Istituto Nazionale di Fisica Nucleare

Searches for new physics with leptons using the ATLAS detector

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on behalf of the ATLAS Collaboration

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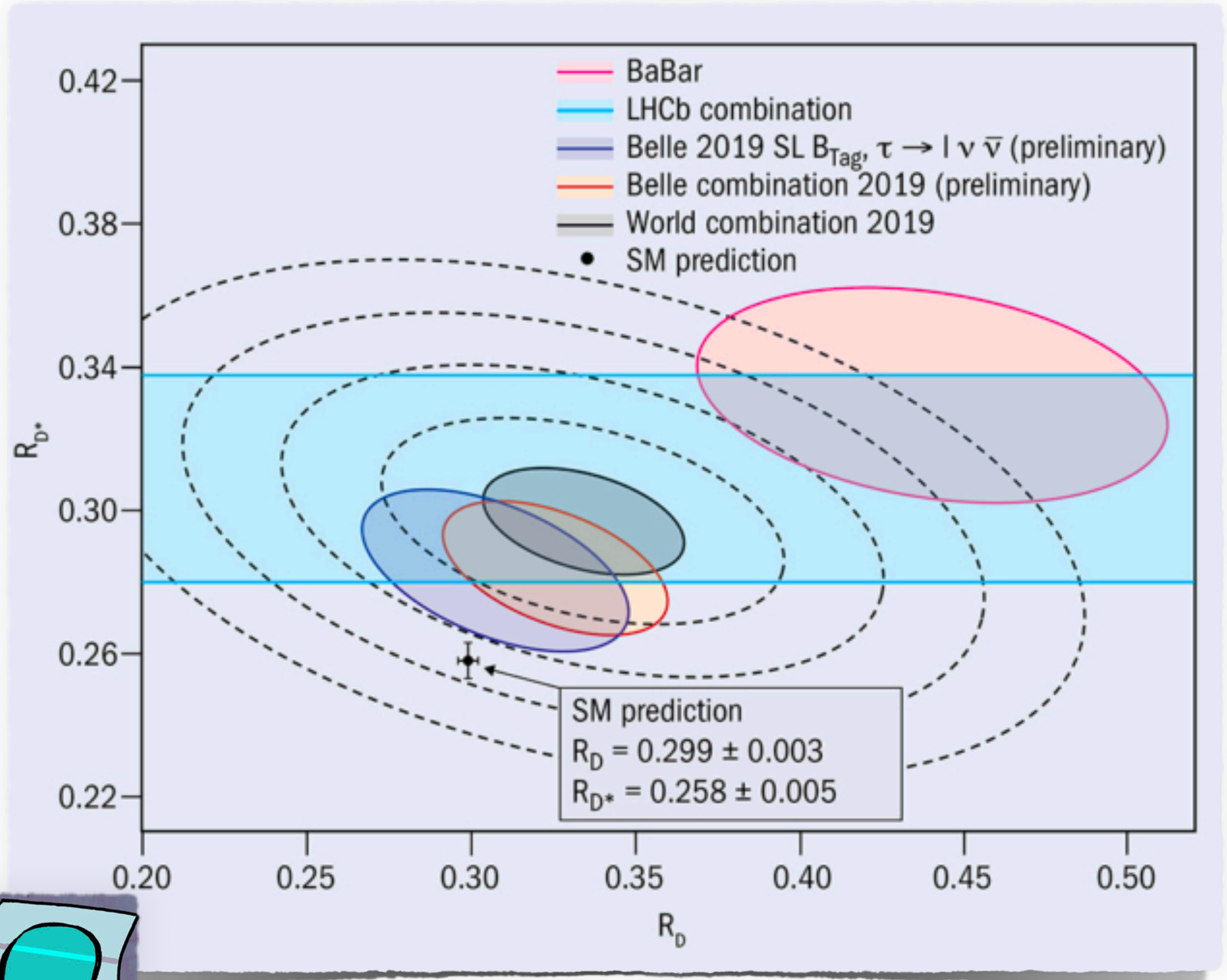
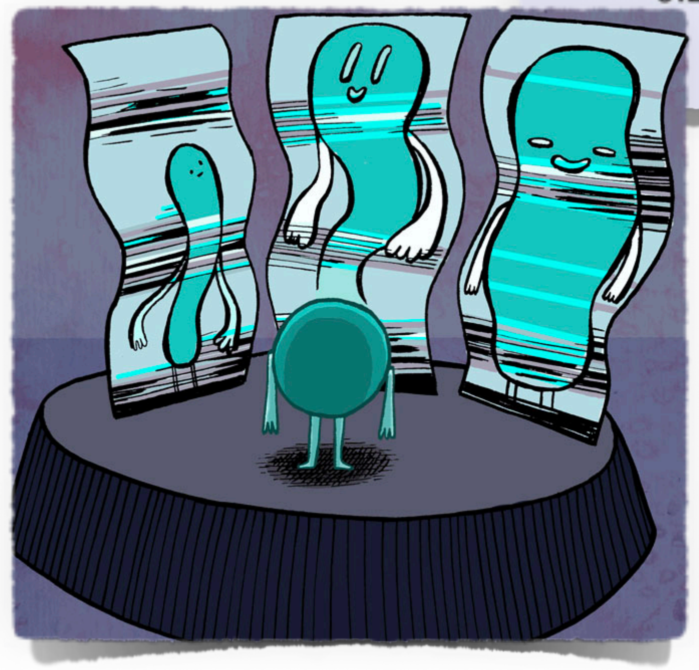
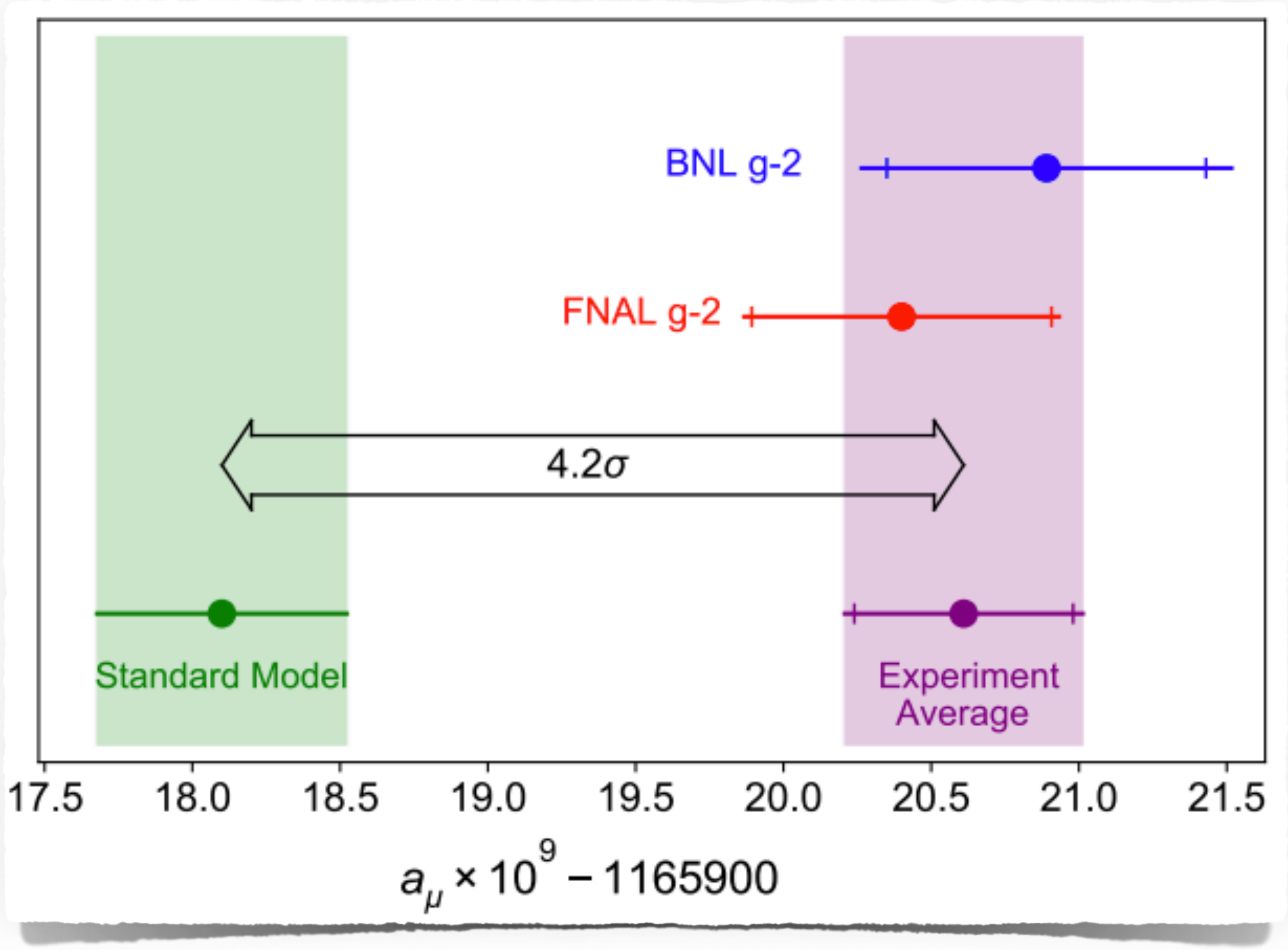
ATLAS EXPERIMENT

Searching new physics

* The SM is a very successful theory, but not everything still understood
* Hints that new physics might be hidden into the leptonic sector:
  * origin of neutrino mass,
  * violation of lepton flavour universality (LFU) in B-meson decays (see talk by Luca Fiornini)
  * (g-2) muon magnetic momentum anomaly
  * R(K*) (see lepto-quark talk by Zhiyuan on Wed)
* Many models propose possible solutions at TeV scale: lepto-quarks, heavy leptons, new gauge bosons, SUSY smuons, …

