Alma Mater Studiorum Università di Bologna

Seesaw mechanisms searches at colliders - ATLAS

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On behalf of the **ATLAS Bologna Exotics Group**

Joint Theoretical and Experimental Meeting

Seesaw at colliders

Alma Mater Studiorum - University of Bologna, 11 May 2023

Introduction

Particle accelerators are fundamental tools to test physics models:
Large Hadron Collider (LHC)

LHC is the biggest ever particle accelerator:

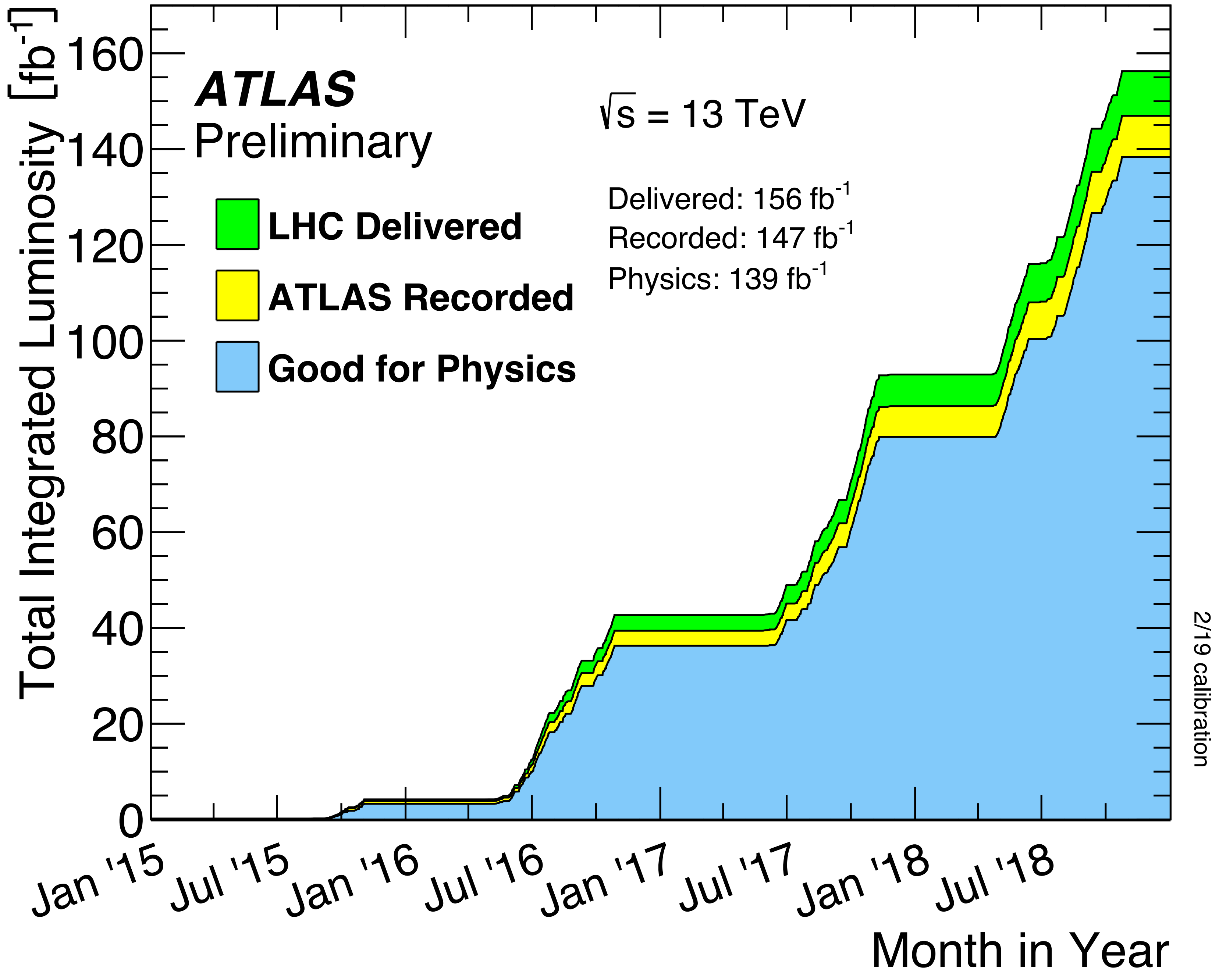
- Reached a **center-of-mass energy** of $\sqrt{s}$ = 13 TeV (Run 2, 8 TeV Run 1)
- Delivered an **integrated luminosity** up to 156 fb^{-1} in Run 2

LHC hosts four big experiments: ALICE, LHCb, CMS, **ATLAS**.

Centre-of-mass energy and integrated luminosity increased during Run 3:

- $\sqrt{s}$ = 13.6 TeV
- Over 300 fb^{-1} before the end of 2023

From: LuminosityPublicResultsRun2



ATLAS (A Toroidal LHC ApparatuS)
is a multipurpose experiment to discover signatures of new physics and to perform precise measurements of Standard Model.

ATLAS recorded 139 fb^{-1} good for physics analyses in Run 2.

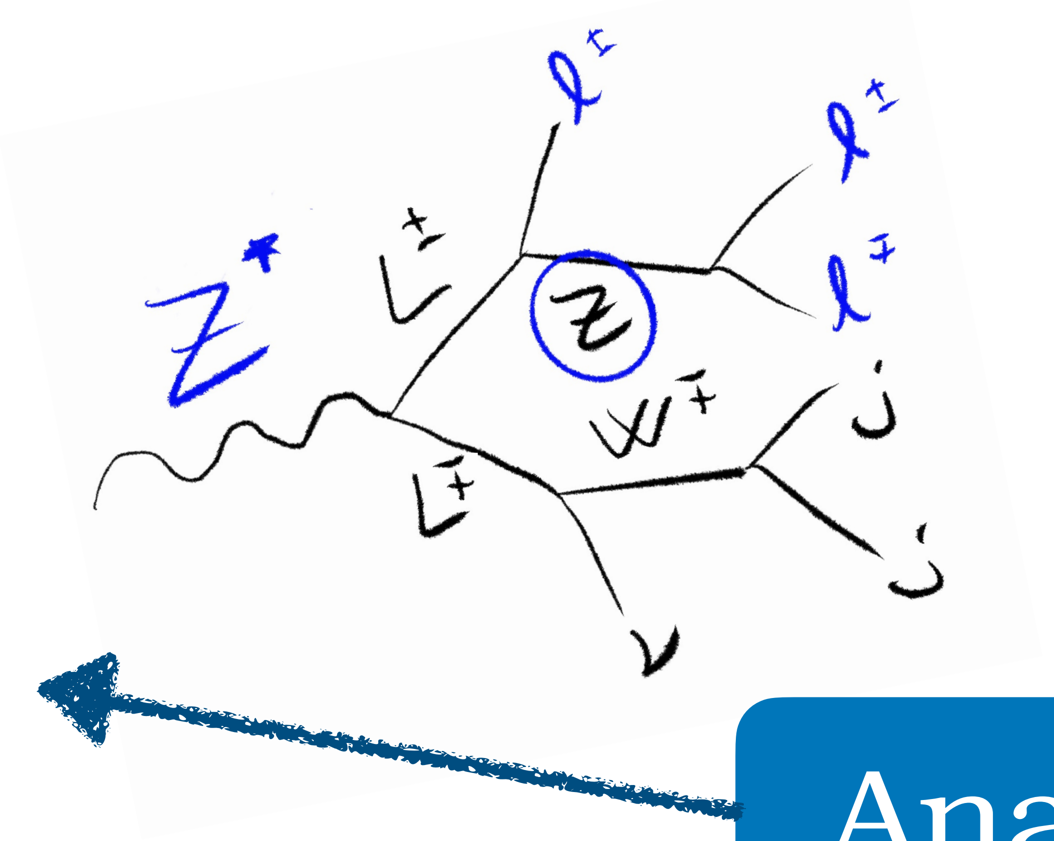
Analysis strategy

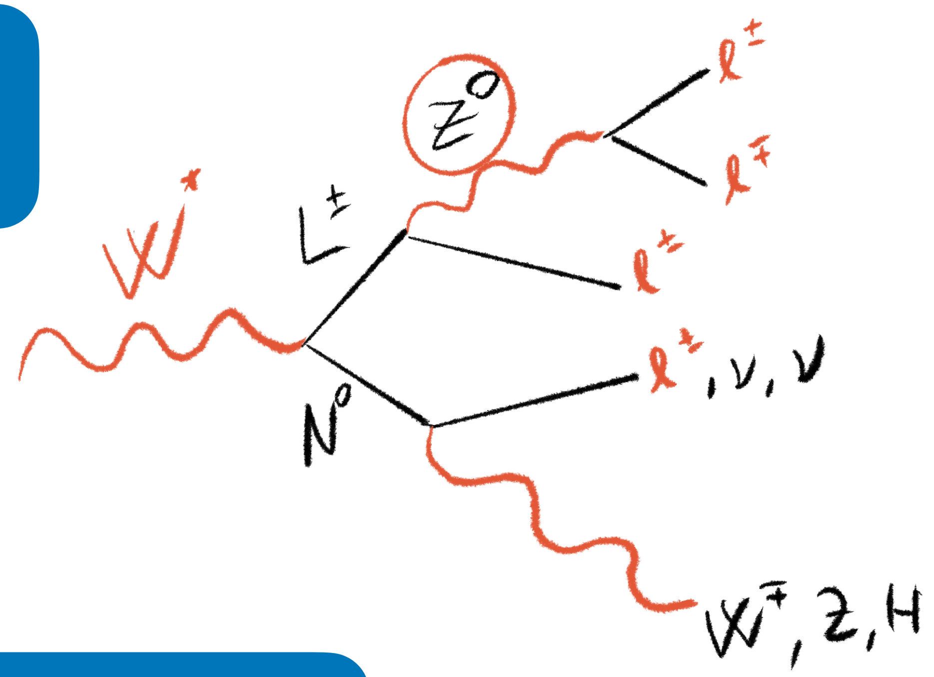
Theory models

Analysis regions definition

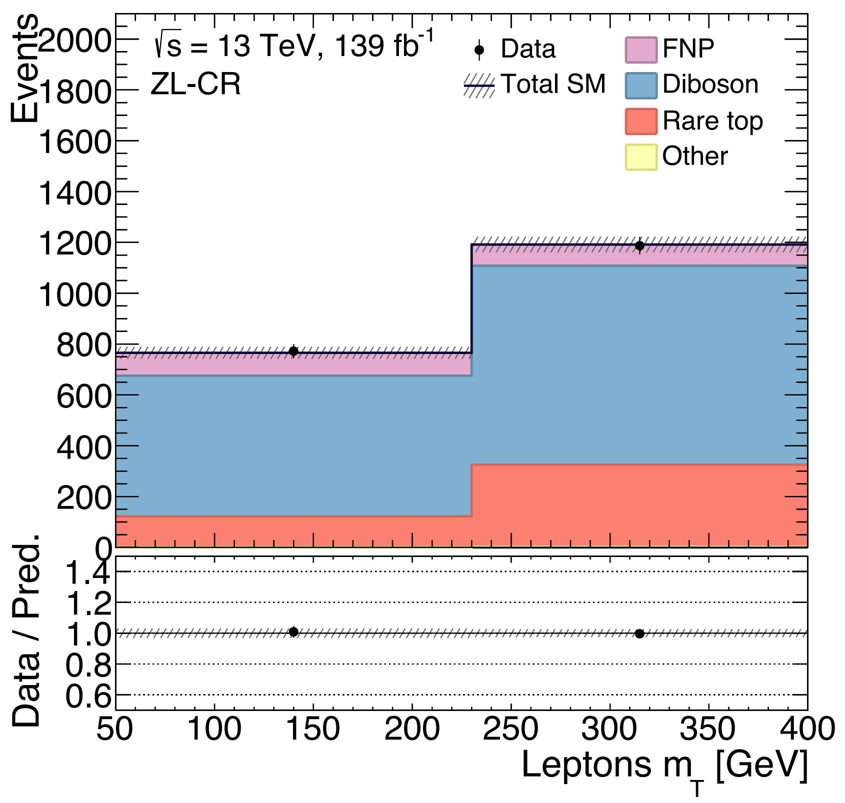
Background estimation

Statistical fit

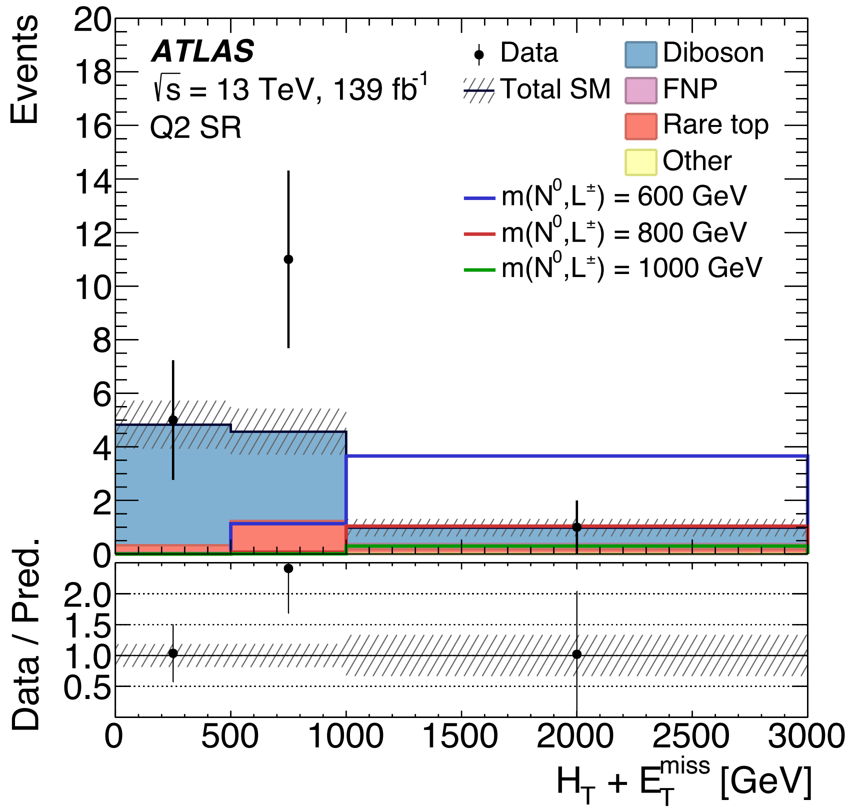




Control Regions



Signal Regions

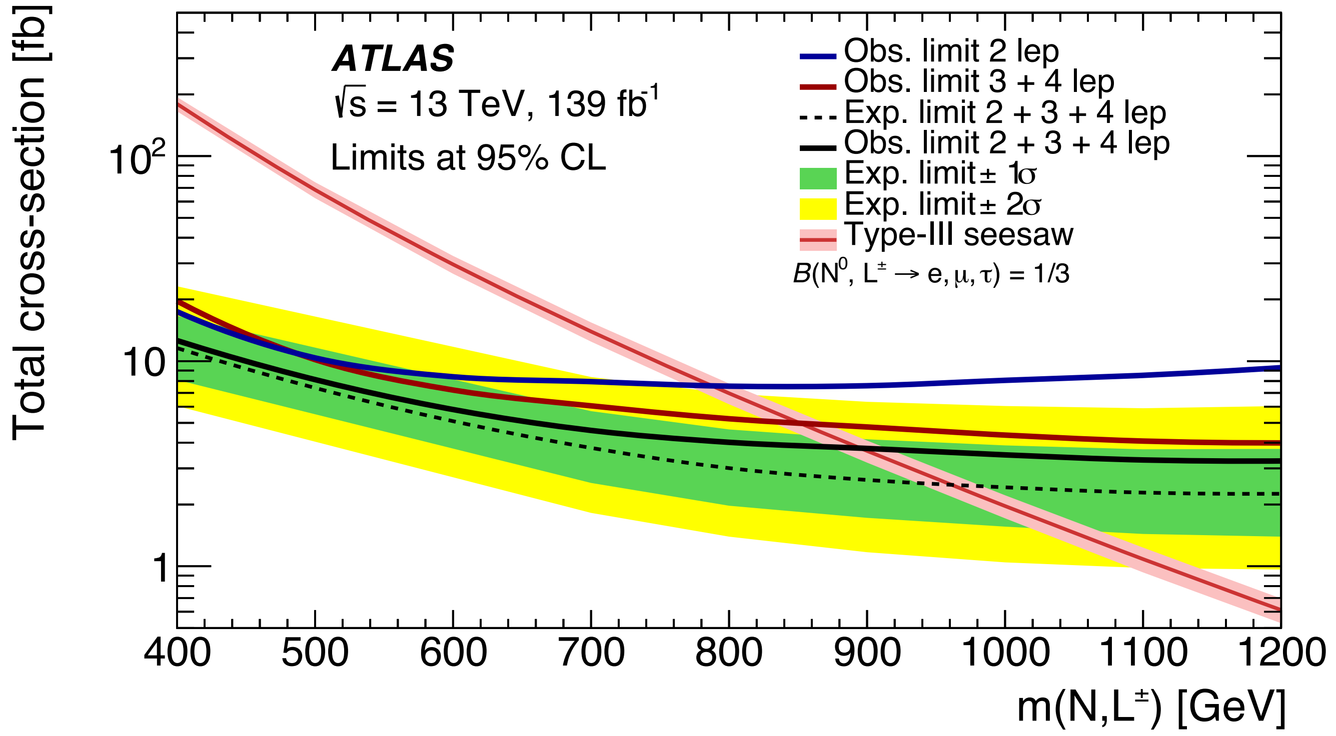


Irreducible background:
(SM processes)
Cut and count analysis

Reducible background:
(Fake leptons, charge flip)
Data-driven technique

Discovery

Upper limit



Fitting strategy

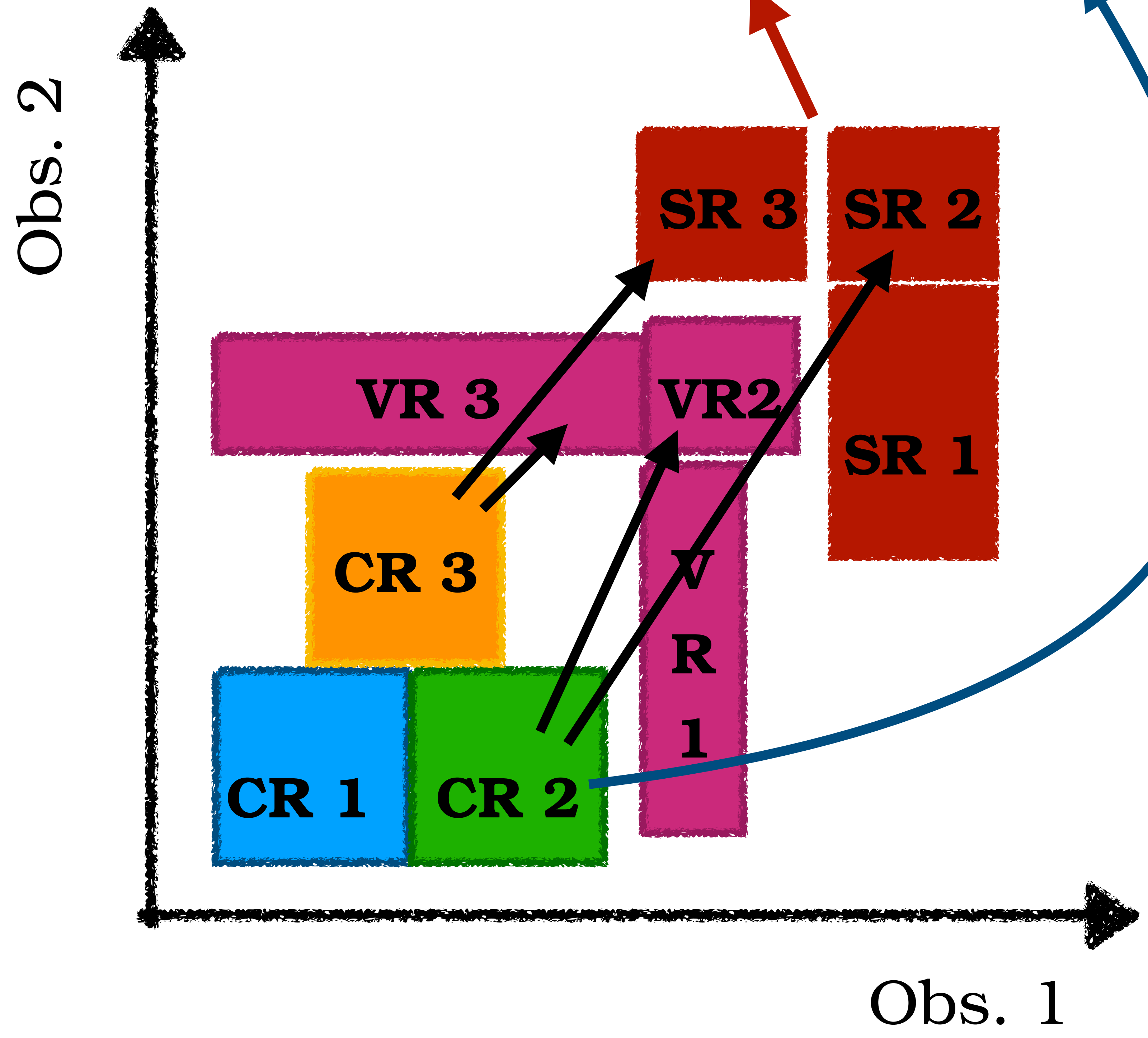
Signal extraction technique based on a binned maximum-**likelihood fit**

$$\mathcal{L}\left(\mathbf{n}, \boldsymbol{\theta}_0 | \mu_{sig}, \boldsymbol{\mu_b}, \boldsymbol{\theta}\right) = P_{SR} \times P_{CR} \times G_{NP}$$

Extract signal strength μ_{sig}

$n = \mu_{sig} \cdot S(\theta) + \mu_b \cdot B(\theta)$

under certain hypothesis (s+b, b)



Signal regions

Designed to contain the **majority of signal events** maximizing signal significance

Control regions

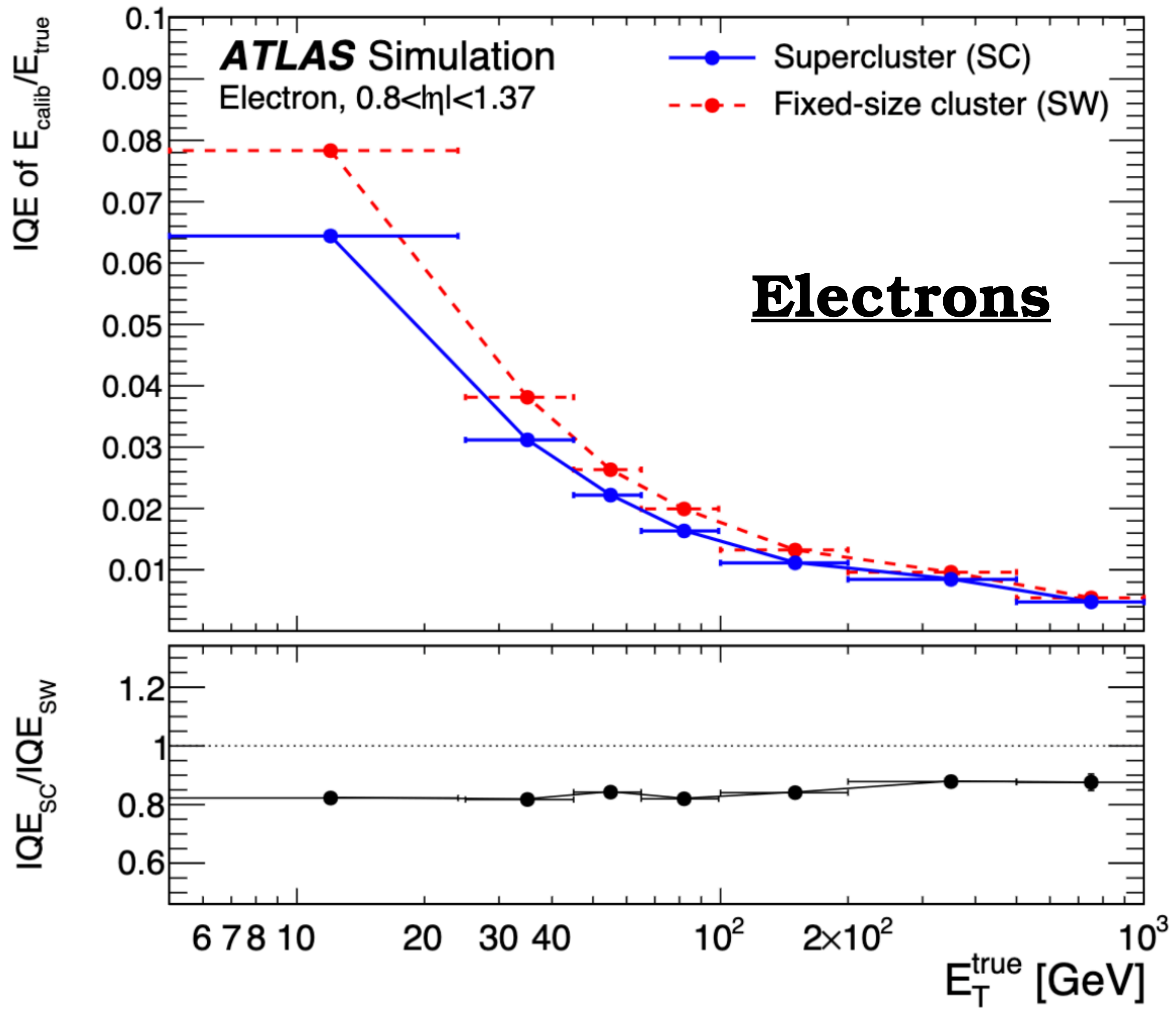
Extract normalization factors (**NF**) for dominant backgrounds (i.e. **diboson, raretop**)

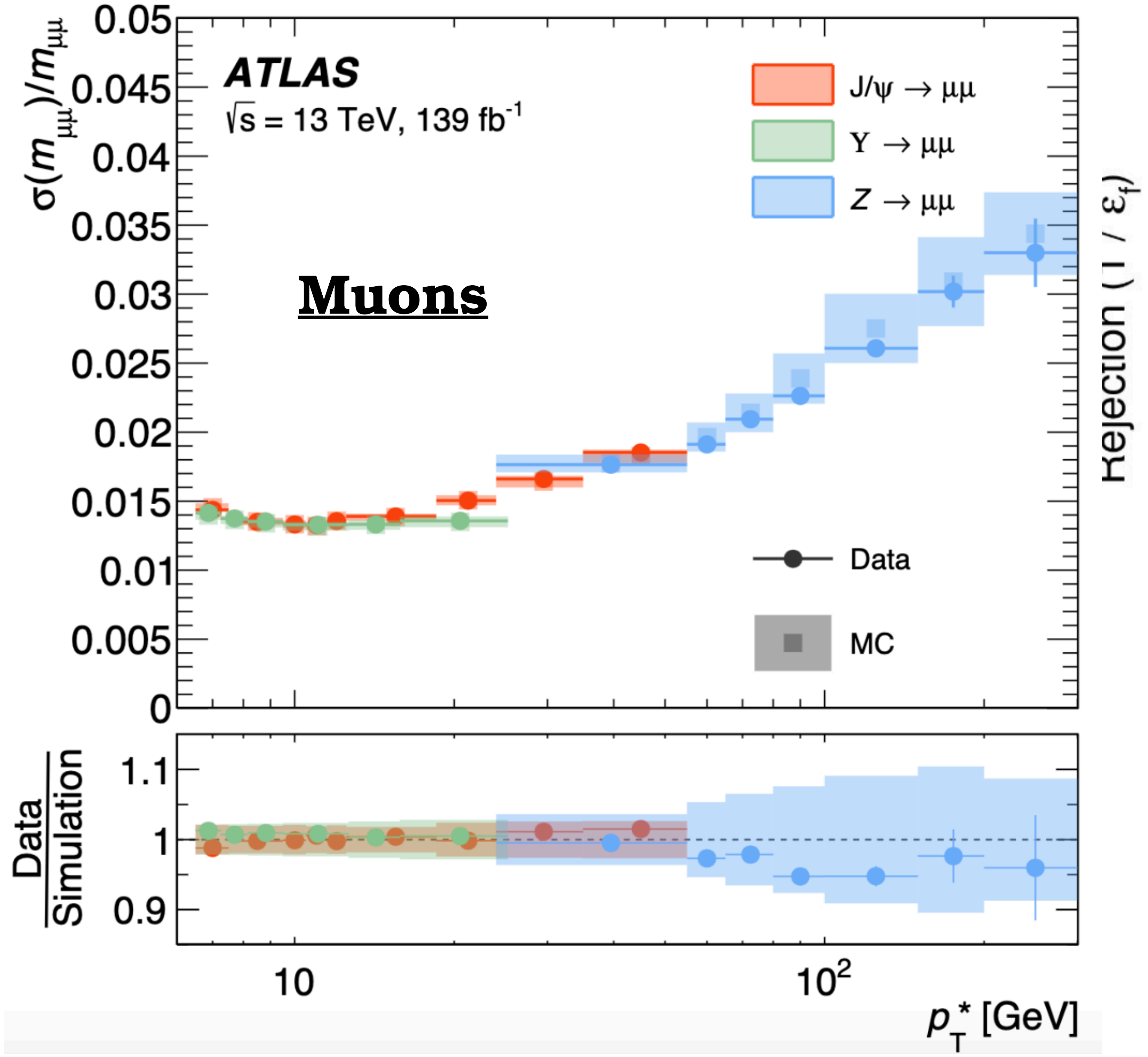
Validation regions

Validate the background estimation performed in the CRs

$$N_p(SR, \text{est.}) = N_p\left(CR, \text{obs.}\right) \cdot \left[\frac{MC_p(SR, \text{MC})}{MC_p(CR, \text{MC})}\right]$$

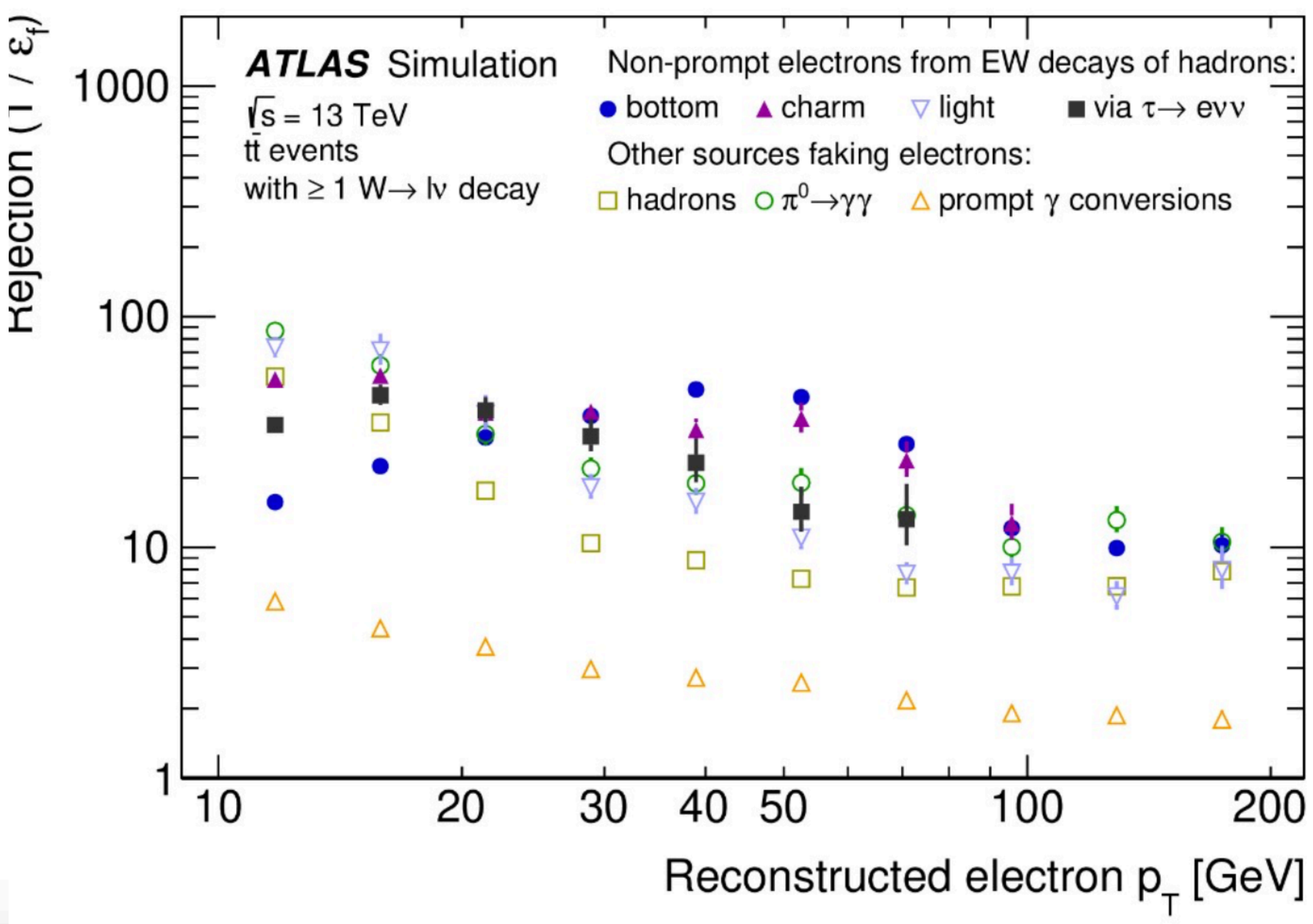
Leptons resolution in ATLAS





Fake Non-Prompt rejection factors

Electrons



Multileptonic final states (2, 3 and ≥ 4 leptons) are shared by many **beyond SM searches** and they are **poor of SM events** → **Increased impact** of **irreducible background** from SM

