ATLAS + CMS Searches Beyond Inclusive Resonances in Leptonic Final States

LHCP 2021, TeV-scale BSM,
June 7, 2021

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on behalf of the ATLAS and CMS collaborations

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Introduction & Outline

- There are many searches performed in leptonic final states beyond the ones with inclusive resonances.
- Covered in this talk:
  - Processes with with a lepton and missing transverse momentum
  - Non-resonant processes in dilepton events
  - Lepton flavour violation searches
  - Multilepton processes and model independent searches
- The following topics will be covered later this week:
  - Resonances and heavy mediators (Joint BSM session, Wednesday)
  - SUSY (TeV-scale BSM: SUSY, Tuesday)
  - Leptoquarks and vector-like quarks (TeV-scale BSM: Third generation and flavour, Thursday)

Processes With One Light Lepton and E_T^{miss}

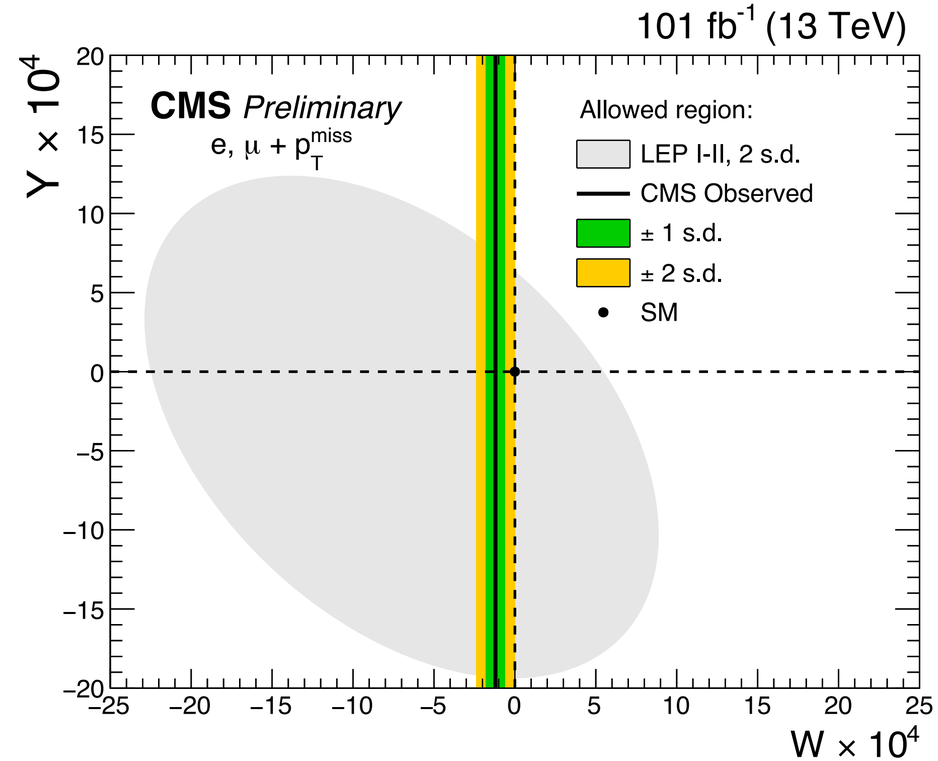
CMS-PAS-EXO-19-017

- The tails of transverse mass M_T in single lepton W+jets events with high missing transverse momentum can also be used for non-resonant searches.

$$M_T = \sqrt{2p_T^{\ell} E_T^{miss} \left(1 - cos[\Delta\phi(\ell, E_T)]\right)}$$

- Effective field theory (EFT) interpretations quantify potential deviations from SM expectations through the oblique electroweak W parameter, as a correction to the propagator $qq \to W \to l\nu$, Phys. Rev. D 46, 381.
  - Selection:
    - high transverse momentum electrons (p_T > 240 GeV) or muons (p_T > 53 GeV)
    - E_T^{miss} with p_T/E_T^{miss} between 0.4 and 1.5 and $\Delta\phi(p_T, E_T^{miss})$ > 2.5
  - Fit result using 2017 and 2018 data:

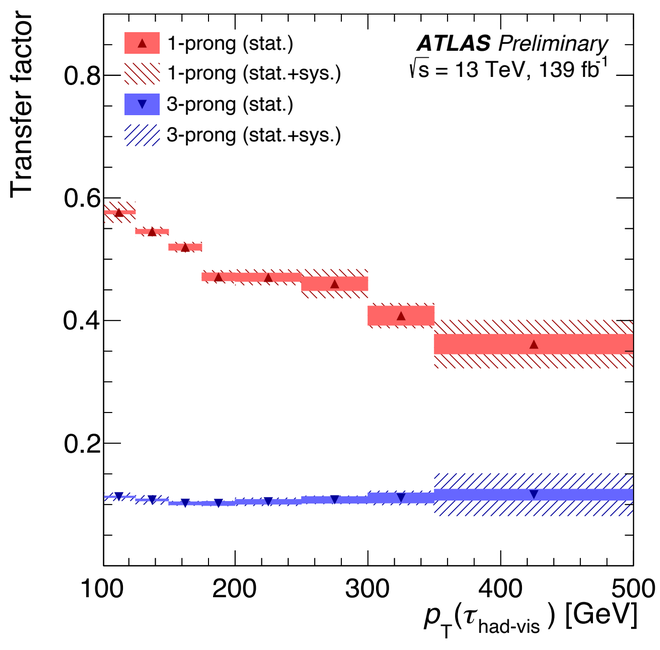
$$W = -12^{+5}_{-6} \times 10^{-5}$$

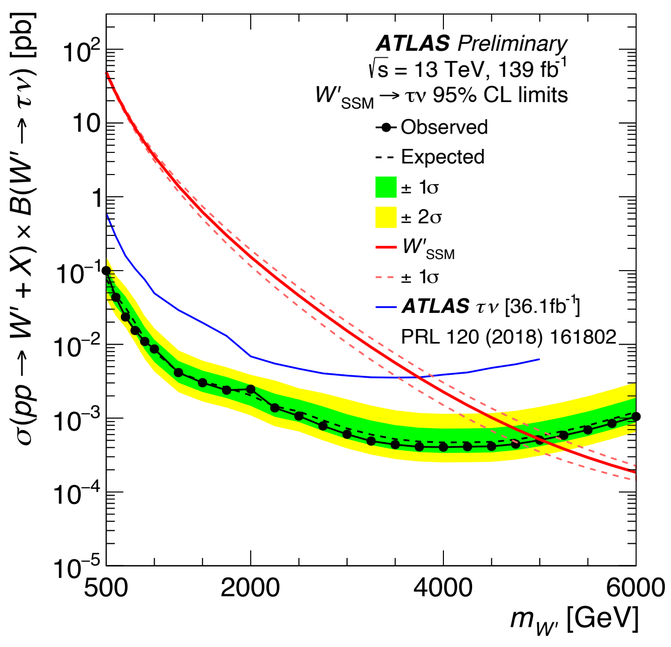


Processes With Tau-Lepton and E_T^{miss}

ATLAS-CONF-2021-025

- Events with τ-leptons in the final state yield wide resonances due to secondary (hadronic) τ decays.
- Looking for Sequential Standard Model (SSM) W' boson, Z. Phys. C 45 (1989) 109.
- Misidentification probability of jets as tau candidates propagated from control regions as transfer factors.
- W' masses excluded up to 5.0 TeV.
- Model-independent limits set on signal yields above certain transverse mass thresholds, m_T^{thresh}.

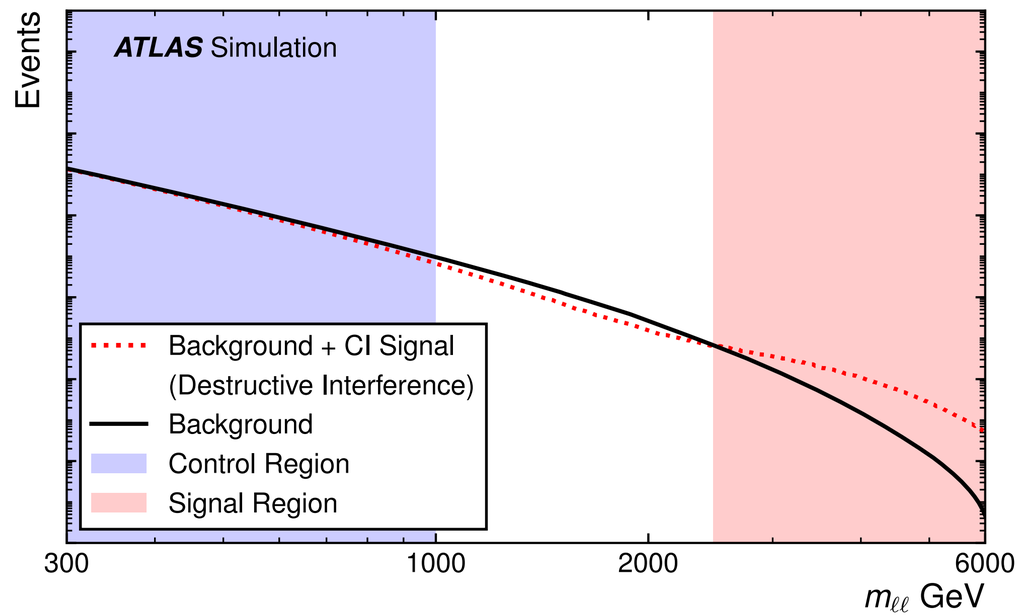




Background Modelling of Dilepton Events

Before searching for processes in dilepton events, backgrounds need to be modelled well.

