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Searches for type-III (and type-II) seesaw heavy leptons with the ATLAS detector

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Outline

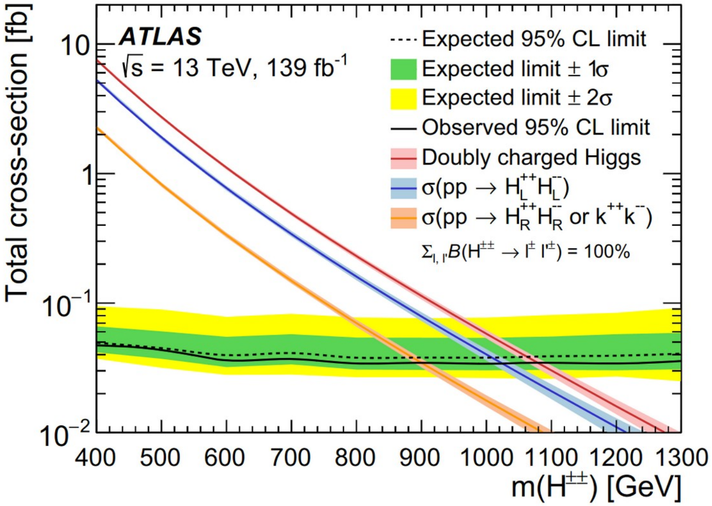
- Past ATLAS analyses on type-II and type-III seesaw
- Overview of latest type-III seesaw analyses with 2-, 3- and 4-lepton final states
  - Analysis strategy and approach
  - (type-II covered in Blaž Leban's talk tomorrow)
- Current latest results
- Status of new ongoing analyses for type-II and type-III seesaw
  - Planned improvements to increase sensitivity

Past ATLAS type-II and type-III seesaw analyses

Type-II

- Run 2 (140 fb^{-1}, √s = 13 TeV)
  - 2015-2016 data only – M ≳ 870 GeV
    Eur. Phys. J. C 78, 199 (2018)
  - $H^{\pm\pm} \to W^{\pm} W^{\pm}$ – M > 350 GeV
    J. High Energy Phys. 2021 (6), 146
  - $H^{\pm\pm} \to \ell^{\pm}\ell'^{\pm}$ – M > 1080 GeV
    Eur. Phys. J. C 83, 605 (2023)

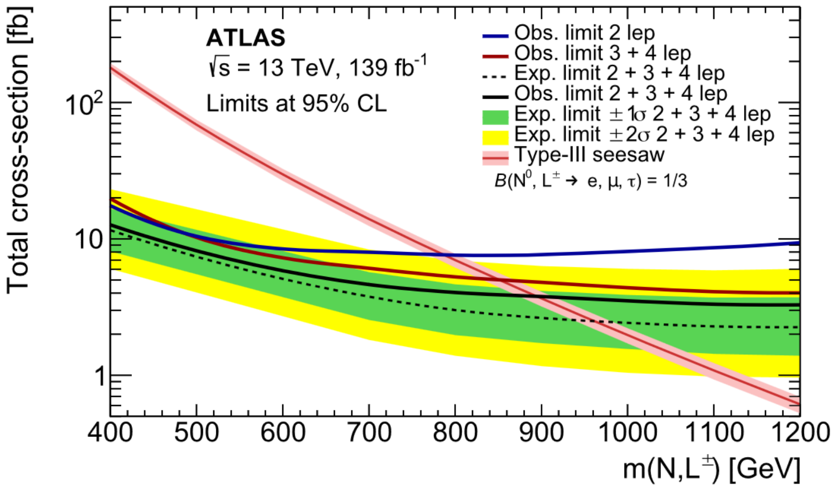
Covered in talk by Blaž Leban



Type-III

- Run 1 (20.3 fb^{-1}, √s = 8 TeV)
  - 2-lepton final state – M > 335 GeV
    Phys. Rev. D 92, 032001 (2015)
  - 3-lepton final state – M > 400 GeV
    J. High Energy Phys. 2015 (9), 108
- Run 2 (140 fb^{-1}, √s = 13 TeV)
  - 2-lepton final state – M > 790 GeV
    Eur. Phys. J. C 81, 218 (2021)
  - Combined 2 + 3,4-lepton final state – M > 910 GeV
    Eur. Phys. J. C 82, 988 (2022)

Covered in this talk



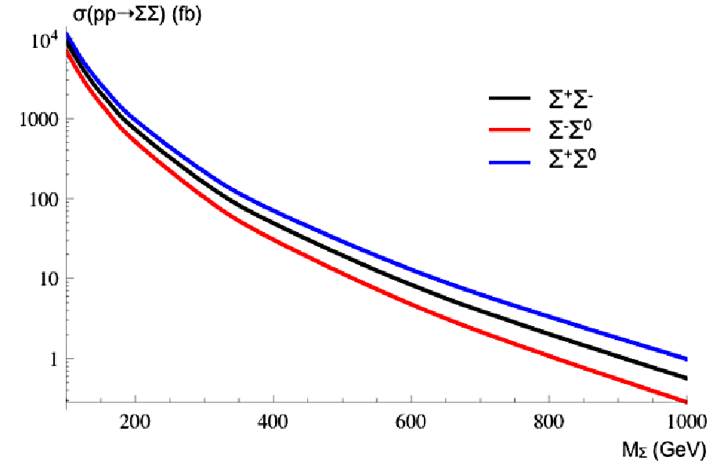
Latest type-III seesaw analyses at ATLAS

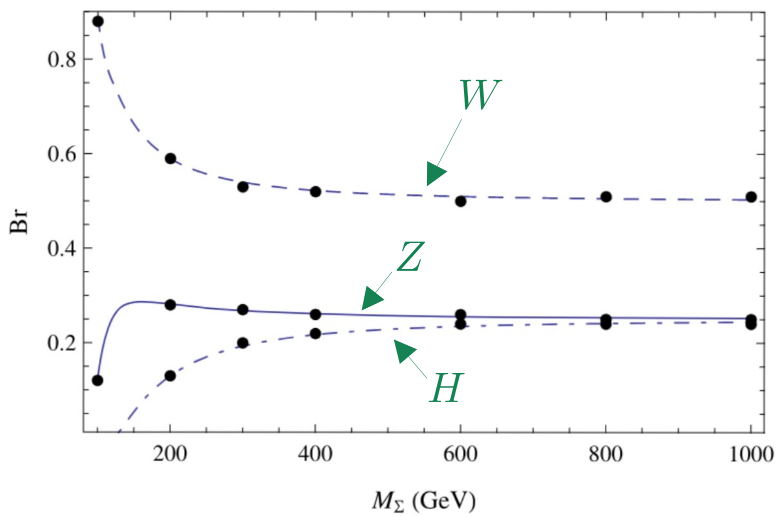
$$\mathrm{Br}_\ell \propto \frac{|V_\ell|^2}{\sum_i |V_i|^2}$$

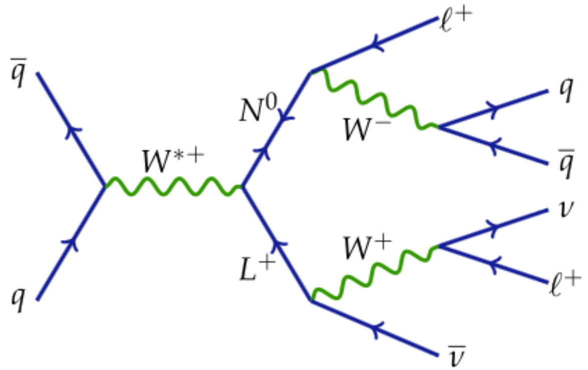
- Simplified model with single heavy triplet
- Predominantly associated and pair production via gauge interaction (single triplet production suppressed)
- Set equal mixing angles to get equal branching ratios into SM leptons

$$V_e = V_\mu = V_\tau$$

- Largest decay branching ratio into W
- Consider final states with …
  - At least two leptons
  - Light leptons (e, μ) only – leptonic tau decays included
- Cut-based approach → Kinematic cuts to maximize signal significance
  - Define dedicated signal regions (SR) and control regions (CR)

