Tests of neutrino mass models at ATLAS

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On behalf of the ATLAS collaboration
University of Edinburgh

05/08/22

What is a heavy neutrino?

Standard model neutrinos were massless in theory

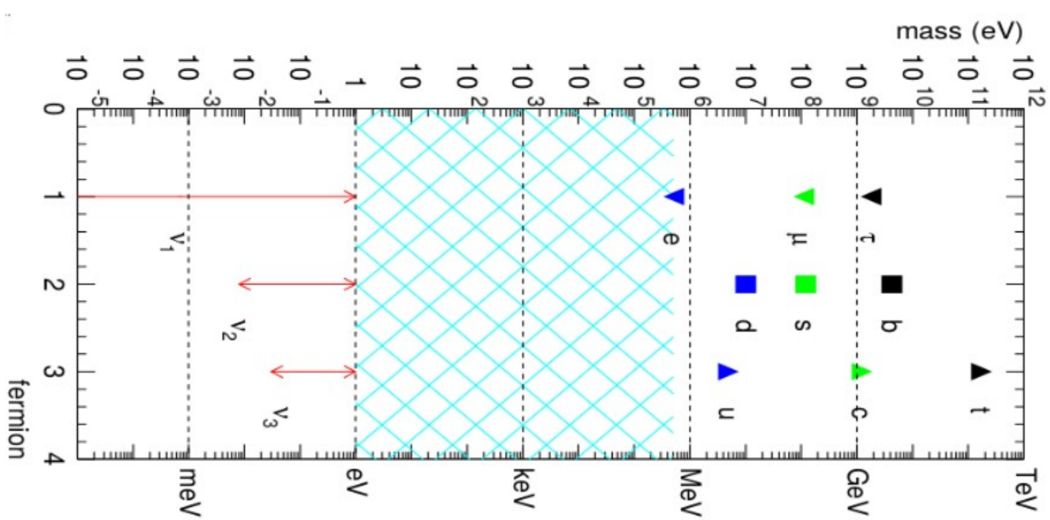
Neutrino oscillation observations show that they have non-zero masses

Nonetheless, neutrinos are “light” with masses < 1eV
 - other SM particles start in the ~MeV range (or are massless)

“Heavy” implies a mass in the MeV range or (a lot) higher

I’ll mostly be talking about “Heavy Neutral Leptons” - HNLs

Thanks to Alain Blondel for the discussion in his talk about terminology



Heavy ---------- ?

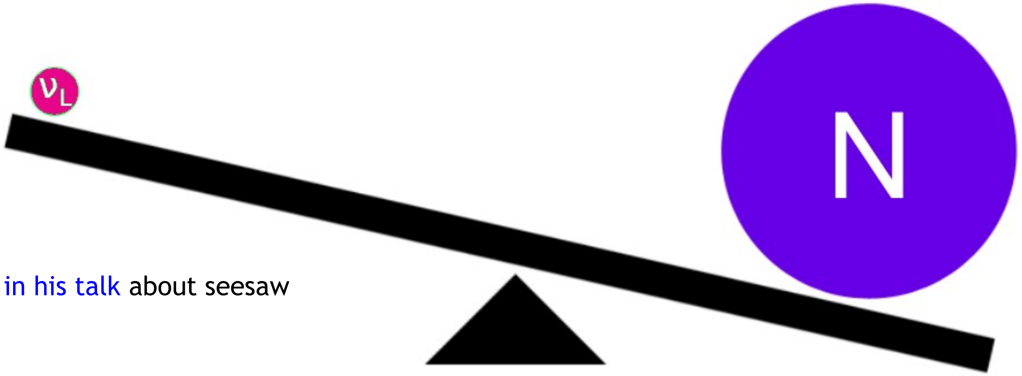
Seesaw mechanisms

Light neutrinos could couple to heavier partners
Type 1: Up to three fermion singlets, each a HNL
Type 2: A scalar triplet
Type 3: A fermion triplet, with one HNL as well as +ve and -ve particles

The "seesaw" part refers to the feature of the theory that a neutrino can be made lighter simply by making a corresponding increase to the mass of their partner

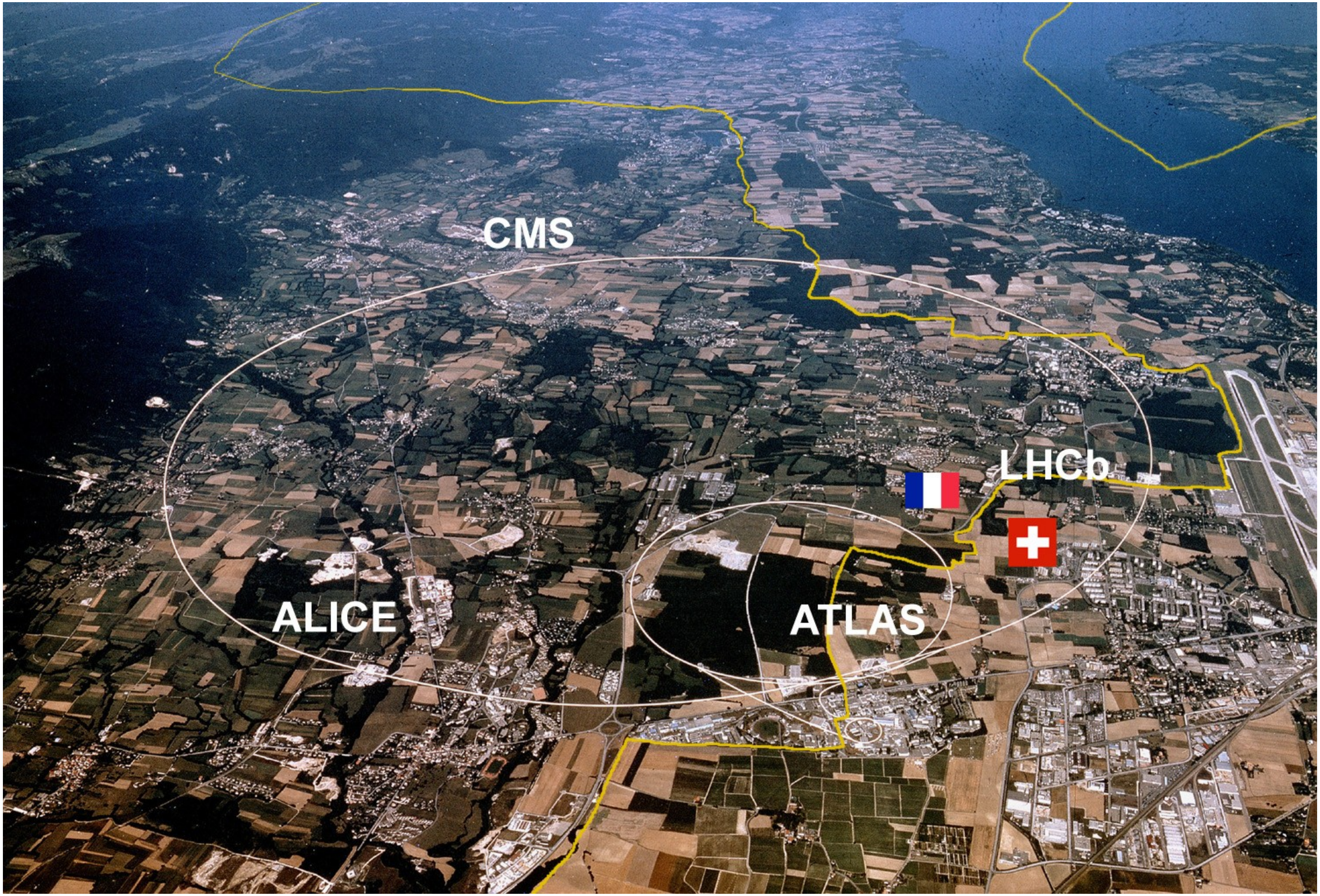
Another nice feature is that the mass mixing matrix could now include some additional CP-violating phases that could explain the matter/antimatter asymmetry of the universe

Type 1 seesaw could appear as part of the Left-Right Symmetric Model, where the HNLs can couple to right-handed versions of the W and Z

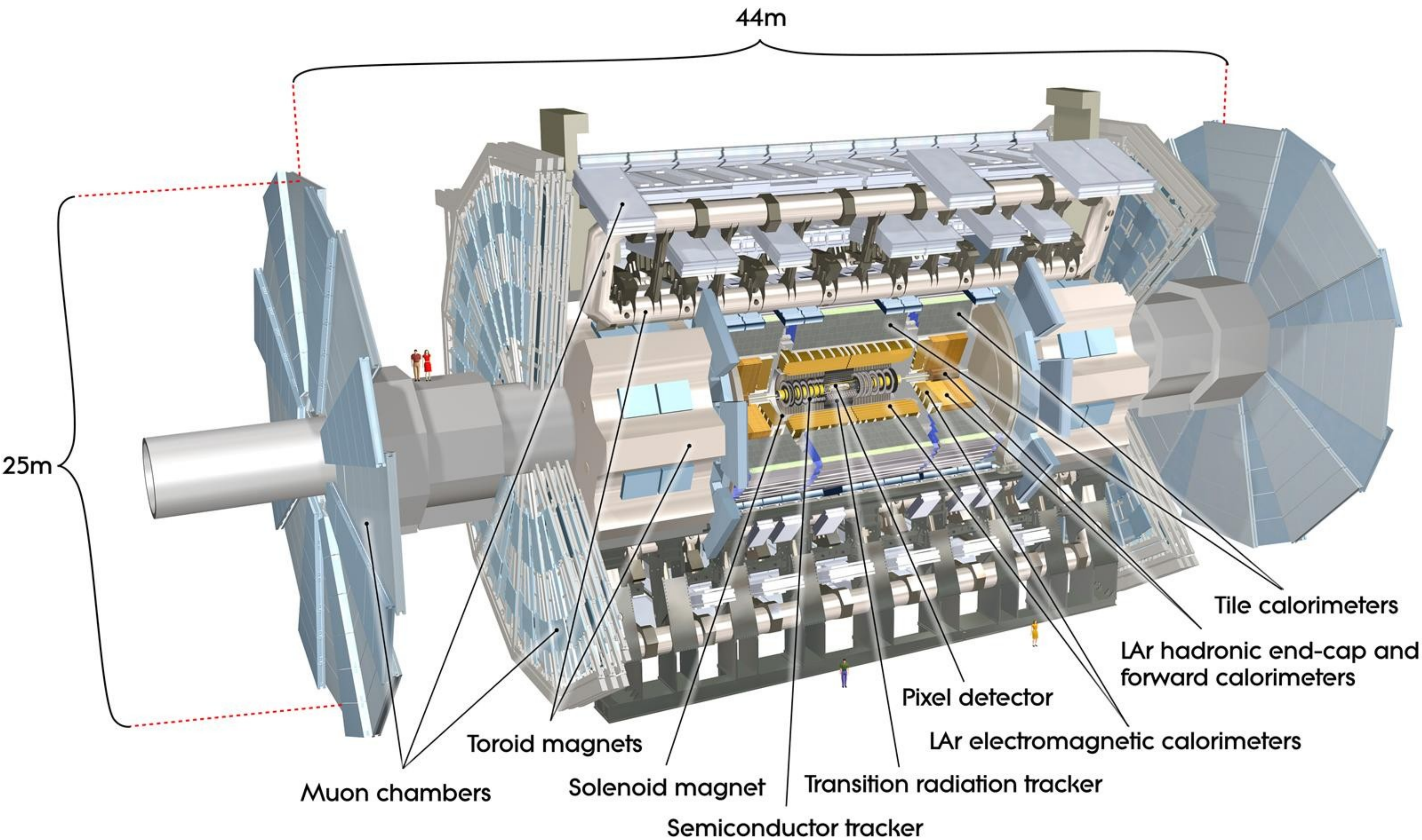


Thanks to Julian Heeck for the discussion in his talk about seesaw models and LFV

Large Hadron Collider

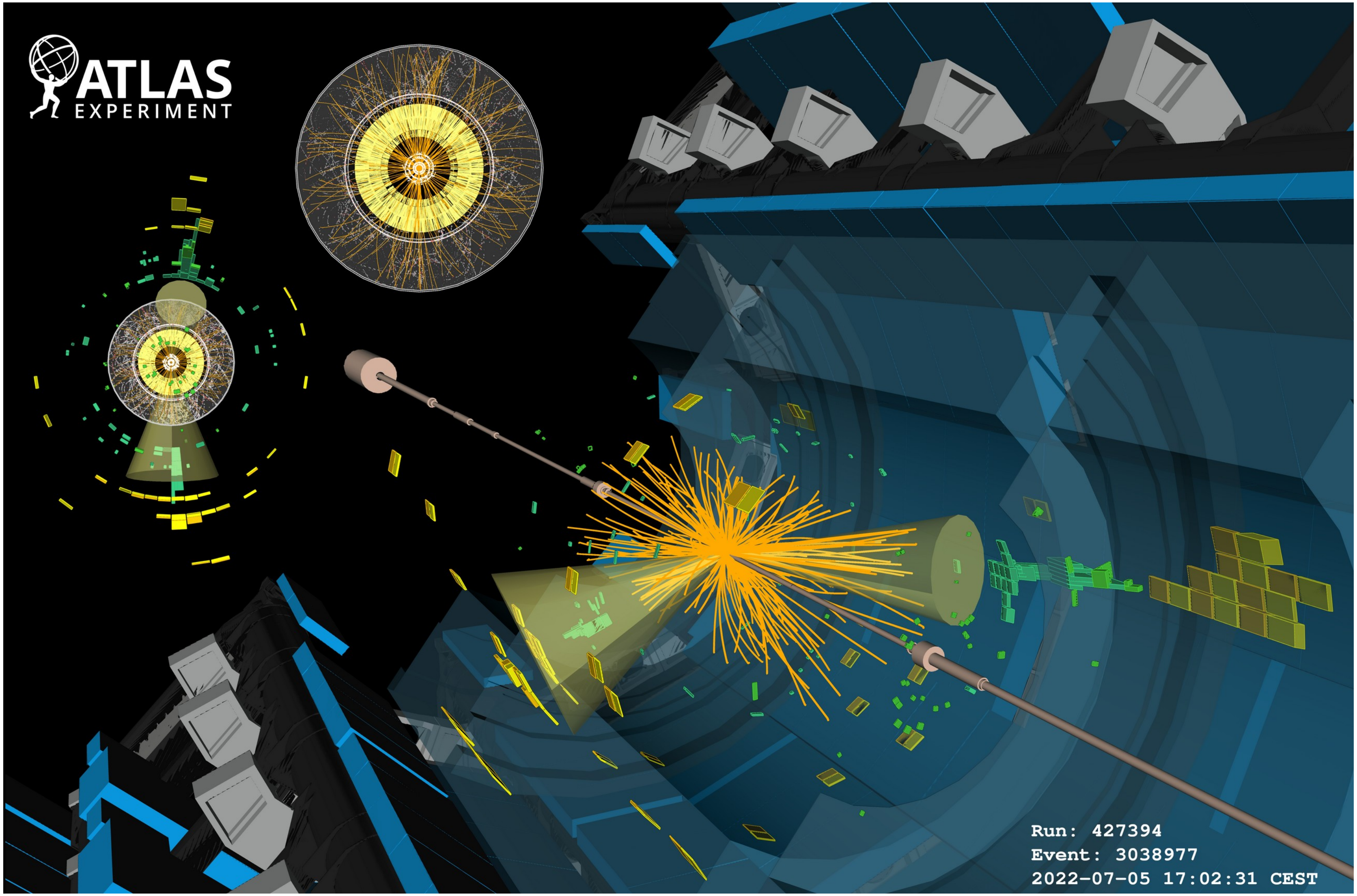


ATLAS detector



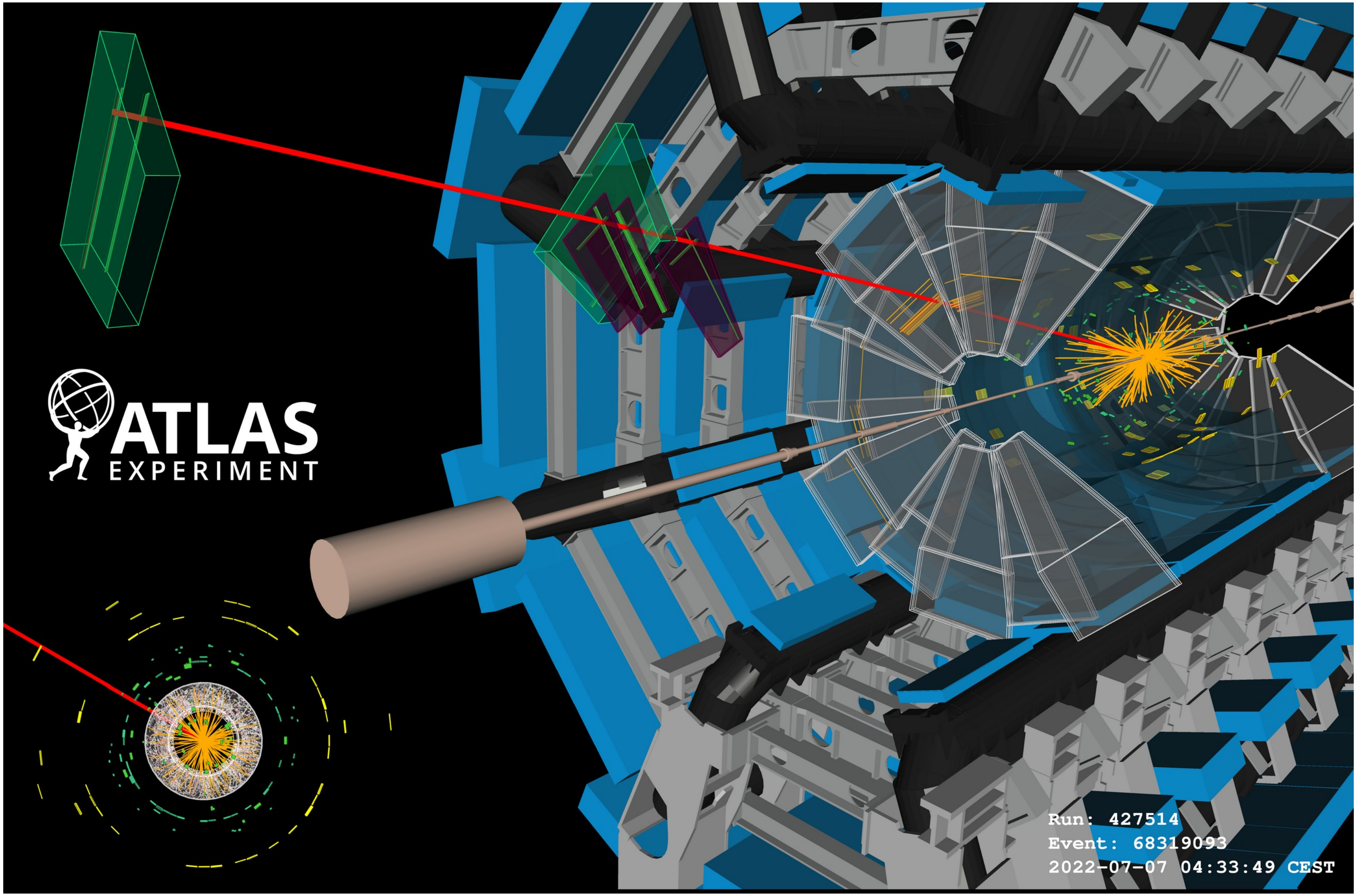
Run 3 has started!

