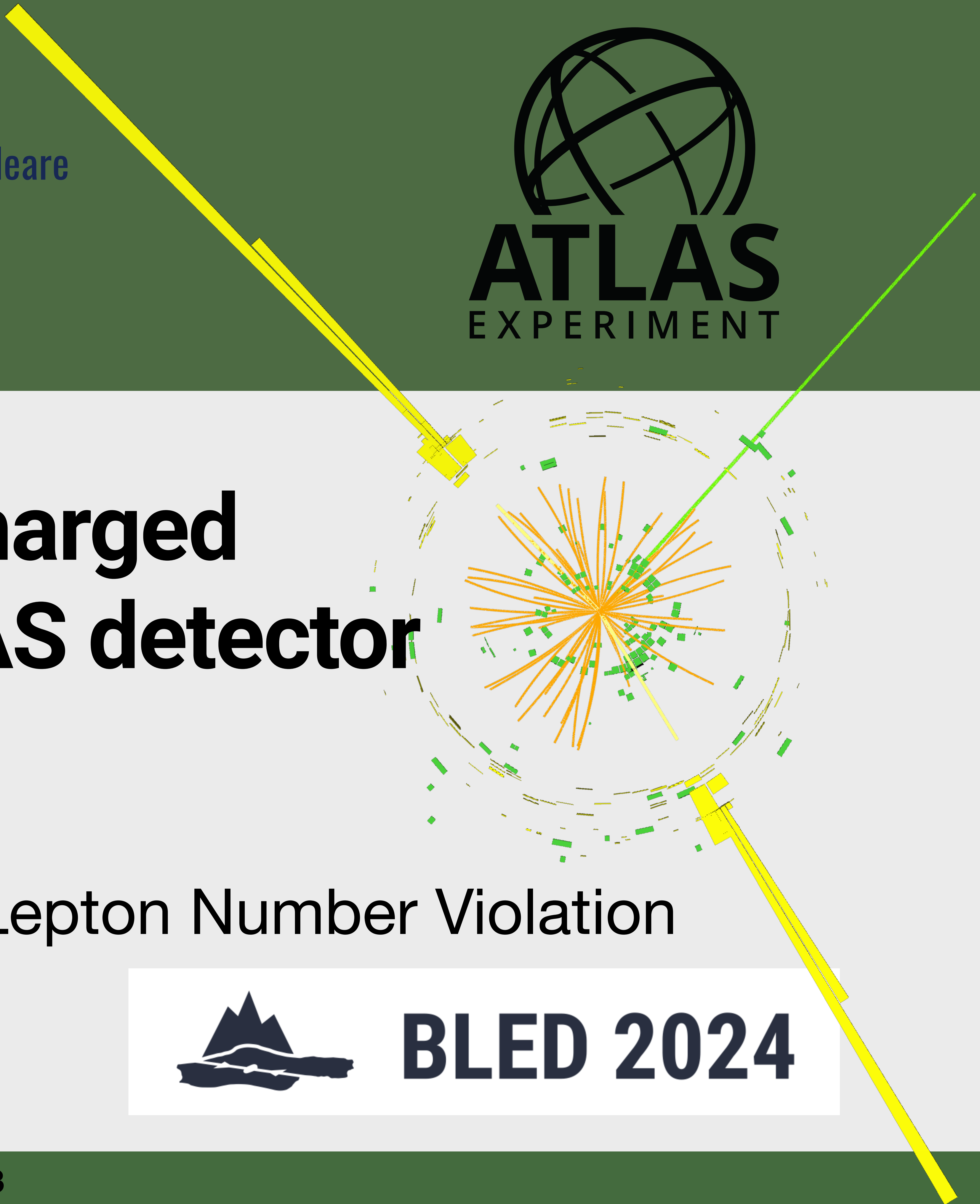
INFN

Istituto Nazionale di Fisica Nucleare
SEZIONE DI BOLOGNA

ATLAS
EXPERIMENT



LRSM: Search for Doubly Charged Higgs bosons with the ATLAS detector + LNV Higgs decays

Bled 2024: International Workshop on Lepton Number Violation
Blaž Leban

BLED 2024

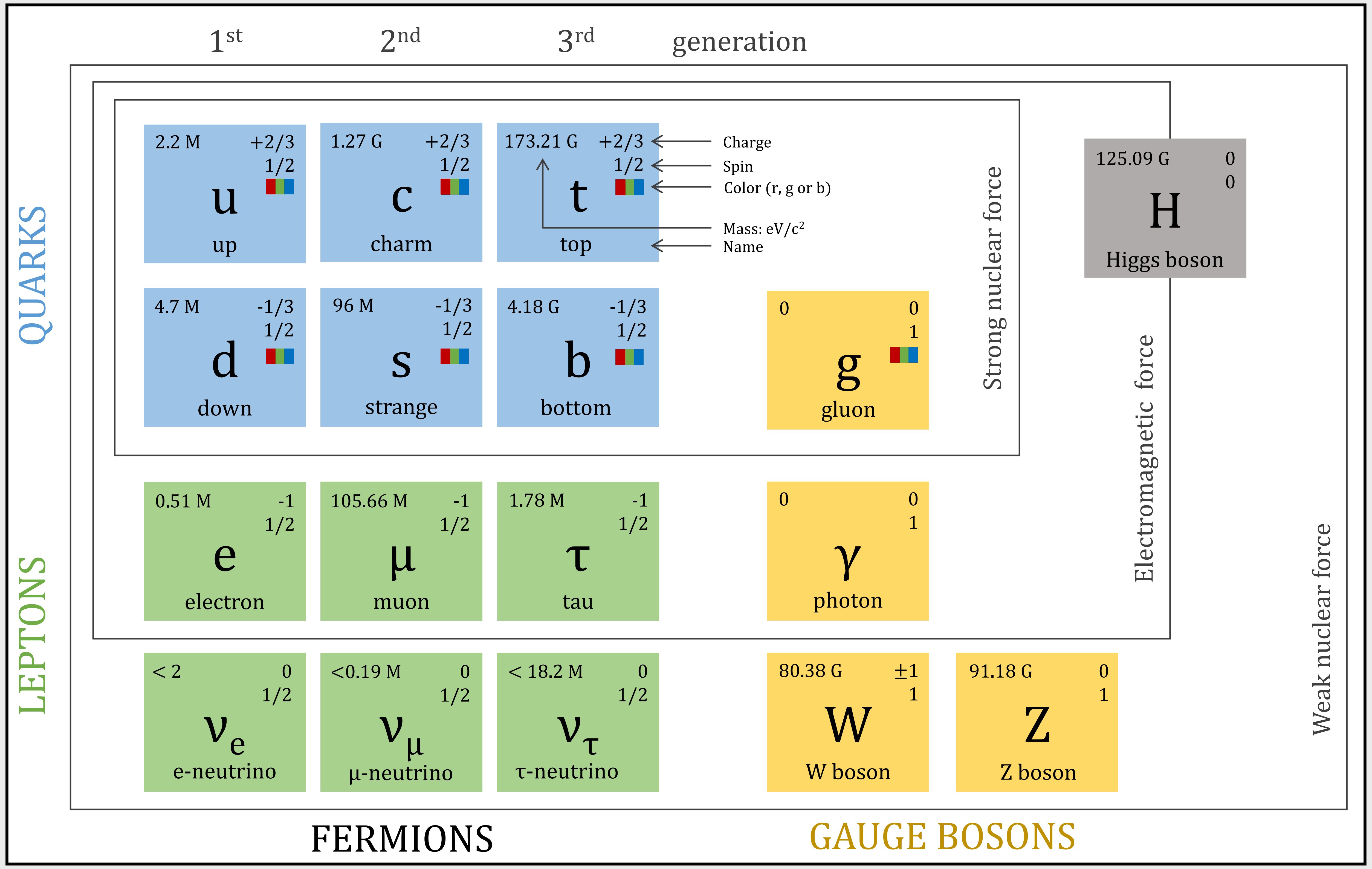
21 June 2023

Outline

- Introduction to the Standard Model (SM)
- Beyond the Standard Models (BSMs):
  - Seesaw mechanism,
  - Left-Right Symmetric Model (LRSM),
  - Zee-Babu model.
- Search for heavy doubly charged Higgs (DCH) bosons:
  - Analysis strategy,
  - Background estimation,
  - Statistical Analysis and Results.
- Lepton Number Violating Higgs decays:
  - Test of the KNN UFO model → signal sample validation.

Introduction to the Standard Model

- Well-established quantum field theory of elementary particles and their interactions with high predictive power.
- Gives accurate predictions, which (mostly) very well agree with the experiments.



Shortcomings:

- Many free parameters,
- Dark matter and dark energy,
- Matter - antimatter asymmetry,
- Hierarchy problem and naturalness,
- **Neutrino masses,**
- ***Weak interaction is completely asymmetric between left- and right-handed fields.***

Seesaw Mechanism

- The SM cannot explain non-zero neutrino masses at the re-normalisable level. Neutrino masses can only be obtained by:
  - Introducing a new degree of freedom, i.e. a right-handed neutrino to build the **Dirac mass** term:

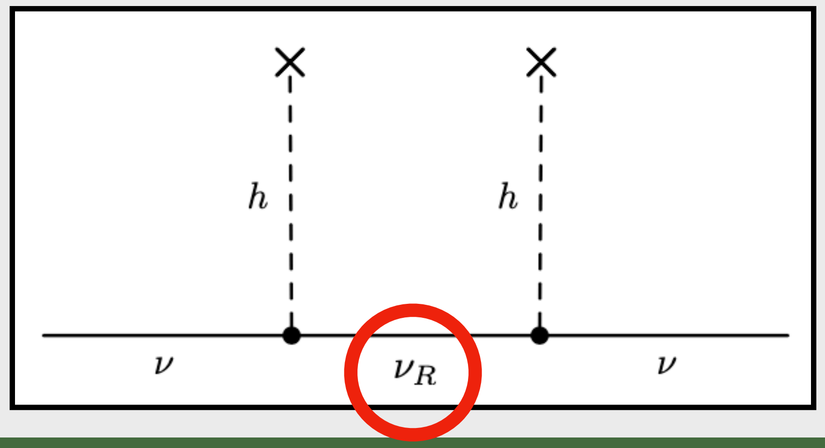
$$\mathscr{L}_D = -m_D\,(\bar{\nu}_R\nu_L + \bar{\nu}_L\nu_R), \qquad \text{where} \qquad m_D = y_D\, v/\sqrt{2}.$$

  - Using non-renormalisable *dimension-5 Weinberg operator* to get **Majorana masses:**

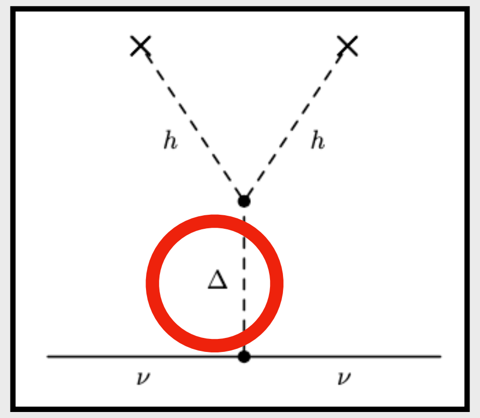
$$\mathscr{L}_M = -\frac{1}{2}m_M\,(\nu_L^T C\nu_L + h\,.\,c.), \qquad \text{where} \qquad m_M = y_M\frac{v^2}{\Lambda}.$$

- The observations of small neutrino masses indicate that either Λ is very large, $\Lambda \gg v$, or y must be small.
- The **seesaw mechanism** offers an explanation of small neutrino masses compared to those of quarks and charged leptons. Three types:

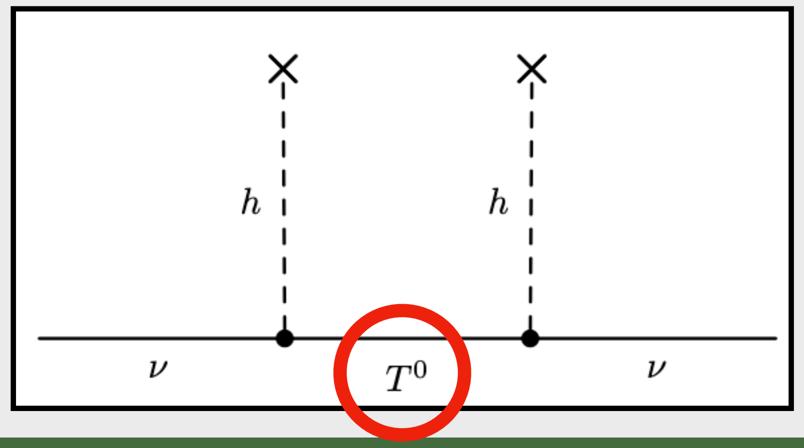
type-I: fermionic singlet



type-II: scalar triplet



type-III: fermionic triplet



Left-Right Symmetric Model

- Parity violation remains unexplained within the SM, therefore we seek higher symmetry, which is then spontaneously broken at lower energy scales.
- Pati, Salam, Mohapatra, and Senjanović proposed the **left-right symmetric model**:
  - Extend SM gauge group by an $\mathrm{SU}(2)_R$ local symmetry:

$$\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L}.$$

  - Quarks and leptons become completely symmetric:

$$Q_{L,R} = \begin{pmatrix} u \\ d \end{pmatrix}_{L,R}, \qquad L_{L,R} = \begin{pmatrix} \nu \\ e \end{pmatrix}_{L,R}.$$

  - Interaction Lagrangian is written as $\mathscr{L} = \bar{f} i \gamma^\mu D_\mu f$, with the covariant derivative containing coupling strengths:

$$D_\mu = \partial_\mu - i \left(g_S A^a_\mu T^a_{ij} + g_L W^a_{\mu L} \frac{\sigma^L_a}{2} + g_R W^a_{\mu R} \frac{\sigma^R_a}{2} + g' B_\mu \frac{B-L}{2} \right).$$

LRSM Spontaneous Symmetry Breaking

- Higgs sector is extended with two $\mathrm{SU}(2)$ **triplets** $\Delta_{L,R}$ and a **bi-doublet** Φ:

$$\Delta_{L,R} = \begin{pmatrix} \Delta^{+}/\sqrt{2} & \Delta^{++} \\ \Delta^{0} & -\Delta^{+}/\sqrt{2} \end{pmatrix}_{L,R}, \qquad \Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}.$$

- Spontaneous Symmetry Breaking (SSB) happens in two consecutive steps:

LRSM → SM

- $\Delta_L(1,3,1,2)$ and $\Delta_R(1,1,3,2)$ triplets,
- $\langle \Delta_L \rangle = 0$ and $\langle \Delta_R \rangle = \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix}$.

SM → EM

- $\Phi(1,2,2,0)$ (includes SM Higgs boson),
- $\langle \Phi \rangle = \begin{pmatrix} v_1 & 0 \\ 0 & v_2 e^{i\alpha} \end{pmatrix}$,
- In turn, Δ_L develops a tiny induced vev $v_L = \langle \Delta_L \rangle \propto v^2/v_R$.

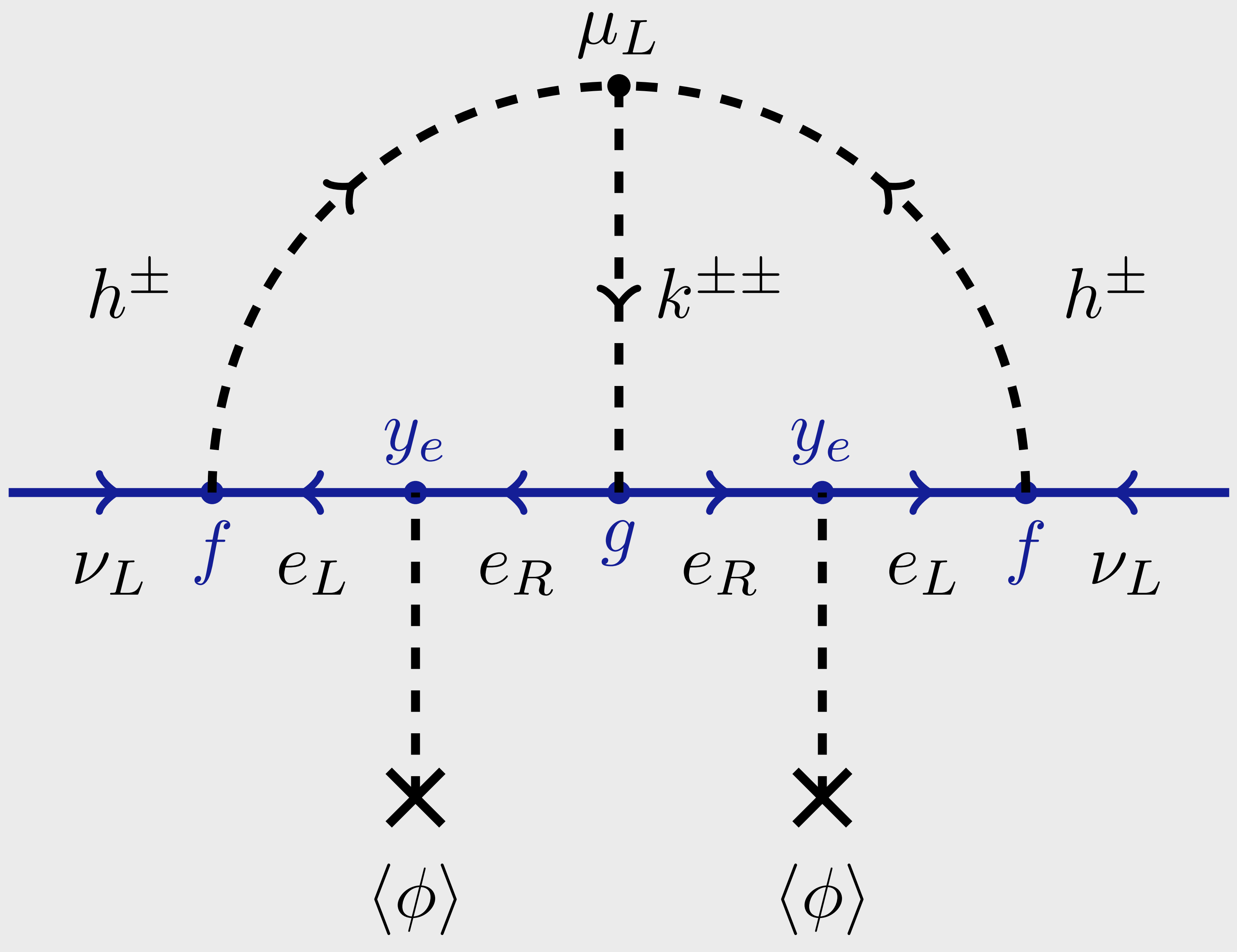
- Right-handed counterparts of W and Z bosons acquire masses as a result of the SSB.

Zee-Babu Model

- The existence of two scalar $\mathrm{SU}(2)_L$ singlets k and h, which carry hypercharge, is hypothesised:

$$h^{\pm} \sim (1, 1, +1),$$
$$k^{\pm\pm} \sim (1, 1, +2)\,.$$

- Since there are no right-handed neutrinos in the Zee–Babu model, Dirac mass terms can not be constructed. Furthermore, k and h cannot contract with lepton and Higgs doublets to generate Majorana masses at the tree level.
- Left-handed Majorana **neutrino masses** are generated **radiatively via two-loop diagrams**.
- Total and differential **production rates** for $H_R^{\pm\pm}$ and $k^{\pm\pm}$ **are identical** in shape and can only differ in normalisation.



Doubly Charged Higgs Boson Production

- Various BSM theories predict the existence of doubly charged bosons.

LRSM

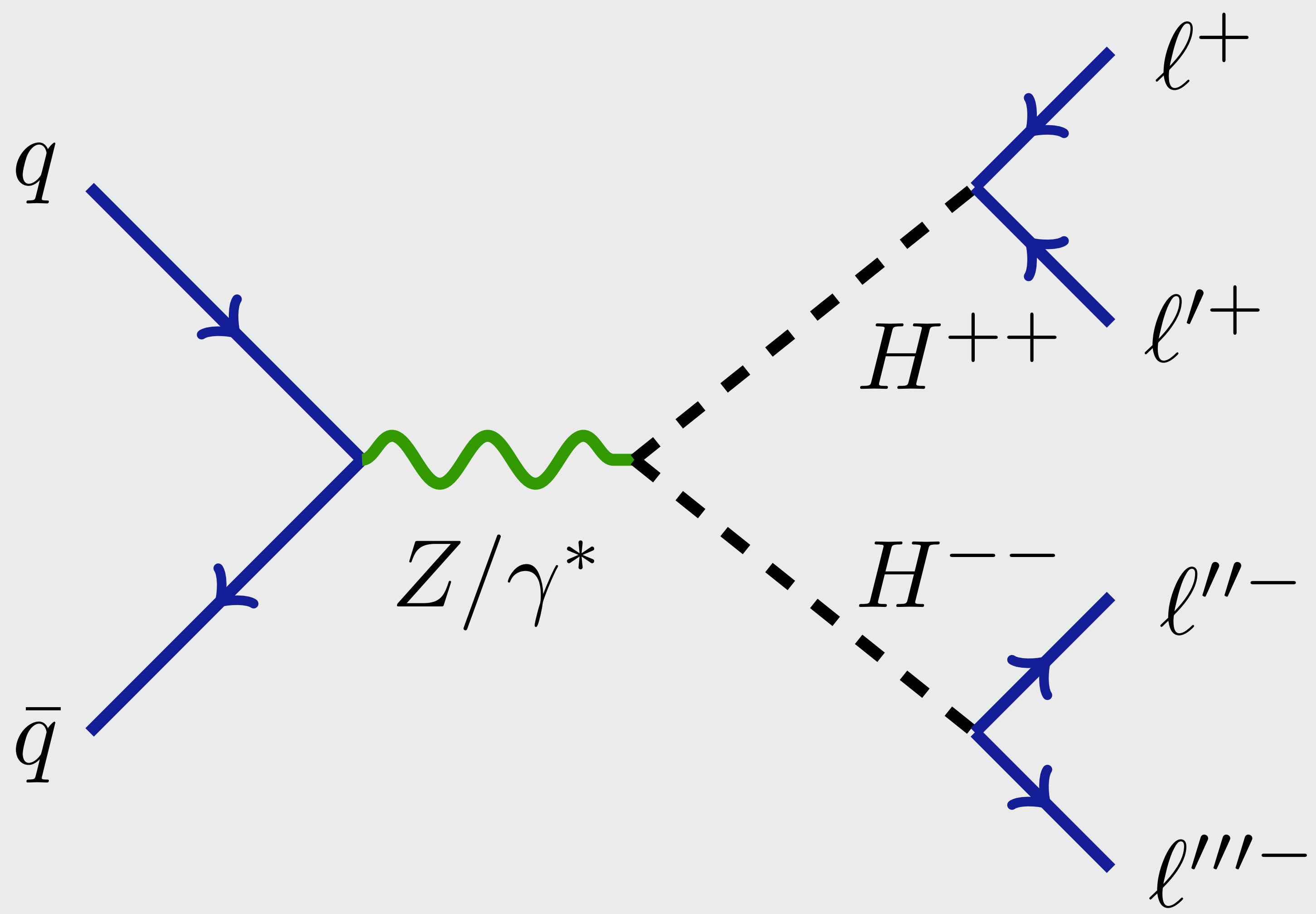
- Two chiralities $H_L^{\pm\pm}$ and $H_R^{\pm\pm}$.
- Can couple to left-, right-handed leptons, vector bosons or scalars from the triplet. **Lepton flavour violation is allowed.**
- The dominant production mechanism is the Drell-Yan process through an s-channel photon or a Z boson exchange.

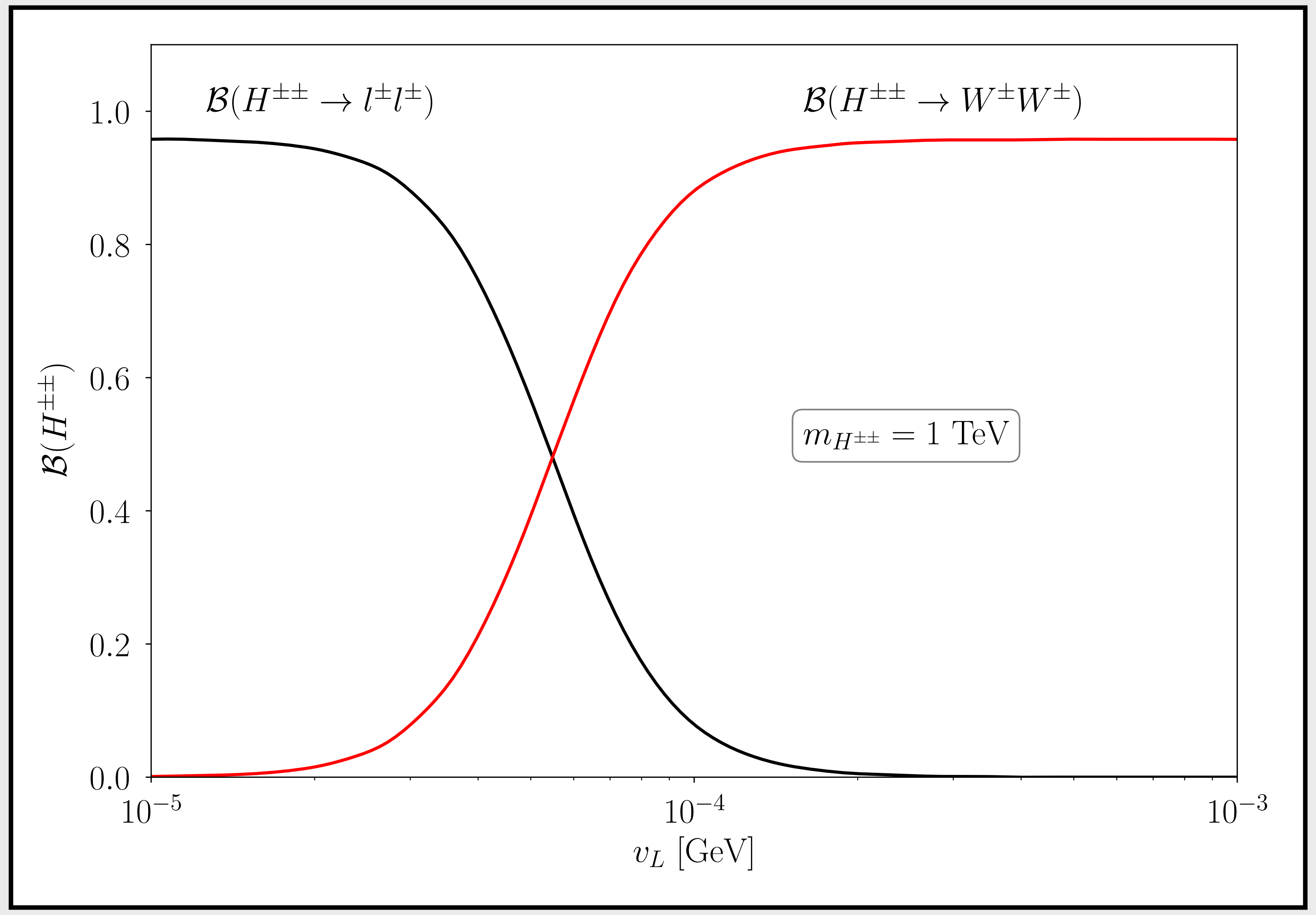
$$\Gamma(H^{\pm\pm} \to \ell^{\pm}\ell'^{\pm}) = \frac{1}{1+\delta_{\ell\ell'}} \frac{h_{\ell\ell'}^2}{16\pi} m_{H^{\pm\pm}}$$

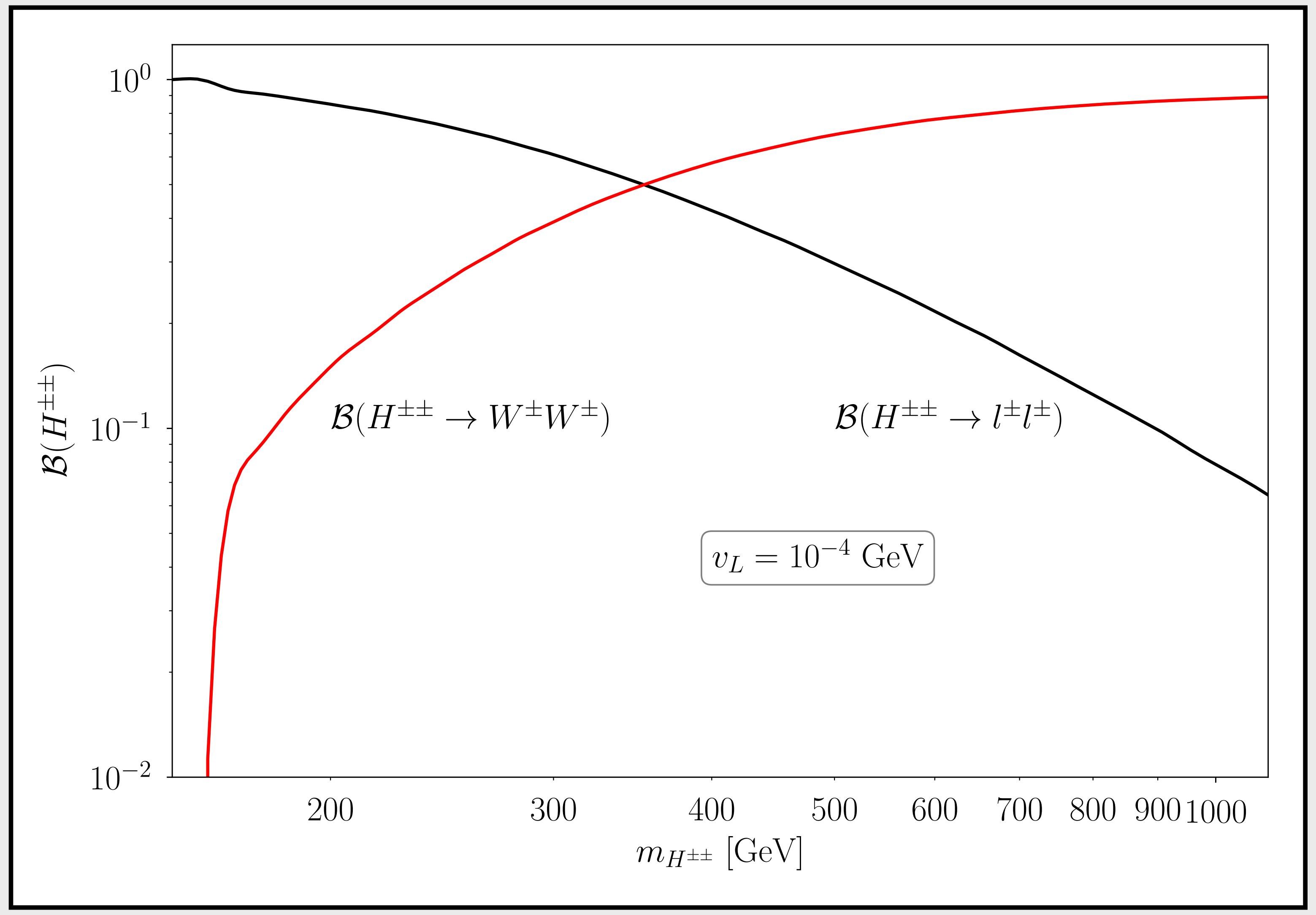
Zee-Babu model

- The $k^{\pm\pm}$ has the same quantum numbers as $H_R^{\pm\pm}$ so their electroweak production is the same.
- For the Drell–Yan production mechanism, cross-sections and differential scalar distributions in the Zee–Babu and type-II seesaw models differ at most by a normalisation factor.

$$\Gamma(k^{\pm\pm} \to \ell^{\pm}\ell'^{\pm}) = \frac{1}{1+\delta_{\ell\ell'}} \frac{|g_{\ell\ell'}|^2}{4\pi} m_{k^{\pm\pm}}$$







