Heavy neutrinos at the LHC

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21/09/18

What is a heavy neutrino?

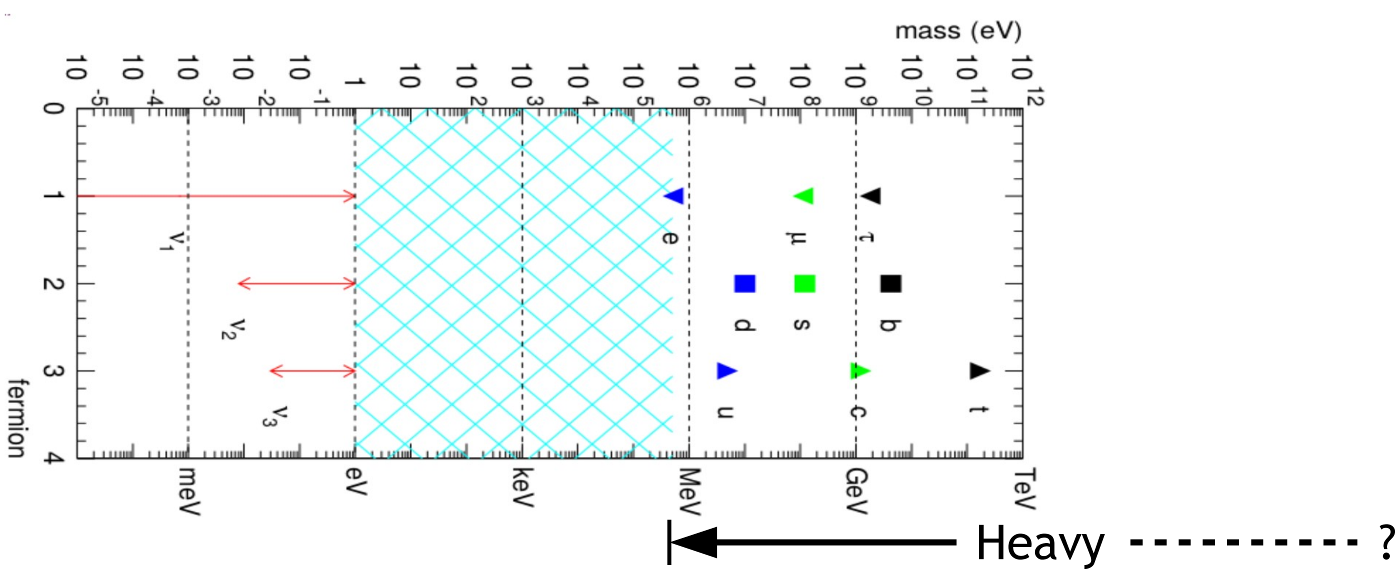
Standard model neutrinos were massless in theory

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”



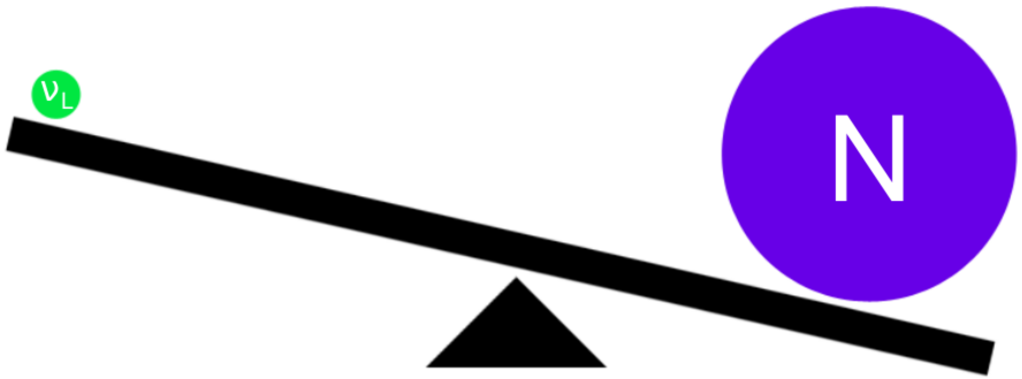
Why heavy neutrinos?

The known, “light” neutrinos are considered to be anomalously light, compared to the other massive fundamental particles

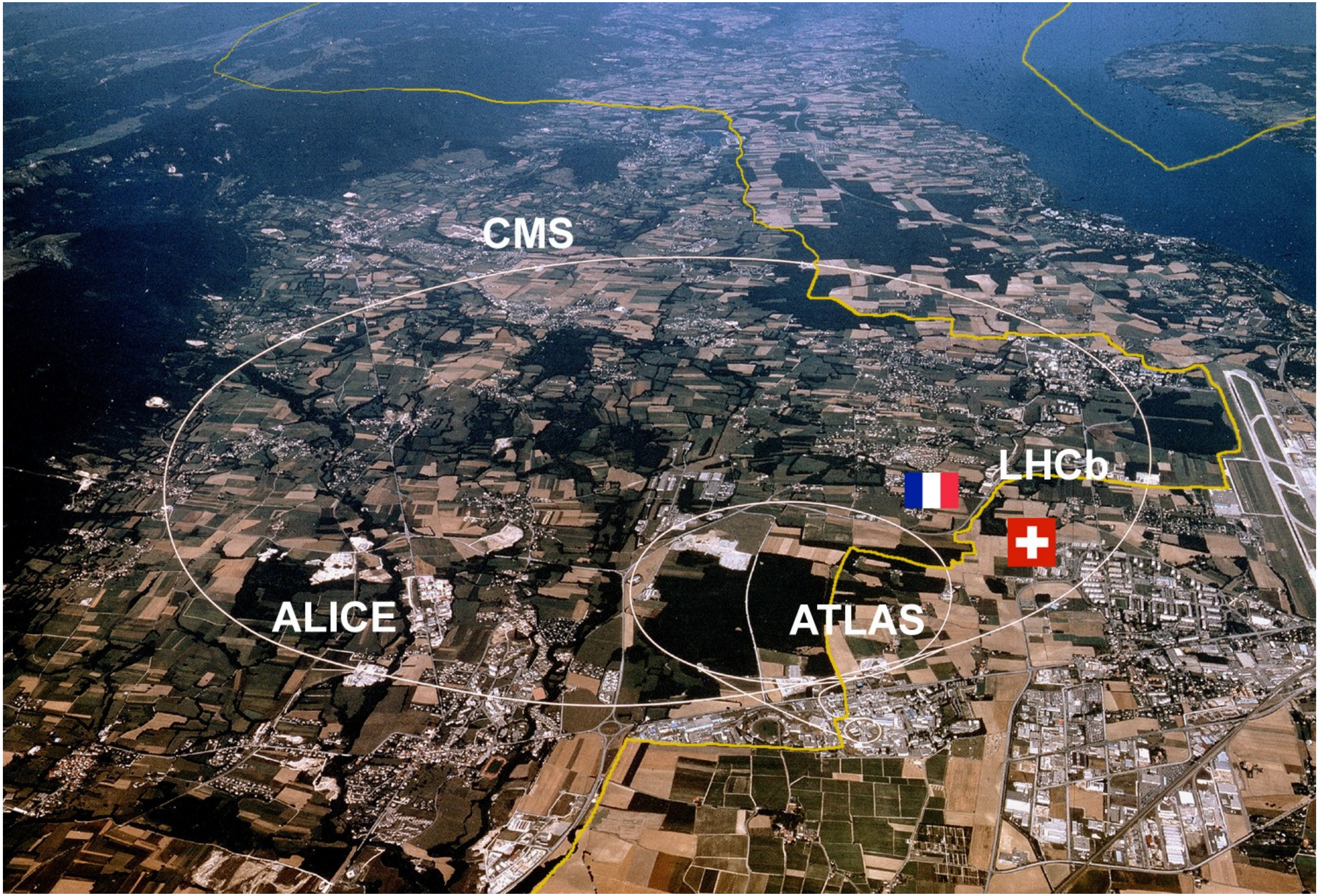
A common explanation for this is the seesaw mechanism, whereby each light neutrino couples to a heavier partner

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

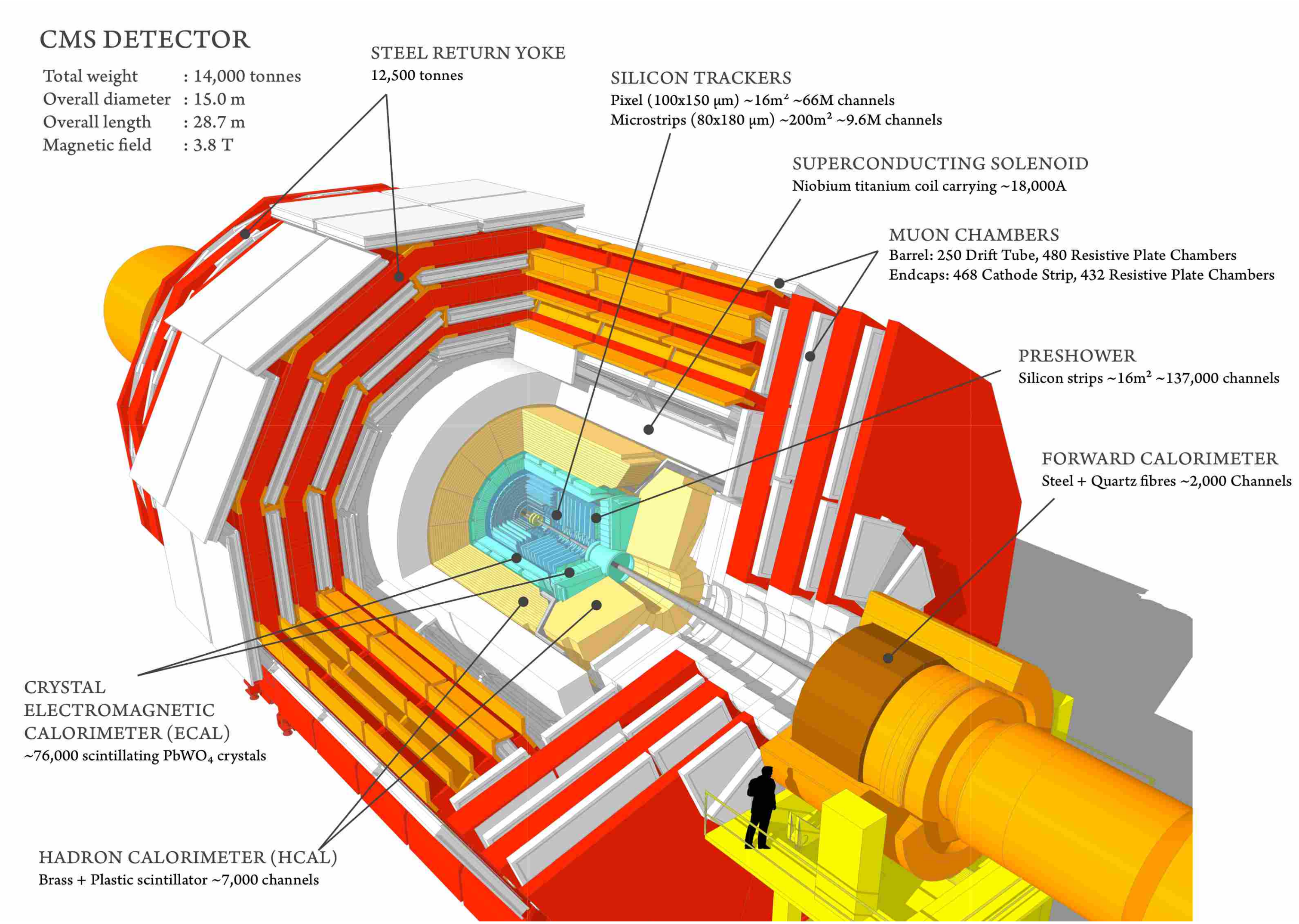


Large Hadron Collider



Prompt decays with CMS

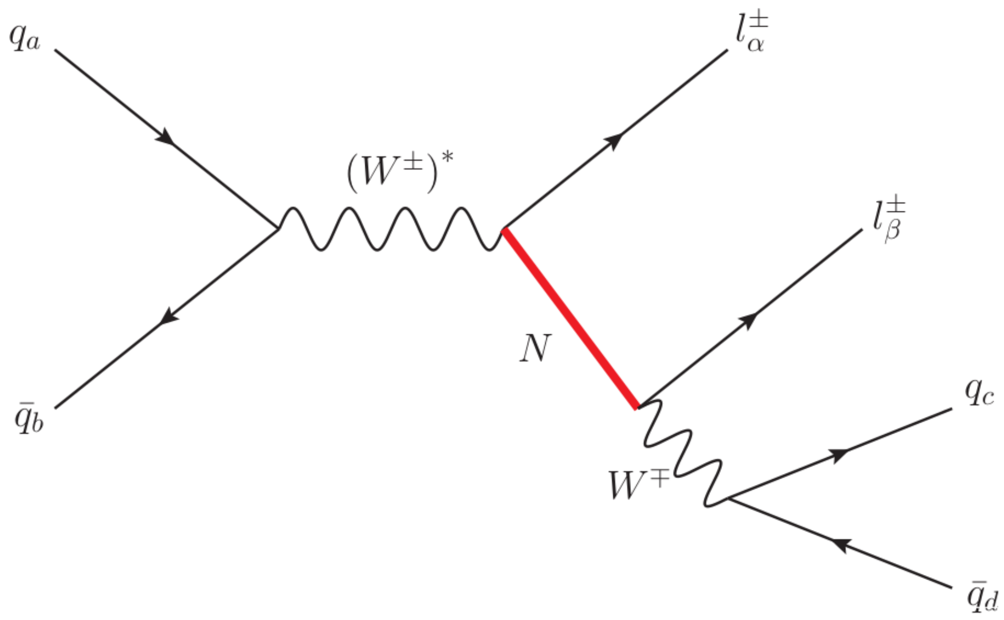
There are several recent results from CMS searching for decays where the heavy neutrino lifetime is short, and so it decays near the interaction point: a "prompt" decay

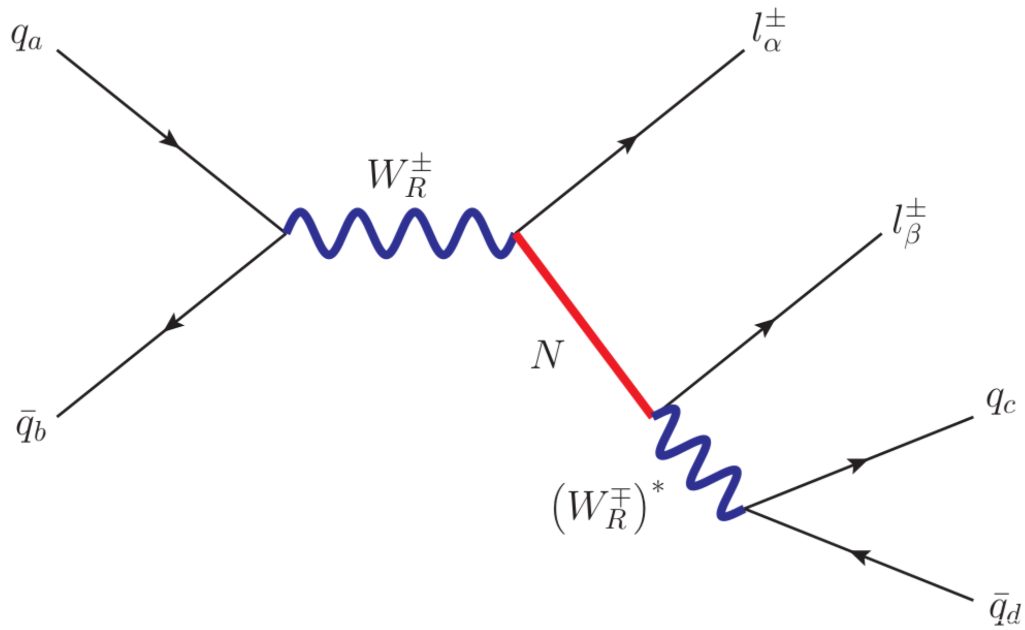


Prompt decays with CMS

Typical final states are a pair of leptons and a pair of quarks

In Left-Right Symmetric Models (LRSM), the decay chain may include a right-handed W-boson



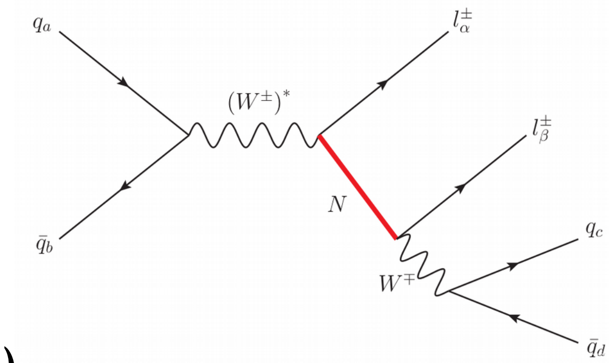


If the heavy neutrino is a Majorana fermion, the final state leptons may have the same charge – selecting for this reduces backgrounds dramatically

