# SEARCH FOR HIGH MASS RESONANCES IN LEPTONIC FINAL STATES WITH THE ATLAS DETECTOR

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On behalf of the ATLAS collaboration

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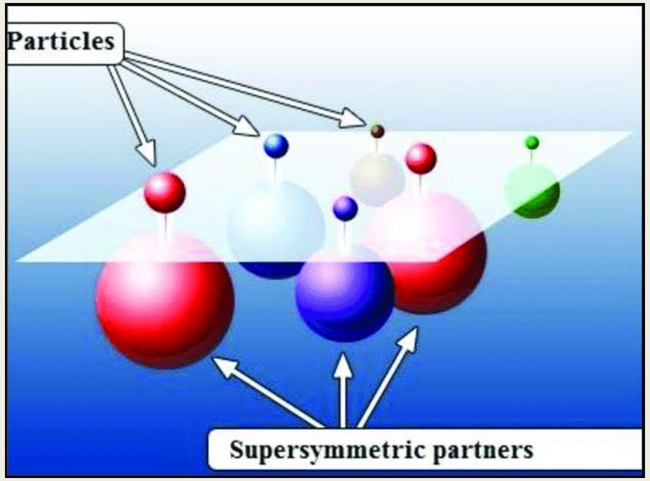
Florida (USA)

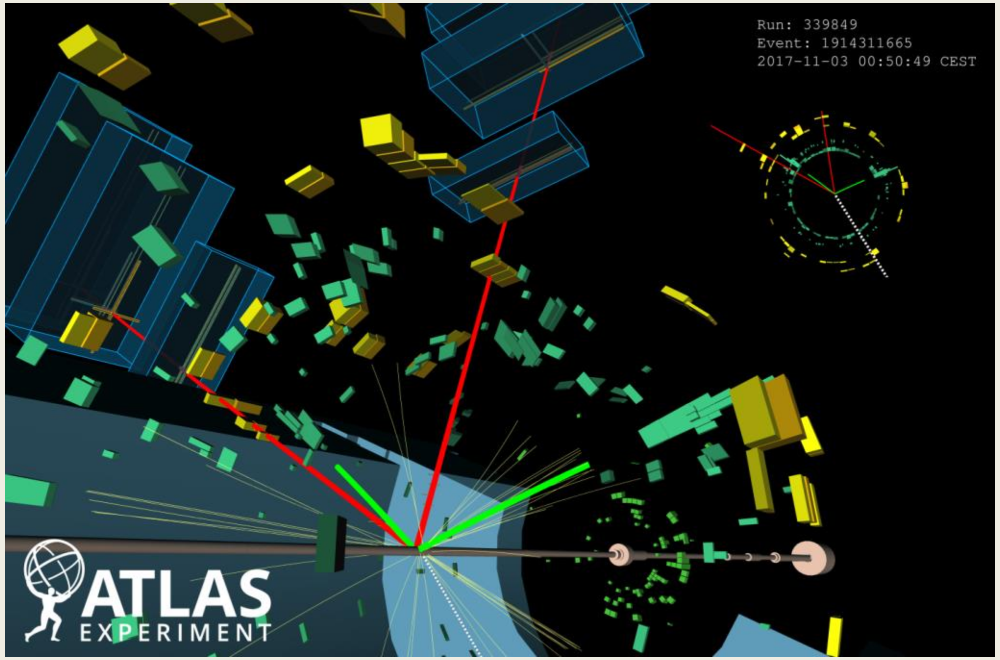
# Overview

## Charged leptons: clear signature at hadron colliders



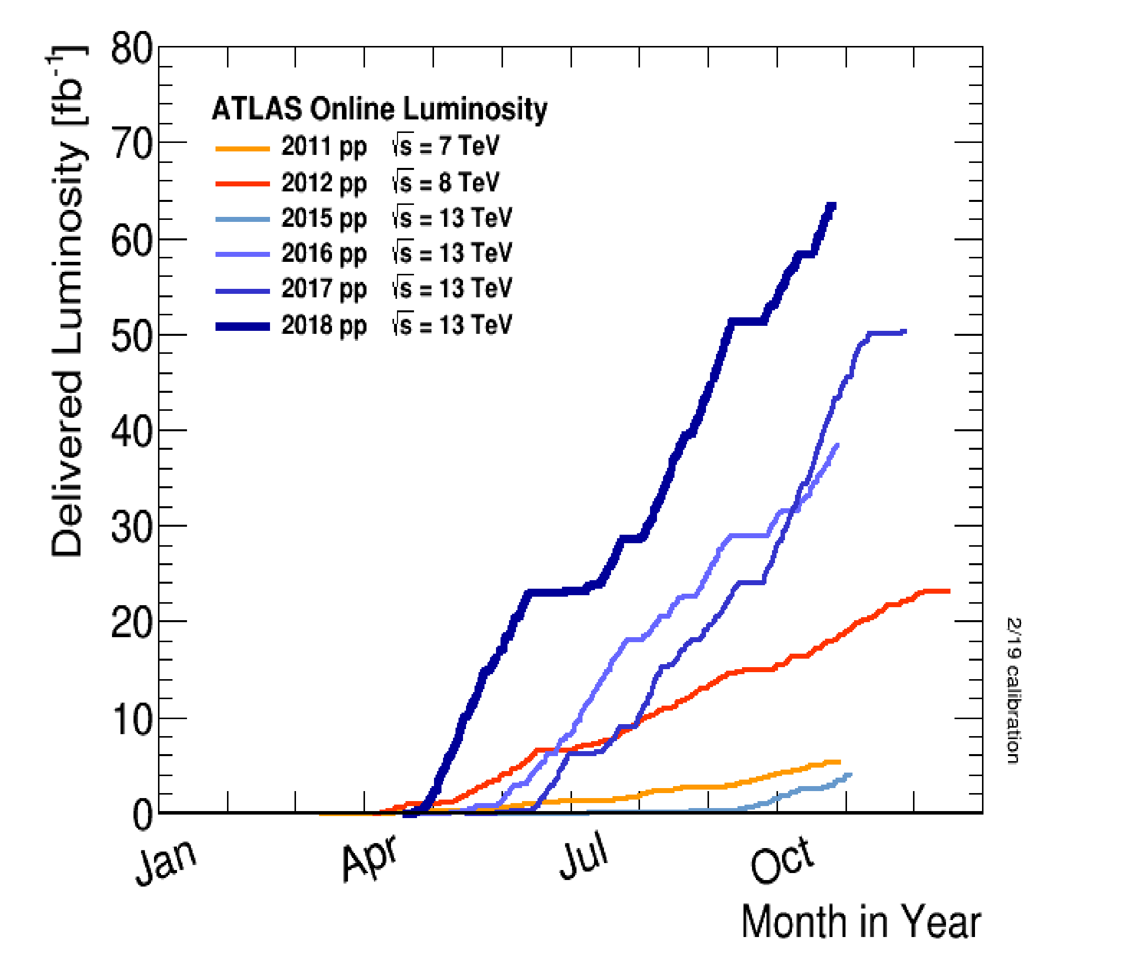

Wide variety of BSM physics searches involve leptons:

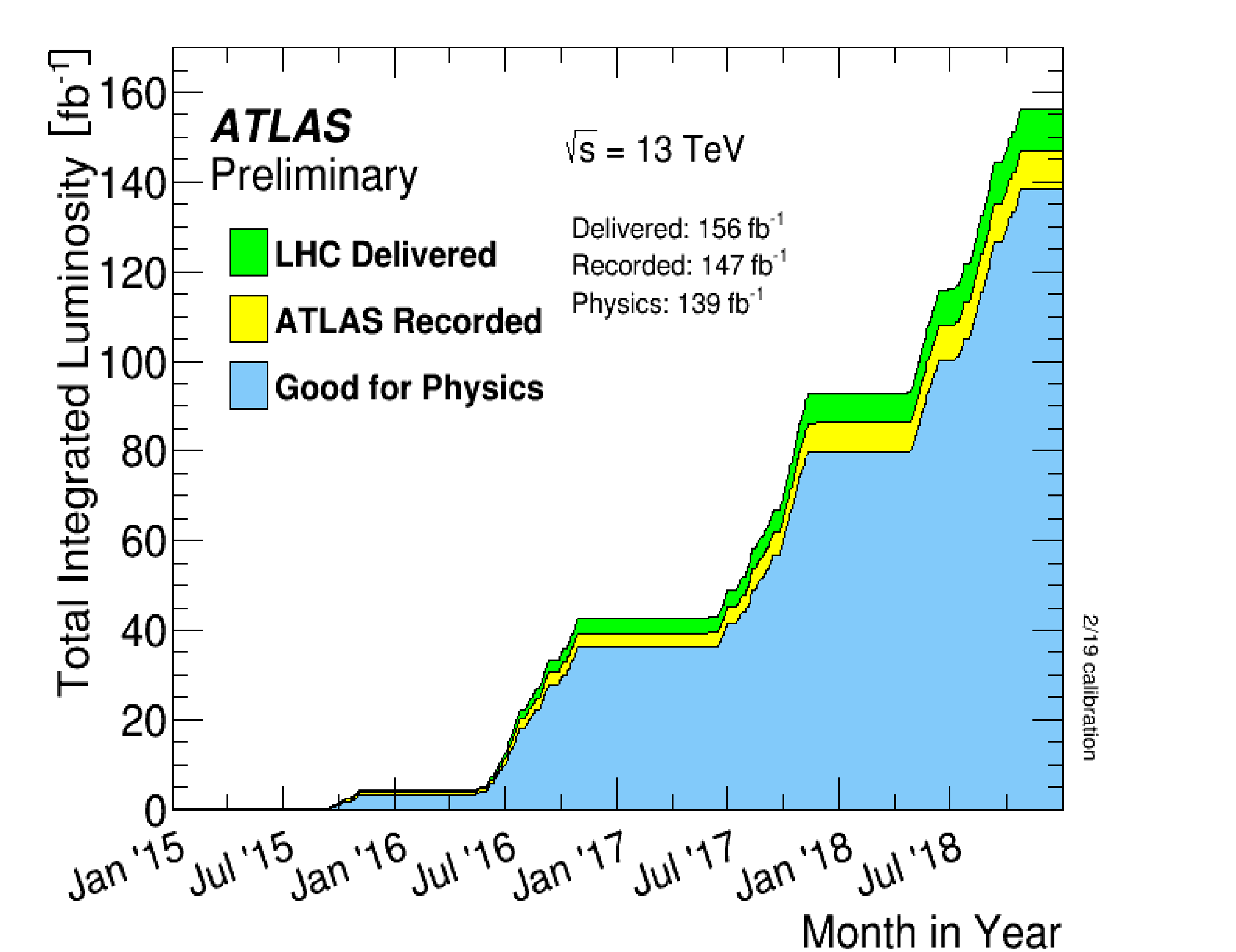
- Super Symmetry (SUSY): stops, neutralinos, charginos…
- Dark Matter searches
- New resonances (W’, Z’, Gravitons…)
- Heavy or composite fermions
- Lepton Flavour Violation


2e+2μ event

# Performance of the LHC & ATLAS detector



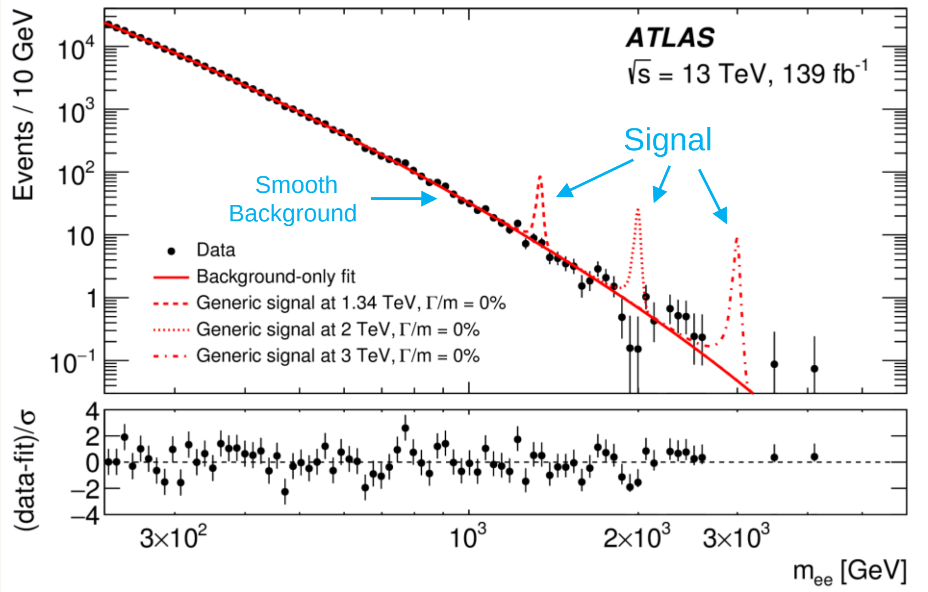

- A total of 139 $fb^{-1}$ collected during the 2015-18 period at $\sqrt{s}$ = 13 TeV
- Currently in Long Shutdown 2, expect to start operations again by the end of 2021

# Outline

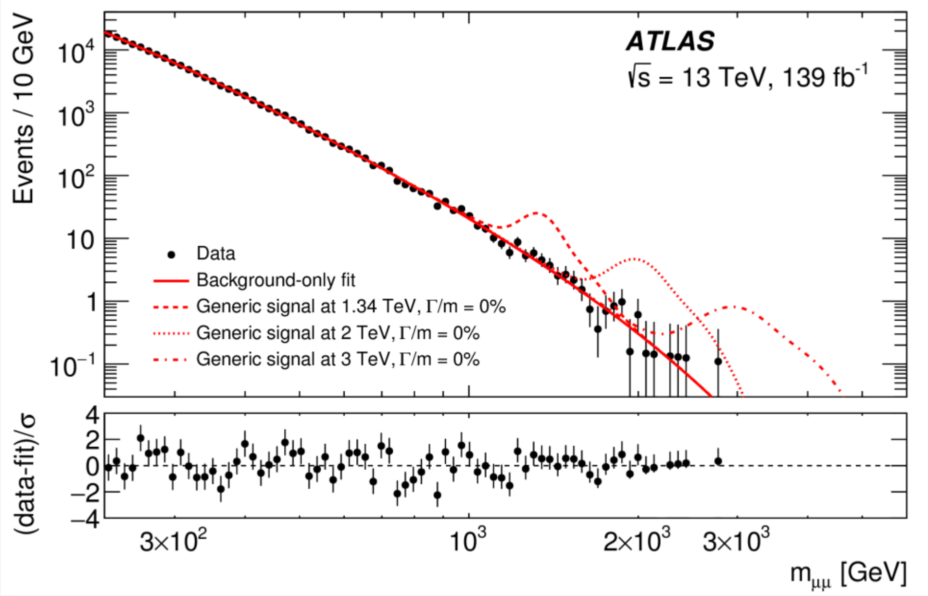
- Search in high-mass same-flavor dilepton final state (Phys Lett 796 (2019) 68)
- Search for a right-handed gauge boson decaying into a high-momentum heavy neutrino and a charged lepton (Phys Lett B 798 (2019) 134942)
- Search for a new heavy gauge boson resonance decaying into a lepton and missing transverse momentum (Phys Rev D 100 (2019) 052013)
- Search for Dark Matter in association with a single top quark and one or two charged leptons (arXiv 2011.09308)
- Search for pairs of scalar leptoquarks decaying into quarks and electrons or muons (JHEP 10 (2020) 112)
- Search for trilepton resonances from chargino and neutralino pair production (arXiv 2011.10543)
- Search for lepton-flavor violation in different-flavor, high-mass final states (Phys Rev D 98 092008 (2018))

# Dilepton Search: Analysis Strategy

Dielectron




Dimuon




- First ATLAS full Run-2 result


AIM

- Search for “bumps” in the dielectron and dimuon invariant mass spectra

EVENT SELECTION

- Look for events with exactly two electrons or two muons and an invariant mass below 6000 GeV

CERN-EP-2019-030

arXiv 1903.06248

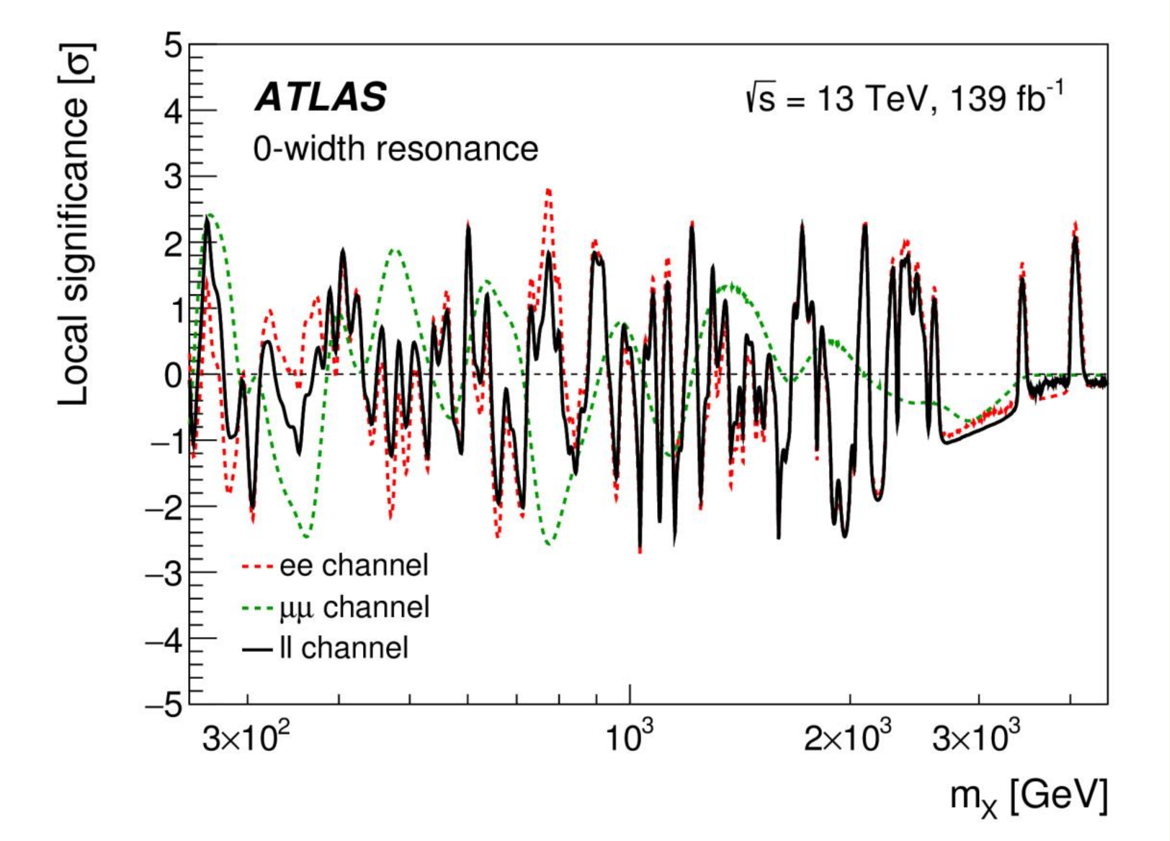
BACKGROUND ESTIMATION

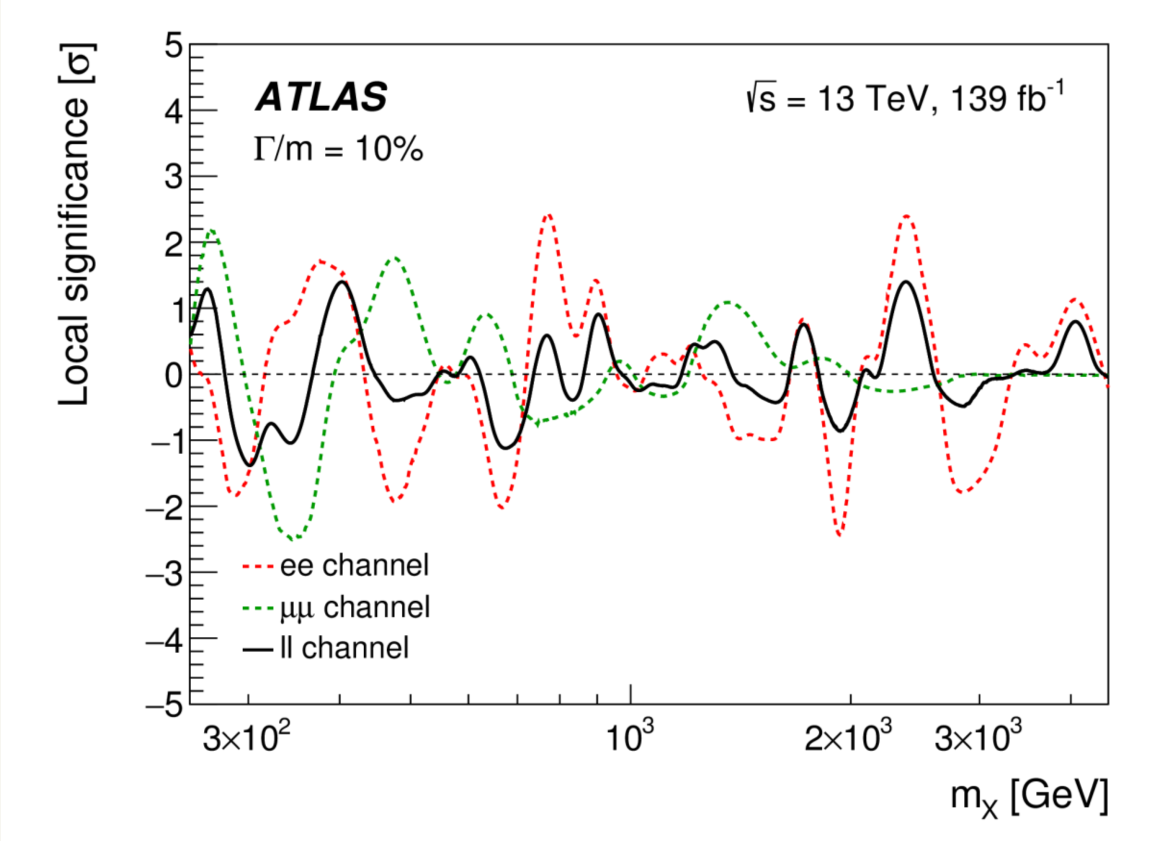
- Largely dominated by the Drell-Yan process
- Fit parametric function to data to model background (new with respect to previous versions of the analysis)
- Leads to spurious signal uncertainties, but those have a small impact on the final result

SIGNAL MODELLING

- Generic signal modelling using a convolution of Breitt-Wigner and a Gaussian to parametrize for various pole mass and width values
- Results interpreted in terms of Sequential Standard Model (SSM) and Heavy Vector Triplet (HVT)

