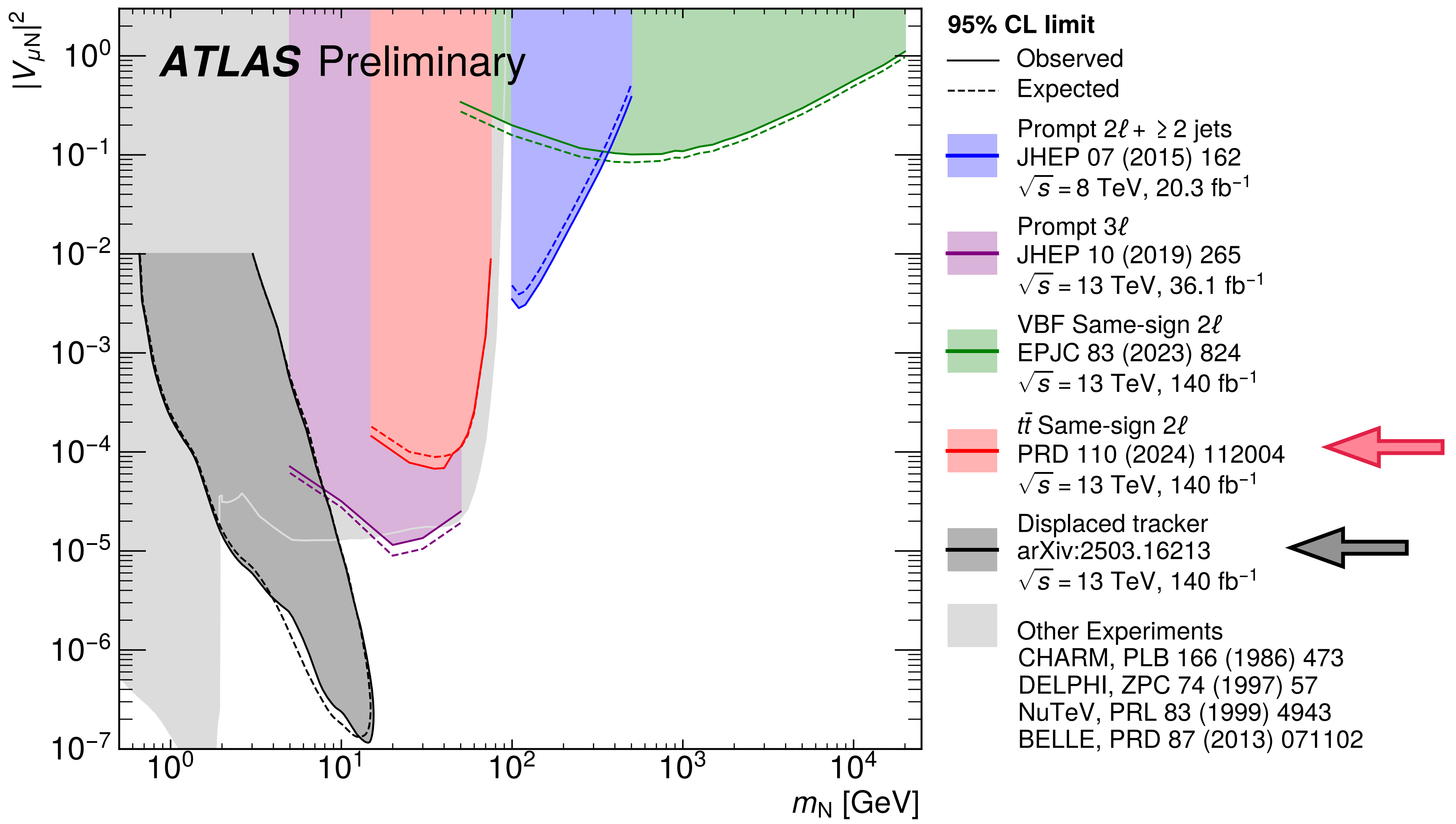
Direct searches for new neutral leptons with ATLAS

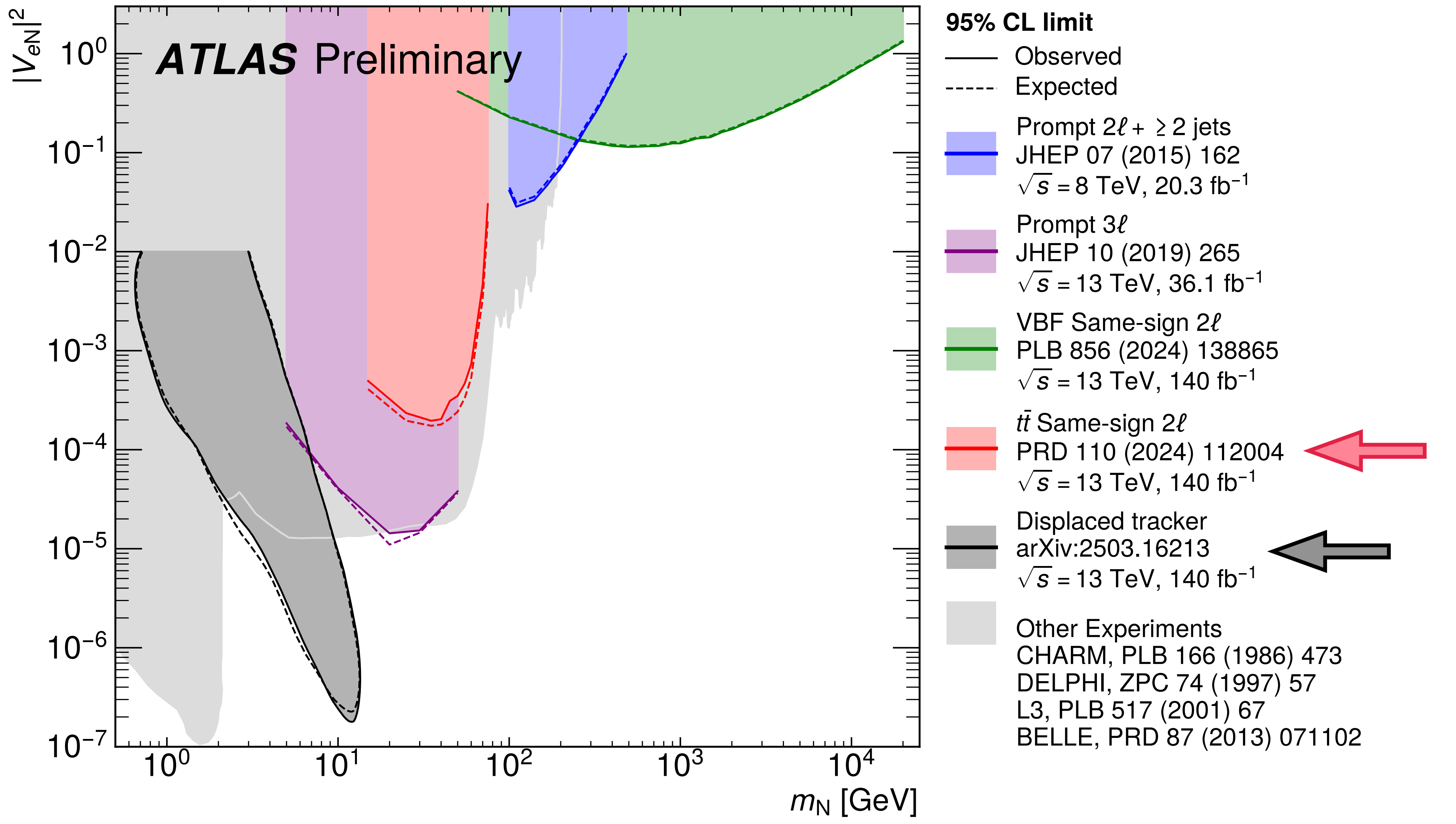
Margaret Lutz

New-ν physics
Durham
10 April 2025

Neutral lepton searches in ATLAS

- Wide ranging searches for neutral leptons
- **Look for very heavy - ~TeV scale**
  - Heavy W_R decaying to heavy N_R
- **Look in decays of tt - ~15 - 75 GeV**
  - First time exploiting tt decays for heavy right-handed neutrino search
  - Complementary to other searches
- **Look for long-lived - ~1 - 20 GeV**
  - Focus on more-displaced decays requires specialized reconstruction
  - Nicely complementary in mass and cτ



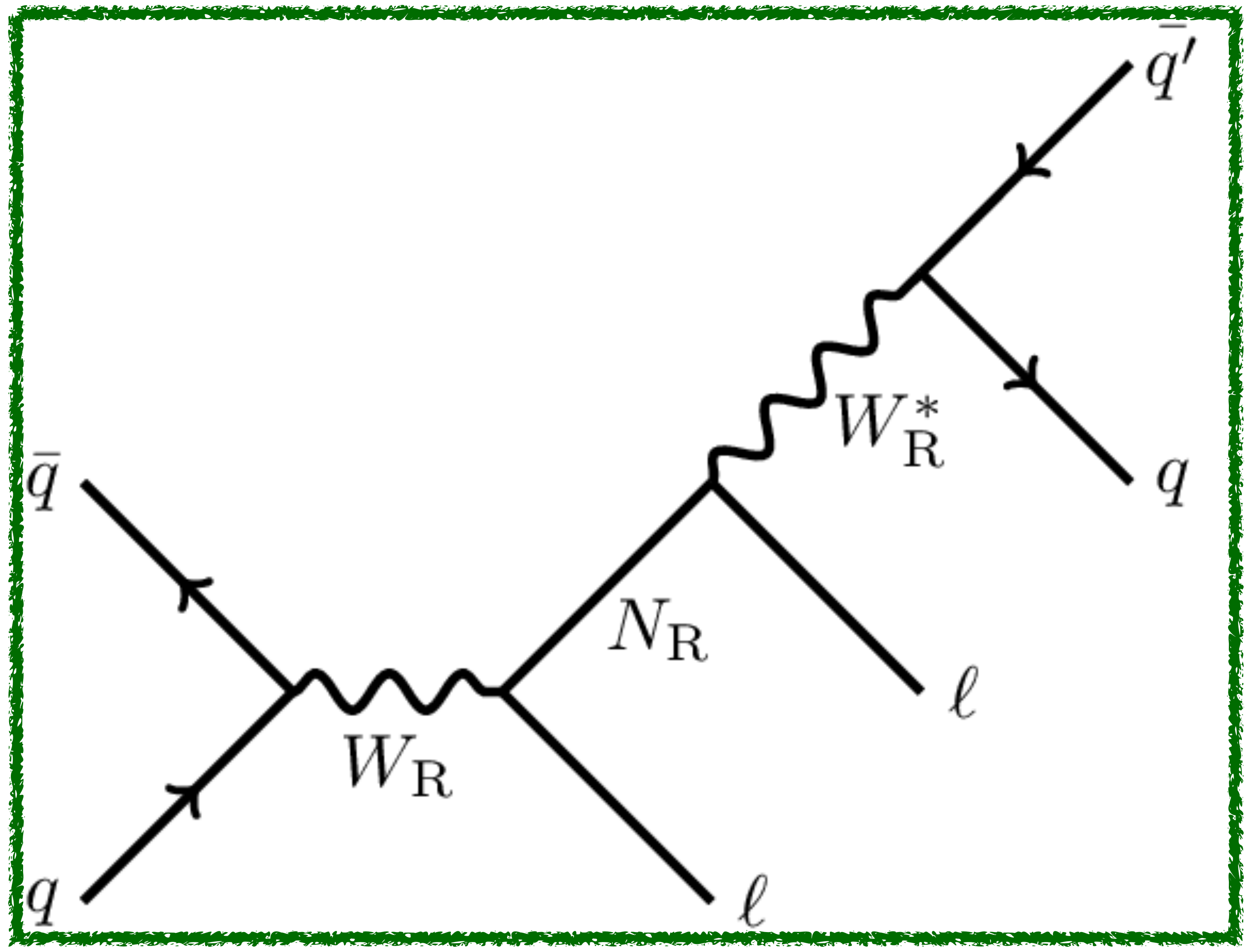


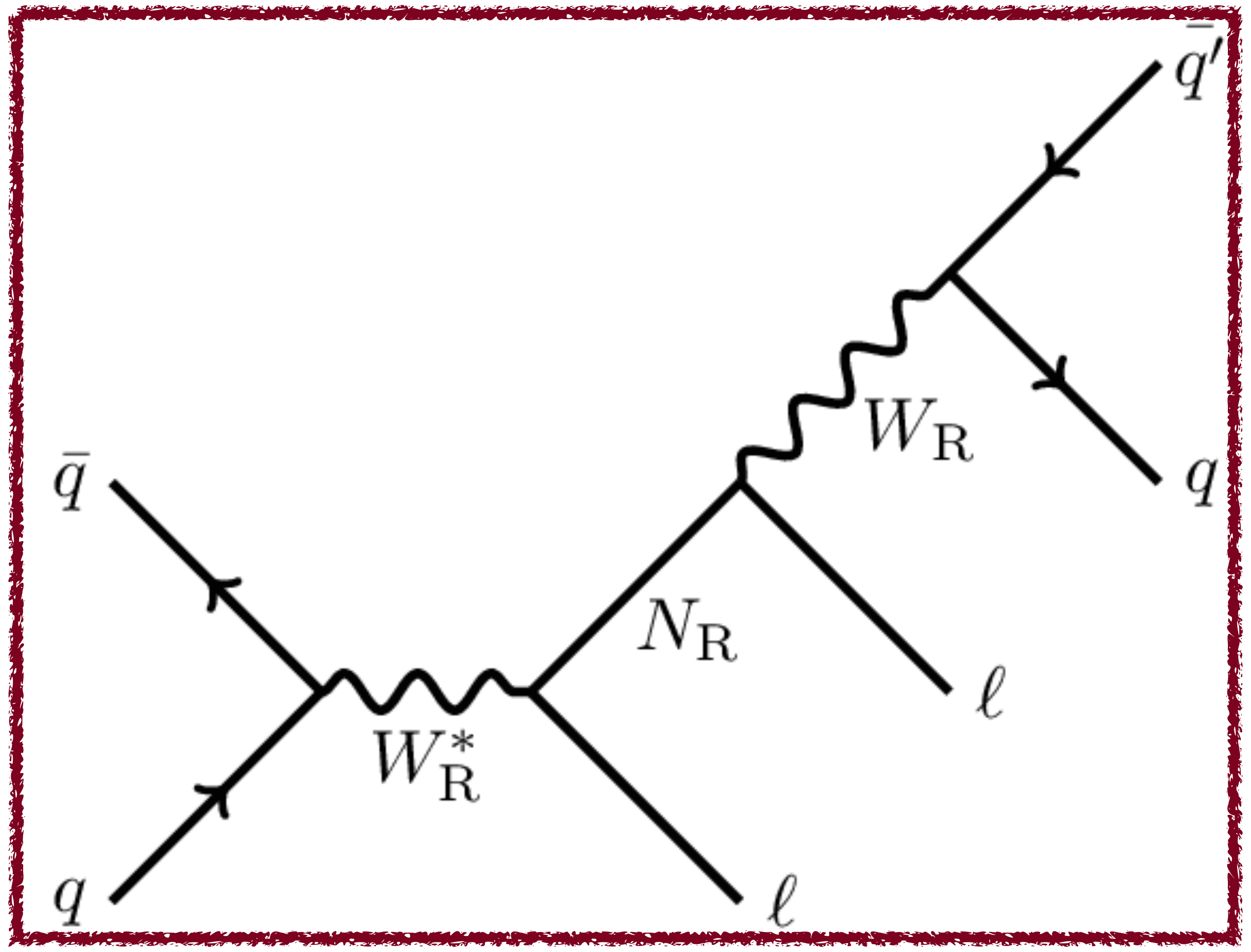
ATL-PHYS-PUB-2025-008

Heavy right handed W_R and N_R

Heavy right handed W_R and N_R

- Left right symmetric model
  - Compatible with type-I and type-II seesaw mechanisms
  - Introduces heavy right handed W_R and N_R
  - N_R gauge partners - left-handed neutrino fields
  - Single flavor coupling to *e*, *μ,* assuming no flavor mixing
  - Dirac - 100% LNC, and Majorana - 50% LNC, 50% LNV
- Highest end of the mass range - promptly decay
- Analysis targets Keung-Senjanović process
- Two scenarios - **$m_{W_R} > m_{N_R}$** and **$m_{N_R} > m_{W_R}$**
  - If $m_{W_R} \sim m_{N_R}$ or $m_{W_R} < m_{N_R}$, resolved regime
  - If $m_{W_R} >> m_{N_R}$ - boosted regime

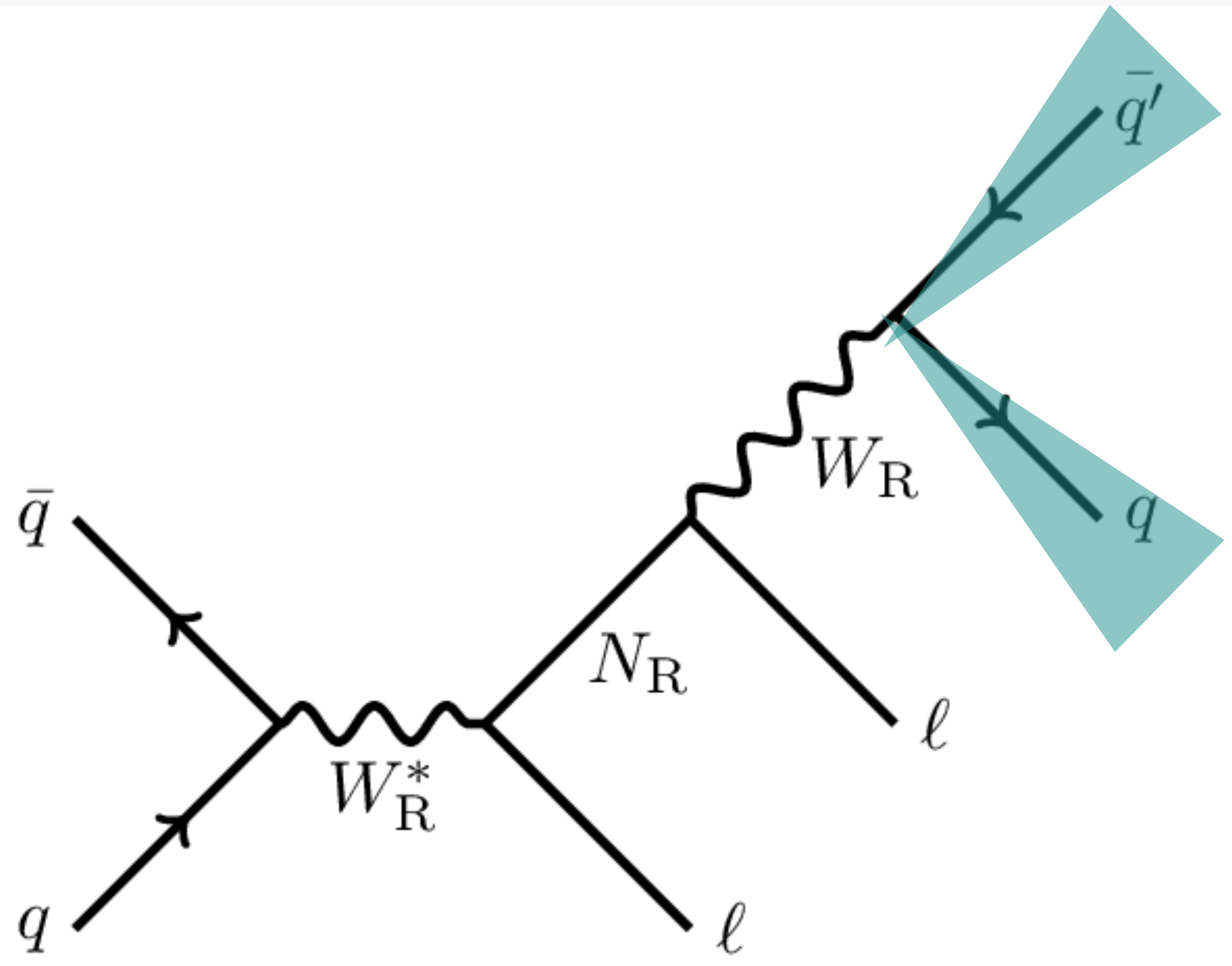


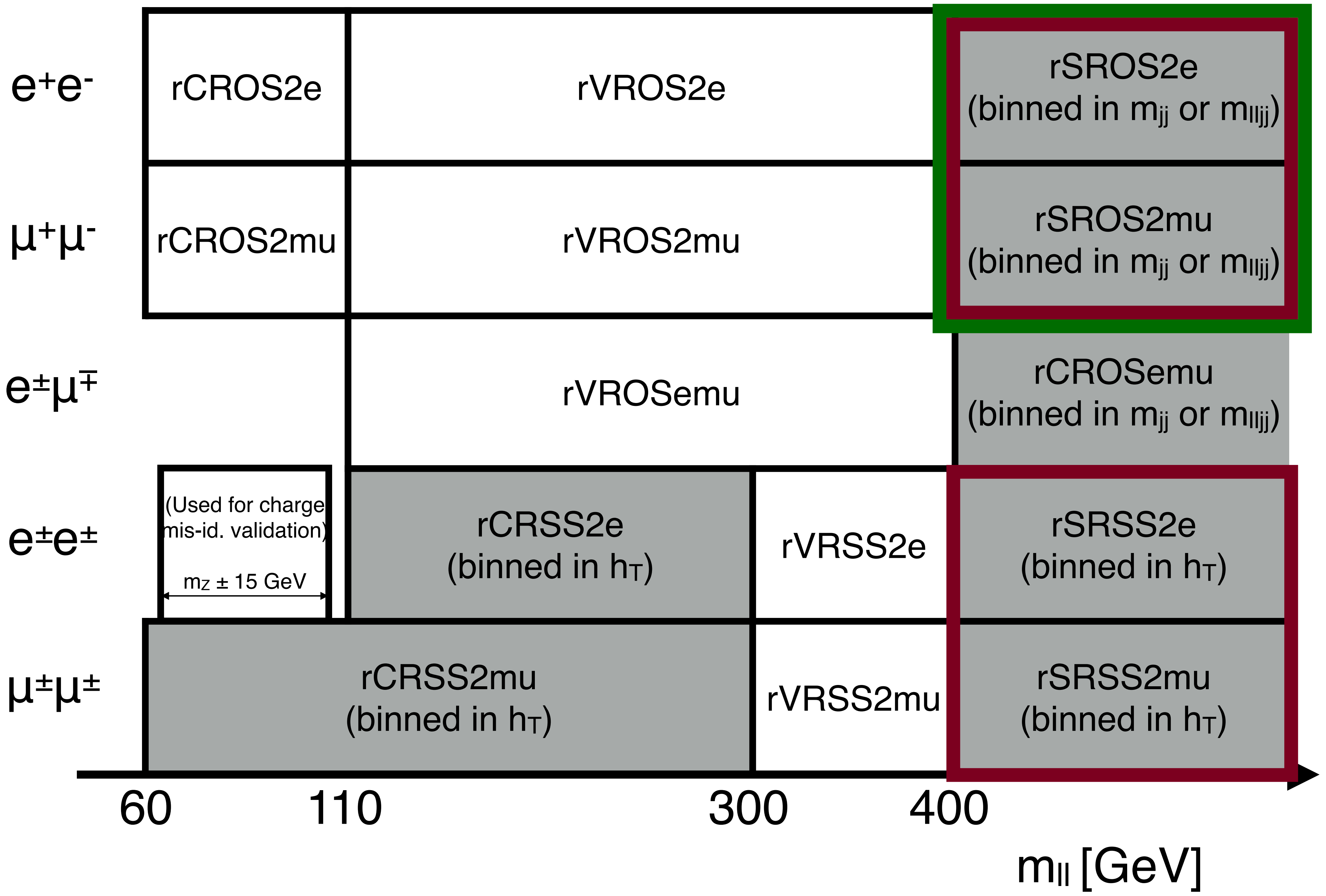


arXiv:2304.09553

Heavy right handed W_R and N_R - Resolved

- m_{W_R} - m_{N_R} < 4 TeV (including $m_{W_R} < m_{N_R}$), resolved regime
  Two distinctly reconstructed R = 0.4 jets
- Four different signal regions for **Majorana** interpretation
  Two signal regions for **Dirac**
- Fit variable in rSROS:
  - $m_{W_R} = m_{lljj}$ (if $m_{W_R} > m_{N_R}$)
    - Binned 0 - 5 TeV in 500 GeV steps
  - $m_{W_R} = m_{jj}$ (if $m_{W_R} < m_{N_R}$)
    - Binned 0 - 3 TeV in 500 GeV steps
- Fit variable in rSRSS:
  - $h_T = p_T(\ell_1) + p_T(\ell_2) + p_T(j_1) + p_T(j_2)$
    - Five variable bins 400 GeV - 2.2 TeV





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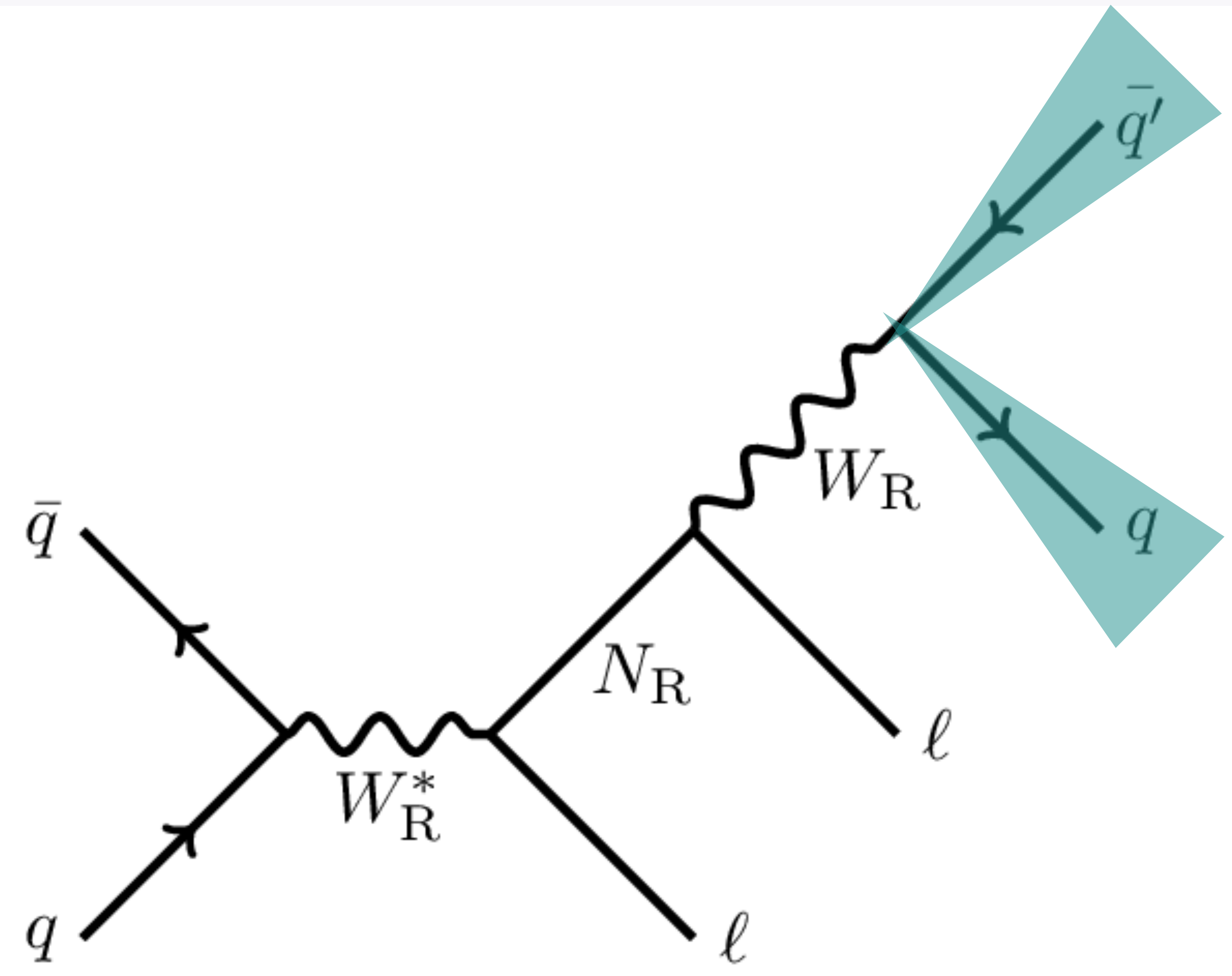
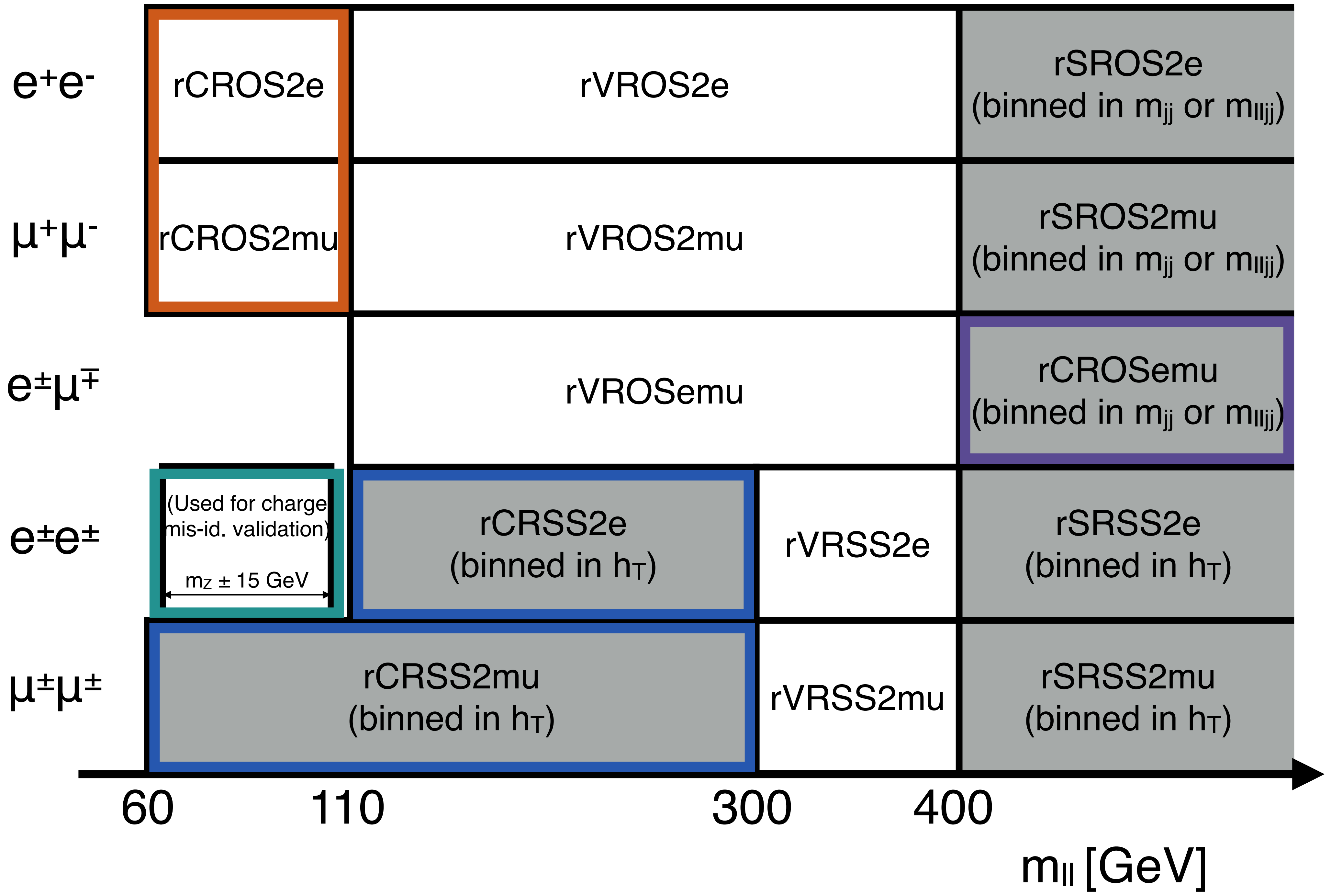
Heavy right handed W_R and N_R - Resolved

- Main backgrounds in rSROS category - **tt** and **Z+jets**
  - Normalization factor for Z+jets to correct multijet mismodelling
  - **rCROS** not used in fit because of this
- Main backgrounds in rSRSS category
  - **WZ** $\rightarrow \ell\ell$, **WZ** $\rightarrow \ell\nu\ell\nu$
  - Z $\rightarrow ee$ (+jets), t events with charge misidentification
    - Charge flip probability determined in **extra control region**
- Small extra background from misidentified leptons calculated through fake factor
- Shaded bins used in the fit





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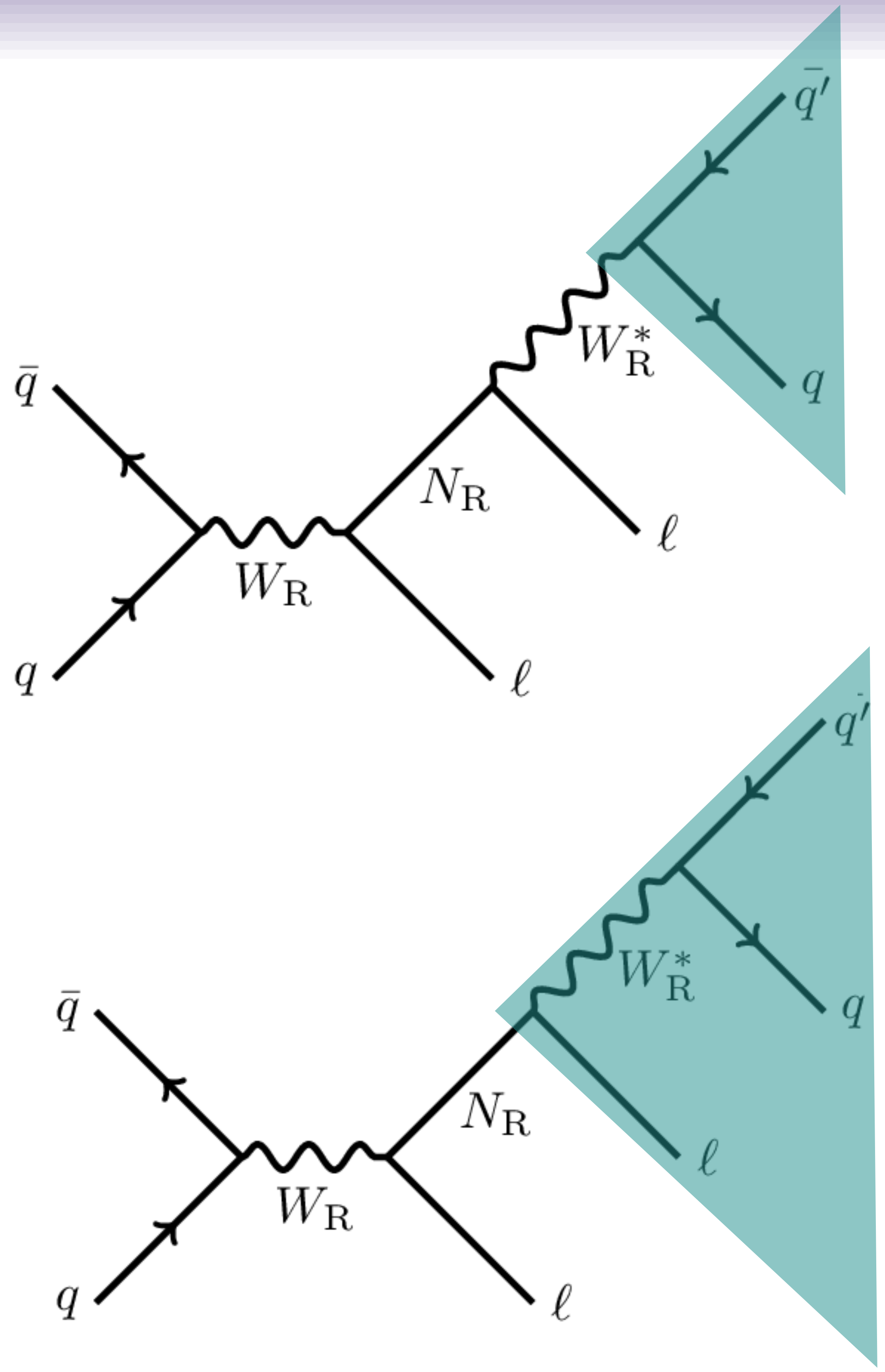
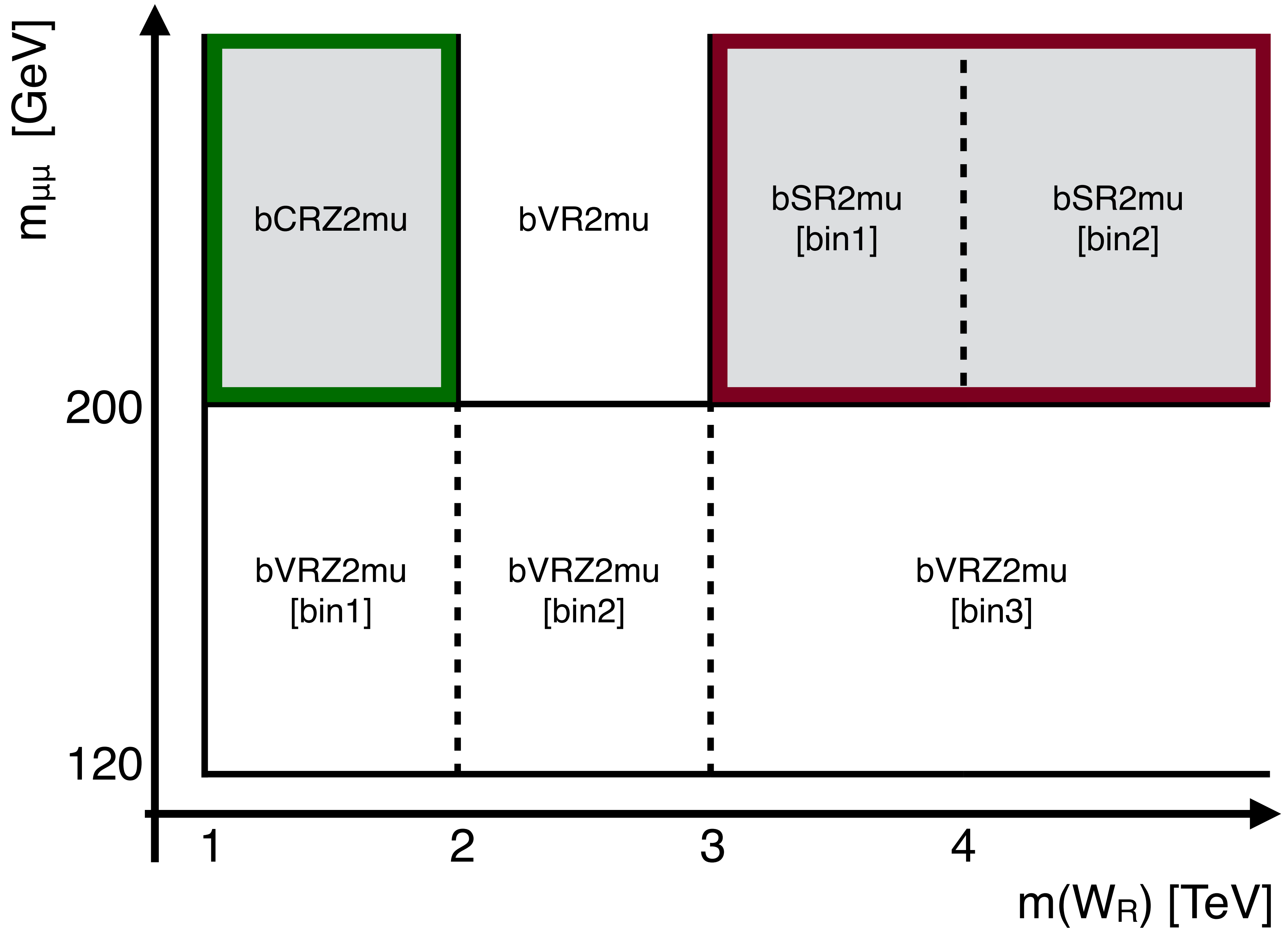
Heavy right handed W_R and N_R - Boosted

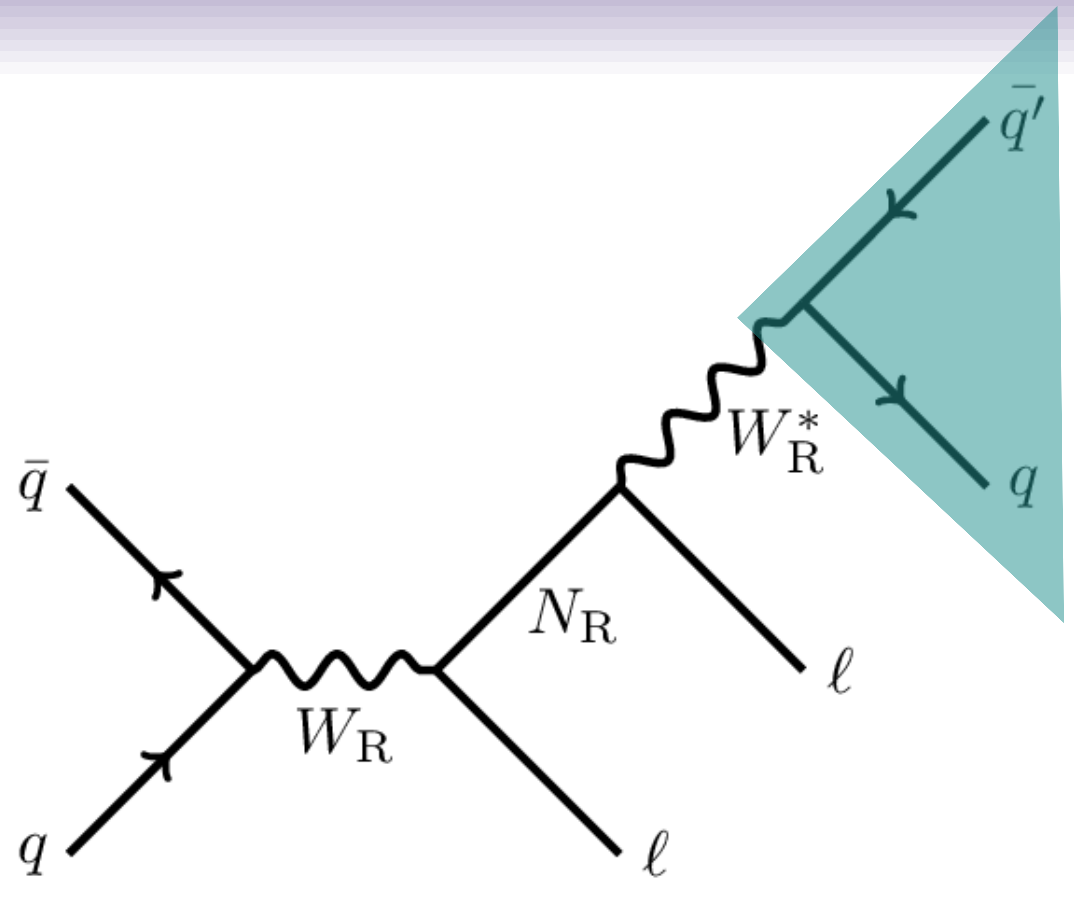
- m_{W_R} - m_{N_R} > 4 TeV boosted regime
  Reconstruct one large-R (R = 1.0) jet and 2 leptons
  or
  Reconstruct large-R jet and one *e* (*μ* can be distinguished within jet)