Doubly charged Higgs analysis

Analysis Strategy

- **Prompt**, **highly energetic**, **same-charge** lepton pairs represent a striking signature for BSM physics - such events are produced rarely in pp collisions by the SM processes.
- Considering only final states containing **light leptons**, including leptonic τ decays.
- Branching fraction to each possible leptonic final state is assumed equal:

$$\mathscr{B}(H^{\pm\pm} \rightarrow e^{\pm}e^{\pm} / e^{\pm}\mu^{\pm} / \mu^{\pm}\mu^{\pm} / e^{\pm}\tau^{\pm} / \mu^{\pm}\tau^{\pm} / \tau^{\pm}\tau^{\pm}) = 1/6$$

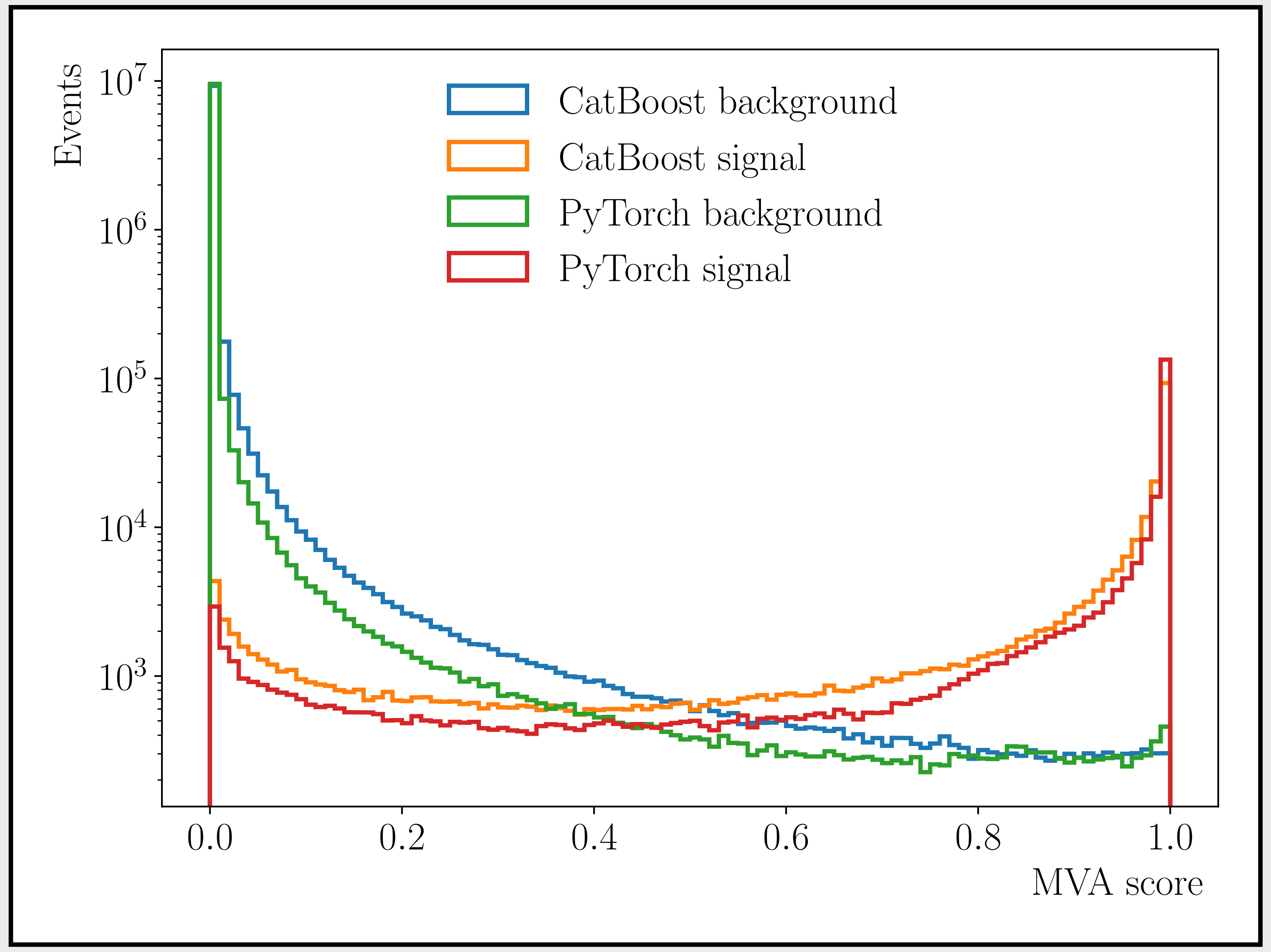
- Two analysis approaches were tested:
  - **Cut-based analysis (CB)**: selection requirements on kinematic variables are chosen orthogonally. Published in Eur. Phys. J C 83 (2023) 605.
  - **Multivariate analysis (MVA)**: a functional dependence on a combination of observables is implemented.
- A binned maximum-likelihood fit to data is performed on:
  - $m(\ell^{\pm}\ell'^{\pm})_{\mathrm{lead}}$ and event yield in the CB analysis,
  - logit MVA score in MVA analysis.

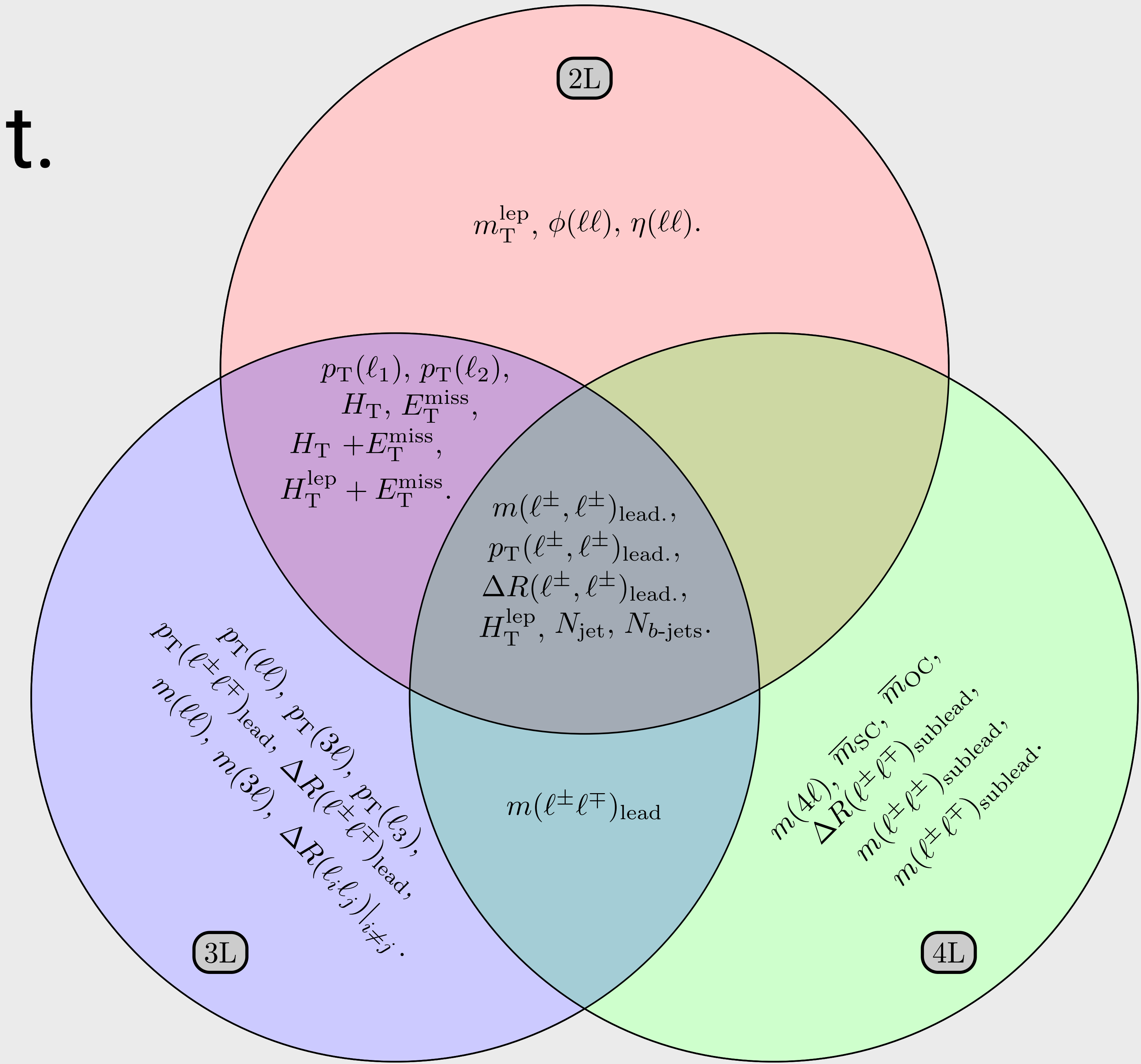
} Fit the dominant Drell-Yan and diboson backgrounds

MVA analysis strategy

- Two different binary classification algorithms are tested:
  - a gradient boosting on decision trees (BDT) implemented in CatBoost,
  - a deep neural network (DNN) provided by an ML library PyTorch.
- Due to the different topologies, an individual model is trained for each lepton multiplicity.
- Samples are split in 50% (training) : 25% (test) : 25% (validation) ratio, using stratified sampling.
- Features selected based on the BDT feature importance output.
- Neural Networks expectedly outperformed the BDTs.
- Signal to background was separated well, so it was challenging to construct sensible region definitions:

➡ **use logit MVA score**





Analysis Regions

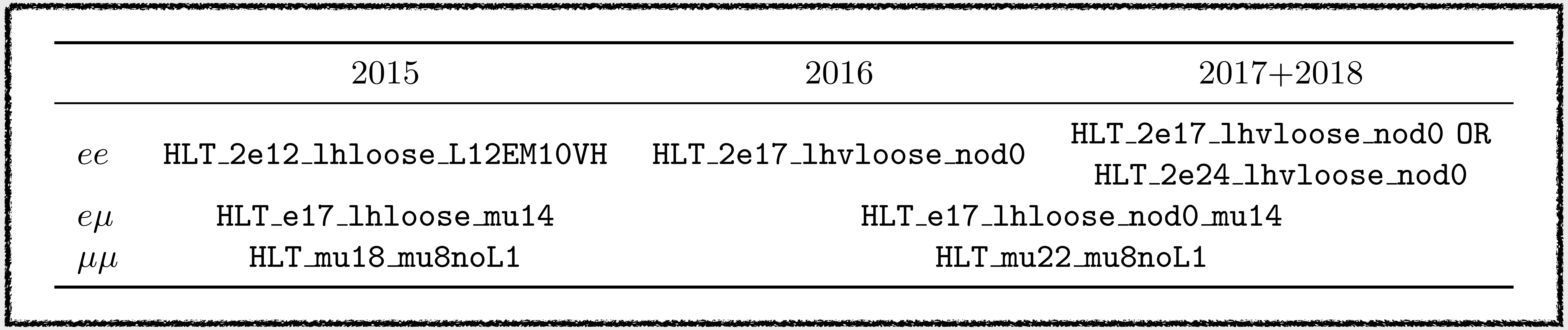
- Six **control regions (CR)** for:
  - Constraining nuisance parameters related to systematic uncertainties,
  - Fitting the dominant SM backgrounds: DY (2ℓ) and diboson $(2\ell, 3\ell, 4\ell)$.
- Five **validation regions (VR)** are used to cross-check the background modelling.
- Five **signal regions (SR)** as parts of phase space where a signal model predicts a significant excess of events over the expected background level.

		Control regions					Signal regions			Validation regions			
		DYCR	DBCR2L		DBCR3L	CR4L	SR2L	SR3L	SR4L	VR2L		VR3L	VR4L
Cut-based analysis	Channel	e^+e^-	$e^\pm e^\pm$	$e^\pm\mu^\pm$ $\mu^\pm\mu^\pm$	$\ell^\pm\ell^\pm\ell^\mp$	$\ell^+\ell^+\ell^-\ell^-$	$e^\pm e^\pm$ $e^\pm\mu^\pm$ $\mu^\pm\mu^\pm$	$\ell^\pm\ell^\pm\ell^\mp$	$\ell^+\ell^+\ell^-\ell^-$	$e^\pm e^\pm$	$e^\pm\mu^\pm$ $\mu^\pm\mu^\pm$	$\ell^\pm\ell^\pm\ell^\mp$	$\ell^+\ell^+\ell^-\ell^-$
	$m(\ell^\pm,\ell^\pm)_{\text{lead.}}$ [GeV]*	≥ 300	$[200,\ 300)$		≥ 300	$[100,\ 200)$	≥ 300	≥ 300	≥ 300	≥ 300		$[100,\ 300)$	$[200,\ 300)$
	$p_{\text{T}}(\ell^\pm,\ell^\pm)_{\text{lead.}}$ [GeV]	-	-		-	-	≥ 300	≥ 300	-	$[200,\ 300)$		-	-
	$\Delta R(\ell^\pm,\ell^\pm)_{\text{lead.}}$	-	-		-	-	< 3.5	-	-	< 3.5		-	-
	$\overline{m}_{\text{SC}}$ [GeV]	-	-		-	-	-	-	≥ 300	-		-	-
	$E_{\text{T}}^{\text{miss}}$ [GeV]	-	> 30	-	-	-	-	-	-	> 30	-	-	-
	$\lvert\eta(\ell,\ell')\rvert$	-	< 3.0	-	-	-	-	-	-	< 3.0	-	-	-
	Z-boson veto	-	-		inverted	-	-	✓	✓	-		✓	-
MVA analysis	logit MVA result	-	-		-	-	≥ 0	≥ 3	≥ 0	< 0		< 3	< 0
	$m(\ell^\pm,\ell^\pm)_{\text{lead.}}$ [GeV]*	≥ 300	$[200,\ 300)$		-	-	≥ 300	-	-	≥ 300		-	-
	$p_{\text{T}}(\ell^\pm,\ell^\pm)_{\text{lead.}}$ [GeV]	-	-		-	-	≥ 300	-	-	-		-	-
	$\overline{m}_{\text{SC}}$ [GeV]	-	-		-	< 200	-	-	≥ 200	-		-	≥ 200
	$\lvert\eta(\ell,\ell')\rvert$	-	-	-	-	-	-	-	< 3.0	-	-		
	Z-boson veto	-	-		inverted	-	-	✓	-	-		✓	-

*Note that the cut on the invariant mass of the leading **opposite-charge** lepton pair is applied in DYCR region.

Triggers used in the analysis

DiLepton Triggers

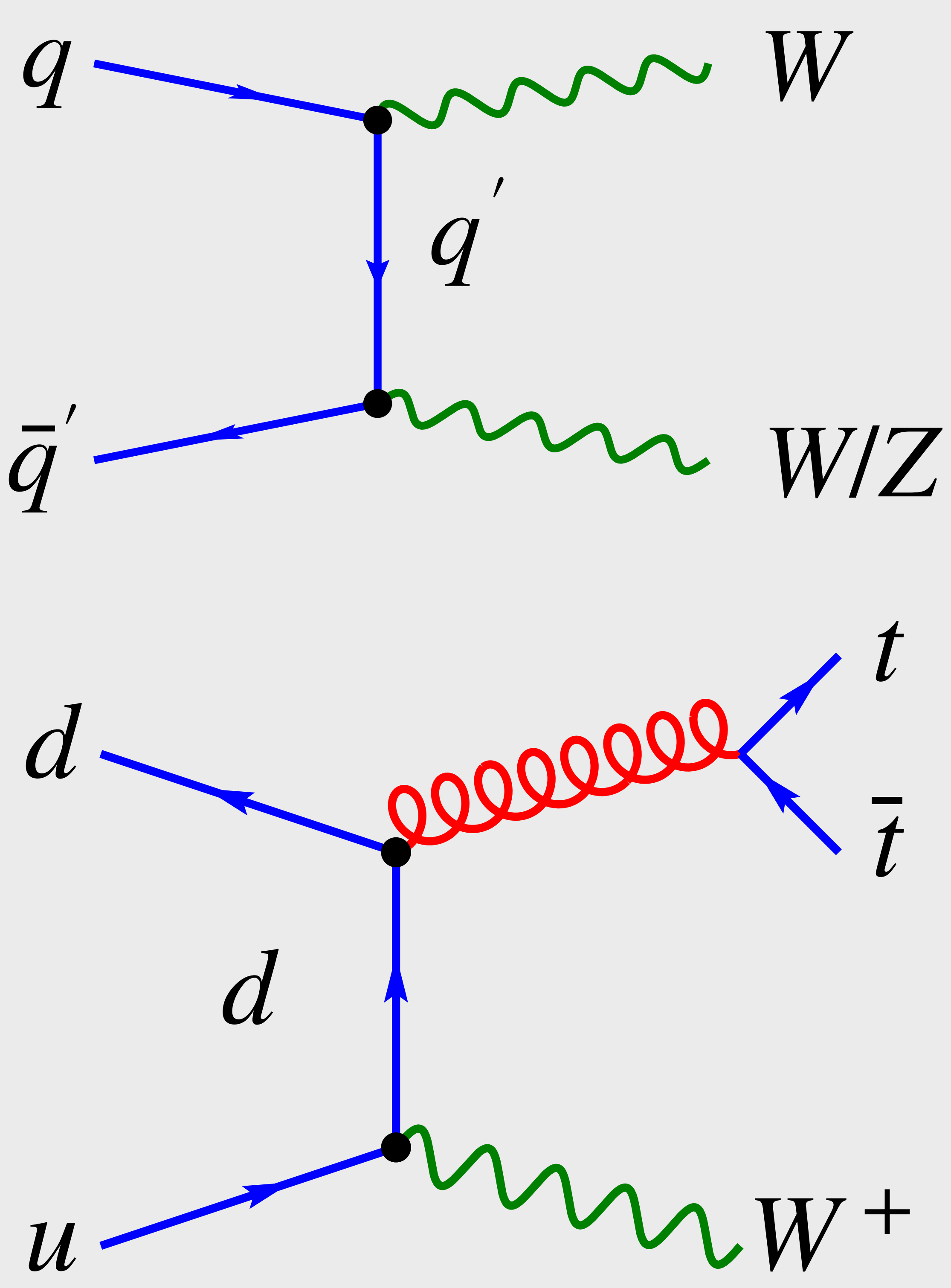


	2015	2016	2017+2018
ee	HLT_2e12_lhloose_L12EM10VH	HLT_2e17_lhvloose_nod0	HLT_2e17_lhvloose_nod0 OR HLT_2e24_lhvloose_nod0
$e\mu$	HLT_e17_lhloose_mu14	HLT_e17_lhloose_nod0_mu14	
$\mu\mu$	HLT_mu18_mu8noL1	HLT_mu22_mu8noL1	

- To extract the signal, **dilepton triggers** are used in the analysis - main reason is to avoid trigger bias on fakes.
- Prescaled single lepton triggers are used for fake estimation (see next slides):
  - Average prescales which are derived from luminosity blocks are used.

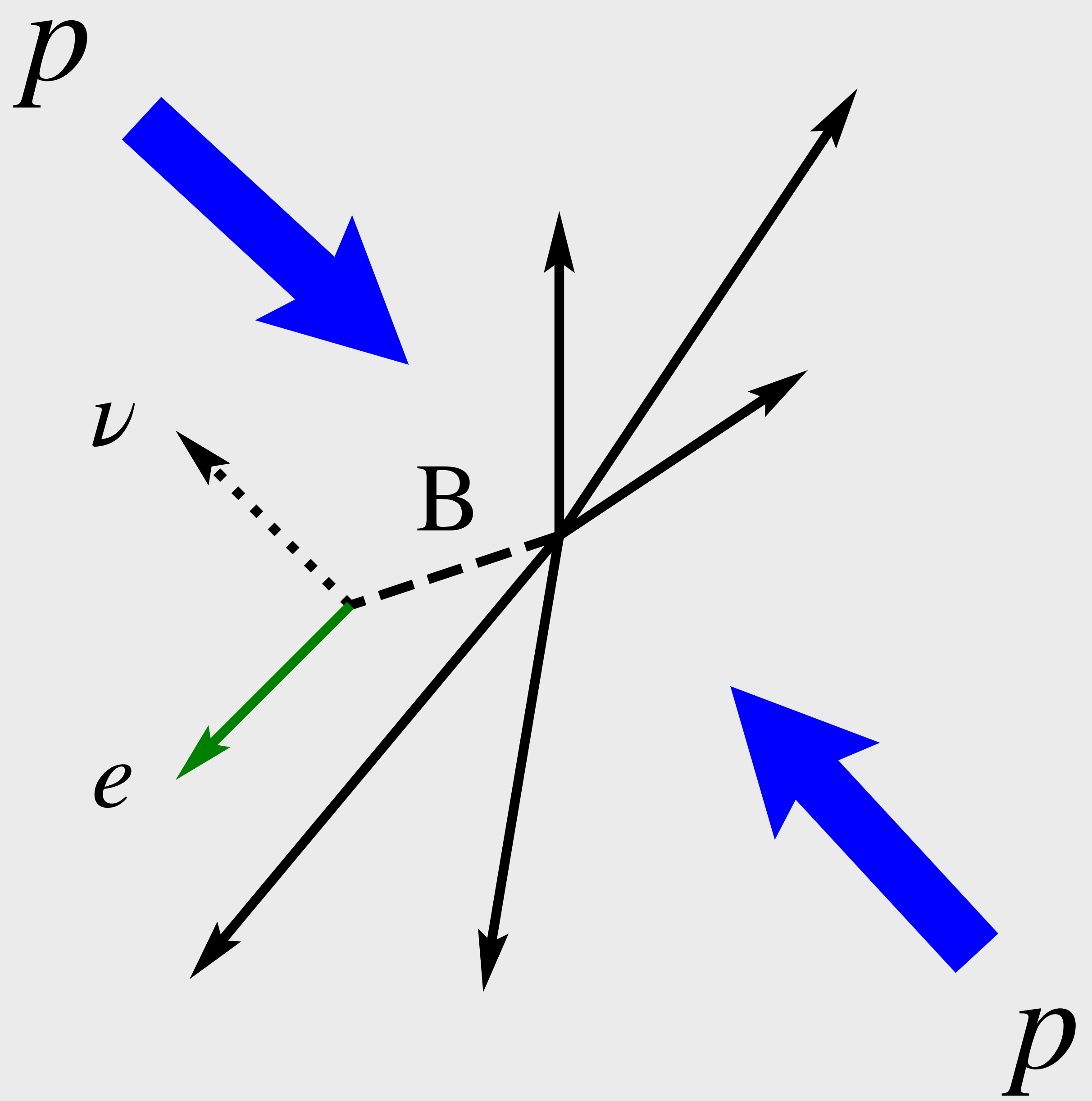
Types of Backgrounds

- **Prompt**



Produced in hard interaction, e.g. diboson, $t\bar{t}W$ backgrounds **estimated from MC simulations.**

- **Fake/non-prompt**

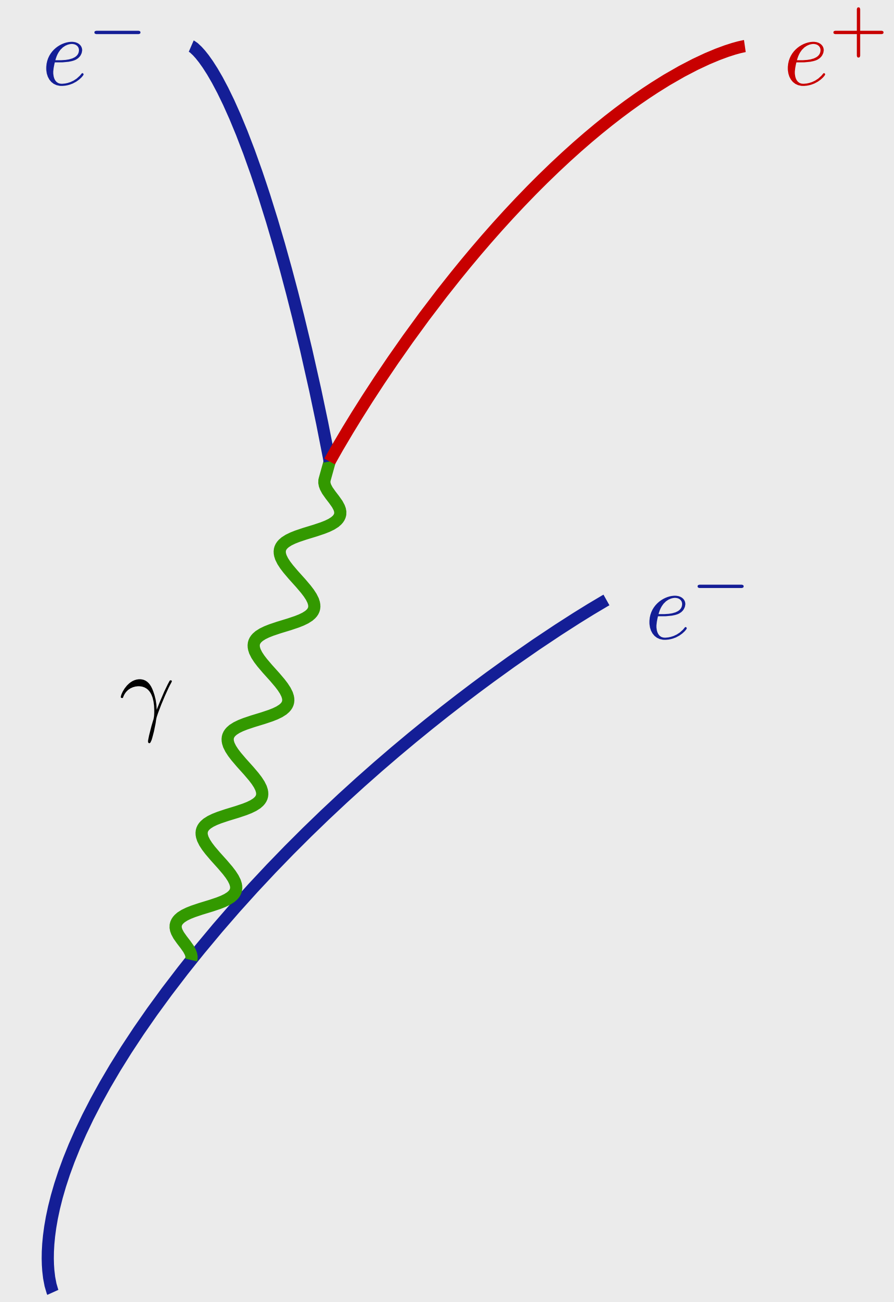


Any other object misidentified as lepton (jets, muons, hadrons, …).

Leptons coming from heavy flavoured mesons or mis-identified jets.

Estimated with **data-driven fake factor method.**

- **Misidentified charge**



Charge misidentification **estimated by comparing data to MC**, simulated events corrected with scale factors.

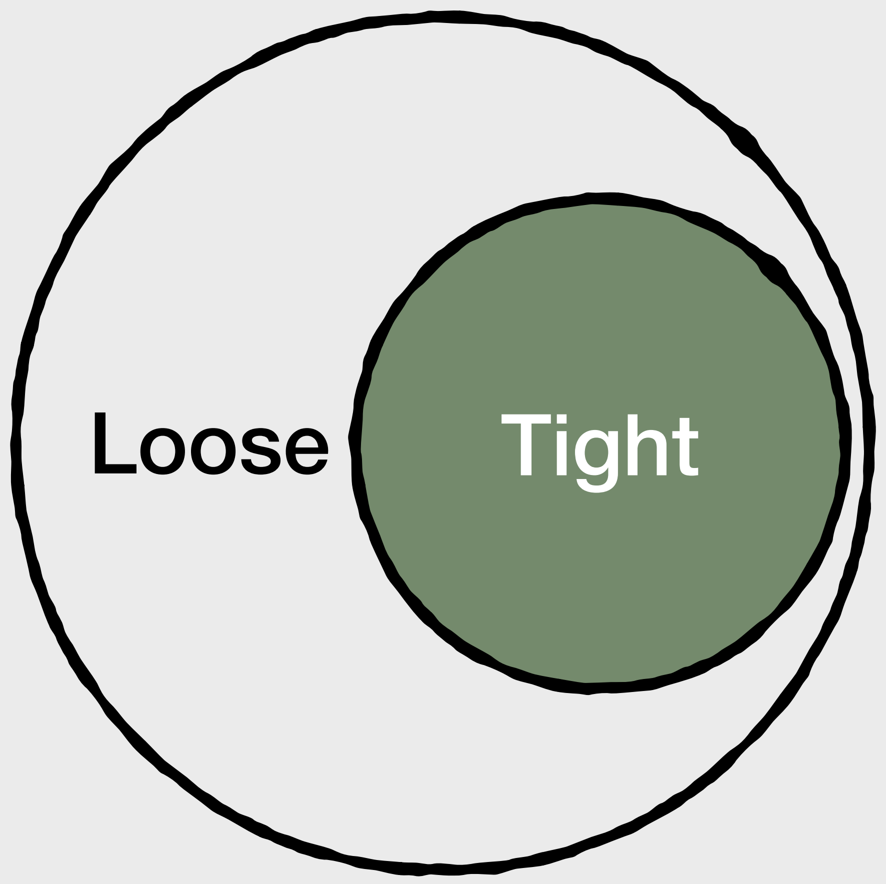
Fake Estimation

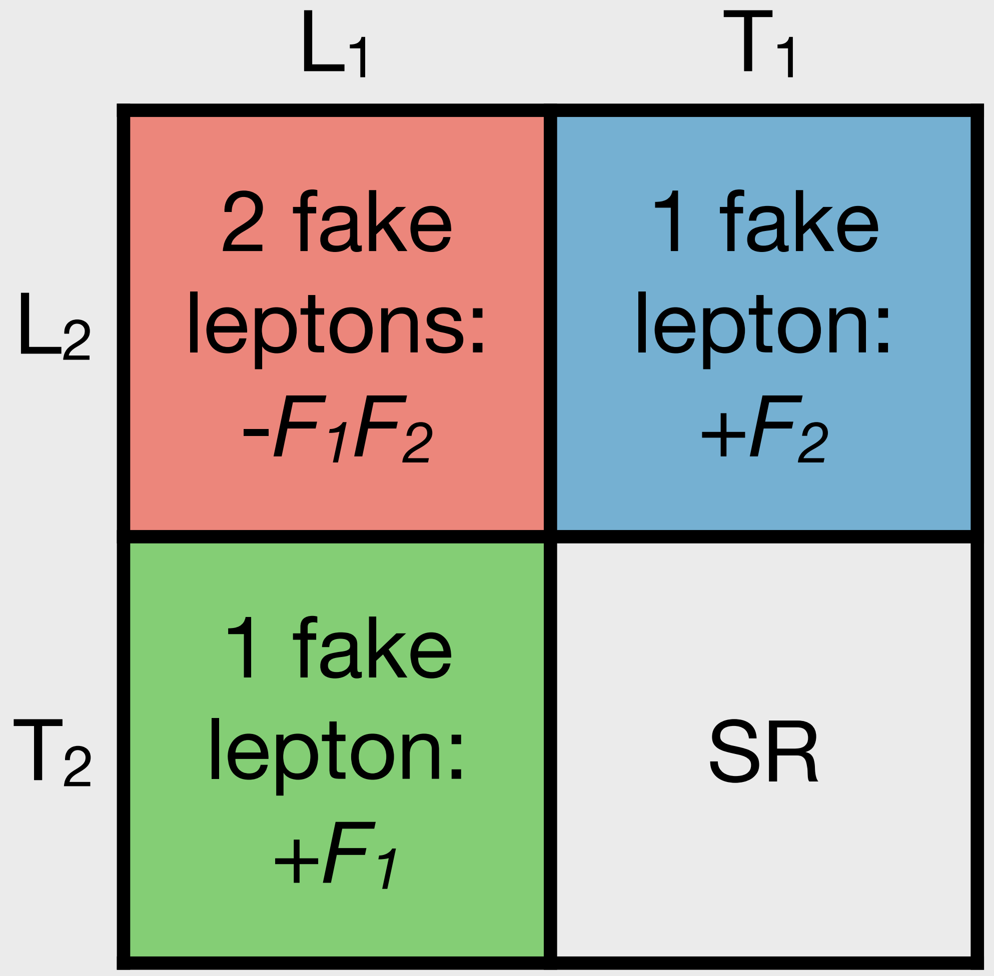
- Fake-factor method is a simplified matrix method - we define loose (not tight) and tight regions that are orthogonal to each other.
- Two lepton definitions:
  - ***tight***: nominal signal selection - leptons used in the analysis,
  - ***loose***: relaxed identification, isolation cuts.
- Fake-factor is the ratio of tight and loose leptons: $F_\ell = \frac{N_{tight}}{N_{loose}}$.
- Fake estimation is done in **fake enriched regions**, see next slides.
- Fake factors are applied to each fake lepton individually:

$$N^{fake} = \sum_{i=1}^{N_{SB}^{data}} (-1)^{N_{L,i}+1} \prod_{l=1}^{N_{L,i}} F_l - \sum_{i=1}^{N_{SB}^{MC}} (-1)^{N_{L,i}+1} \prod_{l=1}^{N_{L,i}} F_l$$

$$\overset{l=2}{=} \Big[\sum_{TL} F_2 + \sum_{LT} F_1 - \sum_{LL} F_1 F_2\Big]_{data} - \Big[\sum_{TL} F_2 + \sum_{LT} F_1 - \sum_{LL} F_1 F_2\Big]_{prompt}$$