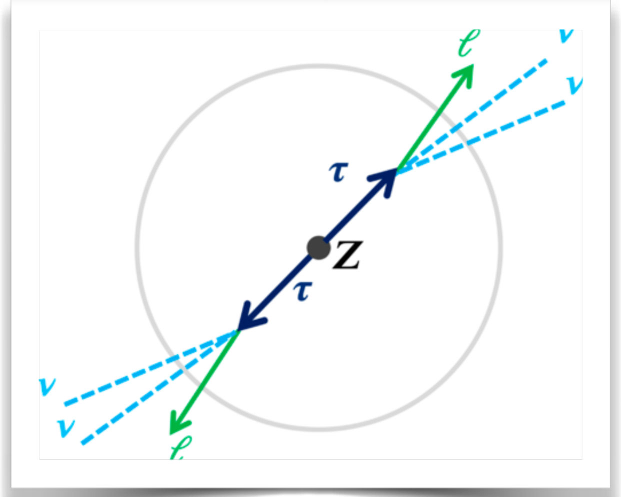


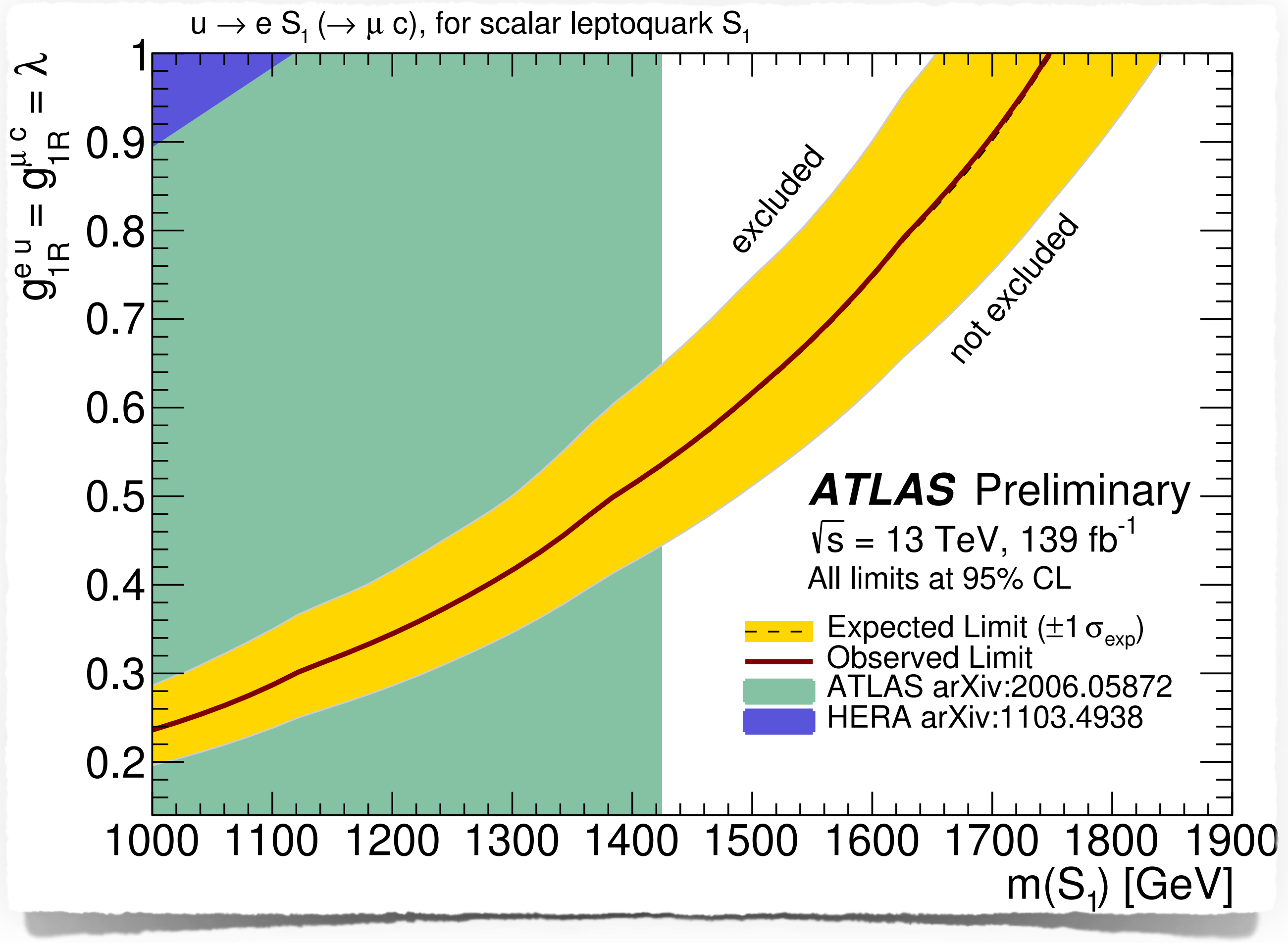


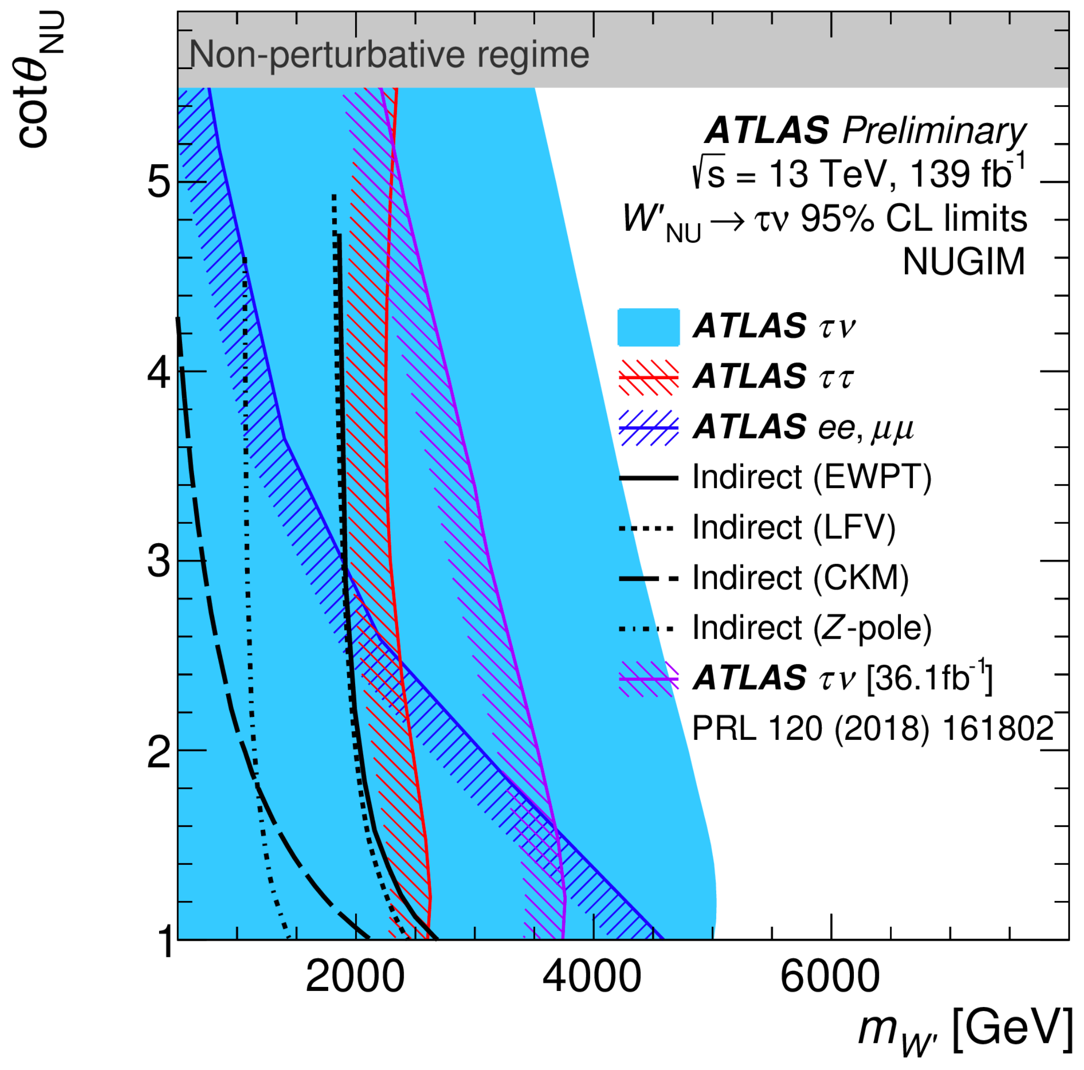


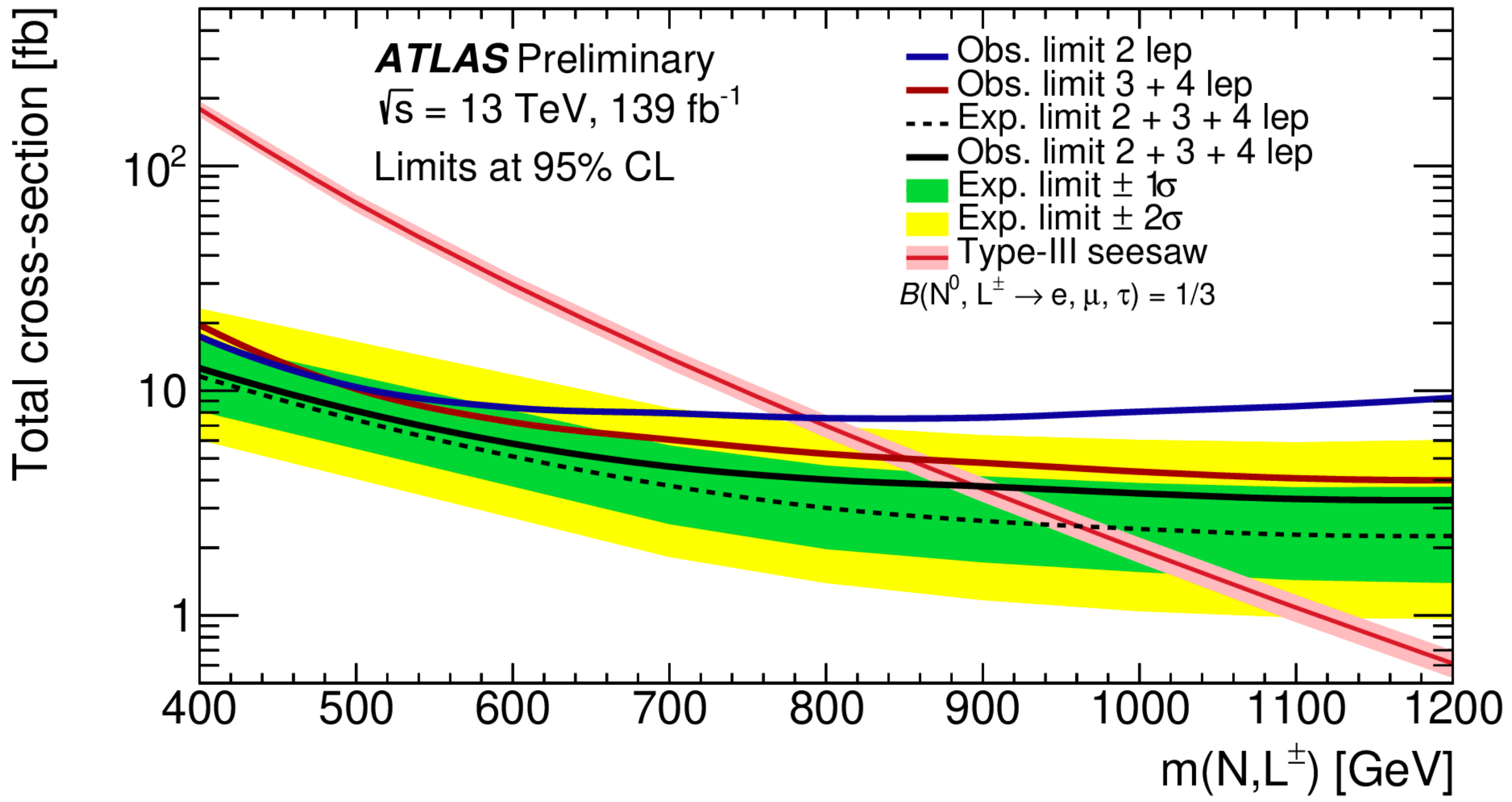
Outline

- Inputs from different searches are needed to confirm or disprove physics BSM
- ATLAS is moving in this direction with a broad program of searches
- Test of SM symmetries
  - Lepton Flavour Violation searches in $Z \to \ell\ell'$ with $(\ell, \ell' = e, \mu, \tau)$
  - Measurement of $(e^+\mu^-/e^-\mu^+)$ ratio
- Search for new heavy particles predicted in UV-complete SM extensions
  - Search for type-III seesaw heavy leptons
  - Search for $W' \to \ell\tau$









Lepton Flavour Violation in Z decay

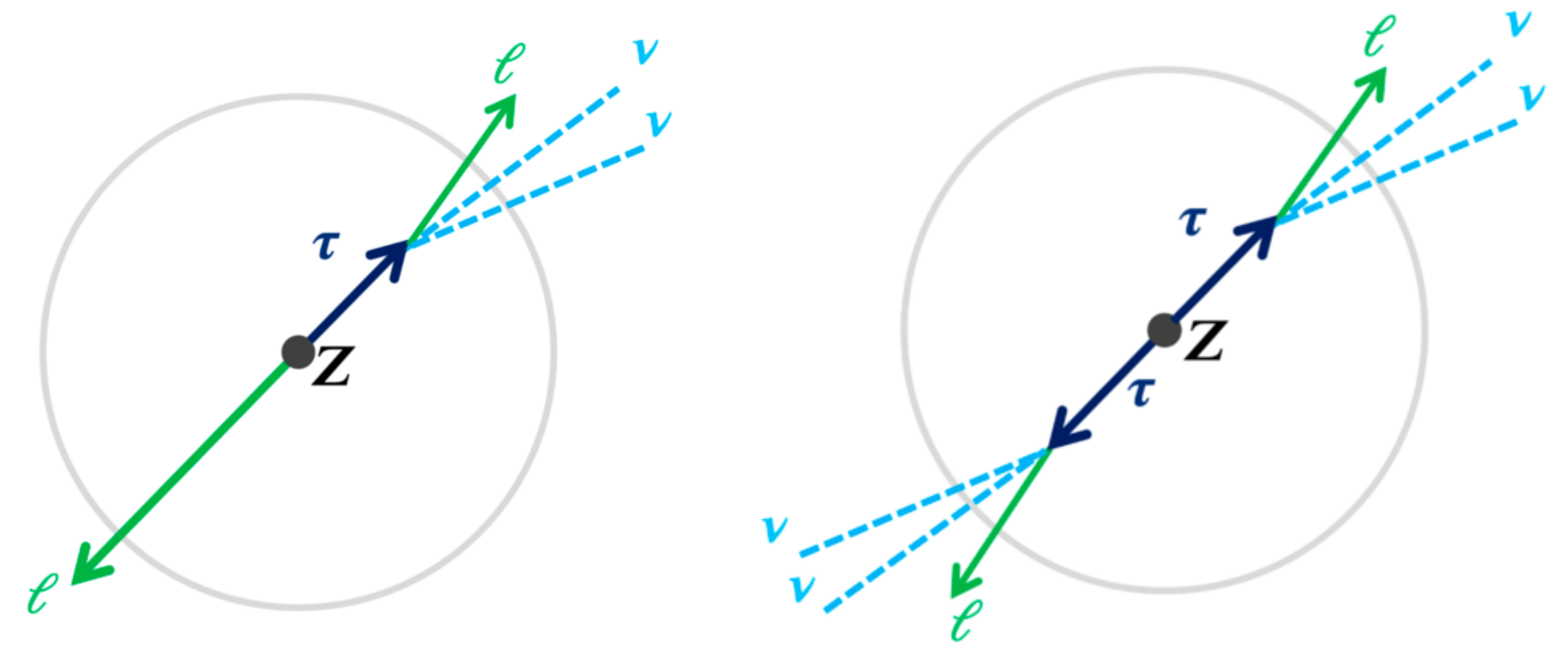
- Violation of lepton flavour conservation (LFV) not forbidden by any fundamental symmetry in SM
  - Any observation is a clear indication of new physics!