Too early for any published results, but it's nice to see everything up-and-running again after a long break:
AtlasPublic/EventDisplayRun3Collisions#13_6_TeV_collisions_2022



Run 3 has started!

In this display you can see one of the first muons recorded with the New Small Wheel muon detector, installed during the long shutdown



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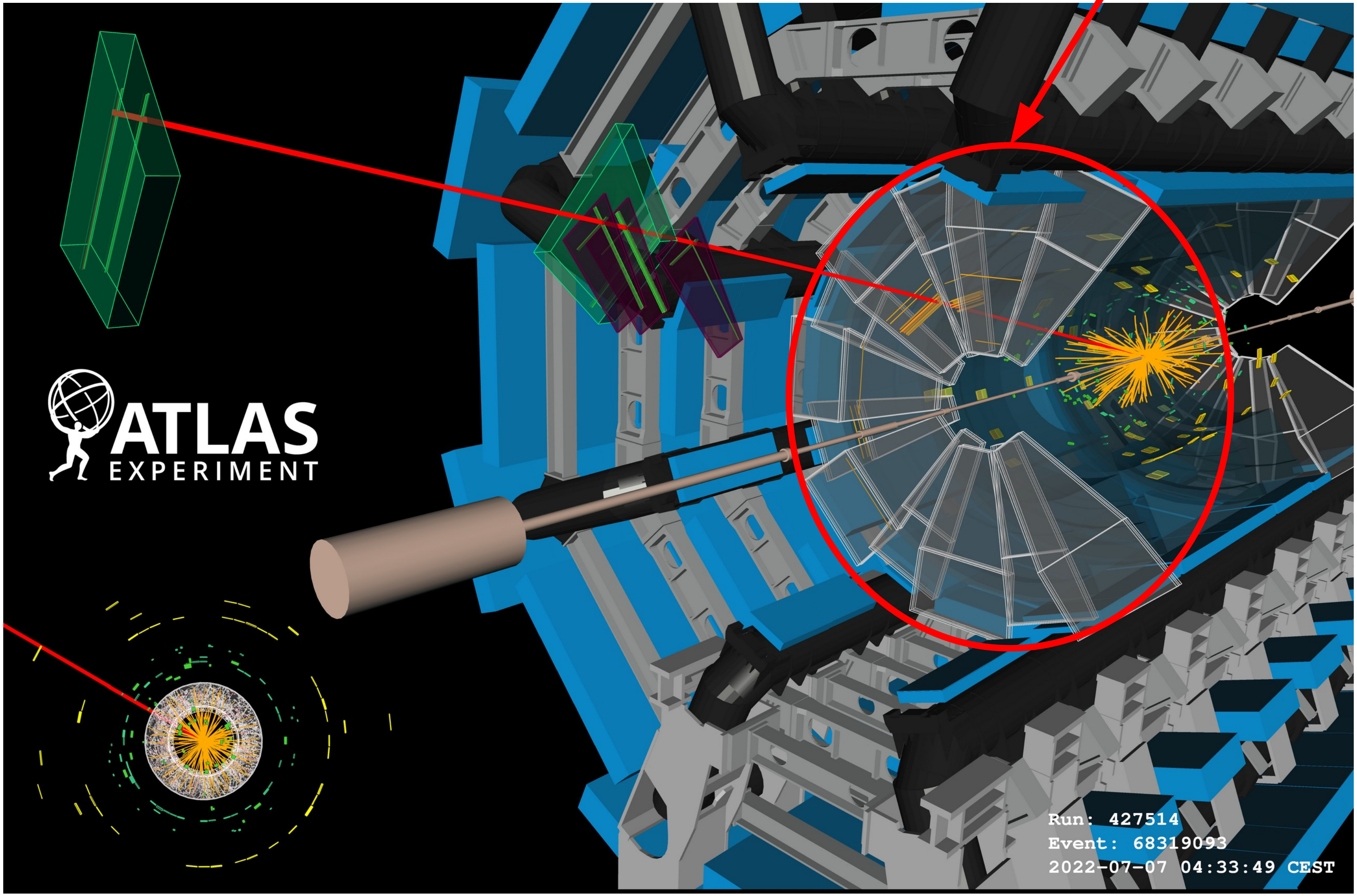
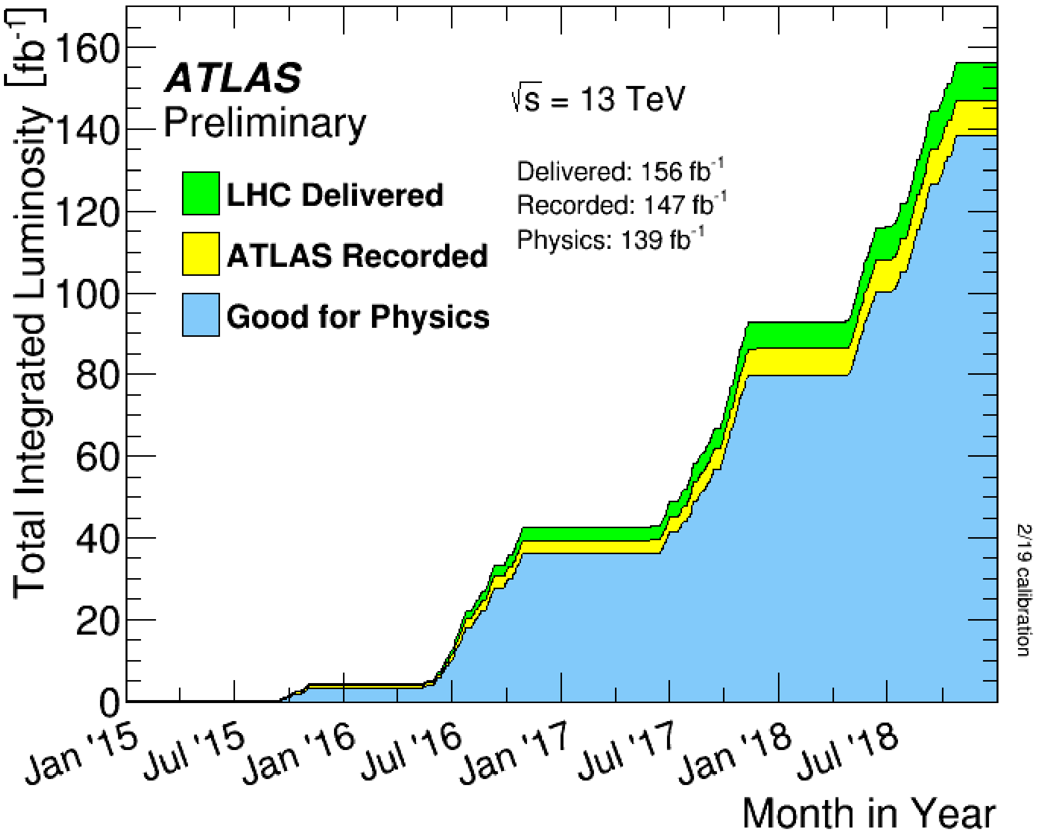


Run 2 data

All the analyses in this talk use Run 2 data, i.e. up to 139 fb^{-1} of proton-proton collisions at $\sqrt{s}$ = 13TeV

If you'll allow me to pretend to be a neutrino physicist for a bit, that's about 1.39×10^{16} protons on target, but please remember that our target is another proton…

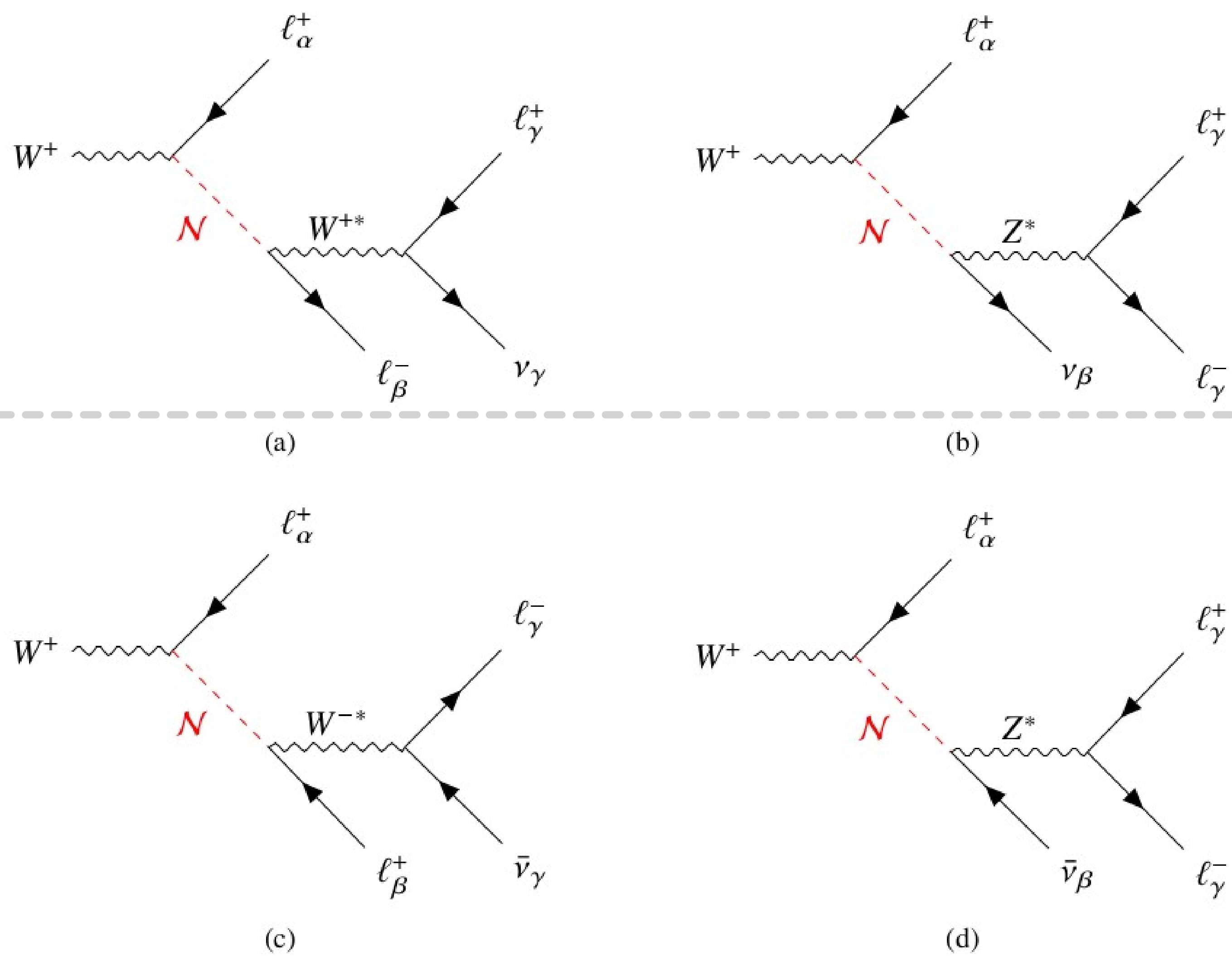


writing-guidelines.web.cern.ch/entries/inverse-femtobarn.html
AtlasPublic/LuminosityPublicResultsRun2

Type 1 seesaw HNL search

2022

Searching for HNLs decaying to a displaced vertex, with leptonic final states



Lepton-number conserving

Lepton-number violating

HNLs (*N*) mix with light flavour eigenstates α, giving weak force couplings U_a

arxiv:2204.11988

Type 1 seesaw HNL search

2022

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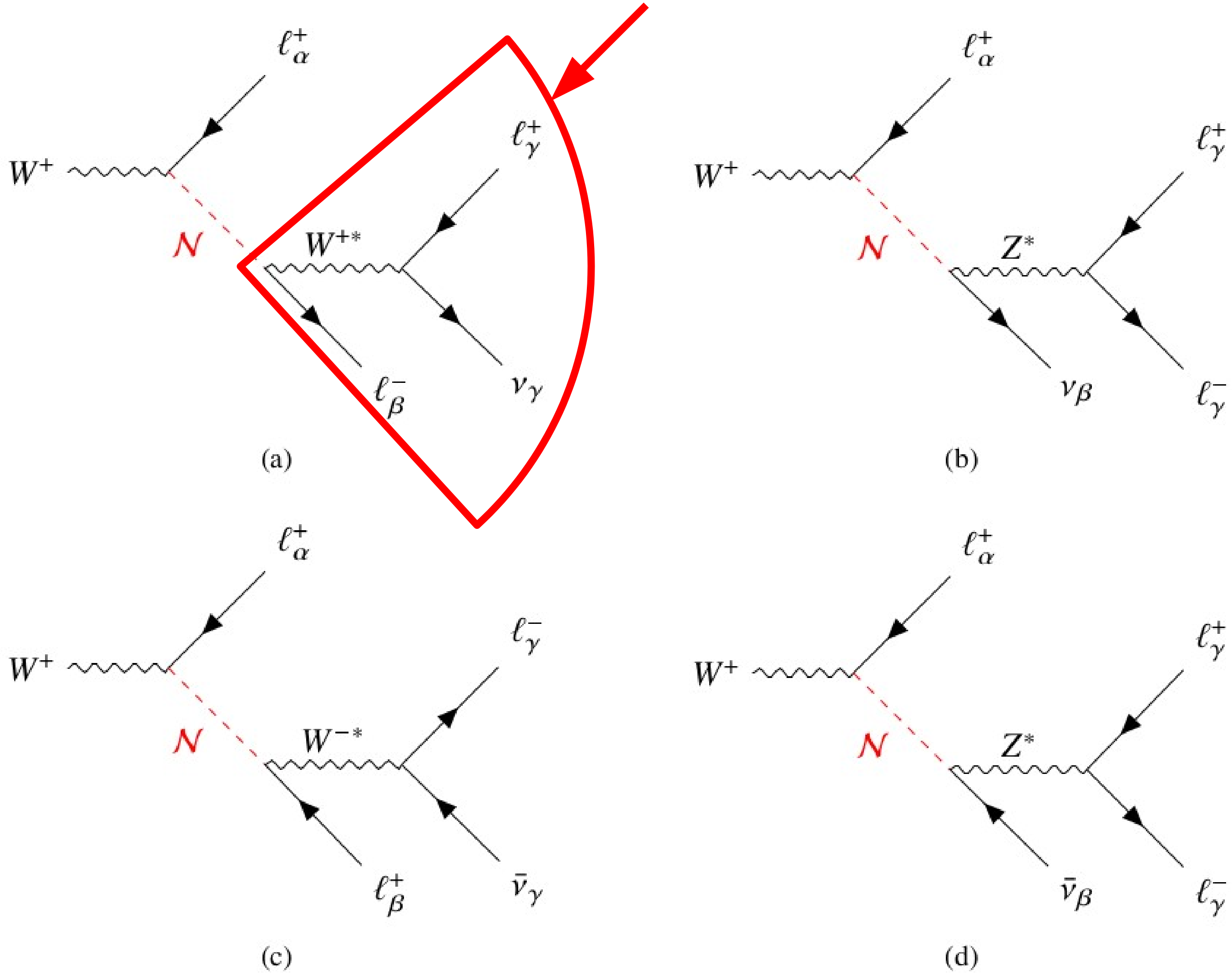


Lepton-number conserving

Lepton-number violating

$\tau_{HNL} \approx (4.3 \times 10^{-12}\ \mathrm{s})|U_{e,\mu}|^{-2}\ (m_{HNL}\ /\ \mathrm{GeV})^{-5}$, here radial displacement < 300mm

arxiv:2204.11988

Type 1 seesaw HNL search

2022

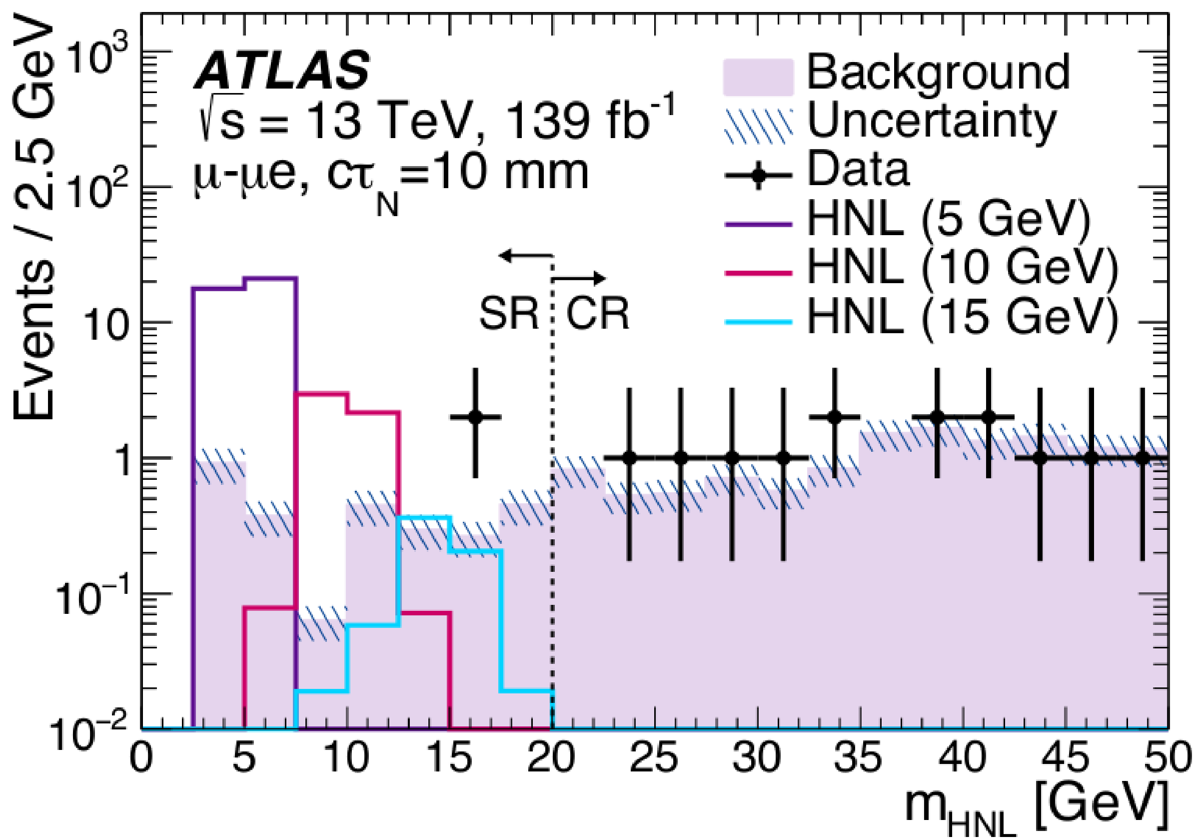
Dedicated large-radius tracking algorithm and displaced vertex reconstruction
- cosmic ray suppression: require displaced leptons not back-to-back
- veto vertices inside detector material
- suppress heavy flavour by requiring vertex mass >5.5 GeV *