Some models also allow for lepton flavour mixing

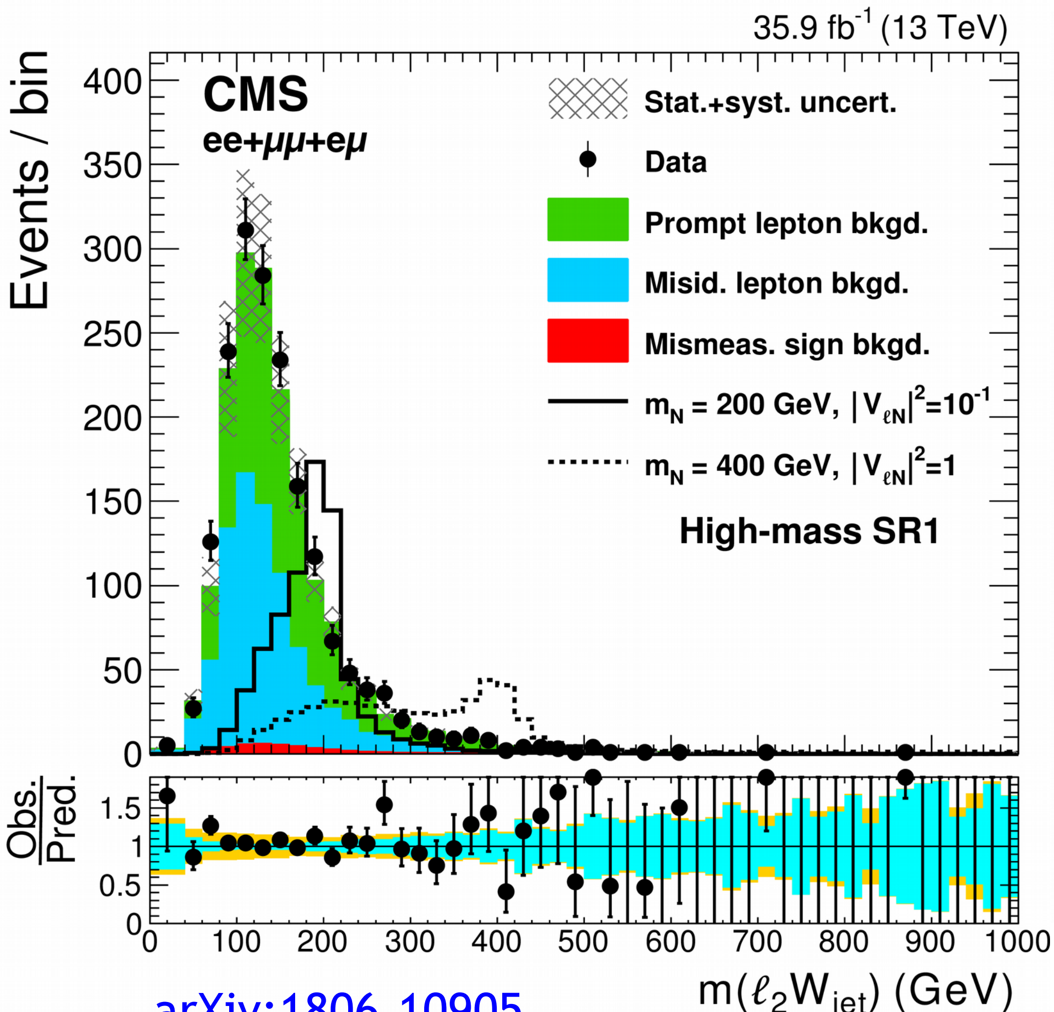
Prompt decays with CMS

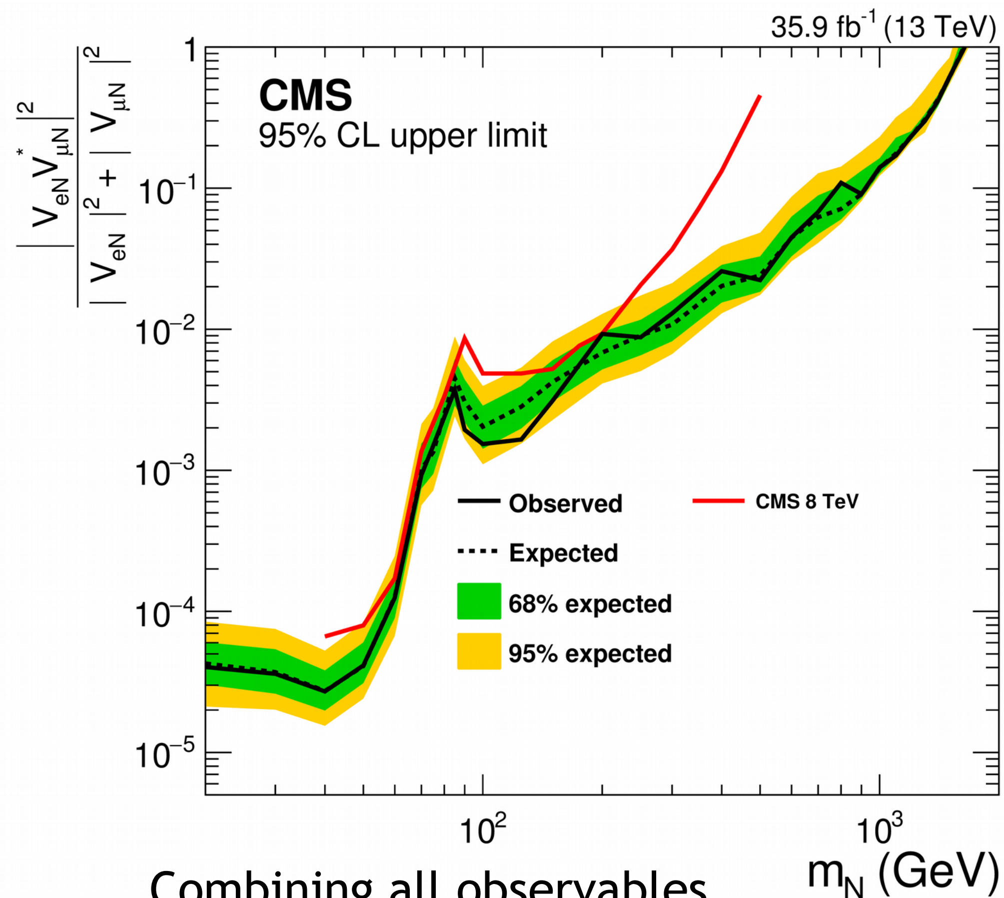
2018



Searching for a Majorana heavy neutrino, arising from the neutrino minimal standard model (νMSM, Type-1 seesaw)

Two leptons with same charge but any flavour (ee, eμ or μμ) and >1 jet: all flavours combined for different mass final states



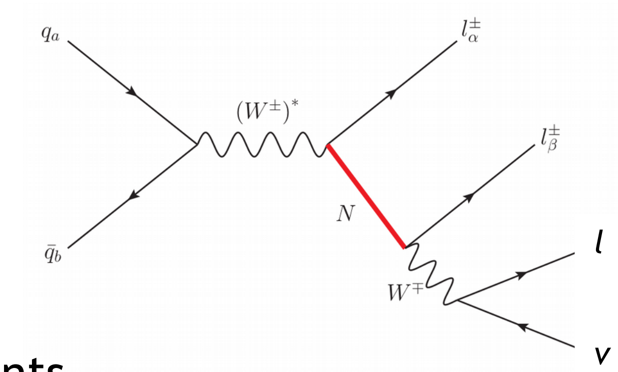


Combining all observables

arXiv:1806.10905

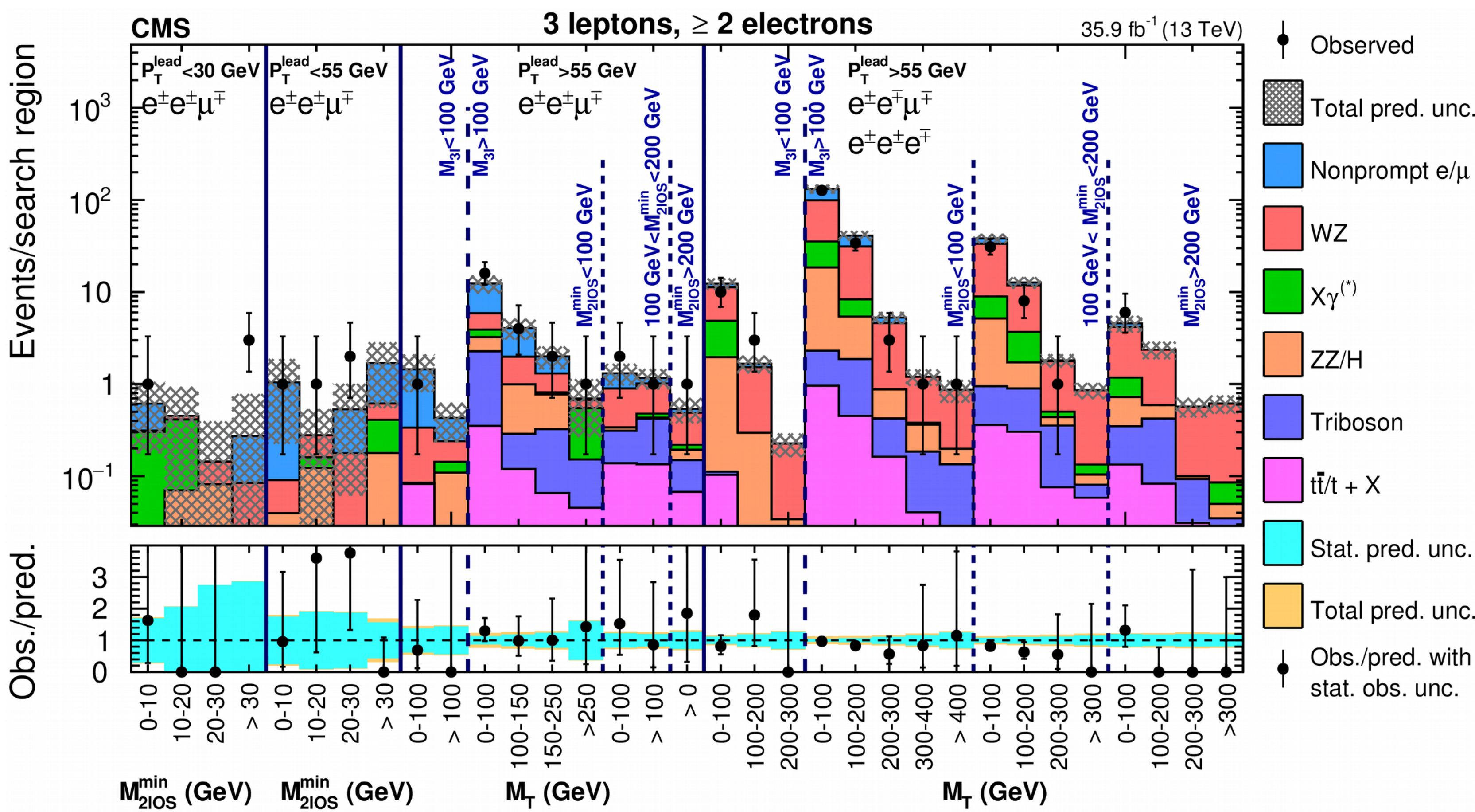
Prompt decays with CMS

2018



Searching for a Majorana heavy neutrino, arising from the neutrino minimal standard model (νMSM, Type-1 seesaw)

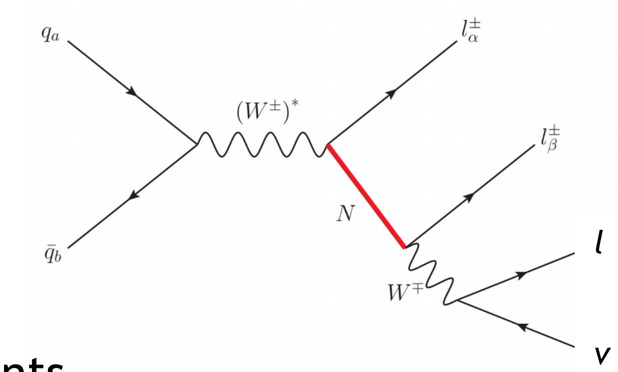
This decay chain ends with W→lν, so the search counts events for several combinations of e and μ in different mass bins (ee+X below)



arXiv:1802.02965

Prompt decays with CMS

2018



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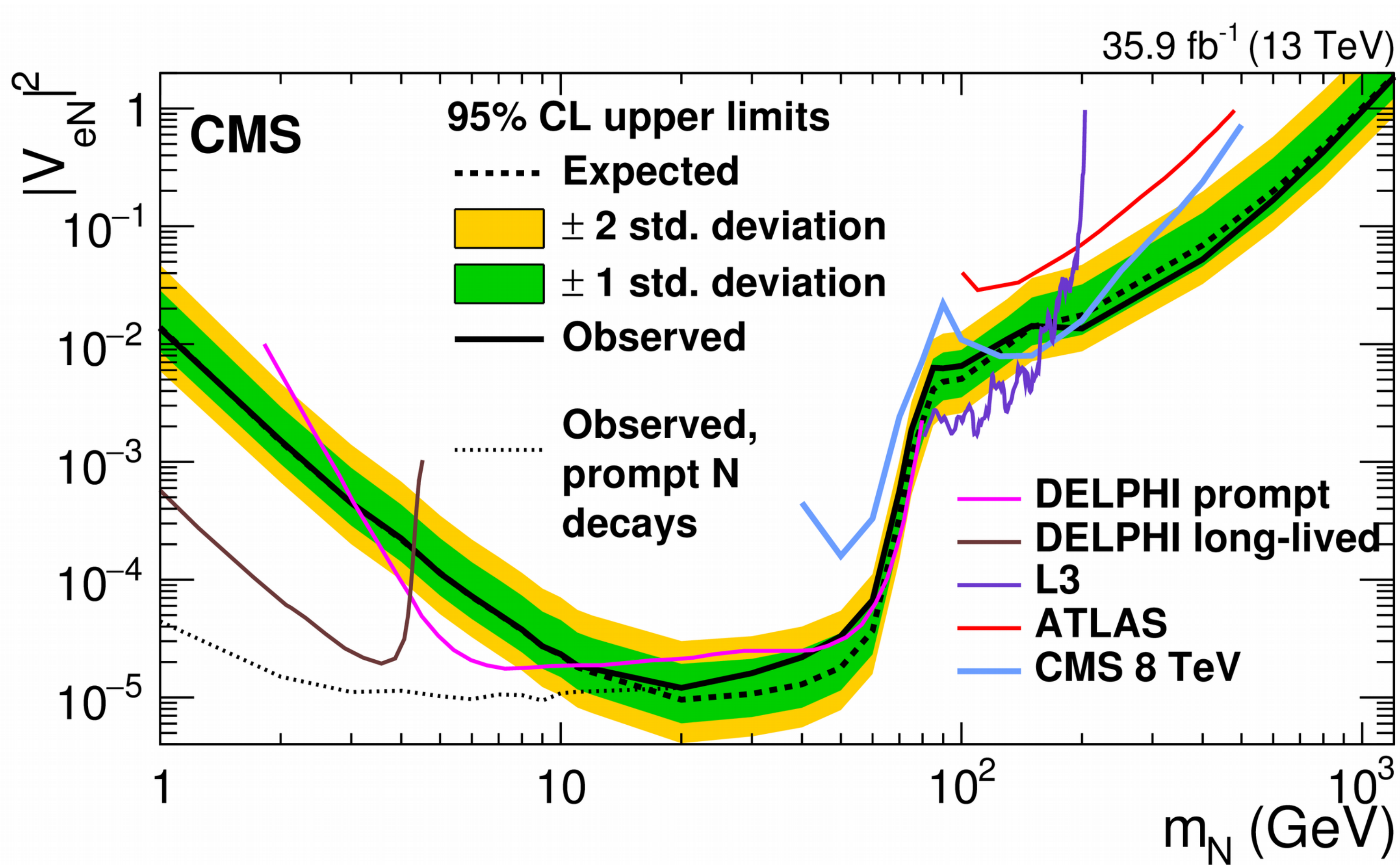


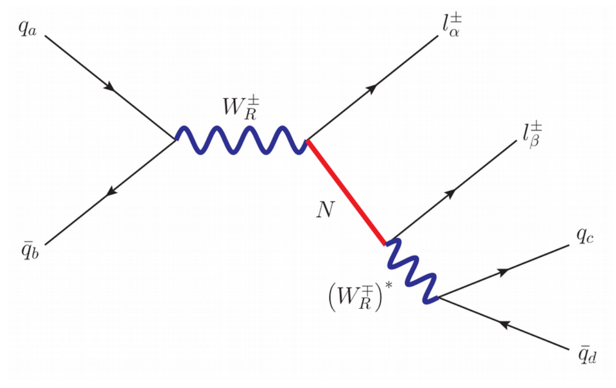
arXiv:1802.02965

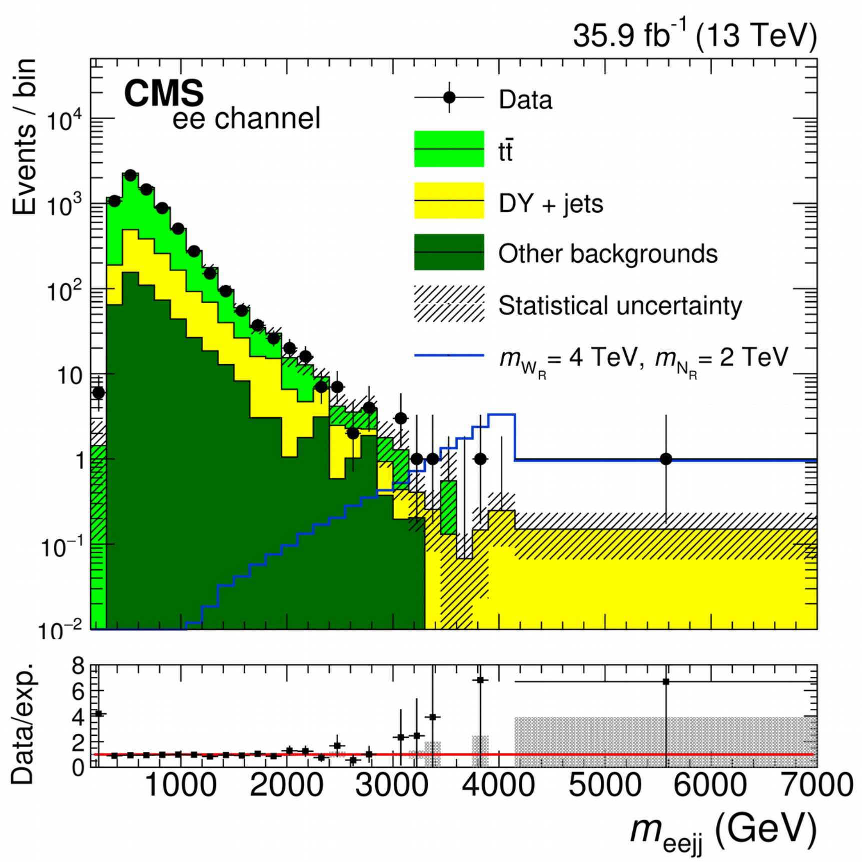
Prompt decays with CMS

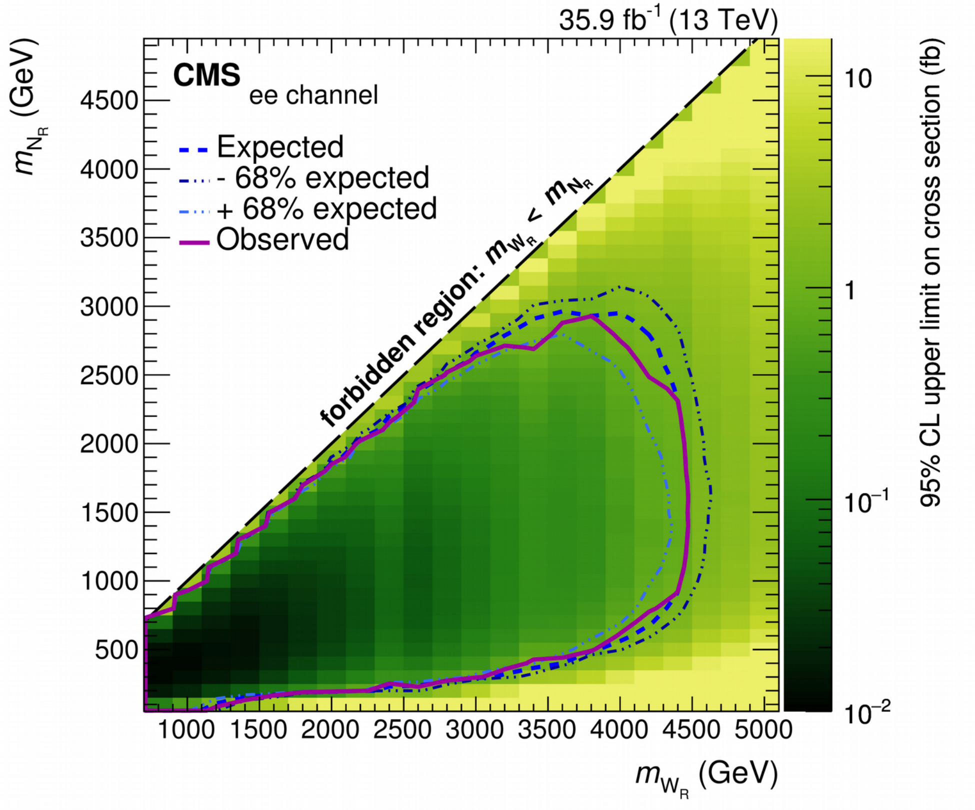
2018

Searching for LRSM decay, final states with 2 leptons of same flavour (ee or μμ) and any charge combination