- ATLAS search for $Z \to \ell\ell'$ complementary to electroweak energy-scale searches
  - $Z \to \ell\tau$ where $\ell = e, \mu$ and τ may decay both hadronic [Nature Physics (2021)] and leptonic [EXOT-2018-36]. Combined limit extracted.
  - $Z \to e\mu$ [ATLAS-CONF-2021-042]

- **Challenge:** look for tiny signal in background using Machine Learning methods for signal/bkg discrimination

Search for $Z \to \ell\tau$

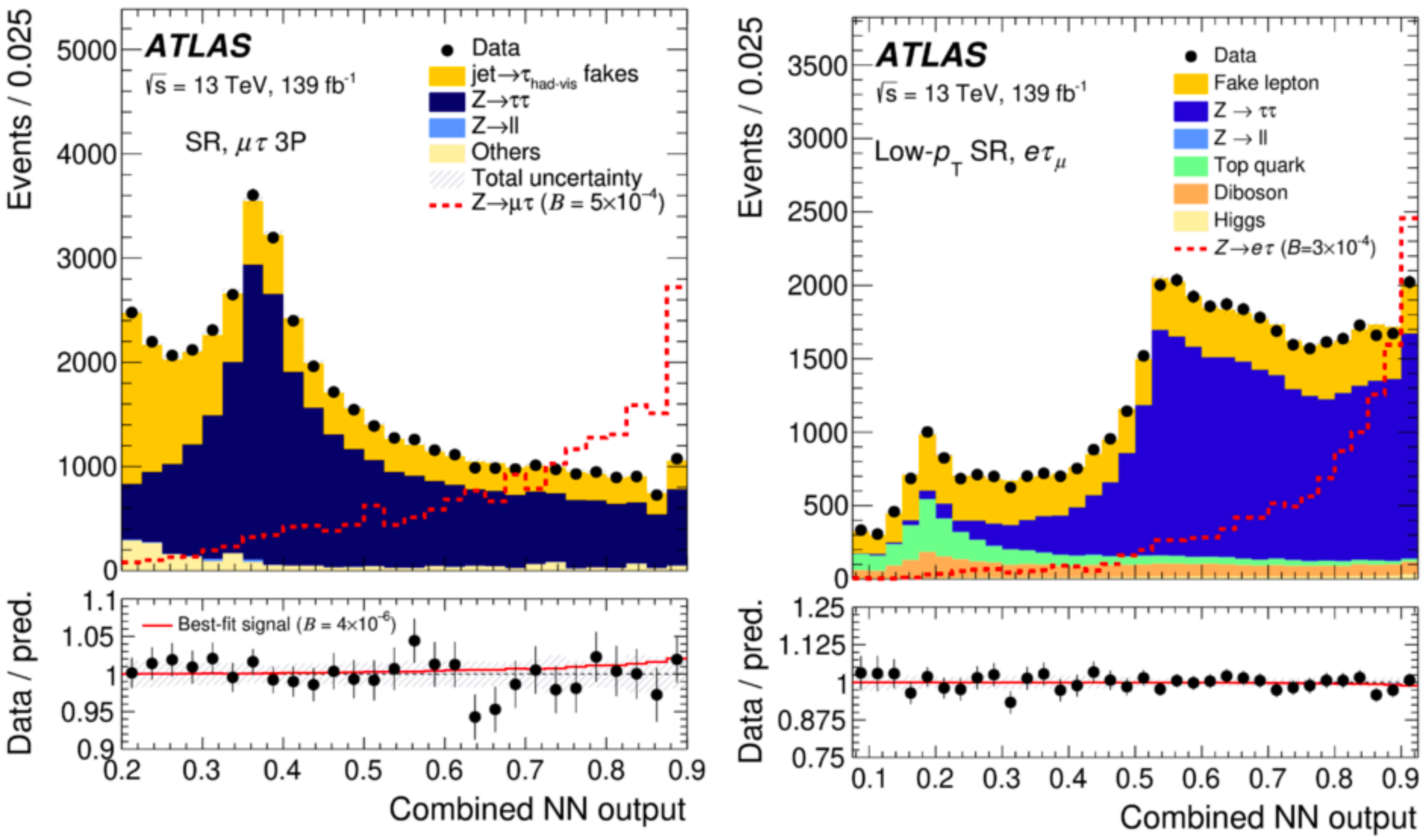
* Signal searched in Neural Network output, studying τ polarisation effects
* **Dominant backgrounds:** $Z \to \tau\tau$, fake-lepton background
* Largest impact on $\mathscr{B}$ uncertainty given by **statistical uncertainties**



Source of uncertainty	Uncertainty in $\mathcal{B}(Z \to \ell\tau)$ [$\times 10^{-6}$] $e\tau$	$\mu\tau$
Statistical	±3.5	±3.9
Fake leptons (statistical)	±0.1	±0.1
Systematic	±2.7	±3.4
Light leptons	±0.4	±0.4
E_T^{miss}, jets and flavor tagging	±2.1	±2.4
E_T^{miss}	±0.4	±0.8
Jets	±1.9	±2.2
Flavor tagging	±0.5	±0.9
Z-boson modeling	<0.1	±0.1
$Z \to \mu\mu$ yield	–	±0.8
Other backgrounds	±0.1	±0.6
Fake leptons (systematic)	±0.4	±0.9
Total	±4.4	±5.2

Search for $Z \to \ell\tau$

- **Result (Run 1+ Run 2) and combining both τ_{had} and τ_{lep}:**
  - $\mathcal{B}(Z \to e\tau) < 5.0 \times 10^{-6}$ (DELPHI :12.0×10^{-6})
  - $\mathcal{B}(Z \to \mu\tau) < 6.5 \times 10^{-6}$ (OPAL : 9.8×10^{-6})

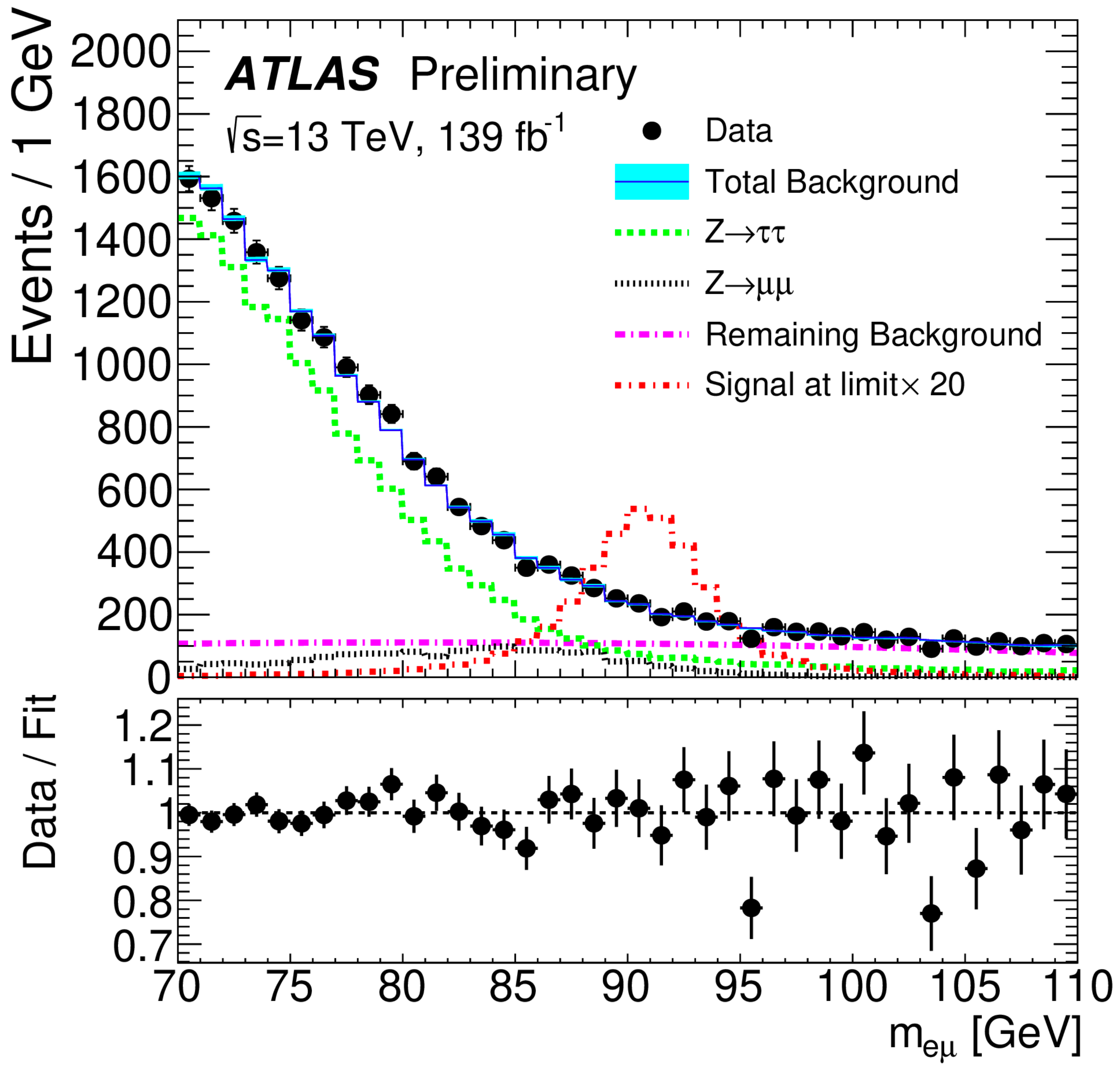


Search for $Z \to e\mu$

ATLAS-CONF-2021-042

- Signal searched using $m_{e\mu}$
- Dominant backgrounds : Z → ττ, Z→ μμ, WW and top
- Event selection:
  - Veto events with jets with large p_T, E_T^{miss} and b-tagged jets
  - BDT used for further background rejection
- Analysis statistically limited (data and simulation)

Source of uncertainty	Degradation of $\mathcal{B}^{95\%\text{CL}}(Z \to e\mu)$
Limited simulated events	9.5%
$Z \to \tau\tau$	4.7%
$Z \to \mu\mu$	6.1%
All other sources	2.4%
Jet energy scale and resolution	1.2%
Pile-up	1.2%
Electron energy scale and resolution	0.8%
Lepton efficiency	0.7%
b-tagging	0.6%
Muon resolution and bias correction	0.6%



Result: $\mathcal{B}(Z \to e\mu) < 3.04 \times 10^{-7}$

(ATLAS-Run1 : 7.5×10^{-7})

Search for heavy gauge bosons ($\tau\nu$)