Fake-factor Method



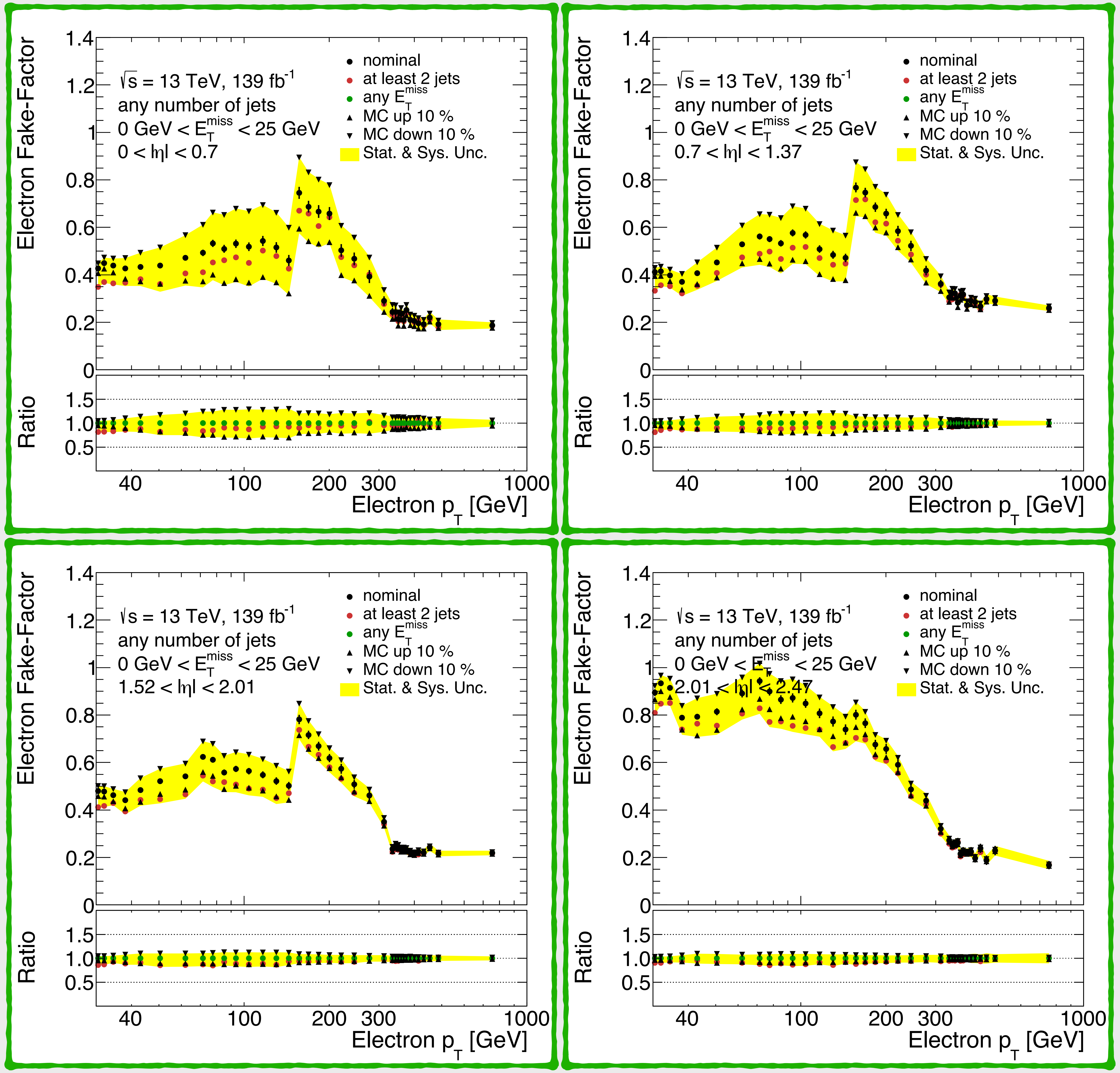


	L₁	T₁
L₂	2 fake leptons: $-F_1F_2$	1 fake lepton: $+F_2$
T₂	1 fake lepton: $+F_1$	SR

Electron Fakes

- Fake enriched region requires:
  - exactly 1 baseline electron,
  - any number of jets,
  - b - jet veto.
- Four η bins, two E_T^{miss} bins, variable p_T binning to ensure statistical error below a fixed threshold.

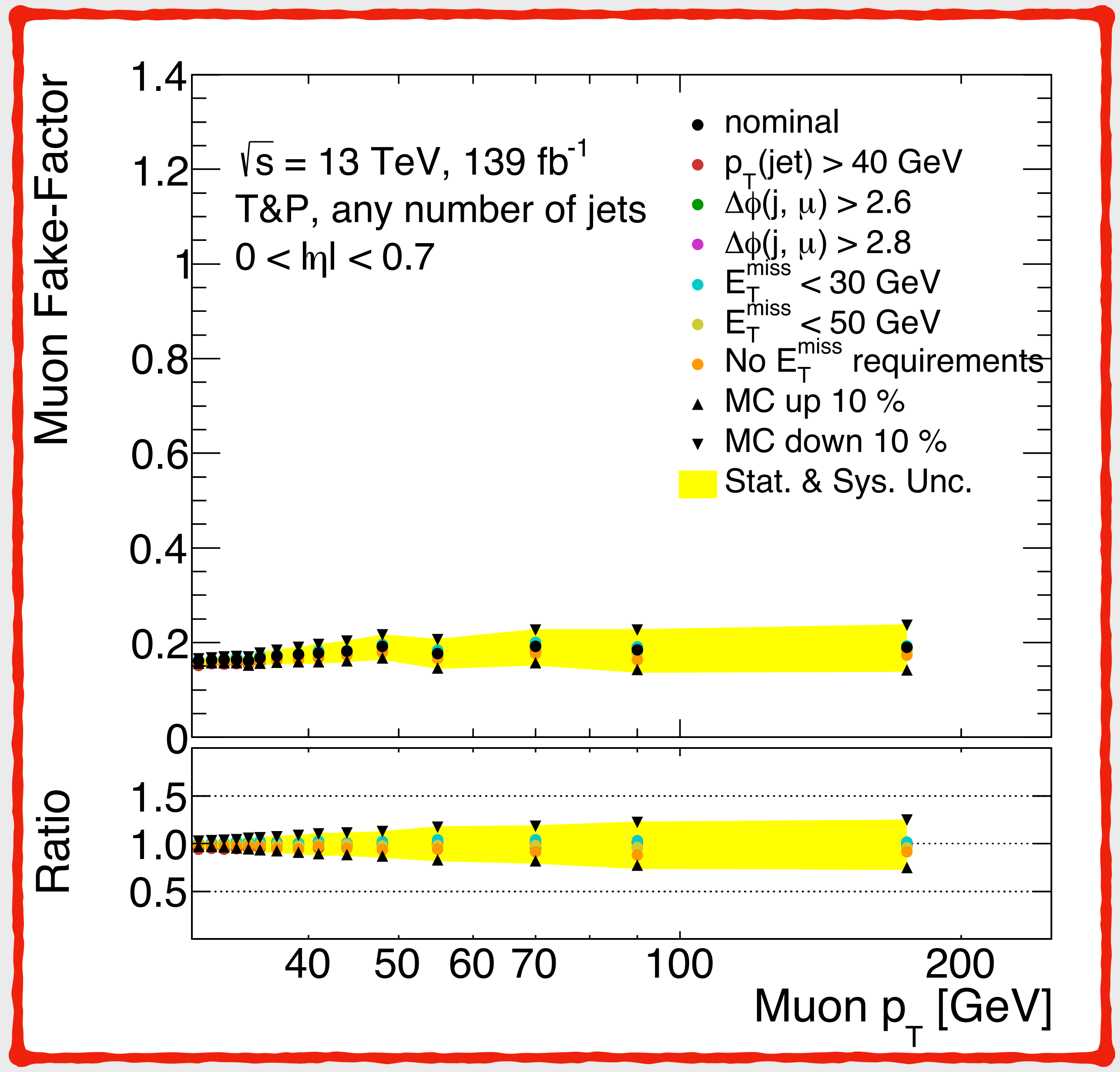
Trigger	Average prescale	Period
HLT_e26_lhvloose_nod0_L1EM20VH	111.2	2015-2016
HLT_e28_lhvloose_nod0_L1EM20VH	367.6	2017
HLT_e28_lhvloose_nod0_L1EM22VH	384.5	2018
HLT_e60_lhvloose_nod0	32.93	2015-2018
HLT_e70_lhvloose_nod0	64.13	2018
HLT_e80_lhvloose_nod0	40.43	2018
HLT_e100_lhvloose_nod0	19.45	2018
HLT_e120_lhvloose_nod0	12.15	2016, 2018
HLT_e140_lhvloose_nod0	2.637	2017-2018
HLT_e160_lhvloose_nod0	1.601	2017-2018
HLT_e200_etcut	-	2015
HLT_e300_etcut	-	2016-2018

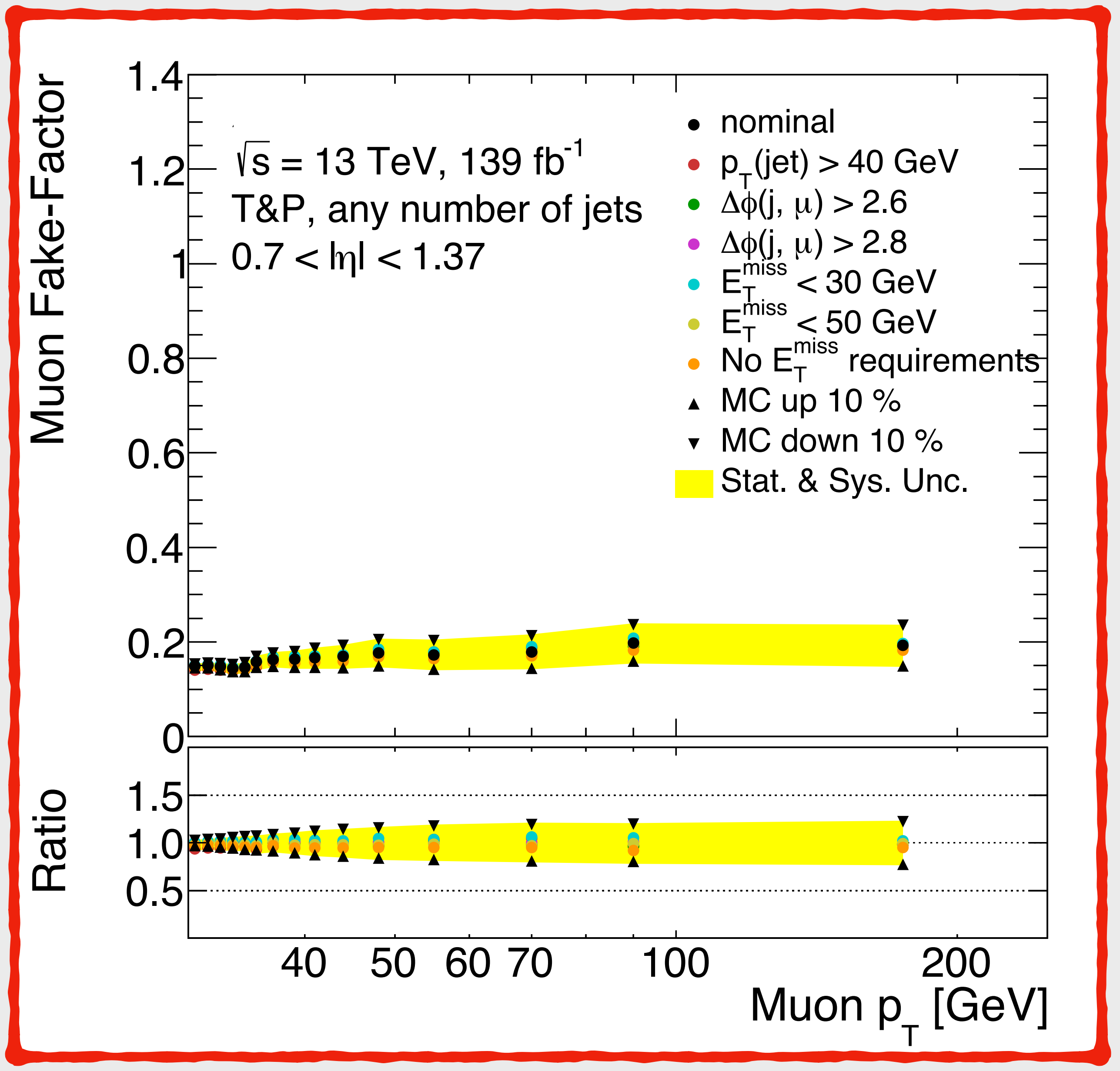


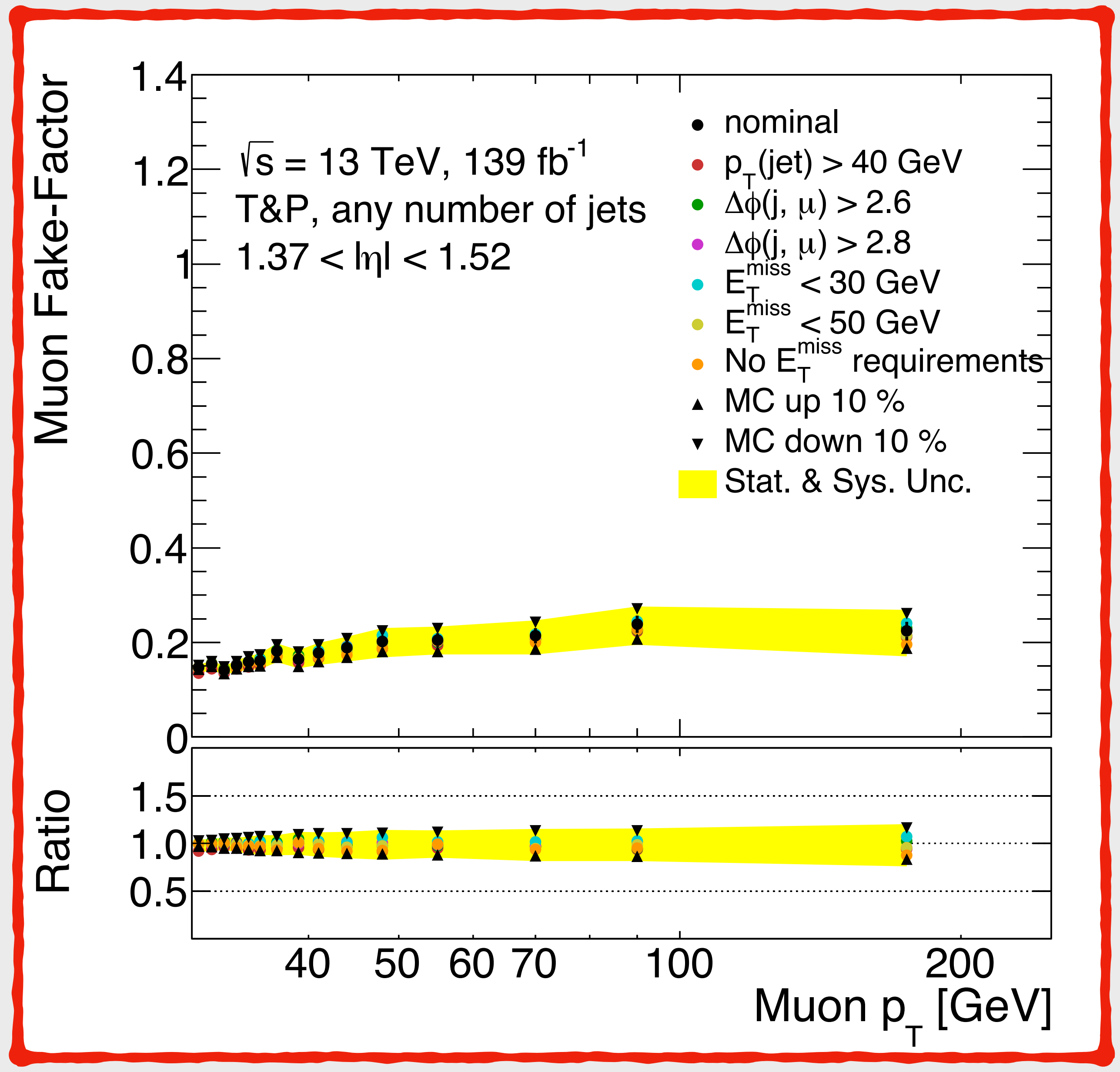
Muon Fakes

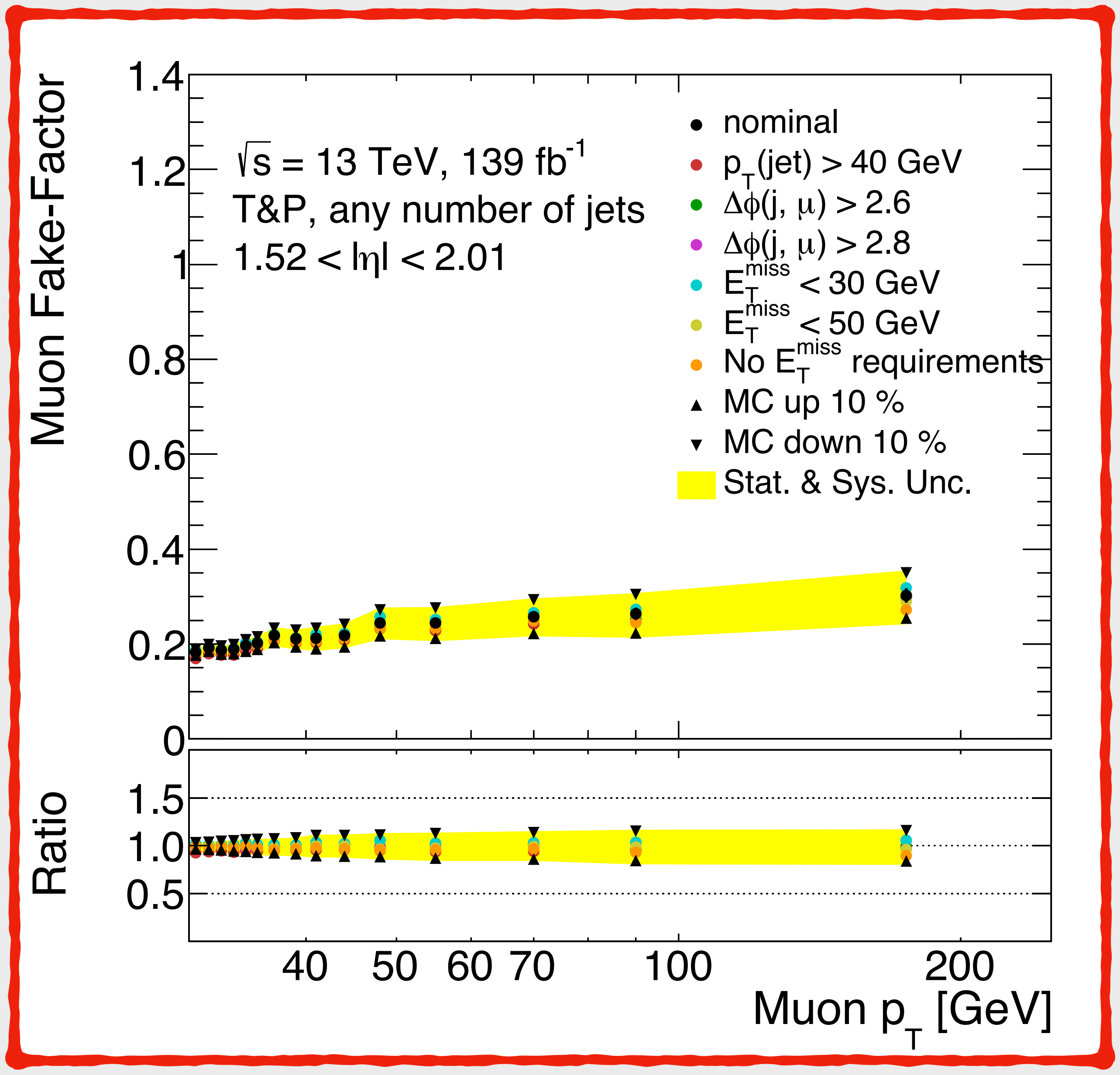
- Fake enriched region:
  - exactly 1 baseline muon,
  - any number of jets,
  - b - jet veto,
  - $E_T^{miss} < 40\ GeV, p_T(j) > 35\ GeV,$ $\Delta\varphi(\mu, j) > 2.7.$
- Five η bins.
- Triggers used:

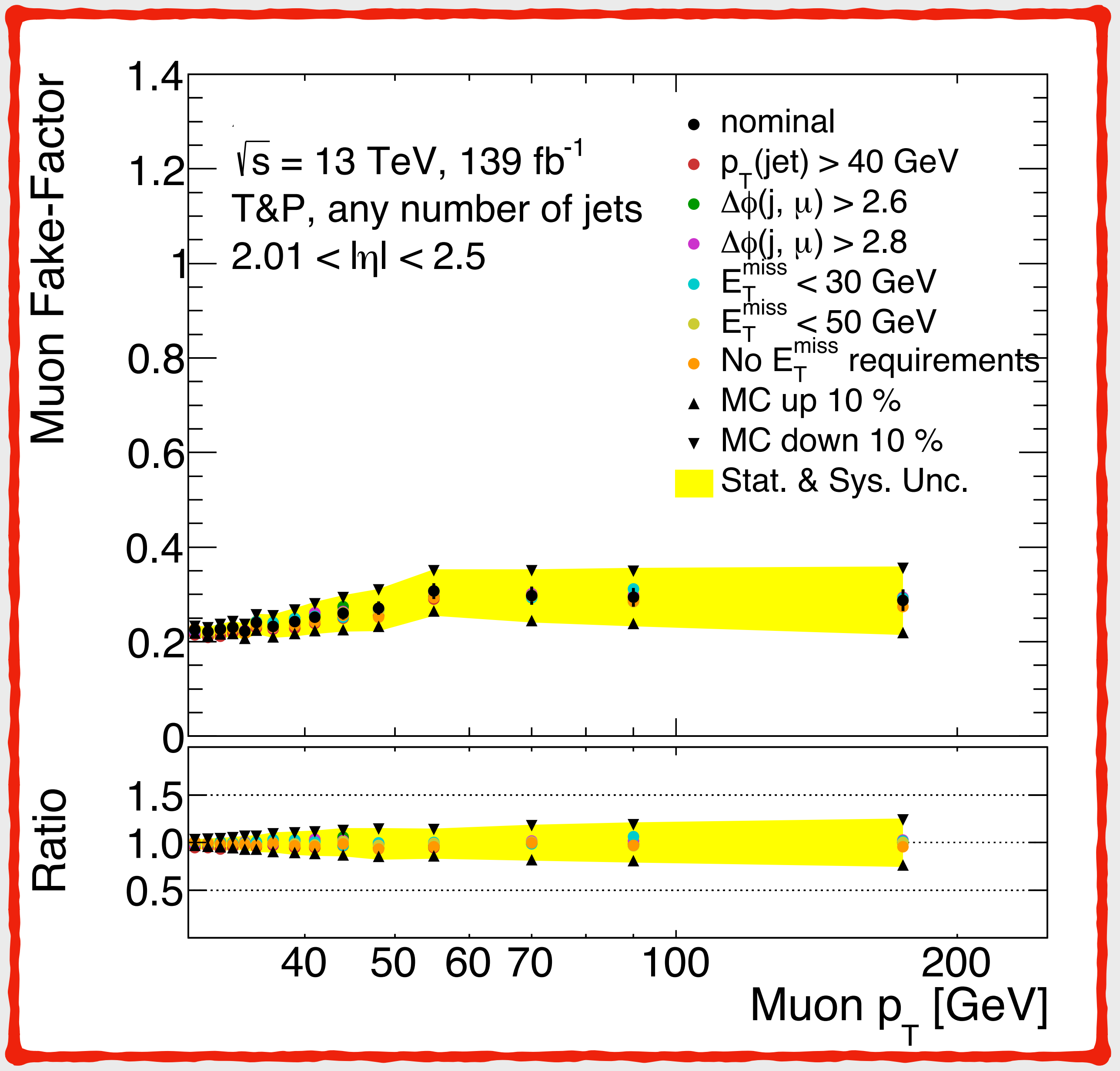
Trigger	Average prescale	Period
HLT_mu24	49.36	2015-2018
HLT_mu50	-	2015-2018





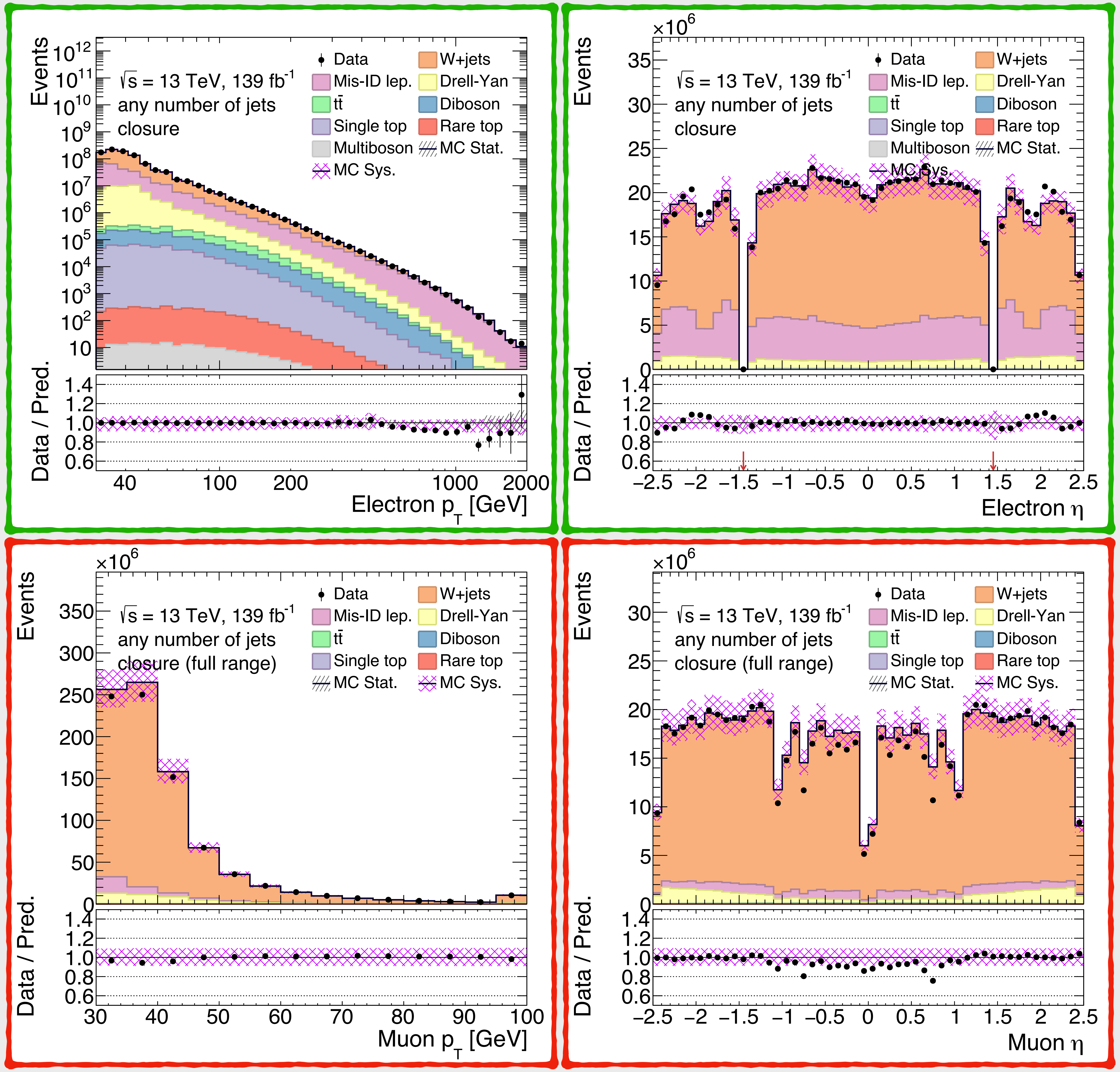






Electron and Muon Fake Factor Closure

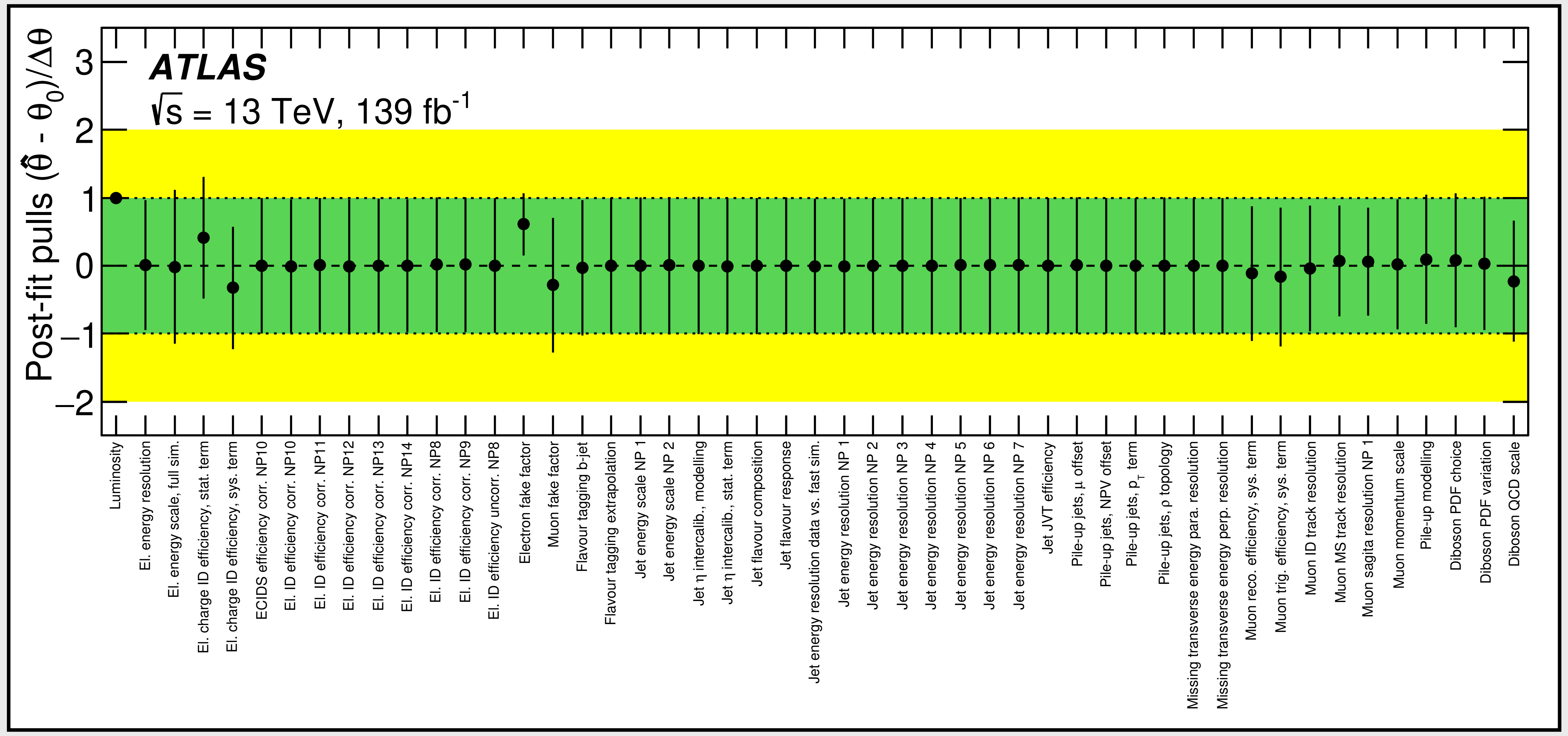
- We see good agreement in the whole p_T range.
- Muon fakes mainly present in low p_T region ($\lesssim 100\ GeV$).
- Systematic uncertainty only from fakes and W+jets normalisation in muon case.