Observable plotted is the mass of the combined final state eejj (μμjj gives similar results)





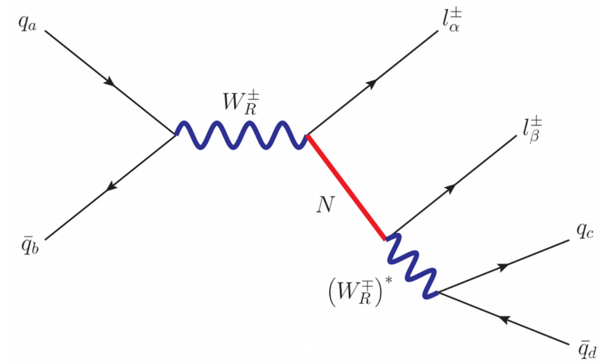


arXiv:1803.11116

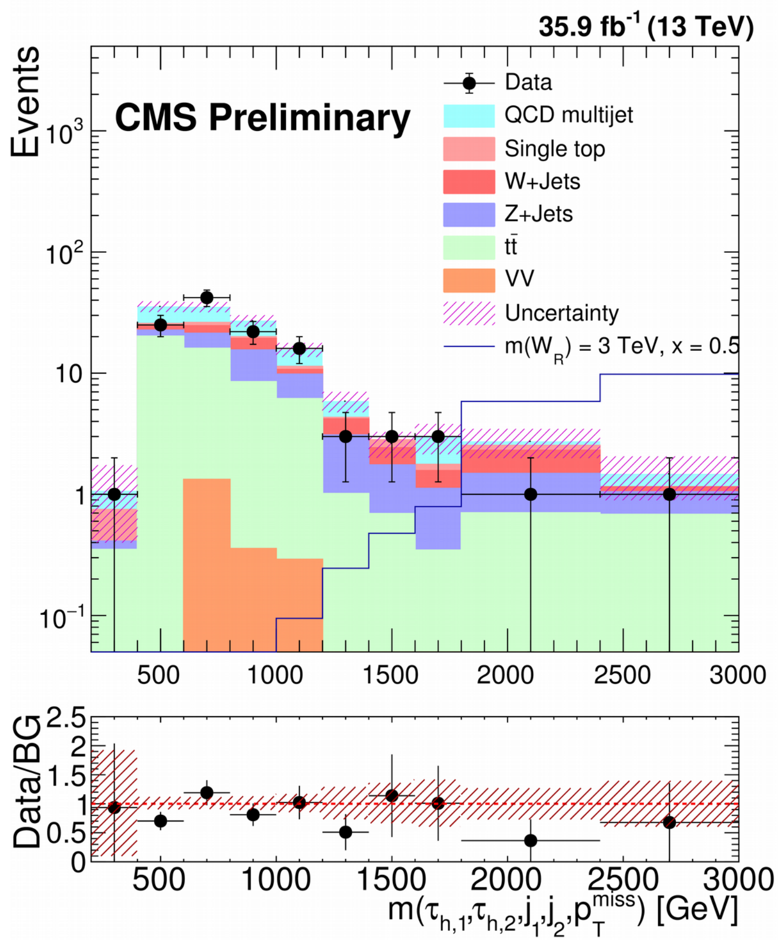
Prompt decays with CMS

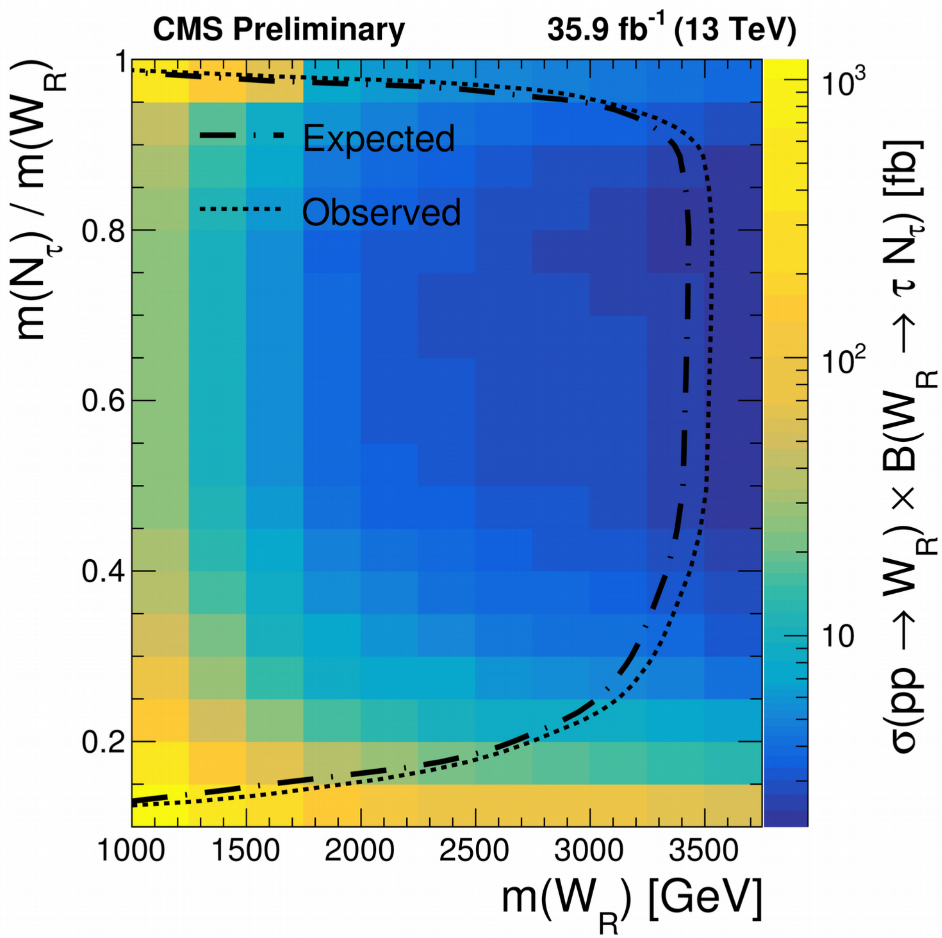
2018

Searching for LRSM decay, final states with 2 τ-leptons decaying hadronically, and 2 jets from the W decay



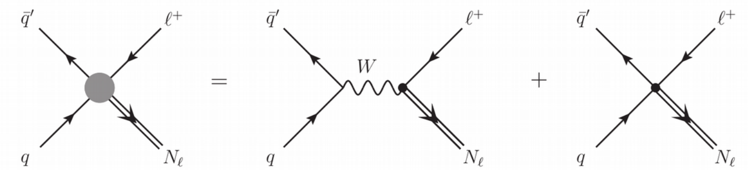
Observable plotted is the combined mass of the final state particles and missing transverse momentum





CMS-PAS-EXO-17-016

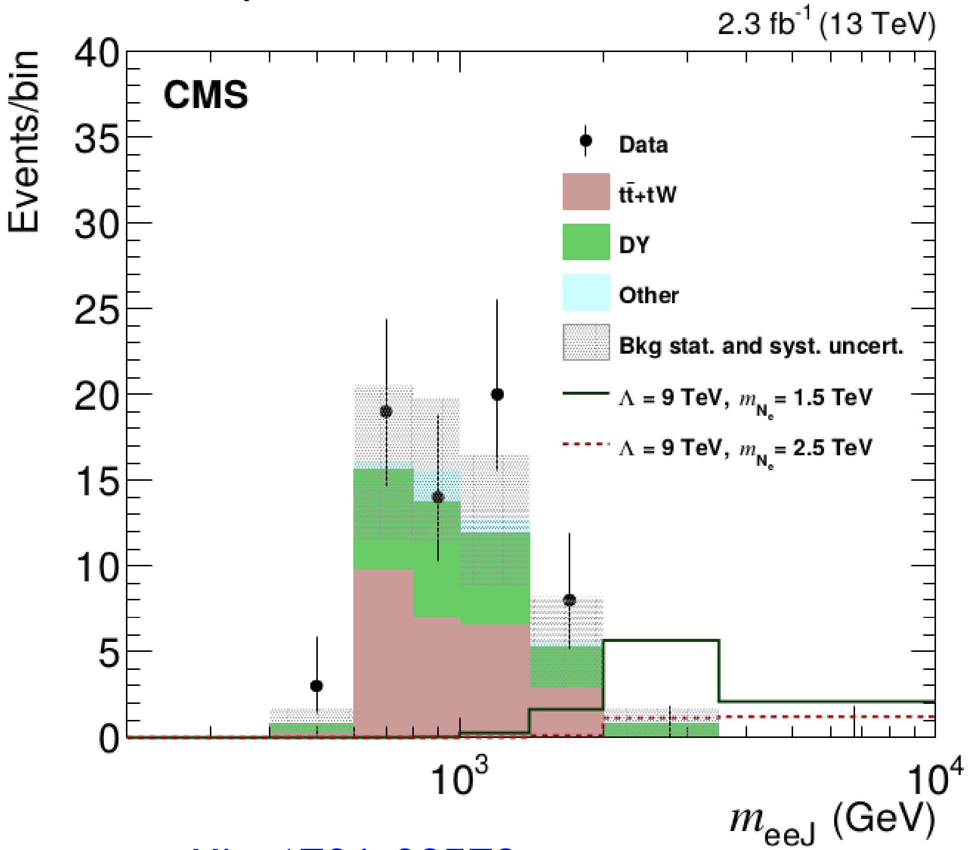
Prompt decays with CMS

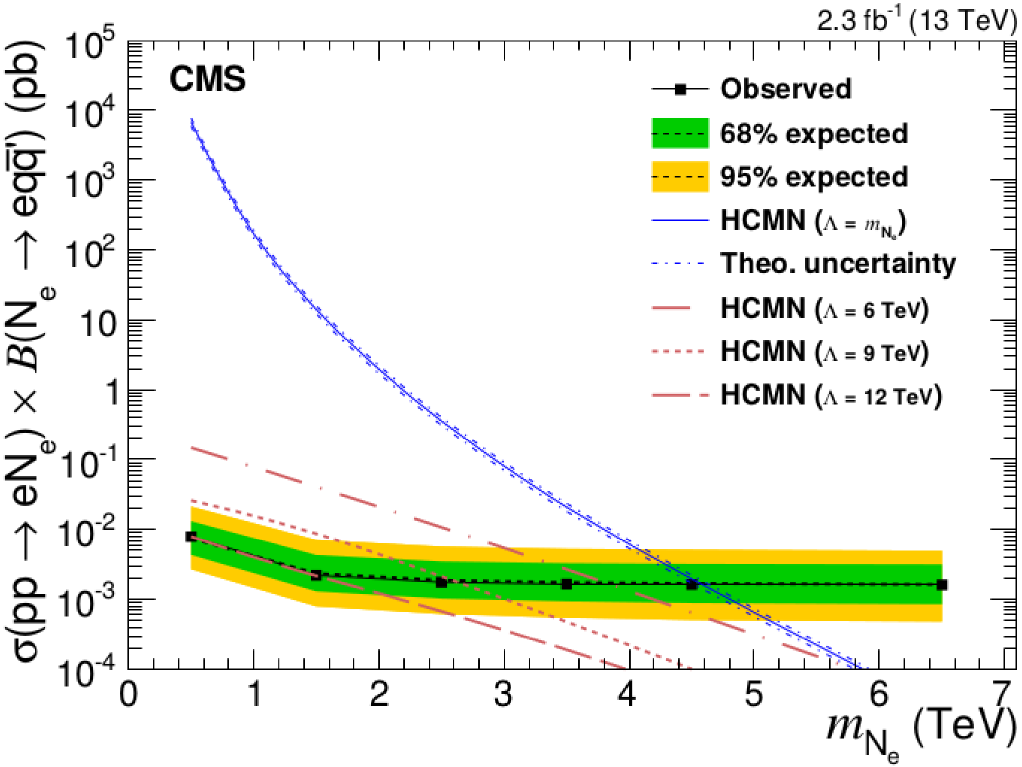


Searching for a heavy composite
Majorana neutrino decay, i.e. the neutrino here is not a fundamental particle

Final states with a pair of either electrons or muons, and a single large jet containing the collimated decay products of the 2 quarks

Limits compared with a variety of different choices of the compositeness scale Λ, and production cross-section dominated by contact-interaction component

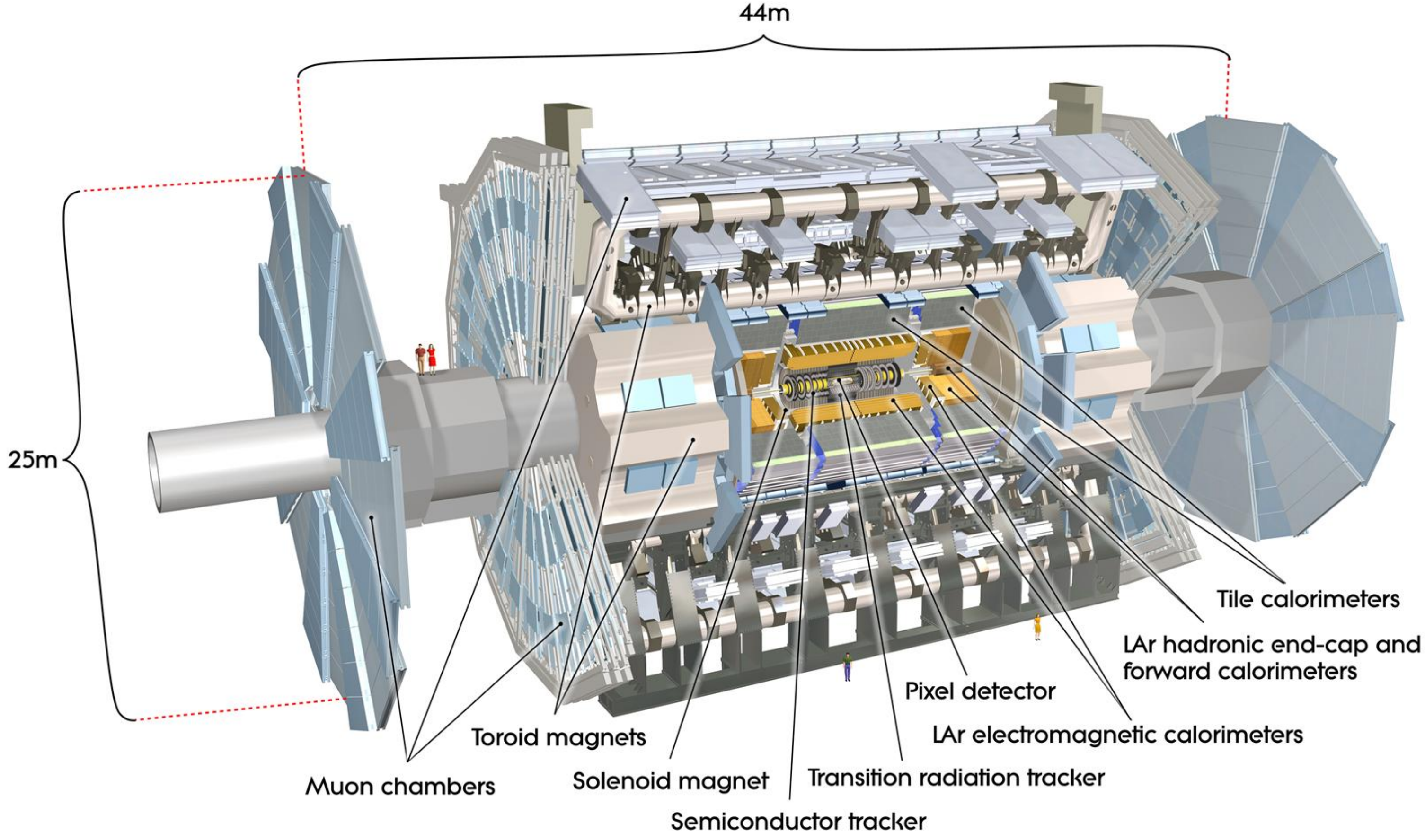




arXiv:1706.08578

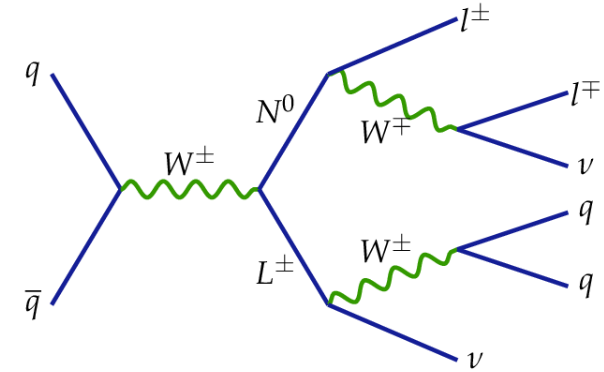
Searches with ATLAS

There's a recent result for Heavy Neutrino prompt decays from ATLAS, as well as a number of Dark Matter searches that are compatible with HN models