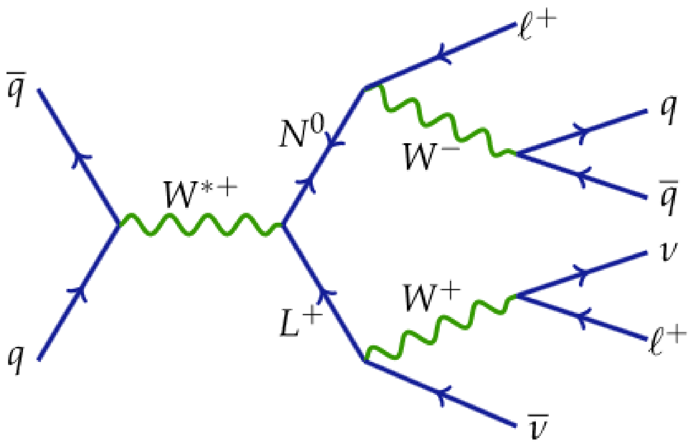






Type-III seesaw analysis approach

- **Event selection**
  - Dilepton (ee, $e\mu$, $\mu\mu$) triggers without isolation requirement – p_{T} thresholds all below 24 GeV
- **Baseline object definition (for counting and data-driven background estimation)**
  - Electrons and muons
    - Requirements on identification and isolation
    - $p_{\mathrm{T}} > 10\,\mathrm{GeV}$
    - $|\eta| < 2.5$
  - Jets
    - $p_{\mathrm{T}} > 20\,\mathrm{GeV}$
    - $|\eta| < 2.5$
    - b-tagging (for b-jet veto)
  - Missing transverse energy (MET)
- Apply corrections to MC correct mismodelings of identification, isolation and trigger efficienices

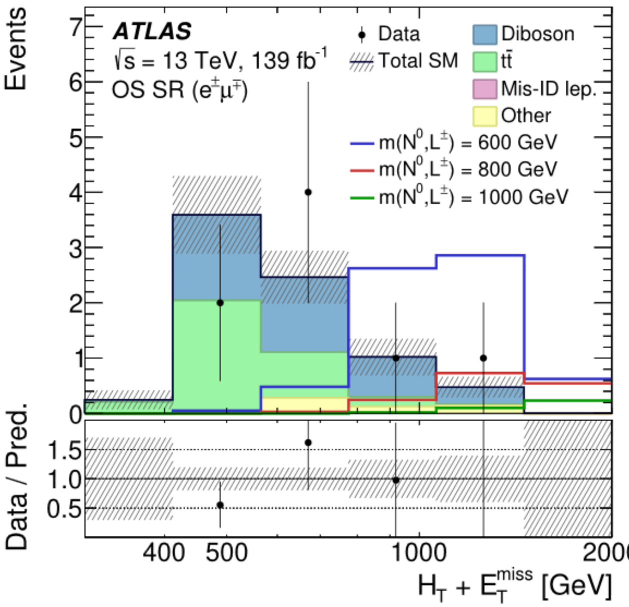


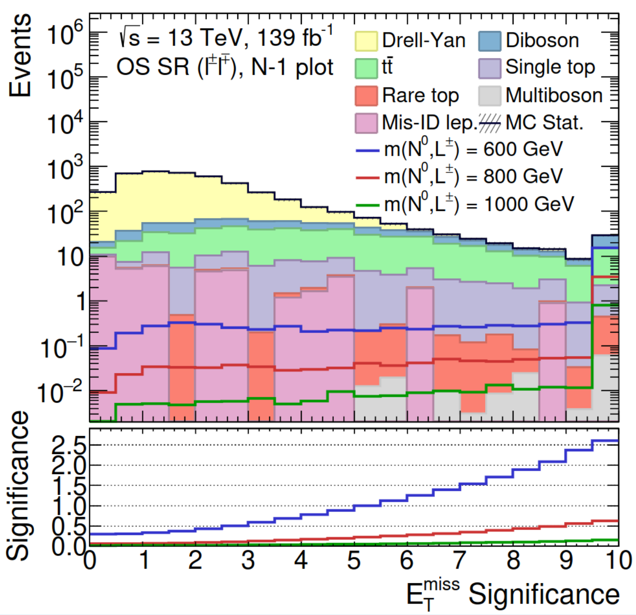
Signal region selection

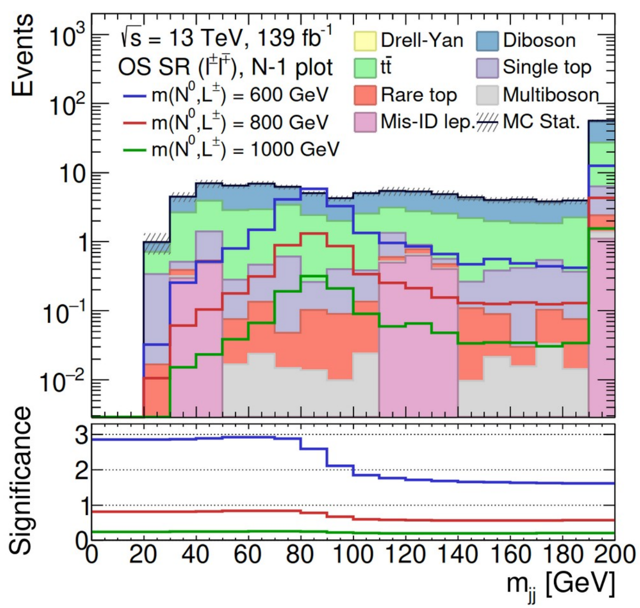
- p_{T} cut increased to $40\ \mathrm{GeV}$ for leading leptons
- Important cuts on $\mathrm{Sig}(E_{\mathrm{T}}^{\mathrm{miss}})$ at 5 or more and $H_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}} > 300\ \mathrm{GeV}$
- **SRs are divided by lepton multiplicity in the final state**

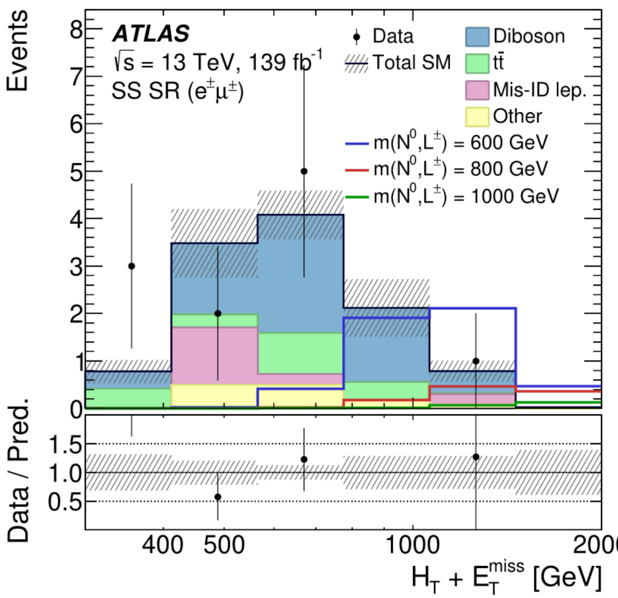
2 leptons

- Separate same sign (SS) and opposite sign (OS)
- At least two jets – b-jet veto
- Main cuts on dilepton mass above Z peak, dijet mass kept around W peak









