Jožef Stefan Institute
Ljubljana, Slovenia

ATLAS EXPERIMENT

Hadronic Taus in the ATLAS Type-II/III Seesaw Analyses

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Type-II/III Seesaw

- Paper: *Phys. Rev. Lett. 81, 1171 (1998)*
- Extension of the Standard Model by addition of dimension-5 effective operator

$$\mathcal{L}_{\text{eff}} = \frac{y}{\Lambda} L_L \phi \, \phi L_L$$

  - Three possible realizations at high energy
  - Type-I: Additional fermionic singlet
  - **Type-II:** Additional scalar $SU(2)_L$ triplet
    - Contains a doubly-charged Higgs component ***H***$^{++}$

$$\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}$$

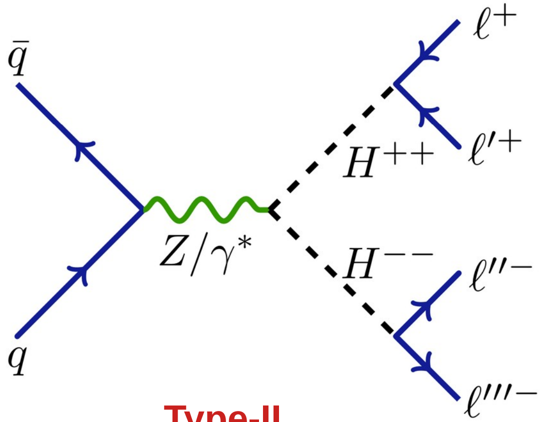
  - **Type-III:** Additional fermionic $SU(2)_L$ triplet

$$\Sigma = \begin{pmatrix} \Sigma^0/\sqrt{2} & \Sigma^+ \\ \Sigma^- & -\Sigma^0/\sqrt{2} \end{pmatrix}$$

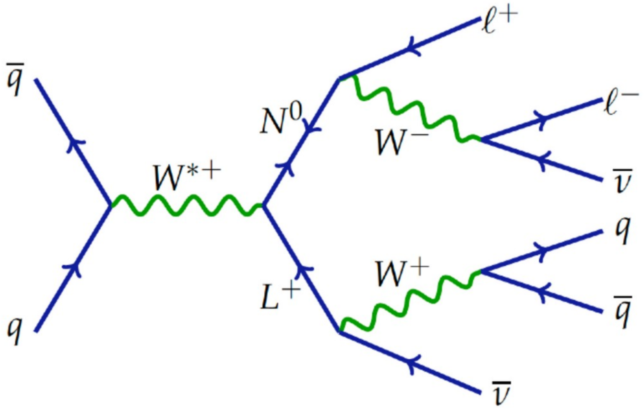
- **Neutrino mass models**
  - Explanation for the origin and smallness of neutrino masses
  - Lepton number violating

$$m_\nu = y \frac{v^2}{\Lambda}$$

- Focusing on final states with 2+ leptons



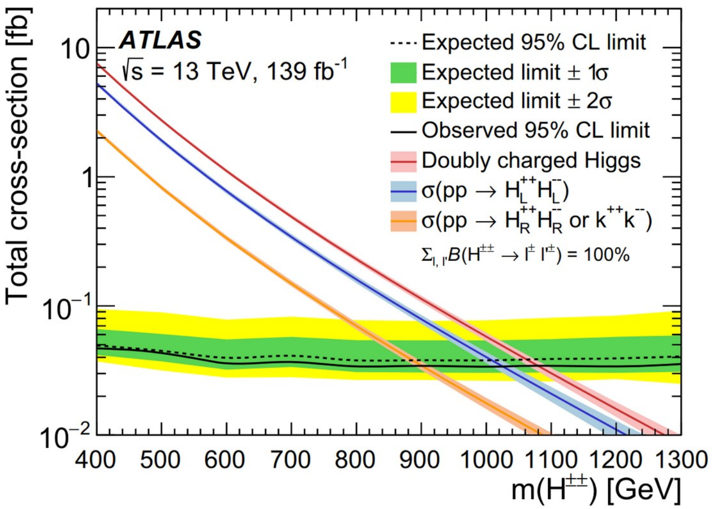
Type-II



Type-III

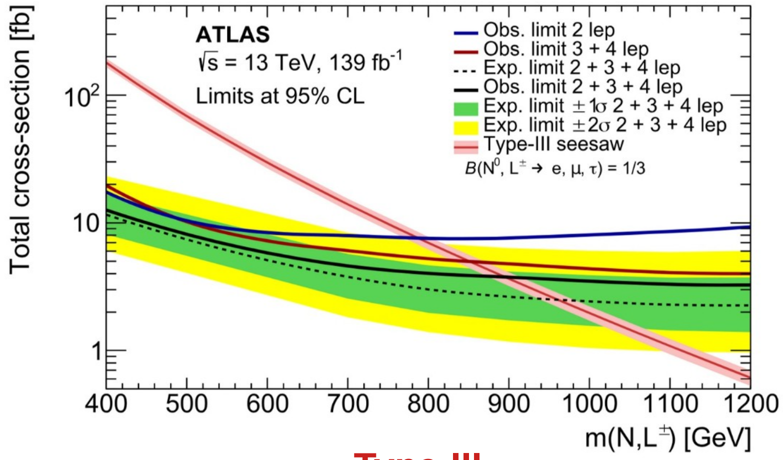
Type-II/III Seesaw in ATLAS

- **Previously published ATLAS analyses on type-II/III seesaw**
  - **Type-II:** Eur. Phys. J. C 83, 605 (2023)
    - Limit on H^{++} mass: **1080 GeV**
  - **Type-III:**
    - 2-lepton final states: Eur. Phys. J. C 81, 218 (2021)
    - 3- and 4-lepton final states: Eur. Phys. J. C 82, 988 (2022)
    - Limit on triplet mass (combined 2- and 3/4-lepton final states): **910 GeV**



Type-II

- **Notable improvements and new developments for this iteration:**
  - Addition of **Run 3** data (possibly full Run 3)
  - **Introducing machine learning techniques** at different stages
    - Signal–background separation (replacing cut-based approach)
    - Novel ML-based data-driven fake estimation (replacing binned fake factor) → **See Jan's talk**
  - **Including final states with hadronic taus**