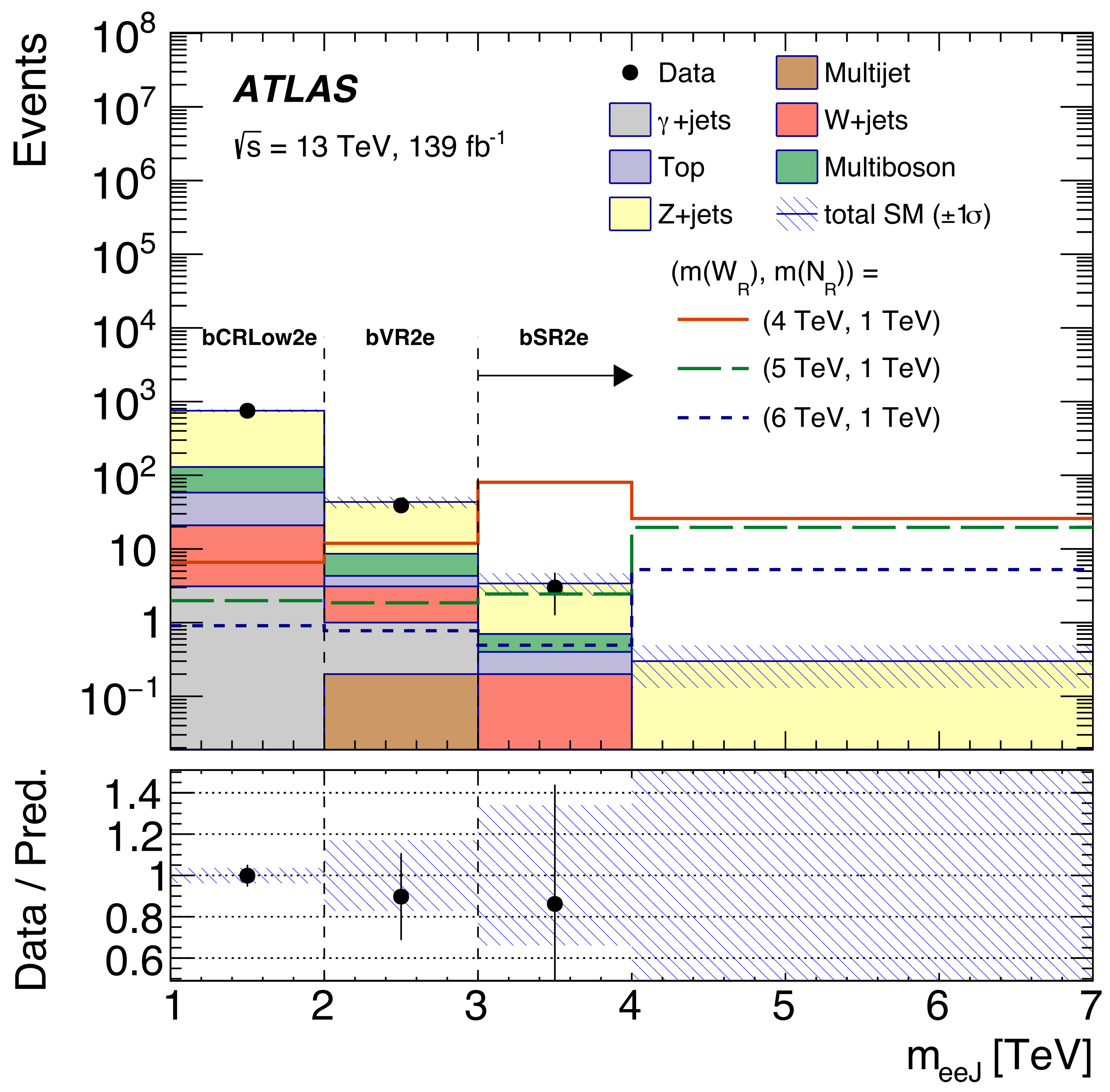


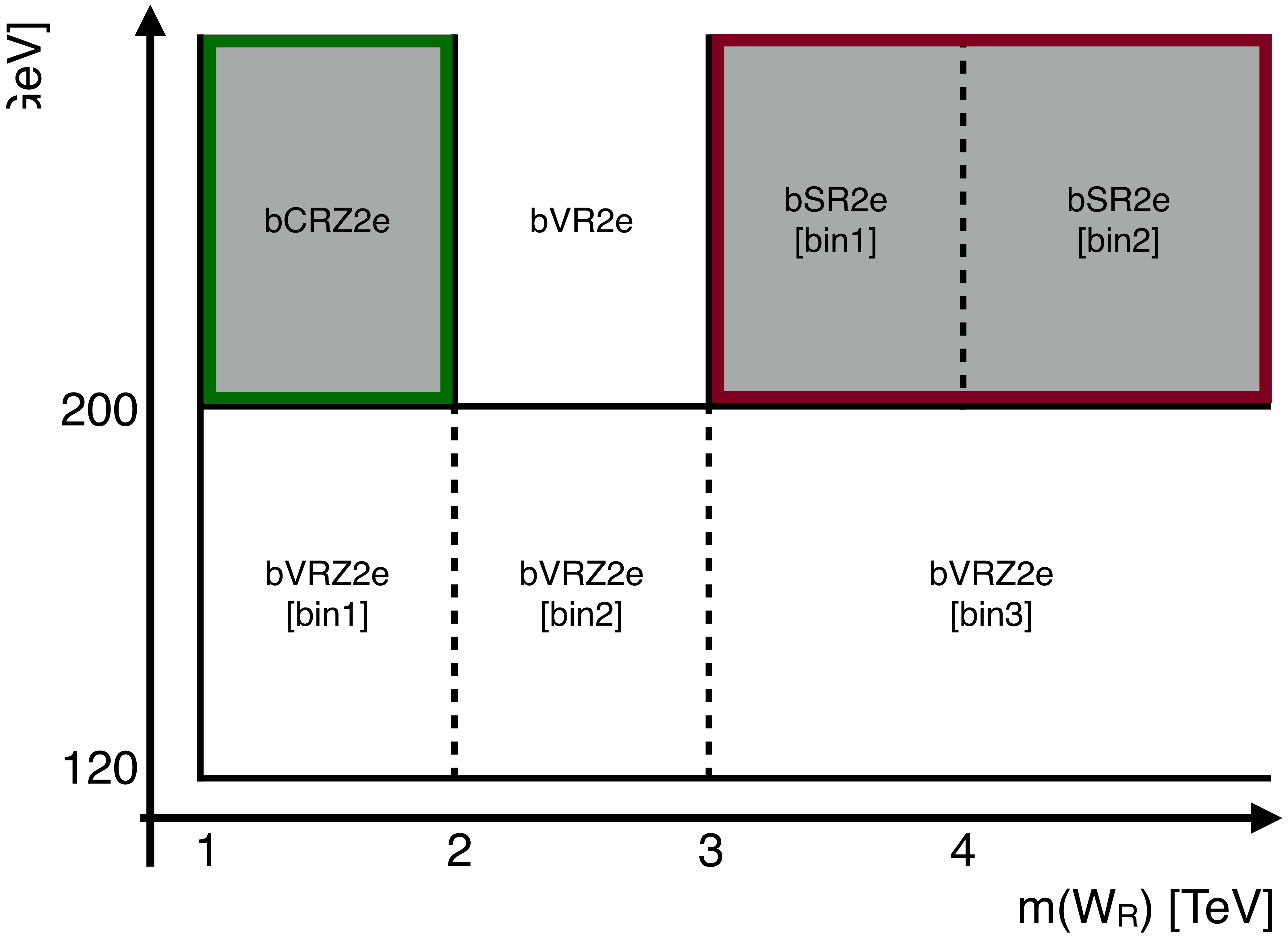
- Discriminant variable becomes $m_{W_R} = m_{llJ}$ or $m_{W_R} = m_{eJ}$
- Divided into 4x 1 TeV bins - expect signal in **two highest mass bins**
- In μ channel, require $m_{\mu\mu}$ > 200 GeV
- Main background from **Z+jets**
  - Only one jet, so no mismodelling issue
- VR regions used to verify method and extrapolations to higher mass bins

Heavy right handed W_R and N_R - Boosted



- For the 1 large-R jet + 2e regions, $m_{W_R} = m_{eeJ}$
  - Target range where $m_{W_R} - m_{N_R} > 4$ TeV but m_{W_R} ! >> m_{N_R}
  - Expect signal in **two highest mass bins**
- Main background from **Z+jets**
- Validation regions used to check data vs MC shape
- Good agreement seen





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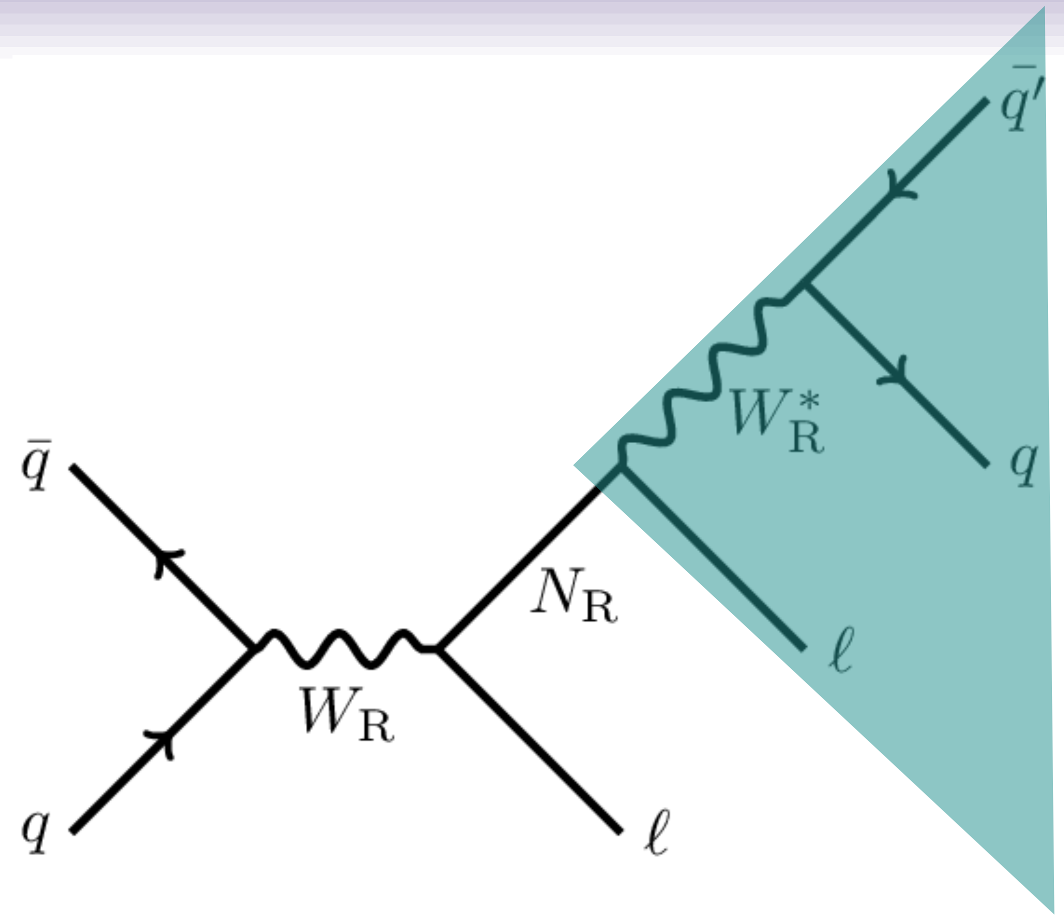
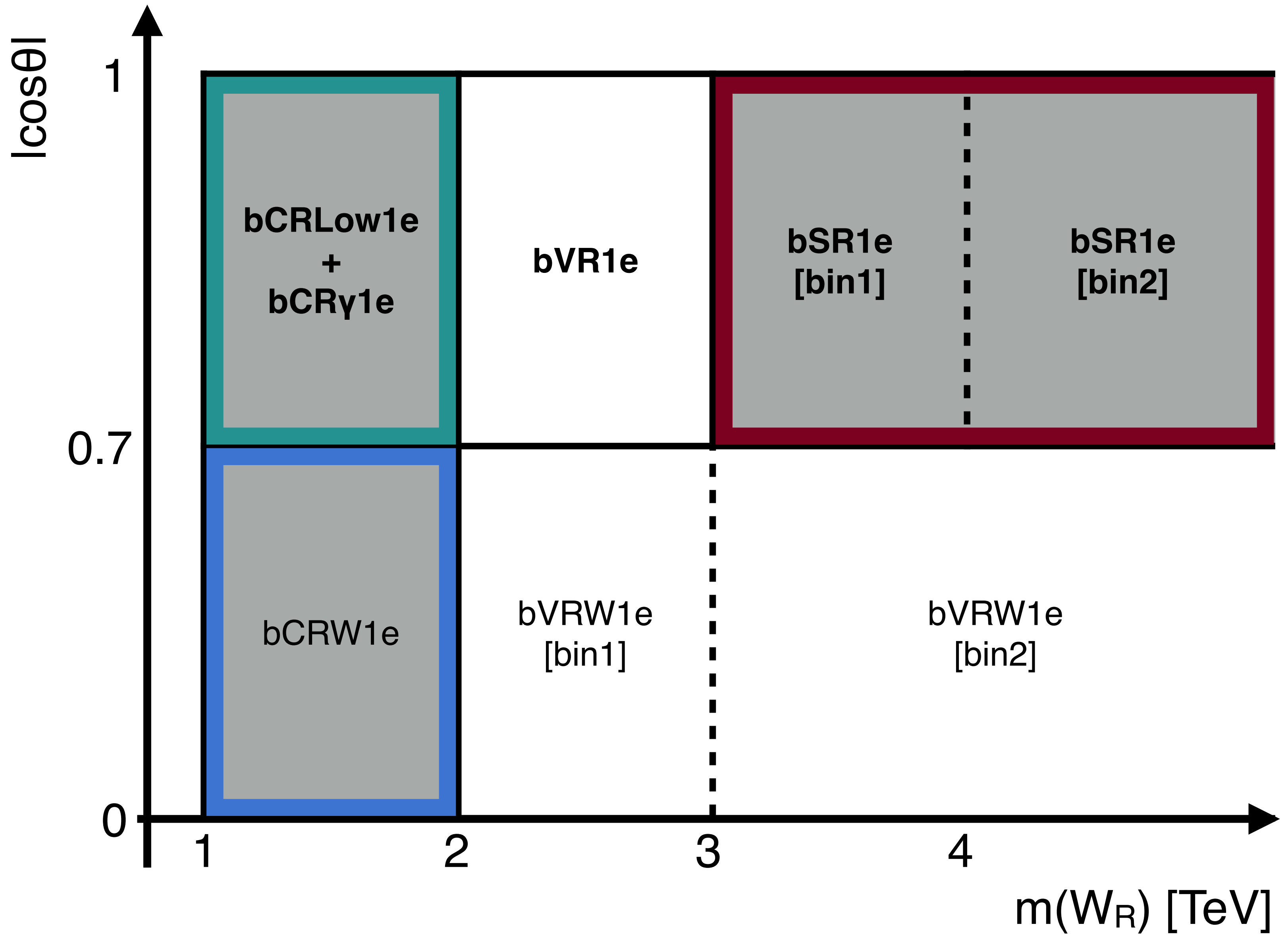
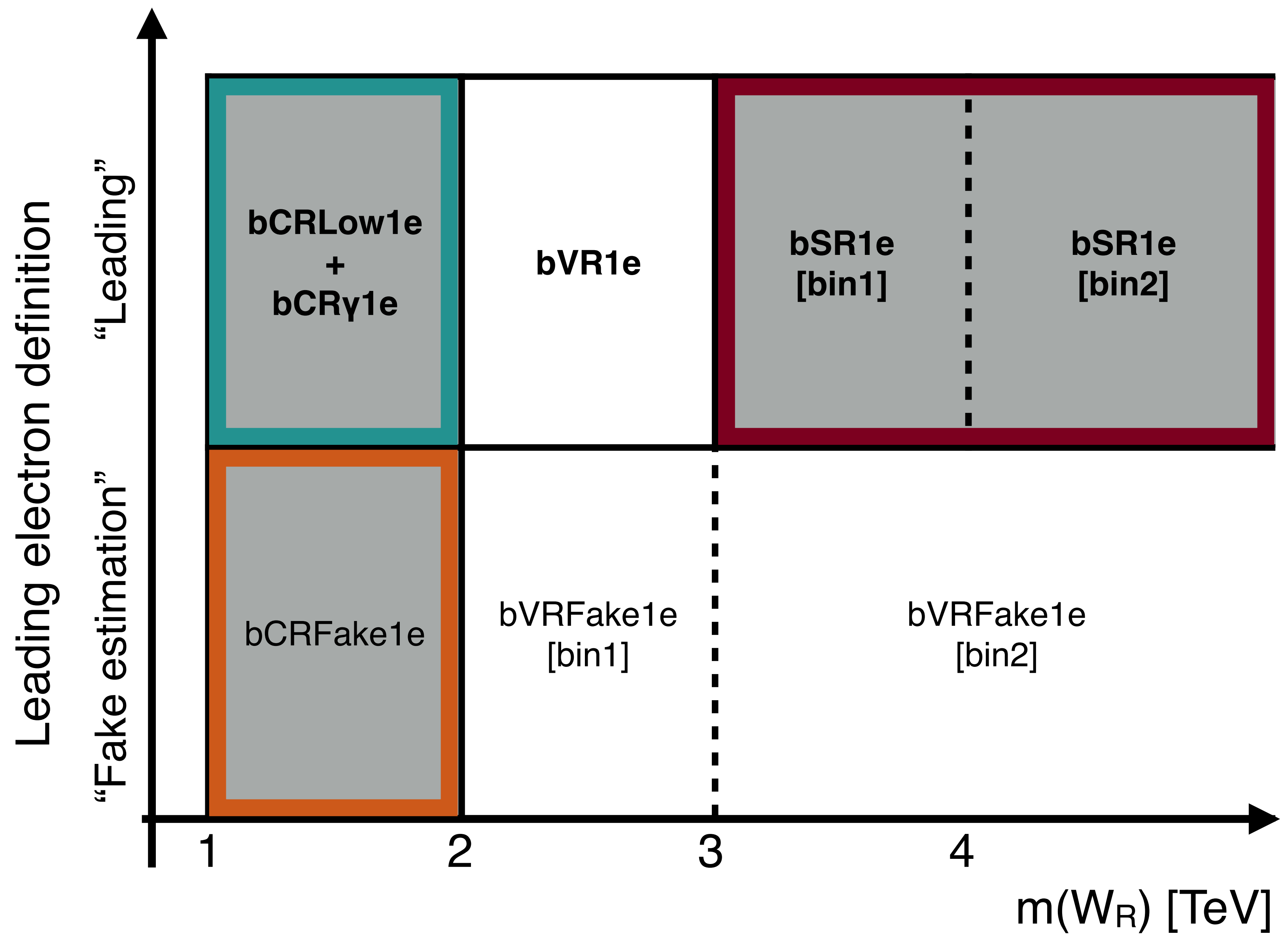
Heavy right handed W_R and N_R - Boosted

- New category added since previous version of search
  - Target higher m_{W_R} - m_{N_R}, orthogonal to 2e channel
  - **Signal regions** are 3-4 and 4+ TeV bins of $m_{W_R} = m_{eJ}$
  - Here, no m_{ll} variable - use cos(θ), polar angle of *e* from W decay, and quality of the *e*
  - Main backgrounds: **W+jets**, **di-jet** and **γ+jets**, with a **fake *e***
  - Shaded regions used in the fit

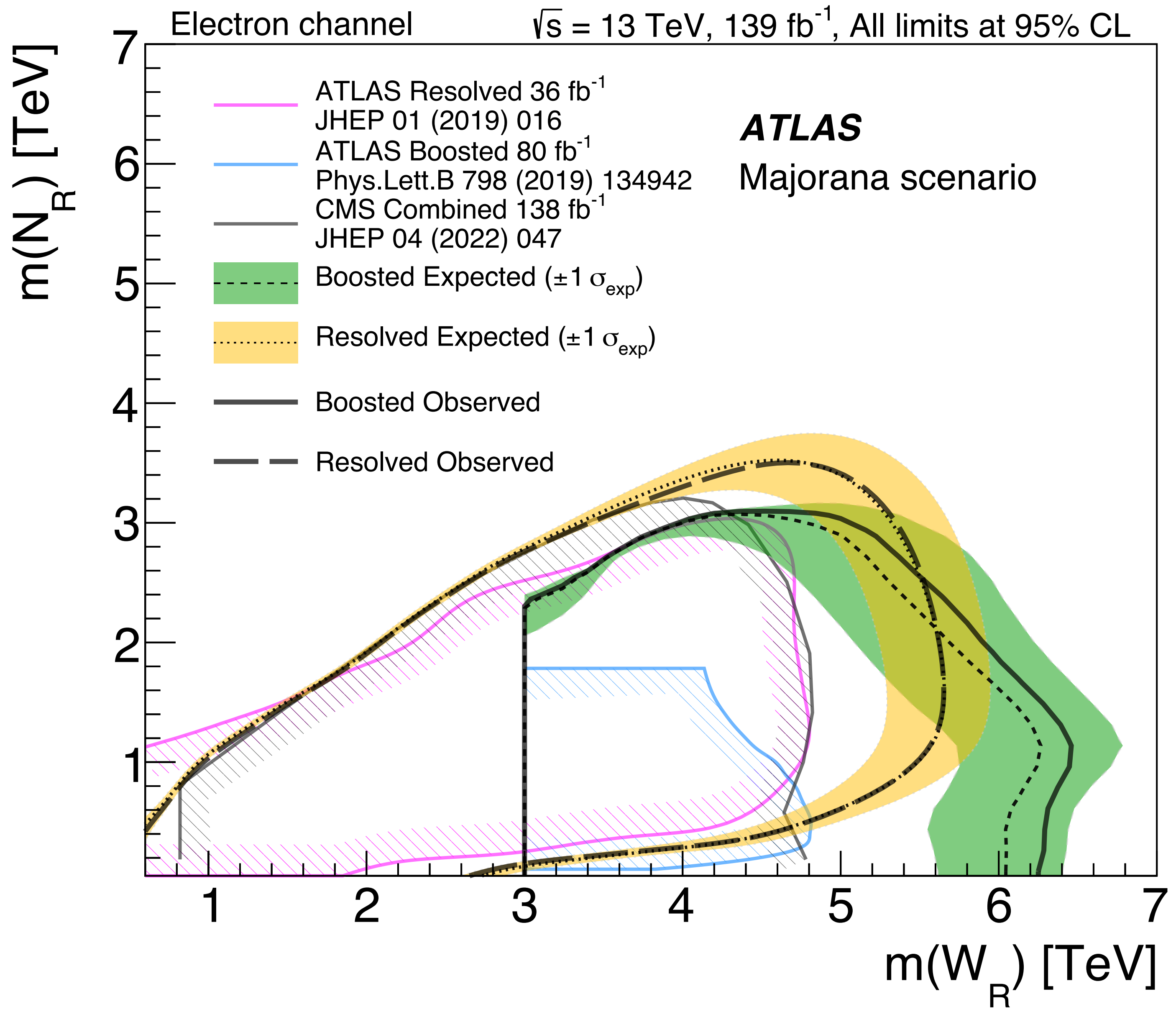


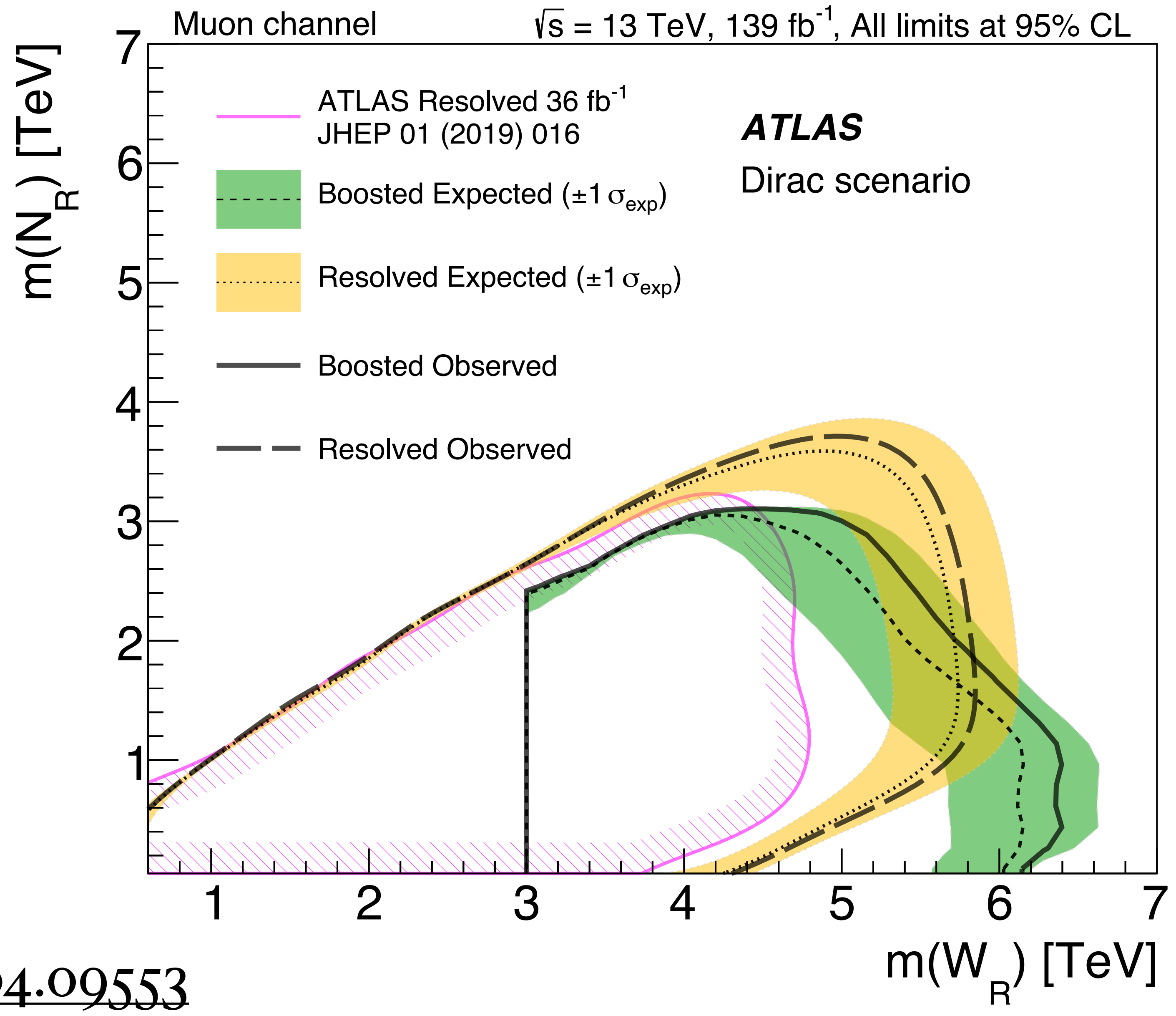


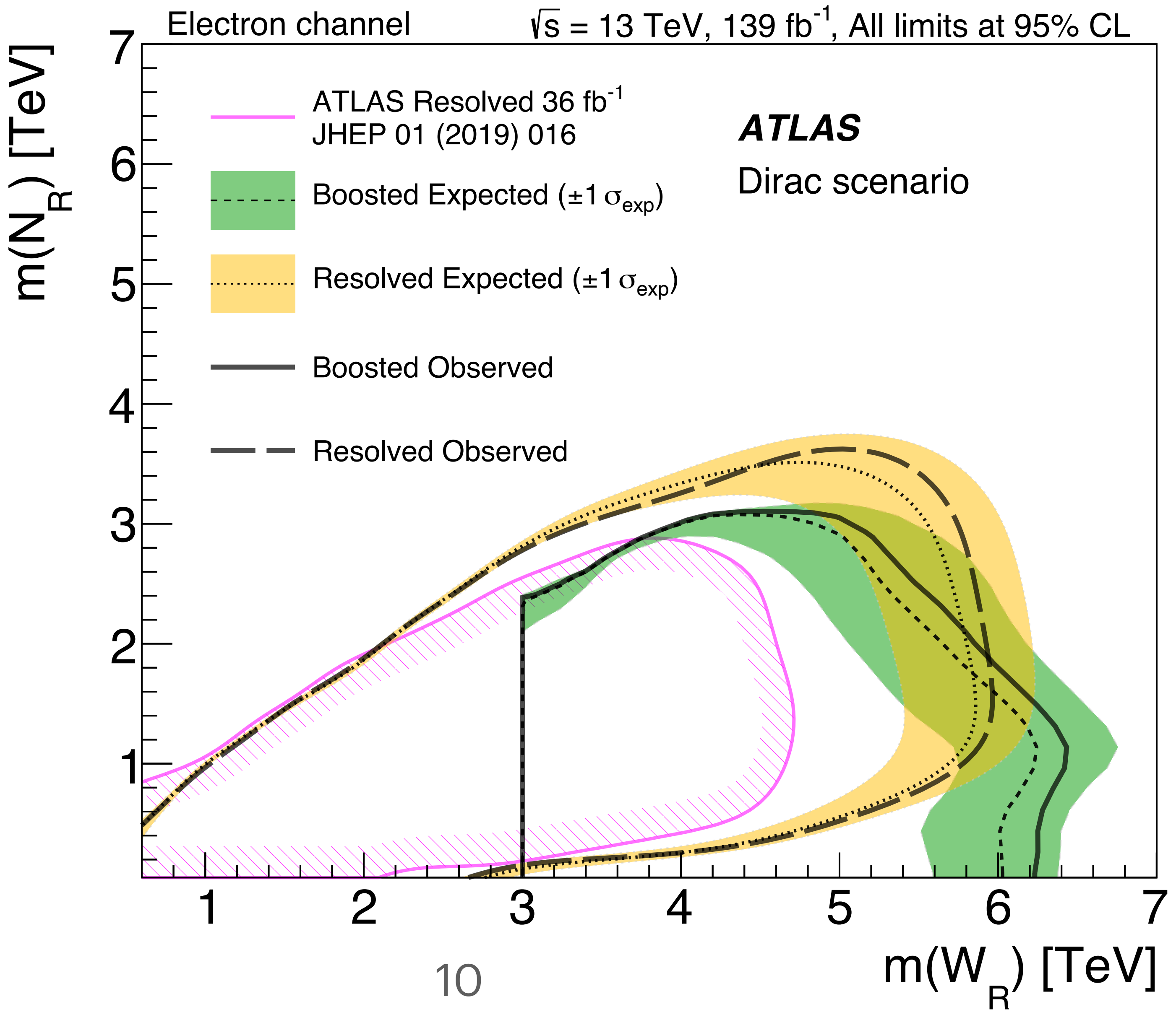


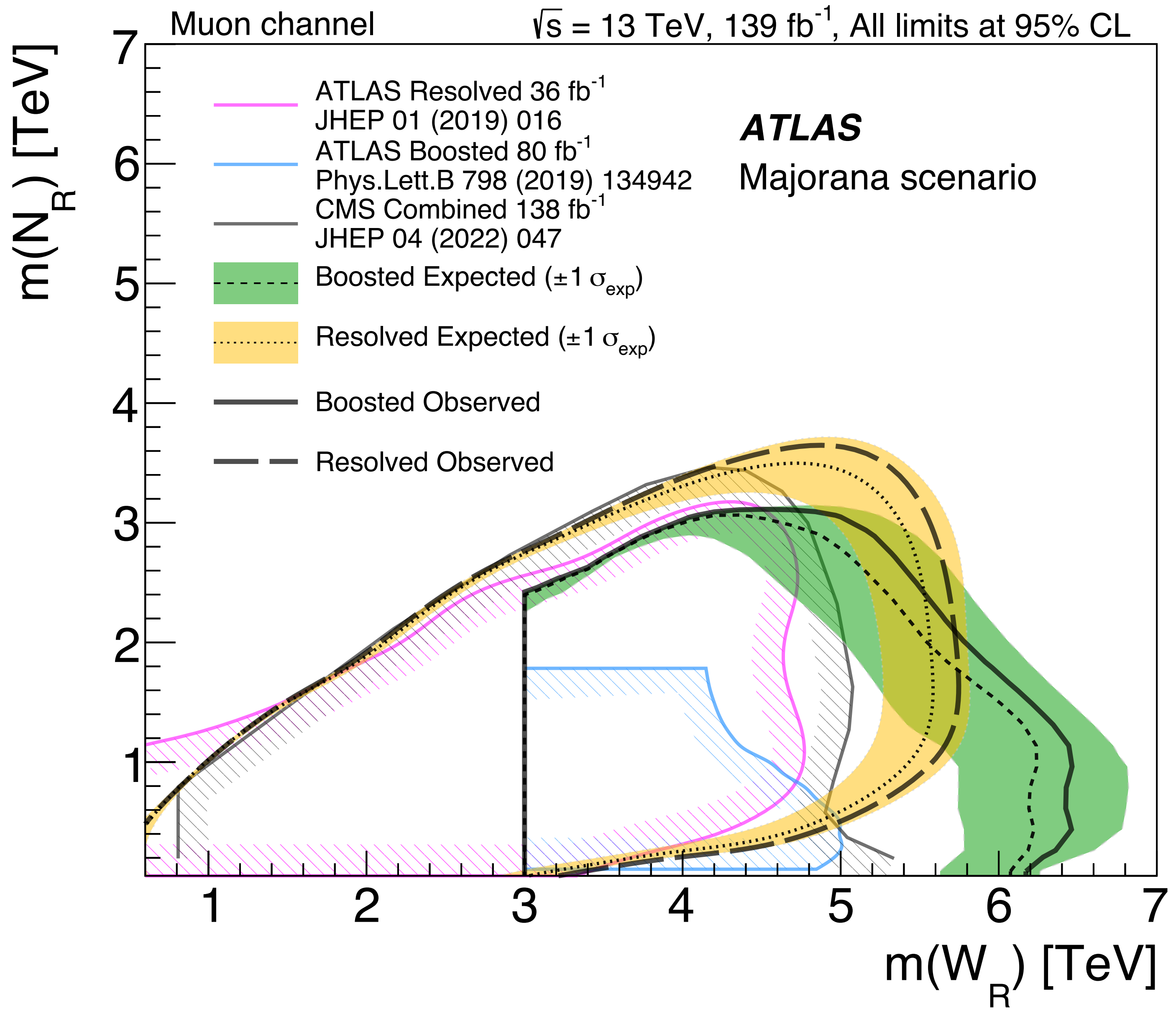
Heavy right handed W_R and N_R

- No significant excess seen, set limits at 95% CL
- Resolved and boosted channels not orthogonal and are not combined
- Significant increase in sensitivity in Dirac and Majorana scenarios for *e* and *μ* coupling
- Does not see the same ~3σ local excess observed by previous CMS search







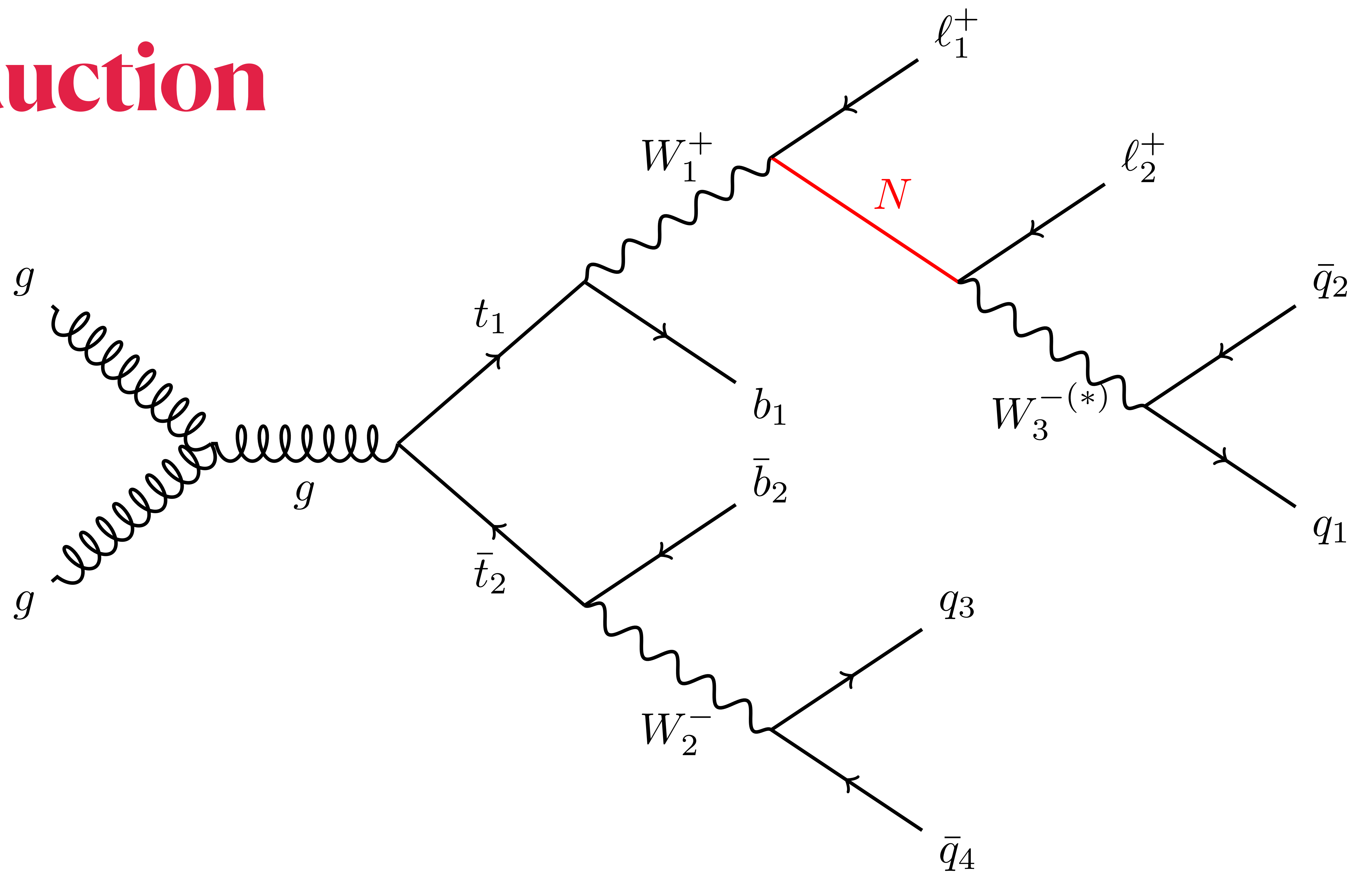


arXiv:2304.09553

Heavy neutrino via top production

Heavy neutrino via top production

- First time searching for HNL in tt events
- Type-I seesaw mechanism
  - 3 Majorana HNL candidates, with single flavor mixing to *e*, *μ*, *τ*
- Target final state in which ℓ_1, ℓ_2 are same-charge *ee* or *μμ*
  - Only focus on LNV processes
- Consider N mass range 10 - 75 GeV
  - HNL decays promptly
- Other W and W* both decay hadronically
  - Final state - 2 same sign, same flavor leptons, 2 b-jets, 4 light jets

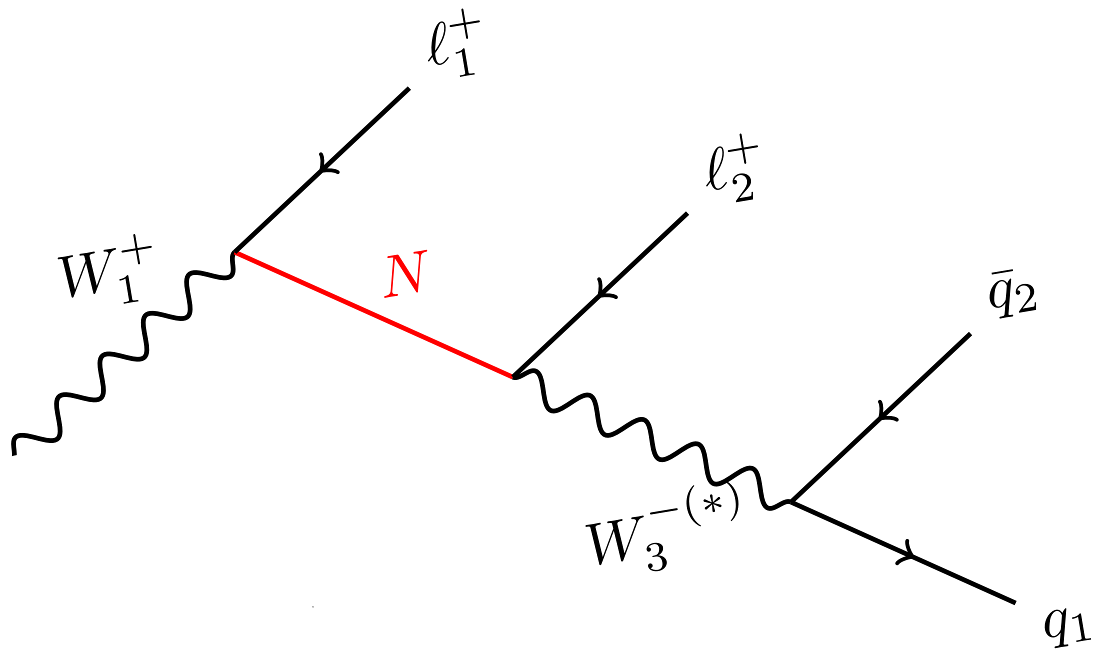


charge conjugate also considered

arXiv:2408.05000

Heavy neutrino via top production - *ee* analysis regions

- Prominent backgrounds from ttW, (also ttH, ttZ, ttγ), as well as from photon conversion, mis-identified charge, mis-reconstructed hadrons
- Electron charge determined by curvature of the track - more difficult for high-p_T e
  - BDT-based tool used, known as “electron charge identity selector” (ECIDS)
- Likelihood based discriminant used for e/γ ambiguity removal
- m_{ll} < 80 GeV - m_{ll} < mW



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

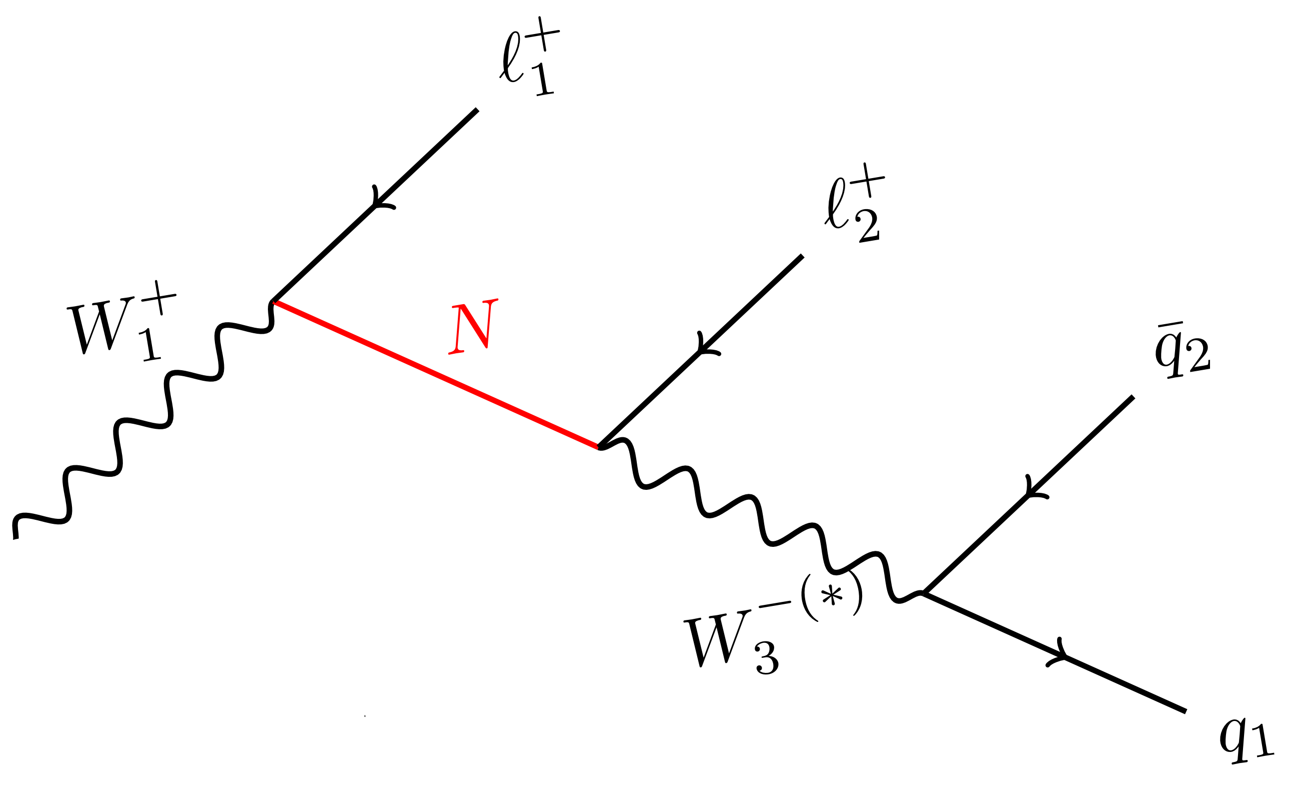
arXiv:2408.05000

Heavy neutrino via top production - $\mu\mu$ analysis regions

- Again, ttW is a dominant background process
- For μ charge flipping found to be negligible
- Main source of same-sign $\mu\mu$ pairs from heavy flavor decays
- Once again, m_{ll} < 80 GeV - m_{ll} < mW
- For $\mu\mu$ channel, no Z-mass veto needed
- For HF CR, despite isolation criteria on ≤ 1 of the muons, $m_{\mu\mu}$ requirement > 75 GeV to reduce signal contamination
- For all signal regions, BDT used to further separate signal from background

