ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Searches for new phenomena in final states with taus using the ATLAS detector

17th International Workshop on Tau Lepton Physics (TAU2023)

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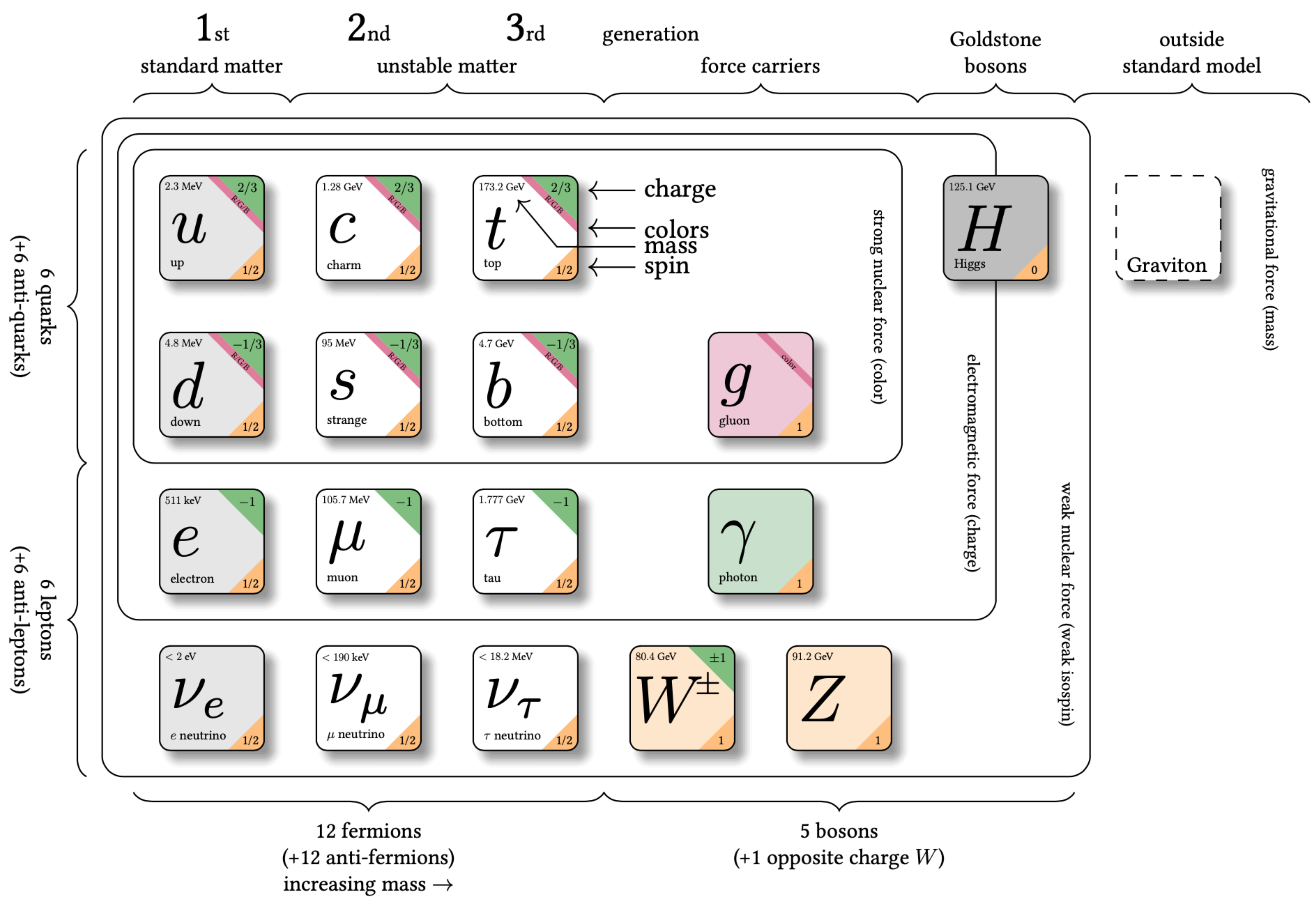
Giuseppe Carratta,
University and INFN - Bologna
on behalf of the ATLAS Collaboration

Introduction

The **Standard Model** of particle physics has been verified to high precision. **Despite its success**, several **observations** have been made which have **exposed the theory's shortcomings** in various aspects and fostered new theoretical ideas.



Many theories **Beyond the SM predict new phenomena** in **final states with isolated**, high-p_T **τ-leptons**. Searches with these signatures, produced either **resonantly or non-resonantly**, are performed by the ATLAS Collaboration.

In this talk we will explore searches in several scenarios:

- **Higgs**
- **Leptoquarks**
- **Vector-like leptons**
- **SUSY**
- **Lepton Flavour Violation**
- **Dark matter**

Introduction - II

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

LHC is the biggest ever particle accelerator:

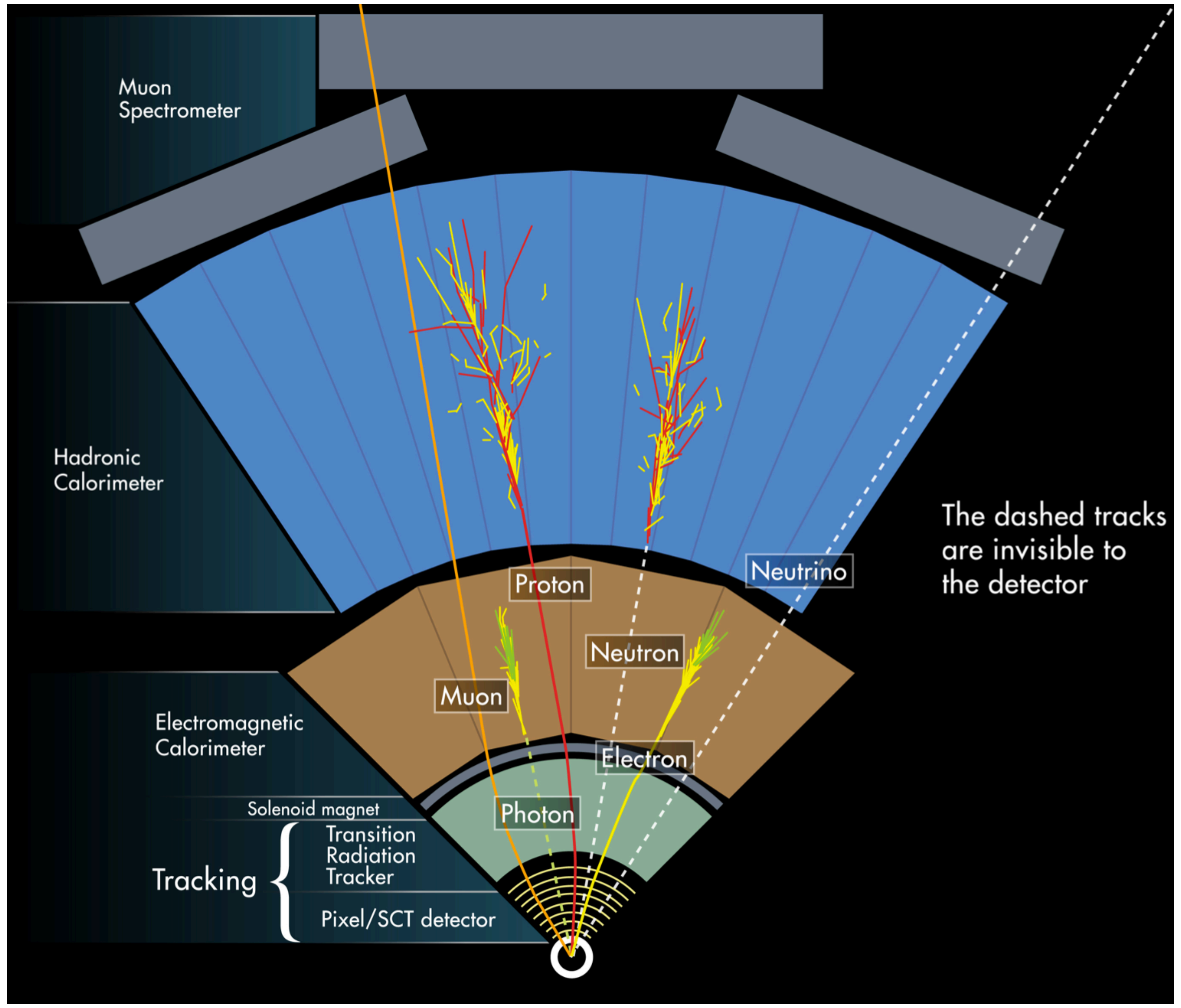
- Reached a **center-of-mass energy** of $\sqrt{s}$ = 13 TeV
- Delivered an **integrated luminosity** up to 156 fb^{-1} in Run 2

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

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 140 fb^{-1} **good for physics** analyses in Run 2.

Phenomenology and signatures

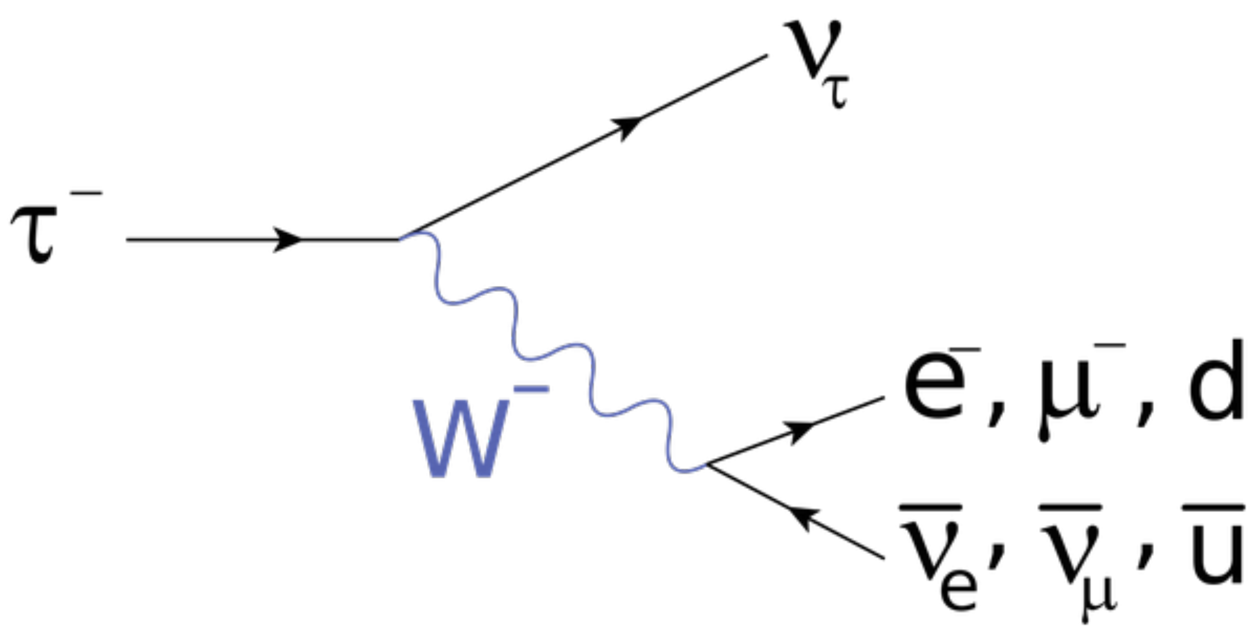


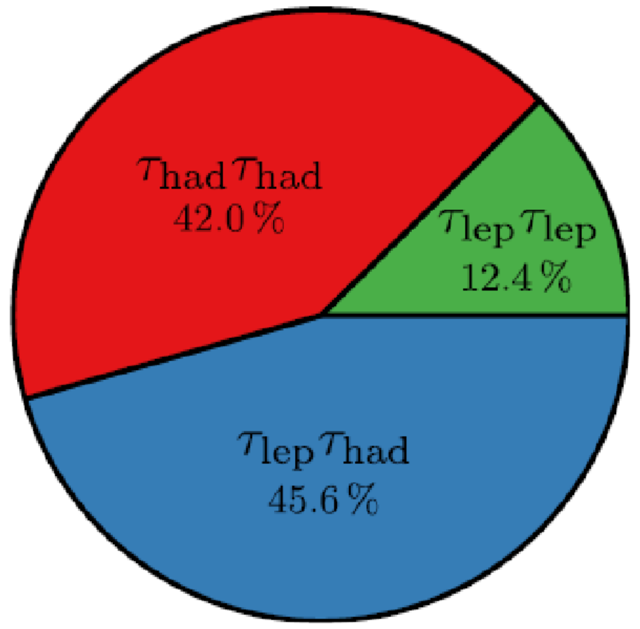
ATLAS reconstructs several **particles according** to their **different interactions** with materials

- Recurrent neural network (**RNN**) used to **discriminate** the visible **decay products of the** τ_{had} candidates from jets initiated by quarks or gluons.

Final states with high-p_T leptons are shared by many **beyond SM searches** and they are **poor of SM events**

→ **High background rejection** and **signal-to-noise ratio**





Unlike the light leptons, ***τ*-leptons** are recognized from their decays products:

- Electrons or muons (usually tagged as τ_{lep})
- Missing energy transverse
- Jets (usually tagged as τ_{had}), dedicated reconstruction using seeds from anti-k_T jets, remaining independent thereafter

Events from:

- **Irreducible background** (From SM processes)
- **Reducible background** (Fake and charge mis-identified taus)

Contents of the talk

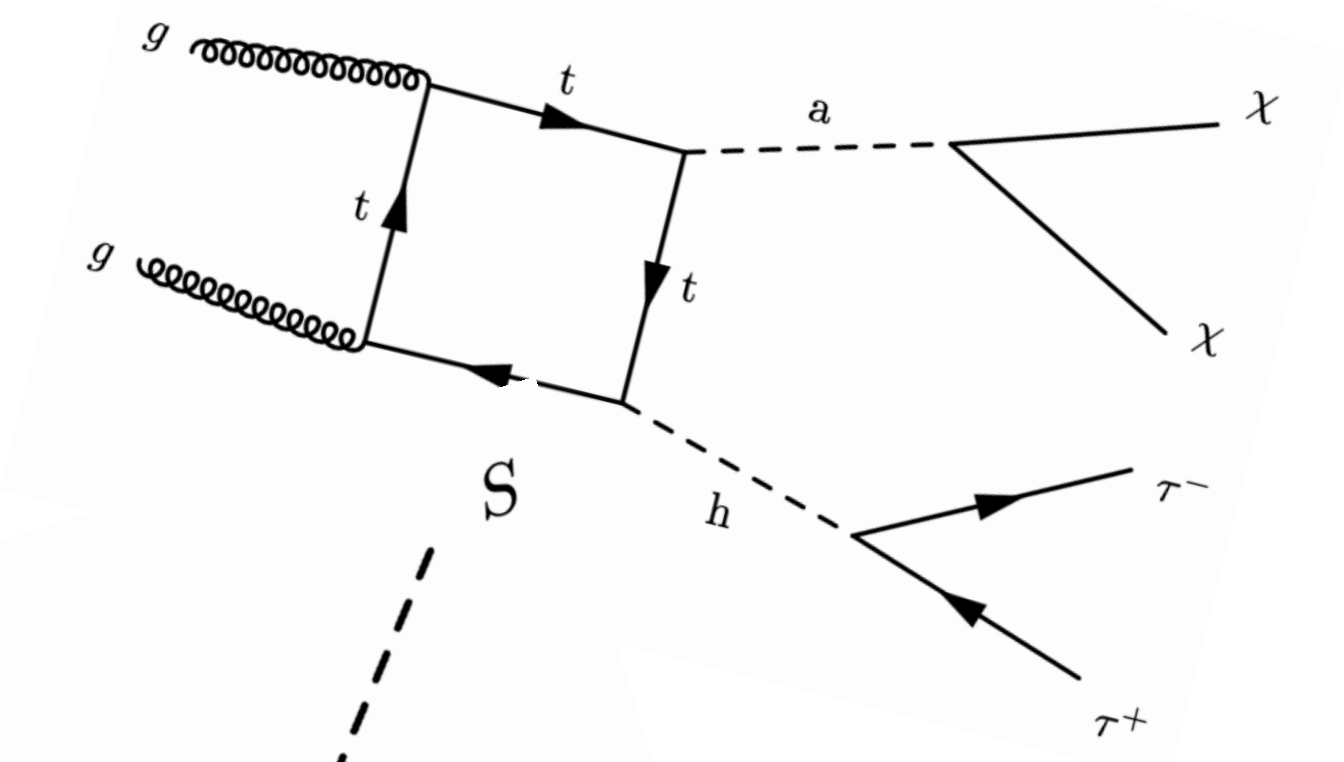
All the analyses use full Run 2 dataset

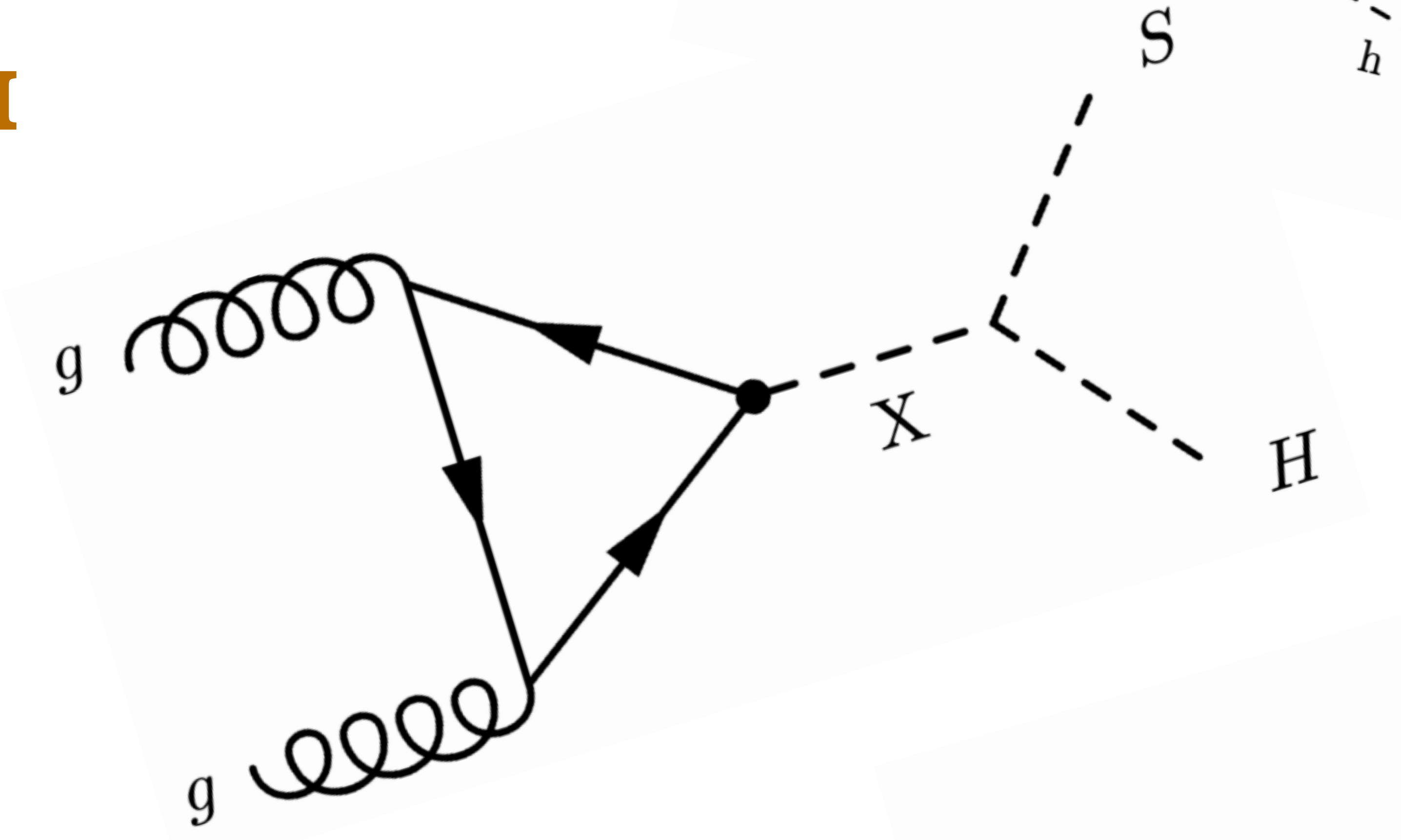
- $H \rightarrow \tau\tau + E_T^{miss}$, in **JHEP09(2023)189**
- $HH \rightarrow bb\tau\tau$, in **ATLAS-CONF-2023-071**
- $X \rightarrow SH \rightarrow VV\tau\tau$, in **JHEP10(2023)009**

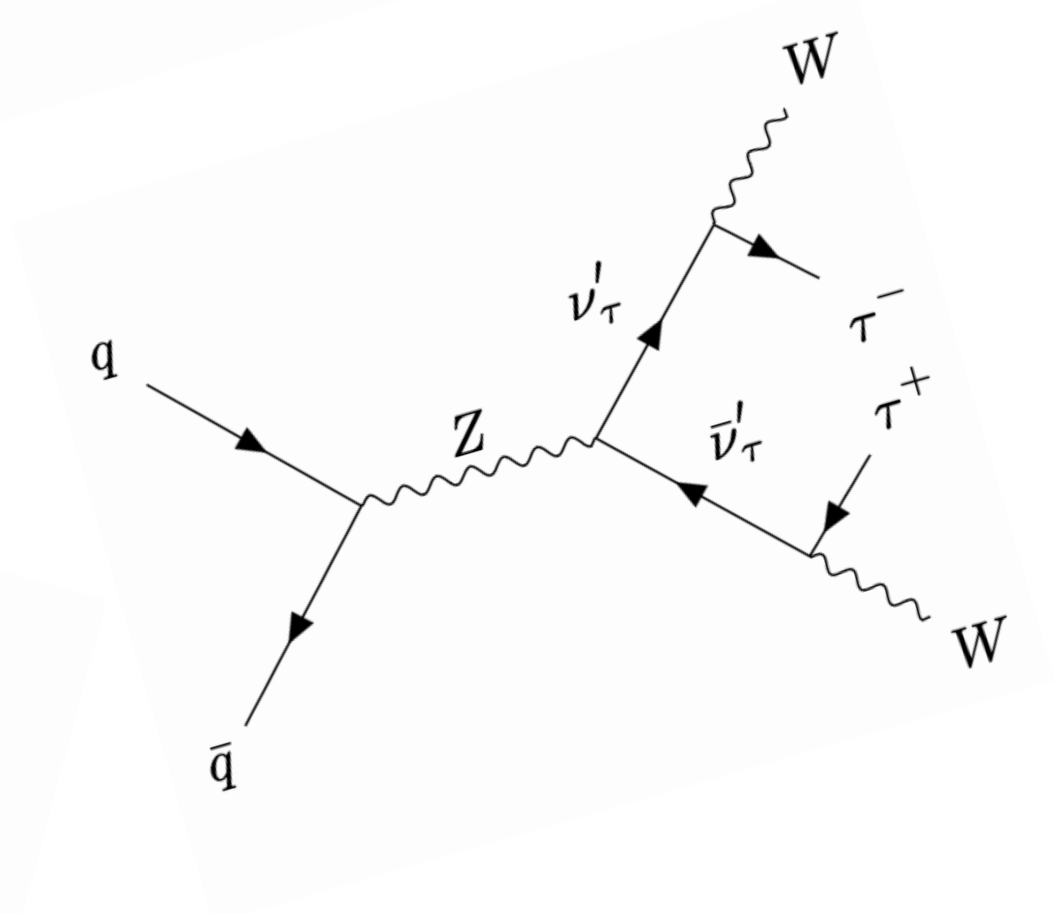
τ from SM particles

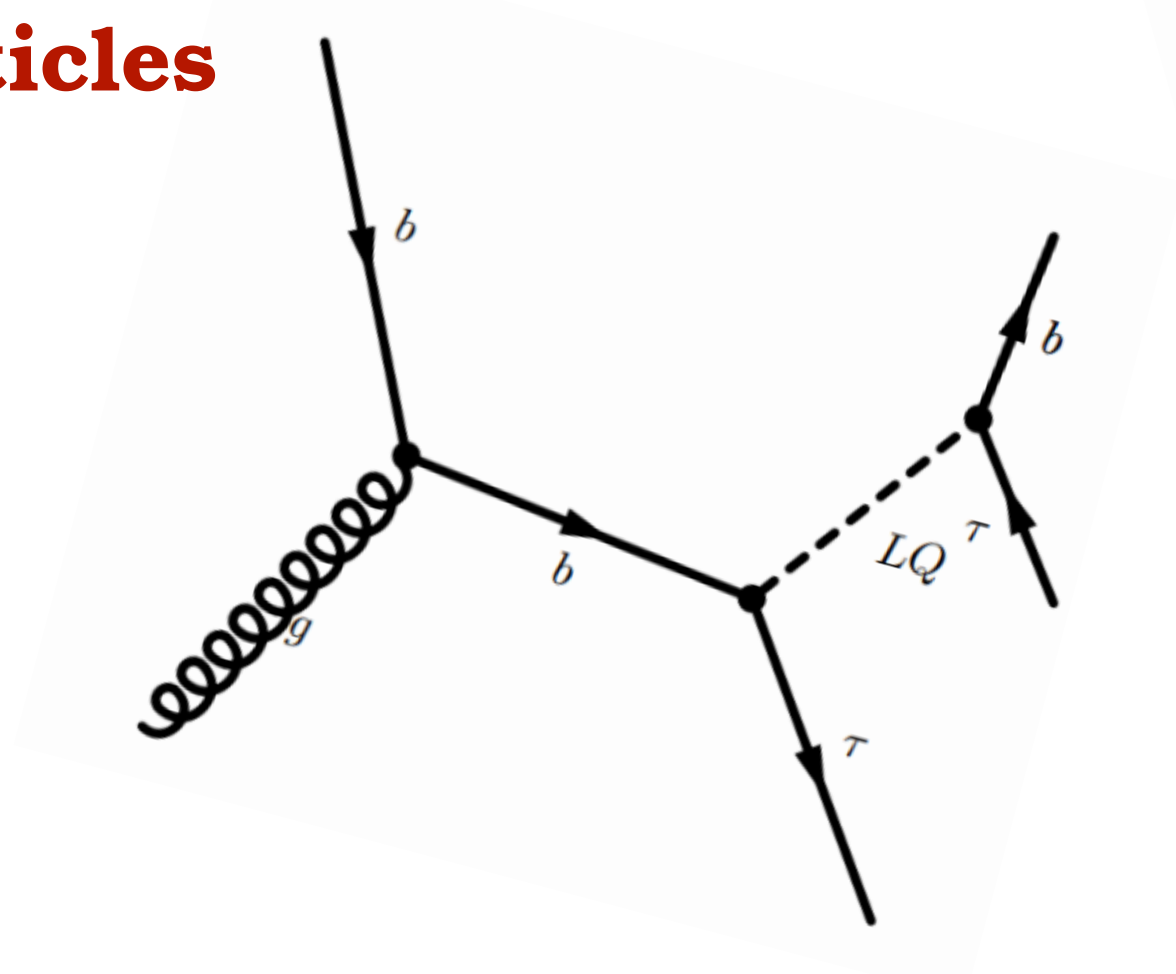
- VLL in a doublet model, in **JHEP07(2023)118**
- $LQ \rightarrow b\tau$, in **JHEP10(2023)001**
- $LQLQ \rightarrow b\tau b\tau$, in **EPJC 83(2023)1075**
- Excited τ-leptons, in **JHEP06(2023)199**
- LFV $Z' \rightarrow \ell\ell'$, in **JHEP10(2023)082**
- EW SUSY, in **ATLAS-CONF-2023-029**