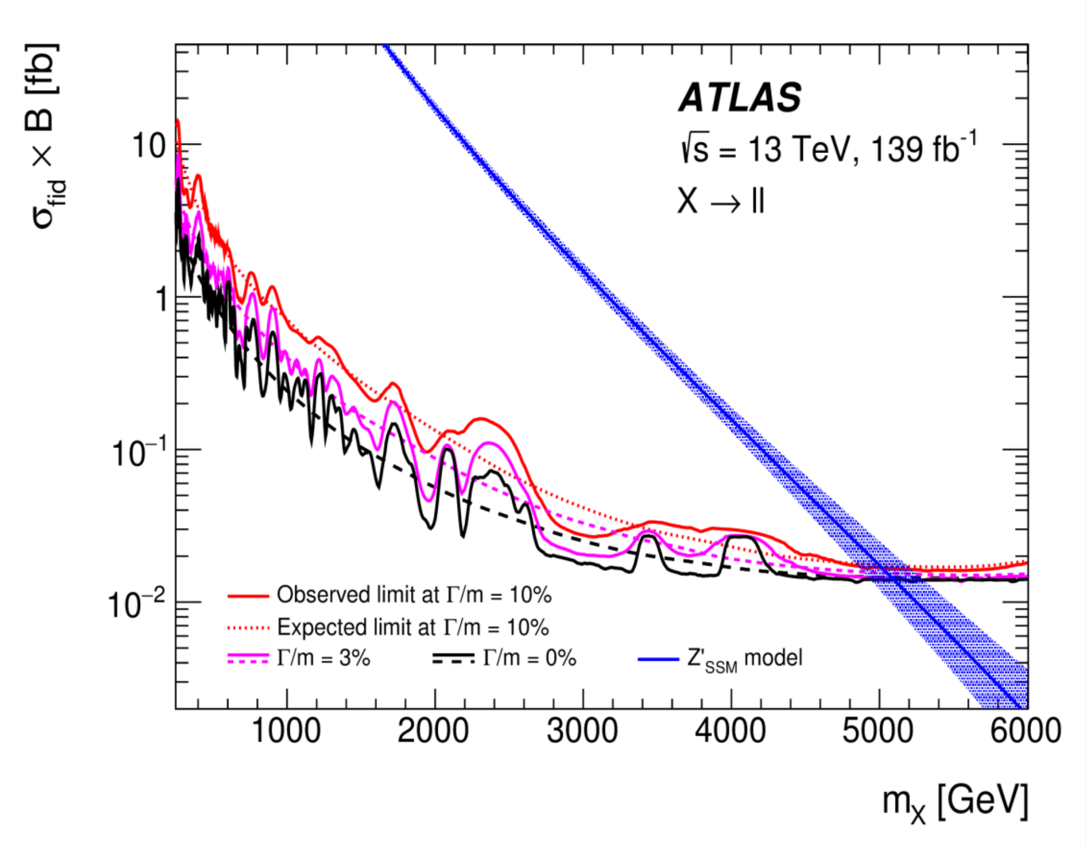
# Dilepton Search: Results

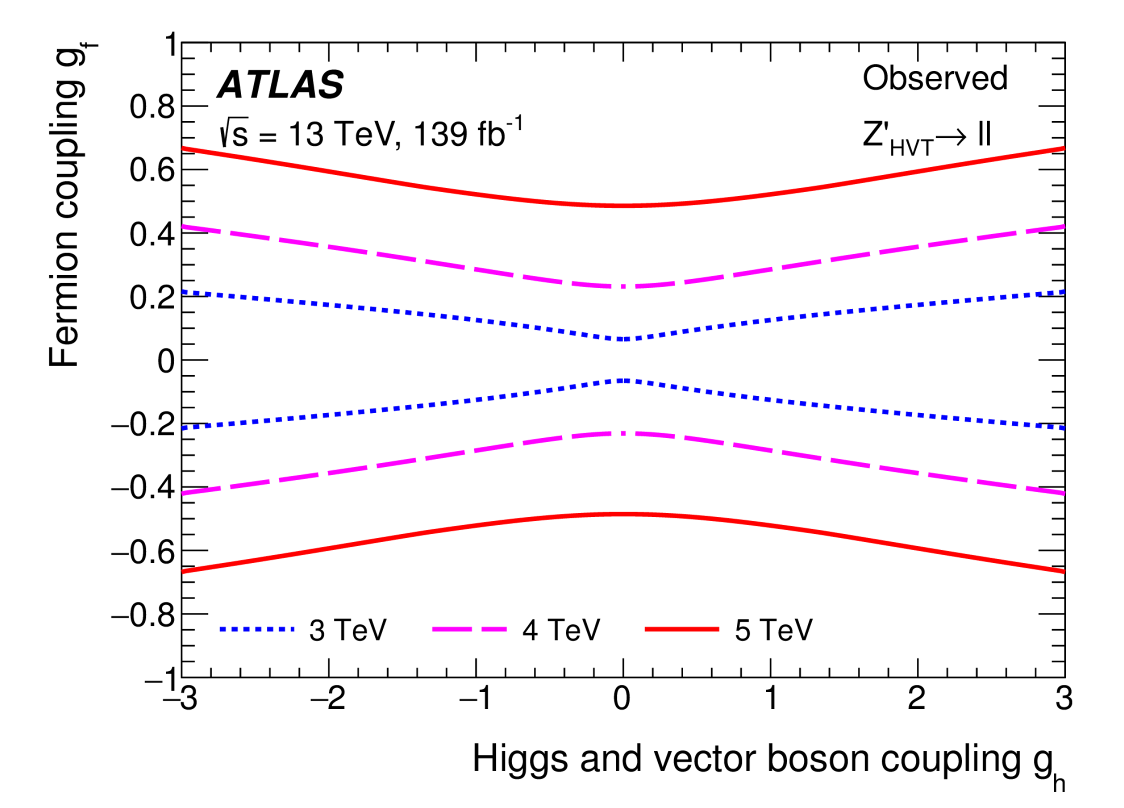



- Largest excess found at 264 GeV for 0-width with a local significance of 2.3σ for the combination of the dielectron and dimuon channels (assuming lepton flavor universality)
- No significant deviations for larger widths

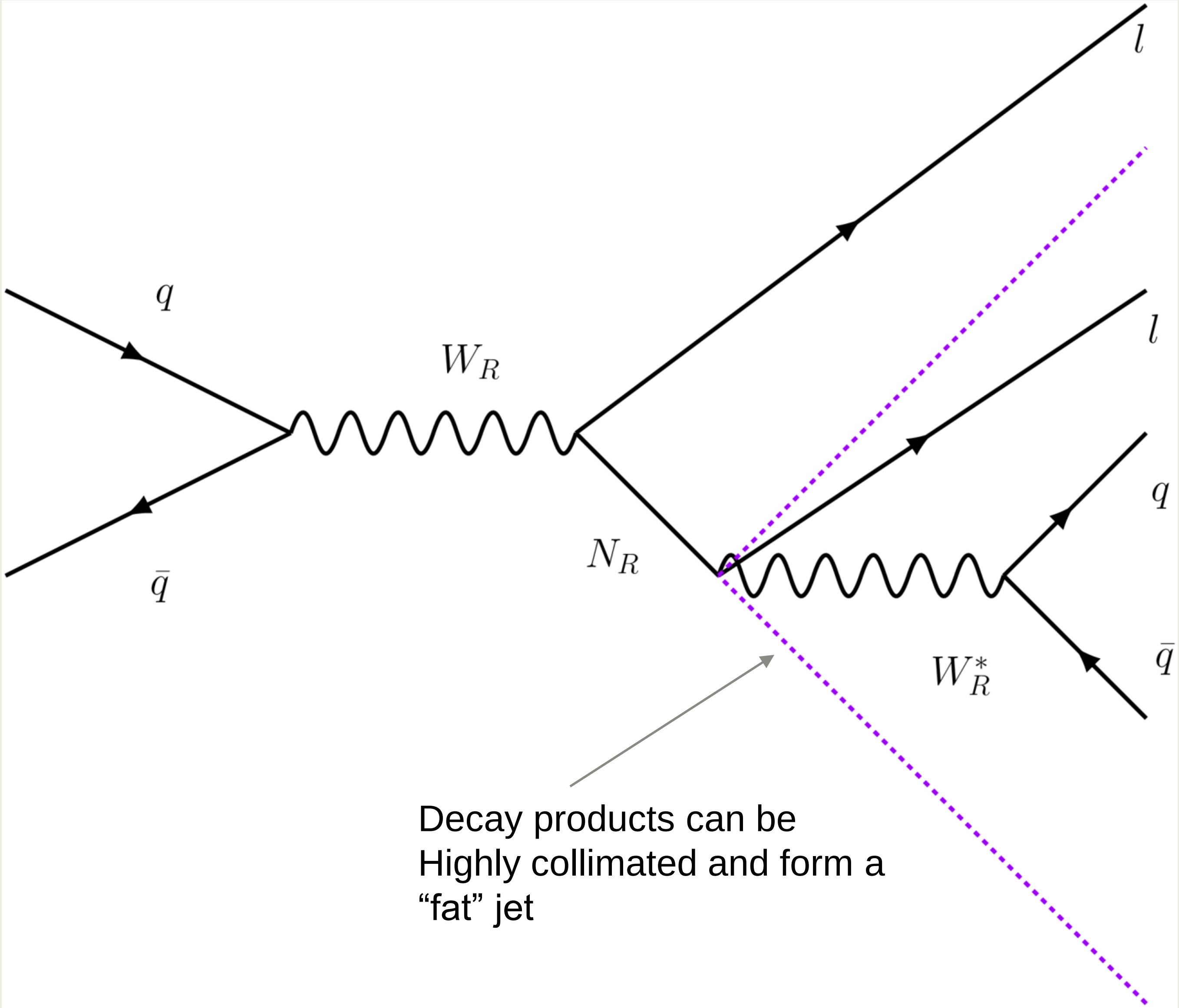
# Dilepton Search: Exclusion Limits




- Model-independent calculated for various width scenarios
- Limits can be re-interpreted for specific models
- Results re-interpreted in terms of HVT couplings, and will eventually be combined with an analogous W' search

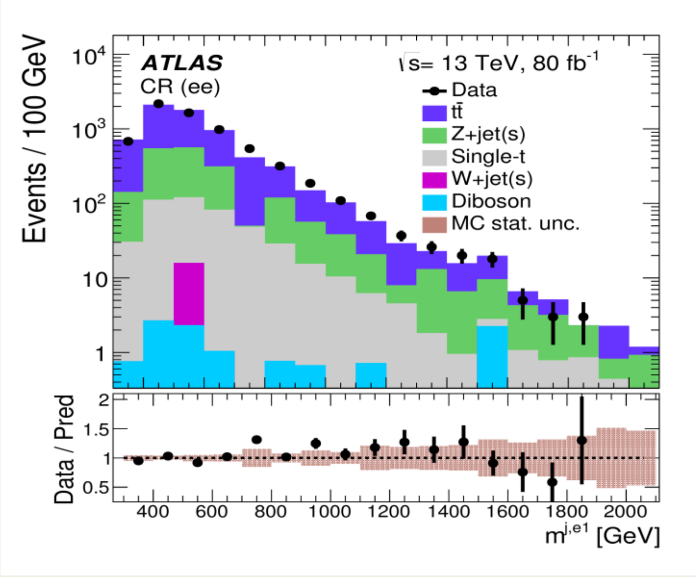
# Heavy Neutrino search: arXiv 1904.12679

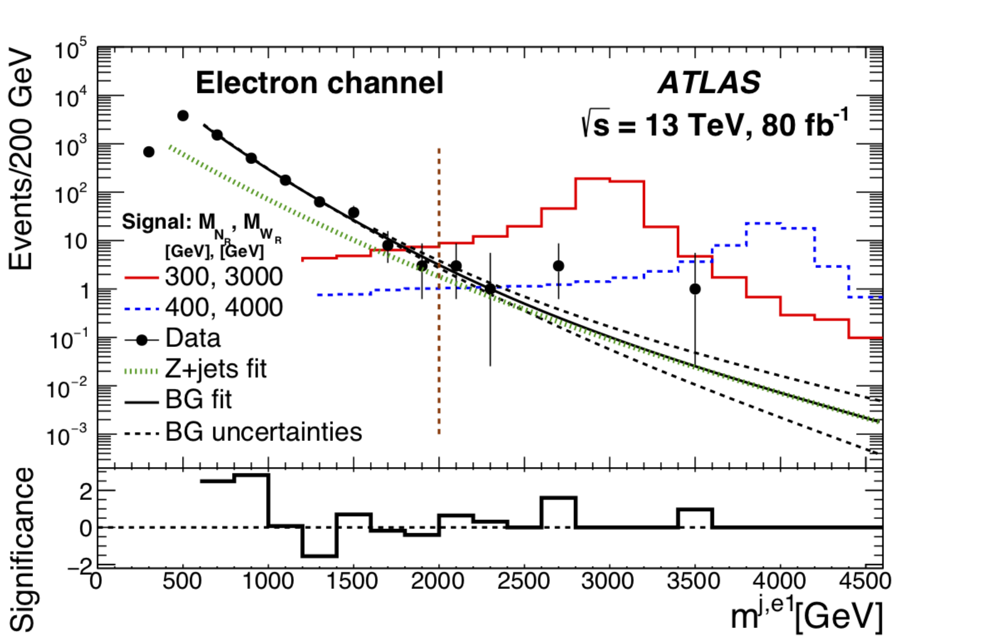


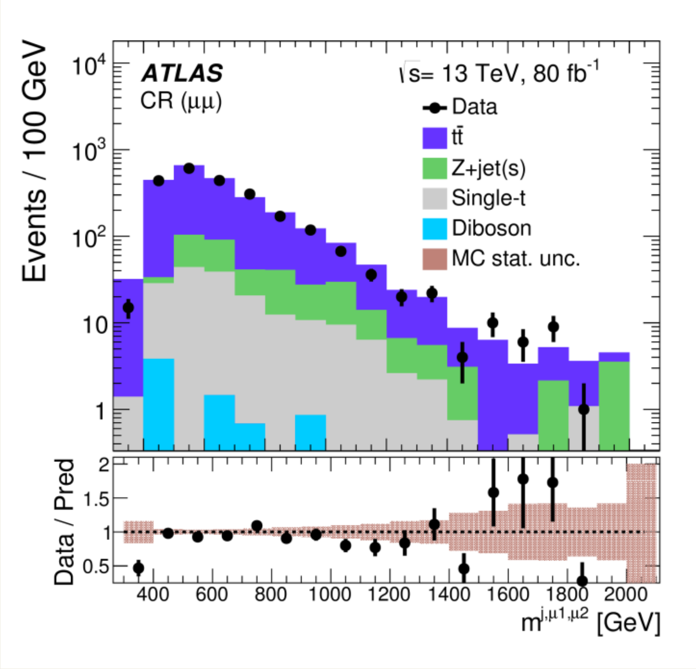

- Search for a right-handed gauge boson ( $W_R$ ) decaying into a boosted right-handed heavy neutrino ( $N_R$ ) together with a lepton in the context of a Left-Right Symmetric model (LRSM)
- Focused on the regime where the mass of the heavy neutrino is less than 10% of the right-handed gauge boson
- The decay products of the heavy neutrino can be found within a jet within a large-R(or fat) jet
- For the electron channel the energy deposit is included in the large-R jet

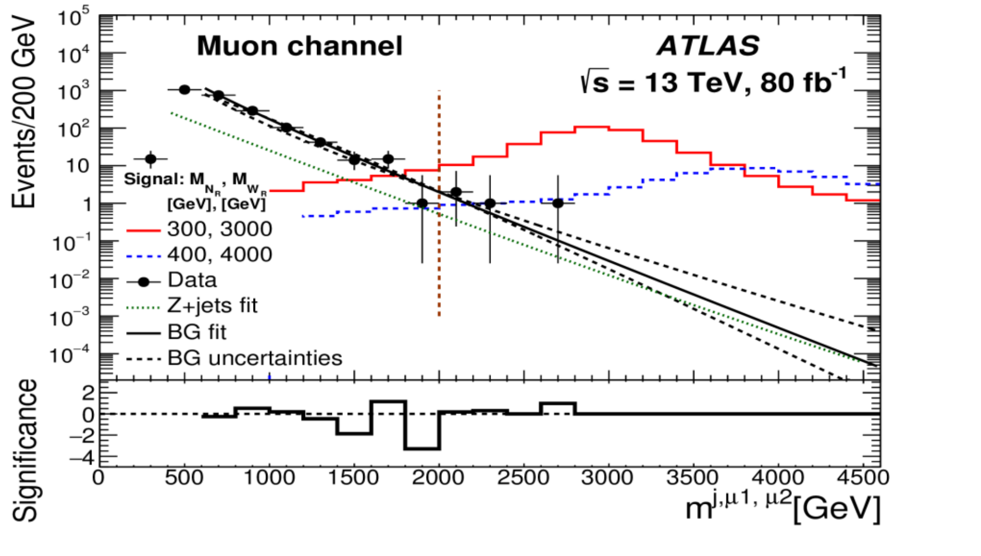
# Heavy neutrino search: $m_{W_R}$

| | Electron Channel | Muon Channel |
|---|---|---|
| Signal ($m_{W_R}$ = 3 TeV, $m_{N_R}$ = 150 GeV) | $346^{+48}_{-75}$ | $411^{+36}_{-48}$ |
| Signal ($m_{W_R}$ = 3 TeV, $m_{N_R}$ = 300 GeV) | $471^{+42}_{-69}$ | $429^{+29}_{-40}$ |
| Signal ($m_{W_R}$ = 4 TeV, $m_{N_R}$ = 400 GeV) | $66^{+6}_{-10}$ | $57^{+4}_{-4}$ |
| Expected background | $2.8^{+0.5}_{-0.7}$ | $1.9^{+0.5}_{-0.7}$ |
| Observed events | 8 | 4 |
| Significance | $2.4\sigma$ | $1.2\sigma$ |
| $p$-value | 0.0082 | 0.12 |

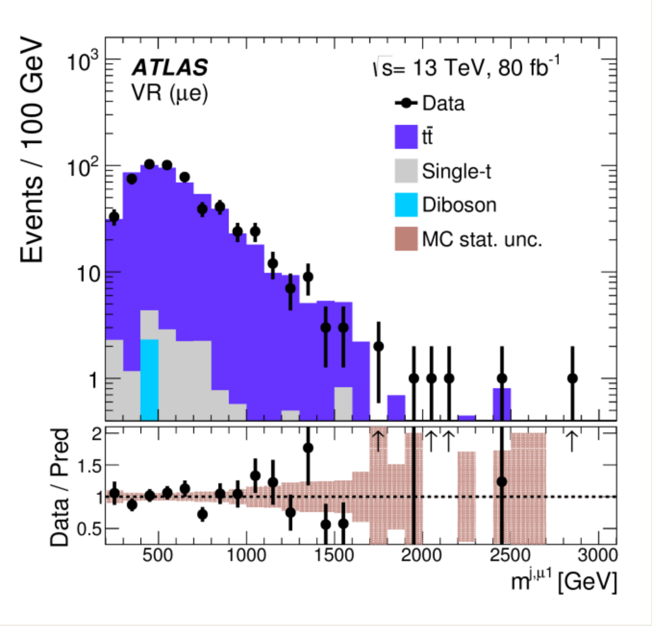


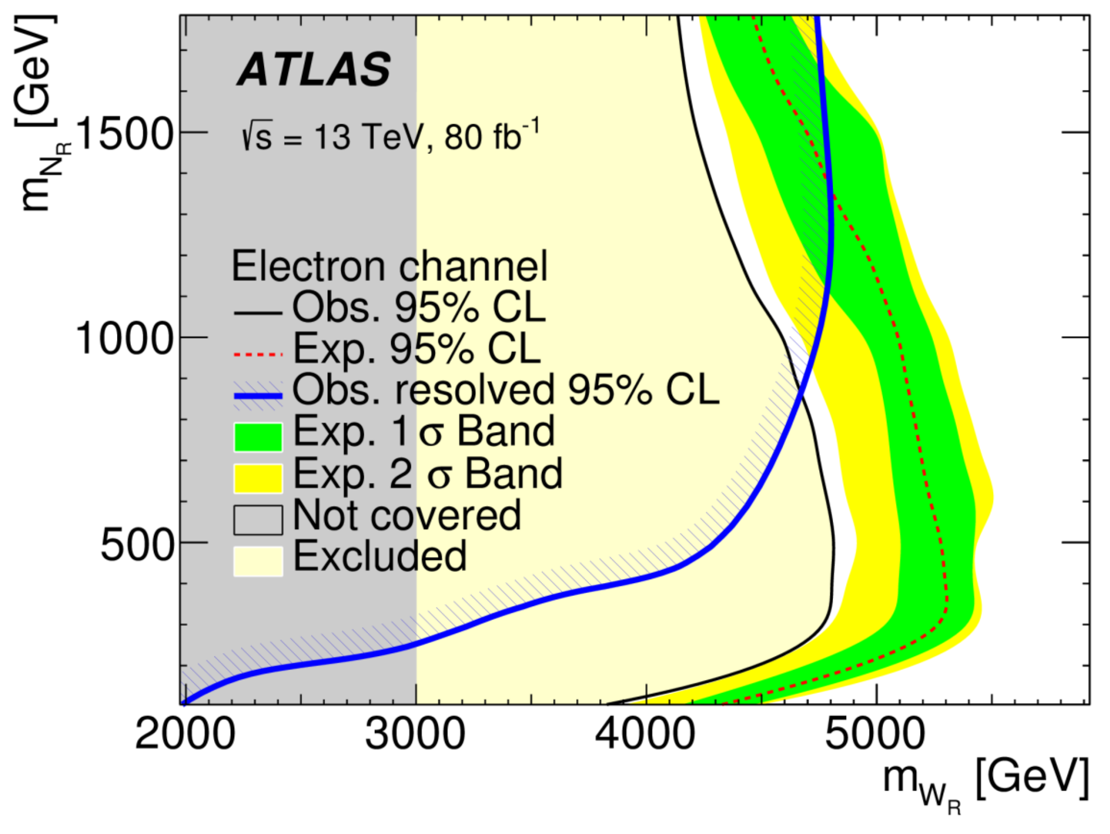



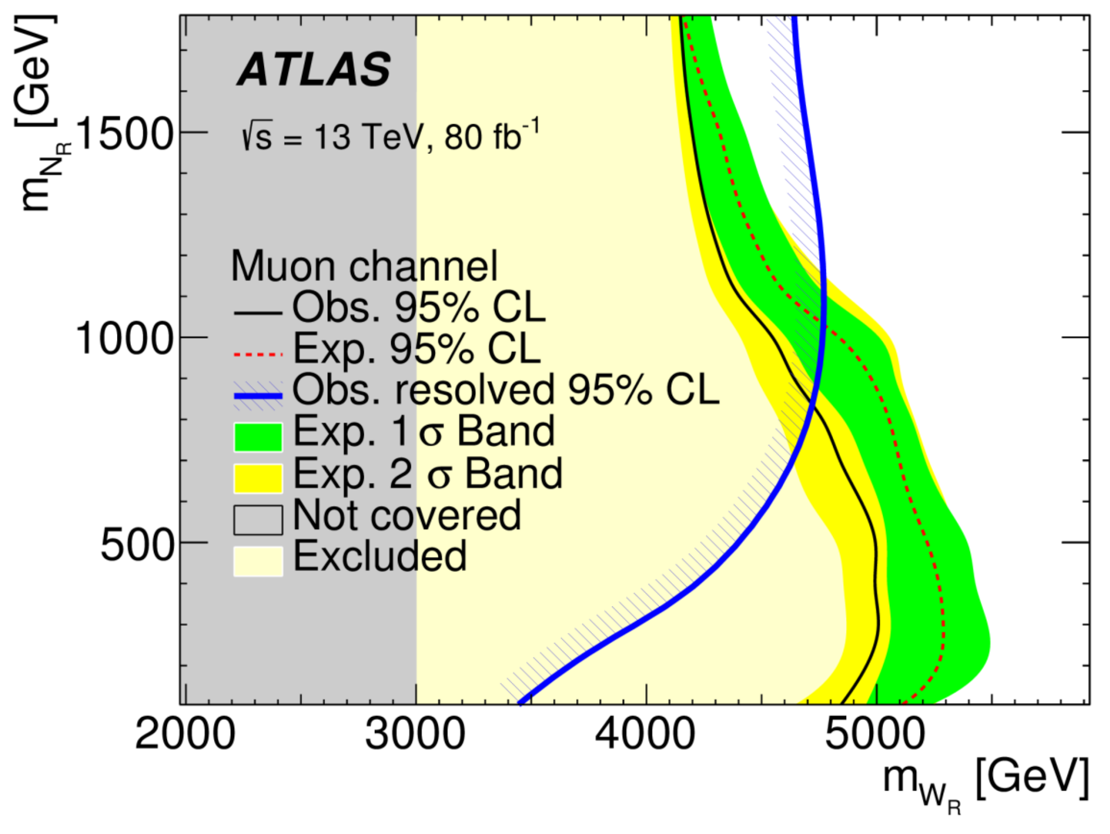




- Signal region is defined to be above 2 TeV in fat jet-lepton invariant mass
- A validation region is defined with eμ events
- Excess observed in the electron channel, but still in agreement with expectation