Analysis regions for the $\mu\mu$ channel

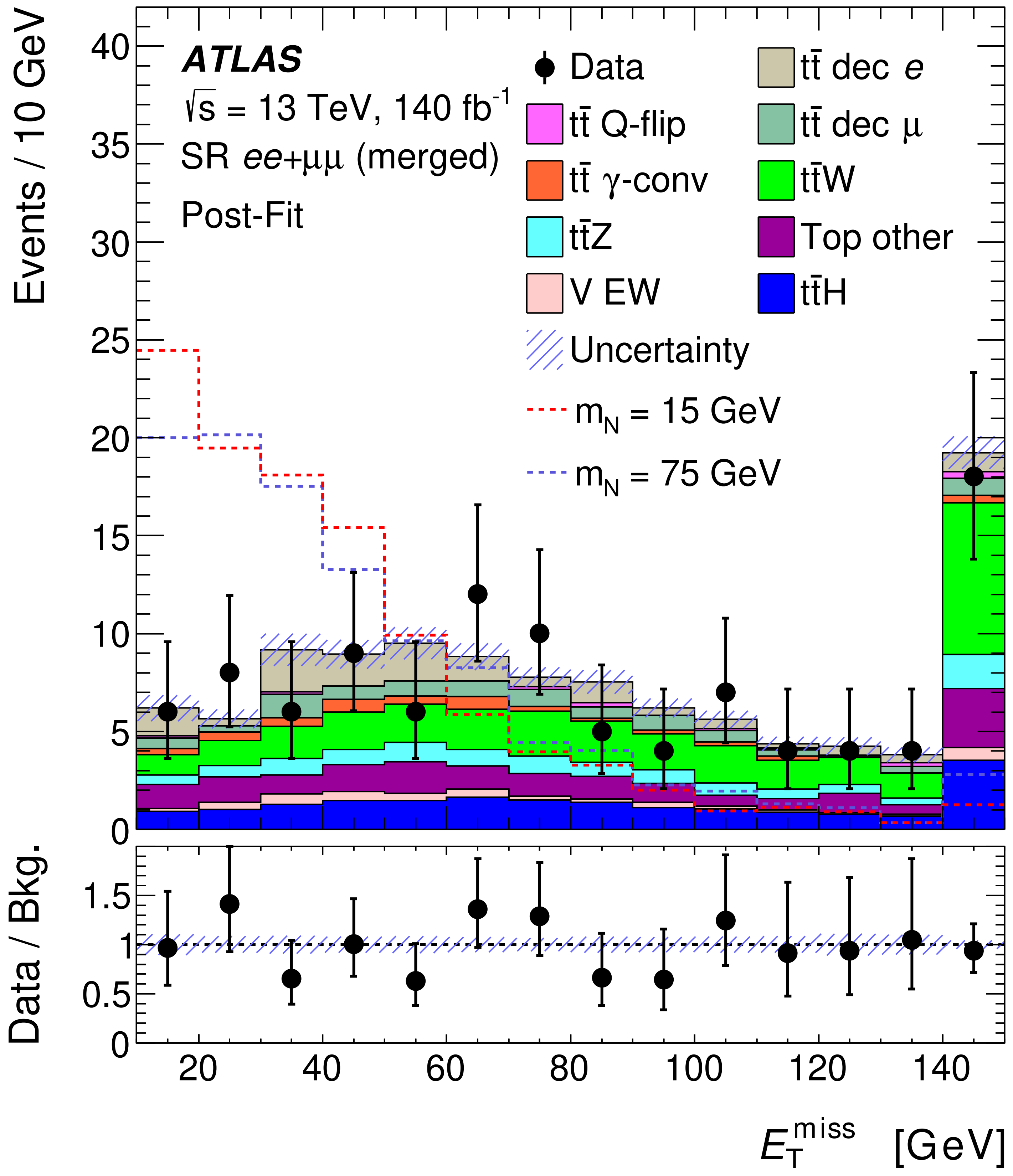
Region	Isolation criteria	$m_{\mu\mu}$ requirement
SR	Both μ	< 80 GeV
$t\bar{t}W$ CR	Both μ	> 80 GeV
HF CR	At most one μ	> 75 GeV

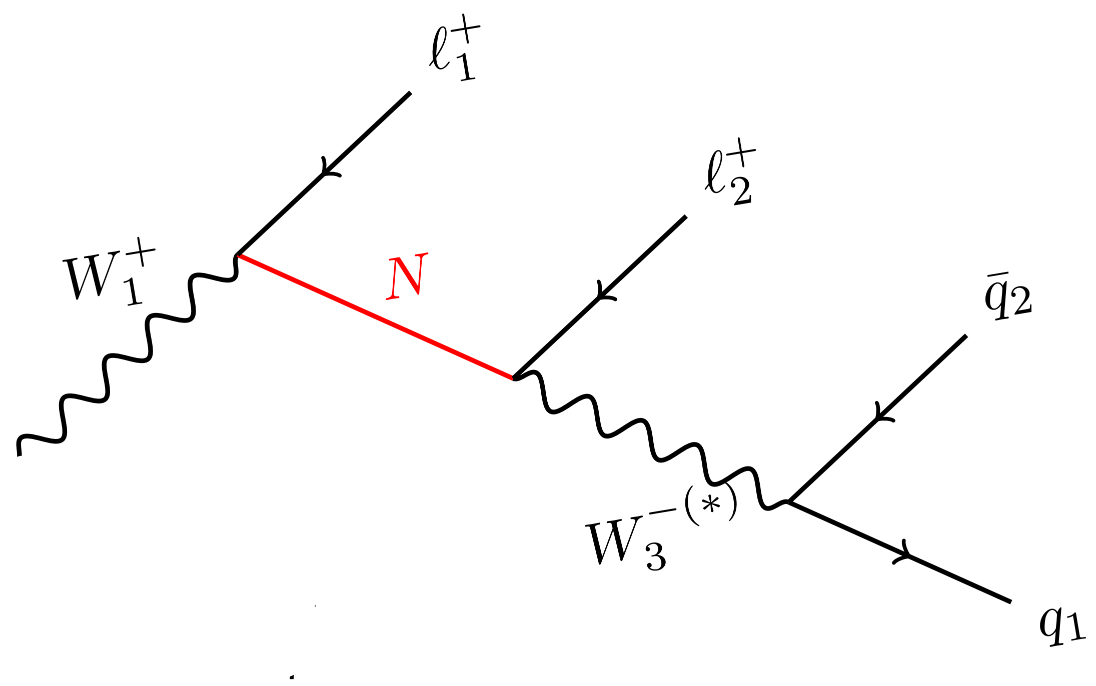


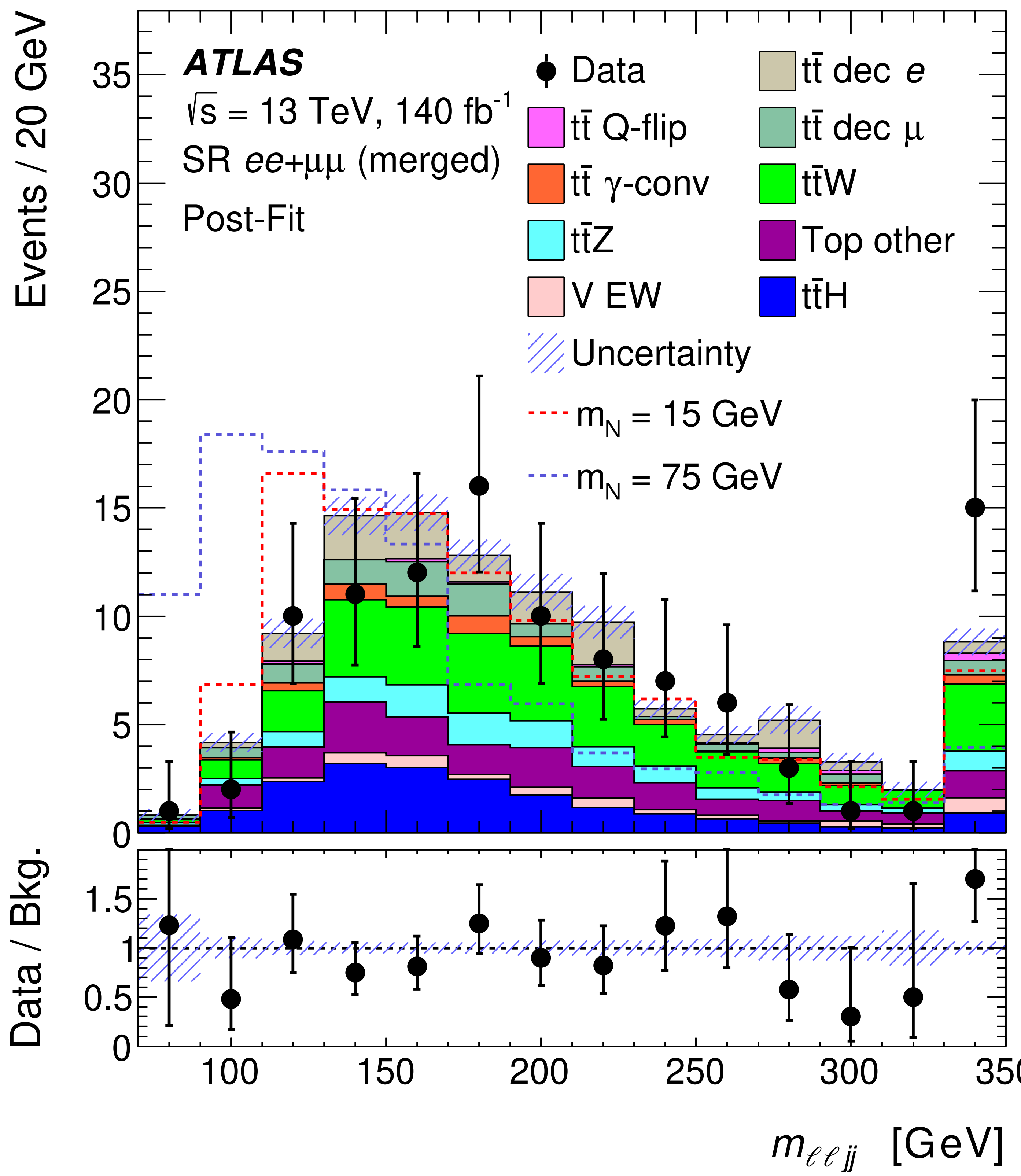
arXiv:2408.05000

Heavy neutrino via top production - BDT

- Two BDTs trained -
  low mass (15 - 40 GeV)
  high mass (45 - 75 GeV)
- Mixture of signal samples and all background samples
- Key variables:
  - Invariant mass m_{ll}
  - Missing energy - E_T^{miss}
  - Invariant mass of W_1 - m_{lljj}
  - p_T of the subleading lepton $p_T^{\ell_2}$







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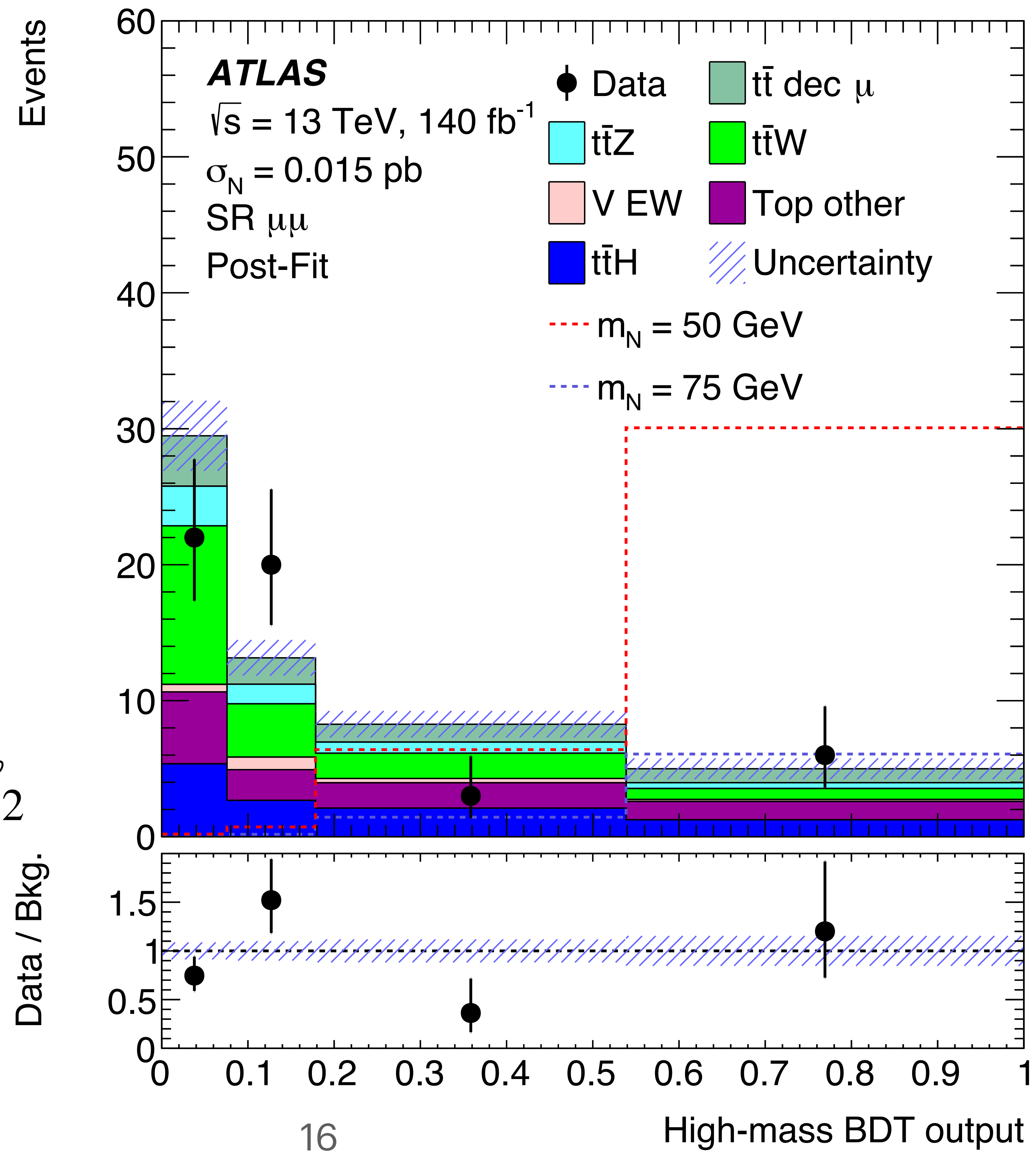
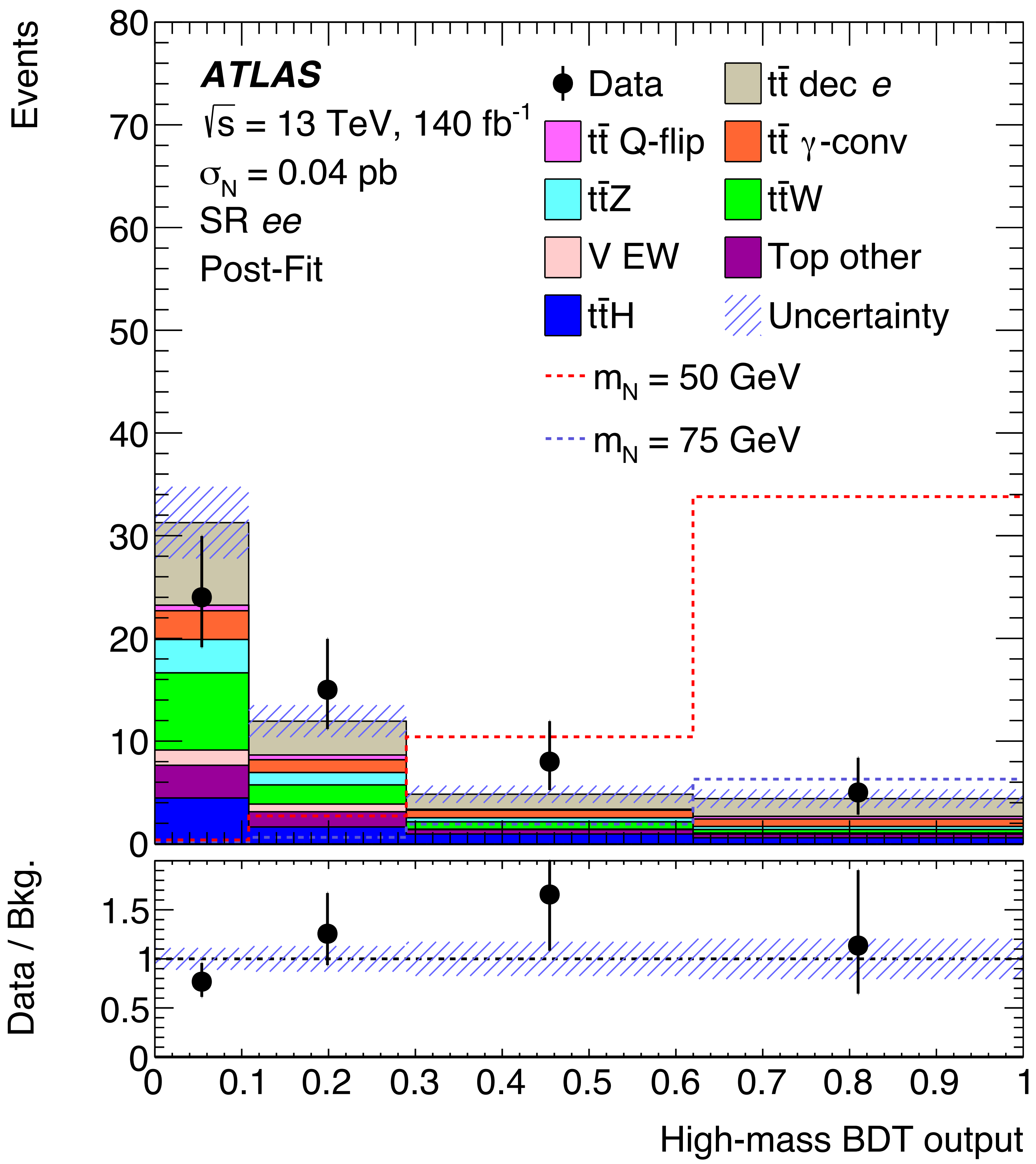


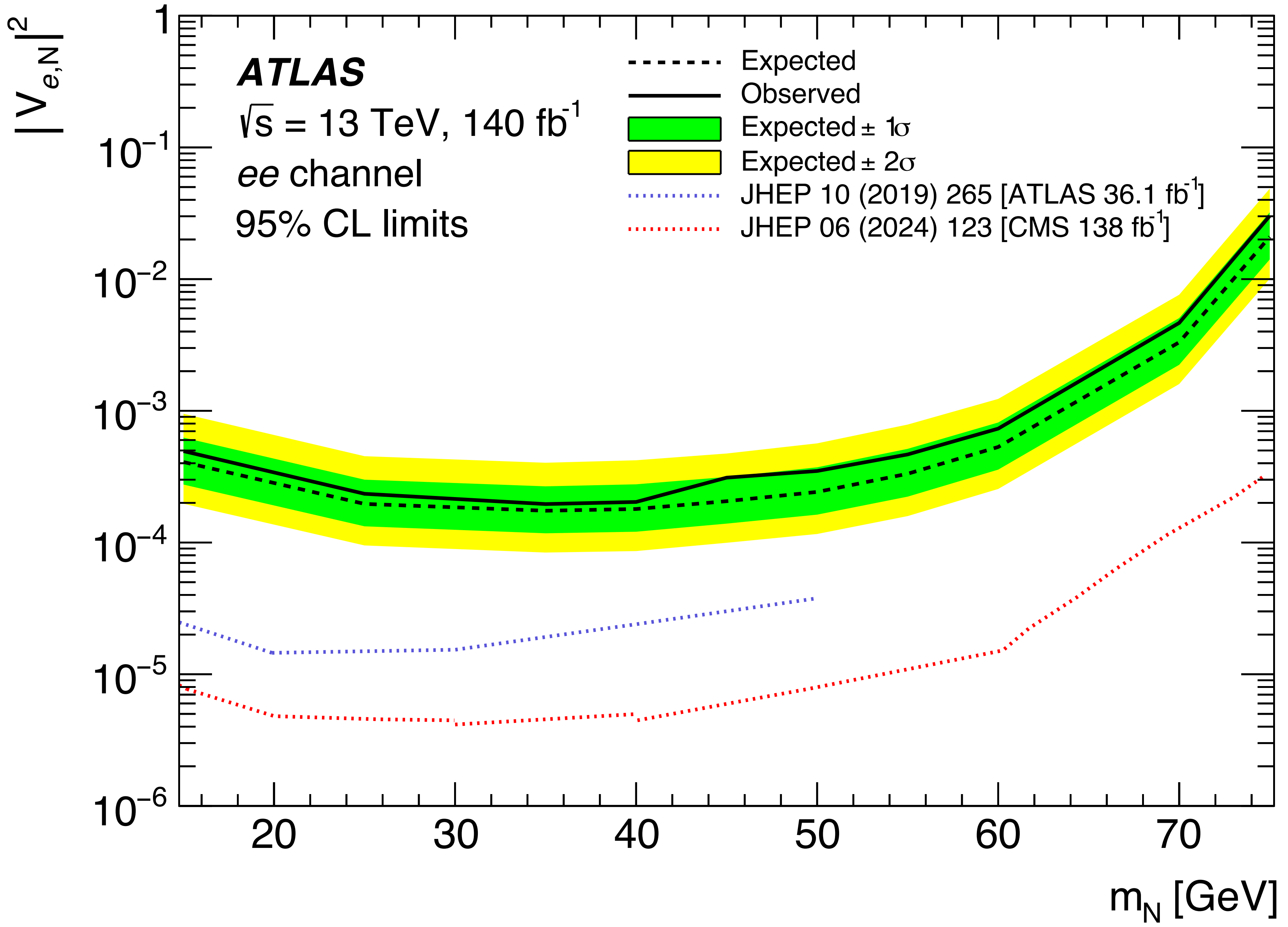


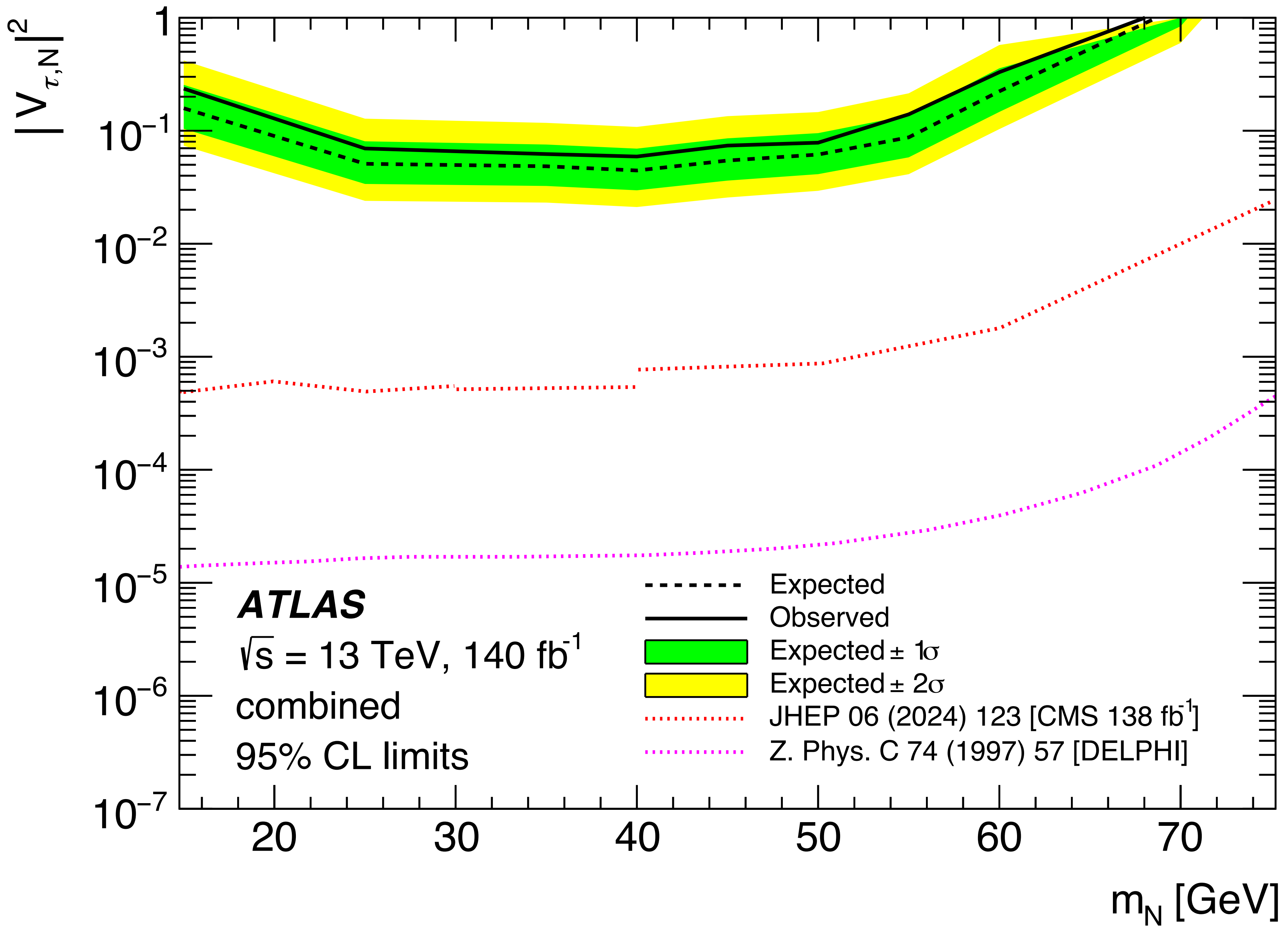
- BDT found to provide better separation than the individual inputs

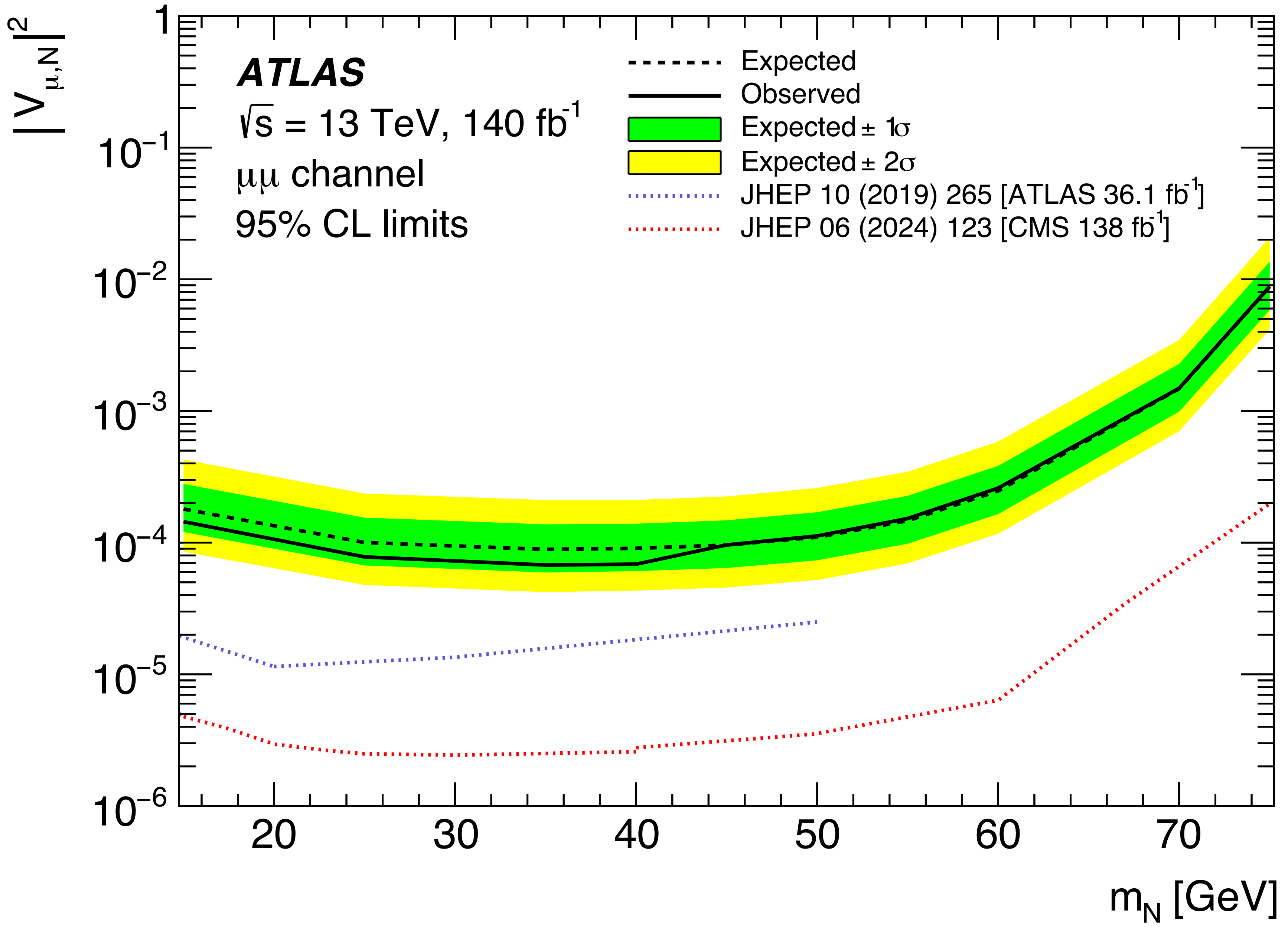
arXiv:2408.05000

Heavy neutrino via top production

- No significant excess found
- Limits set for coupling to e, μ, and τ
  - First ATLAS search to target τ coupling
  - Extends the mass range of the previous ATLAS prompt search







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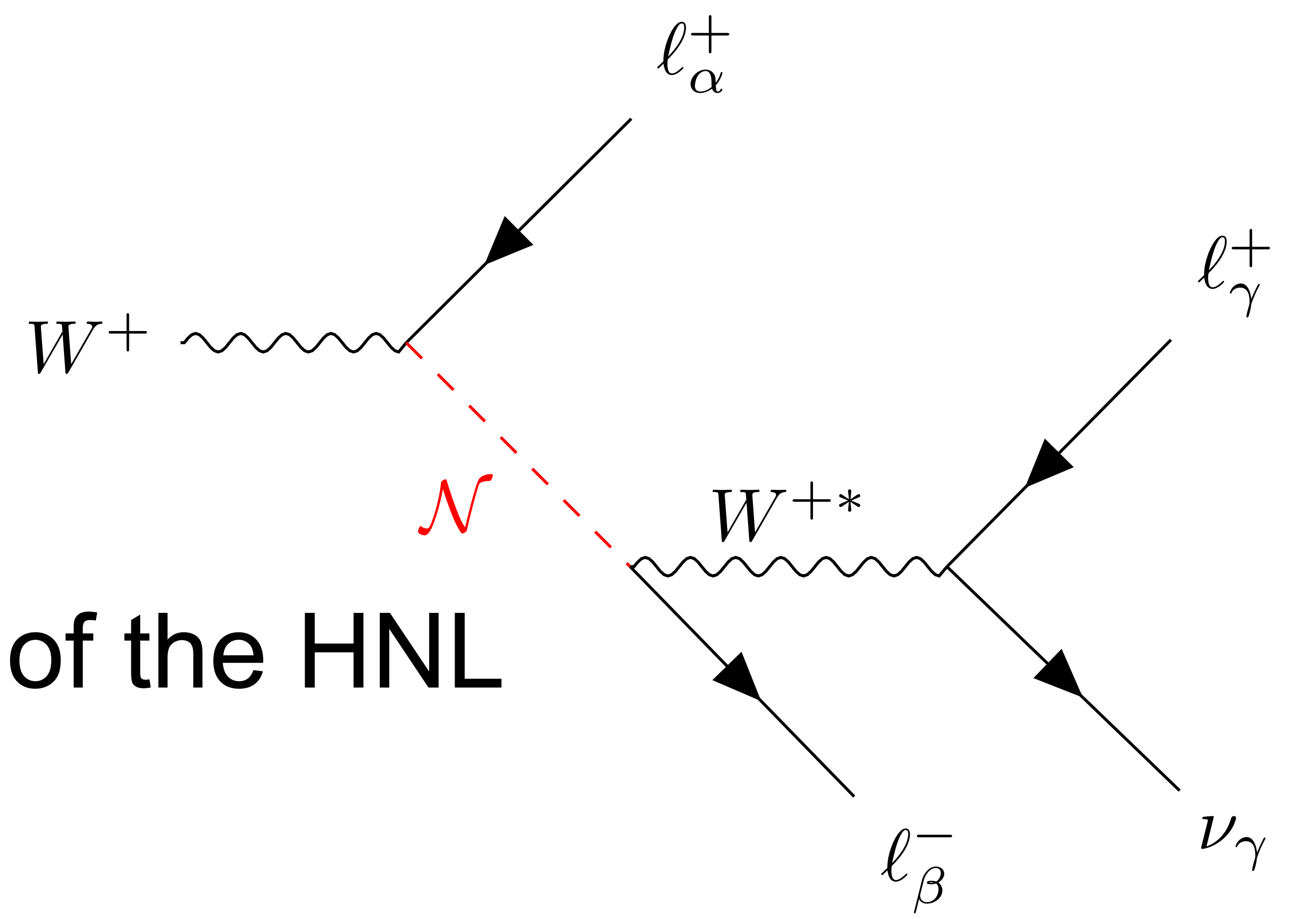
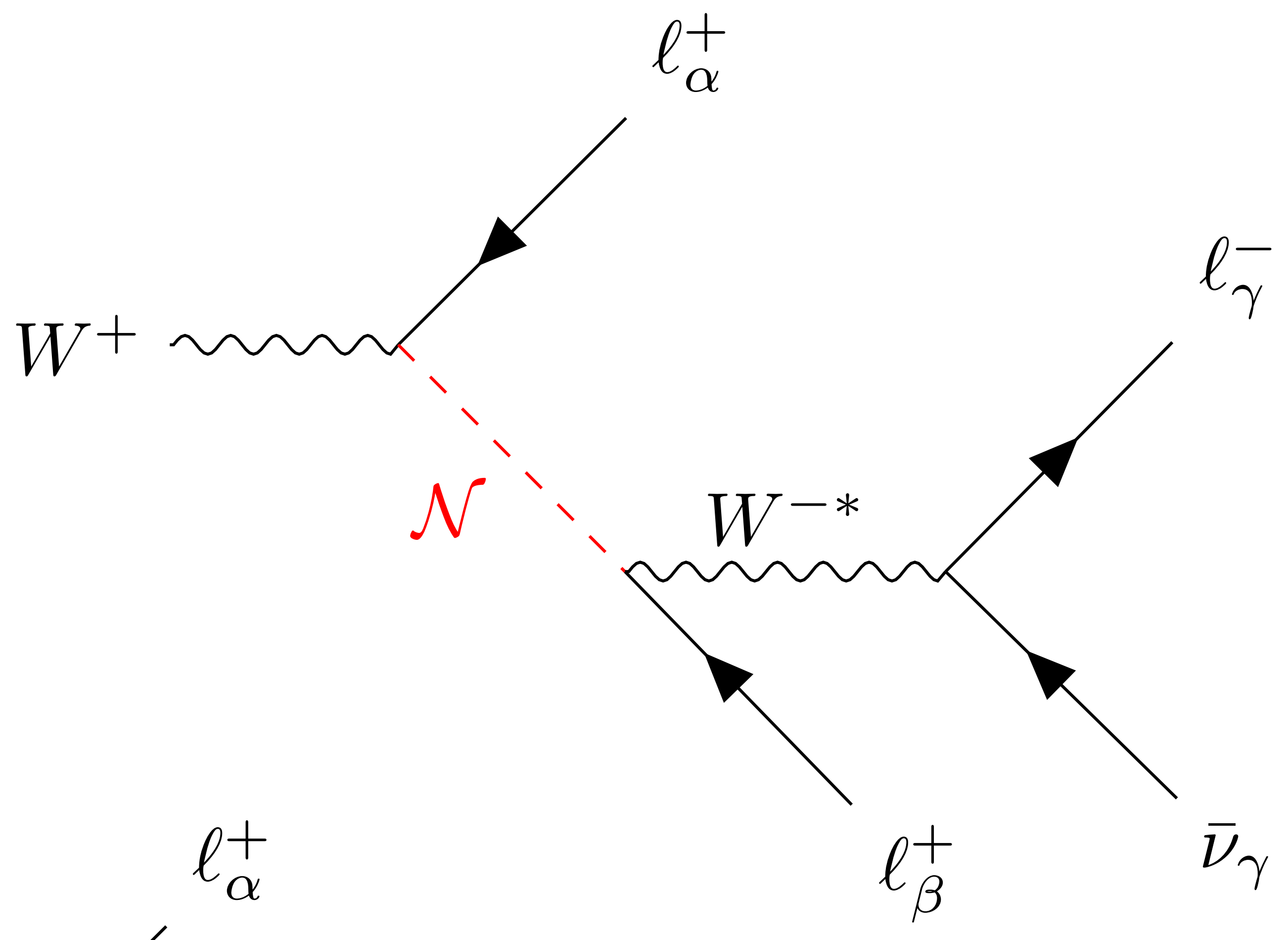
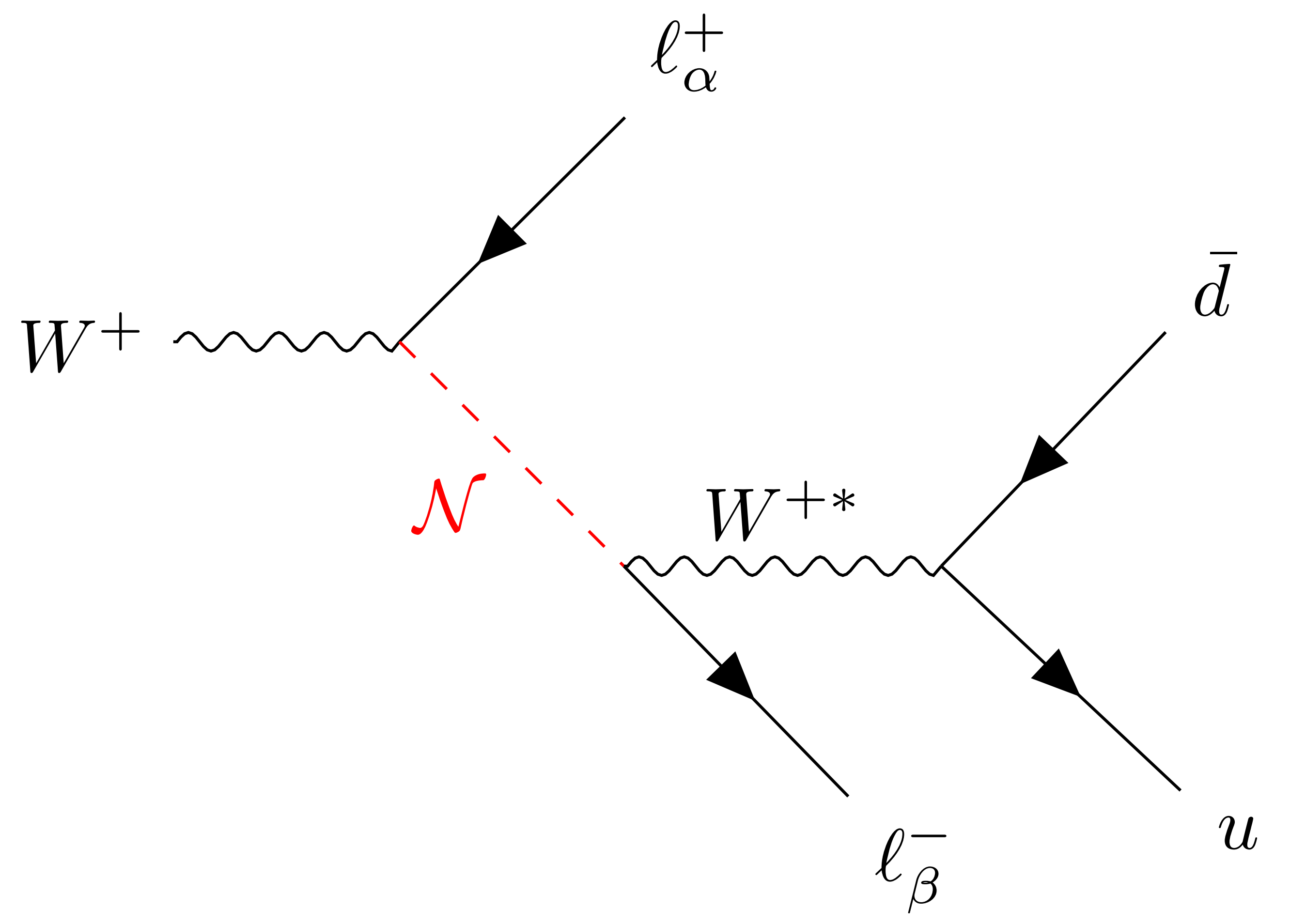
Displaced HNL search

Displaced HNL







- A search for long-lived HNLs
  - Leptonic and semi-leptonic decays of the HNL
- Analysis includes
  - Simplified single flavor mixing (1SFH) model to *e*, *μ*
  - More realistic 2 quasi-degenerate HNL (2QDH) model
    - Normal mass hierarchy: x_e = 0.06, x_μ = 0.48, and x_τ = 0.46
    - Inverted mass hierarchy: $x_e = x_\mu = x_\tau$ = ⅓
  - Dirac-type limits - LNC only
  - Majorana-type limits - both LNC and LNV
    - When $M_1 \neq M_2$ but $\Delta M \ll M_N$
  - HNL has non-zero mixing with all three neutrino flavors - no inherent flavor conservation