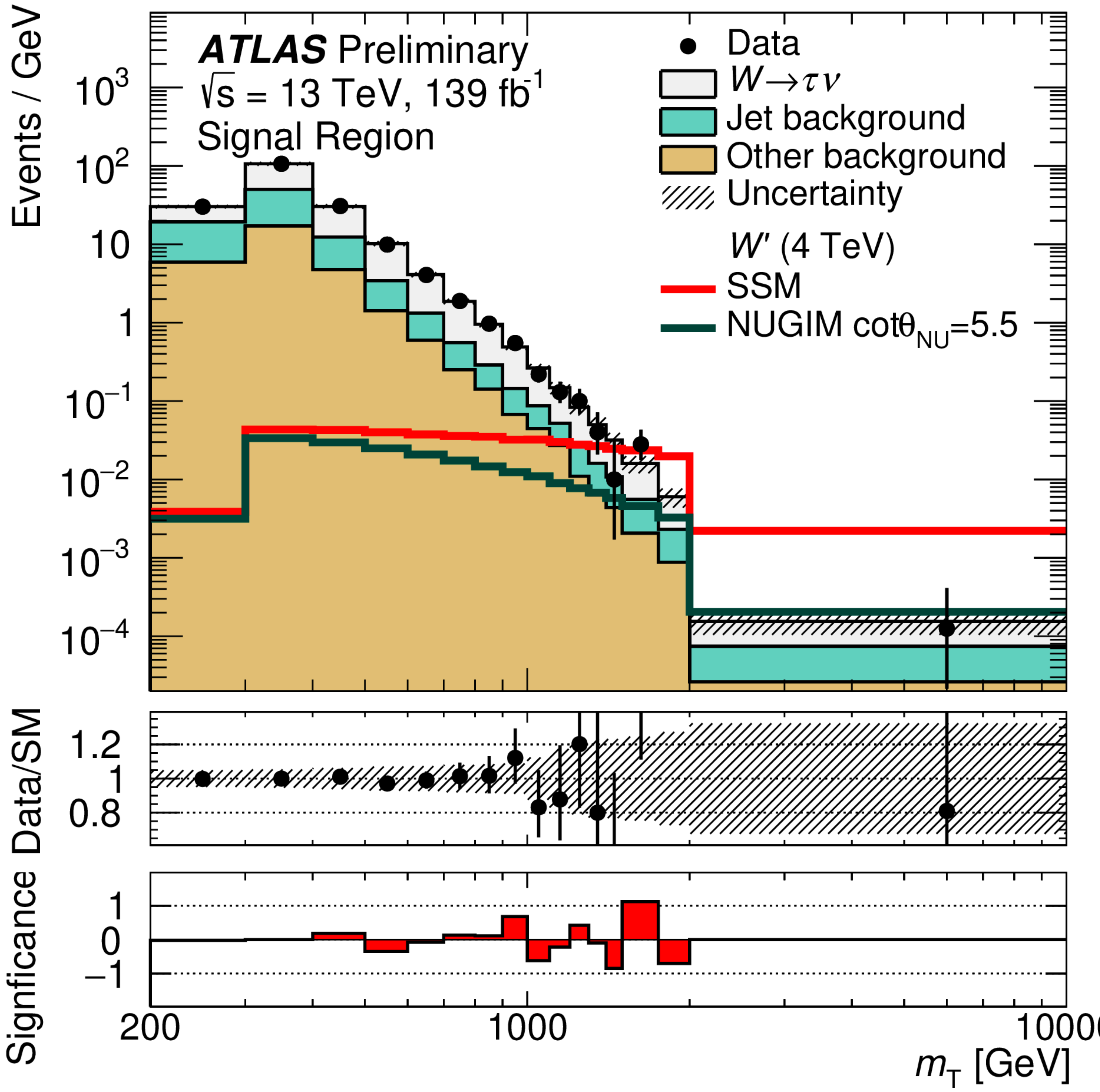
- New heavy gauge bosons (W′, Z′) appear in many extensions of SM
  - **Benchmark model:** *Sequential Standard Model (SSM)* → Same couplings to fermions as the SM

- Searches for new bosons decaying to leptons:
  - W′ → ℓν (ℓ= e , μ) [EXOT-2018-30]
  - Z′ → ℓℓ [EXOT-2018-08]
  - have been performed and exclude SSM boson masses below 6 TeV (W′) and 5.1 TeV (Z′)

- **New results** searching for W′ → τν [ATLAS-CONF-2021-025]
  - Search for high-mass resonances in events with hadronically decaying τ, lepton and missing transverse energy E_T^{miss}
  - Searches in 3rd generation final states: interesting for explaining B-meson anomalies or high mass of top quark

Search for heavy gauge bosons ($\tau\nu$)

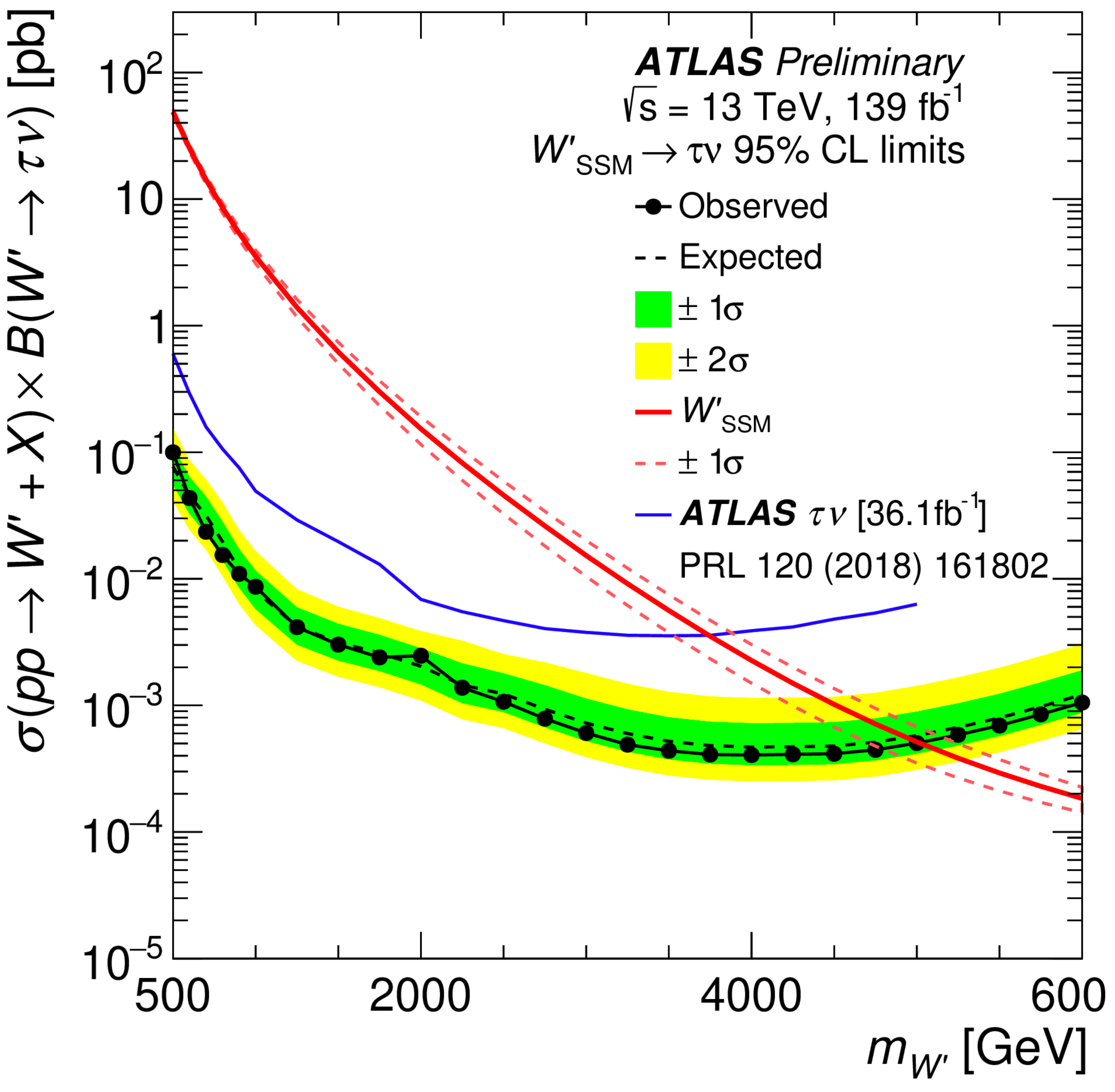
- Signal events expected to have:
  - back-to-back and balanced τ_{had} and E_T^{miss}
  - high $m_T = \sqrt{2E_T^{miss} p_T \left(1 - \cos\Delta\phi\right)}$
- Dominant backgrounds:
  - Off-shell MC production of $W \to \tau\nu$
  - events with jets misidentified as τ_{had} (DataDriven)

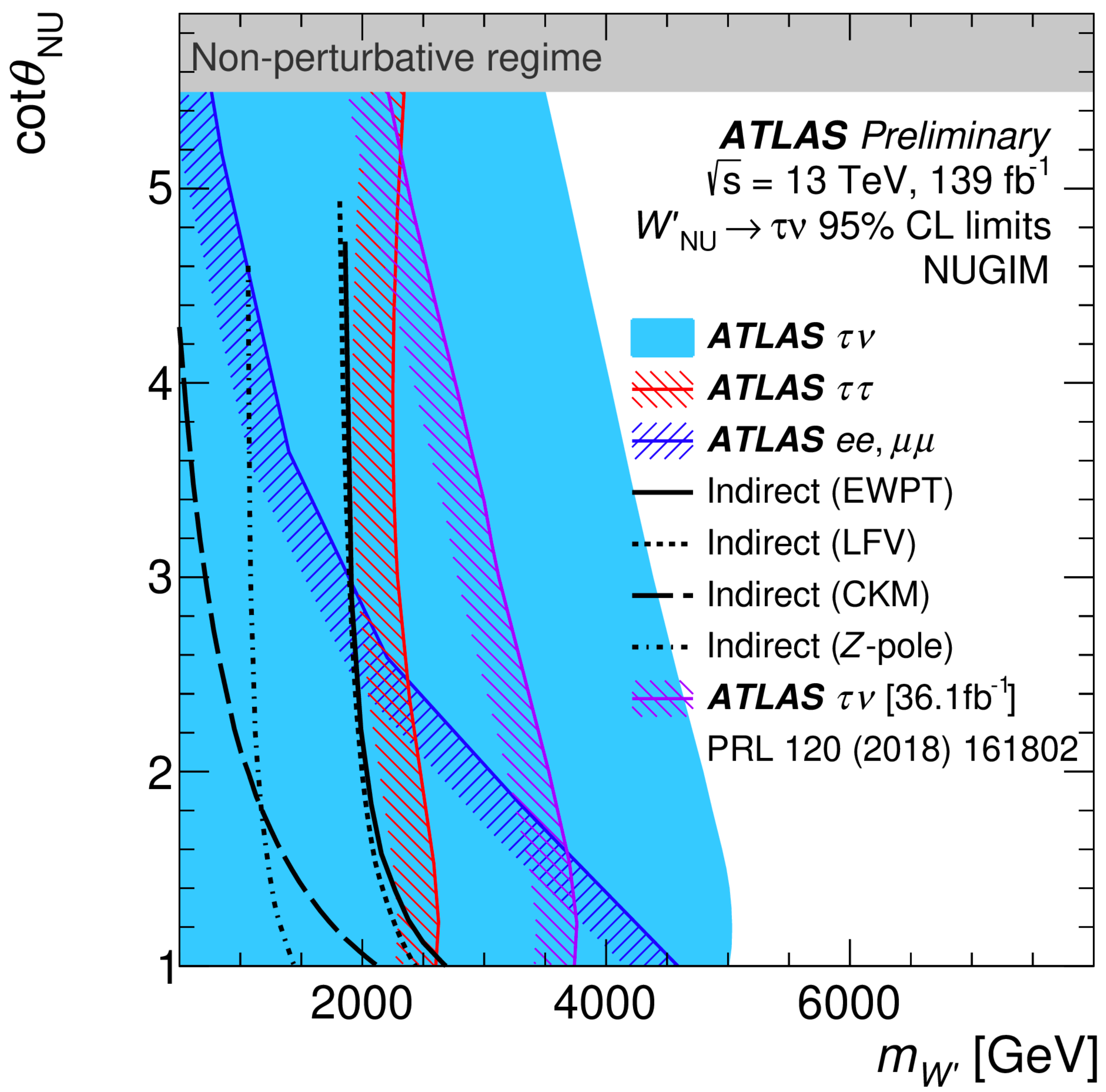


Search for heavy gauge bosons ($\tau\nu$)