τ from BSM particles

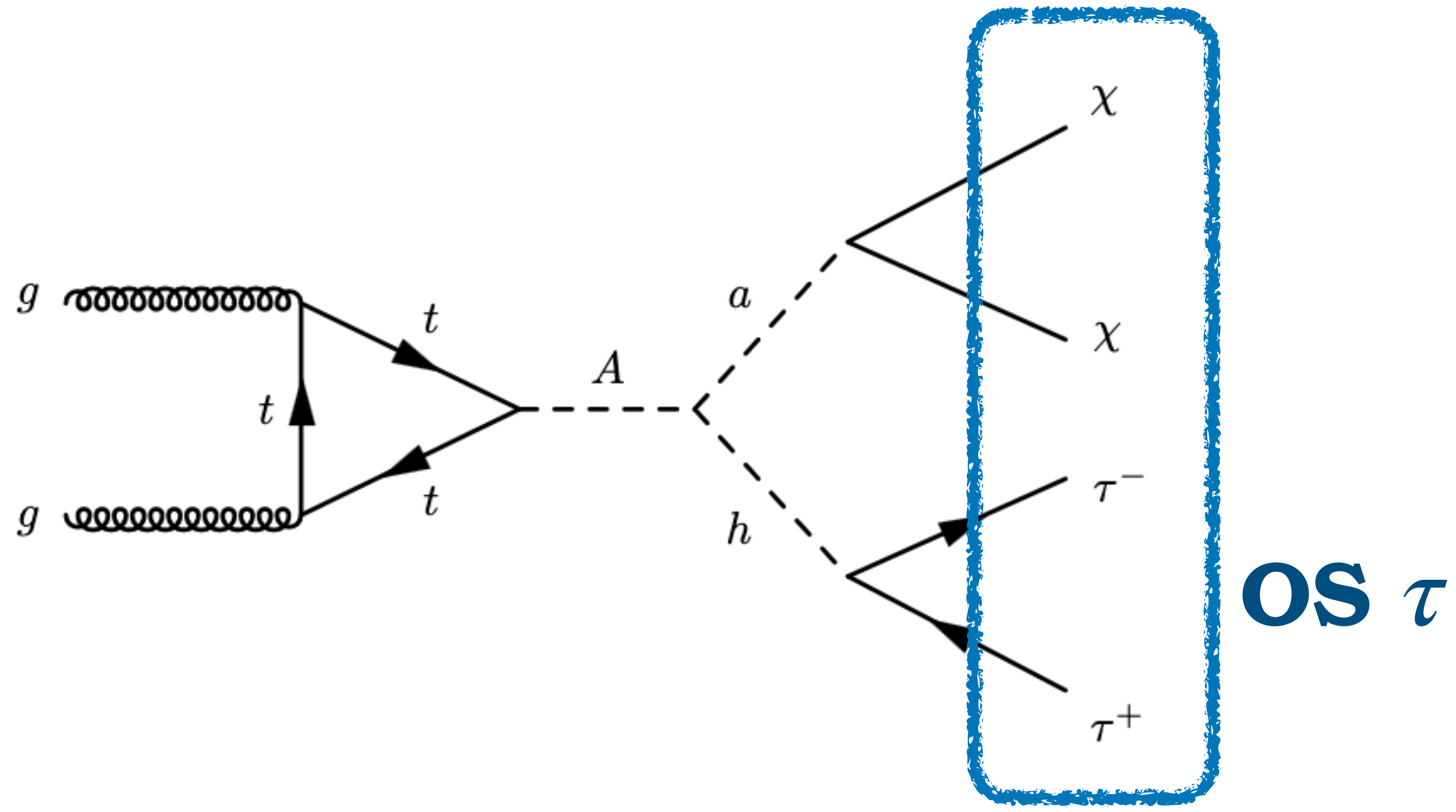


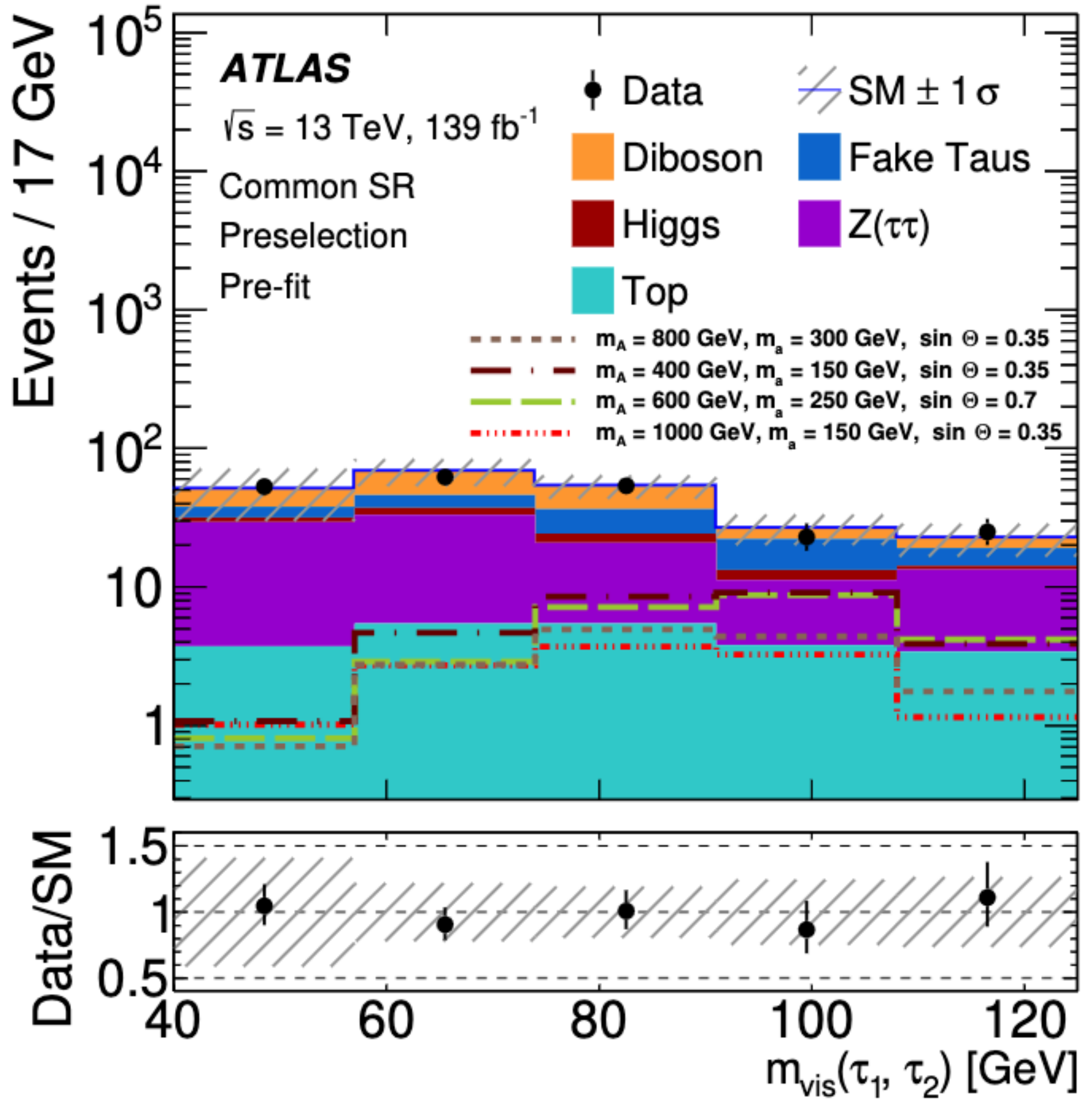


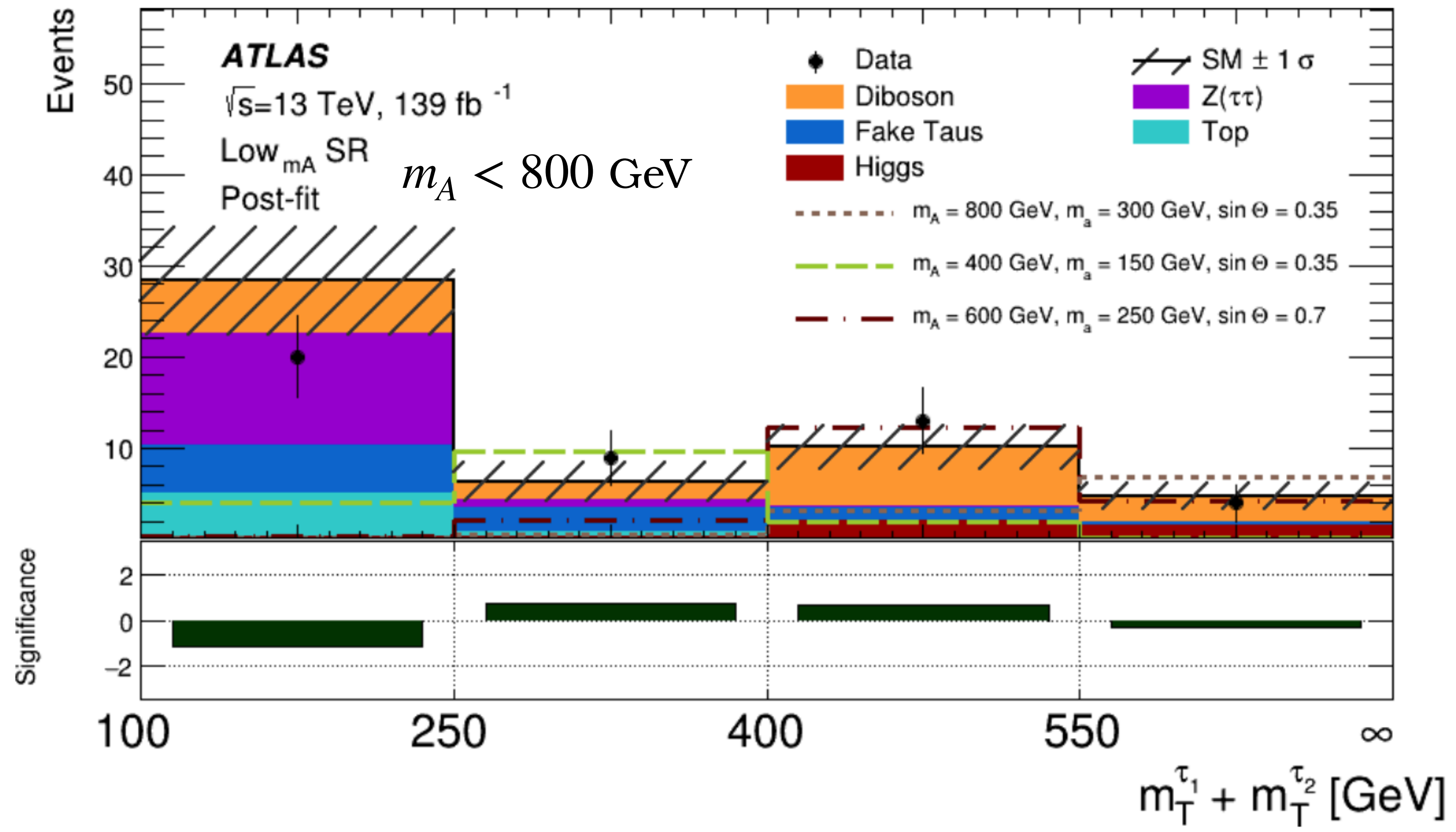


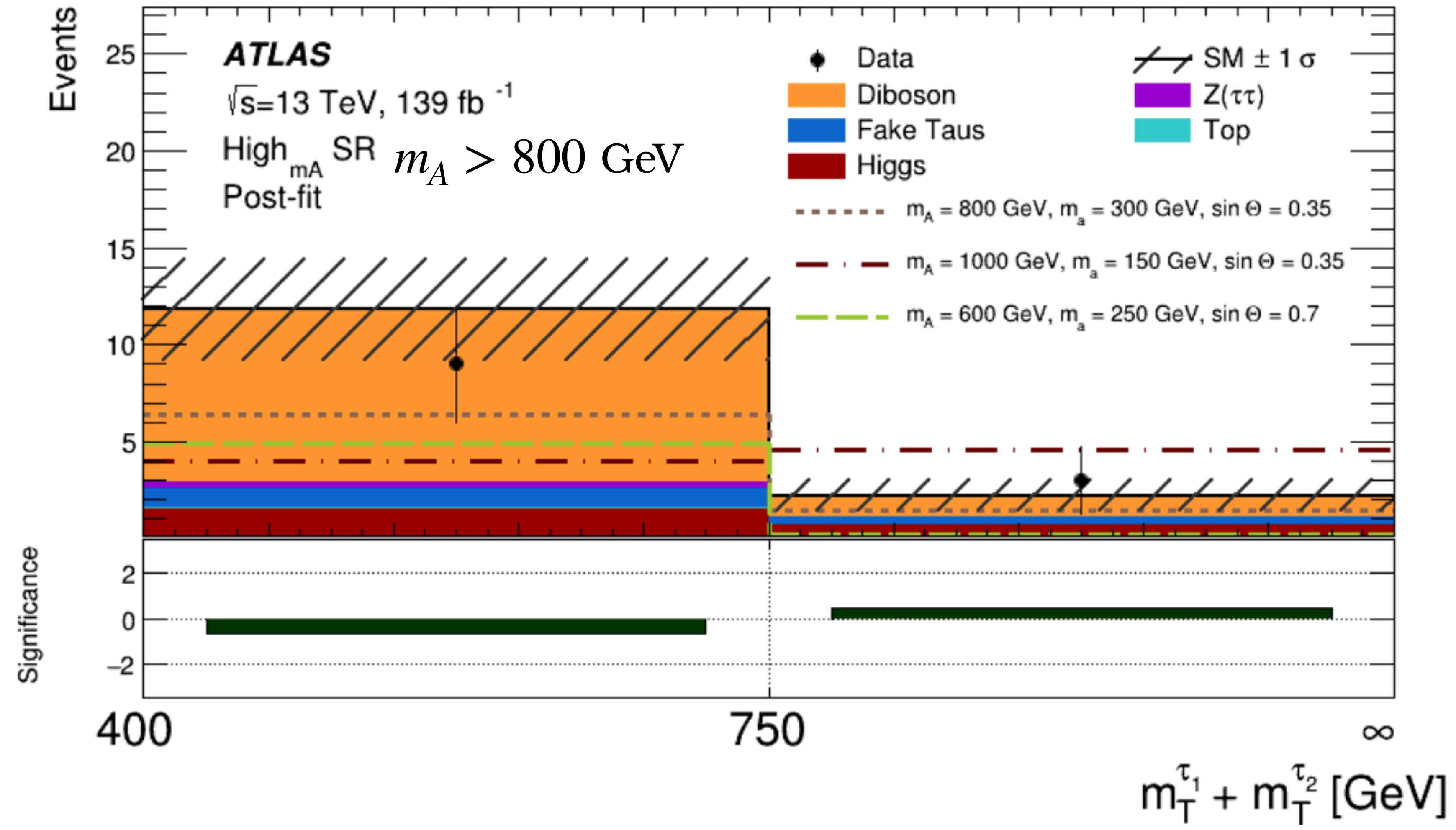


- **Dark matter** searches in signature with h + E_T^{miss}
- **Model-independent topology**, reinterpretations: 2HDM+a, DM, Z', 2D parameter scan.
- Most discriminating observables: $m_{vis}(\tau, \tau)$, $\Delta R(\tau, \tau)$, m_T^{tot}.
- **Signal regions** defined for **different mass-hypotheses** of m_A, binned in transverse mass of τ-leptons $m_T^{\tau_1} + m_T^{\tau_2}$
- **Control regions** to study the main backgrounds from SM events: Z **and multiboson production,** $t\bar{t}$**.**
- **Data driven technique** (fake-factor) to estimate fake taus, parametrized in p_T, η, number of tracks and jet origin.





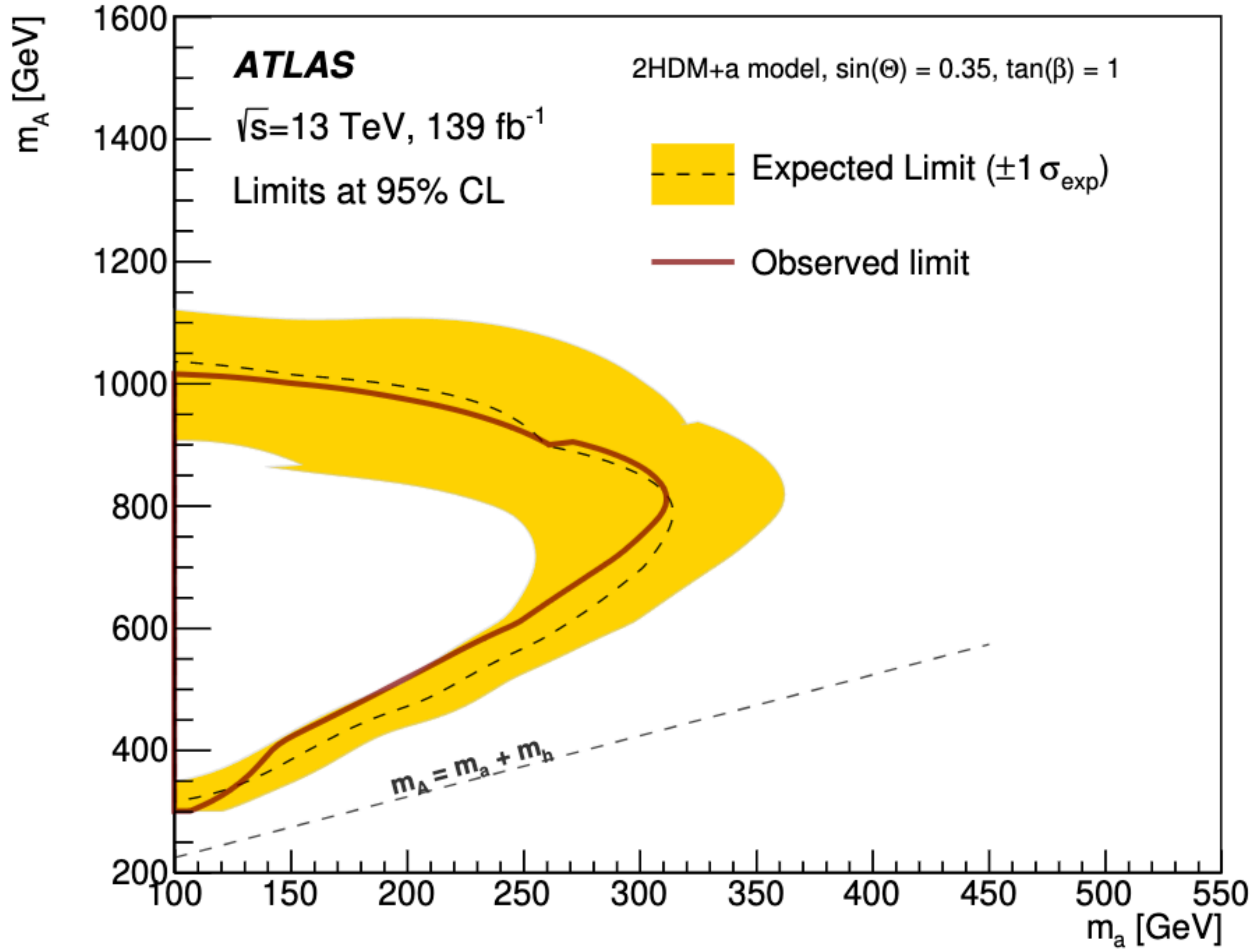




Lower panel shows the statistical significance of the observation given the predicted number of events

Most impacting systematics arise from **theoretical** uncertainties, **fake** estimation and MC **statistics**.

Contour plot considering 2HDM+a model, as function of m_a and m_A



Pseudoscalar singlets a with masses up to 300 GeV are excluded for m_A = 800 GeV.

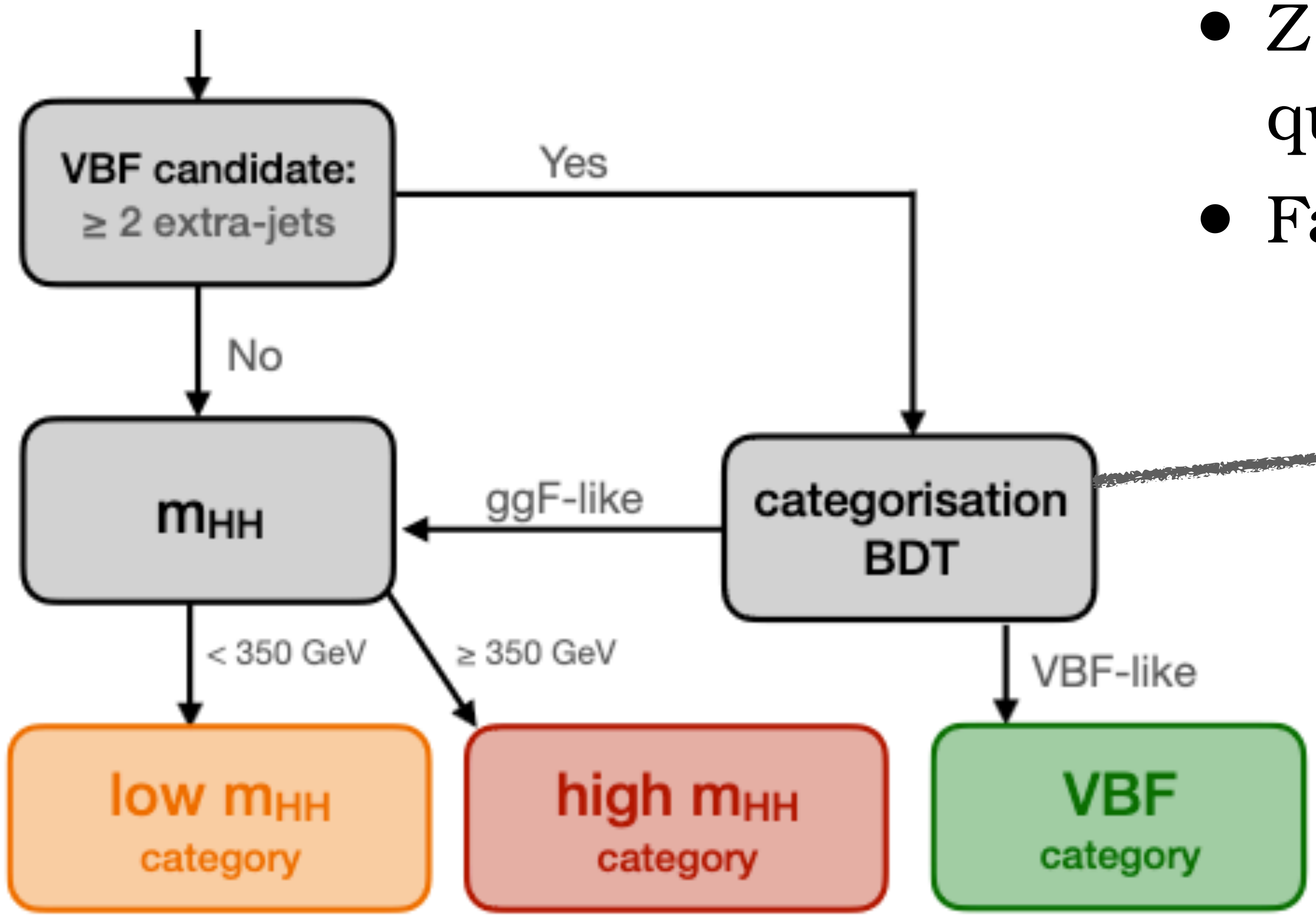
The analysis provides also upper limits at 95% CL on the σ_{vis} for BSM processes among 0.04 and 0.08 fb, depending on the considered SR bin.