# Heavy neutrino search: Exclusion contour

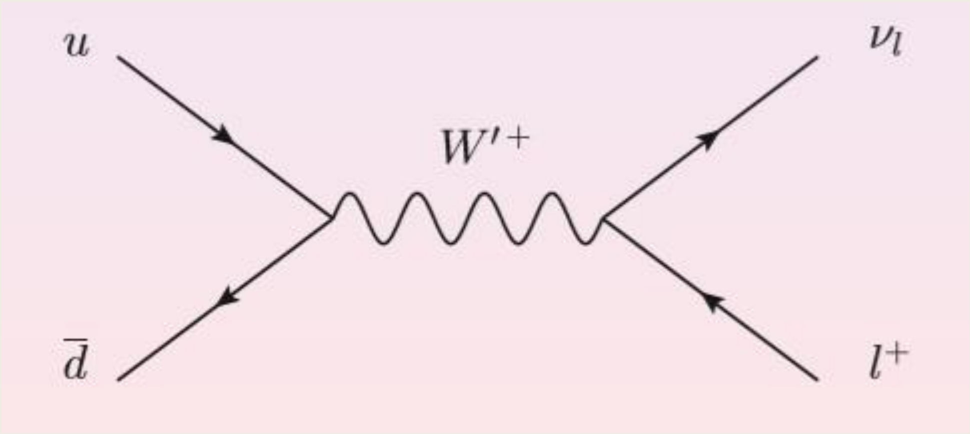



- Limits extracted in the $m_{N_R}$-$m_{w_R}$ plane
- Slightly worse limits for the muon channel at high mass due to worse resolution
- Observed limits also shown for the resolved topology. The two approaches yield complementary results

# Lepton+MET: Analysis Strategy

arXiv 1906.05609



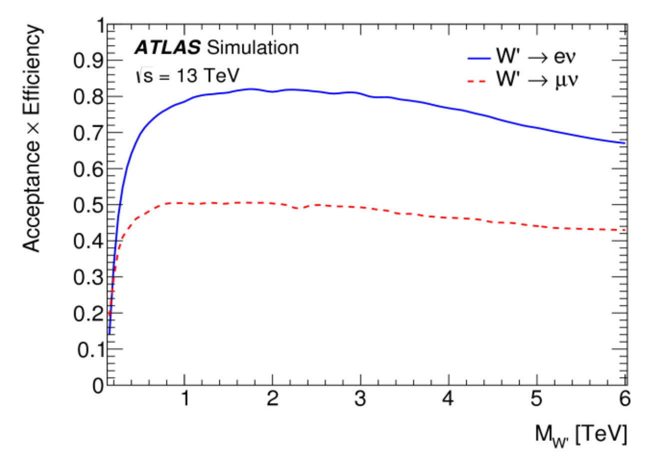

- Possible additional charged gauge bosons
- Its decay would produce a signature with a lepton and missing transverse energy coming from the neutrino
- Benchmark model used is the Sequential Standard Model
- No interference between W and W’ considered

AIM

Search for deviations from Standard Model predictions in the $m_T$ distribution

EVENT SELECTION

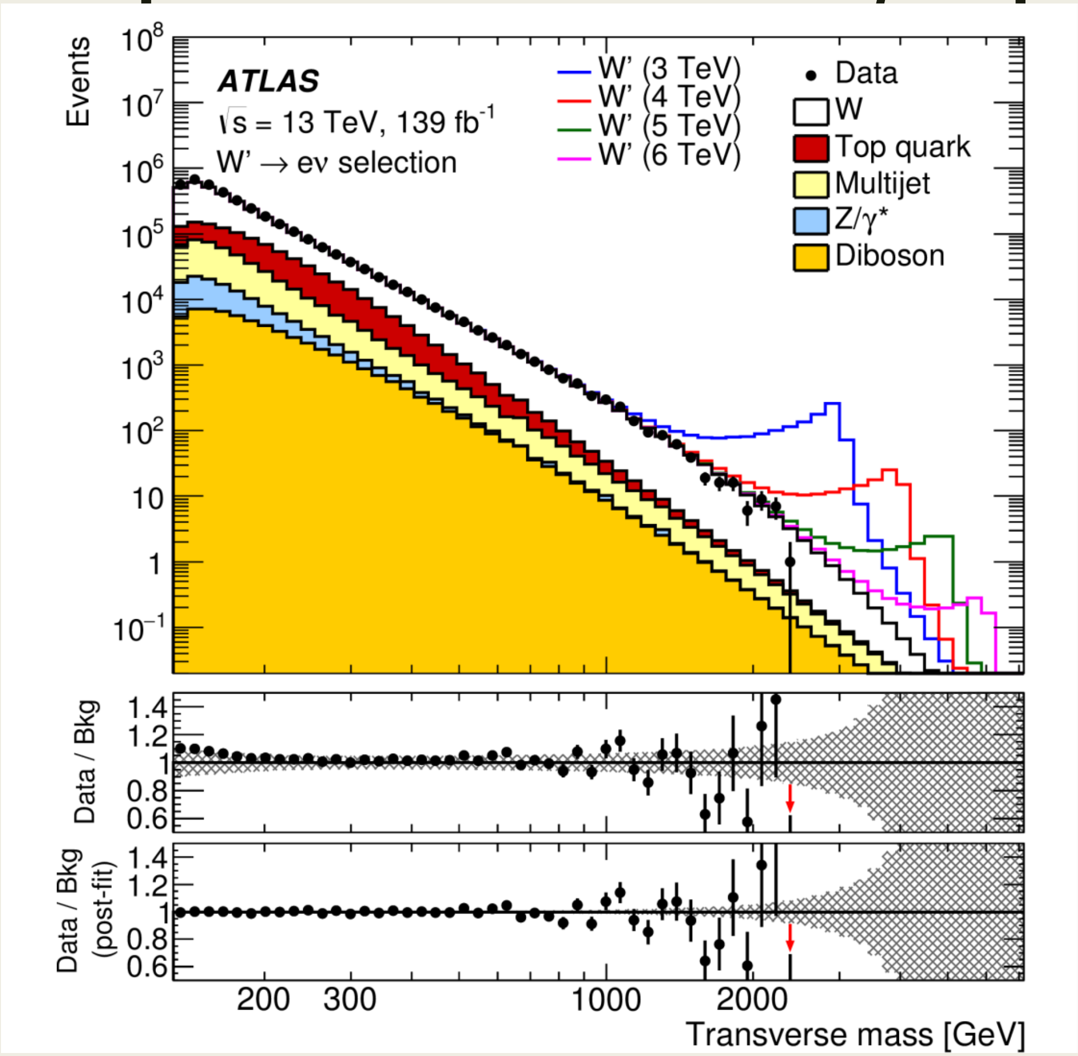
Identify events with one high-pT lepton and large missing transverse energy

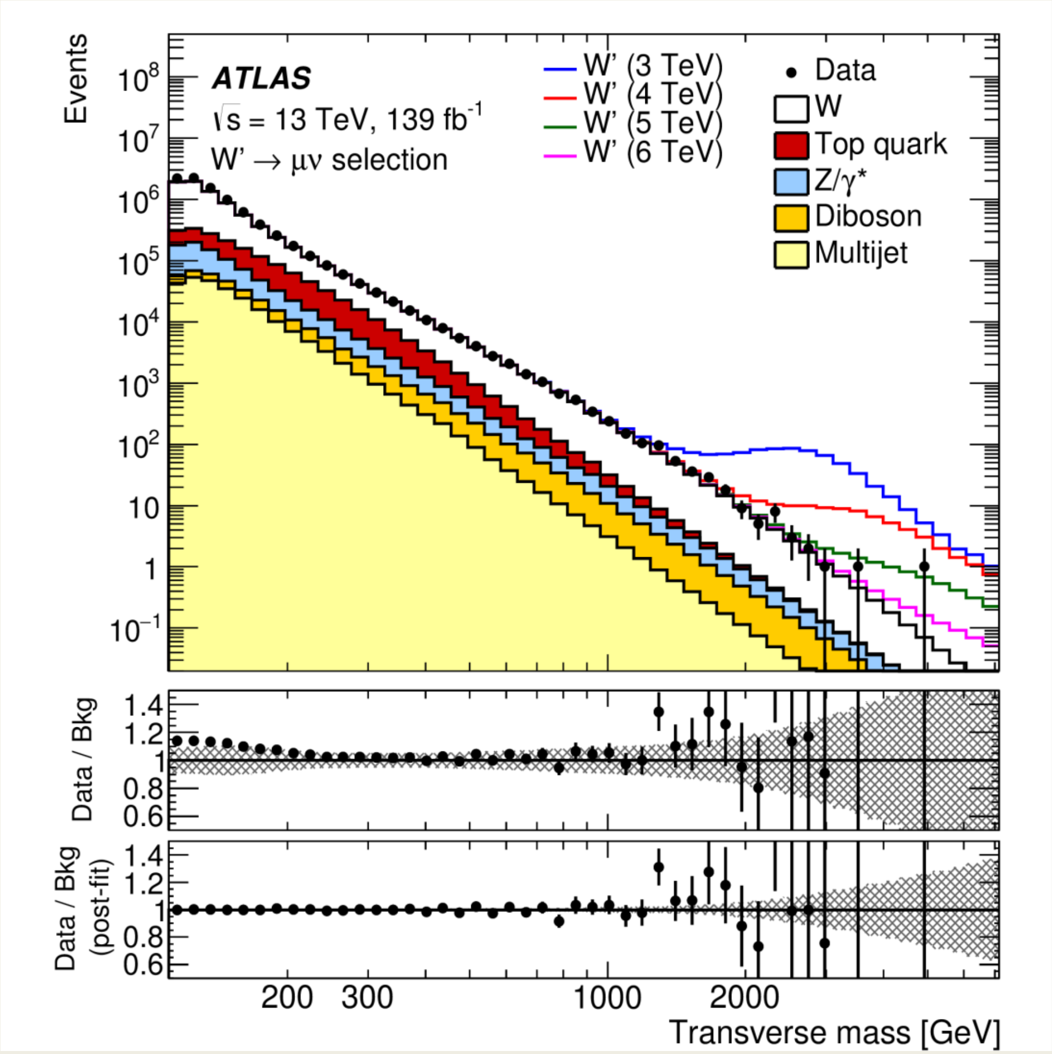



BACKGROUND ESTIMATION

- Events with prompt leptons are estimated through the use of Monte Carlo simulation
- Backgrounds coming from non-prompt leptons are estimated through data-driven methods

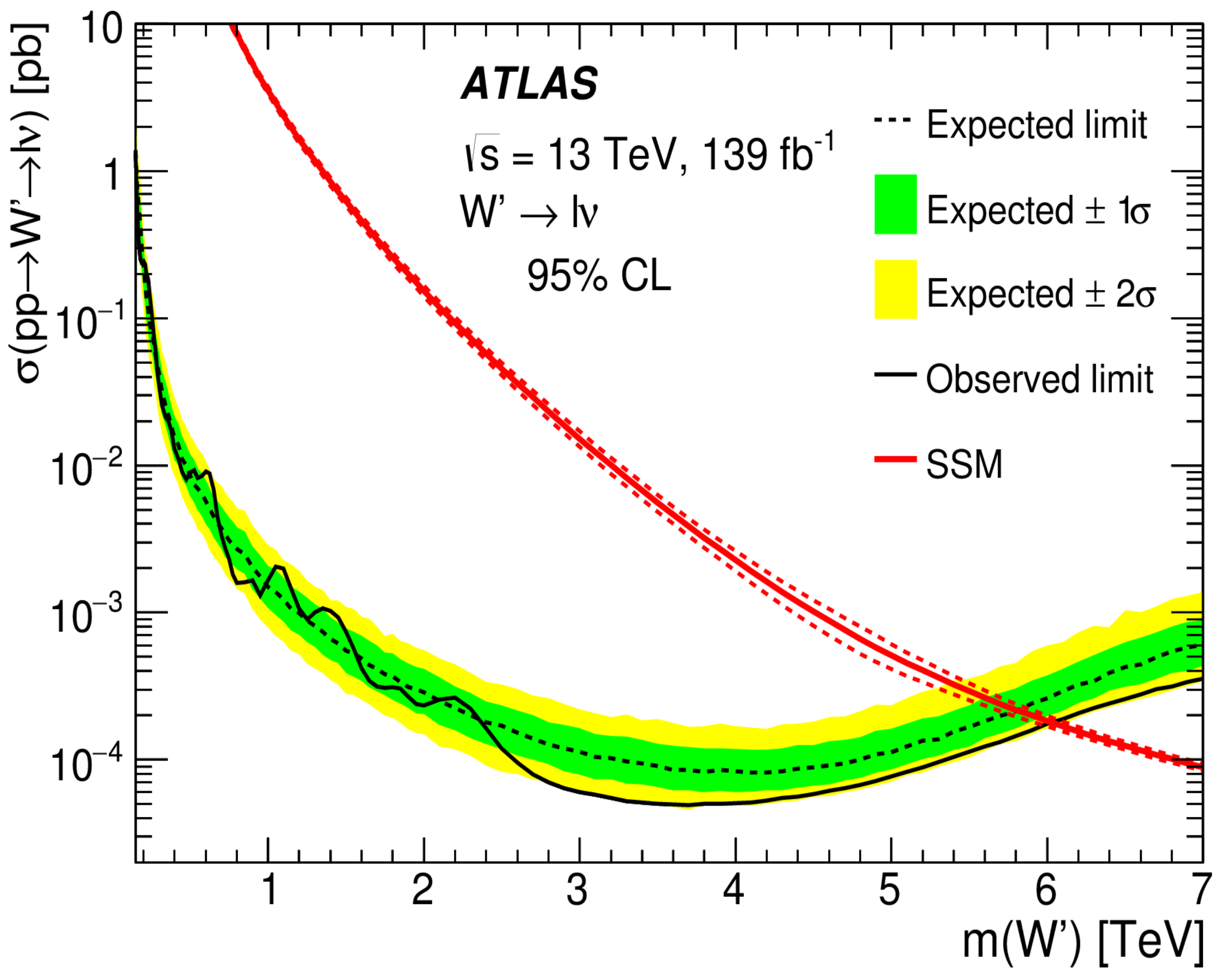
# Lepton+MET: $m_T$ spectrum



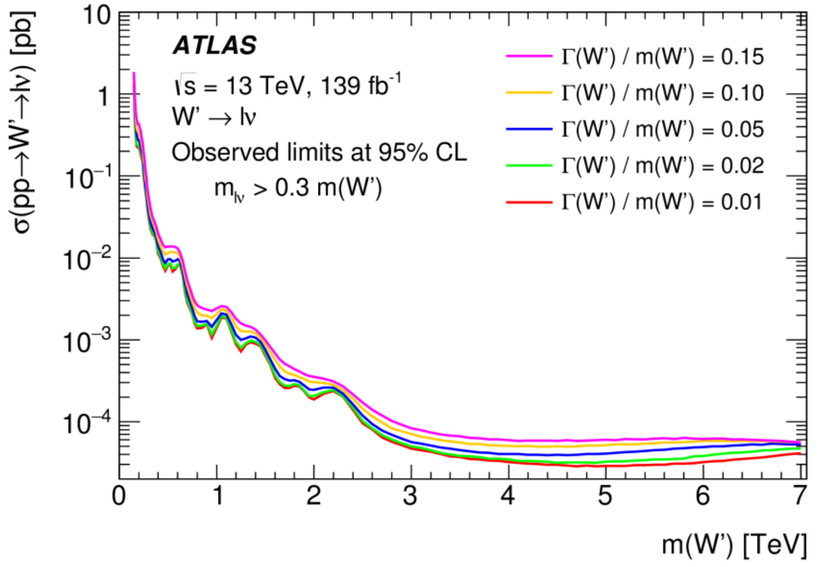

- Largest deviation found at 625 GeV in the muon channel with a local significance of 2.8σ (1.3σ global)
- Proceed to extract limits on the BSM model considered

# Lepton+MET: Exclusion Limits



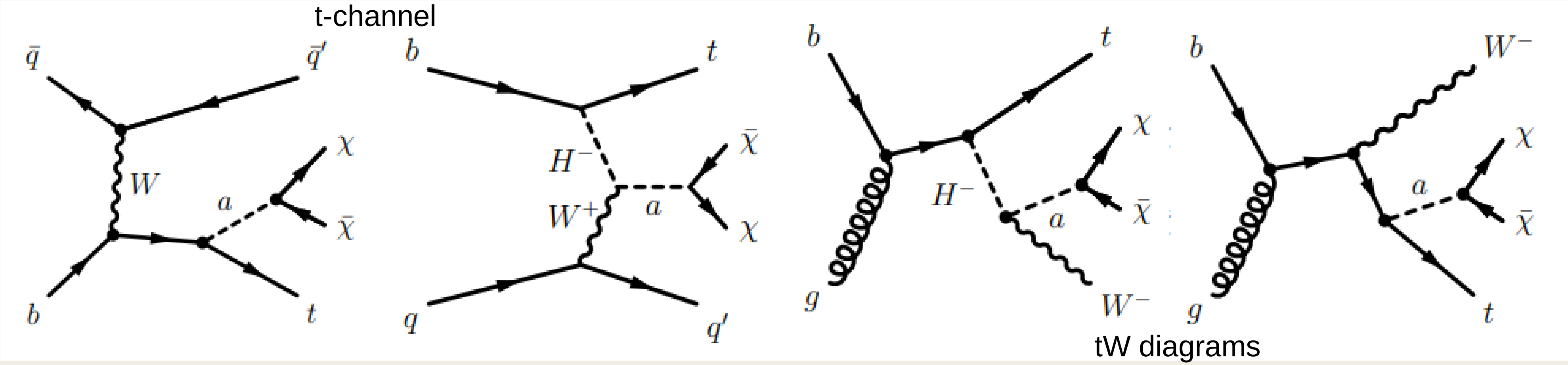

| | $m(W')$ lower limit [TeV] | |
|---|---|---|
| Decay | Observed | Expected |
| $W' \to e\nu$ | 6.0 | 5.7 |
| $W' \to \mu\nu$ | 5.1 | 5.1 |
| $W' \to \ell\nu$ | 6.0 | 5.8 |

- Bayesian Limits with flat prior on the signal cross-section as well as model independent results on generic resonances with varying width values



# 2HDM+*a* Dark Matter search

arXiv 2011.09308




- Searches for Dark Matter (DM) usually rely on the presence of Weakly Interacting Massive Particle (WIMP), which would show up as missing transverse energy
- This paper considers a Two Higgs Doublet Model (2HDM) with an additional pseudoscalar (*a*) towards DM production
- Events with a single top quark are found to be sensitive to 2HDM+*a* type of models, with the tW diagrams providing the leading contributions to DM production
- Three channels are defined to exploit the characteristics of each of the final state, depending on its topology: $tW_{1L}$ , $tW_{2L}$ and $tj_{1L}$

Requirements for each Signal Region

| Variable | $tW_{1L}$ | $tW_{2L}$ | $tj_{1L}$ |
|---|---|---|---|
| Trigger | $E_T^{miss}$ | dilepton | $E_T^{miss}$ OR one-lepton |
| $N_\ell^{signal}$ | $= 1$ | $= 2$ (OS) | $= 1$ |
| $p_T(\ell_1)$ [GeV] | $> 30$ | $> 25$ | $> 30$ |
| $p_T(\ell_2)$ [GeV] | - | $> 20$ | - |
| $N_{jet}$ | $\geq 3$ | $\geq 1$ | $\in [1, 4]$ |
| $p_T$(jet) [GeV] | $> 30$ | $> 30$ | $> 30$ |
| $N_{b\text{-jet}}$ | $\geq 1$ | $\geq 1$ | $\in [1, 2]$ |
| $p_T(b_1)$ [GeV] | $> 50$ | $> 50$ | $> 50$ |
| $E_T^{miss}$ [GeV] | $> 250$ | $> 200$ | $> 200$ |
| $m_T^{lep}$ [GeV] | $> 30$ | - | $> 60$ |
| $m_{\ell\ell}$ [GeV] | - | $\geq 40, \notin [71, 111]$ $(ee/\mu\mu)$ | - |
| $\Delta\phi_{min}$ [rad] | $> 0.5$ | - | $> 0.5$ |

# 2HDM+*a* Dark Matter search

| Process | Generator | PDF set | PS and frag./hadr. | UE tune | Cross-section accuracy |
|---|---|---|---|---|---|
| Top pair ($t\bar{t}$) | Powheg-Box v2 | NNPDF 3.0 NLO | Pythia 8 | A14 | NNLO+NNLL |
| Single-top: $t$-channel | Powheg-Box v1 | NNPDF 3.0 NLO | Pythia 8 | A14 | NNLO+NNLL |
| Single-top: $s$- and $Wt$-channel | Powheg-Box v2 | NNPDF 3.0 NLO | Pythia 8 | A14 | NNLO+NNLL |
| $V$+jets ($V = W/Z$) | Sherpa 2.2.1 | NNPDF 3.0 NNLO | Sherpa | Default | NNLO |
| Diboson | Sherpa 2.2.1 or 2.2.2 | NNPDF 3.0 NNLO | Sherpa | Default | NLO |
| $t\bar{t}+V$, $V = W, Z, h$ | MadGraph5_aMC@NLO 2.3.3 | NNPDF 3.0 NLO | Pythia 8 | A14 | NLO |
| $tWZ$ | MadGraph5_aMC@NLO 2.6.7 | NNPDF 3.0 NLO | Pythia 8 | A14 | NLO |

- For each channel, Control Regions (CRs) are defined to estimate the leading background in the signal region. A background-only fit is then performed, using the normalization to data in the CRs
- In addition, Validation regions are used to verify the extrapolation of the Monte Carlo simulation estimate
- The main backgrounds are top pair and single-top production, as well as W+jets
- A Boosted Decision Tree (BDT) score is used to further sub-categorize Signal Regions