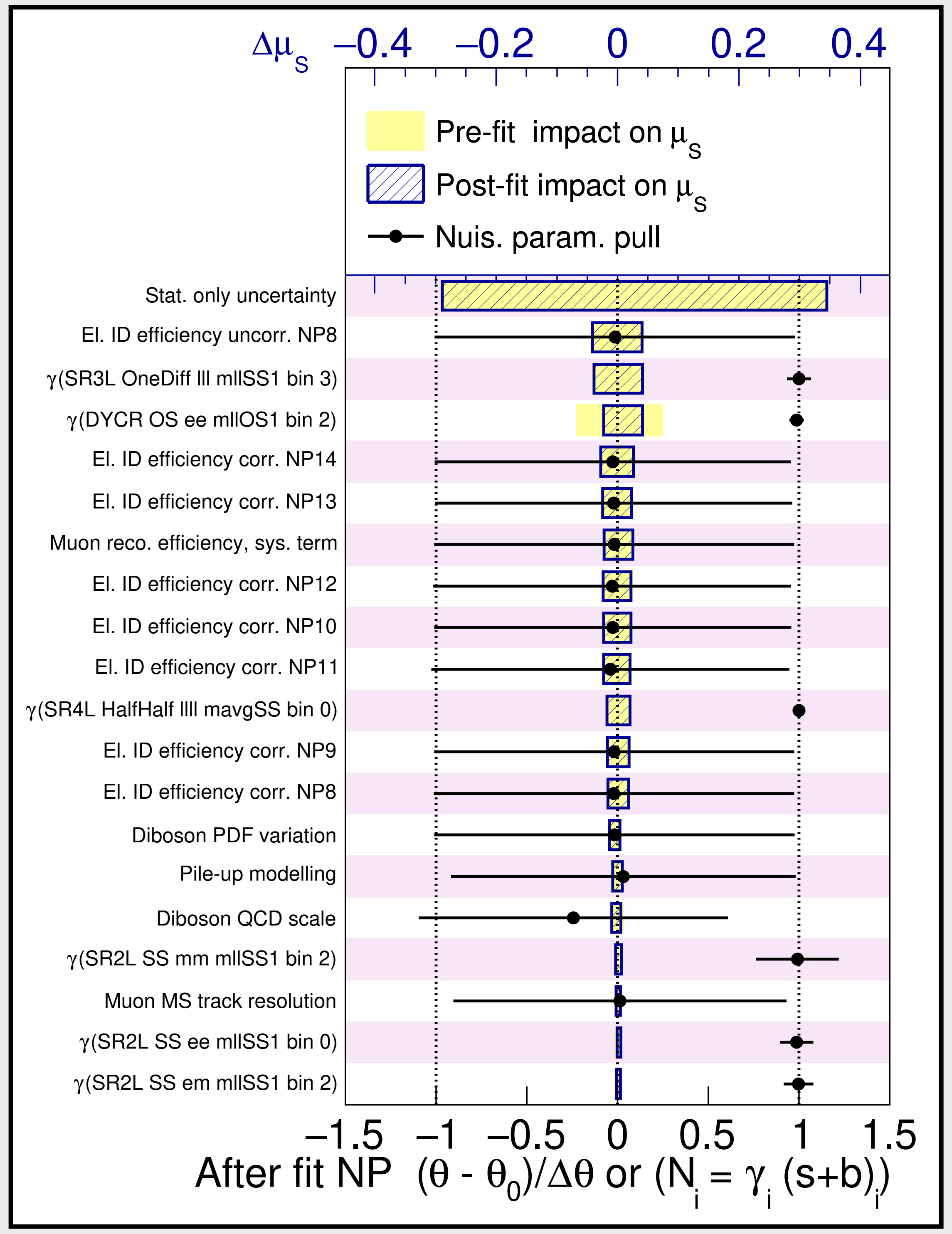


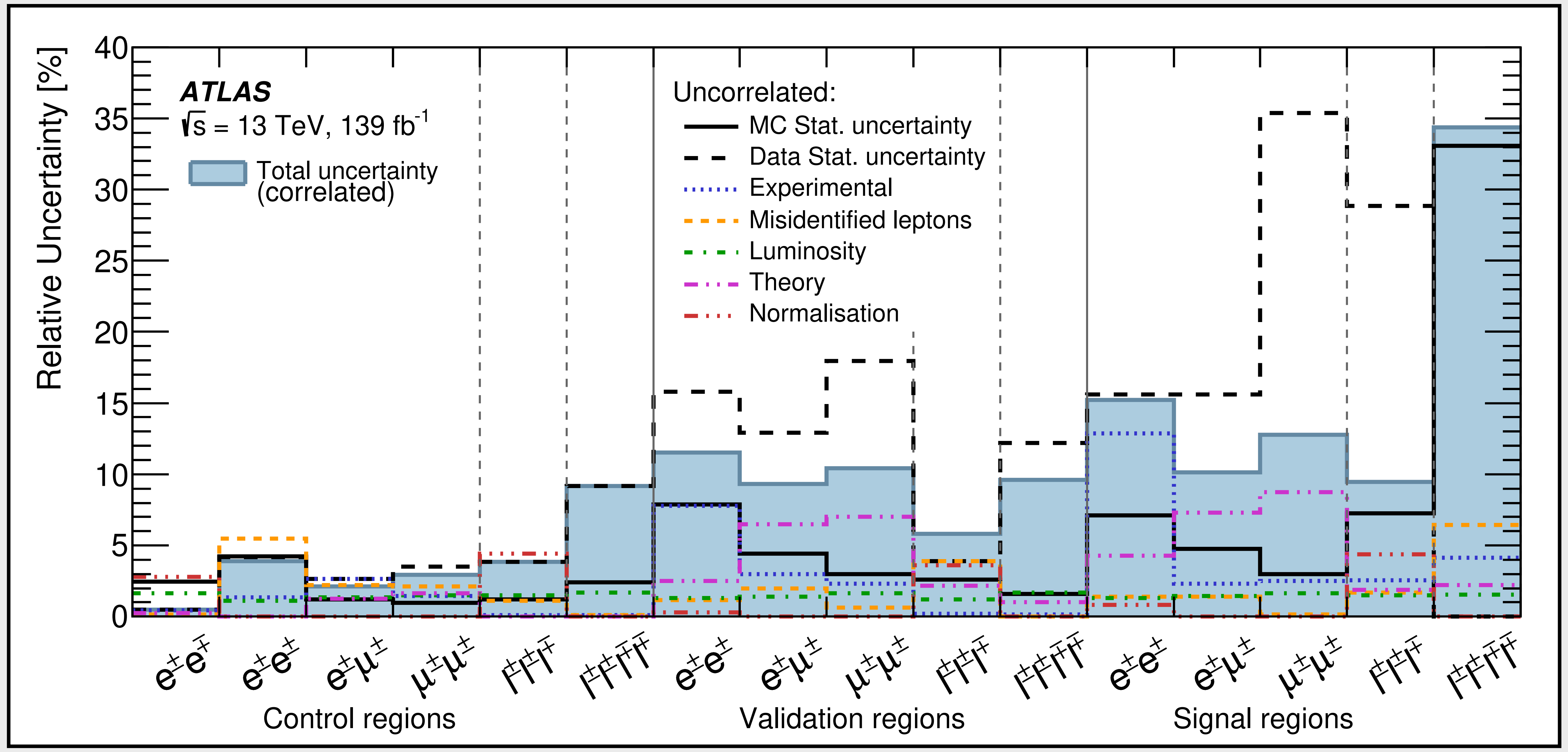
Results of the cut-based analysis

Systematic uncertainties and statistical analysis

- Both theoretical and experimental uncertainties are considered.
- Leading sources of uncertainty:
  - **statistical uncertainty**,
  - electron identification efficiency,
  - fake background estimation.
- Number of nuisance parameters (NPs) used: **254**.
- After using standard HistFitter pruning only **49** NPs remain.

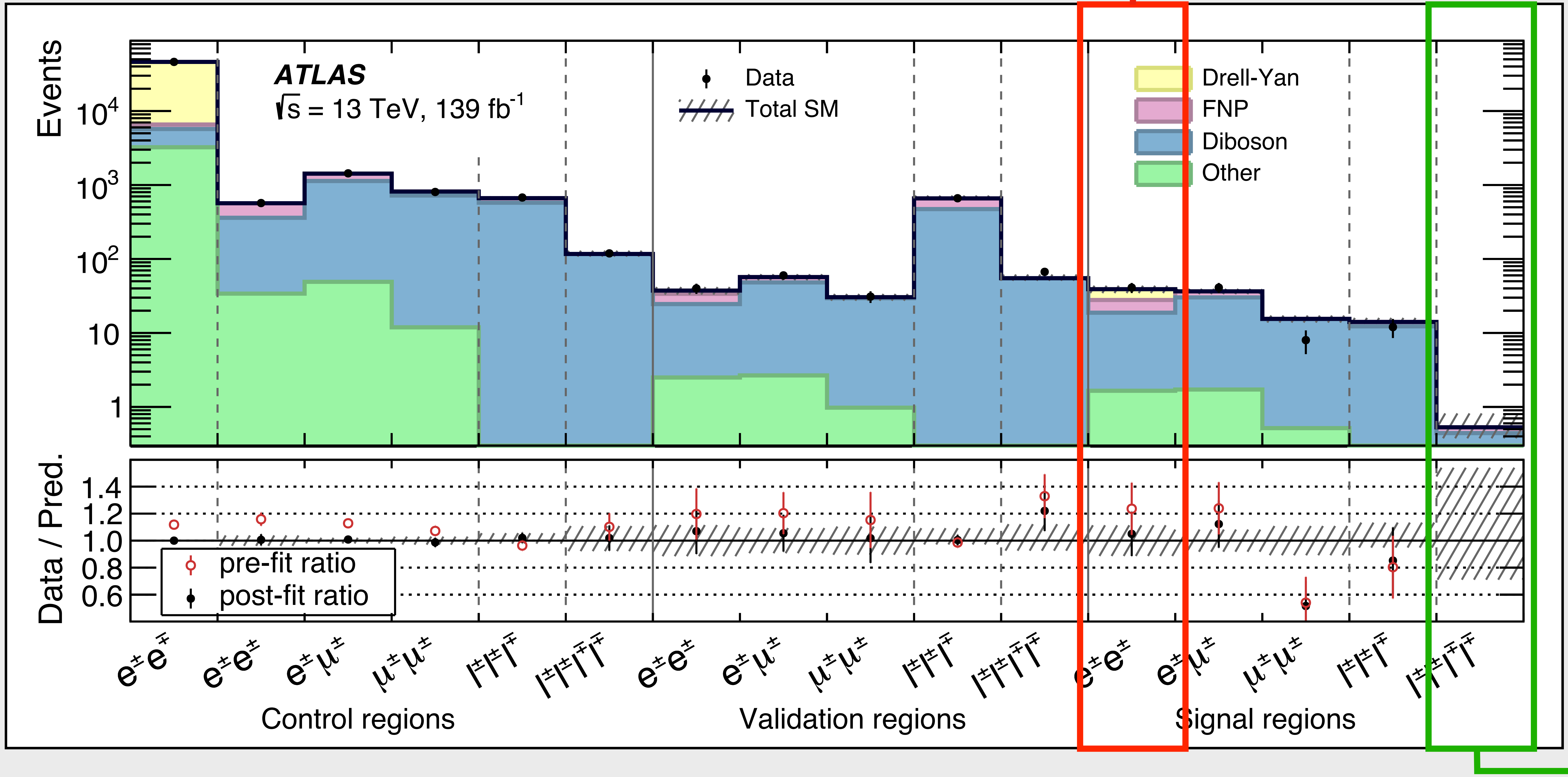


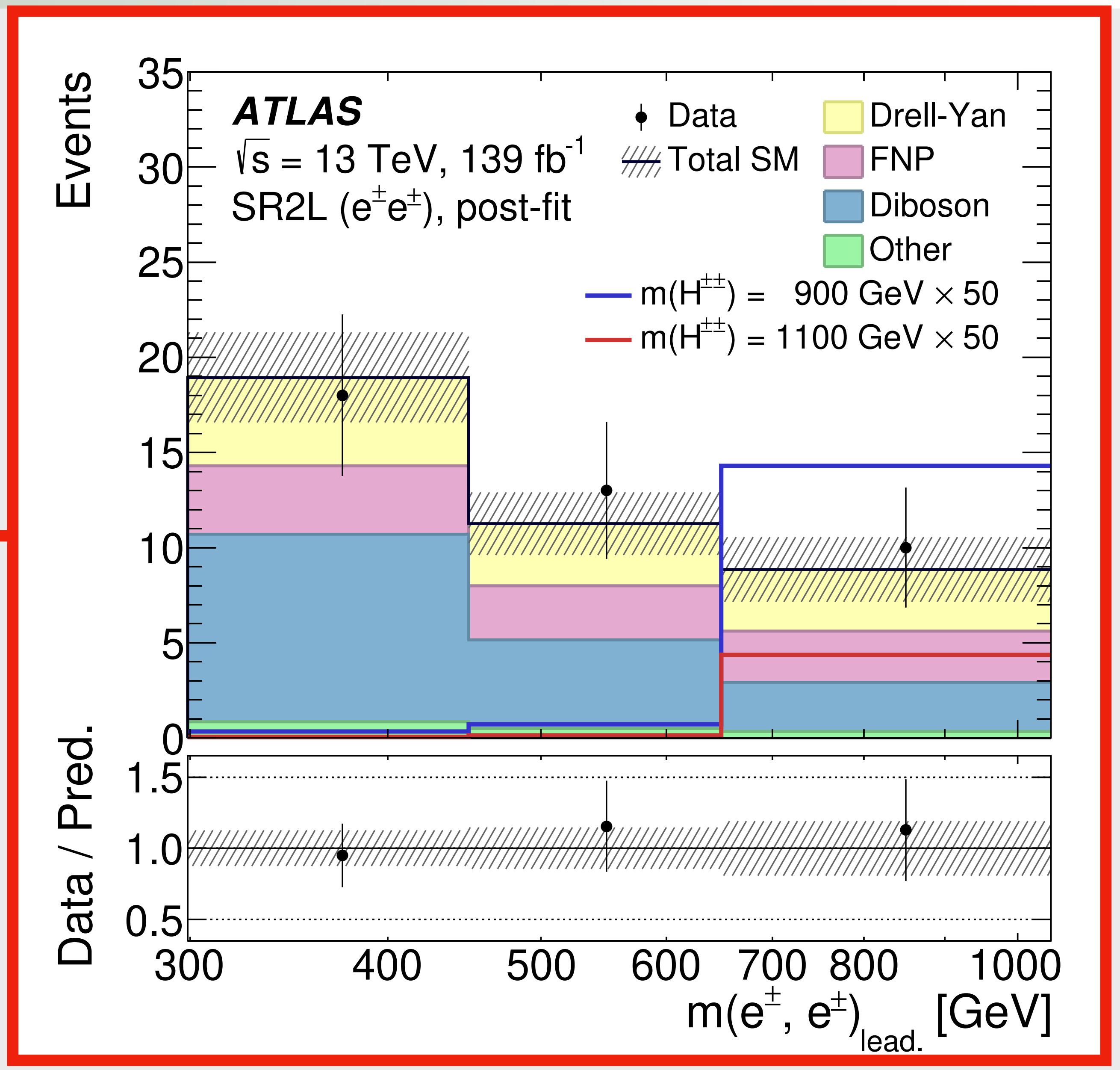


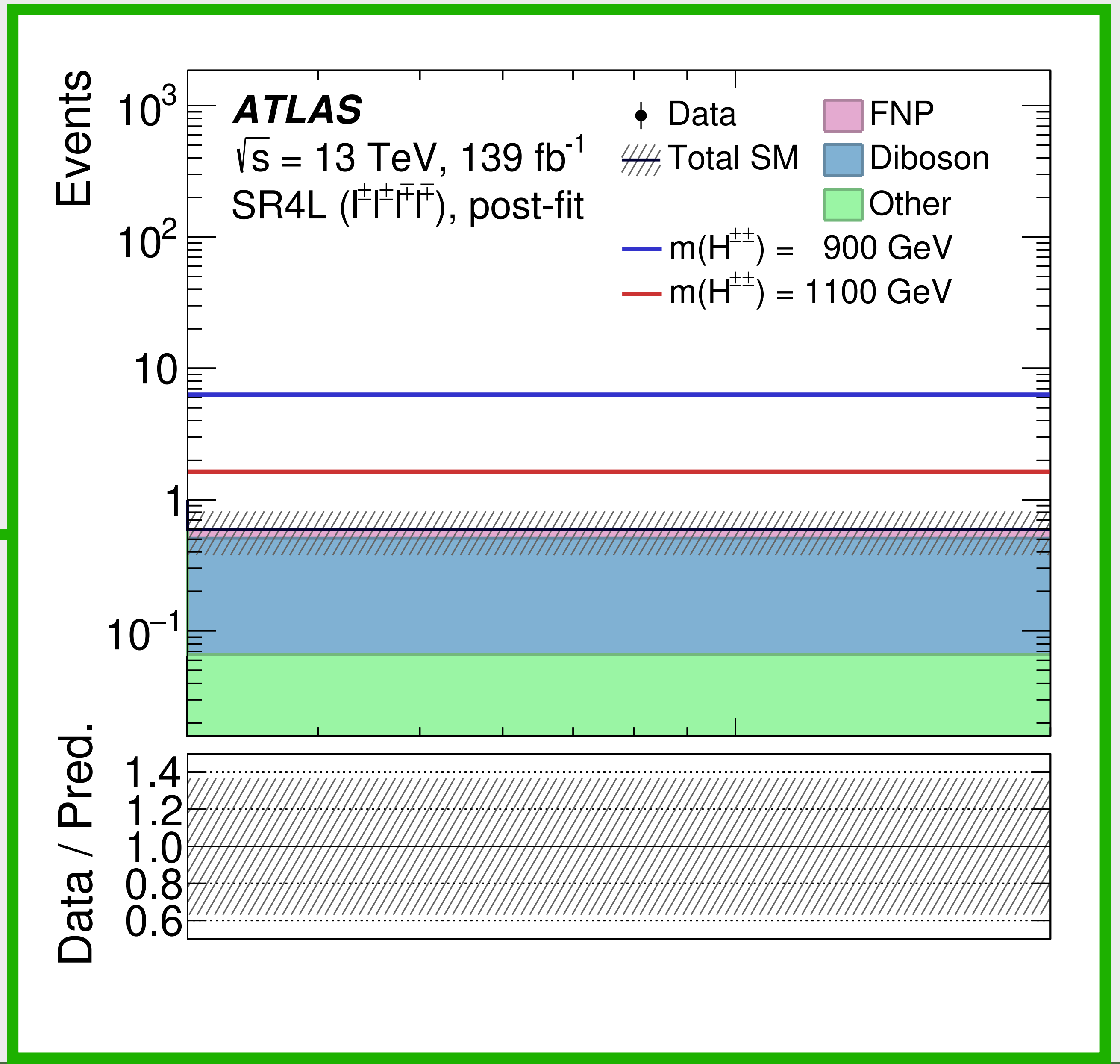


Yields and distributions

- Overall good post-fit agreement between expected and observed events.
- Unfortunately, no data event passed the SR4L requirements.



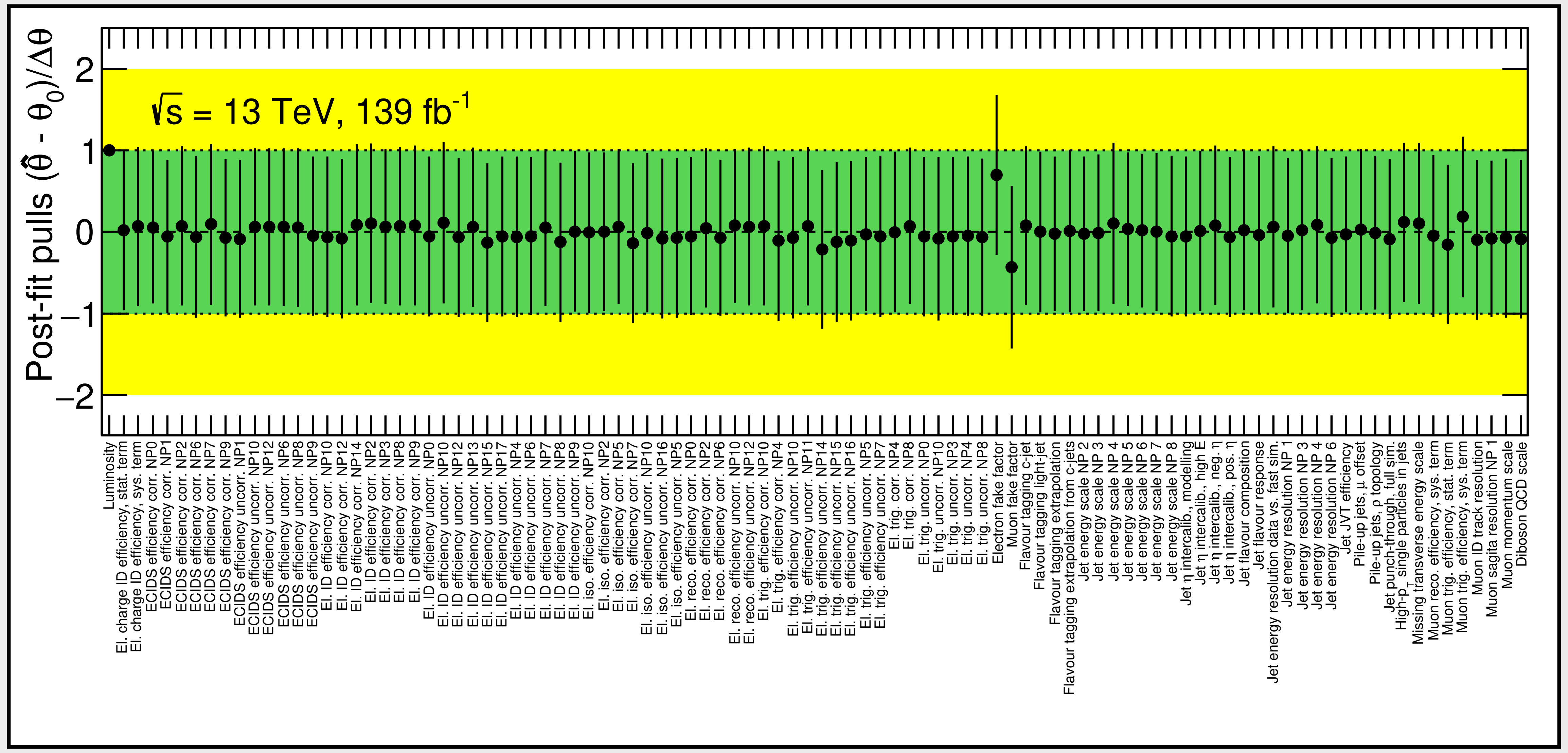


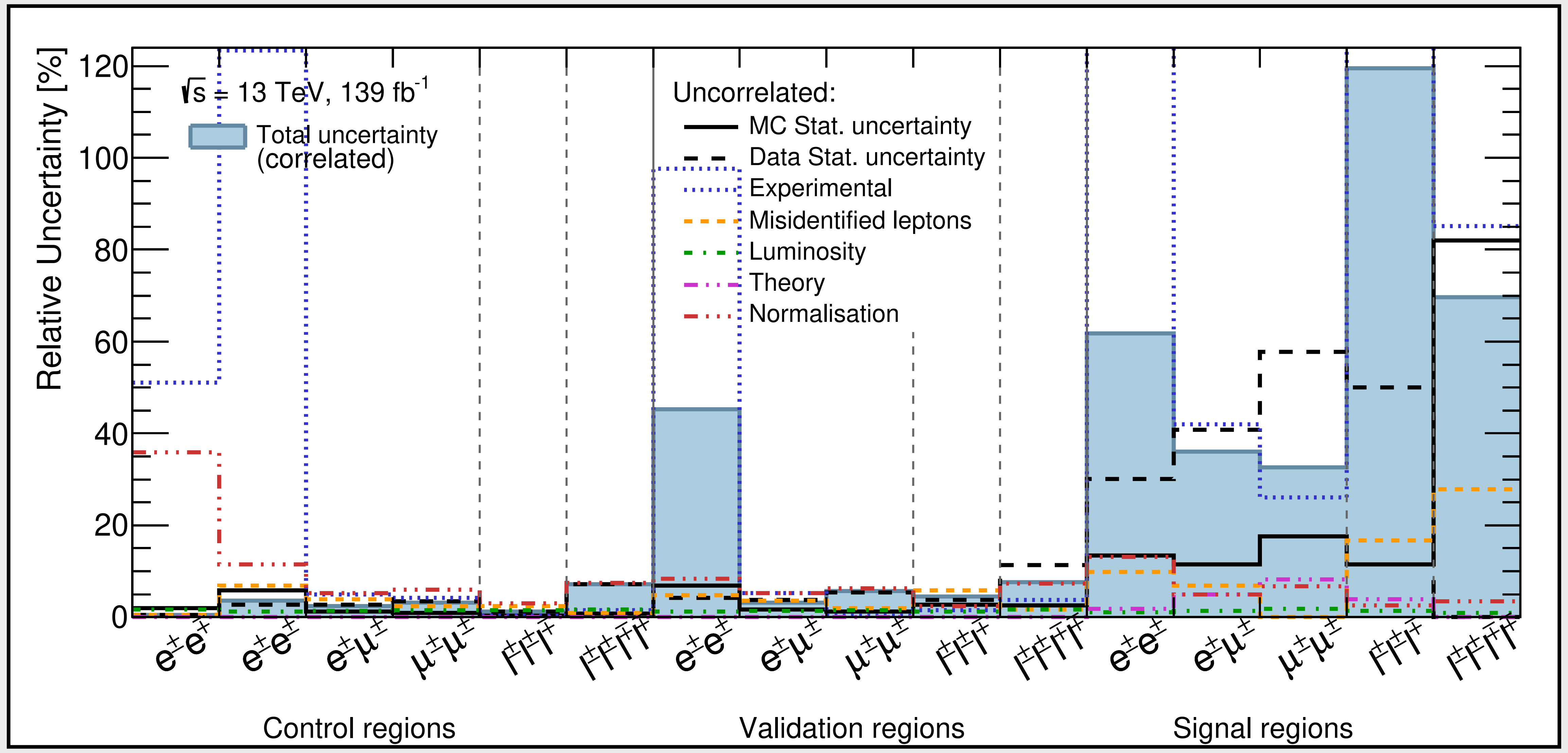


Results of the multivariate analysis

Systematic uncertainties and statistical analysis

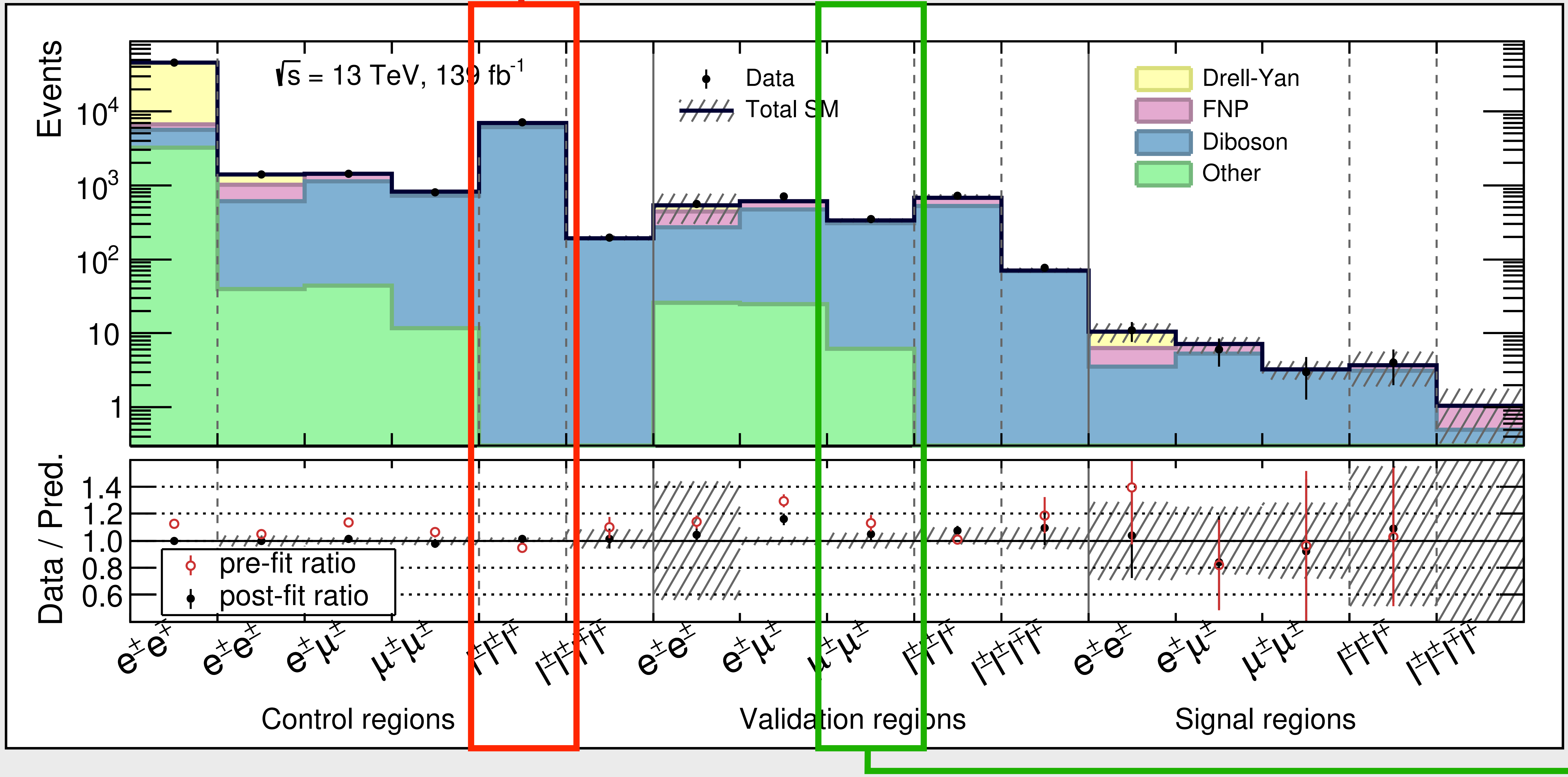
- Systematic uncertainties are **much harder** to keep **under control**:
  - pull plots are more scattered,
  - more NPs remain after pruning,
  - uncertainties exceed 100% in some regions.
- Leading sources of uncertainty:
  - **statistical uncertainty**,
  - muon fake estimation,
  - muon efficiencies.
- Studies indicate that this is due to the sensitive logit MVA score. Slight systematic variation can produce very different output.