- Search for the **non-resonant** production of **Higgs boson pairs** in the $HH \rightarrow bb\tau\tau$
- **Dedicated regions** defined to account for **ggF** and **VBF** production modes.
- Different selections (including triggers) depending on the di-τ decay modes ($\tau_{had}\tau_{had}$, $\tau_{had}\tau_{lep}$)
- MVA approach exploited to categorize events after the preselection

Event selection

1st BDT

2nd BDTs

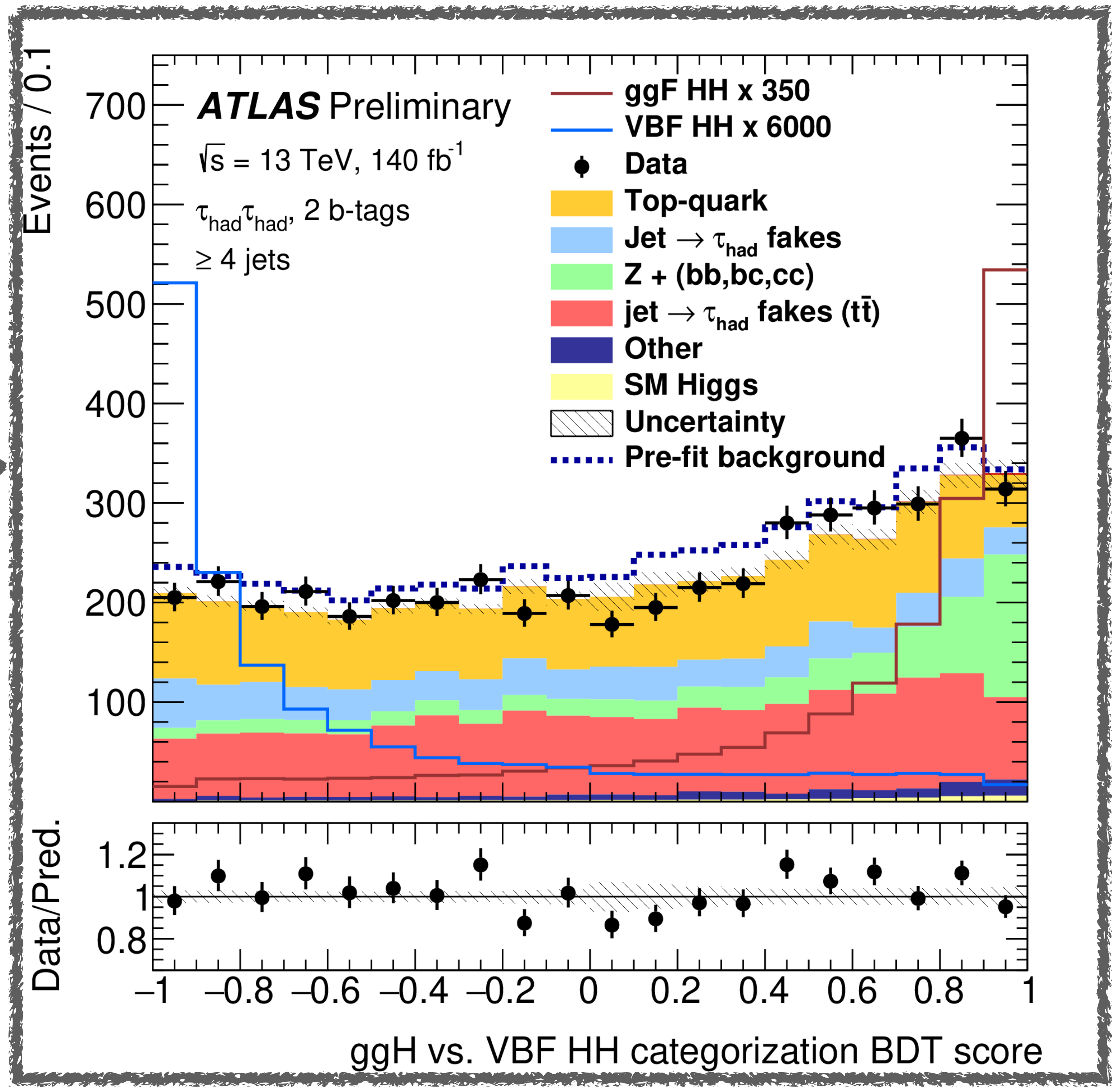


Main backgrounds:

- Z + HF and events with top quarks (estimated via MC)
- Fake taus from $t\bar{t}$ (data-driven)

1st BDT: to separate ggF from VBF production

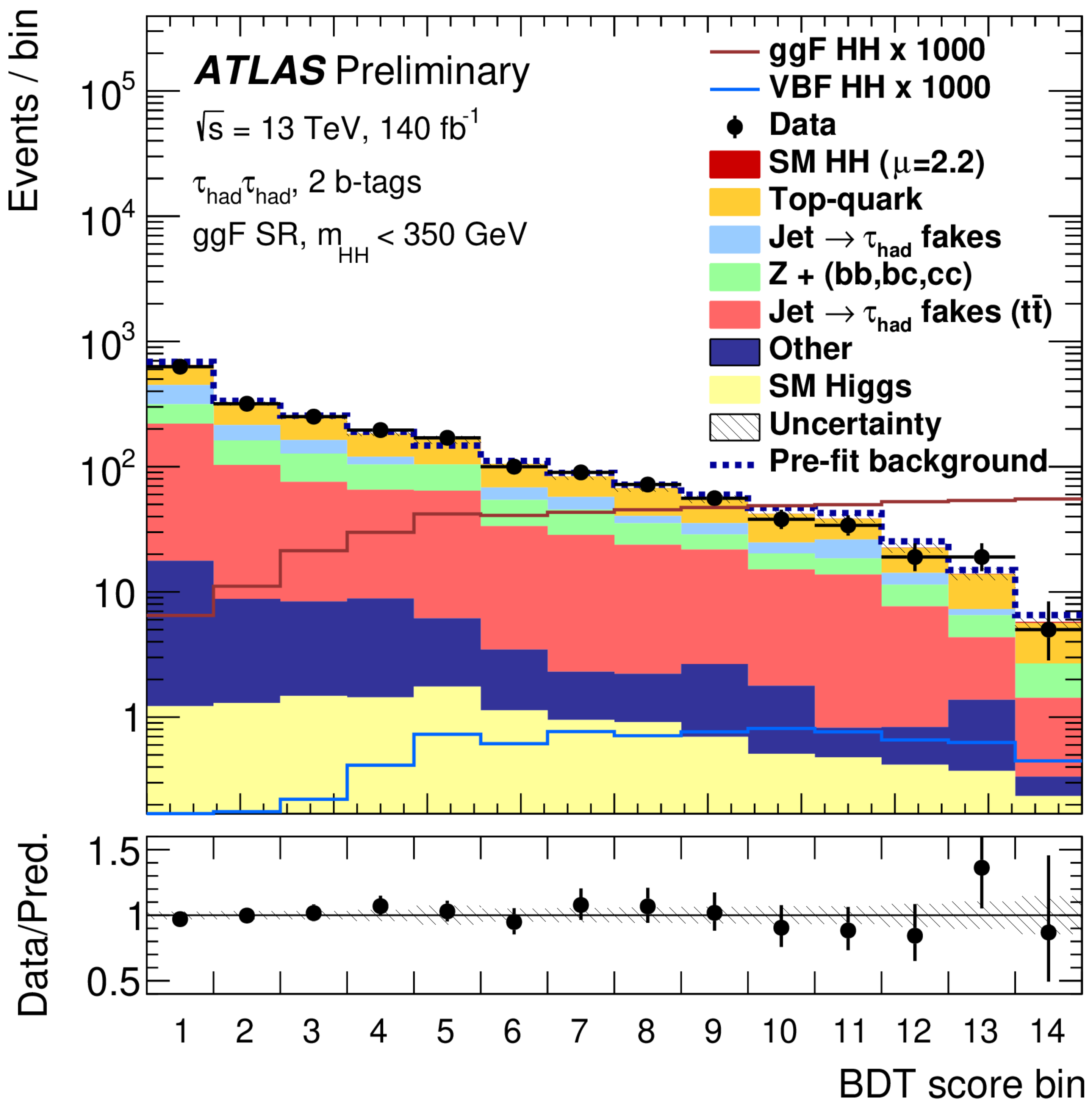
2nd BDTs: to separate signal from background candidates



- **Statistical fit** performed simultaneously on **9 SRs** (BDT score as fitting variable) and **1 CR** ($m_{\ell\ell}$).

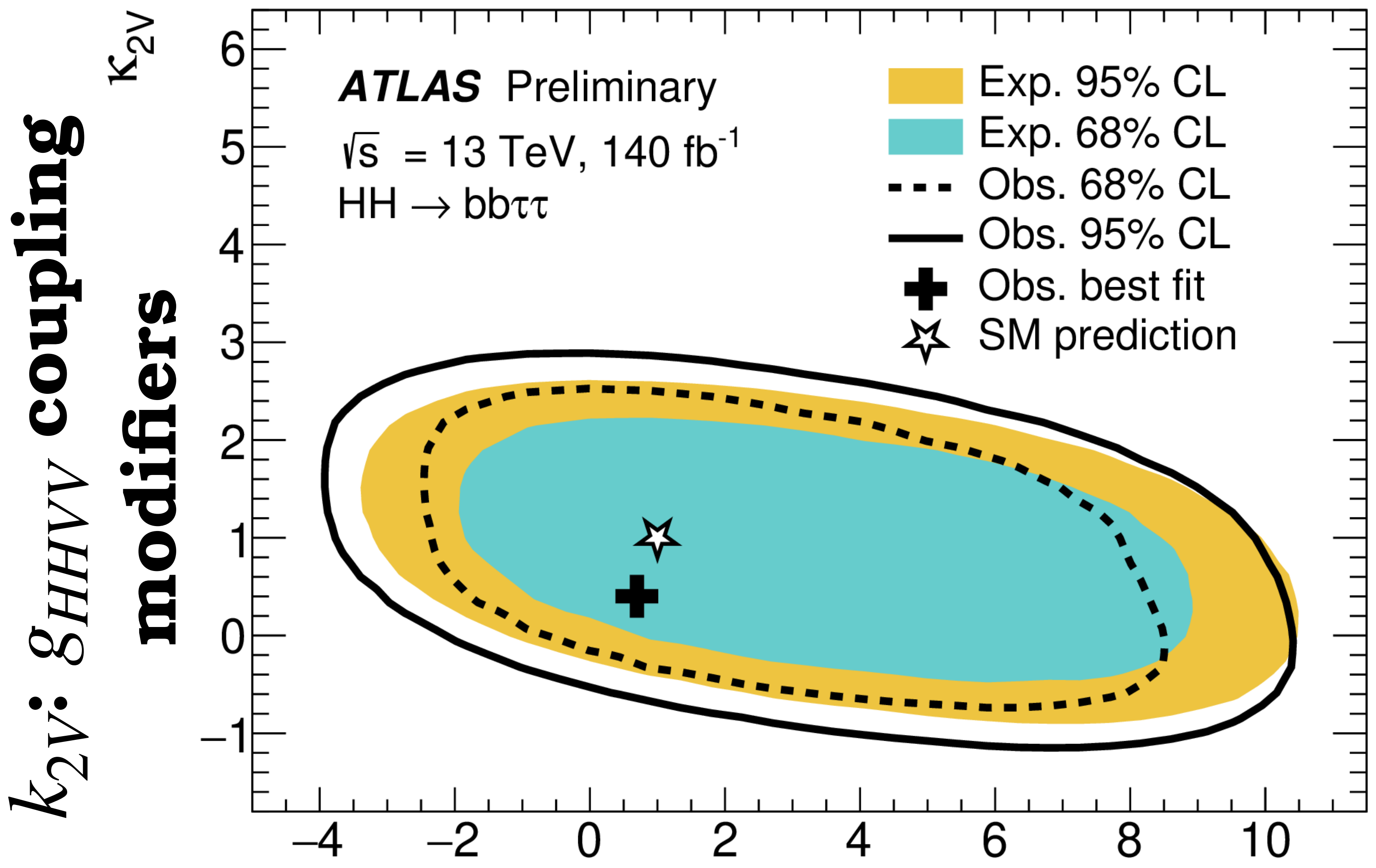
Main uncertainties:

- Signal and background modeling (theoretical)
- MC statistics



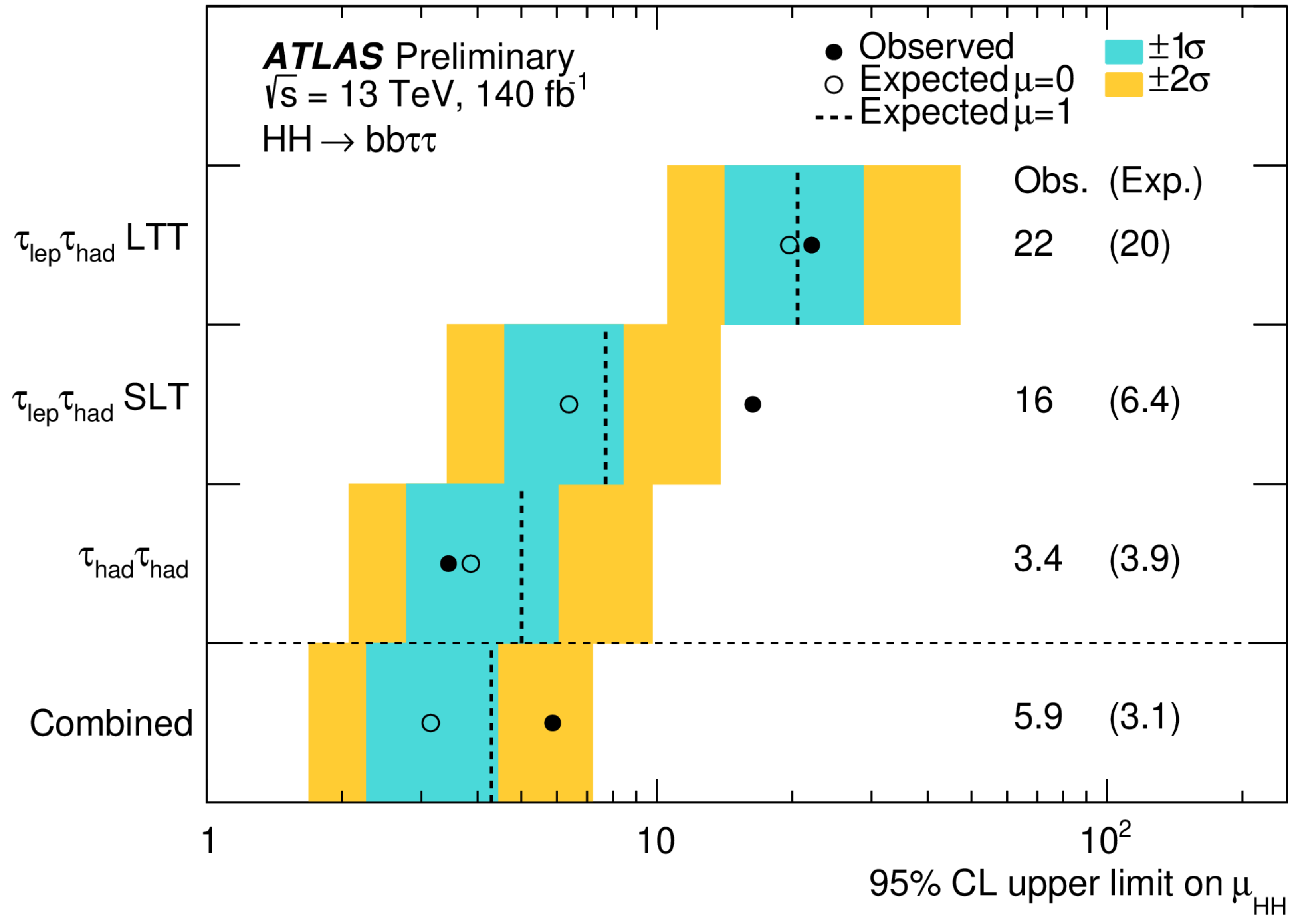
Likelihood contours in the (k_λ, k_{2V}) parameter space

best fit	κ_λ	κ_{2V}
obs	0.7	0.4

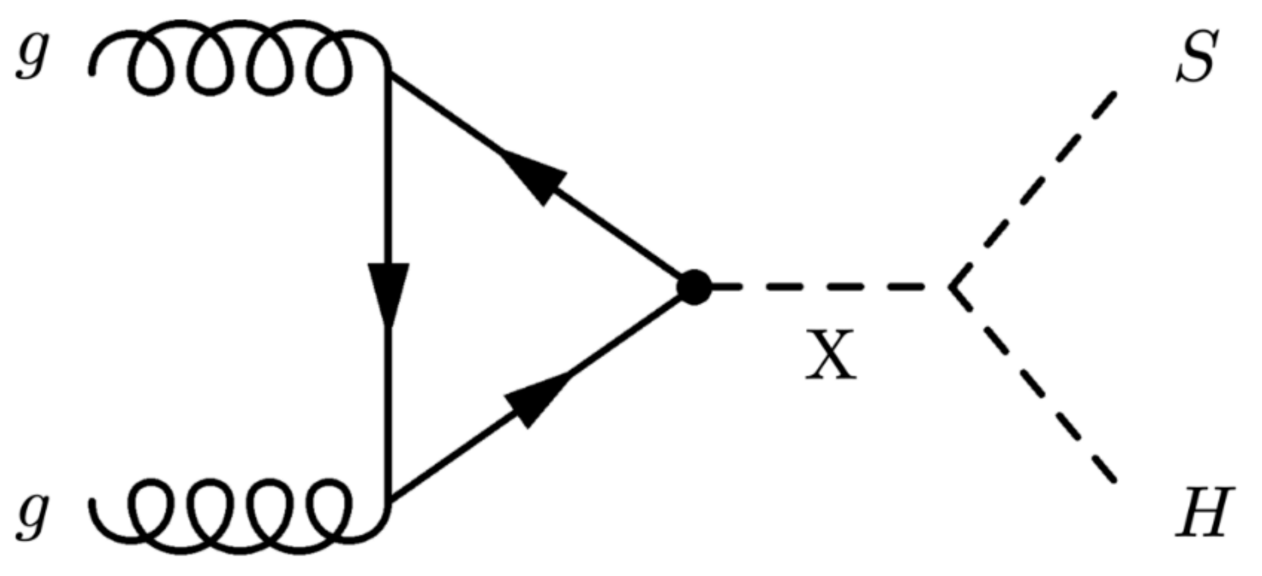


No excess above the SM expectation is observed

Expected and observed 95% CL UL on μ_{HH}



Higgs EFT interpretations also provided.

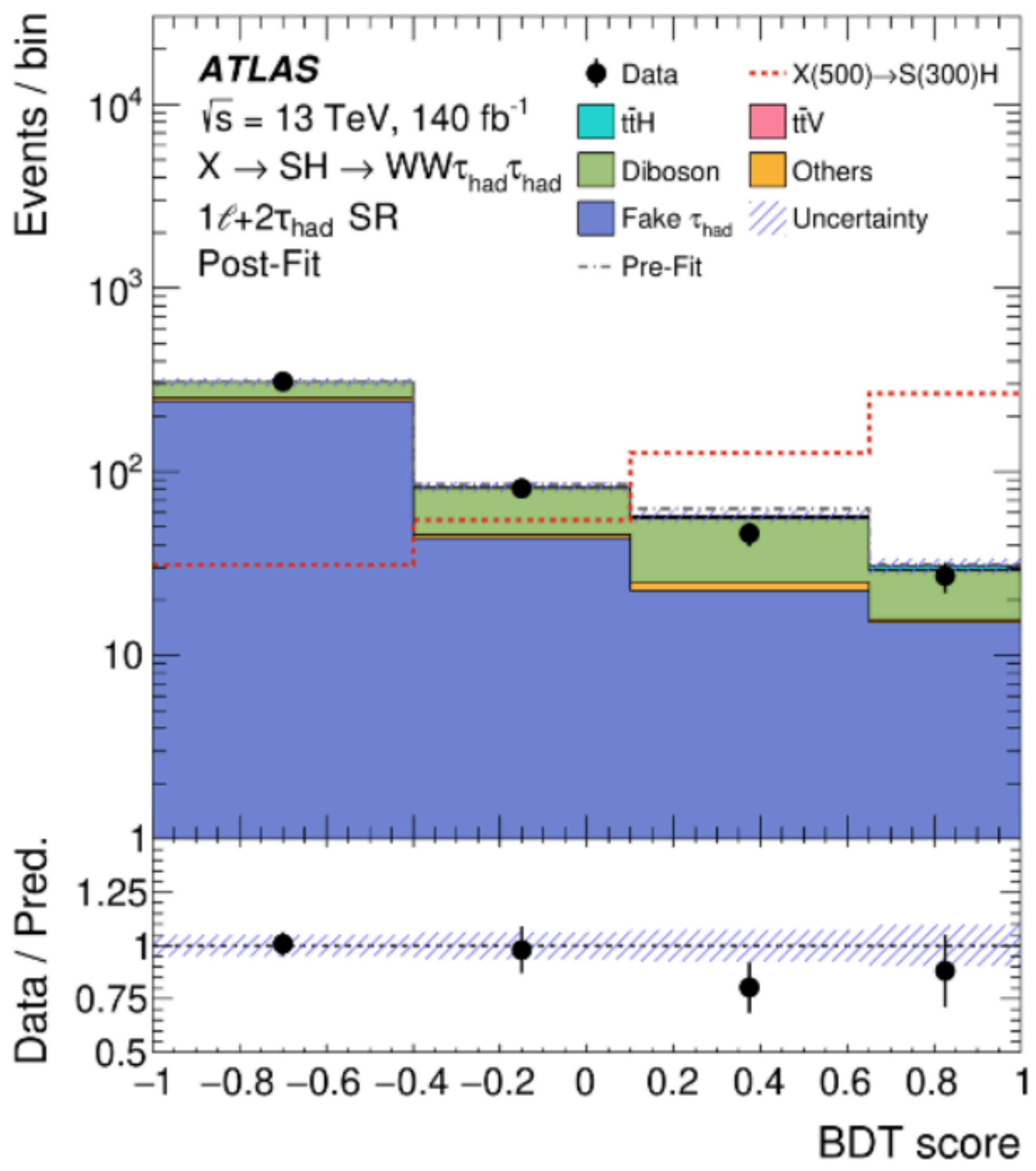


- **Search** based on **signature** $X \to SH \to VV\tau\tau$
- **Provided interpretations** including: 2HDM, 2HDM+S, MSSM, NMSSM
- Analysis **focused** on the most **sensitive final states**: $1\ell 2\tau_{had}$, $2\ell 2\tau_{had}$.

- **Three** Signal regions defined depending on the $S \to VV\,(WW_{had}, WW, ZZ_{had}$ and $ZZ)$ decays.
- Main discriminating observables:
  - $\Delta R(\tau_1, \tau_2)$
  - number of b-jets
  - RNN taus.