Type-III

Benefit of Hadronic Taus

Theoretical arguments

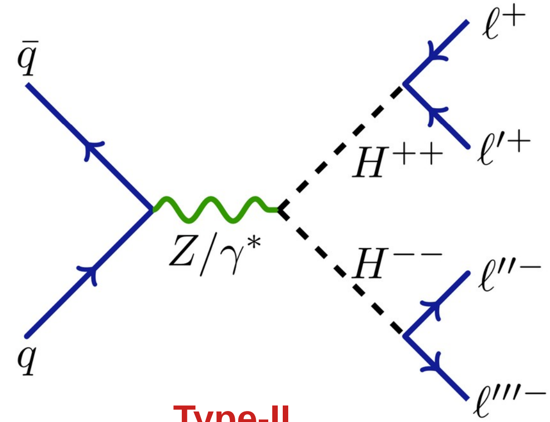
- **Taking type-III as an example:**
  - Interactions with SM fields via gauge and Yukawa coupling
    - Decays governed by Yukawa couplings (mixing parameters *V*)

$$V_\alpha = \frac{v}{\sqrt{2}} M_\Sigma^{-1} Y_{\Sigma_\alpha} \qquad Br_\alpha \propto \frac{\left|V_\alpha\right|^2}{\sum_{i=e,\mu,\tau}\left|V_i\right|^2}$$

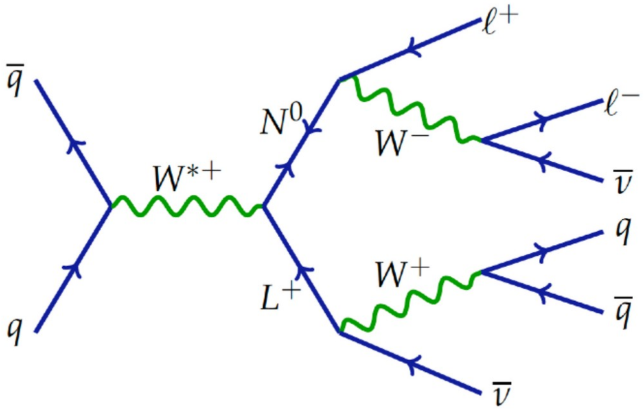
    - Mixings are free parameters of the model → Possibility of preferential decays to taus
- Covers full parameter space of the mixings → **No a priori assumption on the branching ratios required**
- E.g. Type-III: $L^\pm \rightarrow l^\pm H$ and $N \rightarrow \nu H$ much more relevant
- *Note:* Leptonic τ decays ($Br(\tau_{lep})$ ~ 35%) still relevant in light-lepton-only analyses

Experimental arguments

- τ_{had} reconstruction and identification matured substantially in recent years
- *"Use all of the data"*



Type-II



Type-III

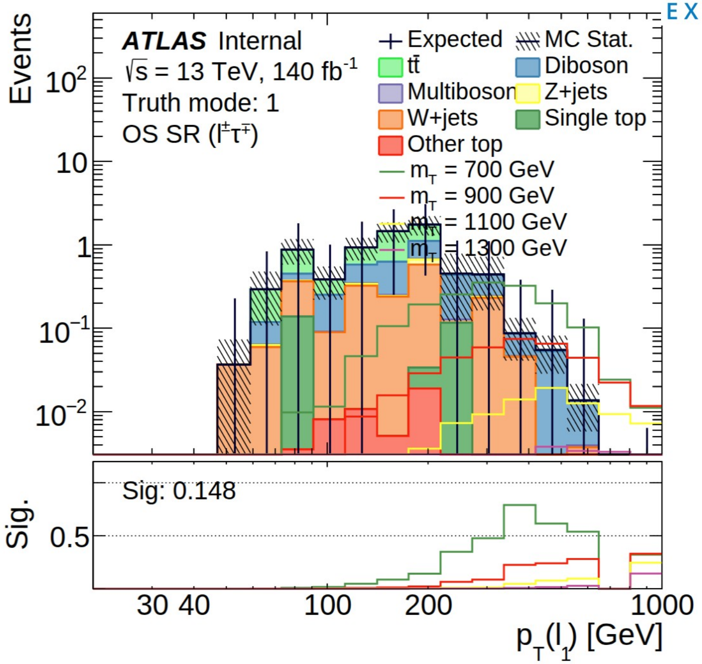
Challenges with Hadronic Taus

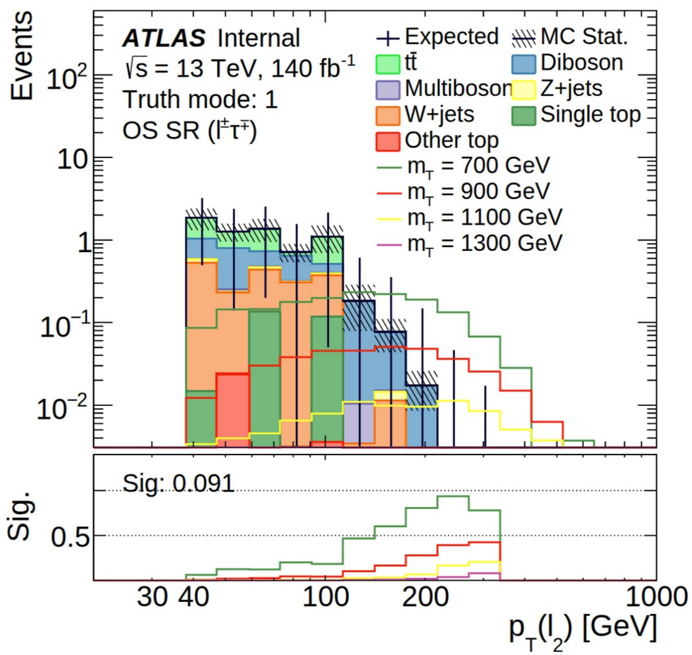
Trigger strategy

- We apply trigger-matching (reco-level leptons matched to triggering objects)
- Used di-lepton triggers historically
- How do we accept events with taus?
  - **Tau triggers** (not supported well with efficiency calibrations)
  - Try to keep light lepton triggers where possible
- New **channel-dependent trigger selection strategy**

Calibration support

- Calibrations for GNTau only starting to become available
  → Validations needed
- τ_{had} ID calibrated up to p_T ~ 250 GeV
  - Our signal can exceed this