*see backup

Remaining background mostly random crossings of lepton tracks, data-driven estimate uses displaced vertices with a "shuffled" prompt lepton from another event

Signal region defined by m_{HNL}<20 GeV, above this value the HNL decay vertex would not pass the displacement cuts

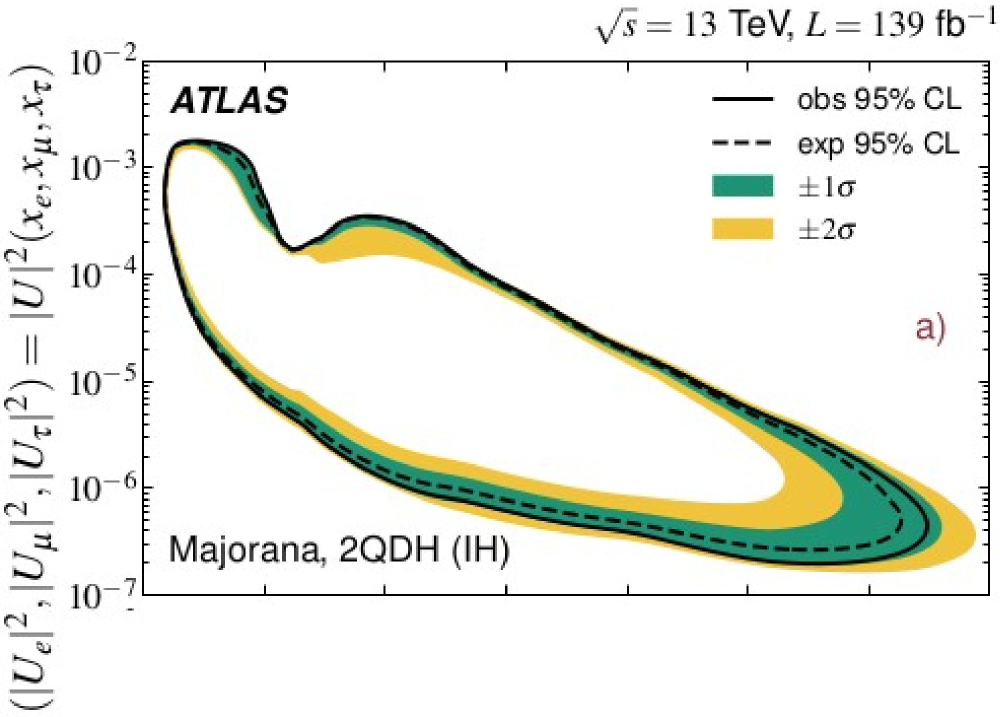
m_{HNL} can be calculated almost exactly by including prompt lepton kinematics

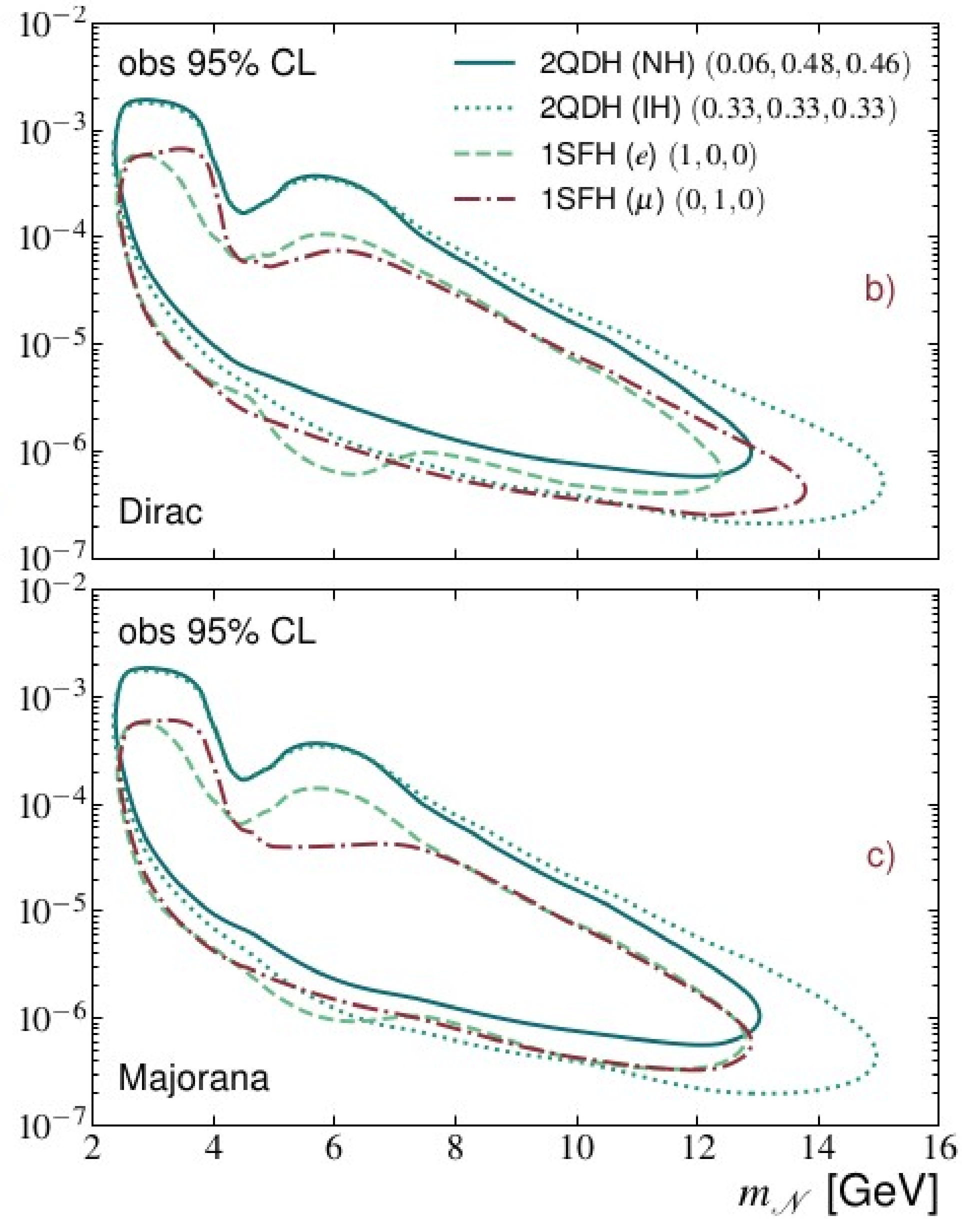


arxiv:2204.11988

Type 1 seesaw HNL search

2022





Two scenarios:
- Single HNL, either e or μ flavour
- Two quasi-degenerate HNLs, either nominal or inverted hierarchy*

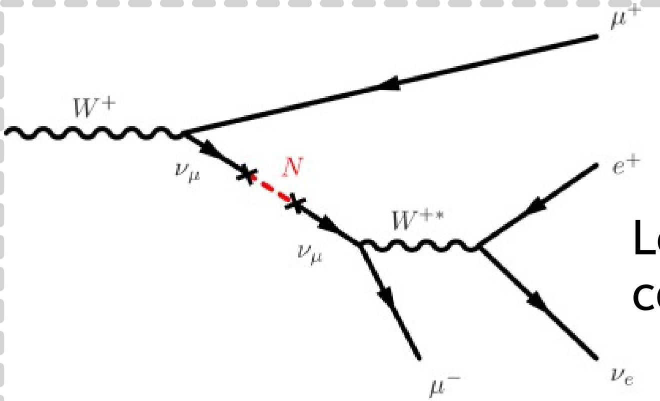
Two "limits" of HNL behaviour:
- Dirac, i.e. lepton number conserved
- Majorana, equal conservation or not

*2QDH is the more realistic model, and this is the first direct search with this interpretation

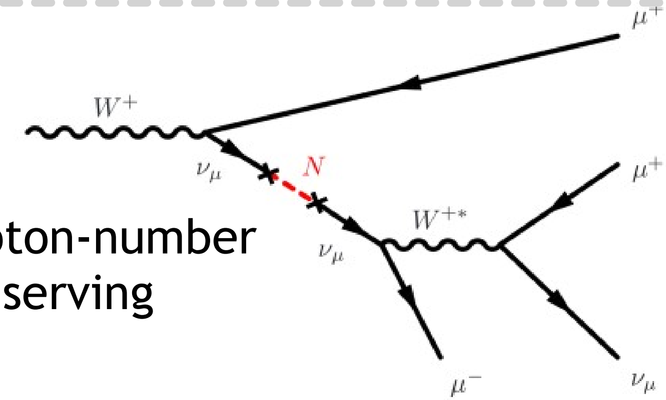
arxiv:2204.11988

Type 1 seesaw HNL search

Older search for prompt and displaced HNL decays, with leptonic final states

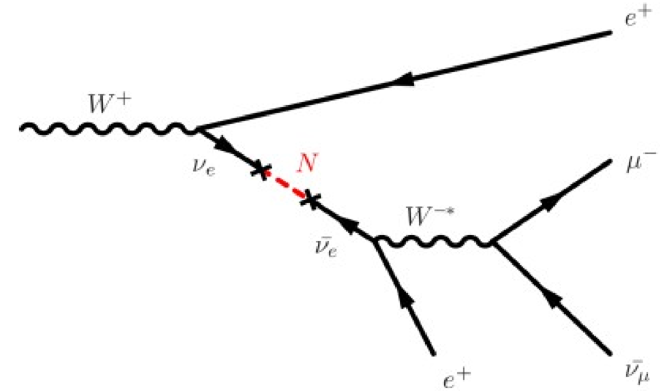


(a)

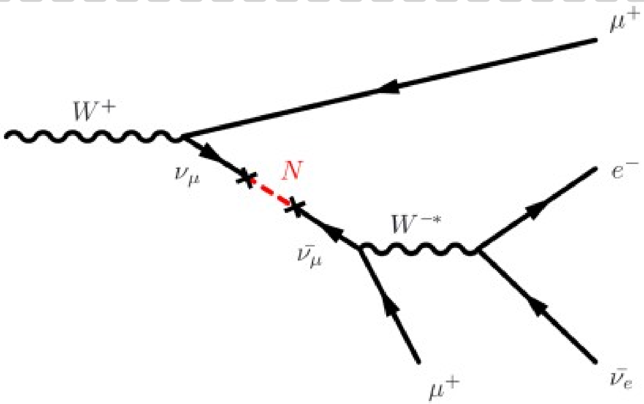


(b)

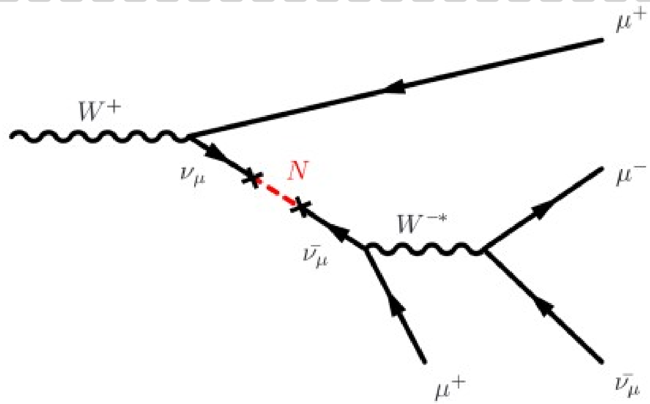
Lepton-number conserving



(e)



(c)



(d)

Lepton-number violating

For displaced HNL (*N*) decay, prompt lepton was required to be μ for efficiency
For prompt decays, cut background by requiring ee or μμ to have same charge

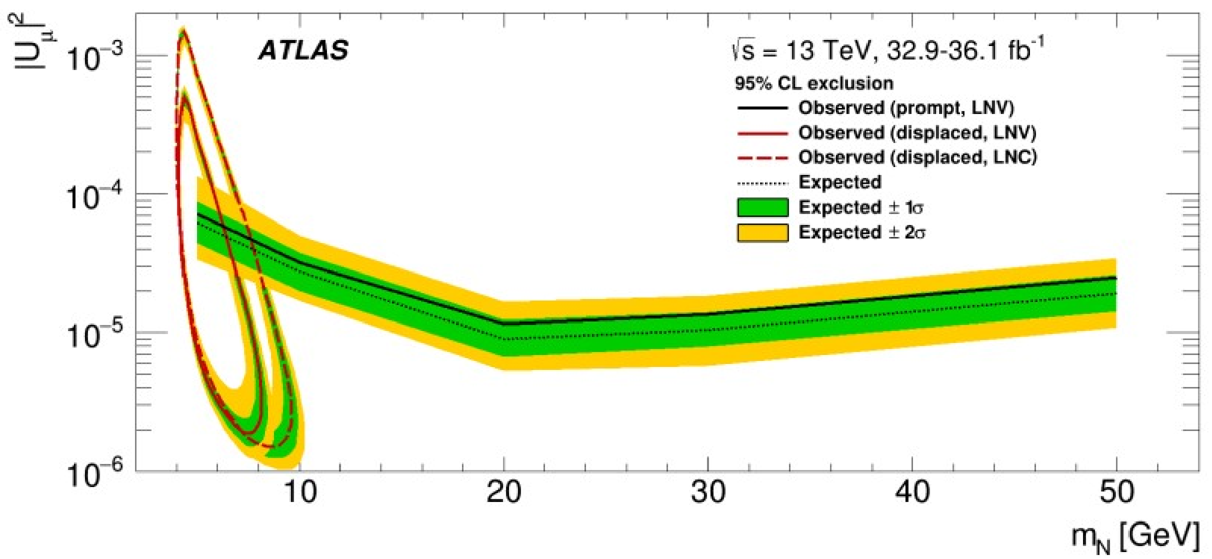
Note also that in this paper a single HNL is modelled, mixing with either e or μ

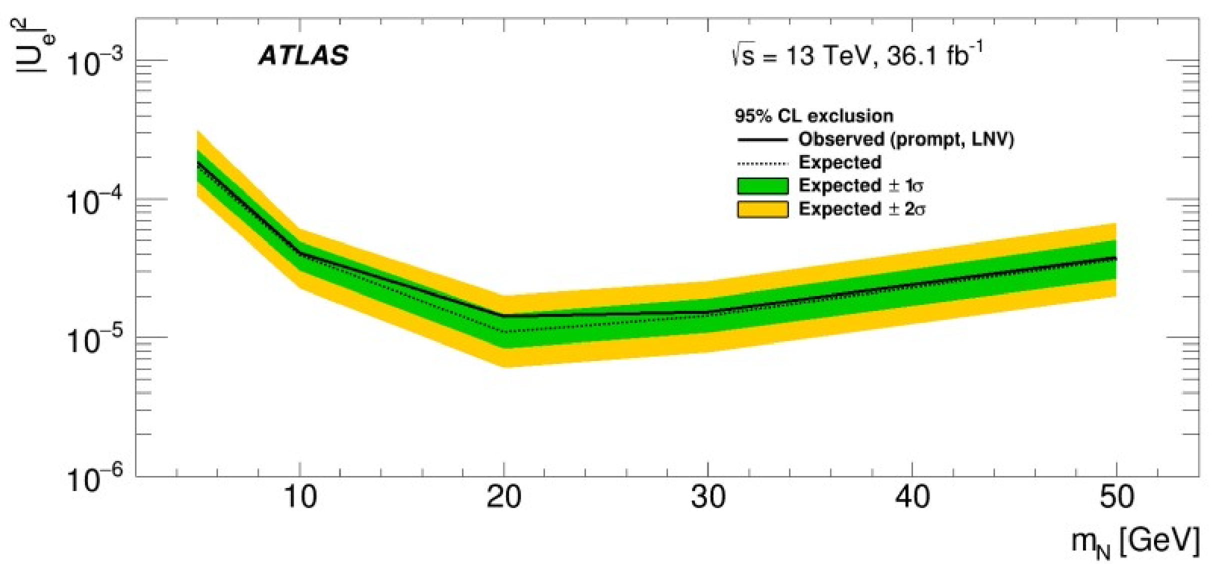
arxiv:1905.09787

Type 1 seesaw HNL search

The displaced limits only exist for the μ channel, and are superseded by the newer result above

The prompt limits remain our best for that signature, and can reach higher HNL masses where the cτ would be too short to construct a displaced vertex

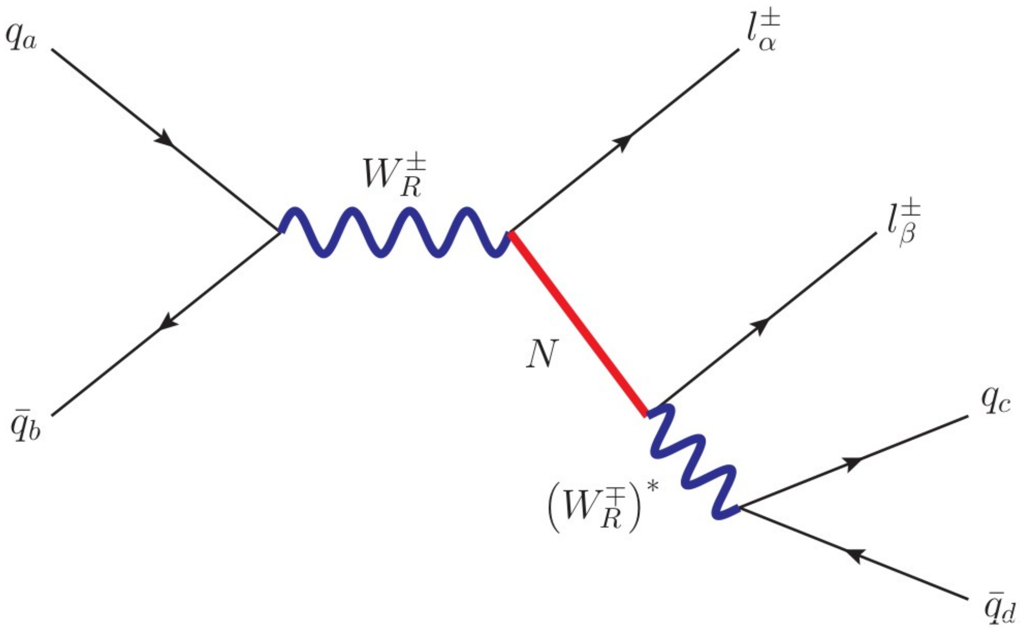


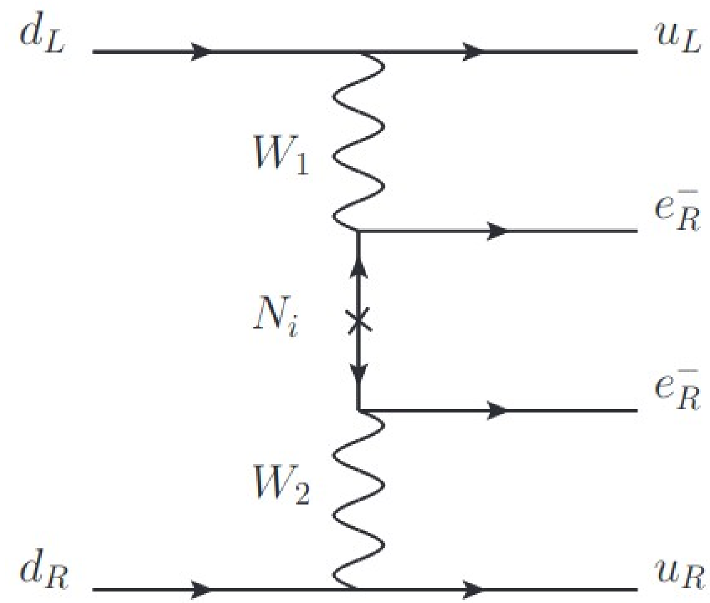


arxiv:1905.09787

LRSM search for HNL+W_R (resolved)