Many final states we have analyzed have **same sign leptons** (less abundant SM background) → **Charge flip electrons**

Type-III

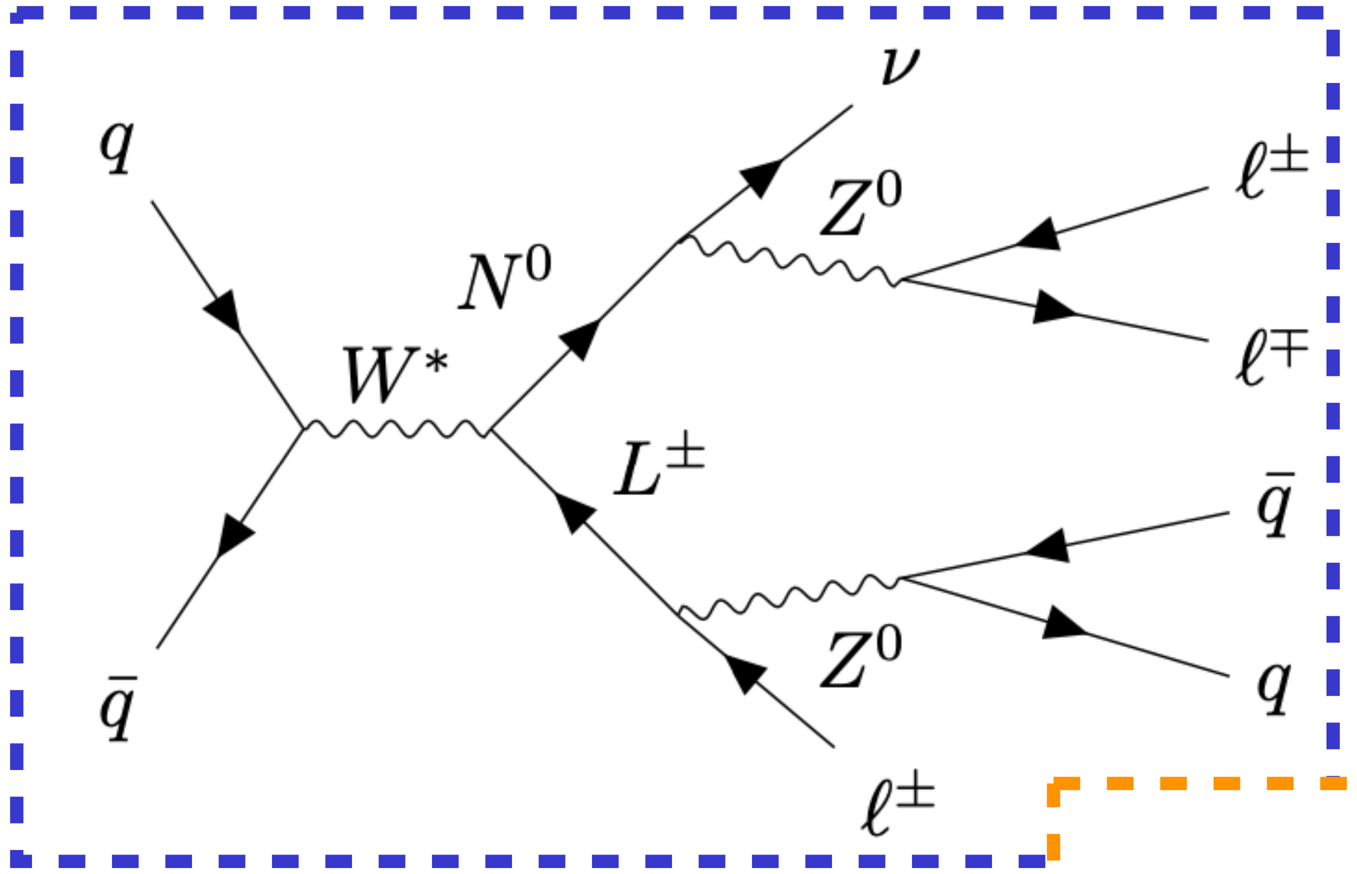
Type-III SeeSaw Search - Introduction

- **Type-III SeeSaw introduces** an extra **fermionic triplet** $(L^{\pm}, N^0)$. **Heavy Leptons (HL)** are considered **degenerate in mass** following the **minimal type-III** seesaw.

- **HL** pair production through virtual W, Z or Higgs bosons and decay into them and SM leptons.
  HL mass hypotheses in **400-1200 GeV** range

- For N^0 **masses larger than a few times the** H mass, the **decays into** different **SM bosons** are independent of the heavy-lepton mass

- **Only light leptons** are considered in the final states (electrons and muons).

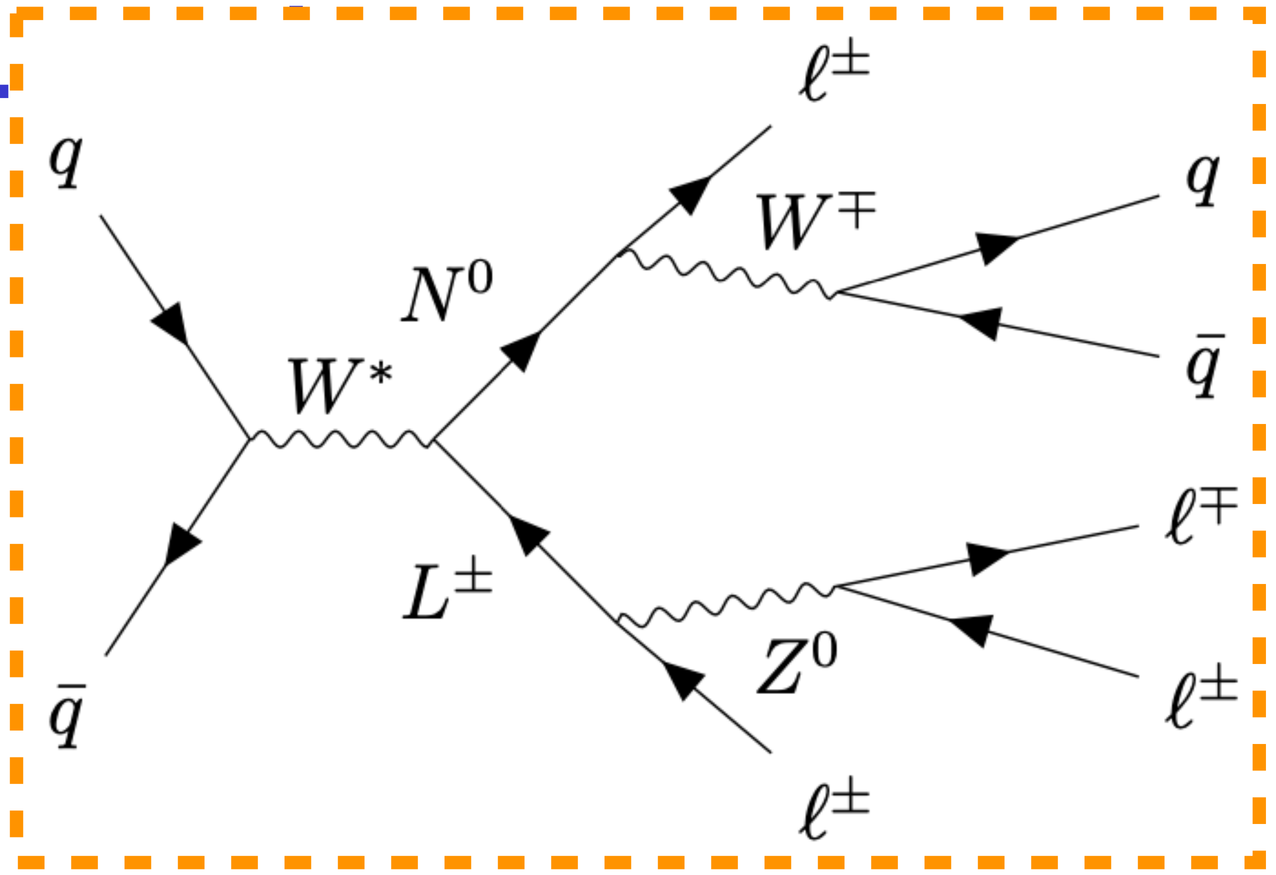


- **Multilepton paper**
- **DiLepton Paper**

Several decay modes to be accounted

⇓

Challenging SRs definition



- Considered two kinds of final states:
  - **3 leptons (0-1 jets or 2+ jets)**
  - **4 leptons**
- **Results combined** with the already published **2 leptons + 2 jets** final states

Type-III SeeSaw Search - Analysis Strategy

Three-lepton channel

Three kinds of final states looking at the HL decay modes:

- **ZL Region**: at least one of the HLs decay into a Z boson decaying leptonically
- **ZL Veto Region**: vetoing the HLs decay into a Z boson decaying leptonically
- **JNLow Region**: no more than 1 jet*

*__LO signal MC samples reweighted at the NLO__. **#jets** is very **sensitive to NLO corrections**. Asking for 0 jets can lead to an **overestimation of the signal efficiency**.

Four main backgrounds:

- **Diboson (WZ)** estimated in **ZL CR** and validated in **ZL DB-VR** and **JNLow VR**
- **RareTop** estimated in the **FourLepton CR** and validated in **ZL RT-VR**
- **Other** group of **minor backgrounds** as DY, $t\bar{t}$, single-top and triboson
- **Fakes estimated** with a **data-driven** technique and **validated** in **Fake-VR**

Four-lepton channel

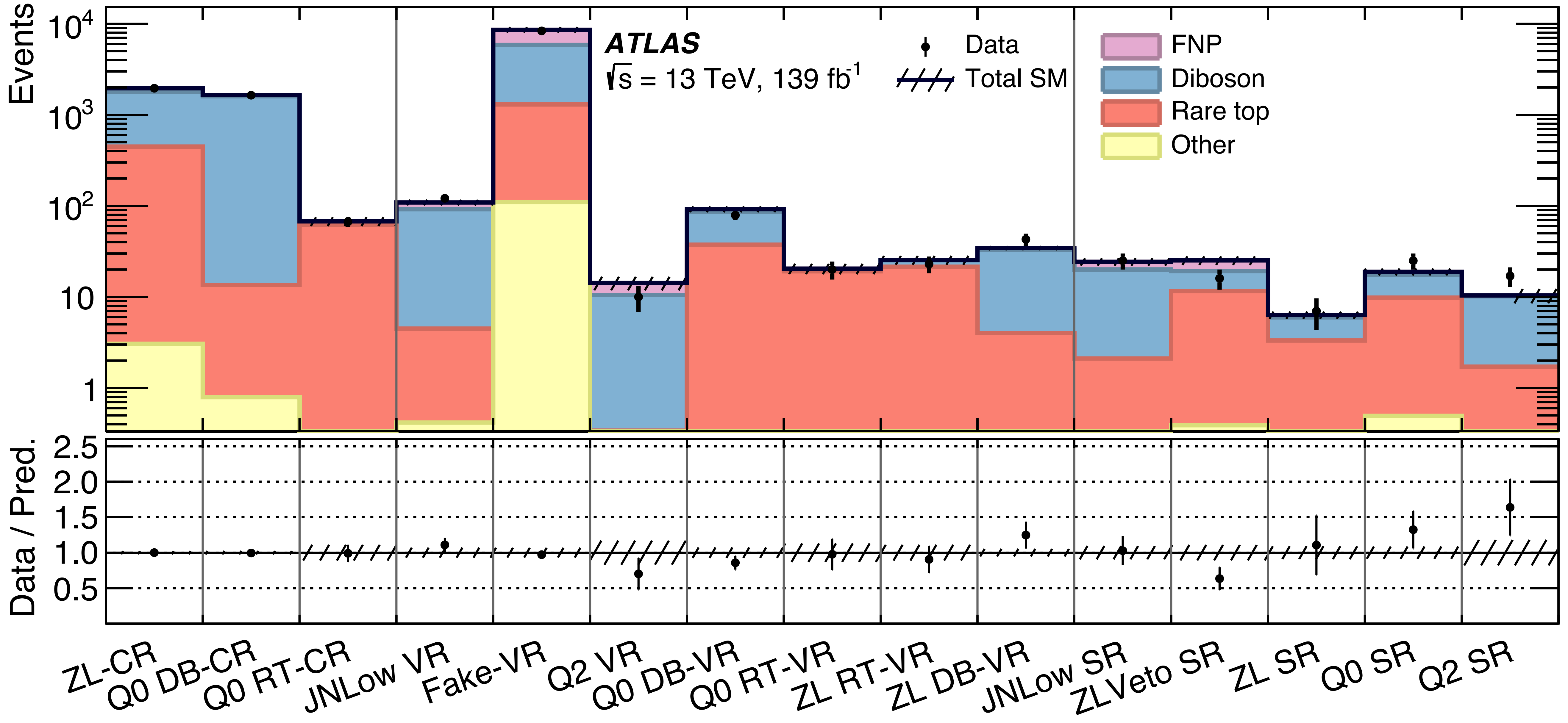
Two different phase spaces looking at the total charge of the final states:

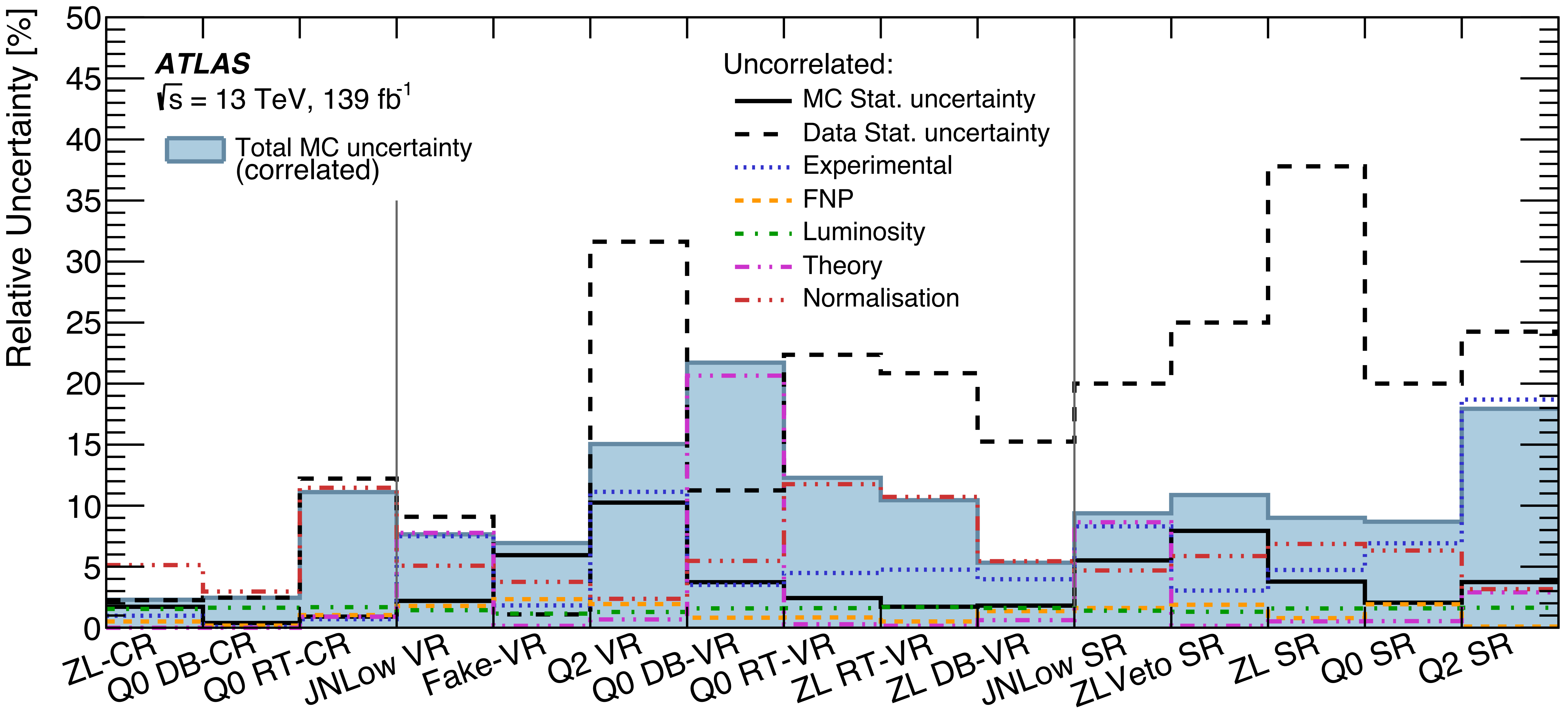
- **Q0**: total charge of the system is 0
- **Q2**: total charge of the system is ± 2

Four main backgrounds:

- **Diboson (ZZ)** estimated in **Q0 CR** and validated in **Q0 DB-VR** and **Q2 VR**
- **RareTop** estimated in **Q0 RT-CR** and validated in **Q0 RT-VR**
- **Other** group of **minor backgrounds** as DY, $t\bar{t}$, single-top and triboson
- **Fakes estimated** with a **data-driven** technique

Type-III SeeSaw Search - Results





Binned maximum-likelihood fit:

- 2L split in flavours $ee/e\mu/\mu\mu$ and charge OS/SS (*previous analysis, combined here*)
- 3L combined flavours $\ell\ell\ell$, transverse mass of three-lepton system as discriminant
- 4L combined flavours $\ell\ell\ell\ell$, $H_T + E_T^{miss}$ as discriminant
- Combination 3L + 4L, 2L + 3L + 4L

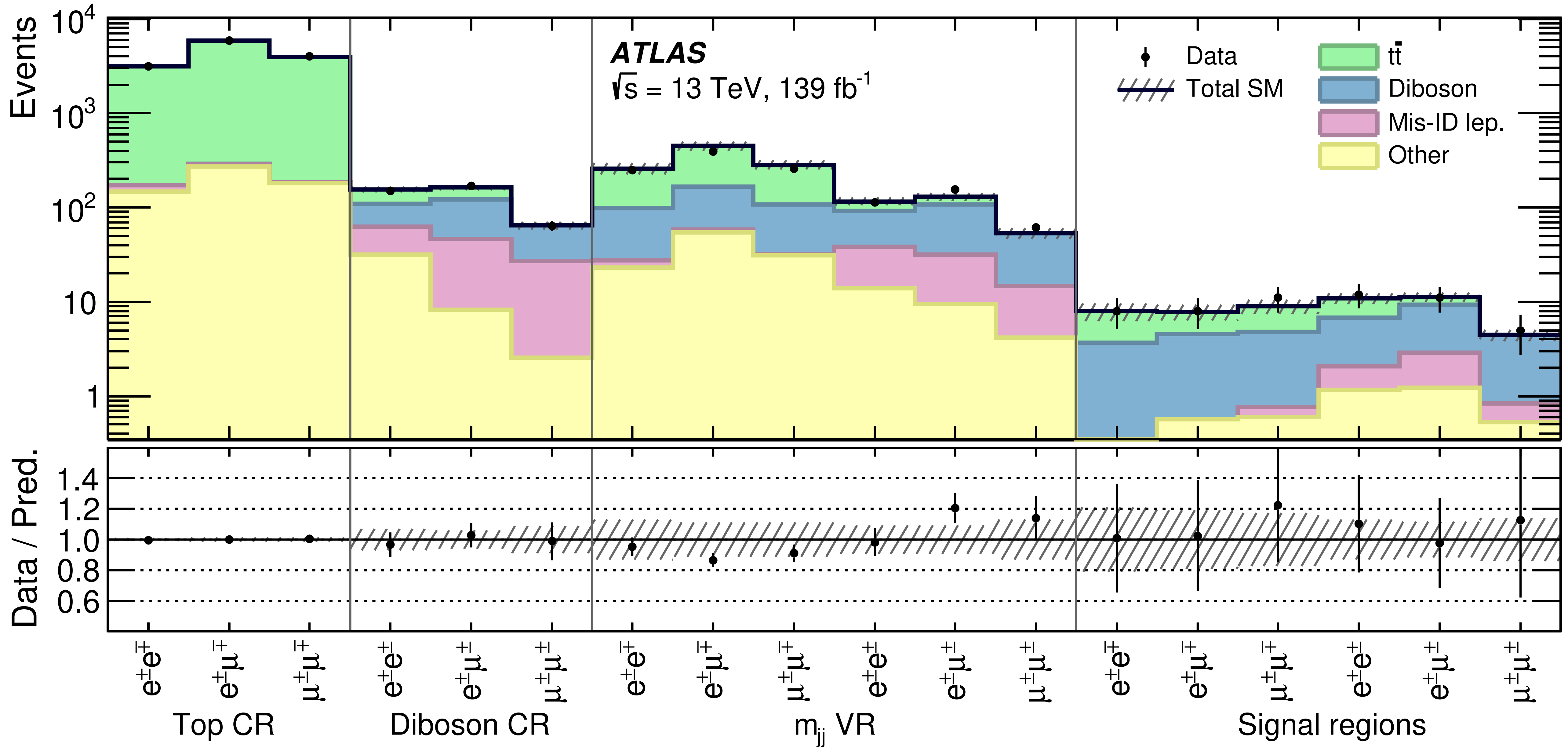
Main backgrounds floating in the fit

- **Diboson-3l (WZ):** from ZL CR to TriLepton regions
- **Diboson-4l (ZZ):** from Q0 Diboson CR to FourLepton regions
- **RareTop:** from Q0 RareTop CR to Tri- and FourLepton regions

Normalization Factor	μ_{norm} - 3lep	μ_{norm} - 4lep
diboson-3l	0.85 ± 0.03	-
diboson-4l	-	1.08 ± 0.03
raretop	-	1.4 ± 0.2

From 3L + 4L combination fit

Type-III SeeSaw Search - Results



Binned maximum-likelihood fit:

- 2L split in flavours $ee/e\mu/\mu\mu$ and charge OS/SS (*previous analysis, combined here*)
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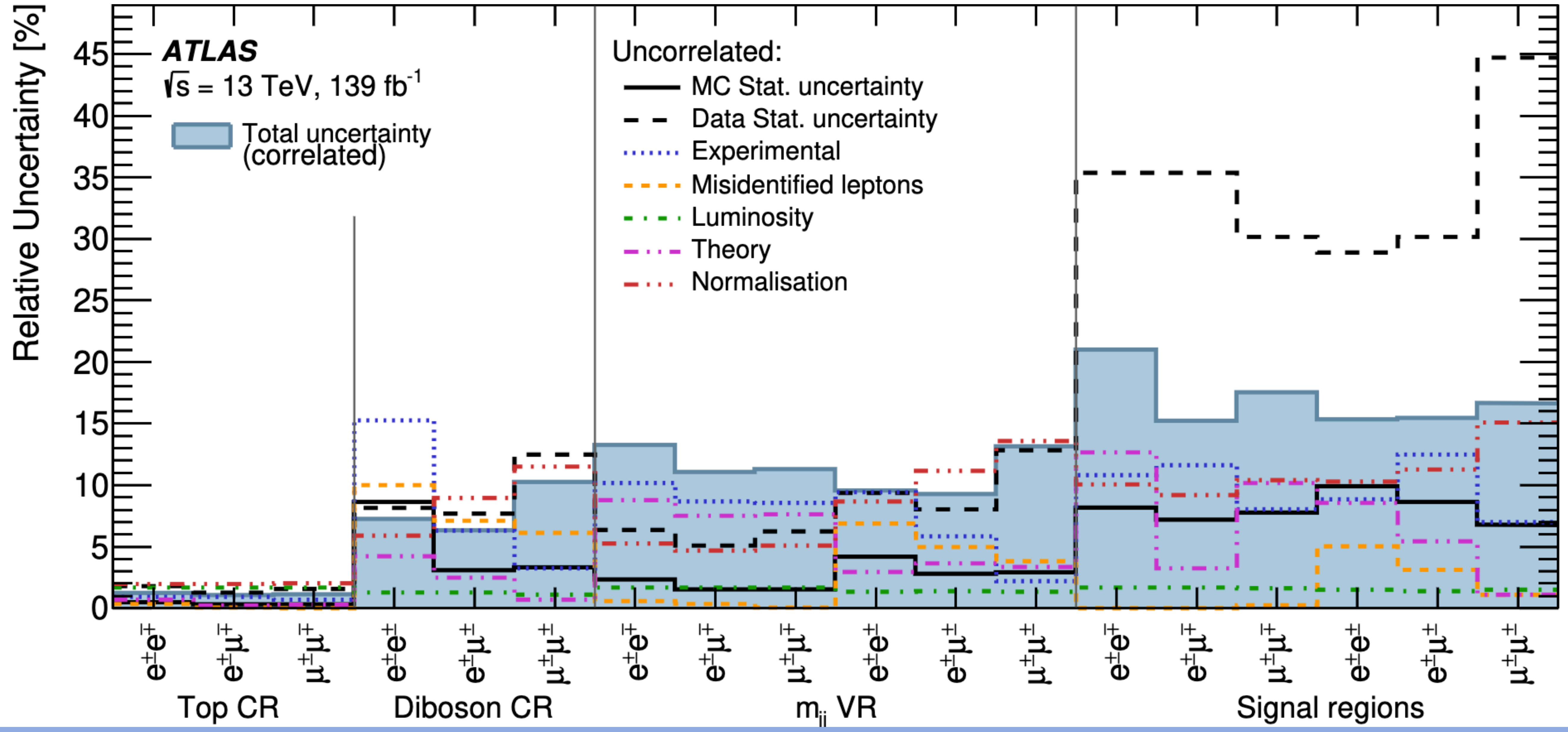
- Combination 3L + 4L, 2L + 3L + 4L



Main backgrounds floating in the fit

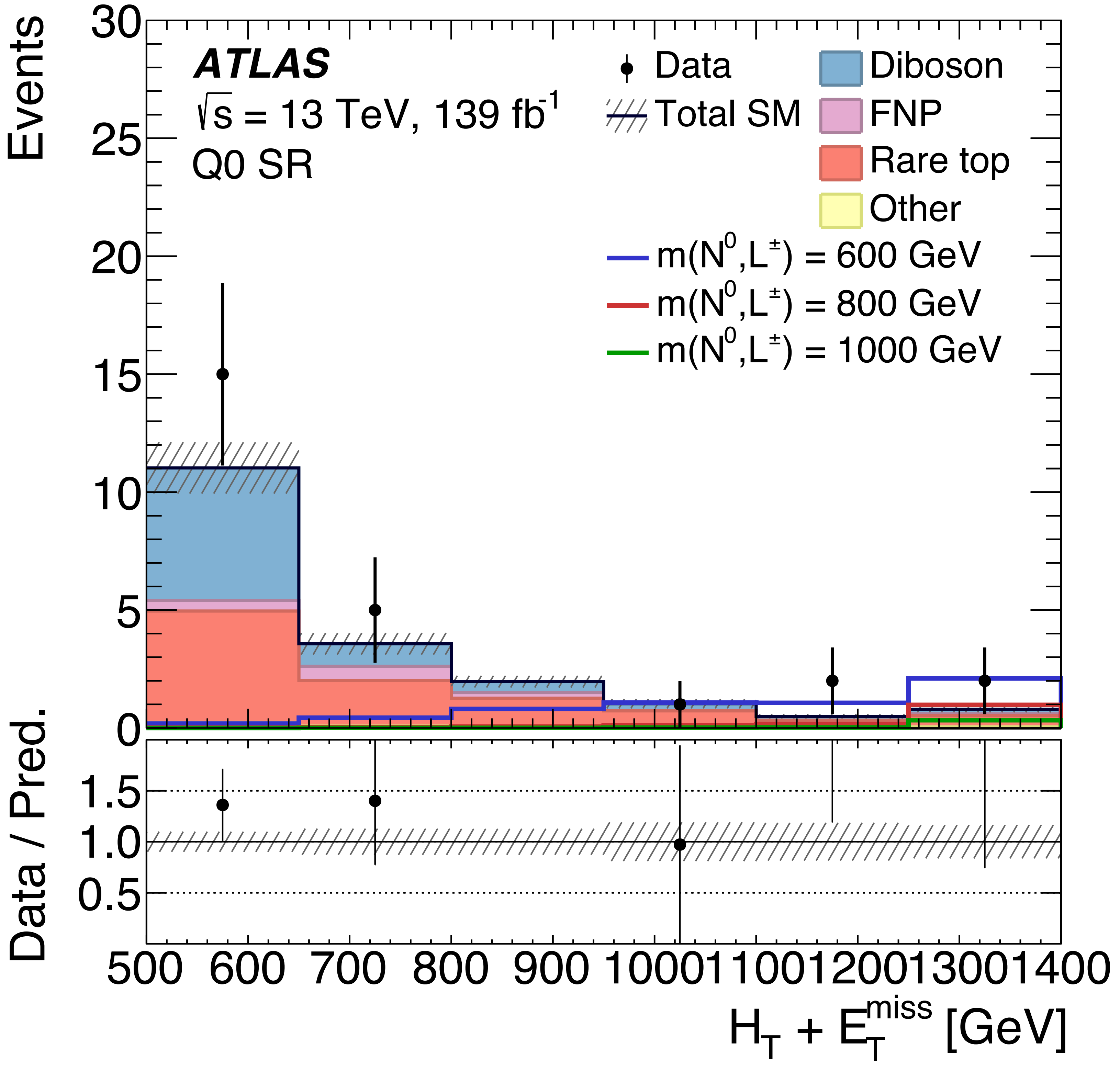
- **Diboson-2l (WW):** from Diboson CR
- **$t\bar{t}$:** from Top CR

MC process	scaling factor
$t\bar{t}$	0.96 ± 0.02
diboson	1.03 ± 0.14

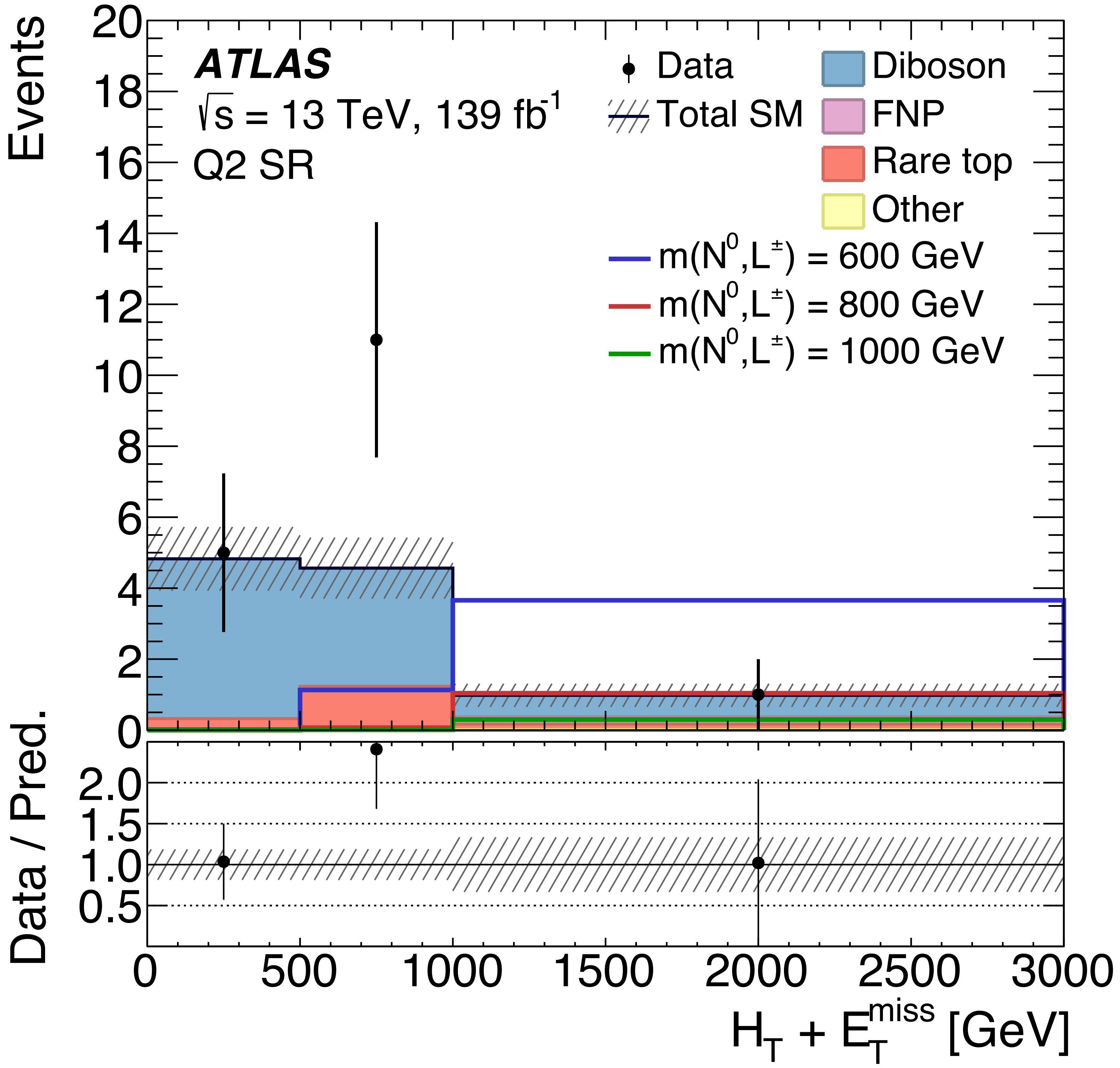
From 2L only fit

Type-III SeeSaw Search - Discrepancy on 4L

Some discrepancies observed in the four-lepton final states.