    → LNC/LNV refers to the total lepton number

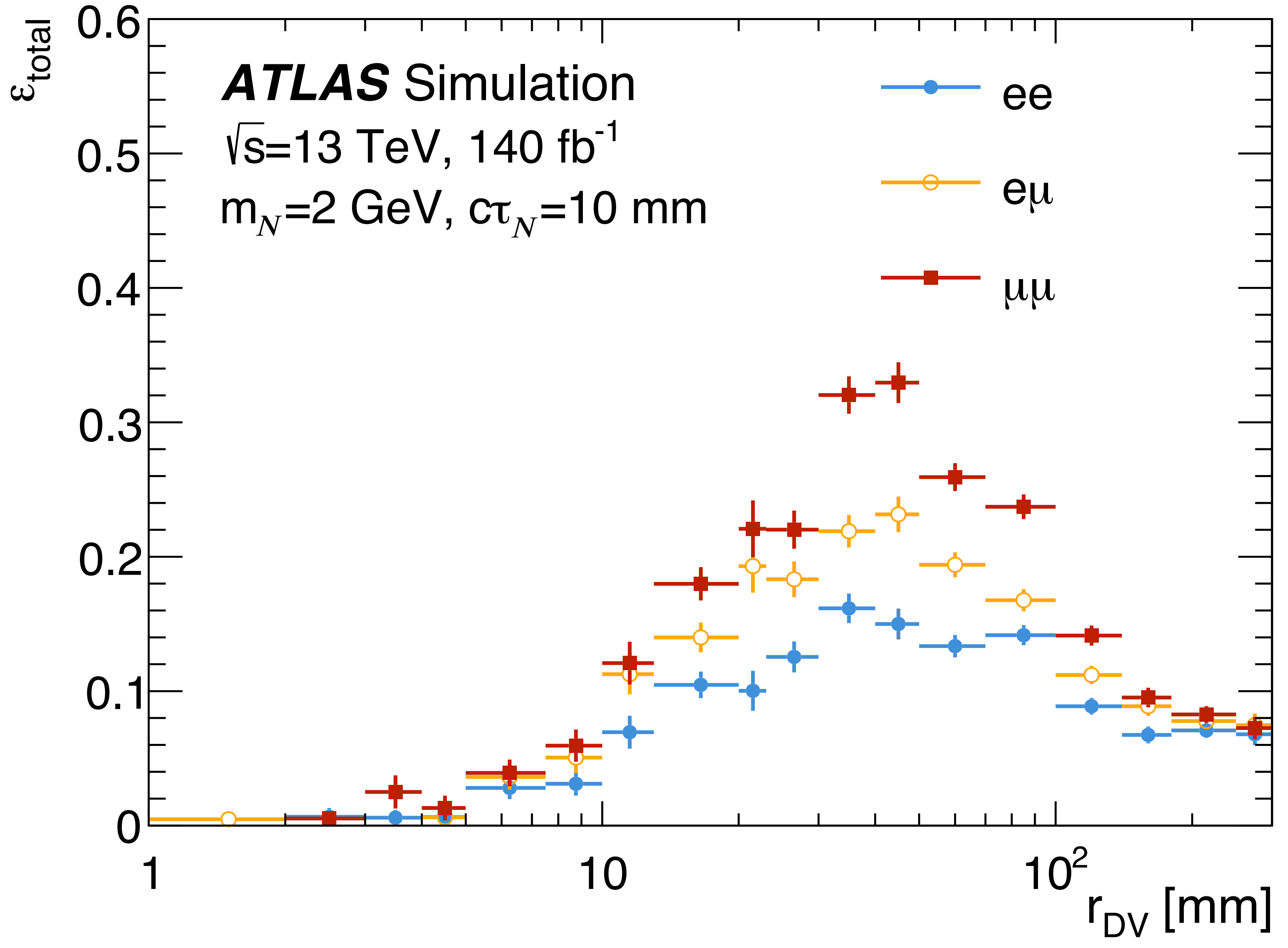
arXiv:2503.16213

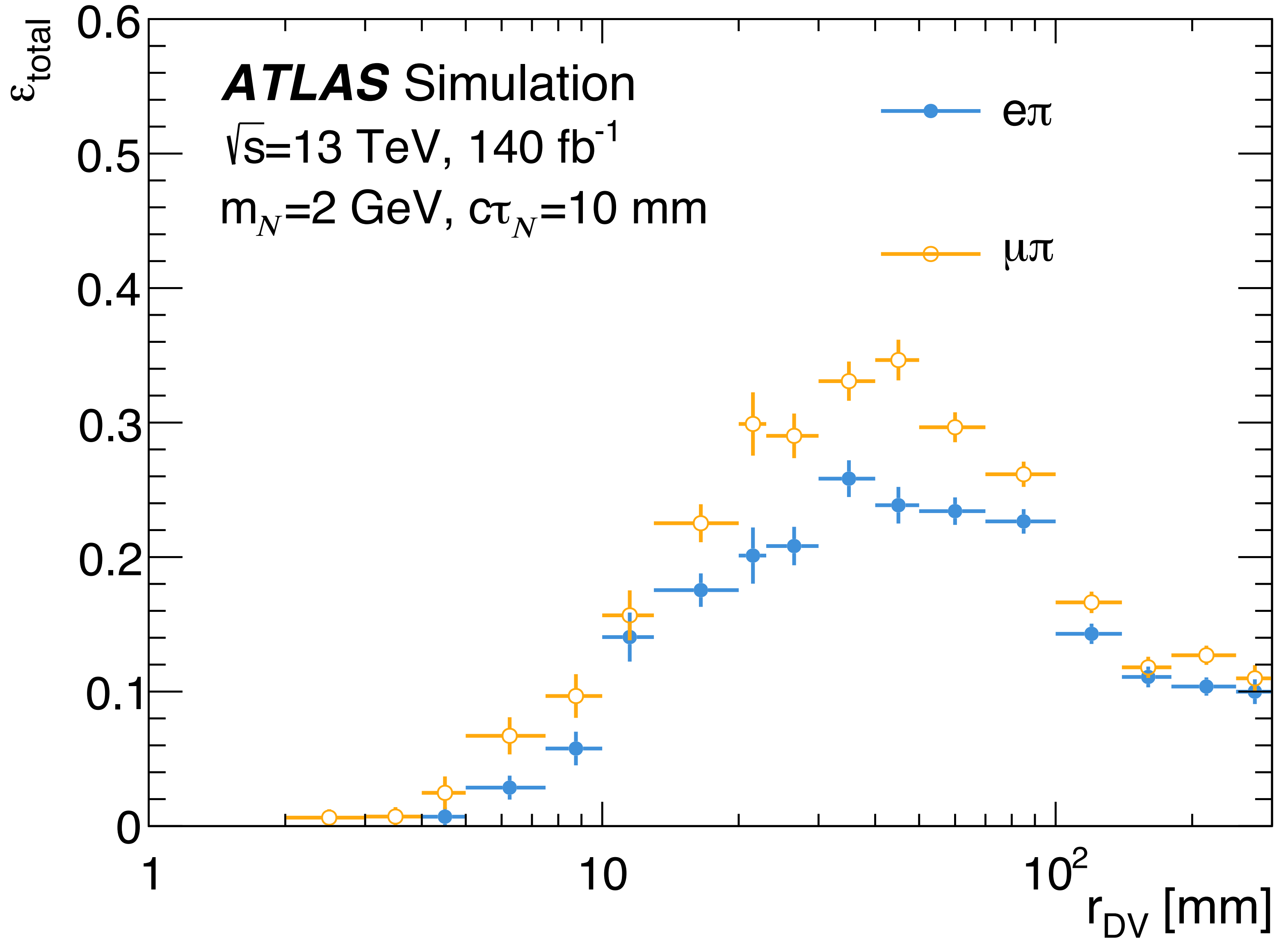
Displaced HNL - displaced vertex

- Search targets the long-lived, less massive HNLs, with access to lower coupling values

$$|U_{tot}|^2 \sim \frac{1}{c\tau m_{\mathcal{N}}^5}$$

  - HNL mass < 20 GeV, cτ 0.1 - 1000 mm
- Decay of the HNL reconstructed as a displaced vertex (DV) via customized algorithm
  - Uses standard ATLAS tracks and displaced tracks
  - Makes a two track seed, strict track requirements
  - Track attachment step - counterintuitive but reduces background
- Select two-track vertices with == 2 leptons (leptonic)
  == 1 lepton (semi-leptonic)





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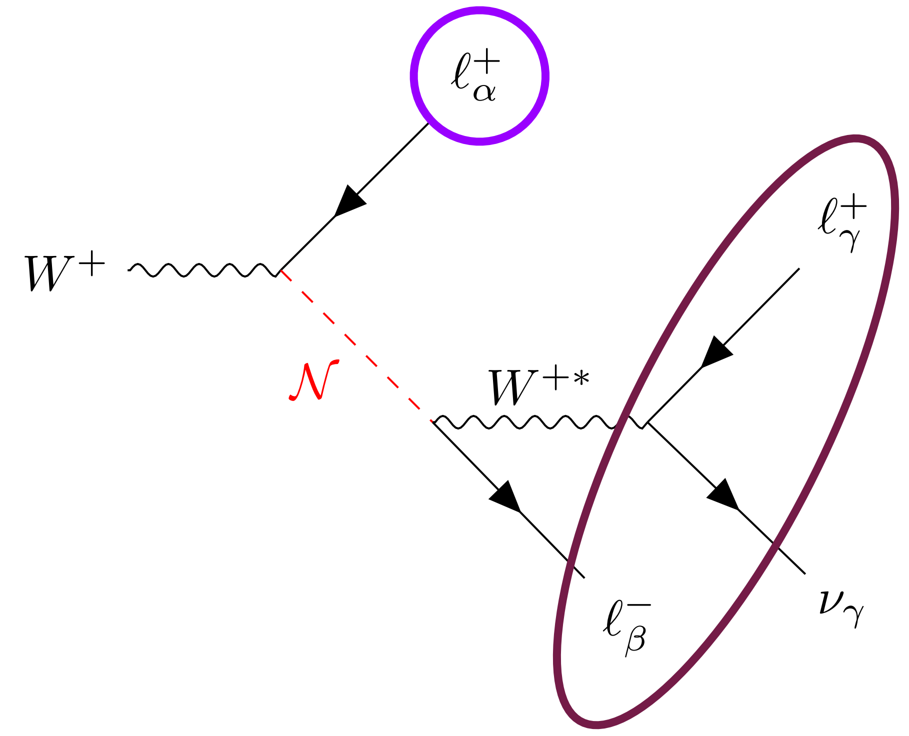
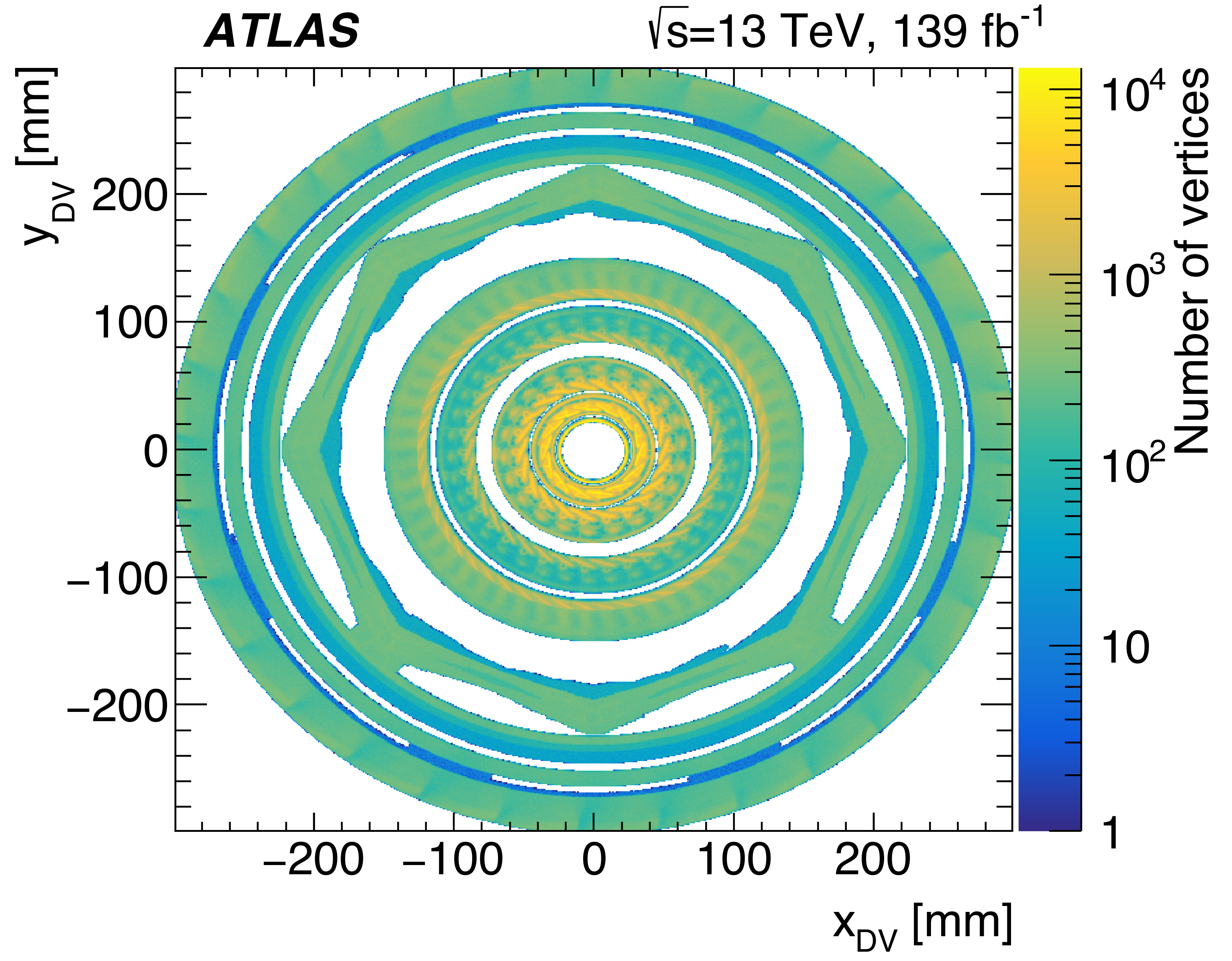
Displaced HNL - Signal Region selections



- Final state - prompt lepton and displaced vertex
    - Single lepton trigger from prompt lepton
    - Custom 2-track displaced vertex
- Fiducial requirements:
  Leptonic: 4 < r_{DV} < 300 mm, material veto on *ee* DVs
  Semi-leptonic: 20 < r_{DV} < 300 mm, material veto on all DVs

  Material veto cuts out 42% of fiducial volume
- Mass vetos in place for Z-boson, K_S, J/ψ
- Main discriminant for Signal Region - W-mass selection
    - 40 < m_{lll} < 90 GeV, 70 < $m_{ll\pi}$ < 90 GeV

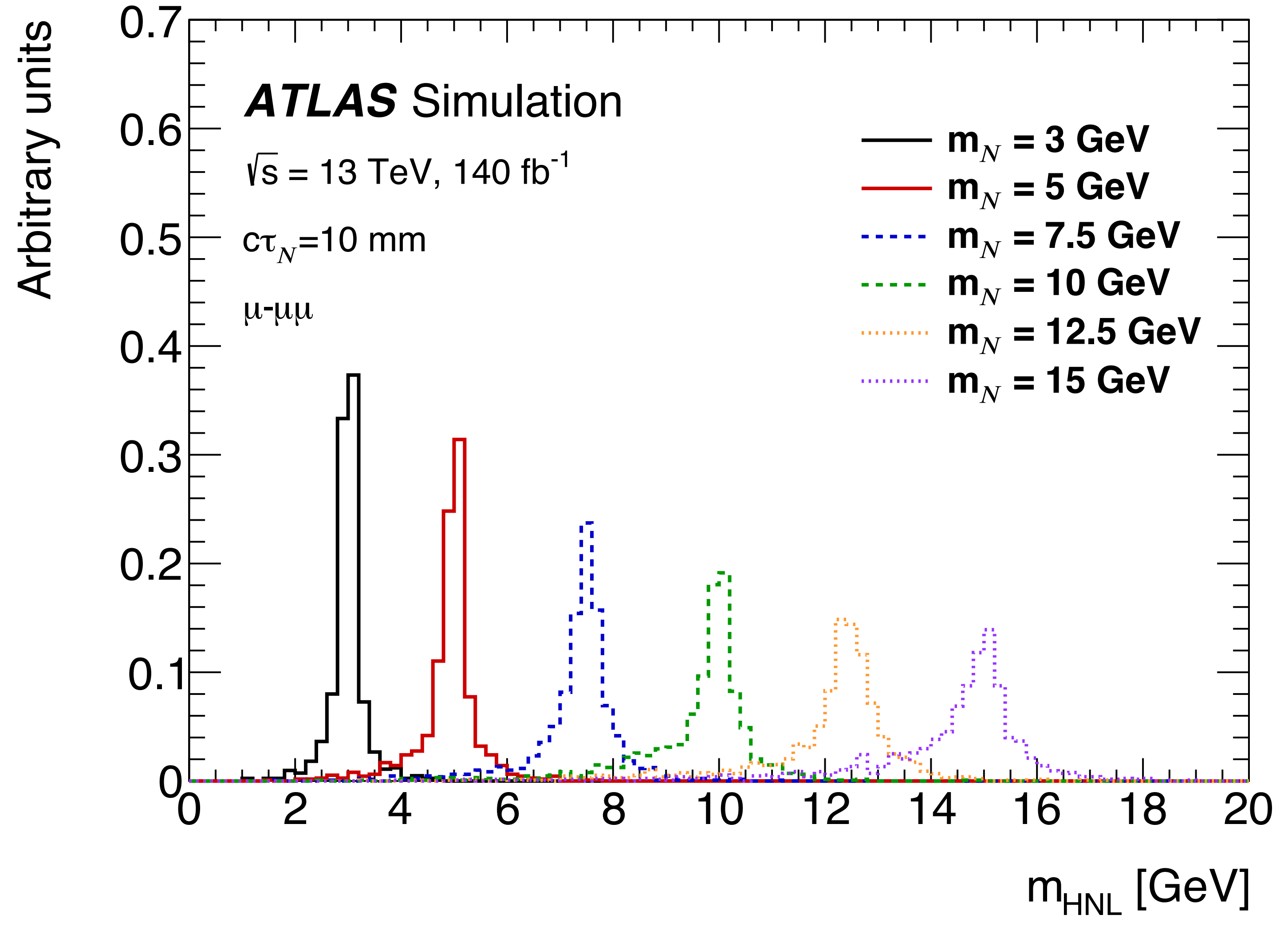


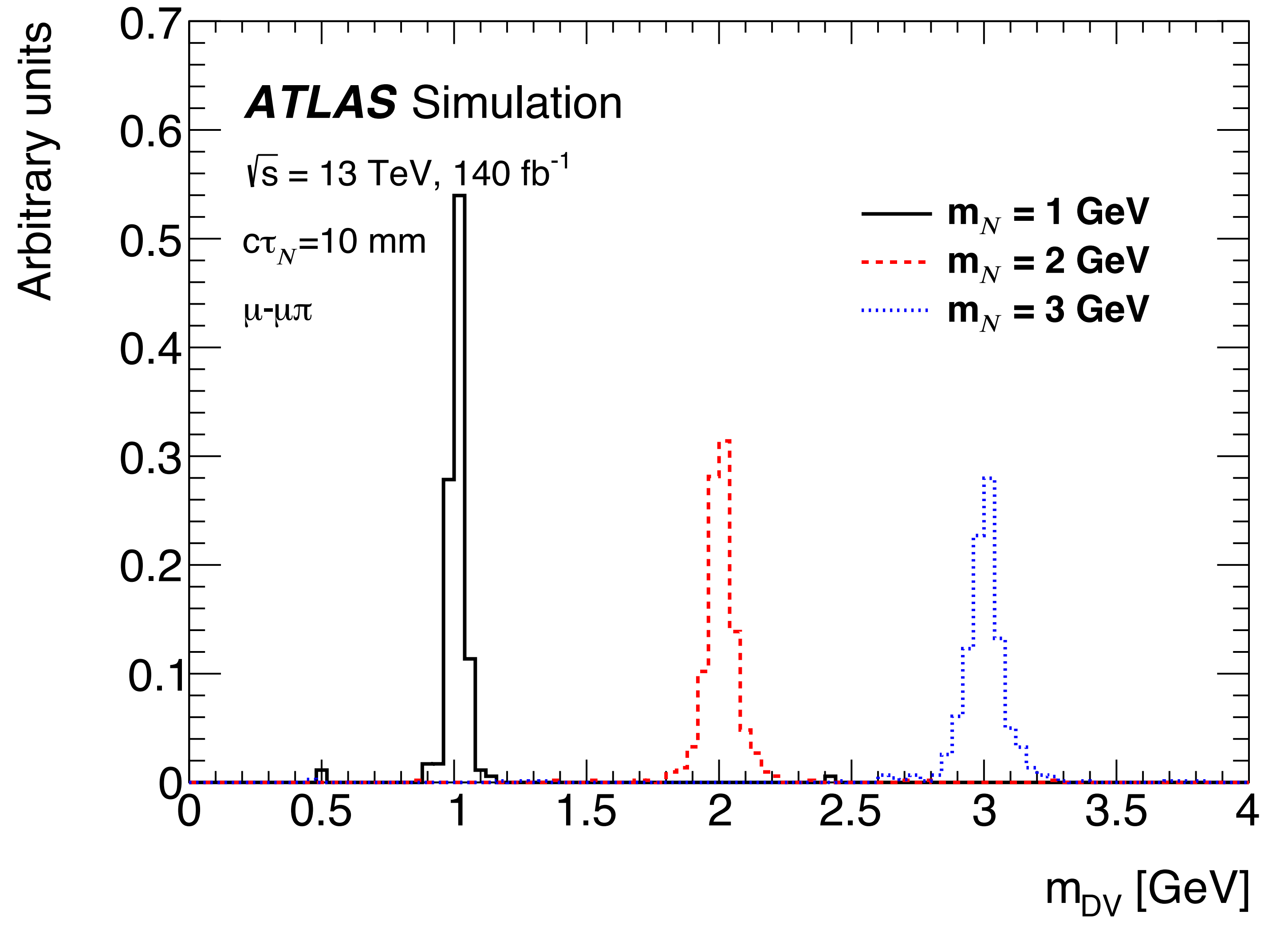
arXiv:2503.16213

Displaced HNL - discriminating variable

- In the leptonic channel, the reconstructed HNL mass, m_{HNL}, is calculated using the W mass and energy-momentum conservation
  - In leptonic channel $m_{DV} < m_{HNL}$
  - Allows for clean reconstructed mass variable despite missing energy from the neutrino
  - Mass calculation fully detailed in arXiv:2204.11988
- In the semileptonic channel m_{HNL} is equivalent to m_{DV}
  - Only charged decay products
- m_{HNL} and m_{DV} used as the fitted variable

$$m_{\mathrm{HNL}}^2 = (p_{\ell_1} + p_{\ell_2} + p_\nu)^2$$



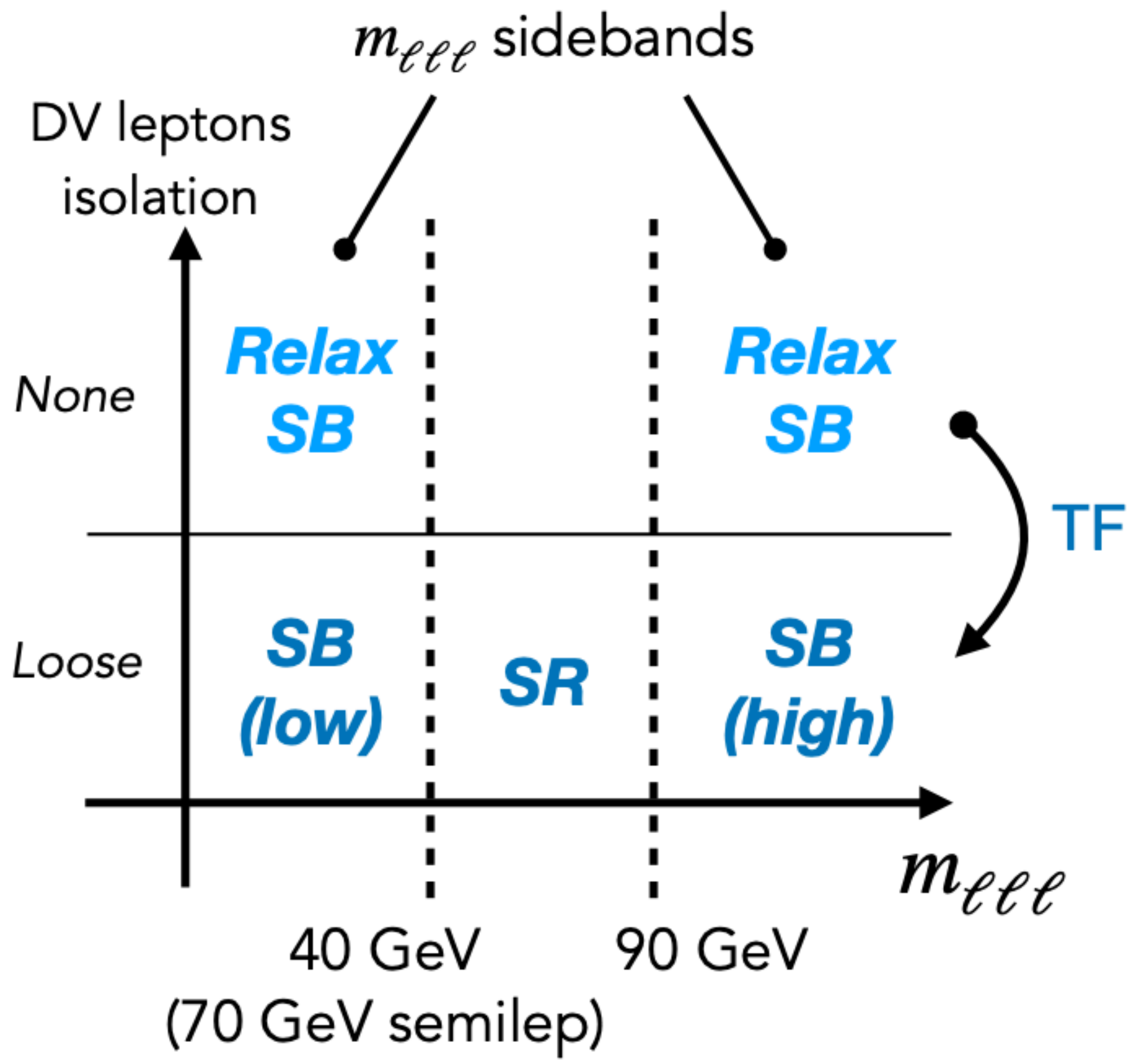


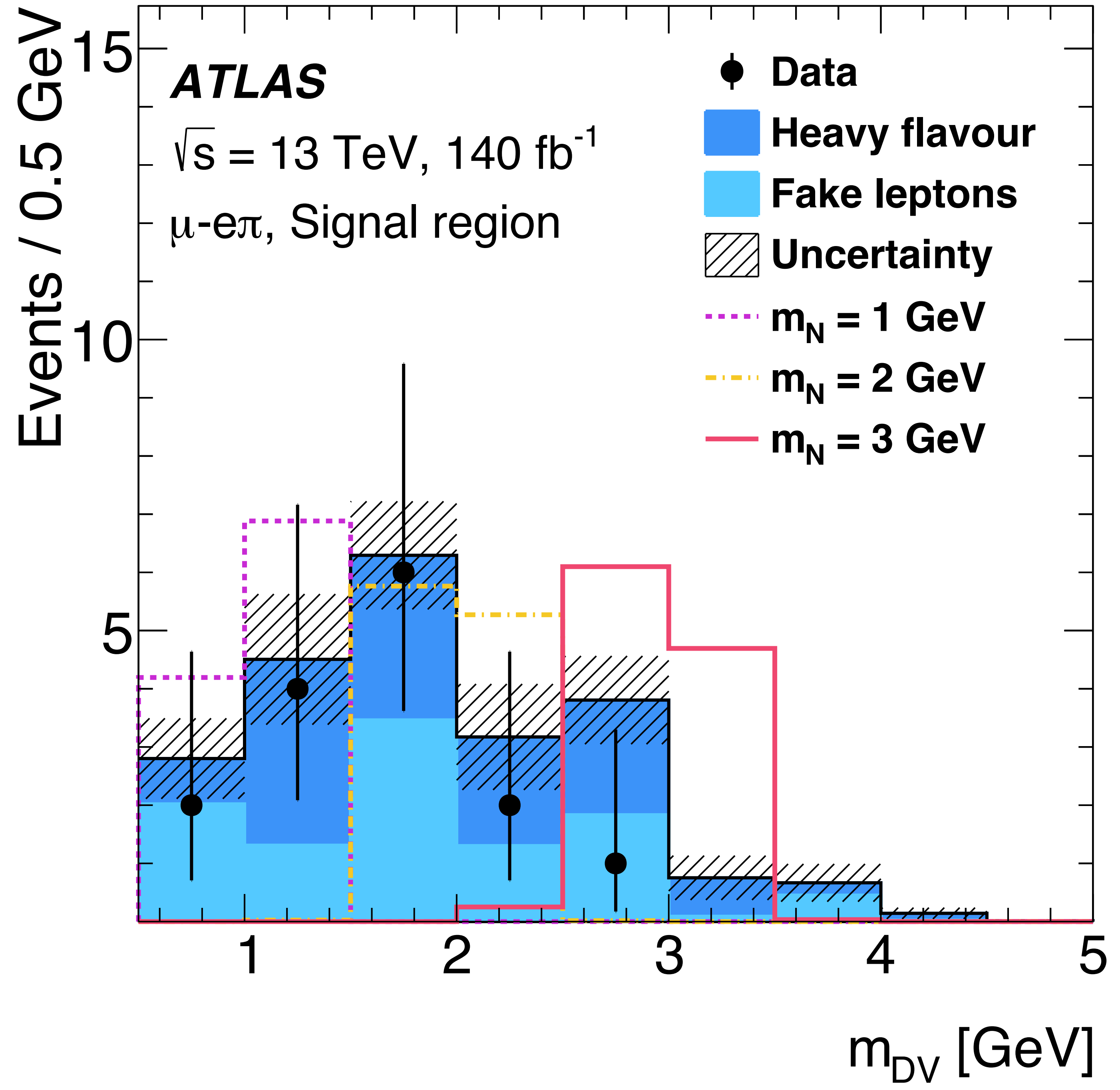
$$m_{\mathrm{HNL}}^2 = (p_\ell + p_\pi)^2$$

arXiv:2503.16213

Displaced HNL - backgrounds

- Main backgrounds after signal selection
  - Heavy flavor decays - template from MC samples of tt and vector boson production in association with heavy-flavor jets (V+HF) production
  - Mis-reconstructed leptons - estimated using data
  - Use background enriched “relaxed” sideband regions in the W-boson mass
    - Loosened isolation criteria
    - Heavy flavor template subtracted
  - Take shape from relaxed regions and use a transfer factor to apply to SR-like sideband regions
  - Use the average shape between low and high sidebands

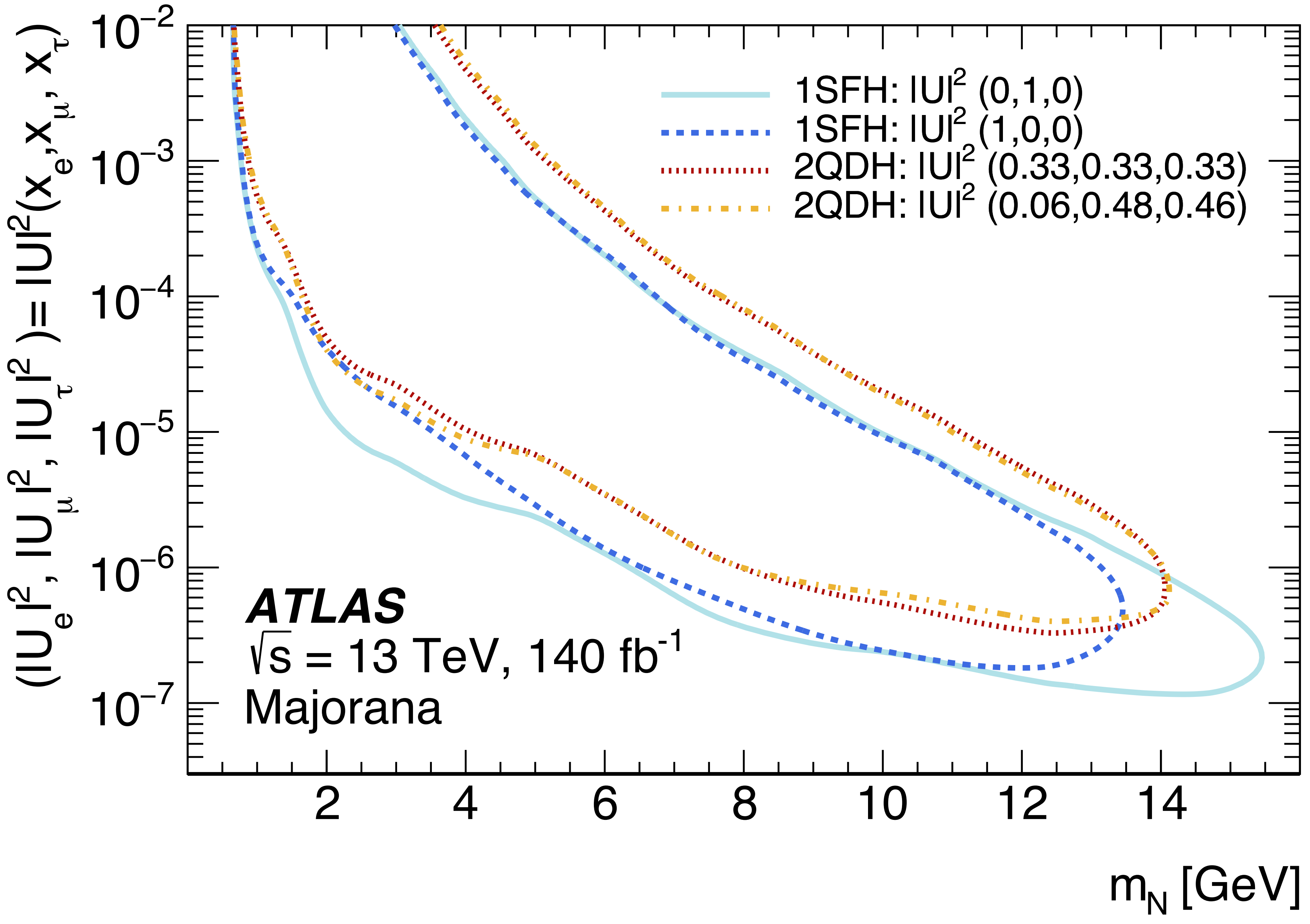


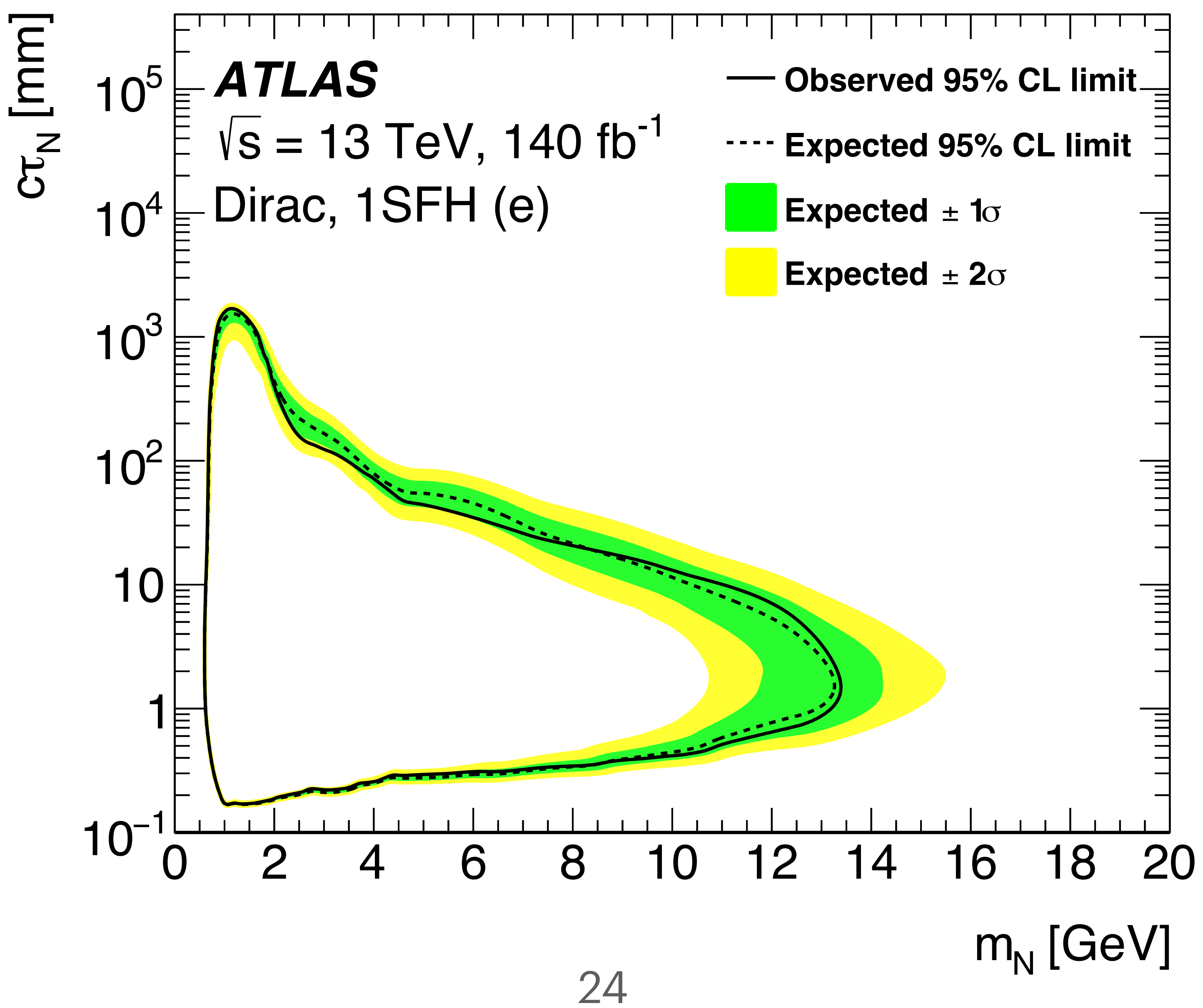


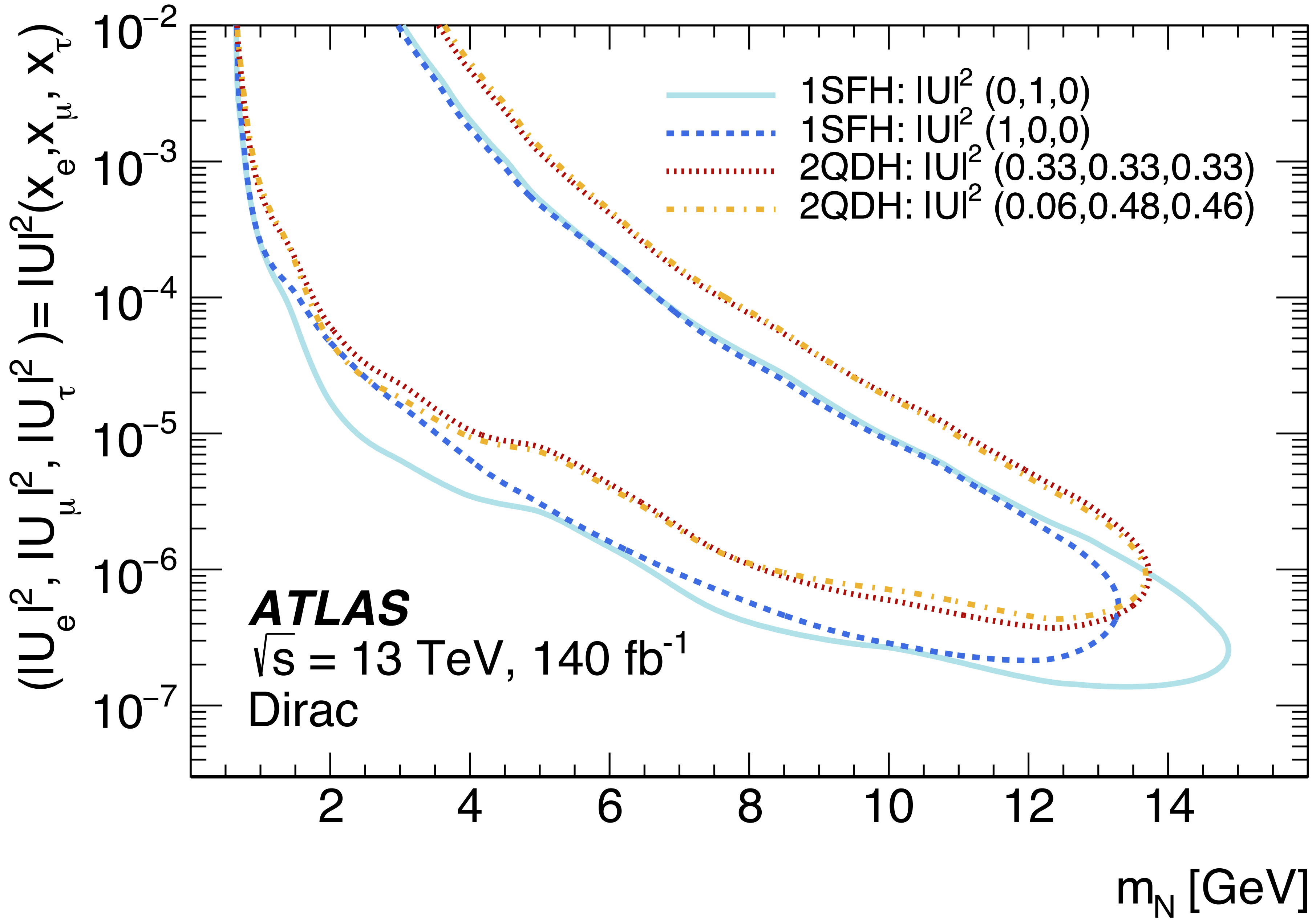
arXiv:2503.16213

Displaced HNL

- Fit performed across signal and control regions, with 21 bins across the m_{HNL} and m_{DV} variables
- No significant excess found - limits set at 95% CL
- Extending limits from previous ATLAS searches
- Complementary in mass and lifetime reach to other ATLAS searches
- First ATLAS search to include semi-leptonic decays



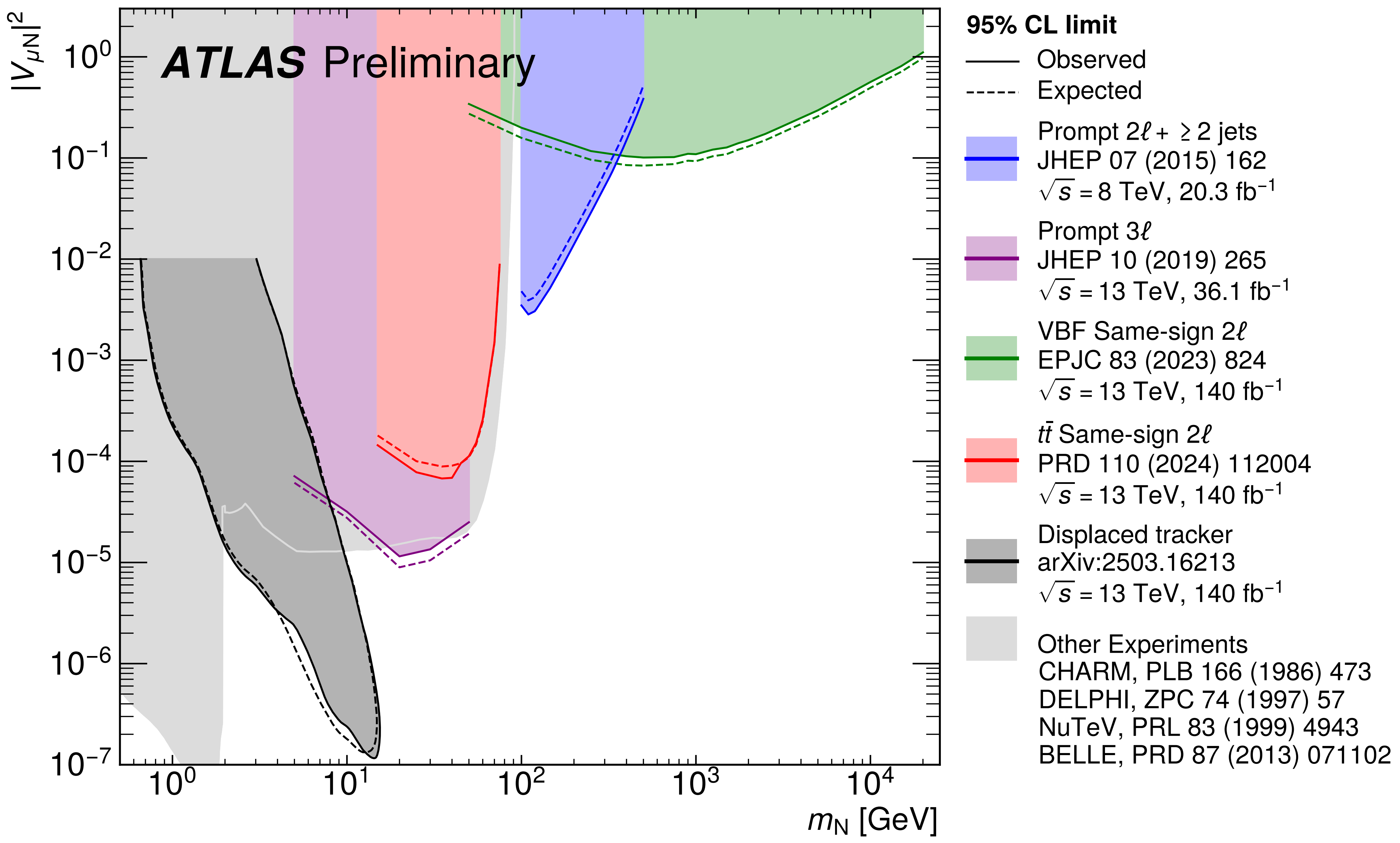


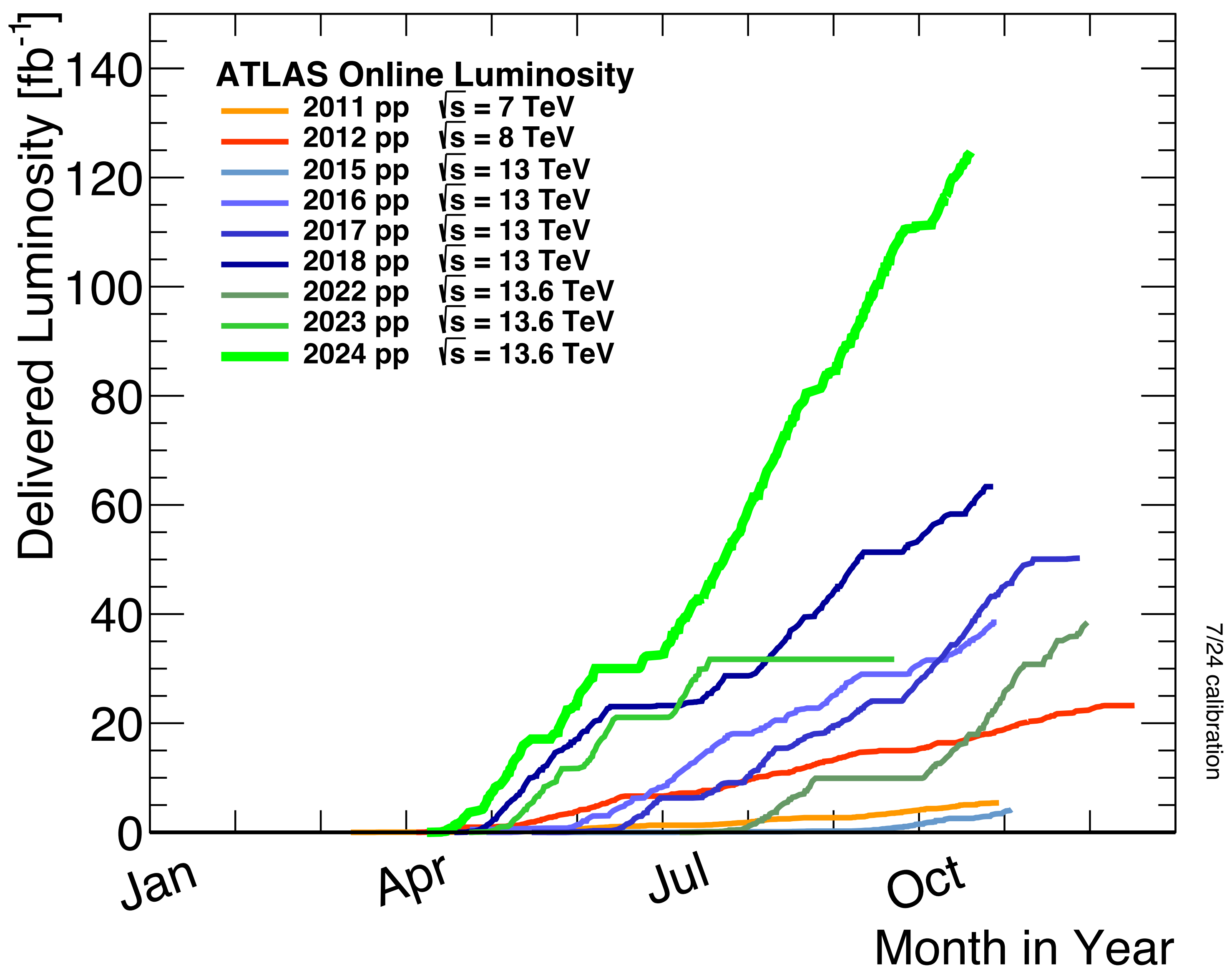


arXiv:2503.16213

Overall

- Very exciting HNL search program at ATLAS
  - Some older results in the backup and new coming soon
  - No new physics yet :(
- Only just getting started on searches with Run 3 data
- Plenty of upgrades underway to prepare for the HL-LHC era
- Thanks for listening!