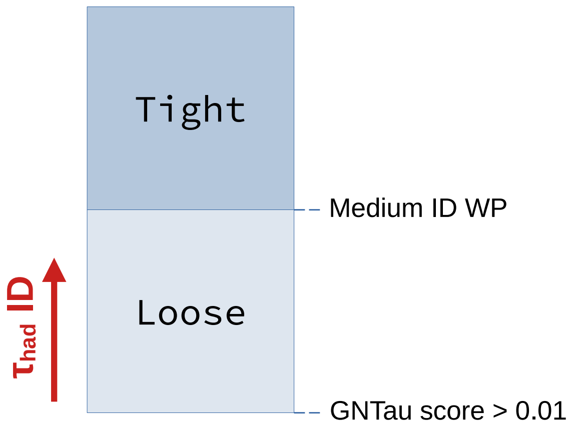


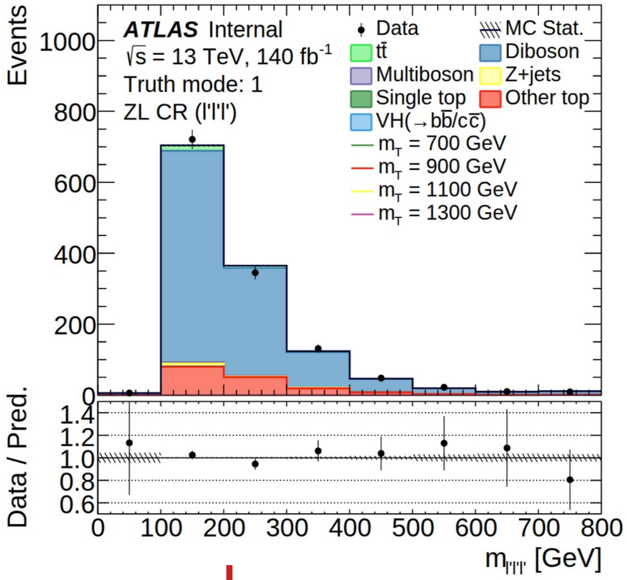
Challenges with Hadronic Taus – τ_{had} Fakes

Fake background

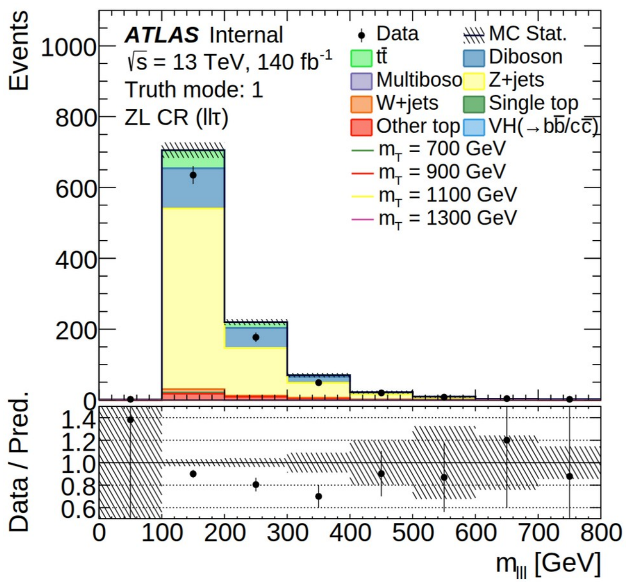
- **Large fake rates** for τ_{had} relative to light leptons
- **Dominant background** in many analysis channels
  - Channels with τ_{had} often with significant background composition difference
- Need to control the background well
  → **Data-driven approach** (jet fakes only)

- **Fake factor has more complex dependence than for light leptons. Depends on:**
  - N constituent tracks of τ_{had}
  - ***Truth origin of the jet*** (light quark, *b*-quark, gluon, pileup jet)
  - τ_{had} fired the trigger? (biases ID requirement of *loose* selection)





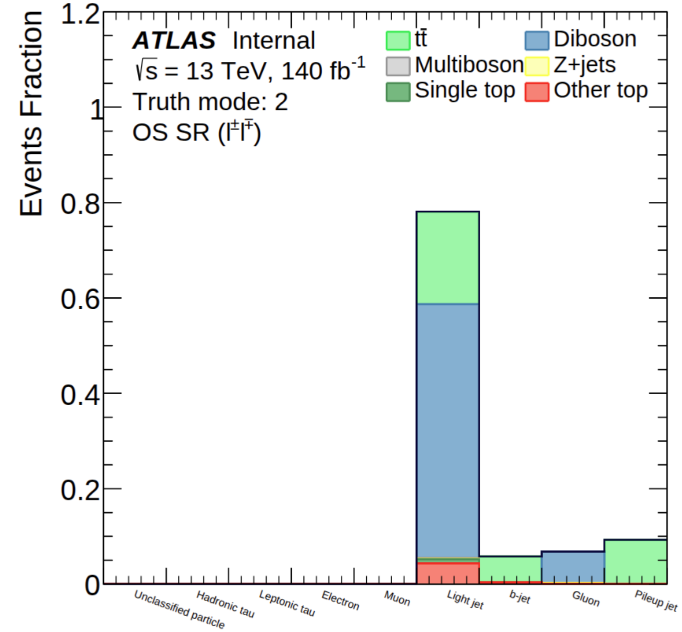
Same kinematic region, background composition changes significantly