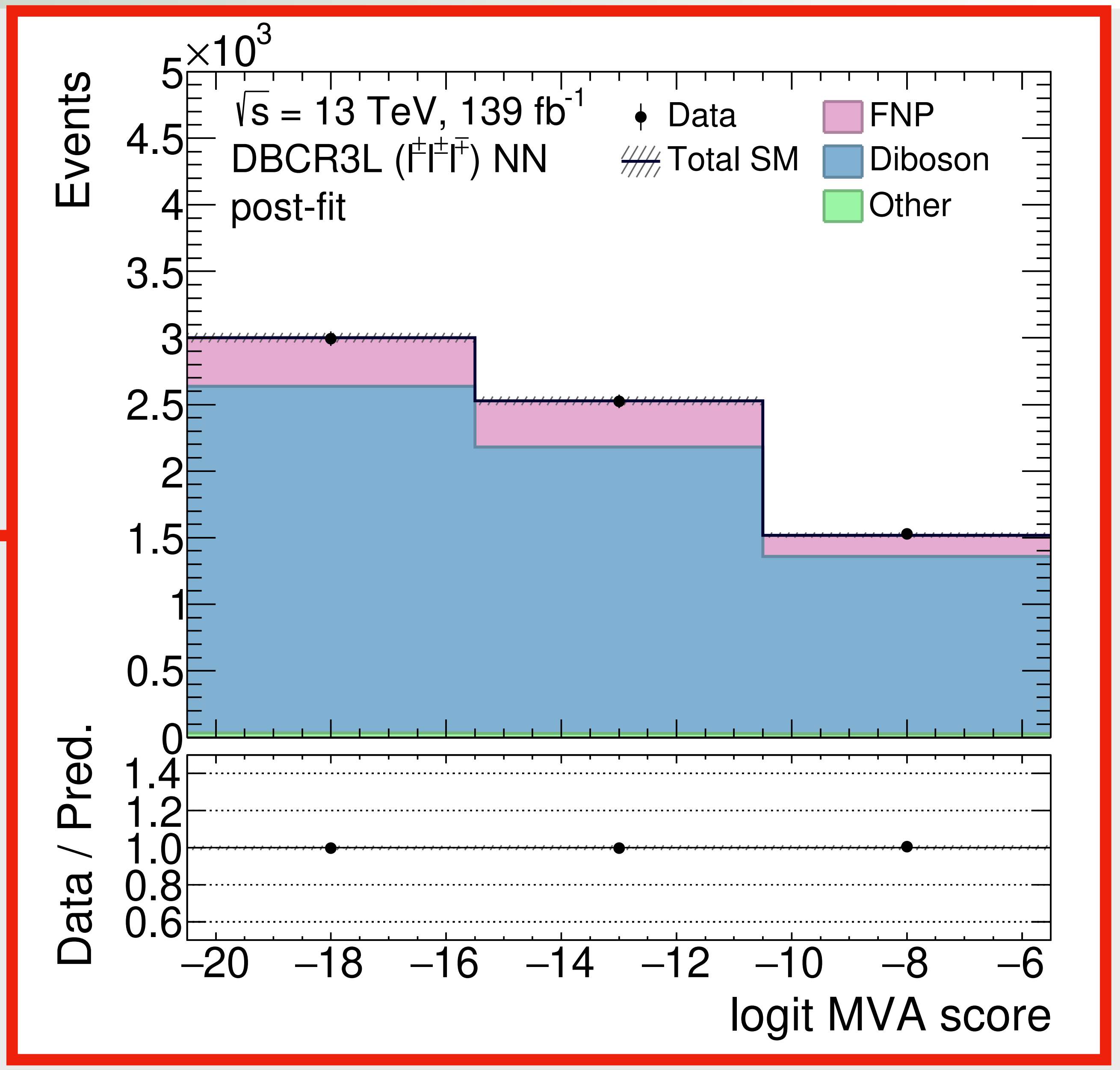


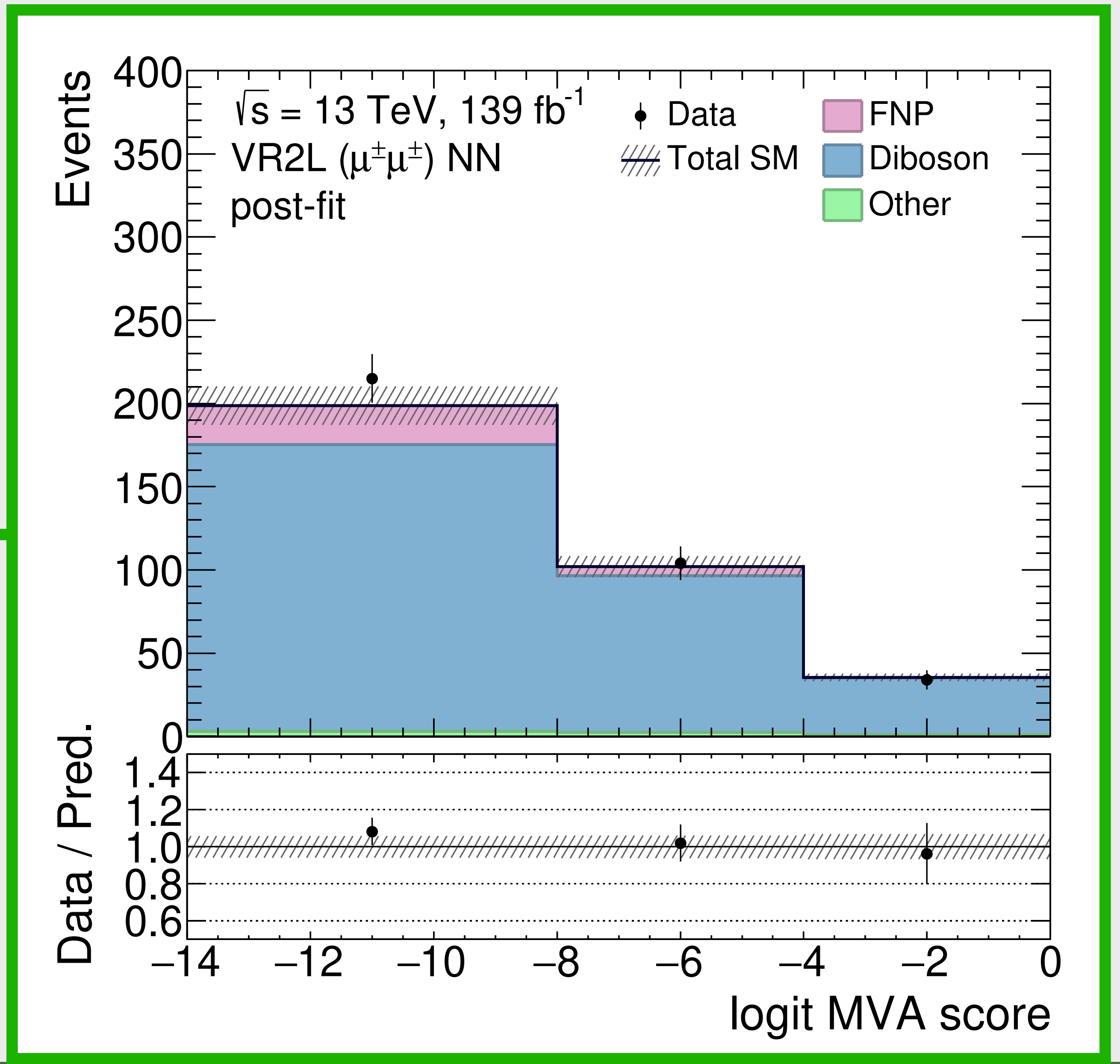


Yields and distributions

- Overall good post-fit agreement between expected and observed events with **higher uncertainties**.
- No data event passed the SR4L requirements in the MVA analysis, too.



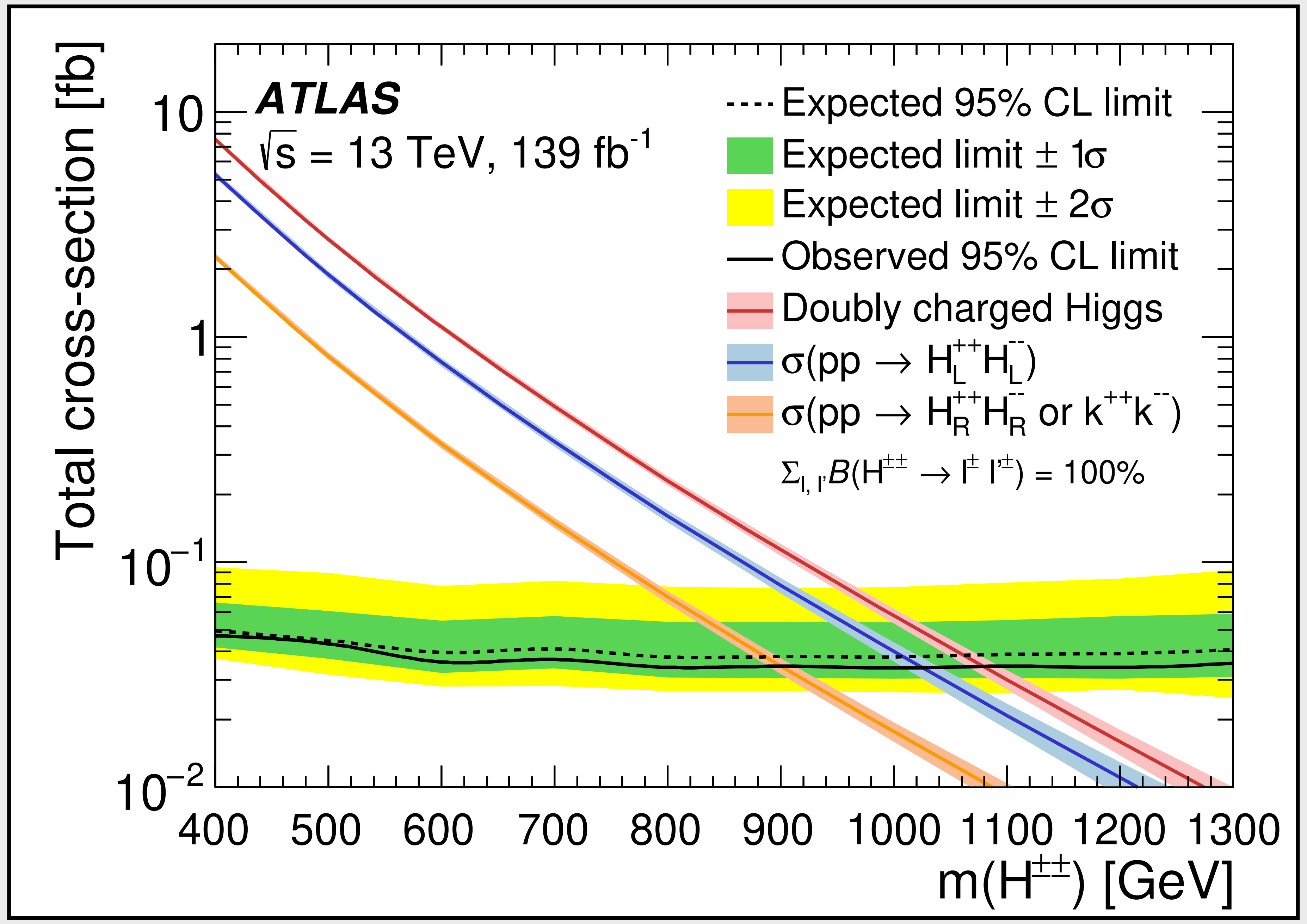




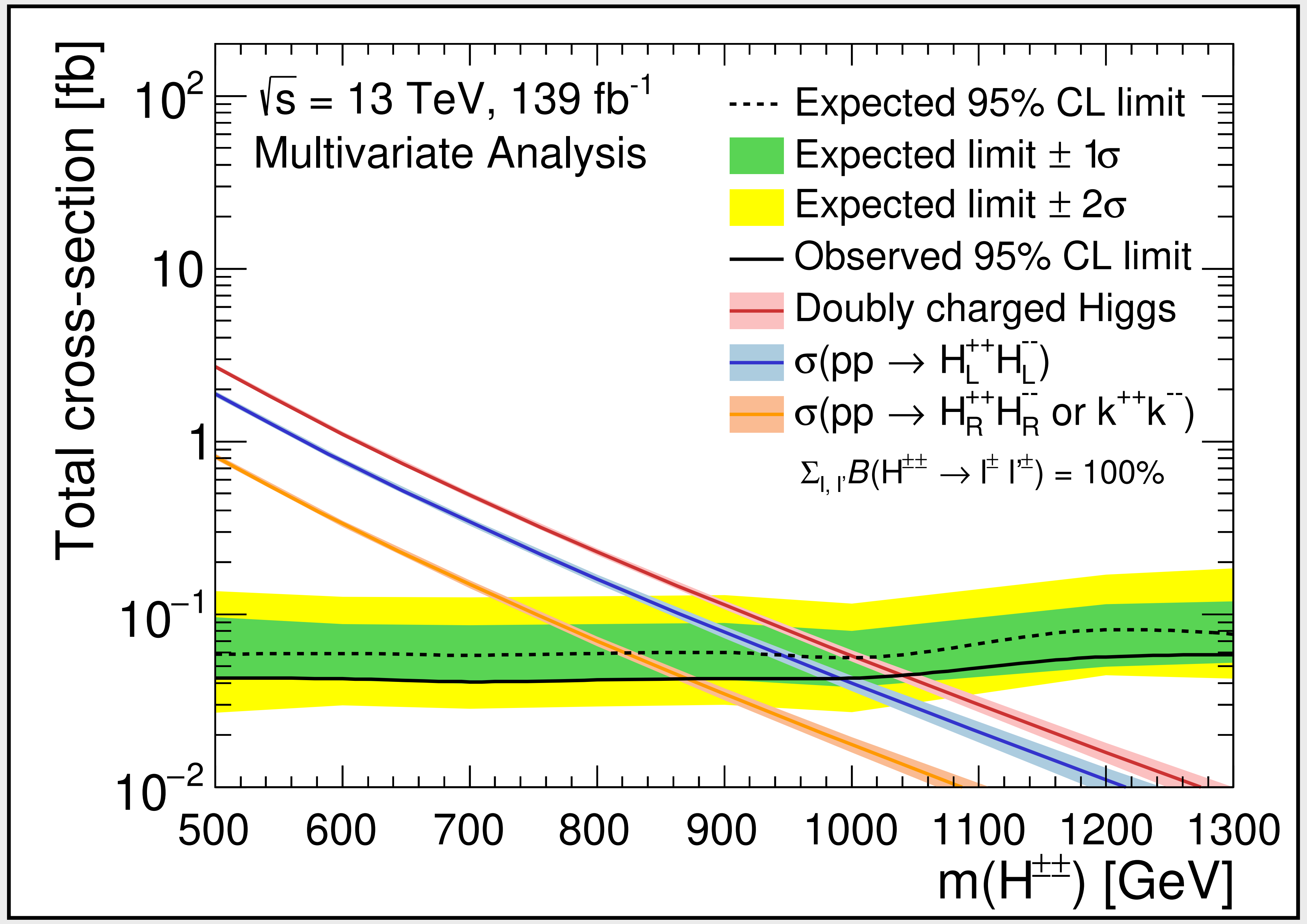
Lower $H^{\pm\pm}$ mass limits

- The expected exclusion limit is **1065^{+30}_{-50} GeV** for LRSM and **880^{+30}_{-40} GeV** for the Zee-Babu model.
- The observed lower limit on the $H^{\pm\pm}$ mass reaches **1080 GeV** and **900 GeV** when combining all three channels for LRSM and the Zee-Babu model, respectively.
- The four-lepton channel limit is is the strongest and drives the combined result.
- MVA did **not** provide **much improvement** with respect to the cut-based analysis.

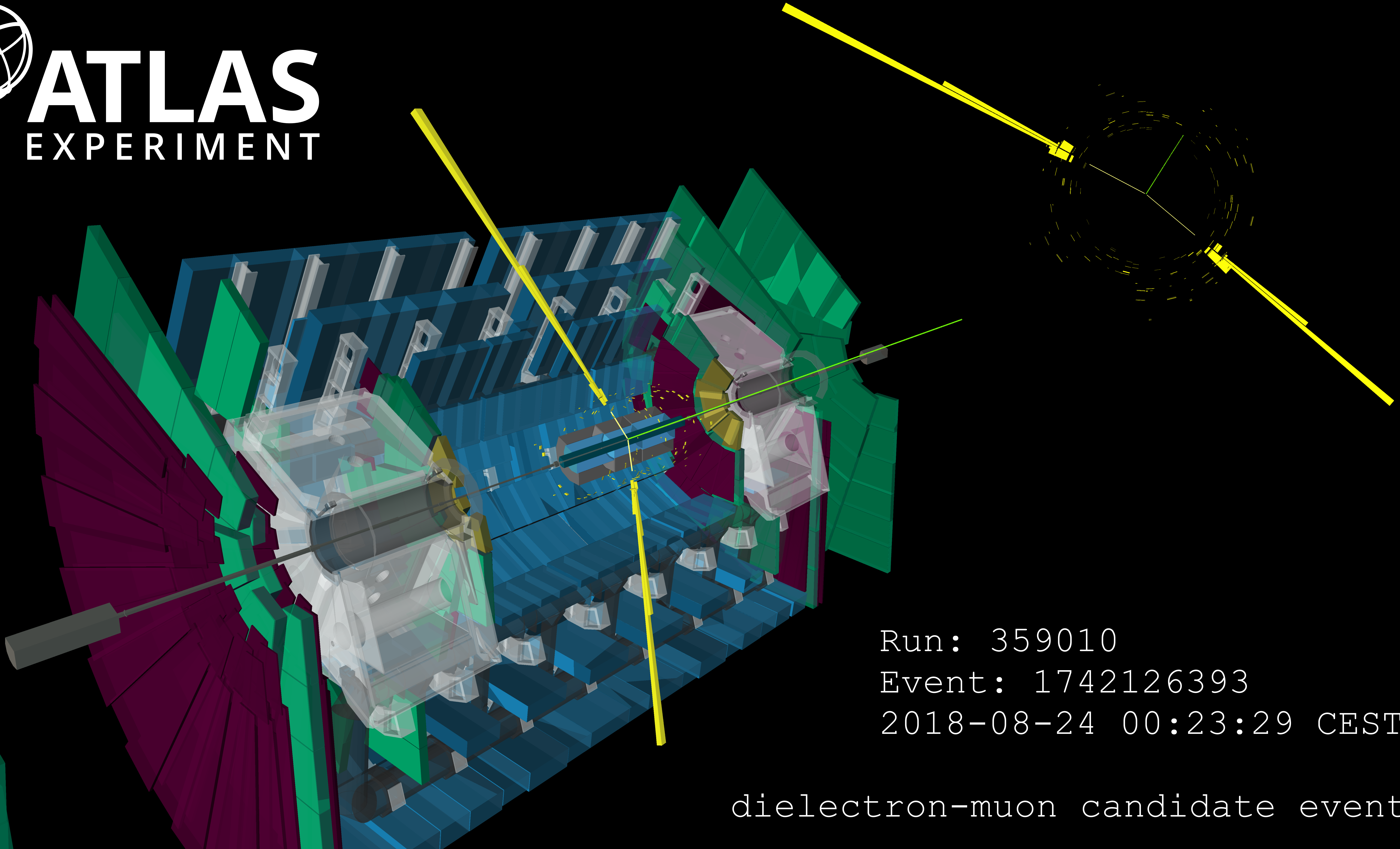
Cut-based analysis



Multivariate analysis



ATLAS
EXPERIMENT



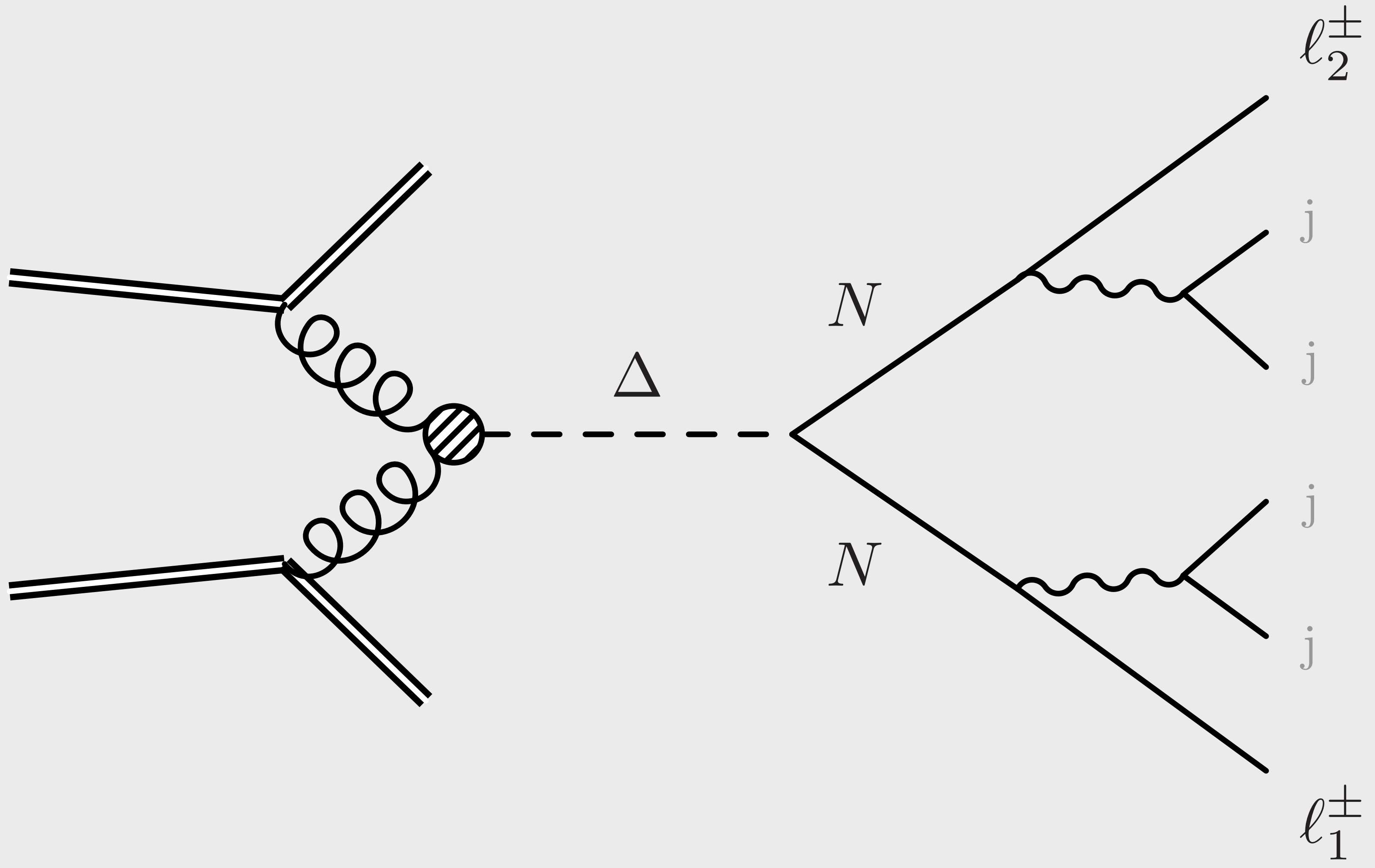
Run: 359010
Event: 1742126393
2018-08-24 00:23:29 CEST

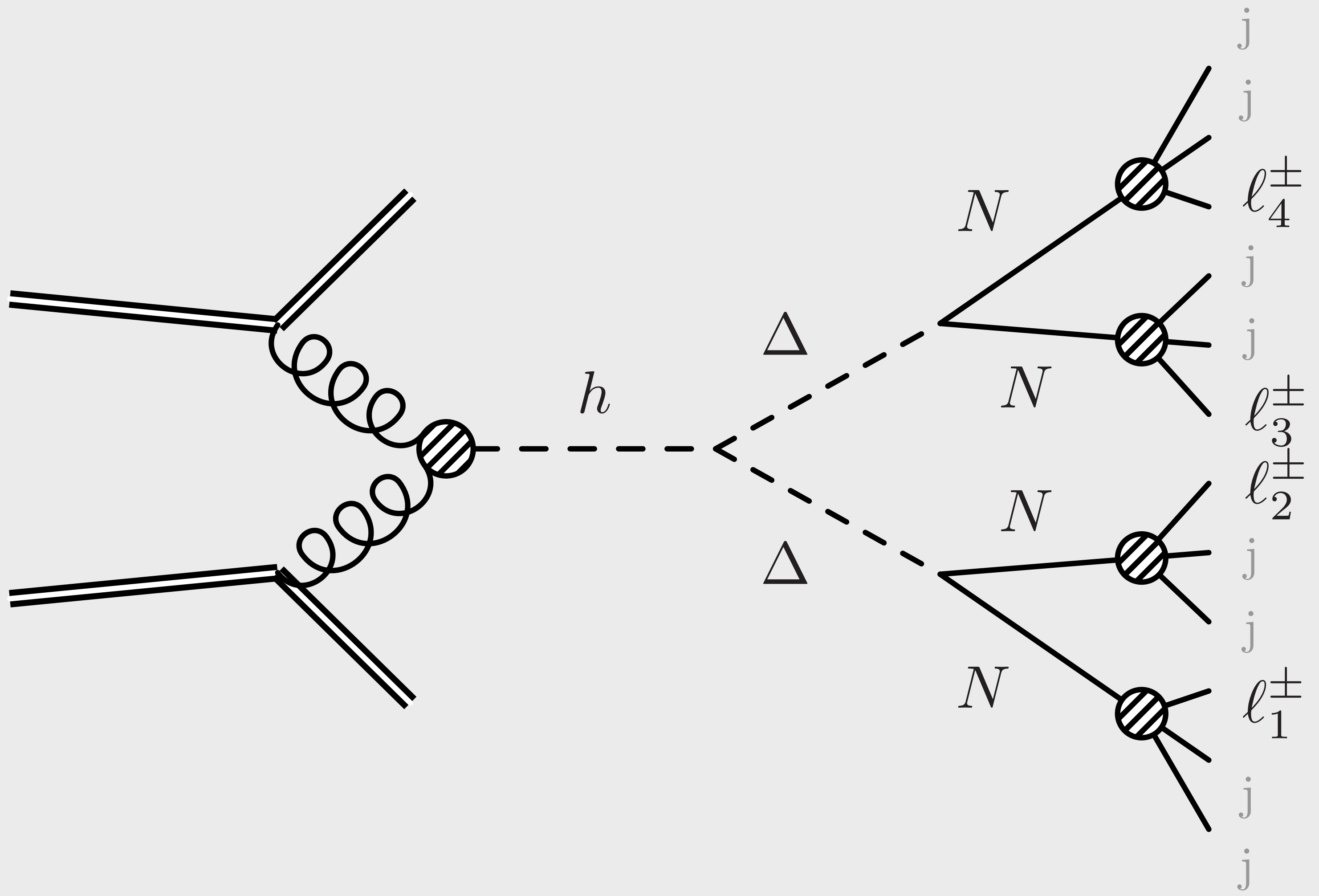
dielectron-muon candidate event

LNV Higgs Decays

Motivation for our future work

- Lepton Number Violating Higgs decay is a signal within the Left-Right Symmetric Model that can create a (same-sign) two-lepton final state.
- The Higgs can act as a gateway to the **origin of heavy Majorana neutrino mass**. This process is complementary to the existing nuclear and collider searches for lepton number violation and can probe the scale of parity restoration even above other direct searches.
- We relaxed the "Δ constraint" and are generating inclusive $gg \to NN$ process (goes through $\Delta/A/H/Z/Z_R/h$. Gain O(20%) in production cross-section.