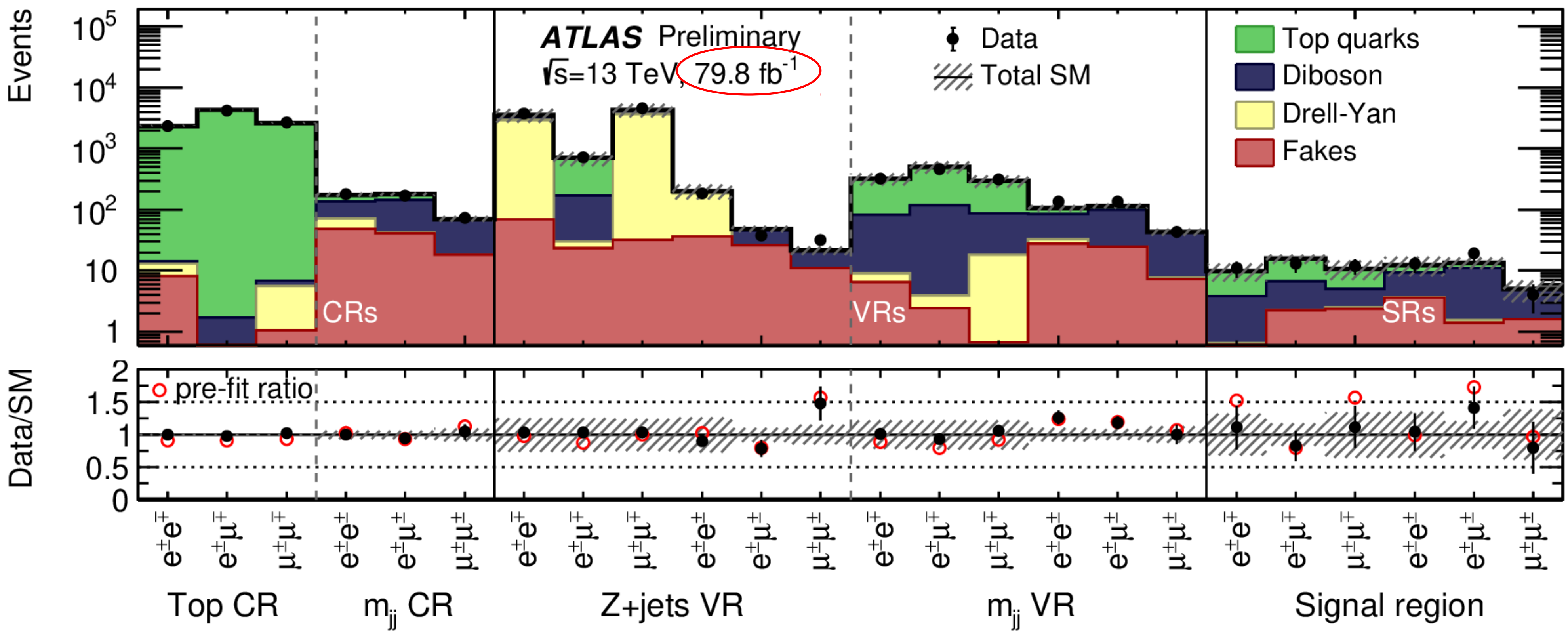
Prompt decays with ATLAS

2018



Searching for Type-3 seesaw mechanism decays
(includes a heavy neutral Majorana lepton)
in final states with 2 jets, MET, and ee, eμ, or μμ

For more information see Daniela's talk on Tuesday



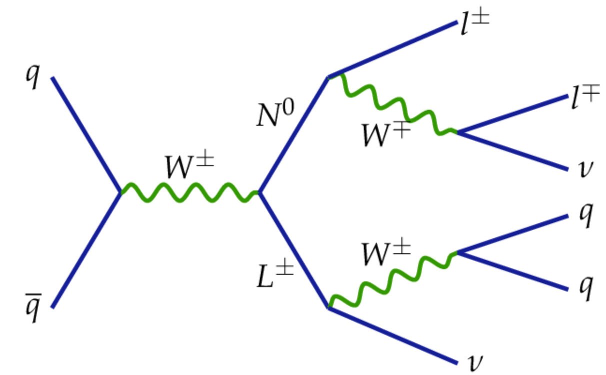
(CR = control region for background fitting; VR = validation region to test fitting)

ATLAS-CONF-2018-020

2017 CMS result (36 fb-1)

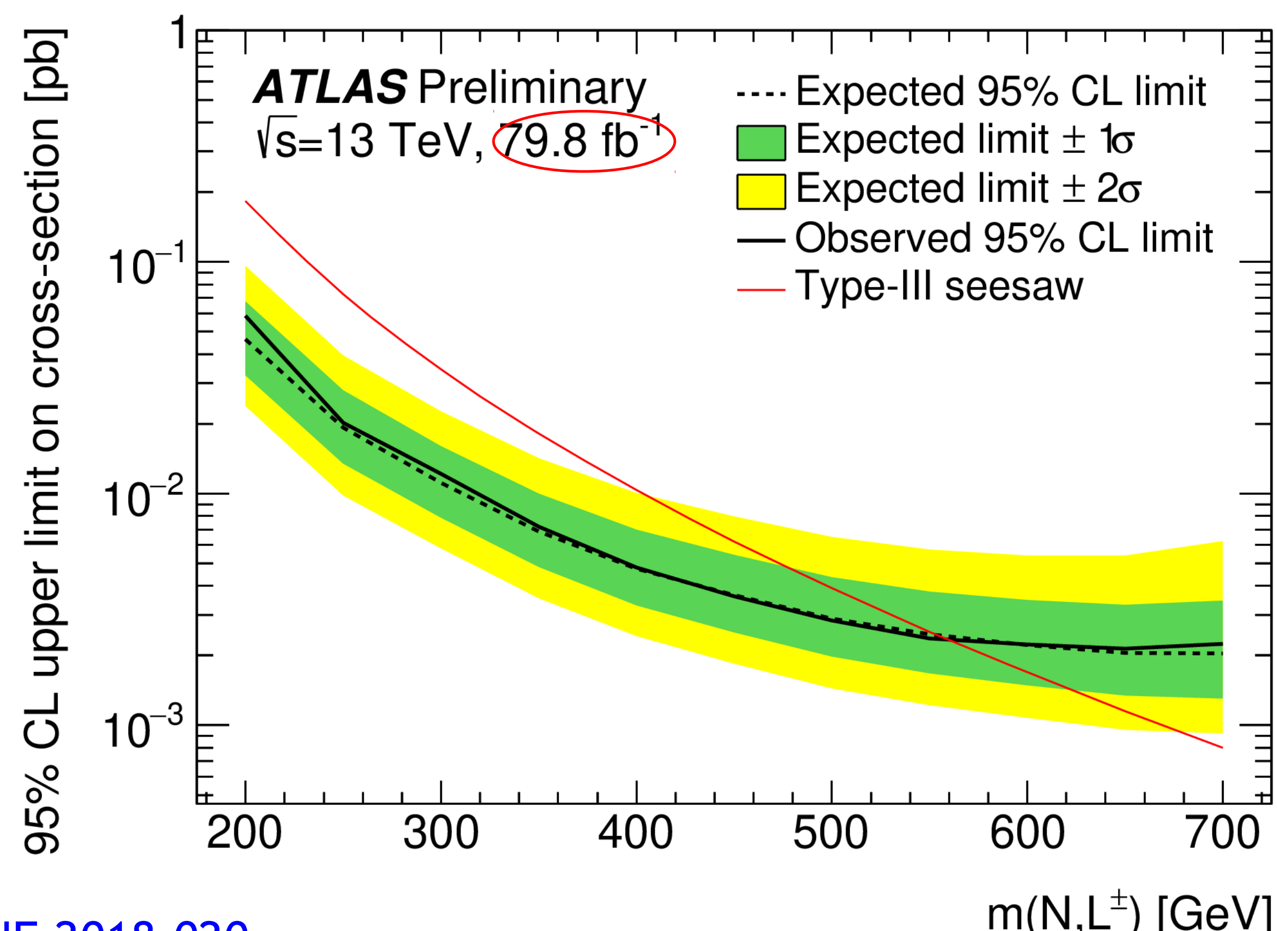
Prompt decays with ATLAS

2018



Searching for Type-3 seesaw mechanism decays
(includes a heavy neutral Majorana lepton)
in final states with 2 jets, MET, and ee, eμ, or μμ

Final state leptons may have arisen from τ decays, exclusion limit assumes the branching fractions to all lepton flavours are equal

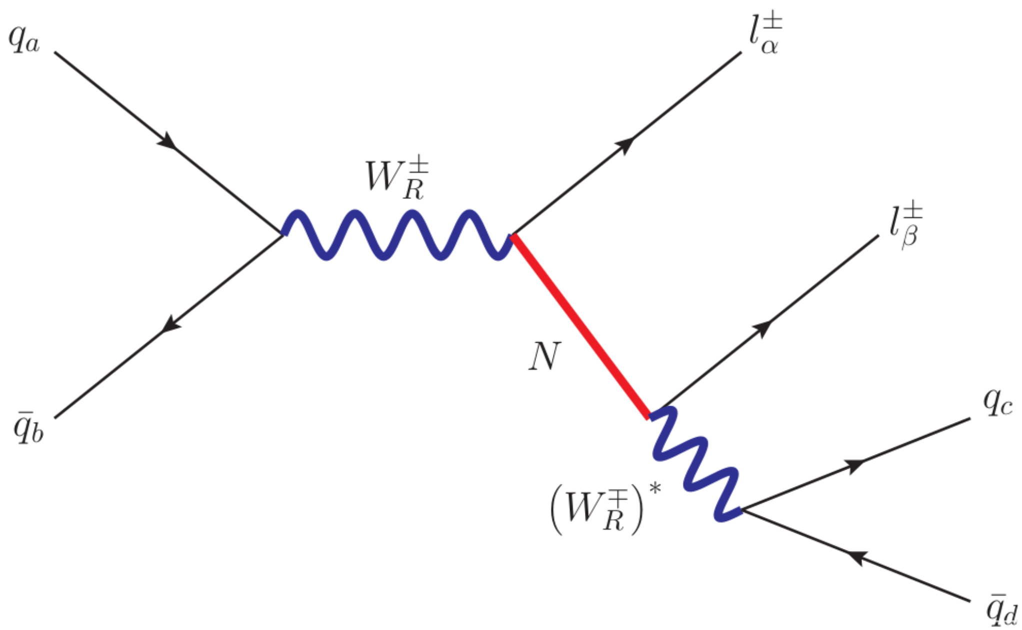


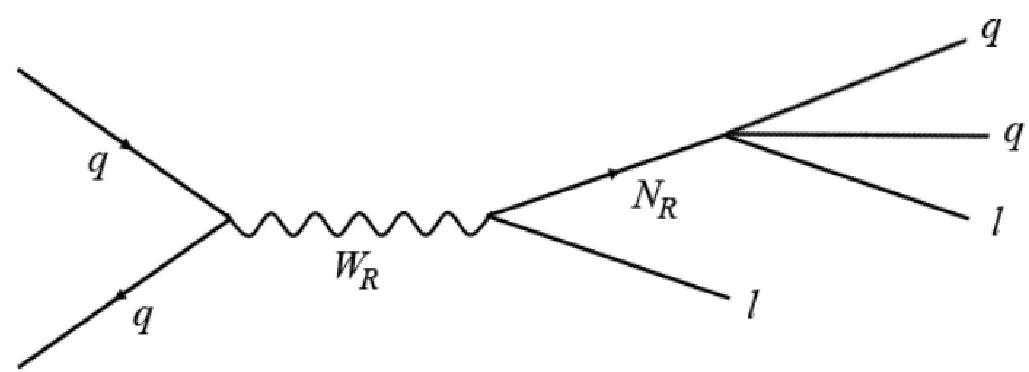
ATLAS-CONF-2018-020

A word about modelling

The LRSM decay chain shown on the left has been extensively studied in LHC Run 1, and in the CMS results shown earlier

However, signal simulation in Pythia treated the NR decay as a single vertex (see right) which affects the decay kinematics in many samples





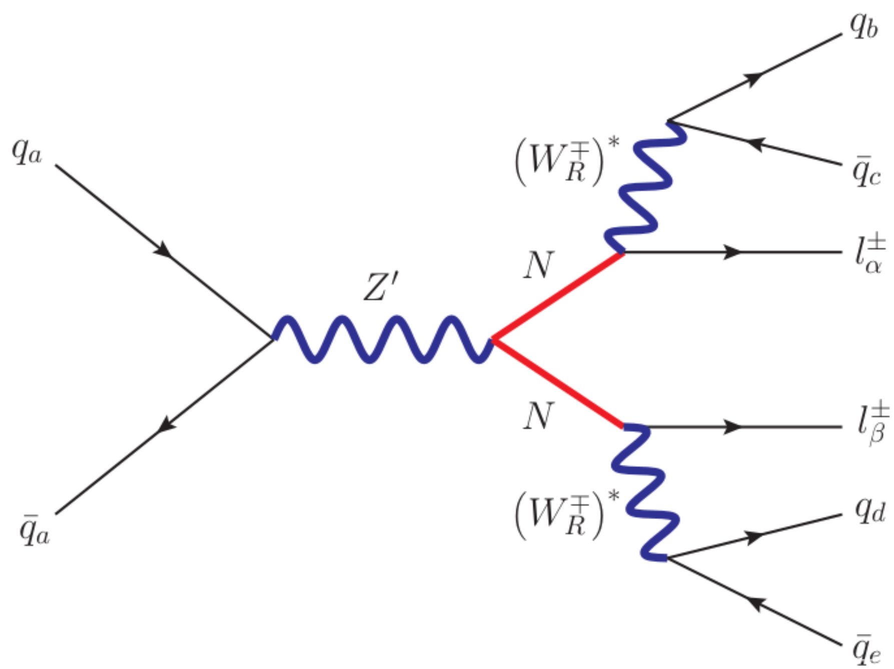
This Pythia model cannot generate signal samples with $m(N_R) > m(W_R)$

Searches are currently underway to set limits with the decay fully modelled in MadGraph, using Run 2 data

Dark Matter?

A stable heavy neutrino would be a potential Dark Matter candidate

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

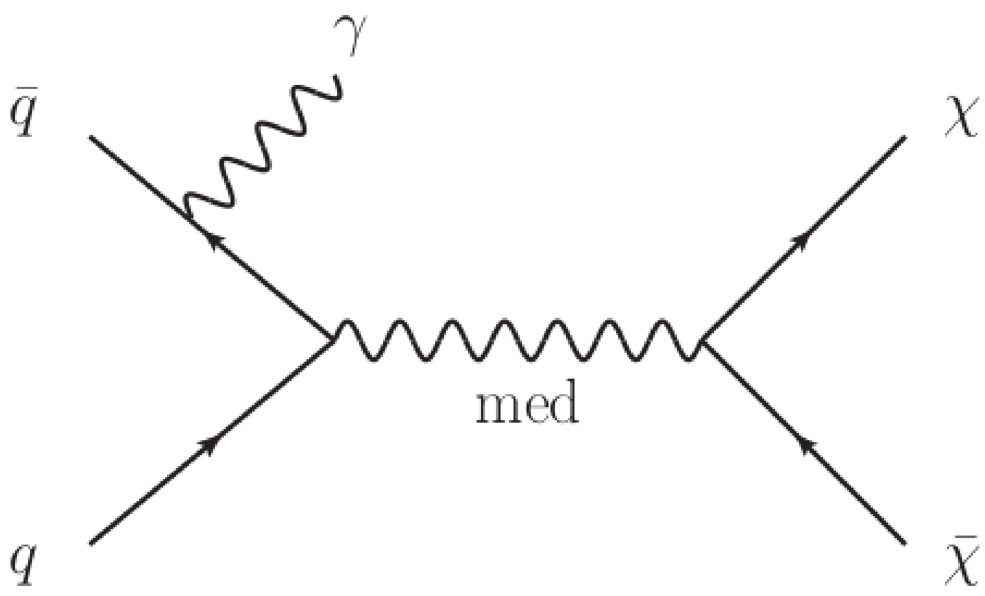


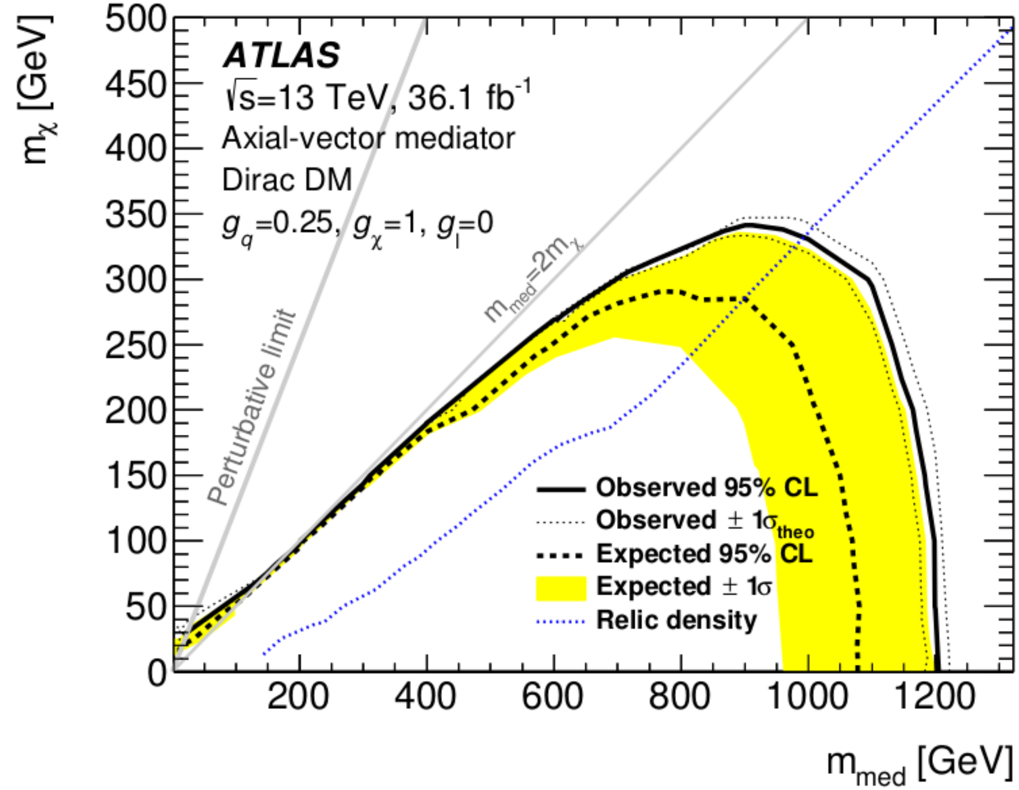
νMSM introduces a stable heavy neutrino as a Dark Matter candidate (as well as the decays examined on previous slides)