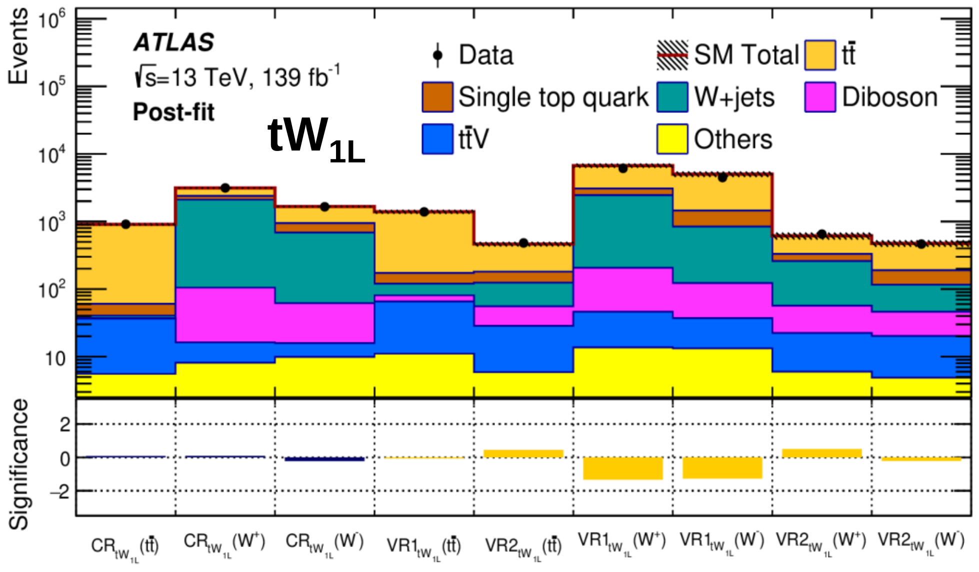
Signal, control and validation region definitions used in $tW_{1L}$

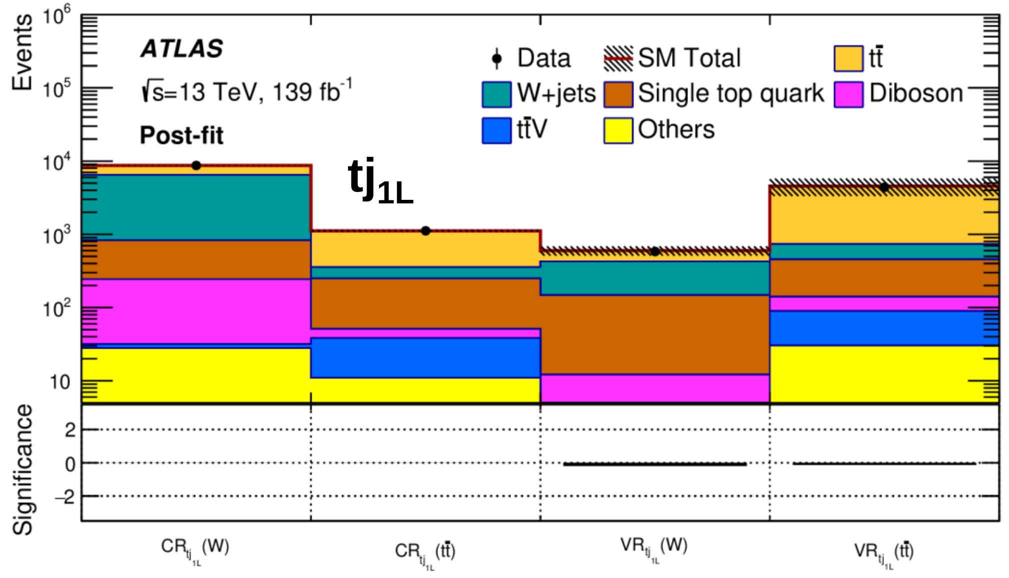
| Variable | SR | CR($t\bar{t}$) | CR(W) | VR1($t\bar{t}$) | VR2($t\bar{t}$) | VR1(W) | VR2(W) |
|---|---|---|---|---|---|---|---|
| $N_{b\text{-jet}}$ | = 1 | ≥ 2 | = 1 | = 1 | = 1 | = 1 | = 1 |
| $p_T(b_2)$ [GeV] | < 50 | > 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| $m_W^{\text{reclustered}}$ [GeV] | > 60 | – | < 60 | – | < 60 | > 60 | < 60 |
| $m_T^{\text{lep}}$ [GeV] | > 200 | > 200 | ∈ [40, 100] | > 200 | > 200 | ∈ [40, 100] | > 100 |
| $am_{T2}$ [GeV] | > 220 | < 220 | > 220 | < 220 | > 220 | > 220 | > 220 |

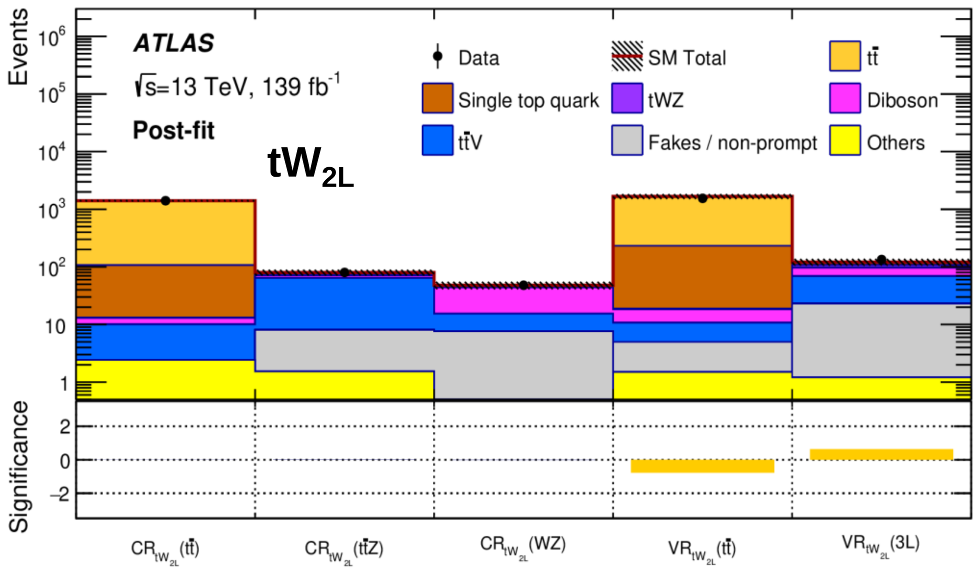
Signal, control and validation region definitions used in $tW_{2L}$

| Variable | SR | CR($t\bar{t}$) | CR($t\bar{t}Z$) | CR(WZ) | VR($t\bar{t}$) | VR($3\ell$) |
|---|---|---|---|---|---|---|
| $N_\ell^{\text{signal}}$ | = 2 (OS) | = 2 (OS) | = 3 (≥ 1 SFOS) | = 3 (≥ 1 SFOS) | = 2 (OS) | = 3 (≥ 1 SFOS) |
| $p_T(\ell_3)$ [GeV] | - | - | > 20 | > 20 | - | > 20 |
| $m_{ee/\mu\mu}$ [GeV] | ∉ [71, 111] | ∉ [71, 111] | ∈ [71, 111] | ∈ [71, 111] | ∉ [71, 111] | ∈ [71, 111] |
| $N_{\text{jet}}$ | ≥ 1 | ≥ 1 | ≥ 3 | ∈ [1, 3] | ≥ 1 | ≥ 1 |
| $N_{b\text{-jet}}$ | ≥ 1 | ≥ 1 | ≥ 1 (≥ 2 if $N_{\text{jet}}$ = 3) | = 1 | ≥ 1 | ≥ 1 |
| $m_{b\ell}^{\text{min}}$ [GeV] | < 170 | < 170 | < 170 | > 170 | < 170 | varies |
| $m_{b\ell}^{\text{t}}$ [GeV] | > 150 | < 150 | – | – | > 150 | – |
| $m_{T2}$ [GeV] | > 130 | ∈ [40, 80] | > 90 | > 90 | ∈ [40, 80] | > 90 |
| $\Delta\phi_{\text{min}}$ [rad] | > 1.1 | > 1.1 | – | – | > 1.1 | – |

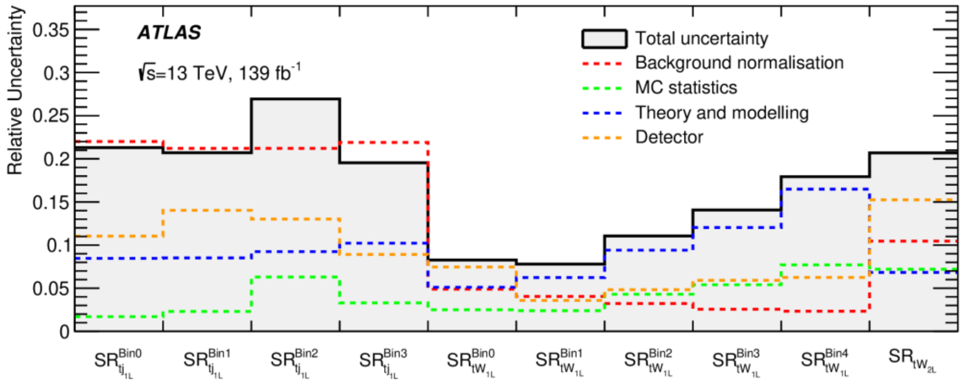
# 2HDM+*a* Dark Matter: Validation region



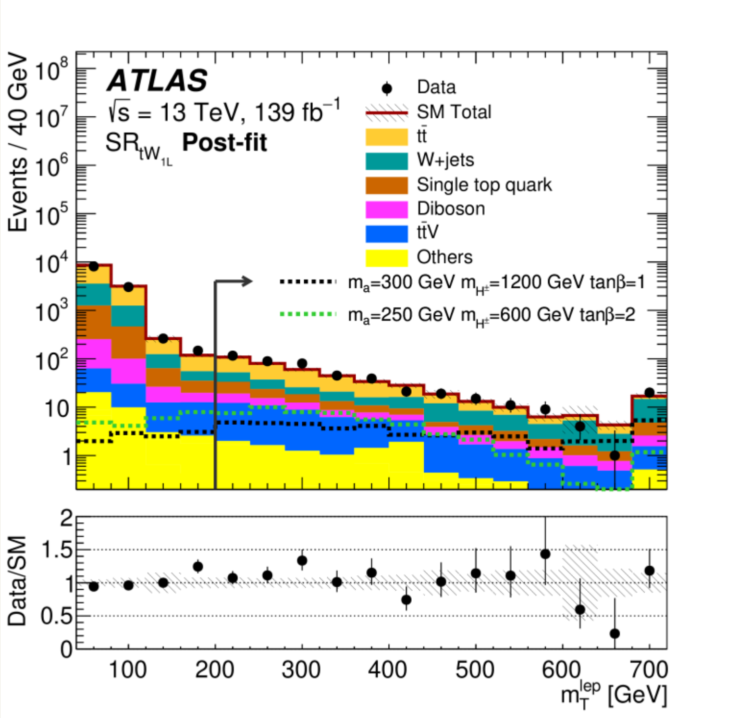



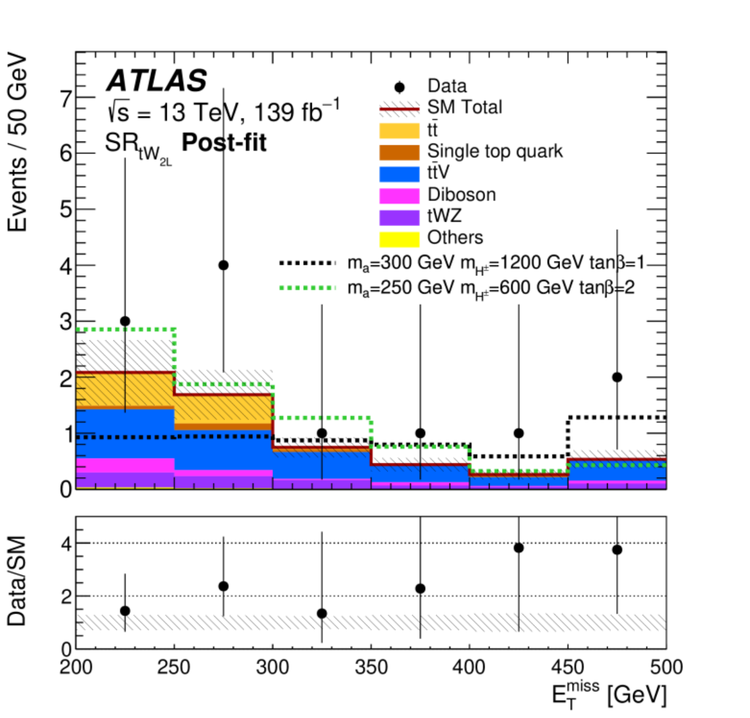



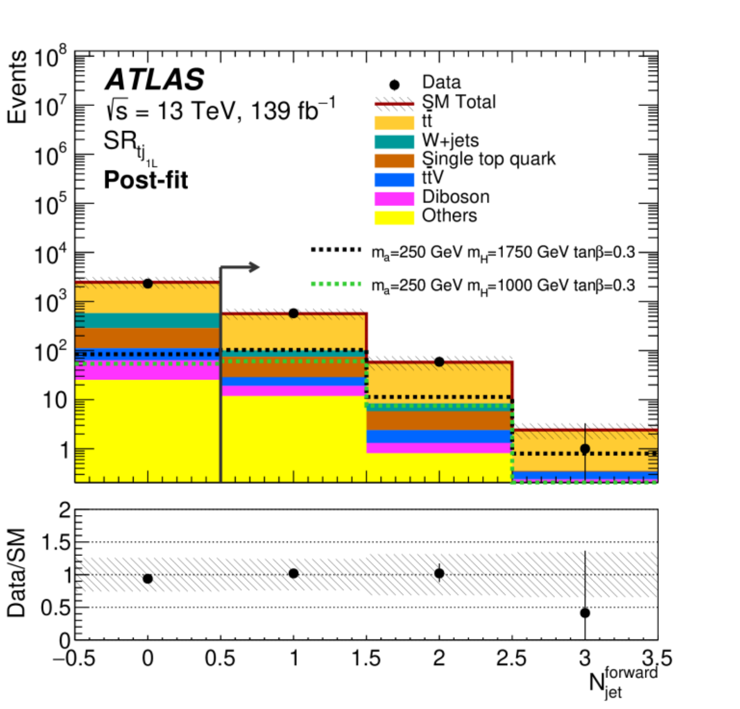

- Good agreement is found in the validation region between expected and observed yields

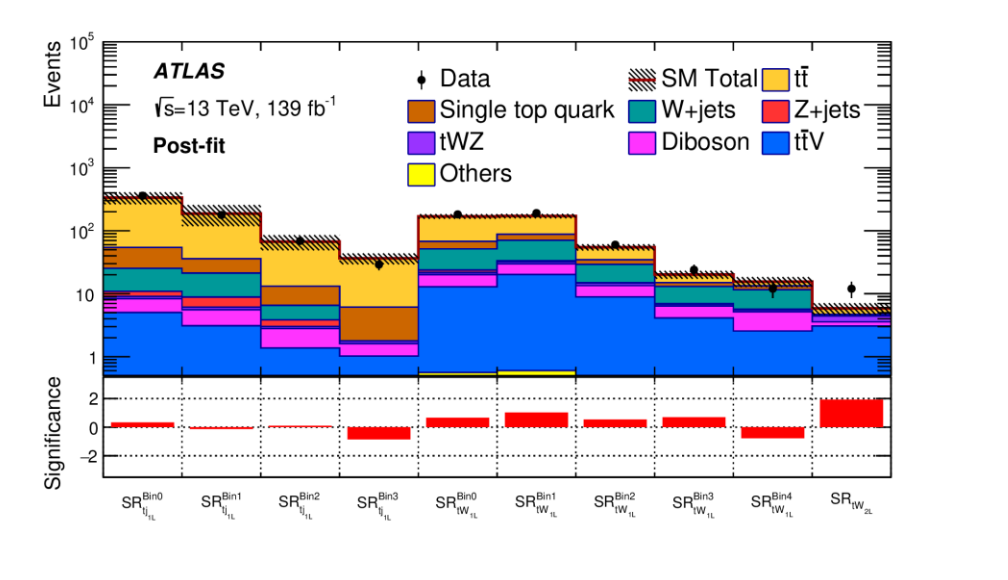


# 2HDM+a Dark Matter: Results



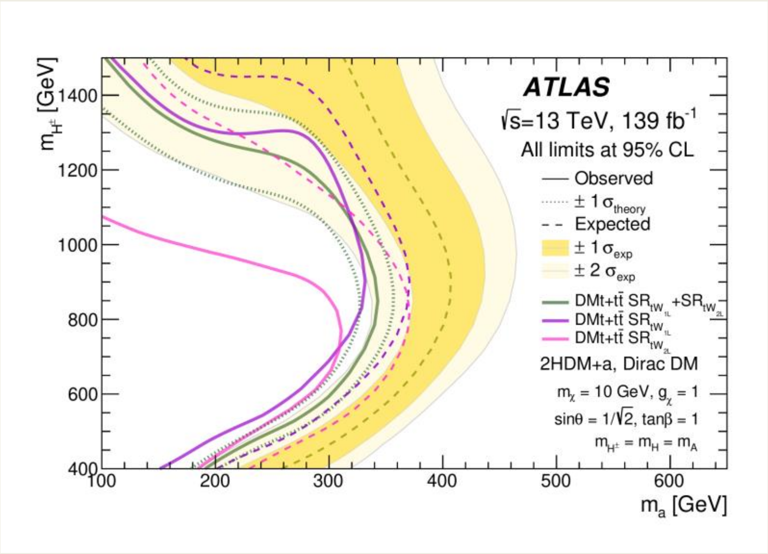



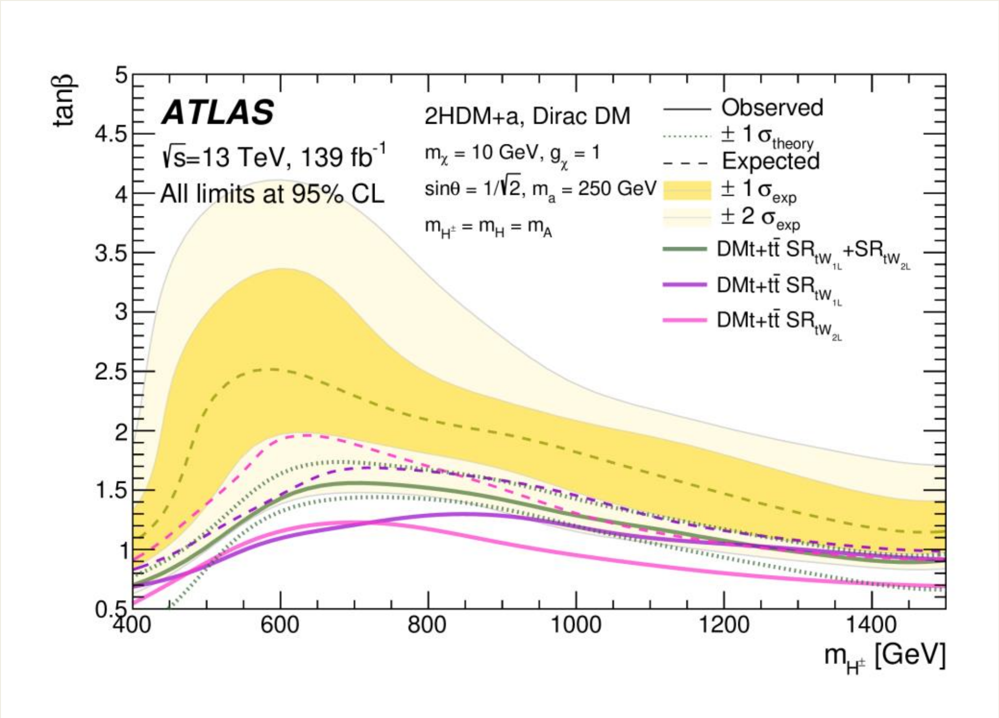



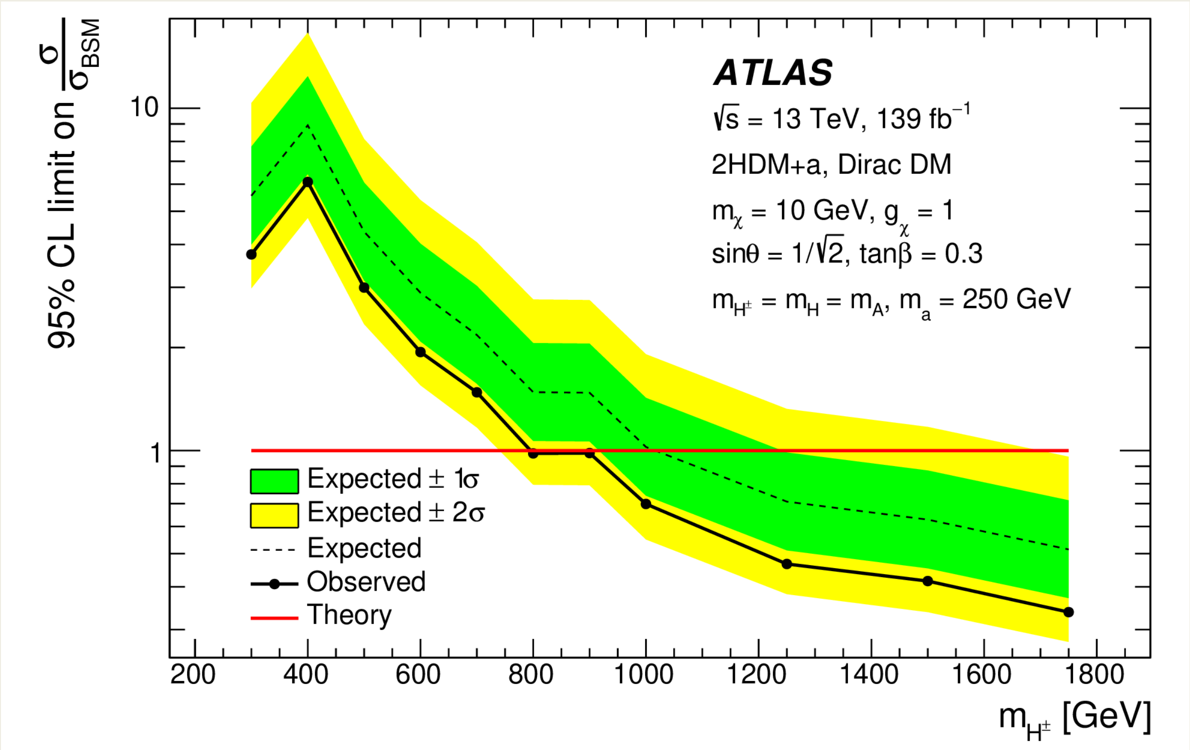

| | $SR^{Bin0}_{tW_{1L}}$ | $SR^{Bin1}_{tW_{1L}}$ | $SR^{Bin2}_{tW_{1L}}$ | $SR^{Bin3}_{tW_{1L}}$ | $SR^{Bin4}_{tW_{1L}}$ | $SR_{tW_{2L}}$ |
|---|---|---|---|---|---|---|
| Observed events | 182 | 191 | 60 | 24 | 12 | 12 |
| Fitted SM bkg events | 169 ± 14 | 171 ± 13 | 55 ± 6 | 20.1 ± 2.8 | 15.6 ± 2.8 | 5.9 ± 1.2 |
| $t\bar{t}$ | 101 ± 12 | 84 ± 12 | 20 ± 5 | 5.1 ± 1.7 | 2.3 ± 1.5 | 1.2 ± 0.9 |
| Single top | 16.3 ± 5.2 | 17.3 ± 5.2 | 5.4 ± 3.2 | 2.0 ± 1.8 | $1.7^{+2.0}_{-1.7}$ | $0.26^{+0.27}_{-0.26}$ |
| $W$+jets | 28 ± 4 | 37.0 ± 4.3 | 14.2 ± 2.4 | 6 ± 1 | 5.9 ± 1.1 | – |
| $Z$+jets | 2.0 ± 0.9 | 1.1 ± 0.7 | 0.3 ± 0.1 | 0.15 ± 0.04 | 0.15 ± 0.02 | – |
| Diboson | 7.2 ± 1.7 | 9.6 ± 2.0 | 4.6 ± 1.0 | 2.2 ± 0.5 | 2.7 ± 0.6 | 0.5 ± 0.2 |
| $t\bar{t}V$ | 12.3 ± 1.4 | 19.5 ± 3.5 | 8.7 ± 1.2 | 4.0 ± 0.7 | 2.5 ± 0.5 | 2.9 ± 0.7 |
| $tWZ$ | 1.7 ± 0.2 | 2.4 ± 0.5 | 1.17 ± 0.15 | 0.42 ± 0.09 | 0.39 ± 0.09 | 0.8 ± 0.1 |
| Others | 0.6 ± 0.1 | 0.6 ± 0.1 | 0.17 ± 0.02 | 0.06 ± 0.02 | 0.03 ± 0.01 | 0.16 ± 0.08 |