ATLAS-EXOT-2019-16

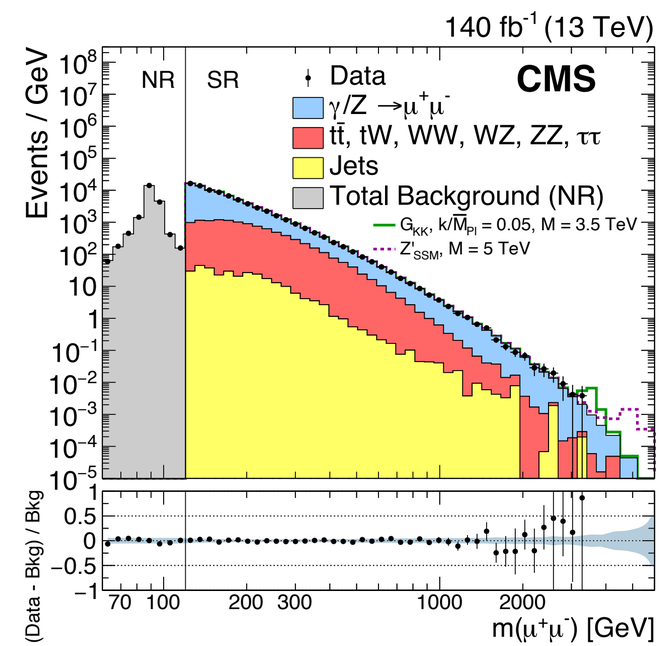


- m_{ll} distribution is fit from data by a parametric background function in a low-mass control region.
- Extrapolated to single-bin signal regions.
- Fit parameters b, c, p_i.

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

CMS-EXO-19-019

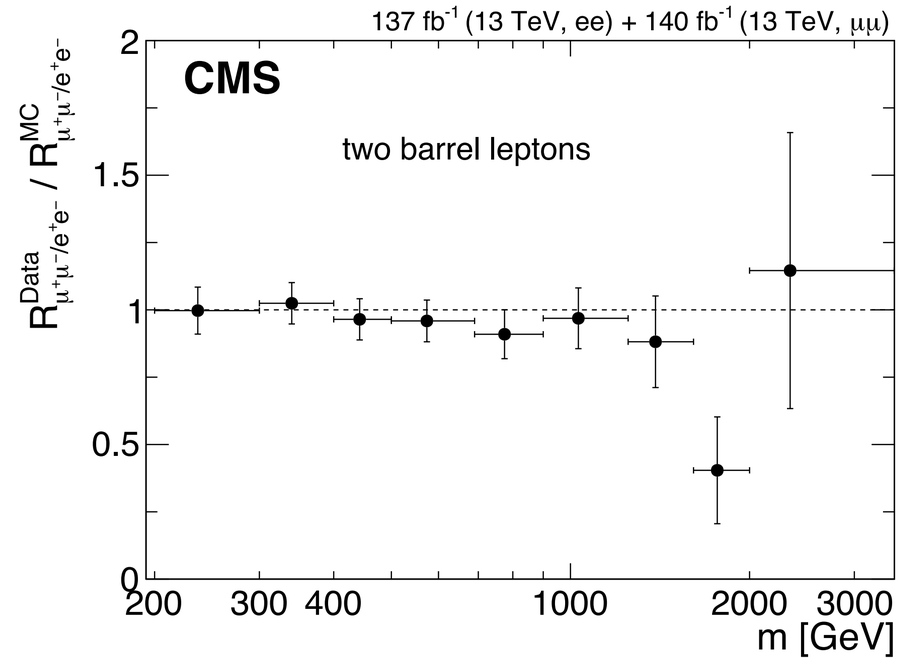
- Dominant background: Drell-Yan process, estimated from simulation.
- Jets misidentified as electrons are estimated from data.
- Combined background shape normalised to data around the Z boson mass.



Lepton Flavour Universality Violations in Dilepton Events

- Lepton flavour universality violations, other flavour anomalies, would indicate a deviation from unity of the ratio of the dimuon to dielectron differential cross section, J. Phys. G: Nucl. Part. Phys. 46 023001.
- Mass distributions in data are unfolded after subtracting all backgrounds except for DY.
- Normalised to 1 in the range 200–400 GeV to correct efficiencies between e/μ.
- Corrected with simulated DY events.
- Good agreement up to 1.5 TeV.
- One-sided p-values of 0.067 and 0.185.

$$R_{\mu^+\mu^-/e^+e^-} = \frac{d\sigma(q\bar{q} \to \mu^+\mu^-)/dm_{\ell\ell}}{d\sigma(q\bar{q} \to e^+e^-)/dm_{\ell\ell}}$$



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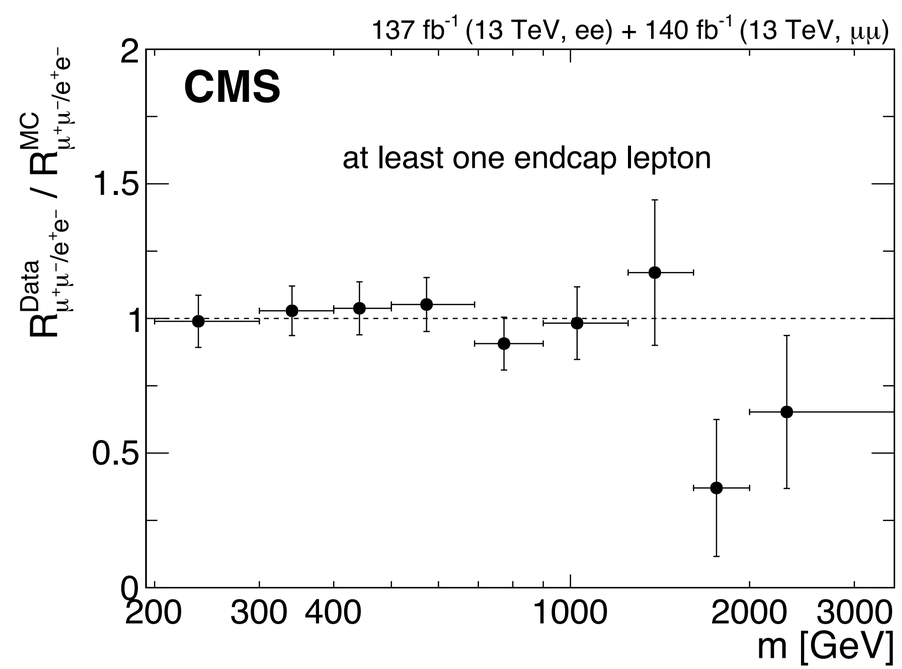


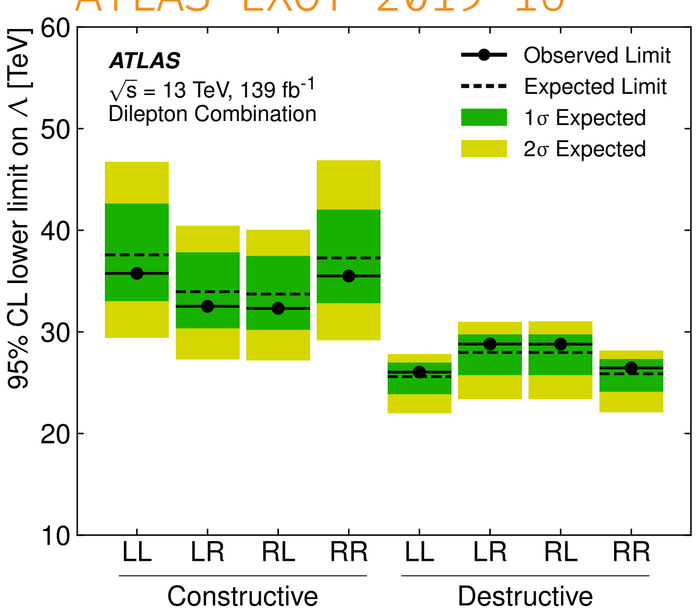
Four-fermion Contact Interaction in Dilepton Events (1)

- Quarks and leptons may be composite with at least one common constituent → effective four-fermion contact interaction at scale Λ, Rev. Mod. Phys. 56, 579, Phys. Rev. Lett. 50, 811.
- CMS studied the angle θ^* of the outgoing negatively charged lepton with respect to the z axis in the Collins–Soper frame (2 bins).