Dark matter searches with ATLAS

A final state with large MET, tagged with a radiated photon

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



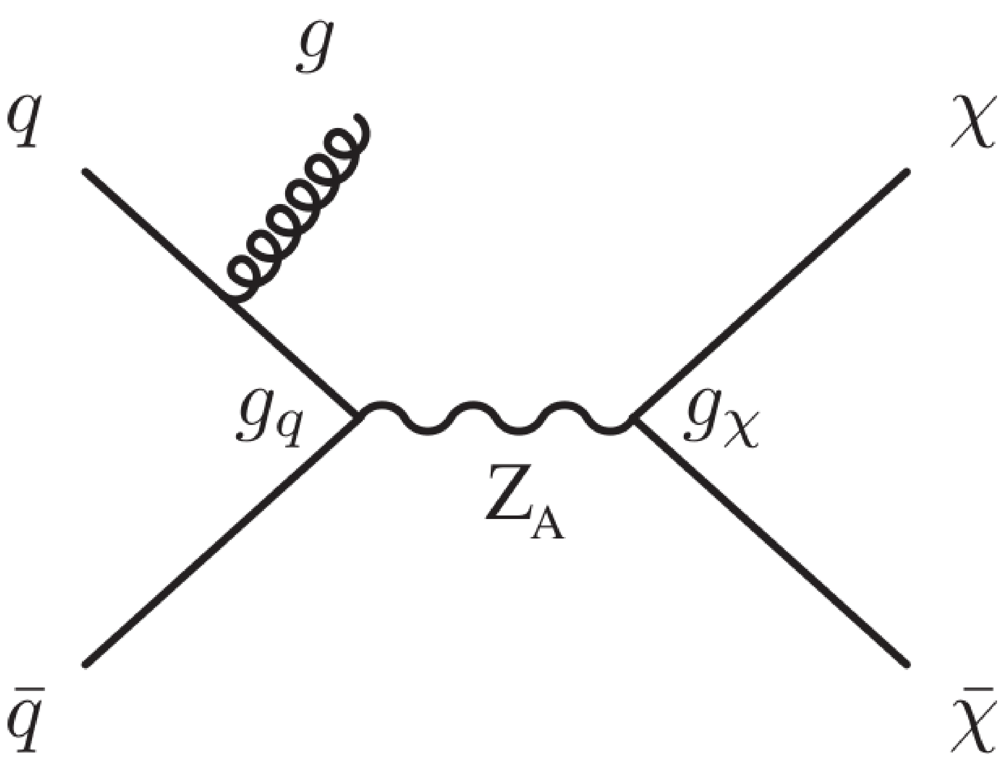


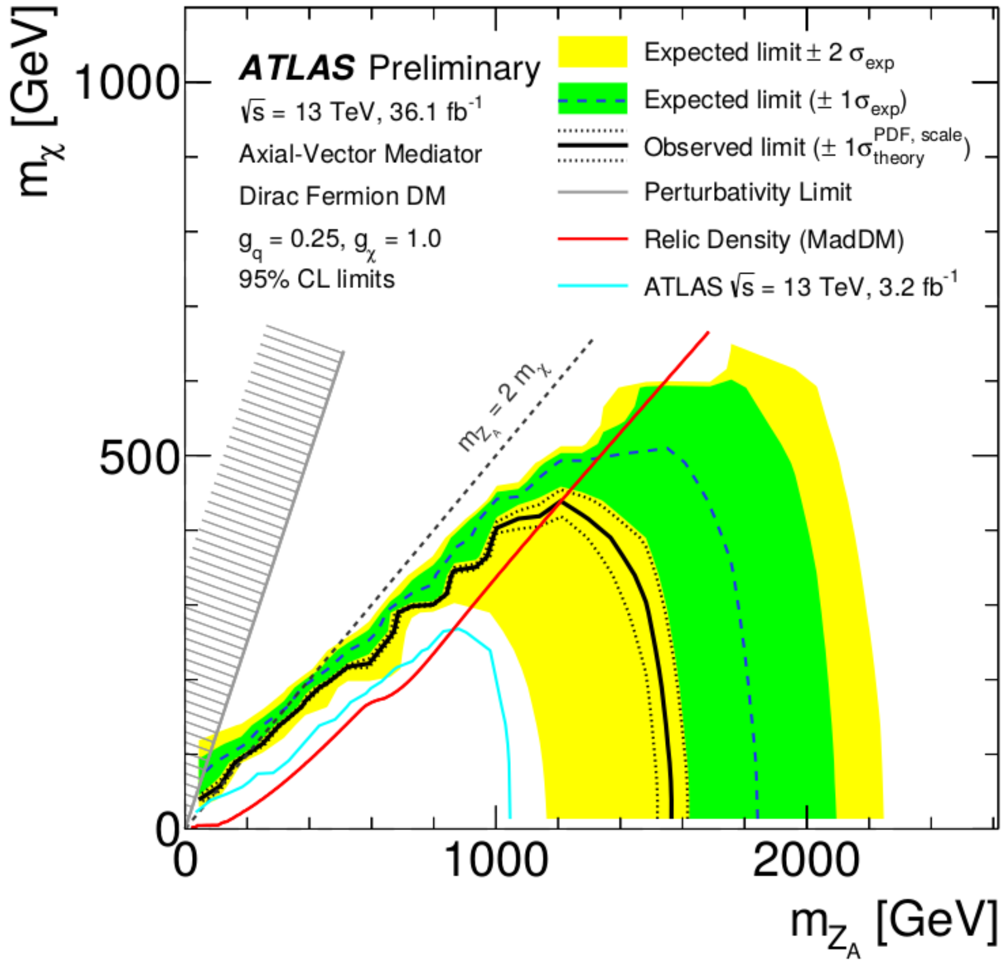
arXiv:1704.03848

Dark matter searches with ATLAS

A final state with large MET, tagged with a radiated gluon jet

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



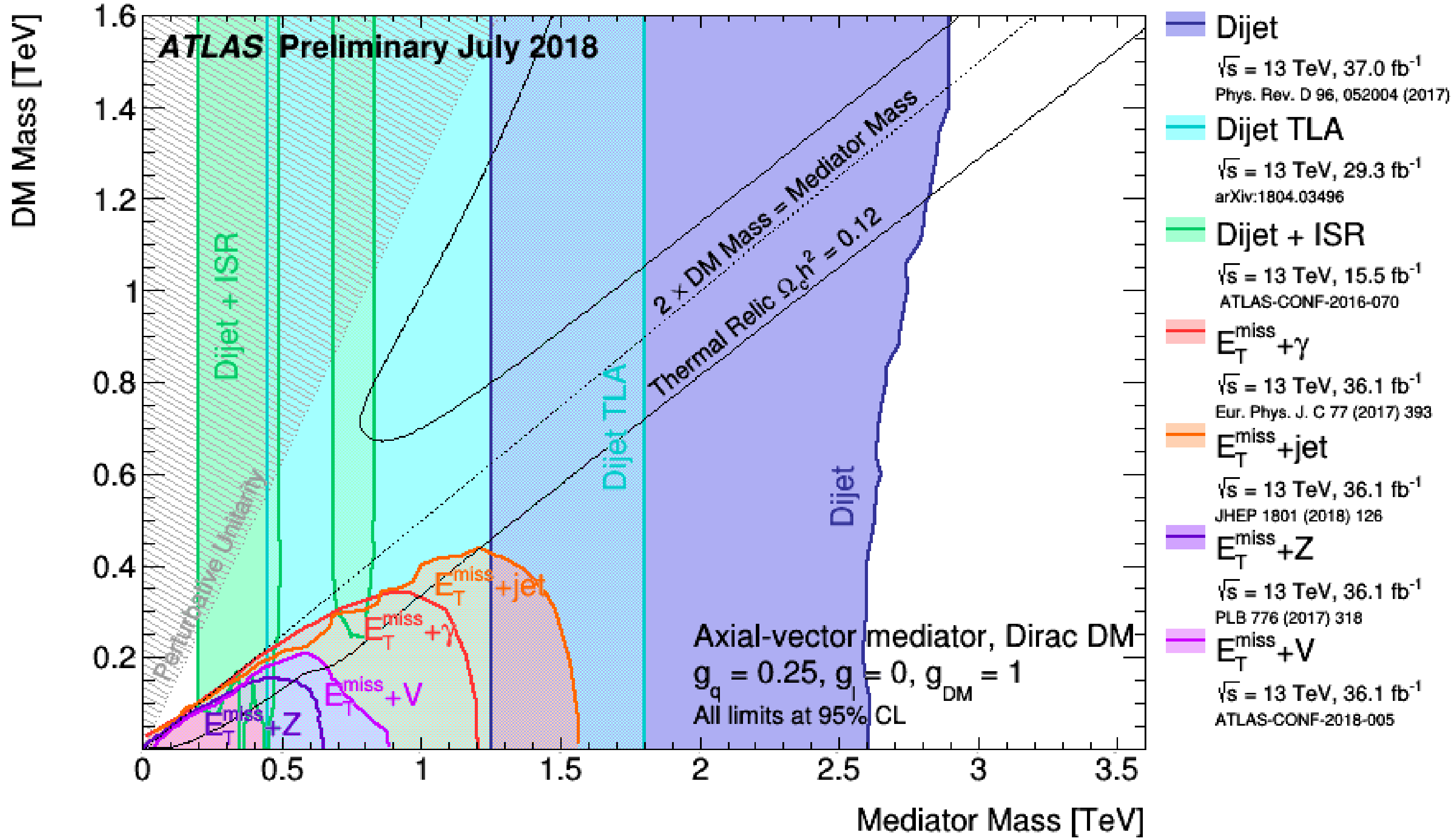


ATLAS-CONF-2017-060

Dark matter searches with ATLAS

2018

Combined exclusion limits have been produced for these searches



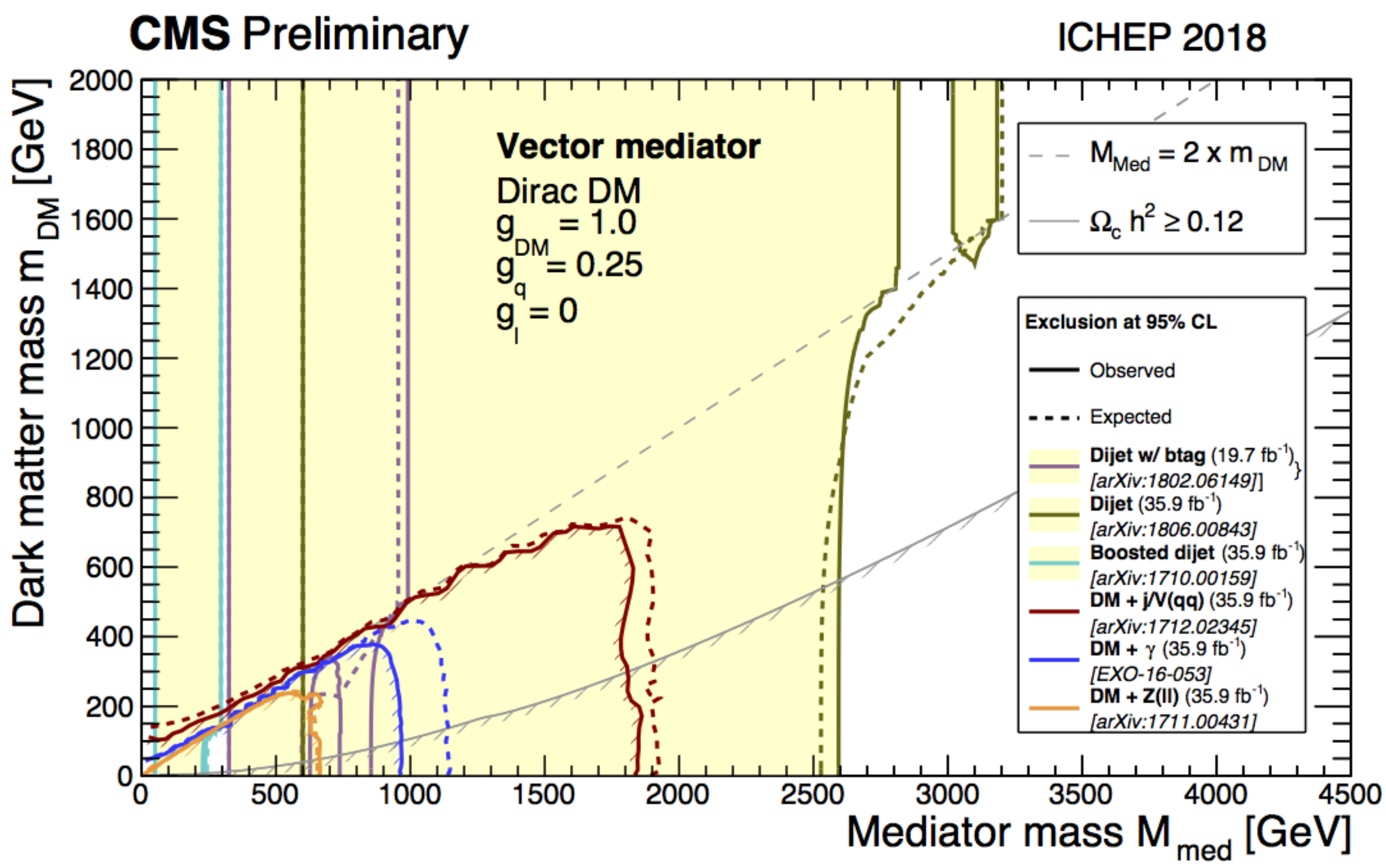
However, note that searches for dijet resonances are much more sensitive, since the propagator in our simplified model must couple to quarks

ATLAS Summary Plots

Dark matter searches with CMS

2018

Combined exclusion limits have been produced for these searches



CMS produce a similar combined exclusion plot (here shown for Vector-like mediator)