Searching for Keung-Senjanović process decays, with lljj final state





(a) $0\nu\beta\beta$ decay

If the HNL (N_R) is a Majorana particle this is the collider equivalent to searches for 0νββ decay, with additional LRSM motivation
- a (pseudo-)Dirac HNL would yield only opposite-charge leptons

In this search we require ee or μμ, and a resolved pair of jets (quarks)
- assume no lepton flavour mixing

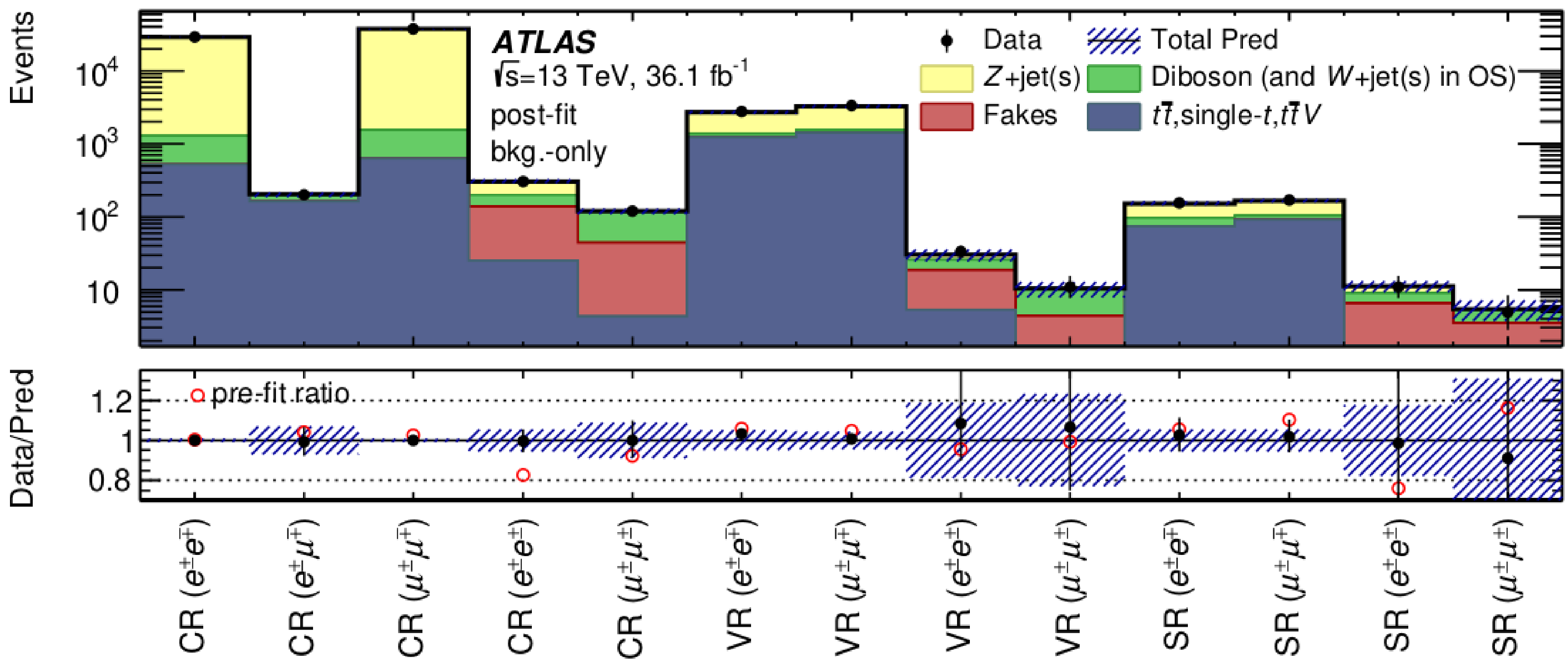
arxiv:1809.11105

LRSM search for HNL+W_R (resolved)

Opposite- and same-charge lepton channels have quite different behaviour, and similar overall sensitivity

Same-charge lepton requirement suppresses background heavily
- requires a data-driven estimation of the rate of misidentified leptons (fakes)

Opposite-charged leptons have higher background, relatively well simulated

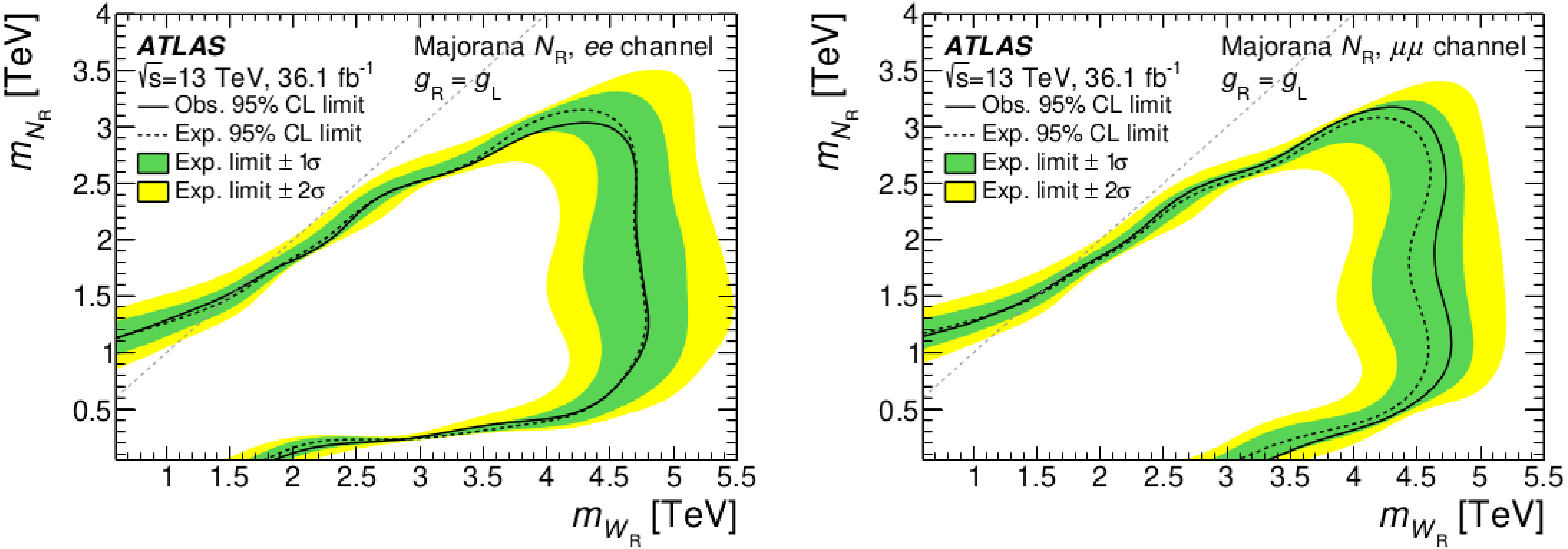


arxiv:1809.11105

LRSM search for HNL+W_R (resolved)

Exclusion can enter region where HNL heavier than W_R due to improved MC modelling of the final decay vertex

- in this case the first W_R is off-shell, and the resonant mass is given by m(jj) rather than m(lljj)



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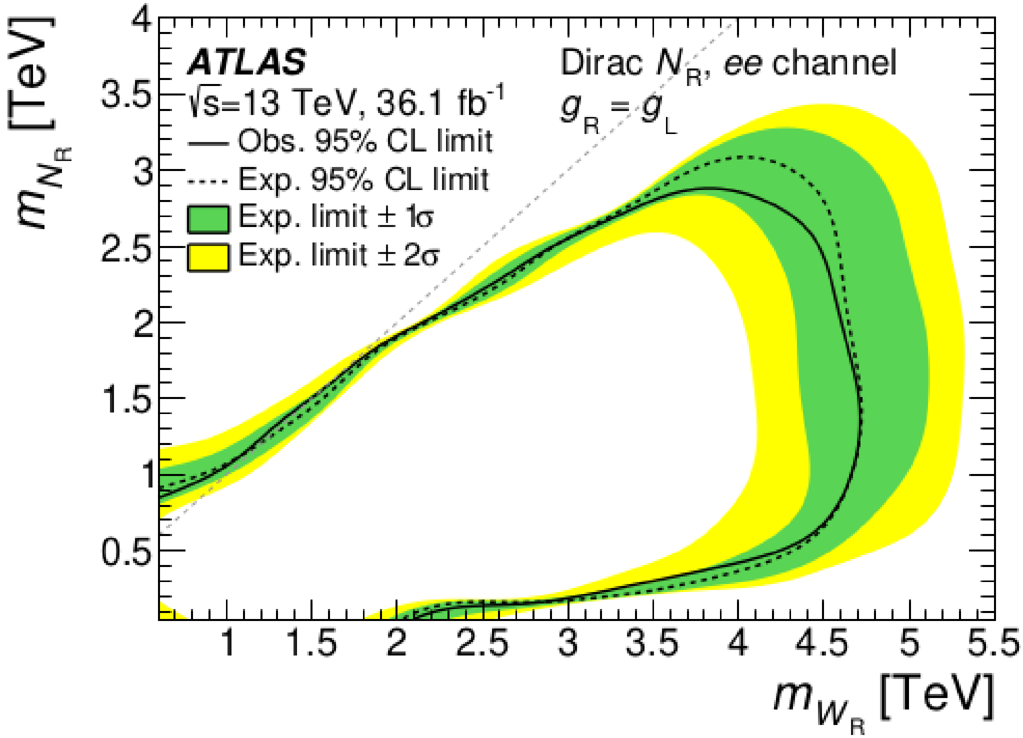
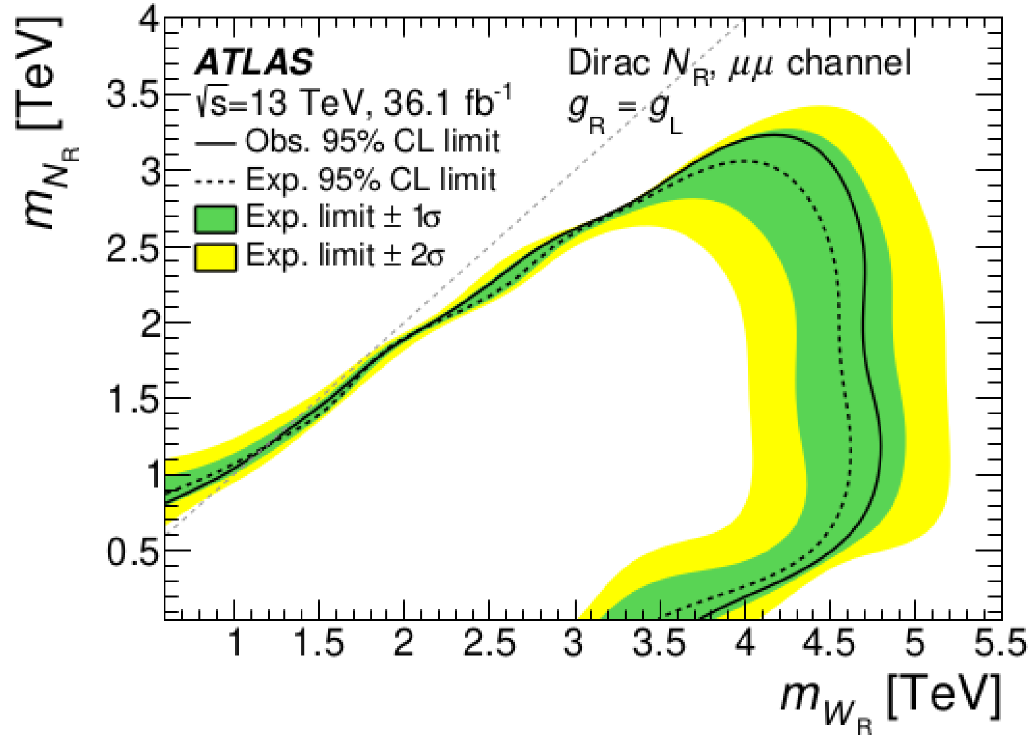
A limit for models without lepton number violation presented using the opposite-charged lepton channel only



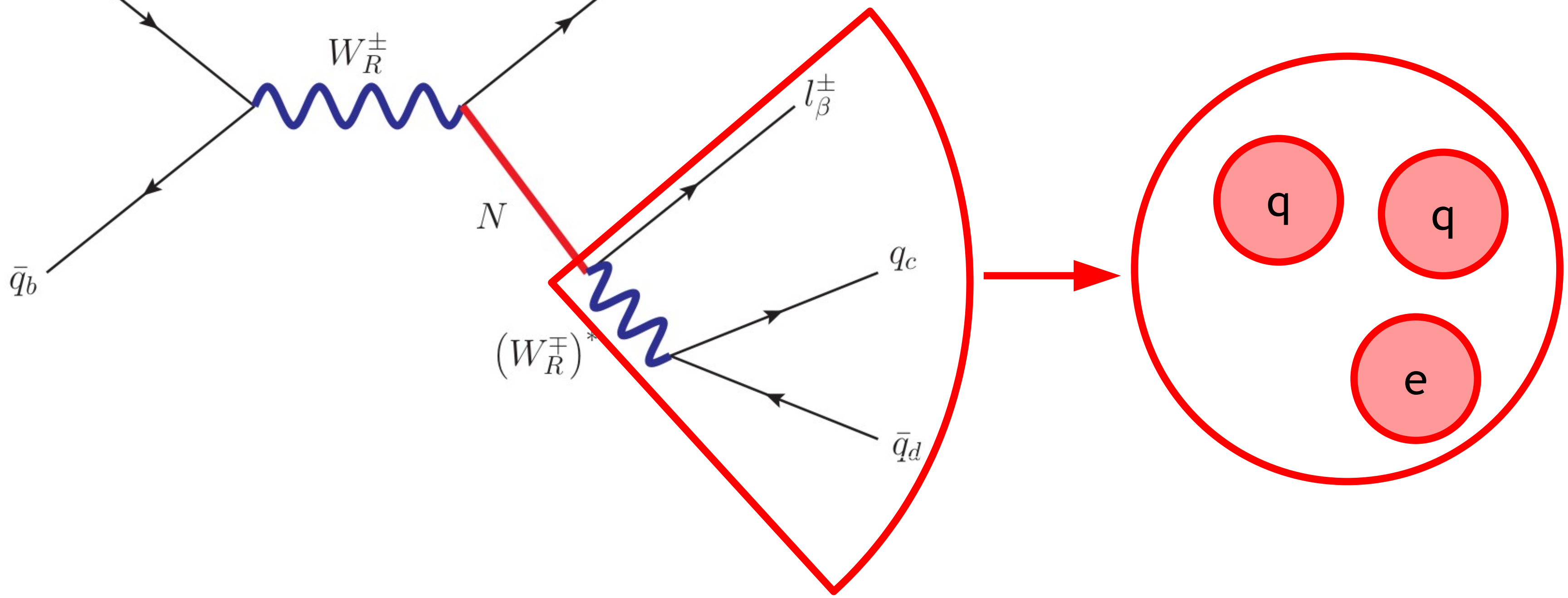


arxiv:1809.11105

LRSM search for HNL+W_R (boosted)

When the HNL is very much lighter than the W_R, its decay products are boosted

Identified as a single large jet with sub-structure



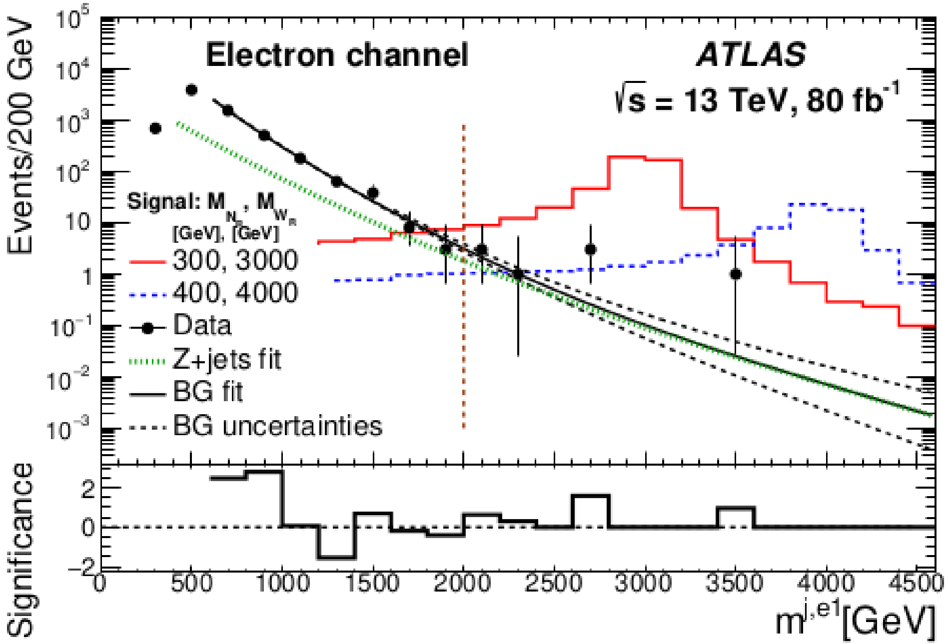
ATLAS routinely identifies boosted hadronic decays of W, Z, H or top
 - this analysis includes electron reconstruction within a substructured jet