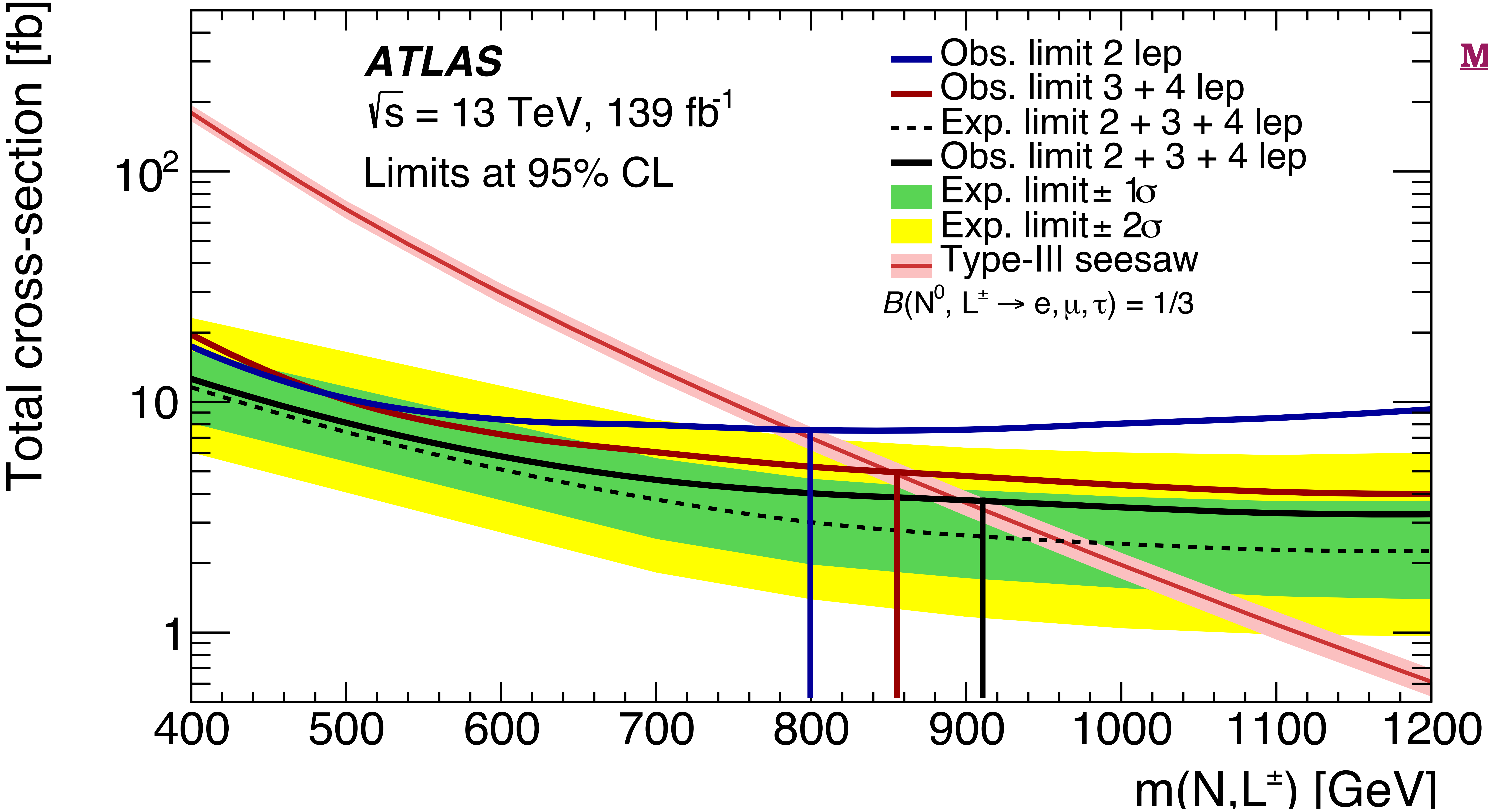
Very low statistics in the last two bins of the **4L Q0 SR**.



Clear discrepancy in the **second bin** of the **4L Q2 SR**.

Excess deeply studied: underestimation of the electron charge-flip contribution (coming from a semi-data driven technique).

Type-III SeeSaw Search - Results



MultiLep HEPData

DiLep HEPData

DiLepton fit:

2 lepton final state

- **Expected limit:** 820^{+40}_{-60} GeV
- **Observed limit:** 790 GeV

Combined fit:

3 + 4 lepton final states

- **Expected limit:** 900^{+80}_{-80} GeV
- **Observed limit:** 870 GeV

Full fit:

2 + 3 + 4 lepton final states

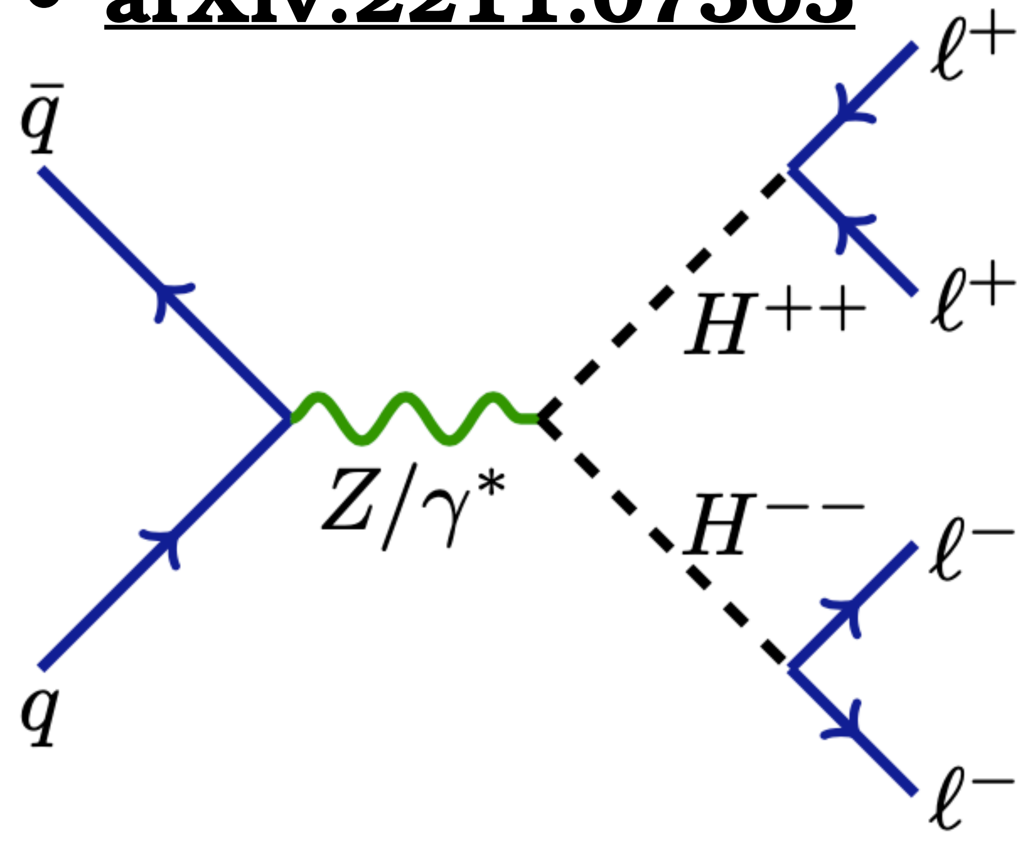
- **Expected limit:** 960^{+90}_{-90} GeV
- **Observed limit:** 910 GeV

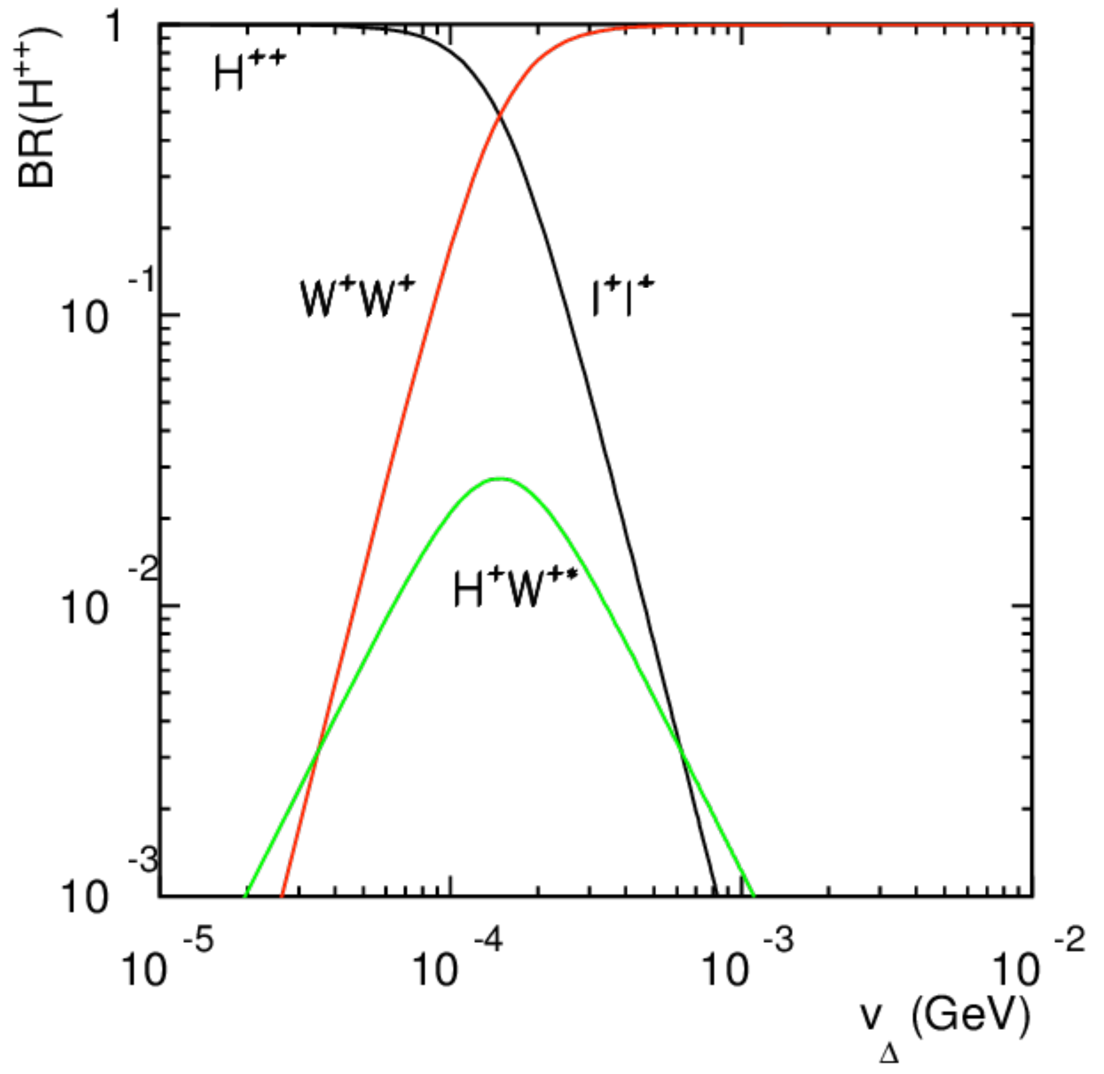
Type-II

Type-II SeeSaw Search - Introduction

- **Left-Right Symmetric Model within Type-II Seesaw mechanism:** two chiralities $H_L^{\pm\pm}$ and $H_R^{\pm\pm}$
- **Searching for $H^{\pm\pm}$ pair production** in all lepton flavour and charge combinations: $H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$, where $\ell = e, \mu, \tau$
- Lepton-Flavour Violation is allowed.
- $v_\Delta \to 0$ GeV to exclude decays to W bosons.
- Search for $m_{H^{\pm\pm}}$ in a range 300-1300 GeV focusing on two-lepton, three-lepton and four-lepton final states
- Only light leptons (electrons and muons) are considered in this analysis (also the ones from τ leptonic decays).

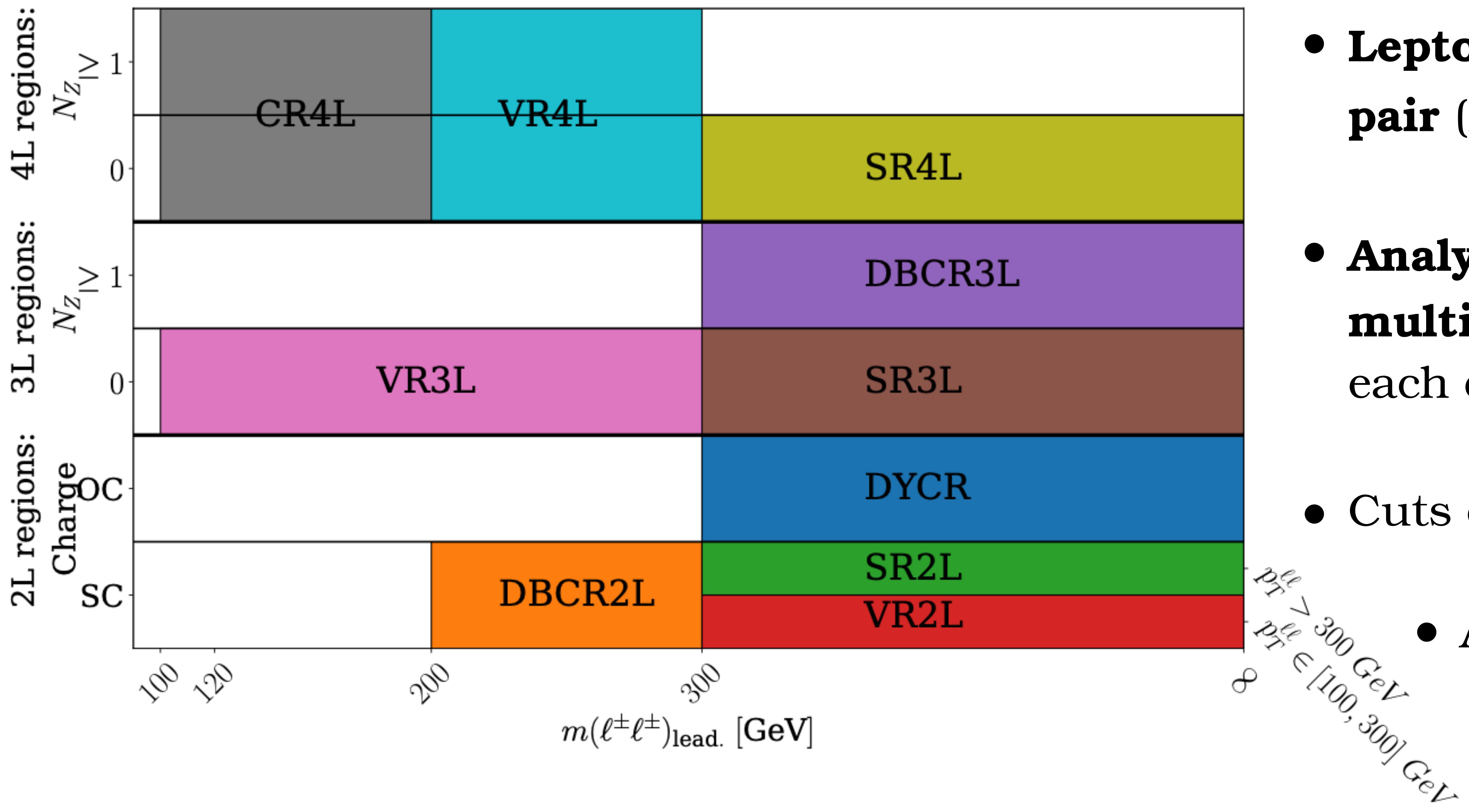
- **arXiv:2211.07505**





Search for $H^{\pm\pm} \to W^{\pm}W^{\pm}$ also **performed by ATLAS**, providing lower mass limits.
JHEP06 (2021) 146

Type-II SeeSaw Search - Analysis Strategy



- **Lepton multiplicity** and **invariant mass of SS leading lepton pair** ($m\left(\ell^{\pm}\ell^{\pm}\right)_{\text{lead.}}$) ensure **analysis regions orthogonality.**
- **Analysis regions** are **defined** on the basis of the event **lepton multiplicity** and **flavour combinations** - optimised cuts for each channel
- Cuts on p_T and ΔR of $\ell^{\pm}\ell^{\pm}_{\text{lead.}}$ reflect boosted topology
  - Additional E_T^{miss} and $\eta(\ell\ell)$ in ee channel to remove Drell-Yan.
- Final discriminant:
  - $m\left(\ell^{\pm}\ell^{\pm}\right)_{\text{lead.}}$ for two- and three- lepton channels
  - $\bar{M}$ for four-lepton channel.

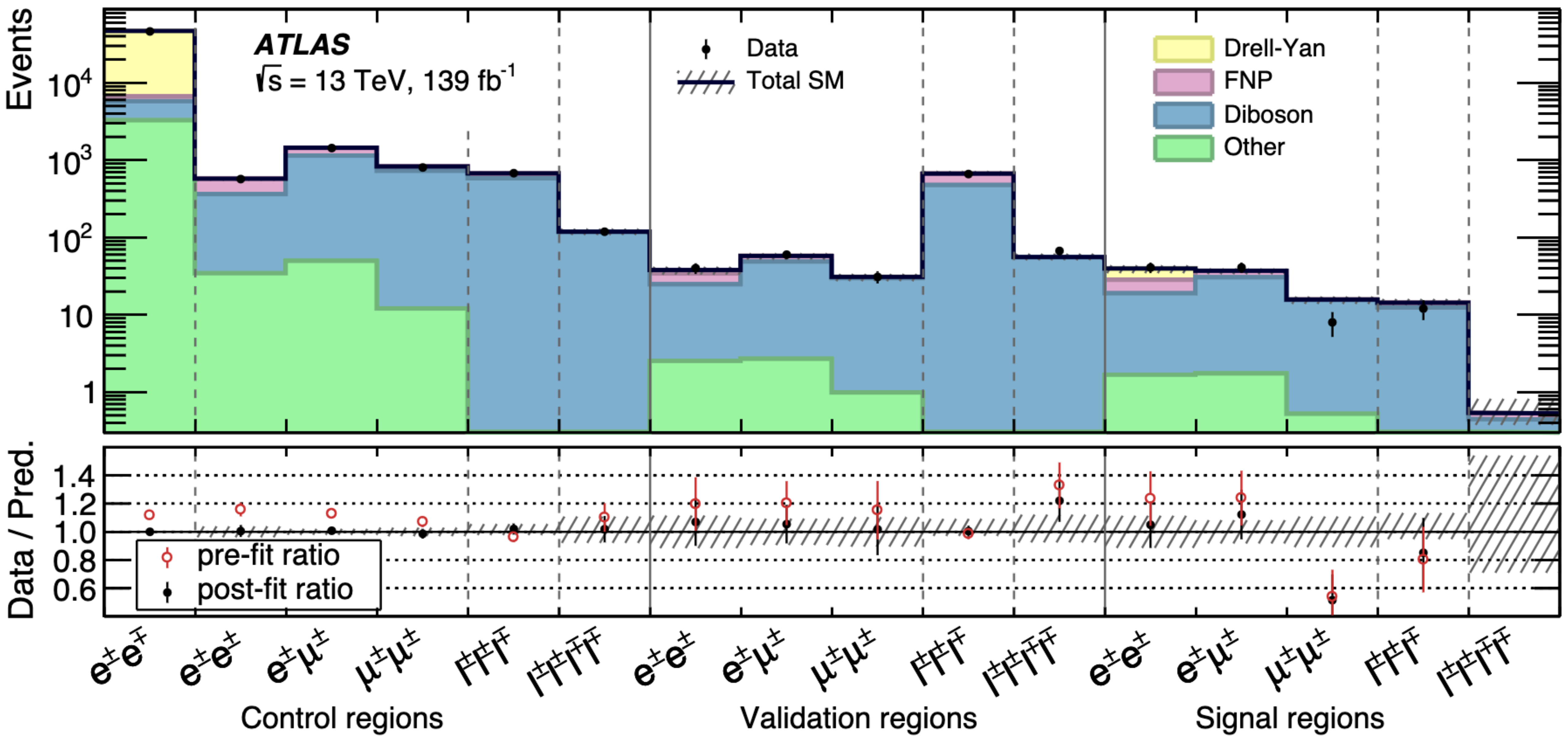
$$\bar{M} = \frac{m\left(\ell^{+}\ell^{+}\right) + m\left(\ell^{-}\ell^{-}\right)}{2}$$

Main backgrounds: fakes, diboson, Drell-Yan, other (rare-top, single-top, ttbar, multi boson)

Background estimation:

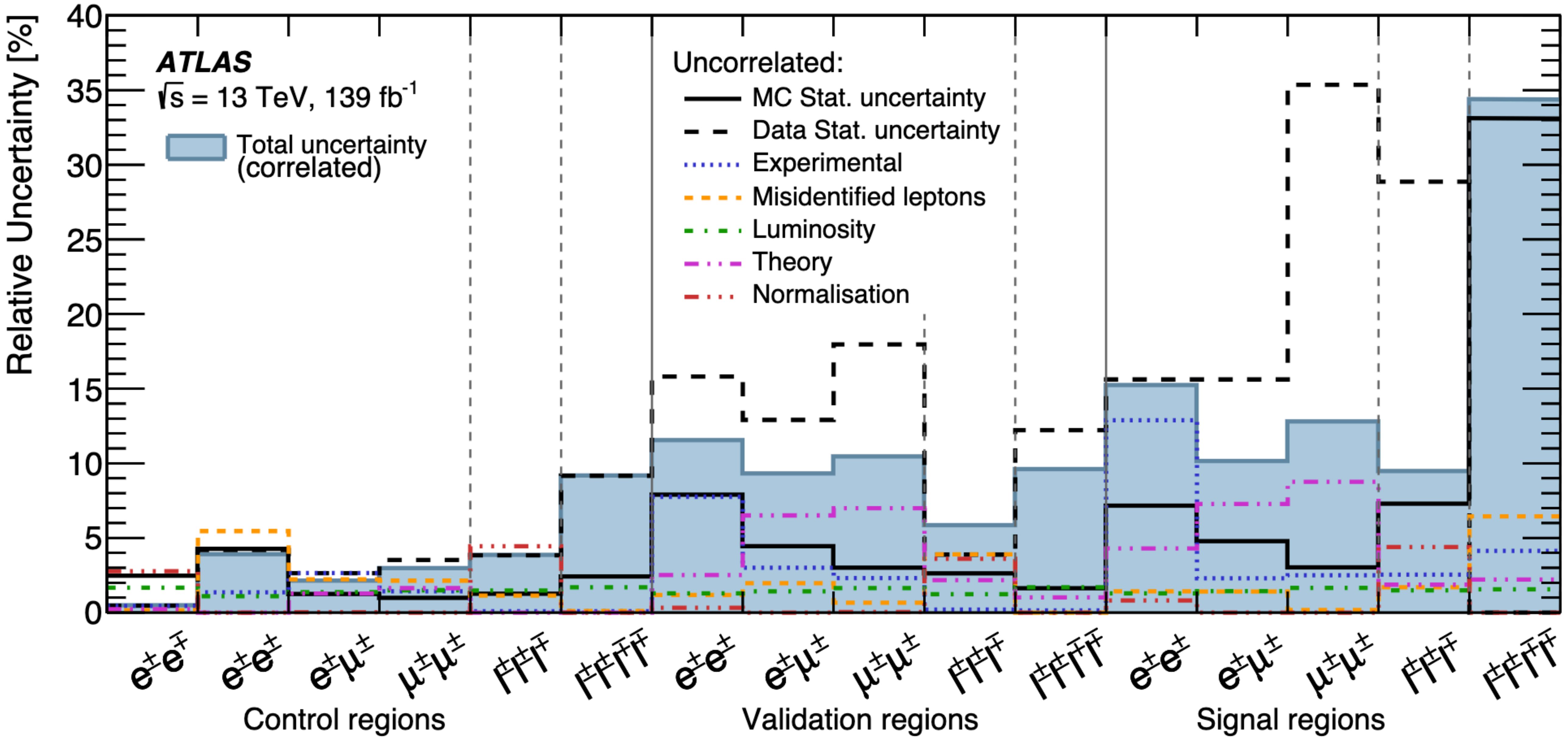
- prompt SM backgrounds (diboson, DY, …) estimated from MC simulation
- events containing at least one fake lepton are estimated using data-driven matrix method
- electron charge flip weight from semi data-driven technique

Type-II SeeSaw Search - Results



Binned maximum-likelihood fit:

- 2L split in flavours $ee/e\mu/\mu\mu$, variable binning in CRs and SRs
- 3L combined flavours $\ell\ell\ell$, variable binning in CRs and SRs
- 4L combined flavours $\ell\ell\ell\ell$, single bin $\bar{M}$ = event yield
- Combination of 2L + 3L + 4L



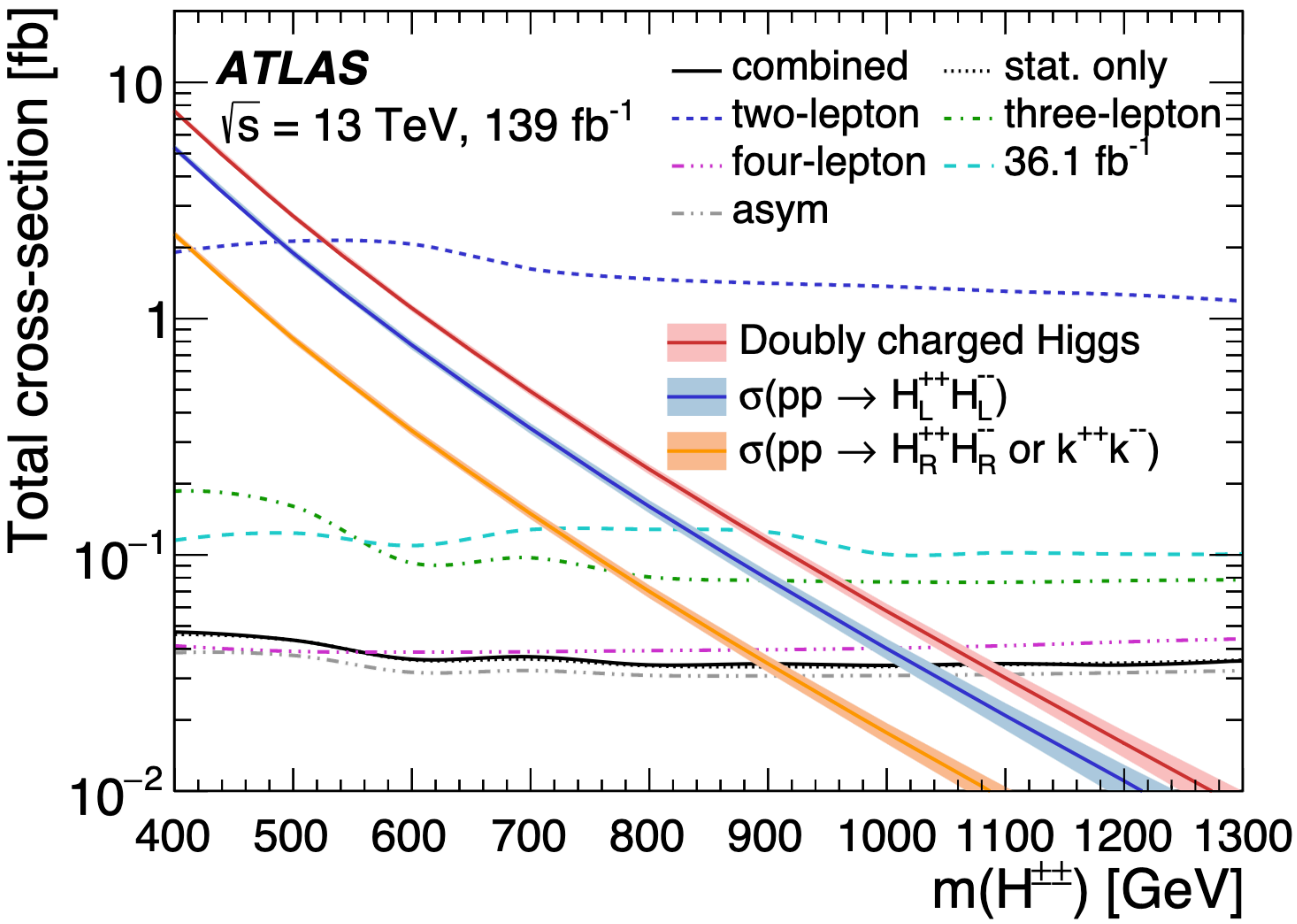
Main backgrounds are floating in the fit to extrapolate normalisation factors:

- Drell-Yan and diboson-2l (WW) in two-lepton regions
- Diboson-3l (WZ) in three-lepton regions
- Diboson-4l (ZZ) in four-lepton regions

normalisation factors	
μ^{DY}	1.13 ± 0.04
μ^{DB}_{2l}	1.10 ± 0.06
μ^{DB}_{3l}	0.92 ± 0.05
μ^{DB}_{4l}	1.08 ± 0.11

From combination fit

Type-II SeeSaw Search - Results



DCH HEPData

Channel	Expected limit [GeV]	Observed limit [GeV]
2l	540^{+40}_{-60}	520
3l	920^{+70}_{-50}	930
4l	990^{+70}_{-80}	1030

Global limits:

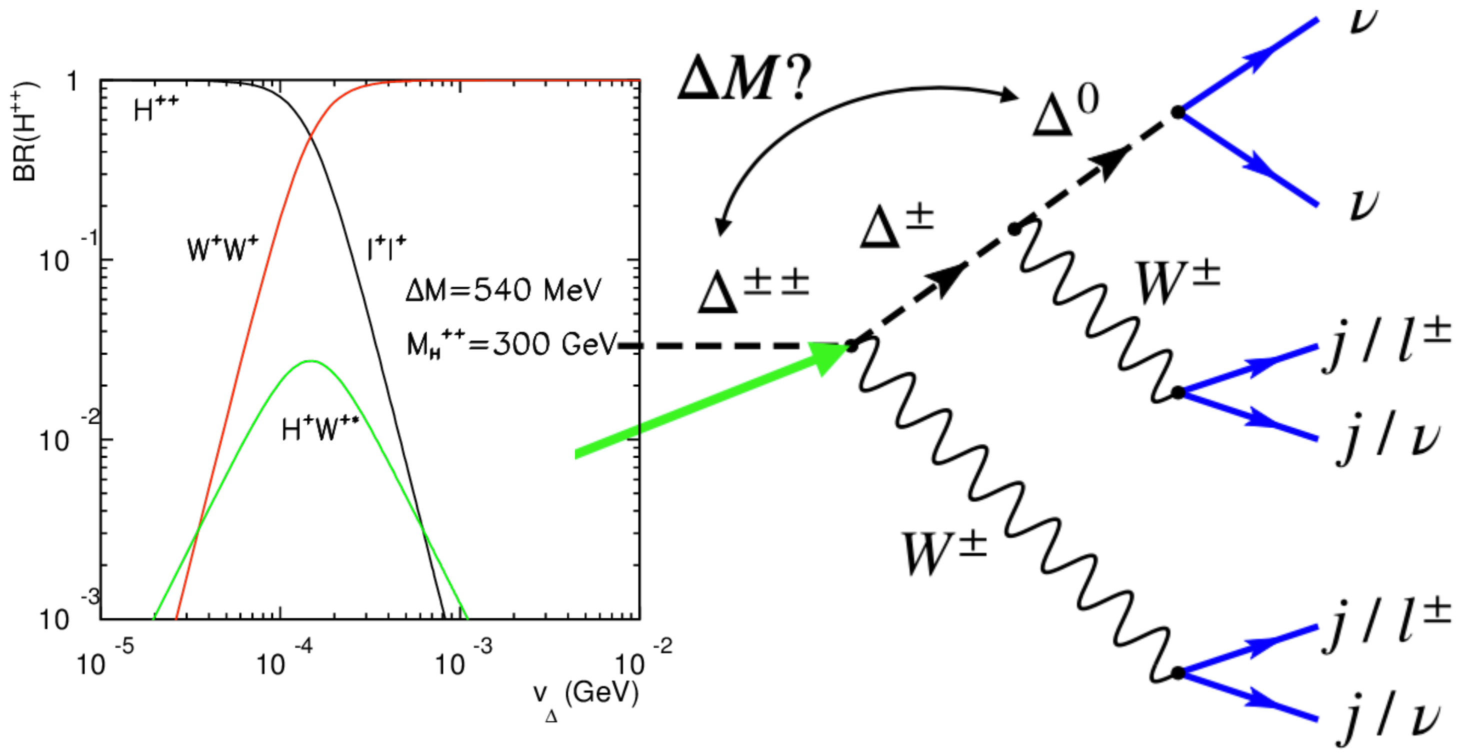
- Combination (2l+3l+4l):
  - Observed 1080 GeV
  - Expected 1065^{+30}_{-50} GeV
- Right-handed $H^{\pm\pm}$:
  - Observed: 900 GeV
  - Expected 880^{+30}_{-40} GeV

Provided also an **interpretation of the Zee–Babu model**, with the same limits of the right-handed component.