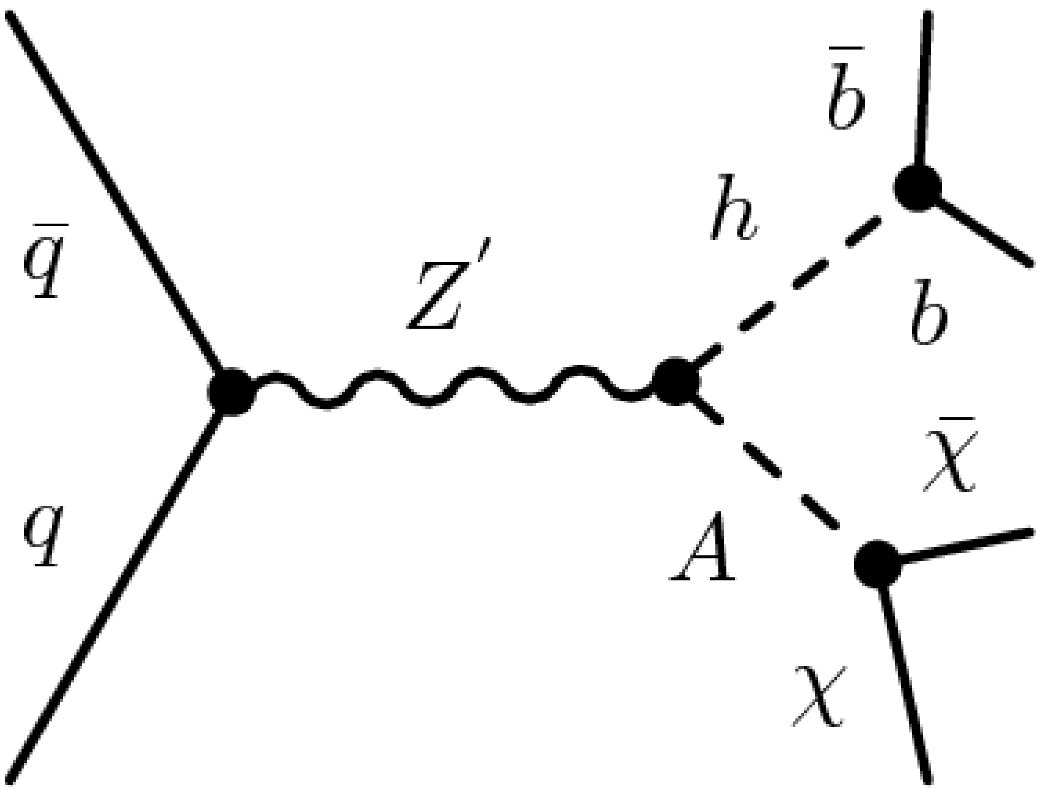
CMS Summary Plots

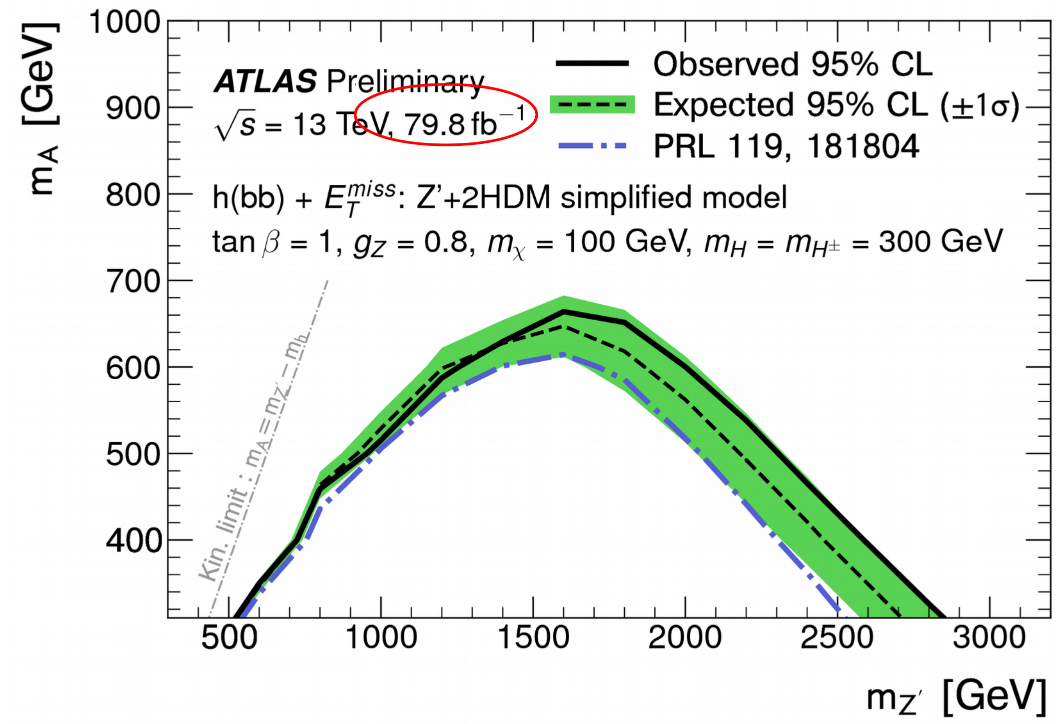
Dark matter searches with ATLAS

2018

A final state with large MET, and a Higgs boson decaying to a pair of b quarks

Limit set using a 2 Higgs Doublet Model



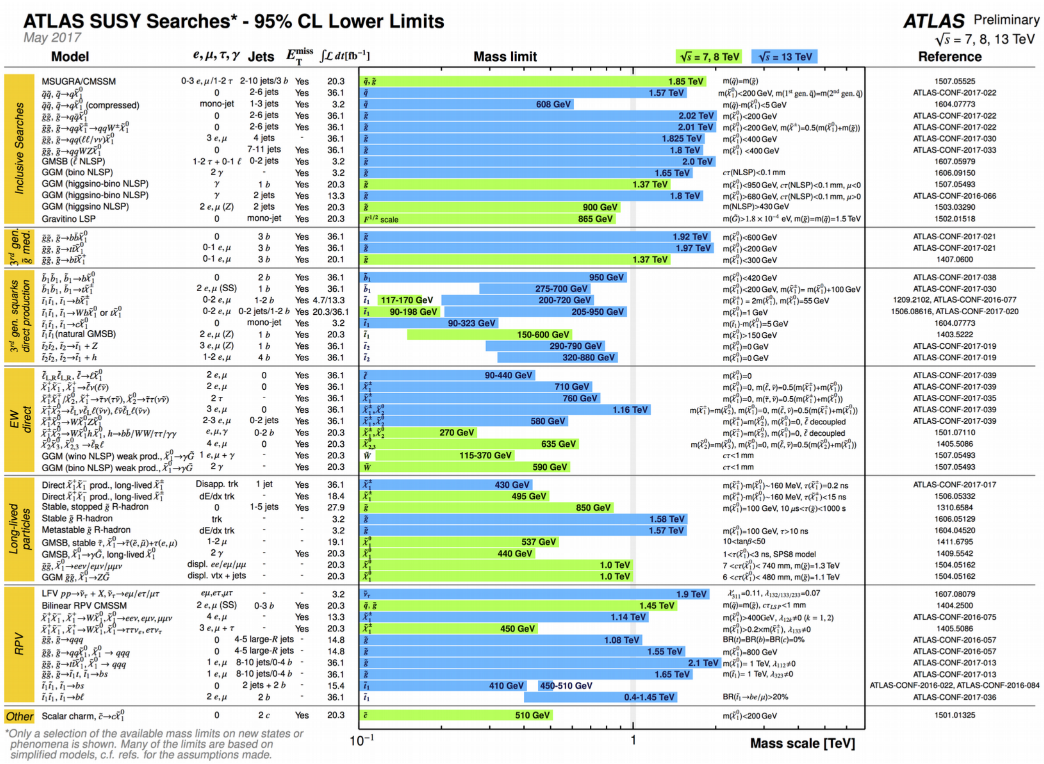


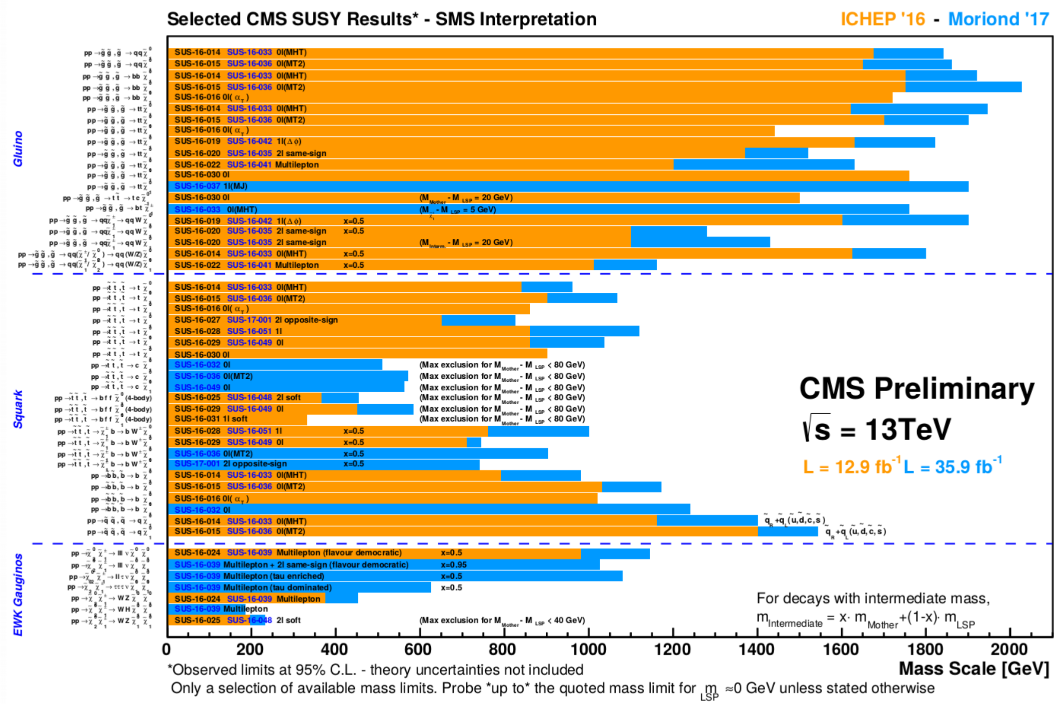
ATLAS-CONF-2018-039

Supersymmetry at the LHC

Now I’m definitely stretching the definition of “Heavy Neutrino”

There are a vast number of SUSY searches, past and ongoing, which mostly include neutralinos in the final state



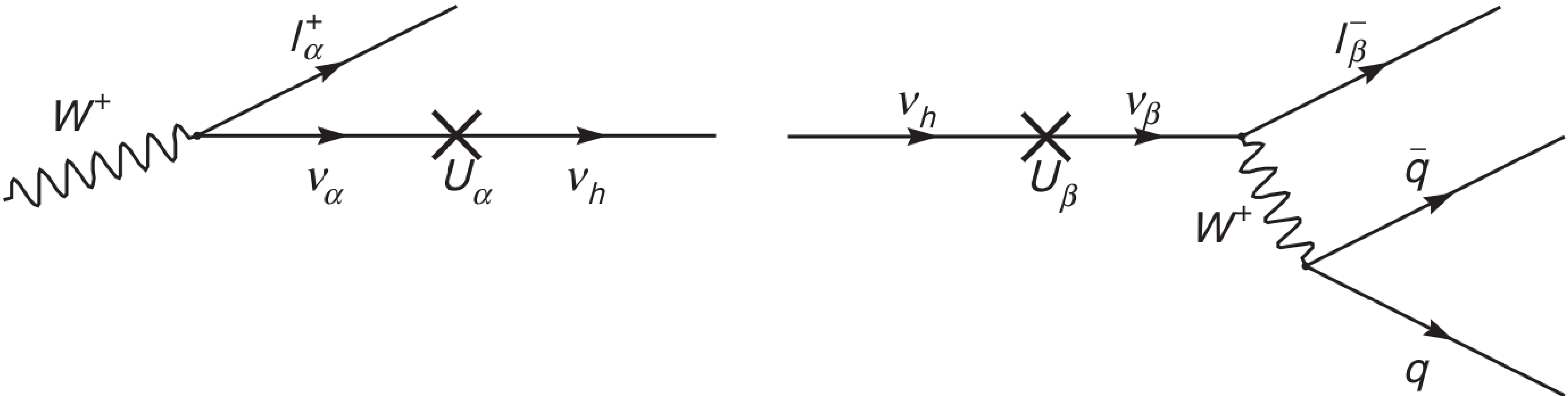


Not planning to go into this in any depth, suffice it to say that we’re still looking

ATLAS Summary Plots CMS Summary Plots

Displaced vertices

Somewhere in-between prompt decays and long-lived Dark Matter candidates are heavy neutrinos likely to decay after travelling a significant distance



These models don't even rely on the seesaw mechanism – simply adding an extra neutrino mass eigenstate is enough

However, throwing in some sensible values for the coupling strength (U_α~10^{-4}), a heavy neutrino with mass 1 GeV decays after O(10) meters

Displaced vertices

There are lots of displaced vertex searches past and ongoing at LHC collider experiments (ATLAS, CMS and LHCb at least)

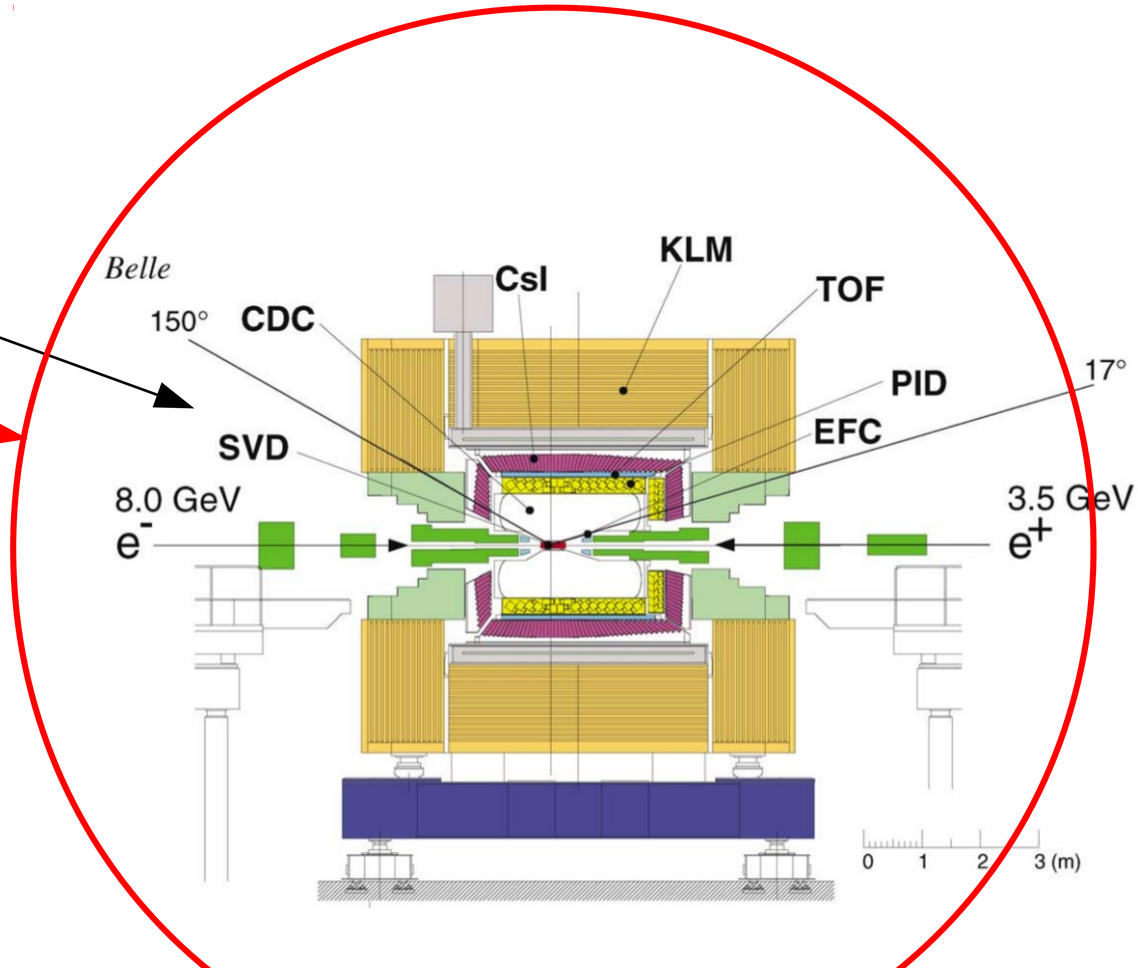
Searches rarely target Heavy Neutrinos, although should be possible to search in the O(10 GeV) mass region

Credit to Belle (and others) for looking: arXiv:1301.1105

Still, the problem remains

Belle detector

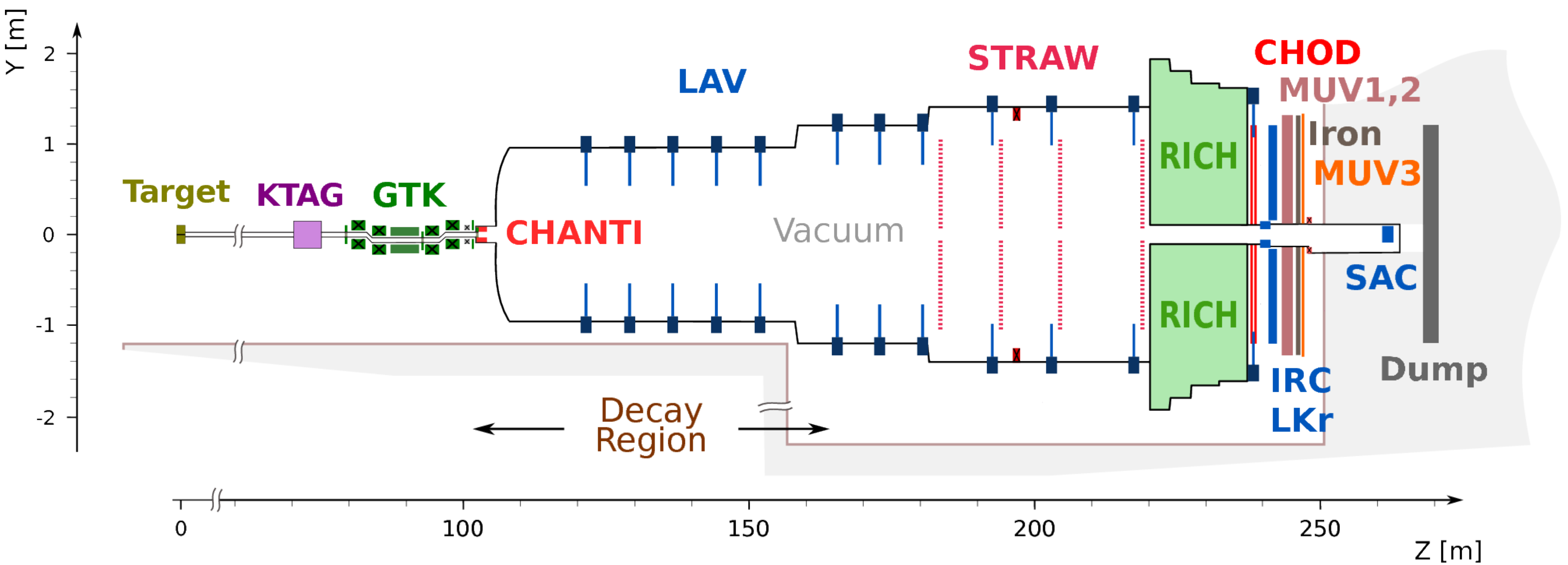
10m radius from interaction point (roughly)



NA62 experiment

Rather than trying to instrument an unfeasibly large volume, beam dump experiments need only instrument the region along the beam axis

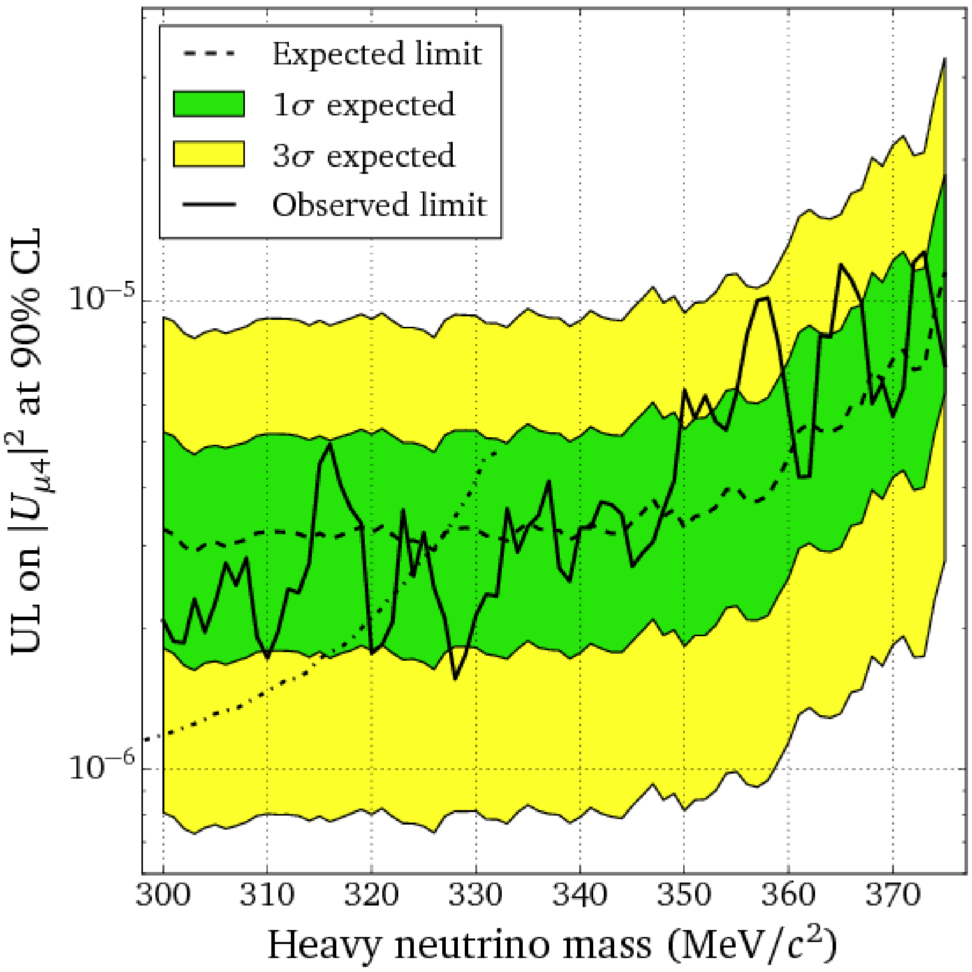
The NA62 experiment at CERN uses 400 GeV protons from the SPS (the same accelerator that feeds the LHC) impinging on a Berillium target



NA62 experiment

NA62 already has a result searching for heavy neutrinos (300-375 MeV) originating from Kaon decays: arXiv:1705.07510