$$p^{\pm} = \frac{1}{\sqrt{2}}(E \pm p_z)$$

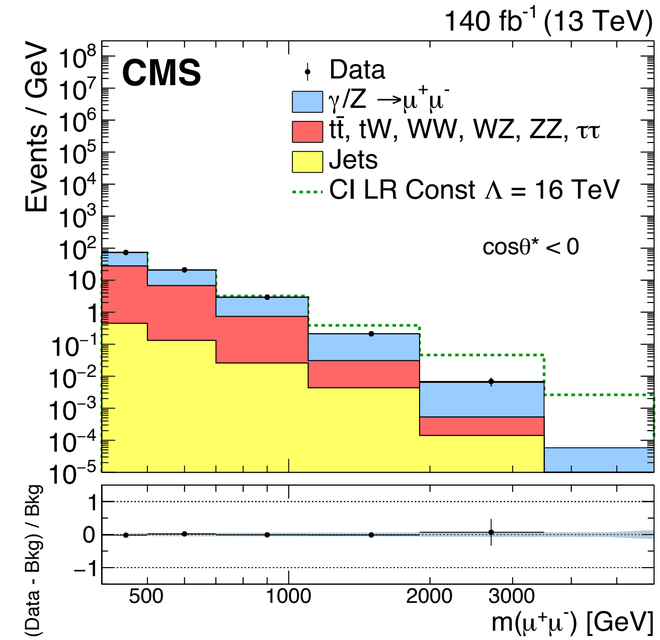
$$\cos\theta^* = \frac{p_z(\ell^+\ell^-)}{|p_z(\ell^+\ell^-)|}\frac{2(p_1^+p_2^- - p_1^-p_2^+)}{m(\ell^+\ell^-)\sqrt{m(\ell^+\ell^-)^2 + p_T(\ell^+\ell^-)^2}}$$

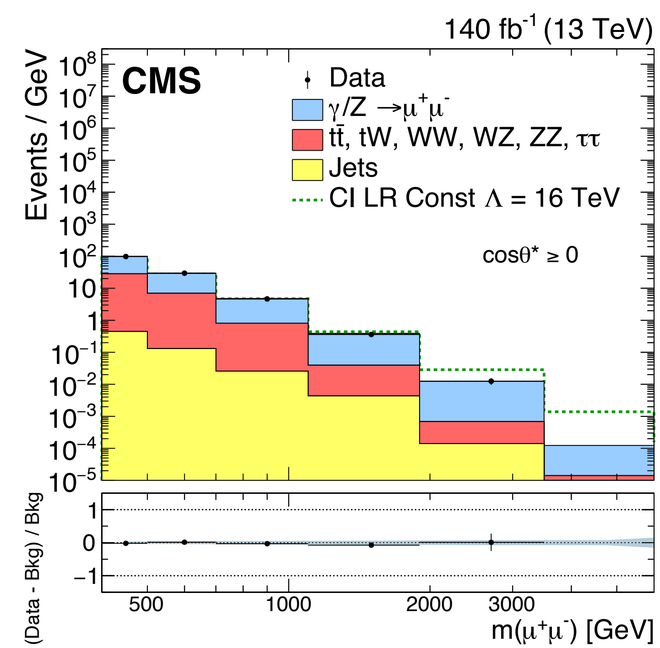
ATLAS-EXOT-2019-16



- Lower limits on the contact interaction scale Λ are set:
  - ATLAS: from 22.3 to 35.8 TeV
  - CMS: from 23.9 to 36.4 TeV
- Same regions used to search for extra dimensions in ADD models, ATL-PHYS-PUB-2021-021, CMS-EXO-19-019.

CMS-EXO-19-019

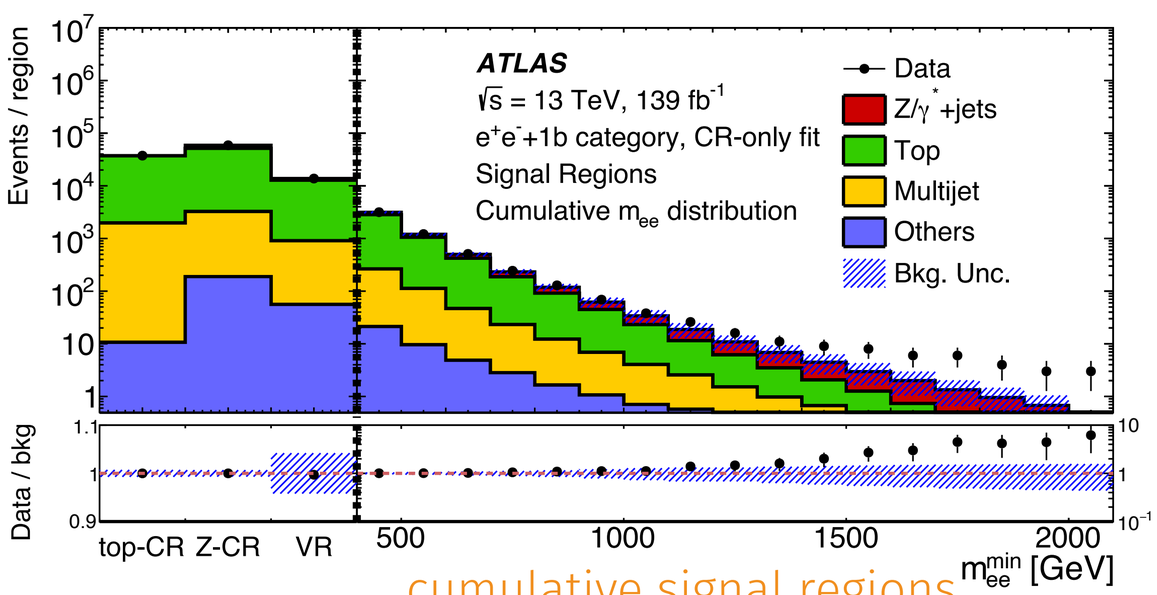




Four-fermion Contact Interaction in Dilepton Events (2)

ATLAS-EXOT-2018-16

- To explain the asymmetries measured in the B-meson decays, the $bsll$ interaction would have to be different between electrons and muons → $bsll$ contact interaction with scale Λ and coupling g_*, JHEP 08 (2018) 056, Eur. Phys. J. C 79 (2019) 714, Eur. Phys. J. C 77 (2017) 548.
- 4 categories: $e^+e^-/\mu^+\mu^-$ with 0 or 1 b-jet.
- Signal regions (SR) with lower bounds on $m_{ll}^{\min}$ starting at 400 GeV.



cumulative signal regions

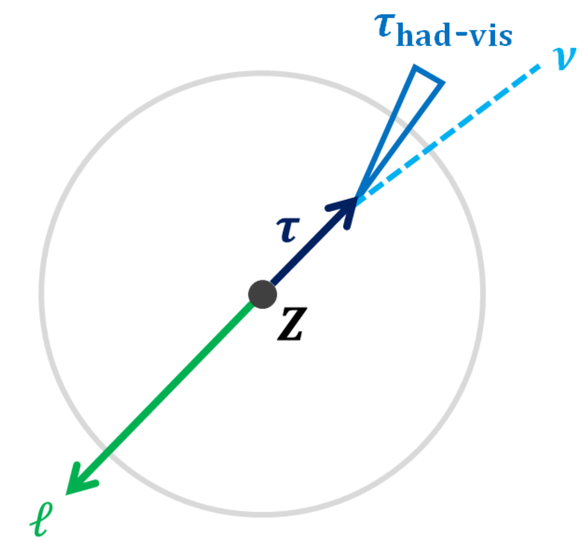
- Top and multijet backgrounds estimated from simulation, extrapolated from a $2b$ region using parametric functions.
- Z+jets fitted with for $130 < m_{ll} < 250$ GeV.
- Largest observed local significance 2.6 σ.
- Lower limits: from 1.8 to 2.4 TeV.

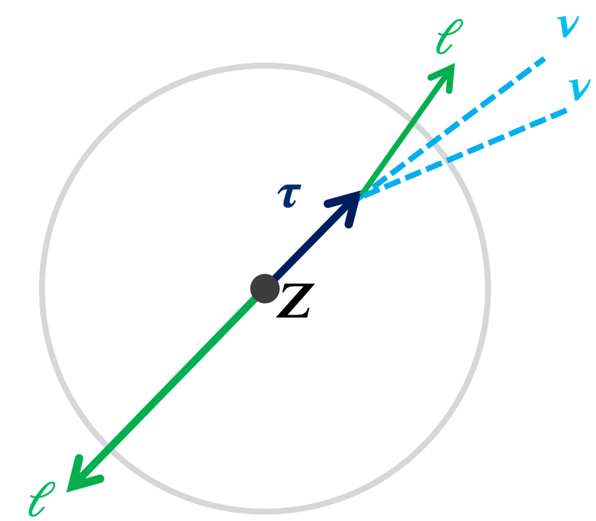
Lepton Flavour Violating Z-boson Decays (1)

ATLAS-EXOT-2020-28
ATLAS-EXOT-2018-36

- The number of leptons of each family is conserved in weak interactions, and violation of this assumption is known as lepton flavour violation (LFV).
- One in 10^{54} Z bosons would decay into a muon and a τ-lepton via neutrino mixing, one in 10^{5} in presence of heavy neutrinos, Phys. Rev. D 63, 053004.
- Searches performed in ATLAS with both leptonically and hadronically decaying τ-leptons (accepted in Nature Physics).
- Using multiple neural network classifiers (one per bkg.) and optimising their combination for the best sensitivity.