Type-II SeeSaw Search - New Scenario

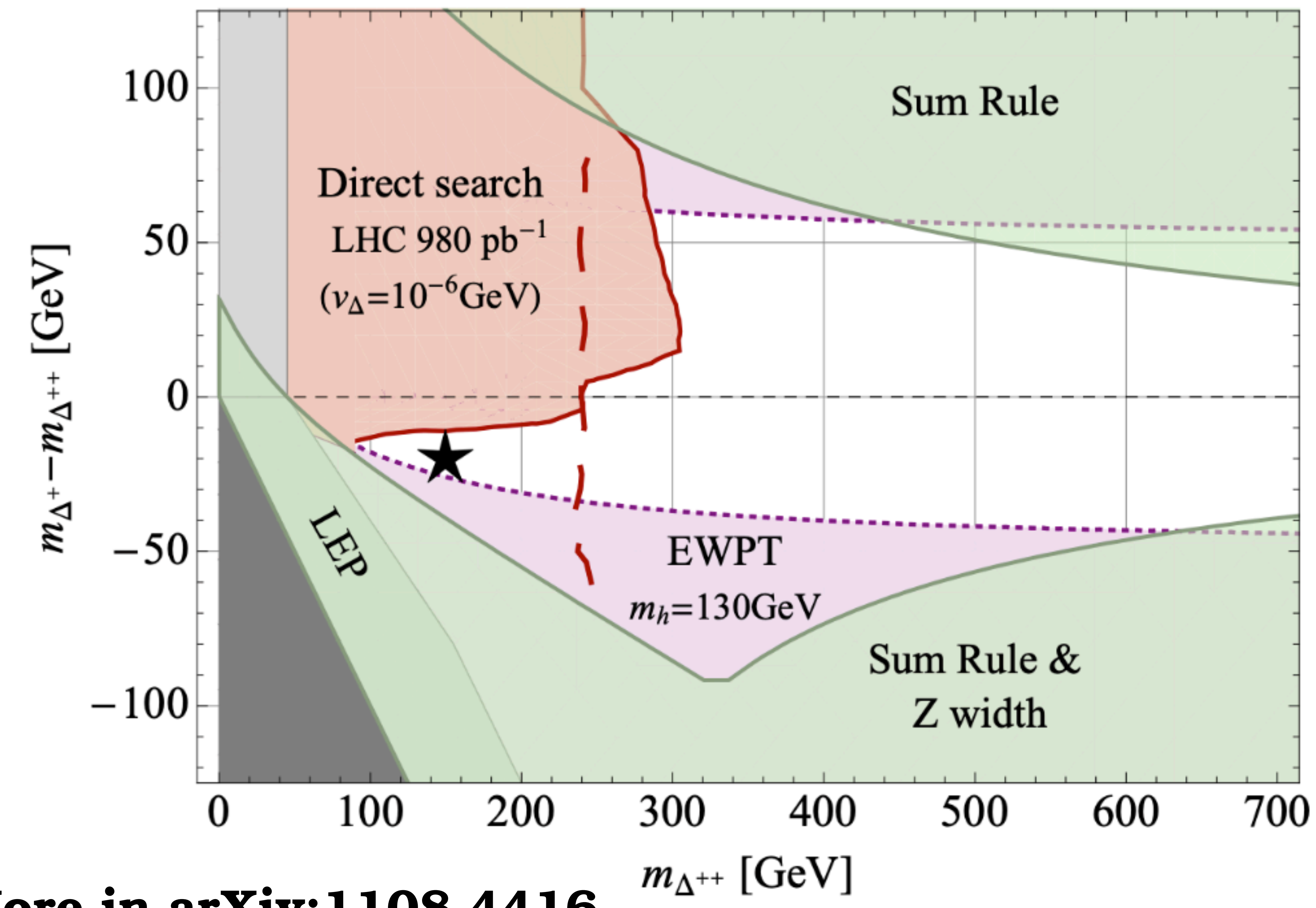
Our colleagues from Ljubljana proposed **two different scenarios within the canonical** (not LRSM) **type-II seesaw model** which we may study:

- Increase the vet v_Δ to higher values (around 10^{-4} GeV) so that $H^{\pm\pm} \to \ell^\pm \ell^\pm / W^\pm W^\pm$ are possible
- **Cascades model**: Up to now, we consider only the case where $m_{\Delta^\pm} = m_{\Delta^{\pm\pm}}$, while if we account also the case where $\Delta M = m_{\Delta^\pm} - m_{\Delta^{\pm\pm}}$, a whole new spectra of possible decay channels occurs. This scenario can be called the "**Cascades**", since Δ^0 decays consecutively to $\Delta^\pm W^\mp$ and $\Delta^\pm$ further down to $\Delta^{\pm\pm} W^\mp$



Since the mass splitting is not expected to be very large:

- Δ^0 predominantly decays into a pair of ν, at large enough energies also to a pair of Hs or Zs
- $\Delta^{\pm\pm}$decays into a $\ell^\pm \ell^\pm$ or $W^\pm W^\pm$, which depend on ν_Δ value. This means that we are eventually looking for the same final state as the previous analysis (and a couple of low energy jets/ lepton from W emission).



- **More in arXiv:1108.4416**

Type-II SeeSaw Search - 331 Model

Possible **reinterpretation of the analysis** in terms of **vector bosons** from the **Dilepton Model** (331)

The **331 Model introduces** three types of **new particles beyond the SM**: *gauge bosons, exotic quarks* and *additional scalars*

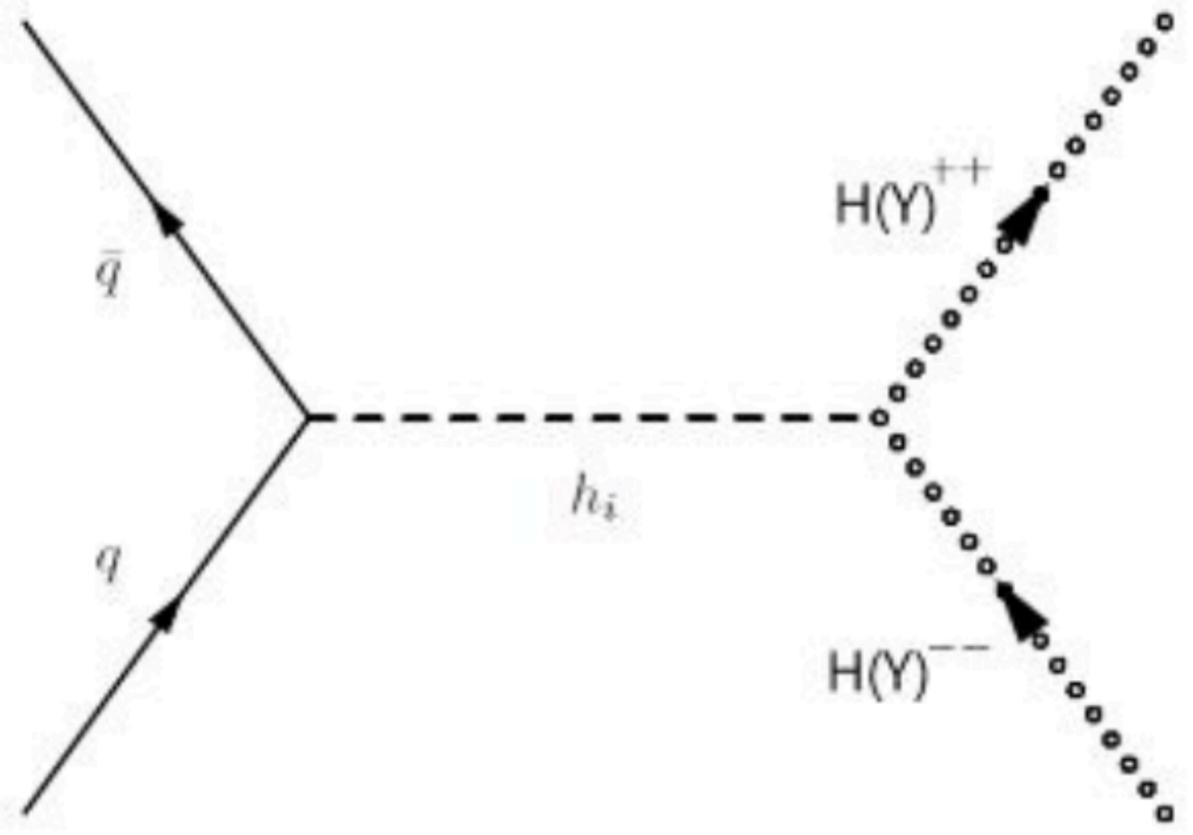
Strong interaction $SU(3)_C \times SU(3)_L \times U(1)_X$ **Electroweak sector extended**

LFV not allowed in 331 model

5 extra gauge bosons (including Z') and four bileptons

$$W_\mu^{\pm} = \frac{W_\mu^1 \mp iW_\mu^2}{\sqrt{2}} \qquad Y_\mu^{\pm} = \frac{W_\mu^4 \mp iW_\mu^5}{\sqrt{2}} \qquad Y_\mu^{\pm\pm} = \frac{W_\mu^6 \mp iW_\mu^7}{\sqrt{2}}$$

Weak SM — **New bosons (Dileptons) with $L = \pm 2$**



Doubly charged vector dileptons (Y) along with doubly charged scalars (H): **interesting** because **their decay leads to a signature rarely produced by SM** processes (**same charge same flavour lepton pairs**)

Gauge anomalies cancellations achieved among the fermion families → Number of fermion generations = 3

- **More in arXiv:1806.04536**

Conclusions and Next Steps - Points of discussions

- Several **SeeSaw searches performed in ATLAS**, using a **cut-and-count approach**

  ⇓

- Very **challenging final states**, they need **Machine Learning** techniques to **improve SRs definition**

- **Fake non-prompt leptons** have **high contribution** in these topologies, which is **difficult to estimate**. **ML** methods (unsupervised) can be used to increase the goodness of the fake estimation

- **Theory systematics** have important **impact** on our **SRs**. Is there a clever way to minimize it?

- **Hadronic decays** of τ-leptons are very challenging, but we want to include them in the next iteration. Are τ-leptons more sensible to BSM scenarios?

- **Reinterpretation in terms of LLP** could lead to **new** interesting **phase spaces**. Are they theoretically well motivated or not forbidden?

For the **diboson** processes, we are **not using** the **highest-order computations** for QCD and EW

⇒ **Impact on the background estimation**

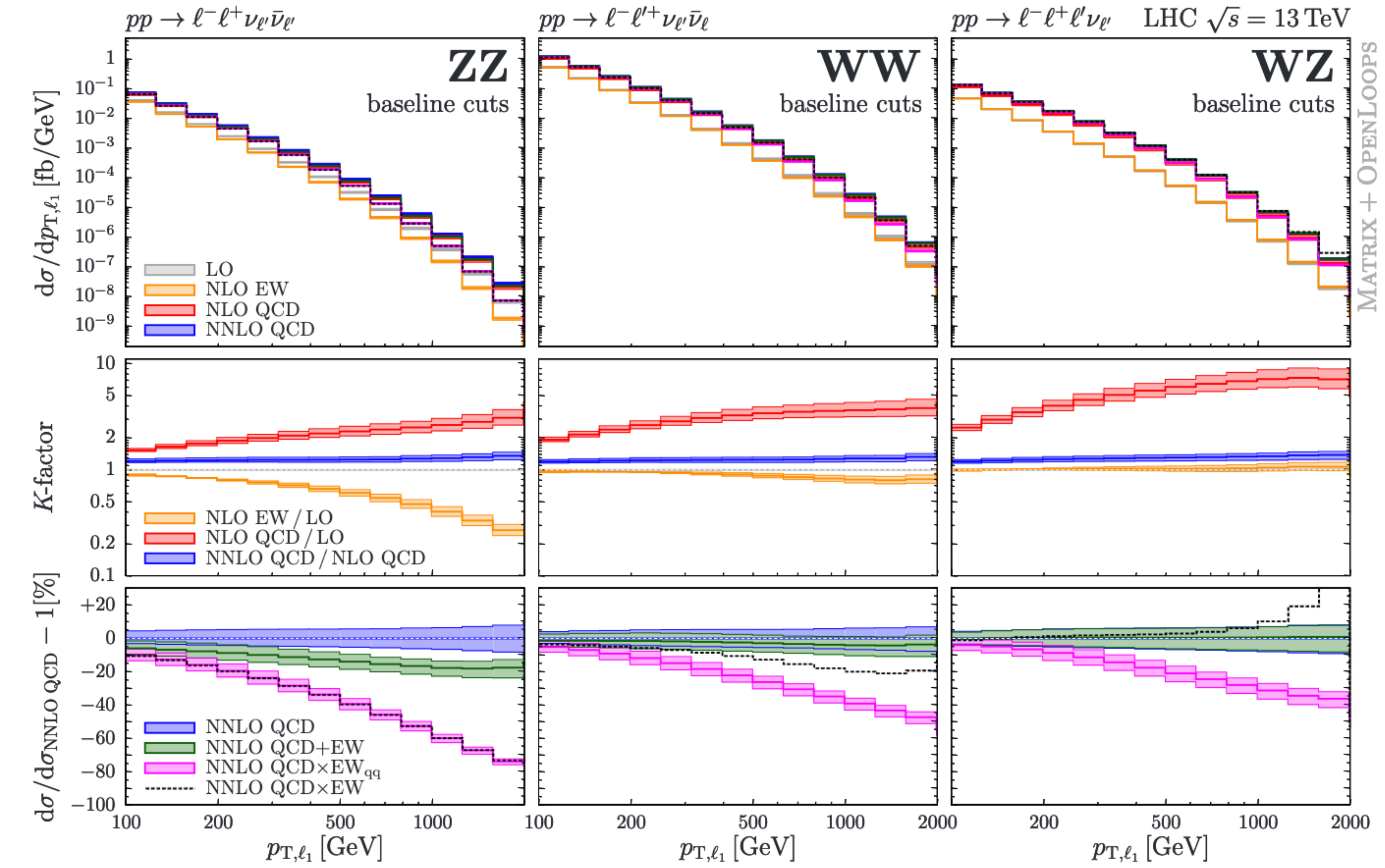
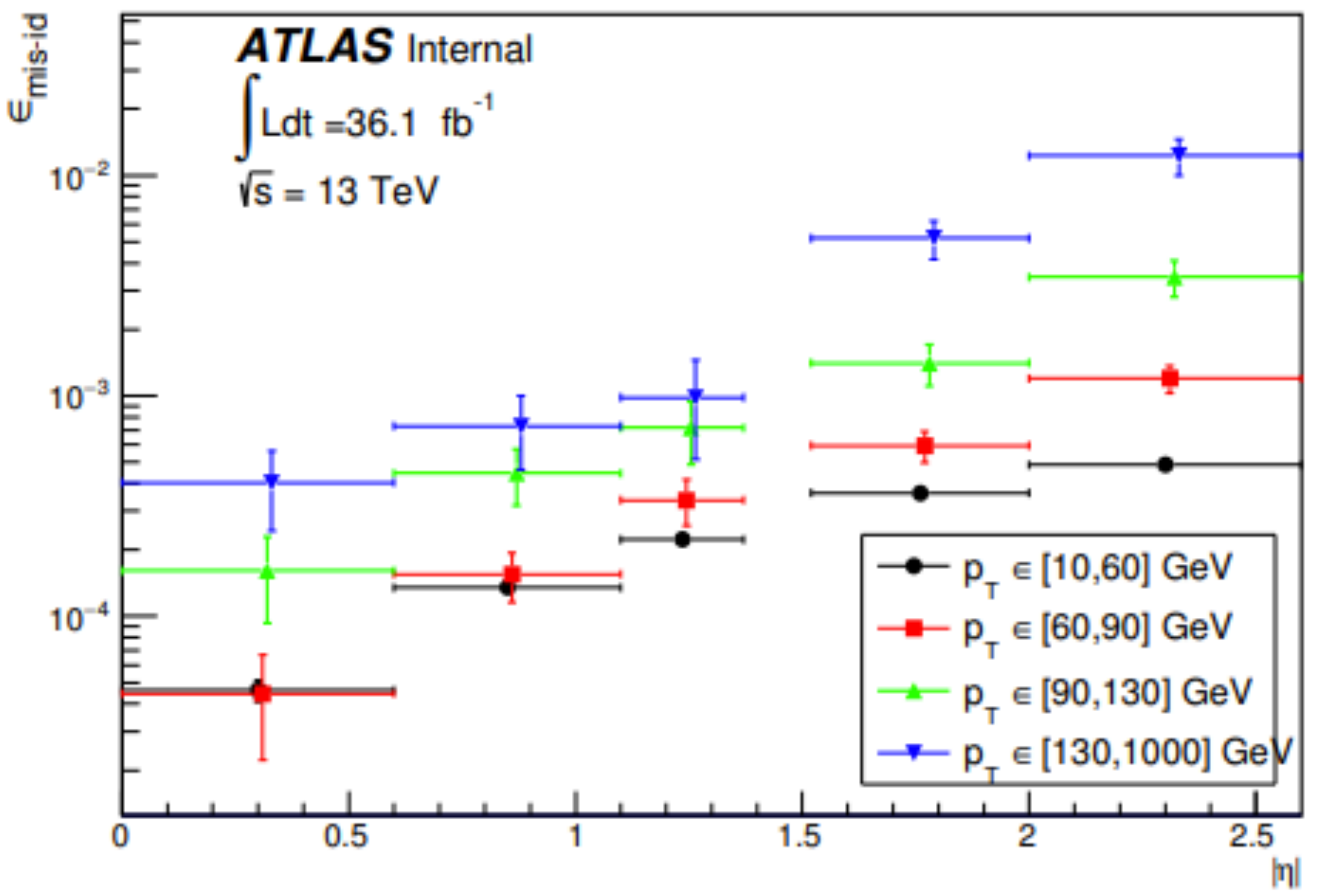


Figure 9. Distribution in the transverse momentum of the hardest charged lepton for the processes (3.1)–(3.3) at 13 TeV. Baseline cuts are applied without jet veto. Plot format and predictions as in figure 6.

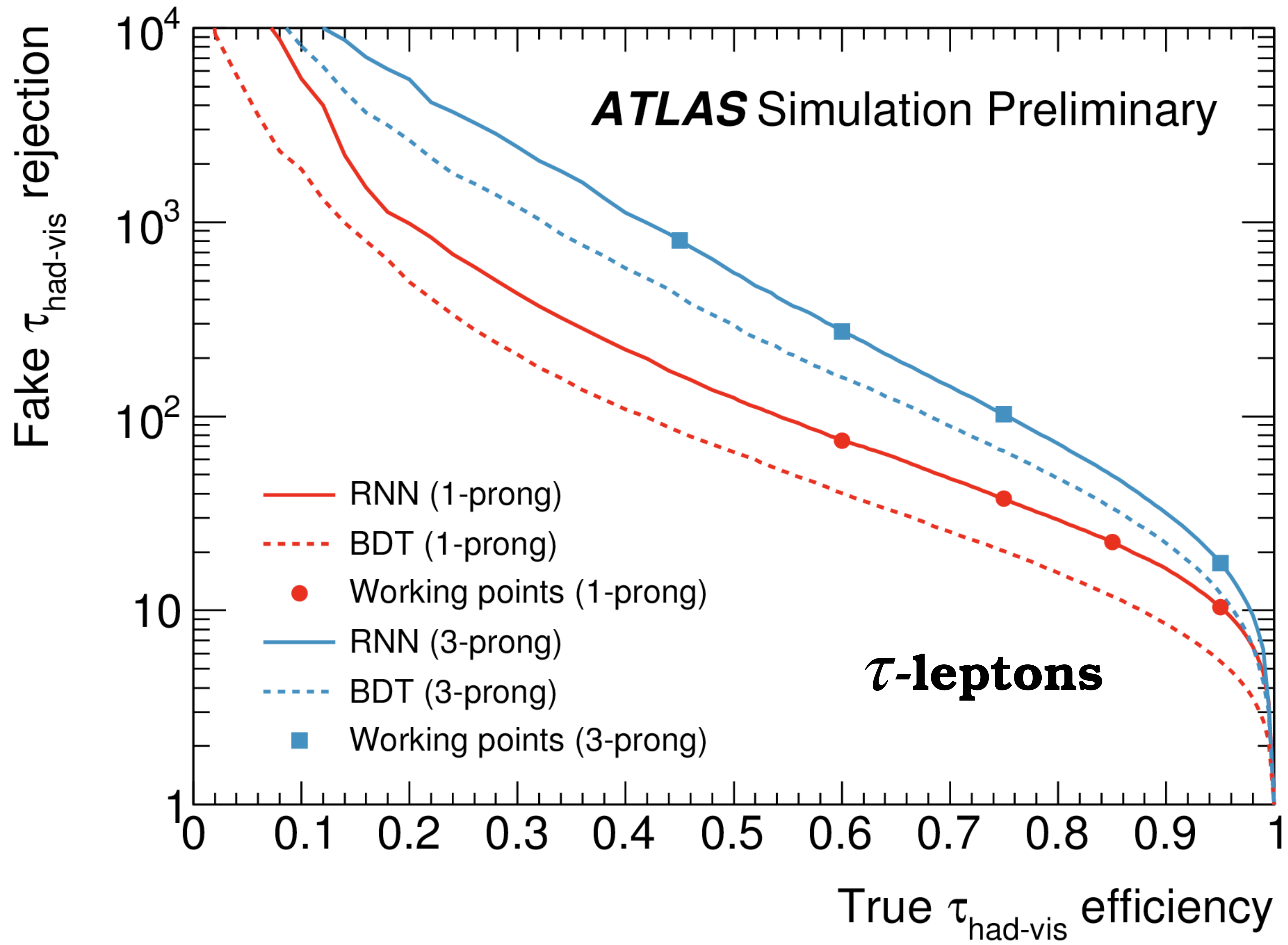
From JHEP02 (2020) 087

BACKUP

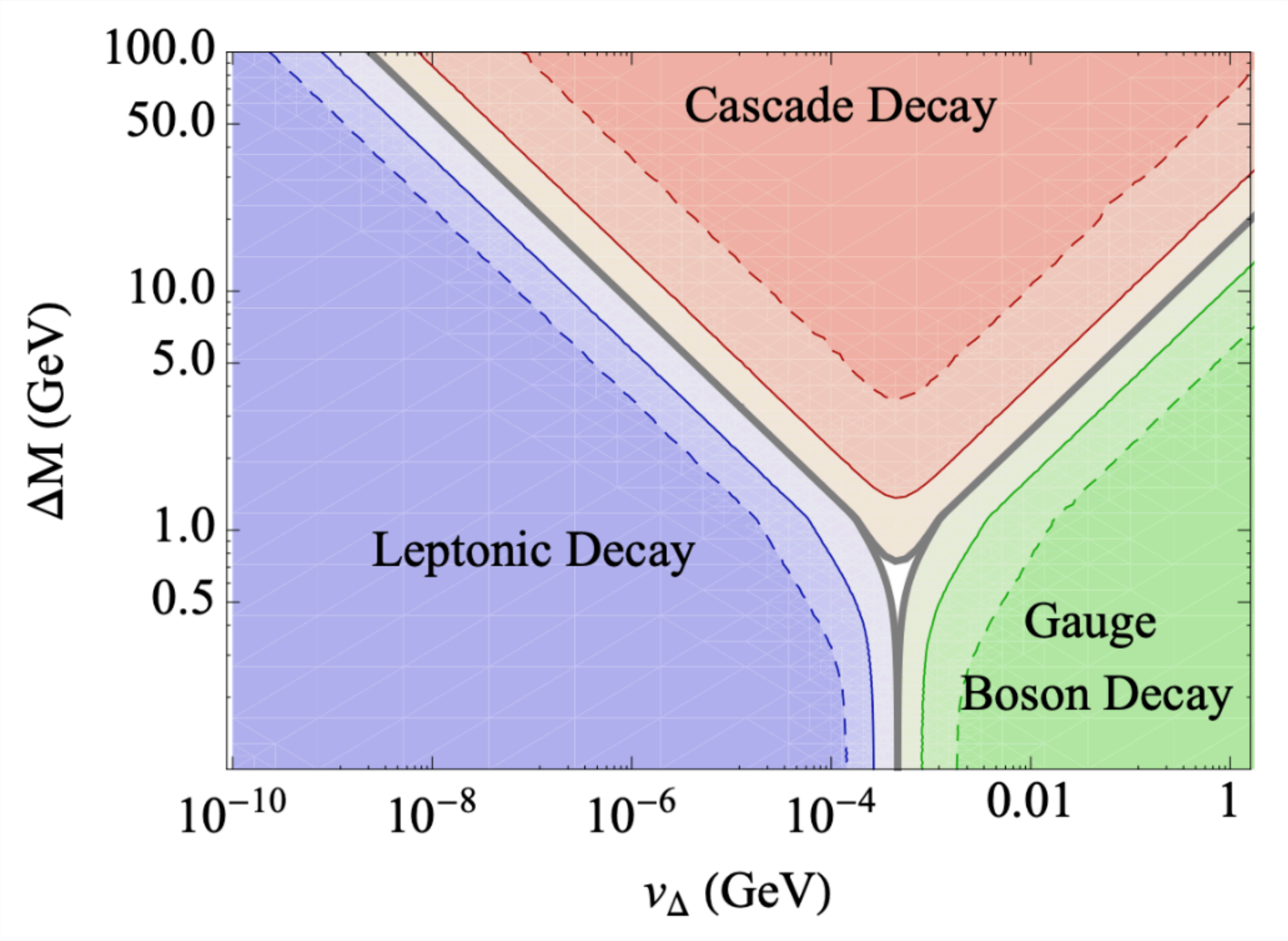
Leptons resolution in ATLAS



Electron Charge-flip probability as function of η and p_T

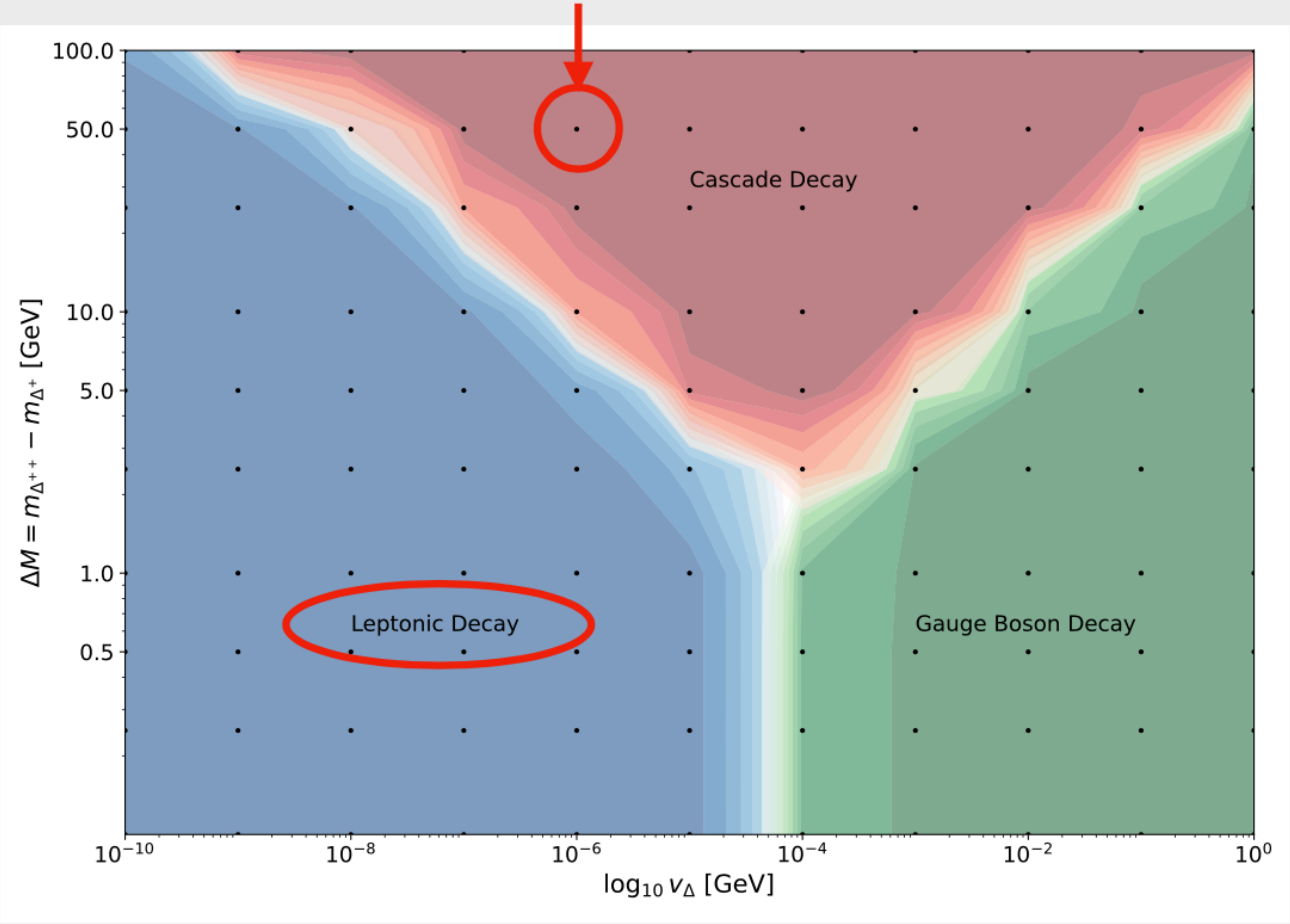


BR dependence on $H^{\pm\pm}$



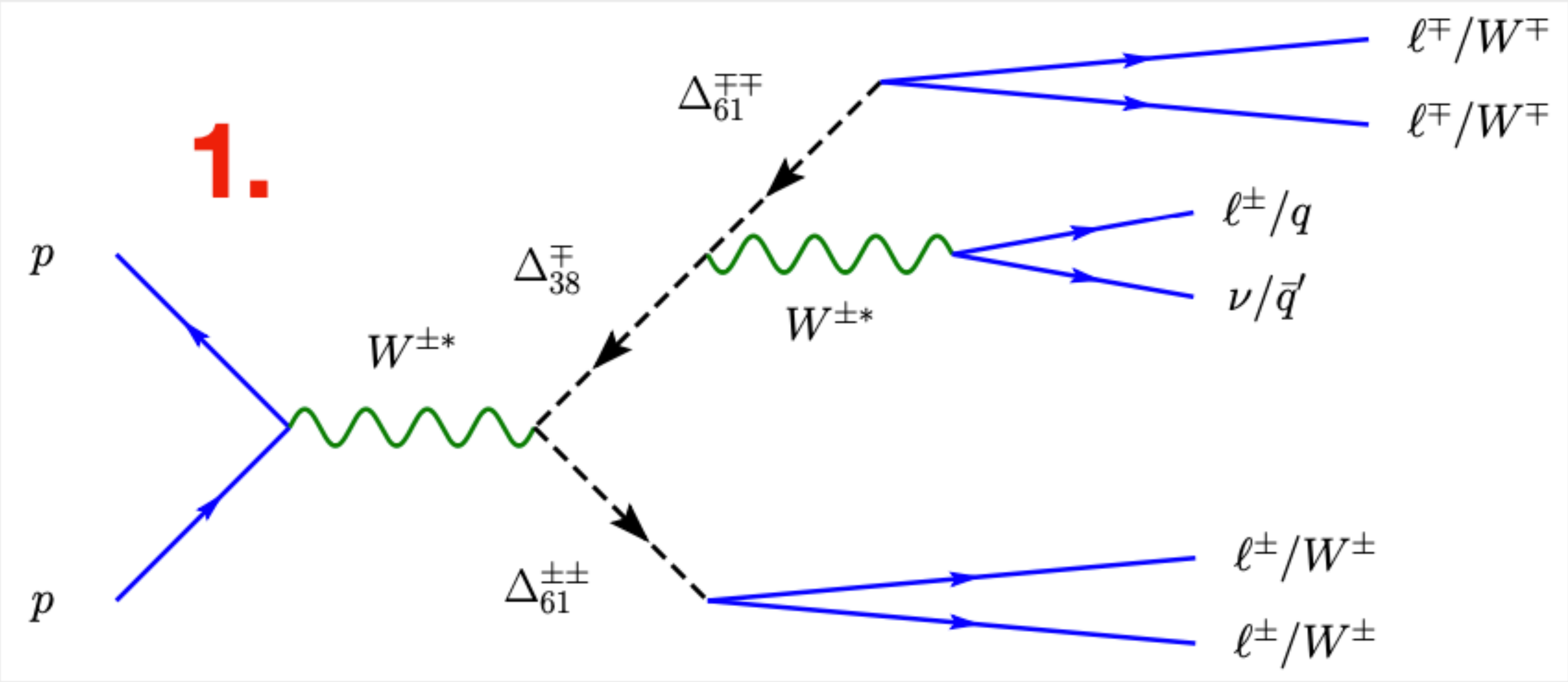
$m_{\Delta^{\pm\pm}} = 150\ GeV$. Taken from arXiv:1108.4416