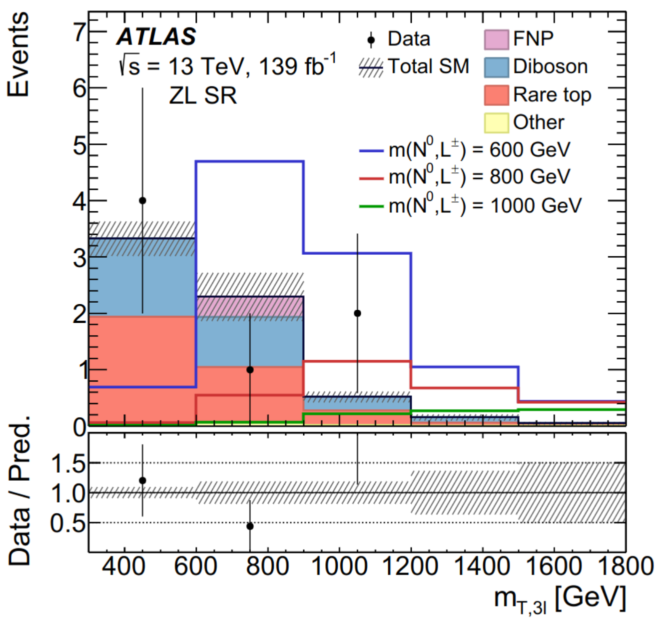
Signal region selection

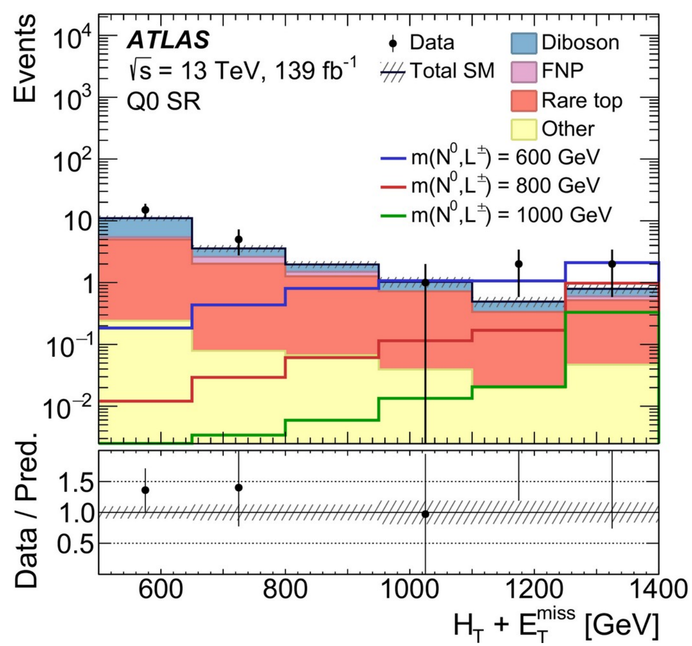
3 leptons

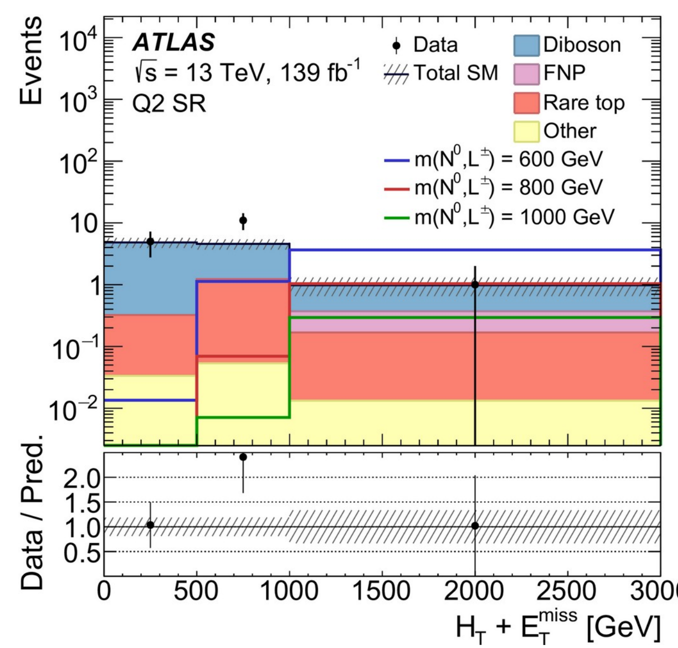
- Separation by signal event topology
  - Triplet decay into leptonic Z
    - $m_{LL}(OSSF) = [80, 100)\ \mathrm{GeV}$, 2 jets
  - No triplet decay into leptonic Z
    - $m_{LL}(OSSF) > 150\ \mathrm{GeV}$, 2 jets
  - No jets

4 leptons

- Relatively low SM background
- Separation by two possible lepton charge configurations
  - |Total charge| = 0
  - |Total charge| = 2



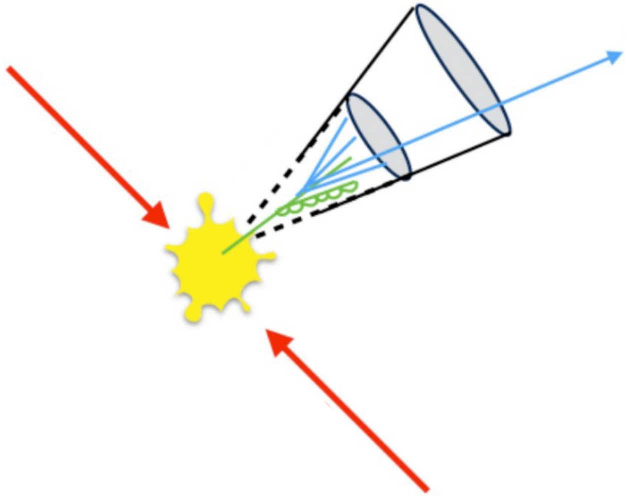


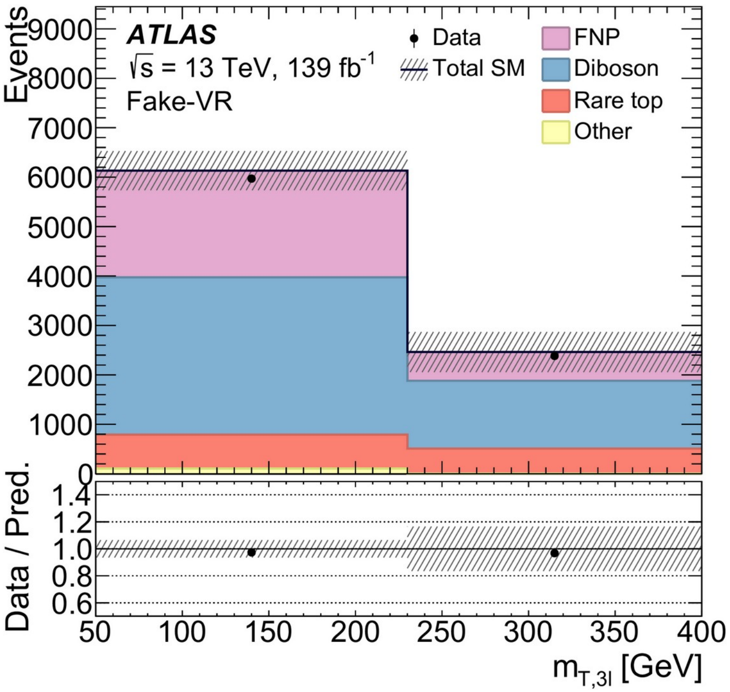


Complete region definitions in backup

Background estimation

- Significant source of background from misreconstructed objects – reducible background
  - Misreconstructed sign of lepton charge (charge flip)
  - Incorrectly reconstructed jets, non-prompt leptons from meson decay within jets and electron-photon conversions (fakes)
- Usually modeled relatively poorly in MC → data-driven approaches