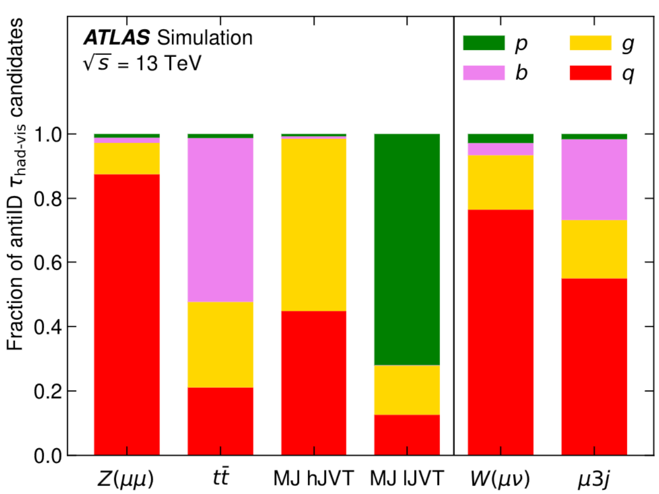


Challenges with Hadronic Taus – τ_{had} Fakes

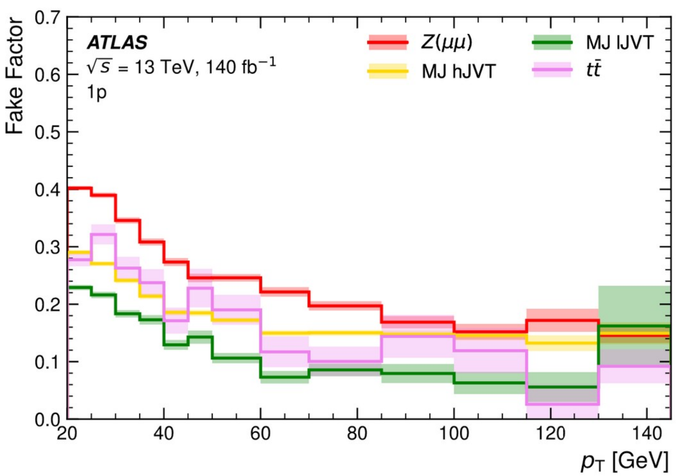
Dealing with different jet truth origins

- **Universal Fake Factor (UFF)** method developed within ATLAS
  - Eur. Phys. J. C 85, 1441 (2025)
- Fake factor for each jet origin evaluated in dedicated regions enriched in one type of fake
- Templates provided for fit of relative jet origin contribution per analysis signal region
- Final FF linear combination of per-origin FFs
- Important limitation: FFs available only up to $p_T \sim 300$ GeV (binned approach → stat limited)





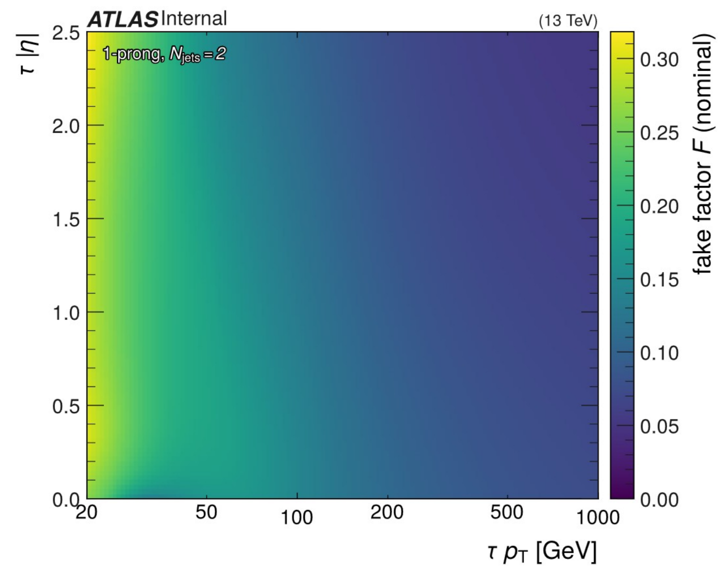
Fake factor determined per region



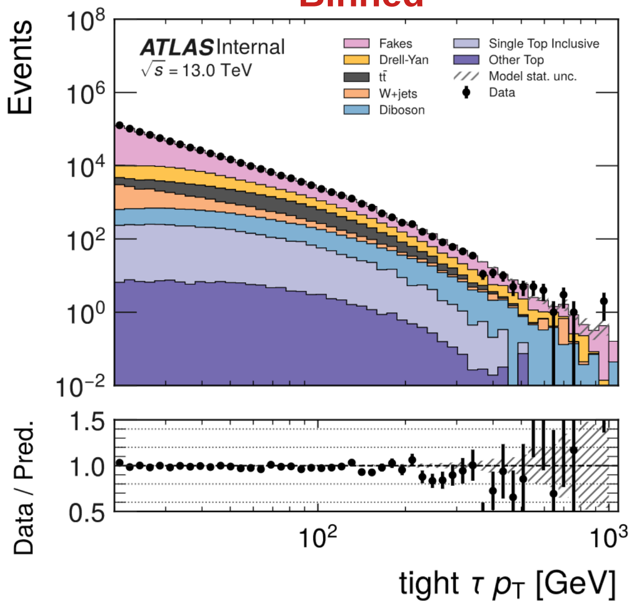
Challenges with Hadronic Taus – τ_{had} Fakes

ML approach

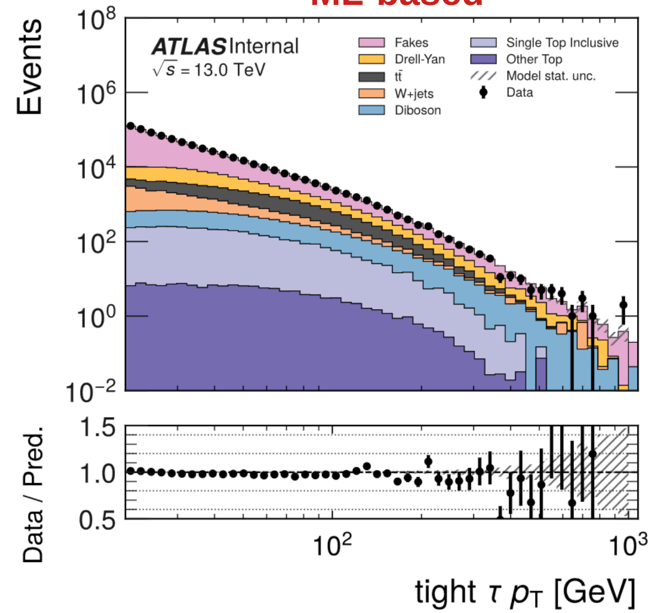
- Very similar approach as with light leptons → ***See Jan's talk for details***
- Benefits:
  - Continuous (unbinned) fake factor
  - Higher-dimensional feature space compared to binned
  - Stat limitation in high-p_T region less problematic (smoothly modeled up to 1000 GeV)