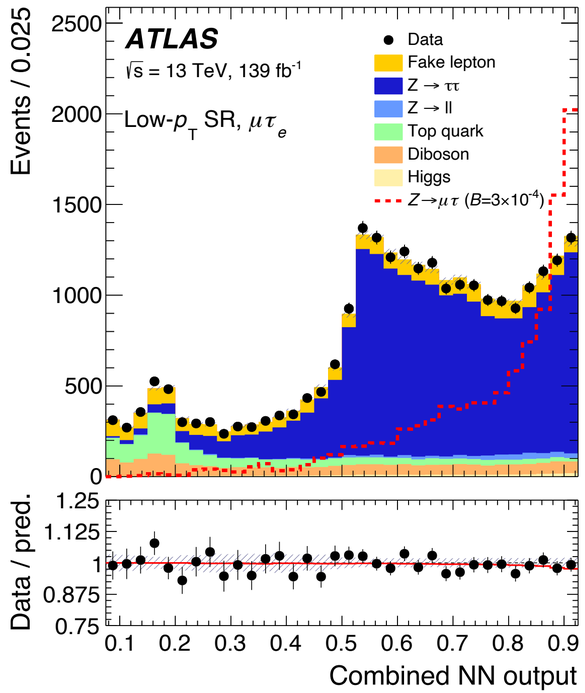
$$\text{combined NN output} = 1 - \sqrt{\frac{\sum_i w_i \times (1 - NN_i)}{\sum_i w_i}}$$



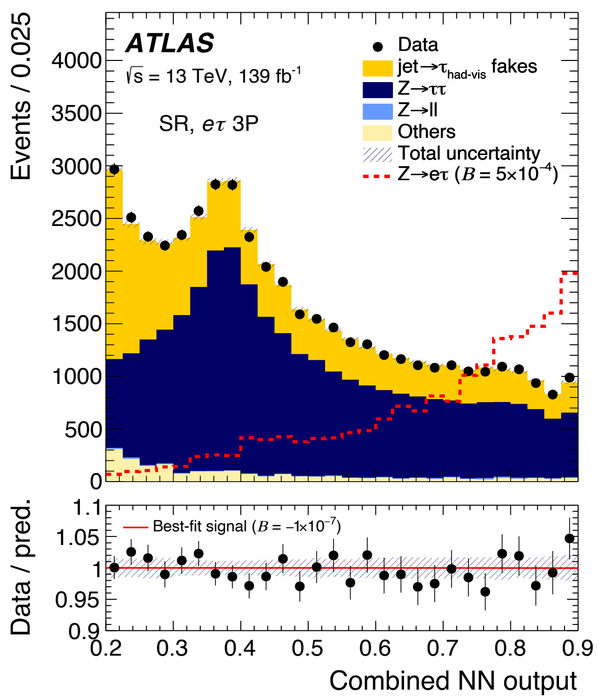


Lepton Flavour Violating Z-boson Decays (2)

τ_{lep}
$Z \to \tau\tau$
top quark
diboson



τ_{had}
$Z \to \tau\tau$
$Z \to ll$
W+jets

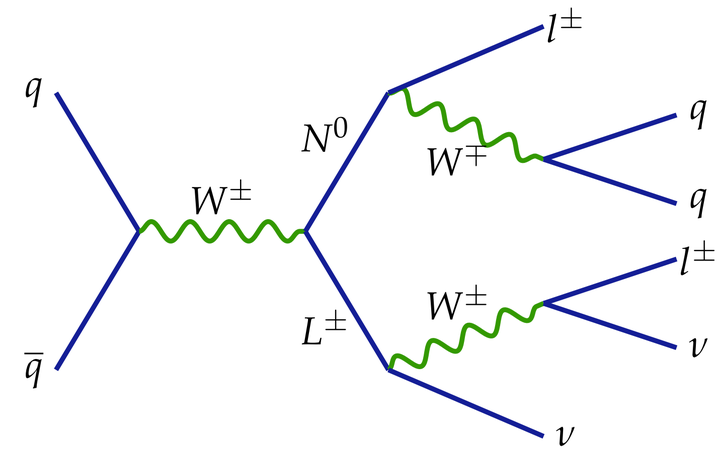


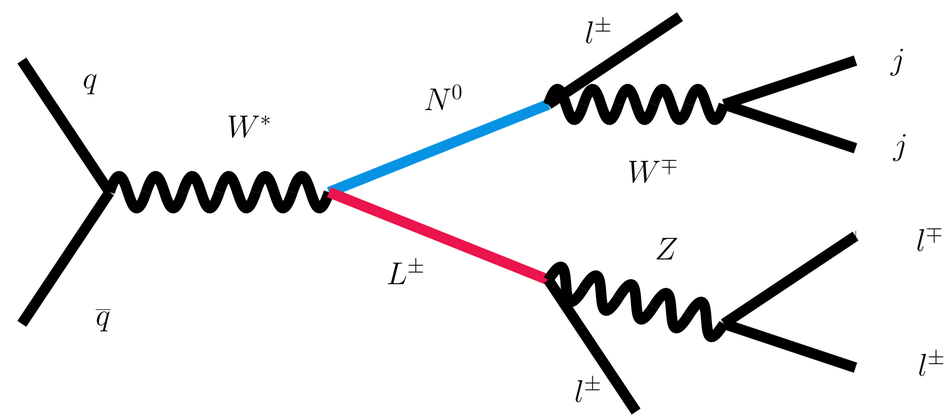
- 8 signal regions:
  - τ_{lep}: $e\tau_{lep}$ and $\mu\tau_{lep}$ split by $p_T(l_2) < 20$ (25) GeV.
  - τ_{had}: $e\tau_{had}$ and $\mu\tau_{had}$ split by the number of tracks τ-leptons decay into (1P or 3P).
- Signal region fit variable combined NN output.
- Z control region fit variable $m_{coll}(l_1, l_2)$ = invariant mass of l_1–l_2–2ν system where neutrinos are assumed collinear with l_2.
- Fitted parameters:
  - τ_{lep}: yields of signal, $Z \to \tau\tau$, top quarks, and misidentified leptons.
  - τ_{had}: yields of signal, $Z \to \tau\tau$, misidentified τ-jets separately for 1P or 3P τ_{had}.
- Combined limit on $B(Z \to e\tau)$ set to 5×10^{-6} and on $B(Z \to \mu\tau)$ to 6.5×10^{-6}.

Multilepton Final States: Type-III Seesaw Heavy Leptons (1)

ATLAS-CONF-2021-023
ATLAS-EXOT-2018-33

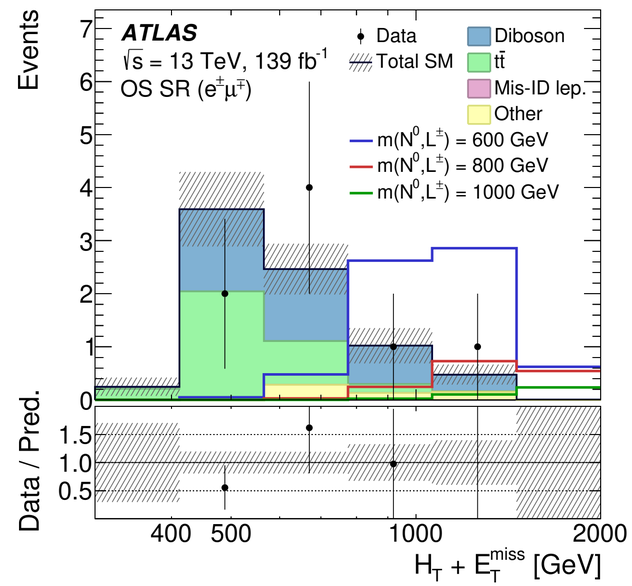
- The seesaw mechanism: explaining the relative smallness of the neutrino masses.
- Minimal type-III seesaw — an extra fermionic triplet:
  one neutral (N^0) and two oppositely-charged leptons (L^+, L^-),
  Phys. C - Particles and Fields (1989) 44, 441, Eur. Phys. J. C (2012) 72, 1899.
- Decays into a SM lepton and a W, Z or H boson, the highest branching ratio into W.
- Probed a few possible lepton/jet multiplicities:
  - two light leptons, at least two jets
  - three light leptons, zero or one jet
  - three light leptons, at least two jets
  - four light leptons, any number of jets