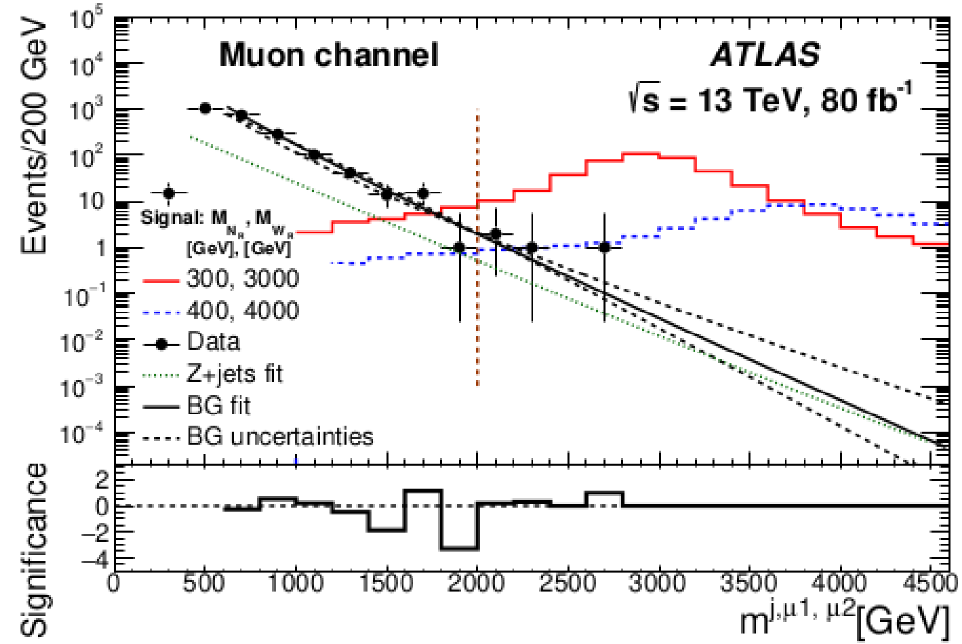
In the muon channel, the jet is reconstructed from qq only, with the muon mass added later

arxiv:1904.12679

LRSM search for HNL+W_R (boosted)

Mass of the W_R is the sum of the large jet and the prompt lepton





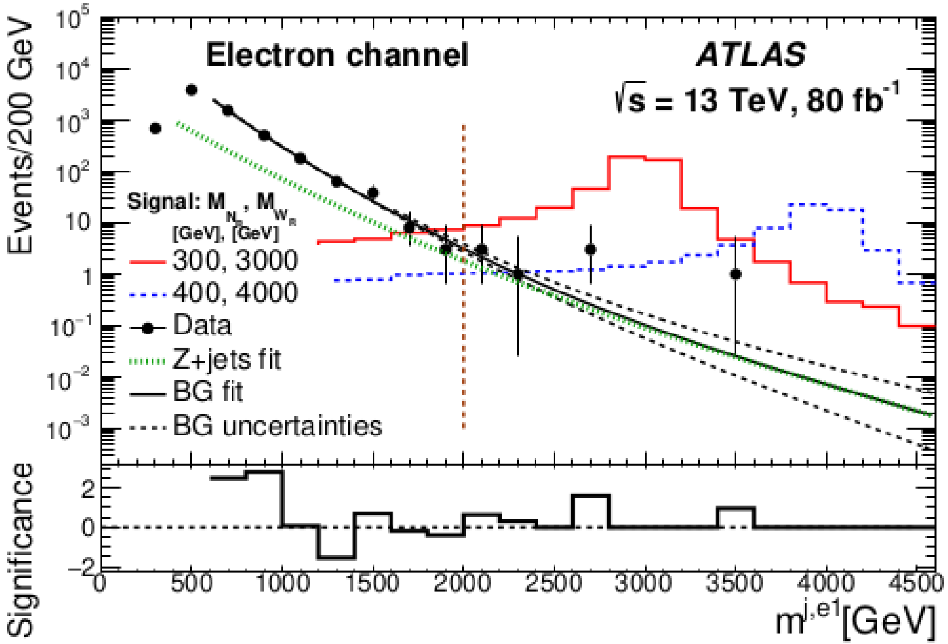
Final statistical analysis is just event-counting, showing a 2.4σ fluctuation in the electron channel

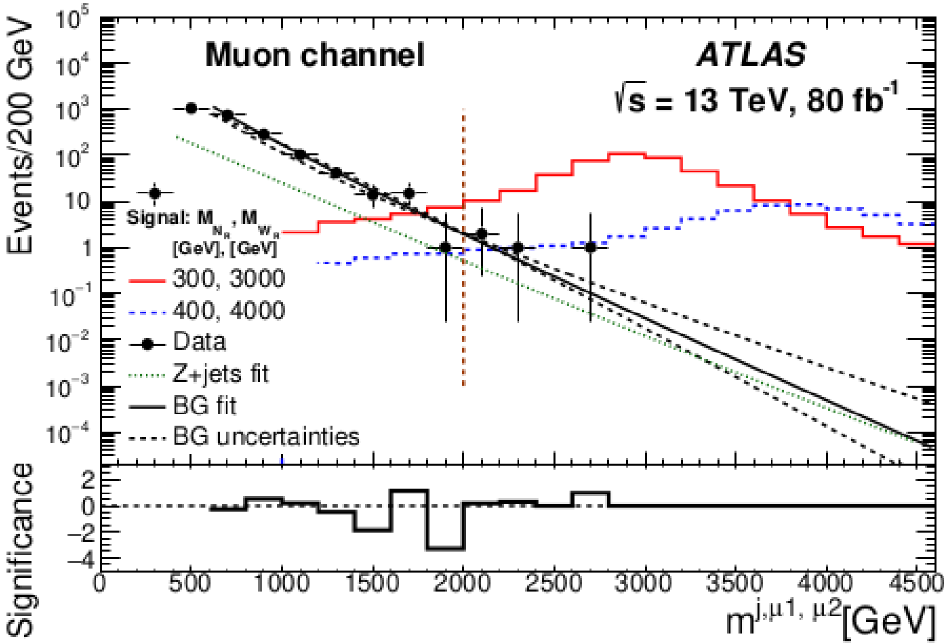
	Electron Channel	Muon Channel
Signal (m_{W_R} = 3 TeV, m_{N_R} = 150 GeV)	346^{+48}_{-75}	411^{+36}_{-48}
Signal (m_{W_R} = 3 TeV, m_{N_R} = 300 GeV)	471^{+42}_{-69}	429^{+29}_{-40}
Signal (m_{W_R} = 4 TeV, m_{N_R} = 400 GeV)	66^{+6}_{-10}	57^{+4}_{-4}
Expected background	$2.8^{+0.5}_{-0.7}$	$1.9^{+0.5}_{-0.7}$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

arxiv:1904.12679

LRSM search for HNL+W_R (boosted)

Mass of the W_R is the sum of the large jet and the prompt lepton





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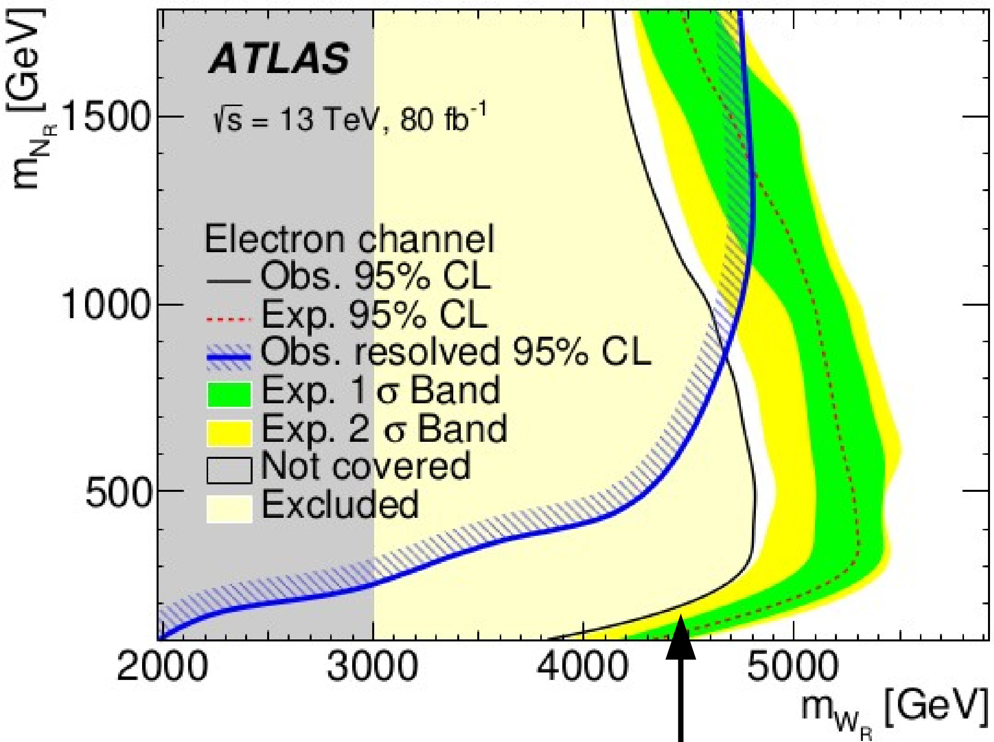
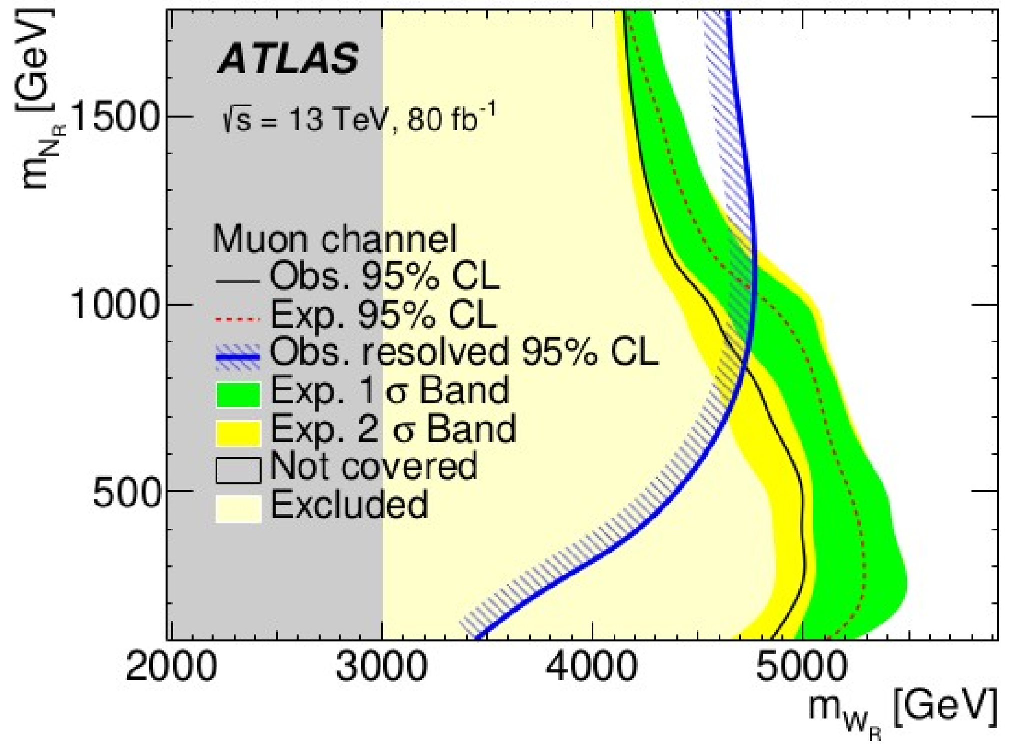
LRSM search for HNL+W_R (boosted)

Exclusion limits overlaid with resolved analysis above





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p-value	0.0082	0.12

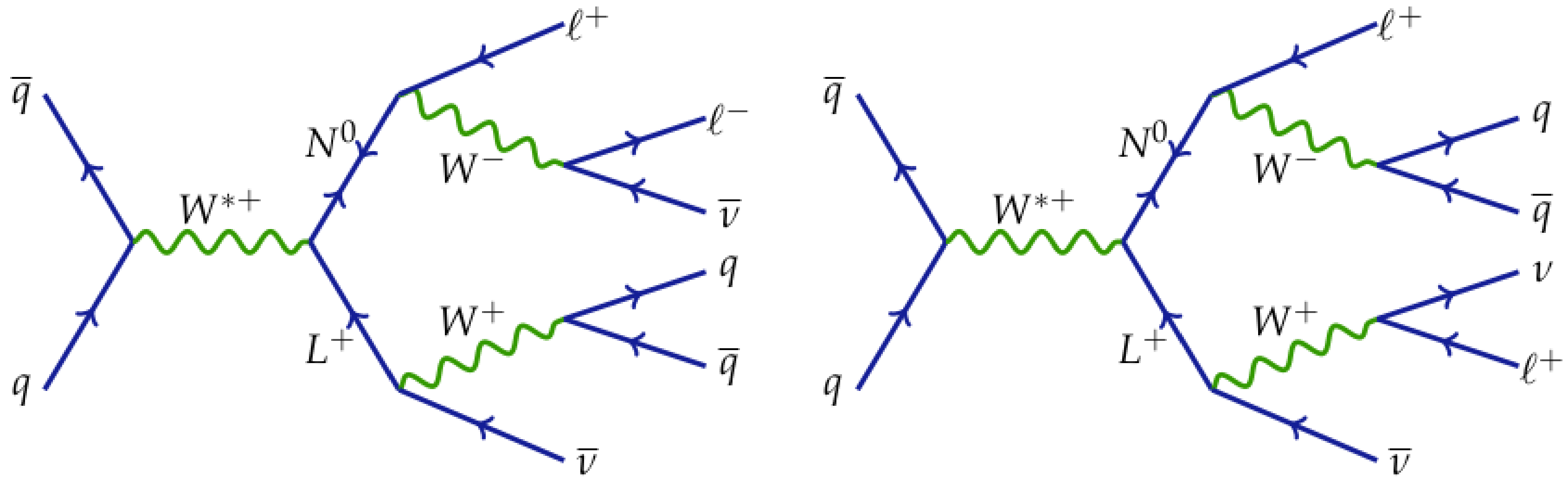
No specific sensitivity to different HNL mass values

Thanks to Janusz Gluza for some interesting discussion about possible LRSM interpretations for an excess, but this result is not a significant fluctuation

arxiv:1904.12679

Type 3 seesaw search (2 lepton)

Searching for leptonic final states arising from Type 3 lepton pair-production



Opposite- or same-charge ee, μμ, or eμ, plus hadronic W-boson decay & MET

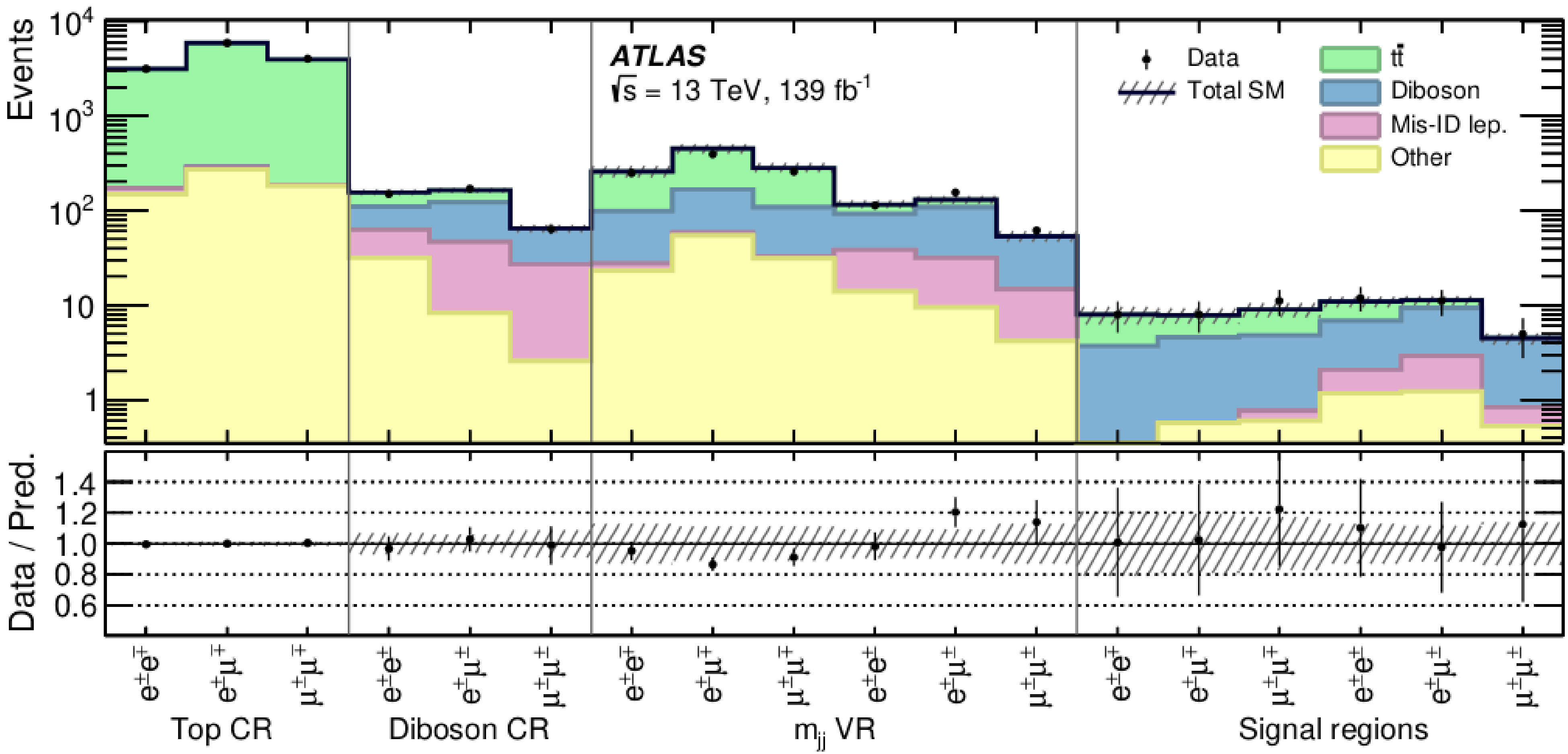
HNL (N^0) and heavy charged leptons ($L^\pm$) are assumed to be mass degenerate, with equal branching ratios to the SM lepton flavours

arxiv:2202.02039

Type 3 seesaw search (2 lepton)

As in the LRSM searches, the same-charge lepton channel has a large background from mis-identified leptons, estimated in data, but lower backgrounds overall