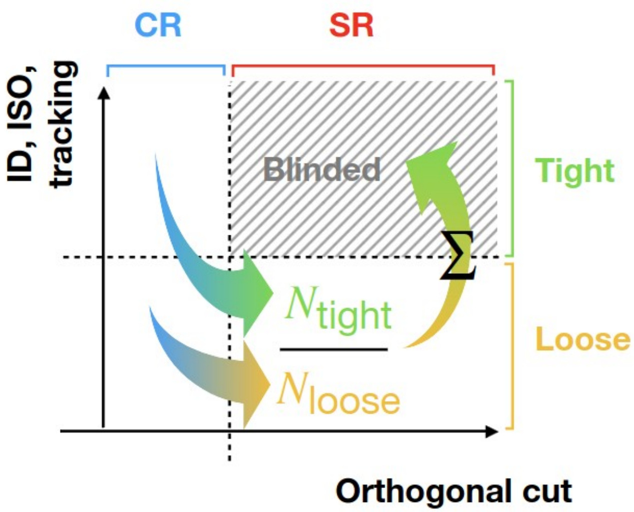
Fake factor method

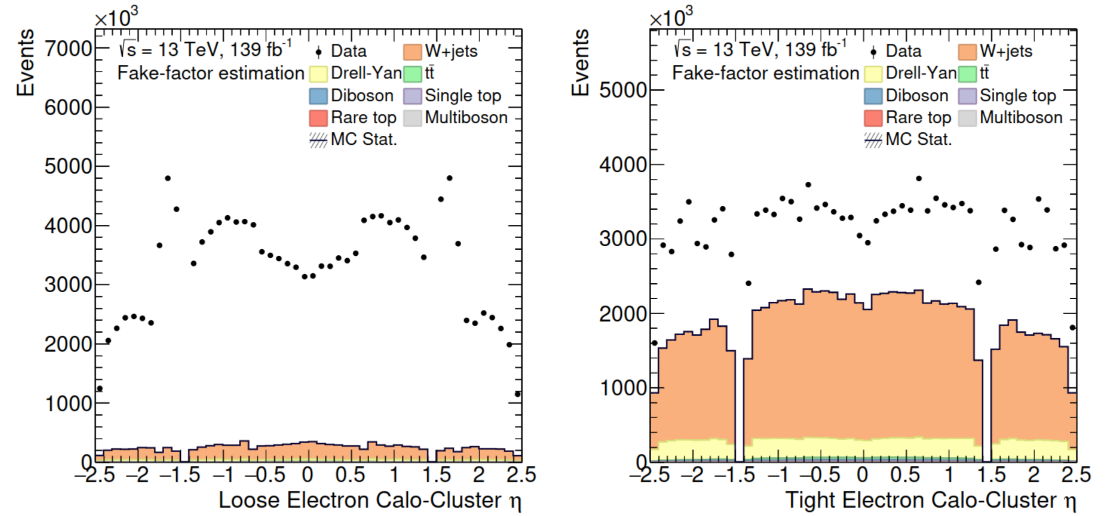
JINST 18 T11004 (2023)

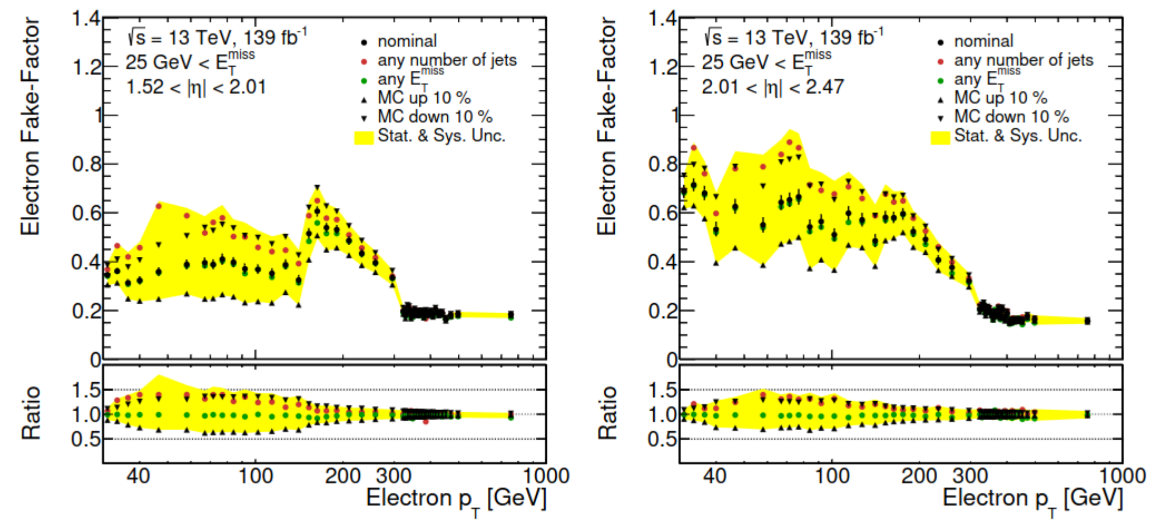
- Based on exploiting the transfer rate of fake leptons from a looser selection into the signal region's selection
- Transfer rate (fake factor) evaluated on data in orthogonal region rich in fake leptons

$$F = \frac{N^{\text{fake}}_{\text{tight}}}{N^{\text{fake}}_{\text{strictly-loose}}}$$

- Obtained fake factors extrapolated to signal region to obtain background contribution
- Usually binned over p_{T} and η
- Uncertainties from MC normalization, MC modeling and fakes composition differences between fake-enriched region and SR