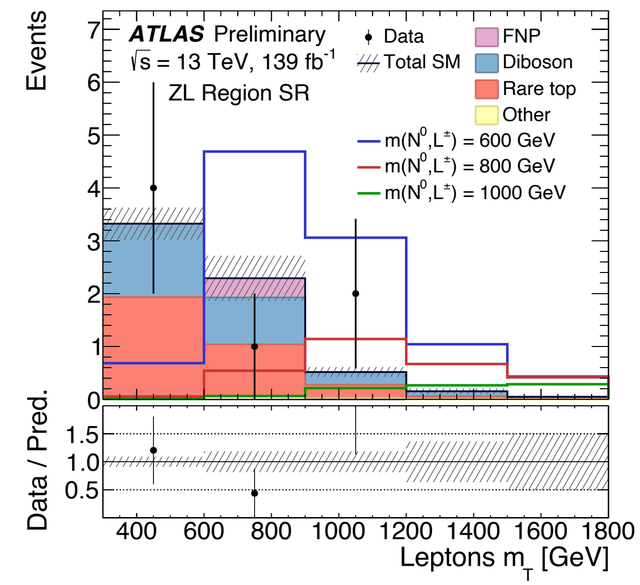


Multilepton Final States: Type-III Seesaw Heavy Leptons (2)

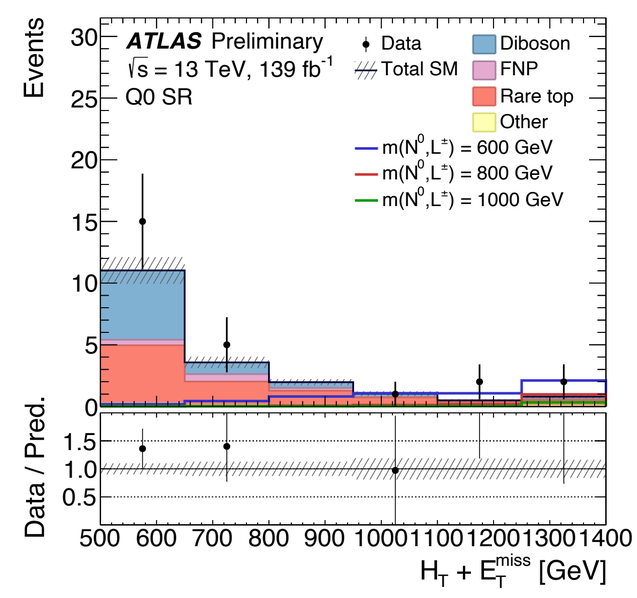
- 11 signal regions (SR) in total:
  - 6 dilepton SRs: all lepton flavour and charge combinations
  - 3 trilepton SRs: on-Z and off-Z with 2+ jets, inclusive with 0-1 jets
  - 2 four lepton SRs: sum of lepton charge 0 or 2
- High E_T^{miss} with good reconstruction significance required — neutrinos.
- Demanding background estimation: large fraction of non-prompt and fake leptons, leptons with misreconstructed charge.
- Heavy leptons with masses below 910 GeV are excluded.



dilepton
OS *eμ*

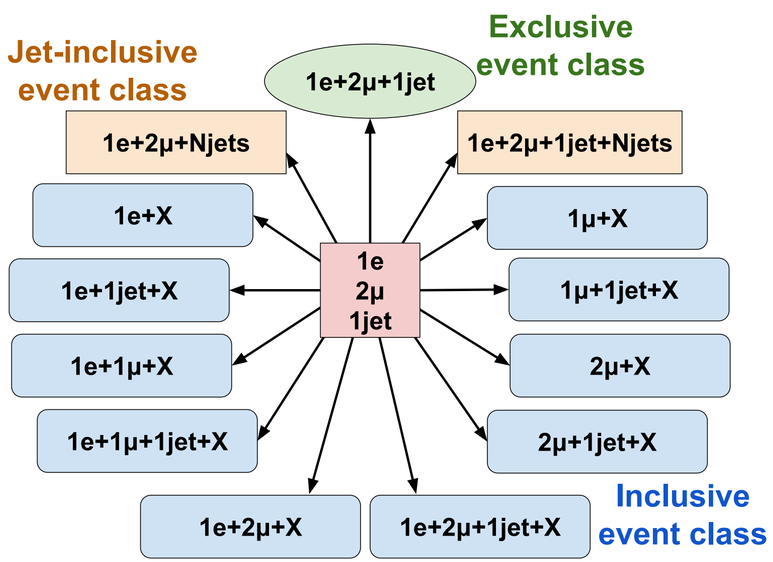


trilepton
on-*Z*, 2+ jets



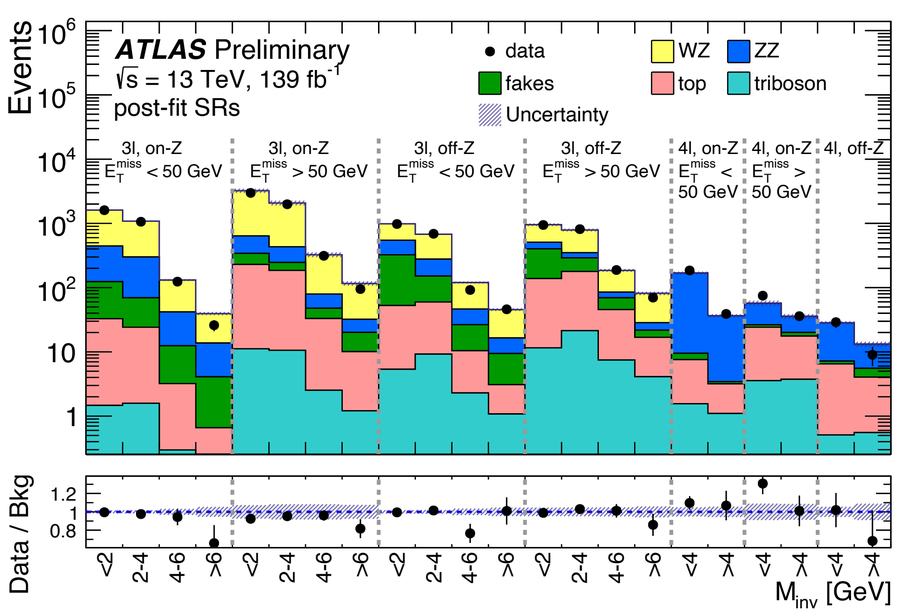
four lepton,
charge = 0

Model Independent Searches

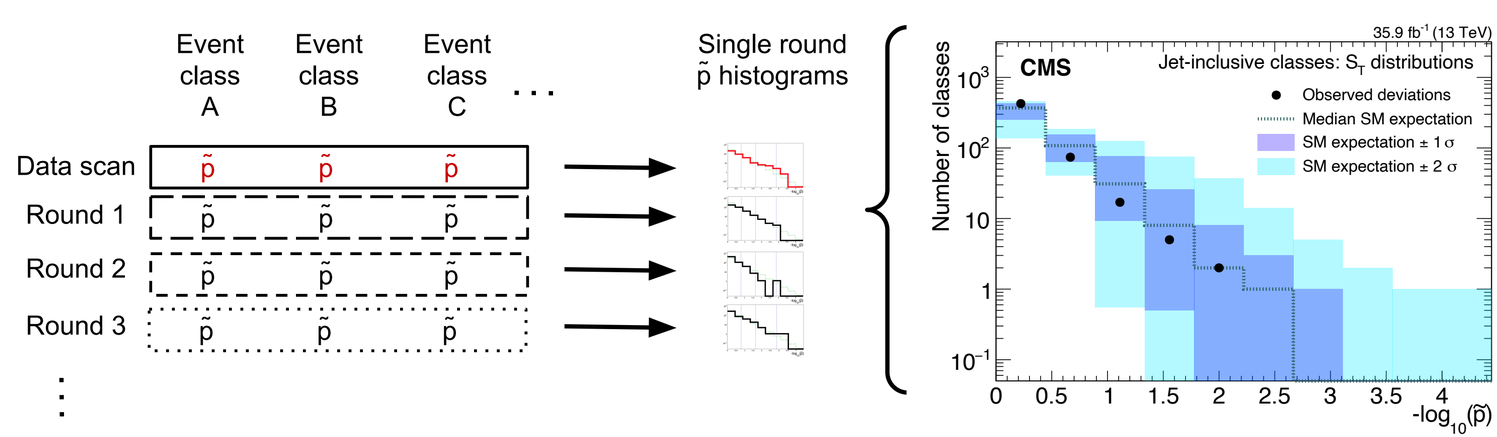


- What if LHC data can not be described with our preferred model? Can a more generalised search be performed?
- ATLAS: 22 single-bin signal regions
  - Measured number of signal events $\hat{N}_{\mathrm{sig}}$ as difference between the estimated background and the data.
- CMS: about 60 classes
  - Search for regions: taking the ones with smallest p-value.
  - Global overview: observed deviations are compared with pseudo-experiments using the SM-only hypothesis.