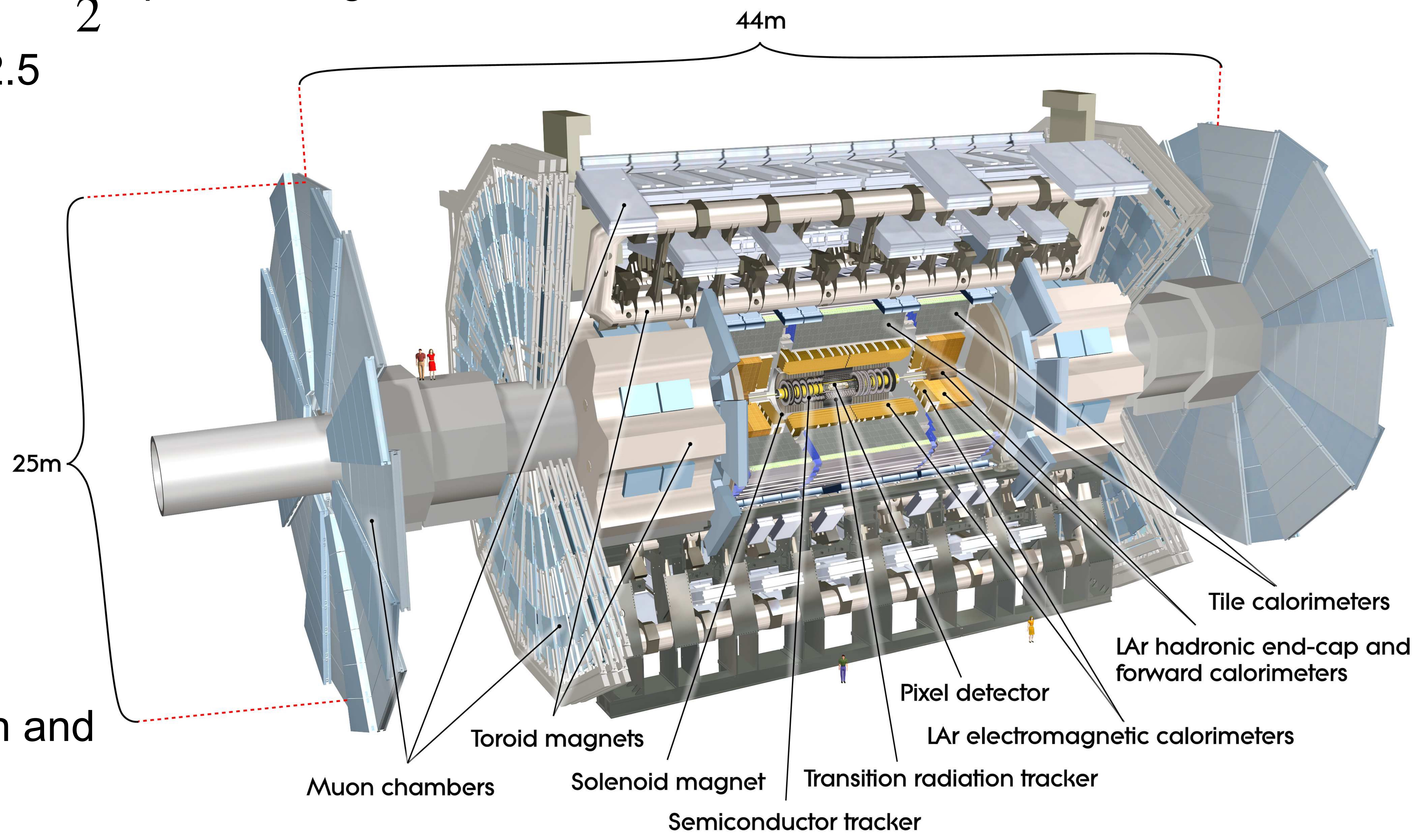




Backup

The ATLAS detector (LHC Run 2 edition)

- A forward-backward symmetric, 4π coverage, right-handed coordinate system (x – towards LHC center, y – up, z – along beamline)
- Cylindrical geometry → R = $\sqrt{x^2+y^2}$, η = $-\ln\tan\frac{\theta}{2}$, φ = 0 along x-axis
- Inner detector (ID) - R < ~1m, |z| < ~ 3m, |η| < 2.5
  - Pixel, SCT - silicon, precision tracking
  - TRT - electron ID
- Calorimeters
  - EM calorimeter (LAr/lead)
  - Hadronic calorimeter (steel/scintillator tile), (copper/LAr)
- Muon spectrometer (MS)
  - MDT and CSC - precision tracking
  - TGC and RPC - triggering, φ measurements
- Two-tiered trigger system with L1 online selection and HLT offline selection



Heavy right handed W_R and N_R

backup

Heavy right handed W_R and N_R - selections

		Resolved		Boosted		
		Baseline	**Fake estimation**	**Baseline**	**Leading**	**Fake estimation**
Electrons	$\|\eta\|$	(0, 1.37] or [1.52, 2.47]				
	p_T (GeV)	> 25		> 25	> 200	
	Quality	`Tight`	`Loose`	`Medium`	`Tight`	
	Isolation	Loose	Fail Loose or `Tight`	`Loose`	`HighPtCaloOnly`	Loose but fail `HighPtCaloOnly`
		Baseline	**Fake estimation**	**Baseline**	**Leading**	
Muons	p_T (GeV)	> 25		> 28	> 200	—
	$\|\eta\|$	< 2.5		< 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				
	$\|\eta\|$	< 2.5				
Large-*R* jet	p_T (GeV)	—		> 200		
	$\|\eta\|$	—		< 2		

Order	Object discarded	Object kept	Matching condition
1.	Electron	Electron	If two electrons share a track, discard the softer electron
2.	Muon	Electron	If they share a track and the muon type is calorimeter-tagged
3.	Electron	Muon	If they share a track with the remaining muon
4.	Small-*R* jet	Electron	$\Delta R < 0.2$, but step is skipped if jet is *b*-tagged and $p_T(e) < 100$ GeV
5.	Electron	Small-*R* jet	$\Delta R < 0.4$
6.	Small-*R* jet	Muon	$\Delta R < 0.2$, number of tracks associated to the jet < 3, $p_T(\mu)/p_T(j) > 0.5$ and $p_T(\mu)/\sum p_T(\mathrm{trk}) > 0.7$
7.	Muon	Small-*R* jet	$\Delta R < 0.4$

arXiv:2304.09553

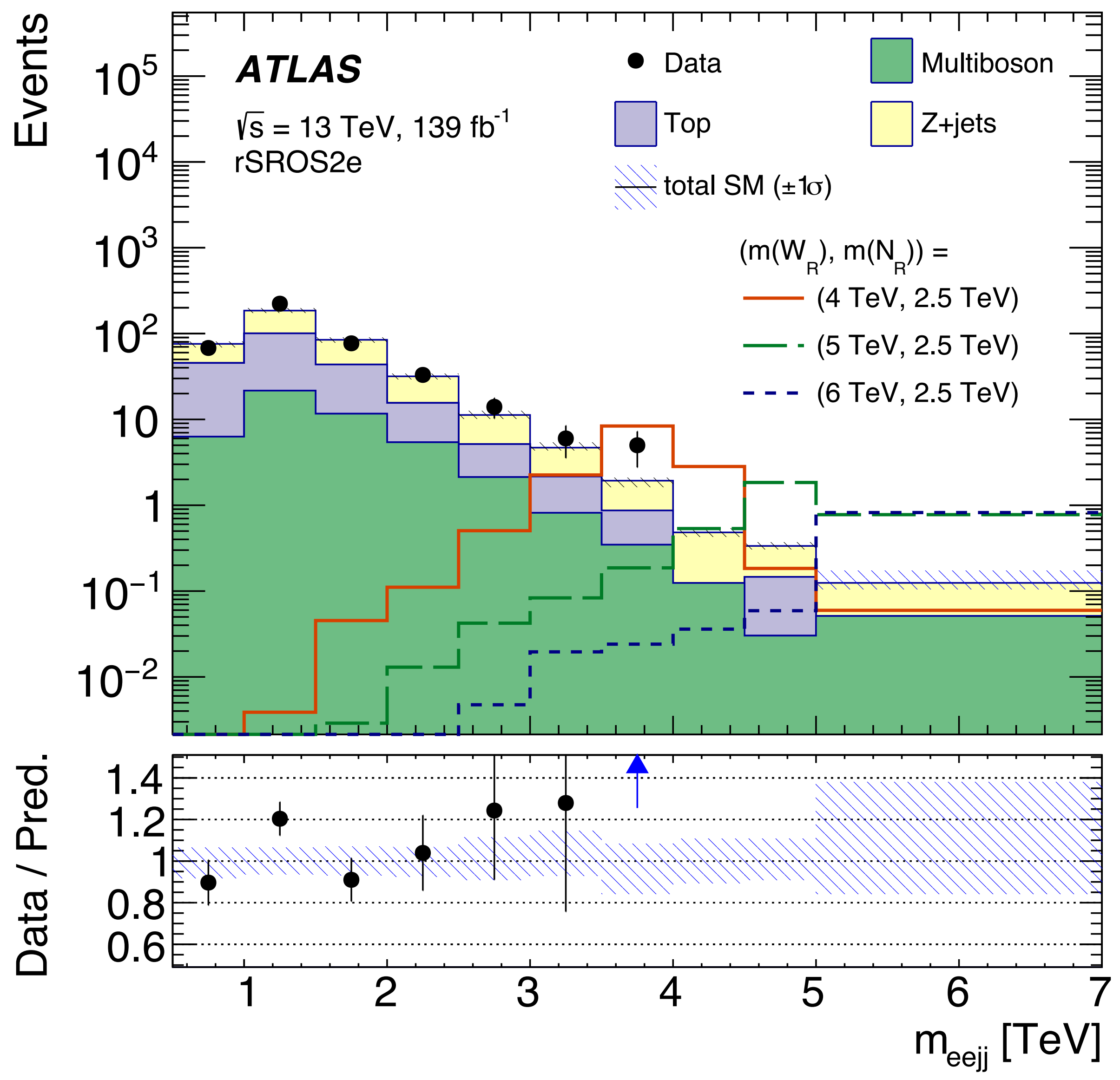
Heavy right handed W_R and N_R - Signal regions

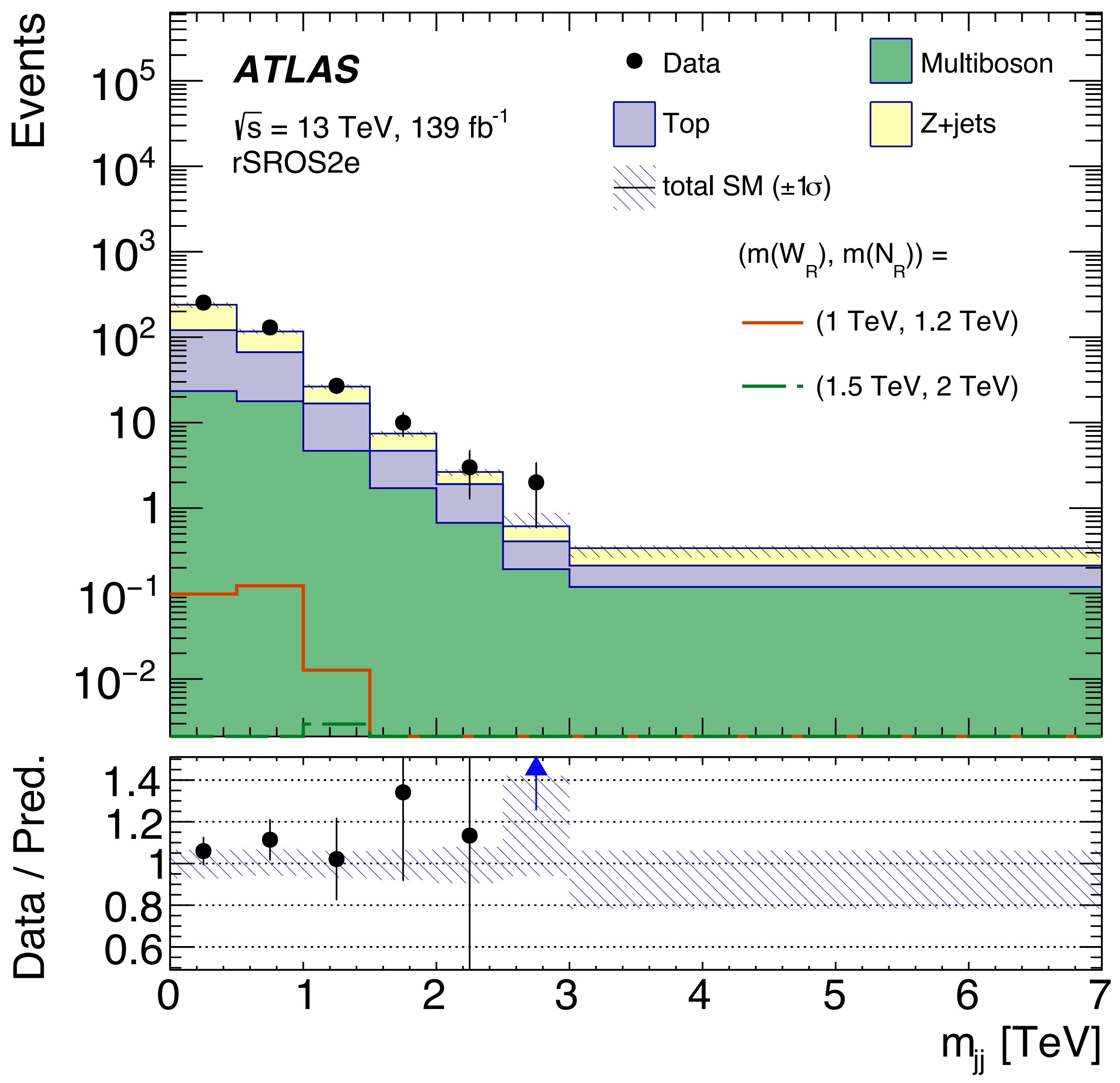
Variable	rSRSS2e	rSRSS2mu	rSROS2e	rSROS2mu
Number of electrons	2	0	2	0
Number of muons	0	2	0	2
Lepton charge	same sign		opposite sign	
Leading lepton p_T [GeV]	> 40			
Dilepton mass $m_{\ell\ell}$ [GeV]	> 400			
$\Delta R_{\ell\ell}$	< 3.9		—	
Number of small-R jets with $p_T > 100$ GeV	≥ 2			
Number of b-tagged jets	0			
Dijet mass m_{jj} [GeV]	> 110			
$h_T \equiv p_T(\ell_1) + p_T(\ell_2) + p_T(j_1) + p_T(j_2)$ [GeV]	> 400			

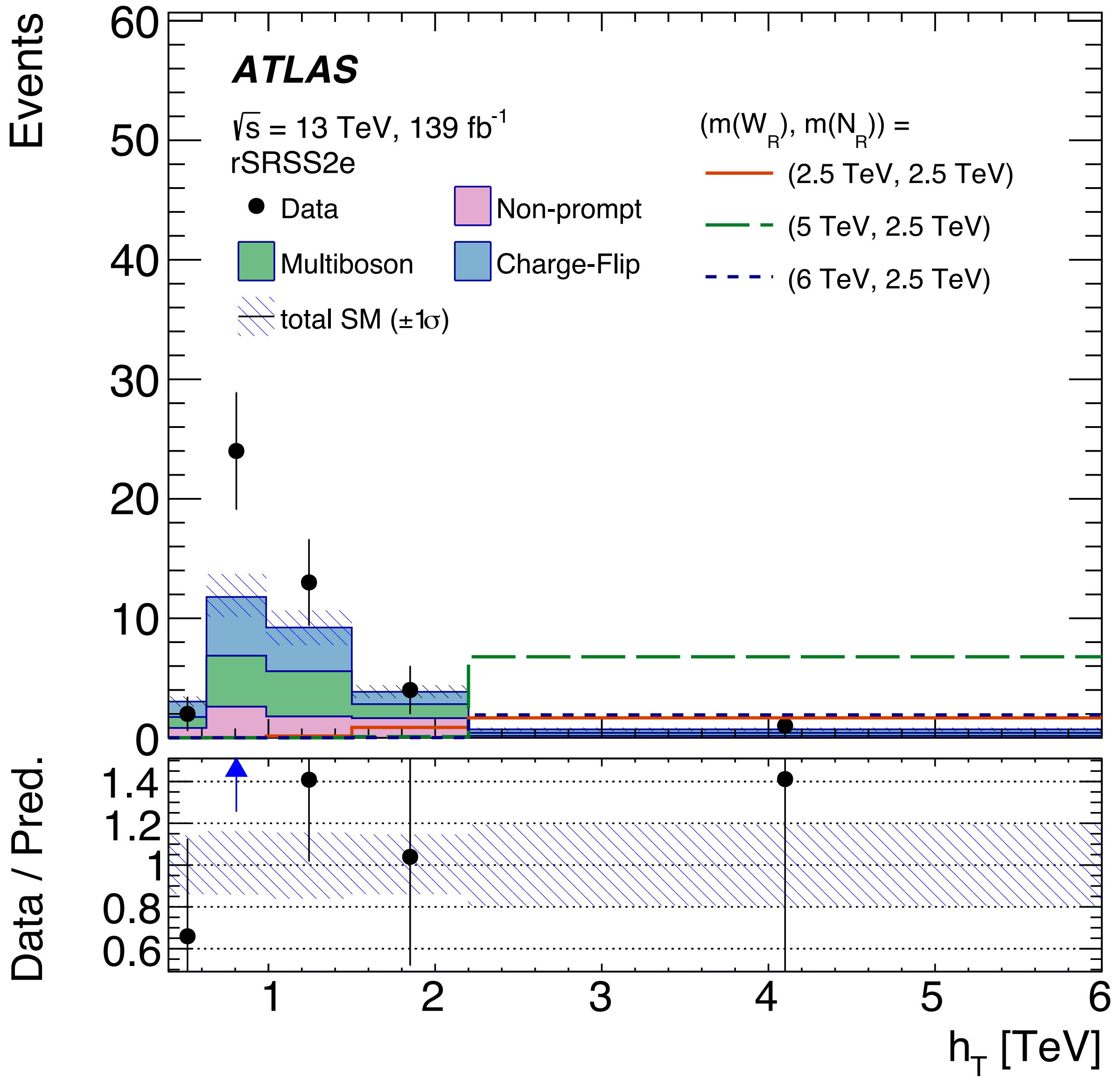
Region	bSR1e (higher Δm)	bSR2e (lower Δm)	bSR2mu
Number of large-R jets	1		
Number of electrons	1	2	0
Number of muons	0	0	2
Leading lepton p_T [GeV]	> 200		
E_T^{miss} [GeV]	< 200		—
$\lvert\cos\theta\rvert$	> 0.7	—	—
$\Delta\phi_{J,\ell_1}$	> 2.0		
$\Delta\eta_{J,\ell_1}$	< 2.0	—	—
Dilepton p_T (GeV)	—	—	> 200
Dilepton mass $m_{\ell\ell}$[GeV]	—	> 200	
Number of b-tagged small-R jets	0		

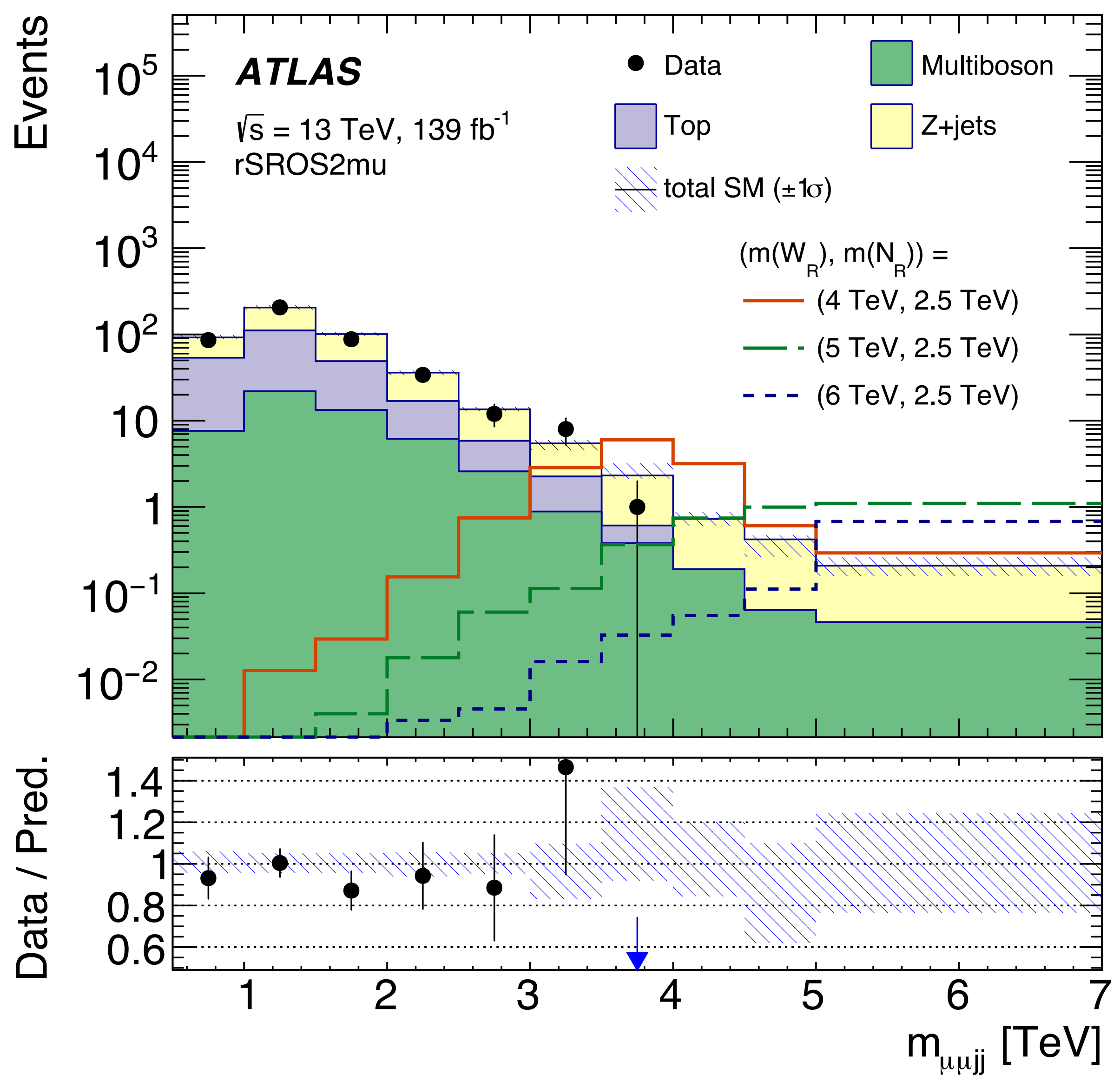
arXiv:2304.09553

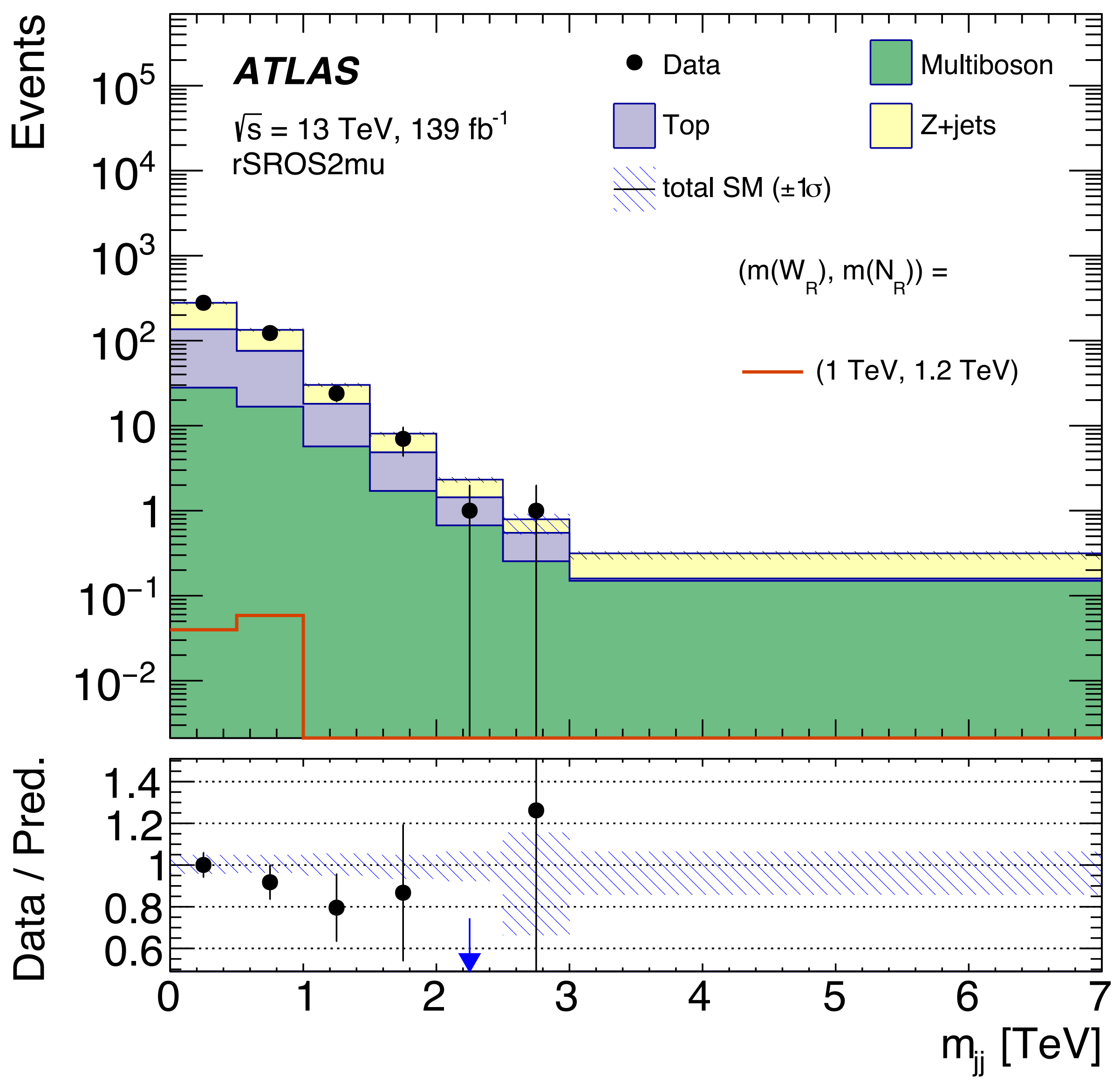
Heavy right handed W_R and N_R - fits in resolved SRs