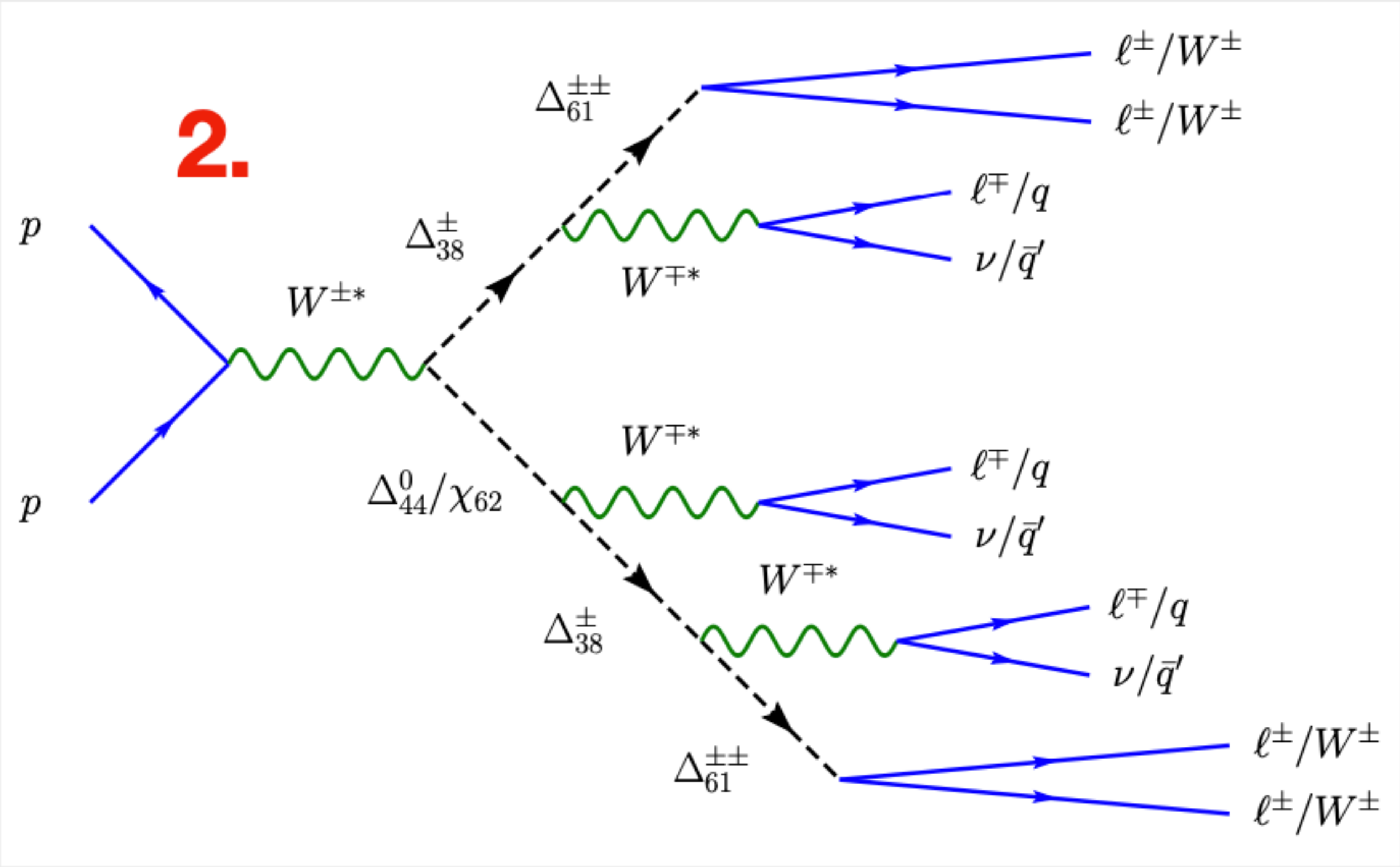
The chosen one

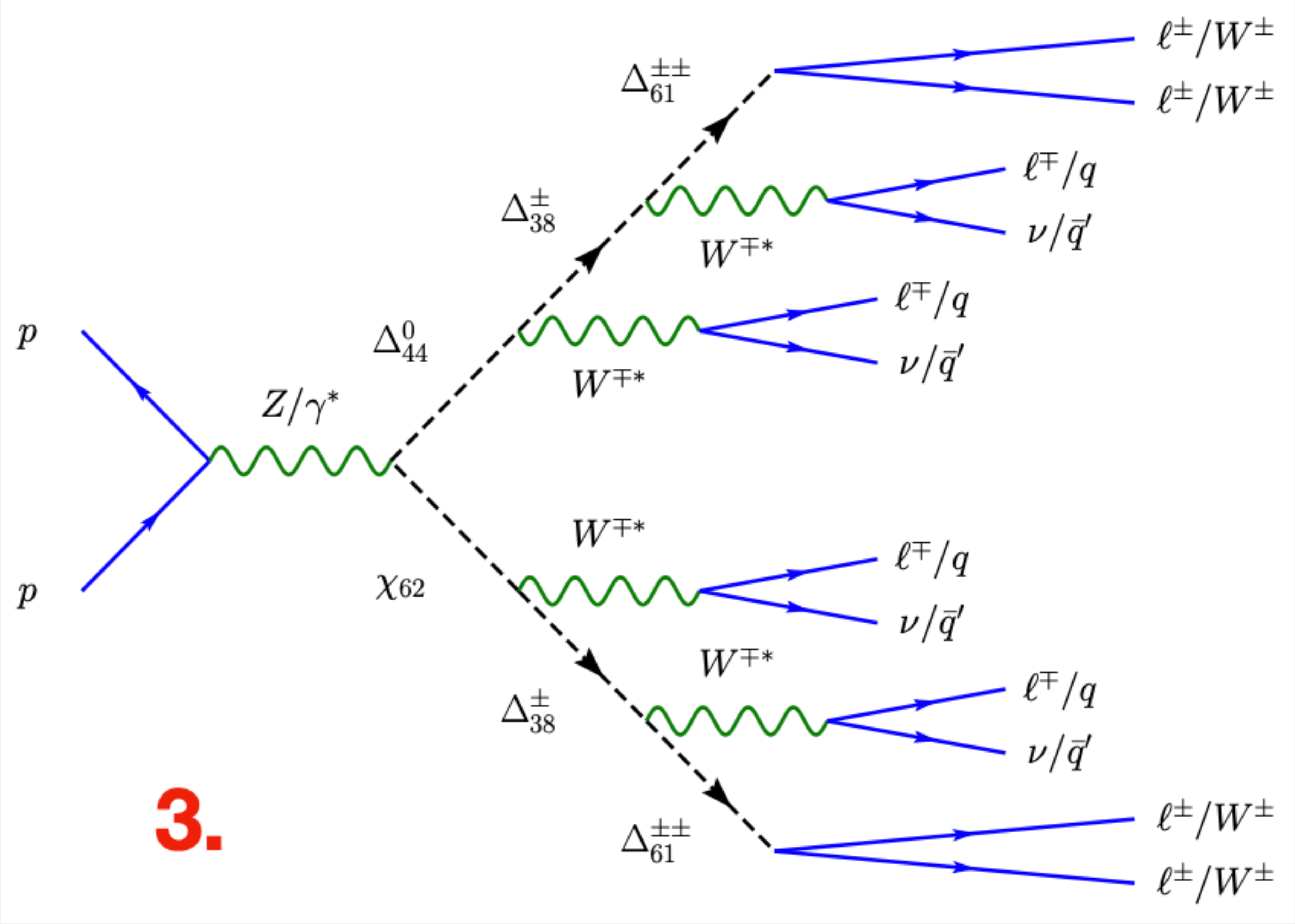


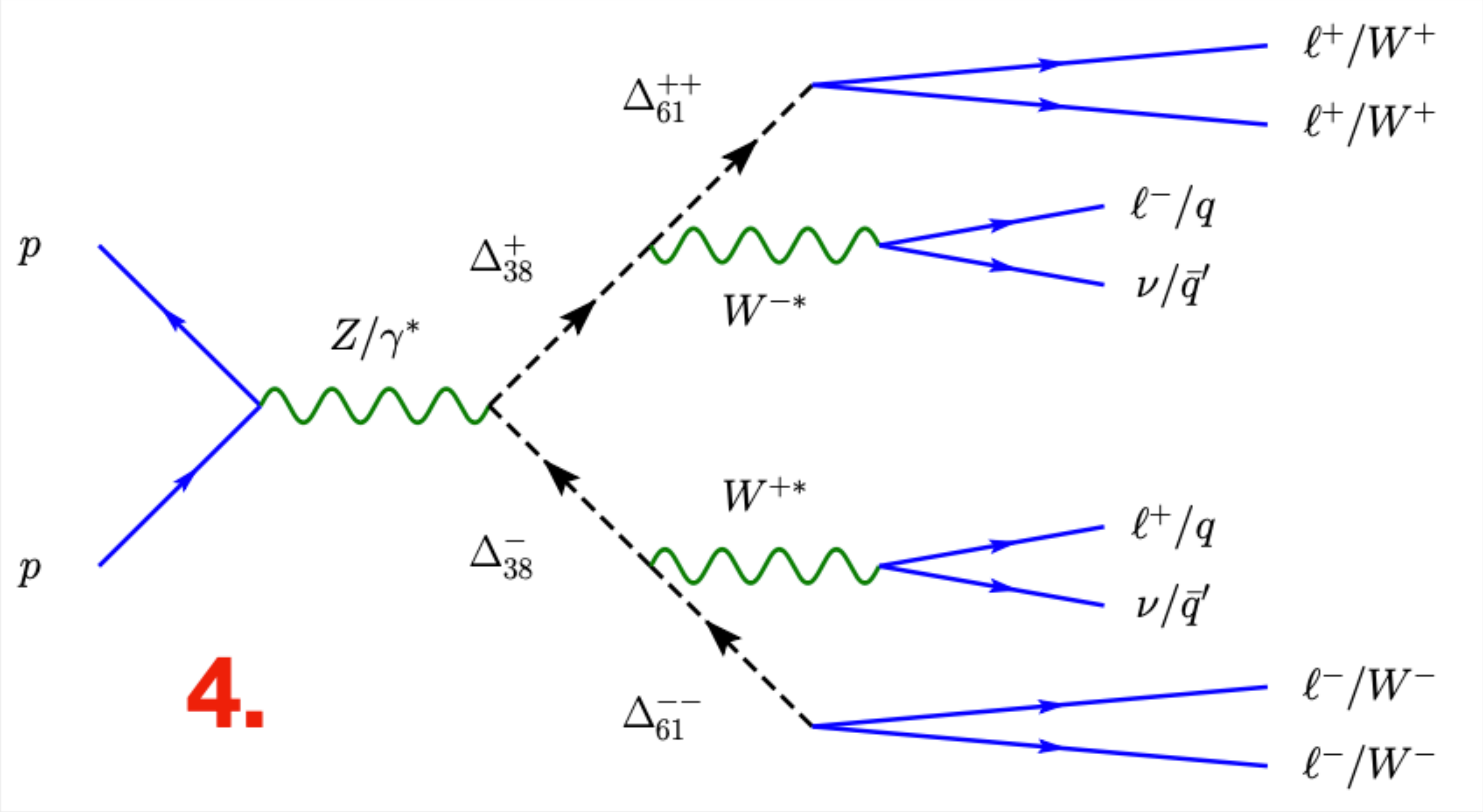
$m_{\Delta^{\pm\pm}} = 1000\ GeV$

Cascades Feynman diagrams for $\Delta M > 0$



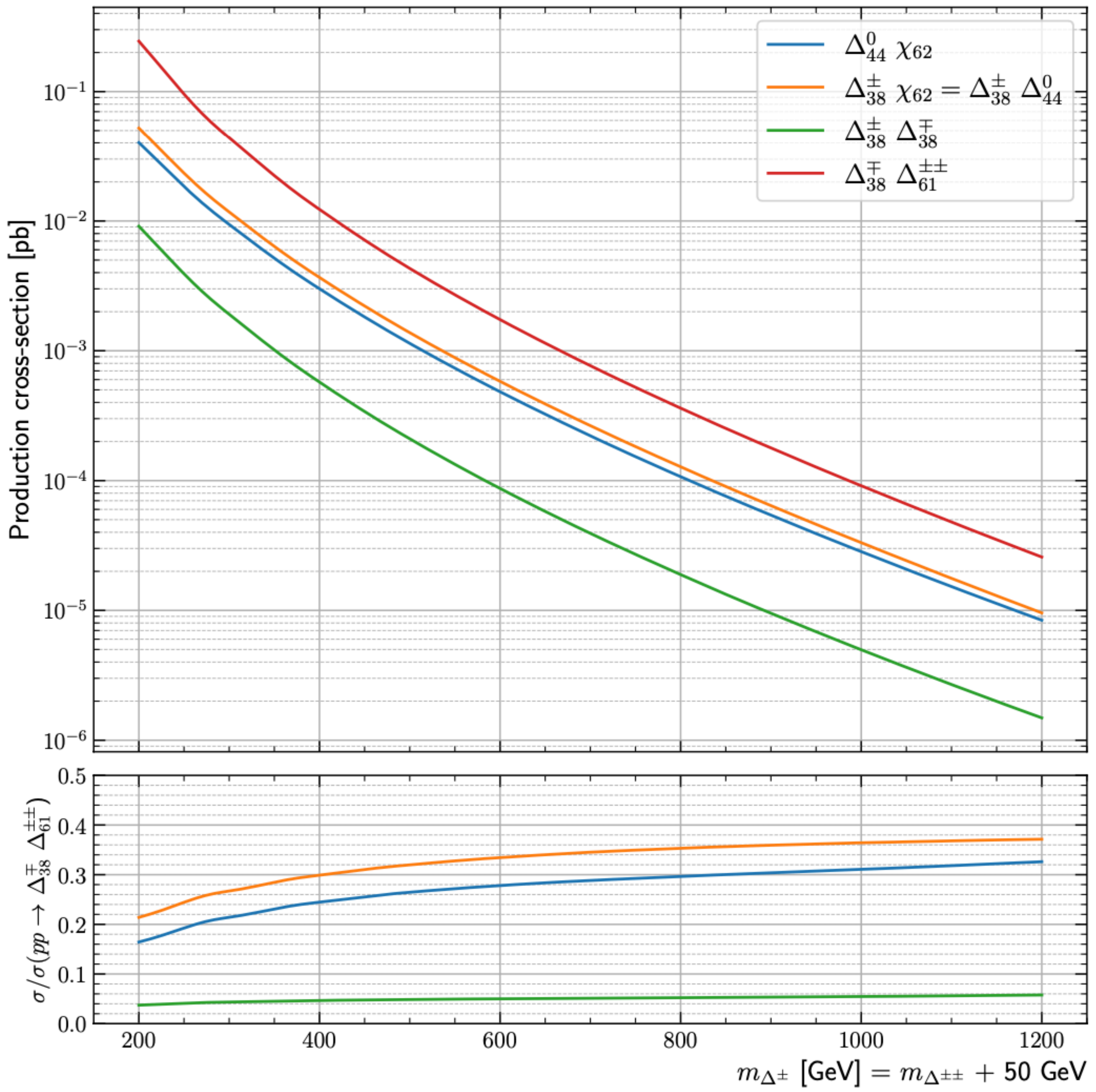






Cascades cross-sections for $\Delta M > 0$

- Theorists suggested:
  - Use $\Delta M \simeq 50$ GeV.
  - Search in the range $[200,\ 1200]$ GeV.



Type-I SeeSaw Search - Introduction

- **Left-Right Symmetric Model** introduces **right-handed counterparts** to the W and Z bosons and also **right-handed neutrinos**.
  Neutrino masses via **Type-I Seesaw**

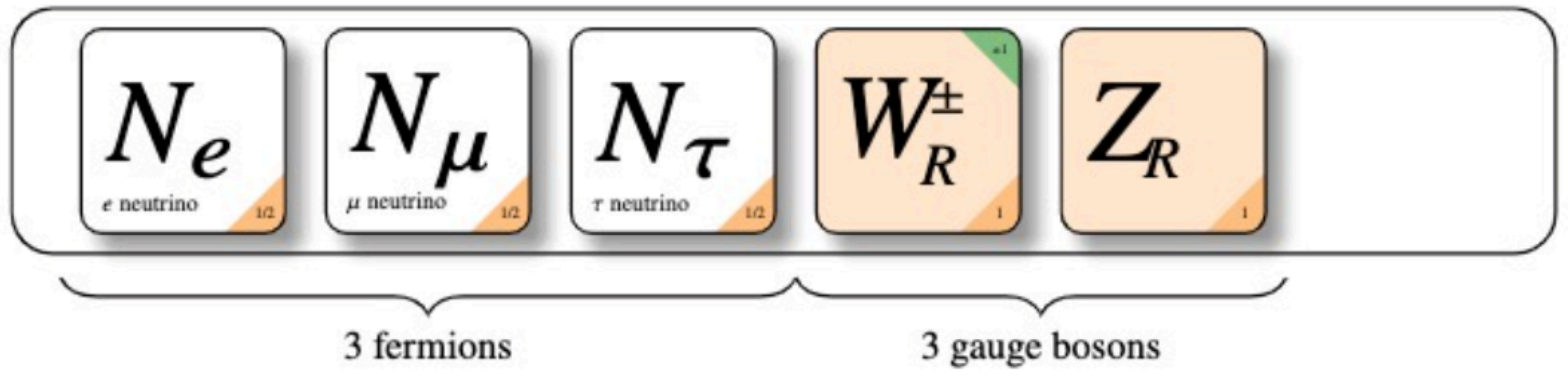
- Considering both normal ($m_{WR} > m_{NR}$) and reversed ($m_{WR} < m_{NR}$) hierarchy.

- Looking for two **same flavor leptons** and **two quarks**.

- W_R reconstructed with $\ell\ell qq$ (normal hierarchy) or qq (reversed hierarchy).

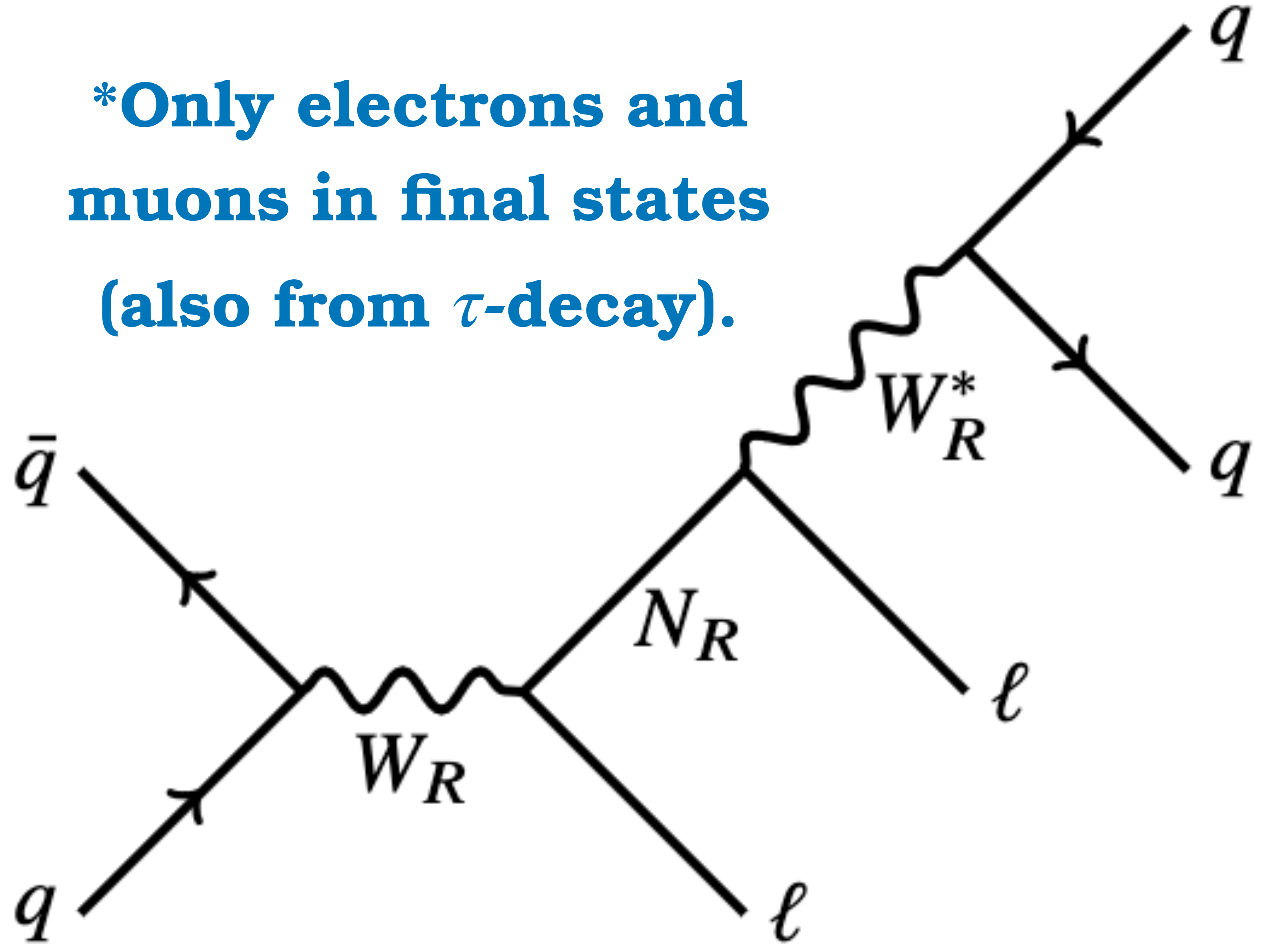
- N_R is **Majorana** particle, **signals** are generated with **50% Opposite Sign (OS)** and **50% Same Sign (SS)** lepton pairs.

- **Interpretations of Dirac type** neutrino can be done **by picking up OS pairs**.



LRSM Particles
(Excluding Higgs sector)

***Only electrons and muons in final states (also from τ-decay).**



Feynman diagram for the Keung-Senjanović process ($m_{WR} > m_{NR}$).

Type-I SeeSaw Search - Introduction

- **Left-Right Symmetric Model** introduces **right-handed counterparts** to the W and Z bosons and also **right-handed neutrinos**.
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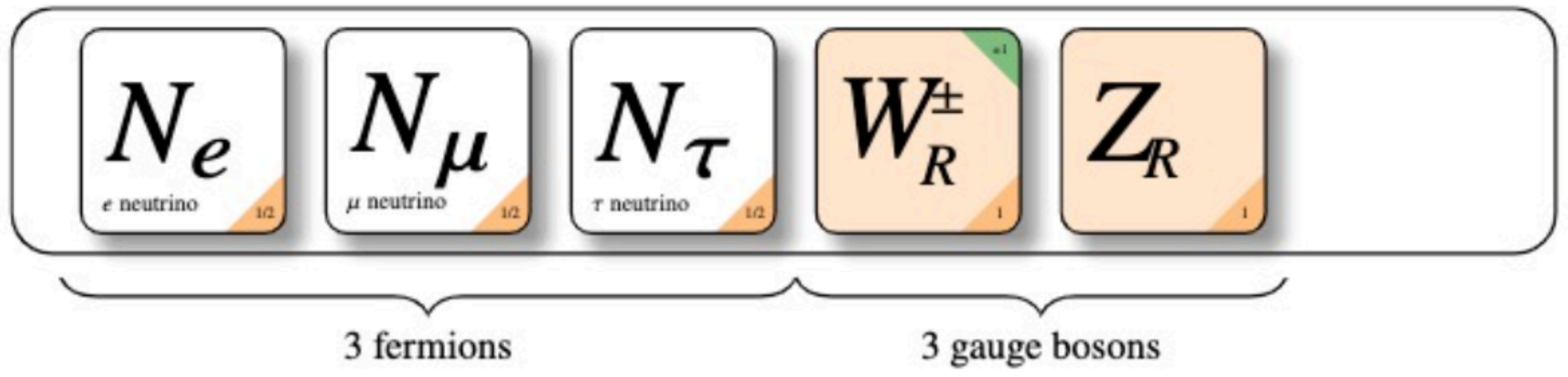
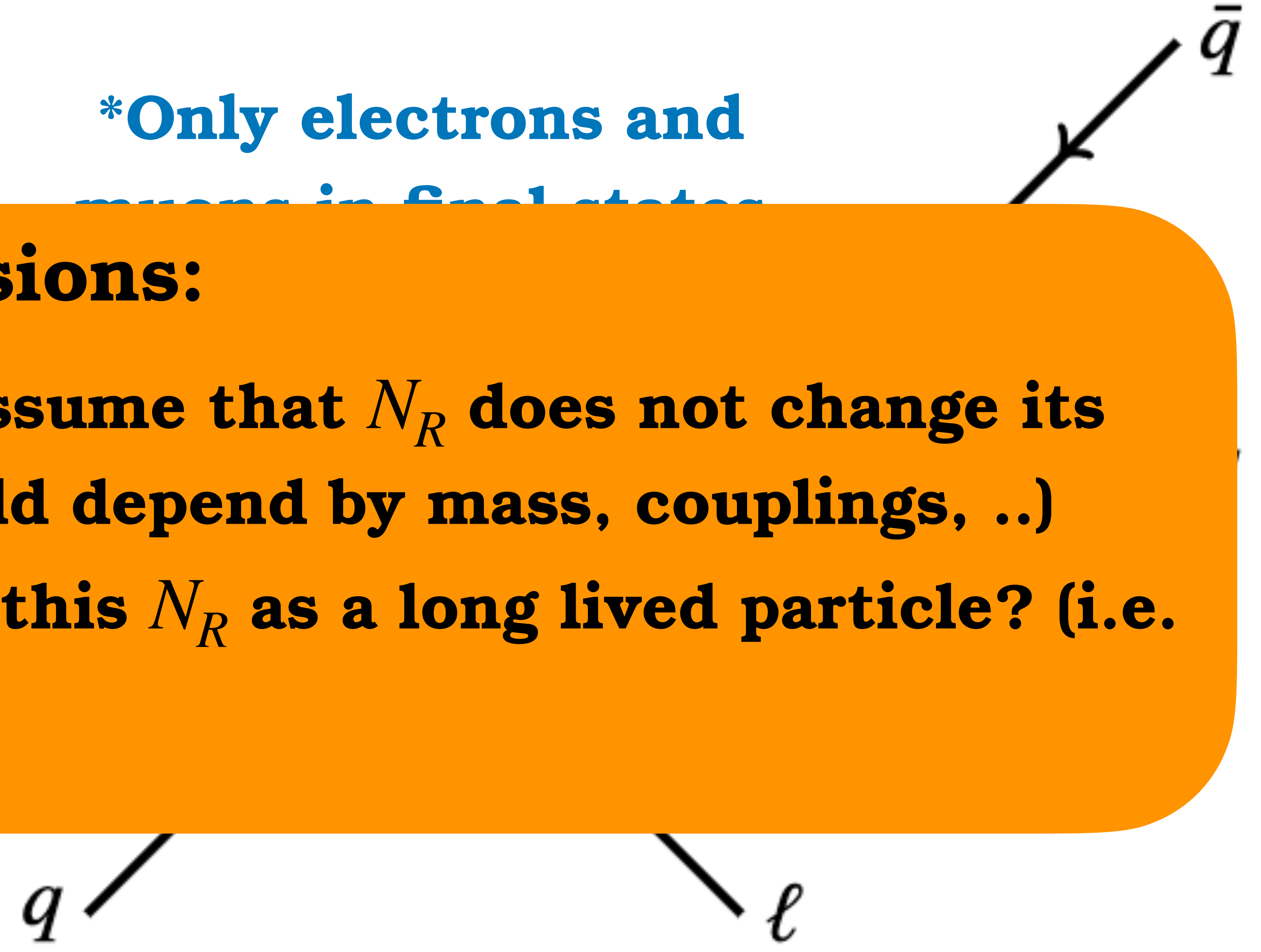


LRSM Particles
(Excluding Higgs sector)

***Only electrons and**



Points of discussions:

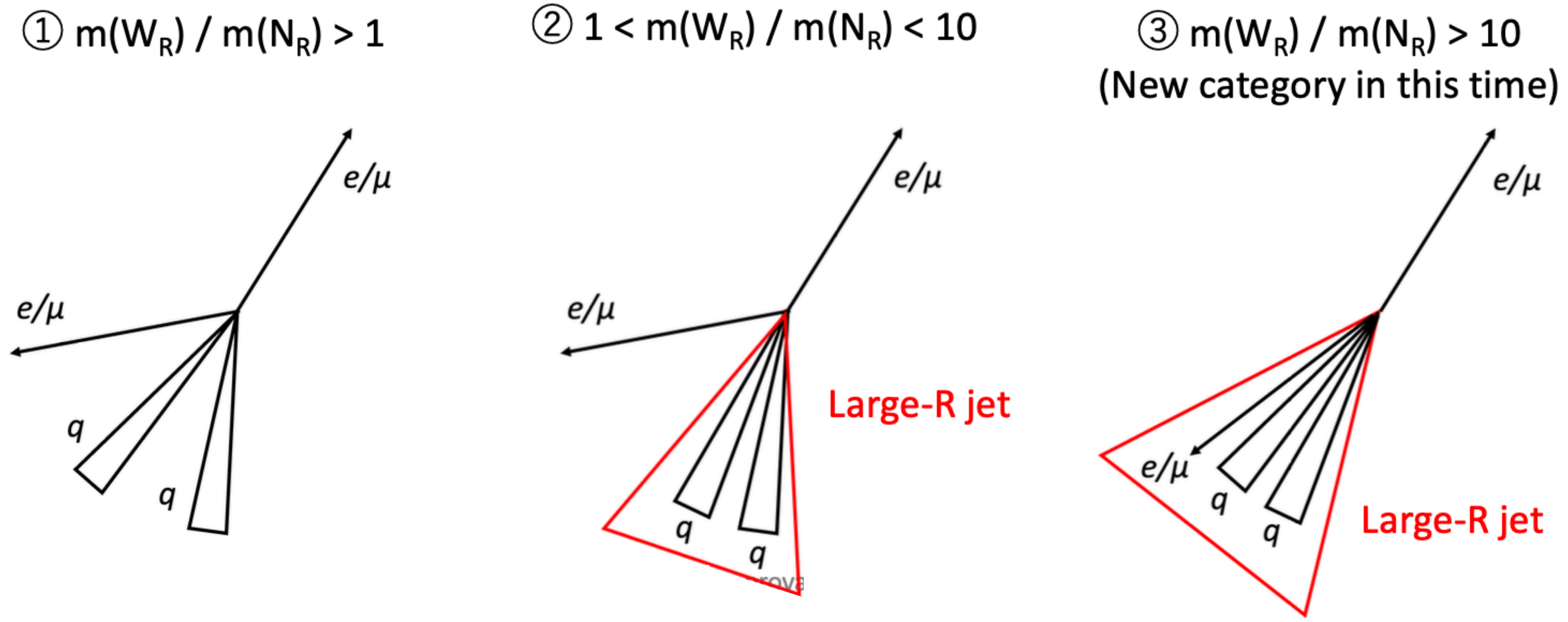
1. **Is it correct to assume that N_R does not change its flavour? (It should depend by mass, couplings, ..)**
2. **Can we consider this N_R as a long lived particle? (i.e. $c\tau \geq$ 1 mm)**

Feynman diagram for the Keung-Senjanović process ($m_{WR} > m_{NR}$).