- No significant excess observed over SM expectation
- Exclude W′ up to 5 TeV (SSM) and 3.5-5 TeV (NUGIM)

- **Model Interpretations**
  - *Sequential Standard Model (SSM)*: W′ couplings to fermions as W
  - *Non-Universal Gauge Interaction Models (NUGIM)*:
    - Enhanced coupling to 3rd generation $(\cot\theta_{NU} > 1)$



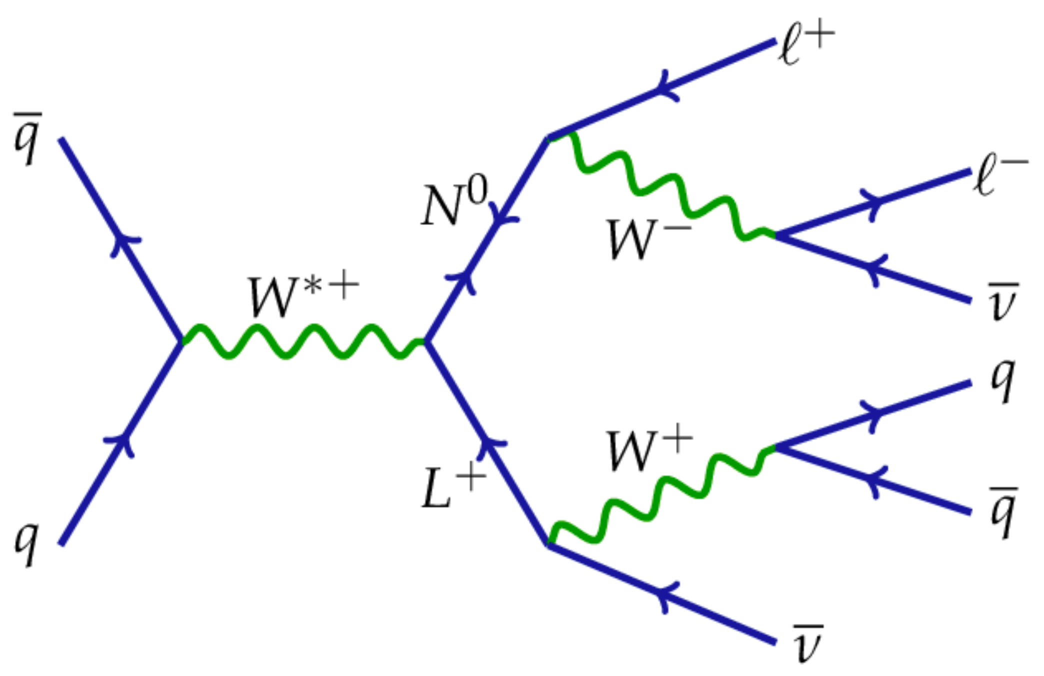


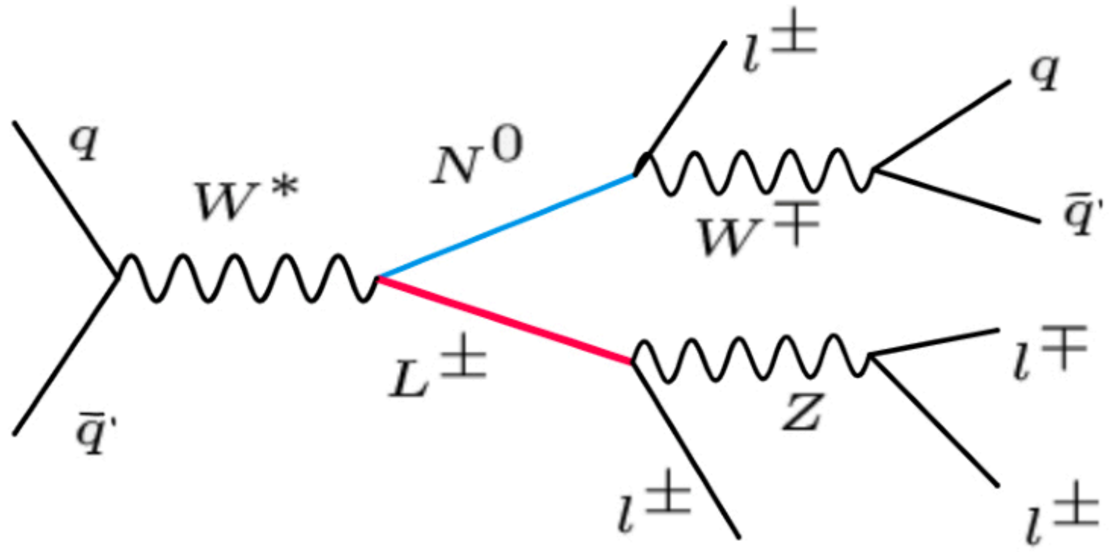
Search for Heavy Leptons

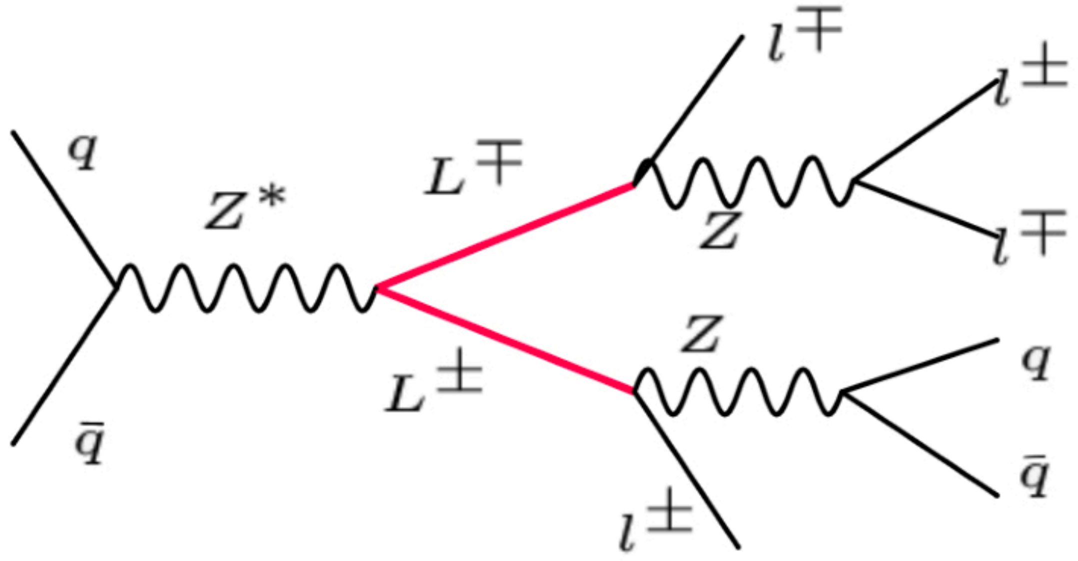
* Searches for Heavy Leptons in multi-lepton final states,
  * 2-lepton channel [Eur. Phys. J. C 81 (2021) 218]
  * 3 and 4-lepton channel [ATLAS-CONF-2021-023]

* Combination of all the channels, for the first time!

* **Benchmark model:** *type-III seesaw* model which provides a heavy Majorana neutrino that could explain small neutrino mass







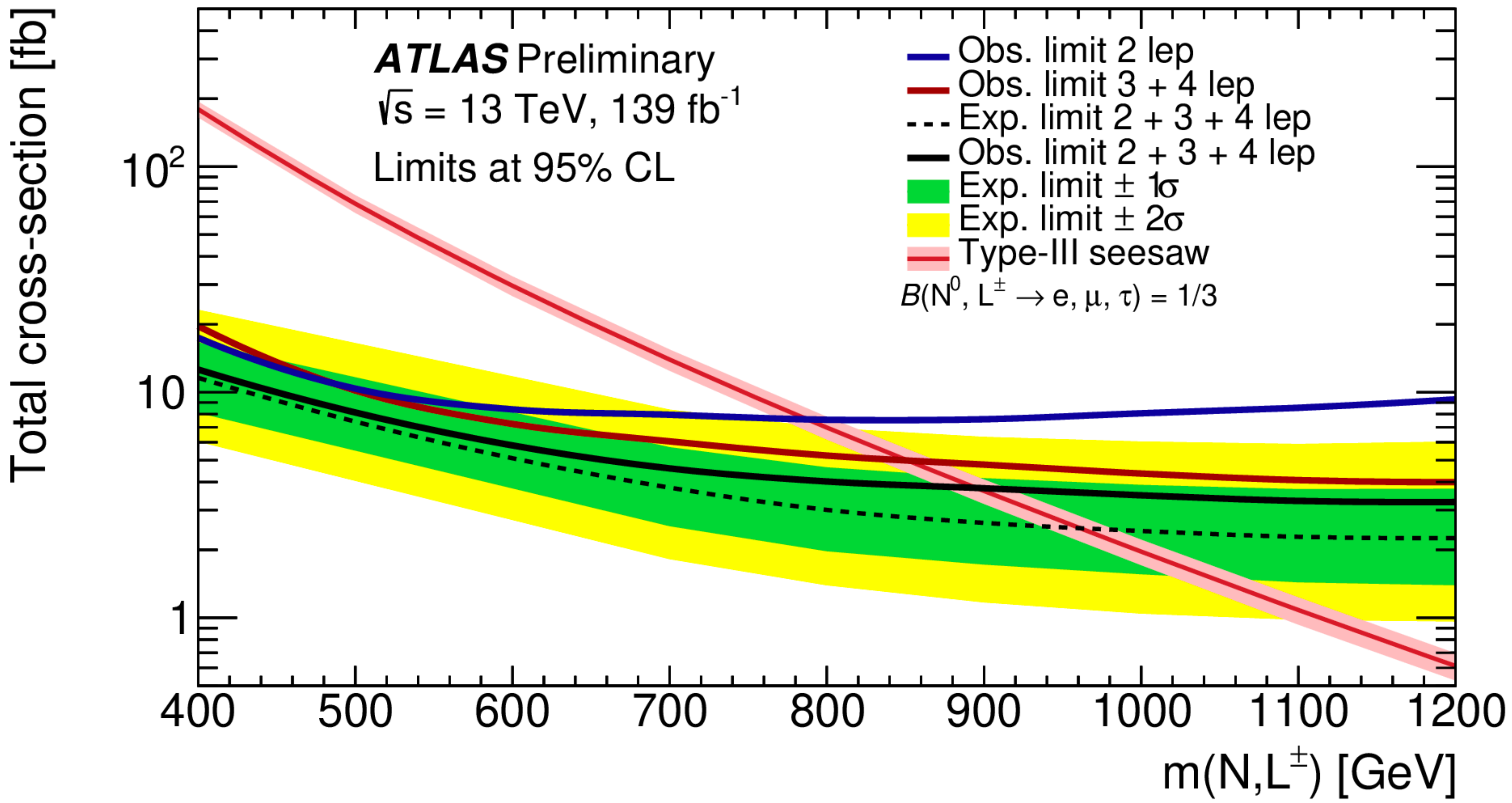
Not yet considered decay channels including τ

