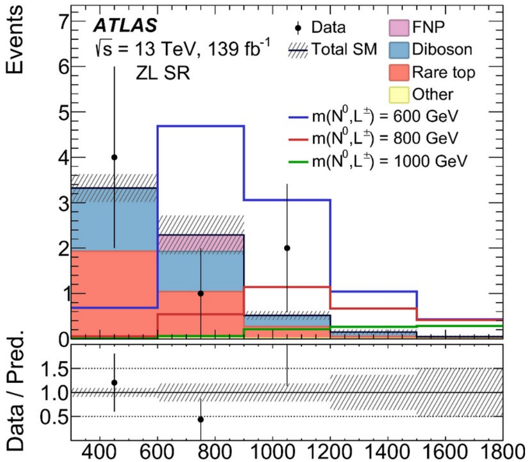
2 lep

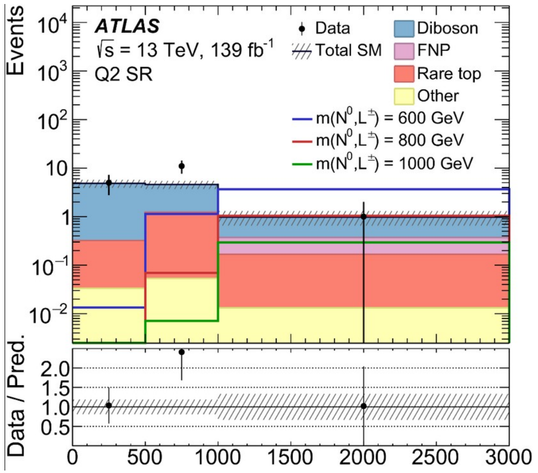


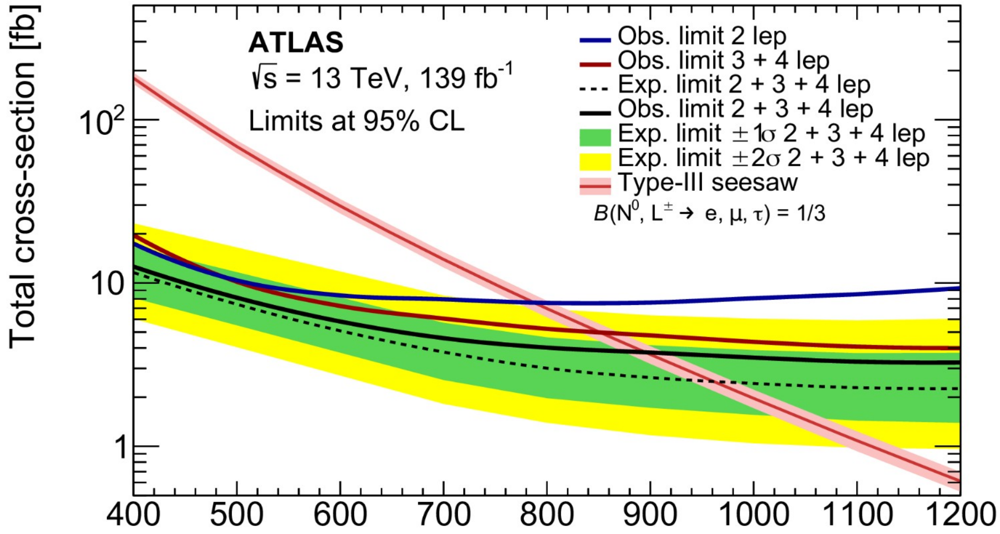
3 and 4 lep

EPJC 81 (2021) 218 (2 lep)
EPJC 82 (2022) 988(3 and 4 lep + comb)


ATLAS
√s = 13 TeV, 139 fb-1
SS SR (e±e±)
Data
Total SM
Diboson
tt̄
Mis-ID lep.
Other
m(N0,L±) = 600 GeV
m(N0,L±) = 800 GeV
m(N0,L±) = 1000 GeV
Events
Data / Pred.


ATLAS
√s = 13 TeV, 139 fb-1
ZL SR
Data
Total SM
FNP
Diboson
Rare top
Other
m(N0,L±) = 600 GeV
m(N0,L±) = 800 GeV
m(N0,L±) = 1000 GeV
Events
Data / Pred.


ATLAS
√s = 13 TeV, 139 fb-1
Q2 SR
Data
Total SM
Diboson
FNP
Rare top
Other
m(N0,L±) = 600 GeV
m(N0,L±) = 800 GeV
m(N0,L±) = 1000 GeV
Events
Data / Pred.


ATLAS
√s = 13 TeV, 139 fb-1
Limits at 95% CL
Obs. limit 2 lep
Obs. limit 3 + 4 lep
Exp. limit 2 + 3 + 4 lep
Obs. limit 2 + 3 + 4 lep
Exp. limit ±1σ 2 + 3 + 4 lep
Exp. limit ±2σ 2 + 3 + 4 lep
Type-III seesaw
B(N0, L± → e, μ, τ) = 1/3
Total cross-section [fb]