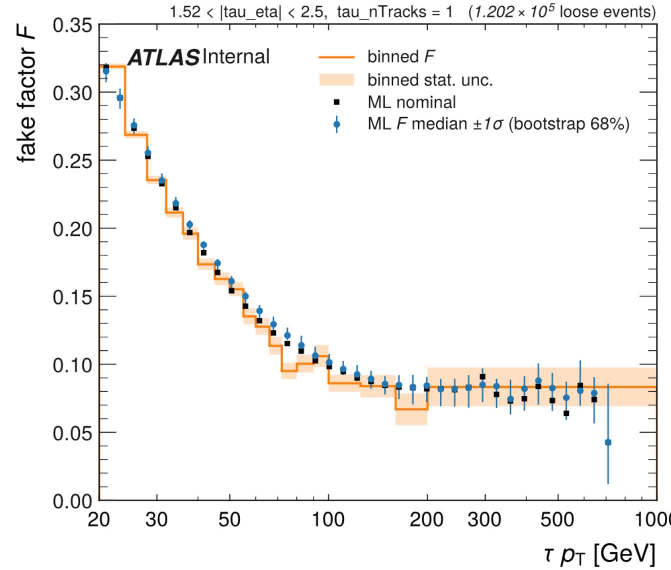


Binned



ML-based

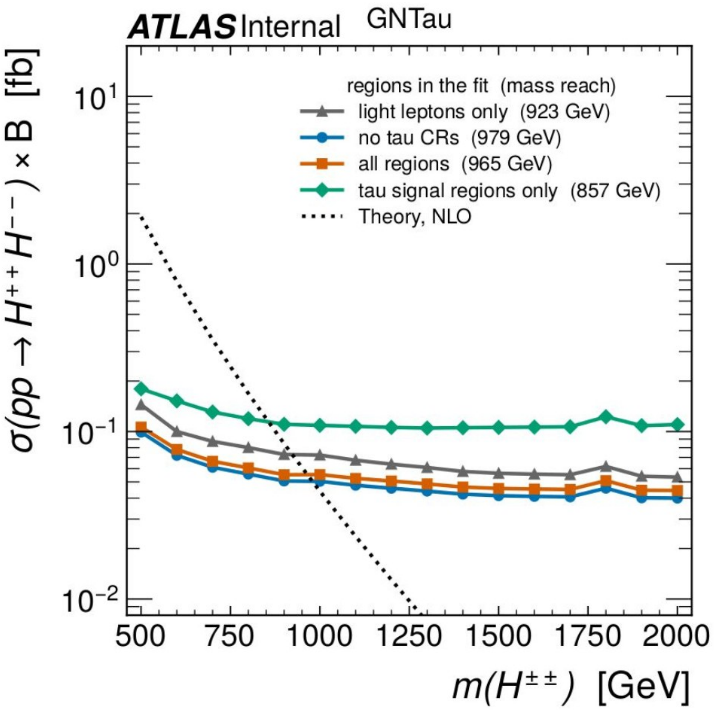




Recent results

Impact of tau channels on final exclusion limit

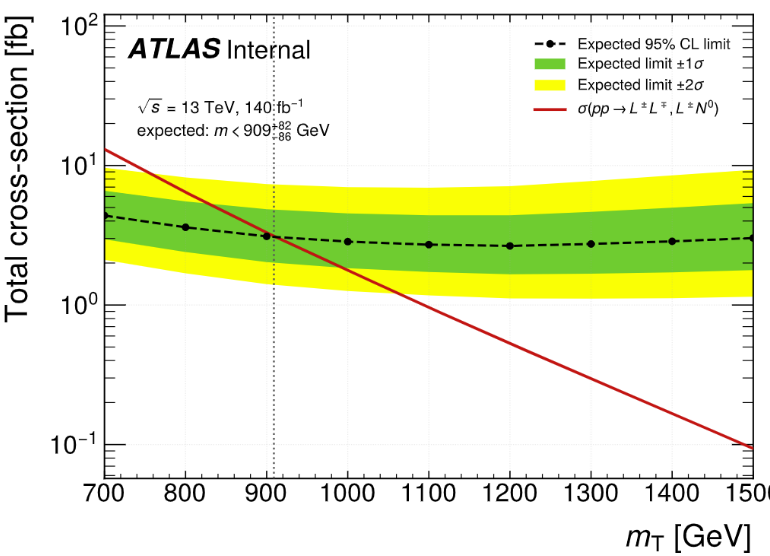
- Evaluated the impact of including tau channels on cut-based analysis approach
- Improvement of 30-50 GeV in (Run 2-only) expected limits seen already