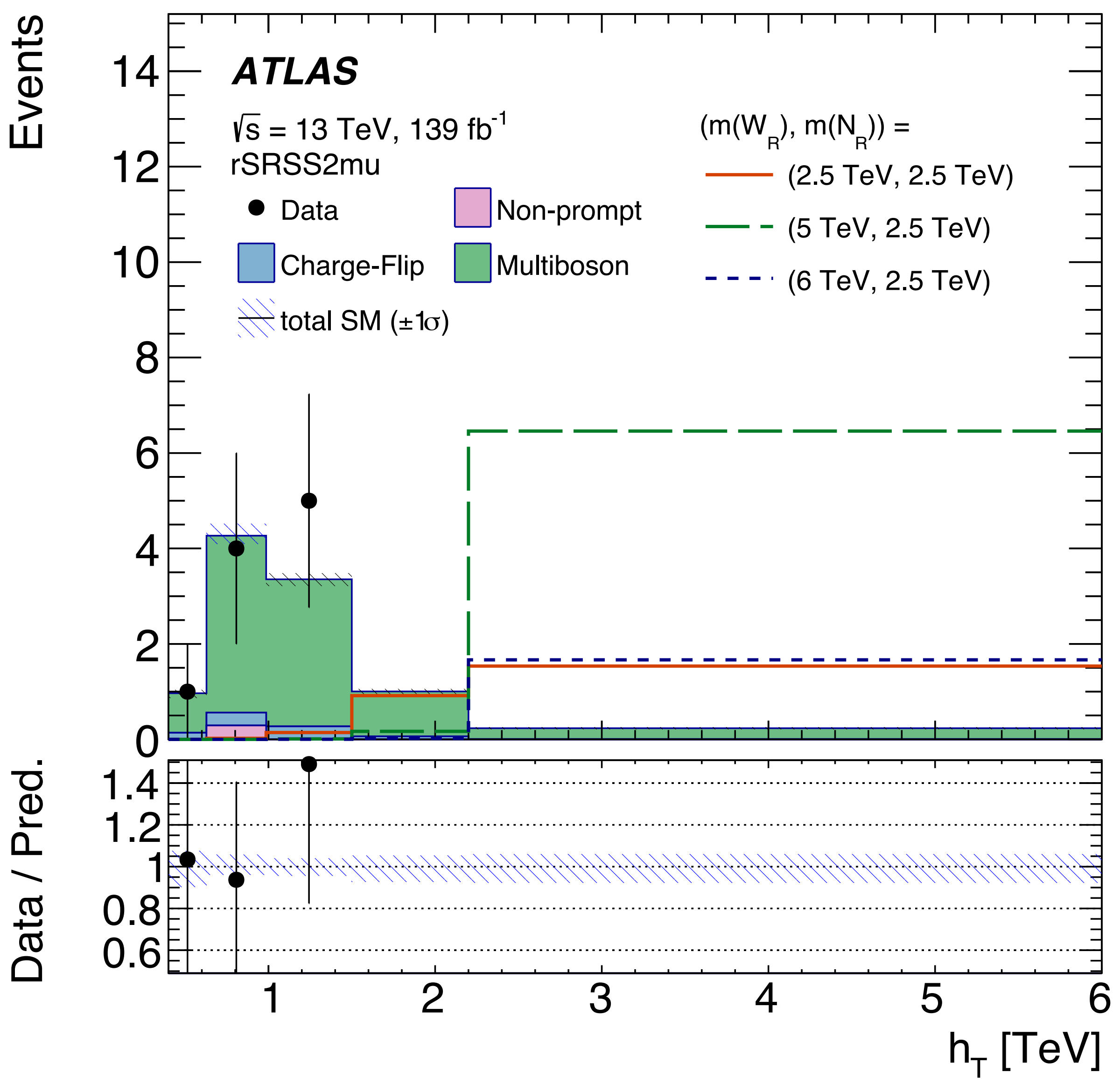




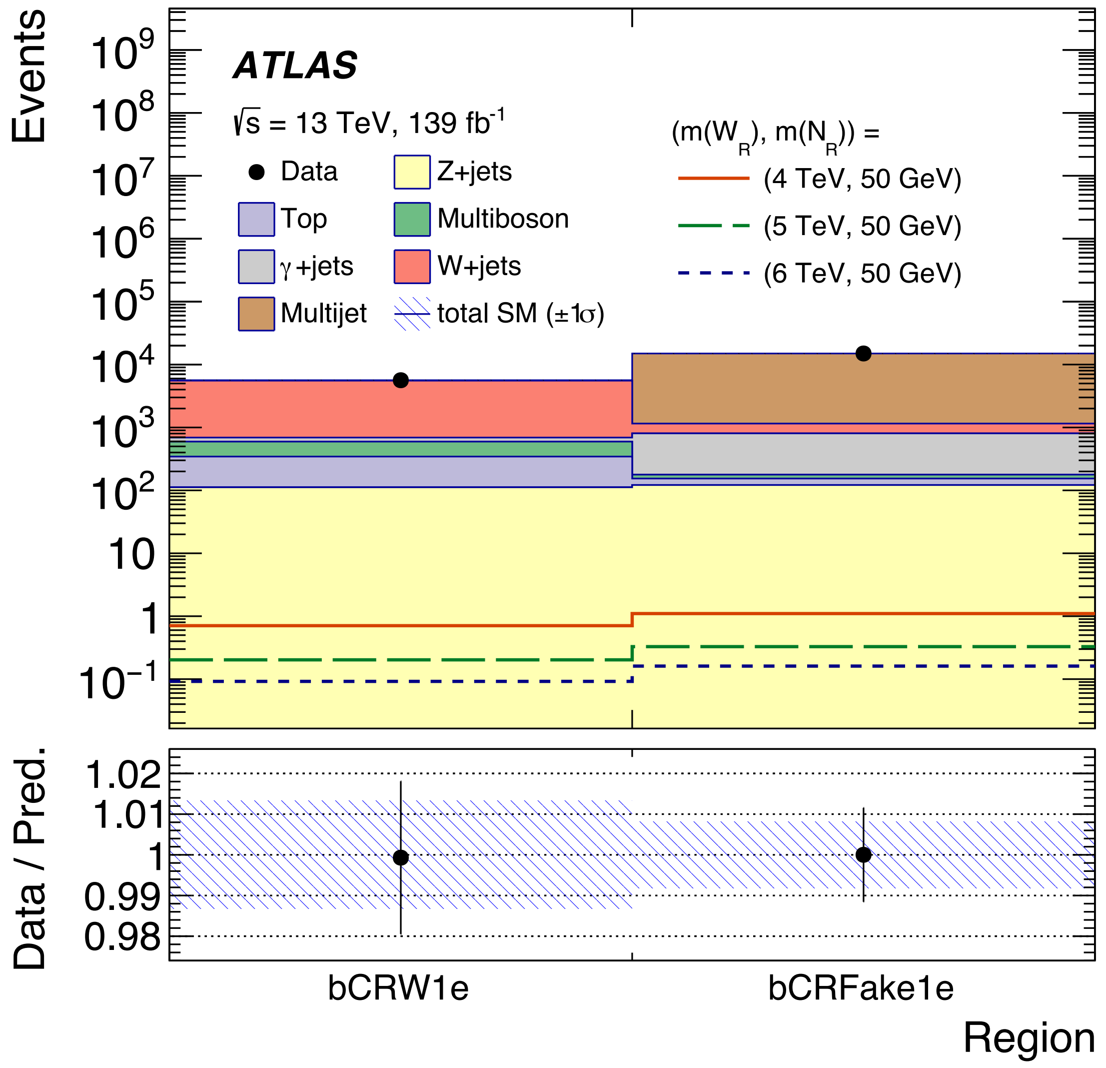


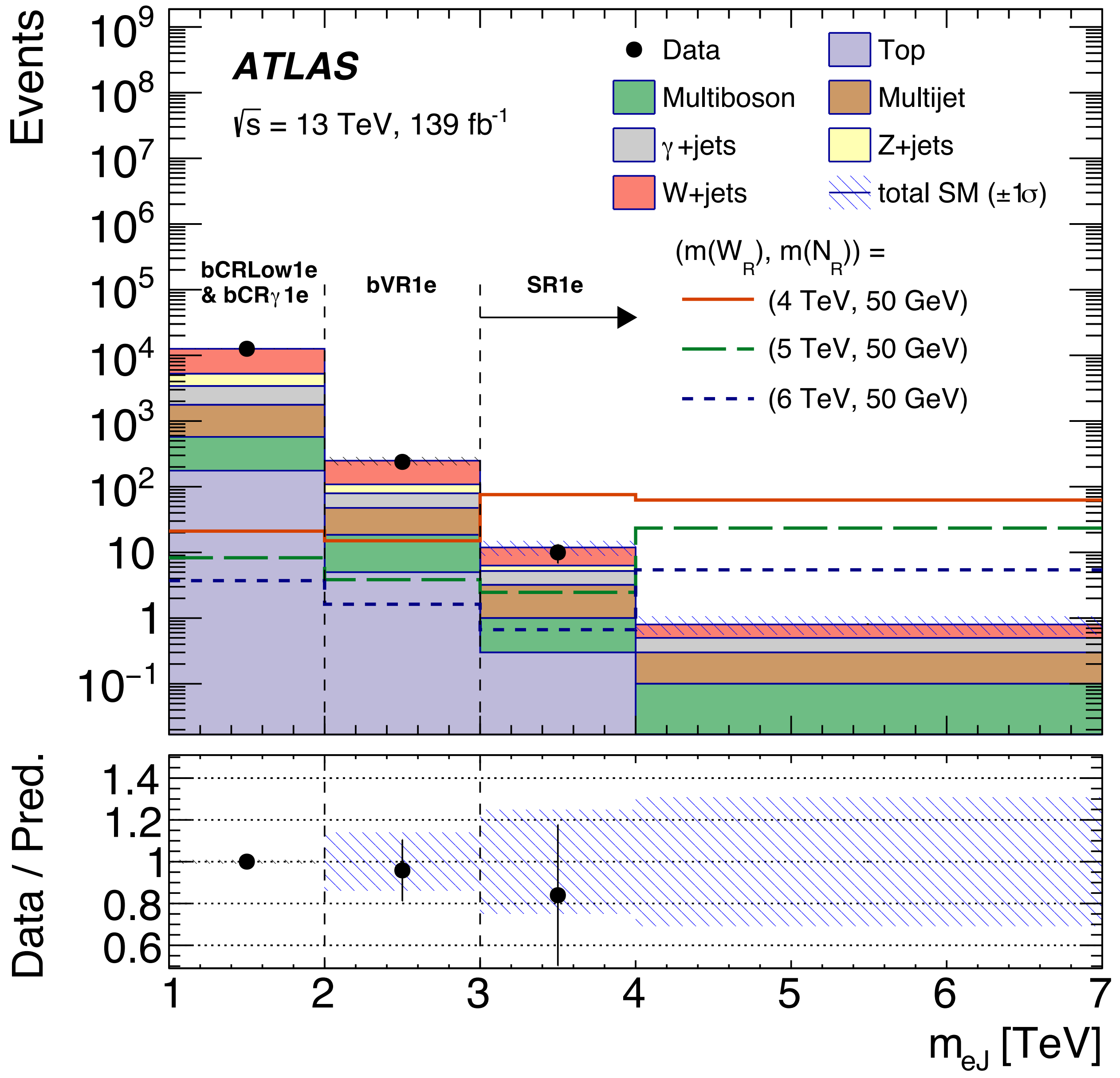


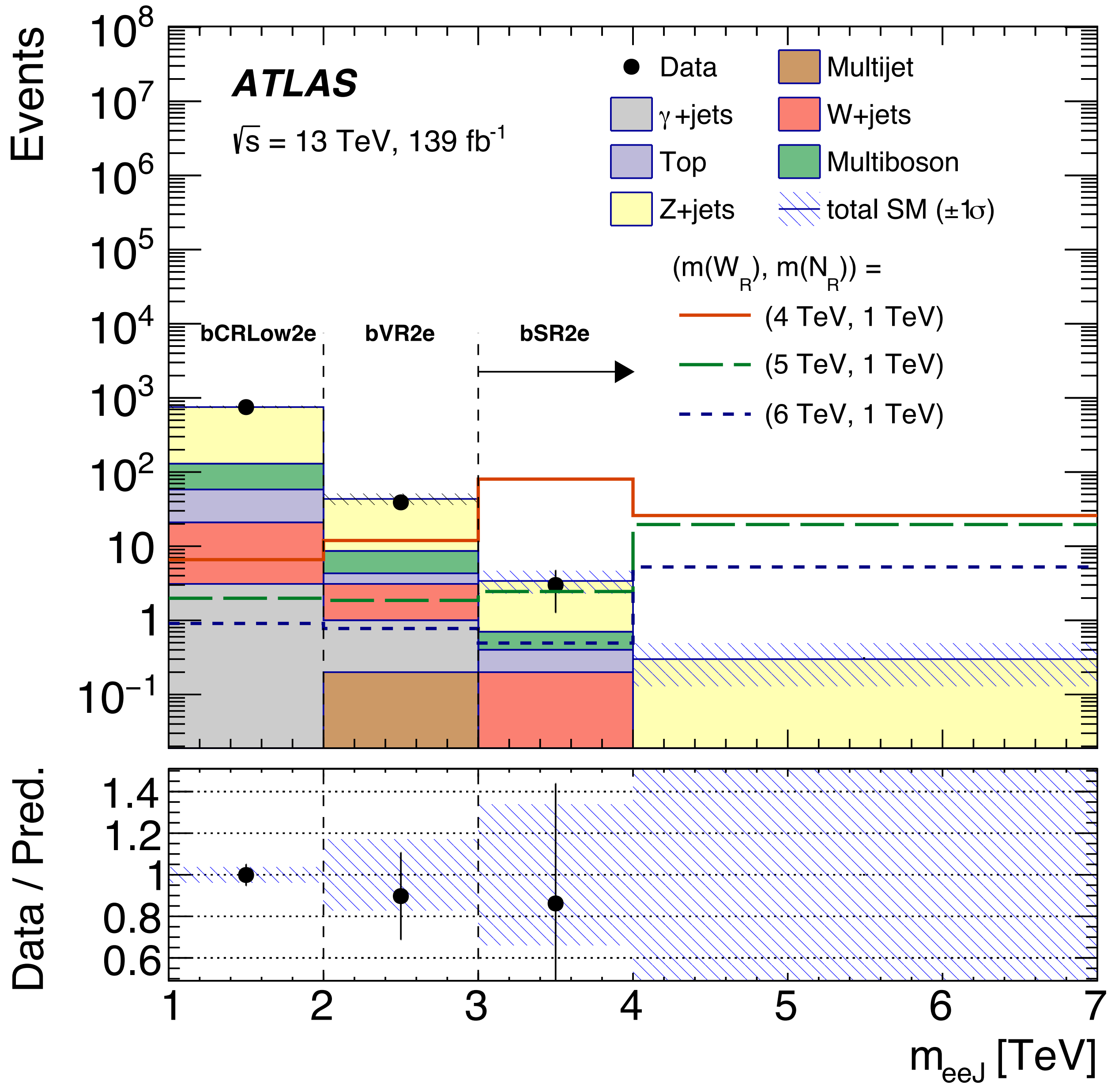


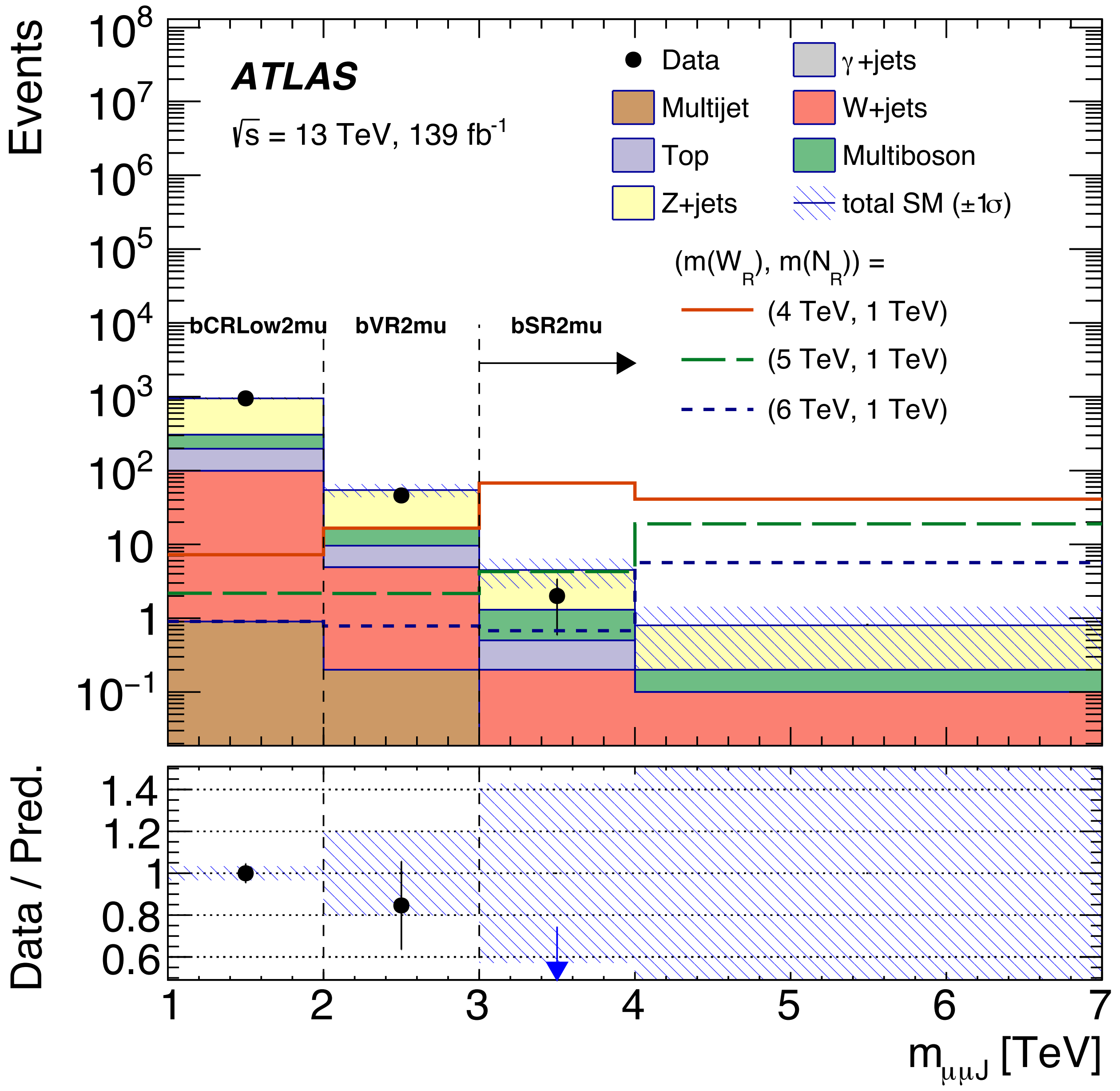


Heavy right handed W_R and N_R - fits in boosted SRs (and CR)









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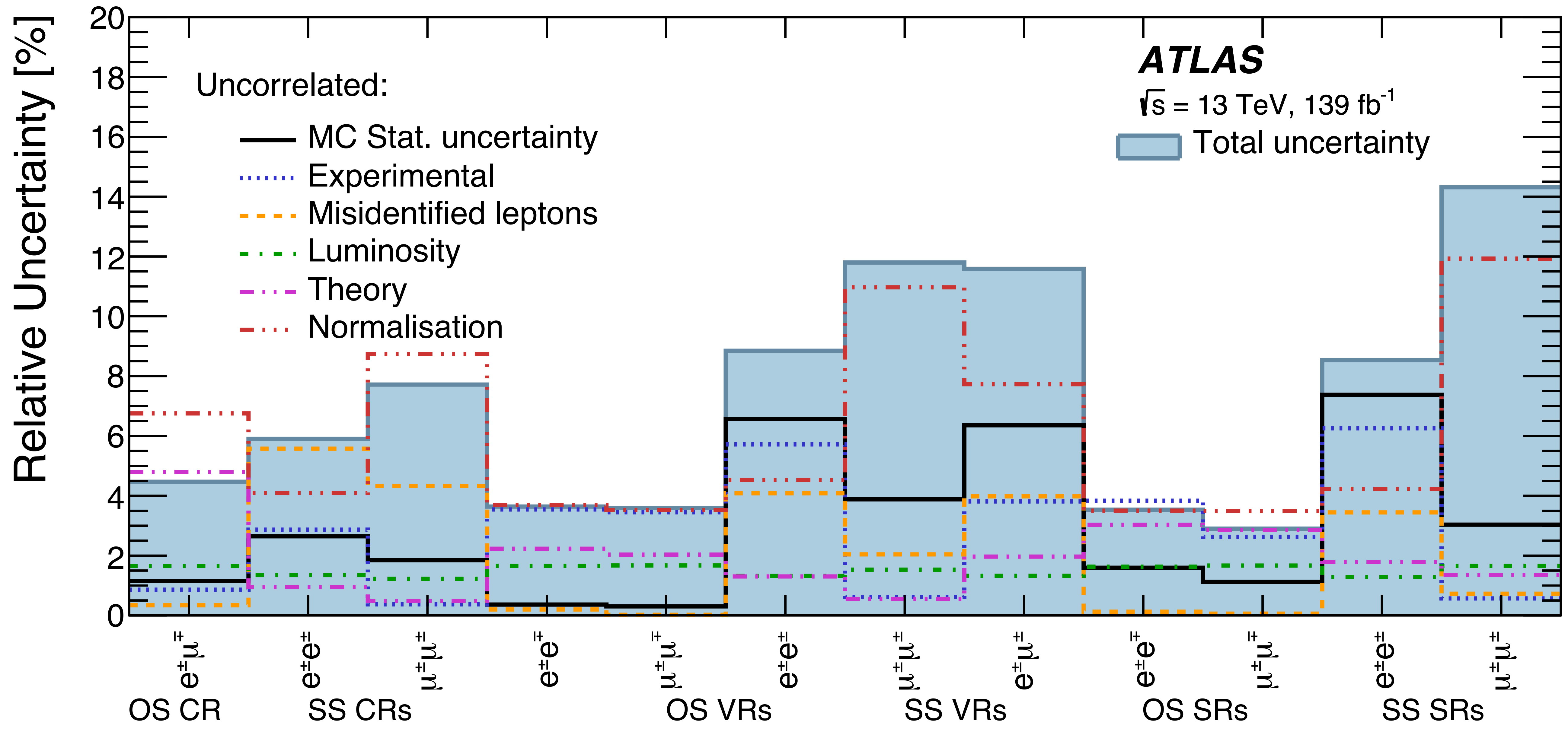
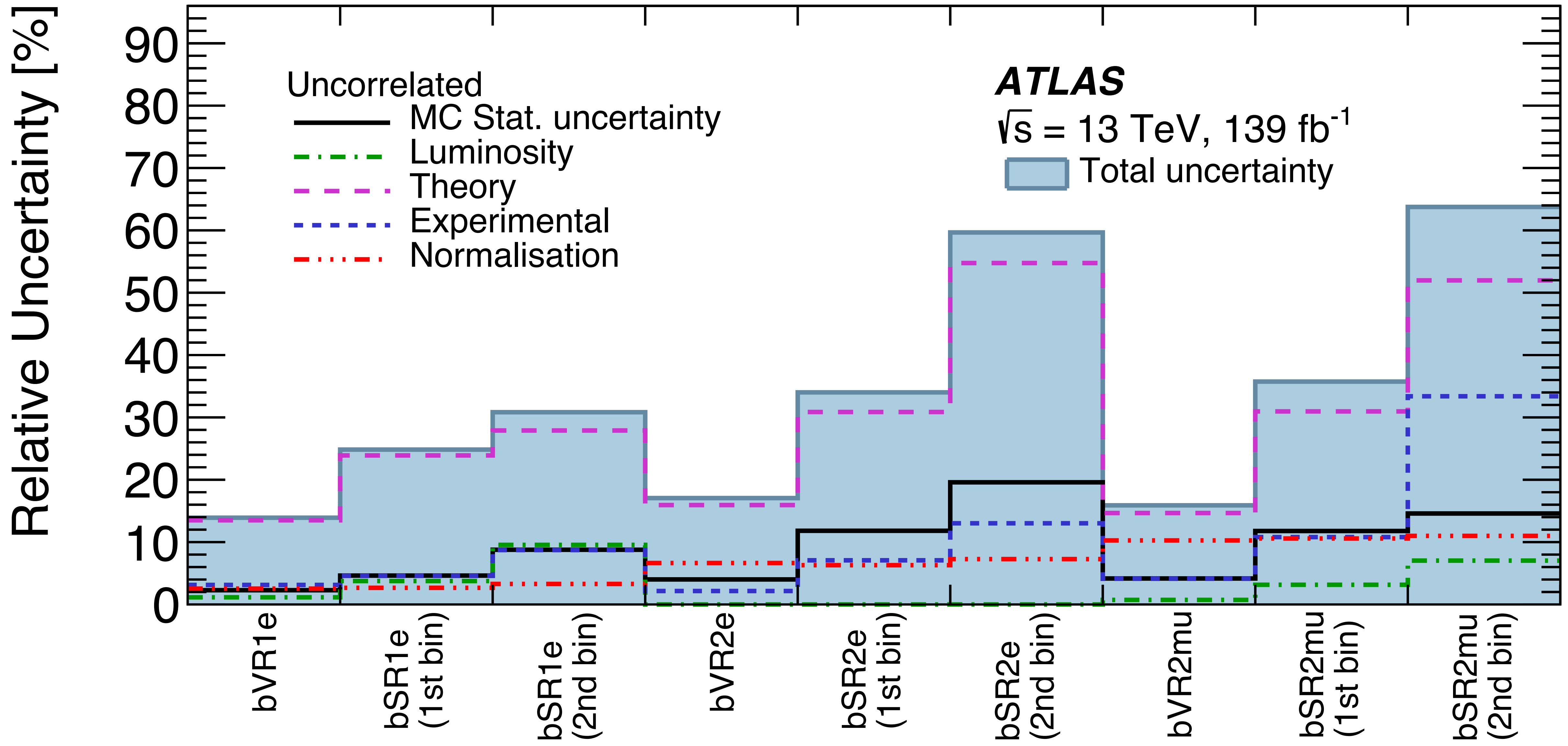
Heavy right handed W_R and N_R - Uncertainties





arXiv:2304.09553

Heavy right handed W_R and N_R - event yields (resolved)

Resolved channel: fit results in signal regions				
# of events	OS ee	OS $\mu\mu$	SS ee	SS $\mu\mu$
Observed in data	426	435	44	10
Total background	414 ± 15	451 ± 13	33.4 ± 2.8	9.6 ± 1.4
WW/ZZ	35 ± 10	43 ± 11	1.53 ± 0.41	0.18 ± 0.05
WZ/SS WW	10.9 ± 1.6	6.82 ± 0.95	9.8 ± 1.5	8.3 ± 1.3
Z+jets OS	191 ± 12	217 ± 11	—	—
Z+jets SS	—	—	8.4 ± 2.7	—
$t\bar{t}$	151 ± 14	164 ± 15	4.0 ± 1.2	—
fakes	9.95 ± 0.60	1.36 ± 0.36	7.6 ± 1.3	0.30 ± 0.07
single top	13.6 ± 1.3	16.2 ± 1.0	1.07 ± 0.32	—
rare top	2.45 ± 0.15	2.41 ± 0.16	0.87 ± 0.07	0.83 ± 0.11
multiboson	0.29 ± 0.02	—	0.13 ± 0.01	—

arXiv:2304.09553

Heavy right handed W_R and N_R - event yields (boosted, 1*e*, 2*e*)

Boosted channel: fit results in $1e$ regions

# of events	bCRLow1e	bCRγ1e	bVR1e	bSR1e 1st bin	bSR1e 2nd bin
Observed in data	7988	4611	239	10	0
Total background	7983 ± 90	4611 ± 68	249 ± 35	11.9 ± 3.0	0.81 ± 0.25
W+jets	5850 ± 160	1500 ± 120	141 ± 33	5.6 ± 2.7	0.2 ± 0.2
γ+jets	279 ± 52	1370 ± 160	31.6 ± 5.4	2.03 ± 0.52	0.21 ± 0.09
dijet	89 ± 54	1102 ± 39	29.1 ± 4.8	2.20 ± 0.75	0.24 ± 0.12
Z+jets	1350 ± 110	483 ± 39	29.4 ± 6.0	1.12 ± 0.46	—
diboson	310 ± 160	88 ± 44	13.5 ± 6.9	0.67 ± 0.42	0.06 ± 0.04
$t\bar{t}$	59 ± 38	53 ± 33	3.0 ± 1.8	0.18 ± 0.11	—
Single top	46 ± 29	18 ± 11	2.0 ± 2.0	$0.10^{+0.17}_{-0.10}$	—

Boosted channel: fit results in $2e$ regions

# of events	bCRZ2e	bVR2e	bSR2e 1st bin	bSR2e 2nd bin
Observed in data	751	39	3	0
Total background	752 ± 28	43.4 ± 7.4	3.5 ± 1.2	0.31 ± 0.18
Z+jets	622 ± 51	34.8 ± 7.6	2.6 ± 1.2	0.27 ± 0.18
$t\bar{t}$	29 ± 18	0.95 ± 0.51	0.24 ± 0.16	—
W+jets	17.8 ± 8.9	2.1 ± 1.1	0.20 ± 0.11	—
single top	8.4 ± 4.9	$0.21^{+0.30}_{-0.21}$	—	—
γ+jets	3.1 ± 1.5	0.80 ± 0.41	—	—
diboson	71 ± 35	4.3 ± 2.1	0.33 ± 0.18	—
dijet	—	0.22 ± 0.12	—	—

arXiv:2304.09553

Heavy right handed W_R and N_R - event yields (boosted, 2μ)

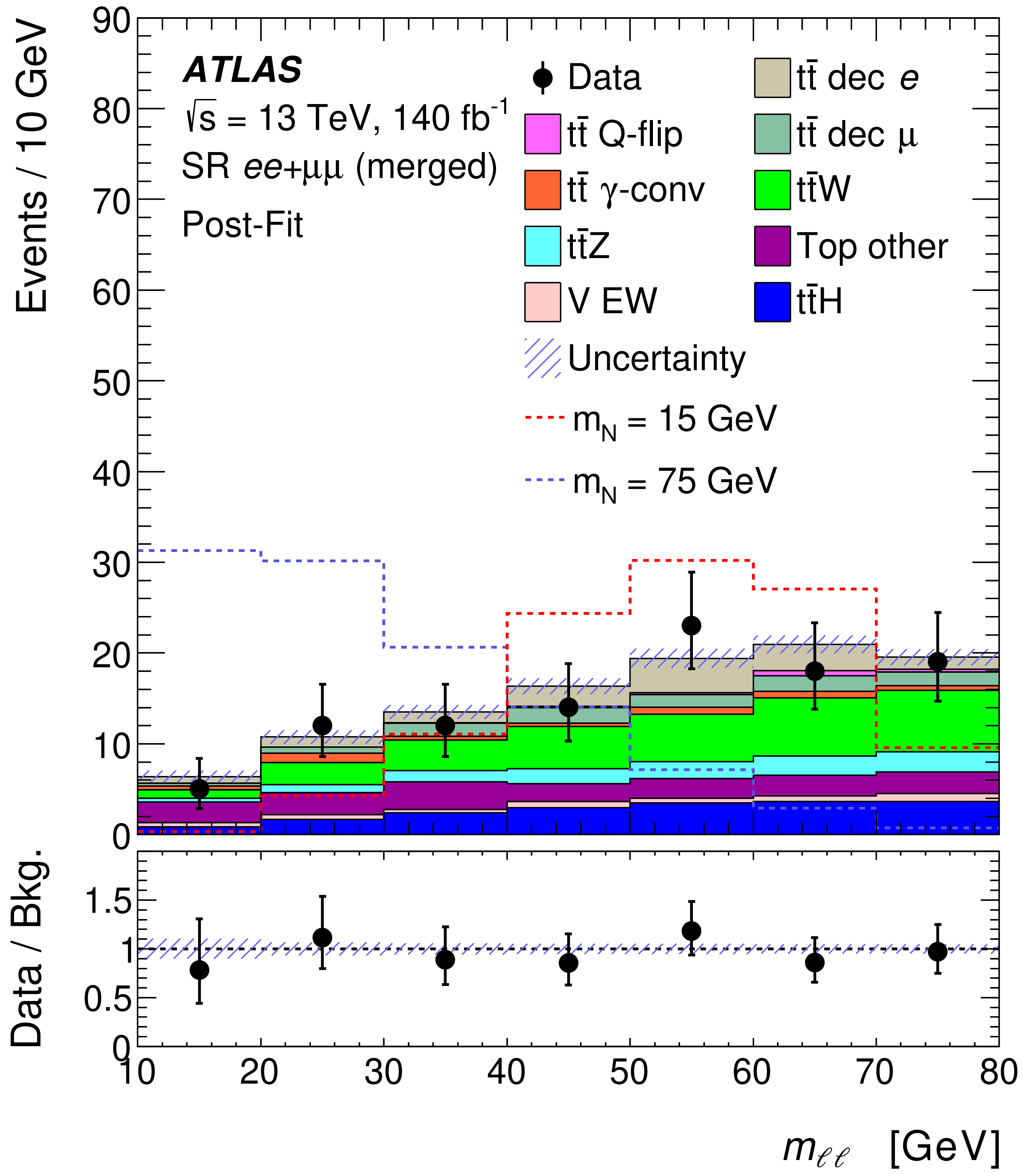
Boosted channel: fit results in 2μ regions

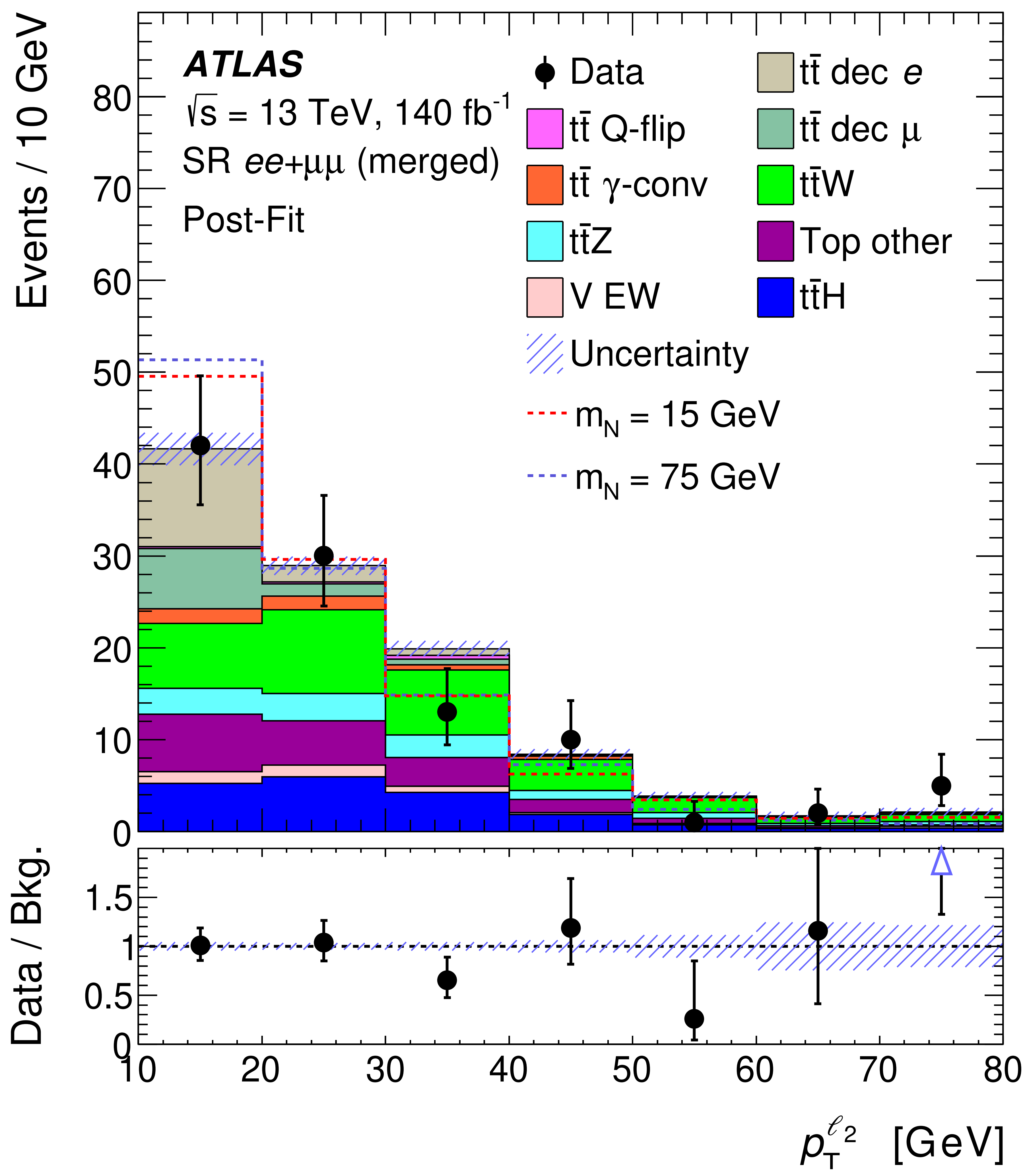
# of events	bCRZ2mu	bVR2mu	bSR2mu 1^{st} bin	bSR2mu 2^{nd} bin
Observed in the data	950	46	2	0
Total background	950 ± 31	54 ± 11	4.4 ± 1.9	0.82 ± 0.61
Z+jets	640 ± 100	38 ± 12	3.2 ± 1.9	0.63 ± 0.59
diboson	108 ± 54	6.7 ± 3.4	0.76 ± 0.40	0.08 ± 0.07
W+jets	98 ± 52	4.7 ± 2.9	0.21 ± 0.21	0.10 ± 0.10
$t\bar{t}$	78 ± 46	3.8 ± 2.2	—	—
single top	20 ± 12	0.88 ± 0.56	0.28 ± 0.28	—
dijet	0.94 ± 0.51	0.17 ± 0.15	—	—

arXiv:2304.09553

Heavy neutrino via top production
backup

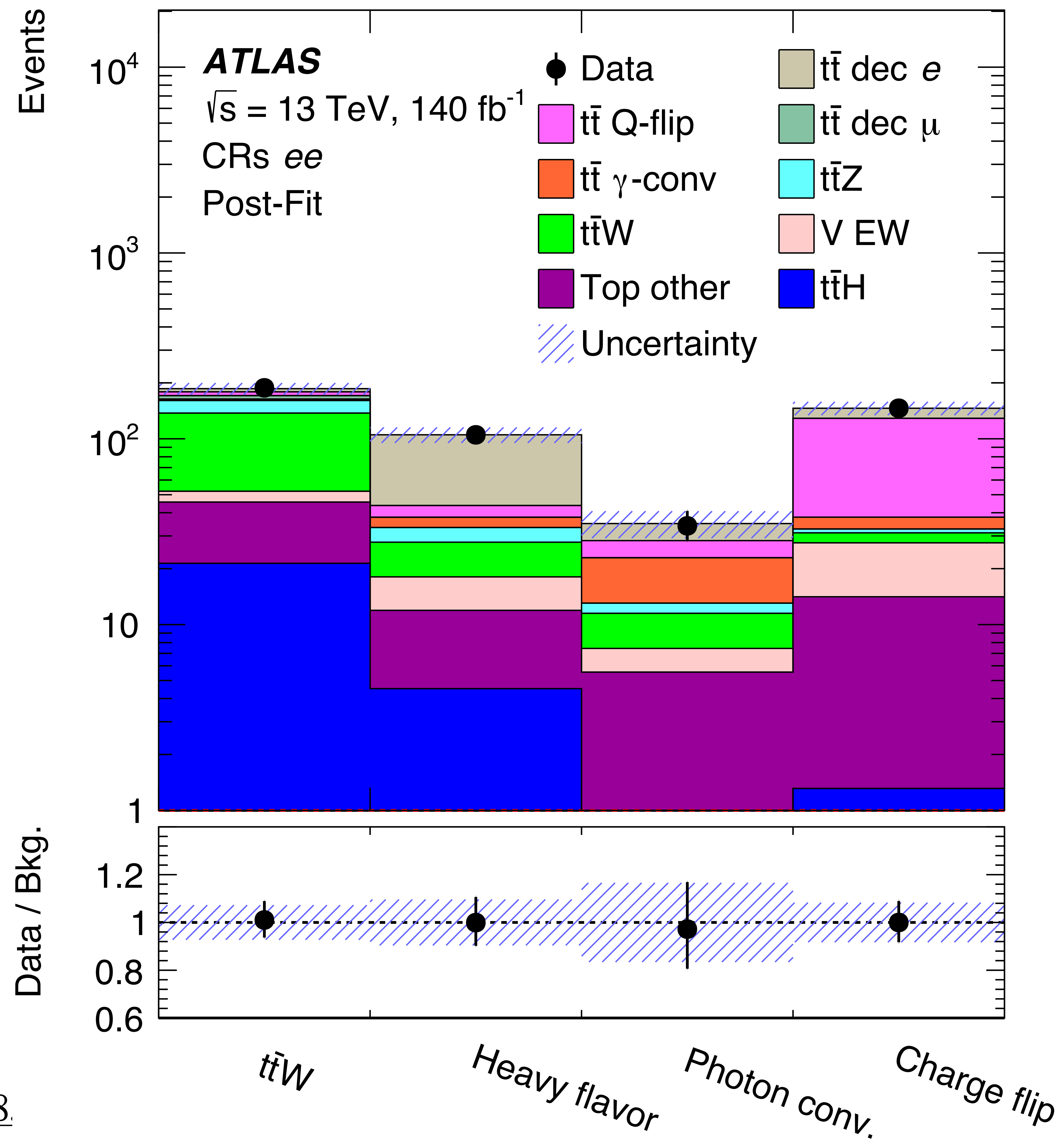
Heavy neutrino via top production - other two BDT input variables

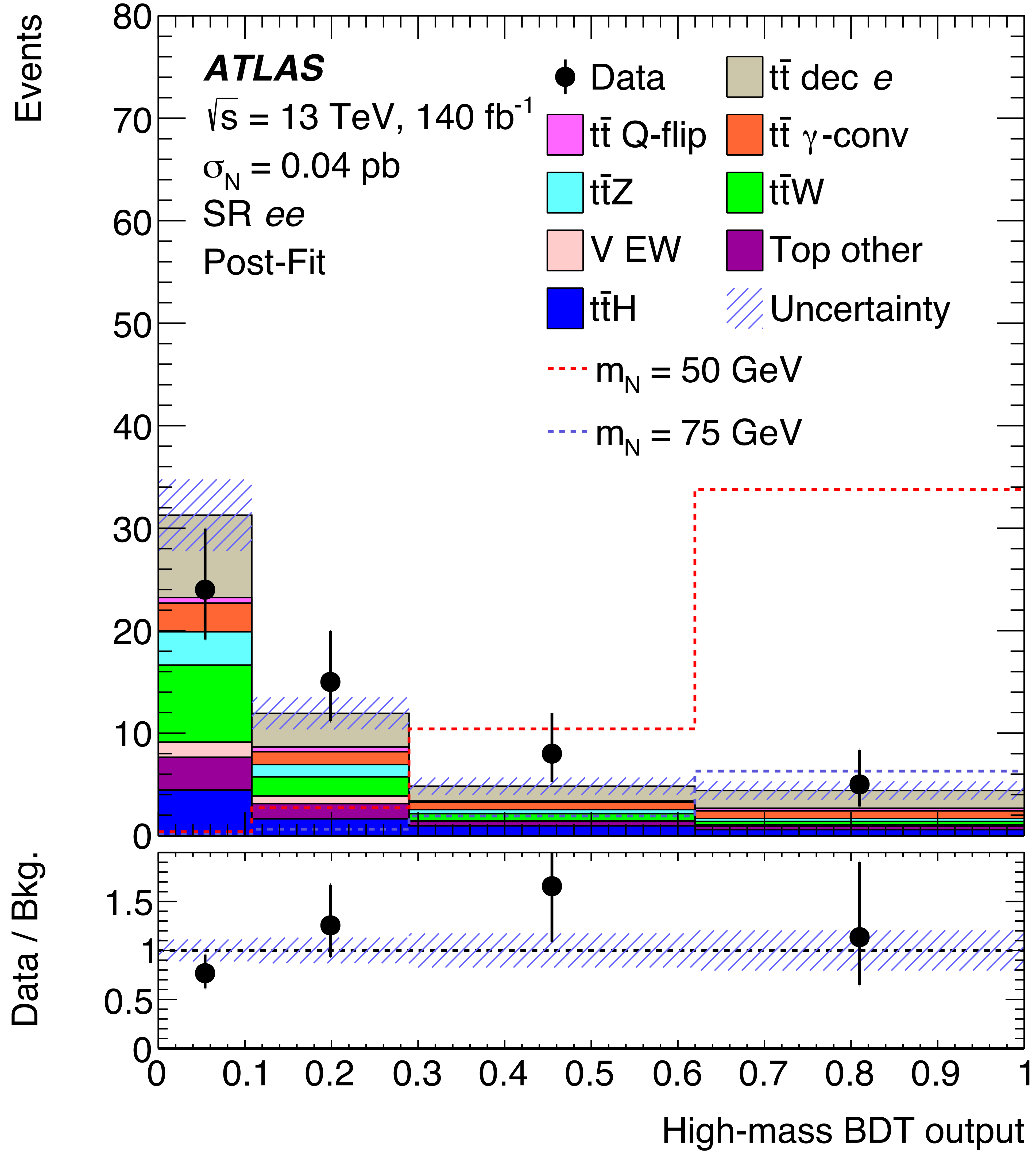




arXiv:2408.05000

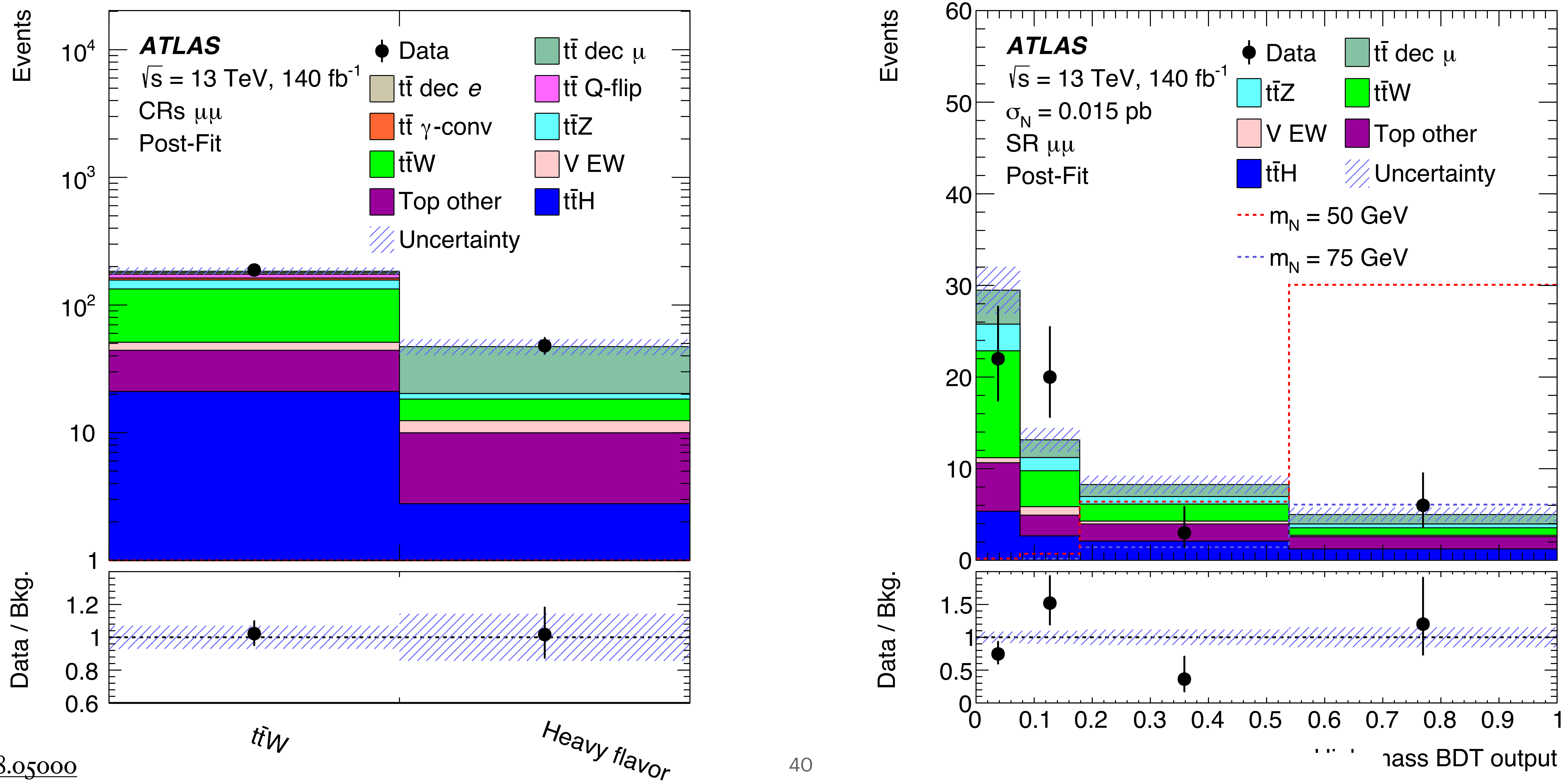
Heavy neutrino via top production - high mass BDT output *ee*





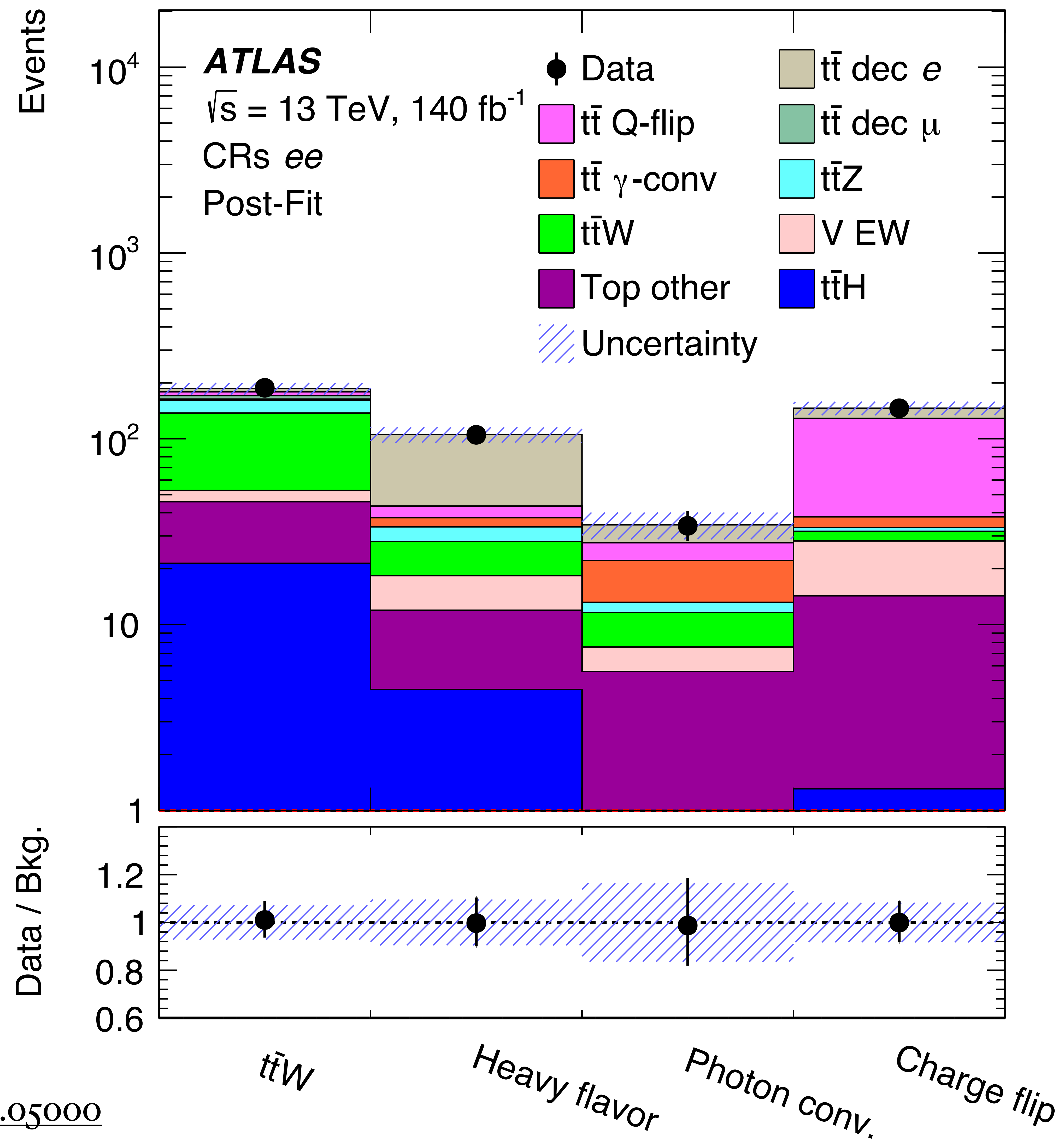
arXiv:2408.