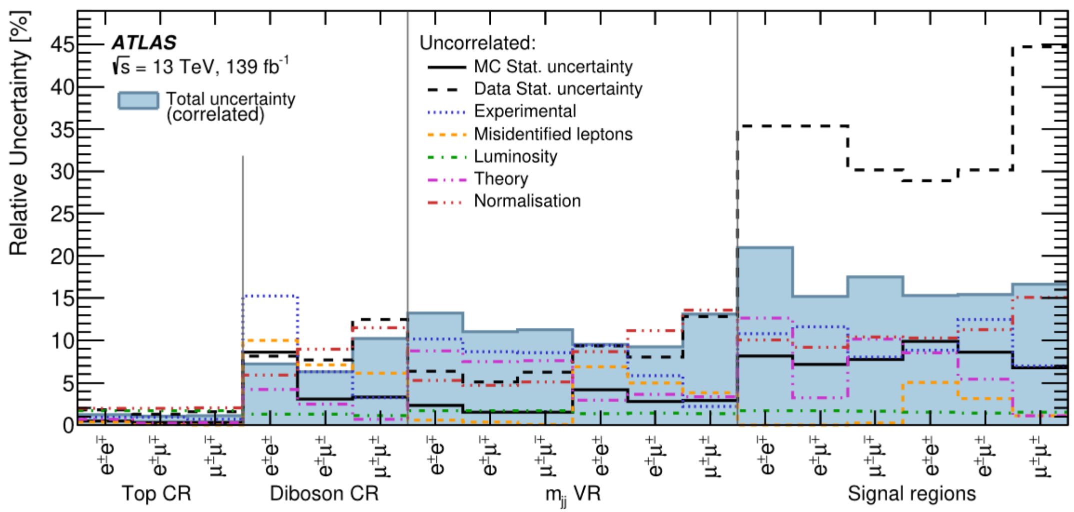


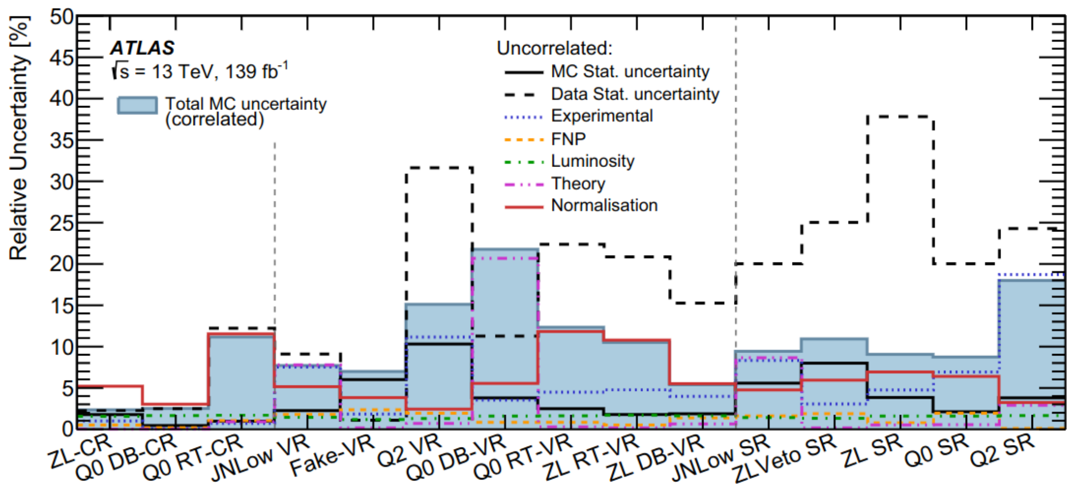
2 lepton case: $N^{\text{fakes}}_{TT} = \left[\sum_{TL} F_2 + \sum_{LT} F_1 - \sum_{LL} F_1 F_2\right]_{\text{data}} - \left[\sum_{TL} F_2 + \sum_{LT} F_1 - \sum_{LL} F_1 F_2\right]_{\text{prompt simulation}}$

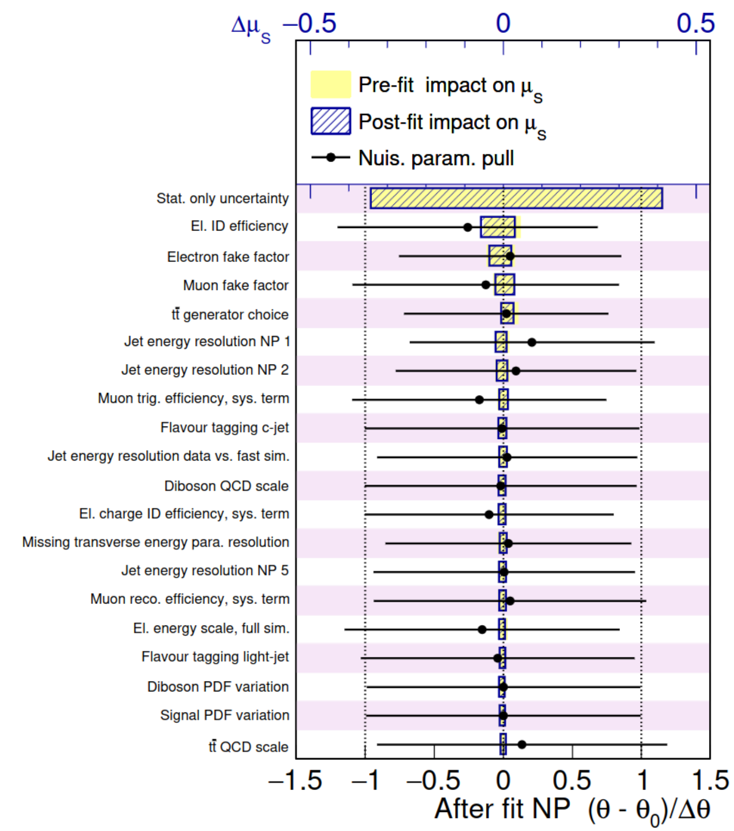
More on this in next talk by Lara

Main sources of uncertainty

- Main source of uncertainty is statistical unc. in data
- ~ 5 % on electron and muon fake factors







How do we improve this?

Strategies for improving analysis sensitivity

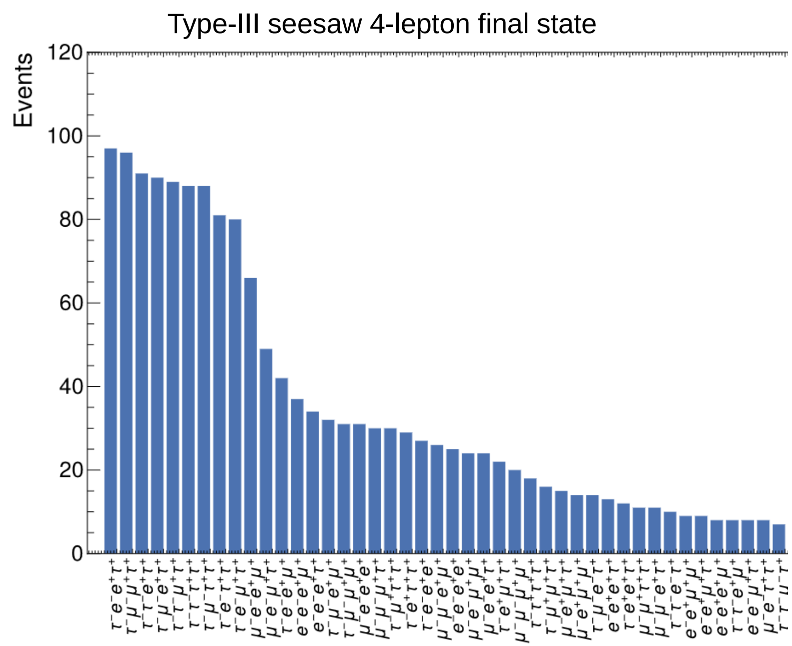
Plans to improve the current results with new set of analyses covering type-II and type-III seesaw

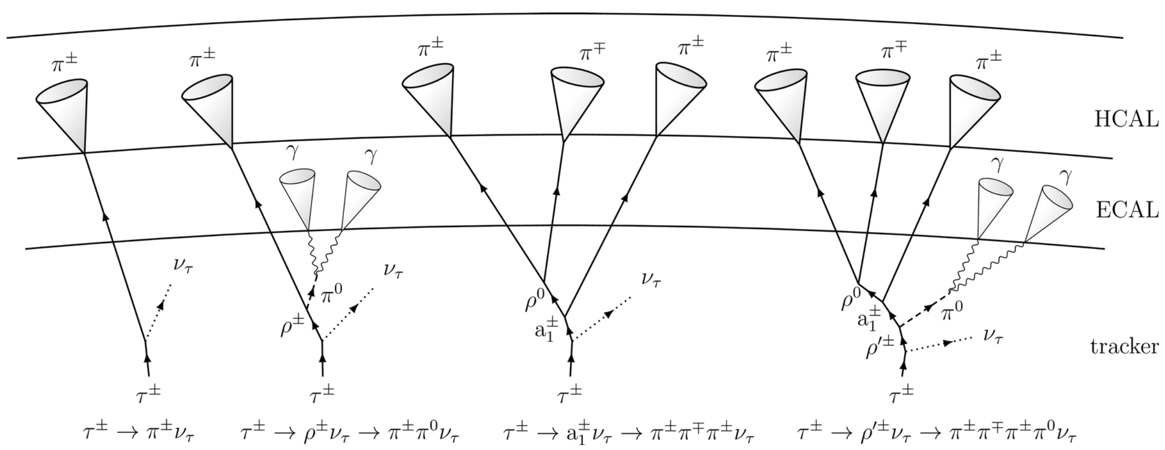
- Higher statistics from Run 3 – 140 fb^{-1} → 450 fb^{-1}
- Consider more final states:
  - Include hadronic tau decays
  - Type-III: Possibly extend final state to up to 6 leptons
- Utilizing machine learning approaches for several aspects in the analysis
  - Signal-background separation (classification)
  - Background estimation - modeling the contribution of fakes