Type-I SeeSaw Search - Analysis Strategy

Depending on the mass balance of m_{WR} and m_{NR}, there are 3 object level final states:

- **Resolved** (1):
  - $\Delta M = m_{WR}$ - m_{NR} < 4 TeV, required 2 or more different small-R jets
- **Boosted** (2 & 3):
  - $\Delta M = m_{WR}$ - m_{NR} > 4 TeV, required 1 large-R jets from all or a part of N_R decay products.



- Since resolved and boosted **channels are not combined statistically**, **object selections** are **optimized separately**.
- Exclusion curves are overlayed
- Each channel has **unique object selections for fake estimation.**

Leptons classifications:

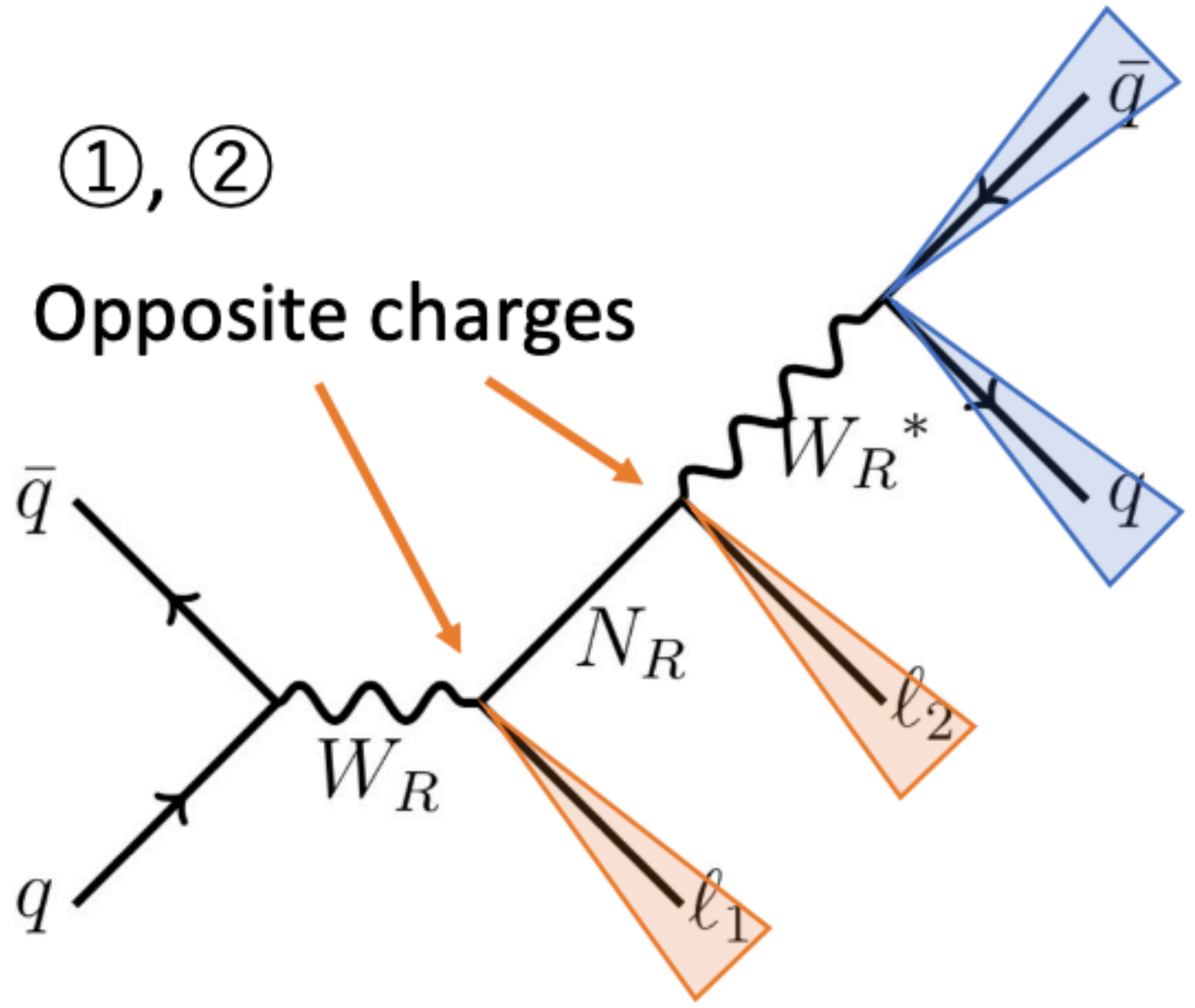
- Resolved
  - **Baseline** (analysis) and **Loose** (fake estimation)
- Boosted
  - **Baseline** (analysis), **Leading** (analysis, more string requirements) and **Loose** (fake estimation)

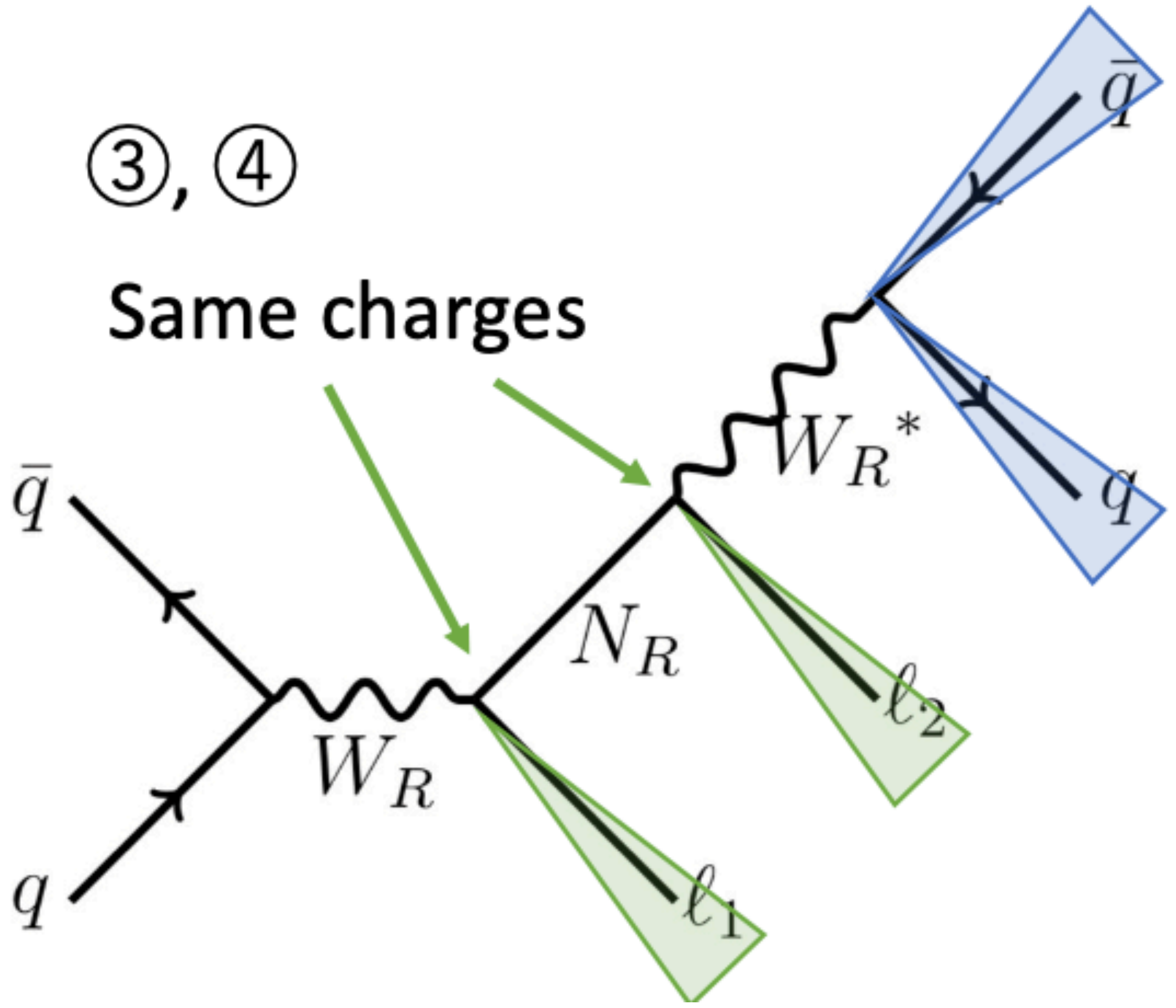
Type-I SeeSaw Search - Resolved

4 sub-channels, 2 for electron and 2 for muon final state

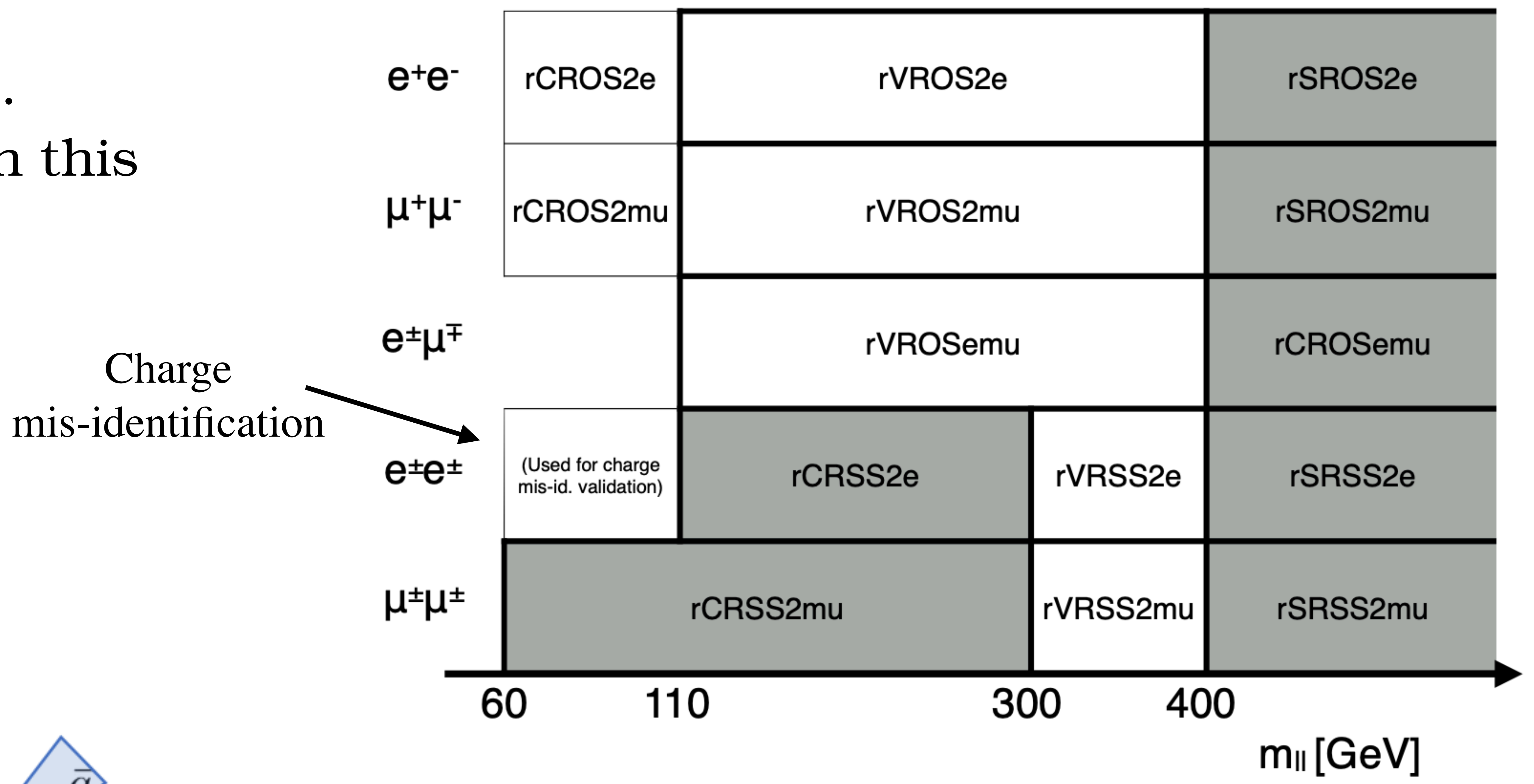
- **OS** (1 & 2):
  - **Z+jets & ttbar** (Tops) are the **dominant backgrounds**.
  - Dirac type neutrino interpretations are performed with this channel.
- **SS** (3 & 4):
  - Di-boson (VV) is the dominant background.
  - Smaller background events than OS.

*Data-driven correction to the MC shape applied for an observed mismodelling in Sherpa Drell-Yan samples.





- $m_{\ell\ell}$ used to ensure orthogonality among regions



- For SS, $\Delta R(\ell\ell) < 3.9$ to reduce some mismodellings derived from di-boson samples.

- Final discriminant: for OS, m_{WR}, for SS, H_T (scalar sum of the p_T of leptons and small-R jets)

Type-I SeeSaw Search - DD Correction

Sherpa 2.2.11 does not correctly model the $m(jj)$ spectrum although most other observables are well-described.
Observed in both di-electrons and di-muon channels.

Correction strategy:

1. **Histogram rebinned** to have enough statistics
2. **Subtract from data** all other **background** contributions **except Z+jets**.
3. Normalise both data and Z+jets histograms
4. Take the ratio of Data/MC and normalize it
5. Perform a χ^2 **fit of the ratio to the Novosibirsk function** with three parameters: **peak, width, tail**
6. An **additional normalisation factor** is **calculated** to match MC and data event numbers in the Z+jets Control Region

$$k_1 = \log\left[1.0 - \frac{(x - peak) \cdot tail}{width}\right]$$

$$k_2 = 2\sqrt{\log 4}$$

$$k_3 = \frac{2.0}{k_2} \sinh^{-1}(0.5\, k_2 \cdot tail)$$

$$y = \exp\left[-\frac{0.5}{k_3^2} k_1^2 - 0.5\, k_3^2\right]$$

Novosibirsk function

Parameter	best fit value
peak	247.188 ± 14
width	5043 ± 33
tail	−36.6 ± 4.1

Type-I SeeSaw Search - DD Correction

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Internal result

Without correction

Internal result

With correction

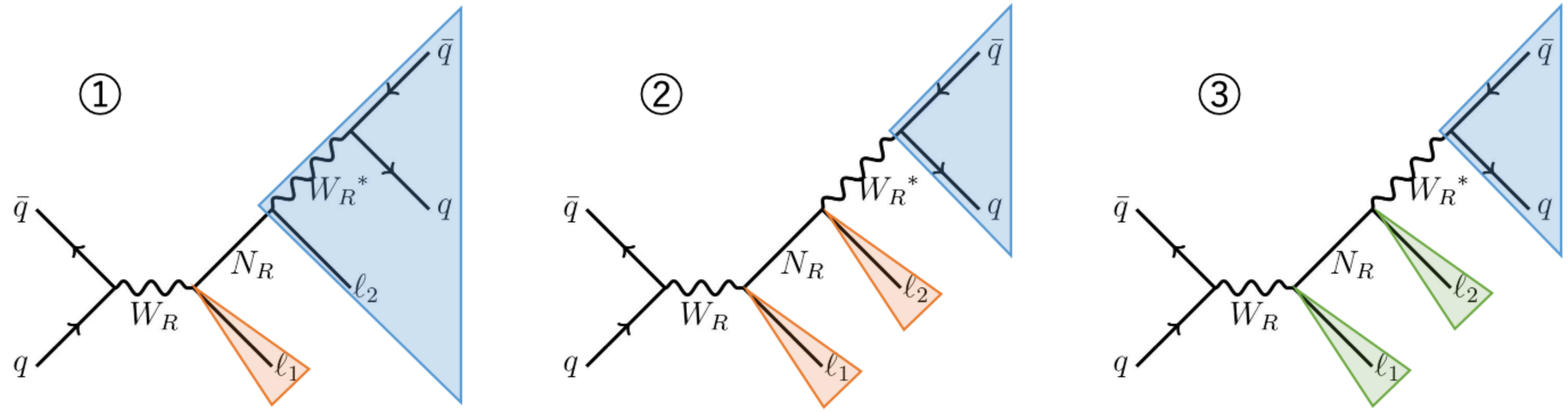
Type-I SeeSaw Search - Boosted

3 sub-channels, 2 for electron and 1 for muon final state

- **One Electron** (1)
  - Main target: m_{WR} > 10 m_{NR}
  - W+jets, Di-jet and γ+jets with a fakes are the dominant
- **Two Electrons** (2, orthogonal with 1)
  - Main target: m_{WR} < 10 m_{NR}
  - Z + jets is dominant
- **Two Muons** (3):
  - Cover a wide range of m_{WR} and m_{NR} plane
  - Z + jets is dominant

Region	bSR1e	bSR2e	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		-
$\cos\theta$	> 0.7	-	-
$\Delta\eta_{J,\ell_1}$	< 2.0	-	-
Dilepton p_T (GeV)	-	-	> 200
Dilepton mass $m_{\ell\ell}$[GeV]	-	> 200	
Number of b-tagged small-R jets	0		

For each SR is imposed that m_{WR} > 3 TeV.



- Fits for electron and muon final state are performed separately
- Every dominant backgrounds are estimated with semi-data-driven method:
  - For one electron channel, 4 different CRs are used for 3 backgrounds (W+jets/γ+jets/Multi jet) estimations.
  - For two lepton channels, only 1 CR for Z+jets.

Type-I SeeSaw Search - Results

< Majorana type Neutrino >

- Excluded region up to m_{WR} = 6.4 TeV and m_{NR} = 1 TeV in both electron and muon channels

- Most stringent limit for $m_{WR} > m_{NR}$.

Resolved

Factor	Value
μ_{tt^-}	1.0 ± 0.1
$\mu_{WZ/ssWW}$	1 ± 0.15
$\mu_{DY(SS)}$	0.9 ± 0.3

Boosted

Floating background	Normalization factor
W+jets	1.0487 ± 0.030
QCD multi-jet	0.5578 ± 0.011
γ+jets	0.3832 ± 0.055
Z+jets	1.2285 ± 0.101

< Dirac type Neutrino >

- Excluded region up to m_{WR} = 6.4 TeV and m_{NR} = 1 TeV in both electron and muon channels

- Most stringent limit for $m_{WR} > m_{NR}$.

Type-I SeeSaw Search - Resolved

Definitions of SRs

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 $p_{\mathrm{T}} > 100$ GeV	≥ 2			
Number of b-tagged jets	0			
Dijet mass m_{jj} [GeV]	> 110			
$h_{\mathrm{T}} \equiv p_{\mathrm{T}}(\ell_1) + p_{\mathrm{T}}(\ell_2) + p_{\mathrm{T}}(j_1) + p_{\mathrm{T}}(j_2)$ [GeV]	> 400			

SeeSaw mechanismes

- Type-I: one scalar singlet (N_R)

$$\mathcal{L} = i\bar{N}_R \partial\!\!\!/ N_R - y_N \ell_L \psi^* N_R - \frac{M}{2}\bar{N}_R^c N_R + h.c. \xrightarrow{\text{SSB}} \begin{array}{l} m_1 \simeq \dfrac{m_D^2}{M} = \dfrac{v^2}{2} y_\nu \dfrac{1}{M} y_\nu^T \\ m_2 \simeq M \end{array}$$

- Type-II: one scalar triplet ($\vec{\Delta}$)

$$\mathcal{L} = \left(D_\mu \vec{\Delta}\right)^\dagger \left(D^\mu \vec{\Delta}\right) + \left[\bar{\tilde{\psi}}_L y_\Delta \Delta \psi_L + \tilde{\phi}^\dagger \mu_\Delta \Delta^\dagger \phi + h.c.\right] - V\left(\vec{\Delta}\right) \xrightarrow{\text{SSB}} m_\nu = y_\Delta v^2 \frac{\mu_\Delta}{M_\Delta^2}$$

- Type-III: one fermionic triplet ($\vec{\Sigma}$)

$$\mathcal{L} = i\bar{\vec{\Sigma}}_R D\!\!\!\!/ \vec{\Sigma}_R - \frac{1}{2}\bar{\vec{\Sigma}}_R M \vec{\Sigma}_R^c - \bar{\vec{\Sigma}}_R y_\Sigma \left(\tilde{\phi}^\dagger \vec{\sigma} \psi_L\right) + h.c. \xrightarrow{\text{SSB}} \begin{array}{l} m_1 = v y_\ell = m_\ell^D \\ m_2 = -v^2 y_\Sigma^T \left|M\right|^{-1} y_\Sigma \end{array}$$

Type-II and Type-III SeeSaw

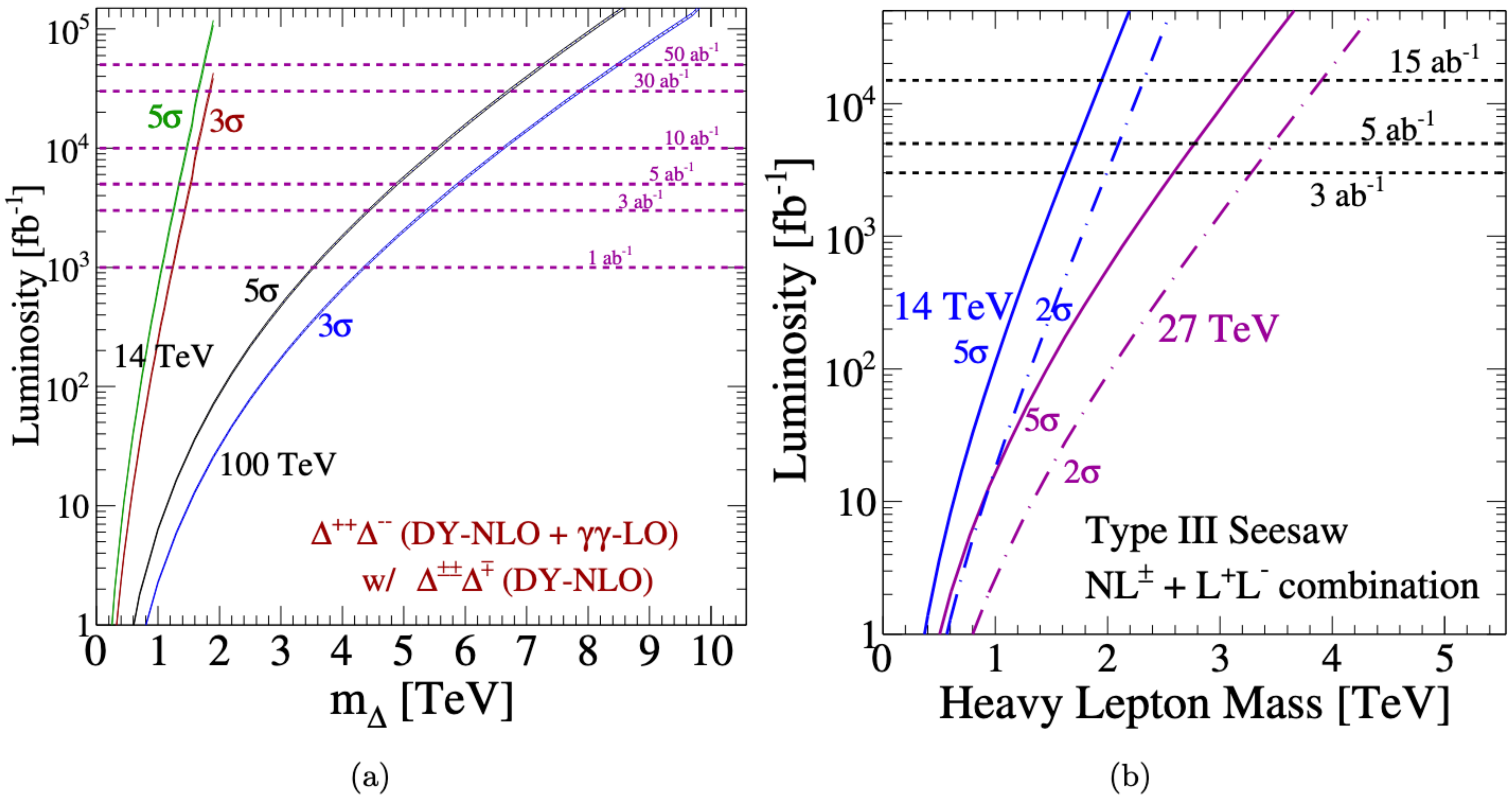


Figure 3. (a) The luminosity required to reach 5σ (3σ) discovery (sensitivity) of Type II Seesaw scalars produced in pairs produced in $\sqrt{s} = 14$ and 100 TeV *pp* collisions, and which subsequently decay to multi-lepton final states. Adapted from Ref. [26]. (b) The same but for Type III leptons produced in pairs in $\sqrt{s} = 14$ and 27 TeV *pp* collisions. Adapted from Ref. [29].