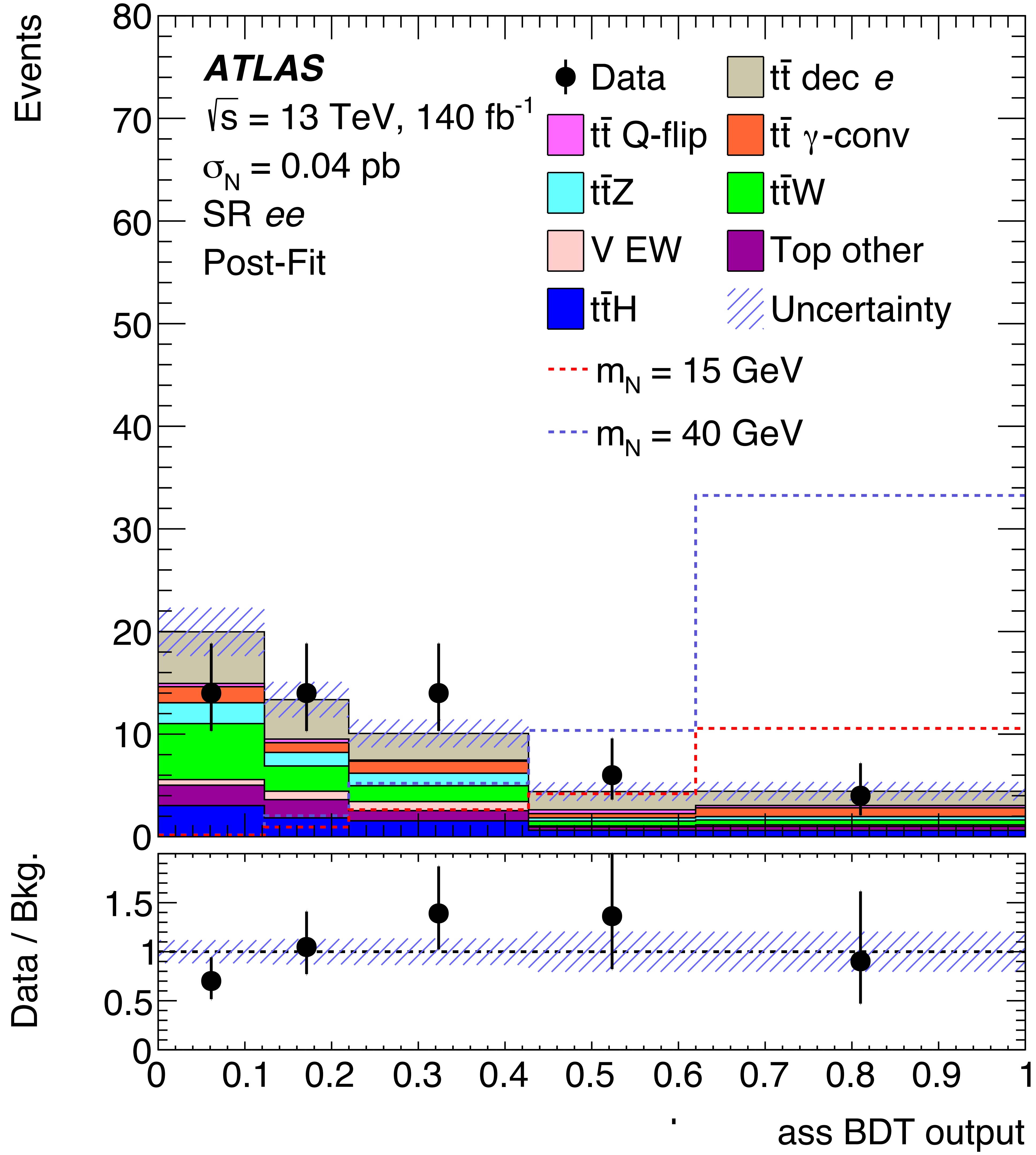
Heavy neutrino via top production - high mass BDT output $\mu\mu$



arXiv:2408.05000

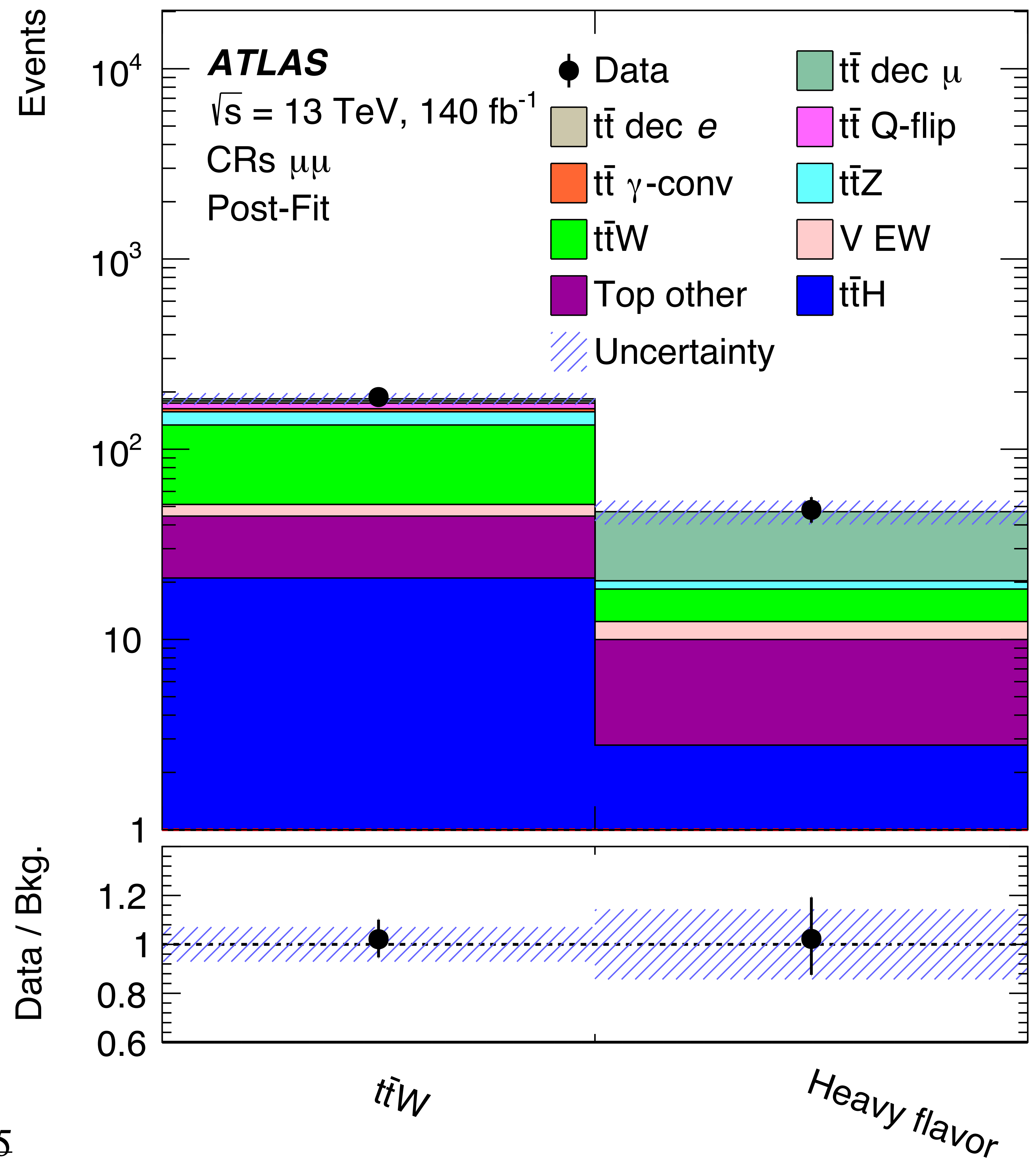
Heavy neutrino via top production - low mass BDT output *ee*

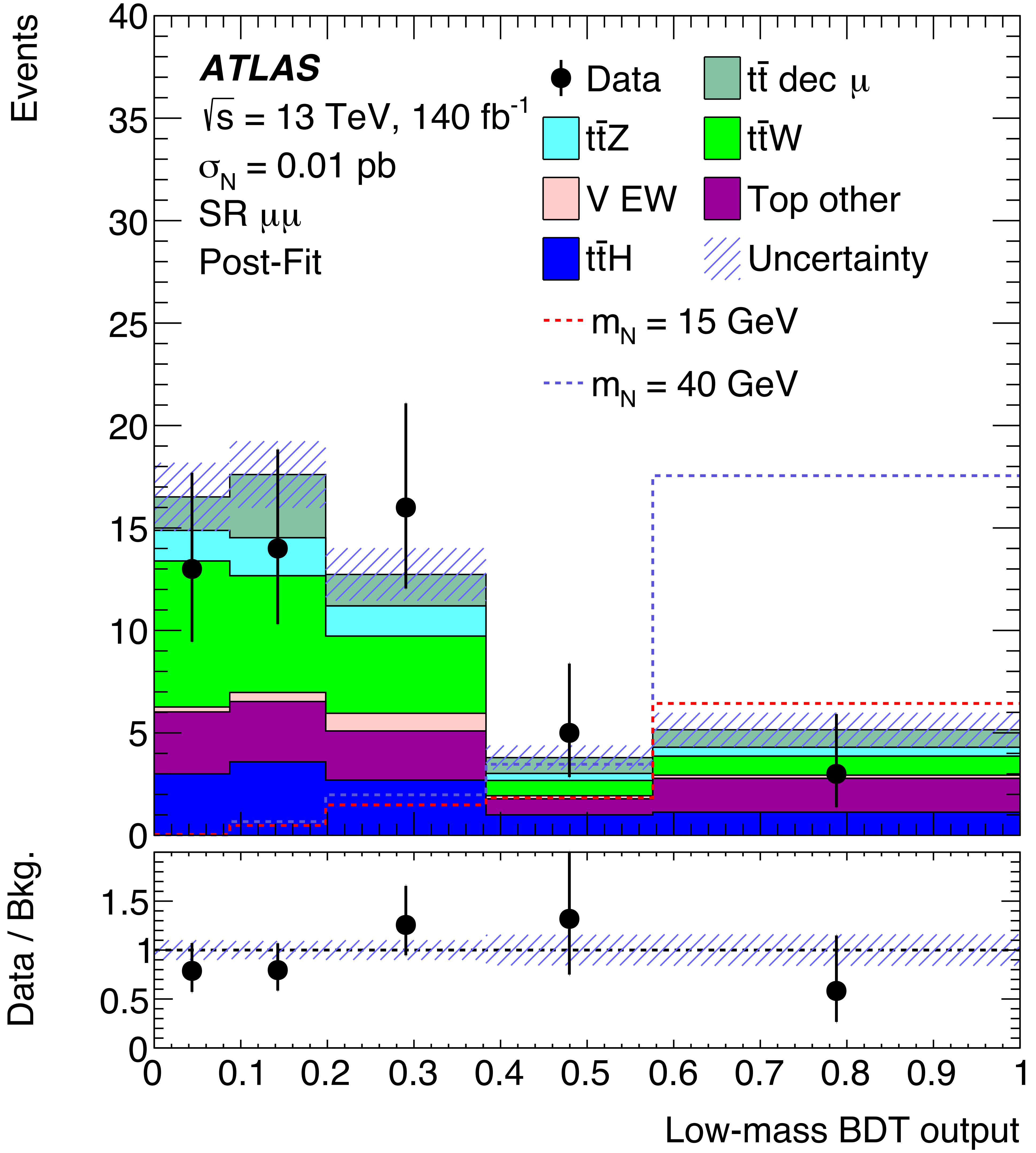




arXiv:2408.05000

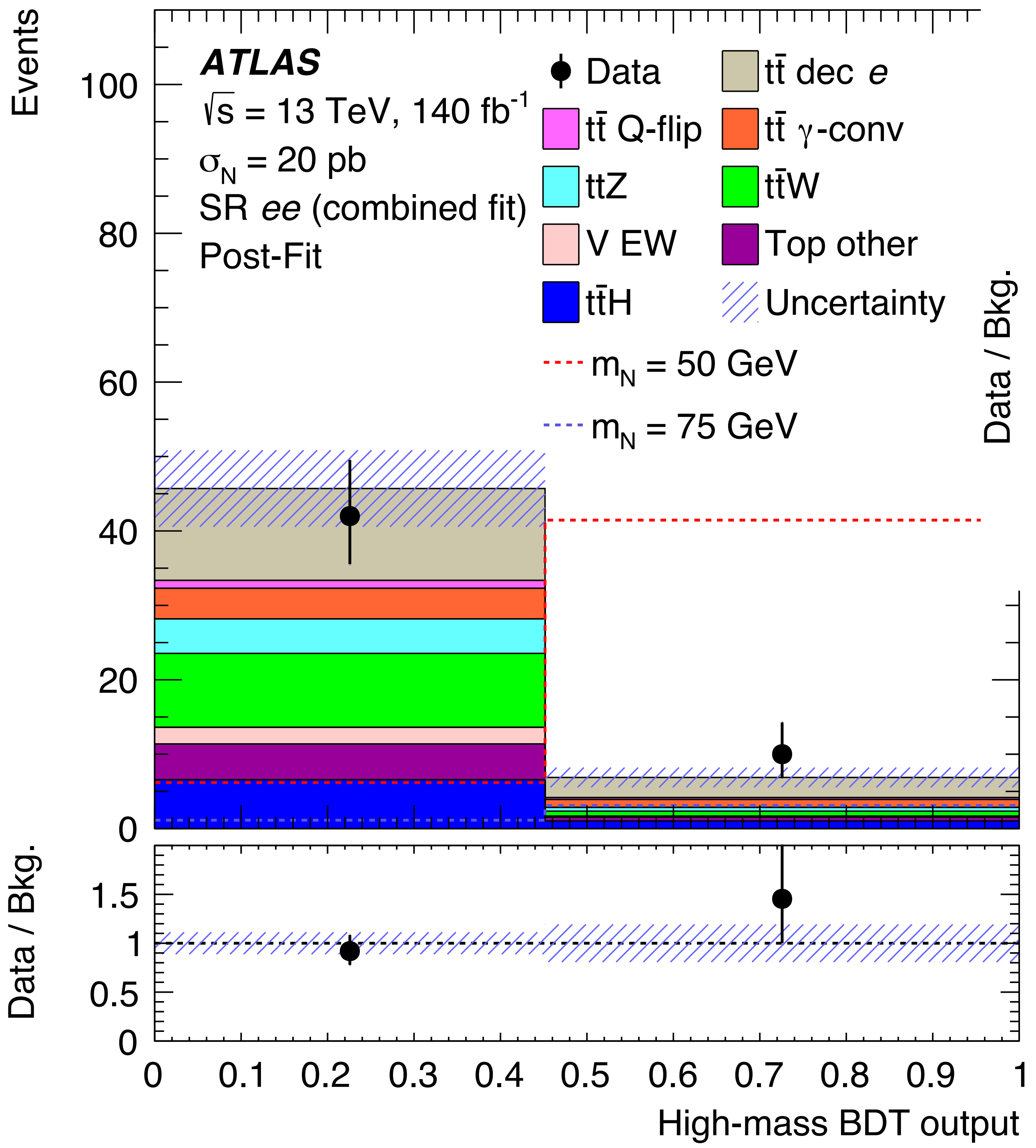
Heavy neutrino via top production - low mass BDT output $\mu\mu$

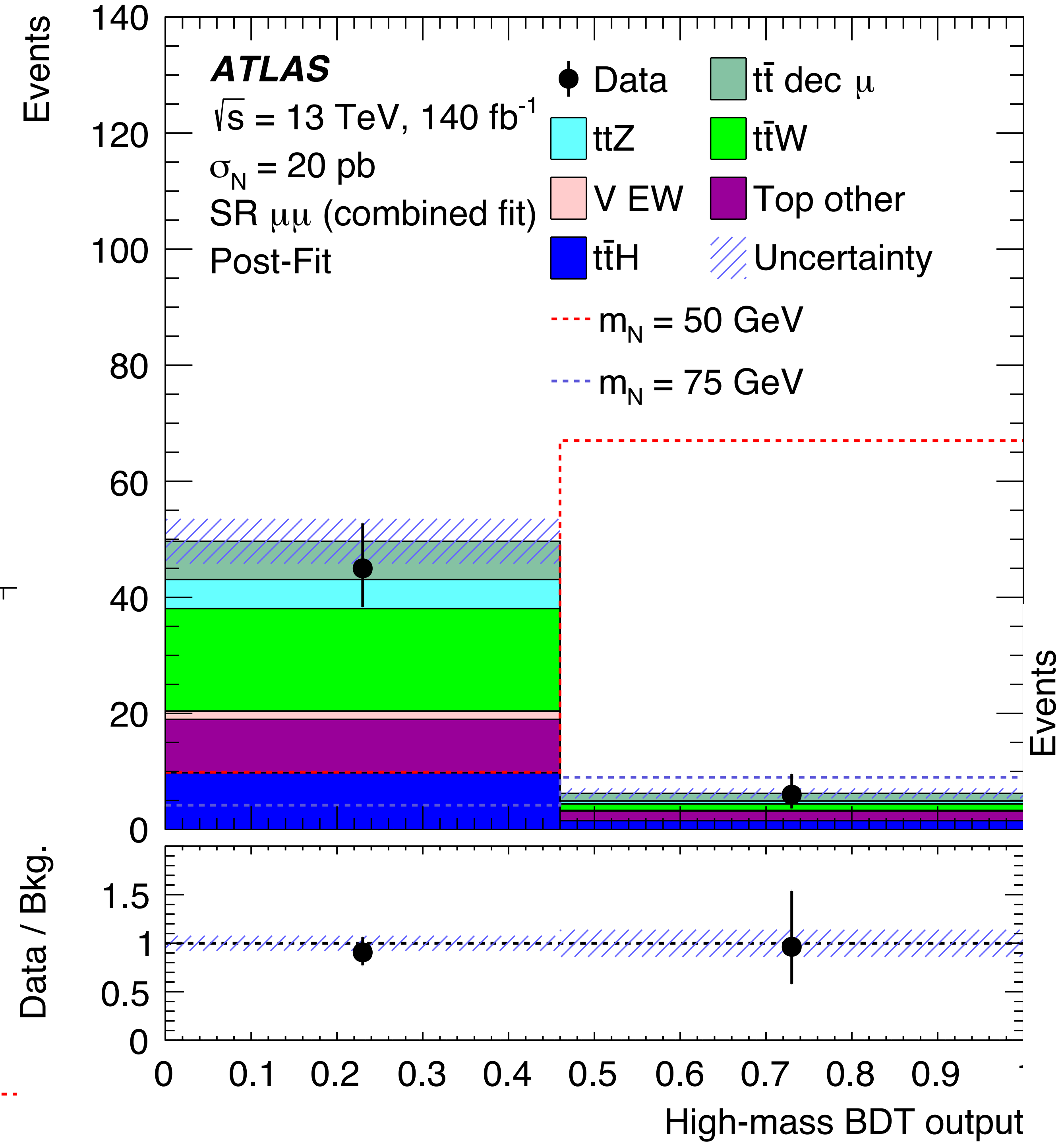


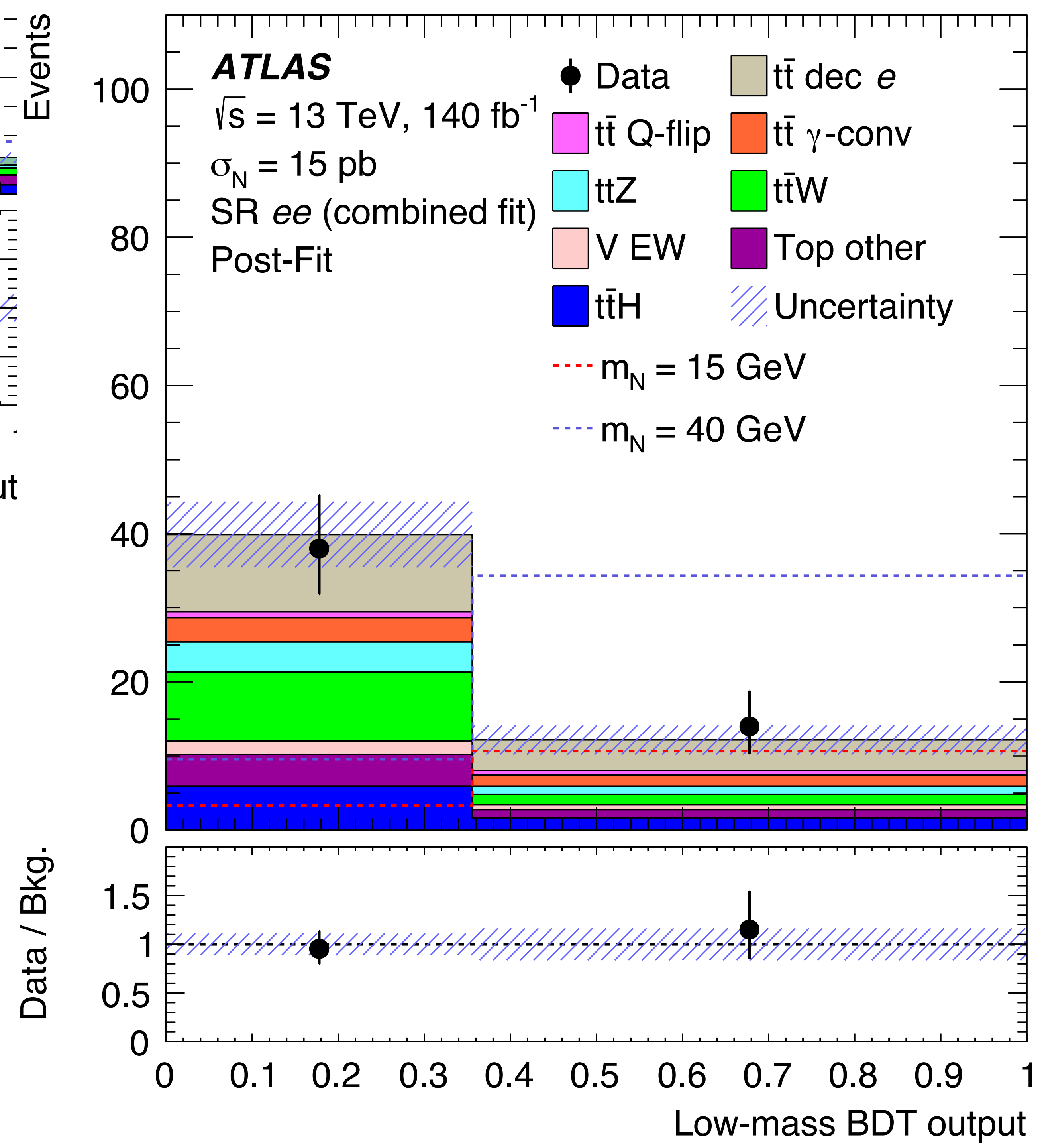


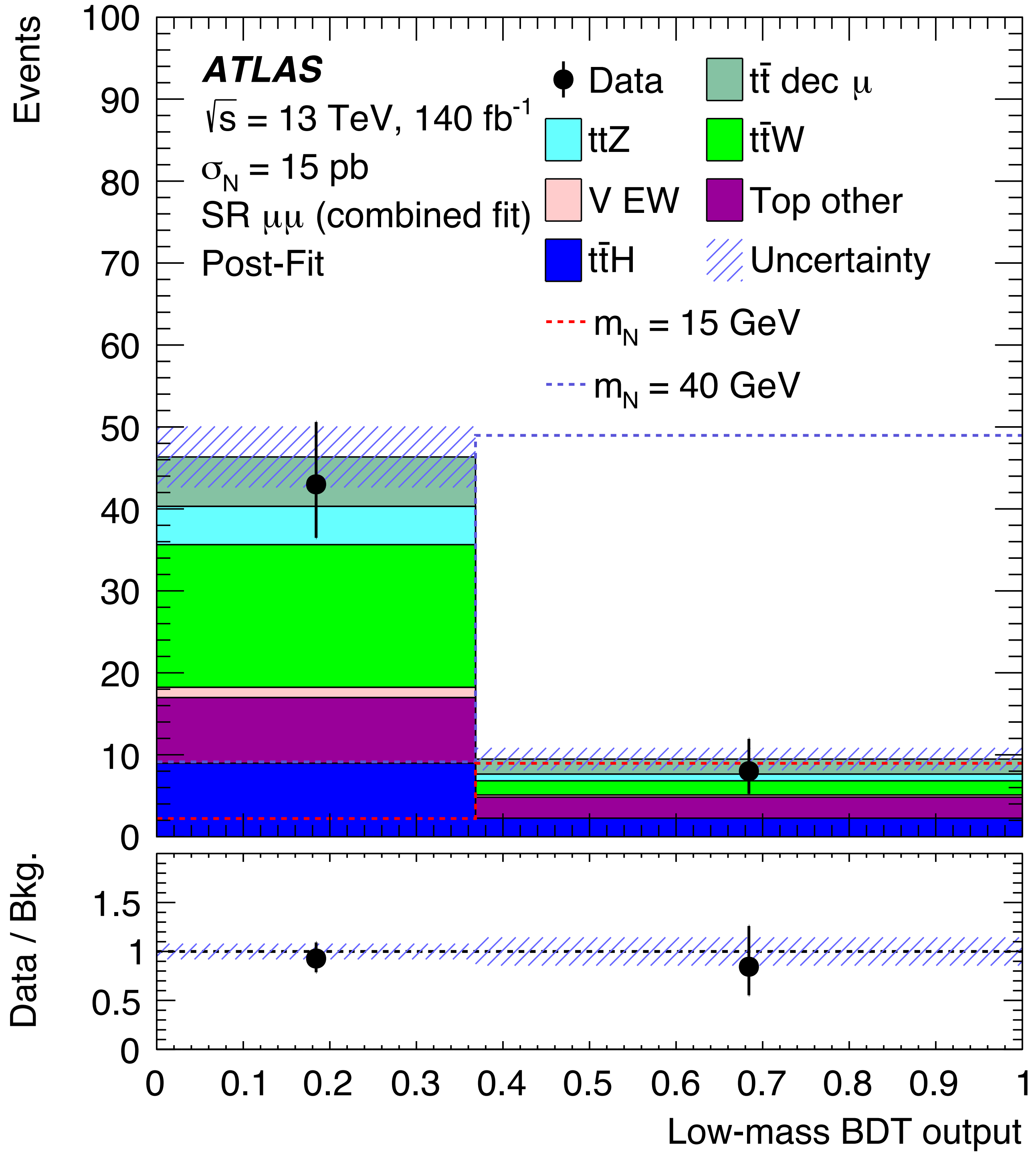
arXiv:2408.05

Heavy neutrino via top production - BDT output $\tau\tau$ interpretation









arXiv:2408.05000

Heavy neutrino via top production - event yields and exclusions

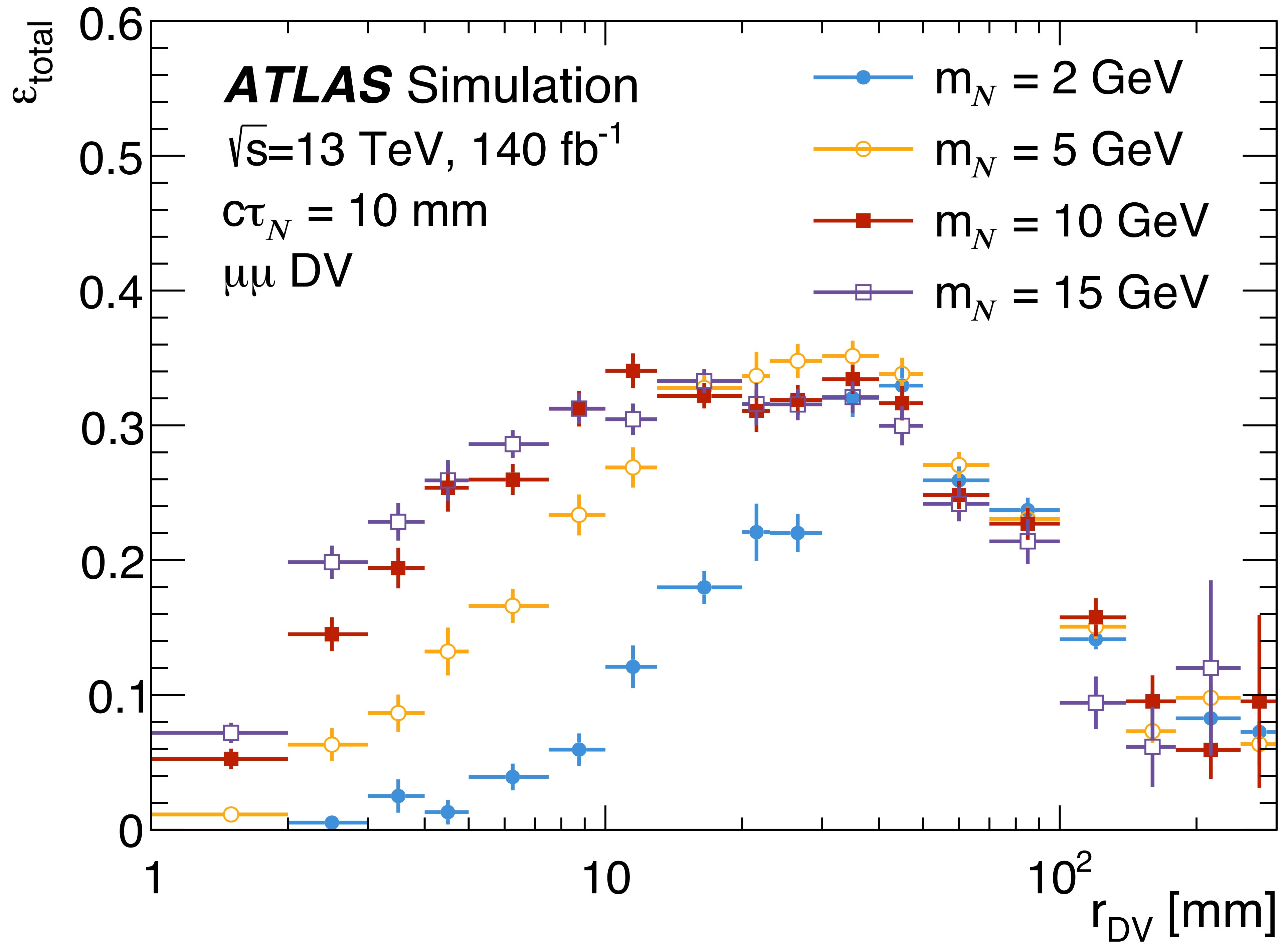
	Separate fits		Combined fit	
	SR ee	SR $\mu\mu$	SR ee	SR $\mu\mu$
$t\bar{t}$ decay e	15 ± 6	–	15 ± 7	–
$t\bar{t}$ Q-flip	1.4 ± 0.9	–	1.3 ± 0.8	–
$t\bar{t}$ γ-conv	6 ± 4	–	5 ± 4	–
$t\bar{t}$ decay μ	–	8.0 ± 3.2	–	8.4 ± 3.0
$t\bar{t}W$	10.4 ± 2.6	18 ± 5	10.4 ± 2.6	19 ± 4
$t\bar{t}Z$	5.2 ± 1.1	5.6 ± 1.1	5.0 ± 1.1	5.5 ± 1.1
$t\bar{t}H$	7.6 ± 1.3	11.4 ± 1.9	7.5 ± 1.3	11.2 ± 1.8
V EW	2.4 ± 0.9	1.9 ± 1.5	2.3 ± 0.8	1.5 ± 1.2
Top other	5.4 ± 2.2	11 ± 4	5.1 ± 2.2	11 ± 4
Total prediction	52 ± 6	56 ± 4	52 ± 6	56 ± 4
Data	52	51	52	51

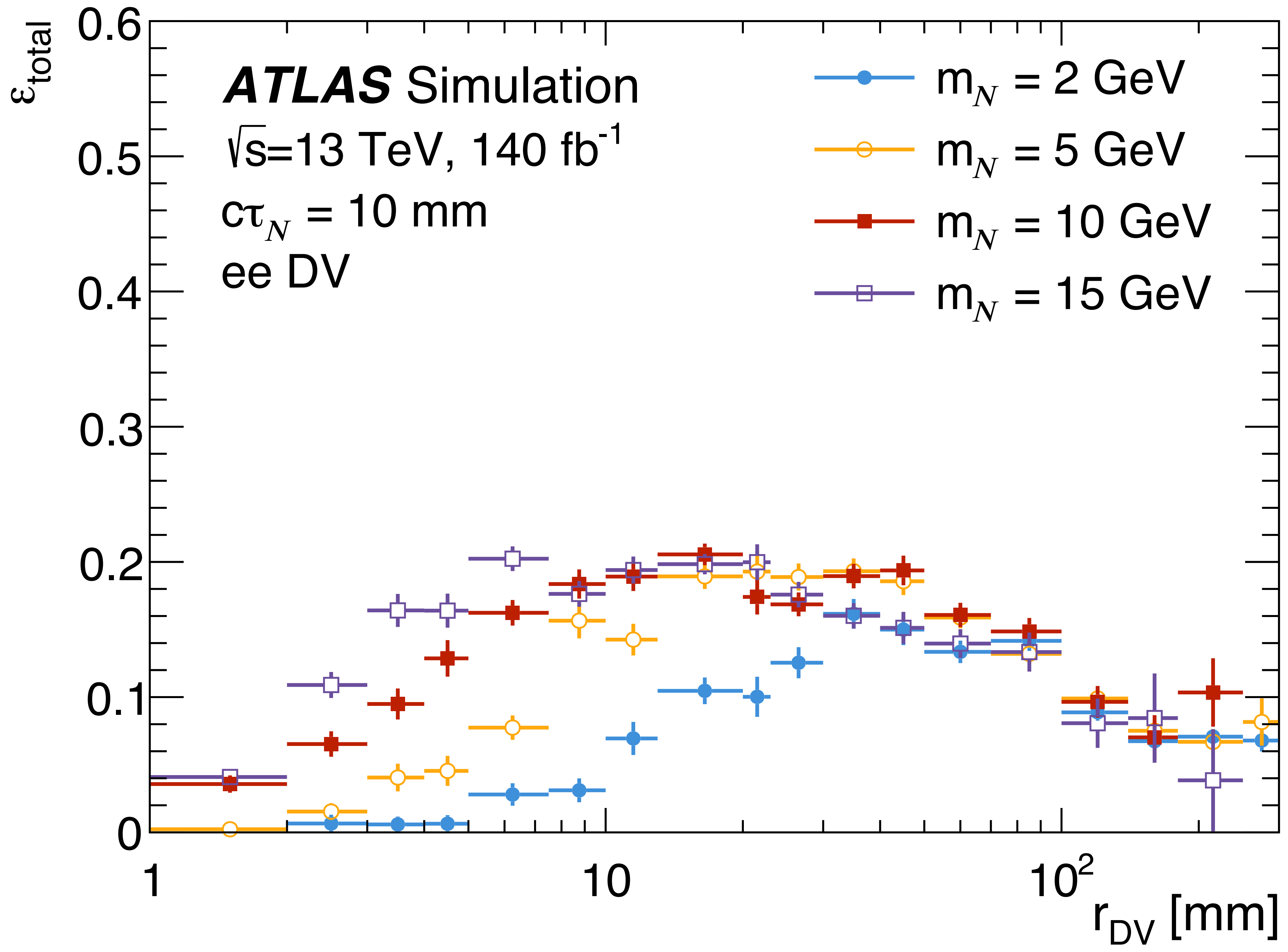
m_N [GeV]	15	25	35	40	45	50	55	60	70	75
Exp. $\sigma_{e,N}$ [fb]	21	9.8	7.3	6.9	6.9	6.7	7.2	8.5	18	36
Obs. $\sigma_{e,N}$ [fb]	26	12	8.2	7.8	10	9.7	10	12	26	52
Exp. $\sigma_{\mu,N}$ [fb]	9.3	5.0	3.7	3.5	3.2	3.1	3.2	4.0	8.2	15
Obs. $\sigma_{\mu,N}$ [fb]	7.5	3.9	2.8	2.6	3.2	3.1	3.3	4.2	8.3	15
Exp. $\sigma_{\tau,N}$ [pb]	8.9	2.6	2.1	1.7	1.8	1.8	2.0	3.7	7.0	19
Obs. $\sigma_{\tau,N}$ [pb]	13	3.6	2.7	2.3	2.5	2.2	3.2	5.5	7.3	20

arXiv:2408.05000

Displaced HNL search
backup

Displaced HNL - Displaced vertex reconstruction efficiency





arXiv:2503.16213

Displaced HNL - Signal Region selections

- Pre-selection

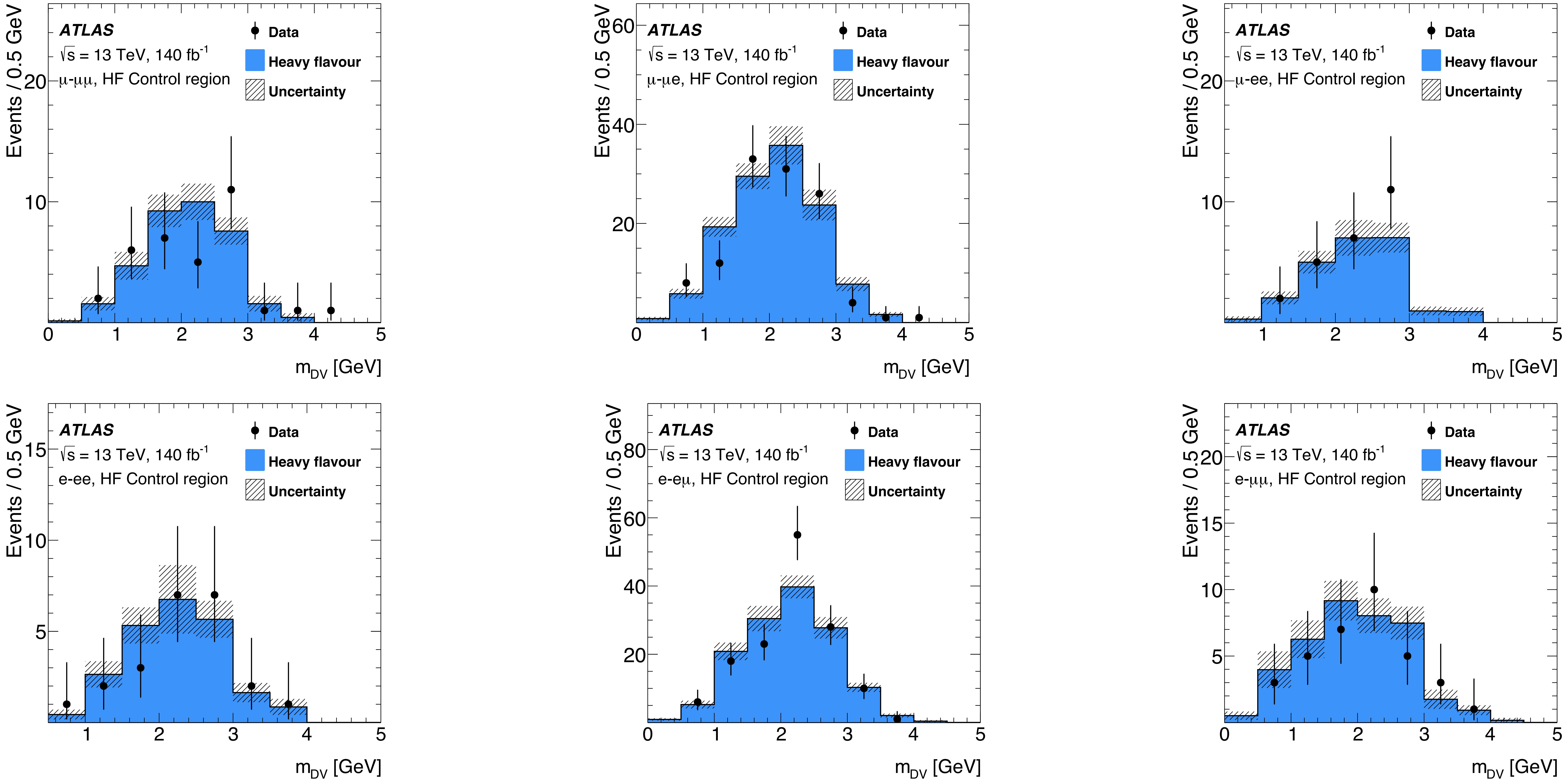
Selection	Leptonic	Semi-leptonic
Trigger	Lowest unprescaled single-lepton triggers, $p_T > 20-26$ GeV	
Prompt lepton selection	Trigger matched electron/muon, passing `Medium` ID WP, with $p_T > 27$ GeV	
Prompt lepton TTVA	$d_{0,\mathrm{sig}} < 5\,(3)$ for electrons (muons), $\lvert z_0 \sin\theta \rvert < 0.5$ mm	
Prompt lepton isolation	`Loose_VarRad` (`PFlowLoose_VarRad`) for electron (muon)	
Displaced vertex	Exactly 2 opposite-sign tracks, with	
	$4\,\mathrm{mm} < r_{\mathrm{DV}} < 300\,\mathrm{mm}$	$20\,\mathrm{mm} < r_{\mathrm{DV}} < 300\,\mathrm{mm}$
Displaced tracks p_T	Leading (subleading) track $p_T > 10\,(5)$ GeV	
Displaced-leptons ID WP	e: `LLP VeryLoose`, μ: `LLP Medium`	
DV track ⇔ lepton match	Only for e, $\lvert$track p_T − lepton $p_T\rvert$/lepton$p_T < 0.5$	
ΔR selection	$\Delta R(DV, \mathrm{jet}) > 0.4$	
Cosmic veto	$\sqrt{(\Sigma\eta)^2 + (\pi - \Delta\phi)^2} > 0.05$	
Z-boson-mass veto	Same-flavour opposite-sign leptons invariant mass, $m_{\ell\ell}$ not in [80, 100] GeV	
K_S^0 veto	-	$m_{\mathrm{DV}} > 0.6$ GeV
J/ψ veto	ee, $\mu\mu$ vertices, $m_{\mathrm{DV}} \notin [3.0, 3.2]$ GeV	-
Material map veto	Applied in ee channels	Applied in all channels
DV discriminant variable	$\mathcal{S} > 100$ if $m_{\mathrm{DV}} < 5$ GeV	

arXiv:2503.16213

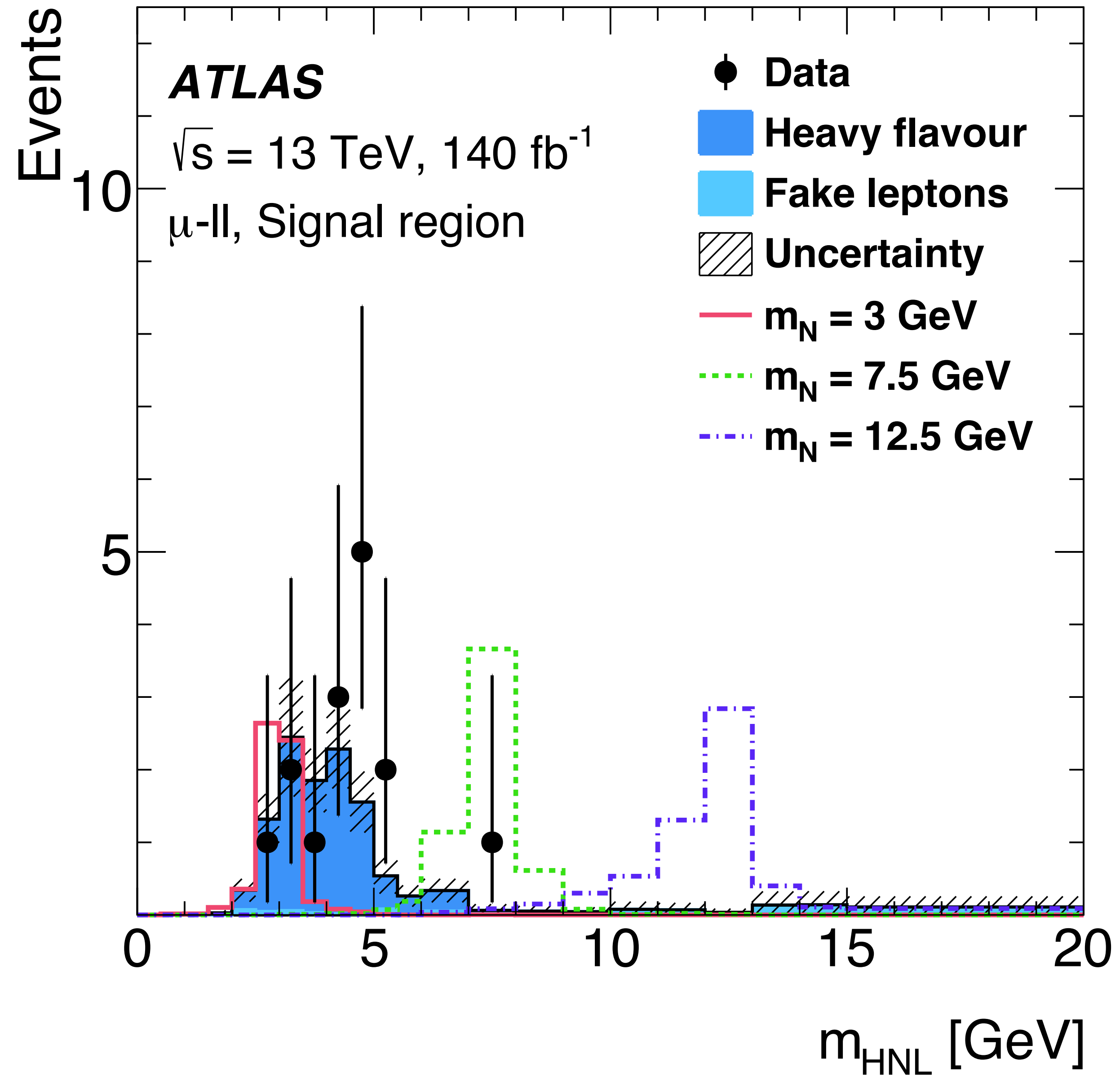
Displaced HNL - Postfit distributions in HF control regions