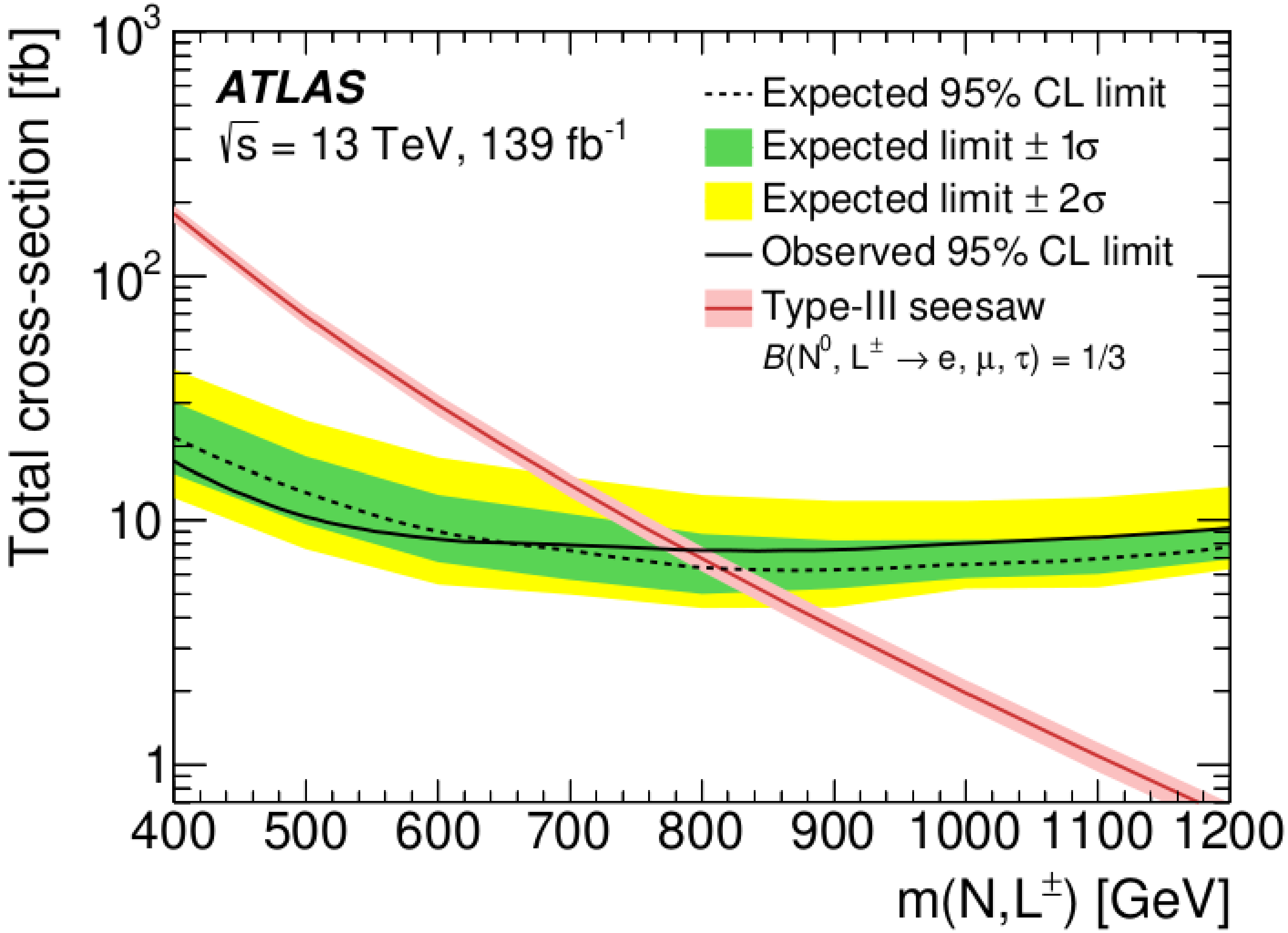
Since the analysis contains an eμ signal channel, top background is measured in a region requiring b-tagged jets



arxiv:2202.02039

Type 3 seesaw search (2 lepton)

Limits set as usual, excluding HNL masses (and those of the charged heavy leptons) below 790 GeV

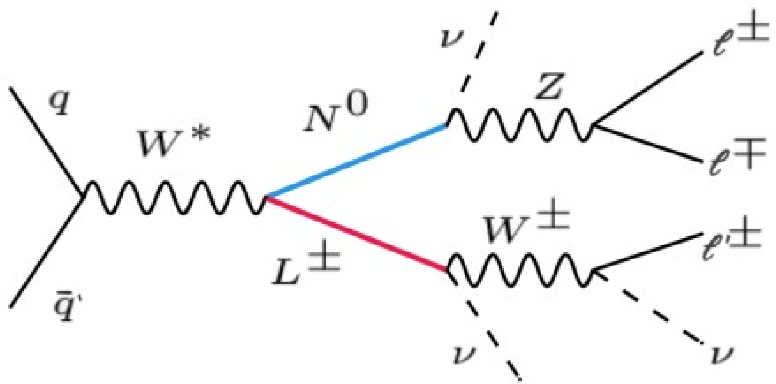


arxiv:2202.02039

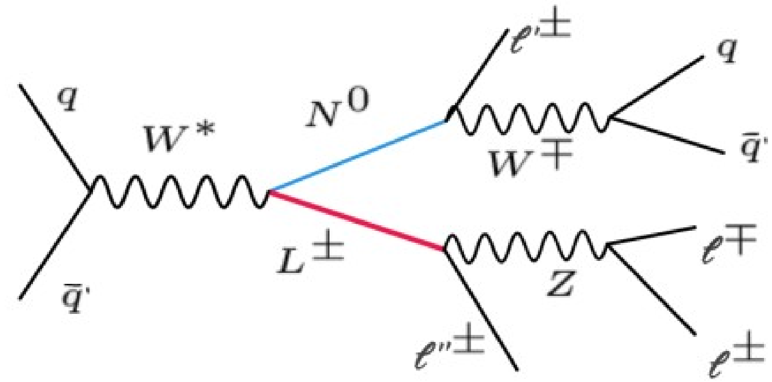
Type 3 seesaw search (3+4 lepton)

2022

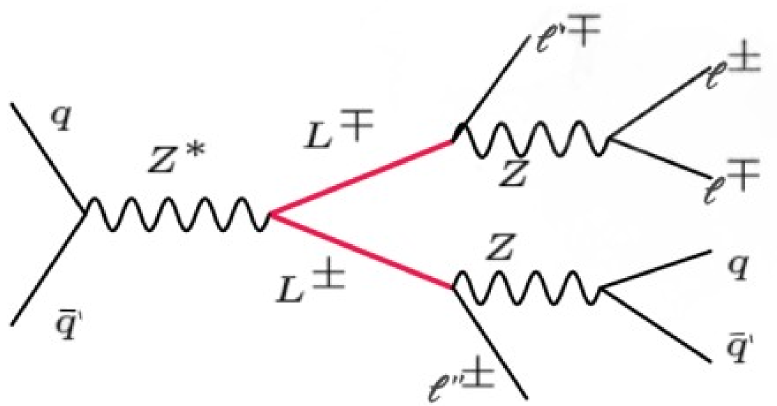
Searching for leptonic final states arising from Type 3 lepton pair-production



(a)



(b)



HNL (N^0) and heavy charged leptons ($L^\pm$) are assumed to be mass degenerate, with equal branching ratios to the SM lepton flavours and bosons

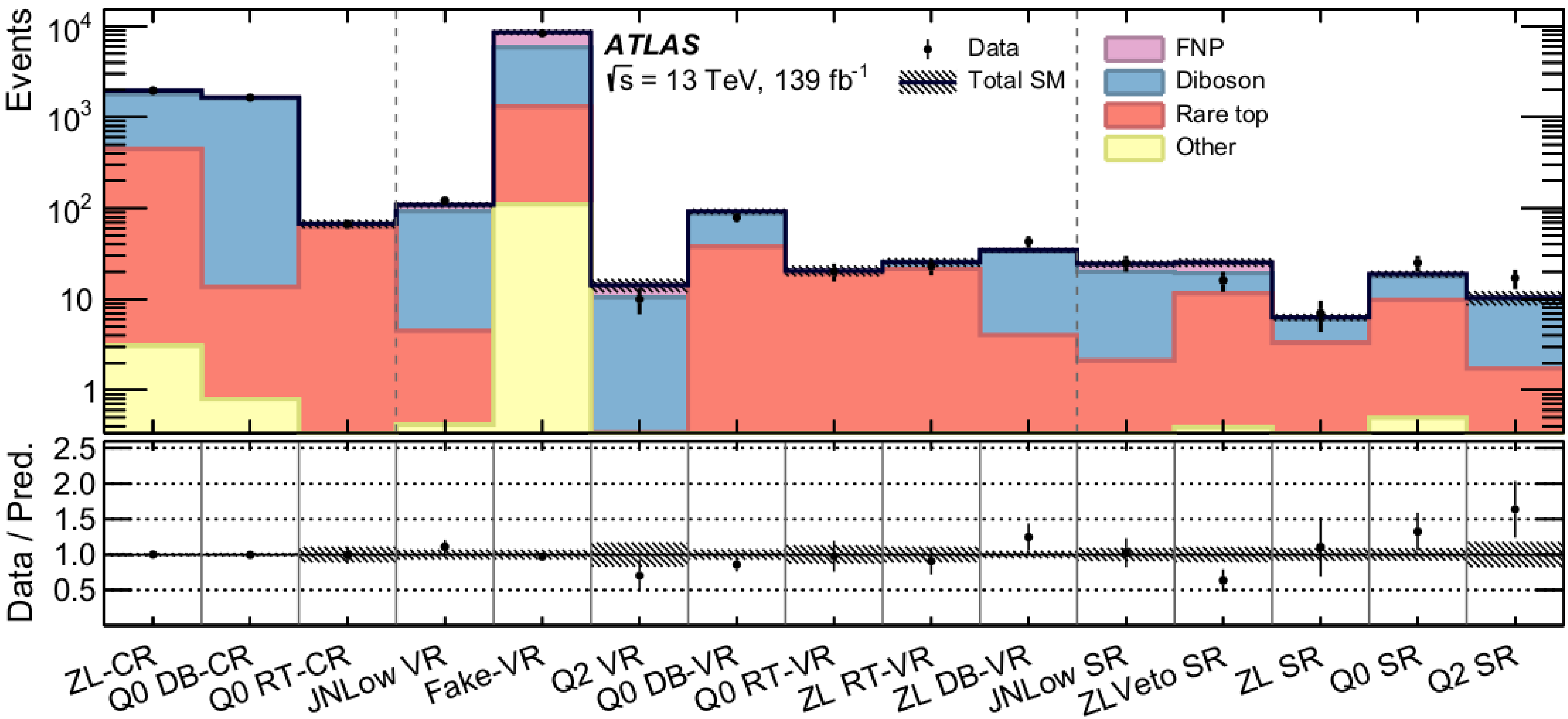
arxiv:2202.02039

Type 3 seesaw search (3+4 lepton)

2022

Three- and four- lepton final states separated, and four-lepton states then subdivided by net charge (0 or 2)

Opposite-charge-same-flavour lepton pairs around Z-boson mass used to identify signals and veto diboson background, plus some other kinematic cuts

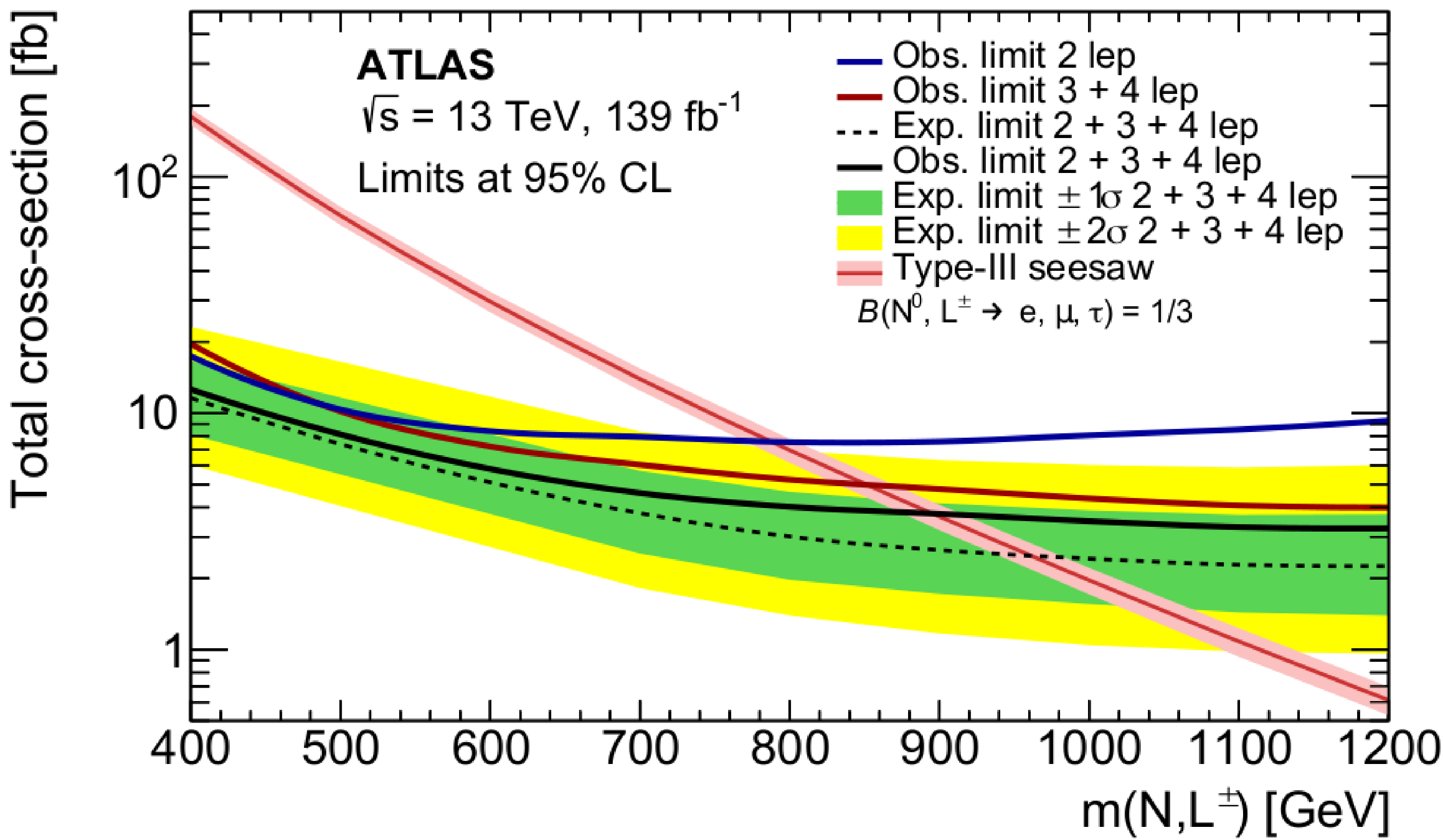


arxiv:2202.02039

Type 3 seesaw search (3+4 lepton)

2022

Final exclusion limit exceeds that of the two-lepton analysis above, and combined result with that analysis gives further improvement

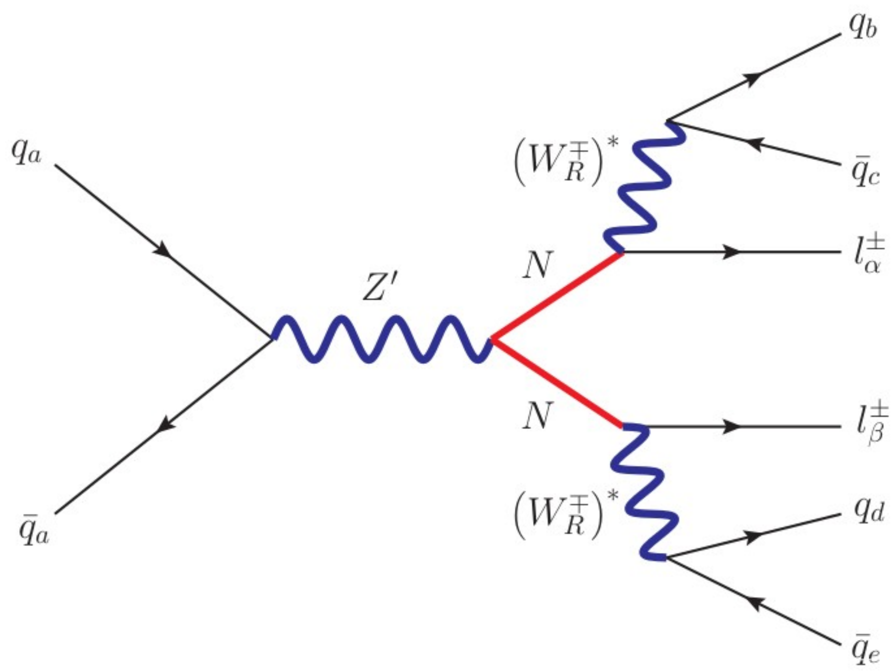


arxiv:2202.02039

Dark Matter?

A stable HNL would be a potential Dark Matter candidate

Possibility to pair-produce heavy neutrinos from a Z as shown in the LRSM-motivated diagram below:



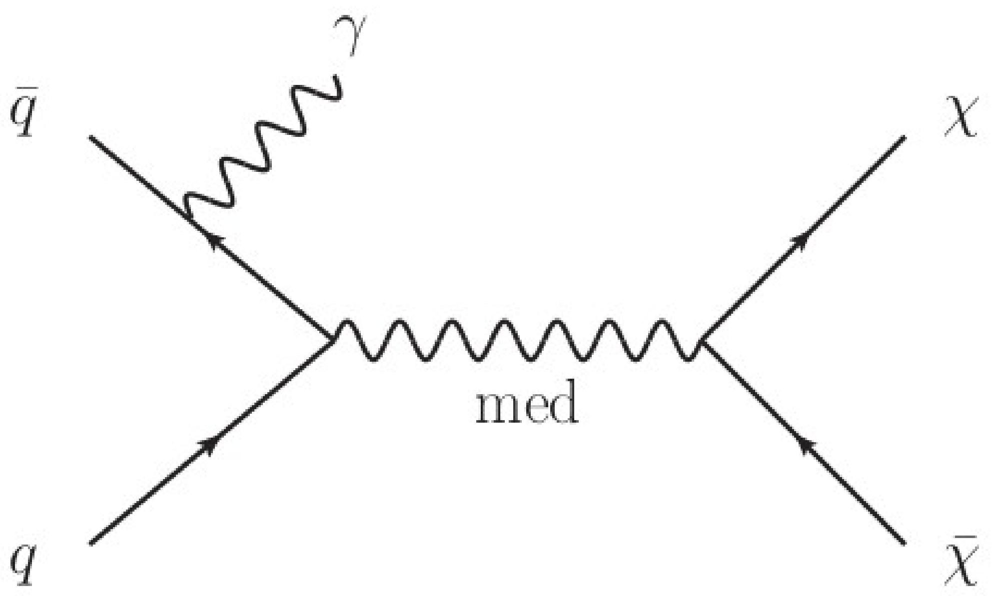
Type 1 seesaw mechanism with 3 HNLs can include a stable heavy neutrino as a Dark Matter candidate (as well as the decays examined on previous slides)