Type-II and Type-III SeeSaw

Physics process	Event generator	PDF set	Cross-section normalisation	Parton shower	Parton shower tune
Signal $H^{\pm\pm}$	PYTHIA 8.212 [38]	NNPDF2.3LO [41]	NLO	PYTHIA 8.230 [54]	A14 [40]

Process	Generator	Cross-section	Parton shower	PDF set	Tune
Type-III seesaw $L^+L^-, L^\pm N^0$	MADGRAPH5_AMC@NLO [29]	NLO+NLL	PYTHIA 8.230 [32]	NNPDF3.0LO [31] NNPDF2.3LO [34]	A14 [33]
Top quark $t\bar{t}$	POWHEG BOX v2 [40–43]	NNLO	PYTHIA 8.230	NNPDF3.0NNLO [31] NNPDF3.0NLO [31]	A14
Single t	POWHEG BOX v2	NNLO	PYTHIA 8.230	NNPDF3.0NNLO NNPDF3.0NLO	A14
Rare top quark $3t, 4t$	MADGRAPH5_AMC@NLO	LO	PYTHIA 8.230	NNPDF3.0LO	A14
$t\bar{t} + W/Z/H, tWZ$	MADGRAPH5_AMC@NLO	NNLO	PYTHIA 8.230	NNPDF3.0NLO	A14
Diboson ZZ, WZ	SHERPA 2.2.1 [44] & 2.2.2	NLO	SHERPA	NNPDF3.0NNLO	SHERPA default
Triboson WWW, WWZ, WZZ, ZZZ	SHERPA 2.2.1 & 2.2.2	NNLO	SHERPA	NNPDF3.0NNLO	SHERPA default
Drell–Yan $Z/\gamma^* \rightarrow e^+e^-/\mu^+\mu^-/\tau^+\tau^-$	SHERPA 2.2.1	NLO	SHERPA	NNPDF3.0NNLO	SHERPA default

Objects definition

Requirement	Signal jets	Baseline jets
Jet type	AntiKt4EMPFlowJets	AntiKt4EMPFlowJets
JVT working point	Medium	Medium
fJVT working point	–	–
p_T cut	$p_T > 20$ GeV	$p_T > 20$ GeV
ηcut	$\lvert\eta\rvert < 2.5$	$\lvert\eta\rvert < 4.5$
b-tagging	MV2c10 with FixedCutBEff_77	

MET

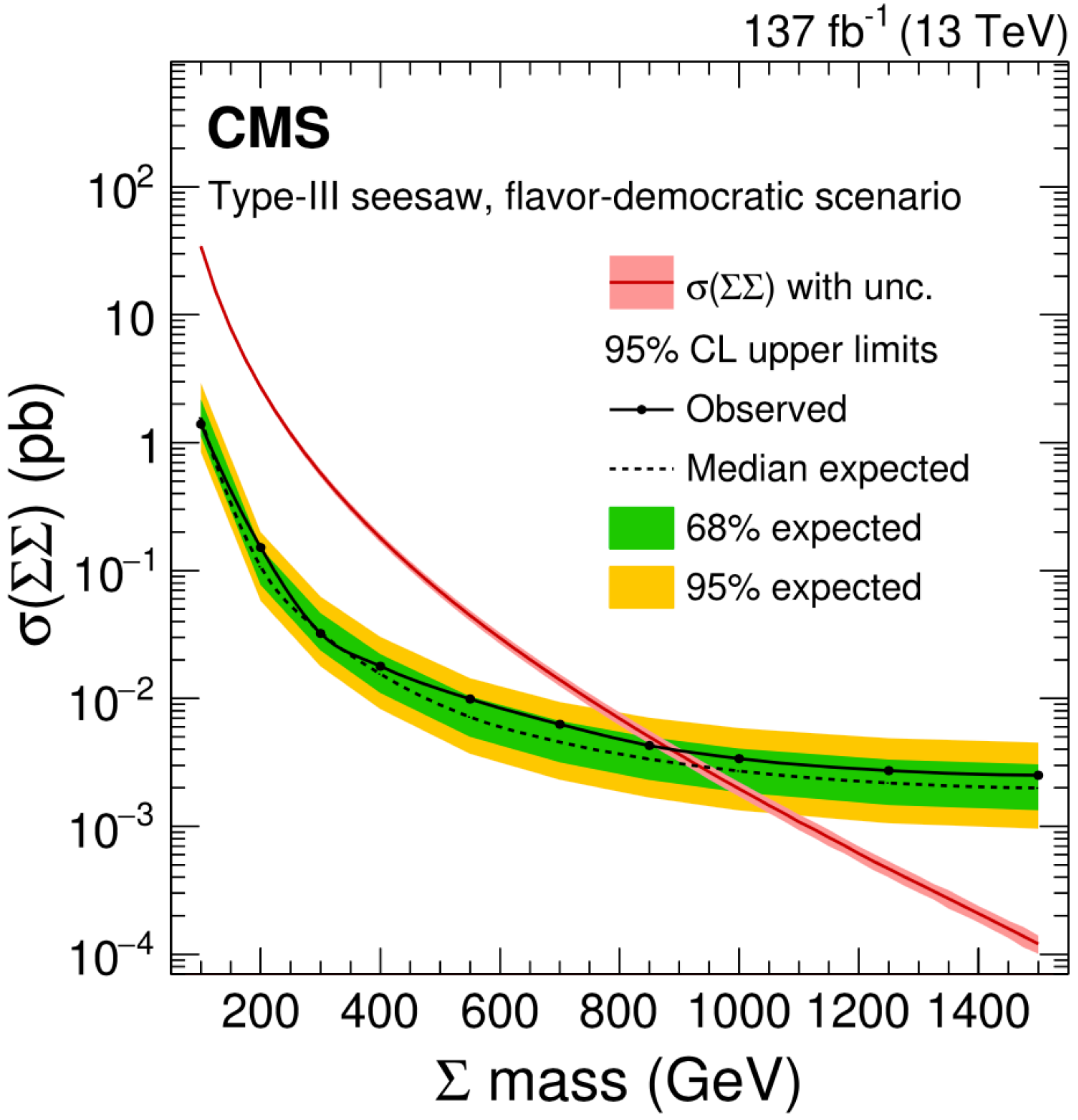
Requirement	Nominal
Type	Track-based Soft Term
Working point	Tight
Forward jets	yes
Pile-up jets in significance calculation	no

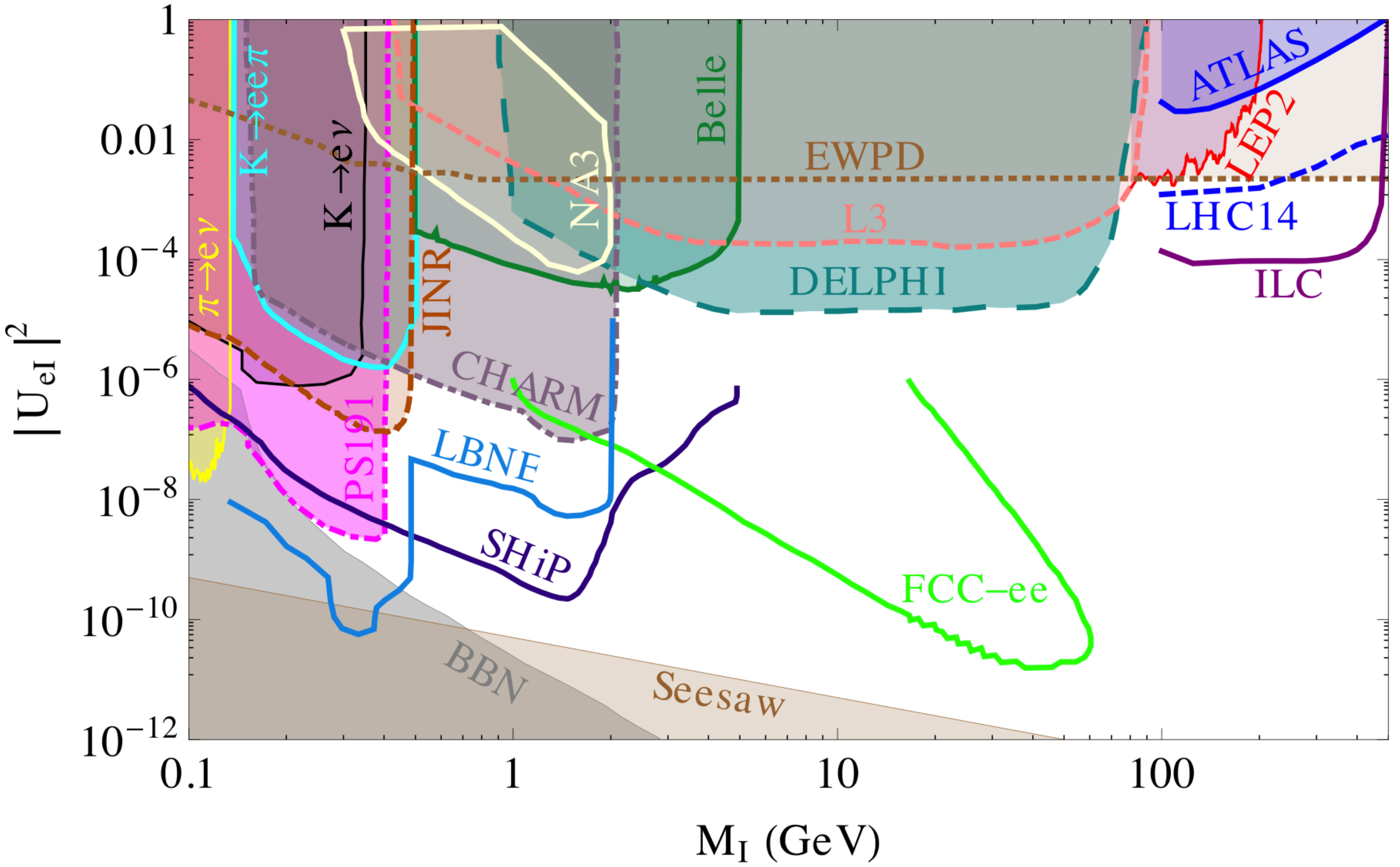
Keep	Remove	ΔR cone size or tracks
electron	muon	sharing an ID track (no MS track)
muon	electron	sharing an ID track
electron	jet	0.2
jet	electron	0.4
muon	jet	0.2 and (jet tracks ≤ 2 or $p_T(\mu)/p_T(\text{jet}) > 0.5$)
jet	muon	0.4 and (jet tracks ≥ 2 or $p_T(\mu)/p_T(\text{jet}) < 0.5$)

Requirement	Signal electrons (tight)	Background electrons (loose)
Identification	LHTight	LHLoose XOR
Isolation	FCLoose	fail FCLoose or fail tight selection
p_T cut	$p_T > 10$ GeV	$p_T > 10$ 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	$\lvert z_0 \sin(\theta)\rvert < 0.5$ mm	$\lvert z_0 \sin(\theta)\rvert < 0.5$ mm
Bad cluster veto	yes	yes

Requirement	Signal muons (tight)	Background muons (loose)
Quality	HighPt if $p_T > 300$ GeV else Medium	HighPt if $p_T > 300$ GeV else Medium
Bad muon veto	yes	yes
Isolation	FixedCutTightTrackOnly	fail FixedCutTightTrackOnly
p_T cut	$p_T > 10$ GeV	$p_T > 10$ 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	$\lvert z_0 \sin(\theta)\rvert < 0.5$ mm	$\lvert z_0 \sin(\theta)\rvert < 0.5$ mm

HL Searches State of Art

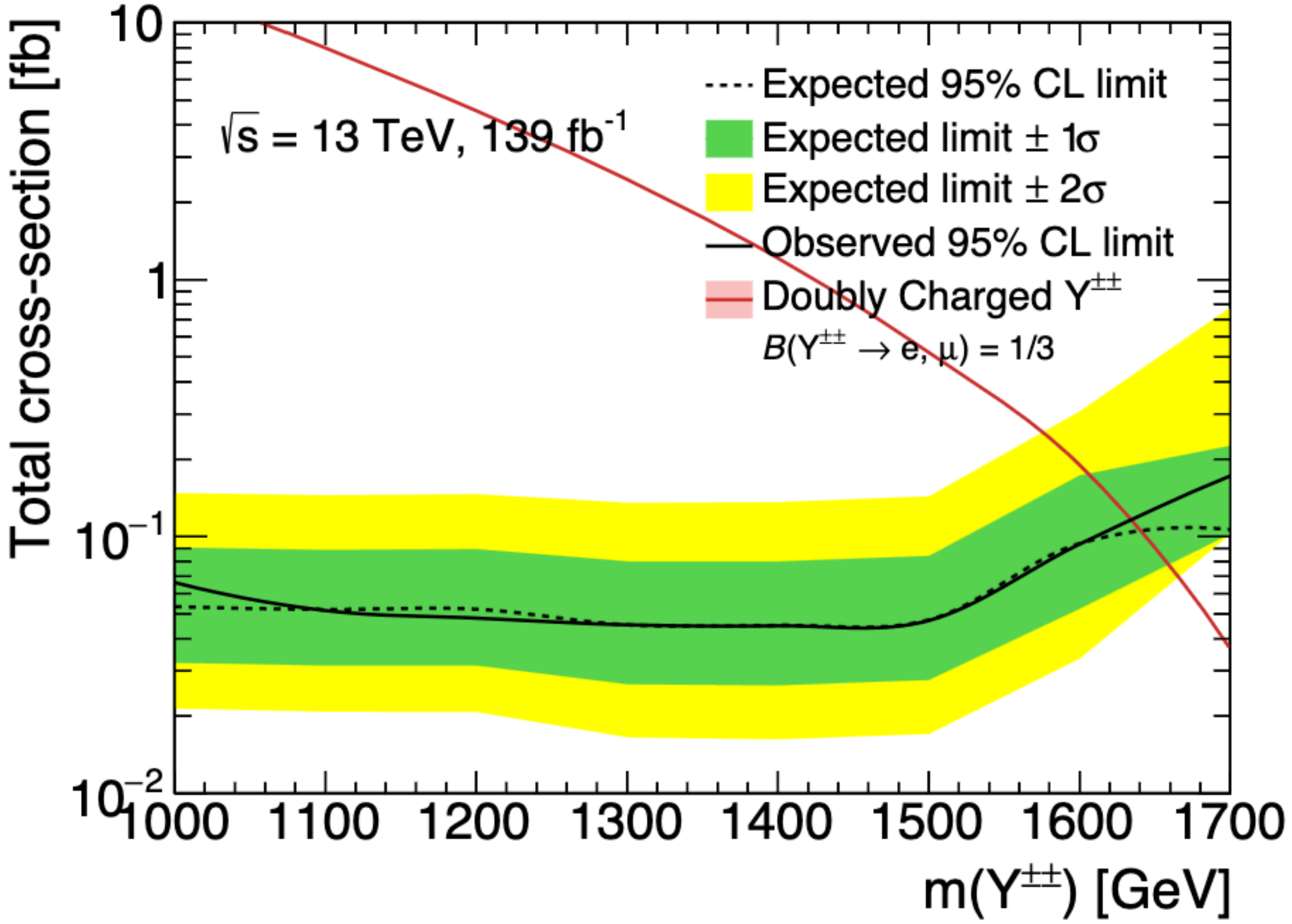


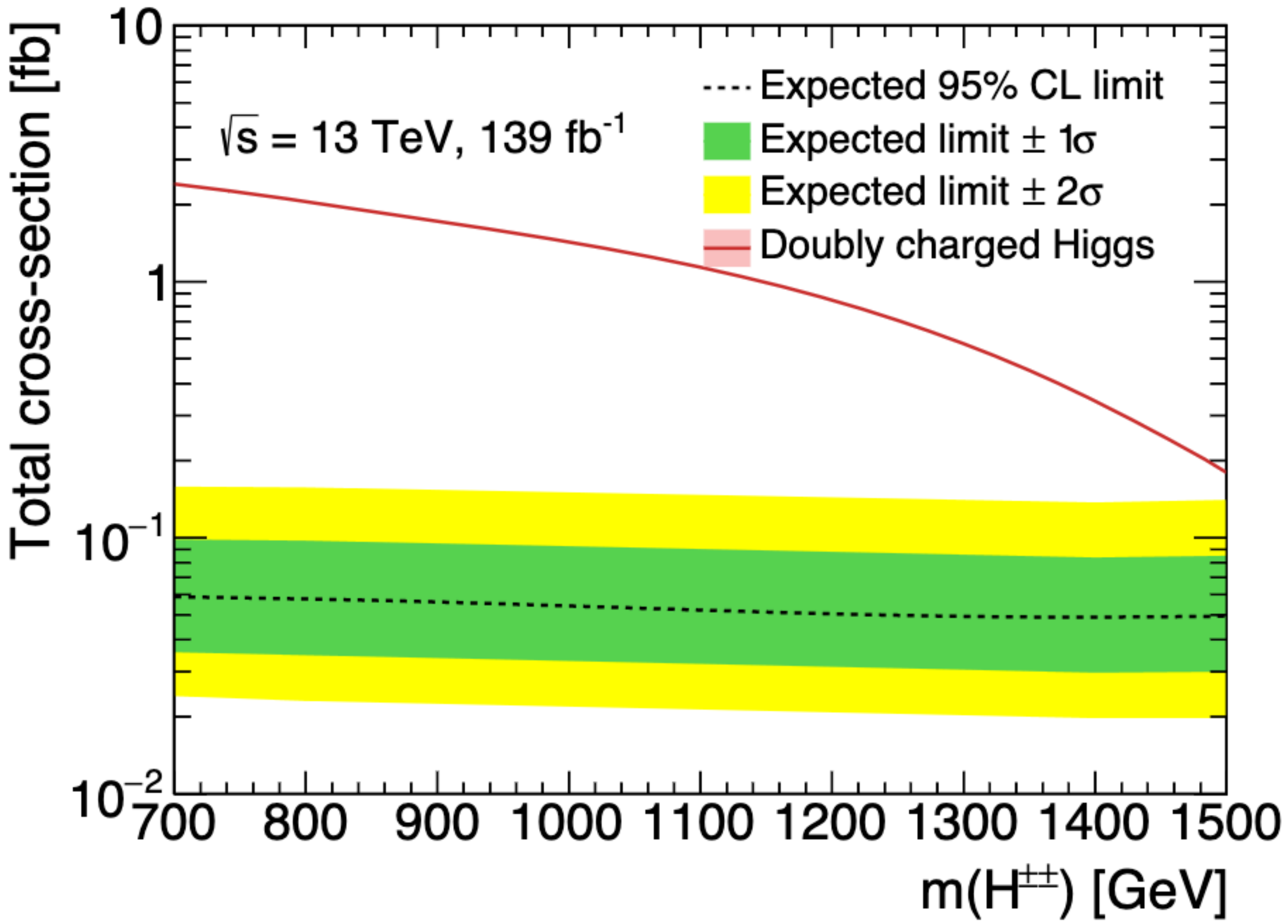


CMS analysis in 3 + 4 lepton final state

Observed: 880 GeV

331 Model Exclusion Limits





$H^{\pm\pm}$ from 331 Model

expected: $m_{Y^{\pm\pm}} < 1642$ GeV are excluded at 95% CL.

observed: $m_{Y^{\pm\pm}} < 1637$ GeV are excluded at 95% CL.

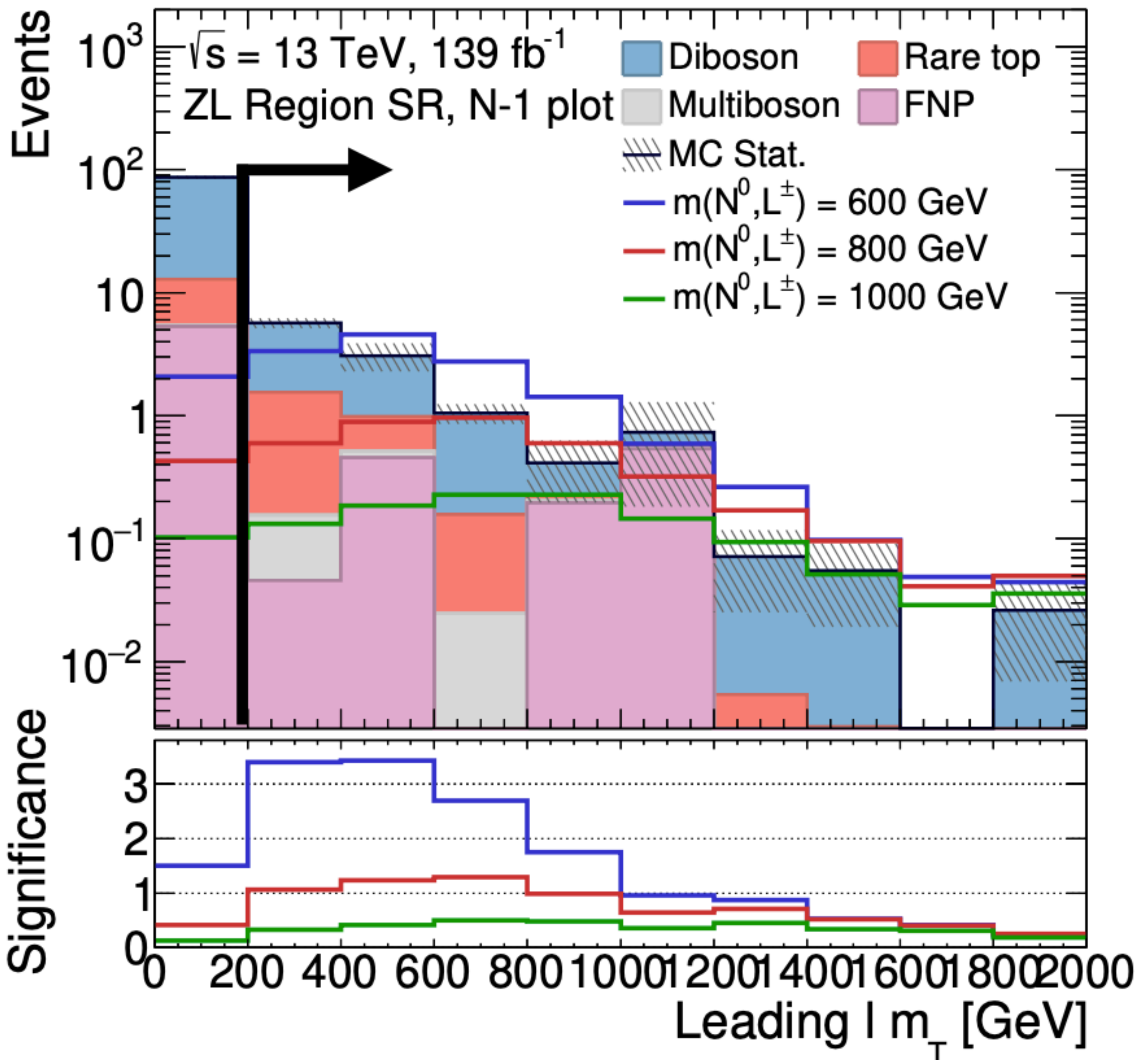
Results from Silvia De Luca' thesis

Signal Significance

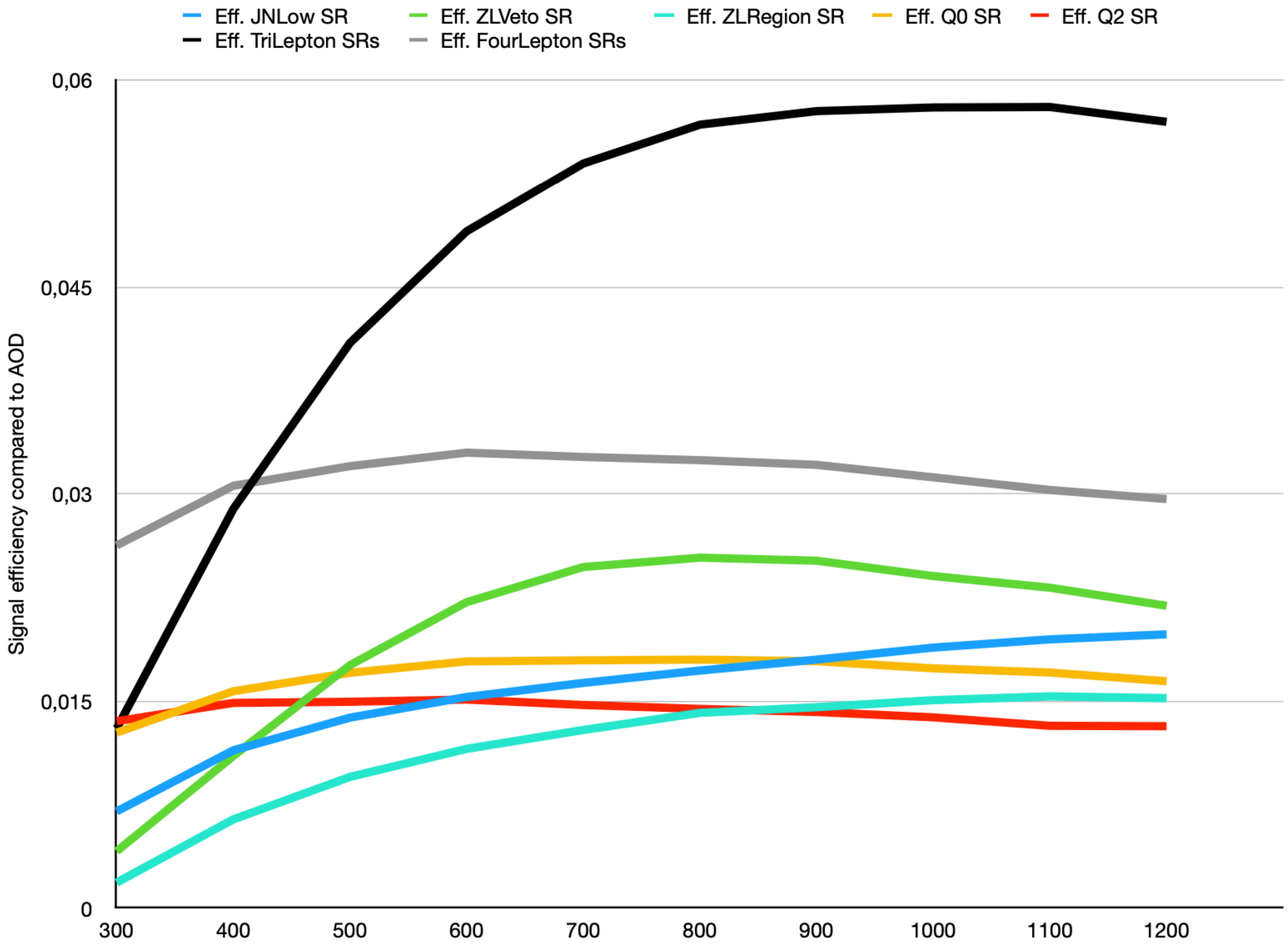
$$\mathcal{S} = \sqrt{2\left[(S+B)\ln\left(1+\frac{S}{B}\right) - S\right]},$$

$S \rightarrow$ Number of signal events

$B \rightarrow$ Number of background events



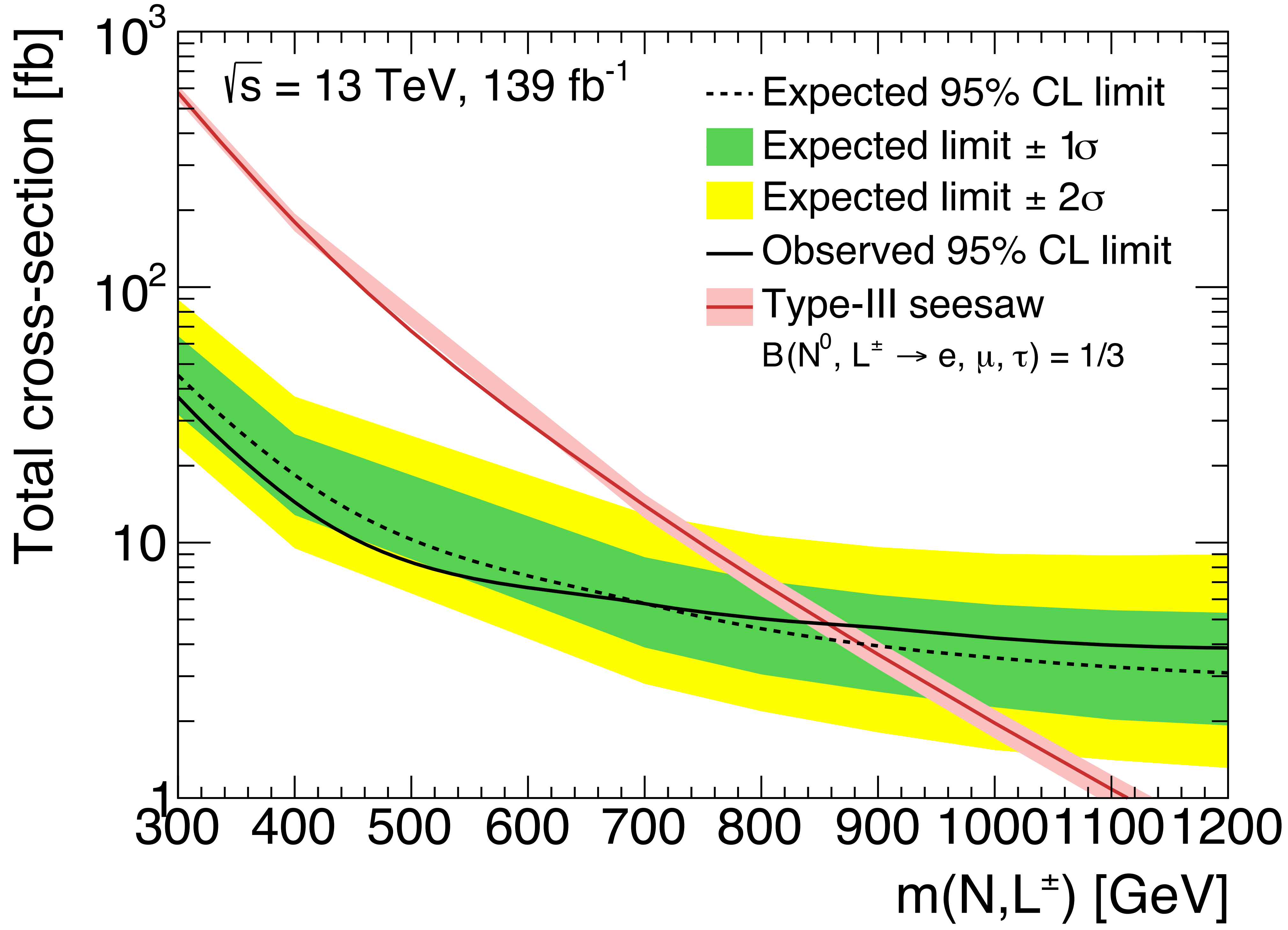
Signal Efficiencies

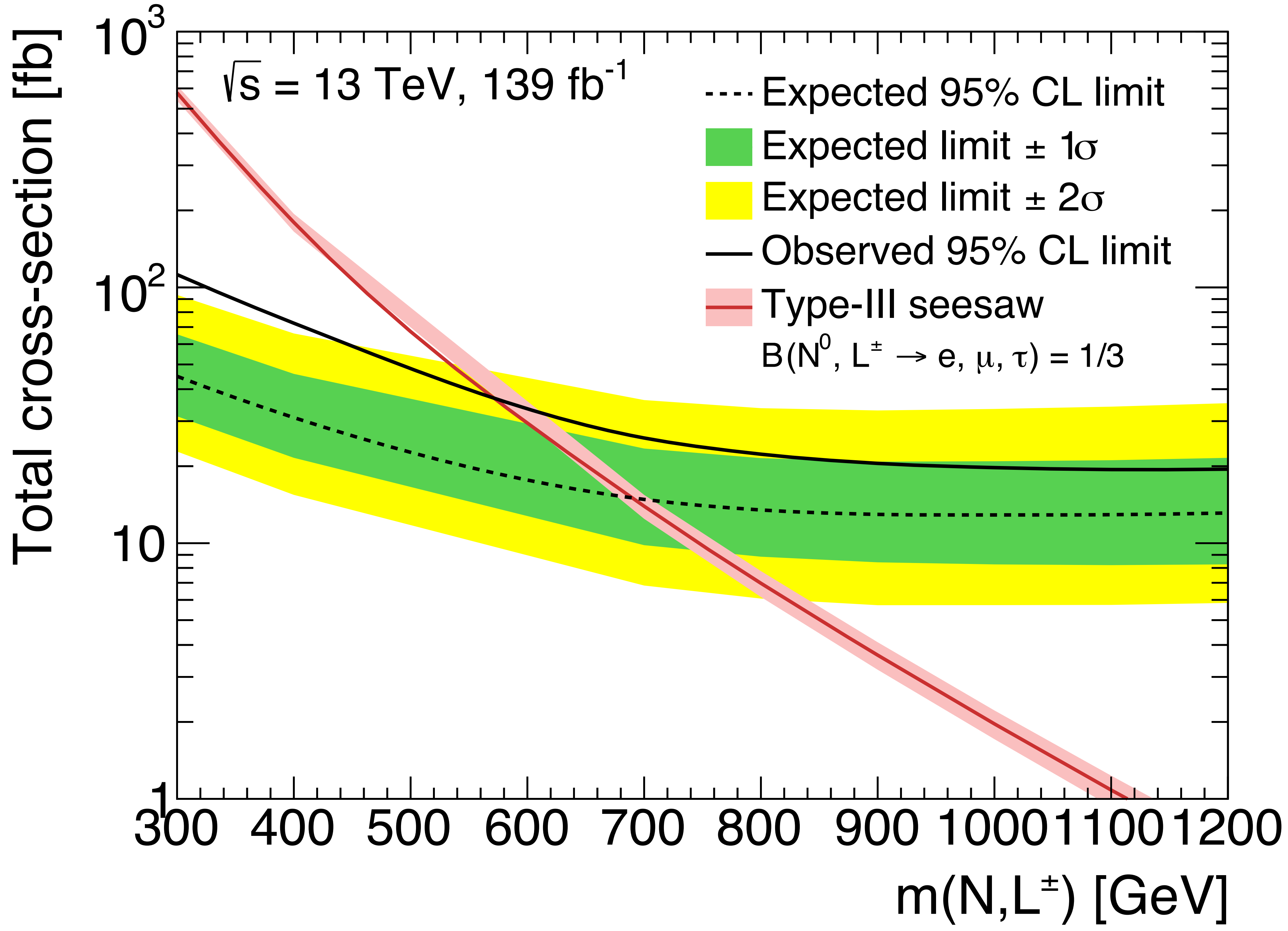


Type-III SeeSaw Systematics

Category	Type	Nuisance Parameters
Luminosity		1
Pile-up reweighting		1
Theory uncertainties	SHERPA 2.2.1 PDF variation	1
	SHERPA 2.2.1 QCD scale variation	1
	SHERPA 2.2.1 PDF choice	1
	Diboson Njet Modelling	1
	Rare Top ttW/ttZ	1
	MADGRAPH5_aMC@NLO PDF variation	1
	MADGRAPH5_aMC@NLO QCD scale variation	1
Data-driven background	Electron fake factors	1
	Muon fake factors	1
Electron calibration	Resolution	1
	Momentum scale	2
Electron efficiencies	ID	1
	Reconstruction	1
	Isolation	1
	Trigger	2
	Charge identification	2
Muon calibration	Smearing of the ID and MS track	2
	Momentum scale	3
Muon efficiencies	Reconstruction	3
	Isolation	2
	TTVA	2
	Trigger	2
Jet calibration	Jet energy scale calibration	14
	Jet energy scale flavour dependence	3
	Jet energy scale pile-up dependence	4
	Jet energy scale calorimeter punch-through	2
	Jet energy scale MC non-closure	2
	Jet energy resolution	9
Jet efficiencies	JVT	1
	Flavour tagging	6
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft track	Offset along the *ptHard* axis	1
	Smearing by resolution uncertainty along and perpendicular to *ptHard* axis	2