# 2HDM+*a* Dark Matter: Exclusion contours




| Signal channel | $\langle\epsilon\sigma\rangle^{95}_{\text{obs}}$ [fb] | $S^{95}_{\text{obs}}$ | $S^{95}_{\text{exp}}$ | $CL_B$ | $p(s=0)$ $(Z)$ |
|---|---|---|---|---|---|
| $\text{SR}^{250}_{tW_{1L}}$ | 0.72 | 100.6 | $67^{+33}_{-16}$ | 0.85 | 0.12 (1.16) |
| $\text{SR}^{300}_{tW_{1L}}$ | 0.51 | 70.8 | $54 \pm 16$ | 0.85 | 0.15 (1.02) |
| $\text{SR}^{400}_{tW_{1L}}$ | 0.24 | 32.9 | $29^{+10}_{-6}$ | 0.64 | 0.30 (0.52) |
| $\text{SR}^{500}_{tW_{1L}}$ | 0.14 | 18.9 | $19^{+8}_{-5}$ | 0.52 | 0.45 (0.13) |
| $\text{SR}^{600}_{tW_{1L}}$ | 0.08 | 10.6 | $12^{+3}_{-4}$ | 0.24 | 0.94 (−1.54) |
| $\text{SR}_{tW_{2L}}$ | 0.10 | 13.8 | $7.3^{+2.9}_{-1.1}$ | 0.97 | 0.02 (2.07) |
| $\text{SR}_{tj_{1L}}$ (BDT>0.9) | 0.10 | 14.4 | $19^{+6}_{-5}$ | 0.24 | 0.50 (0.00) |



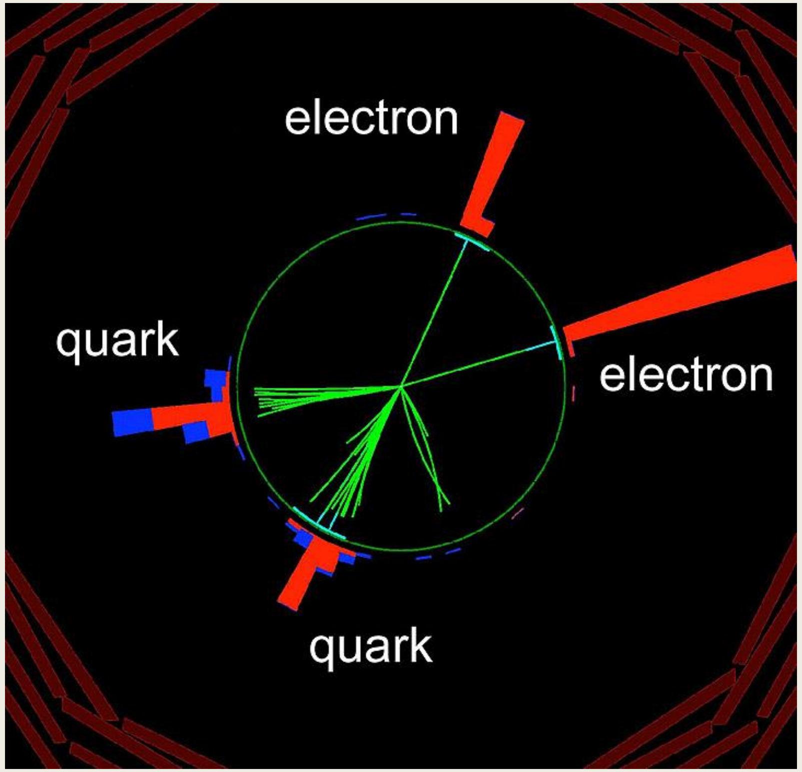



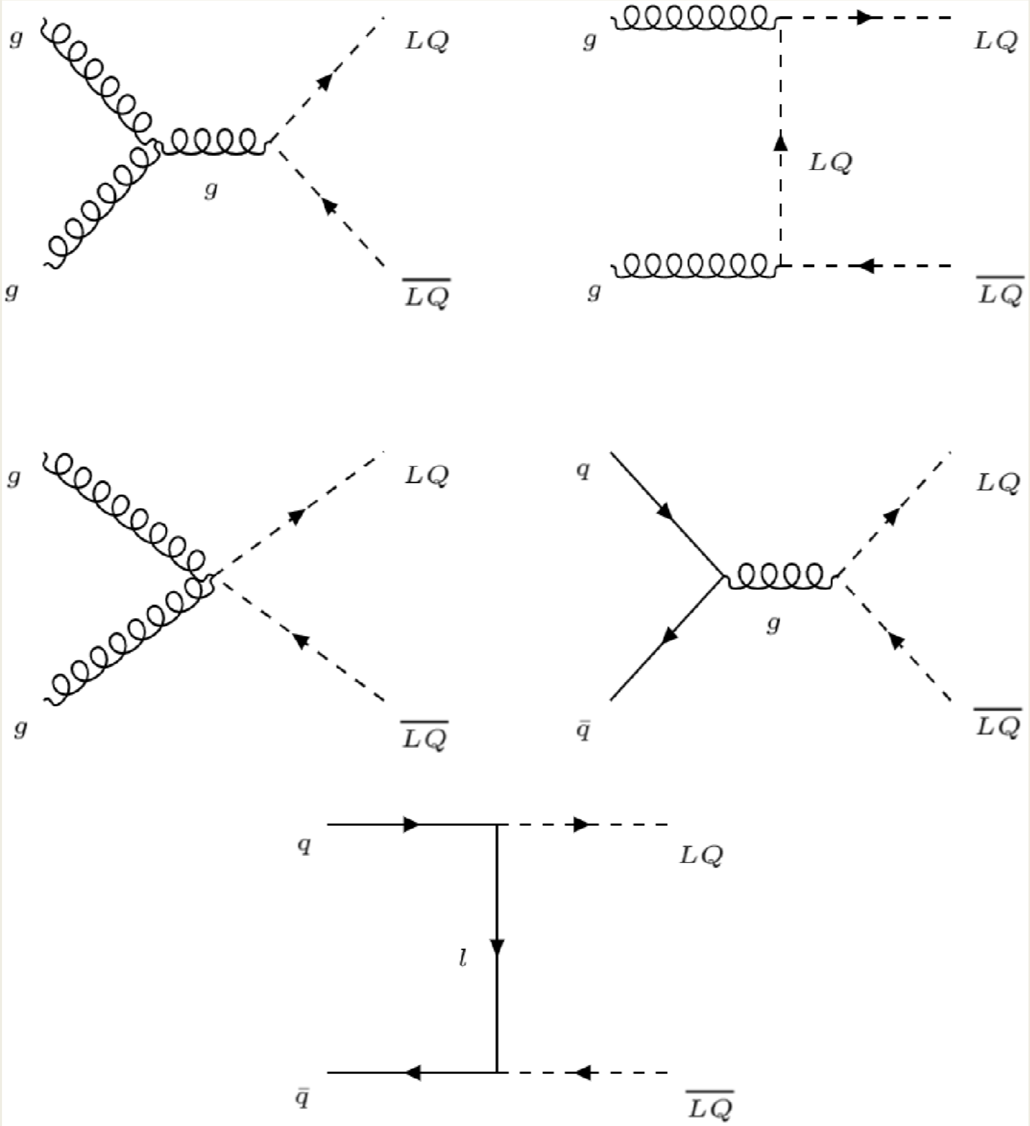
# Scalar Leptoquark searches

ArXiv 2006.05872

ArXiv 2010.02098

- Leptoquarks (LQs) are one of the possible solutions to the flavor anomalies observed at LHCb in B-meson decays
- They couple both to quarks and leptons and can mediate flavour-changing neutral current, enabling violation of Lepton Flavour Universality
- These searches focus LQ pair production, leading to final states with two same-flavor leptons and at least two jets



# Scalar Leptoquark search with b/c jets

ArXiv 2006.05872

| Process | Generator | PDF set | PS and fragmentation/hadronisation | UE tune | Cross-section order |
|---|---|---|---|---|---|
| Top pair ($t\bar{t}$) | Powheg-Box v2 [49] | NNPDF 3.0 [50] | Pythia 8 | A14 | NNLO+NNLL [51] |
| Single-top: $t$-channel | Powheg-Box v1 | NNPDF 3.0 | Pythia 8 | A14 | NNLO+NNLL [52] |
| Single-top: $s$- and $Wt$-channel | Powheg-Box v2 | NNPDF 3.0 | Pythia 8 | A14 | NNLO+NNLL [53,54] |
| $W$+jets, $Z$/Drell–Yan+jets | Sherpa 2.2.1 [55,56,57,58,59] | NNPDF 3.0 | Sherpa | Default | NNLO [60] |
| Diboson | Sherpa 2.2.1 – 2.2.2 | NNPDF 3.0 | Sherpa | Default | NLO [55] |

- Main background is Z/Drell-Yan+Jets, modelled using Sherpa as it does a better job modelling the extra jets
- Top pair production is the subleading background, an eμ control region is used to validate its modelling
- Leptoquark masses from 400 to 2000 GeV are considered
- Events are categorized on the basis of the number of c- or b-tagged jets
- A powerful discriminant variable in the search for leptoquarks is the asymmetric mass, used to define the sideband/signal region:

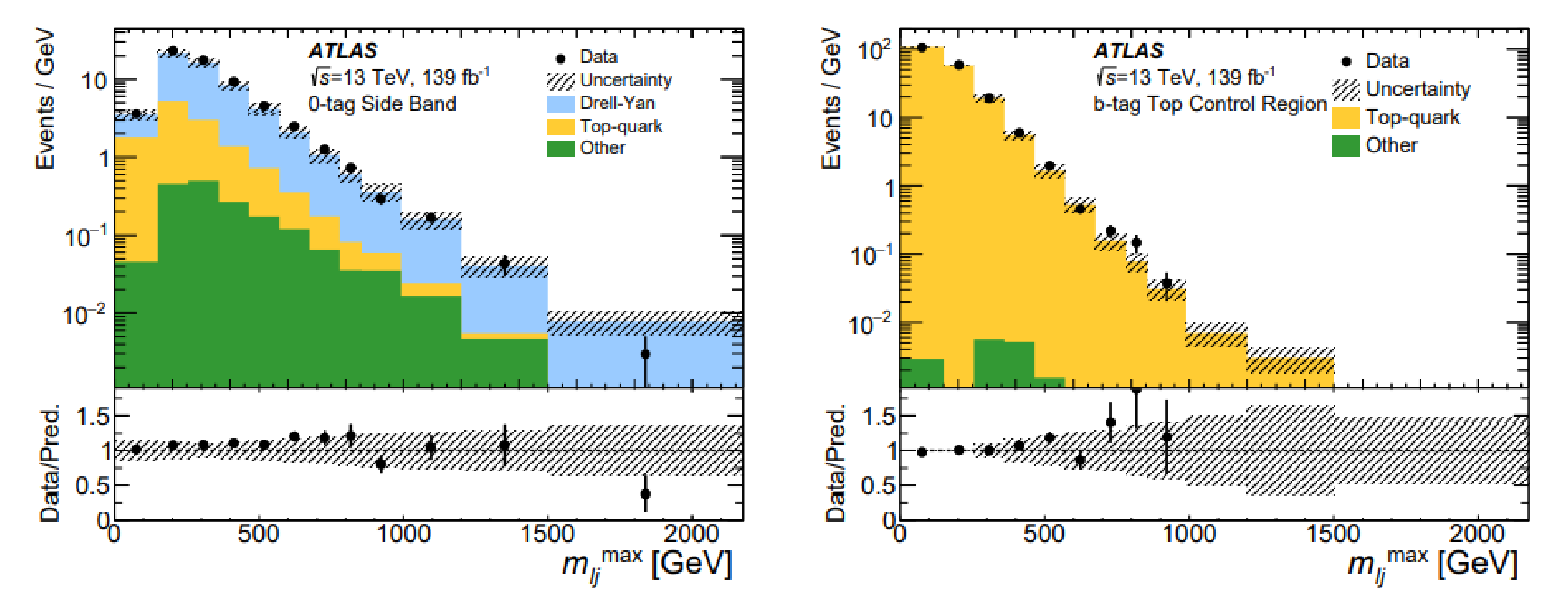
$$m^{\mathrm{asym}} = \frac{m_{\ell j}^{\max} - m_{\ell j}^{\min}}{m_{\ell j}^{\max} + m_{\ell j}^{\min}}$$

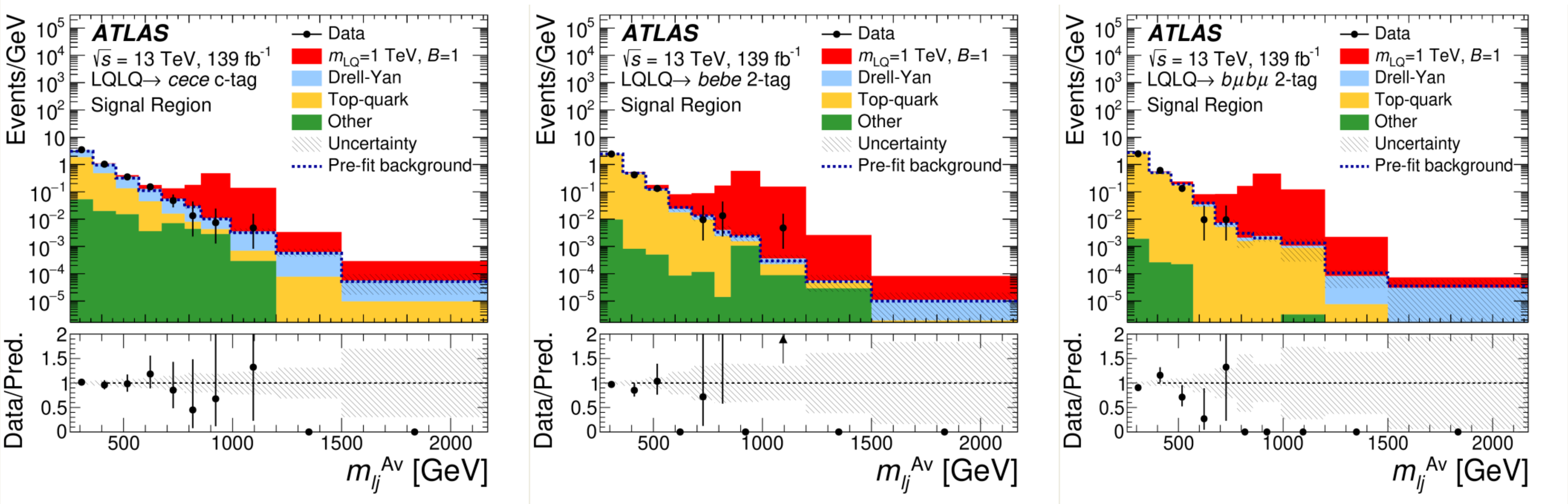
| Preselection | | |
|---|---|---|
| 2 opposite charge leptons ($e$, $\mu$) | | |
| 2 or more jets | | |
| $p_{\mathrm{T}}^{e} > 27$ GeV, $\|\eta_e\| < 2.47$; $p_{\mathrm{T}}^{\mu} > 27$ GeV, $\|\eta_\mu\| < 2.7$ | | |
| $p_{\mathrm{T}}^{j} > 45$ GeV, $\|\eta_j\| < 2.5$ | | |
| $p_{\mathrm{T}}^{\ell\ell} > 75$ GeV | | |
| $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}} < 3.5$ GeV$^{1/2}$ | | |
| $m_{\ell\ell} > 130$ GeV | | |
| SB | SR | Top CR |
| $ee$ or $\mu\mu$ | | $e\mu$ |
| $0.2 < m^{\mathrm{asym}} < 0.4$ | $m^{\mathrm{asym}} < 0.2$ | |

# Scalar Leptoquark search with b/c jets

- The MC simulation of the Drell-Yan and top pair production processes is validated in control regions, which are also used to extract systematic uncertainties on the shape

$$m_{\ell j}^{\mathrm{Av}} = (m_{\ell j}^{\max} + m_{\ell j}^{\min})/2.$$

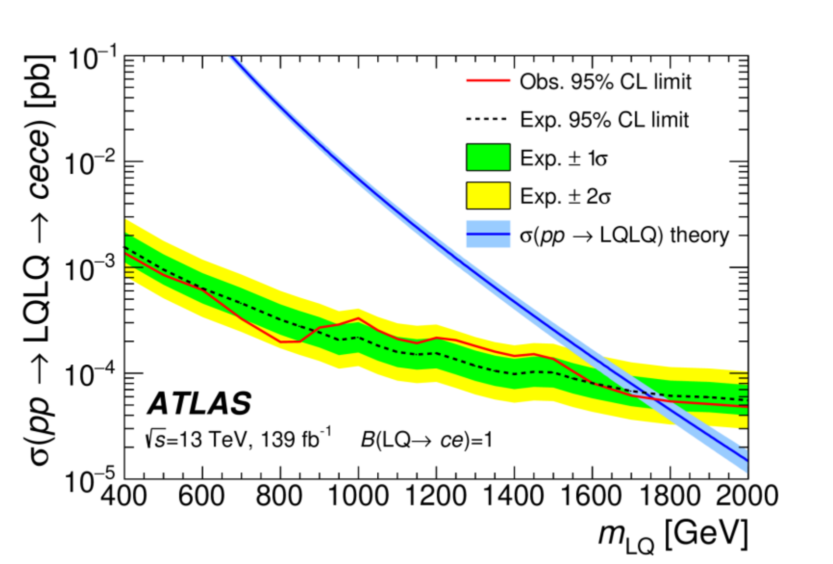


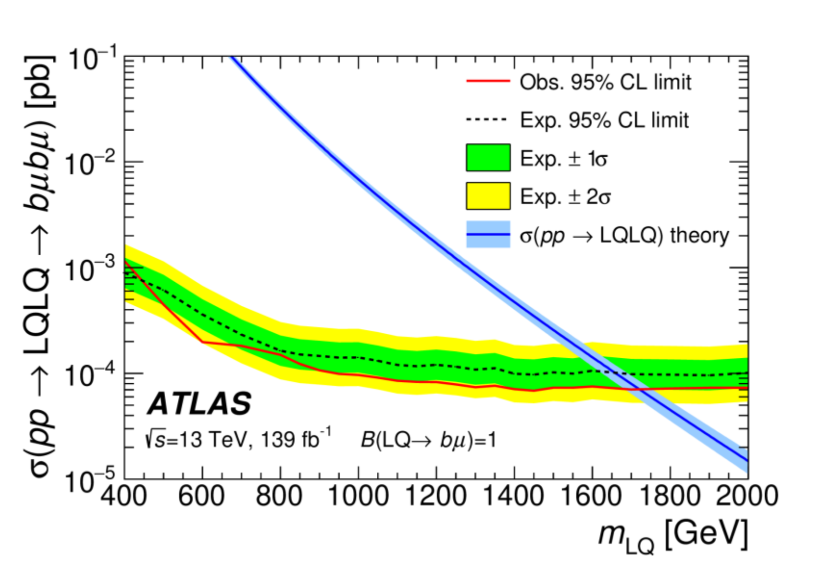



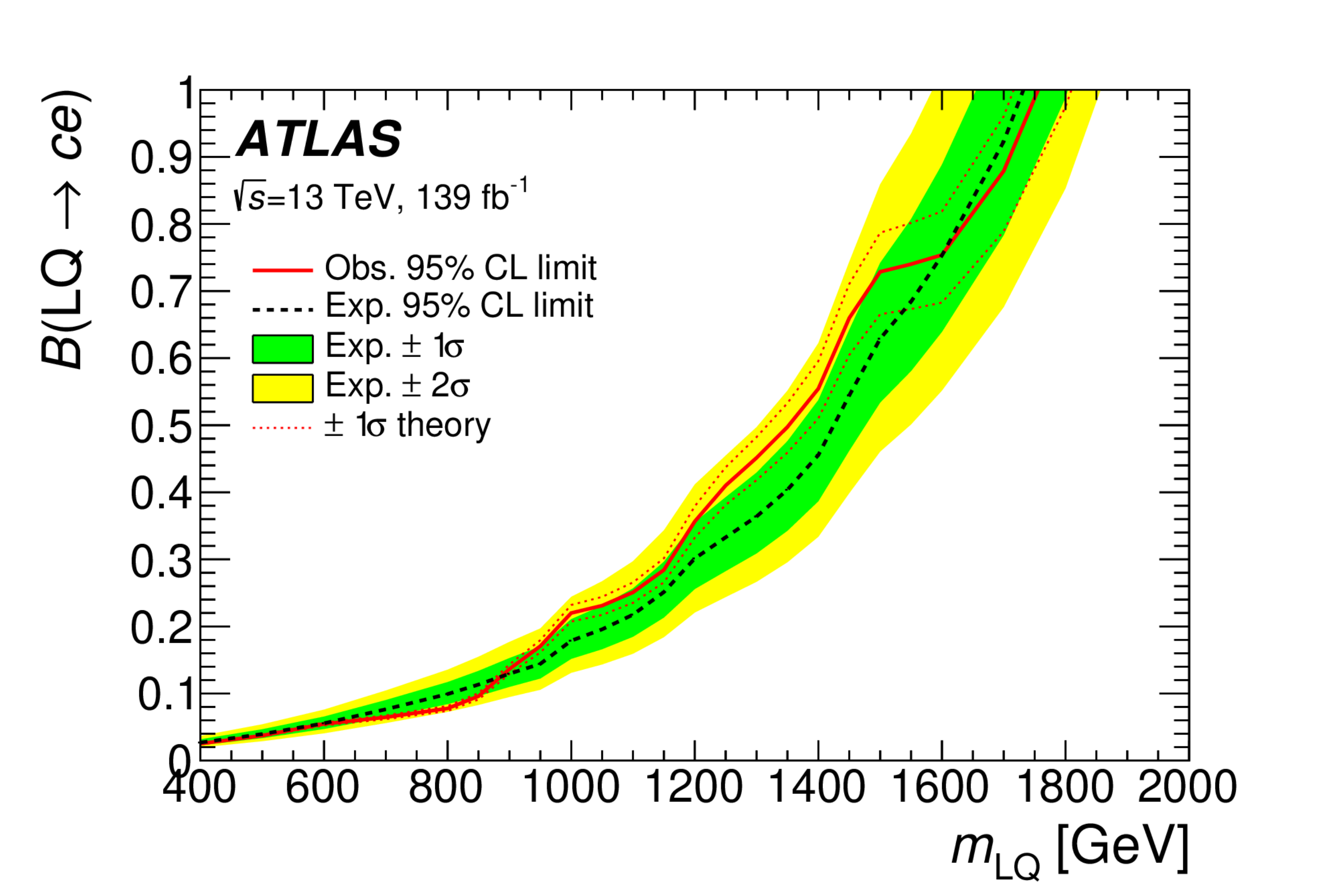

No excess observed above Standard Model Expectation

# Scalar Leptoquark search with b/c jets

Limits are first extracted for each jet flavour and channel: c- and b-jet with 0, 1 and 2 tags, assuming a 100% branching ratio, and are shown as well as a function of the branching ratio chosen