ATLAS-CONF-2021-011



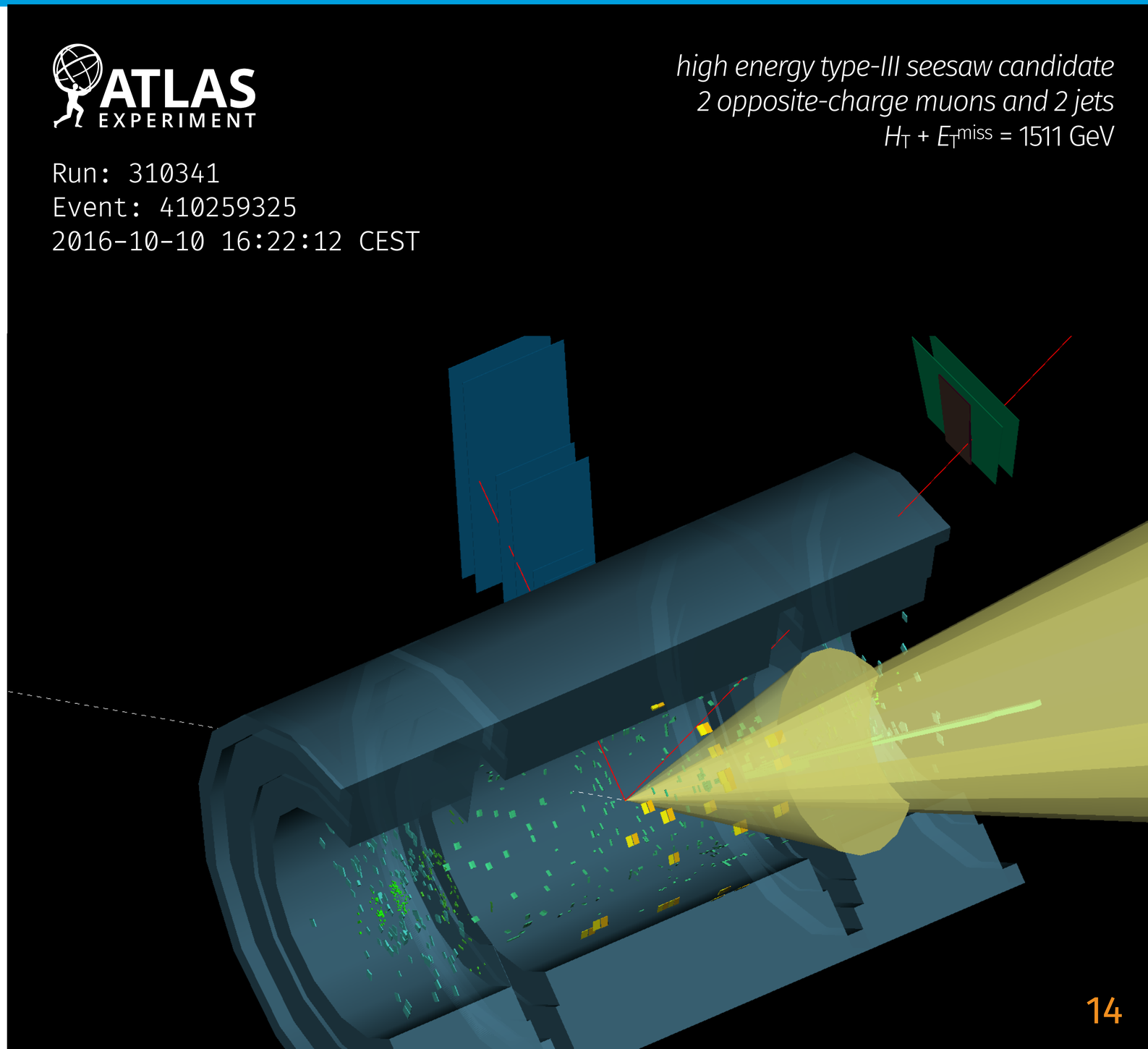
CMS-EXO-19-008



Conclusions

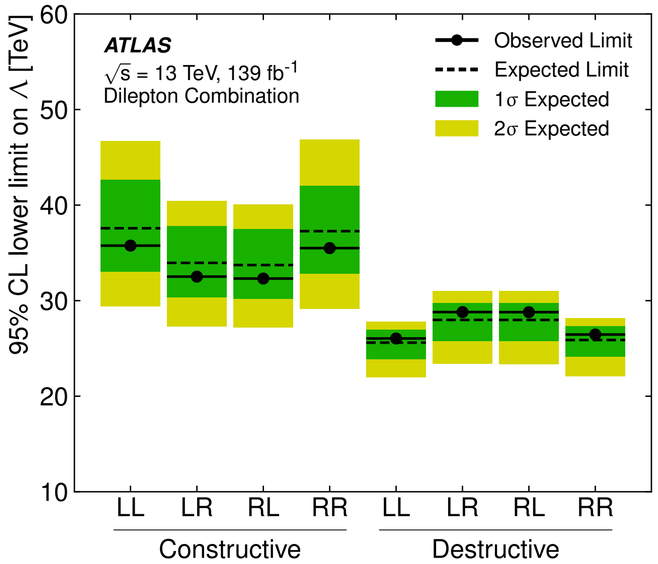
- ATLAS and CMS performed many non-resonant searches with leptons in the final state.
- No significant excess from the Standard Model has been observed.
- Many searches of full Run 2 data still being completed.
- Run 3 just around the corner.

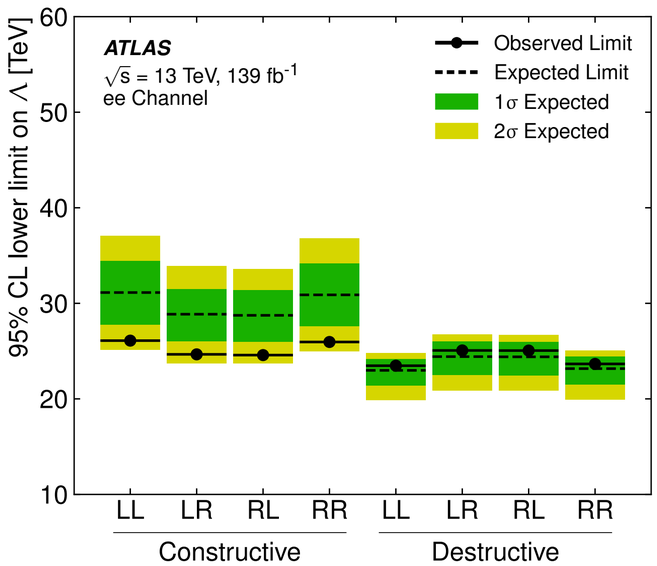
ATLAS Publications
CMS Publications

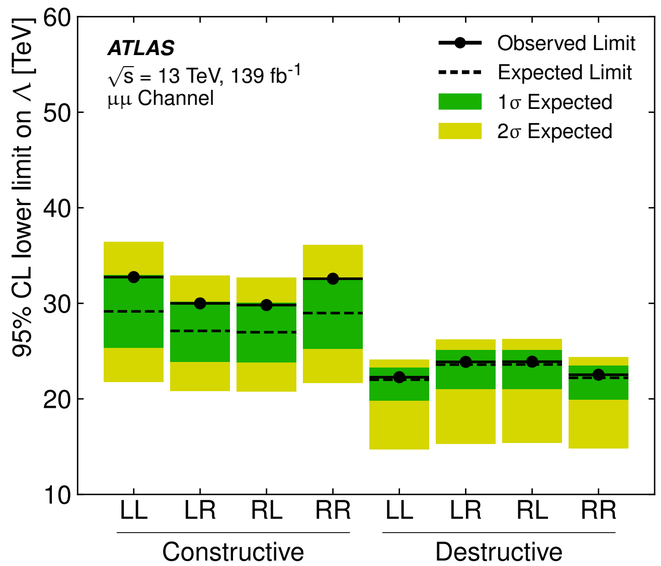


Four-fermion Contact Interaction — All Limits (1)