Hadronic tau decays

$$\mathrm{Br}(\tau \to \mathrm{had}) \sim 65\ \%$$

- Significant gain in additional final states
  - Most frequent 2-, 3- and 4-lepton final states contain taus!
- Detector signature mimics jets
  - 1- or 3-prong decays
- Reconstruction:
  - Seeded from jets ($|\eta| < 2.5$ coverage) → track reco → identification → electron veto

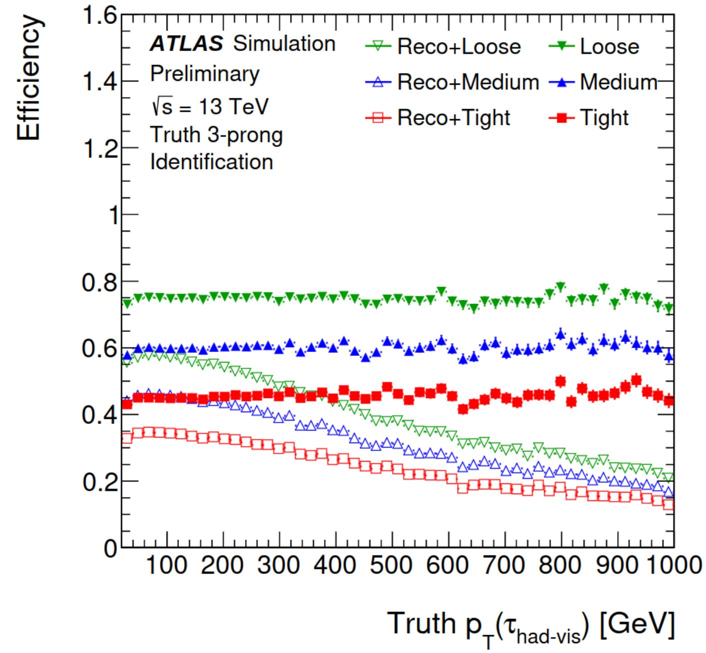


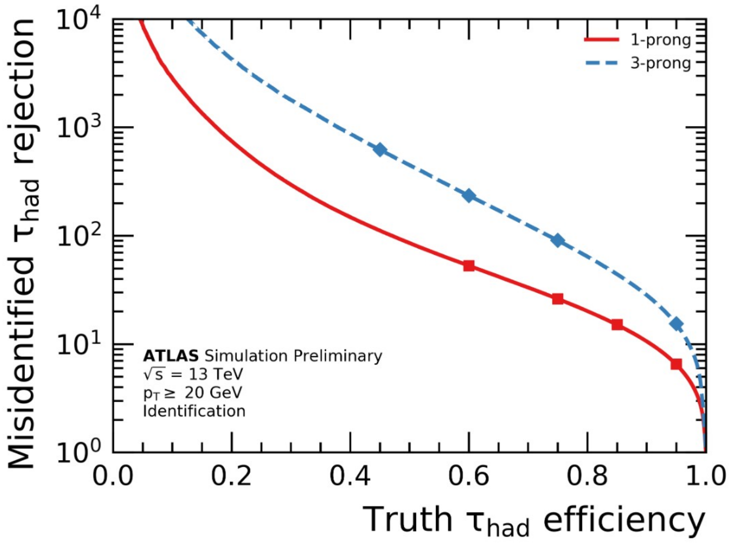


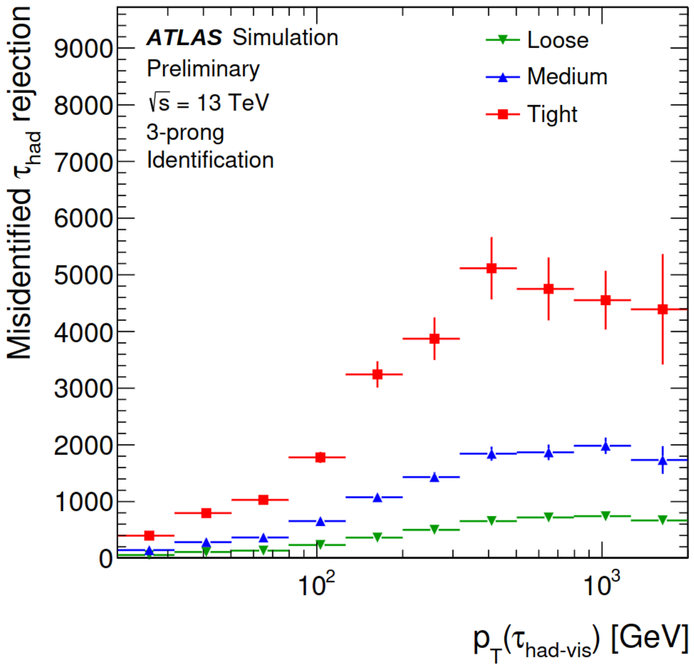
Hadronic tau decays

ATL-PHYS-PUB-2022-044

- Recent improvements for Run 3 and reprocessing of Run 2
  - RNN-based track reconstruction and identification
  - Replaces old BTD algorithms → Large performance improvements (e.g. 75-100 % larger rejection at fixed ID efficiency)
- Significant background from misidentified electrons → electron veto (also RNN, factor 3 improved rejection)