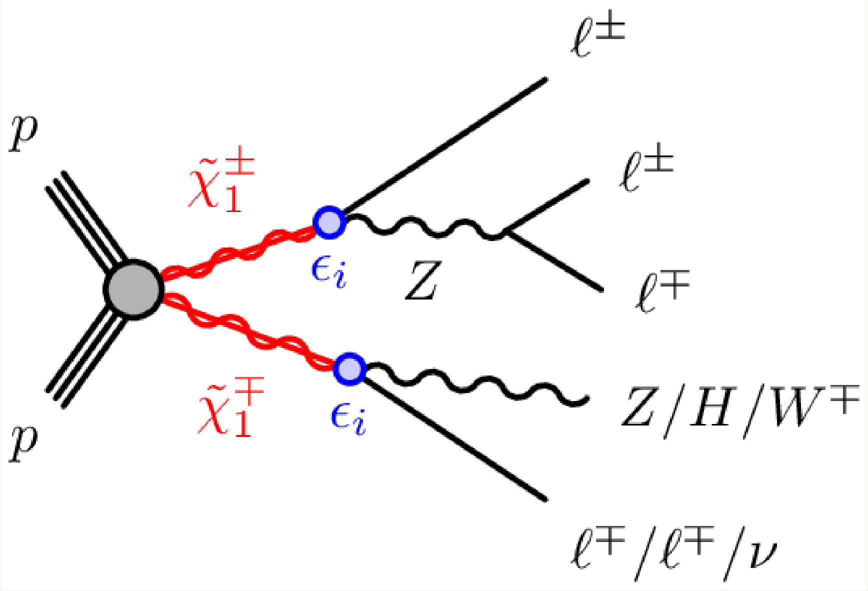


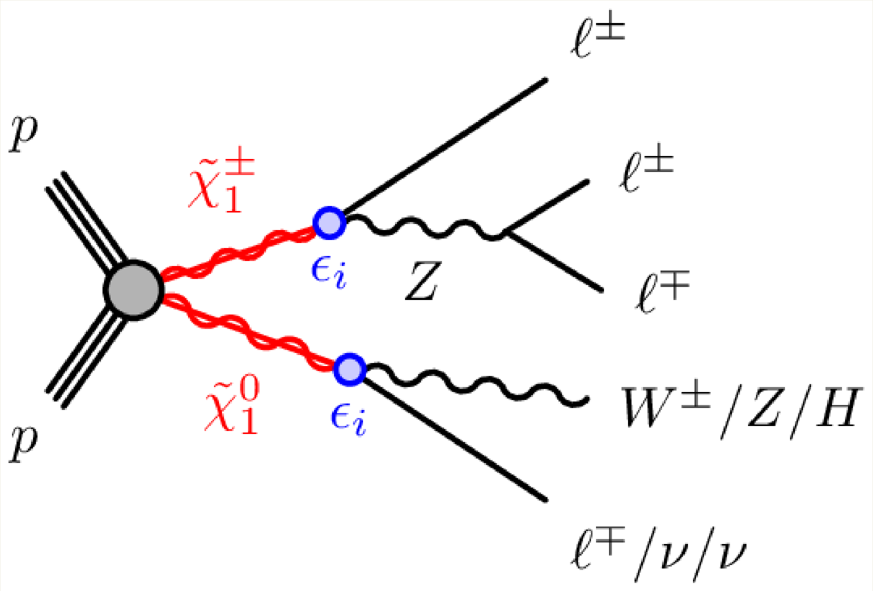



# Search for trilepton resonances

arXiv 2011.10543



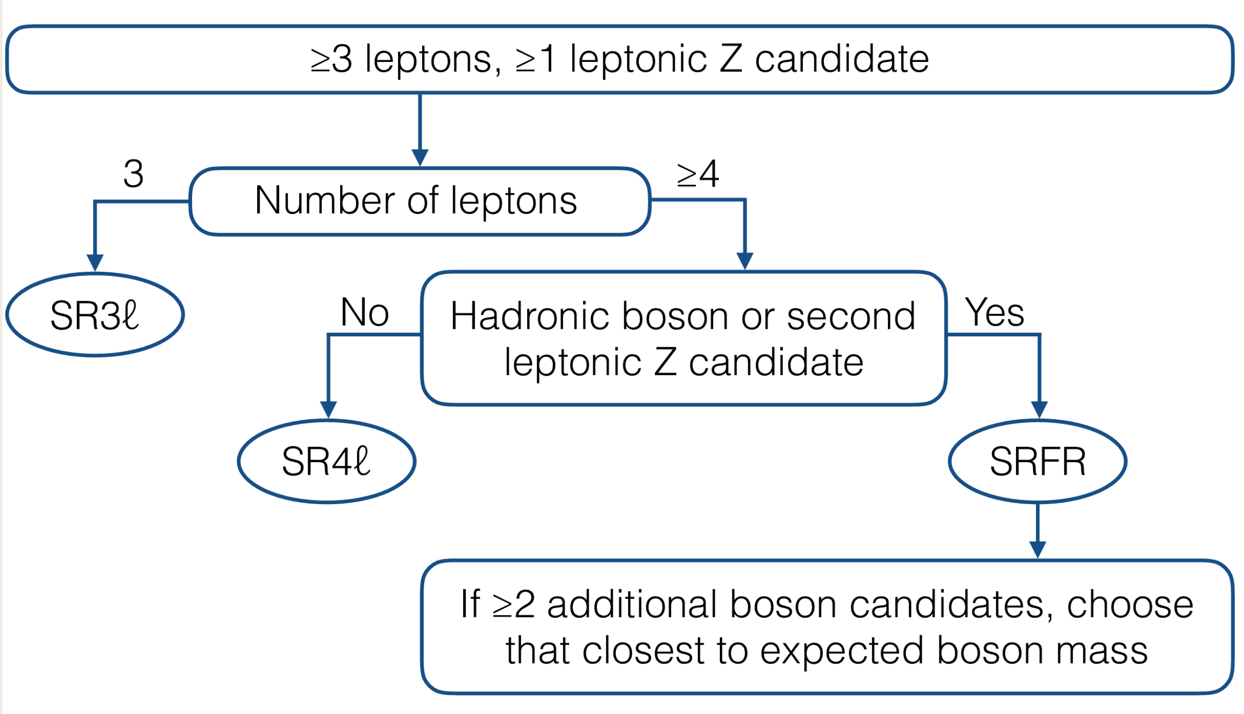




- SUSY can introduce processes that violate Baryon number (B) and lepton number (L) conservation
- This search uses an extended Minimal Supersymmetric Standard Model (MSSM) as a benchmark, including a third generation right-handed sneutrino that can break the B-L symmetry
- In this scenario, two candidates for lightest SUSY particle (LSP) are the chargino and the neutralino, which can decay to SM particles, producing final states with three or more charged leptons, with the target being the trilepton resonance

| Process | Event generator | PS and hadronization | PS tune | Cross section (in QCD) |
|---|---|---|---|---|
| Diboson, triboson, ($Z$+jets) | Sherpa 2.2 | Sherpa 2.2 | Default | NLO (NNLO) |
| $t\bar{t}W$, $t\bar{t}Z$, (Other top) | MadGraph5_aMC@NLO 2 | Pythia 8 | A14 | NLO (LO) |
| $t\bar{t}$, ($tW$), [$t\bar{t}H$] | Powheg-Box v2 | Pythia 8 | A14 | NNLO+NNLL (NLO+NNLL) [NLO] |
| Higgs: ggF, (VBF, $VH$) | Powheg-Box v2 | Pythia 8 | AZNLO | NNNLO (NNLO+NNLL) |
| $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$, $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{0}$ | MadGraph 2.6 | Pythia 8 | A14 | NLO+NLL |

Dominant background contributions are WZ, ZZ and top pair production in association with a Z boson

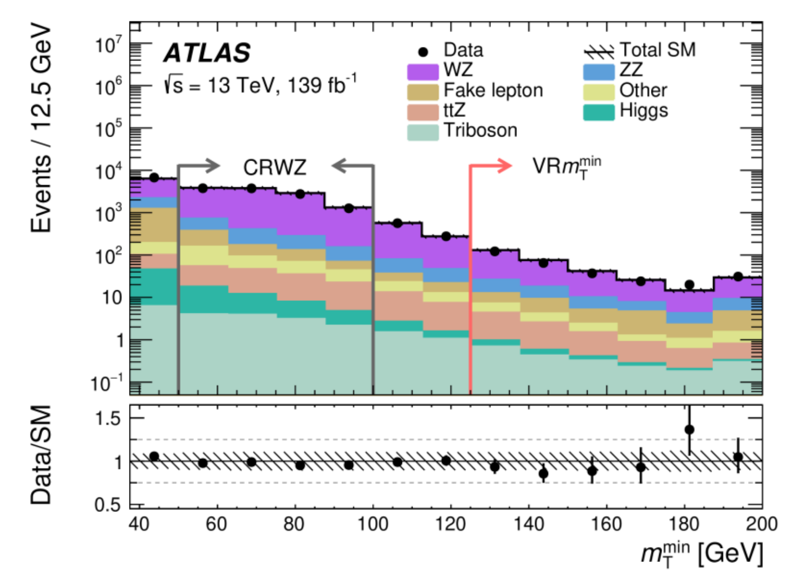
# Search for trilepton resonances

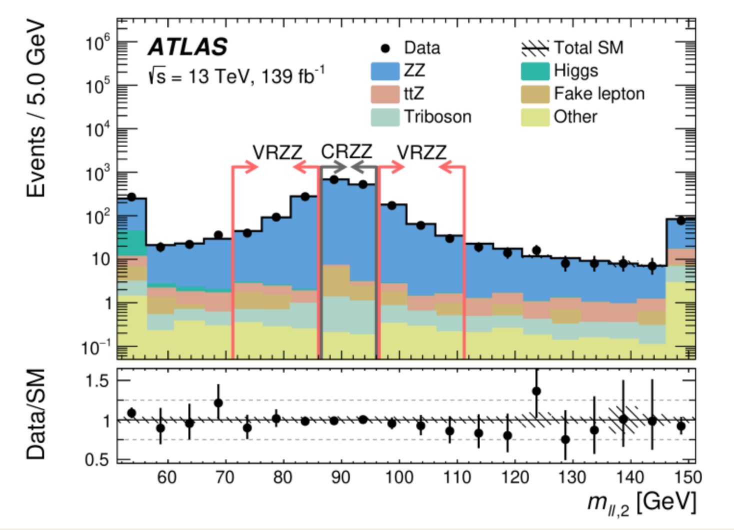


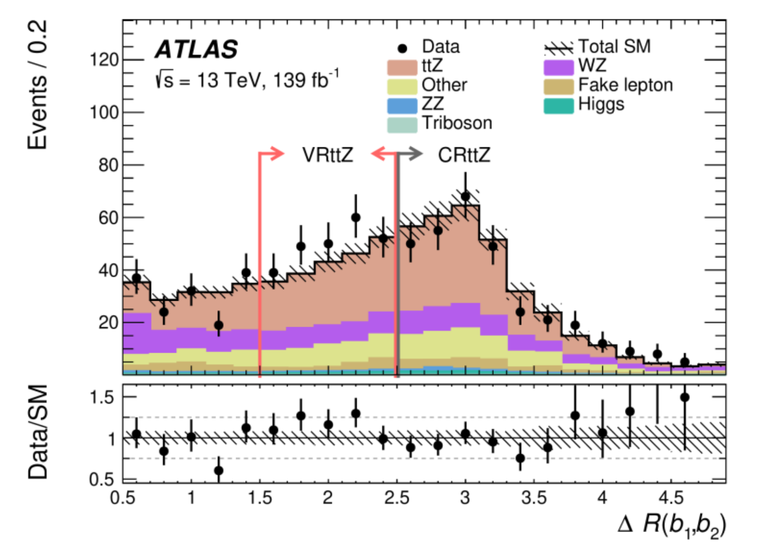

Three signal regions defined to target the different decay modes:

- SR3ℓ targets events with exactly three reconstructed leptons and a significant amount of missing energy
- SR4ℓ looks for events with four or more leptons and a moderate amount of missing energy, assumed to be coming from a neutrino produced in the decay of the additional neutralino/chargino
- SRFR targets processes where all neutralino+chargino decay products are products are fully reconstructible, including a second W, Z or Higgs candidate

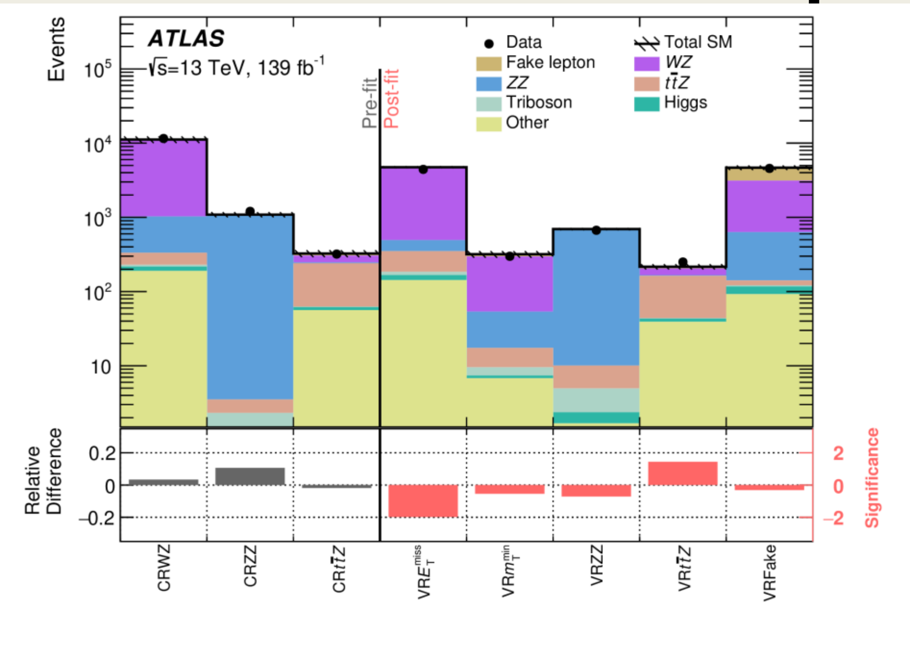
Aim for trilepton events with 90 < $m_{Z\ell}$ < 580 GeV

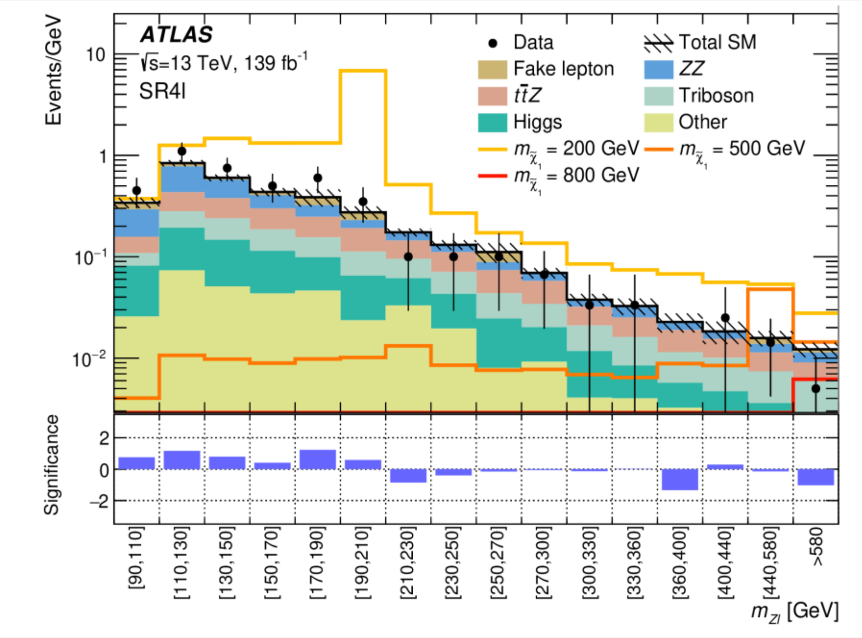


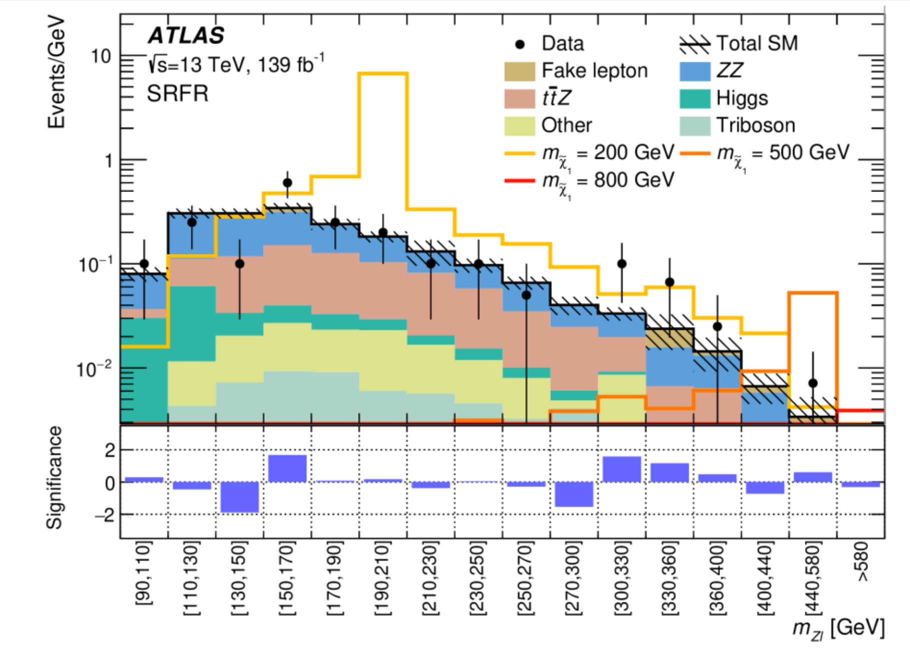



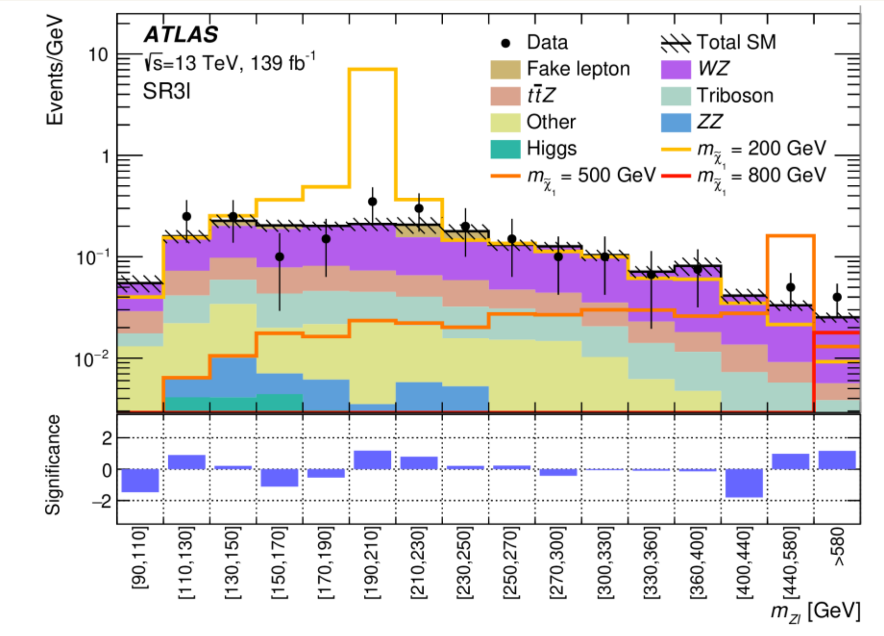
# Search for trilepton resonances: Results



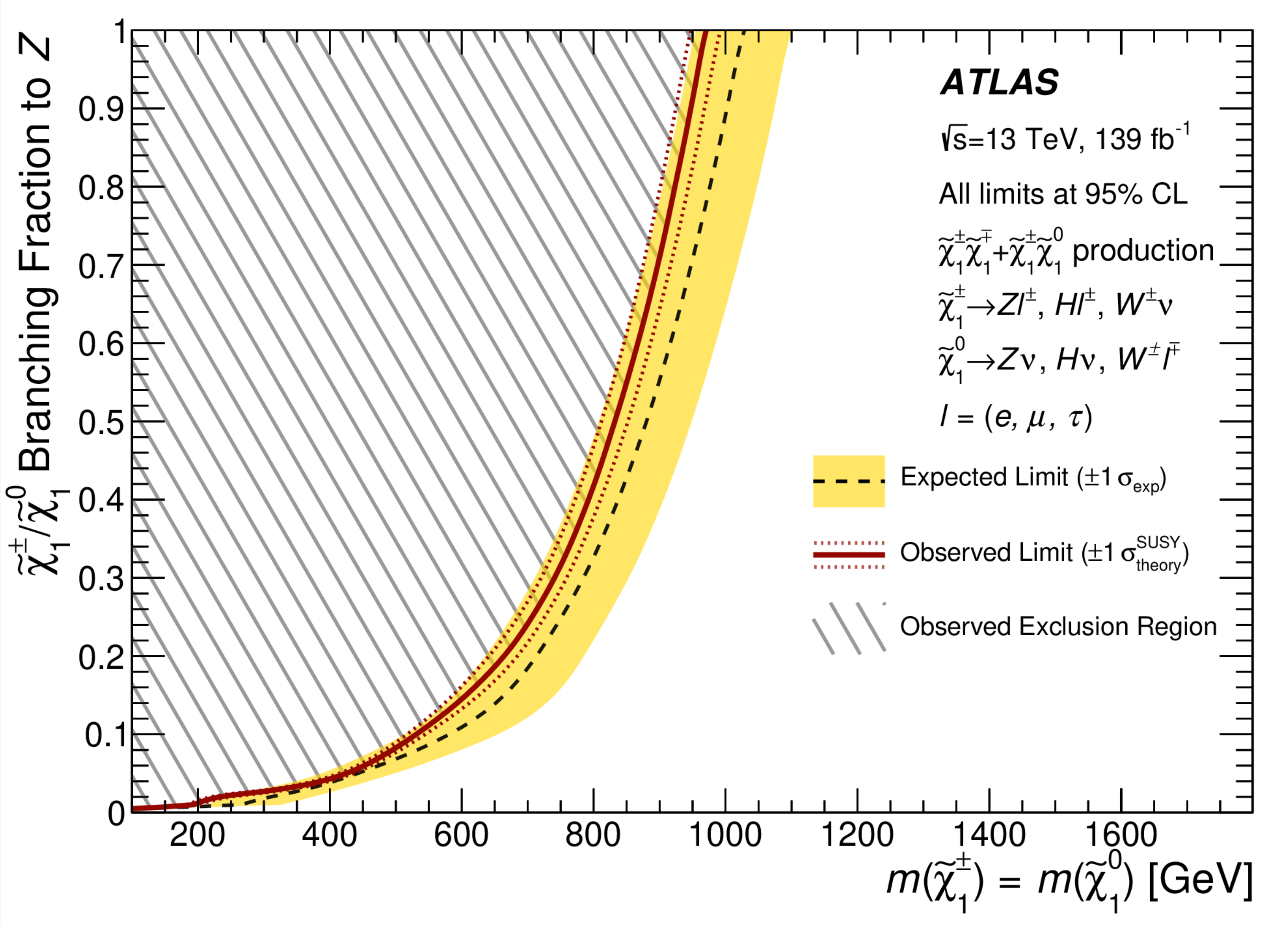

- The data-driven fake lepton estimation uncertainty is dominant in many of the bins due to statistical limitations in the dataset, while experimental uncertainties are dominated by jet energy scale/resolution . Modelling uncertainties on the shape of the main background are also considered