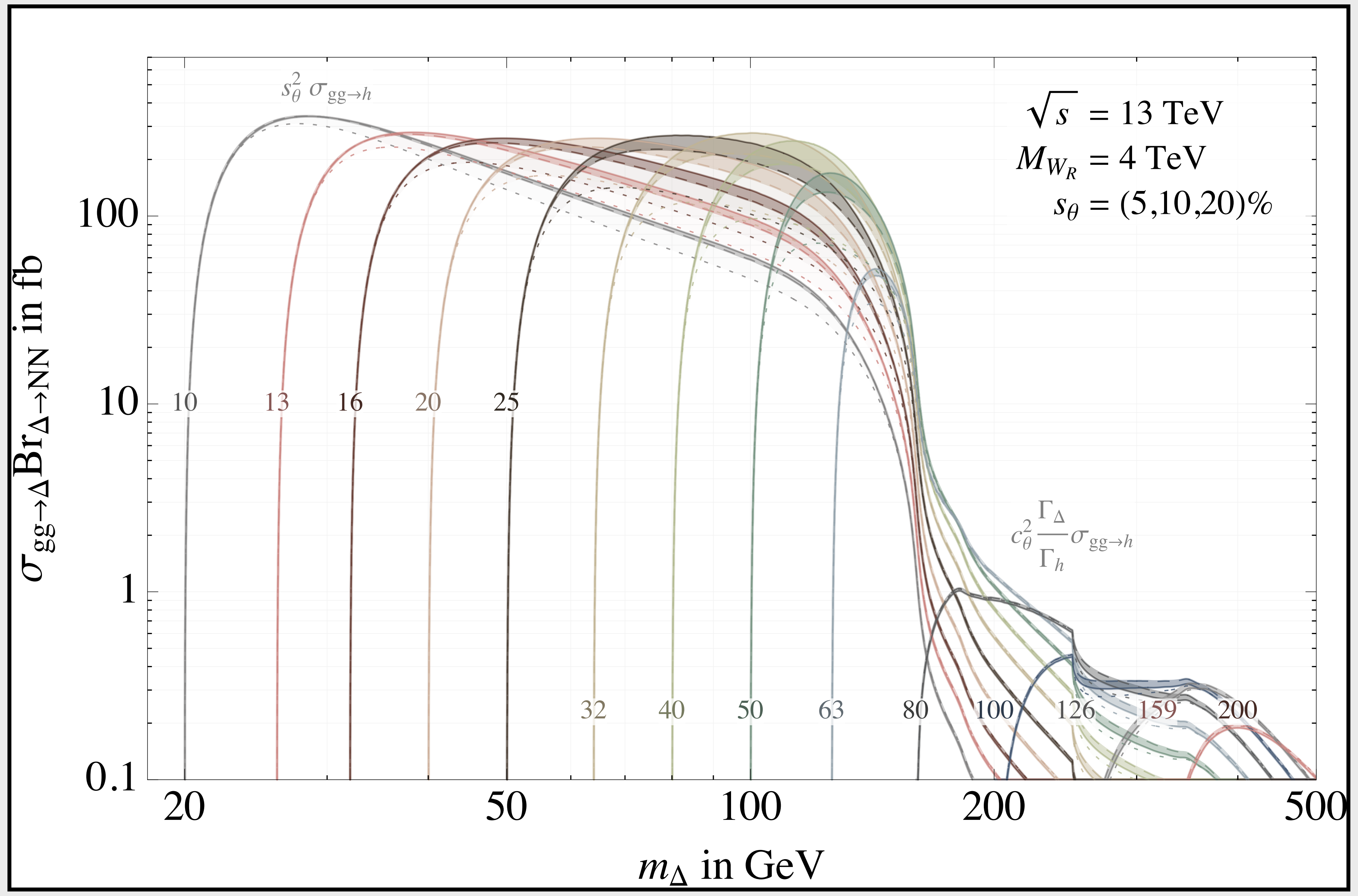


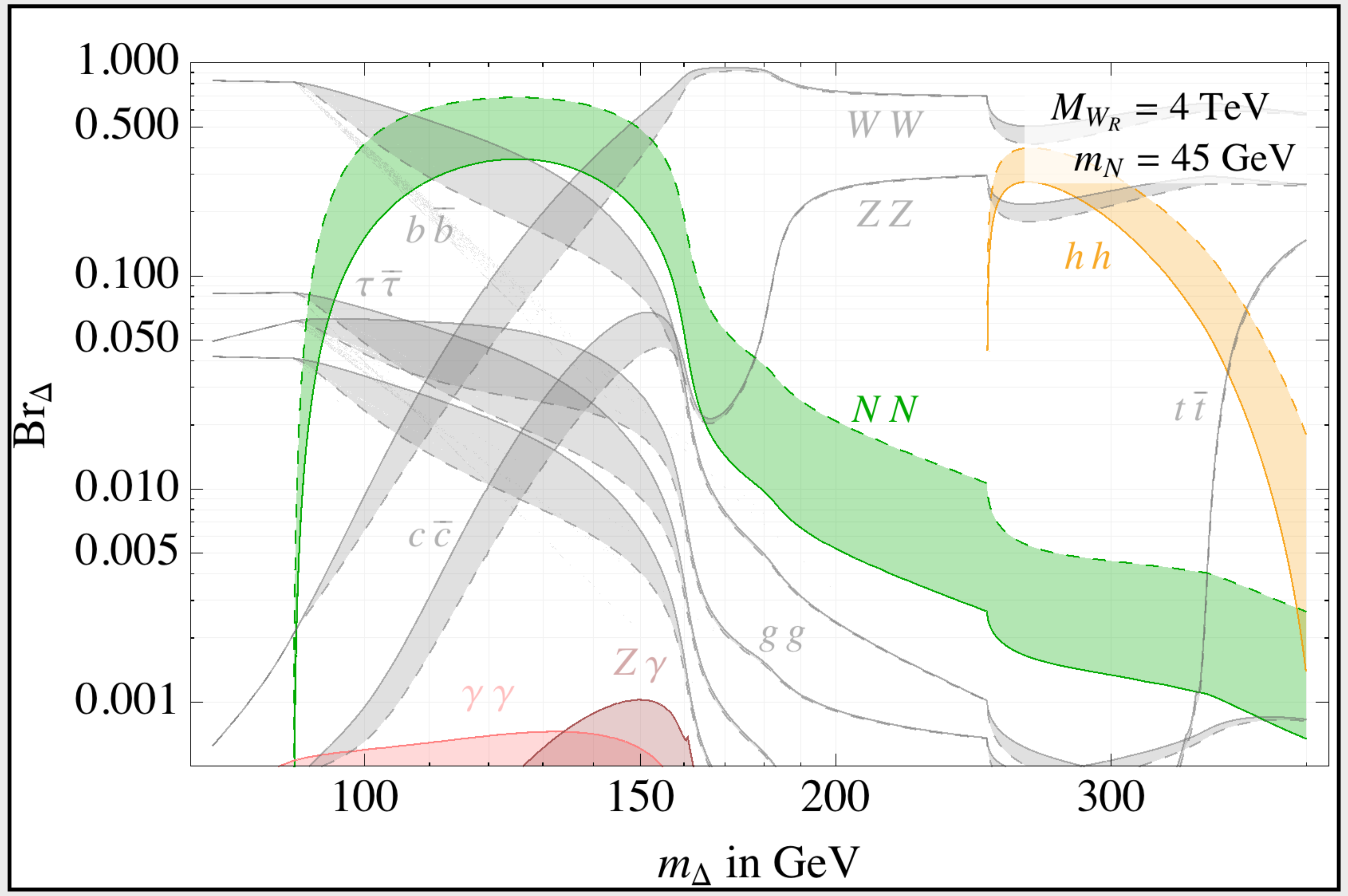


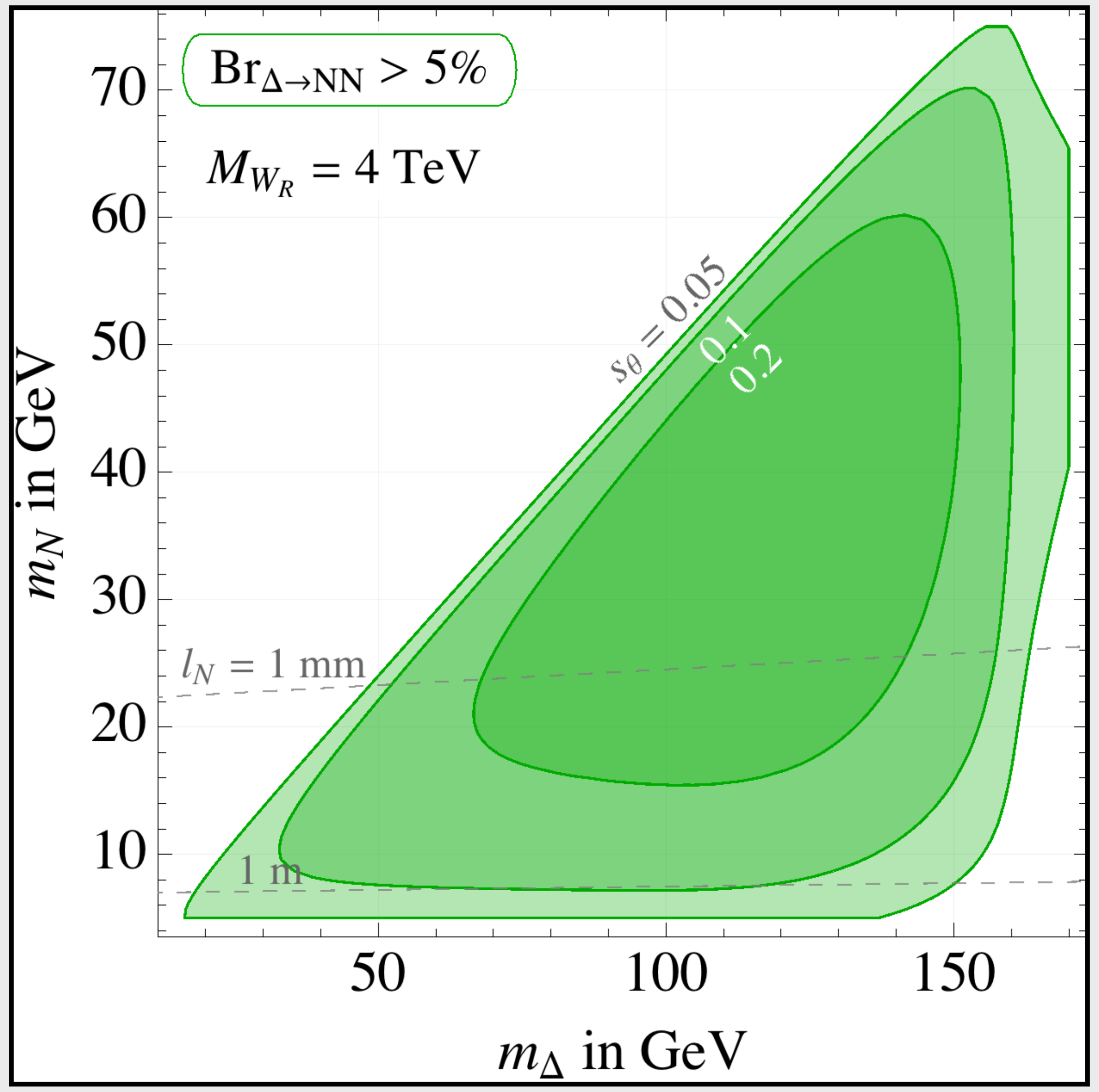
Mass points

- Mass points were chosen based on arXiv:1612.06840 studies. **Masses** of all three heavy neutrino flavours **are degenerate**.

m(N) [GeV]	m(Δ) [GeV]	m(W_R) [TeV]	cross-section [fb] @13 TeV	cross-section [fb] @13.6 TeV
25	65	4.0	4.60	4.90
25	100	4.0	2.59	2.77
25	150	4.0	1.54	1.67
65	150	4.0	1.06	1.15

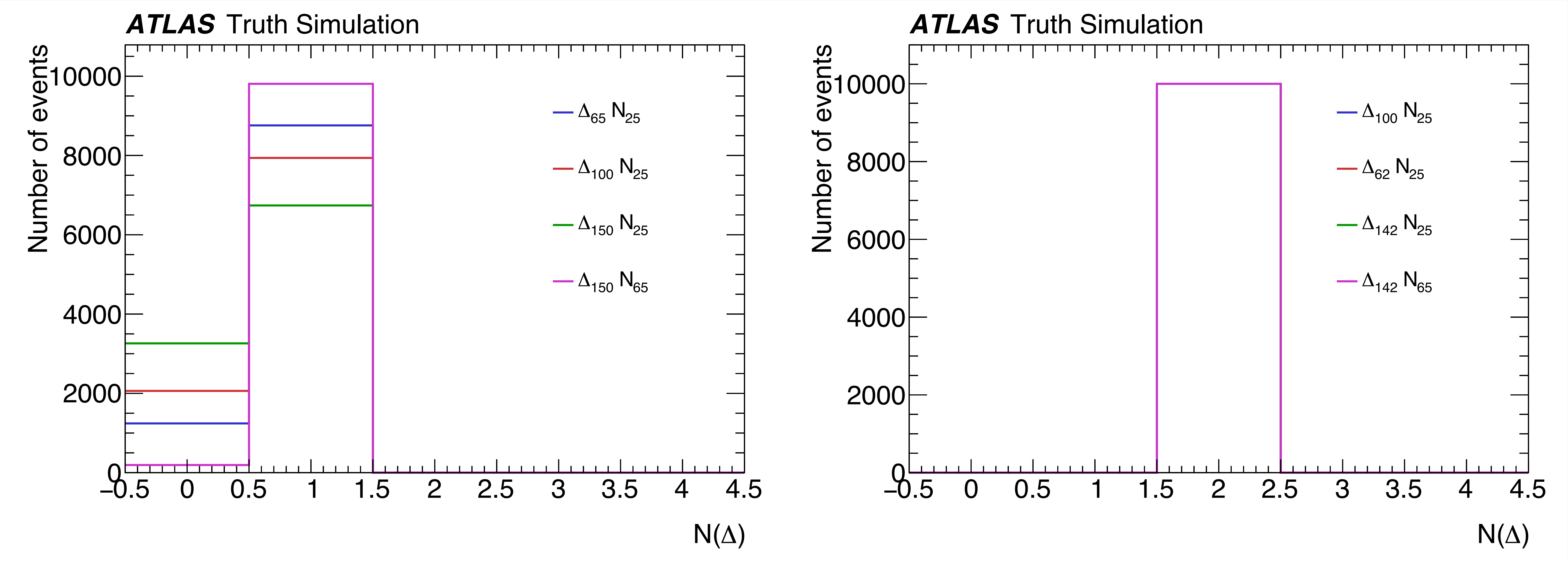


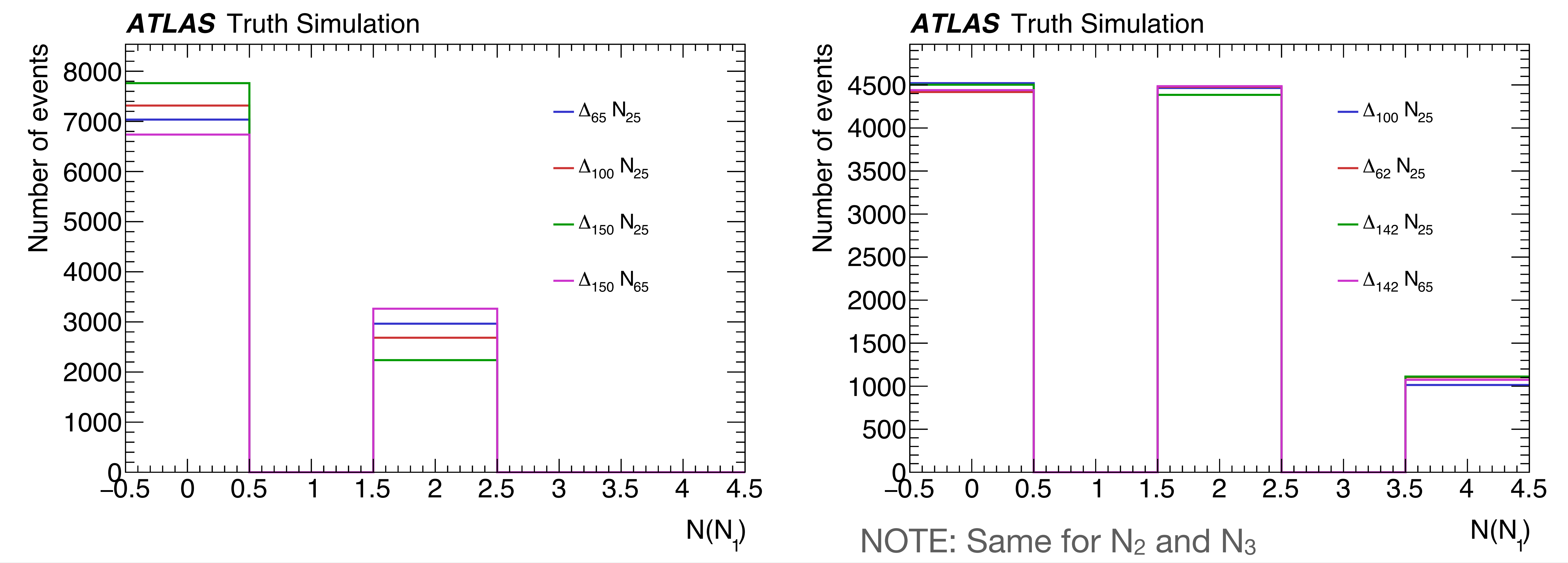




Validation of the new KNN model file, arXiv:2403.07756

- Number of Δs and Heavy neutrinos.

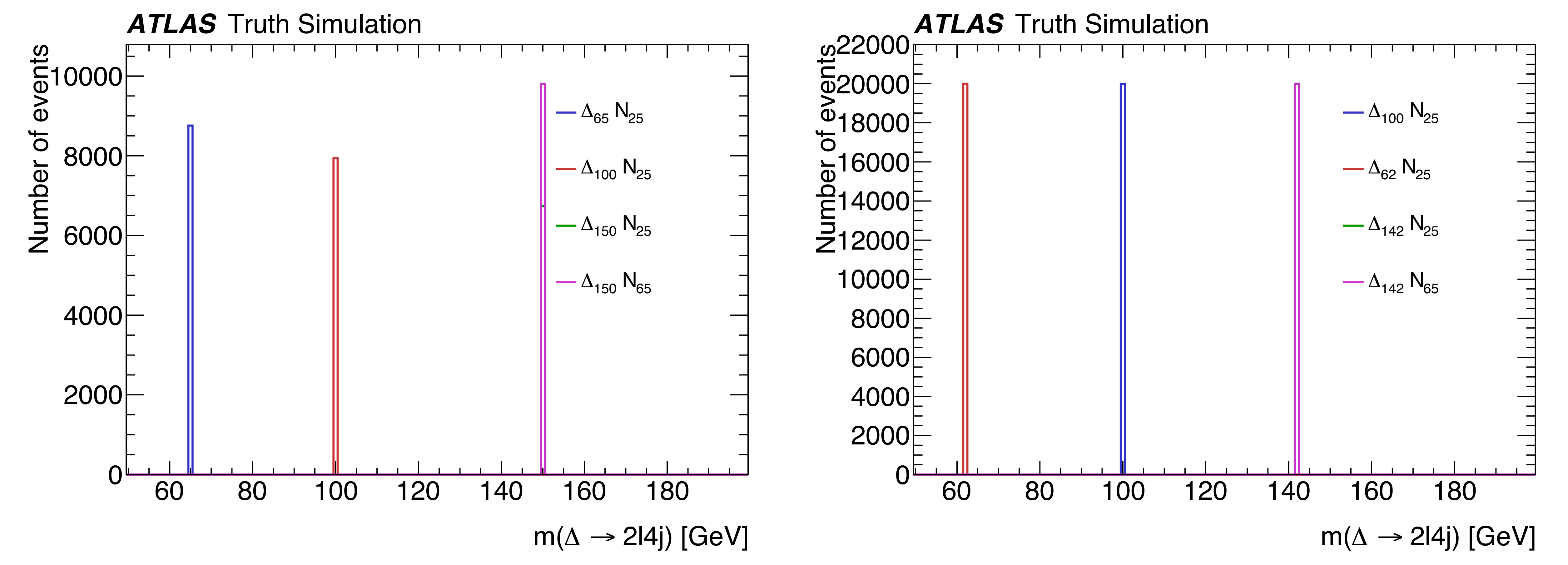


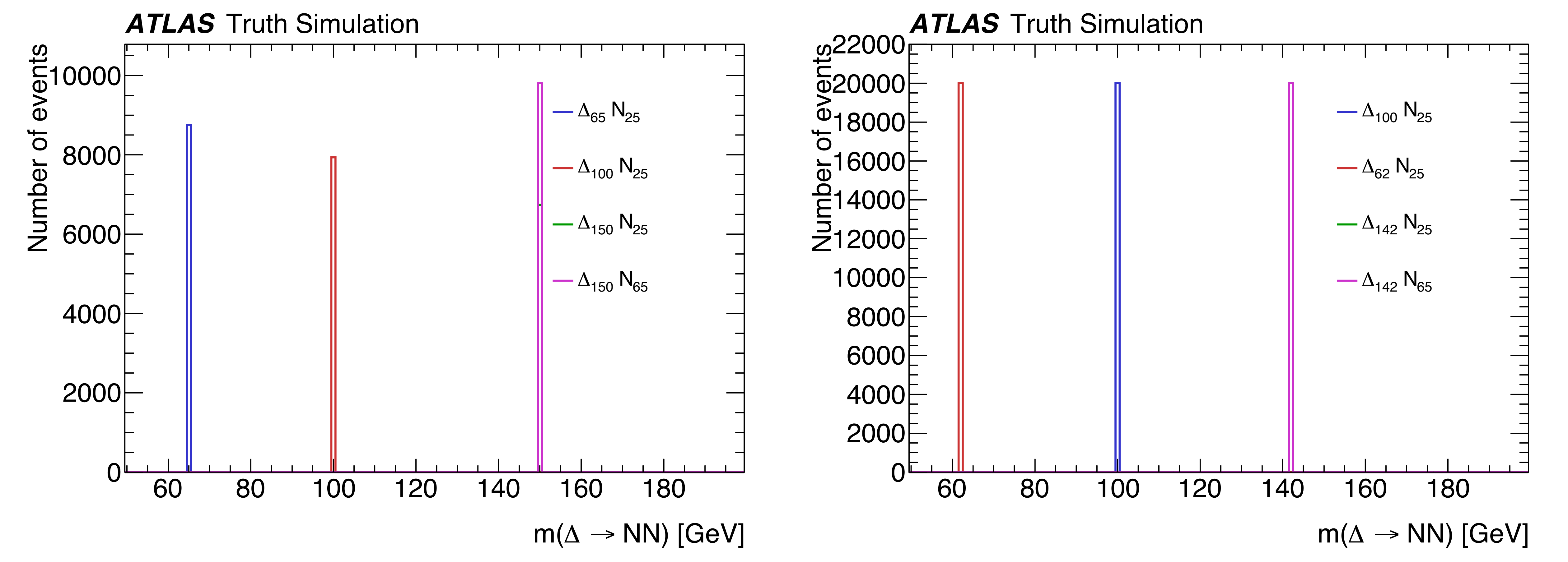


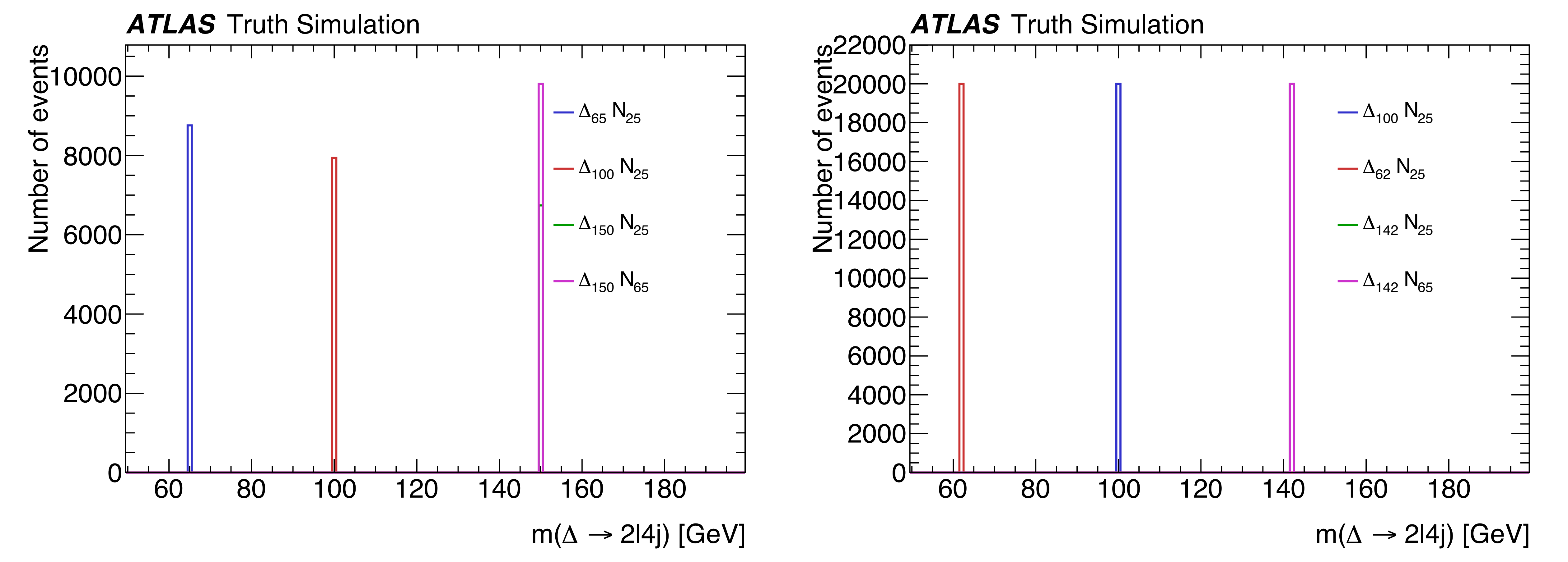
NOTE: Same for N_2 and N_3

Validation of the new KNN model file, arXiv:2403.07756

- Reconstructed invariant masses.

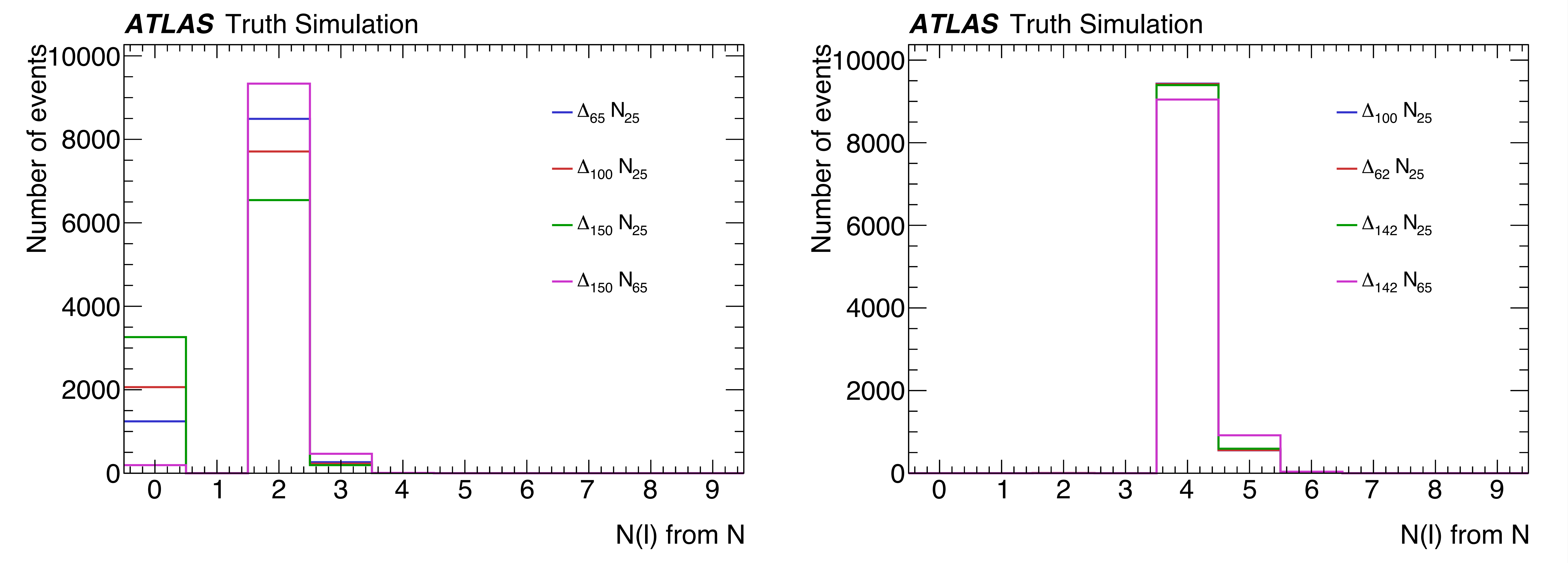


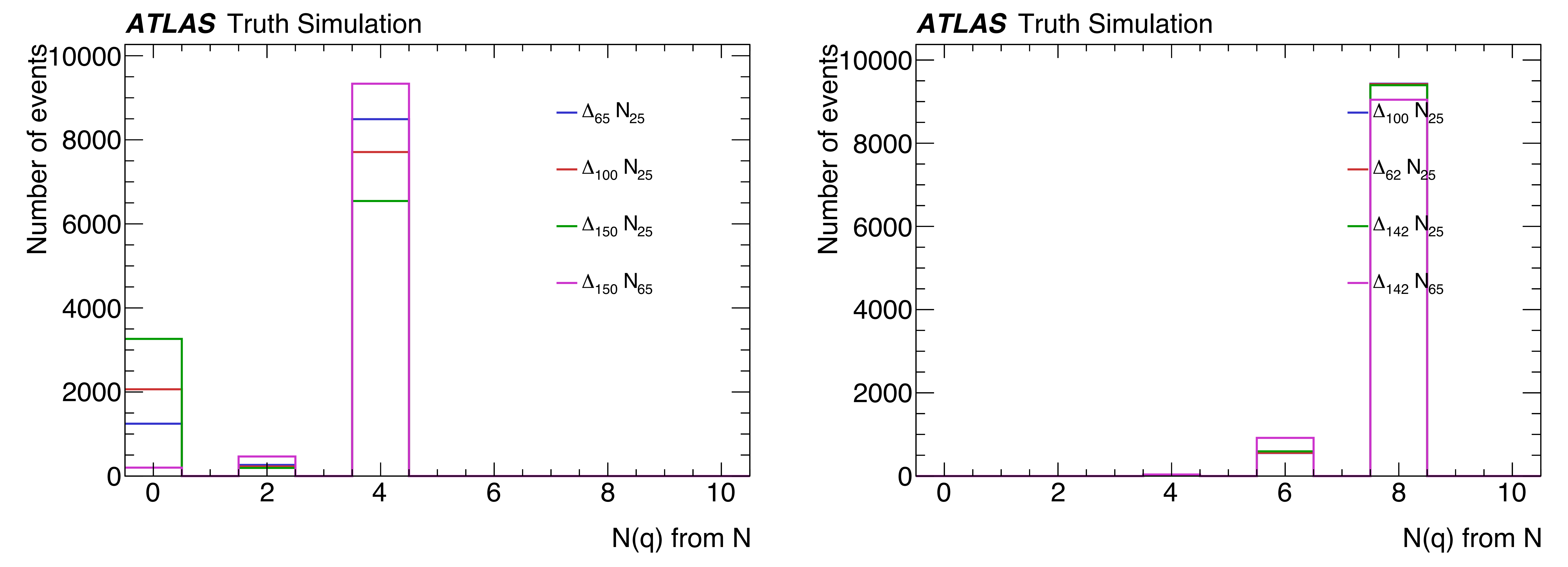




Validation of the new KNN model file, arXiv:2403.07756

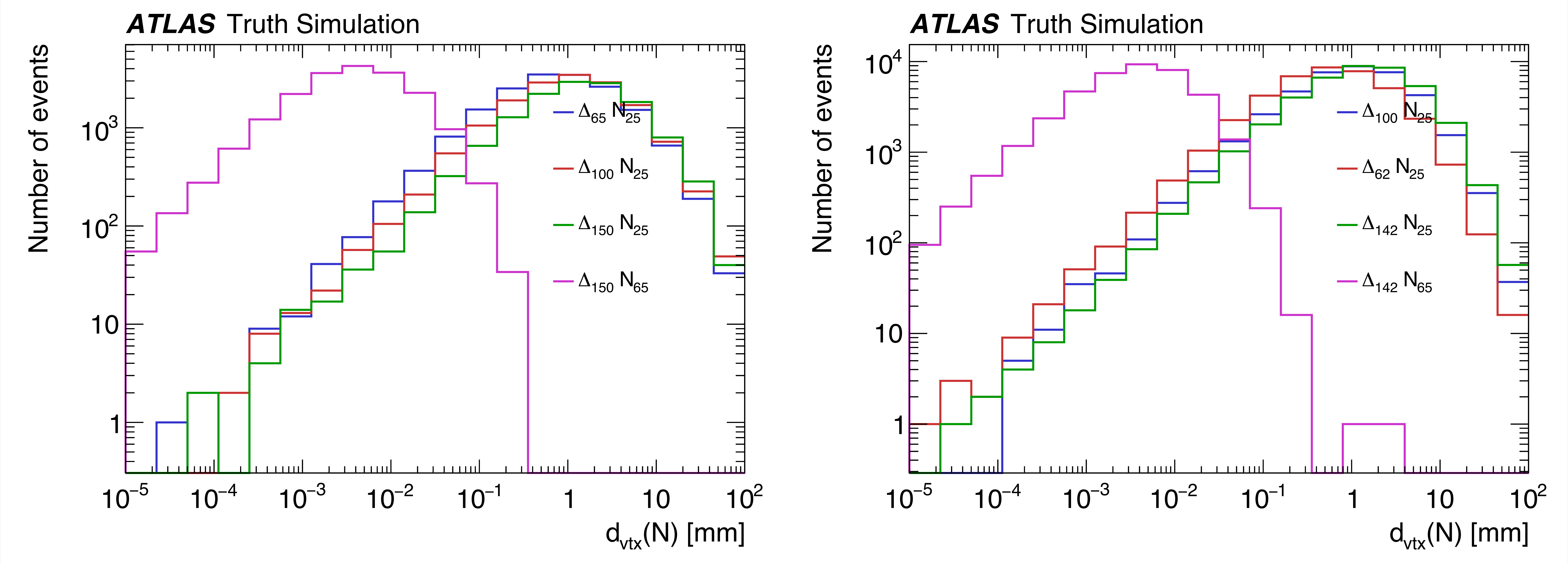
- Number of leptons and quarks.





Validation of the new KNN model file, arXiv:2403.07756

- Heavy neutrino **displacement is detectable** and can play a significant role in our analysis!



$$c\tau = 0.1\text{mm}\left(\frac{40\ \text{GeV}}{m_N}\right)^5\left(\frac{M_{W_R}}{5\ \text{TeV}}\right)^4$$

Summary and outlook

- Theoretical models relevant for the DCH analysis were presented.
- Search for a doubly charged Higgs analysis was outlined:
  - Two analysis approaches were tested,
  - Results are interpreted in different models,
  - Background modelling is crucial,
  - Preliminary studies show that MVA techniques provide modest improvements, indicating that the current cut-based analysis is well executed.
- Improvements can be made in the MVA approach, especially with the new person power joining the new round of the analysis.
- Signal sample validation of the LNV Higgs decays was presented.