Exclusion limits





TriLepton fit:

- **Expected limit:** 885^{+85}_{-90} GeV
- **Observed limit:** 860 GeV

FourLepton fit:

- **Expected limit:** 690^{+70}_{-80} GeV
- **Observed limit:** 580 GeV

Background Composition

ZLRegion CR

Zjets = 0.023267 **<0.1 %**
raretop = 294.308 = **13%**
diboson = 1740.02 = **78%**
singletop = 0.10781 **<0.1 %**
ttbar = 0.909846 **<0.1 %**
multiboson = 2.14734 **<0.1 %**
fakes = 181.122 = **8%**

Total = 2218.64

JNLow VR

Zjets = 0.524453 **<0.1 %**
raretop = 45.2821 = **1.1%**
diboson = 3258.39 = **79%**
singletop = 0.337144 **<0.1 %**
ttbar = 2.62692 **<0.1 %**
multiboson = 3.56526 **<0.1 %**
fakes = 776.853 = **19%**

Total = 4087

ZLRegion VR

Zjets = 0 **= 0 %**
raretop = 17.4531 = **28%**
diboson = 41.9871 = **69%**
singletop = 0 = **0%**
ttbar = 0.0310715 **<0.1 %**
multiboson = 0.139507 = **0.2%**
fakes = 1.68393 = **2,7%**

Total = 61

4l Diboson CR

Zjets = 0 **= 0 %**
raretop = 7.17921 = **0.4%**
diboson = 1469.06 = **96%**
singletop = 0 **= 0 %**
ttbar = 0.067574 **<0.1 %**
multiboson = 0.719344 **<0.1 %**
fakes = 50.7543 = **3.3%**

Total = 1527

4l RareTop CR

Zjets = 0 **= 0 %**
raretop = 43.5846 = **86%**
diboson = 5.39206 = **10%**
singletop = 0 **= 0 %**
ttbar = 0.109355 = **0.2%**
multiboson = 0.00301 < **0.1%**
fakes = 1.5833 = **3.2%**

Total = 50

4l VR

Zjets = 0 **= 0 %**
raretop = 0.591902 = **2.7%**
diboson = 9.74988 = **44%**
singletop = 0 **= 0 %**
ttbar = 0 **= 0 %**
multiboson = 0.04249 = **0.2%**
fakes = 12.1401 = **51%**

Total = 22

ZLRegion SR

Zjets = 0 **= 0%**
raretop = 1.93599 = **33%**
diboson = 3.49411 = **60%**
singletop = 0 **= 0%**
ttbar = 0 **= 0%**
multiboson = 0.115888 = **2%**
fakes = 0.334579 = **5,6%**

Total = 5.88057

JNLow SR

Zjets = 0 **= 0%**
raretop = 1.07499 = **3,5%**
diboson = 21.8564 = **78%**
singletop = 0 **= 0%**
ttbar = 0 **= 0%**
multiboson = 0.318653 = **0,1%**
fakes = 4.69722 = **16%**

Total = 27.9472

ZLVeto SR

Zjets = 0.166773 = **0.6%**
raretop = 8.90412 = **32%**
diboson = 11.0096 = **43%**
singletop = 0 **= 0%**
ttbar = 0.122741 **< 0.1%**
multiboson = 0.192334 **< 0.1%**
fakes = 6.55489 = **24%**

Total = 26.9504

SR tot.charge 0

Zjets = 0 **= 0%**
raretop = 5.25761 = **35%**
diboson = 7.26507 = **47%**
singletop = 0 **= 0%**
ttbar = 0 **= 0%**
multiboson = 0.489794 = **3,2%**
fakes = 2.17128 = **14%**

Total = 15.1838

SR tot charge 1

Zjets = 0 **= 0%**
raretop = 0.766389 = **7,6%**
diboson = 5.8494 = **54%**
singletop = 0 **= 0%**
ttbar = 0 **= 0%**
multiboson = 0.08781 = **0.9%**
fakes = 3.95138 = **37%**

Total = 10.655

Missing Energy Transverse

$$\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}} = \underbrace{\underbrace{-\sum_{\substack{\text{selected}\\\text{electrons}}} \mathbf{p}_{\mathrm{T}}^{e}}_{\mathbf{E}_{\mathrm{T}}^{\mathrm{miss},e}} \underbrace{-\sum_{\substack{\text{selected}\\\text{muons}}} \mathbf{p}_{\mathrm{T}}^{\mu}}_{\mathbf{E}_{\mathrm{T}}^{\mathrm{miss},\mu}} \underbrace{-\sum_{\substack{\text{selected}\\\tau\text{-leptons}}} \mathbf{p}_{\mathrm{T}}^{\tau_{\mathrm{had}}}}_{\mathbf{E}_{\mathrm{T}}^{\mathrm{miss},\tau_{\mathrm{had}}}} \underbrace{-\sum_{\substack{\text{selected}\\\text{photons}}} \mathbf{p}_{\mathrm{T}}^{\gamma}}_{\mathbf{E}_{\mathrm{T}}^{\mathrm{miss},\gamma}} \underbrace{-\sum_{\substack{\text{accepted}\\\text{jets}}} \mathbf{p}_{\mathrm{T}}^{\mathrm{jet}}}_{\mathbf{E}_{\mathrm{T}}^{\mathrm{miss},\mathrm{jet}}}}_{\text{hard term}} \underbrace{\underbrace{-\sum_{\substack{\text{unused}\\\text{tracks}}} \mathbf{p}_{\mathrm{T}}^{\mathrm{track}}}_{\mathbf{E}_{\mathrm{T}}^{\mathrm{miss},\mathrm{soft}}}}_{\text{soft term}} .$$

It is characterised by two contributions:

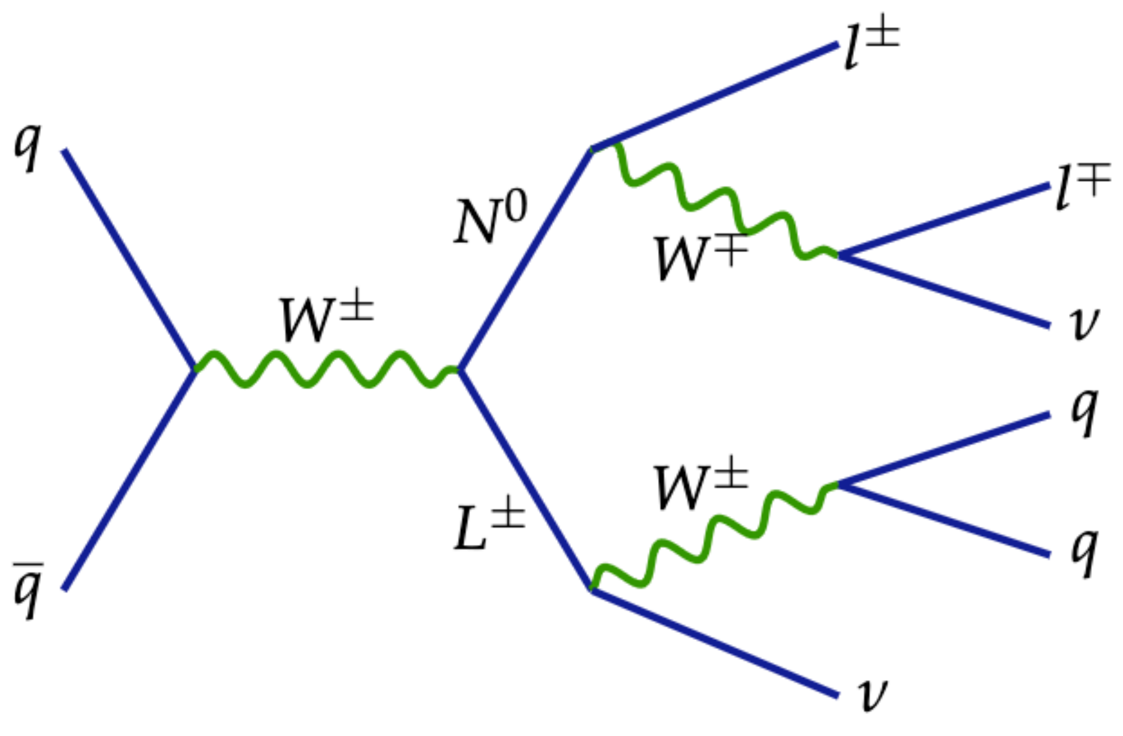
- Hard objects: which include fully reconstructed and calibrated particles, i.e. electrons, photons, τ-leptons, muons and jets;
- Soft term: which consist of signals not associated with any of reconstructed hard objects.

$$\mathcal{S}\left(E_{\mathrm{T}}^{\mathrm{miss}}\right)^{2} = \frac{\left|\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^{2}}{\sigma_{L}^{2}\left(1-\rho_{LT}^{2}\right)},$$

σ_L^2 **is total variance** in the longitudinal direction to $\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}$ and ρ_{LT} **is the correlation factor of the longitudinal** L **and transverse** T measurements. This form shows the **intrinsic meaning of the** $\mathcal{S}$, where the measured variable is in the numerator and the information of the variance is embedded in the denominator

Type-III DiLepton - ML

From Tadej Novak' PhD thesis



No splitting in separate lepton **flavour** or **charge** combinations **during training**.

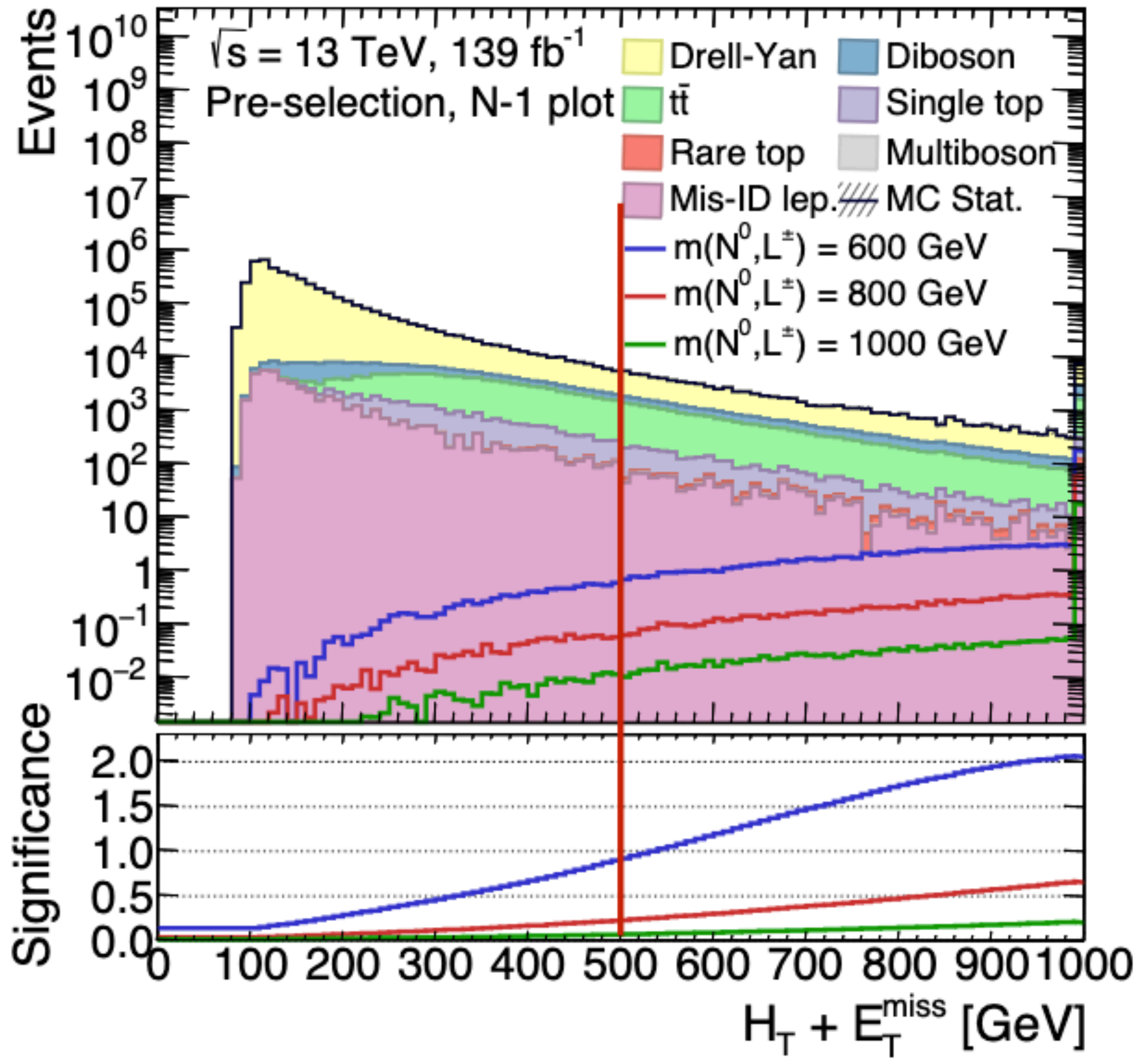
Training features (24)

$p_{\mathrm{T}}(\ell_{\mathrm{lead.}})$	$p_{\mathrm{T}}(\ell_{\mathrm{sub\text{-}lead.}})$	$p_{\mathrm{T}}(\ell\ell)$	$N_{W,H}$
$p_{\mathrm{T}}(j_{\mathrm{lead.}})$	$p_{\mathrm{T}}(j_{\mathrm{sub\text{-}lead.}})$	$p_{\mathrm{T}}(jj)$	N_{jets}
$m(\ell\ell)$	$m(jj)$	$m(jj\ell_{\mathrm{lead.}})$	$m(jj\ell_{\mathrm{sub\text{-}lead.}})$
$m_{\mathrm{T}}(\ell\ell)$	$m_{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}}$	$\mathcal{S}(E_{\mathrm{T}}^{\mathrm{miss}})$
m_{minimax}	$H_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}}$	$p_{\mathrm{T}}(\ell_{\mathrm{lead.}}) + p_{\mathrm{T}}(\ell_{\mathrm{sub\text{-}lead.}}) + E_{\mathrm{T}}^{\mathrm{miss}}$	$\Delta\eta(j_{\mathrm{lead.}}, j_{\mathrm{sub\text{-}lead.}})$
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \ell)_{\mathrm{min}}$	$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, jj)$	$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \ell\ell)$	$\Delta\phi(\ell_{\mathrm{lead.}}, \ell_{\mathrm{sub\text{-}lead.}})$

Chosen based on the effect on the boosted decision tree.

Preselection:

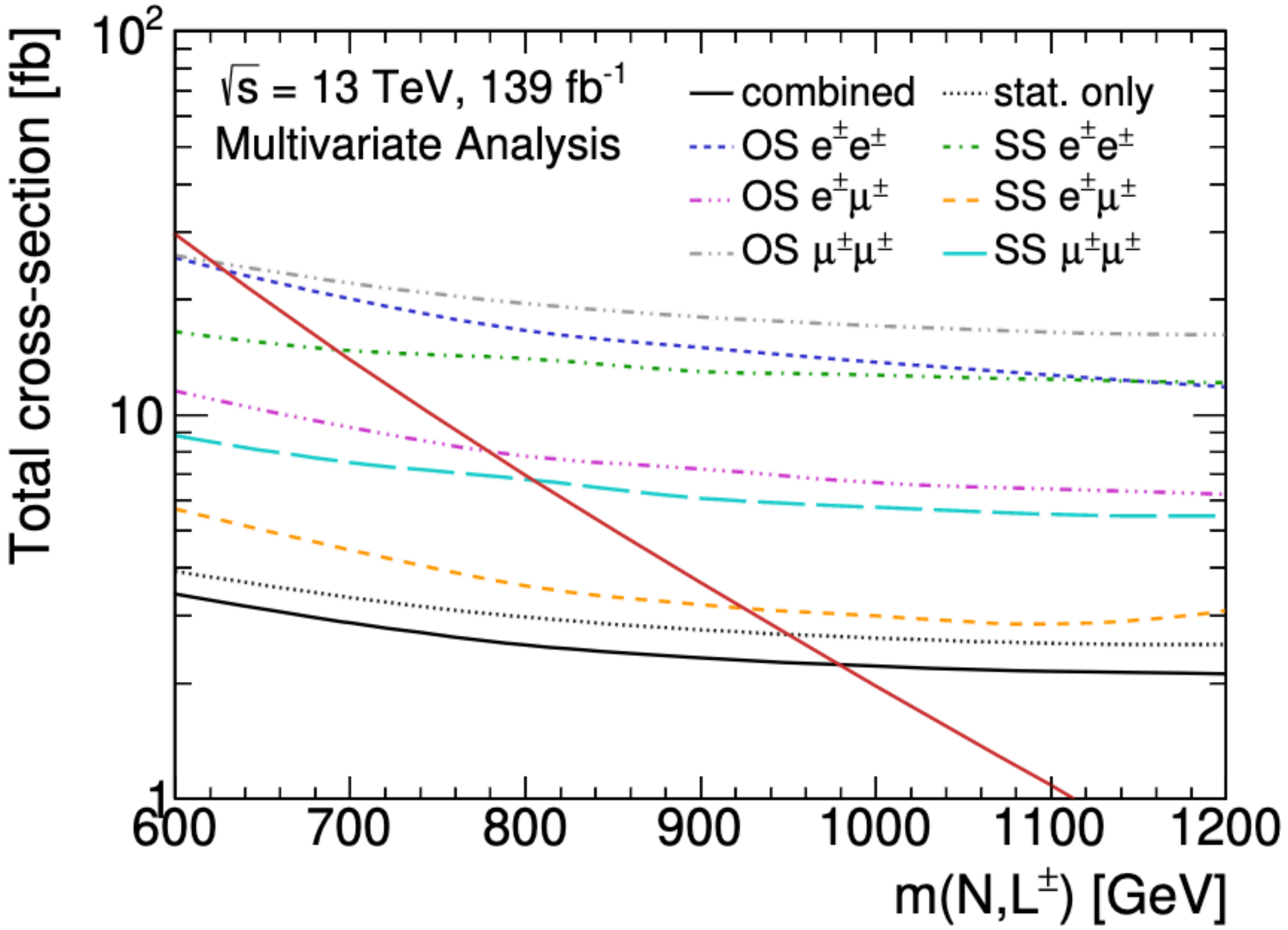
- $m_{\ell\ell} > 100$ GeV
- $H_T + E_T^{miss} > 500$ GeV



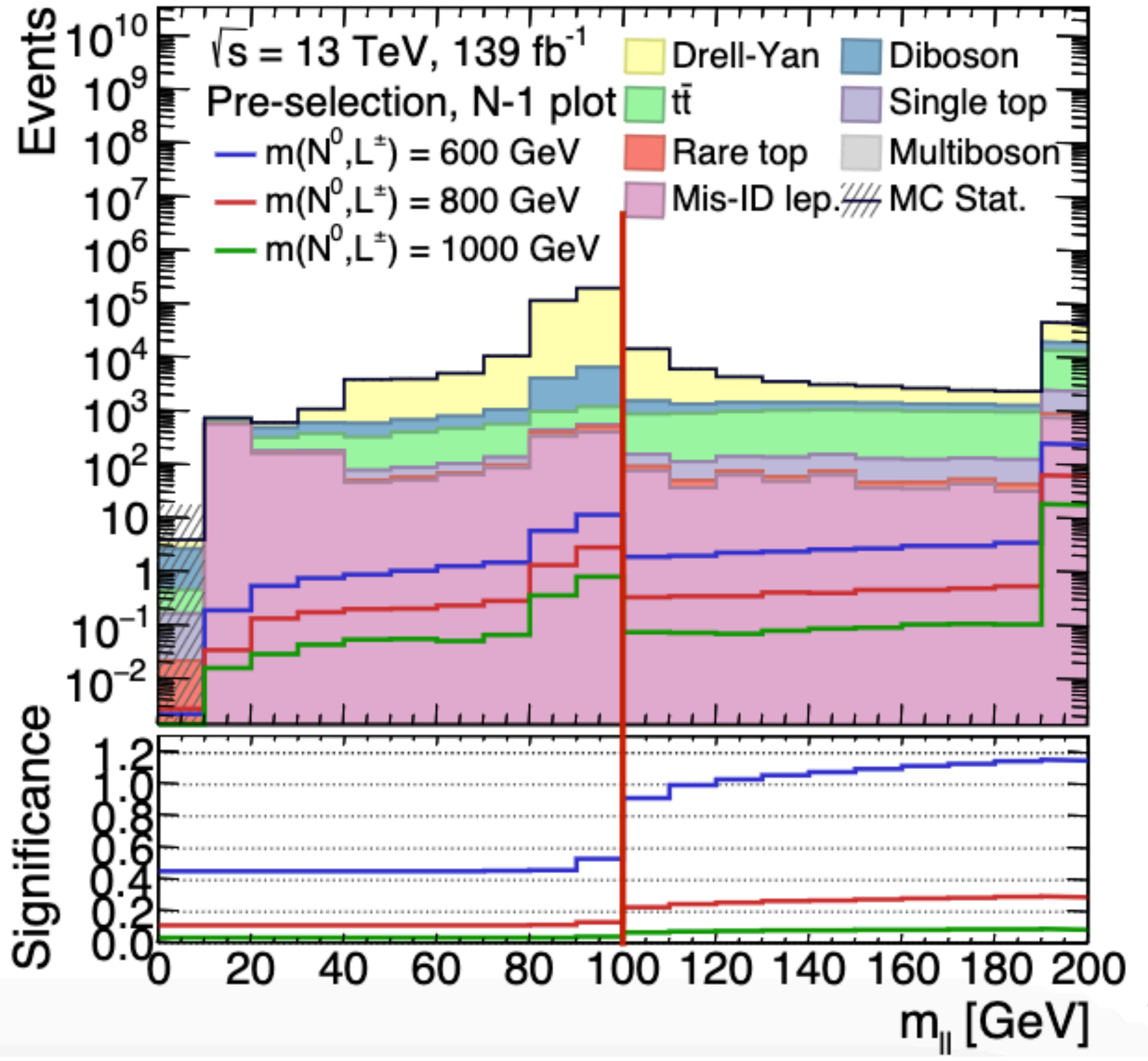
Fitting OS/SS, $ee/\mu\mu/e\mu$ separately.

MVA Score for SRs, $H_T + E_T^{miss}$ for CRs

Background	Normalisation scale
Diboson (OS ee)	0.81 ± 0.07
Diboson (OS $e\mu$)	0.90 ± 0.06
Diboson (OS $\mu\mu$)	0.69 ± 0.06
Diboson (SS ee)	1.21 ± 0.12
Diboson (SS $e\mu$)	1.27 ± 0.06
Diboson (SS $\mu\mu$)	1.10 ± 0.08
$t\bar{t}$ (ee)	0.89 ± 0.01
$t\bar{t}$ ($e\mu$)	0.90 ± 0.01
$t\bar{t}$ ($\mu\mu$)	0.91 ± 0.01



Observed limit of 950 GeV (790 GeV with cut-and-count)



Type-III TriLepton - ML

Preliminary study of **MVA approach** in one region of the **TriLepton channel** from a bachelor thesis

Tabella 4.3: *Ranking* delle variabili classificatrici in ordine decrescente di importanza, per ogni metodo di analisi multivariata implementato nel codice TMVA.

Likelihood	*Fisher Linear Discriminant*	*Boosted Decision Trees*	*Multilayer Perceptron*
$\mathcal{S}(E_T^{miss})$	m_{l1}	ΔR_{lepLS}	m_{l0}
ΔR_{jet}	m_{l0}	m_{l0}	m_{j0}
m_{j1}	H_T	ΔR_{jet}	E_T^{miss}
m_{j0}	E_T^{miss}	m_{l1}	H_T
ΔR_{lep3L}	m_{l2}	ΔR_{lepS3}	m_{j1}
ΔR_{lepLS}	$\mathcal{S}(E_T^{miss})$	ΔR_{lep3L}	m_{l1}
E_T^{miss}	m_{j0}	H_T	m_{l2}
ΔR_{lepS3}	ΔR_{lepS3}	$\mathcal{S}(E_T^{miss})$	$\mathcal{S}(E_T^{miss})$
H_T	ΔR_{jet}	m_{j0}	ΔR_{lep3L}
m_{l1}	m_{j1}	E_T^{miss}	ΔR_{lepS3}
m_{l0}	ΔR_{lep3L}	m_{l2}	ΔR_{lepLS}
m_{l2}	ΔR_{lepLS}	m_{j1}	ΔR_{jet}

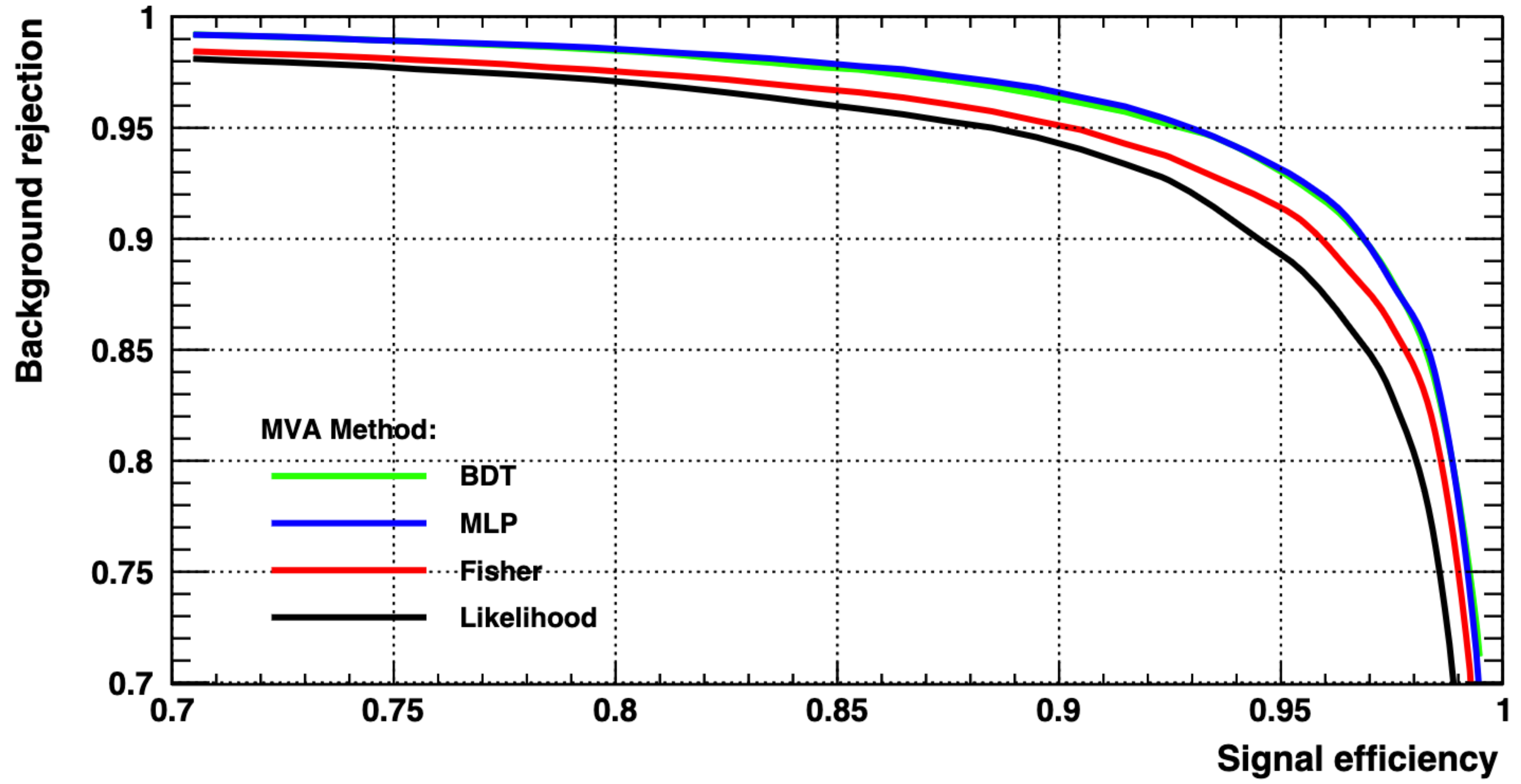


Figura 4.7: Grafico delle quattro curve ROC, distinguibili grazie alla legenda in figura.

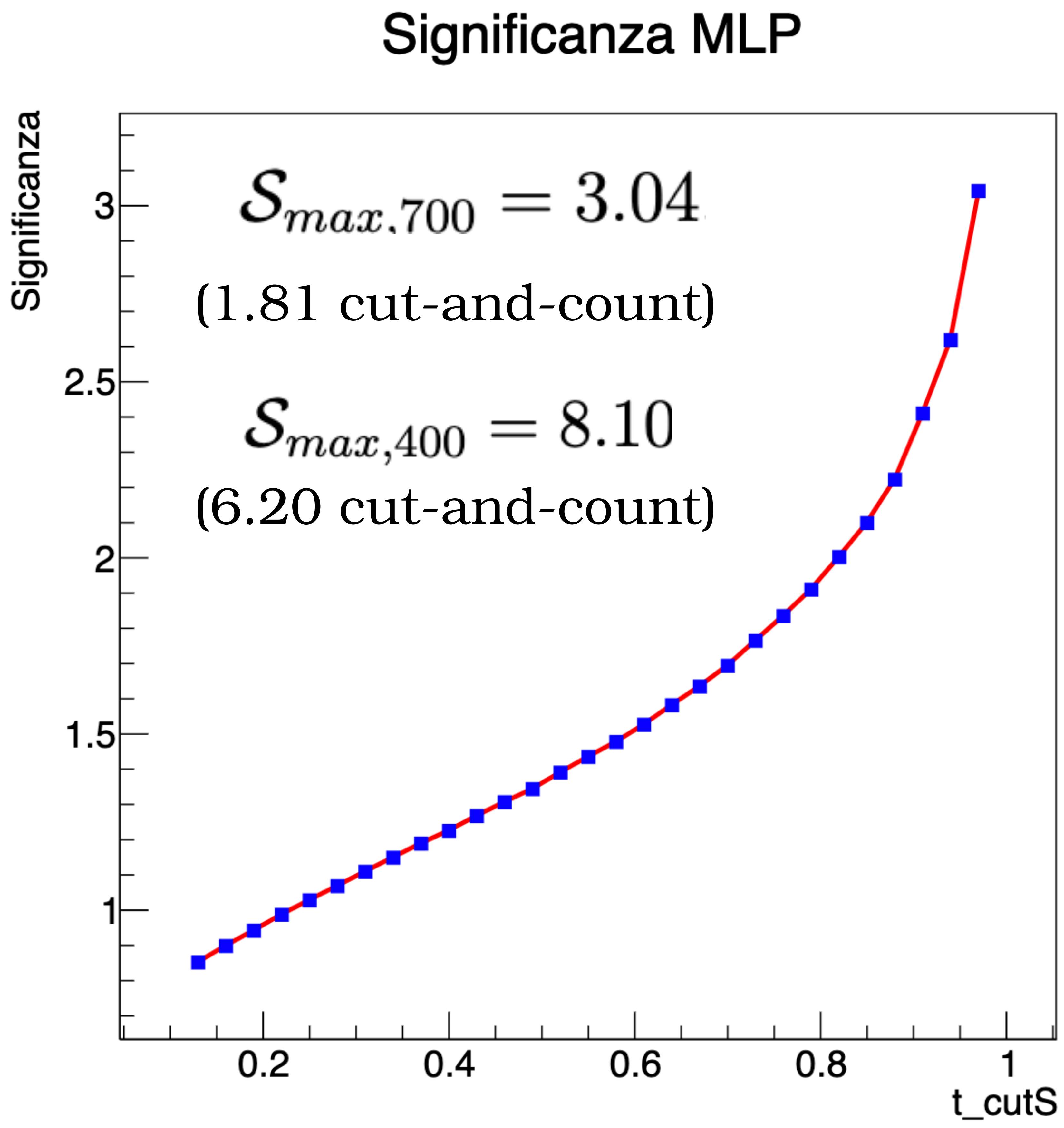


Figura 4.9: Grafico della significanza al variare del valore di $t_{cut,S}$. In azzurro sono riportati i singoli valori di $\mathcal{S}(t_{cut,S})$ calcolati tramite 4.11.