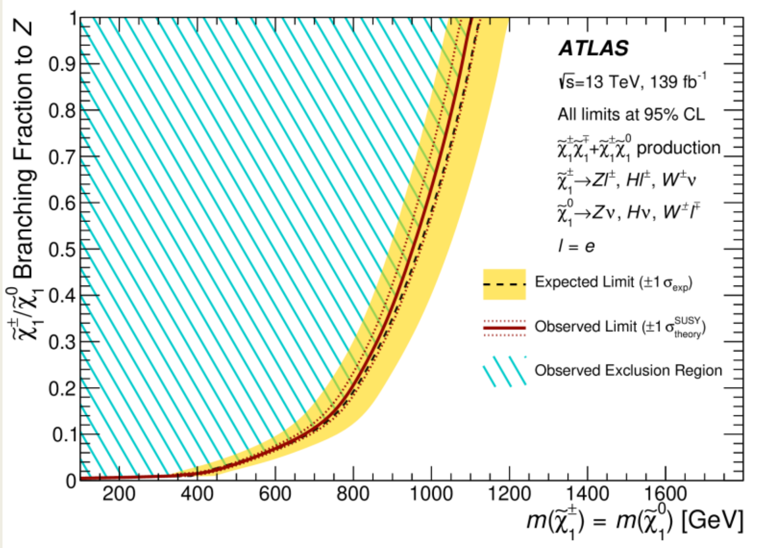




- No significant deviations over Standard Model expectation are observed

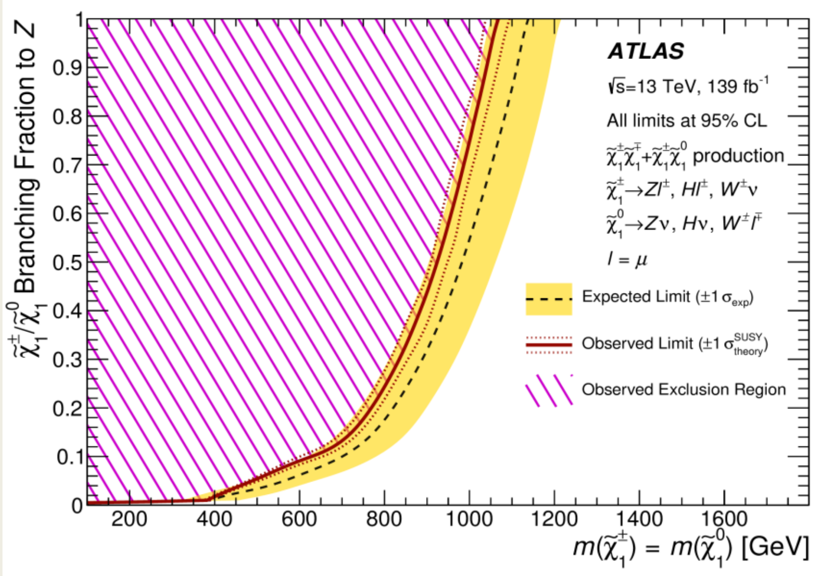
# Search for trilepton resonances: Exc. contours




Assuming decays to any lepton flavour




Assuming only decays to electrons



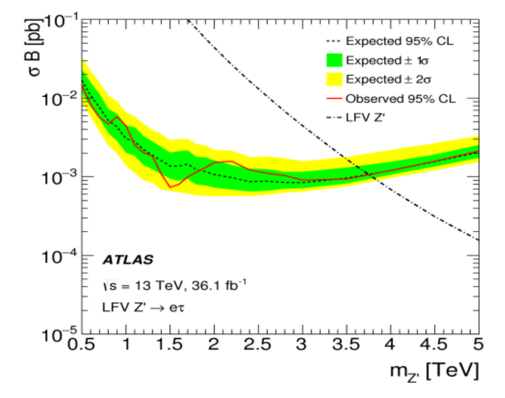

Assuming only decays to muons

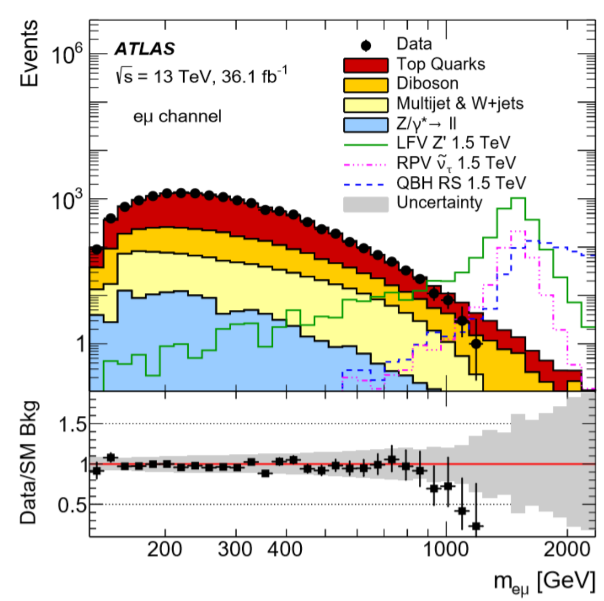
# Lepton Flavour Violation

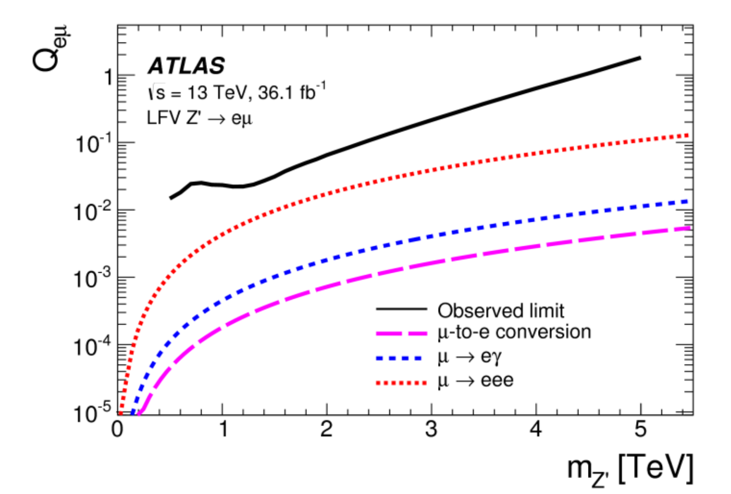
[Phys. Rev D 98 (2018) 112010]

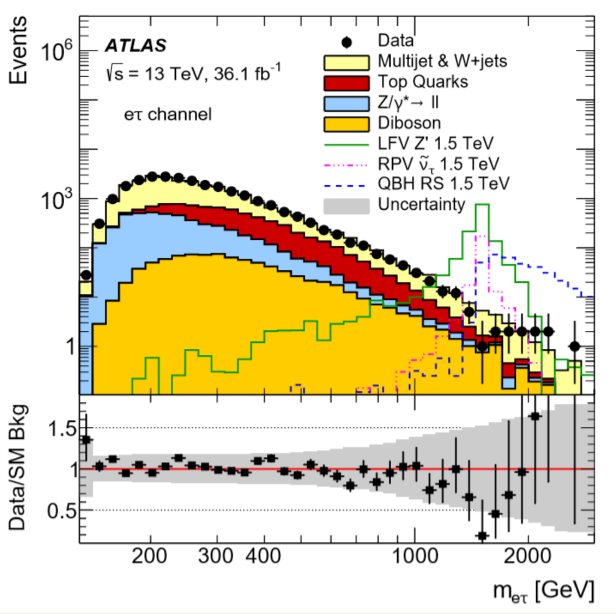
- Follow-up to the result with the 2015+16 dataset
- Search in eμ,eτ and μτ final states at high mass
- No analogous CMS search for τ-final states

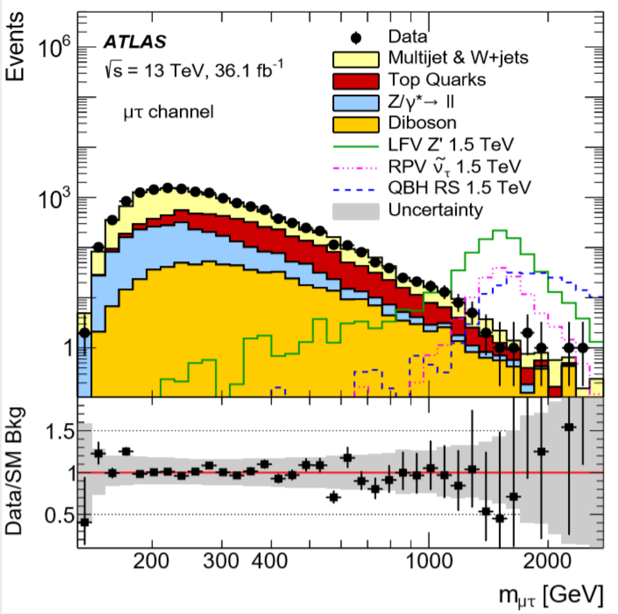
- Main background are Top quark in eμ and W+jets for the τ-final states
- Consider 1 and 3-prong hadronic taus, currently studying if 2-prong are possible
- Cross-section Limits extracted on LFV Z' and RPV SUSY and converted to couplings limits, comparing to low-energy exp results

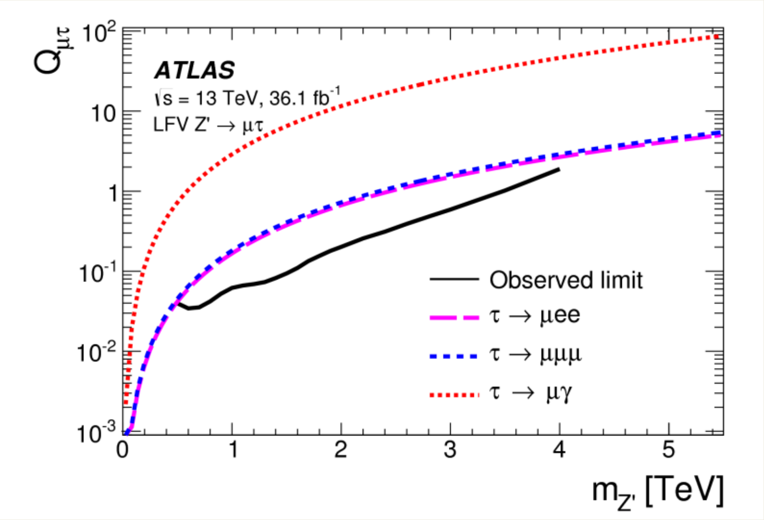


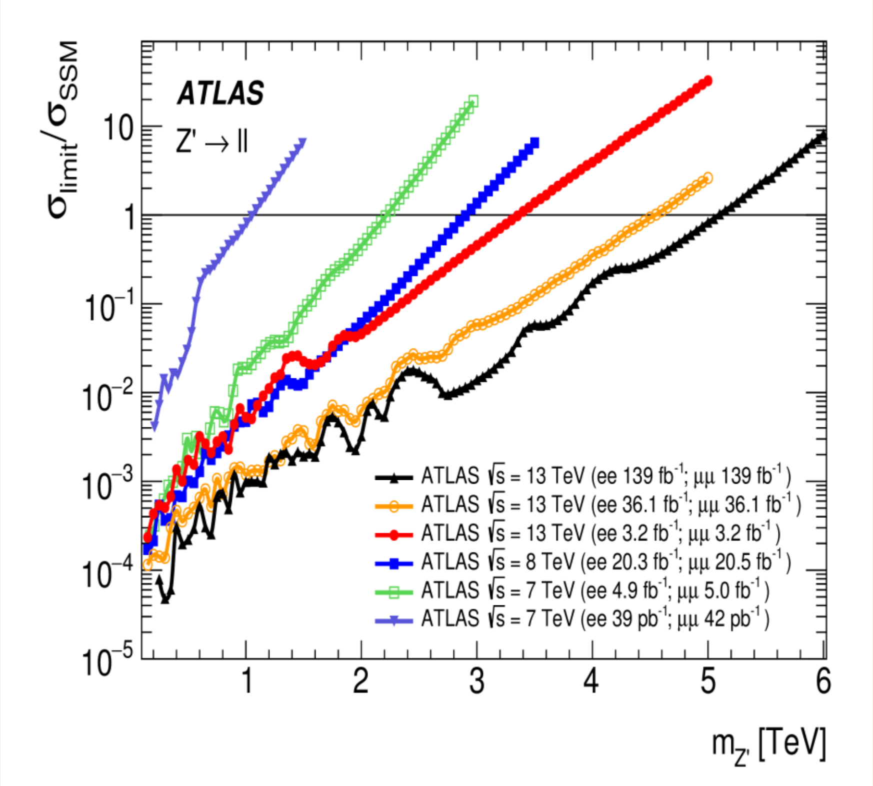



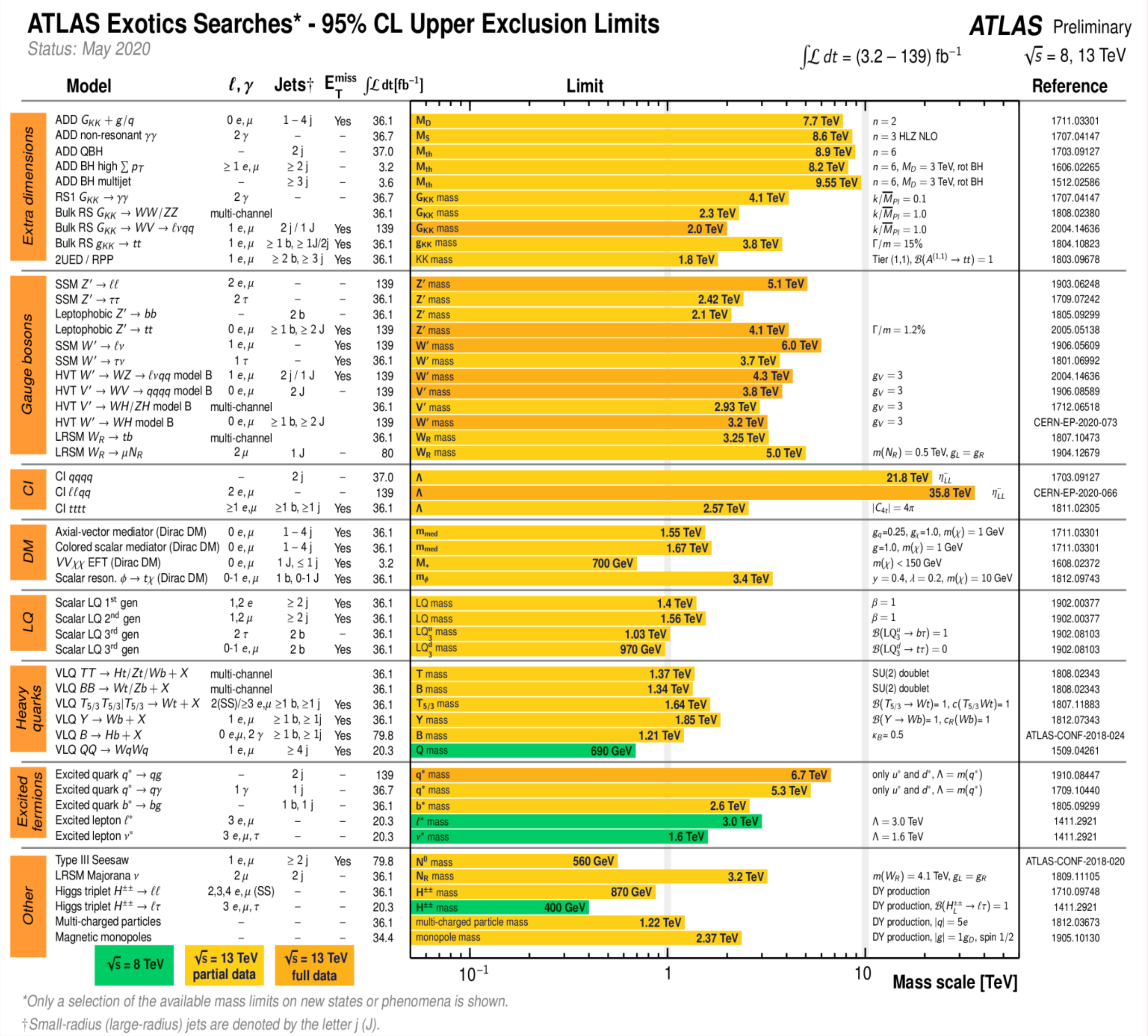



# Summary

- More analyses still to come with the full Run-2 dataset in the coming months!



# Dilepton Search: Systematics

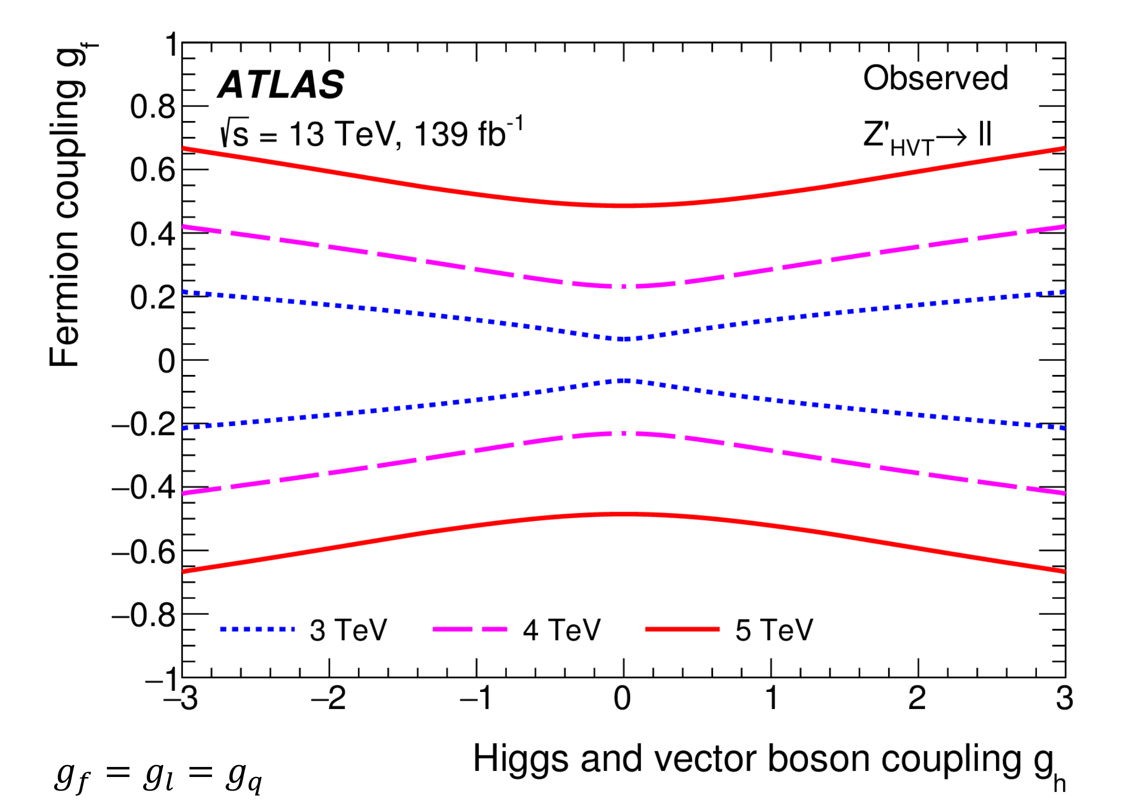
| Uncertainty source for $m_X$ [GeV] | Dielectron 300 | Dielectron 5000 | Dimuon 300 | Dimuon 5000 |
|---|---|---|---|---|
| Spurious signal | $\pm 12.5$ (12.0) | $\pm 0.1$ (1.0) | $\pm 11.7$ (11.0) | $\pm 2.1$ (2.2) |
| Lepton identification | $\pm 1.6$ (1.6) | $\pm 5.6$ (5.6) | $\pm 1.8$ (1.8) | $^{+25}_{-20}$ $\left(^{+25}_{-20}\right)$ |
| Isolation | $\pm 0.3$ (0.3) | $\pm 1.1$ (1.1) | $\pm 0.4$ (0.4) | $\pm 0.4$ (0.5) |
| Luminosity | $\pm 1.7$ (1.7) | $\pm 1.7$ (1.7) | $\pm 1.7$ (1.7) | $\pm 1.7$ (1.7) |
| Electron energy scale | $^{-1.7}_{-4.0}$ $\left(^{+1.0}_{-1.8}\right)$ | $^{+0.1}_{-0.4}$ $(\pm 0.8)$ | - | - |
| Electron energy resolution | $^{+7.9}_{-8.3}$ $\left(^{+1.1}_{-0.9}\right)$ | $^{+0.4}_{-0.9}$ $(\pm 0.1)$ | - | - |
| Muon ID resolution | - | - | $^{+0.8}_{-2.3}$ $\left(^{+0.3}_{-0.8}\right)$ | $^{+0.6}_{-0.4}$ $\left(^{+0.5}_{-0.3}\right)$ |
| Muon MS resolution | - | - | $^{+2.8}_{-3.8}$ $\left(^{+1.0}_{-1.3}\right)$ | $\pm 2.4$ (2.1) |
| 'Good muon' requirement | - | - | $\pm 0.6$ (0.6) | $^{+55}_{-35}$ $\left(^{+55}_{-35}\right)$ |