Main backgrounds:

- Fake τ_{had} (data-driven)
- Diboson, ttV/H



- **Parameterized BDT** (in m_X for given m_S) is used **to separate** the **signal from the background** in each signal region.
- A total of **12 BDTs** are trained

- A **binned likelihood fit** is performed in all the signal regions using **BDT distribution as input**

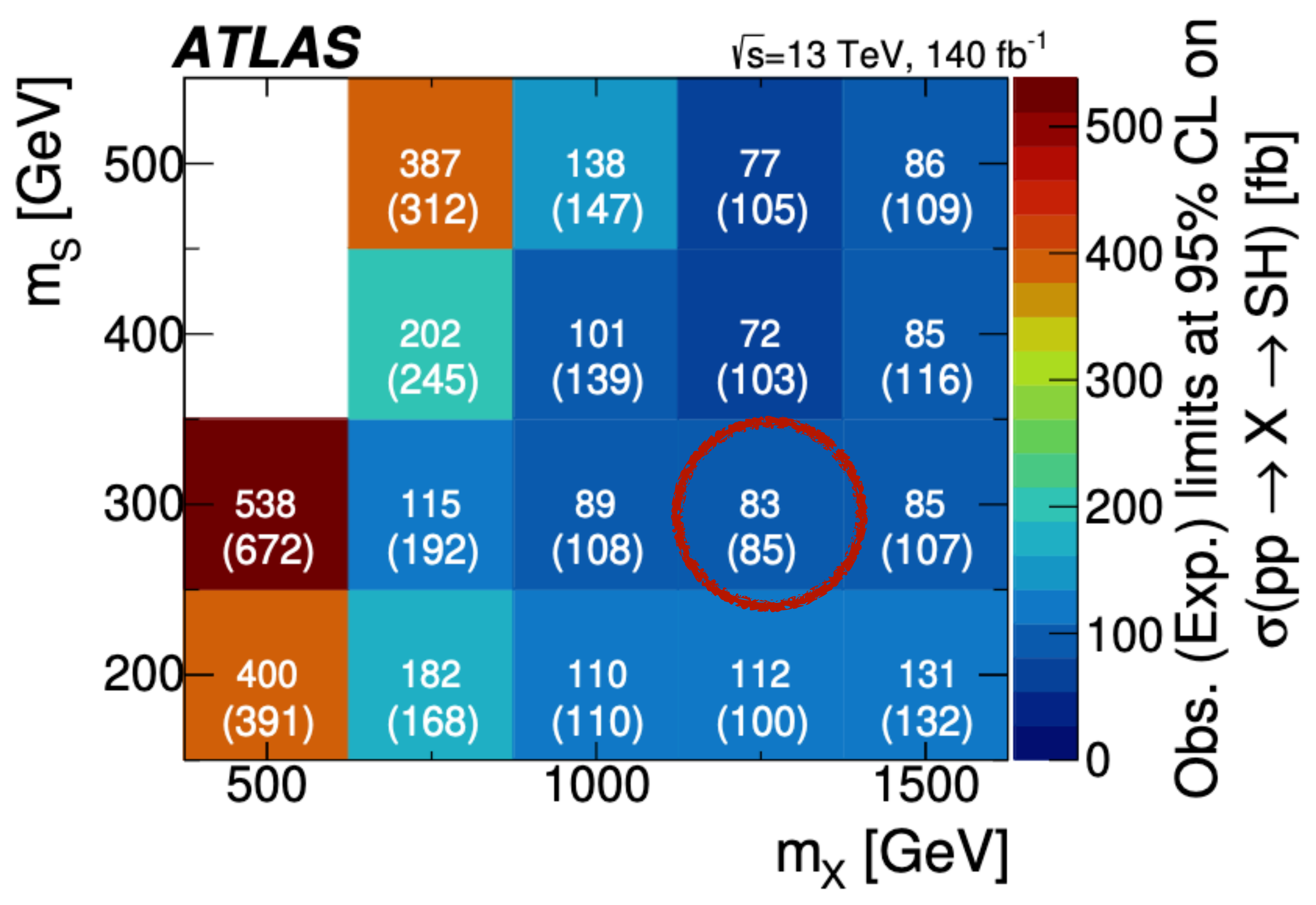
Main uncertainties:

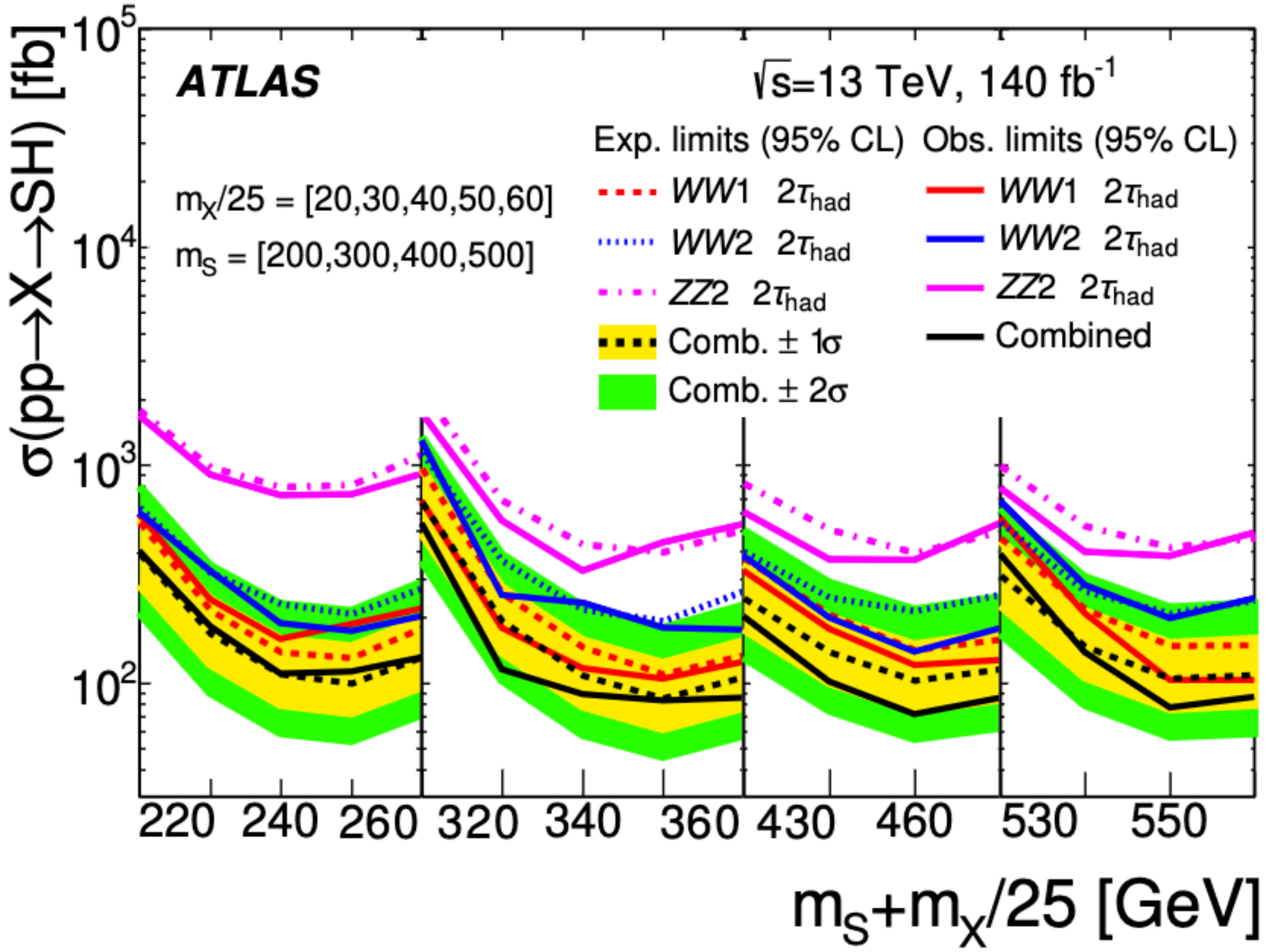
- MC modelling
- τ identification & fake τ modelling
- Data statistical uncertainty

No excess is observed from the data

The **best expected combined limit is 85 fb** for $\sigma\left(pp \rightarrow X \rightarrow SH\right)$ for $m_X = 1250$ GeV and $m_S = 300$ GeV

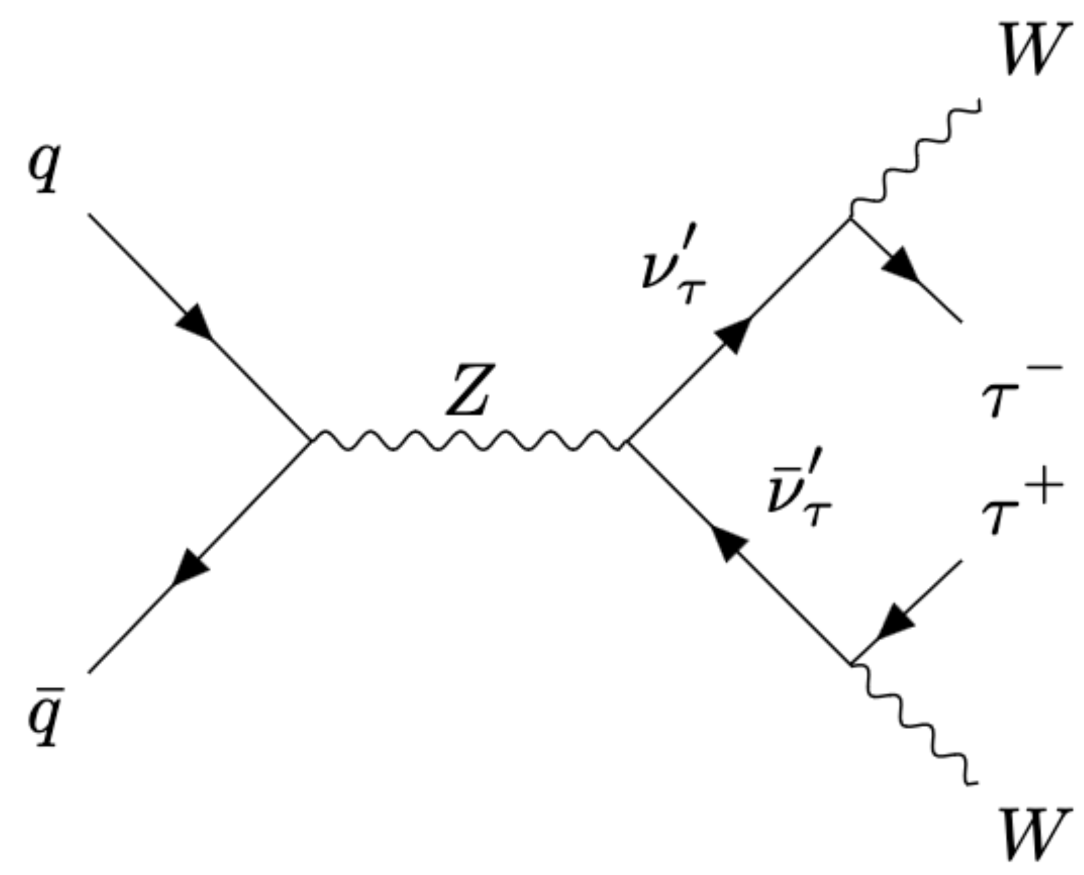
2D upper limits as a function of m_X and m_S





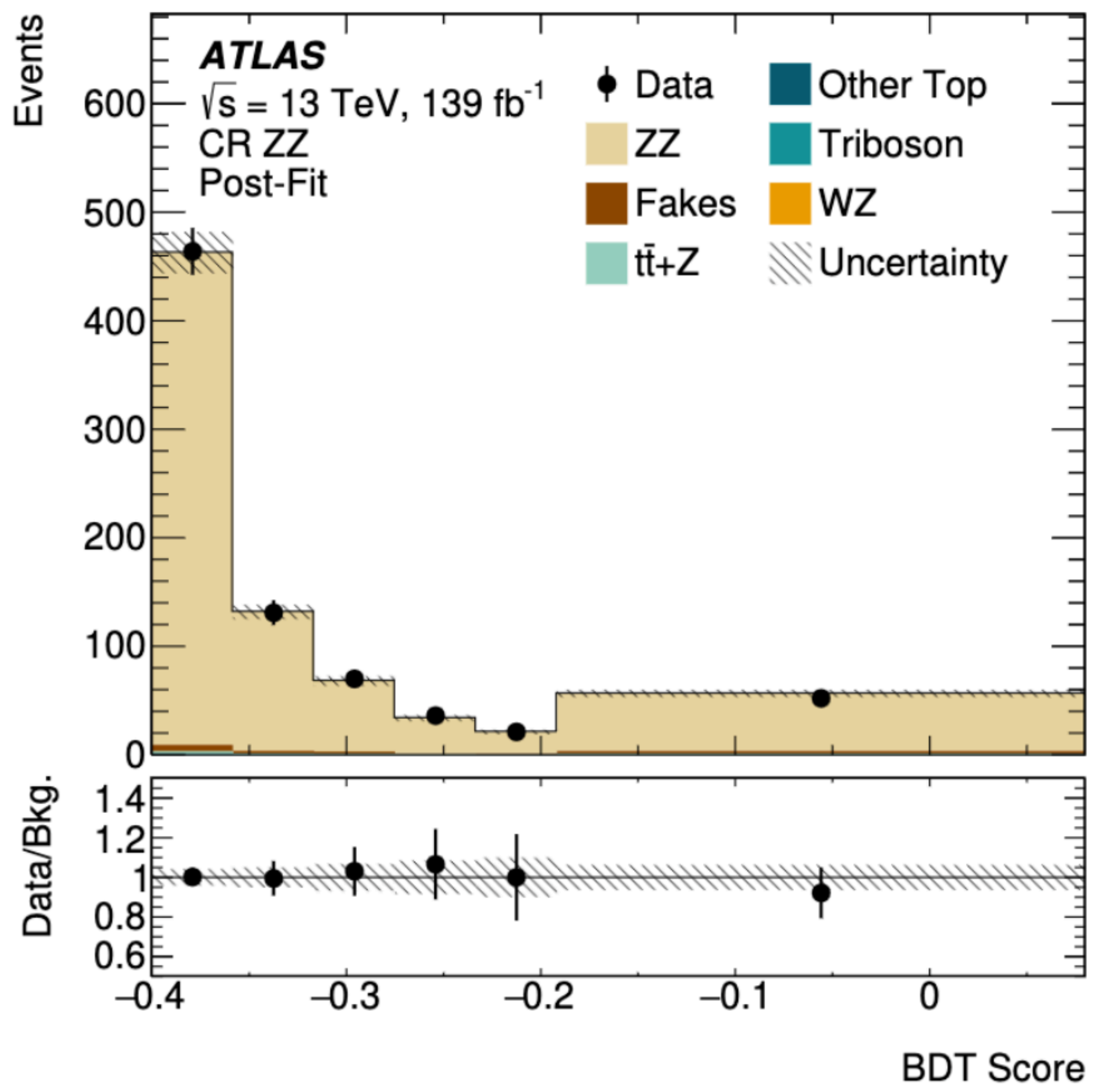
VLL in a doublet model

- **Search** for **VLL** in **multilepton final** states with 0 or more τ_{had}
- VLL in a doublet model introduces **two fermions** $L' = (\nu'_\tau, \tau')$, which are assumed to be **degenerate in mass**
- **BDT** used to maximize signal efficiency vs. background rejection (including fakes). 7 BDTs (one for each SR) trained looking for different leptons multiplicities and leptons charge



Variables	BDT Training Regions						
BDT	2ℓ SSSF, 1τ	2ℓ SSOF, 1τ	2ℓ OSSF, 1τ	2ℓ OSOF, 1τ	2ℓ, $\geq 2\tau$	3ℓ, $\geq 1\tau$	4ℓ, $\geq 0\tau$
N_ℓ	2	2	2	2	2	3	≥ 4
Charge/flavour	SSSF	SSOF	OSSF	OSOF	—	—	—
N_τ	1	1	1	1	≥ 2	≥ 1	≥ 0
E_T^{miss} [GeV]	≥ 120	≥ 90	≥ 60	≥ 100	≥ 60	≥ 90	≥ 60

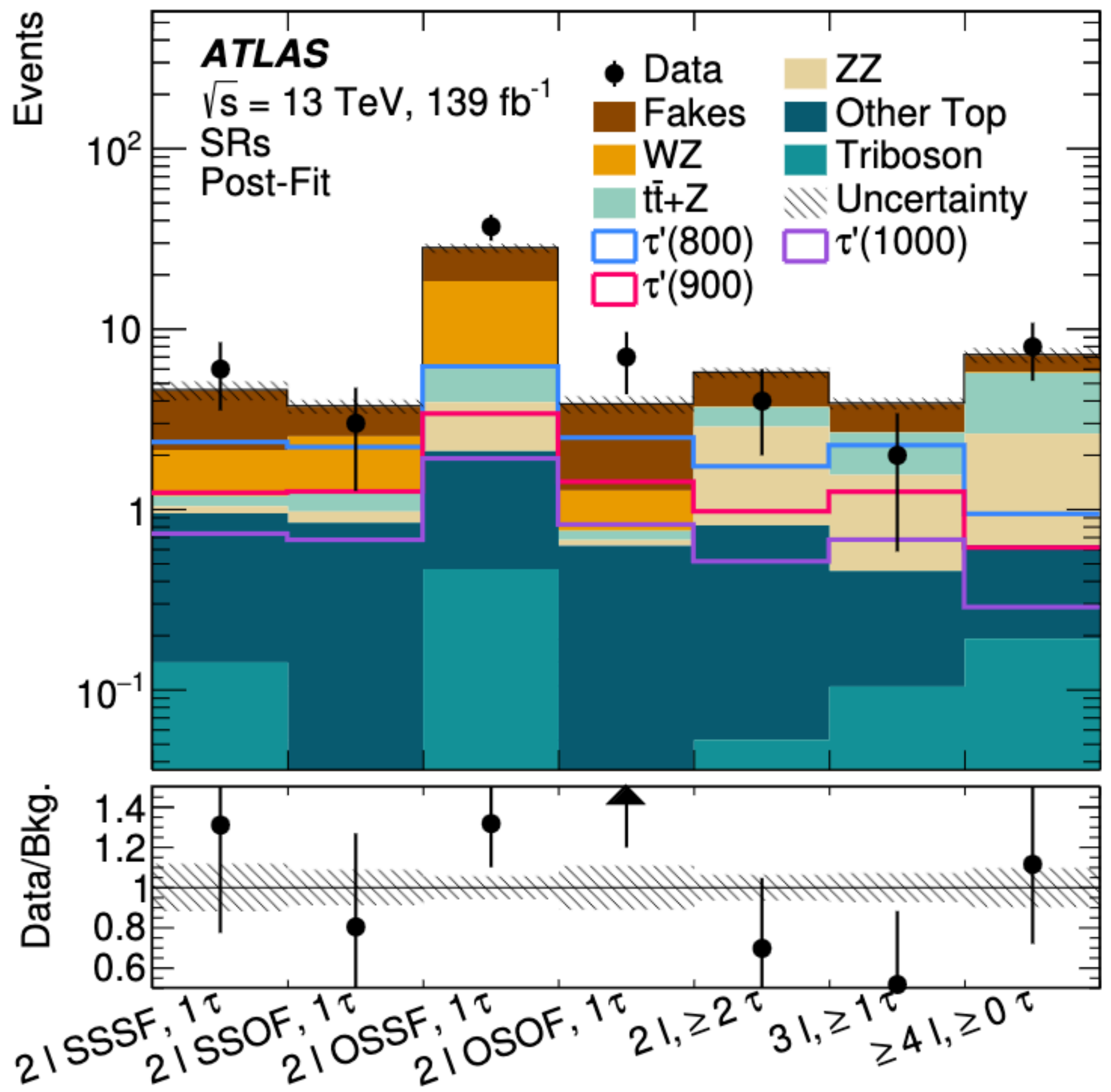
- **Four Control regions** are used to constrain the dominant backgrounds: $t\bar{t} + Z$, diboson (mainly WZ and ZZ); fake τ_{had} (estimated through a data-driven technique)

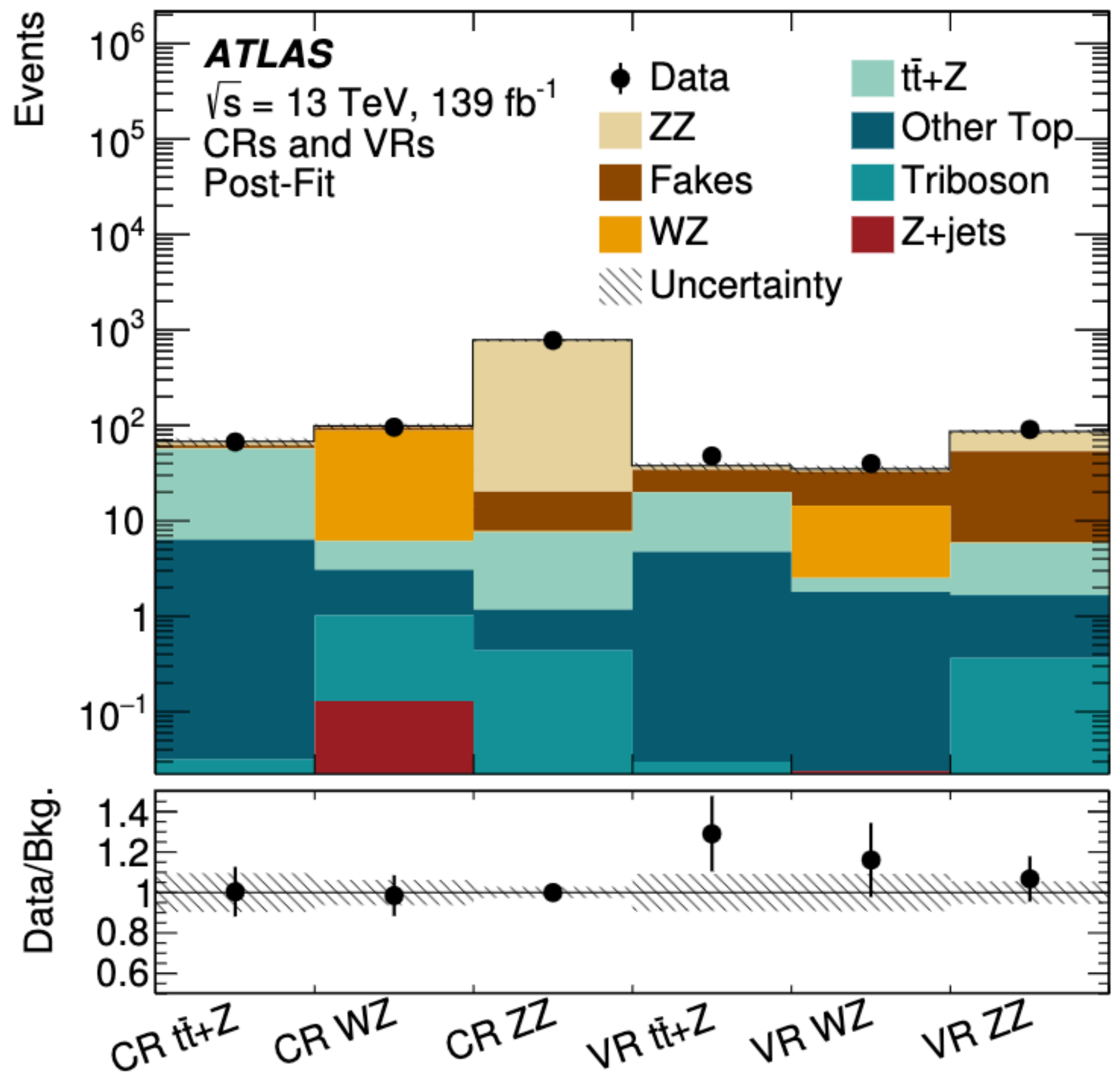


VLL in a doublet model

JHEP07(2023)118

- **SRs** directly defined from output of BDTs (**high BDT score**)
- **Low BDT** score cut used as **VR**





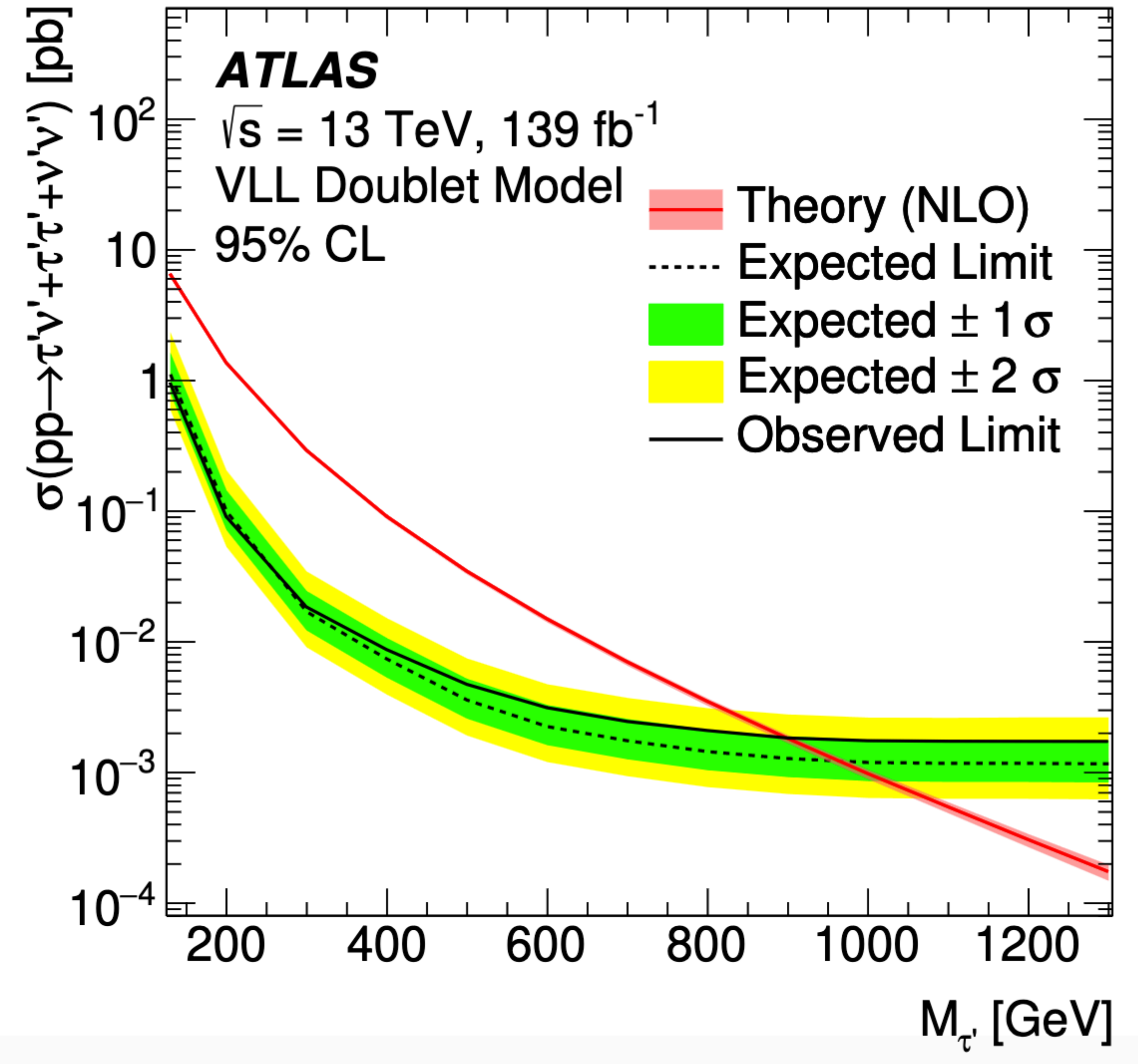
Summary of **post-fit yields** for data and **background**, and **pre-fit yields for signal** modelling

Main uncertainties from:

Normalization factors extrapolations & fakes estimation

Analysis dominated by statistical uncertainty

Observing no excess of events above the SM expectation

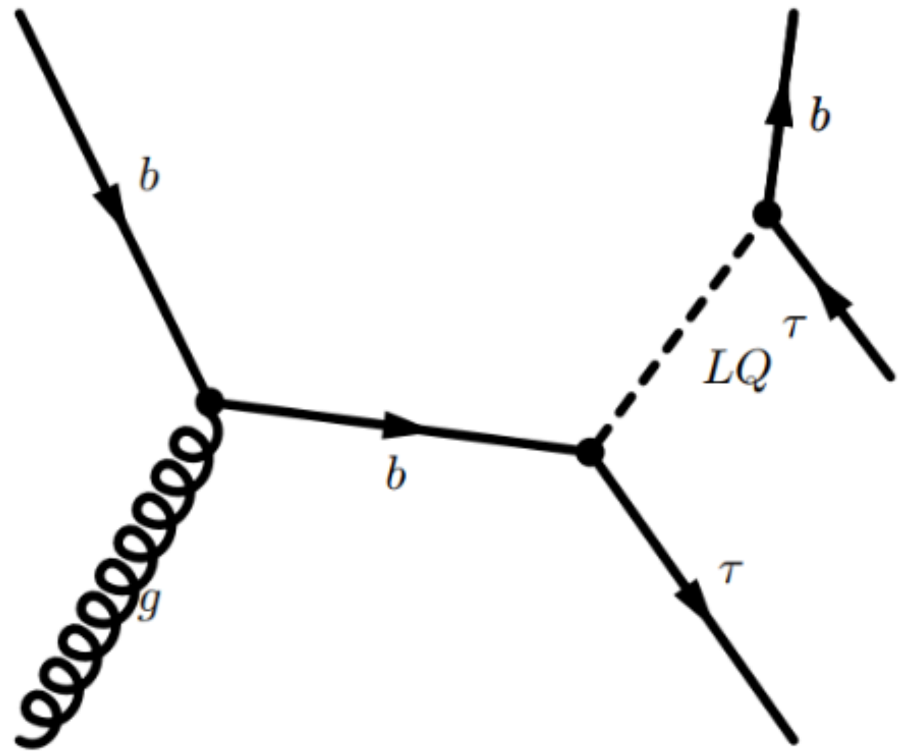


- **Observed** mass range **from 130 to 900 GeV** is **excluded at 95% CL**

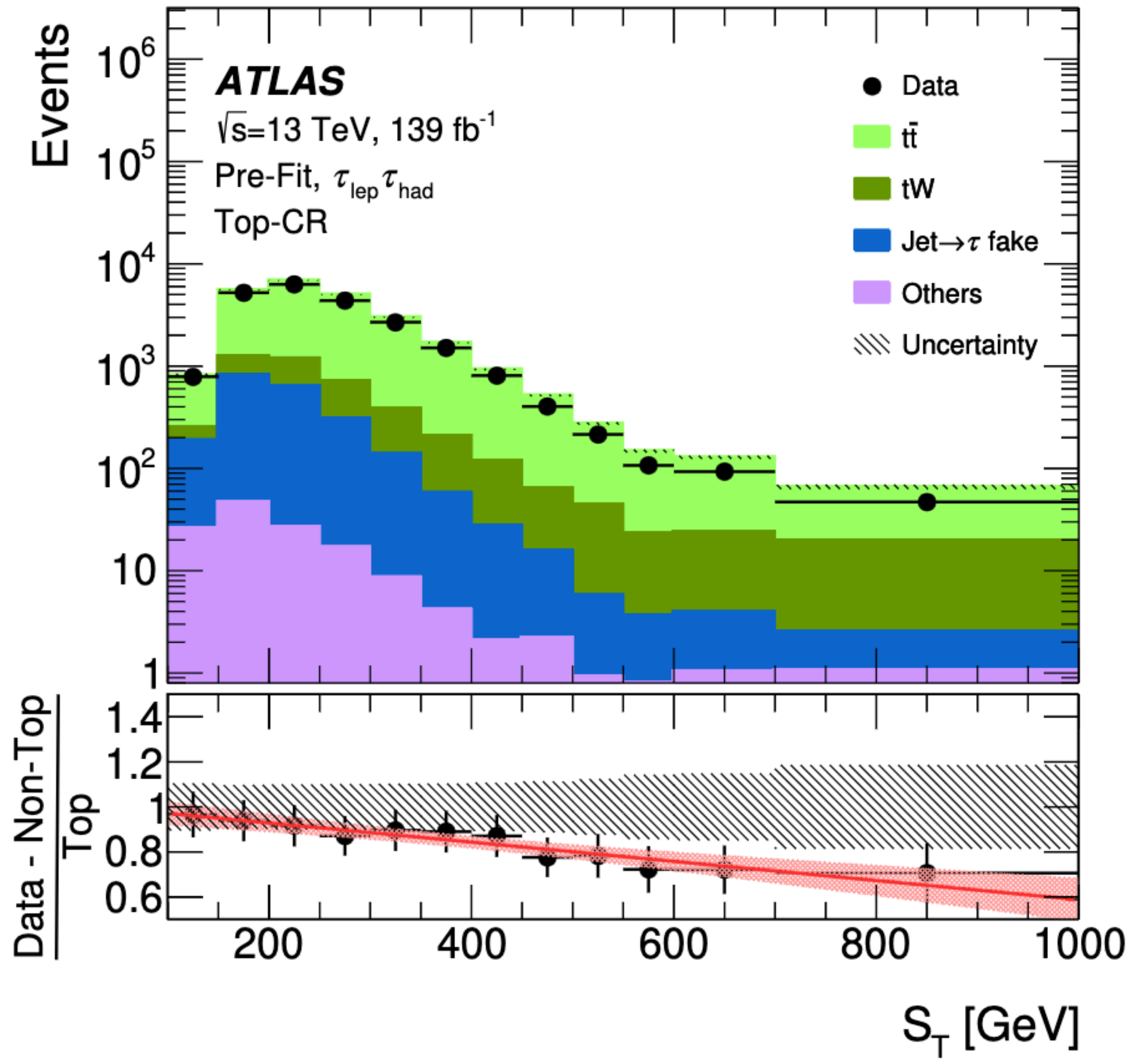
$LQ \to b\tau$

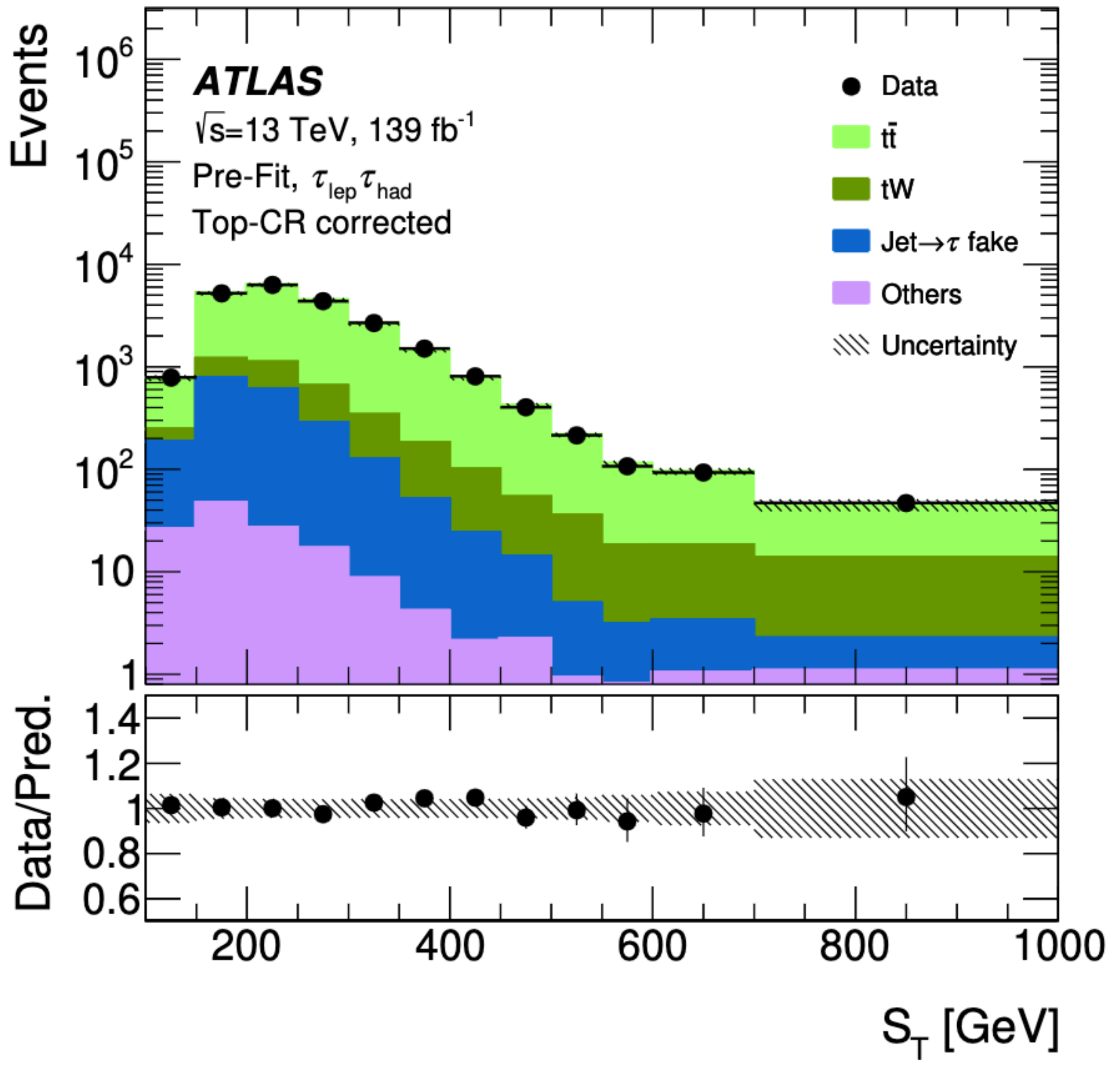
JHEP10(2023)001

- **Search for third generation LQ** into $b\tau\tau$ final states, including also LQ pair and non-resonant production due to similar final states.
- **Two channels** are considered: $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ (ad-hoc selection for each of them)
- **Three interpretations** provided by the analysis:
  - Interpretation for **vector** and **scalar LQ** in **high b-jet p_T** category
  - **Model-independent** interpretation in **low** and **high b-jet p_T** categories
  - **LQ interpretation** considering **both low** and **high b-jet p_T** categories
- **Scalar sum** (S_T) of taus and b-jet p_T used as discriminant variable



Low ***b*-jet** p_T: 25 GeV < $p_T\,(b\text{-jet}) < 200GeV$
High ***b*-jet** p_T: $p_T\,(b\text{-jet}) > 200GeV$





Clear mis-modelling in the Top CR ($\tau_{lep}\tau_{had}$) depending on S_T, corrected by a dedicated SF:

$$SF_{\text{Top}}(S_{\text{T}}) = \frac{(N_{\text{data}} - N_{\text{non-Top}})(S_{\text{T}})}{N_{\text{Top}}(S_{\text{T}})}$$

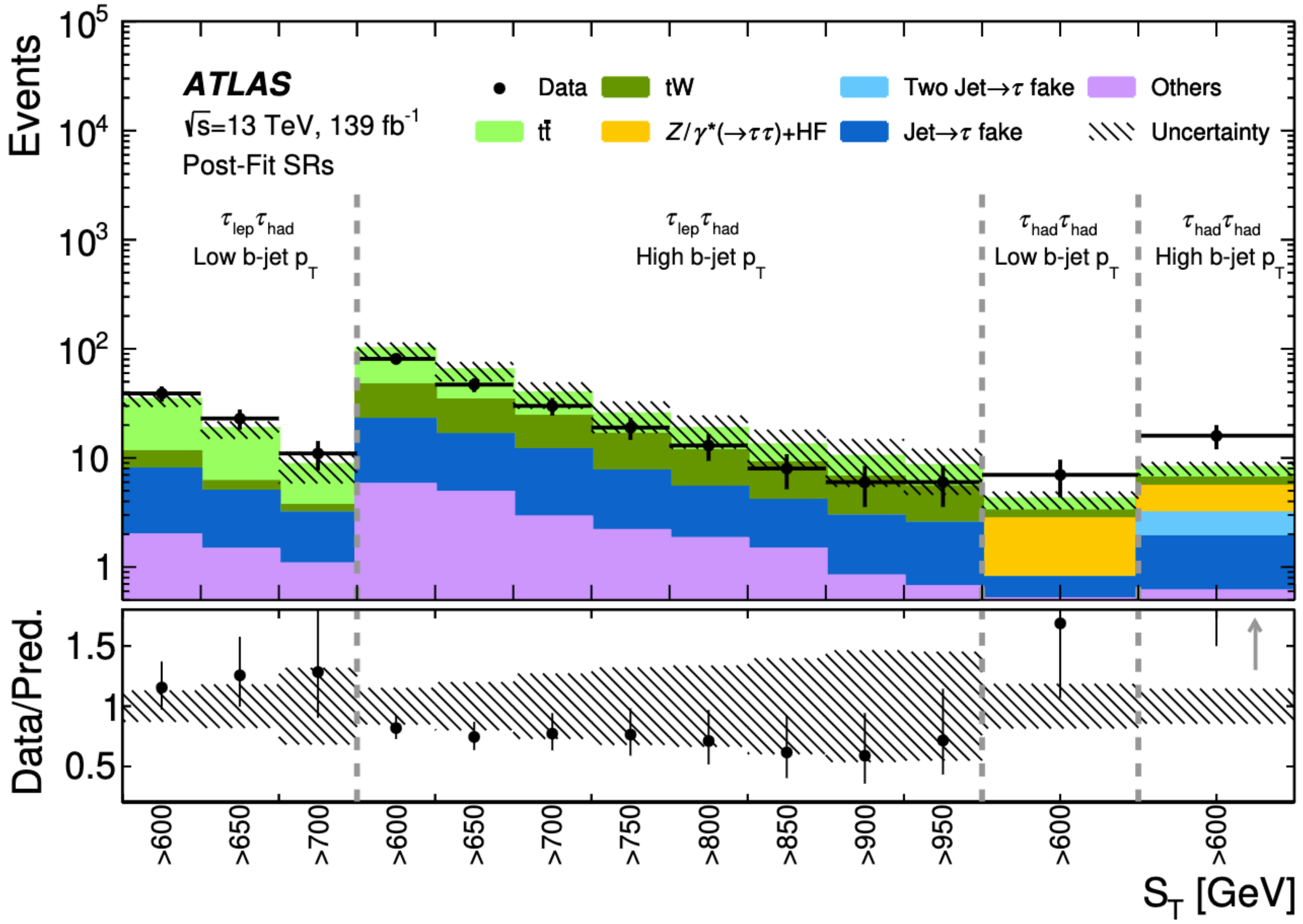
Main backgrounds:

- $t\bar{t}$ and single top events
- Fake τ ($\tau_{lep}\tau_{had}$) & multi-jet ($\tau_{had}\tau_{had}$, data-driven)
- Z + light flavour jets ($\tau_{had}\tau_{had}$)

Main uncertainties:

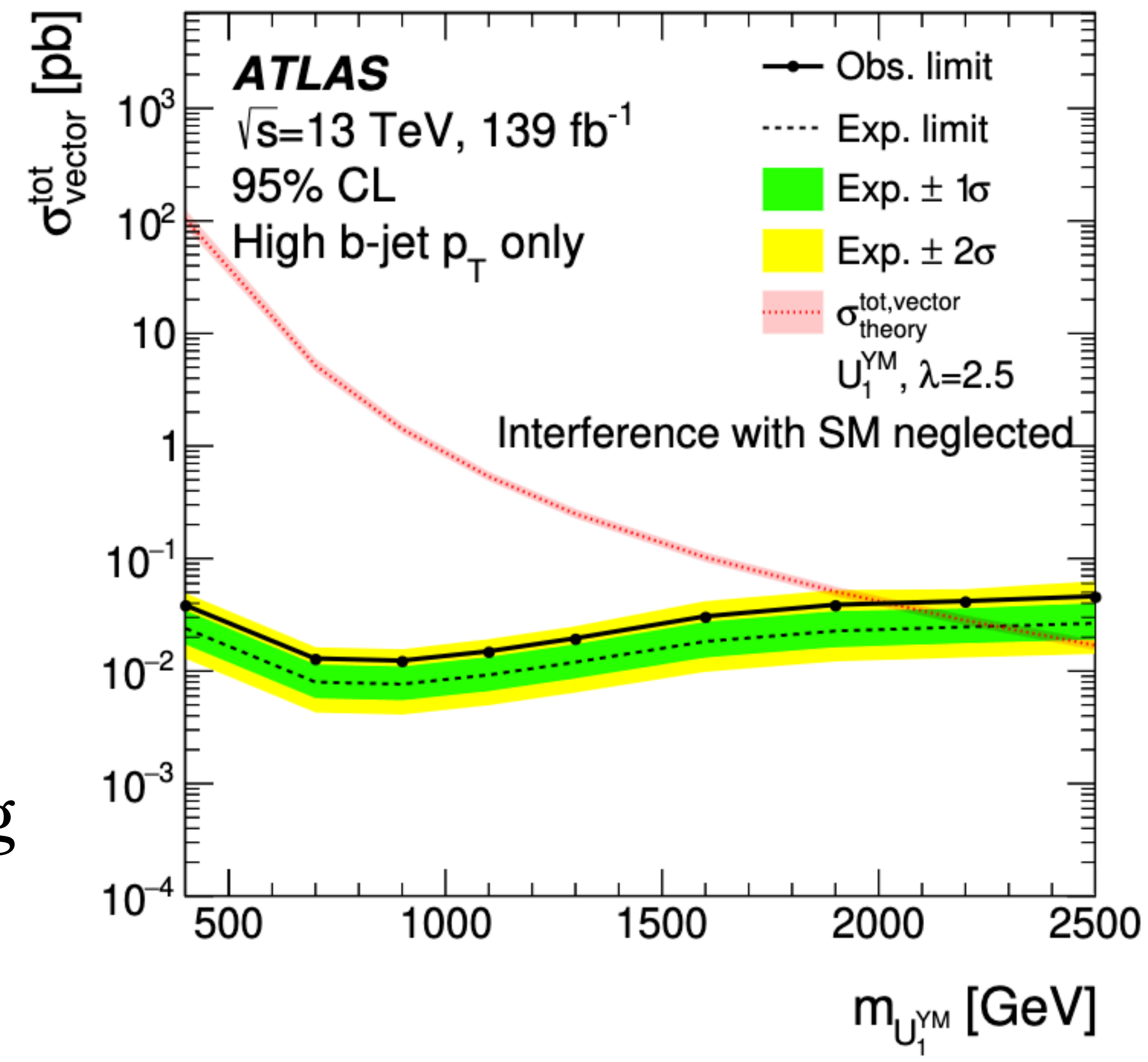
- MC statistics
- Top background modeling
- Fake τ correction

No significant excess observed in data



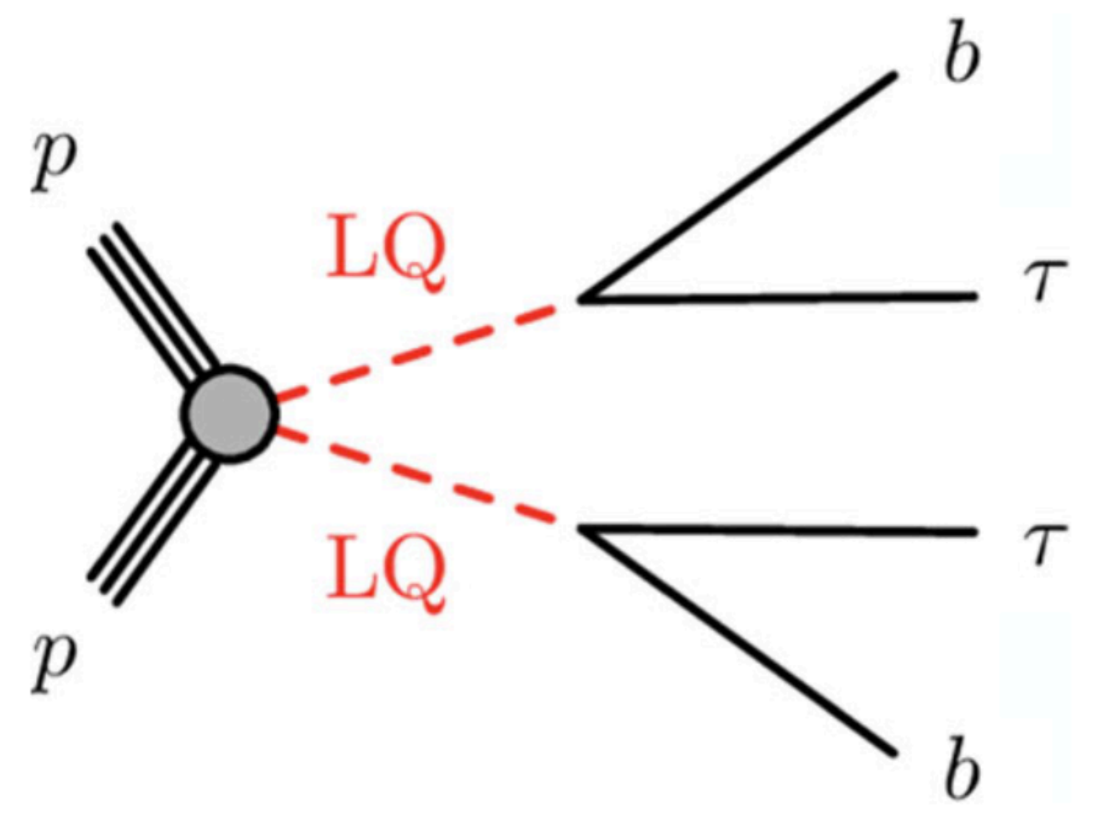
Observed and predicted yields of the background as a function of S_T threshold used to define SRs.

This **analysis sets ULs** at 95% CL **for LQ** via **either single plus non-resonant production**, **or** considering **all production modes**.



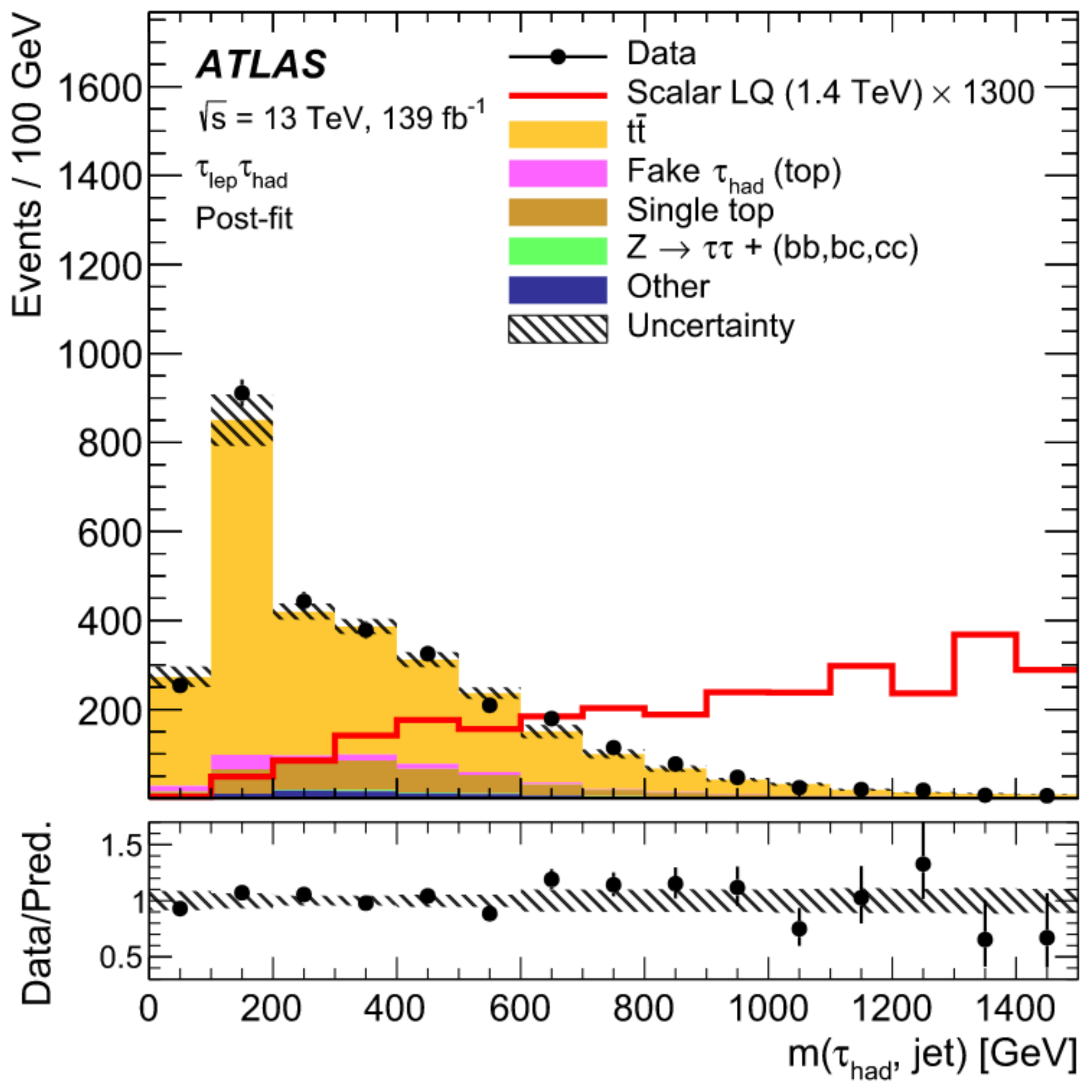
- For a **Yang-Mills coupling of 2.5**, the observed **lower limit** of LQ mass is **2.05 TeV.**
- **Model-independent scenario:** limits on σ_{vis} vary between 0.17 fb and $4.8 \cdot 10^{-2}$ fb.