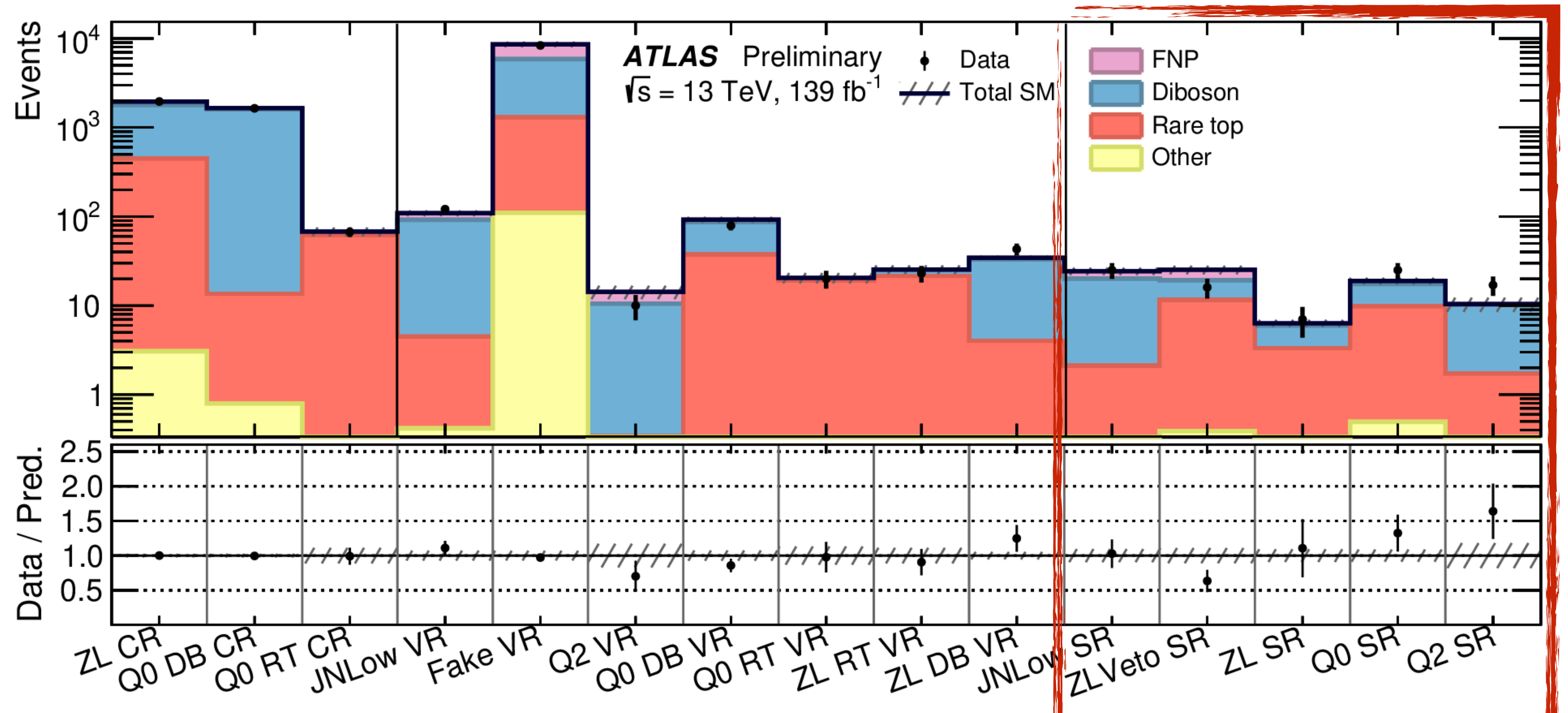
Search for Heavy Leptons

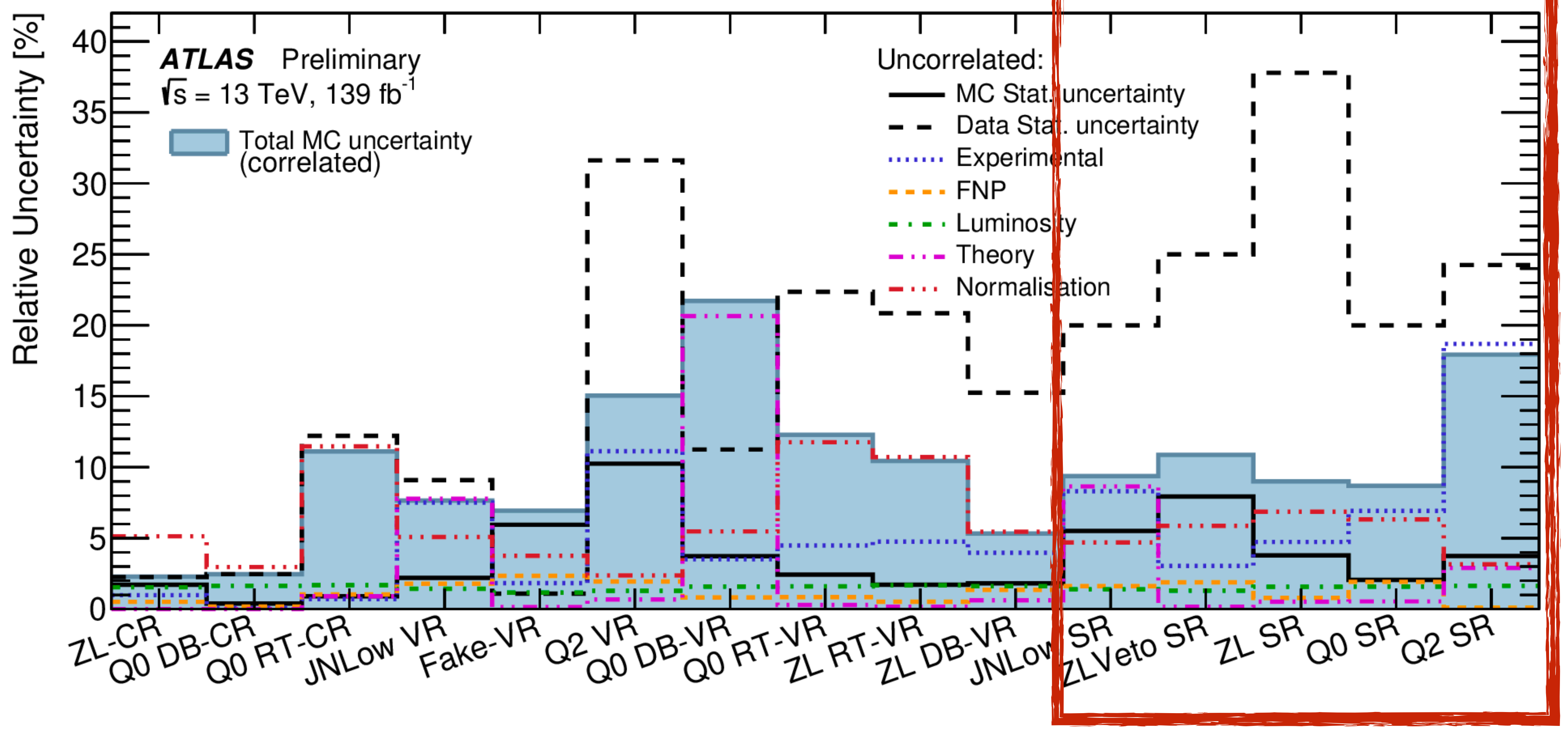
- Search performed in various Signal Regions to categorise the different event topologies of all the possible decays → combined together in the fit **(2+3+4 leptons)**

- **Dominant uncertainty** form data statistic

- Exclude HL masses below **910 GeV** @95% C.L.
  - *Most stringent limits!*

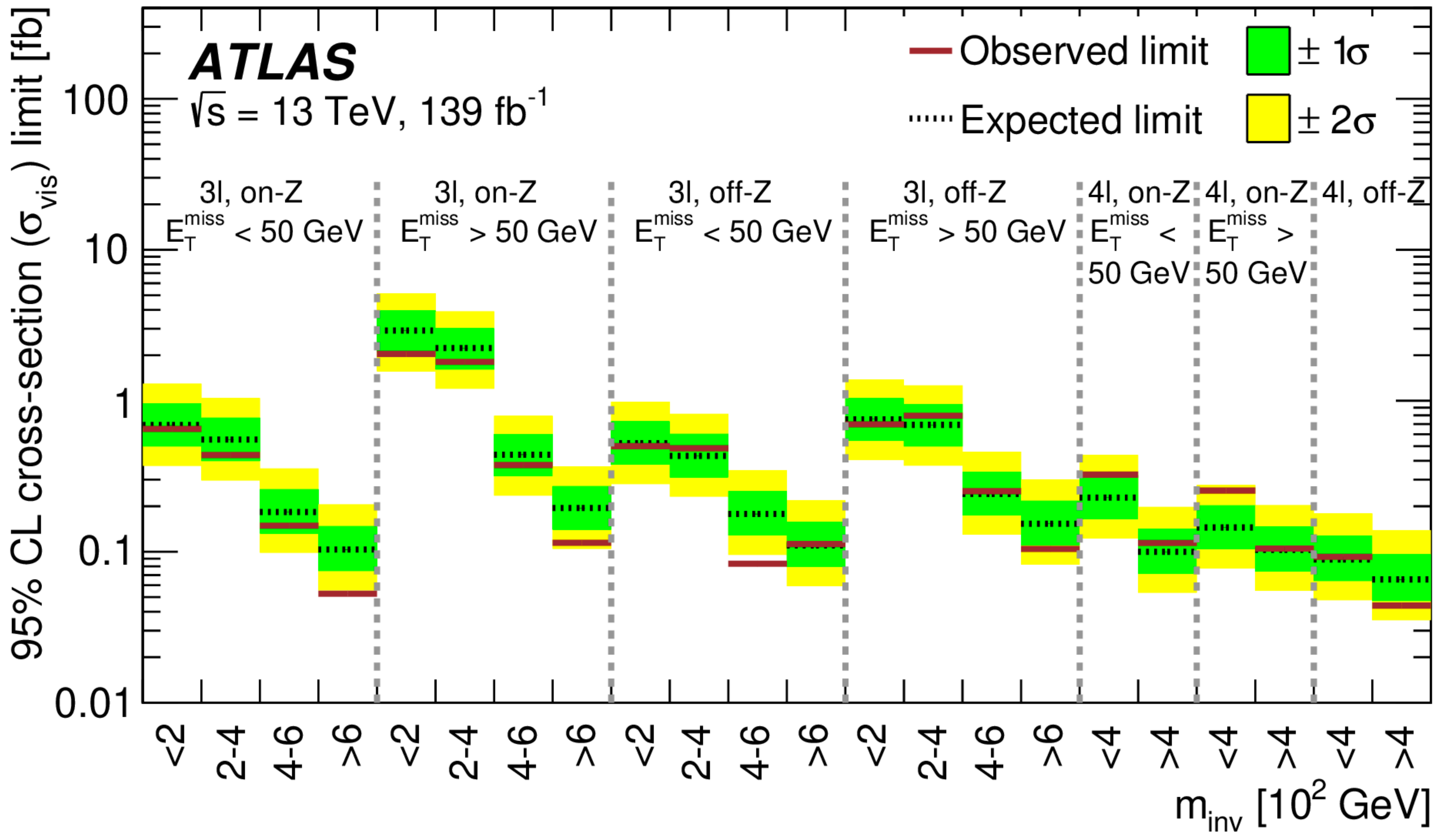


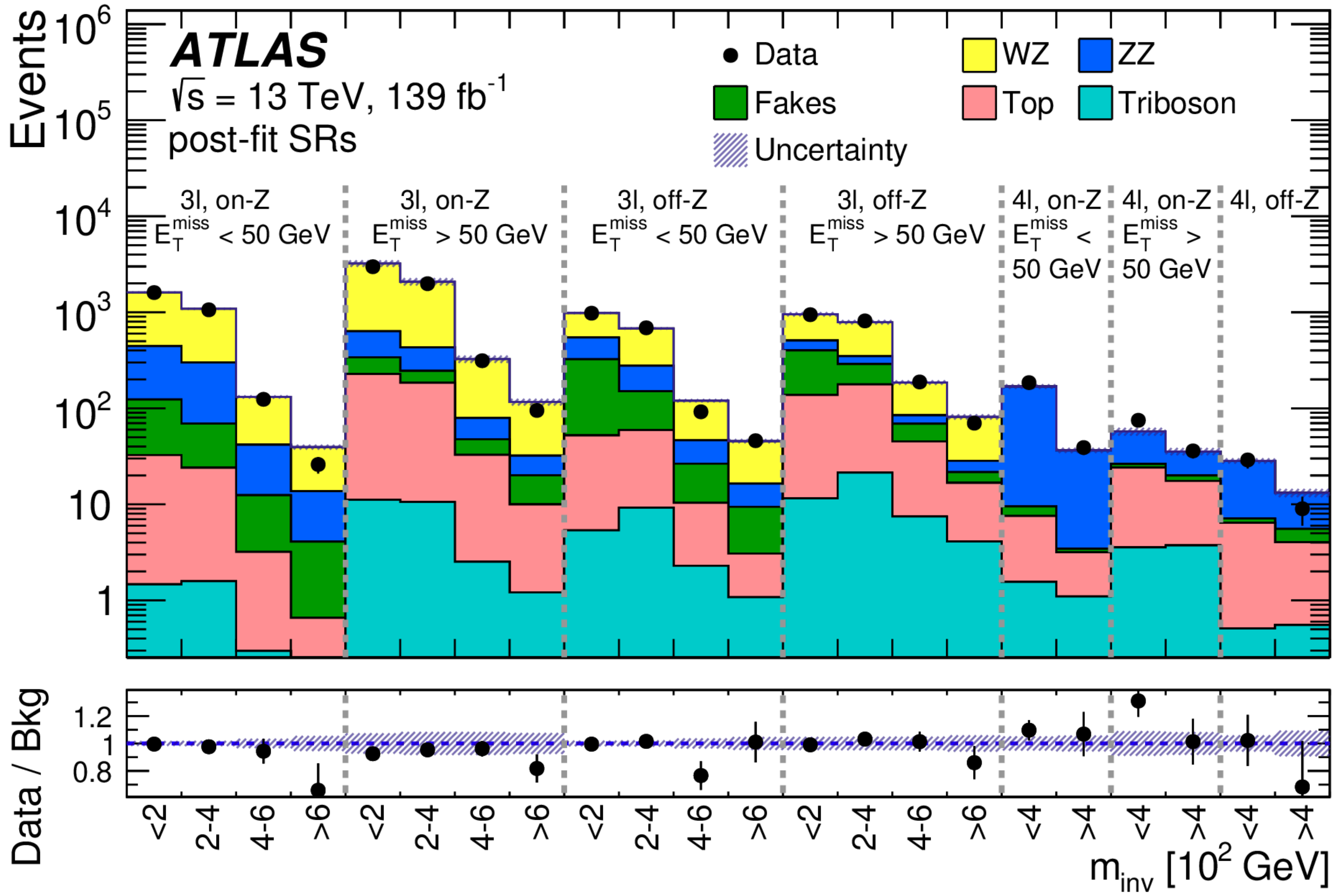




Model independent multi-lepton search

- Several BSM theories can also give similar multi-lepton (>2 leptons) final states (SUSY, H±±, type-III seesaw)
- **Goal:** obtain cross section limits covering for a large variety of BSM scenario [EXOT-2019-36]. Building 22 Signal Regions targeting different final states.
- Upper limits also derived for $H^{\pm\pm}$ and *type-III seesaw* models