Thank you...

INFN
BOLOGNA
Istituto Nazionale di Fisica Nucleare
Sezione di Bologna

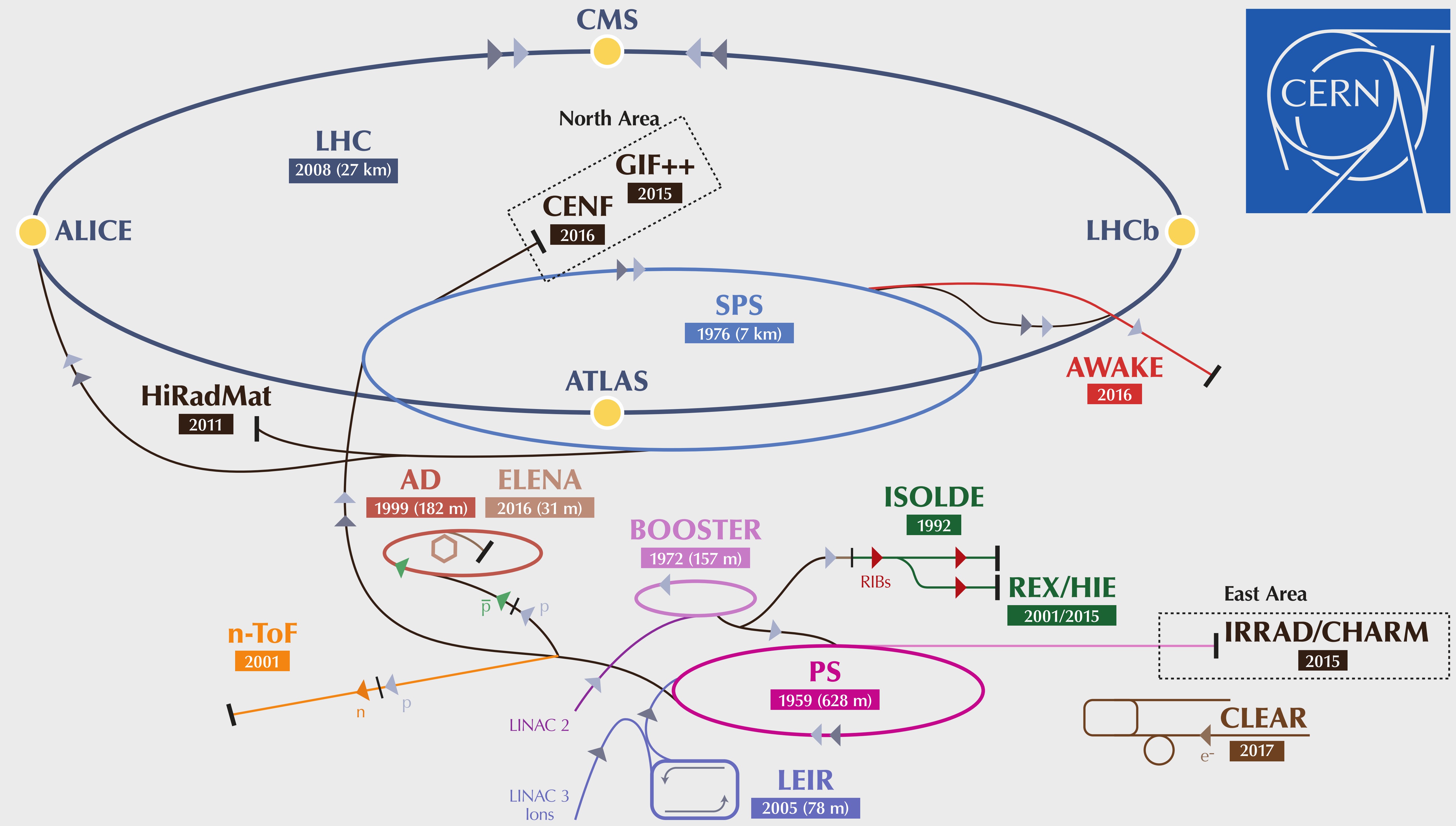
ATLAS
EXPERIMENT

Backup slides

The Large Hadron Collider

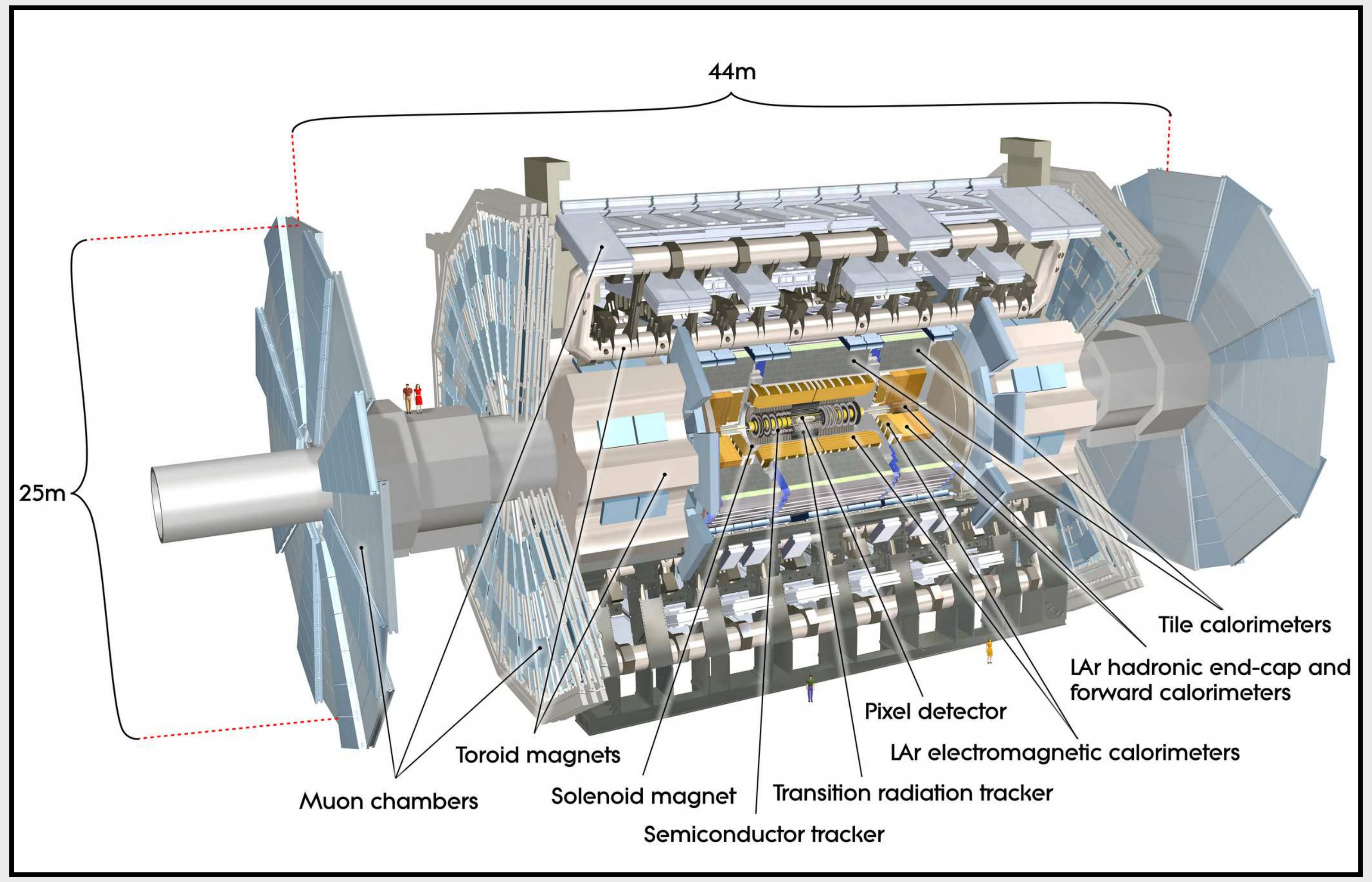
- The Large Hadron Collider (LHC) is the most powerful particle accelerator and collider ever built.
- It is located on France - Switzerland border at CERN ~100m below the surface.
- It can accelerate both **protons** and **heavy ions**, which is done in multiple stages.
- It was designed to reach centre-of-mass energy of pp collisions $\sqrt{s} = 14\ \mathrm{TeV}$.
- Four major experiments:
  - ALICE, **ATLAS**, CMS, LHCb.
- It delivered:
  - 5.46 fb^{-1} + 22.8 fb^{-1} in Run 1,
  - 156 fb^{-1} in Run 2, and
  - 70 fb^{-1} in Run 3

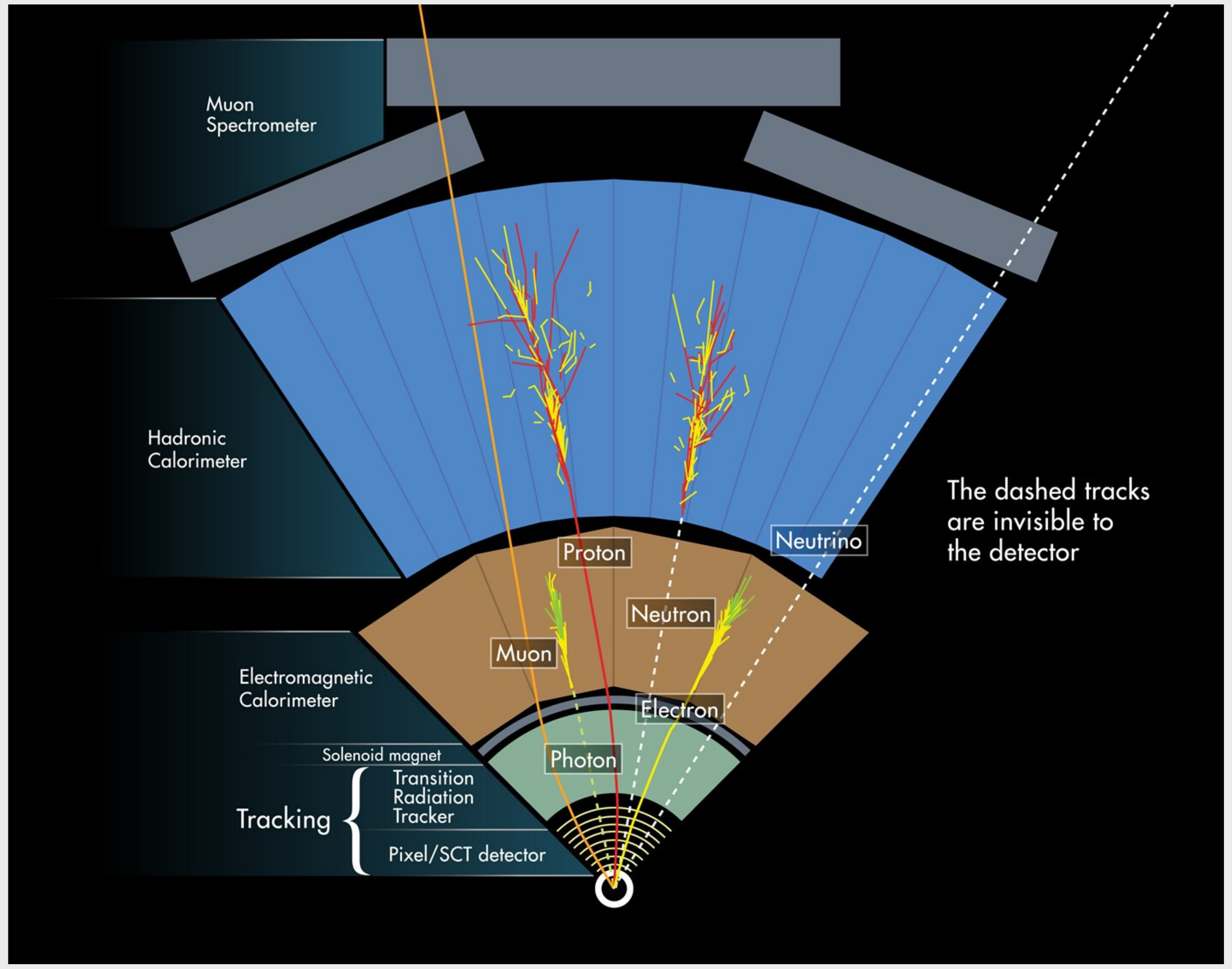
to ATLAS.



ATLAS Detector

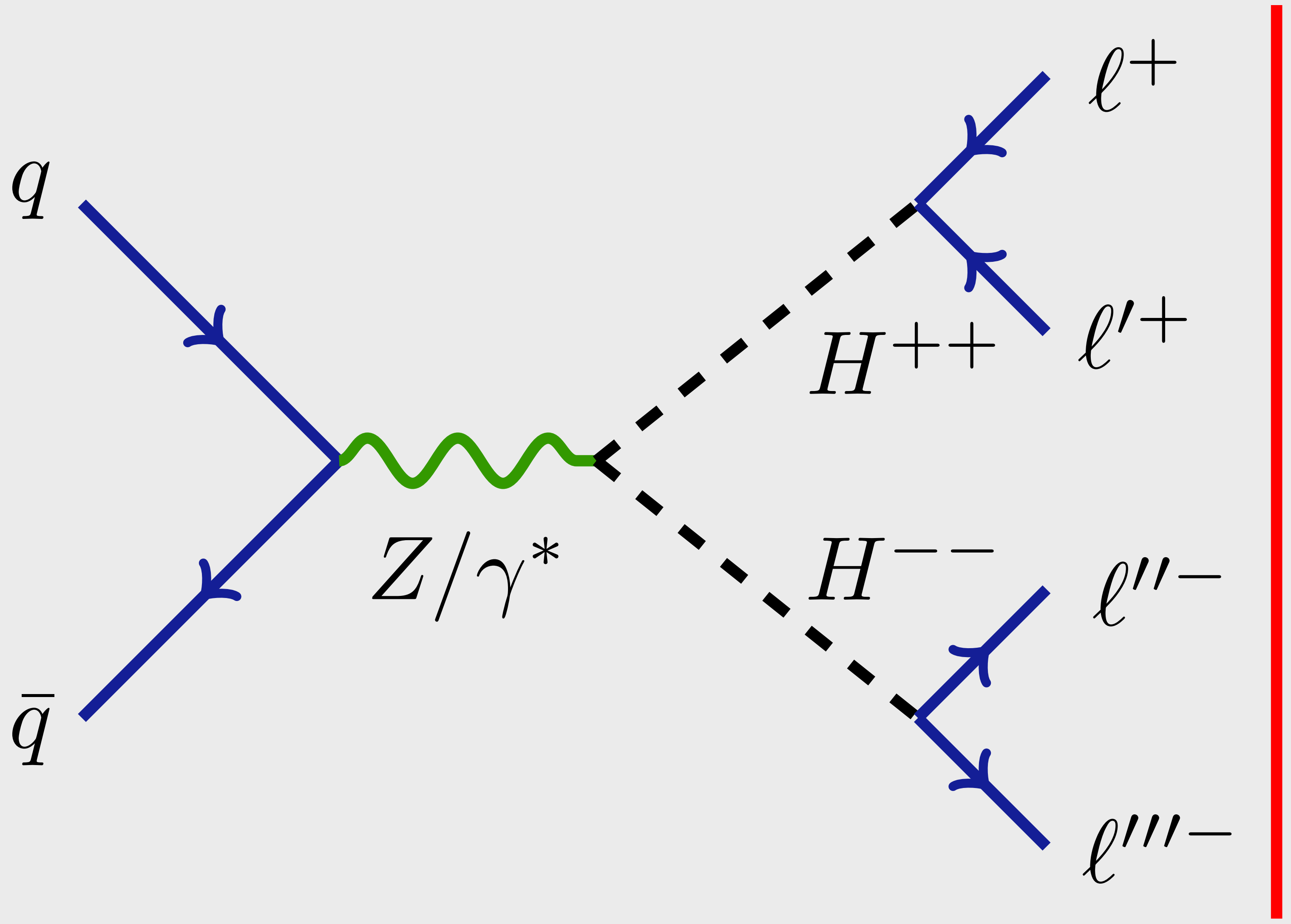
- The ATLAS detector is a multilayered general purpose detector, located at Point 1 of the LHC. It consists of several subsystems:
  - Inner Detector,
  - Electromagnetic and Hadronic calorimeters,
  - Muons spectrometers,
  - Central solenoid and toroid magnets,
  - Forward detectors (luminosity),
  - Two-level trigger.
- It was developed to detect various types of elementary particles with different reconstruction and identification techniques:
  - Electrons, muons, jets,
    tau leptons, missing transverse energy.

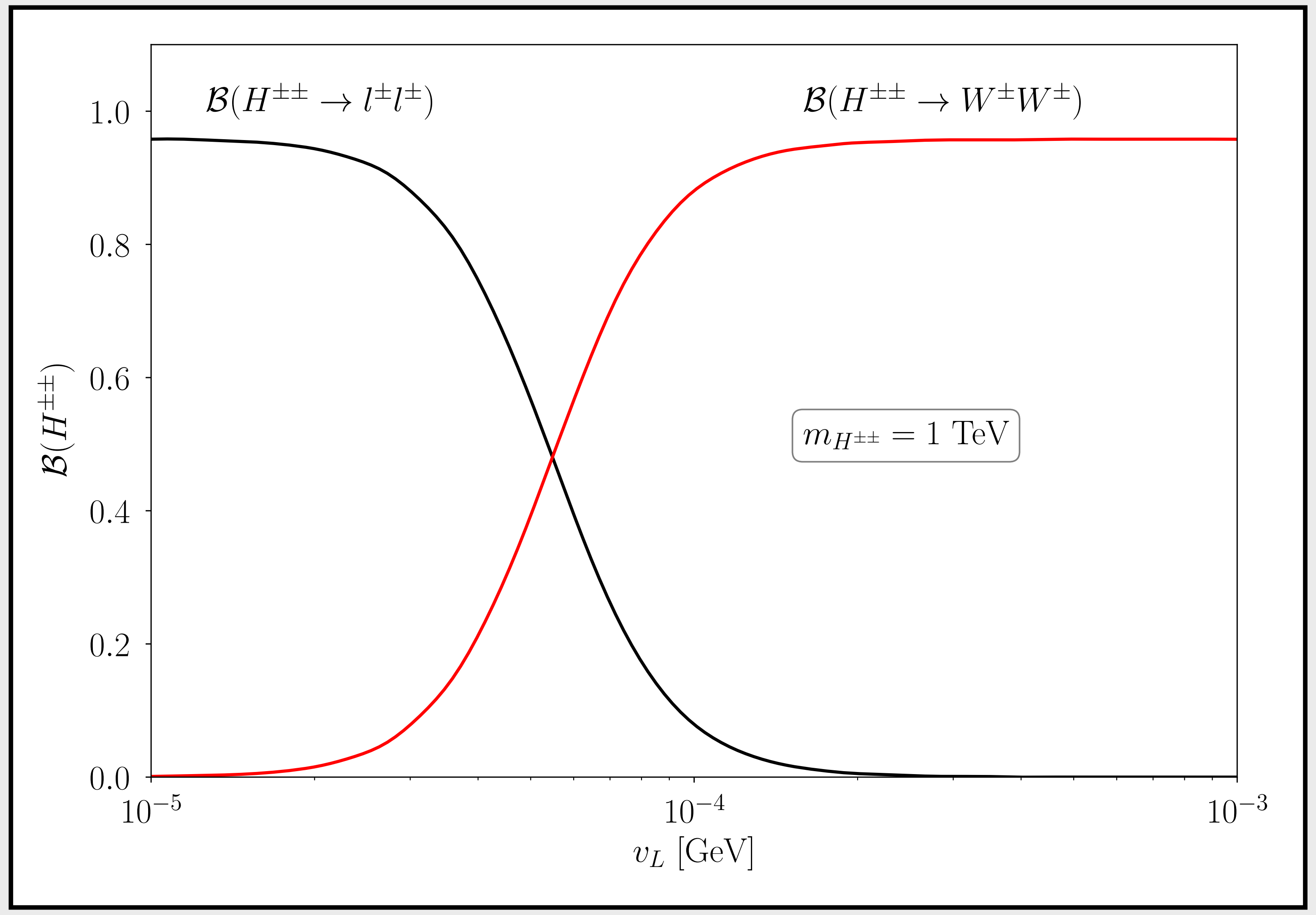




Doubly Charged Higgs Analysis

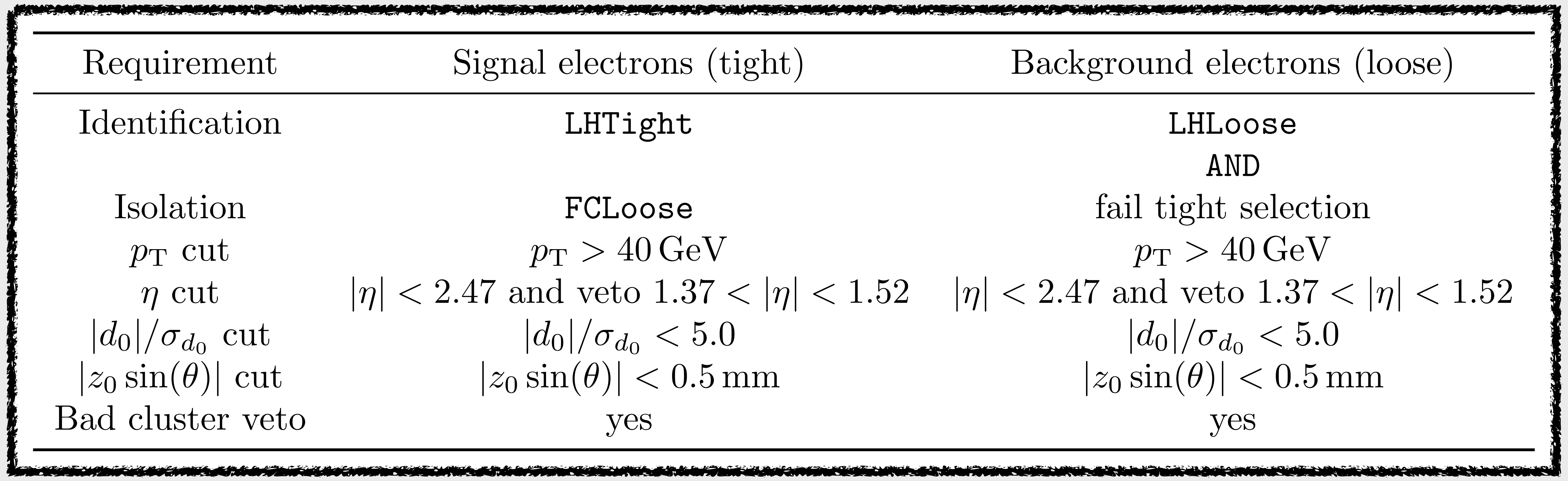
- Search for $H^{\pm\pm}$ pair production in all lepton flavour and charge combinations: $H^{\pm\pm} \to \ell^{\pm}\ell'^{\pm}, \quad \ell, \ell' = e, \mu, \tau.$
- Results can be interpreted for:
  - Type-II Seesaw mechanism within Left-Right Symmetric Model: two chiralities $H_L^{\pm\pm}$ and $H_R^{\pm\pm}$ [arXiv:0305288, arXiv:1105.1379].
  - Zee-Babu neutrino mass model: $k^{\pm\pm}$ [arXiv:2206.14833]
- Type-II seesaw mechanism: one of the **simplest** known ways to account for the **smallness of the neutrino masses**.
- **Lepton flavour violation is allowed.**
- $v_\Delta \to 0$ GeV: exclude decays to W bosons.
- Search for $m(H^{\pm\pm}) \in [300 - 1300]$ GeV and focusing on two-, three- and four-lepton final states.
- Using NLO cross-sections with corresponding uncertainties from Phys. Rev. D 101, 075022.





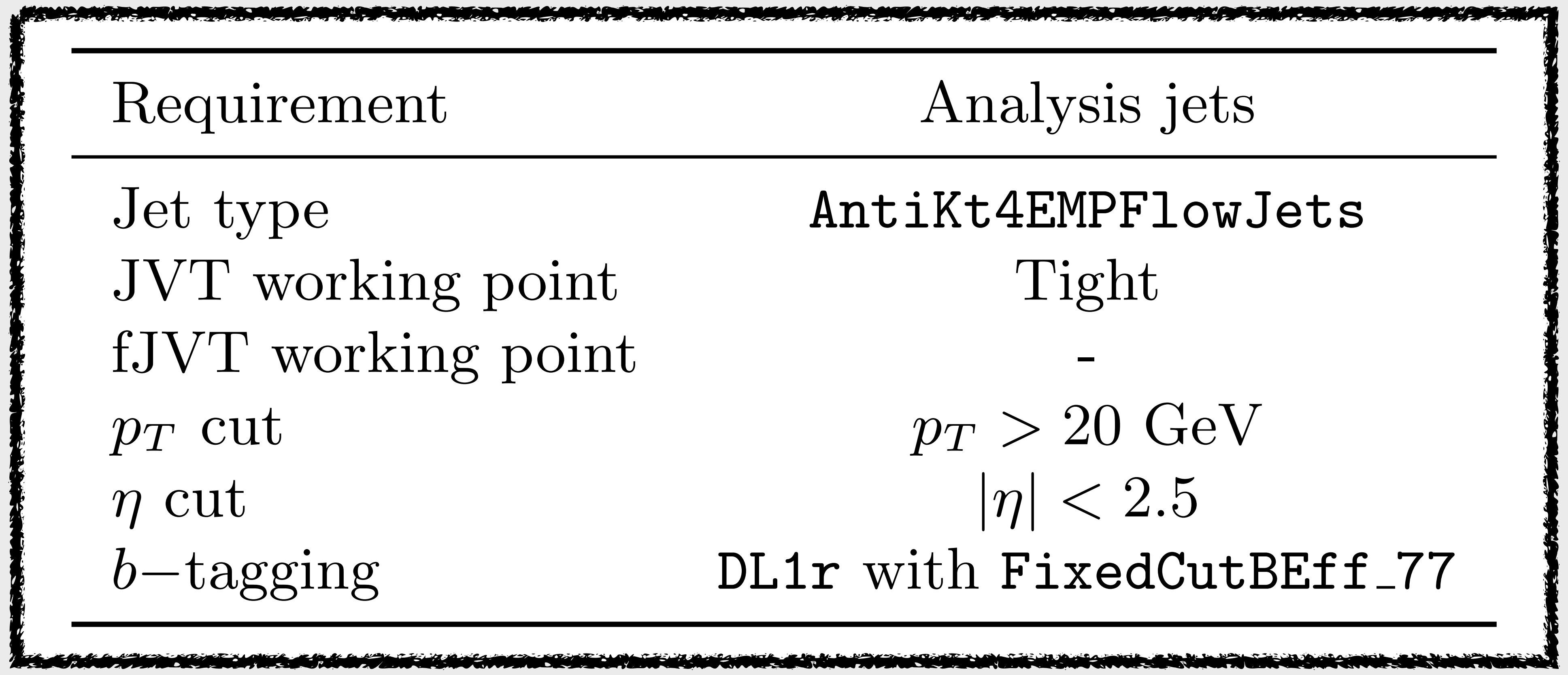
Object Definitions

Electrons e



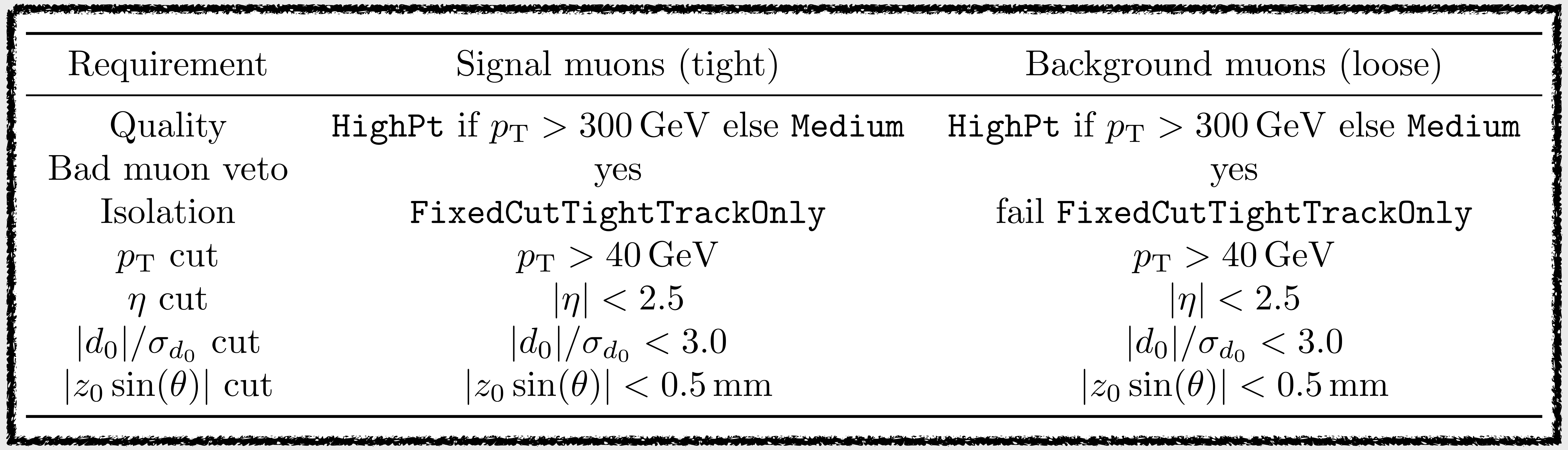
Requirement	Signal electrons (tight)	Background electrons (loose)
Identification	`LHTight`	`LHLoose`
		`AND`
Isolation	`FCLoose`	fail tight selection
p_{T} cut	$p_{\mathrm{T}} > 40\,\mathrm{GeV}$	$p_{\mathrm{T}} > 40\,\mathrm{GeV}$
η cut	$\lvert\eta\rvert < 2.47$ and veto $1.37 < \lvert\eta\rvert < 1.52$	$\lvert\eta\rvert < 2.47$ and veto $1.37 < \lvert\eta\rvert < 1.52$
$\lvert d_0\rvert/\sigma_{d_0}$ cut	$\lvert d_0\rvert/\sigma_{d_0} < 5.0$	$\lvert d_0\rvert/\sigma_{d_0} < 5.0$
$\lvert z_0 \sin(\theta)\rvert$ cut	$\lvert z_0 \sin(\theta)\rvert < 0.5\,\mathrm{mm}$	$\lvert z_0 \sin(\theta)\rvert < 0.5\,\mathrm{mm}$
Bad cluster veto	yes	yes