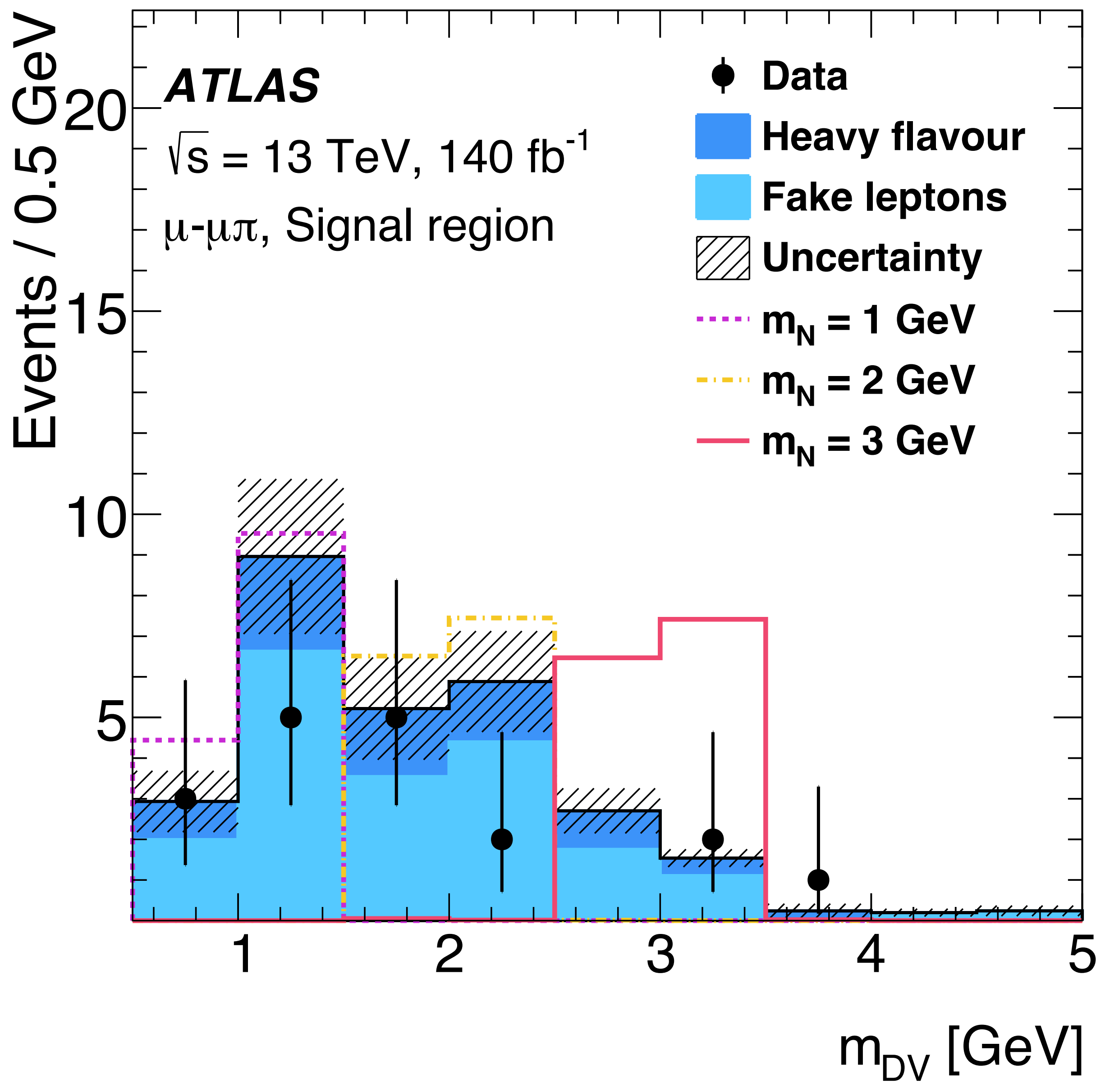
arXiv:2503.16213

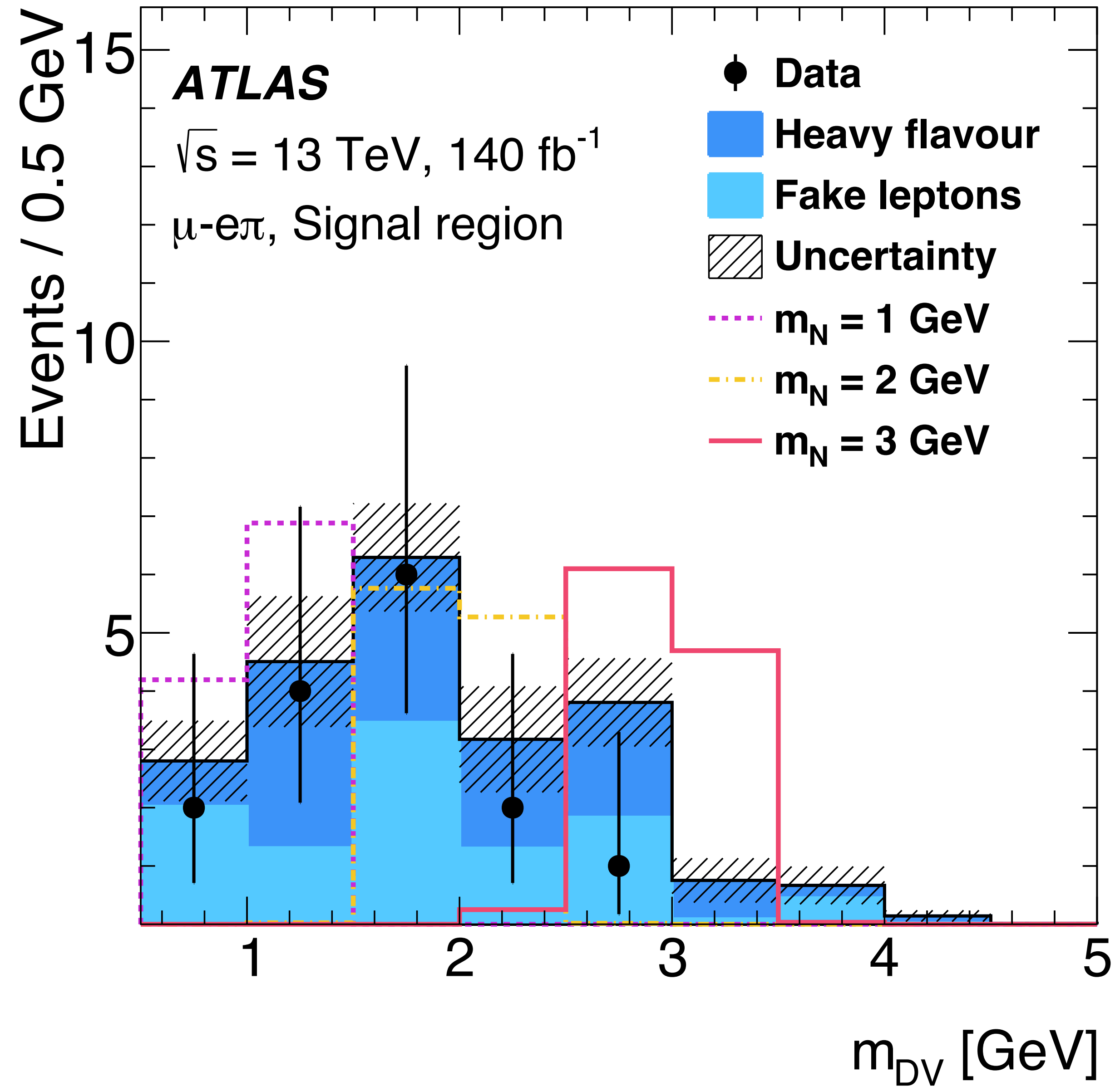
Displaced HNL - Postfit distributions in HF control regions

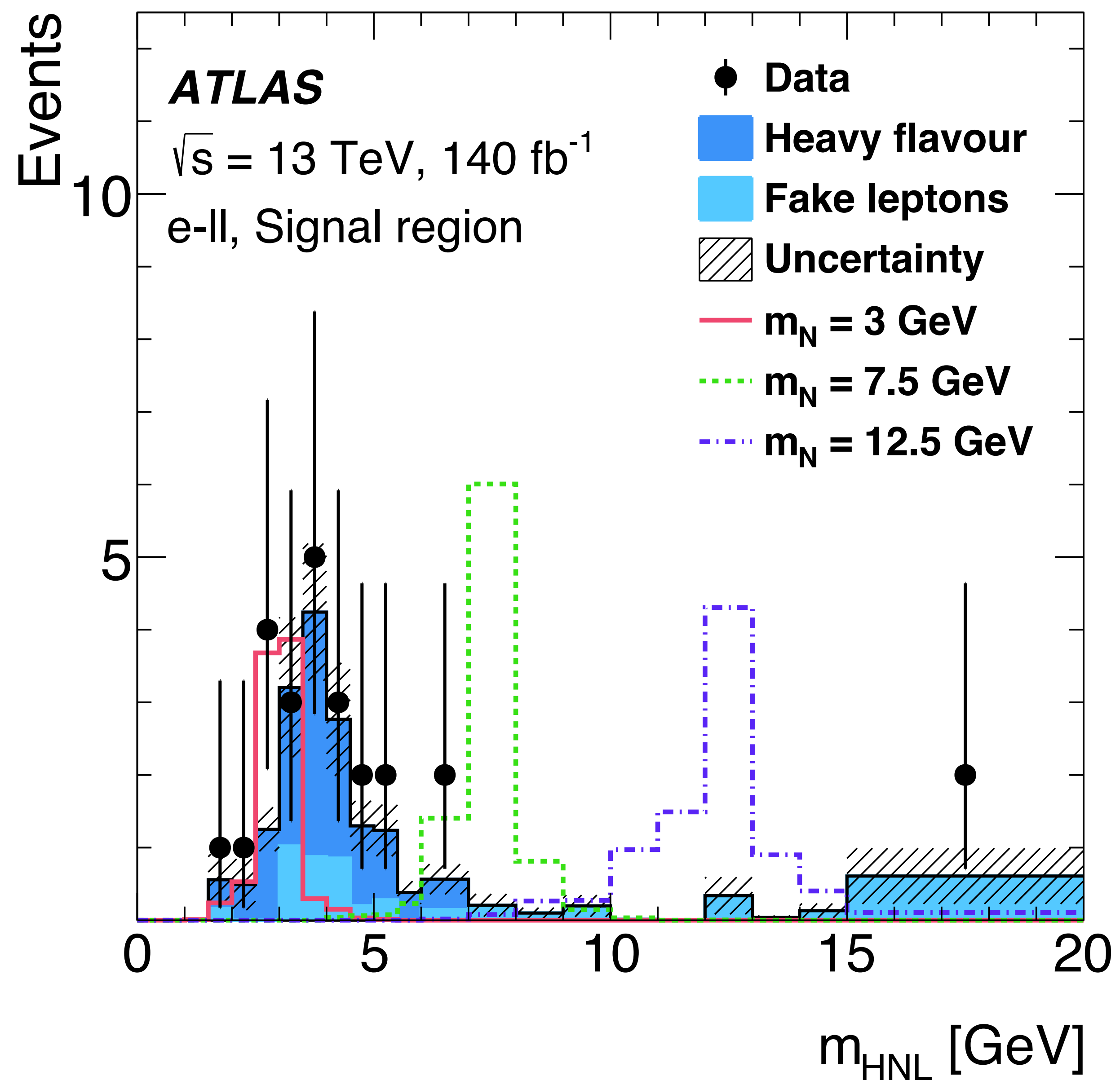


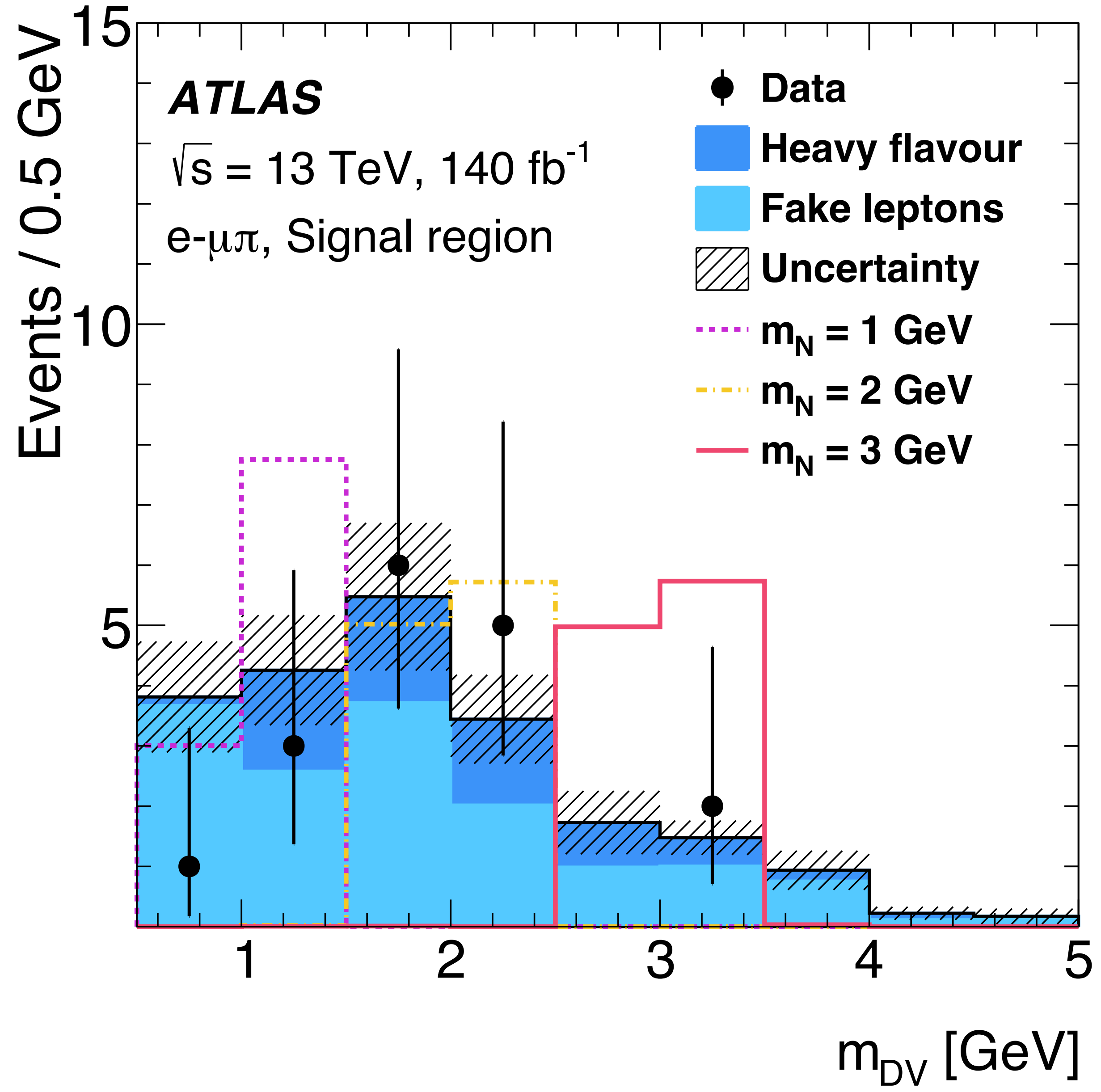
Displaced HNL - Postfit distributions in signal regions

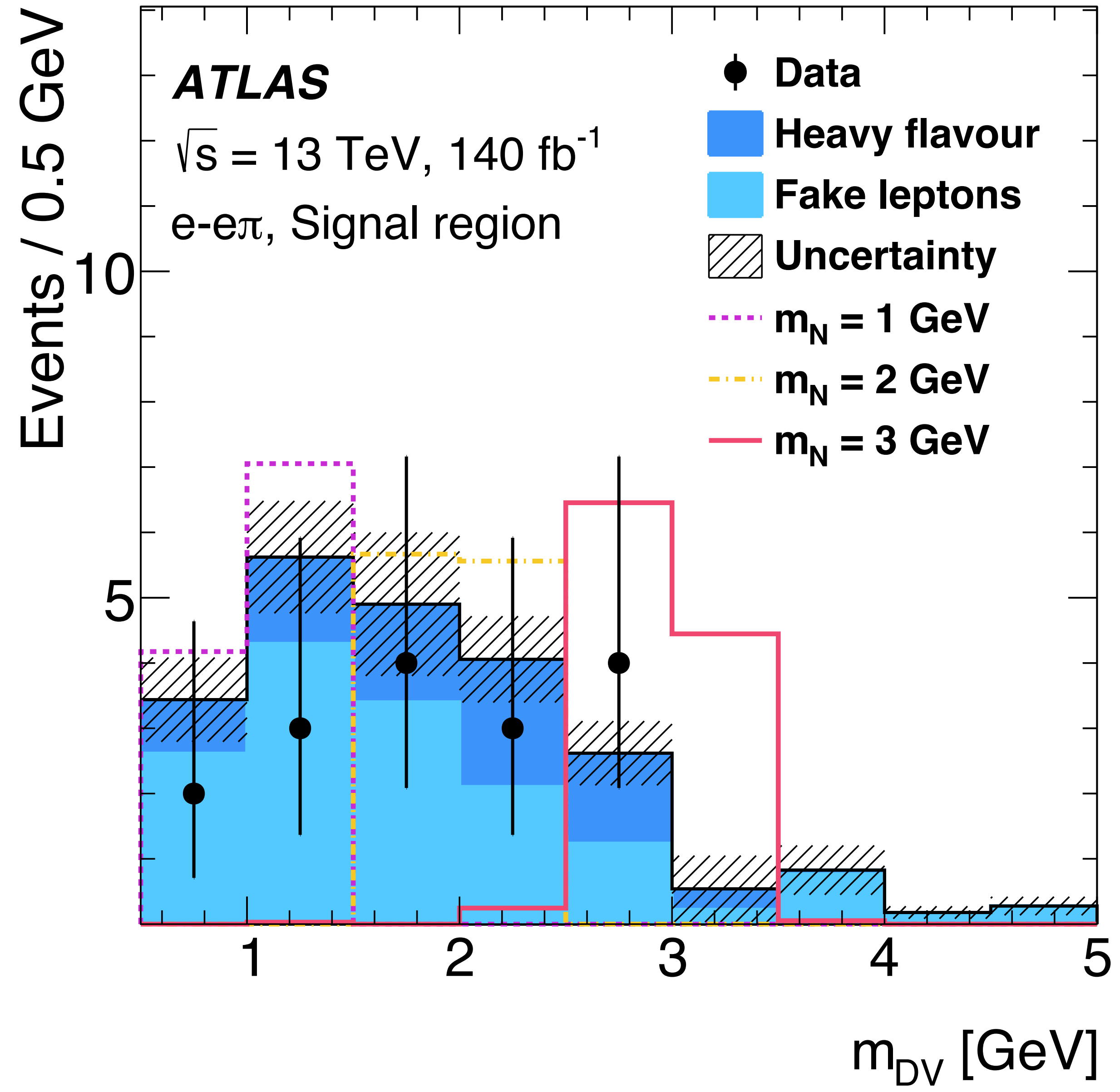












Displaced HNL - transfer factors and event yields

Transfer factor values					
$\mu-\ell\ell$	$e-\ell\ell$	$\mu-\mu\pi$	$e-\mu\pi$	$\mu-e\pi$	$e-e\pi$
$0.009^{+0.09}_{-0.009}$	0.12 ± 0.08	0.74 ± 0.13	0.75 ± 0.20	0.32 ± 0.07	0.41 ± 0.07

Signal region	$\mu-\ell\ell$	$e-\ell\ell$
Heavy flavour	10.6 ± 1.5	12.5 ± 1.7
Fakes	1.1 ± 1.5	5.2 ± 2.8
Total bkg	11.7 ± 2.1	17.6 ± 2.9
Observed data	15	25

Signal region	$\mu-\mu\pi$	$\mu-e\pi$	$e-\mu\pi$	$e-e\pi$
Heavy flavour	8.1 ± 1.3	11.7 ± 1.5	6.5 ± 1.3	7.4 ± 1.1
Fakes	20 ± 4	10.5 ± 2.8	15 ± 4	15 ± 3
Total bkg	28 ± 4	22.1 ± 2.9	22 ± 4	22.5 ± 2.9
Observed data	18	15	17	16

arXiv:2503.16213

Displaced HNL - systematic uncertainties

Systematic	SR $\mu - \ell\ell$	SR $e - \ell\ell$	SR $\mu - \mu\pi$	SR $\mu - e\pi$	SR $e - \mu\pi$	SR $e - e\pi$
Electrons	0.2 %	6 %	–	0.8 %	7 %	6 %
Muons	5 %	2 %	5 %	4 %	1 %	–
Flavour tagging	0.5 %	0.7 %	0.2 %	0.3 %	0.6 %	0.2 %
Pileup reweighting	2 %	2 %	2 %	0.5 %	0.2 %	1 %
Background modelling	12 %	10 %	10 %	9 %	13 %	14 %
SR template building	8 %	8 %	7 %	9 %	15 %	10 %
MC statistics	1.3 %	1.3 %	0.5 %	0.1 %	0.9 %	0.3 %
HF floating normalisation	13 %	13 %	13 %	13 %	13 %	13 %
Total	14 %	14 %	16 %	13 %	20 %	15 %

arXiv:2503.16213

Displaced HNL - region definitions

	Leptonic channels	Semi-leptonic channels
Signal Region	$40 < m_{\ell\ell\ell} < 90$ GeV 2 isolated displaced leptons b-jet veto	$70 < m_{\ell\ell\pi} < 90$ GeV 1 isolated displaced lepton b-jet veto
Heavy Flavour CR	$40 < m_{\ell\ell\ell} < 90$ GeV ≥ 1 non-isolated displaced lepton ≥ 1 b-tagged jet	$40 < m_{\ell\ell\pi} < 90$ GeV 1 non-isolated displaced lepton ≥ 1 b-tagged jet
Sideband CR	low $m_{\ell\ell\ell}$ region: $m_{\ell\ell\ell} < 40$ GeV high $m_{\ell\ell\ell}$ region: $m_{\ell\ell\ell} > 90$ GeV	low $m_{\ell\ell\pi}$ region: $m_{\ell\ell\pi} < 70$ GeV high $m_{\ell\ell\pi}$ region: $m_{\ell\ell\pi} > 90$ GeV
Relaxed Sideband CR	low $m_{\ell\ell\ell}$ region: $m_{\ell\ell\ell} < 40$ GeV high $m_{\ell\ell\ell}$ region: $m_{\ell\ell\ell} > 90$ GeV no displaced lepton isolation requirement	low $m_{\ell\ell\pi}$ region: $m_{\ell\ell\pi} < 70$ GeV high $m_{\ell\ell\pi}$ region: $m_{\ell\ell\pi} > 90$ GeV no displaced lepton isolation requirement

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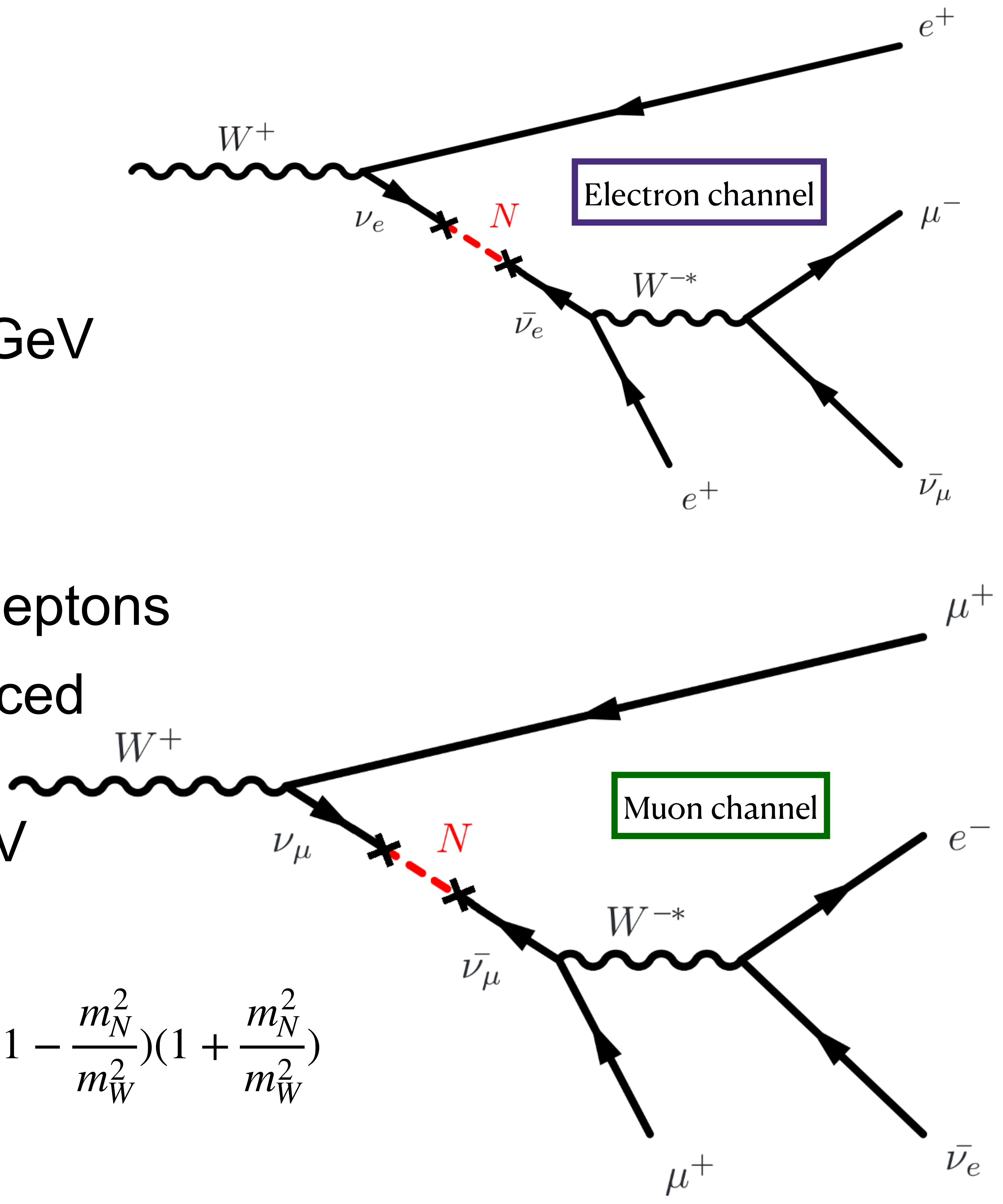
Prompt HNL search

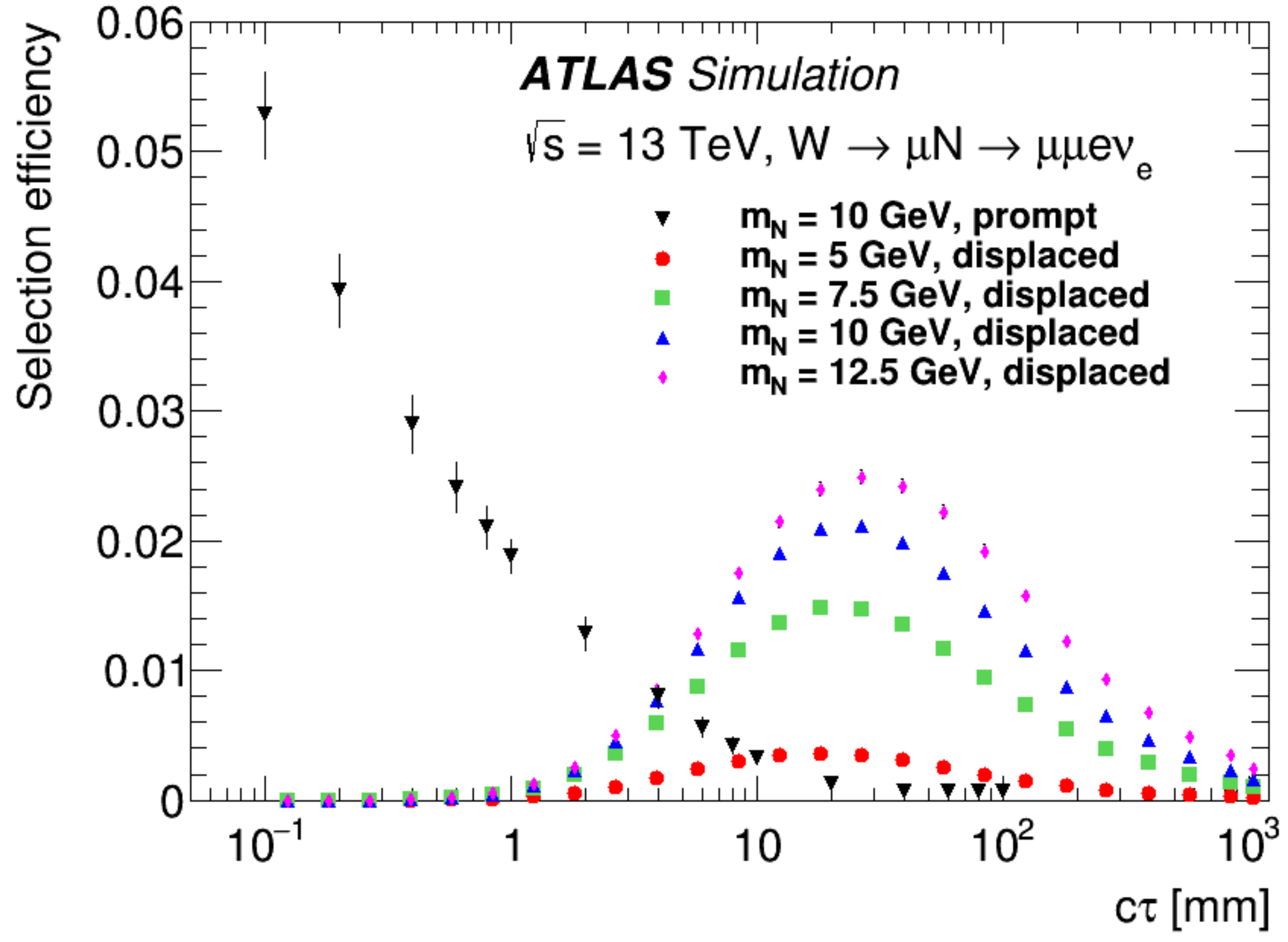
Prompt HNL decays*

- Type-I seesaw mechanism - adding HNLs
- Prompt analysis, considers HNL of $5 < m_N < 50$ GeV
  - LNV only, single flavor mixing only
  - HNL decaying to eu, ue
  - 3L signature with two same-sign, same-flavor leptons
  - Originally published in combination with displaced search, overall samples generated with
    - m_N = 4.5, 5, 7.5, 10, 12.5, 15, 20, 30, 50 GeV
    - τ_N = 0.001, 0.01, 0.1, 1, 10, 100 mm
  - $\sigma(pp \to W) \times \mathscr{B}(W \to \ell N) = \sigma(pp \to W) \times \mathscr{B}(W \to \ell \nu) \times |U|^2 (1 - \frac{m_N^2}{m_W^2})(1 + \frac{m_N^2}{m_W^2})$



Prompt HNL decays*

- Events selected with di-muon or single electron triggers
  - Reconstructed leptons required to be trigger matched
- Main backgrounds - diboson, triboson and ttV
- Also expect backgrounds from misreconstructed leptons
- Fit performed in three control regions and a signal region
- SR is defined by selecting events
  0) Same-charge same-flavour leptons
  1) 40 < m_{lll} < 90 GeV
  2) A b-jet veto
  3) E_T^{miss} < 60 GeV
- CRs invert criteria 1-3

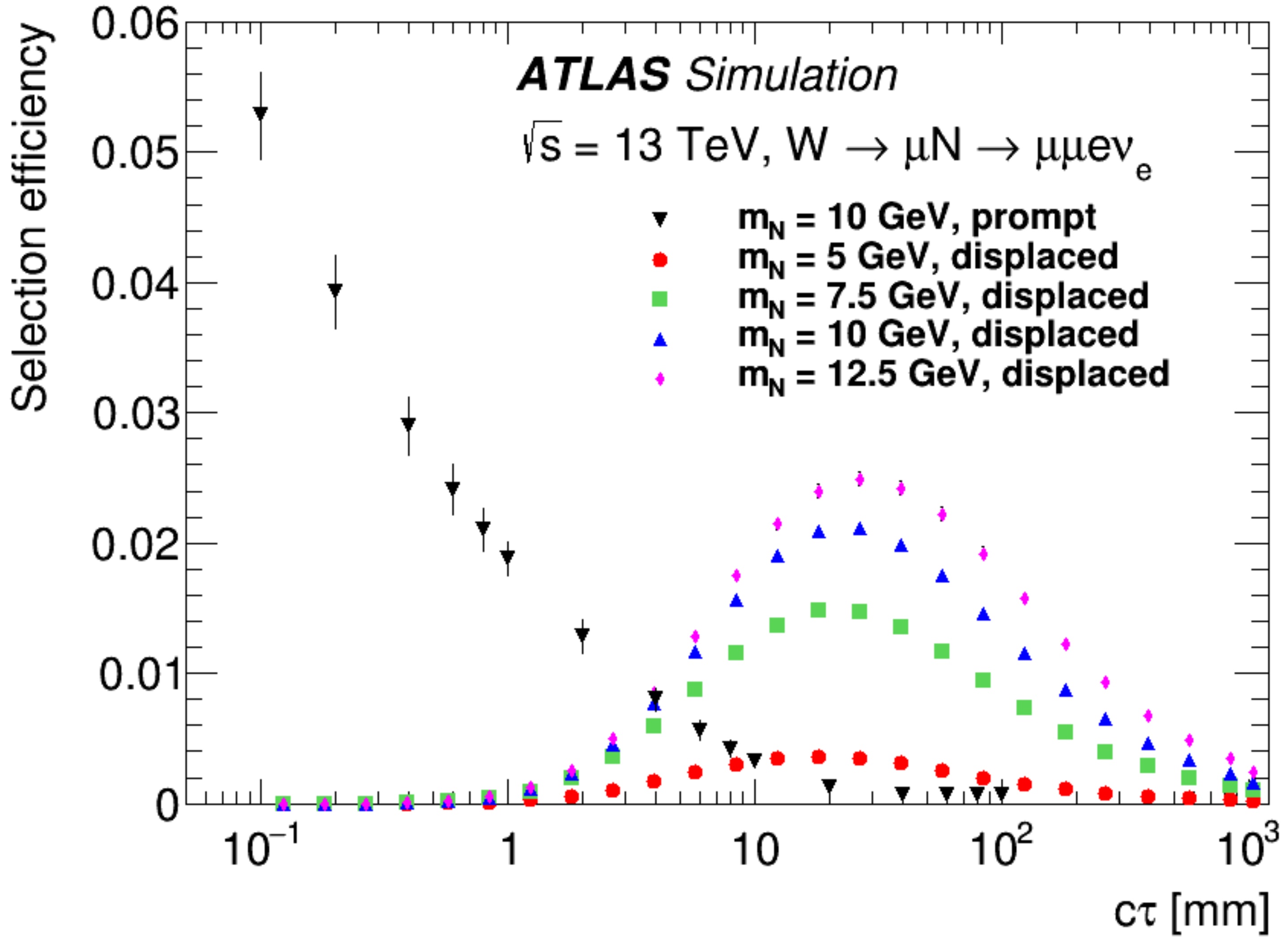


Muon channel	Electron channel
exactly $\mu^{\pm}\mu^{\pm}e^{\mp}$ signature	exactly $e^{\pm}e^{\pm}\mu^{\mp}$ signature
$p_T(\mu) > 4$ GeV $p_T(e) > 7$ GeV (2015), 4.5 GeV (2016)	
leading muon $p_T > 23$ GeV subleading muon $p_T > 14$ GeV	leading electron $p_T > 27$ GeV subleading electron $p_T > 10$ GeV $m(e, e) < 78$ GeV
$40 < m(\ell, \ell, \ell') < 90$ GeV b-jet veto $E_T^{miss} < 60$ GeV	

arXiv:1905.09787

Prompt HNL decays*

- Events selected with di-muon or single electron triggers
  - Reconstructed leptons required to be trigger matched
- Main backgrounds - diboson, triboson and ttV
- Also expect backgrounds from misreconstructed leptons
- Fit performed in three control regions and a signal region
- SR is defined by selecting events
  0) Same-charge same-flavour leptons
  1) 40 < m_{lll} < 90 GeV
  2) A b-jet veto
  3) E_T^{miss} < 60 GeV
- CRs invert criteria 1-3
- Fit variable is p_T of third lepton

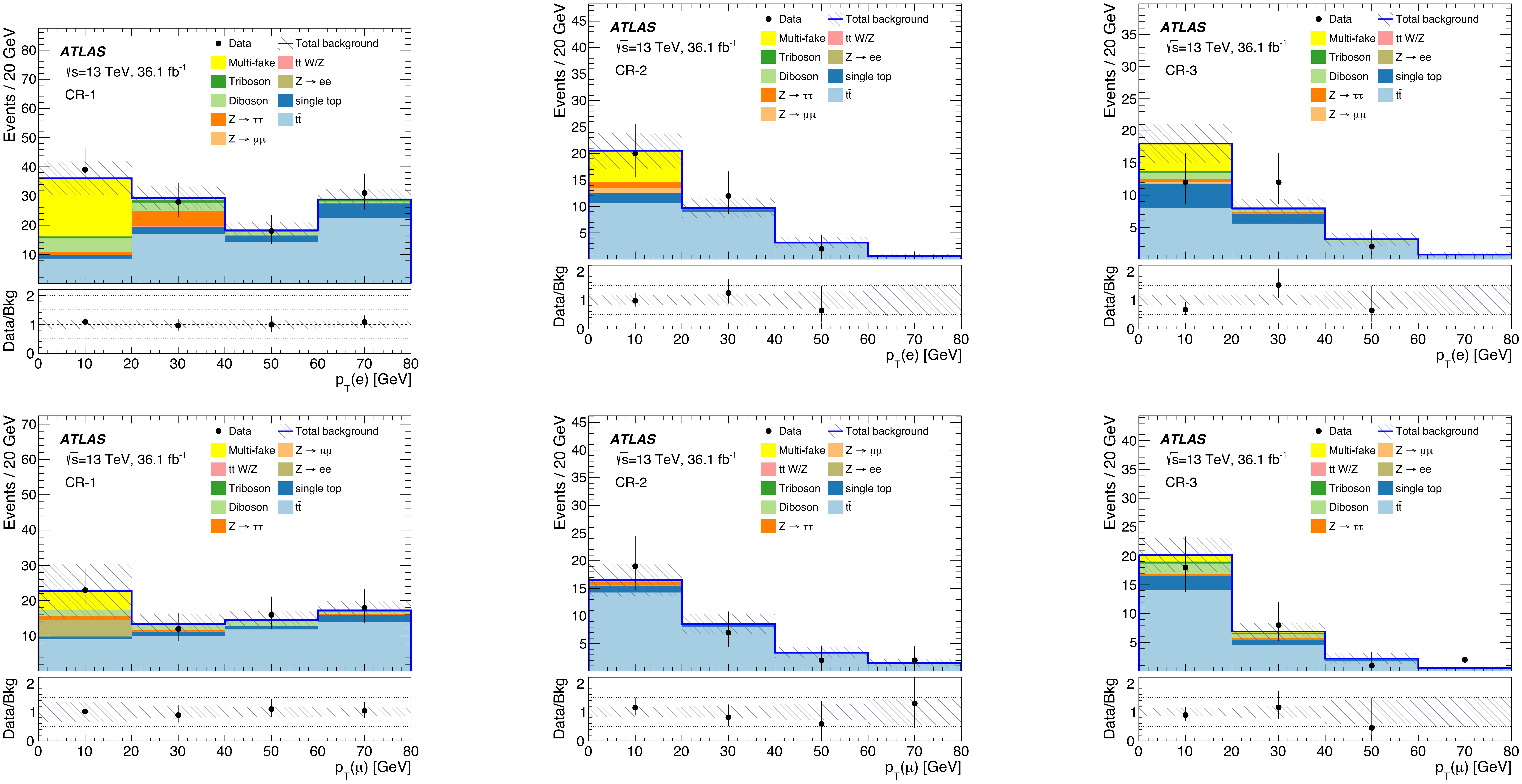


Muon channel	Electron channel
exactly $\mu^\pm\mu^\pm e^\mp$ signature	exactly $e^\pm e^\pm\mu^\mp$ signature
$p_T(\mu) > 4$ GeV $p_T(e) > 7$ GeV (2015), 4.5 GeV (2016)	
leading muon $p_T > 23$ GeV subleading muon $p_T > 14$ GeV	leading electron $p_T > 27$ GeV subleading electron $p_T > 10$ GeV $m(e,e) < 78$ GeV
$40 < m(\ell,\ell,\ell') < 90$ GeV b-jet veto $E_T^{miss} < 60$ GeV	

arXiv:1905.09787

Prompt HNL decays*

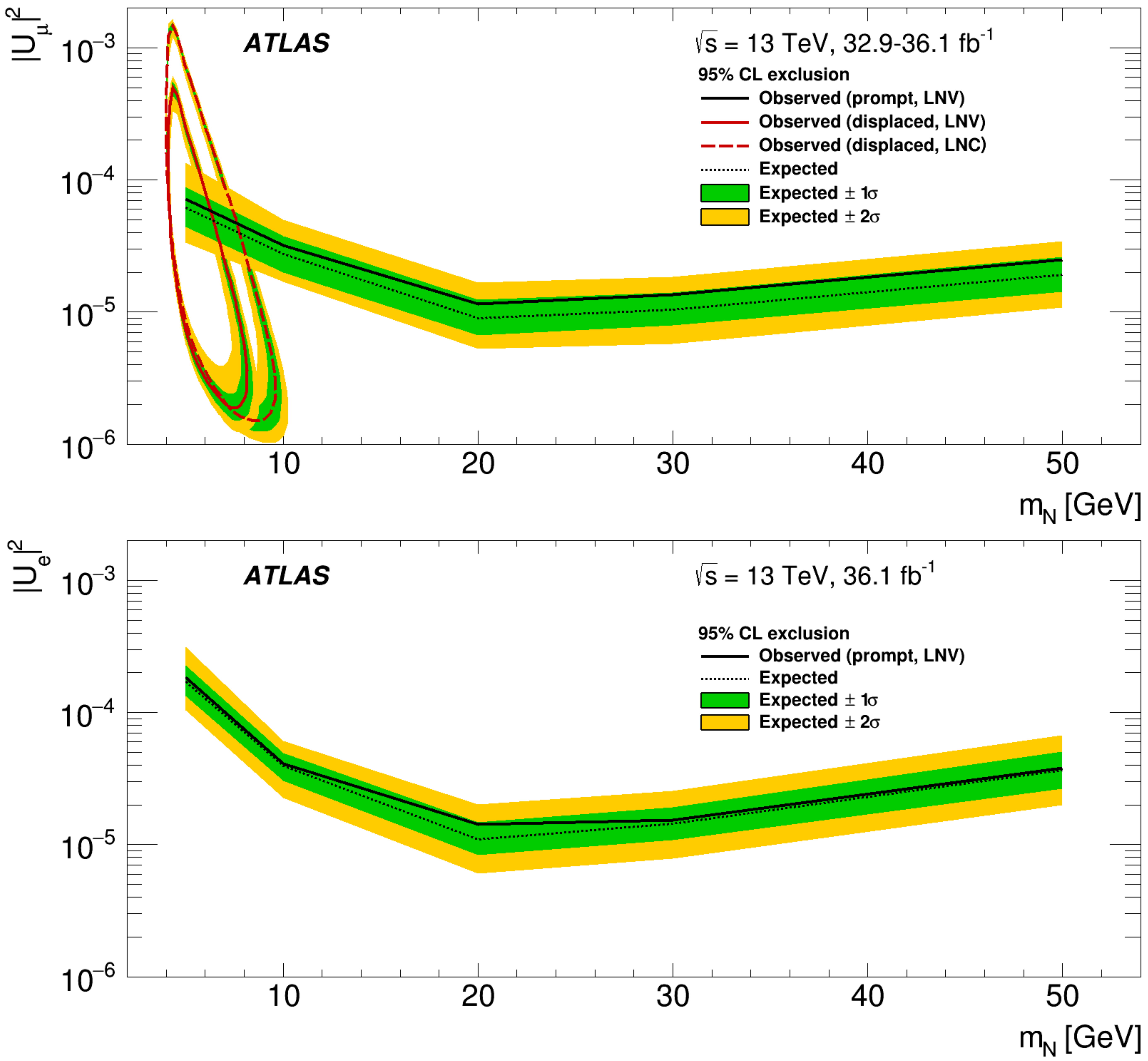
*partial Run 2 result



arXiv:1905.09787

Prompt HNL decays*

- No excess observed - limits set at 95% CL
- Limits for prompt search are straight lines, limits from attached displace search are closed loops
- In mass range 20–30 GeV, regions of $|U_\mu|^2$ and $|U_e|^2$ above 1.4×10^{-5} are excluded



arXiv:1905.09787