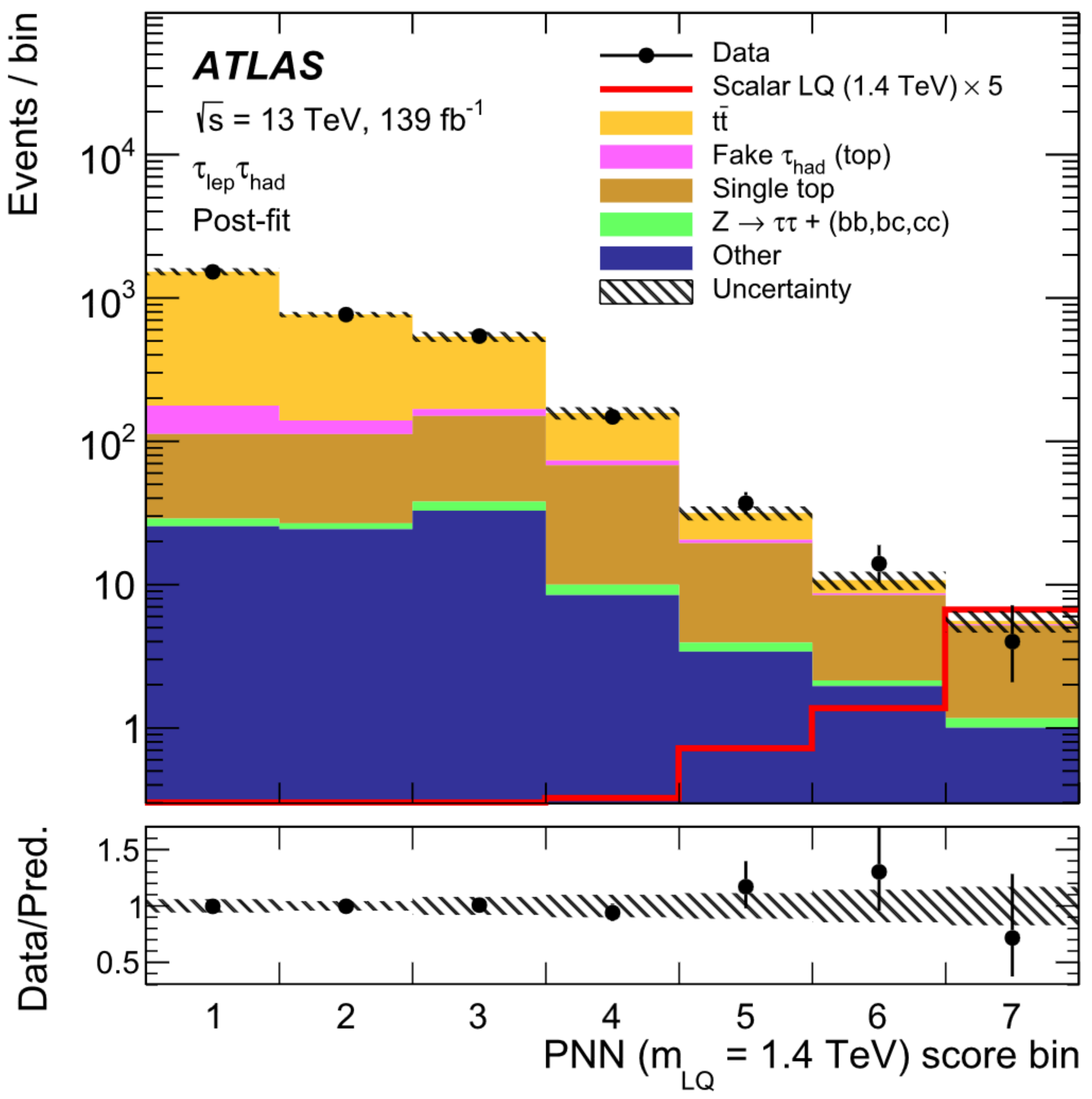
- **Search focusing on third generation LQ pair production**. Both LQs decay into b-quark and τ-lepton.
- In analogy with the previous analysis, **two channels** are considered:
  - $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$, **event selection is optimized for each channel**
- A common selection is applied requiring OS leptons, $E_T^{miss} > 100$ GeV and $S_T > 600$ GeV
- **A parameterised neural network (PNN)** is used to search for a LQ-pair into **two Signal regions**



Main backgrounds:

- Z + heavy flavour jets
- Diboson
- $t\bar{t}$ and single top (similar correction of $LQ \to b\tau$ analysis)
- Fake taus

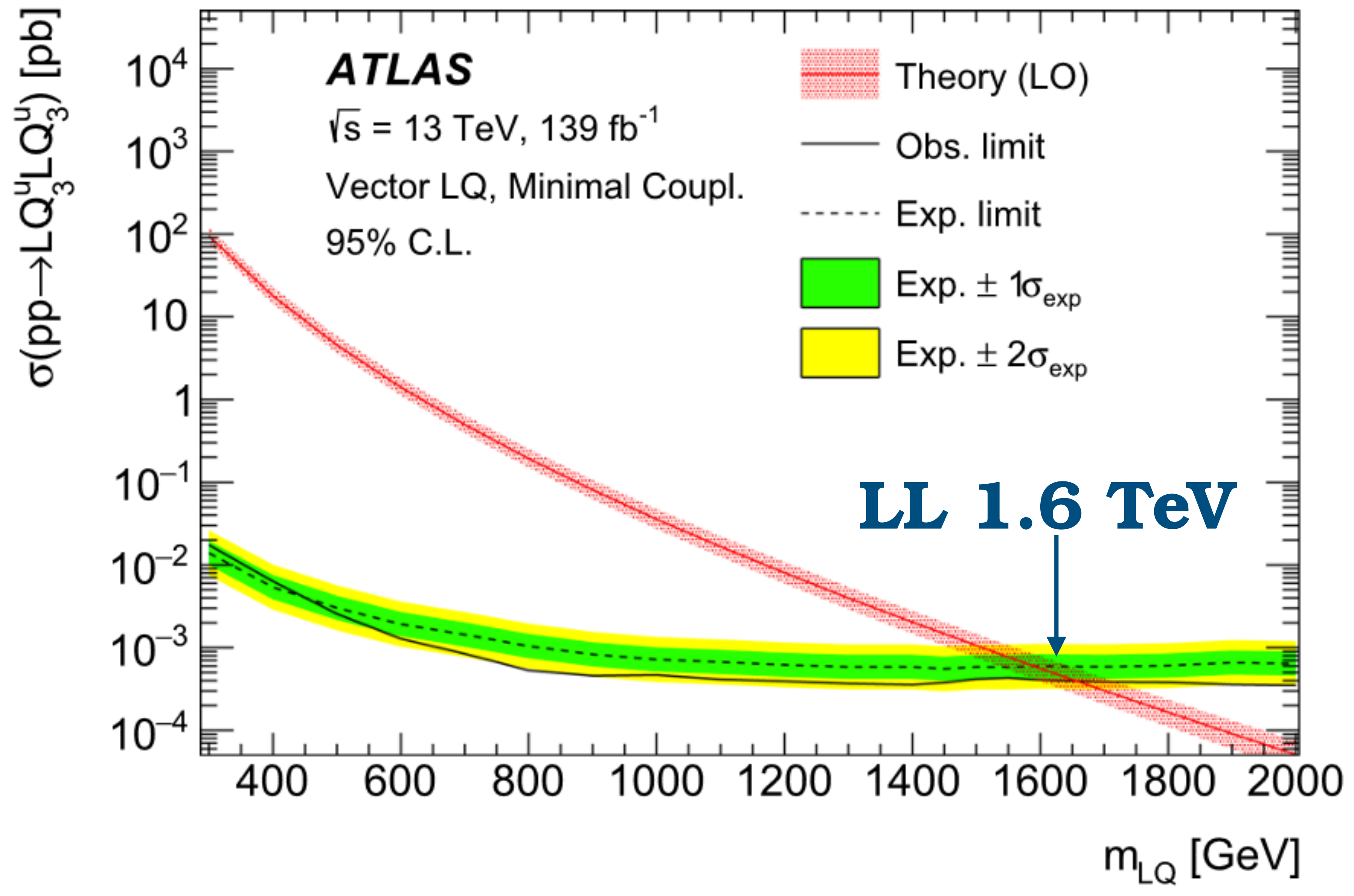




- **Analysis dominated by statistical uncertainties.**

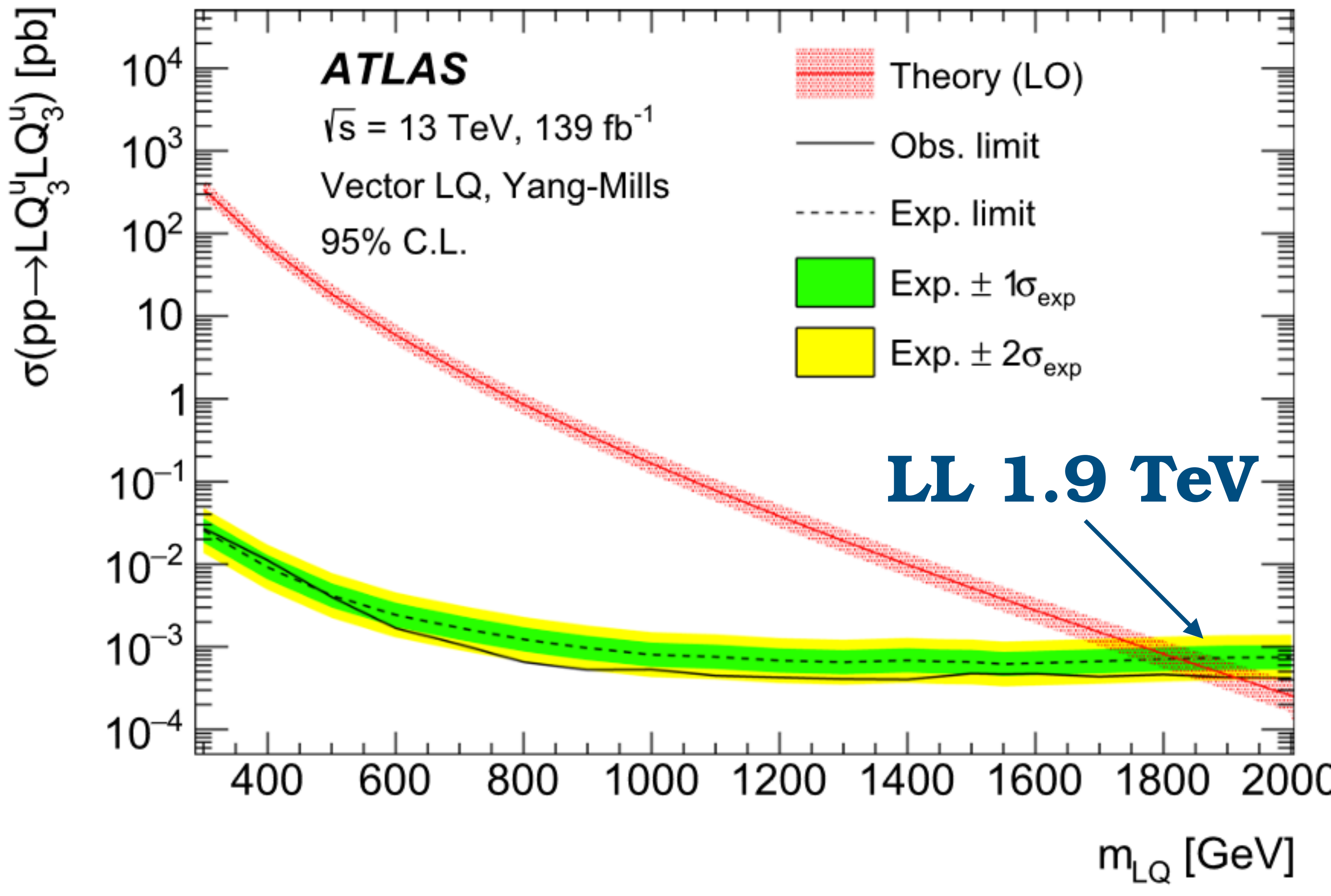
Main systematics due to fakes estimation, $t\bar{t}$ and single top modeling and normalization.

No significant excess over expectation is observed.

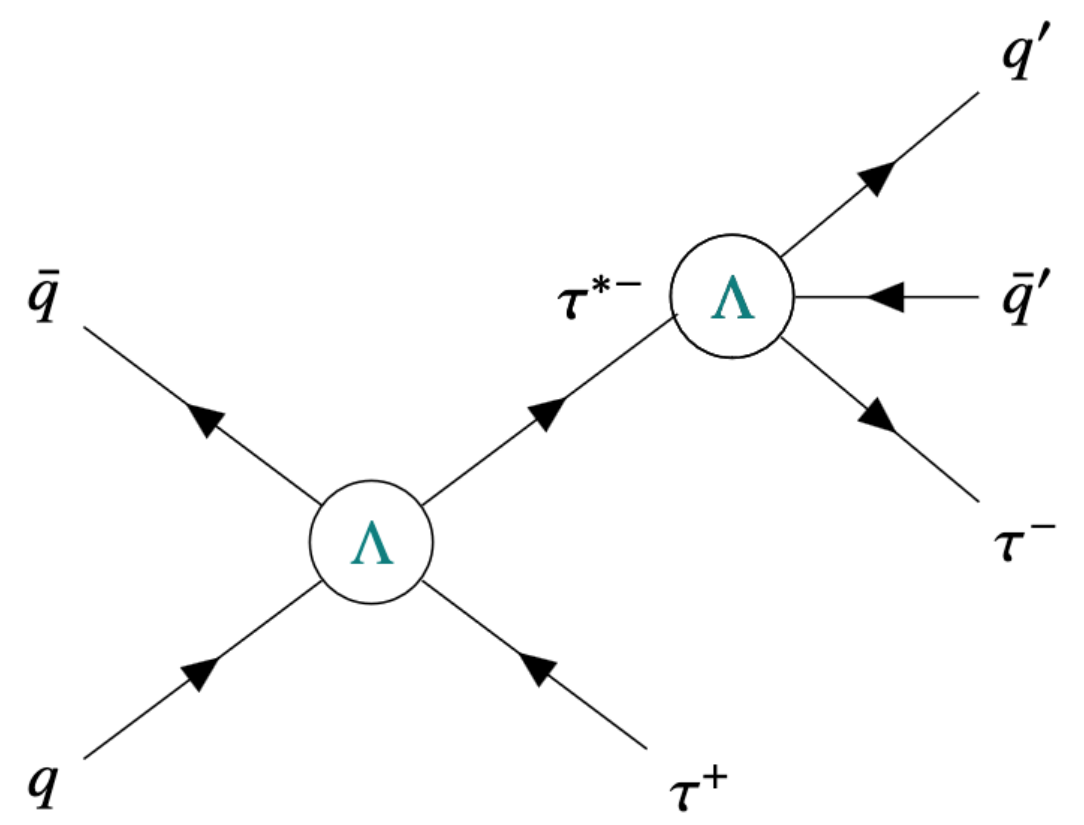


Exclusion limits at 95% CL are set for different LQ scenario and BRs:

- 100% BR:
  - **Scalar LQ** excluded for masses below 1460 GeV
  - LL for **Vector LQs** in the **minimal-coupling** scenario set at 1650 GeV
  - LL for **Vector LQs** in the **Yang-Mills** scenario set at 1910 GeV
- BR < 10%:
  - **Scalar LQ** excluded for masses below 850 GeV
  - LL for **Vector LQs** in the **minimal-coupling** scenario set at 1120 GeV
  - LL for **Vector LQs** in the **Yang-Mills** scenario set at 1360 GeV

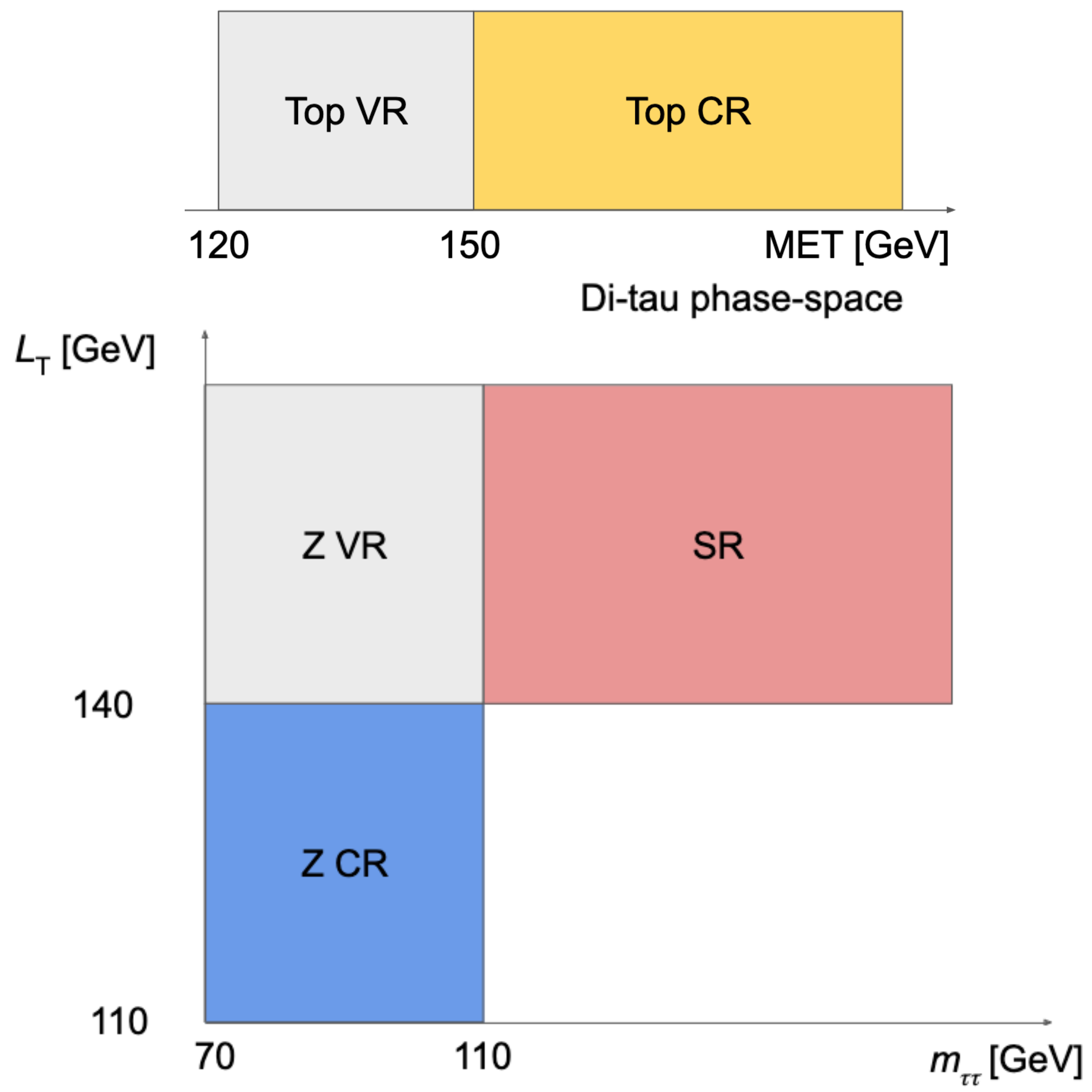


- **Search for excited τ-leptons and LQs** in events with 2 τ_{had} and at least 2 jets
- **According to some models, SM** quarks and leptons, could be composed by particles called ***preons*. They predict the existence of excited states towering over the known SM leptonic and quark ground states.**
- This **analysis uses** an effective **four-fermion contact interaction** (CI).



Main backgrounds:

- Leptonic decay of Z
- $t\bar{t}$ and single top
- Fake taus (fake-factor)

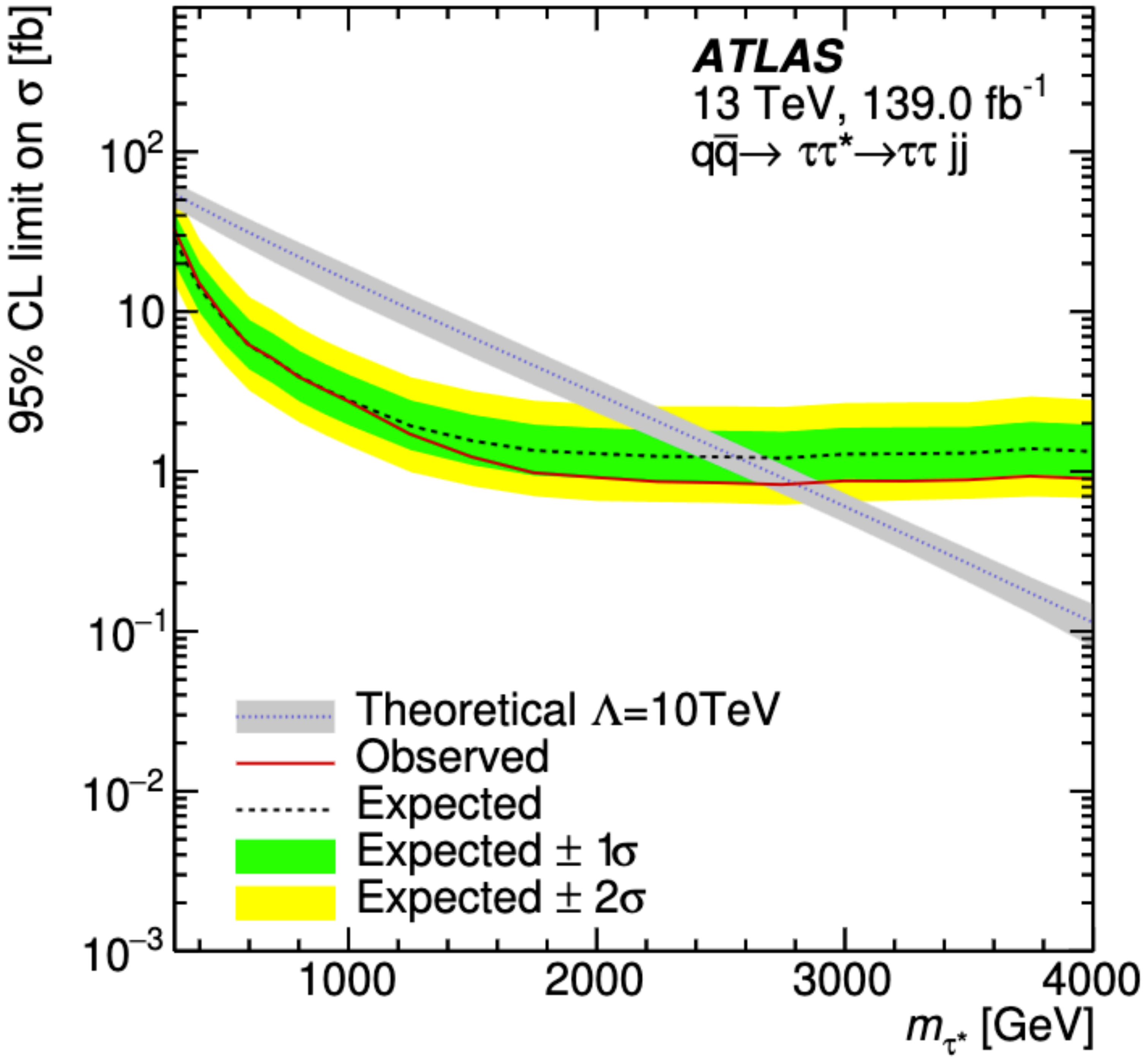


Main systematics:

- $t\bar{t}$ and tW theory (Matrix Element & Parton Shower)
- Fakes estimation

No excess of data over the background prediction is observed.

- **Excited τ-leptons** with masses **below 2.8 (4.6) TeV** are **excluded** at 95% CL for CI scale Λ set to 10 TeV ($m_{\tau*}$).
- **LQs** with masses **below 1.3 TeV** are excluded at 95% CL, for $BR(LQ \to c\tau) = 1$



LFV $Z' \to \ell\ell'$

- **LFV is forbidden in the SM**, but neutrino oscillations have shown that lepton flavour is not a conserved symmetry of nature. **Evidence of charge LFV** could lead to **physics BSM**.
- Analysis results interpreted in terms of: **LFV** Z', **Quantum Black Hole** and **R-Parity Violating SUSY.**
- **Three channels considered:** $e\mu$, $e\tau_{had}$ and $\mu\tau_{had}$ with **opposite charge** and **zero** b**-jets**.
- **Analysis regions** definition **driven by** $m_{\ell\ell'}$ values: above 600 GeV SR, below 600 GeV CR and VR.