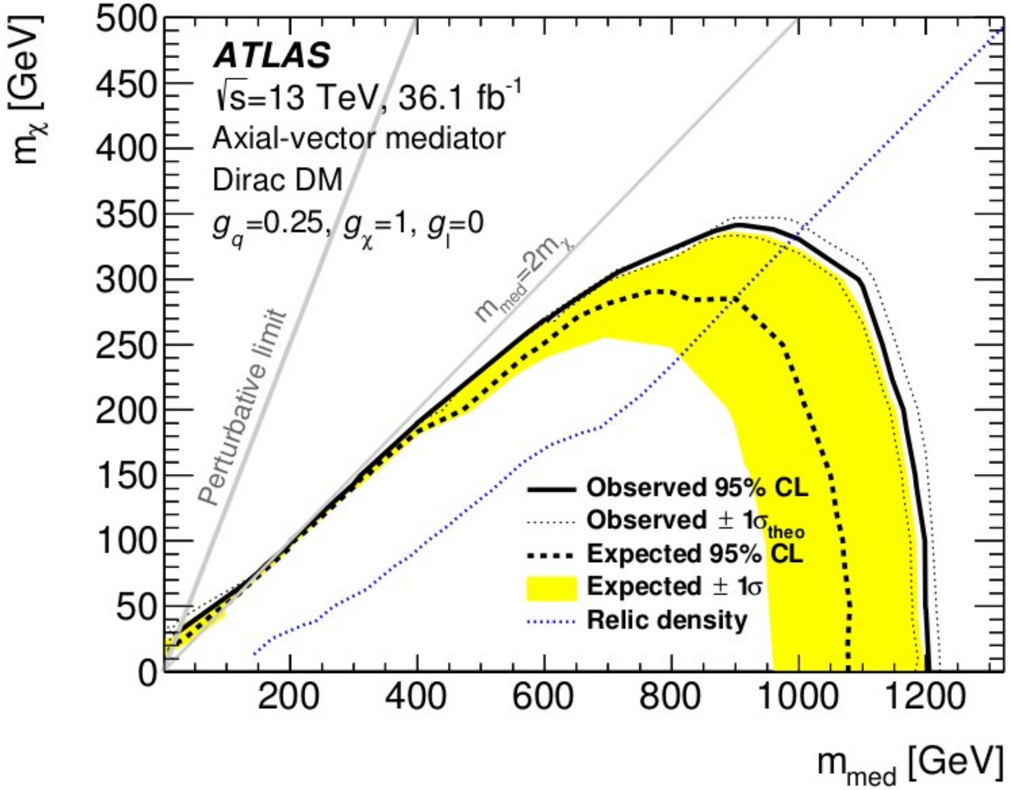
ATLAS has a number of general-purpose Dark Matter searches: some tagging particle plus MET

Dark matter searches with ATLAS

A final state with large MET, tagged with a radiated particle that we can detect
- photon in this example, many similar searches performed

Limit set using a simplified model (arXiv:1703.05703) with an axial-vector mediator



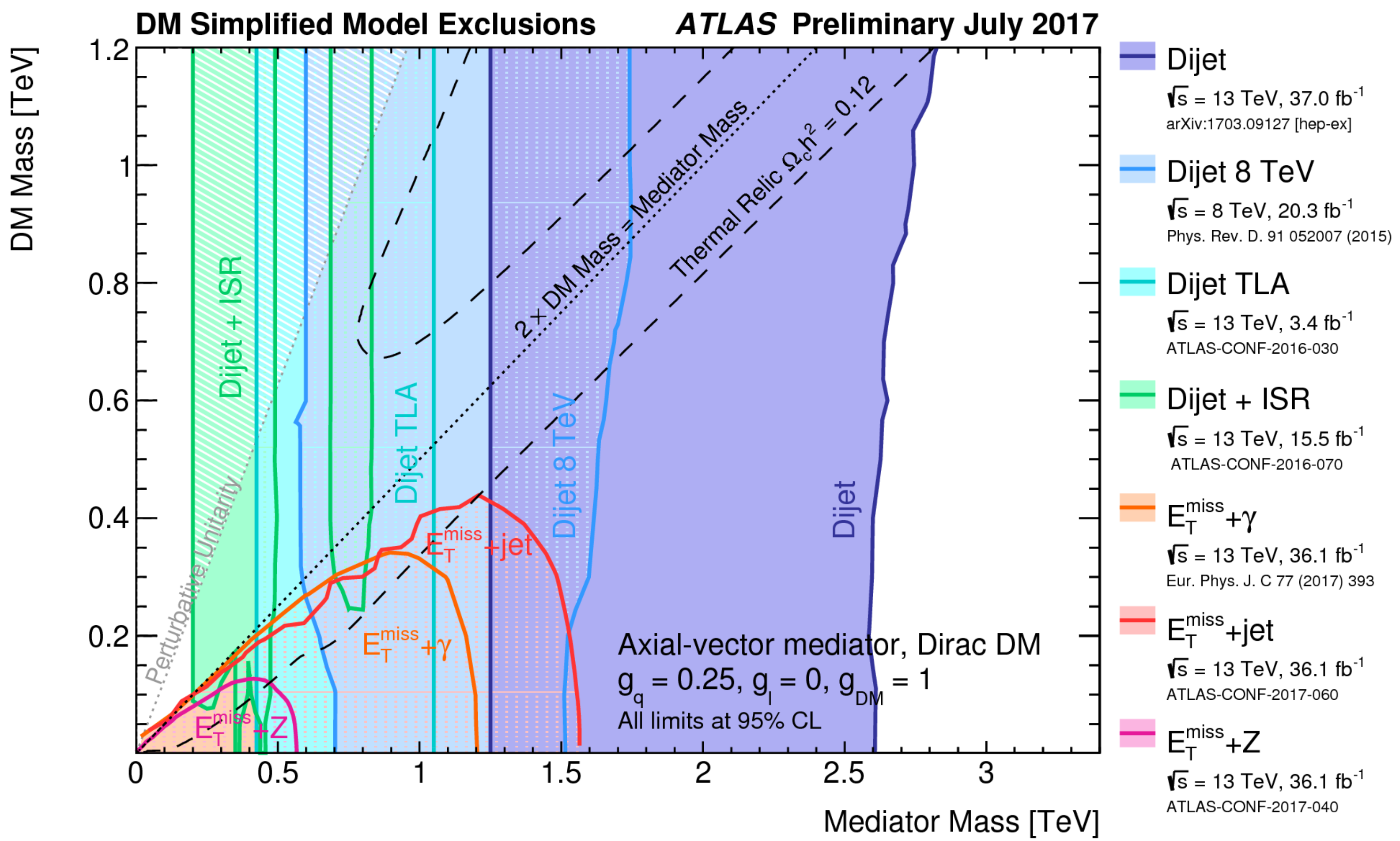


In this simplified model we make some benchmark choices for couplings to quarks (g_q) and leptons (g_l) as well as the hypothetical DM particle (g_X)

arxiv:1704.03848

Dark matter searches with ATLAS

Combined exclusion limits have been produced for these searches

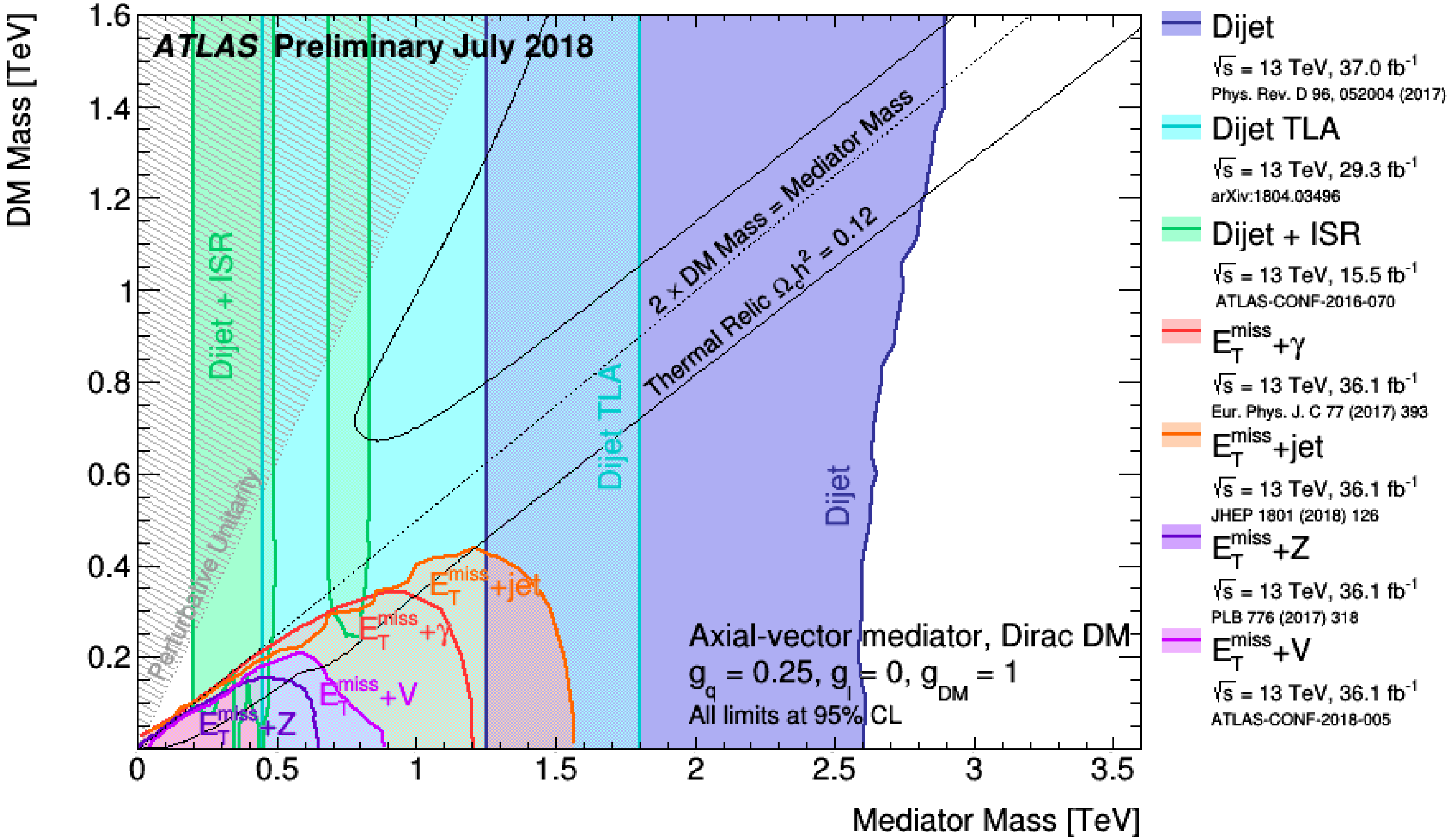


Since the propagator in our simplified model must couple to quarks for production, it should also decay to them

- in this plot, g_l=0 was chosen and so dijet searches are most sensitive

ATLAS Summary Plots

Dark matter searches with ATLAS

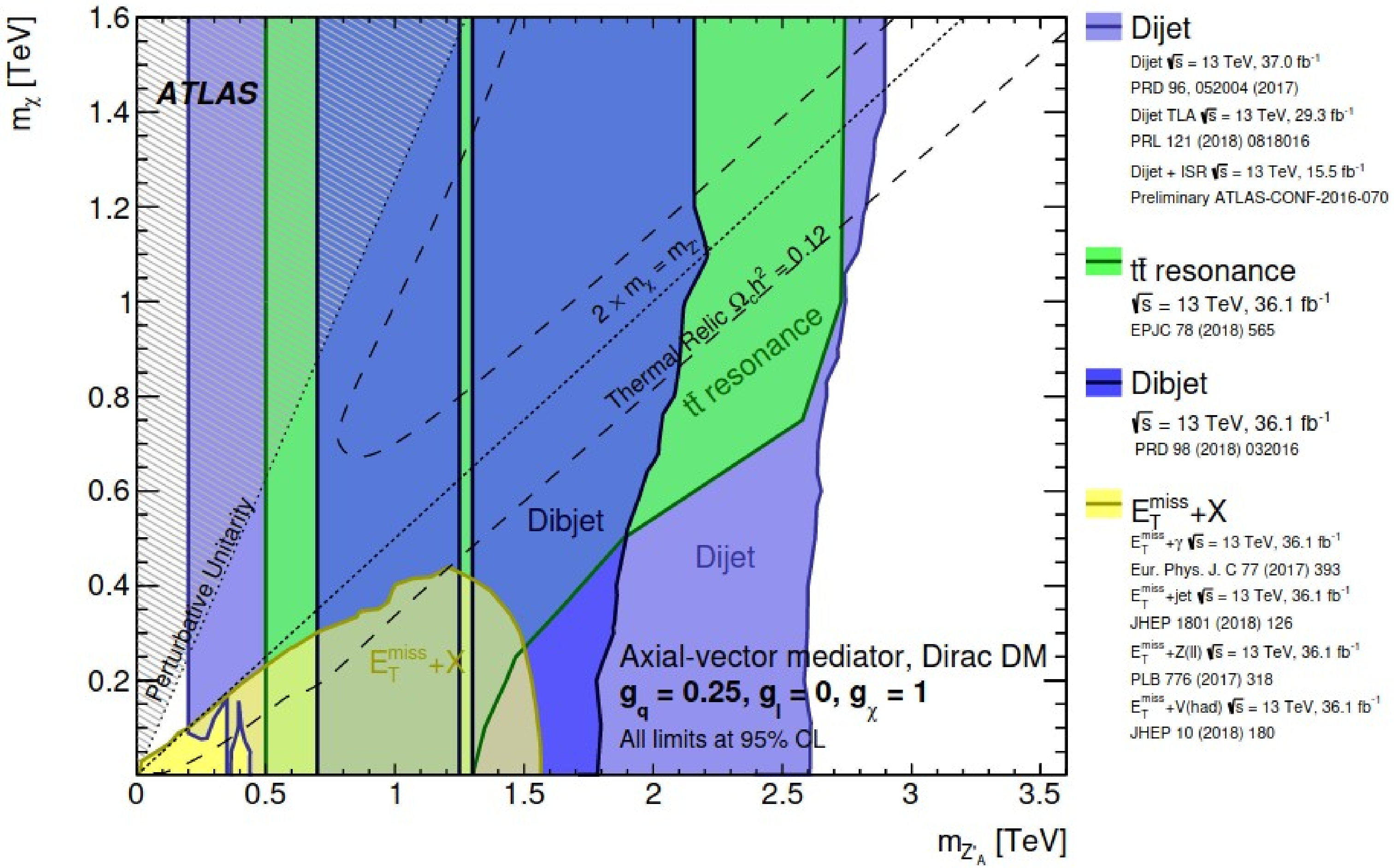


A new search for MET tagged with a vector boson

ATLAS Summary Plots

Dark matter searches with ATLAS

(plot not labelled, but it’s 2019)