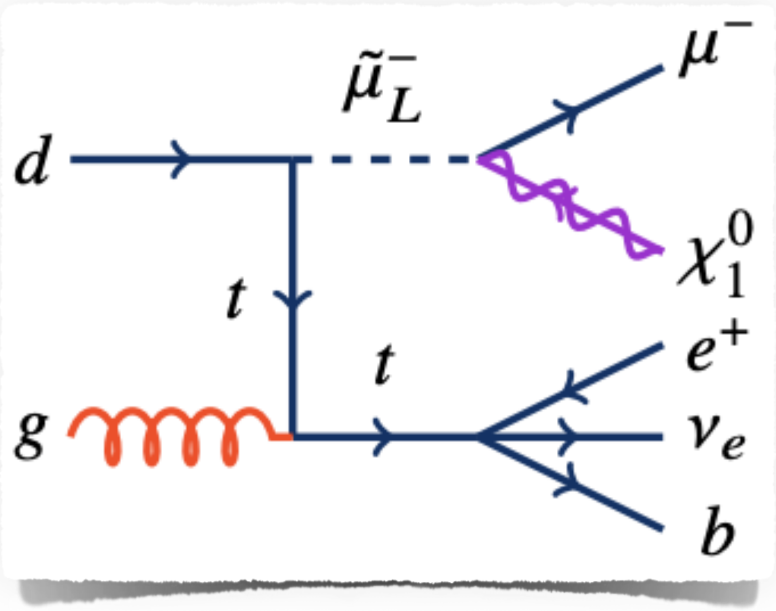


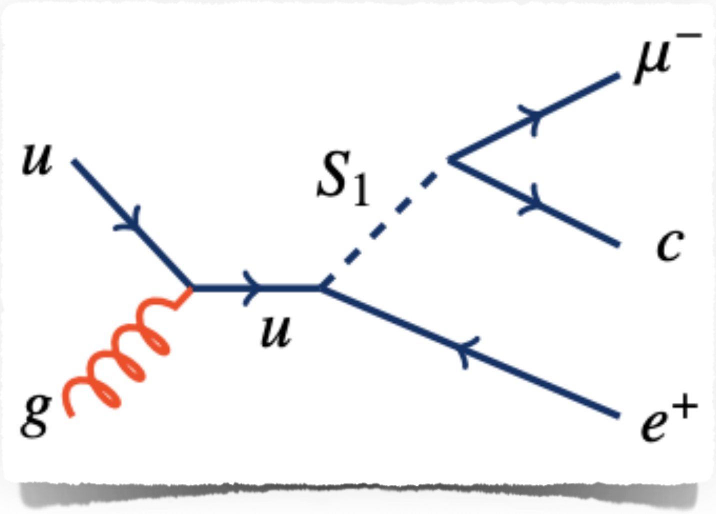


Measurement of the ratio e+μ−/e−μ+

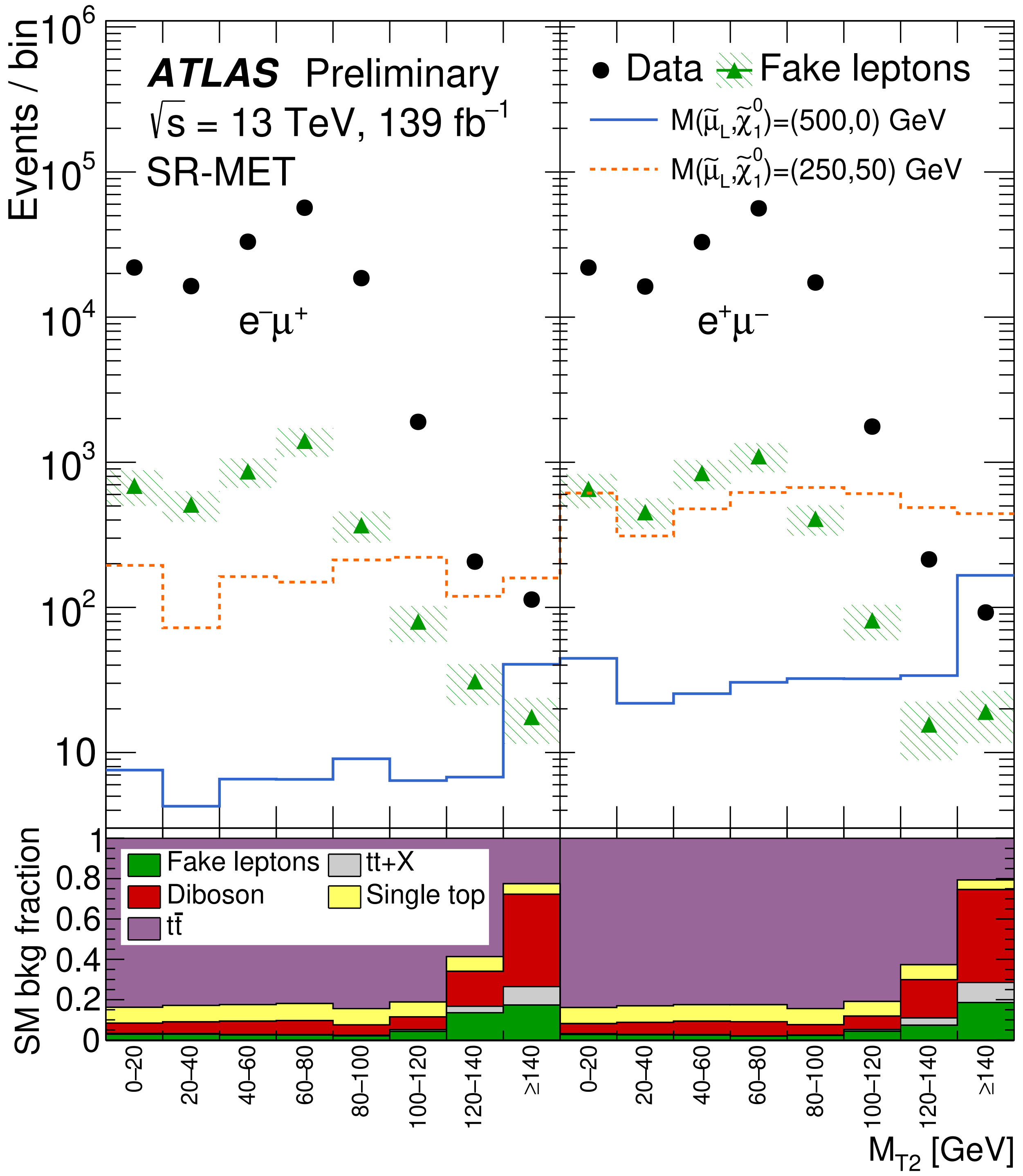
ATLAS-CONF-2021-045

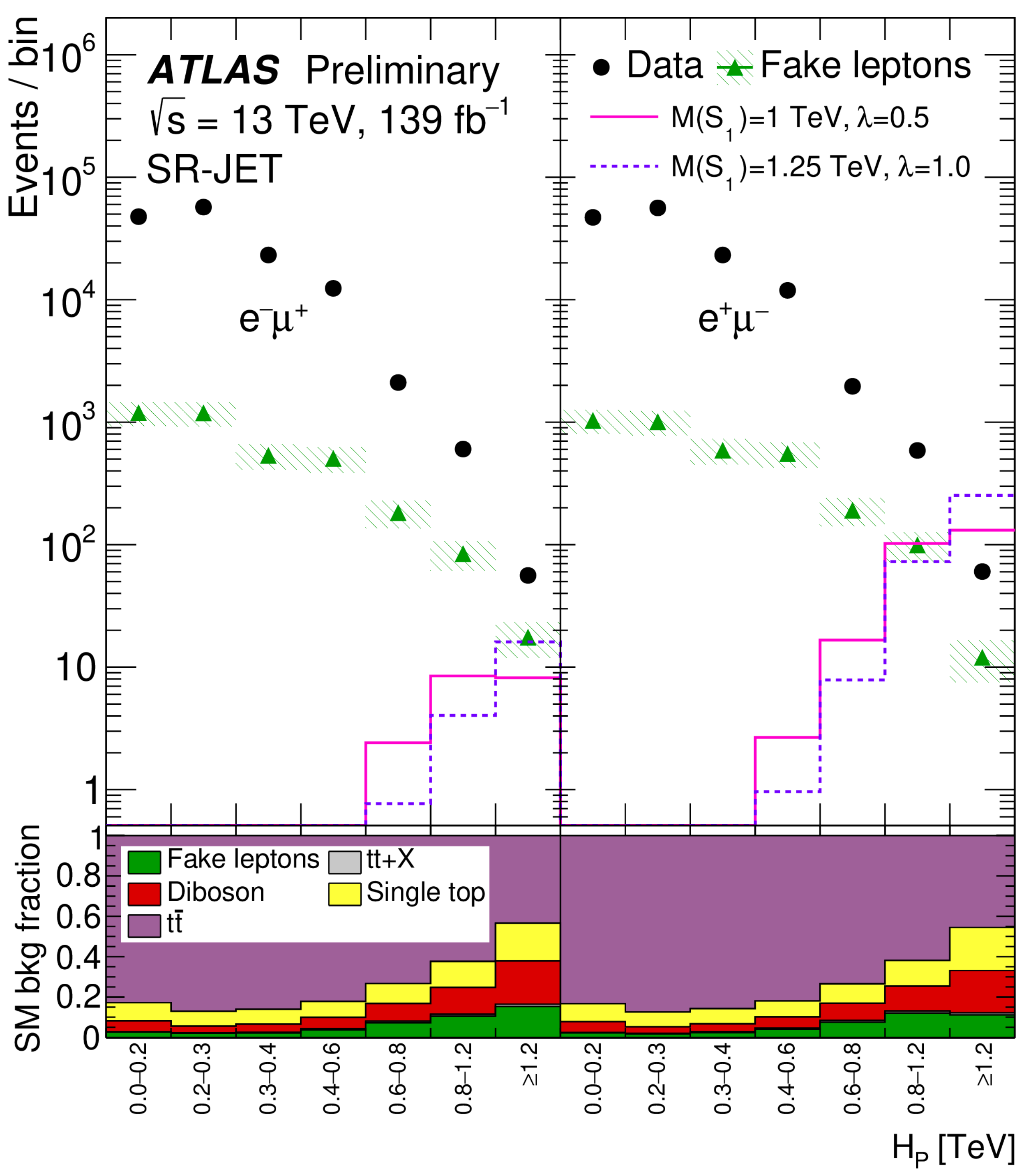
* Measure of the ratio $\rho = \dfrac{\sigma\left(p \rightarrow e^{+}\mu^{-} + X\right)}{\sigma\left(p \rightarrow e^{-}\mu^{+} + X\right)}$ where SM predicts $\rho_{SM} = 1$
* Any findings of $\rho \neq 1$ would lead to new physics (scalar LQ, SUSY, …)