Main backgrounds:

- Leptonic decay of Z
- $t\bar{t}$ and single top
- Fake light-leptons (fake-factor)
- Fake taus (MC extrapolation)

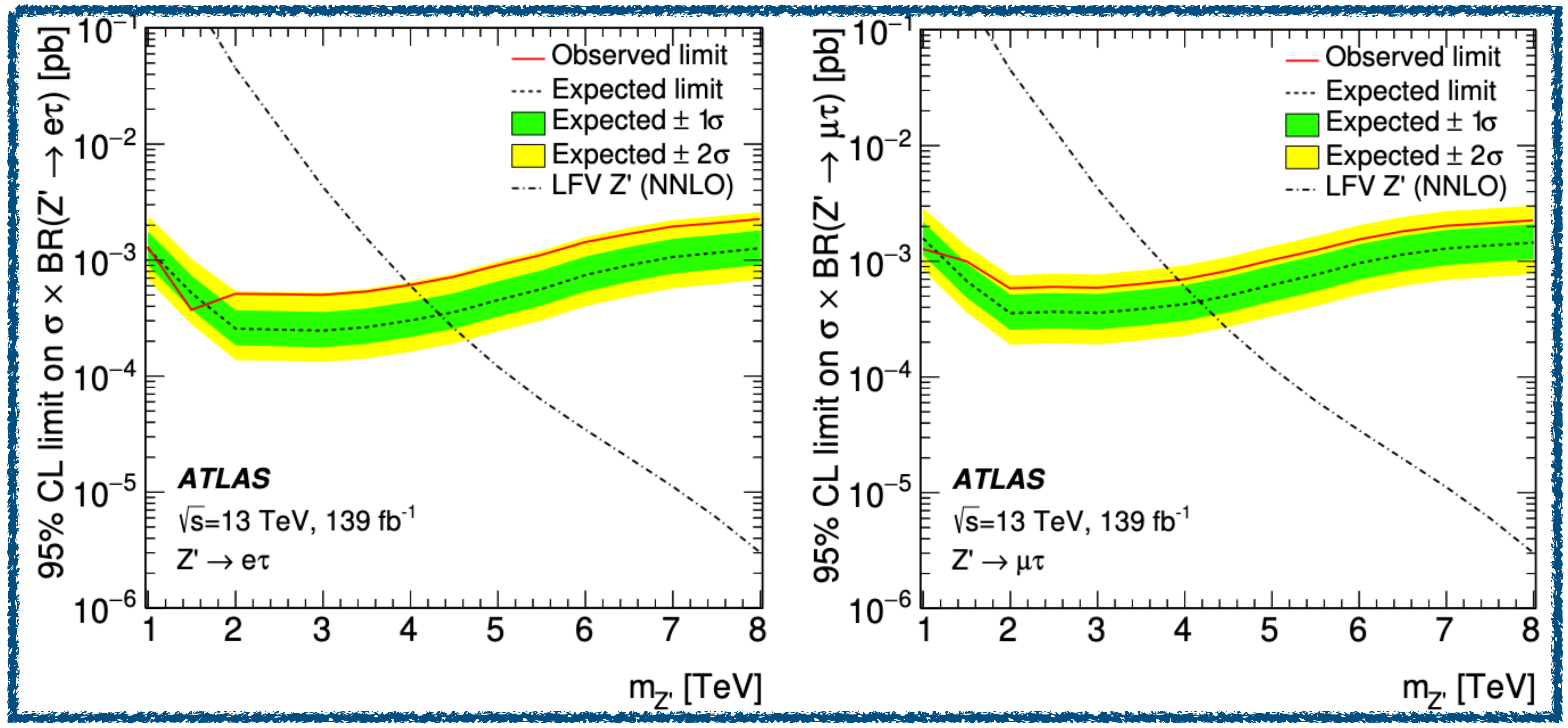
Main uncertainties:

- **Statistical uncertainty dominant** in every channel.
- Backgrounds modeling (channels with μ)
- τ-leptons (Reco, ID, isolation)

No evidence for new physics is found.

Different lower limit on the mass, at 95% CL are set by the analysis depending on the considered scenario.

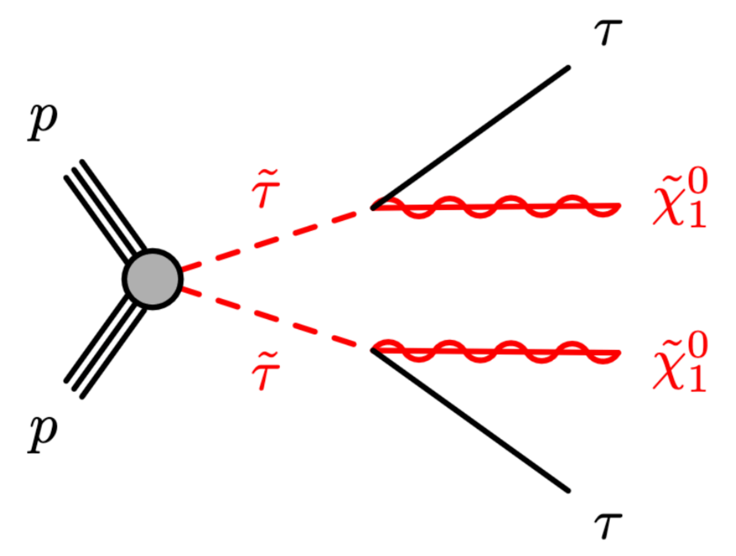
Model	Observed (expected) 95% CL lower limit [TeV]		
	$e\mu$ channel	$e\tau$ channel	$\mu\tau$ channel
LFV Z'	5.0 (4.8)	4.0 (4.3)	3.9 (4.2)
RPV SUSY $\tilde{\nu}_\tau$	3.9 (3.7)	2.8 (3.0)	2.7 (2.9)
QBH ADD $n=6$	5.9 (5.7)	5.2 (5.5)	5.1 (5.2)
QBH RS $n=1$	3.8 (3.6)	3.0 (3.3)	3.0 (3.1)



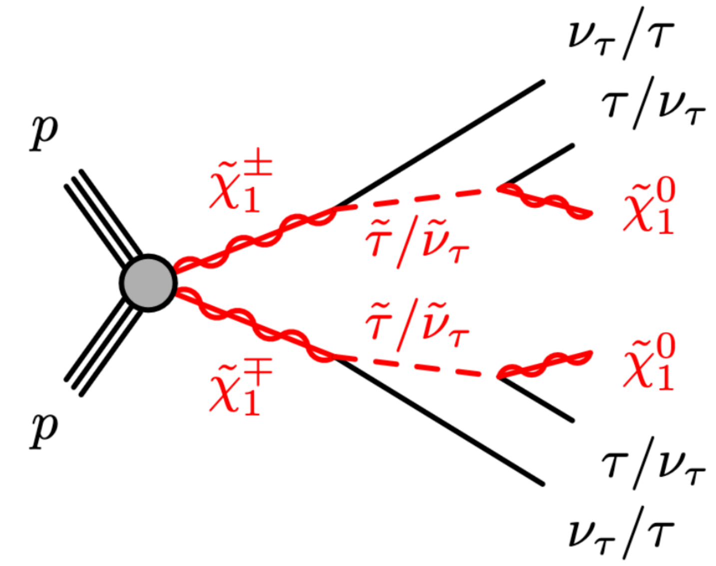
- Analysis **targeting Electroweak SUSY** production **with τ_{had} in the final state.**
- **Three** different **signal models** are **considered:**

Using a simplified model:

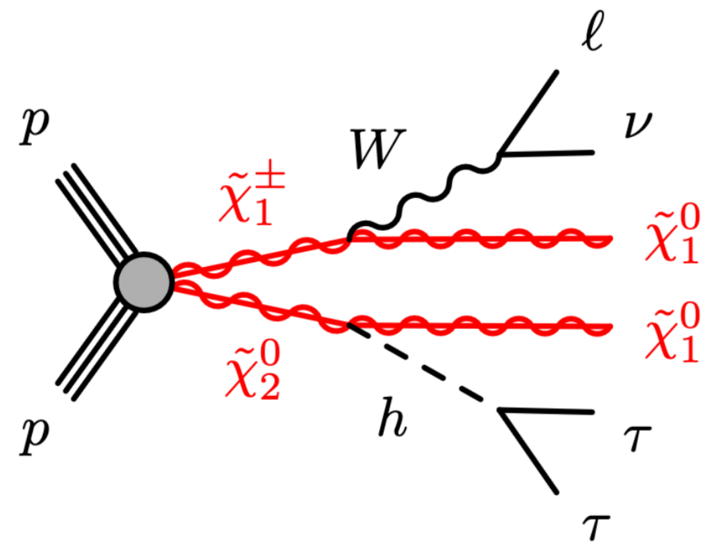
- $BR\left(\tilde{\tau} \to \tilde{\chi}_1^0 \tau\right) = 100\%$



Direct Stau ($\tilde{\tau}$) production



Intermediate Stau
***Chargino-neutralino production also considered**

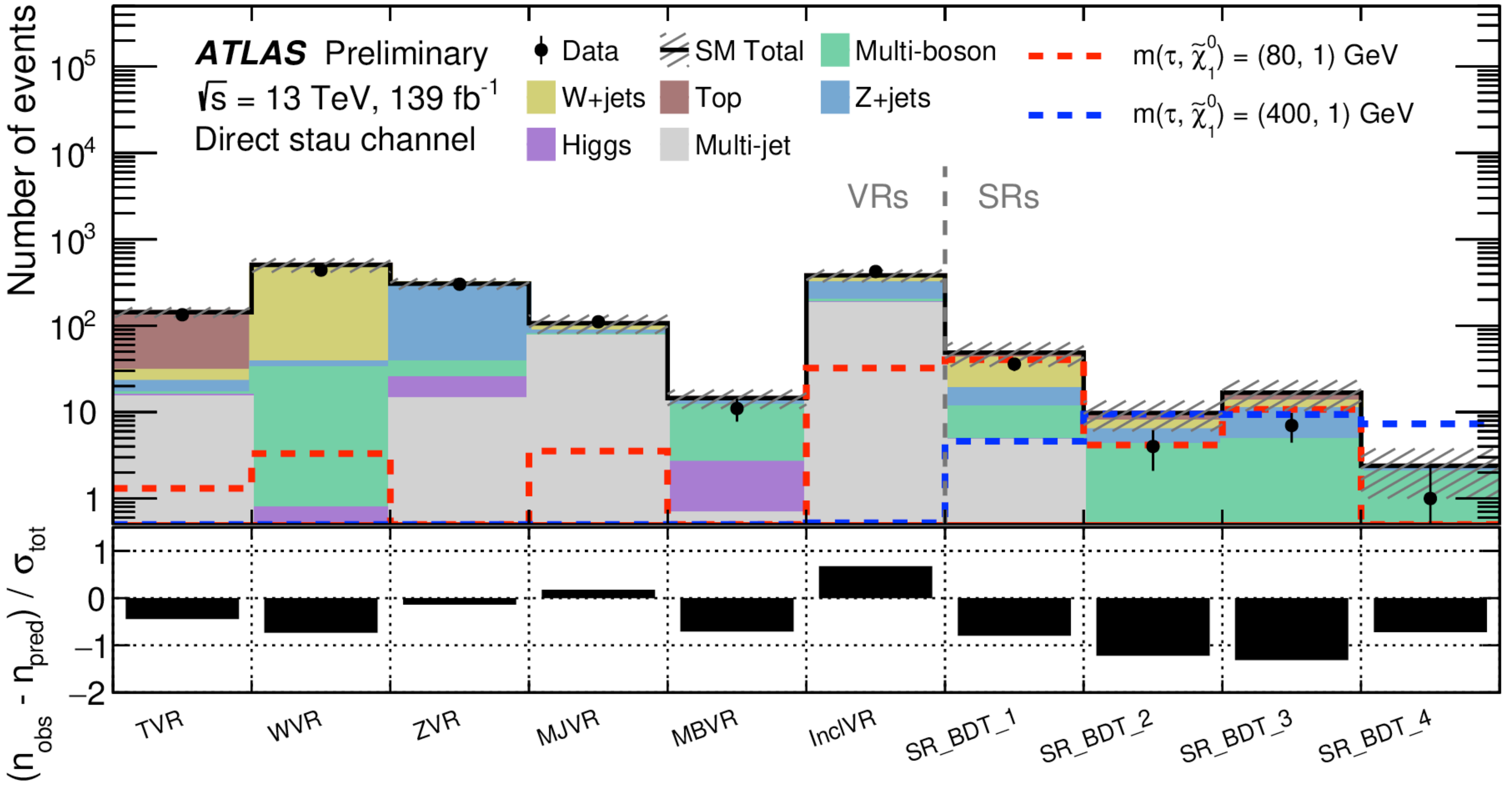


Intermediate Wh bosons

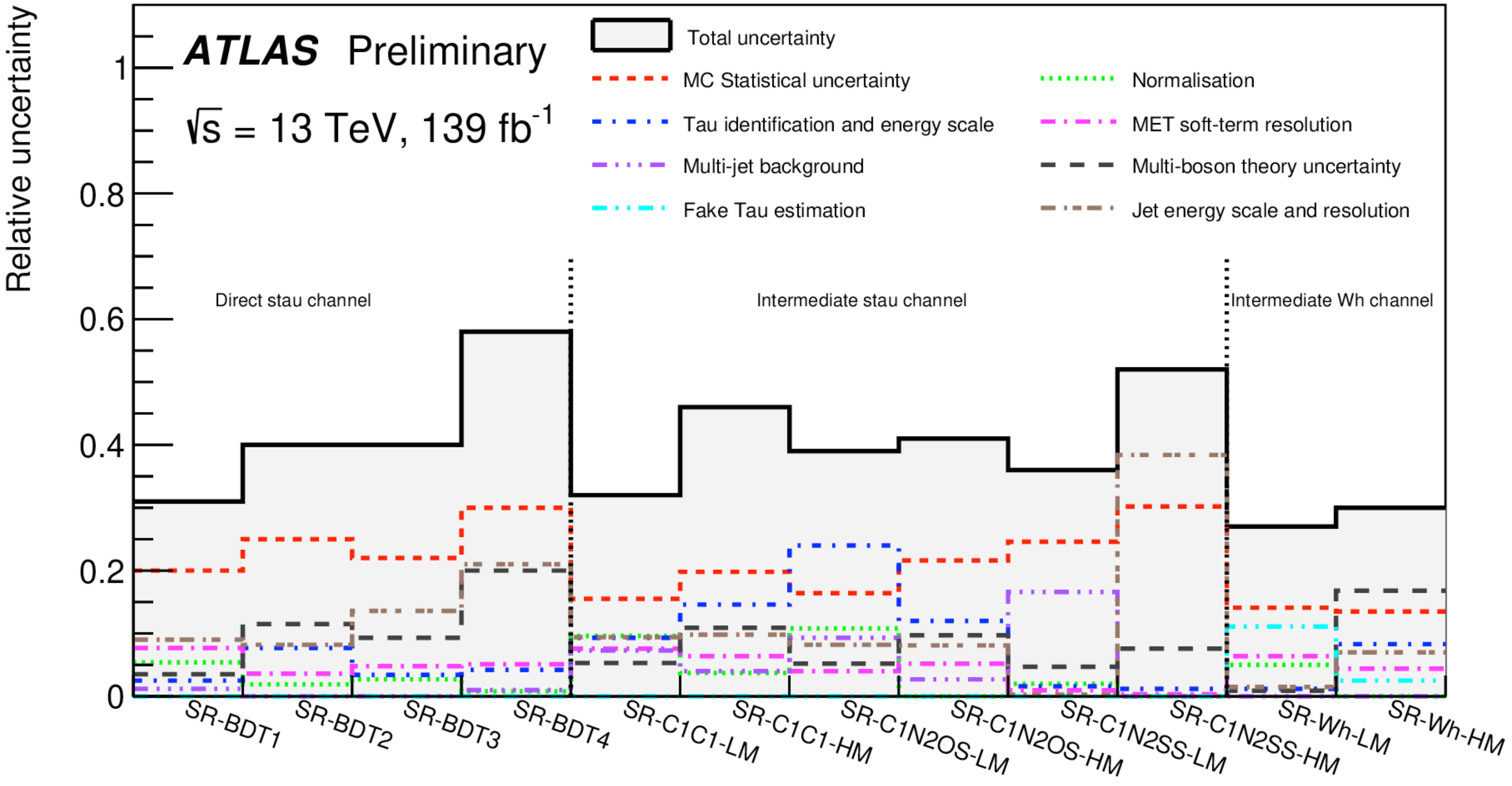
Main backgrounds:

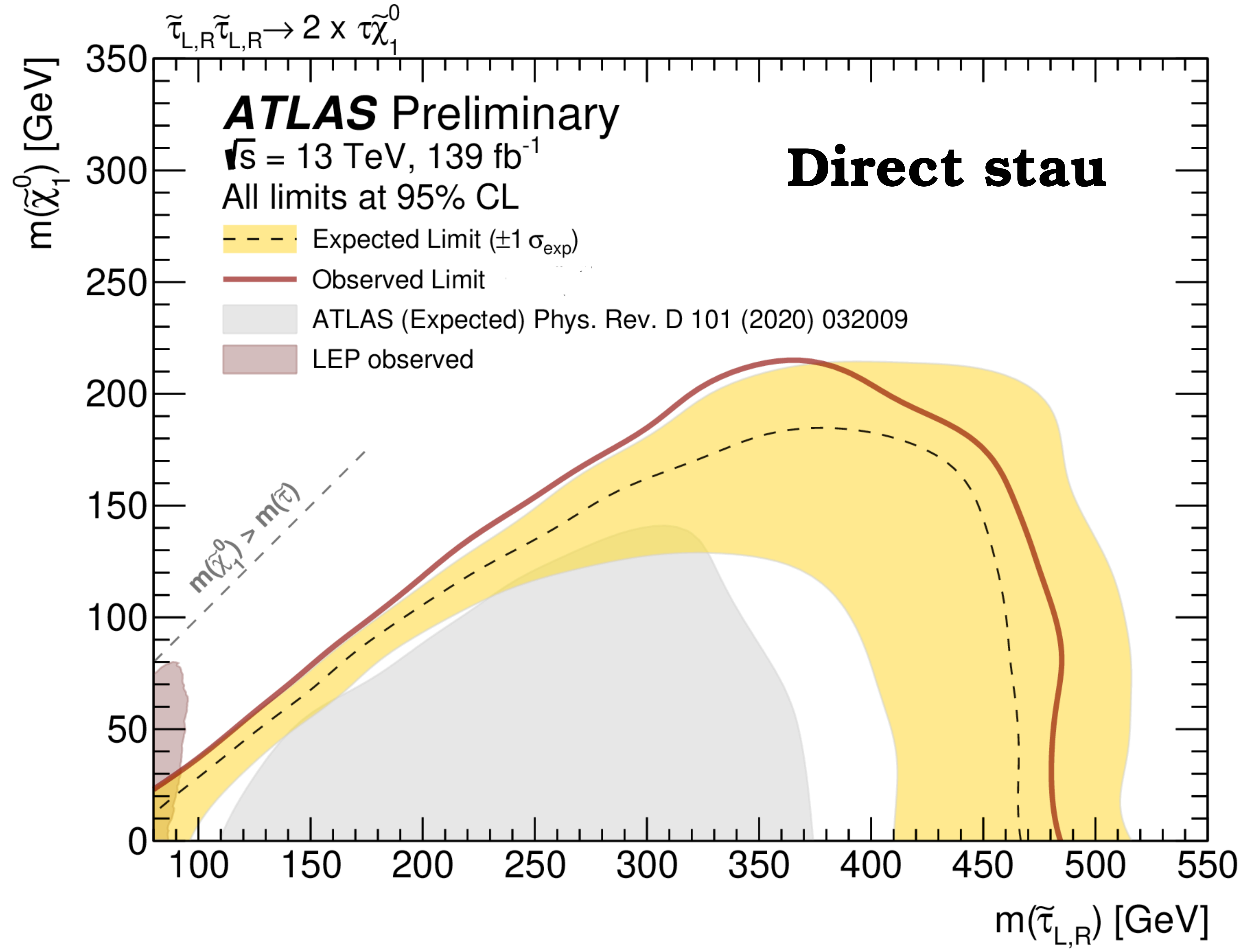
- Z/W + jets
- Top quarks events
- Multiboson

- **Different SRs** are defined **to target** the **specific SUSY scenario.**
- The most important discriminating observables are: transverse mass of two leptons (or 1 lepton and E_T^{miss}), $\Delta R\left(\tau_1, \tau_2\right)$, $m\left(\tau_1, \tau_2\right)$ and $\Delta\phi\left(\tau_1, \tau_2\right)$.
- For the **direct stau production**, 4 **BDTs** are trained to define as many SRs.



Observe no excesses above SM prediction.





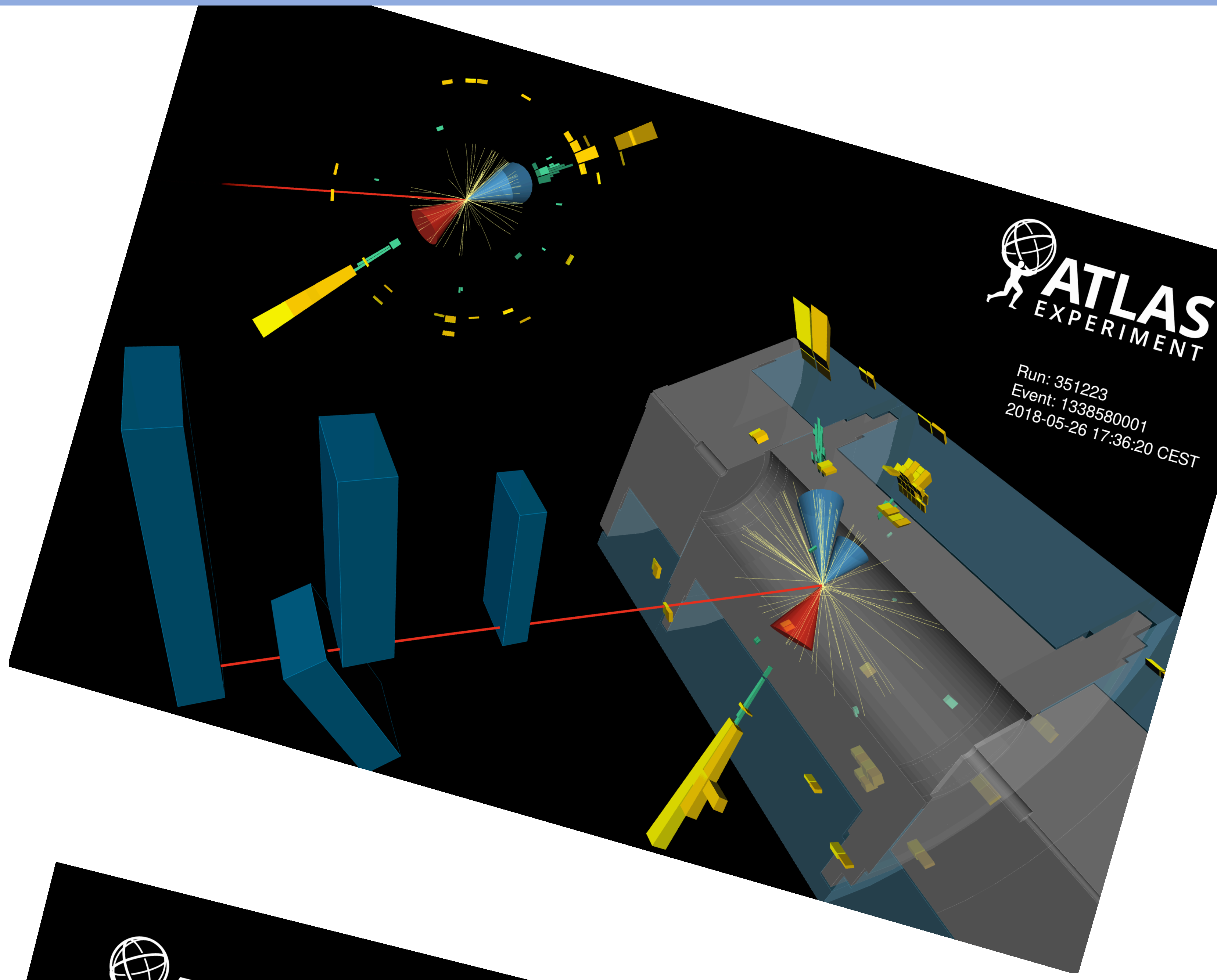
- Analysis **dominated by statistical uncertainty** in every channel
- τ-leptons (Reco, ID, isolation) and JES, JER have an important impact in some regions

Direct stau channel achieved a first sensitivity to right-handed staus

Exclusion limits at 95% CL are set on the different models:

- **Direct stau**: mass-degenerate $\tilde{\tau}_{L,R}$ excluded up to 480 GeV.
- **Intermediate stau**: chargino masses are excluded up to 970 GeV, while $\tilde{\chi}_1^+$ and $\tilde{\chi}_2^0$ masses up to 1160 GeV
- **Intermediate** Wh: excluded $\tilde{\chi}_1^+$ and $\tilde{\chi}_2^0$ masses up to 330 GeV

Conclusions



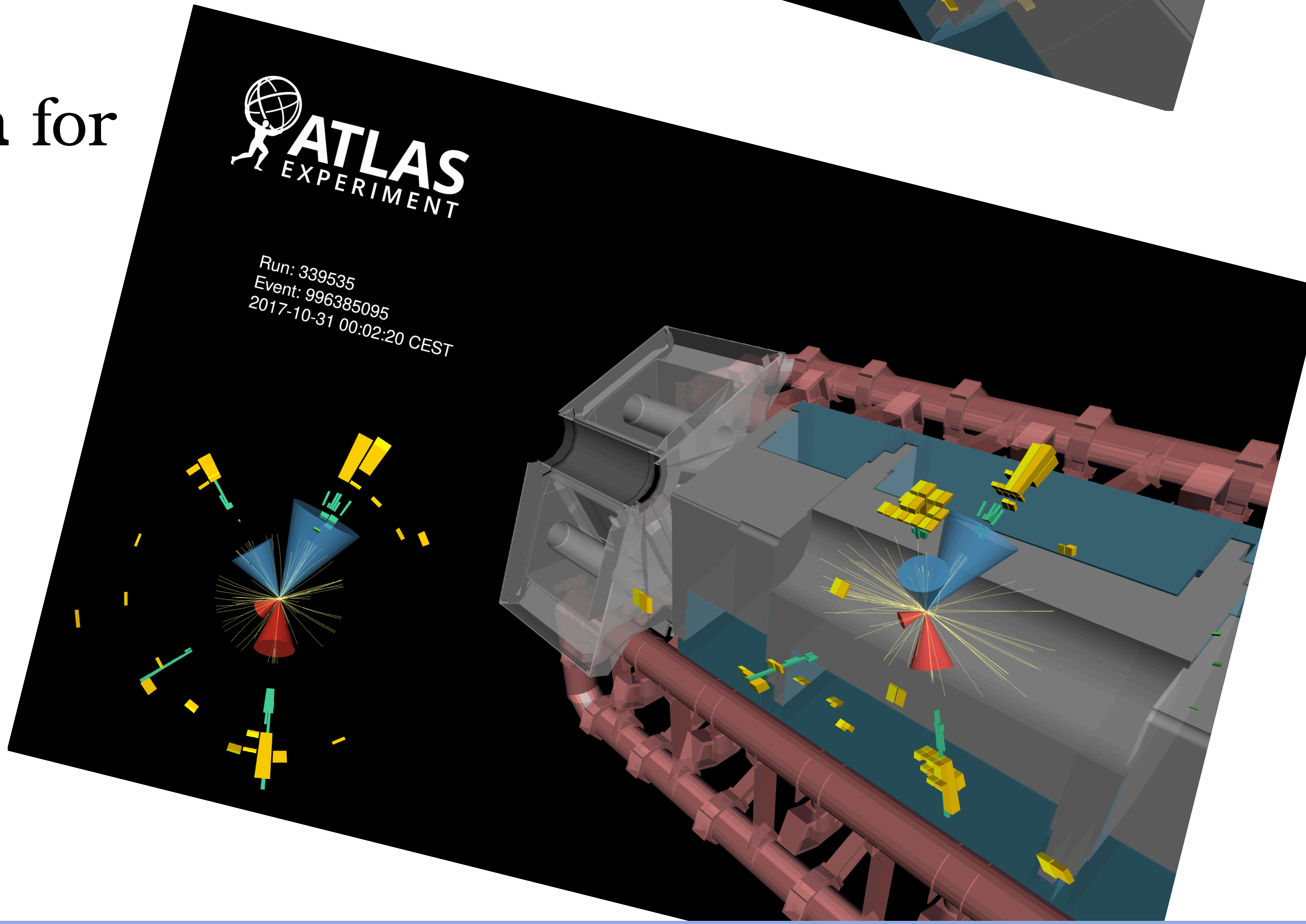
- **Several BSM scenarios** are **covered by** the **ATLAS** Collaboration in **many different** final states and **topologies**.