Type-II

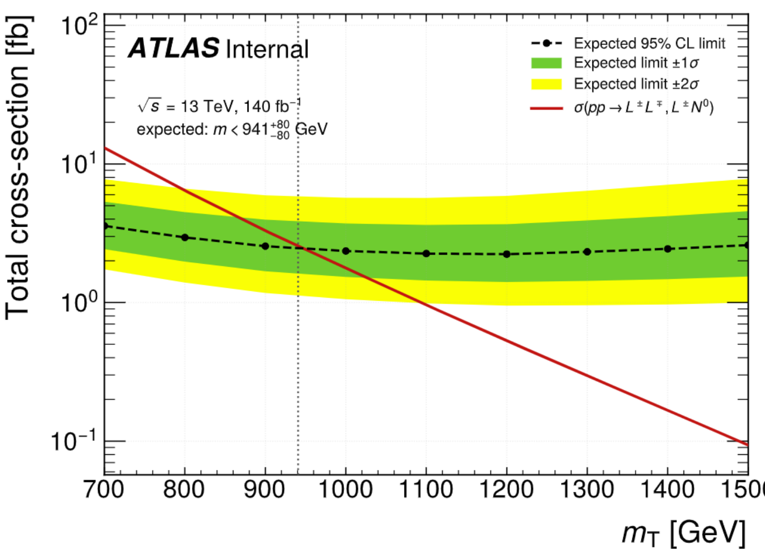
Taus enabled
No tau channels

Type-III



Adding tau channels

Taus enabled
With tau channels

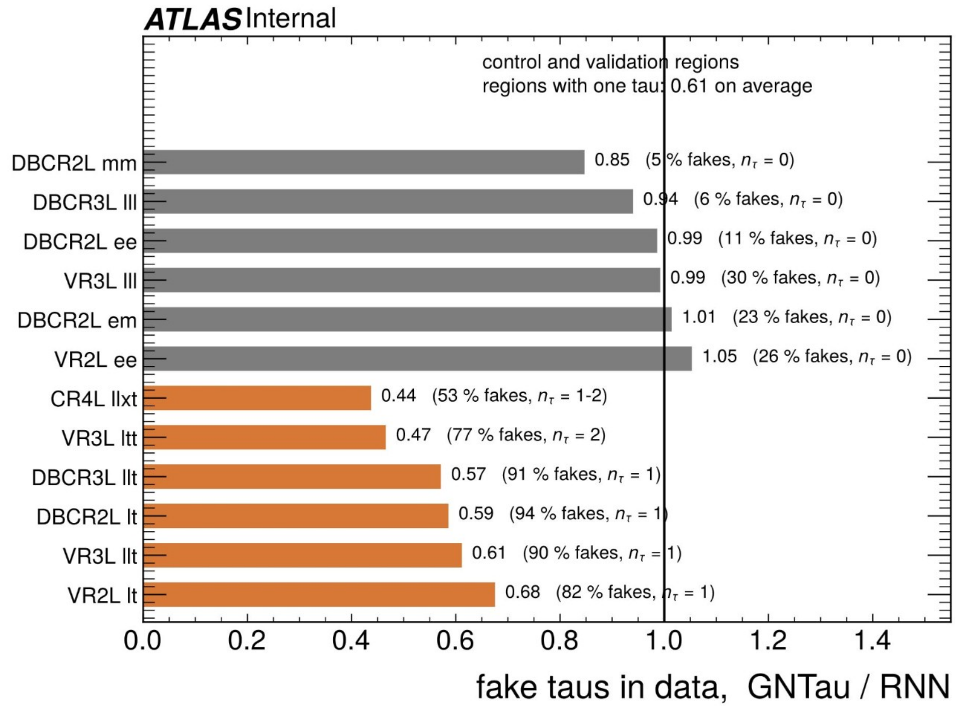


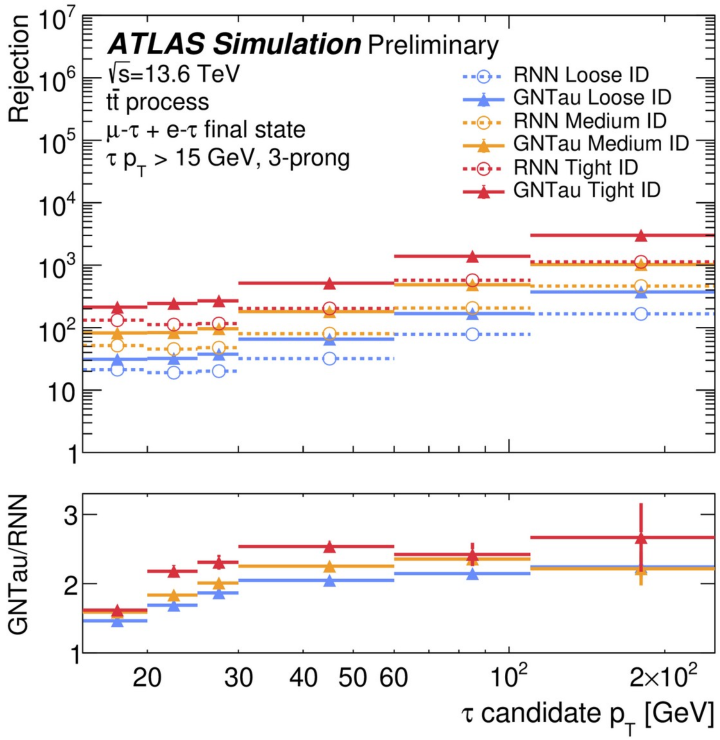
Recent results

Impact of new GNTau ID

- Recently migrated from previous RNN-based ID
- Large improvements in fake jet rejection seen with new transformer-based GNTau algorithm

Type-II





Type-III (loosened 2L SS SR)

τ ID	Background	Signal	Significance	Signal eff. [%]
RNN Loose	3406	0.3035	0.005200	0.3262
RNN Medium	1623	0.2638	0.006546	0.2835
GNTau Loose	1925	0.3086	0.007033	0.3317
GNTau Medium	884.8	0.2586	0.008692	0.2779

+33 % gain

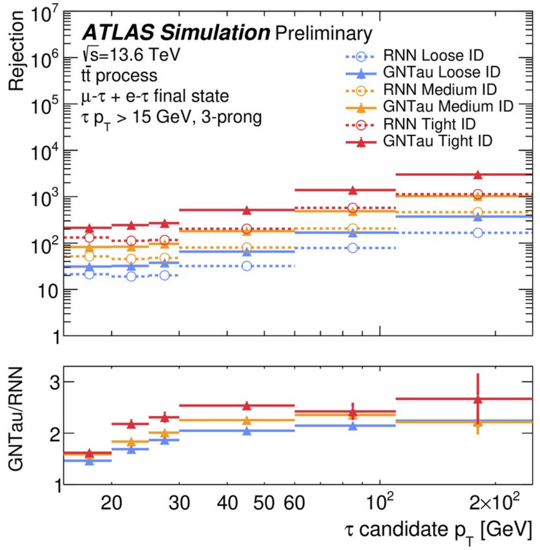
Conclusion

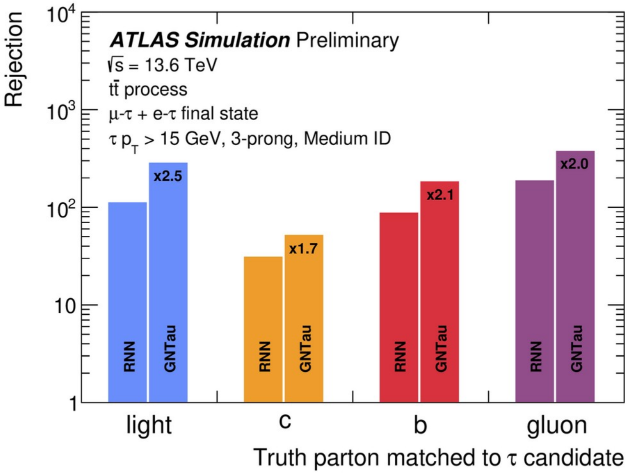
- Presented the status of tau inclusion into the Run 2 + Run 3 Seesaw analyses
  - **First ATLAS analyses at the department looking at taus**
  - **Improvements on final limit** already seen on cut-based Run 2 results
    - Further reach expected with additional Run 3, ML-based sig-bkg separation and once fake tau background modeling is finalized
  - GNTau shows significant improvements
  - Main challenge is **fake taus**
- **Outlook for other tasks for the upcoming months:**
  - Adding Run 3 dataset
  - ML-based signal-background separation