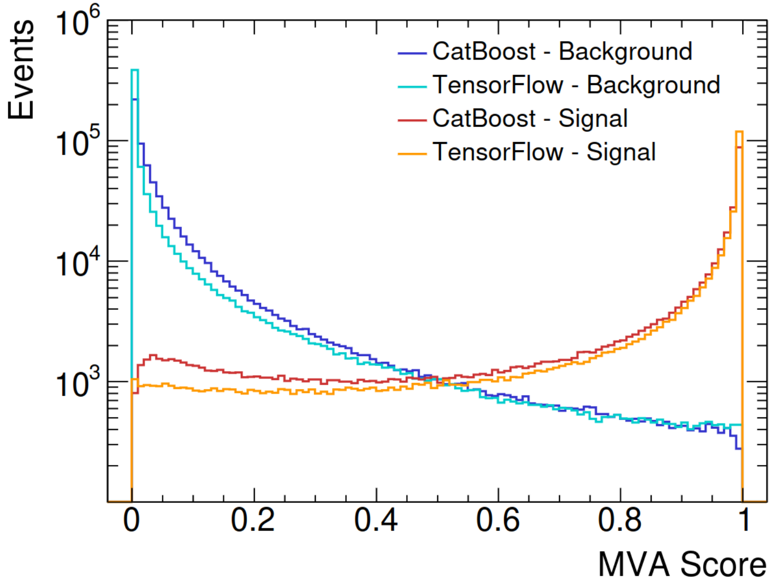


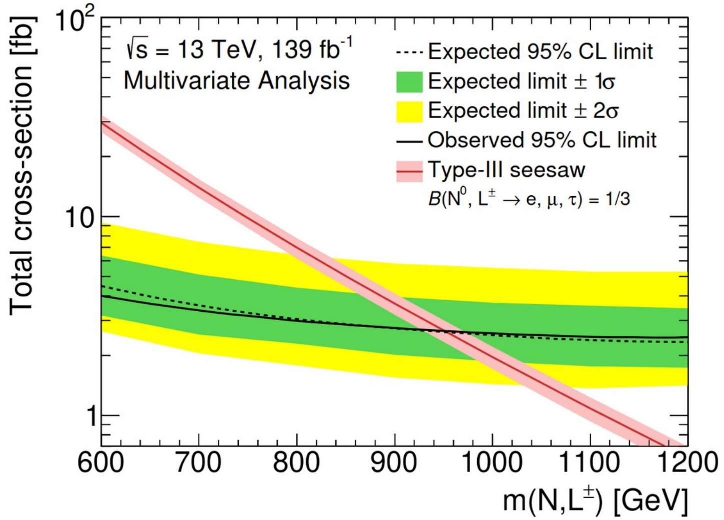


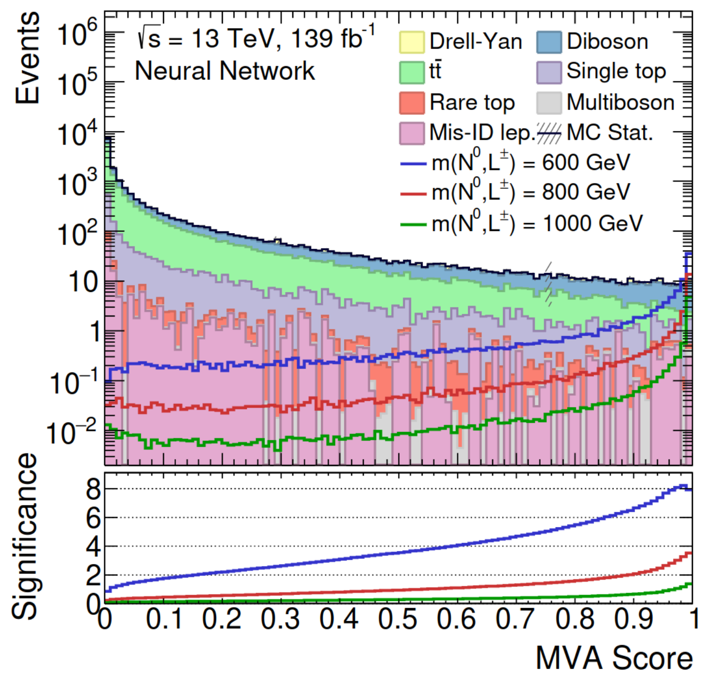


Machine learning approaches

- Promising study already done for type-III seesaw in 2-lepton final state
- Loose preselection as input to binary event classification into signal/background with NN
- Analysis regions defined on cut of NN score
- Lower limit for triplet mass already increased from 790 GeV to 950 GeV!







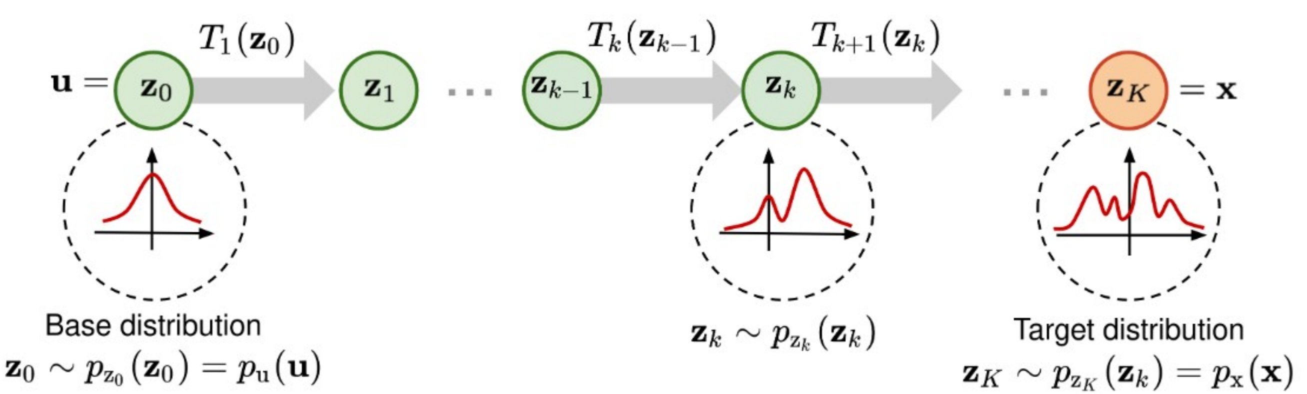
Machine learning approaches

- Plans to use ML in several aspects within the new analyses
  - Improved binary signal/background classification
  - Improve modeling of fakes background
    - Pure fakes sample required → Need a way to remove prompt contamination
  - Employ generative models to enable infinite sampling of background to improve MC statistics
    - Also intended for reducing uncertainty on fakes contribution
    - Viability study of using normalizing flows arXiv:2310.08994 [hep-ph]

$$F = \frac{N^{\text{fake}}_{\text{tight}}}{N^{\text{fake}}_{\text{strictly-loose}}}$$

$$r(x) = \frac{P(x)}{Q(x)} = \frac{p(y=1|x)}{1-p(y=1|x)}$$

Binary classifier output gives density ratio directly!



Conclusions

- Current limits on mass from ATLAS Run 2 analyses at 1080 GeV for DCH and 910 GeV for type-III seesaw
  - Analyses done with a cut-based approach
  - Mainly limited by statistical uncertainty in data
- New analyses focusing on type-II and type-III seesaw ongoing
  - Using Run 2 + Run 3 data
  - Including hadronic tau decays
  - Employing advanced machine learning approaches for signal/background separation, to better model fakes background and improve MC statistics

Thank you!

Backup

2-lepton analysis regions

	OS ($\ell^+\ell^- = e^+e^-, e^\pm\mu^\mp, \mu^+\mu^-$)			**SS** ($\ell^\pm\ell^\pm = e^\pm e^\pm, e^\pm\mu^\pm, \mu^\pm\mu^\pm$)		
	Top CR	m_{jj} VR	SR	Diboson CR	m_{jj} VR	SR
N(jet)	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2
N(b-jet)	≥ 2	0	0	0	0	0
m_{jj} (GeV)	(60, 100)	(35, 60) ∪ (100, 125)	(60, 100)	(0, 60) ∪ (100, 300)	(0, 60) ∪ (100, 300)	(60, 100)
$m_{\ell\ell}$ (GeV)	≥ 110	≥ 110	≥ 110	≥ 100	≥ 100	≥ 100
$\mathcal{S}(E_T^{miss})$	≥ 5	≥ 10	≥ 10	≥ 5	≥ 5	≥ 7.5
$\Delta\phi(E_T^{miss}, \ell)_{min}$	–	–	≥ 1	–	–	–
$p_T(jj)$ (GeV)	–	–	≥ 100	–	–	≥ 60
$p_T(\ell\ell)$ (GeV)	–	–	≥ 100	–	–	≥ 100
$H_T + E_T^{miss}$ (GeV)	≥ 300	≥ 300	≥ 300	(300, 500)	≥ 500	≥ 300