- **No significant deviations from the SM have been observed**, but there is growing evidence for anomalies in lepton interactions

- Channels with **3rd generation fermions** are very **sensitive** to **New Physics** and can lead to evidence of it

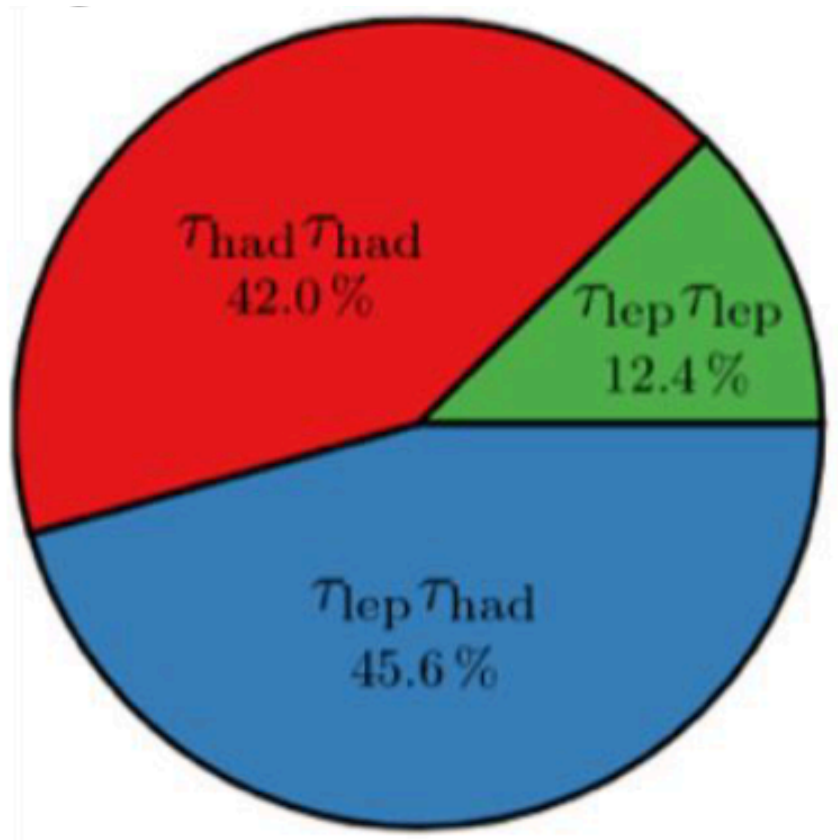
- Due to their fundamental importance, **ATLAS is pushing the search** for new phenomena in **lepton interactions on several fronts**

- **Innovative techniques** are **used to improve the sensitivity of the analyses**, both on objects reconstruction and signal vs. backgrounds discrimination



During Run 3 we will collect a lot of new data, and we are very excited to see the future results!

BACKUP



Di-Tau
Branching Ratios

$\tau^+\tau^-$: $\tau_{had}\tau_{had}$ and τ_{lep} τ_{had}

7.3% BR and one of the 3 most sensitive analysis channels

Tau leptons reconstruction

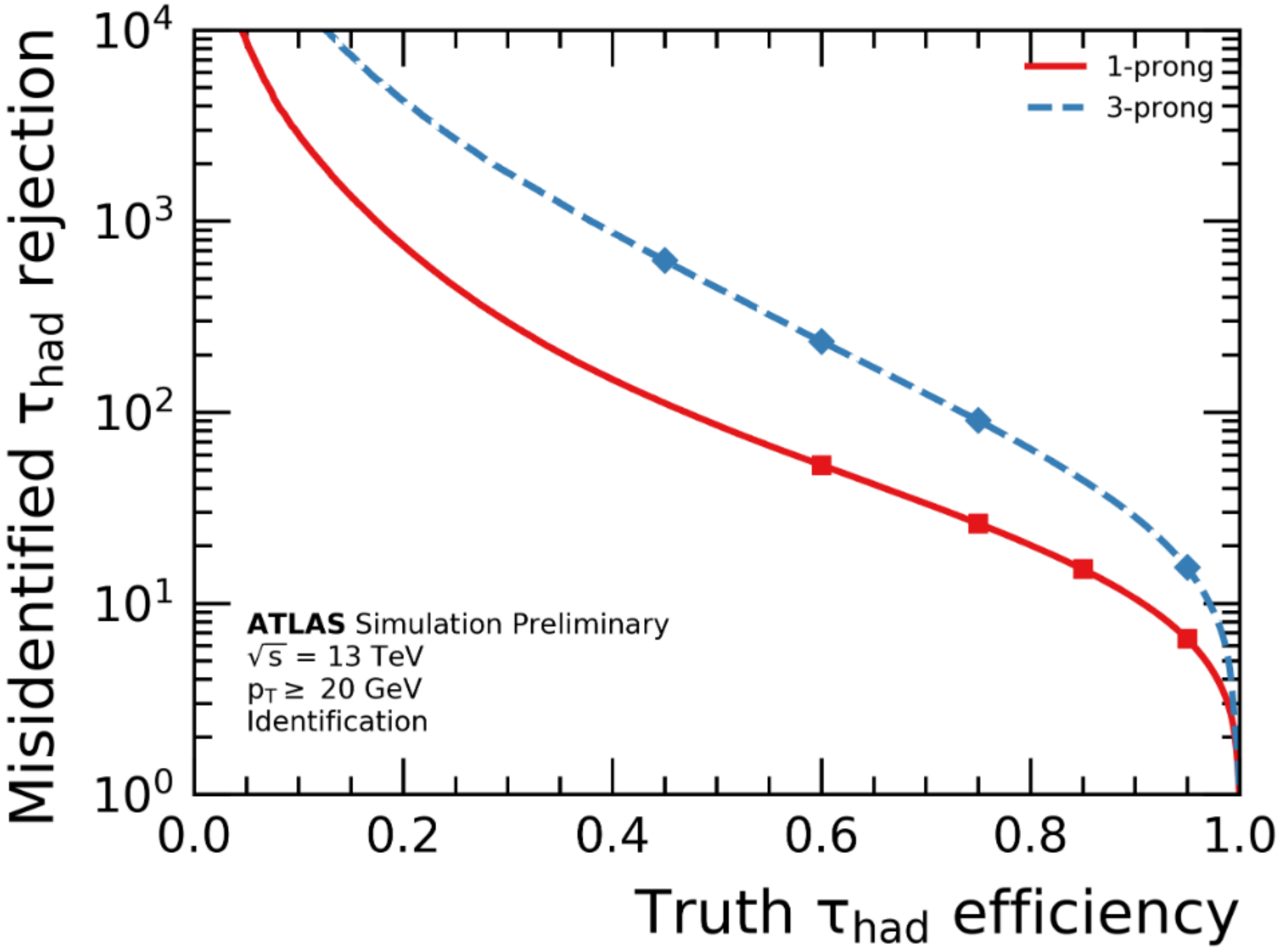
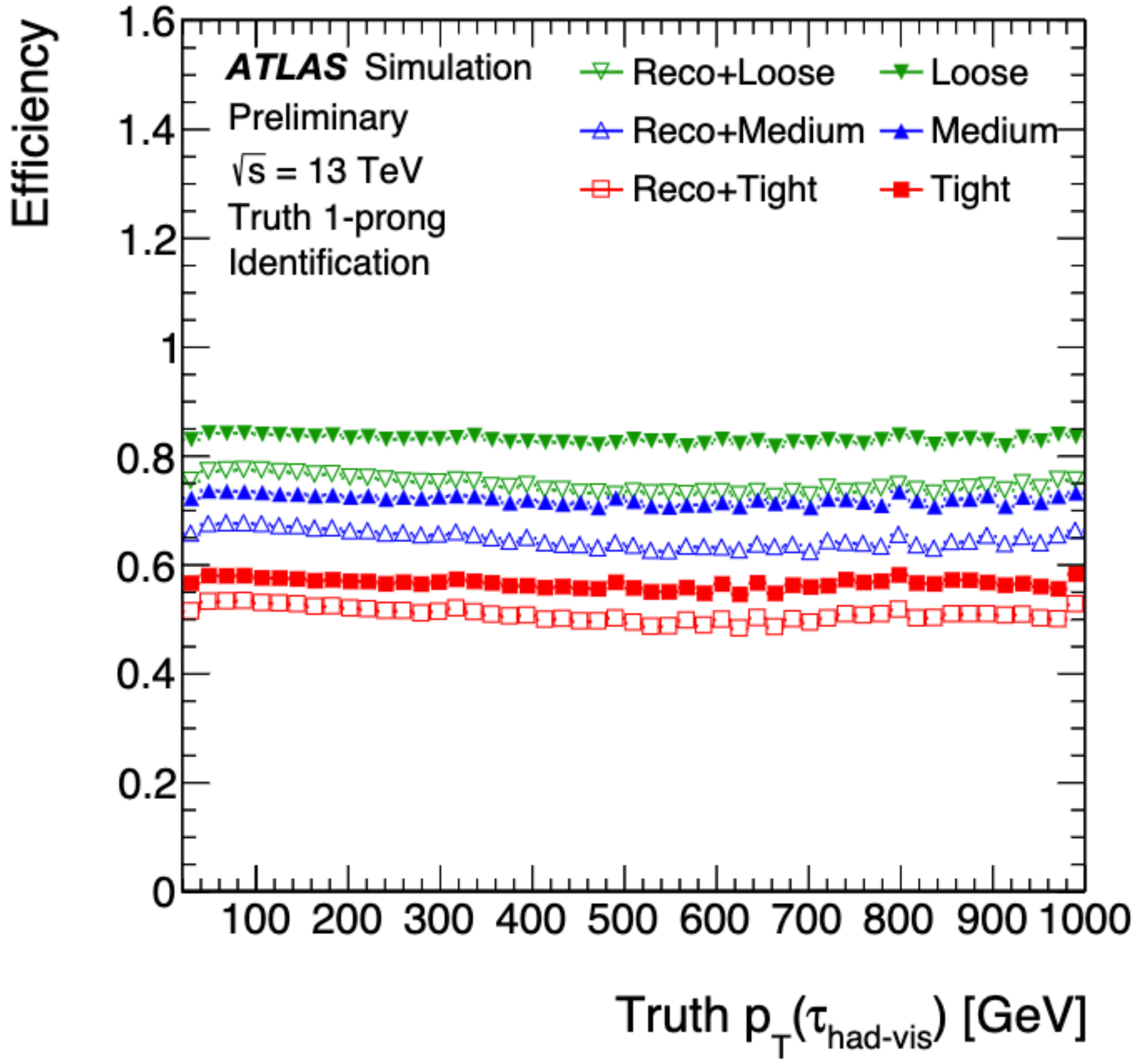
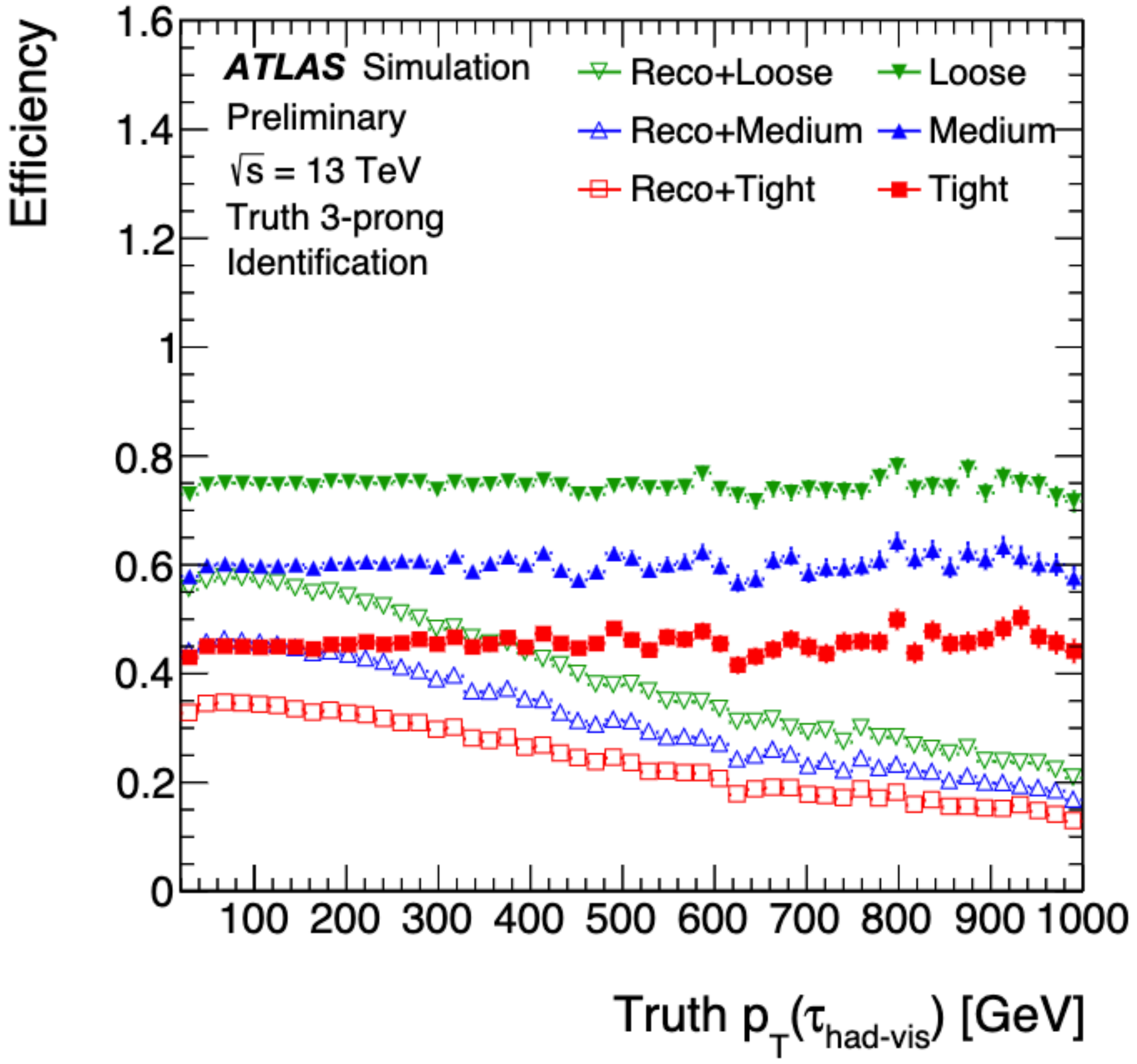


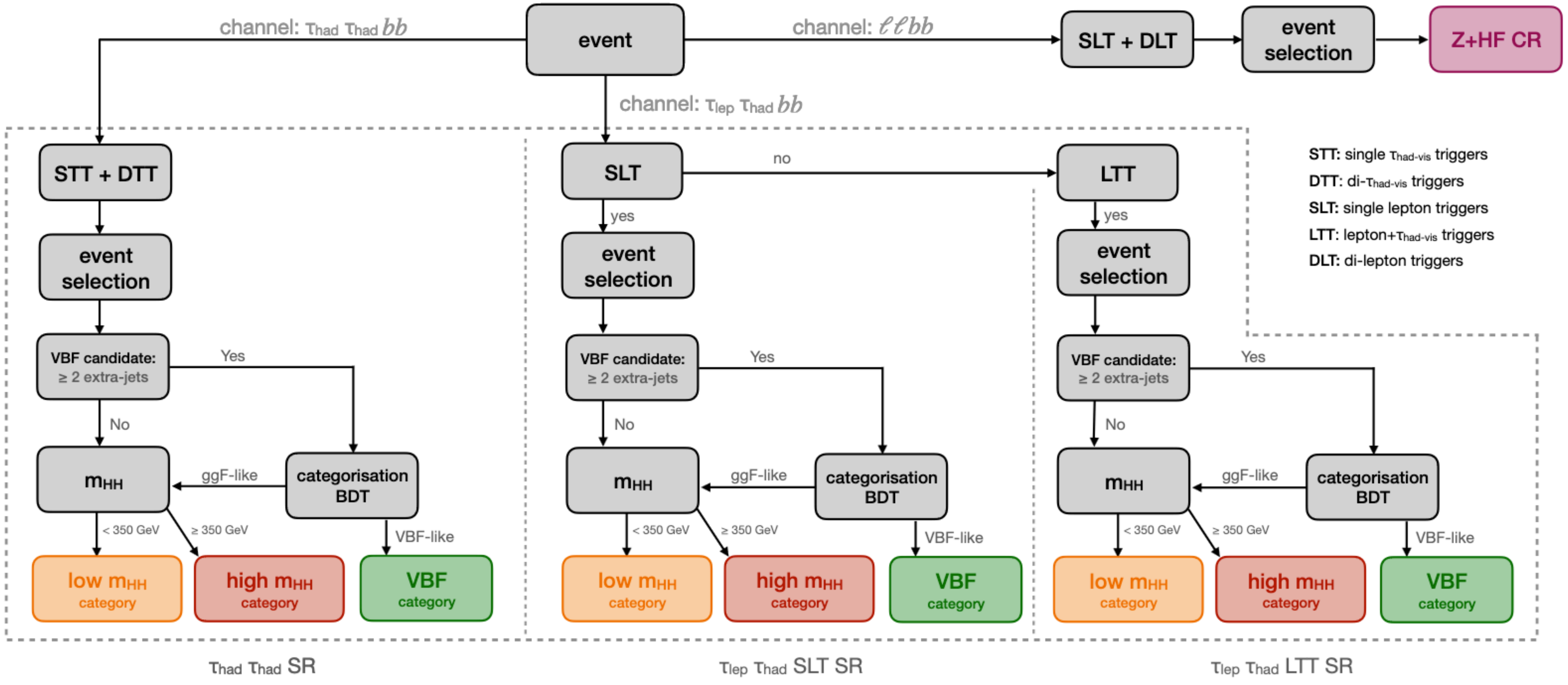
Figure 6: Inverse of the efficiency (rejection) for misidentified 1-prong and 3-prong τ_{had} candidates from dijet background events as a function of the efficiency for truth τ_{had} originating from $\gamma^* \to \tau\tau$ events. The two lines refer to 1-prong and 3-prong τ_{had} candidates and markers demonstrate individual working points (`Very Loose`, `Loose`, `Medium`, `Tight`).





$HH \rightarrow bb\tau\tau$

HDBS-2019-27

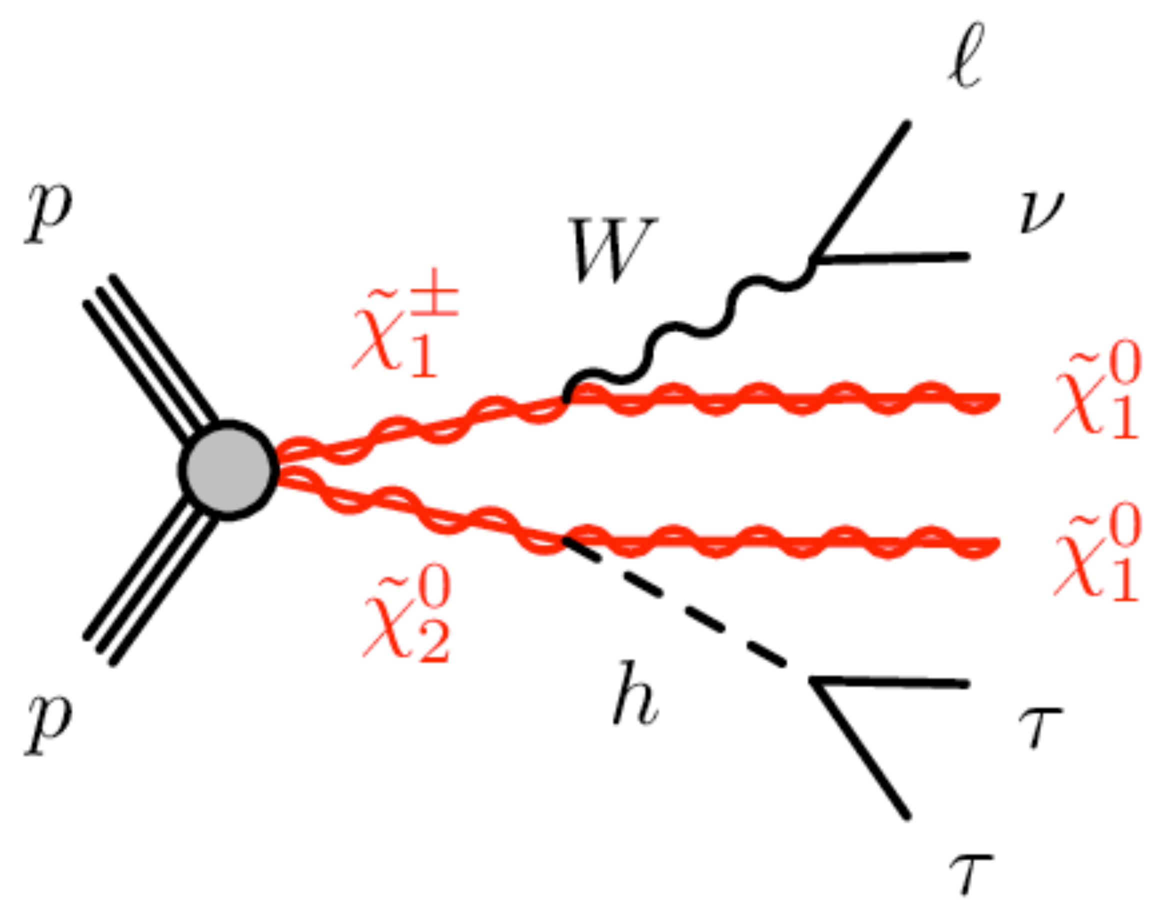


Variable	$\tau_{had}\tau_{had}$	$\tau_{lep}\tau_{had}$ SLT	$\tau_{lep}\tau_{had}$ LTT
m_{jj}^{VBF}	✓	✓	✓
$\Delta\eta_{jj}^{VBF}$	✓	✓	✓
VBF $\eta_0 \times \eta_1$	✓	✓	
$\Delta\phi_{jj}^{VBF}$	✓		
ΔR_{jj}^{VBF}		✓	✓
$\Delta R_{\tau\tau}$	✓		
m_{HH}	✓		
f_2^a	✓		
C^a		✓	✓
m_{Eff}^a		✓	✓
f_0^c		✓	
f_0^a			✓
h_3^a			✓

Process	Generator		PDF set		Tune	Normalisation
	ME	PS	ME	PS		
LQ$\rightarrow b\tau$	MadGraph5_aMC@NLO	PYTHIA 8.244	NNPDF3.0NNLO	NNPDF2.3LO	A14	LO
Scalar LQLQ$\rightarrow b\tau b\tau$	MadGraph5_aMC@NLO	PYTHIA 8.230	NNPDF3.0NNLO	NNPDF2.3LO	A14	NNLO + NNLL
Vector LQLQ$\rightarrow b\tau b\tau$	MadGraph5_aMC@NLO	PYTHIA 8.244	NNPDF3.0NNLO	NNPDF2.3LO	A14	LO
$t\bar{t}$	POWHEG BOX v2	PYTHIA 8.230	NNPDF3.0NNLO	NNPDF2.3LO	A14	NNLO + NNLL
Single top	POWHEG BOX v2	PYTHIA 8.230	NNPDF3.0NNLO	NNPDF2.3LO	A14	NLO
Z/γ^*	POWHEG BOX v1	PYTHIA 8.186	CT10NLO	CTEQ6L1	AZNLO	NLO
W+jets	SHERPA 2.2.1		NNPDF3.0NNLO		SHERPA	NNLO
Diboson	SHERPA 2.2.1/SHERPA 2.2.2		NNPDF3.0NNLO		SHERPA	NLO

Table 1. Overview of the MC generators used for the main signal and background samples. The last column specifies the order in QCD for the cross-section calculation used for the normalisation of the simulated samples.

Recent measurements of differential cross-sections have demonstrated that the current simulations of $t\bar{t}$ processes overestimate the upper tail of the top-quark p_T spectrum: see 1 & 2.



Chargino-neutralino production