* Analysis almost completely **data-driven**:
  * *Mis-identified leptons* estimate with a likelihood-matrix-method
  * *Muon charge-dependent* detector effects in reconstruction correction

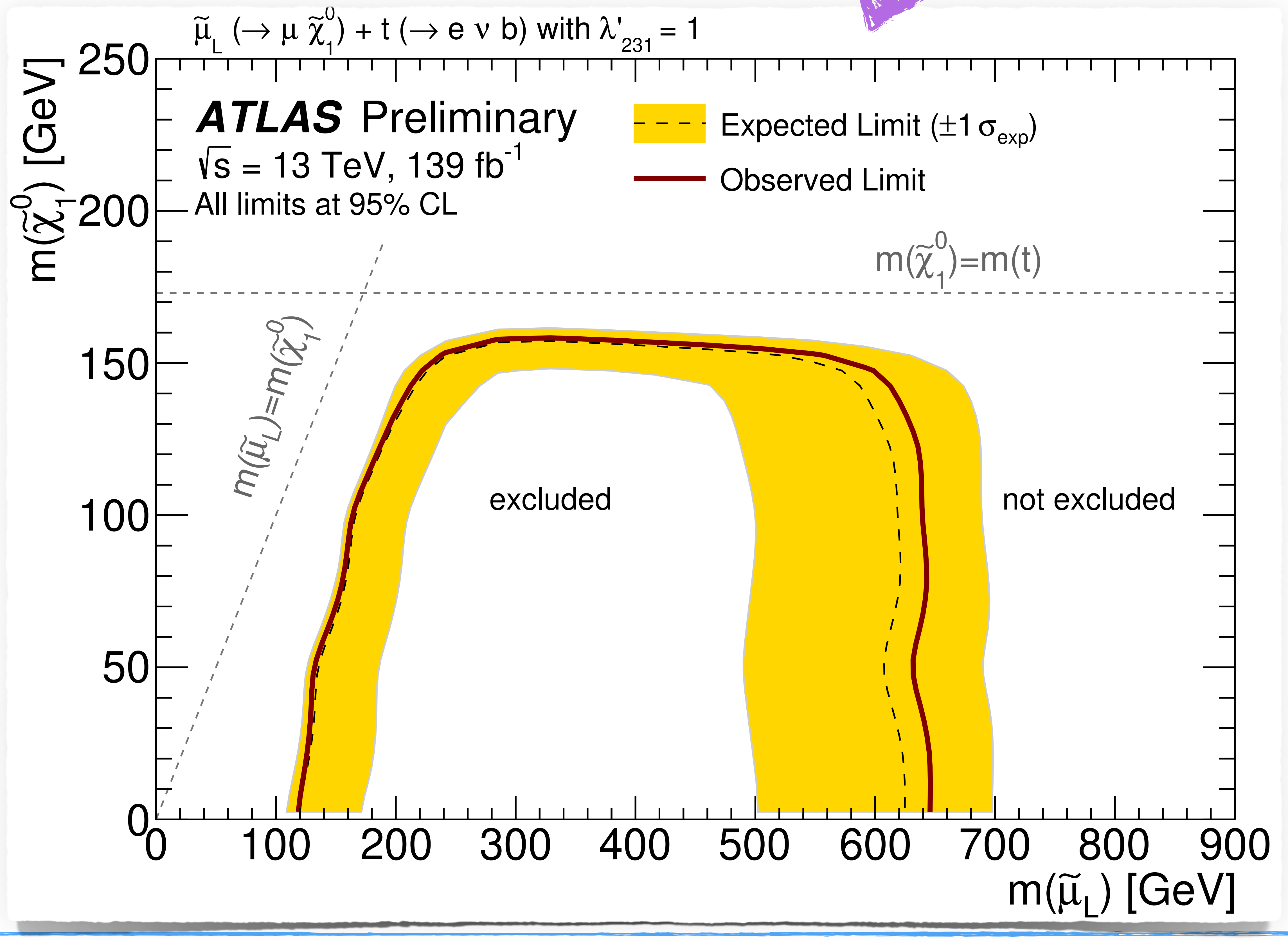


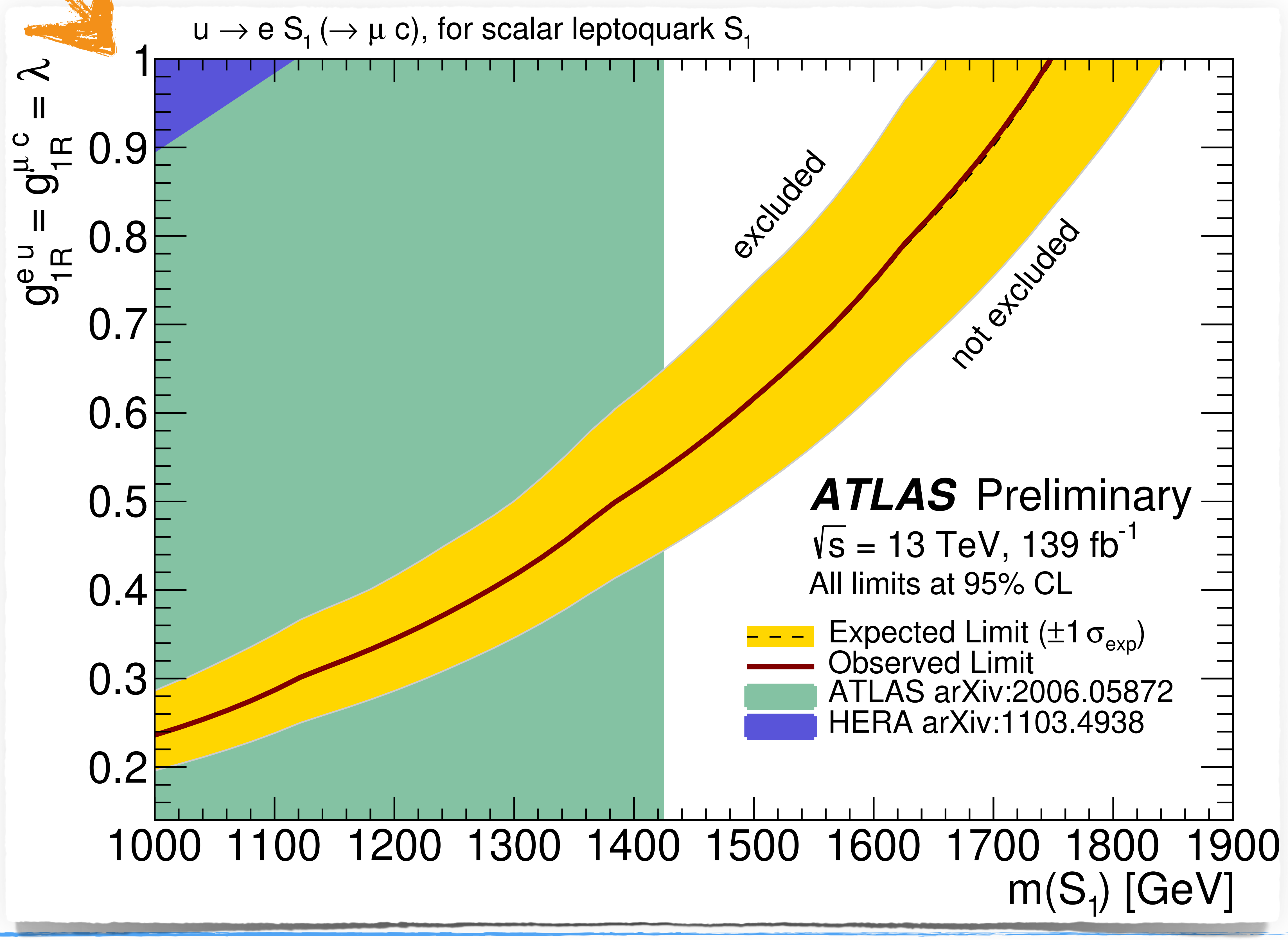


Measurement of the ratio e+μ−/e−μ+

ATLAS-CONF-2021-045

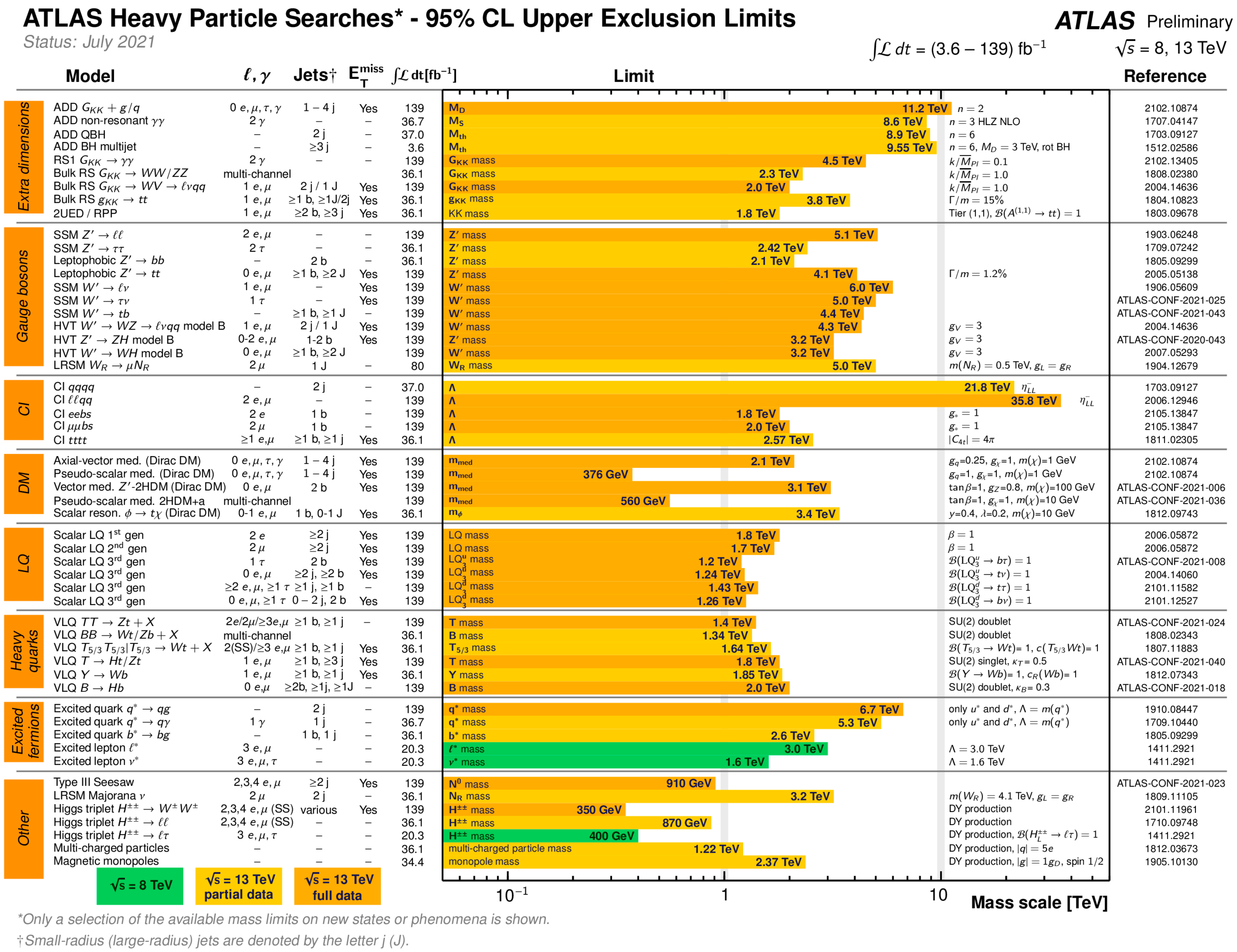
- No significant evidence for observed
  - Upper limits set on **RPV SUSY** and **LQ** models





Conclusion

- Growing evidence for anomalies in lepton interactions
- ATLAS is pushing the search for new phenomena in lepton interactions on several fronts
- Need more attention on the 3rd generation channel, including taus final states, starting already!



Additional Material

Search for $Z \to \ell\tau$

Nature Physics (2021) EXOT-2020-28