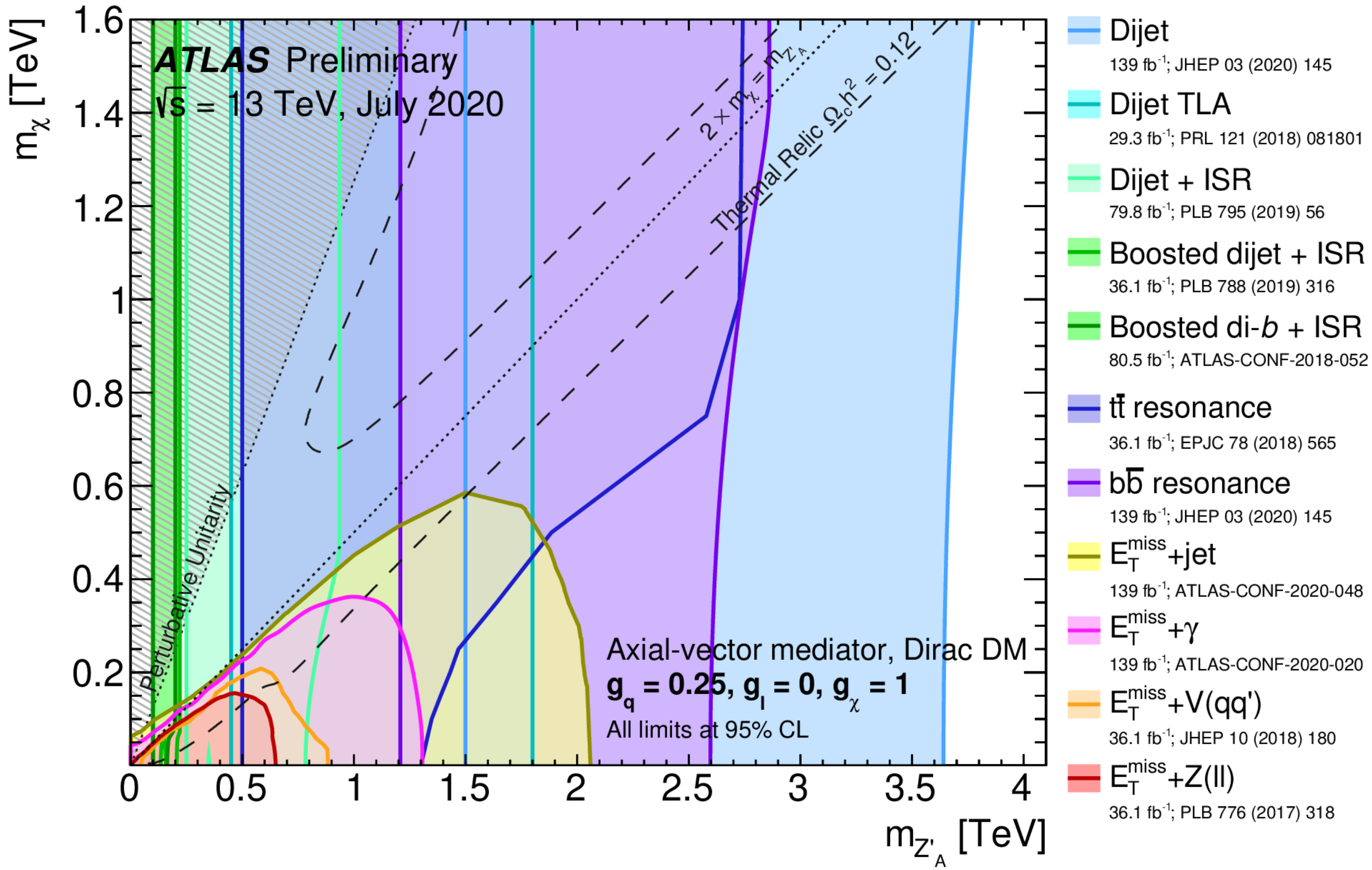


Added searches for bb and tt

The assumptions behind this combination discussed here arxiv:1903.01400

ATLAS Summary Plots

Dark matter searches with ATLAS

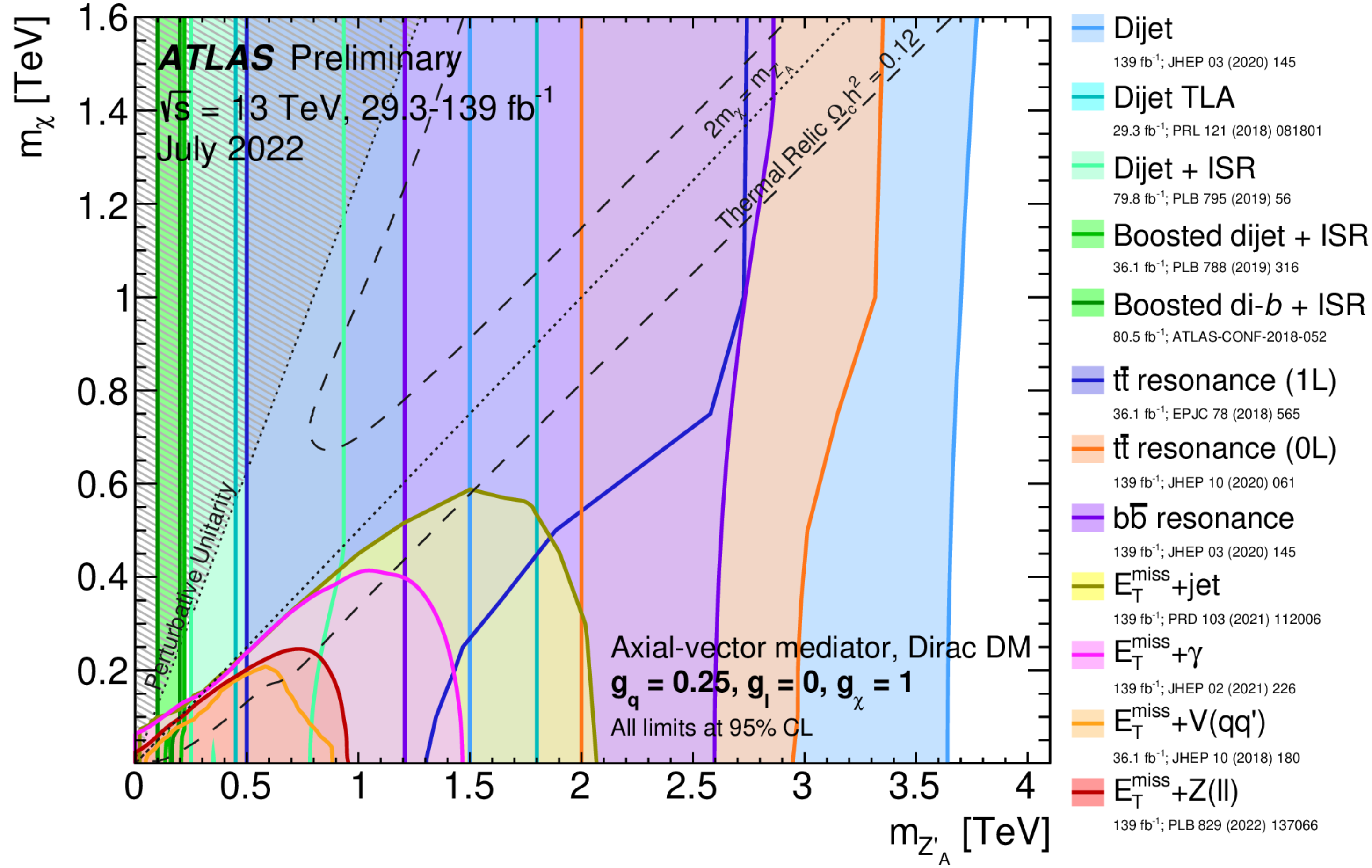


Increased sensitivity in most of the analyses (note x-axis extended)
- particularly bb and inclusive dijet

ATLAS Summary Plots

Dark matter searches with ATLAS

2022

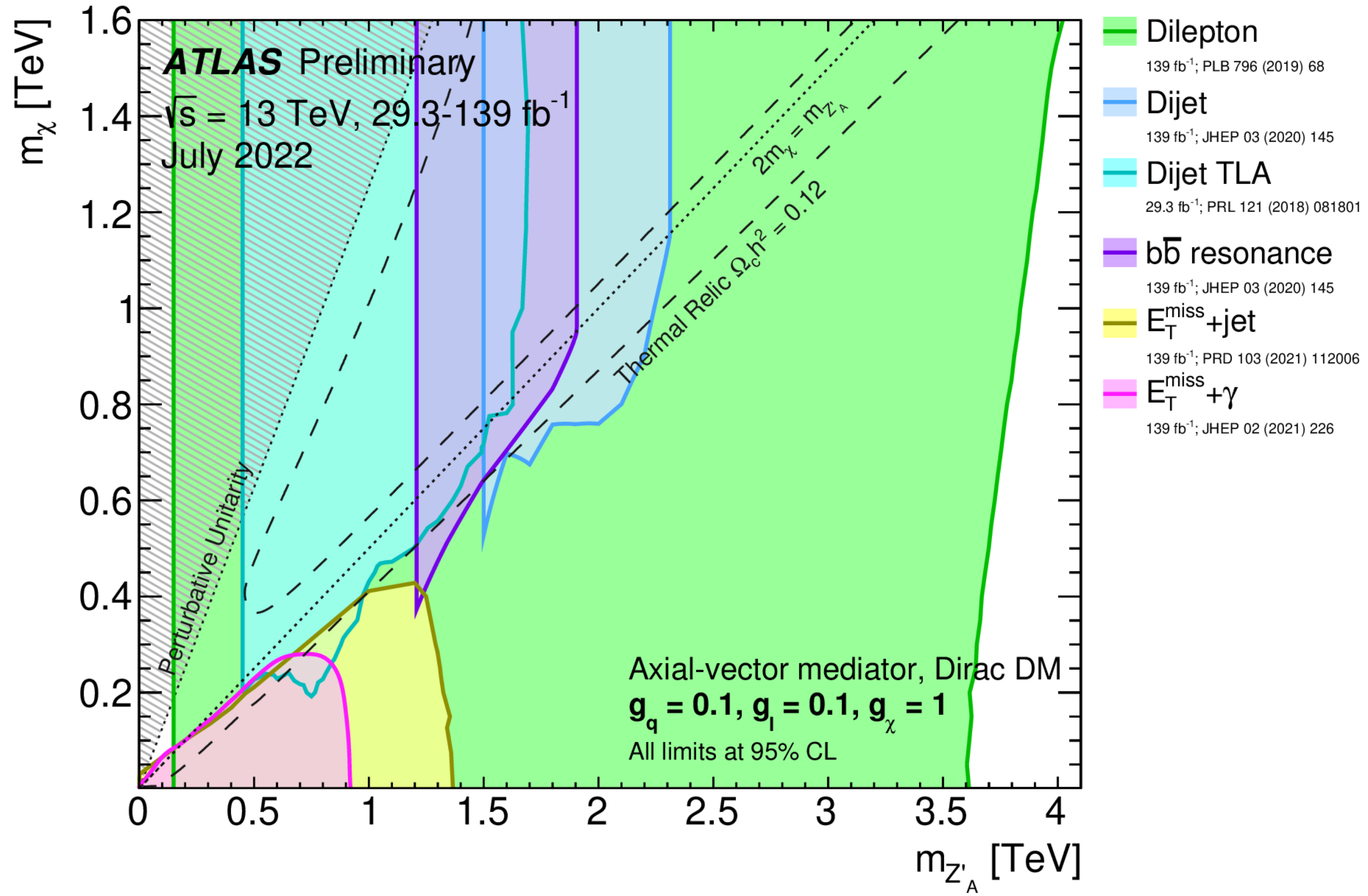


Hadronic tt added
- inclusive dijet still leader with leptophobic model

ATLAS Summary Plots

Dark matter searches with ATLAS

2022

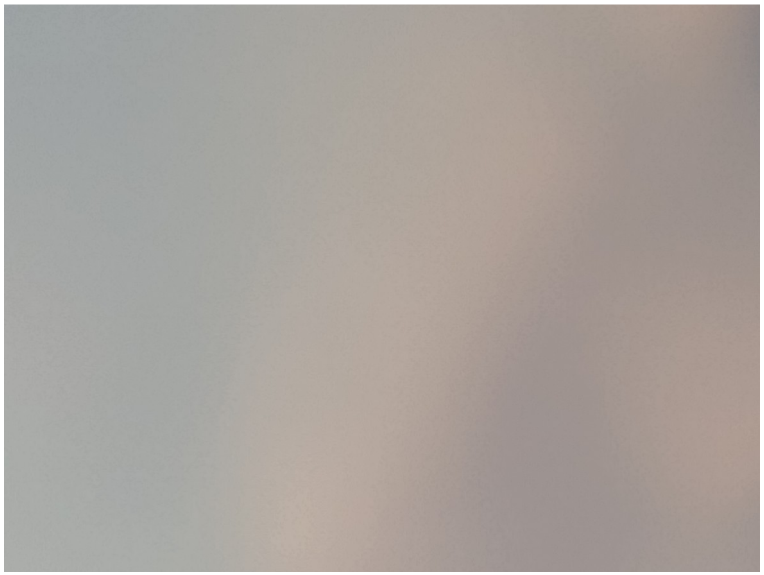


Equivalent plot when decays to leptons are allowed
- dilepton search now more sensitive than dijet

ATLAS Summary Plots

Salamander searches 2022

Thank you to the organisers for bringing us to this beautiful part of the world
- I took the opportunity to search for something I hadn’t seen before



Analysis channel: eV-scale photons incident on pixelated sensor

Salamander searches

2022

Thank you to the organisers for bringing us to this beautiful part of the world
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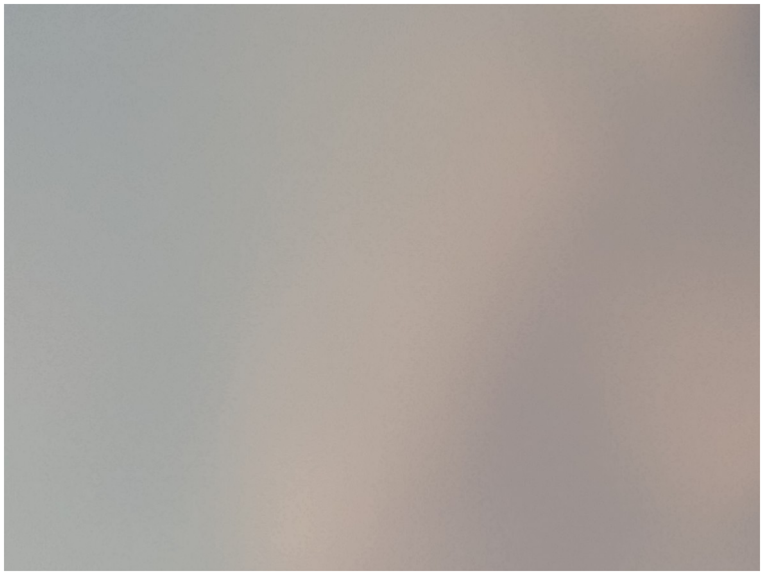

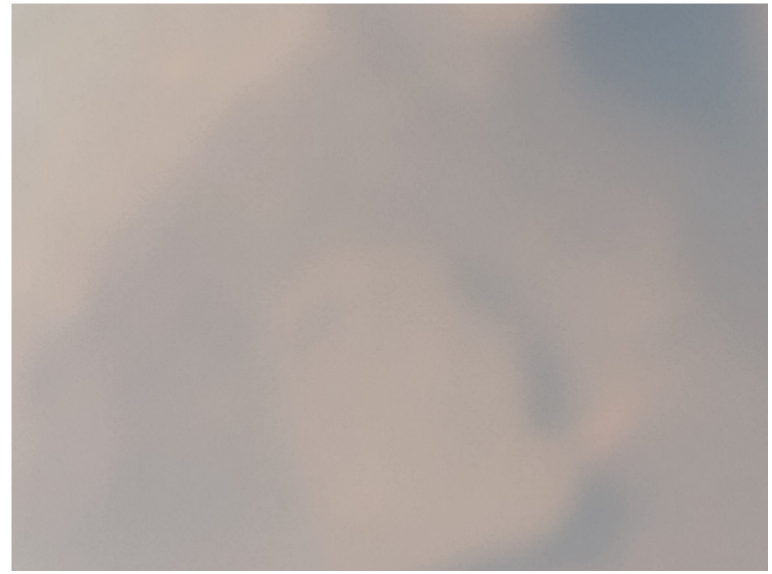

Analysis channel: eV-scale photons incident on pixelated sensor

Salamander searches

2022

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- I took the opportunity to search for something I hadn't seen before

Analysis channel: eV-scale photons incident on pixelated sensor

Salamander searches 2022

After collecting enough data, this story does have a happy ending:

May our searches for new physics be so fortunate!

Summary

Models for prompt decays of Heavy Neutrinos have been (and are still being) studied at the ATLAS experiment

- Type 1 seesaw and LRSM
- Type 3 seesaw

Displaced vertex searches are an evolving field for collider experiments that were designed for prompt decays

- active area of research
- some results already shown
- displacement on the order of a few meters only, otherwise we're just looking for disappearances (MET)

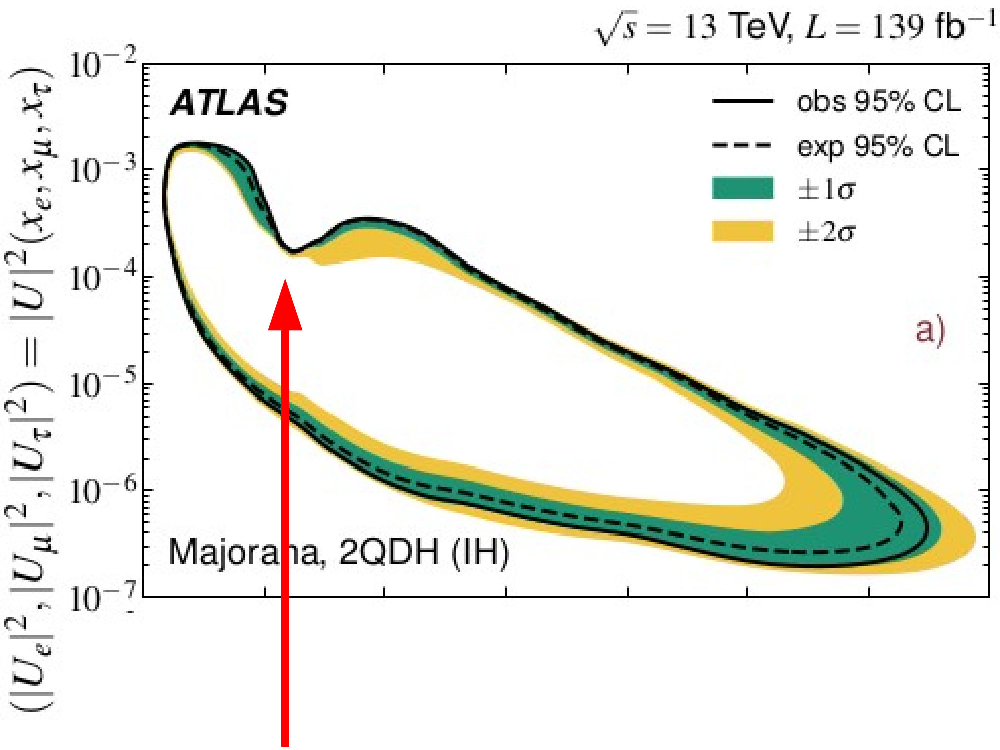
Heavy Neutrinos – if stable – could be Dark Matter candidates

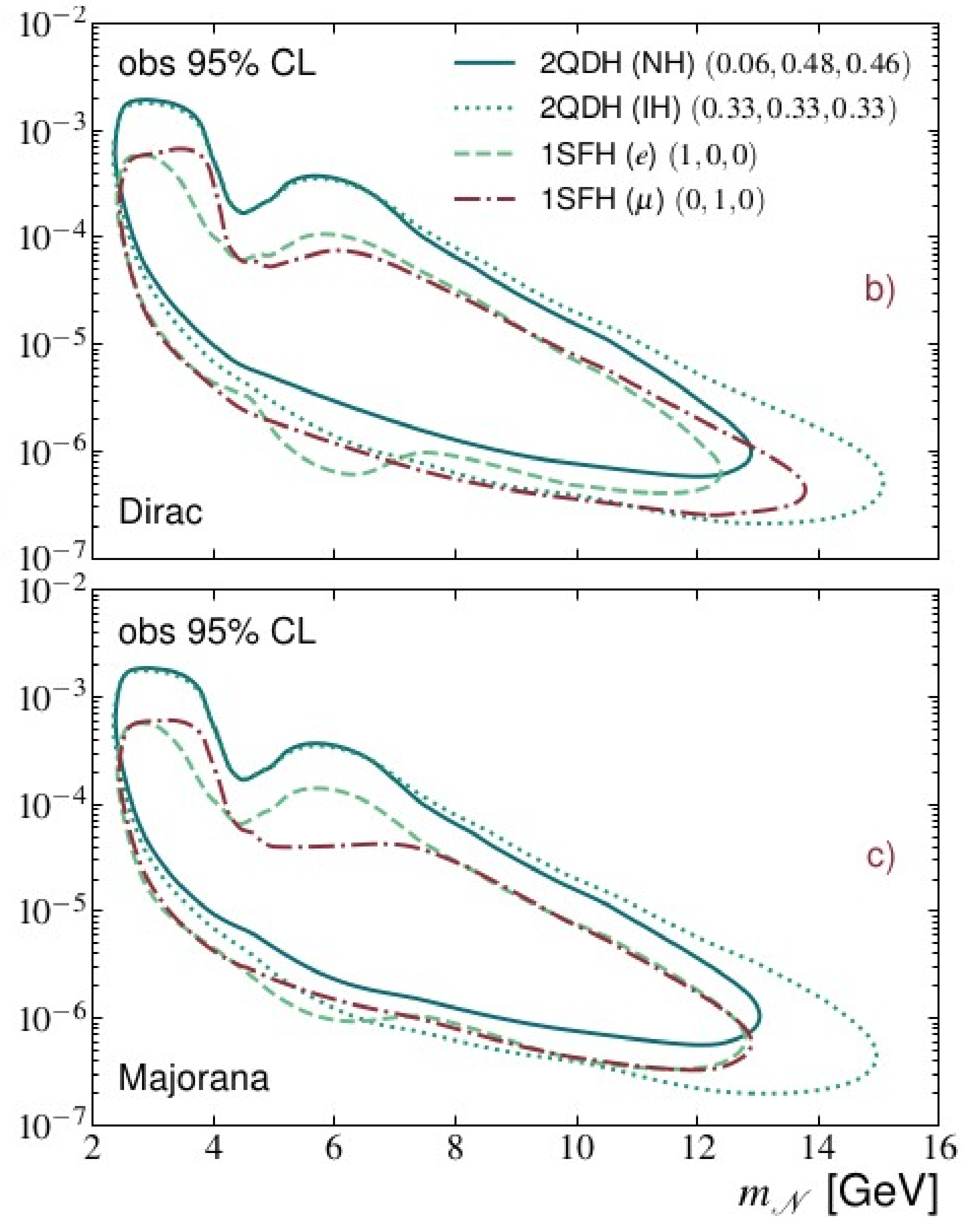
- several dedicated searches for MET associated with an identified particle
- inclusive searches for visible final states more sensitive in simplified model

BACKUP

Type 1 seesaw HNL search

2022





This slightly odd feature is due to a "diagonal" cut in the ee channel
- vertex mass allowed to reduce as displacement increases

Note that the feature appears in the expected limits - it's not a discovery!

arxiv:2204.11988