Here the heavy neutrino is not expected to decay within 10km of the target, and so the search was simply for single muon and missing mass



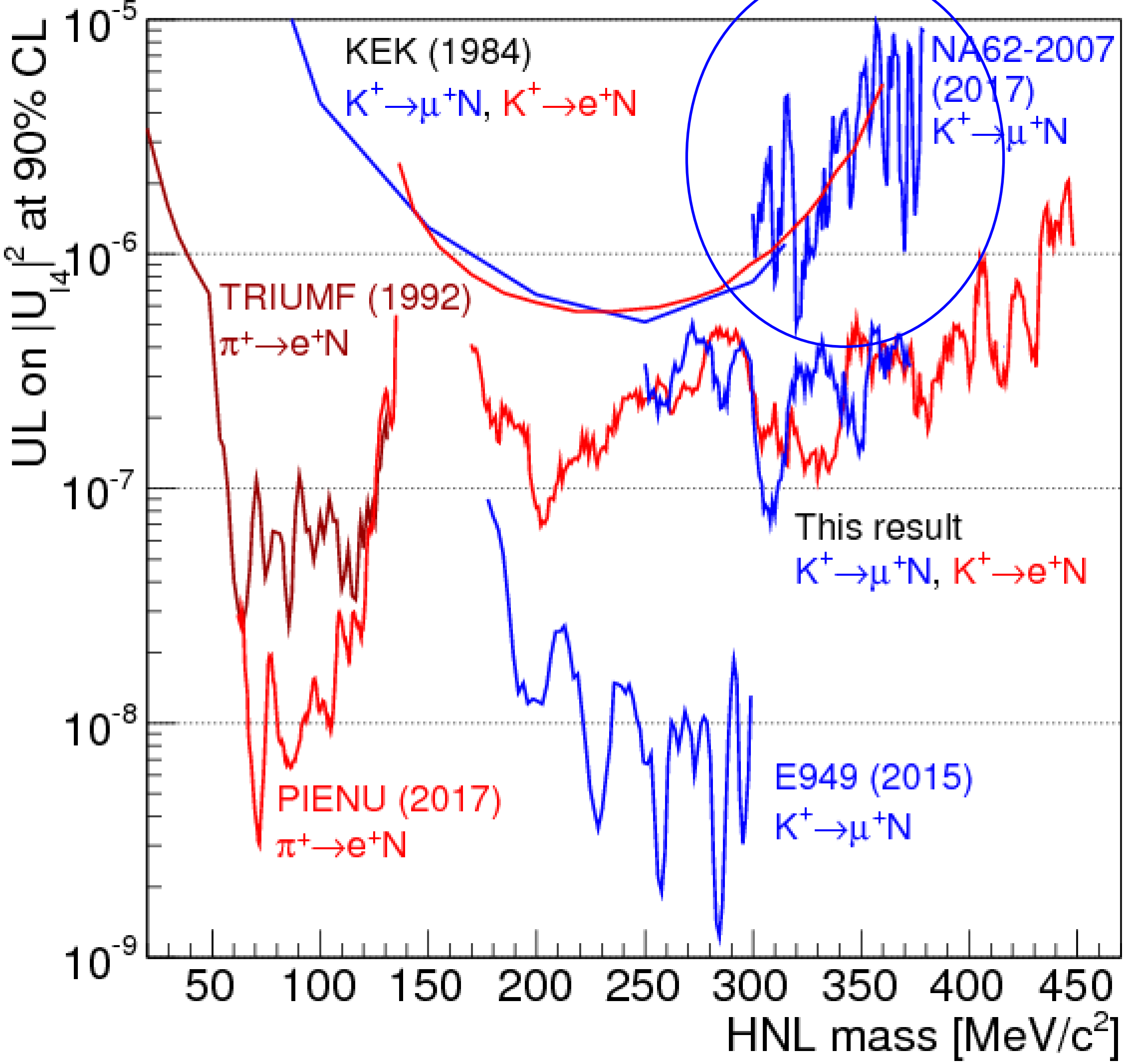
NA62 experiment

2018

Updated result published this year: arXiv:1712.00297

Newer dataset, and including electron channel

Previous result



Summary

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

Heavy Neutrinos – if stable – could be revealed by Dark Matter searches at the LHC

Displaced vertex searches are an evolving field for collider experiments targeting prompt decays, but potential here for further study of Heavy Neutrinos

Beam dump experiments far more sensitive to Heavy Neutrino decays when the couplings are weaker, and so the vertices are more displaced

New experiment planned – SHiP

LHC upgrade schedule on track – higher luminosity for all experiments

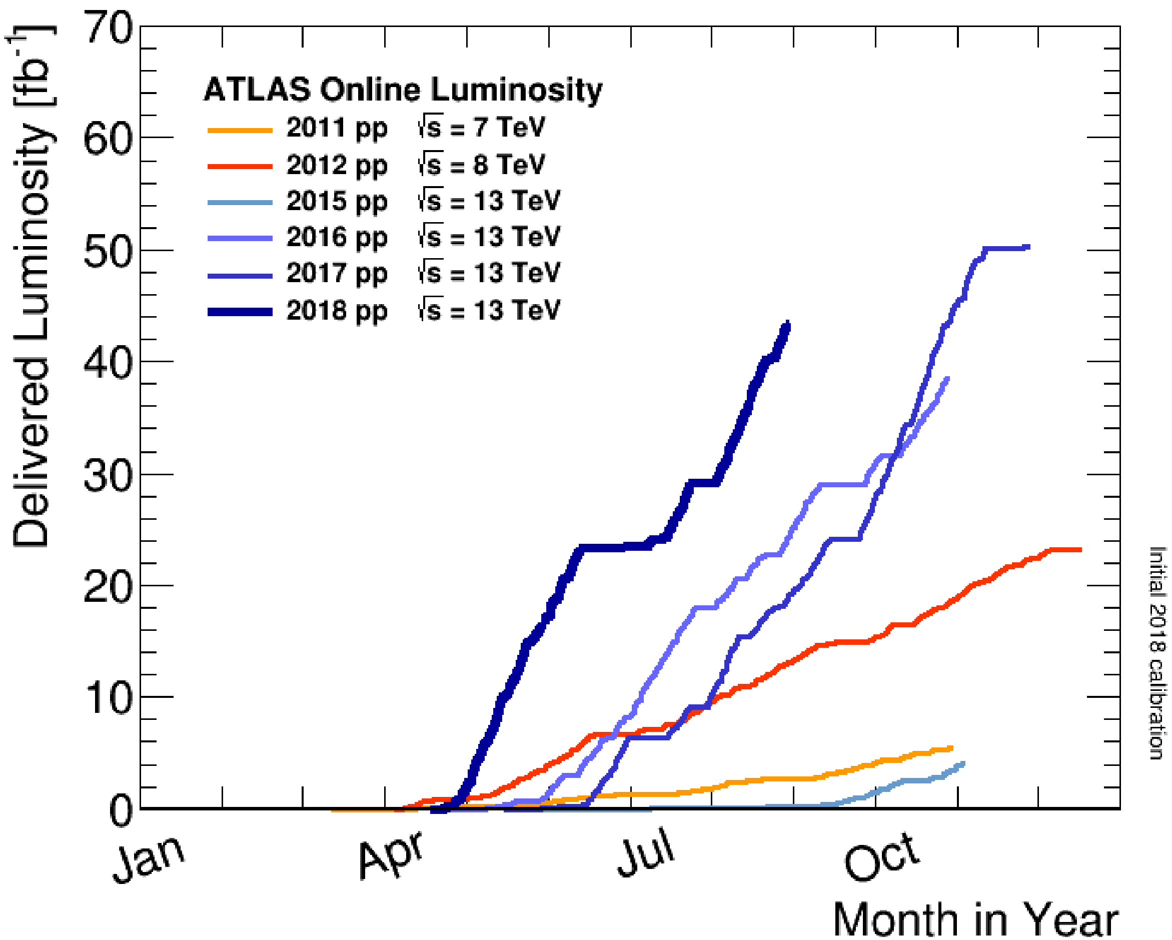
Still bigger colliders are possible...

BACKUP

Large Hadron Collider

The LHC is taking pp collision data at 13 TeV

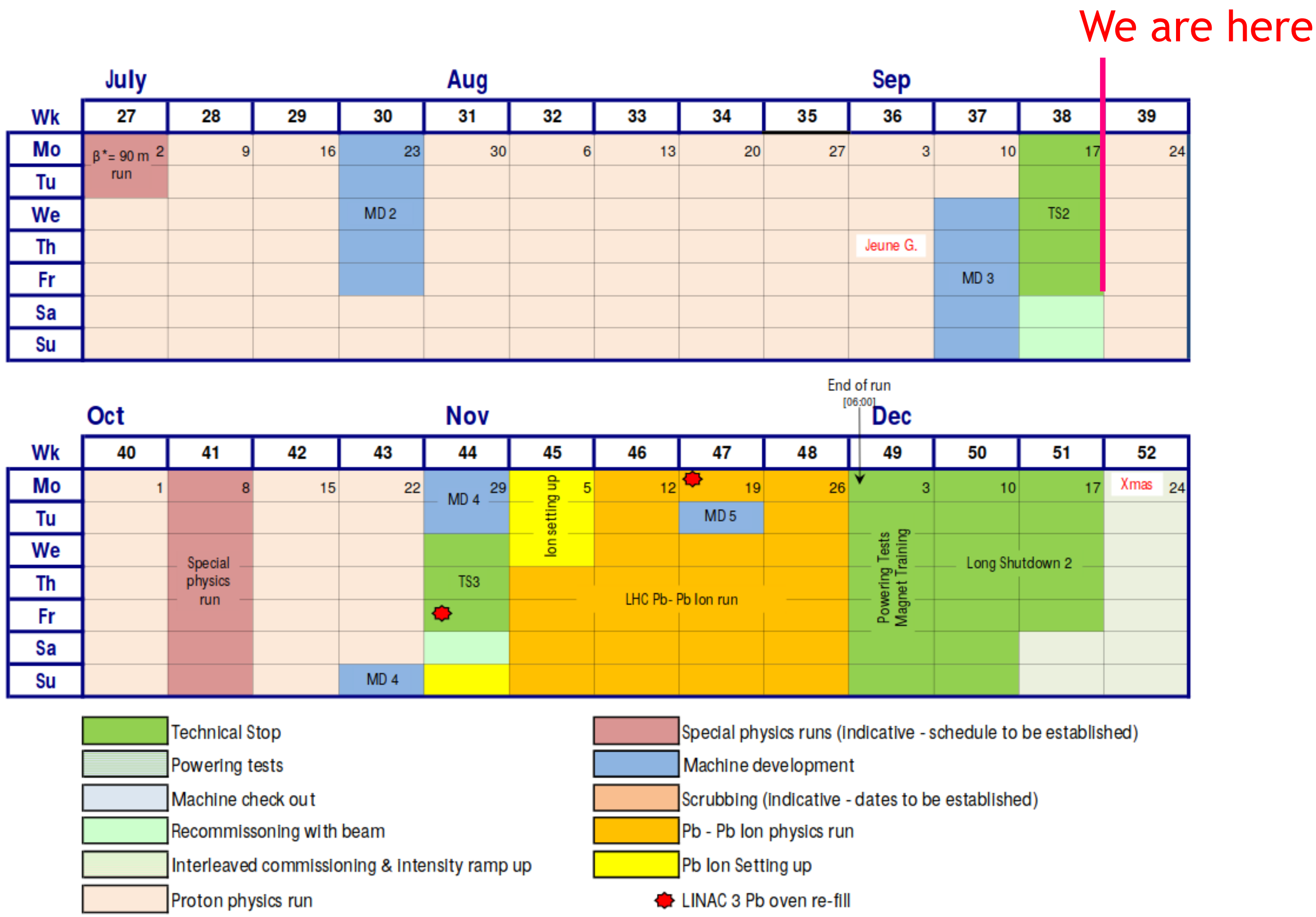
Results with 80 fb^{-1} (2015-2017) are available now
 - Full Run 2 data analyses ongoing



Luminosity summary plots

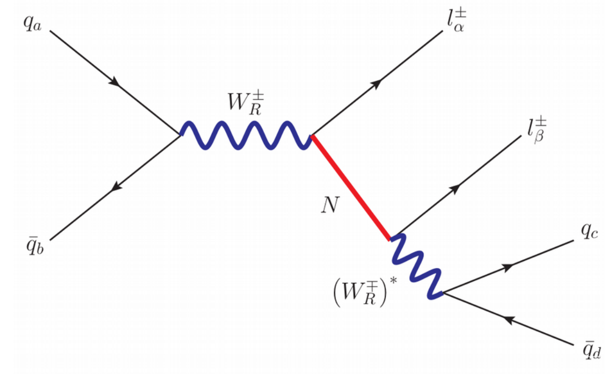
Large Hadron Collider

LHC schedule suggests we have 1-2 more months of data-taking this year, taking us to the end of Run 2, and the long shutdown for the LHC upgrade



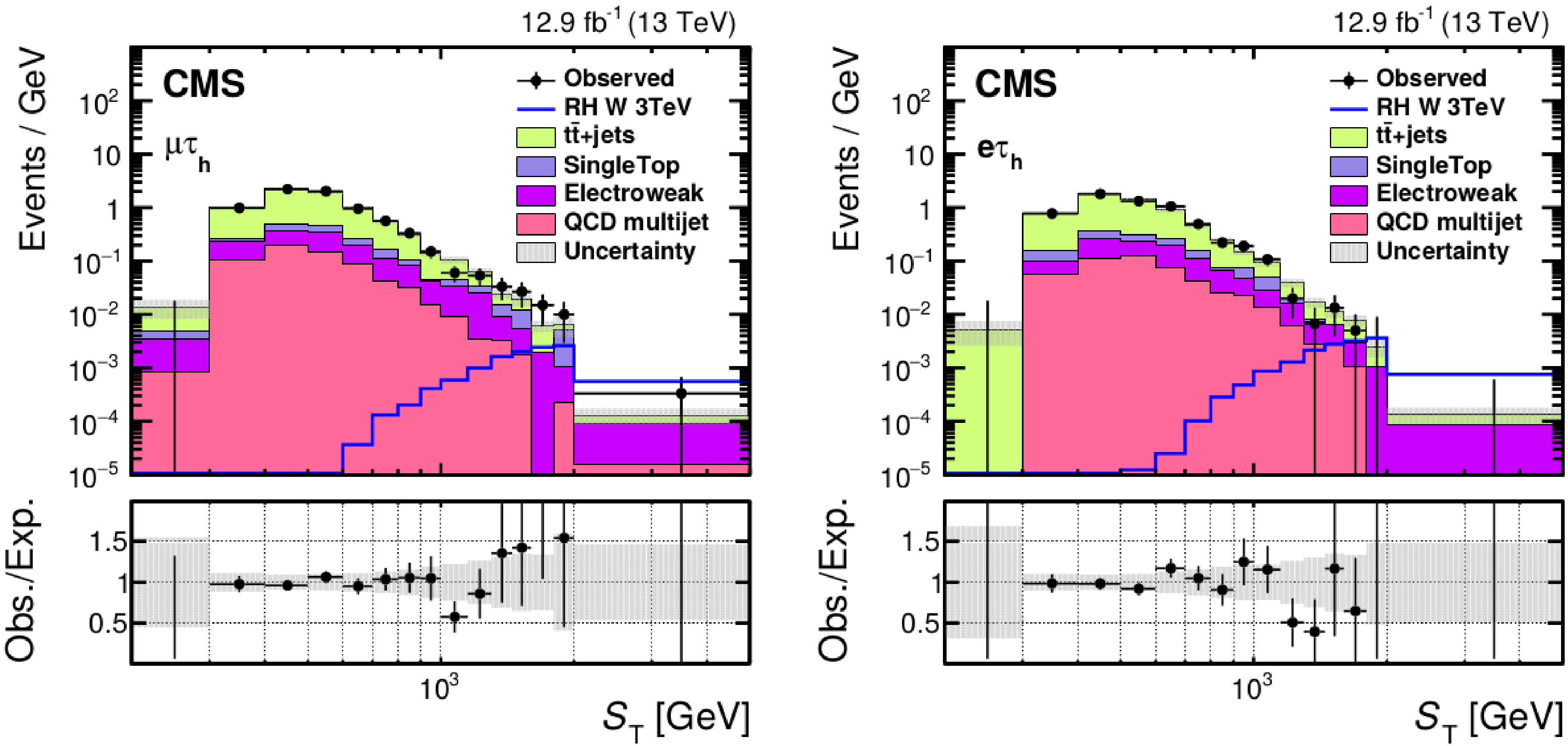
LHC schedule

Prompt decays with CMS



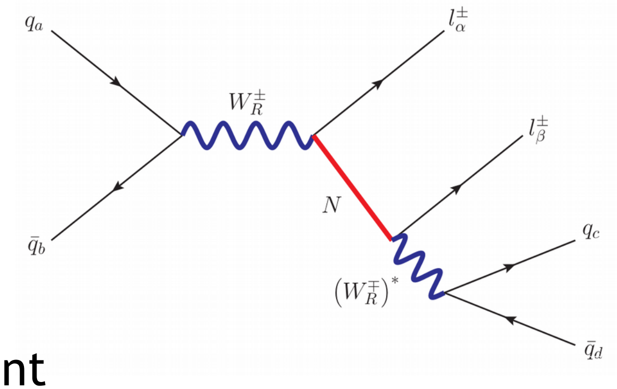
Searching for LRSM decay, final states with 2 τ-leptons where one decays hadronically and one leptonically

Observable plotted is the scalar sum of final state particle transverse momenta (pT) and missing transverse energy