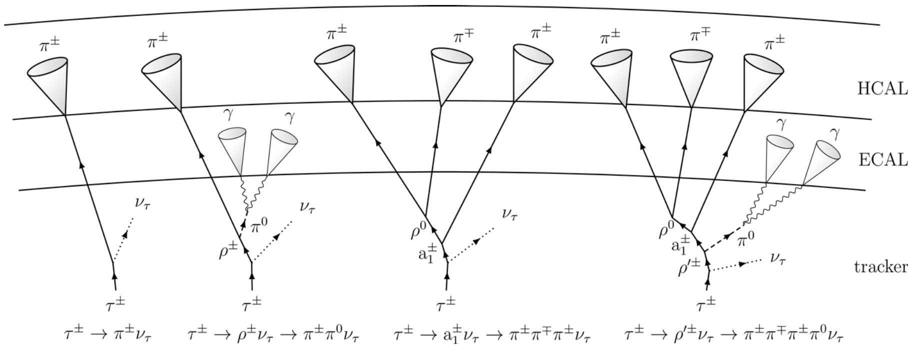
Thank you

Tau reconstruction at ATLAS

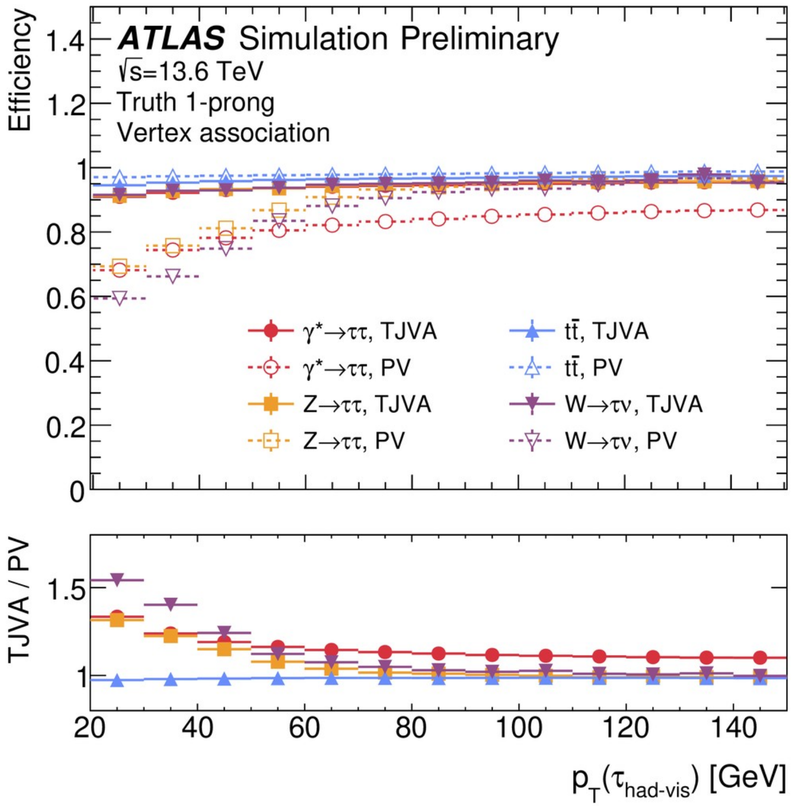
- Reconstruction of the visible hadronic component (τ_{had})
  - 1- and 3-“prong” (charged-track) topologies
- τ_{had} candidates **seeded by jets** formed by calorimeter cell clusters
- Dedicated algorithm to identify τ_{had} production vertex
- Selection of candidate τ_{had} tracks
  - Kinematic requirements relative to the τ_{had} vertex and seed jet
  - RNN-based classifier provides final track selection
- Candidates with N_{tracks} = 1,3 and $|\Sigma q_{track}|$ = 1 → $\boldsymbol{\tau_{had\text{-}vis}}$
- **Identification** to remove fake jet background
  - Large recent improvements with the newest **GNTau transformer-based tagger** (link)
  - Further fake electron and muon suppression algorithms
- *Details in Public Note:* ATL-PHYS-PUB-2022-044