3-lepton analysis regions

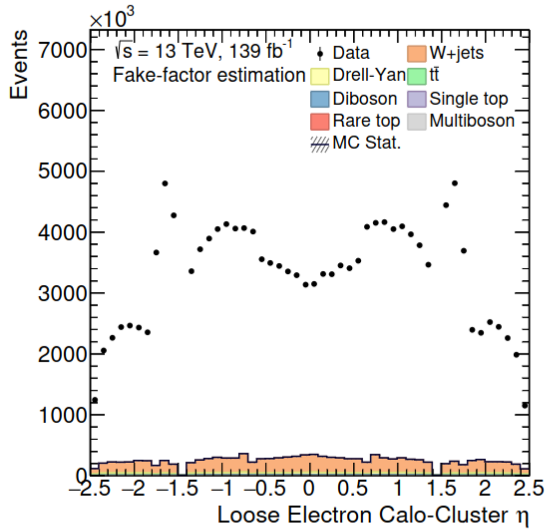
		ZL				ZLveto	JNLow	
	Fake-VR	CR	DB-VR	RT-VR	SR	SR	VR	SR
	$p_{\mathrm{T}}(\ell_1) > 40$ GeV $p_{\mathrm{T}}(\ell_2) > 40$ GeV $p_{\mathrm{T}}(\ell_3) > 15$ GeV							
$\mathcal{S}(E_{\mathrm{T}}^{\mathrm{miss}})$	< 5	≥ 5						
$N(\mathrm{jet})$	-	≥ 2					≤ 1	
$N(b\text{-jet})$	-	-	0	≥ 1	-	-	-	-
$m_{\ell\ell}$ (OSSF) [GeV]	-	80–100				≥ 115	≥ 80	
$H_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	-	-	-	-	-	≥ 600	-	-
$m_{\ell\ell\ell}$ [GeV]	-	-	≥ 300			≥ 300	-	-
$H_{\mathrm{T}}(\mathrm{SS})$ [GeV]	-	-	-	-	-	≥ 300	-	-
m_{jj} [GeV]	-	-	-	-	-	< 300	-	-
$H_{\mathrm{T}}(\ell\ell\ell)$ [GeV]	-	-	-	-	-	-	≥ 230	
$m_{\mathrm{T}}(\ell_1)$ [GeV]	-	-	≥ 200			-	< 240	≥ 240
$m_{\mathrm{T}}(\ell_2)$ [GeV]	-	< 200	≥ 200			-	≥ 150	
$\Delta R(\ell_1, \ell_2)$	-	-	< 1.2		1.2–3.5	-	≥ 1.3	

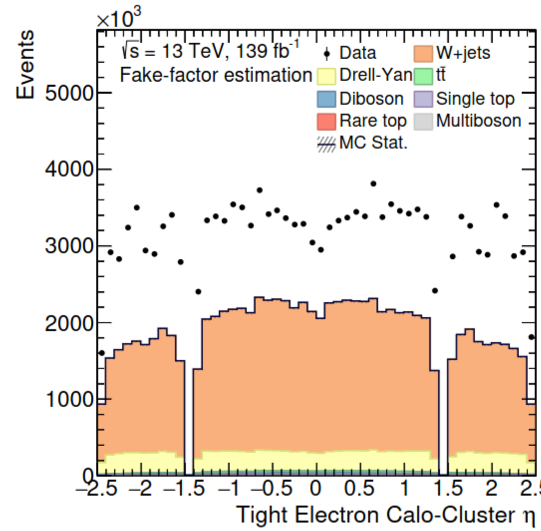
$$m_T^{lep} = \left| \sum_i^{lep} \vec{P}_i(p_T, 0, \phi, E) + \vec{E}_T^{miss} \right|$$

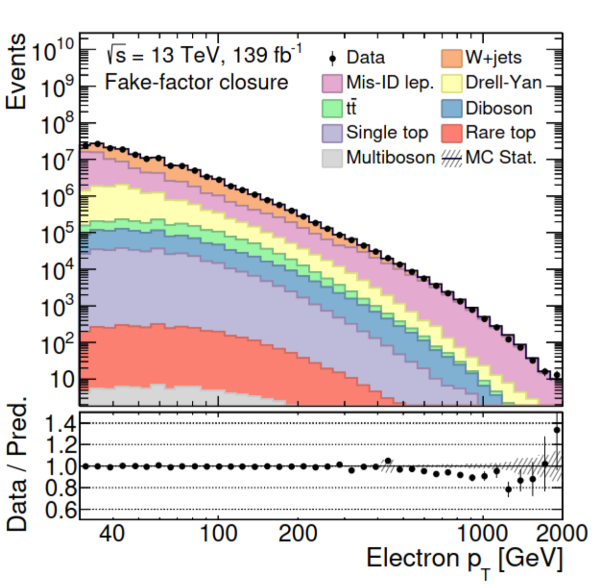
4-lepton analysis regions

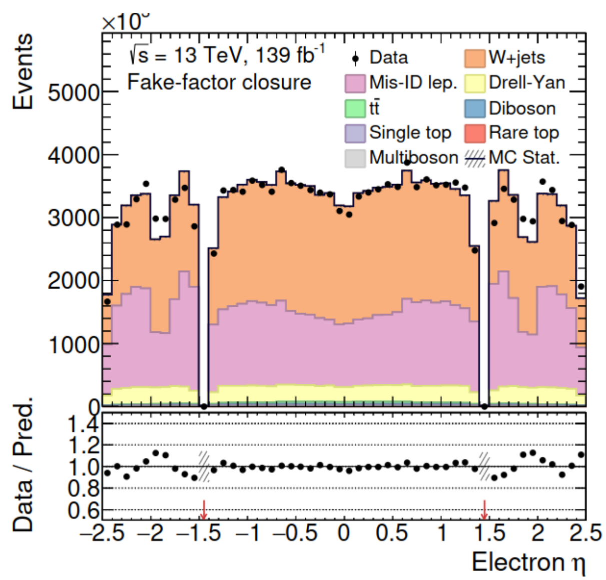
	Q0					Q2	
	DB-CR	RT-CR	DB-VR	RT-VR	SR	VR	SR
	$p_T(\ell_{1,2}) > 40$ GeV $p_T(\ell_3) > 15$ GeV $p_T(\ell_4) > 10$ GeV						
$\lvert \sum q_\ell \rvert$	0					2	
$N(b\text{-jet})$	0	≥ 2	1	1	0	-	-
$m_{\ell\ell\ell\ell}$ [GeV]	170–300	< 500	170–300	300–500	≥ 300	< 200 OR < 300	≥ 300
$H_T + E_T^{miss}$ [GeV]	-	-	-	≥ 400	≥ 300		≥ 300
N_Z	-	-	-	-	≤ 1	-	-
$\mathcal{S}(E_T^{miss})$	-	-	-	≥ 5	≥ 5	-	-

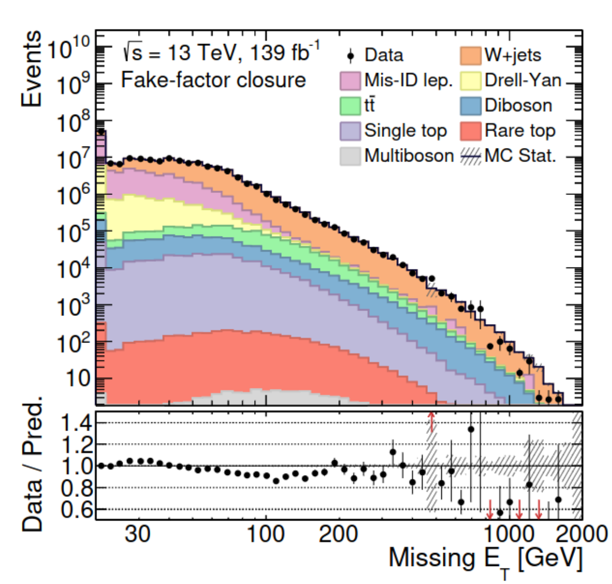
Fake factor method











Tau performance