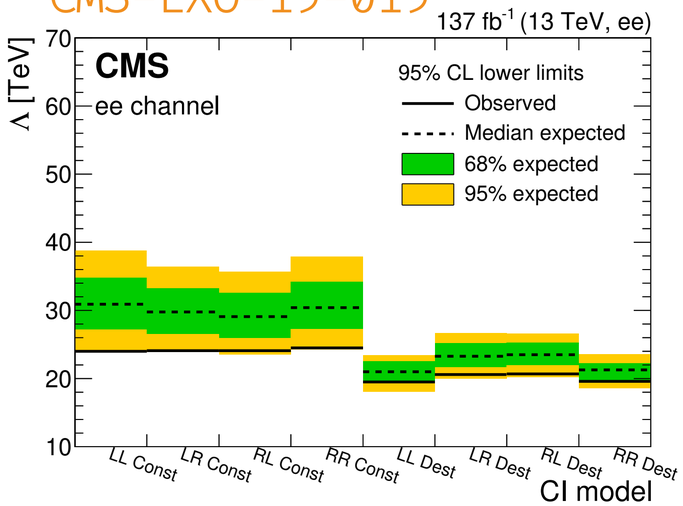
ATLAS-EXOT-2019-16

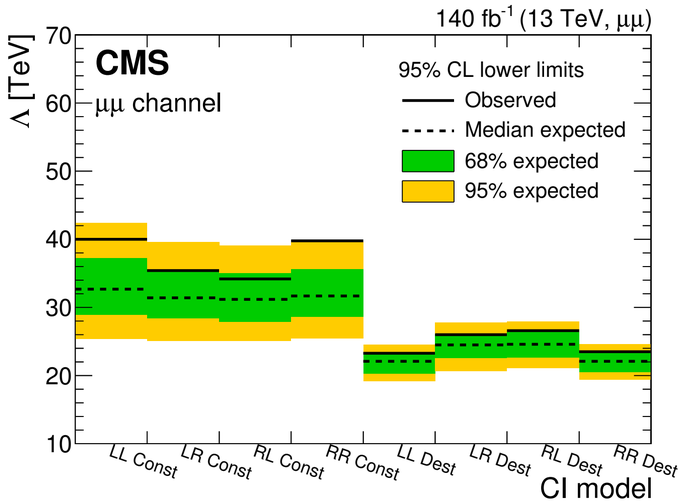


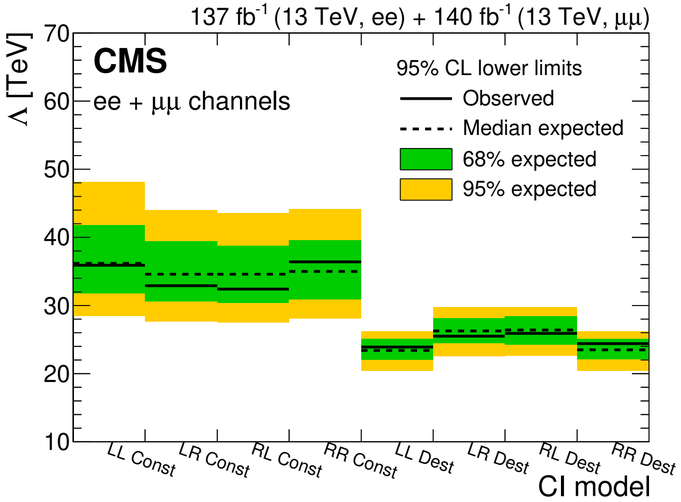




CMS-EXO-19-019

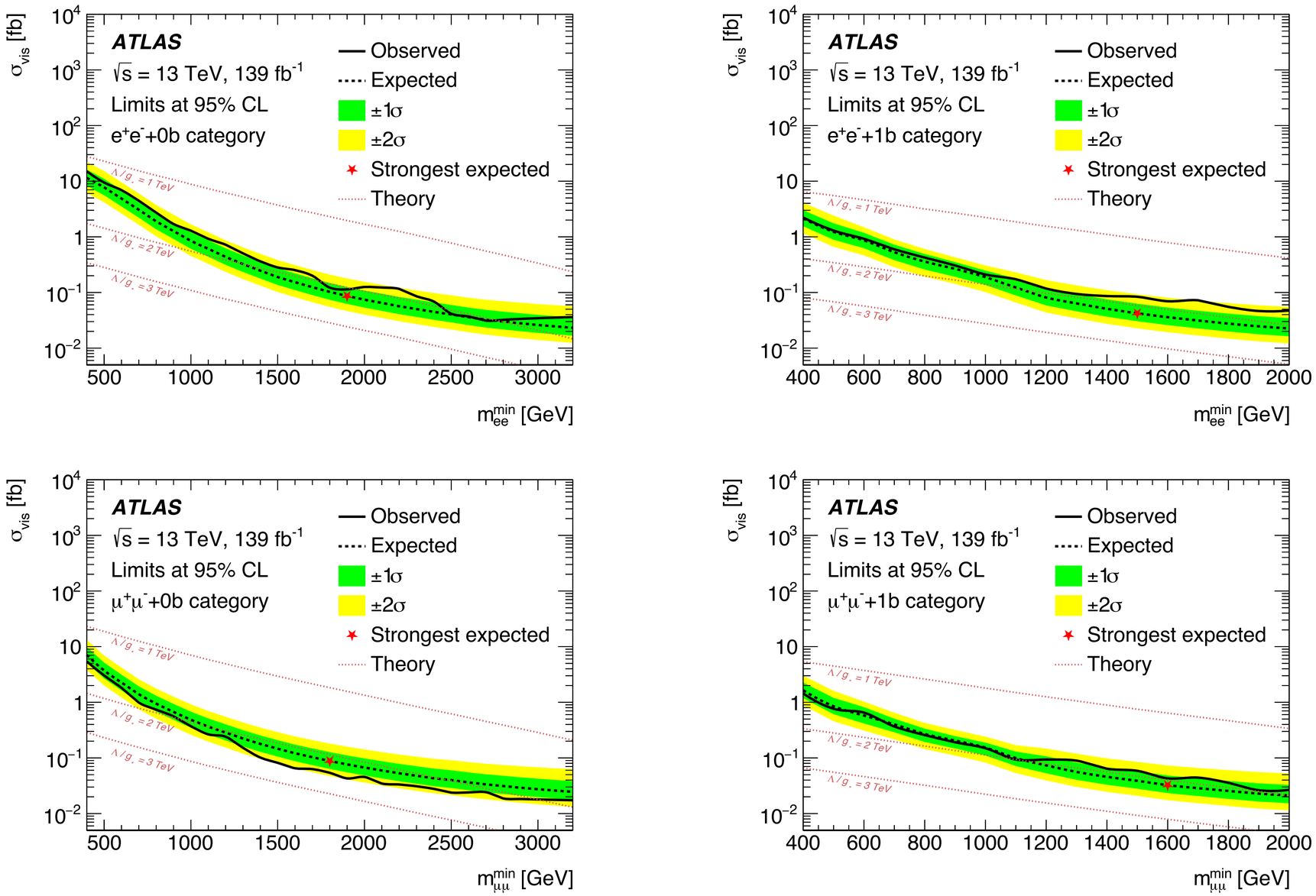






Four-fermion Contact Interaction — All Limits (2)