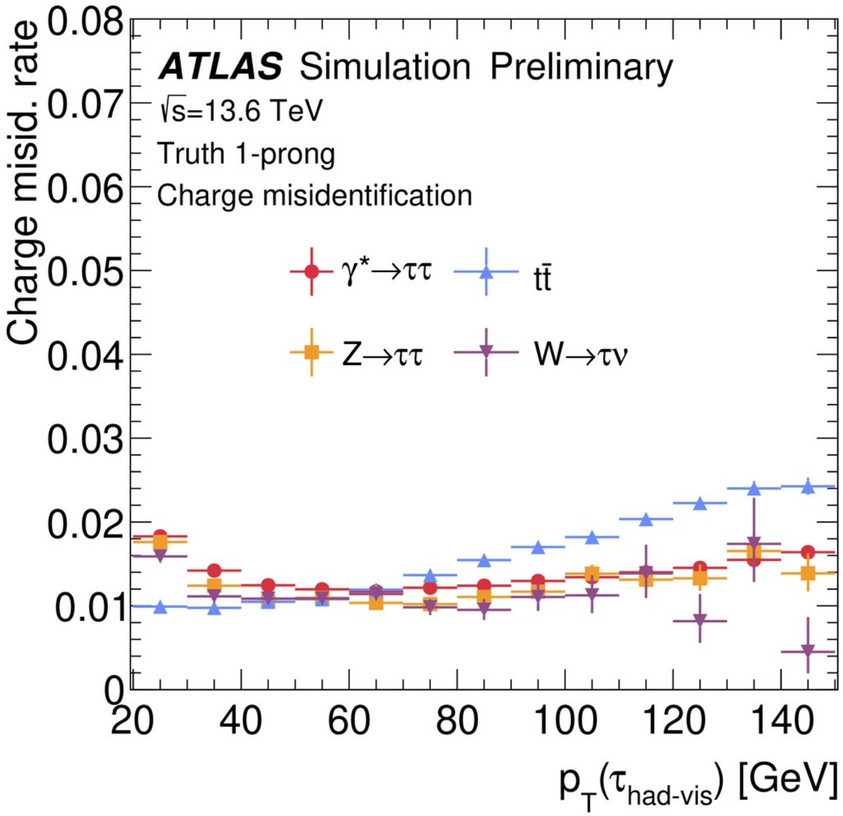






Tau reconstruction at ATLAS





Challenges with Hadronic Taus

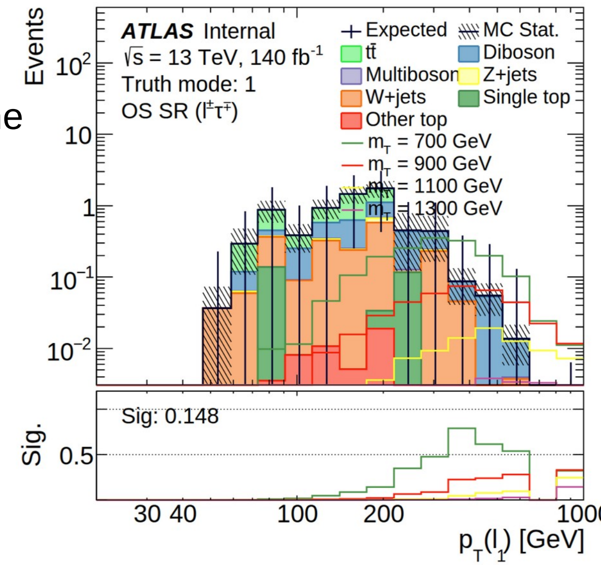
Trigger strategy

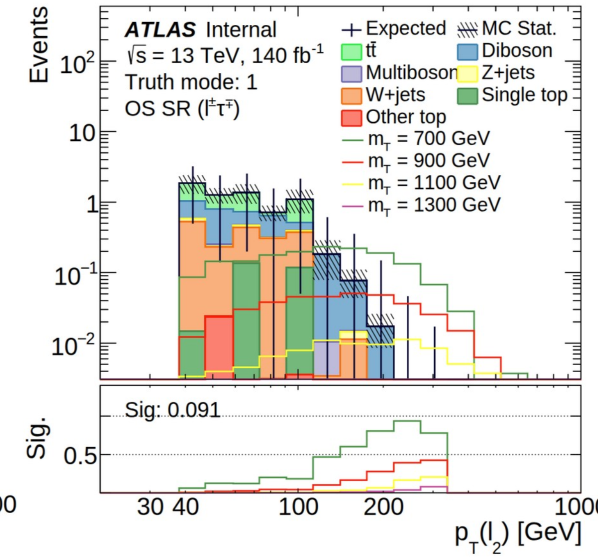
- We apply trigger-matching (reco-level leptons matched to triggering objects)
- Used di-lepton triggers historically
- How do we accept events with taus?
  - **Tau triggers** (not supported well with efficiency calibrations – cannot get global efficiency scale factor!)
  - Try to keep light lepton triggers where possible
- New **channel-dependent trigger selection strategy**

Trigger type used	Channels
Di-lepton	Any channel with at least two light leptons
Single-lepton	Any channel with at least two light leptons
Di-tau	Channels with taus only

Calibration support

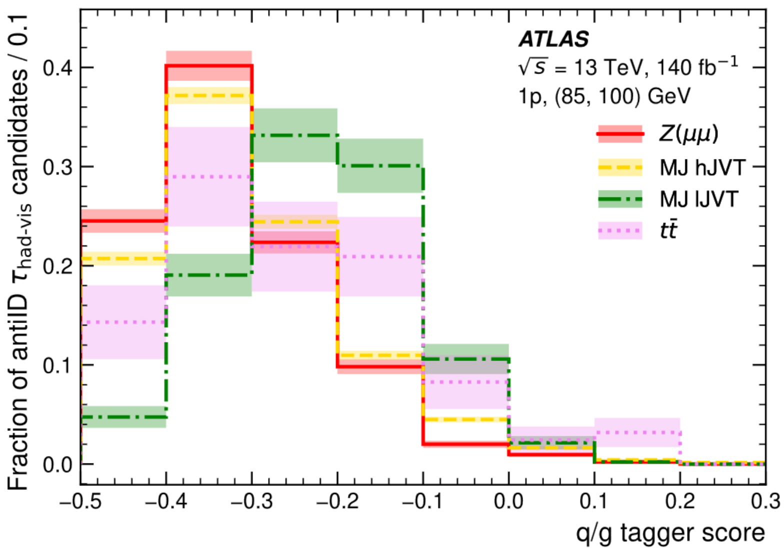
- Calibrations for GNTau only starting to become available → Validations needed
- τ_{had} ID calibrated up to $p_T \sim 250$ GeV
  - Our signal can exceed this

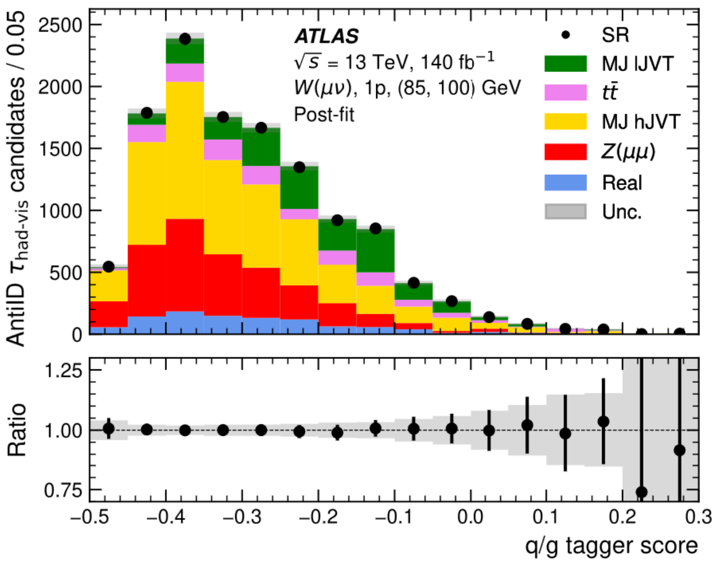




Challenges with Hadronic Taus – τ_{had} Fakes

Universal Fake Factor (UFF)





$$\mathrm{FF}_{\mathrm{UFF}} = \mu_{Z(\mu\mu)} \times \mathrm{FF}_{Z(\mu\mu)} + \mu_{t\bar{t}} \times \mathrm{FF}_{t\bar{t}} + \mu_{\mathrm{MJ\ hJVT}} \times \mathrm{FF}_{\mathrm{MJ\ hJVT}} + \mu_{\mathrm{MJ\ lJVT}} \times \mathrm{FF}_{\mathrm{MJ\ lJVT}}$$