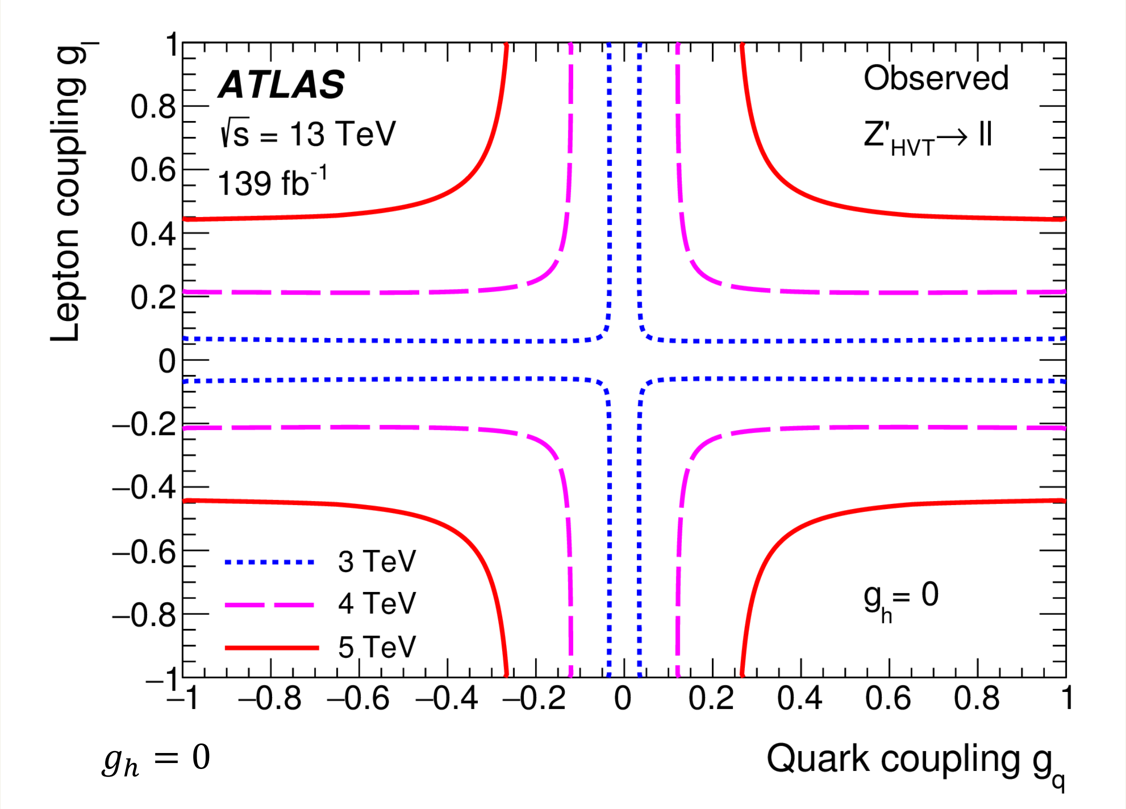
Systematics for zero (10) % width

# Lepton+MET: Systematics

| Source | Electron channel | | Muon channel | |
|---|---|---|---|---|
| | Background | Signal | Background | Signal |
| Trigger | negl. (negl.) | negl. (negl.) | 1% (1%) | 2% (2%) |
| Lepton reconstruction and identification | negl. (negl.) | negl. (negl.) | 7% (21%) | 5% (29%) |
| Lepton momentum scale and resolution | 4% (3%) | 4% (3%) | 3% (12%) | 7% (10%) |
| Multijet background | 7% (113%) | N/A (N/A) | 1% (1%) | N/A (N/A) |
| Top extrapolation | 2% (5%) | N/A (N/A) | 3% (3%) | N/A (N/A) |
| Top normalization | $< 0.5\%$ ($< 0.5\%$) | N/A (N/A) | $< 0.5\%$ ($< 0.5\%$) | N/A (N/A) |
| Diboson extrapolation | 2% (9%) | N/A (N/A) | 3% (10%) | N/A (N/A) |
| PDF choice for DY | 1% (14%) | N/A (N/A) | $< 0.5\%$ ($< 0.5\%$) | N/A (N/A) |
| PDF variation for DY | 8% (12%) | N/A (N/A) | 7% (11%) | N/A (N/A) |
| EW corrections for DY | 4% (5%) | N/A (N/A) | 4% (6%) | N/A (N/A) |
| Luminosity | 2% (1%) | 2% (2%) | 2% (2%) | 2% (2%) |
| Total | 13% (115%) | 4% (4%) | 12% (29%) | 9% (31%) |

# Dilepton Search: HVT Exclusion Contour




- Limits extracted on the Fermion-Higgs/Vector Boson and Quark-lepton coupling parameter space
- Area outside the curve is excluded
- HVT bosons can couple to fermions (f), leptons (l), and Higgs (h)

# Dilepton Search: parametric function

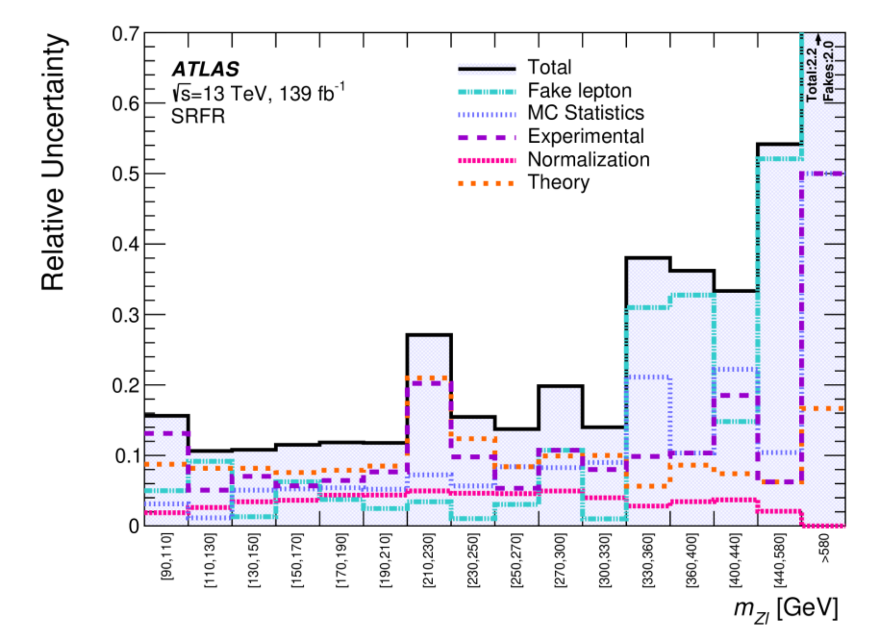
The smooth functional form for the background is based on fit performance studies on a MC background template. The associated uncertainties are also estimated through these studies. In order to minimise the statistical uncertainties in this procedure, the background template for DY is produced from large-statistics samples simulated only at generator level and smeared by the experimental dilepton mass resolution, described in the previous section, with mass-dependent acceptance and efficiency corrections applied. A similar procedure is applied to the generator-level dilepton mass distribution in the $t\bar{t}$ sample exploiting the larger number of events from the generator-level mass distribution. The distributions from the diboson and single-top simulated samples and, in the electron channel, a template for multi-jet and $W$+jet processes are also considered. All MC-based contributions are scaled by their respective cross-sections.

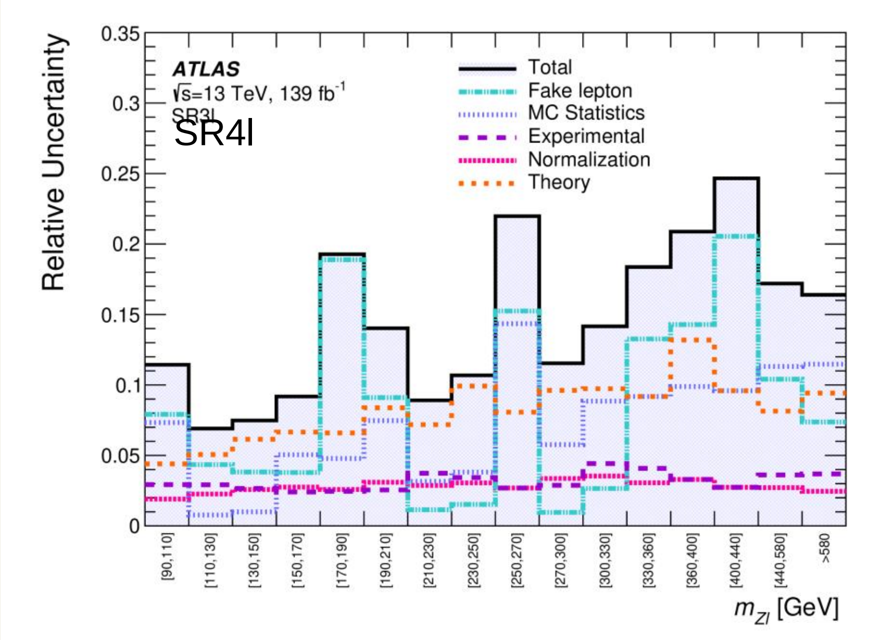
In order to select the background functional form, a fit to the dilepton mass background template is performed, under the signal plus background hypothesis, for various functional forms, following the procedure outlined in Ref. [47]. The chosen functional form is the one with the smallest absolute number of fitted signal events ('spurious signal'), which are determined as as a function of $m_{\ell\ell}$:

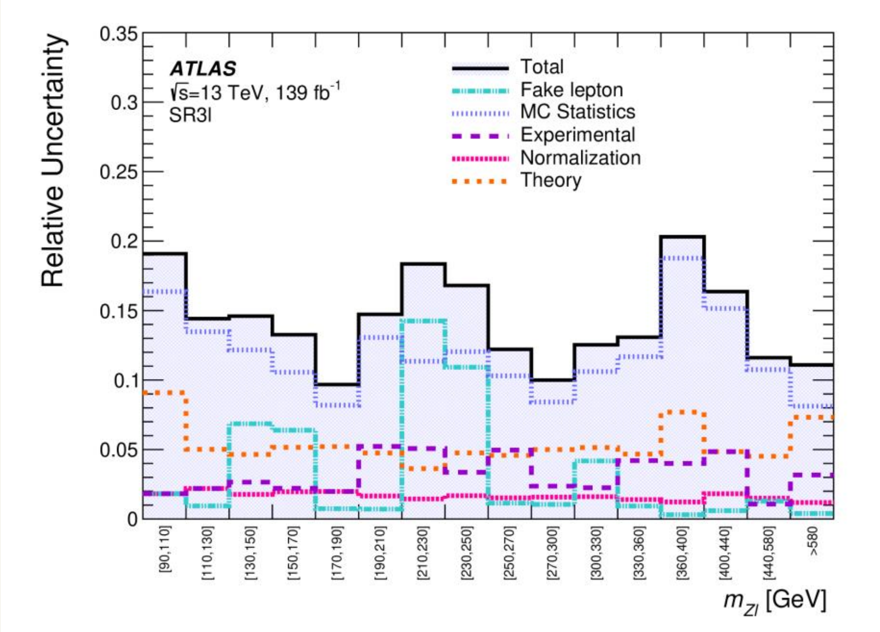
$$f_{\ell\ell}(m_{\ell\ell}) = f_{\mathrm{BW},Z}(m_{\ell\ell}) \cdot (1 - x^c)^b \cdot x^{\sum_{i=0}^{3} p_i \log(x)^i}, \quad (1)$$

where $x = m_{\ell\ell}/\sqrt{s}$ and parameters $b$ and $p_i$ with $i = 0, ..3$ are left free in the fit to data and independent for dielectron and dimuon channels. The parameter $c$ is 1 for the dielectron and 1/3 for the dimuon channel. The function $f_{\mathrm{BW},Z}(m_{\ell\ell})$ is a non-relativistic Breit–Wigner function with $m_Z = 91.1876$ GeV and $\Gamma_Z = 2.4952$ GeV [48]. The normalisation of the background function is such that the integral $a$ corresponds to the total number of background events. To further validate this functional form an extra degree of freedom ($i = 4$) is added to the fit function before the final data analysis, to check if it improves the likelihood value of the fit by more than $2\sigma$. To check the fit stability in the high-mass region, signal injection tests are performed at various mass points. No significant bias in the number of extracted signal events is observed.

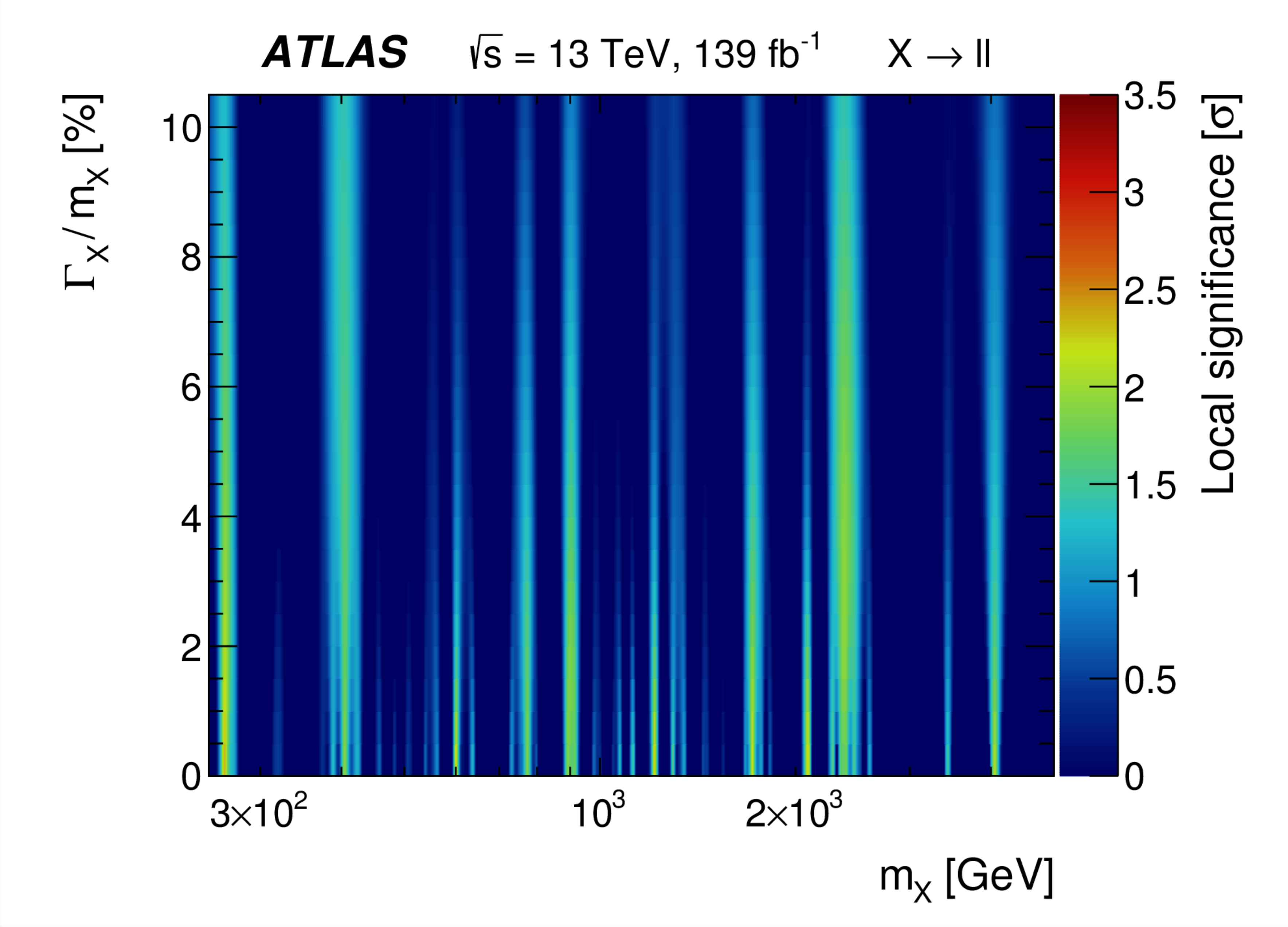
# Search for trilepton resonances: systematics



# Dilepton Search: 2-D width & mass scan

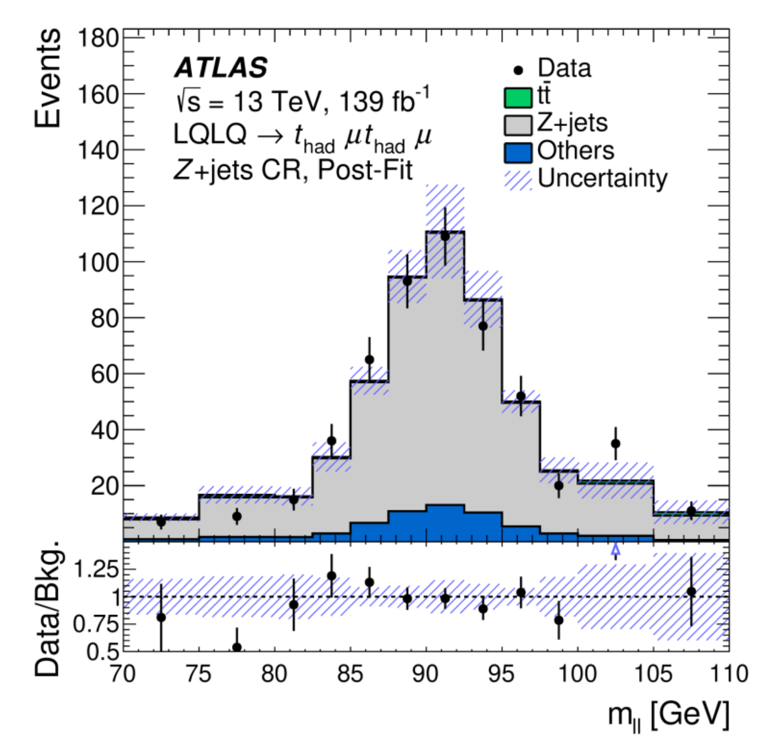


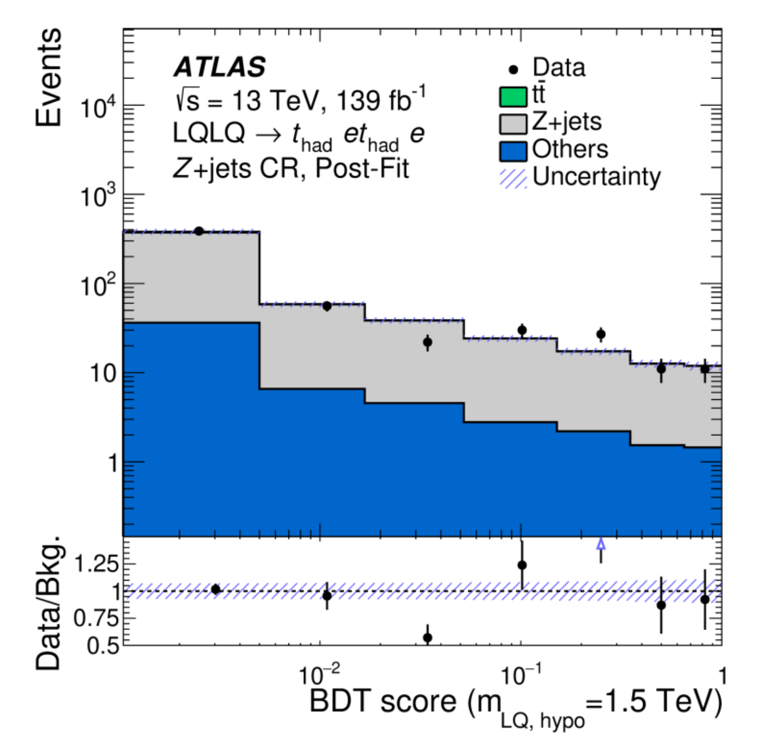
# Scalar Leptoquark search with top quarks

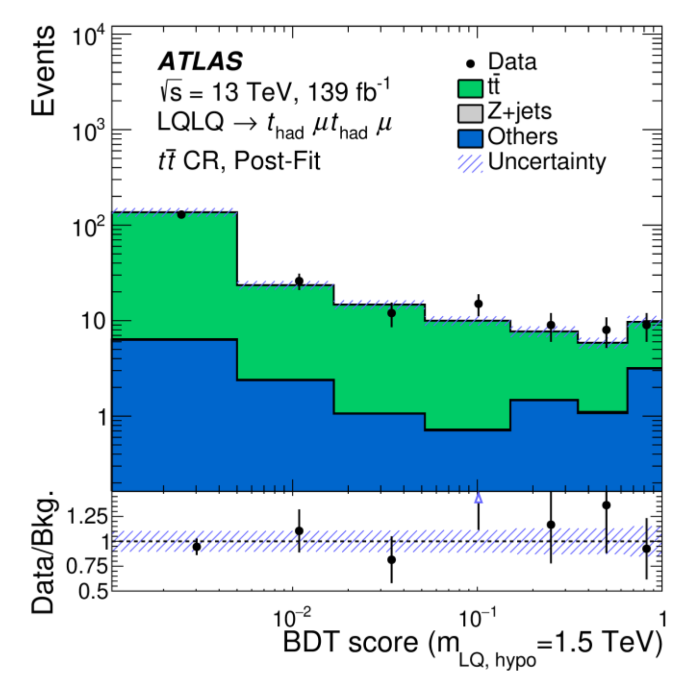
ArXiv 2010.02098

- This search focuses on leptoquarks decaying to electrons/muons+top quarks, where the top decays hadronically
- It is optimized for LQ masses above 1 TeV, where the outgoing top is heavily boosted and a large-R jet can be used as proxy for it
- Control regions are used to extract the background normalization from data
- Due to the higher complexity, a Boosted Decision Tree is used to discriminate between signal- and background-like events

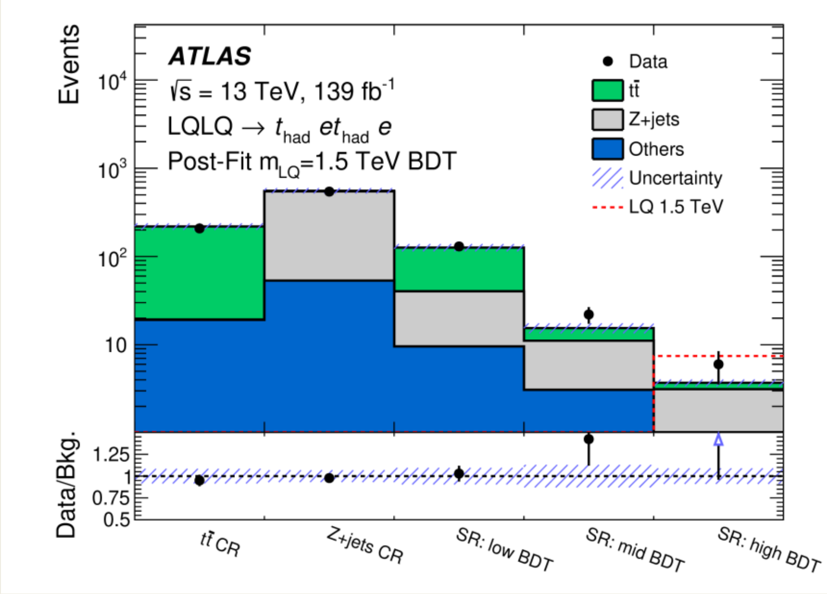
| | $t\bar{t}$ CR | $Z$ + jets CR | SR |
|---|---|---|---|
| Leptons | $p_{\mathrm{T}}^{\ell} > 100$ GeV, $\lvert\eta_e\rvert < 2.47$, $\lvert\eta_\mu\rvert < 2.5$ | | |
| | $N_\ell = 2$; opposite-sign | | |
| Large-$R$ jets | $p_{\mathrm{T}}^{\mathrm{J}} > 200$ GeV, $\lvert\eta_{\mathrm{J}}\rvert < 2.0$, $m_{\mathrm{J}} > 50$ GeV | | |
| | $N_{\mathrm{J}} \geq 2$ | | |
| Dilepton invariant mass | $m_{\ell\ell} > 120$ GeV | 70 GeV < $m_{\ell\ell}$ < 110 GeV | $m_{\ell\ell} > 120$ GeV |
| Lepton flavour | $e\mu$ | $ee$ or $\mu\mu$ | |



# Scalar Leptoquark search with top quarks




No significant excess is found in the observed data