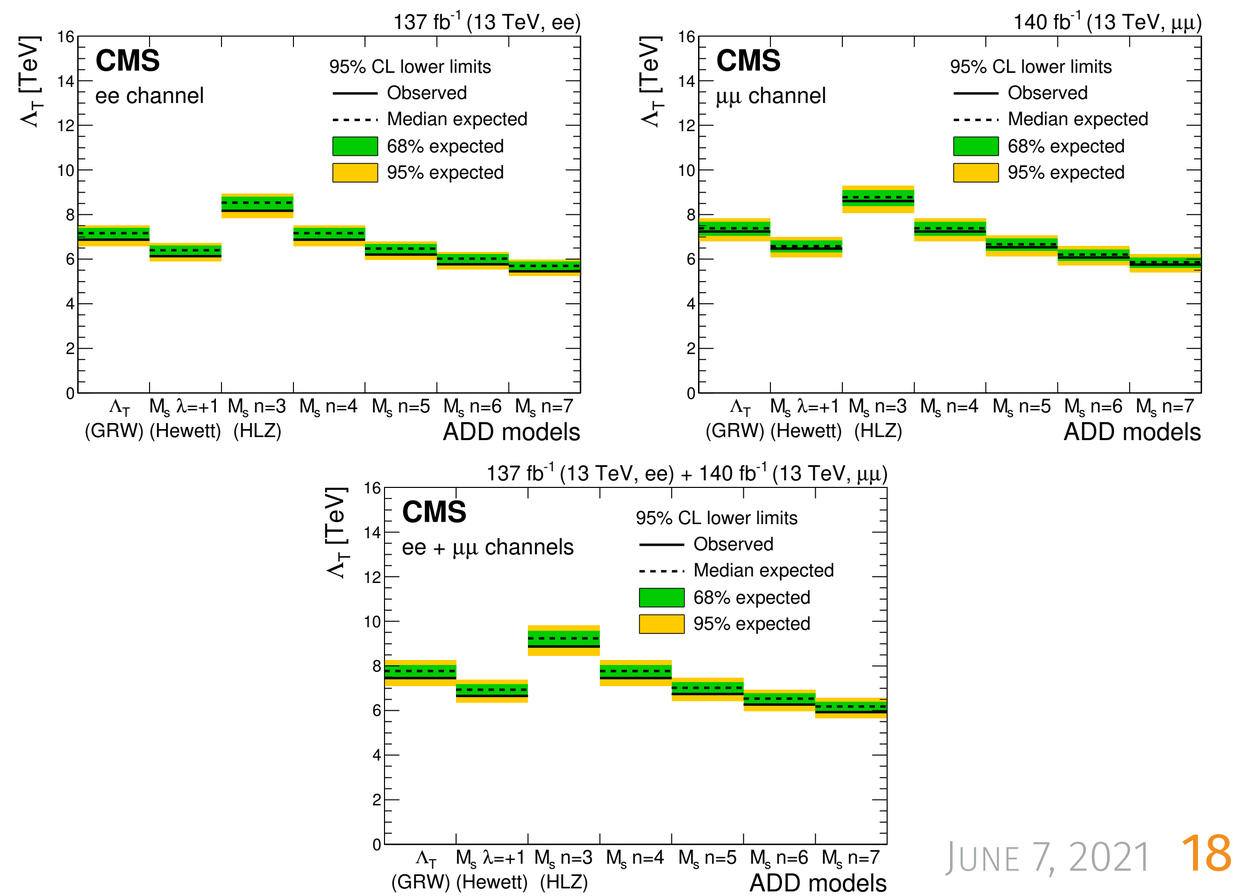
ATLAS-EXOT-2018-16



ADD Models with Extra Dimensions in Dilepton Events

ATL-PHYS-PUB-2021-021
CMS-EXO-19-019

- Large difference between the energy scales of electroweak symmetry breaking and gravitation → gravitational force could propagate into additional dimensions; models by Arkani-Hamed, Dimopoulos, and Dvali (ADD), Phys. Lett. B 429 (1998) 263.
- ATLAS recently performed reinterpretation of the contact interaction search.
- Dedicated CMS search.
- Lower limits on the model parameters in the different ADD conventions are set:
  - Giudice-Rattazzi-Wells
  - Hewett
  - Han-Lykken-Zhang



Lepton Flavour Violating Z-boson Limits

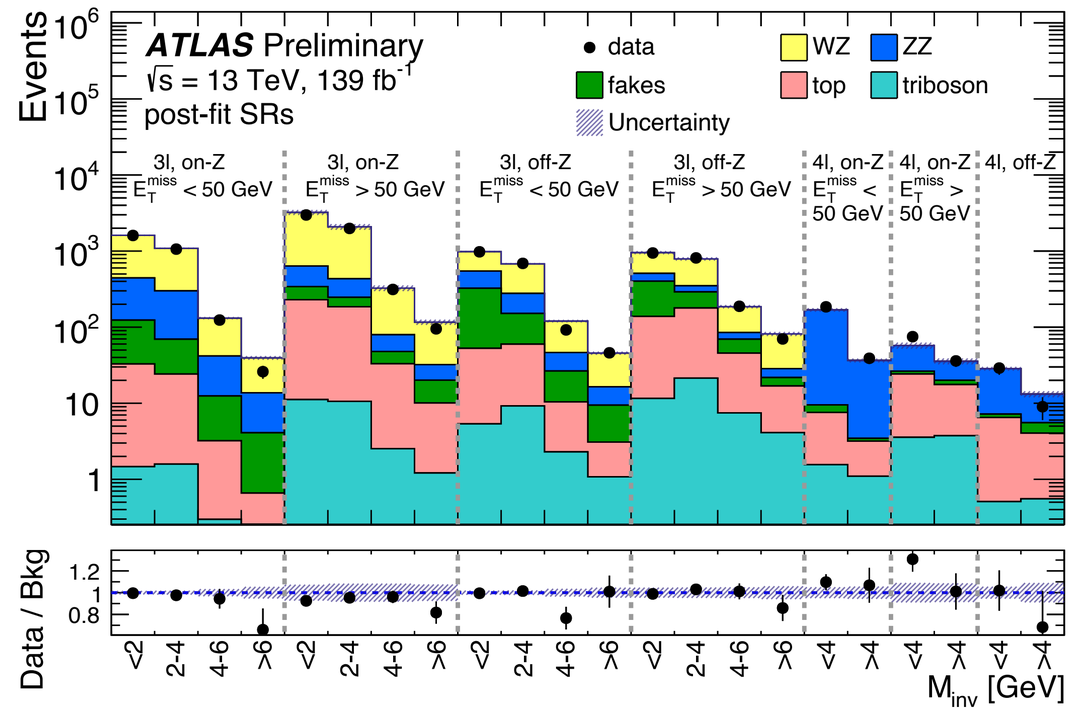
ATLAS-EXOT-2020-28
ATLAS-EXOT-2018-36

Final state, polarization assumption	Observed (expected) upper limit on $\mathcal{B}(Z \to \ell\tau)$ [$\times 10^{-6}$] $e\tau$	$\mu\tau$
$\ell\tau_{\text{had}}$ Run 1 + Run 2, unpolarized τ	8.1 (8.1)	9.5 (6.1)
$\ell\tau_{\text{had}}$ Run 2, left-handed τ	8.2 (8.6)	9.5 (6.7)
$\ell\tau_{\text{had}}$ Run 2, right-handed τ	7.8 (7.6)	10 (5.8)
$\ell\tau_{\ell'}$ Run 2, unpolarized τ	7.0 (8.9)	7.2 (10)
$\ell\tau_{\ell'}$ Run 2, left-handed τ	5.9 (7.5)	5.7 (8.5)
$\ell\tau_{\ell'}$ Run 2, right-handed τ	8.4 (11)	9.2 (13)
Combined $\ell\tau$ Run 1 + Run 2, unpolarized τ	5.0 (6.0)	6.5 (5.3)
Combined $\ell\tau$ Run 2, left-handed τ	4.5 (5.7)	5.6 (5.3)
Combined $\ell\tau$ Run 2, right-handed τ	5.4 (6.2)	7.7 (5.3)

Model Independent Search in ATLAS

ATLAS-CONF-2021-011

- What if LHC data can not be described with out preferred model? Can a more generalised search be performed?
- Very important to estimate background contributions with high precision.
- 22 single-bin signal regions categorised by
  - lepton count (3 or 4 leptons)
  - presence of an on-Z lepton pair
  - magnitude of invariant mass of all leptons
  - E_T^{miss} lower or higher than 50 GeV
- Measured number of signal events $\hat{N}_{sig}$ is defined as the difference between the estimated background and the data.
- No significant deviations observed.



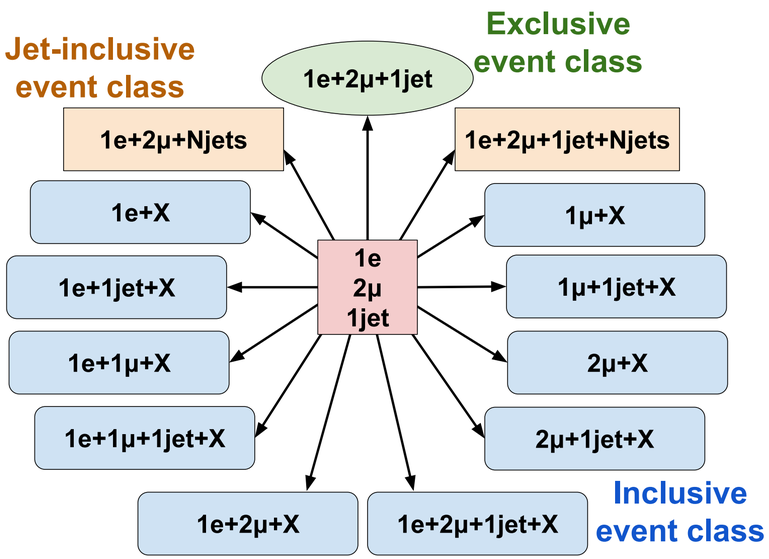
significance $Z = \hat{N}_{sig} / \Delta\hat{N}_{sig}$

SR	0-200 GeV	200-400 GeV	400-600 GeV	>600 GeV
3ℓ, On-Z, $E_T^{miss} < 50$ GeV	-0.2	-0.7	-0.6	-2.5
3ℓ, On-Z, $E_T^{miss} > 50$ GeV	-1.0	-0.5	-0.4	-1.6
3ℓ, Off-Z, $E_T^{miss} < 50$ GeV	-0.1	0.3	-2.7	0.1
3ℓ, Off-Z, $E_T^{miss} > 50$ GeV	-0.2	0.5	0.1	-1.2

SR	0-400 GeV	>400 GeV
4ℓ, On-Z, $E_T^{miss} < 50$ GeV	1.0	0.4
4ℓ, On-Z, $E_T^{miss} > 50$ GeV	1.8	0.1
4ℓ, Off-Z	0.1	-1.3

Model Independent Search in CMS

CMS-EXO-19-008



- Kinematic distributions of interest:
  - scalar sum of p_T of all objects (3+ bins)
  - invariant/transverse mass of all objects (1+ bins)
  - missing transverse momentum (3+ bins)
- Search for regions: taking the ones with smallest p-value.
- Global overview: observed deviations are compared with pseudo-experiments using the SM-only hypothesis.
- No significant deviations found in ~60 classes.