Jets j



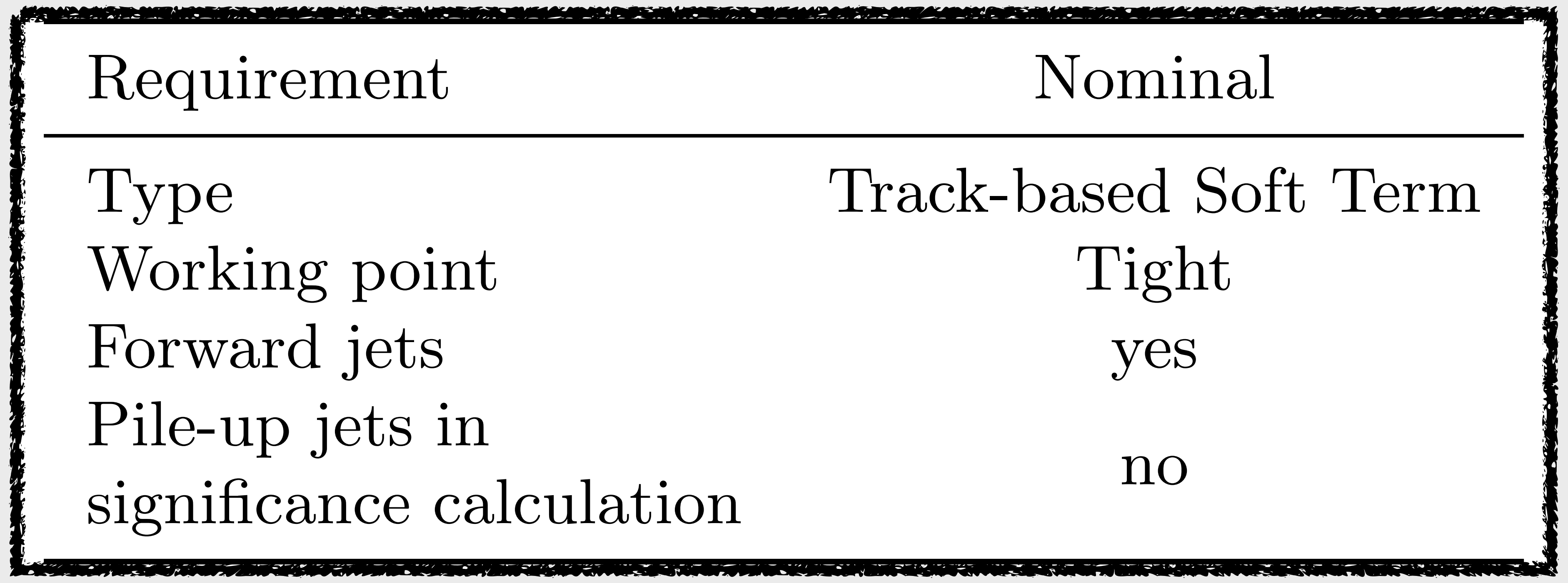
Requirement	Analysis jets
Jet type	`AntiKt4EMPFlowJets`
JVT working point	Tight
fJVT working point	-
p_T cut	$p_T > 20$ GeV
η cut	$\lvert\eta\rvert < 2.5$
$b-$tagging	`DL1r` with `FixedCutBEff_77`

Muons μ



Requirement	Signal muons (tight)	Background muons (loose)
Quality	`HighPt` if $p_{\mathrm{T}} > 300\,\mathrm{GeV}$ else `Medium`	`HighPt` if $p_{\mathrm{T}} > 300\,\mathrm{GeV}$ else `Medium`
Bad muon veto	yes	yes
Isolation	`FixedCutTightTrackOnly`	fail `FixedCutTightTrackOnly`
p_{T} cut	$p_{\mathrm{T}} > 40\,\mathrm{GeV}$	$p_{\mathrm{T}} > 40\,\mathrm{GeV}$
η cut	$\lvert\eta\rvert < 2.5$	$\lvert\eta\rvert < 2.5$
$\lvert d_0\rvert/\sigma_{d_0}$ cut	$\lvert d_0\rvert/\sigma_{d_0} < 3.0$	$\lvert d_0\rvert/\sigma_{d_0} < 3.0$
$\lvert z_0 \sin(\theta)\rvert$ cut	$\lvert z_0 \sin(\theta)\rvert < 0.5\,\mathrm{mm}$	$\lvert z_0 \sin(\theta)\rvert < 0.5\,\mathrm{mm}$

Missing Transverse Energy

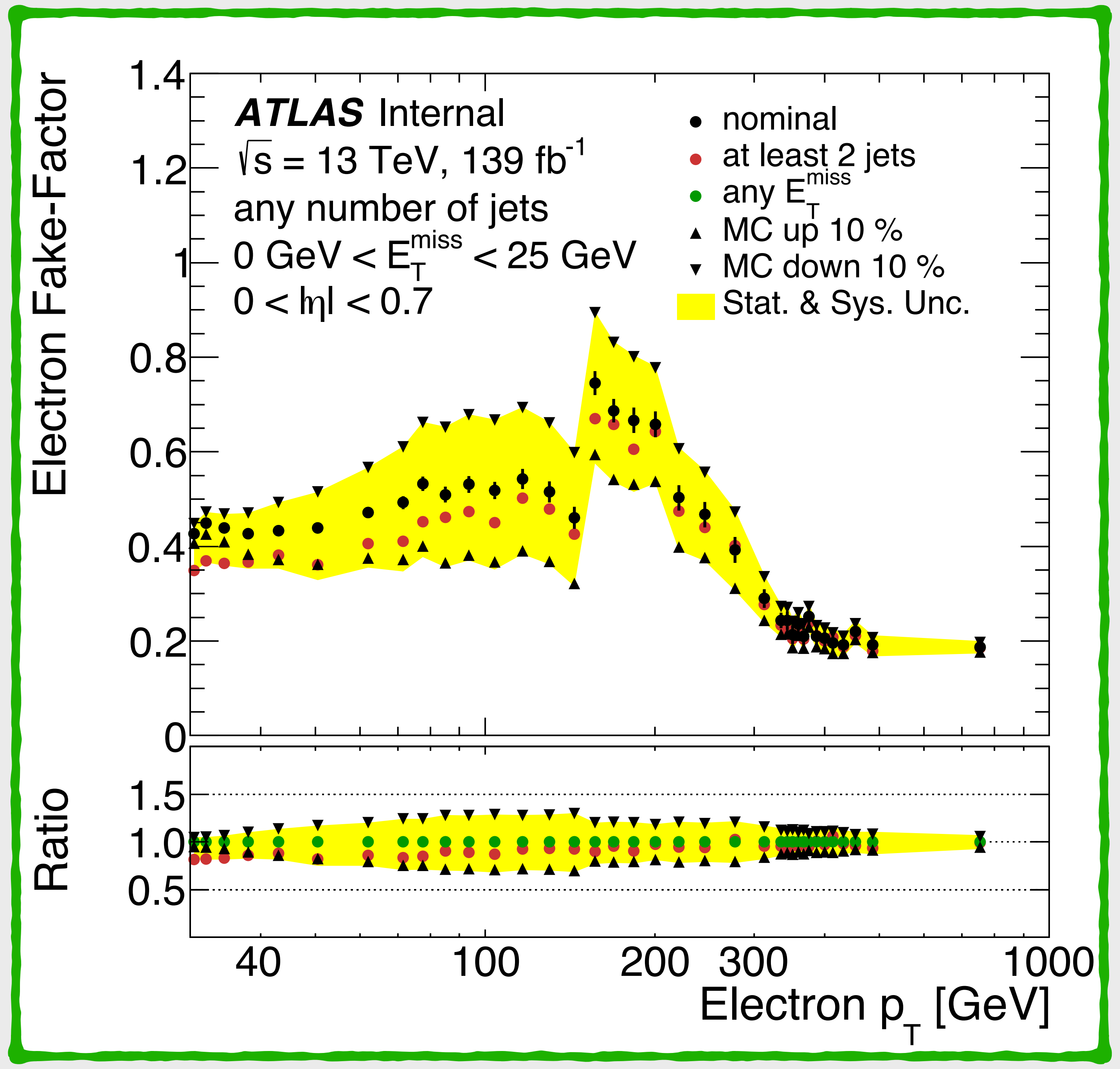


Requirement	Nominal
Type	Track-based Soft Term
Working point	Tight
Forward jets	yes
Pile-up jets in significance calculation	no

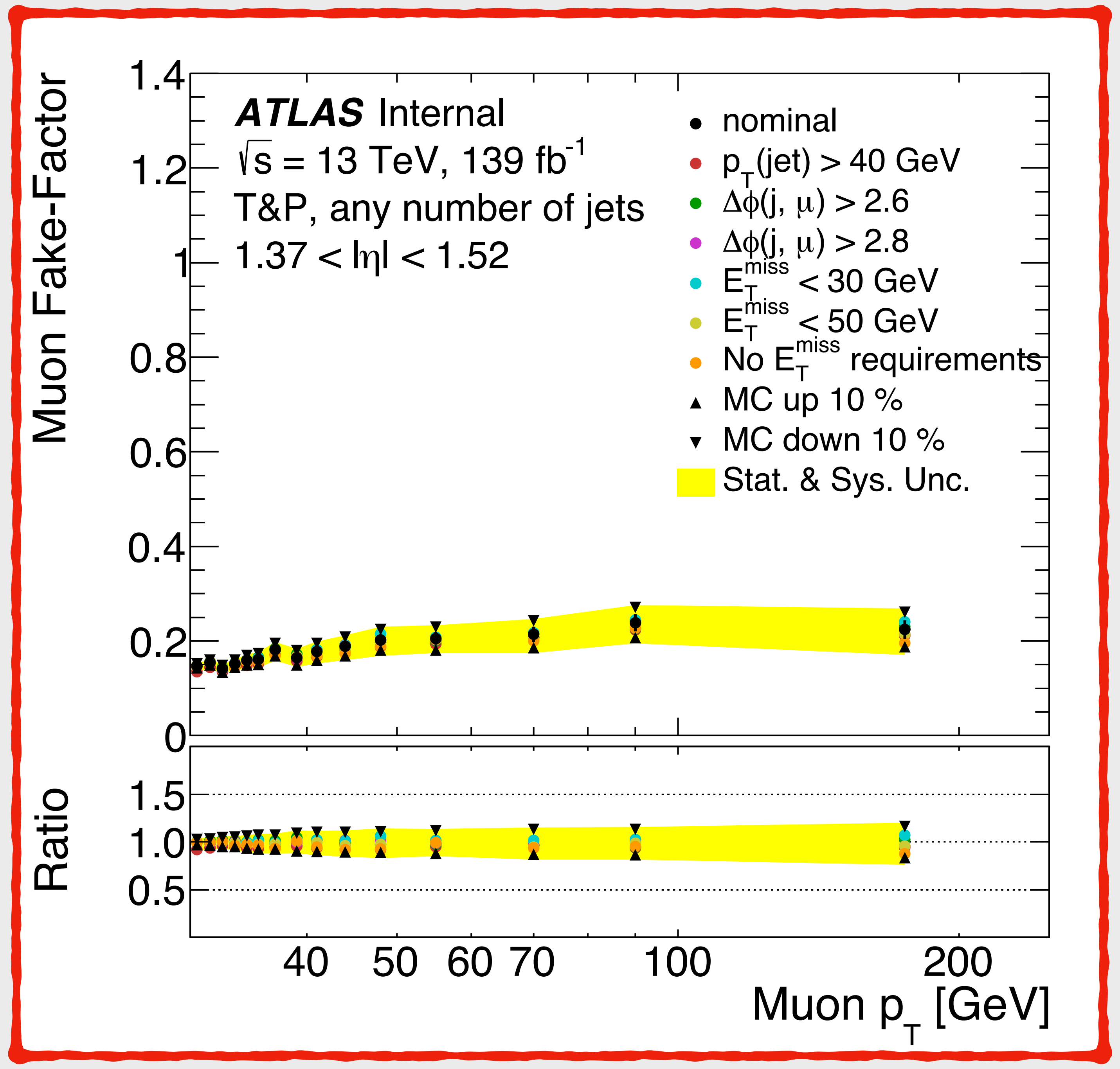
Fake enriched regions

- Fake enriched regions require **exactly 1 baseline lepton** with **any number of jets** and a **b-jet veto** (+ additional kinematic constraints in the muon fake estimation due to tag-and-probe technique).
- Estimation performed in **4** (**5**) η and two E_T^{miss} intervals with variable p_T binning.
- Prescaled single lepton triggers were used.

electrons

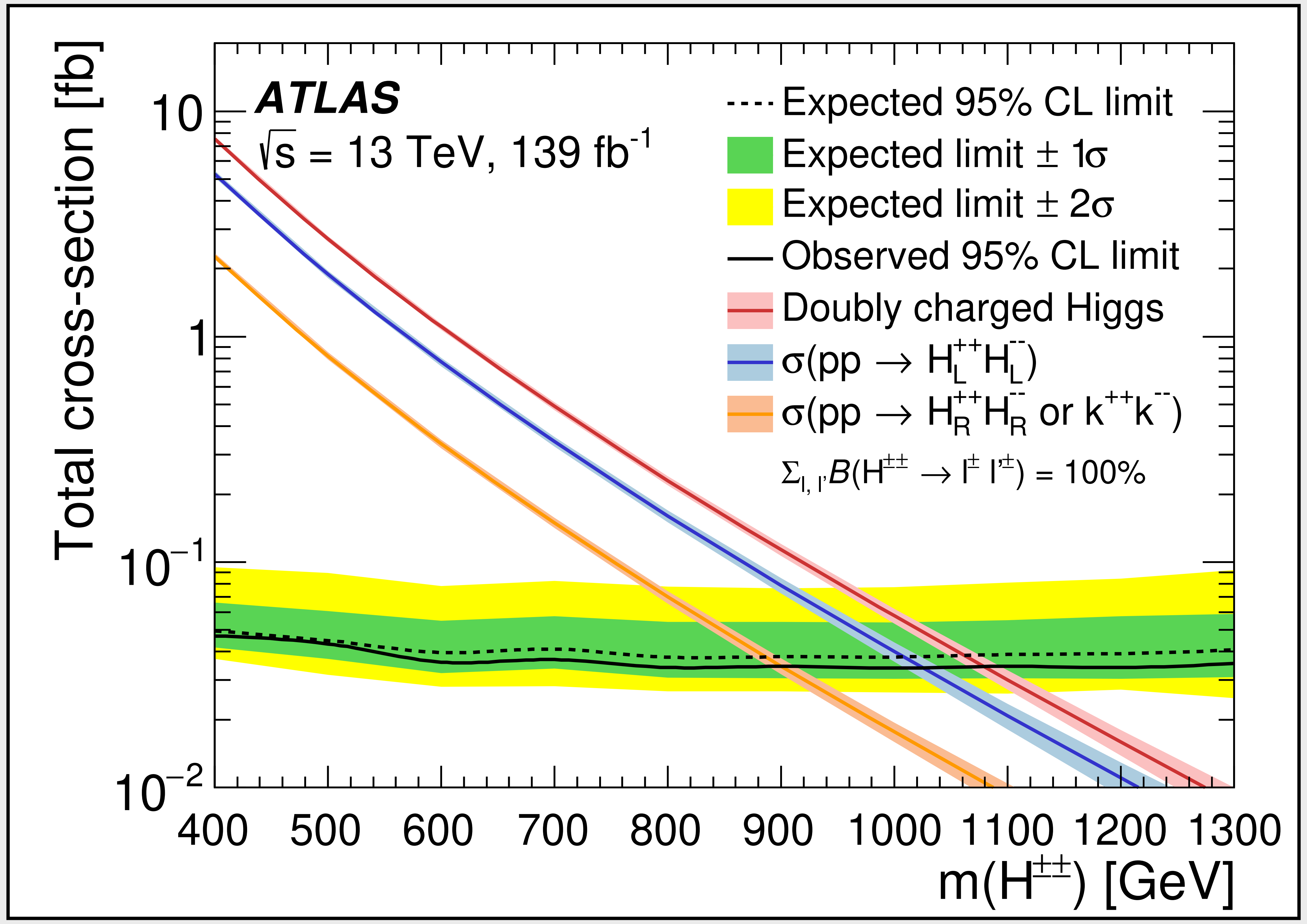


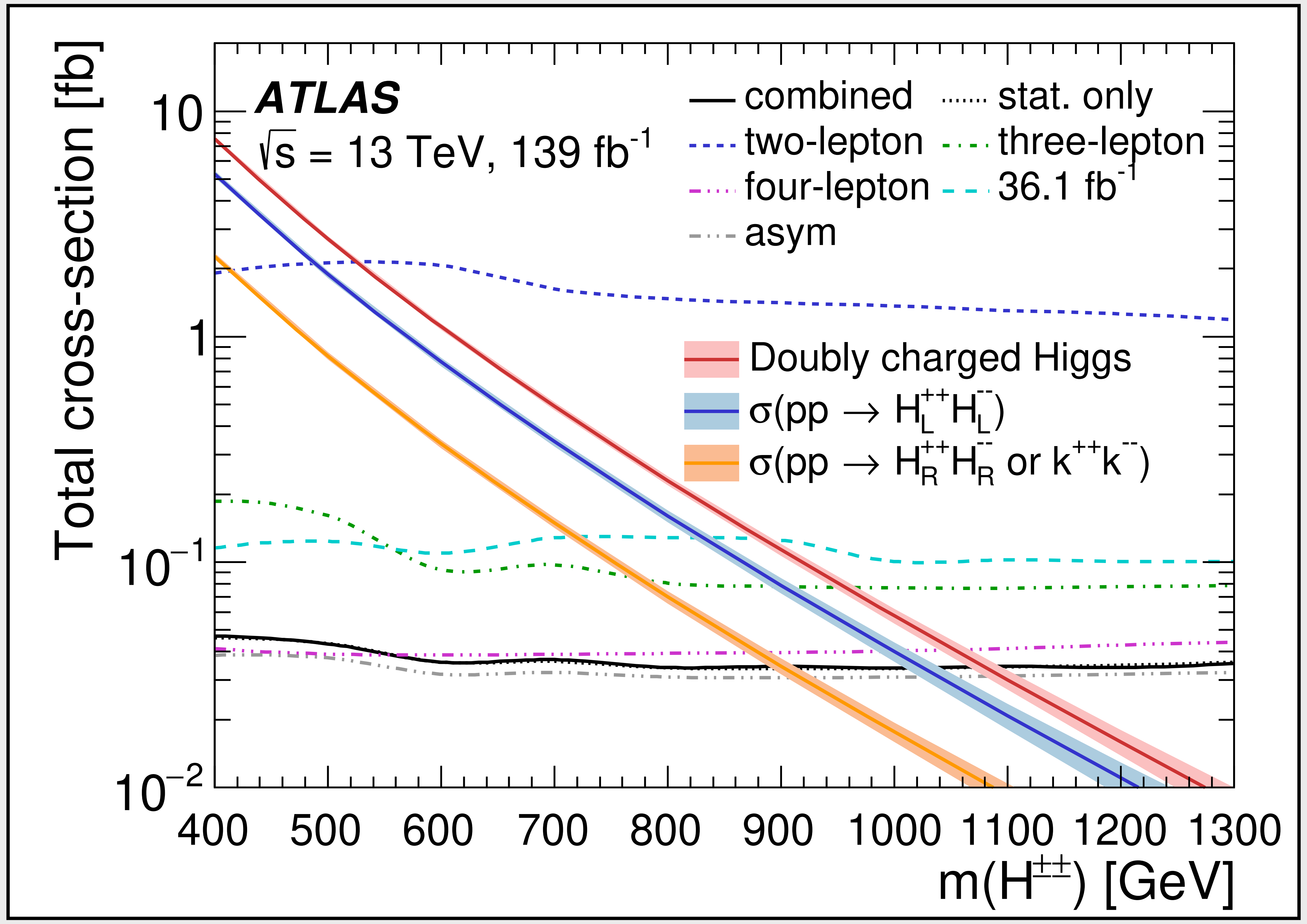
muons



Lower $H^{\pm\pm}$ mass limits

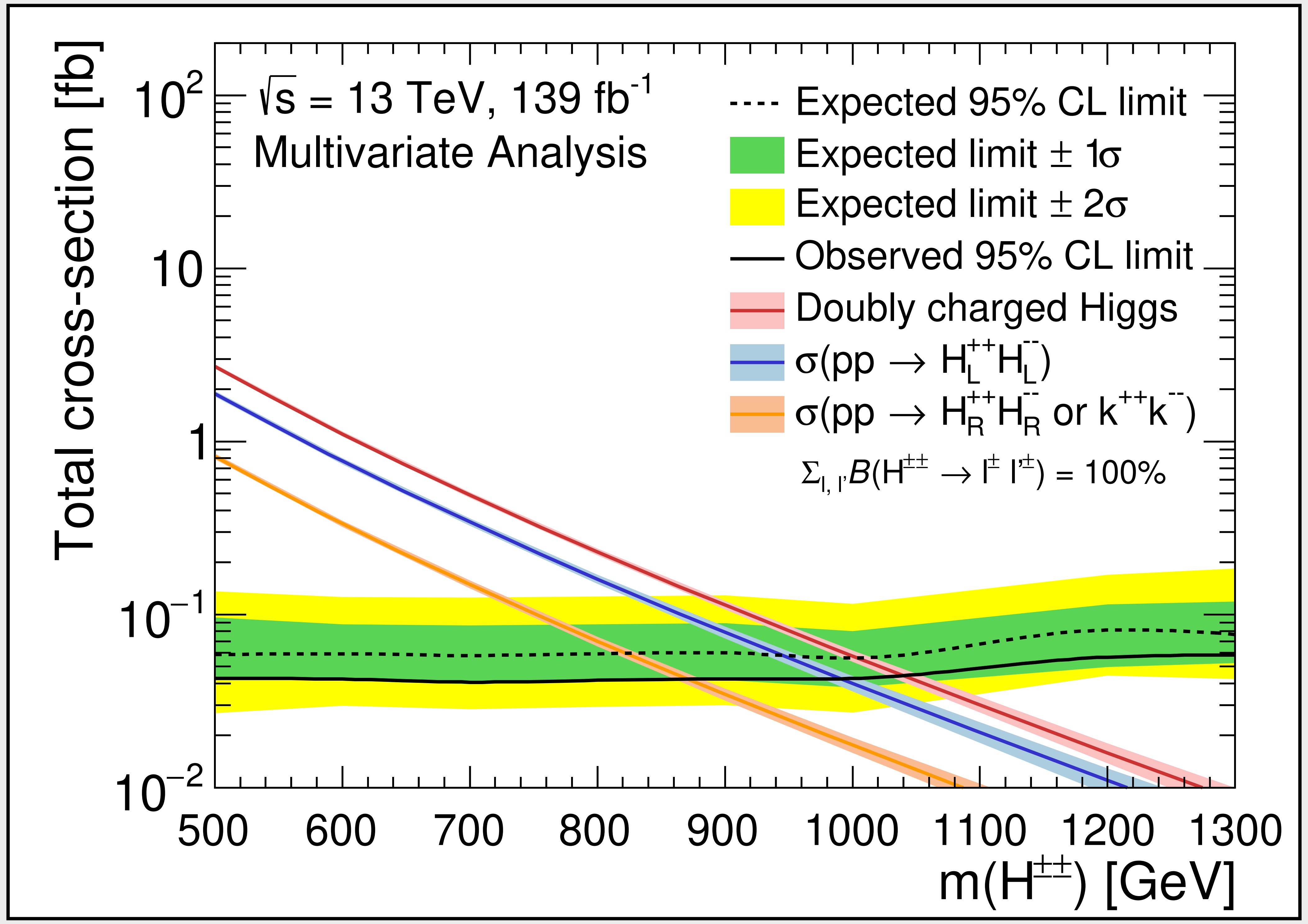
- The expected exclusion limit is **1065^{+30}_{-50} GeV** for LRSM and **880^{+30}_{-40} GeV** for the Zee-Babu model.
- The observed lower limit on the $H^{\pm\pm}$ mass reaches **1080 GeV** and **900 GeV** when combining all three channels for LRSM and the Zee-Babu model, respectively.
- The four-lepton channel limit is is the strongest and drives the combined result.

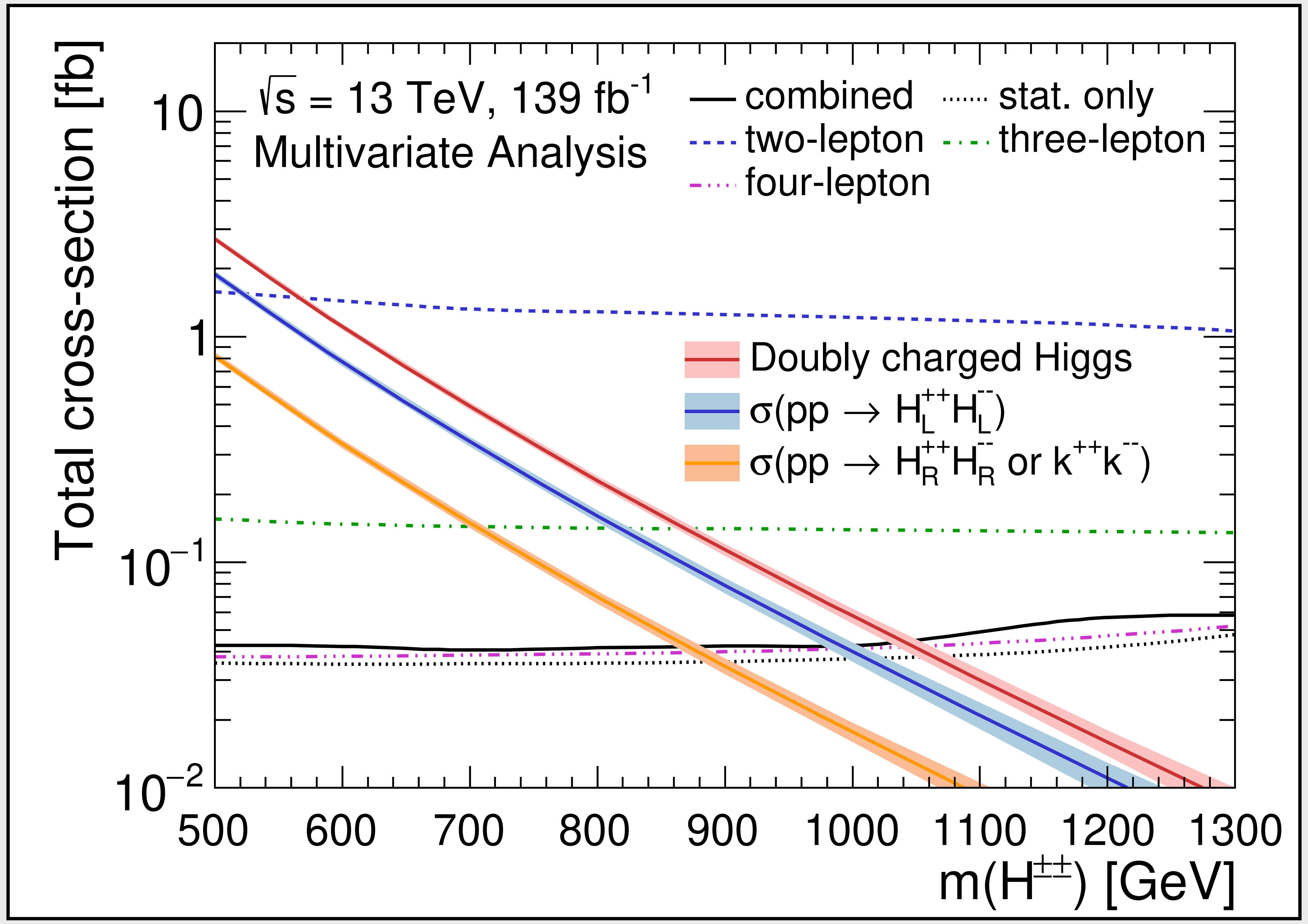




Lower $H^{\pm\pm}$ mass limits

- The expected exclusion limit is **1010^{+80}_{-70} GeV** for LRSM and **810^{+20}_{-30} GeV** for the Zee-Babu model.
- The observed lower limit on the mass reaches **1050 GeV** and **890 GeV** when combining all three channels for LRSM and the Zee-Babu model, respectively.
- **Not much improvement** with respect to the cut-based analysis.

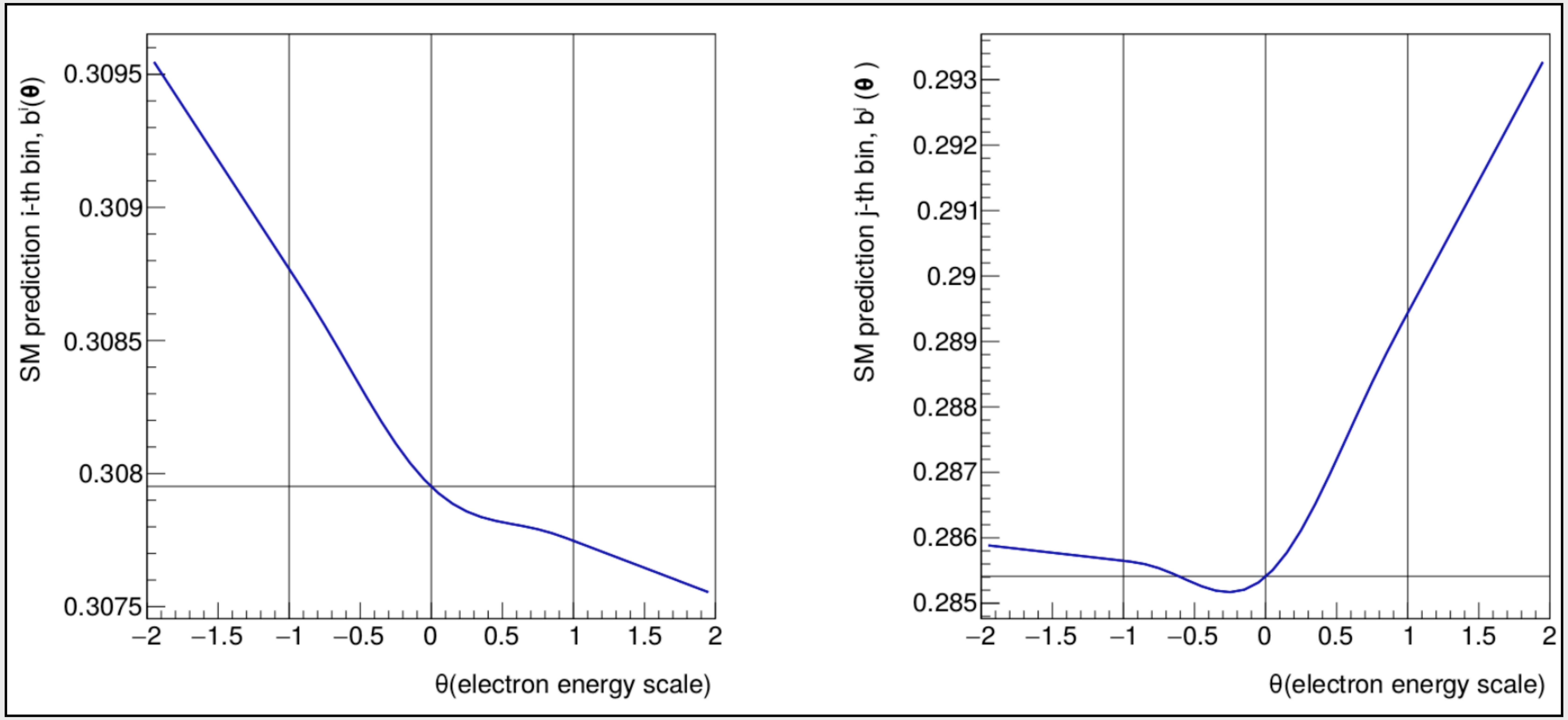




The likelihood function

$$L_{\text{phys}}(\text{data} \mid \mu) = L_{\text{phys}}(\mu) = \prod_{i \in \text{bins}} \text{Pois}(N_i \mid \mu S_i + B_i) = \prod_{i \in \text{bins}} \frac{(\mu S_i + B_i)^{N_i}}{N_i!} e^{-(\mu S_i + B_i)}$$

- The predicted SM yield is a function of the nuisance parameter (systematics).



Hypothesis test

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\boldsymbol{\theta}}}(\mu))}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})}$$

Fixed μ, floating θ

Floating μ, floating θ

$$p_B = P(q_\mu < q_\mu^{ref} \,|\, B) = \int_{-\infty}^{q_\mu^{ref}} f(q_\mu \,|\, B)\, dq_\mu$$

$$p_{S+B} = P(q_\mu > q_\mu^{ref} \,|\, S+B) = \int_{q_\mu^{ref}}^{\infty} f(q_\mu \,|\, S+B)\, dq_\mu$$

$$CL_s = \frac{p_{S+B}}{1 - p_B}$$