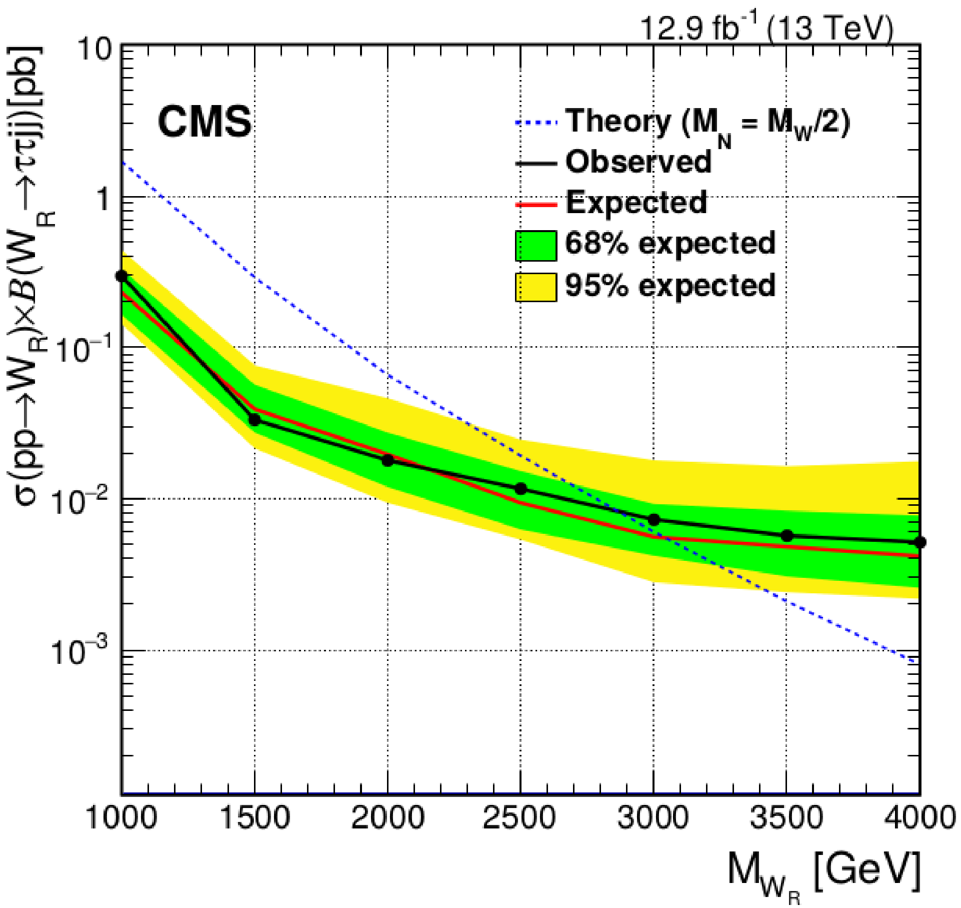
arXiv:1703.03995

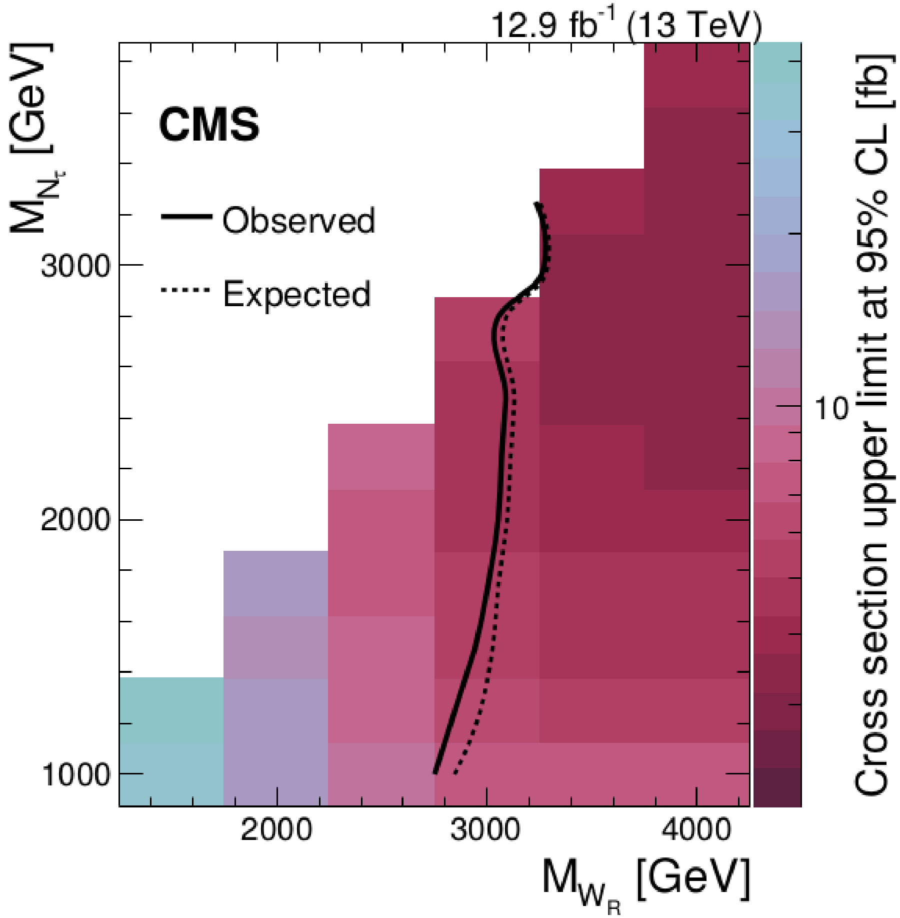
Prompt decays with CMS



Searching for LRSM decay, final states with 2 τ-leptons where one decays hadronically and one leptonically

Limit left for fixed m(NR):m(WR) ratio, and right for different mass working points



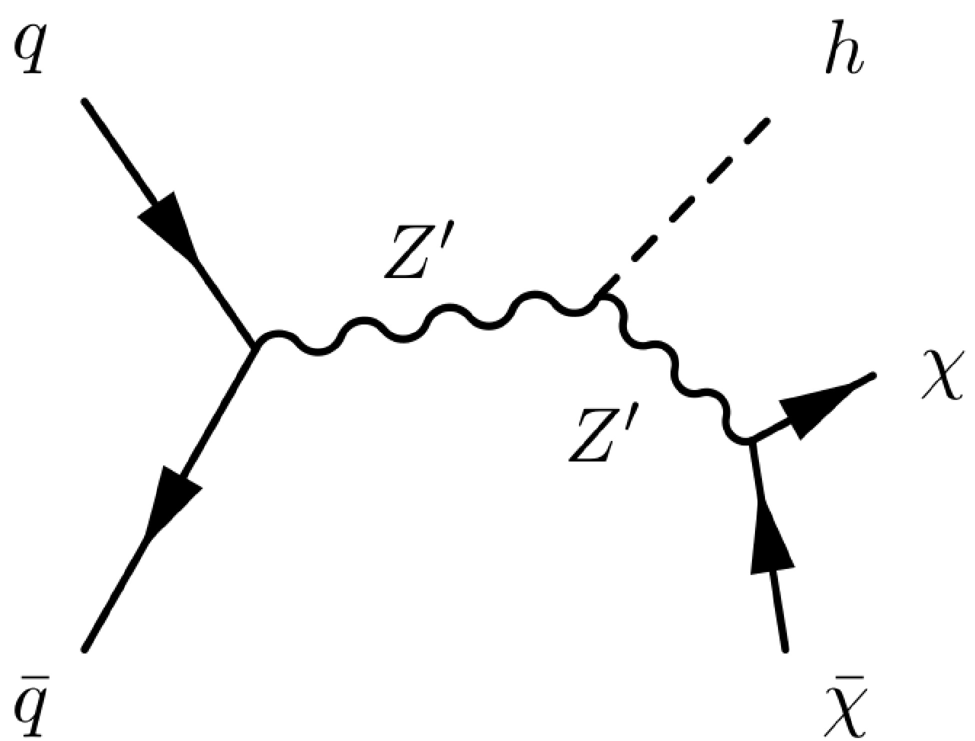


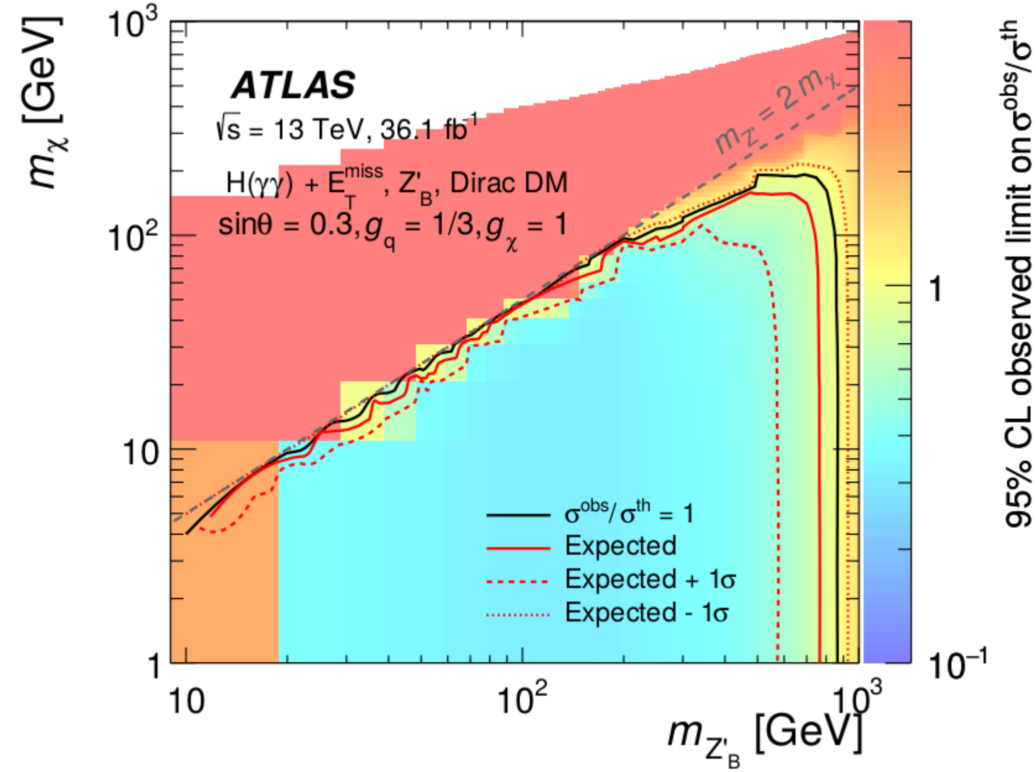
arXiv:1703.03995

Dark matter searches with ATLAS

A final state with large MET, and a Higgs boson decaying to a pair of photons

Limit set using a Z' model where Dark Matter only couples to the Z'



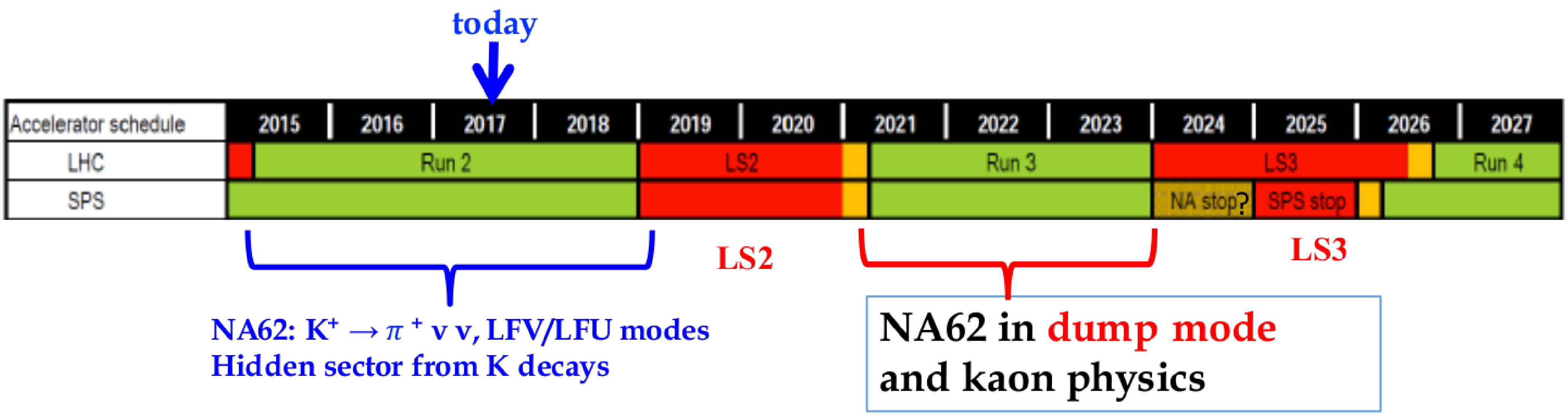


arXiv:1706.03948

NA62 experiment

In LHC Run 3, there is potential to run NA62 in “dump mode” (beam strikes Copper collimators rather than Berillium target)

May allow additional study of Heavy Neutrino decays, and will also allow testing of ideas for the planned future experiment, SHiP

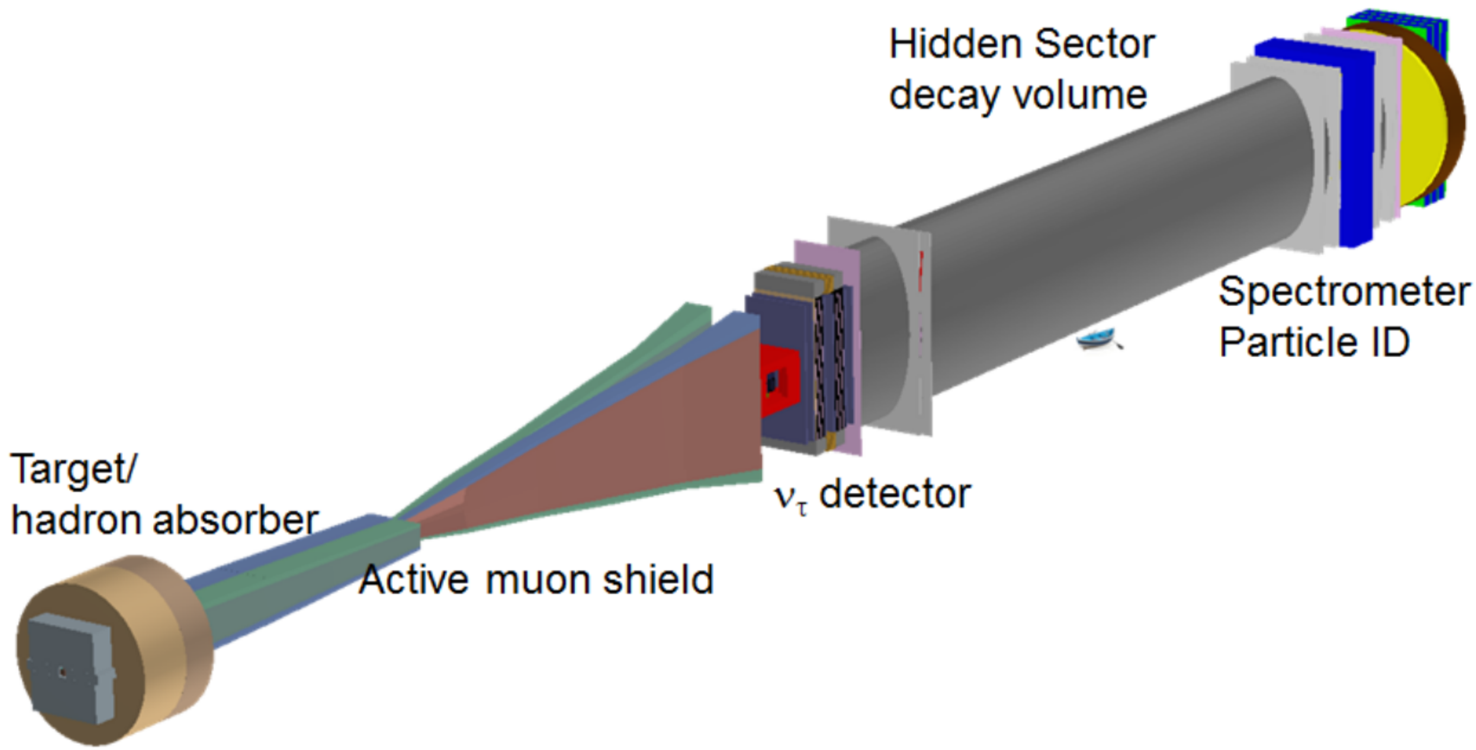


Goal: integrate at least ~10^{18} pot in dump mode by 2023
(corresponding to ~ 3 months of dedicated data taking in 2021-2023)

Slide from G. Lanfranchi @ EPS 2017

Looking into the future...

The proposed **SHiP experiment** has a broadly similar design to NA62, but is specifically intended to search for physics beyond the Standard Model, such as displaced decay vertices from Heavy Neutrinos

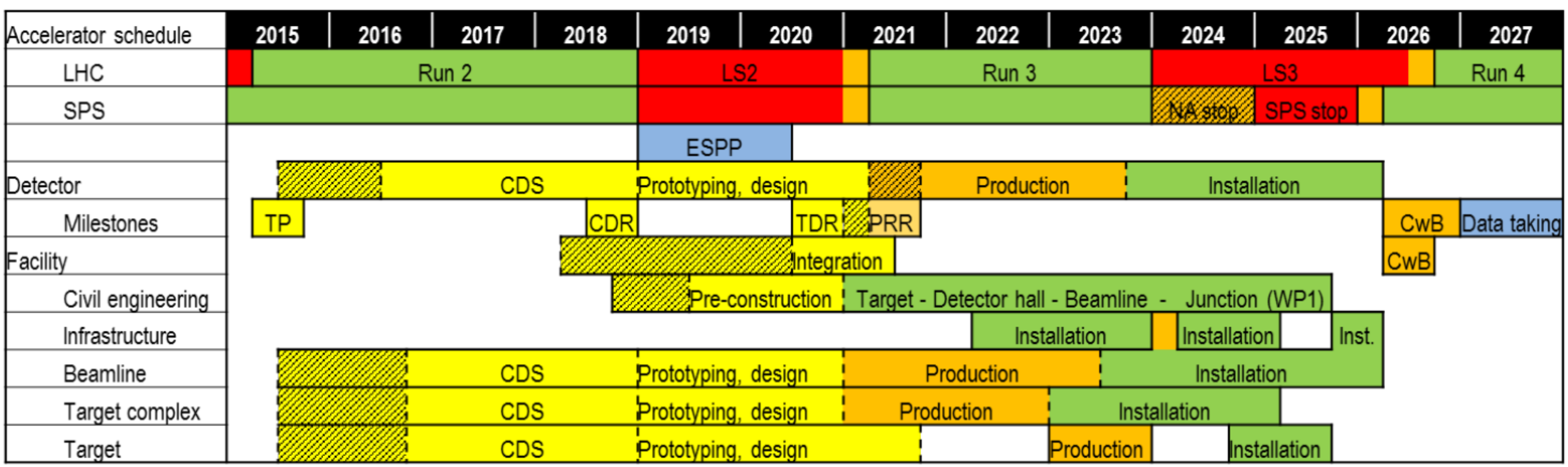


Important features include a magnetic field designed to steer all muons from the target away from the instrumented volume, to reduce background

Looking into the future...

SHiP should eventually be installed using a similar 400 GeV proton beam-line to NA62, and will hopefully be ready for data-taking in 2027

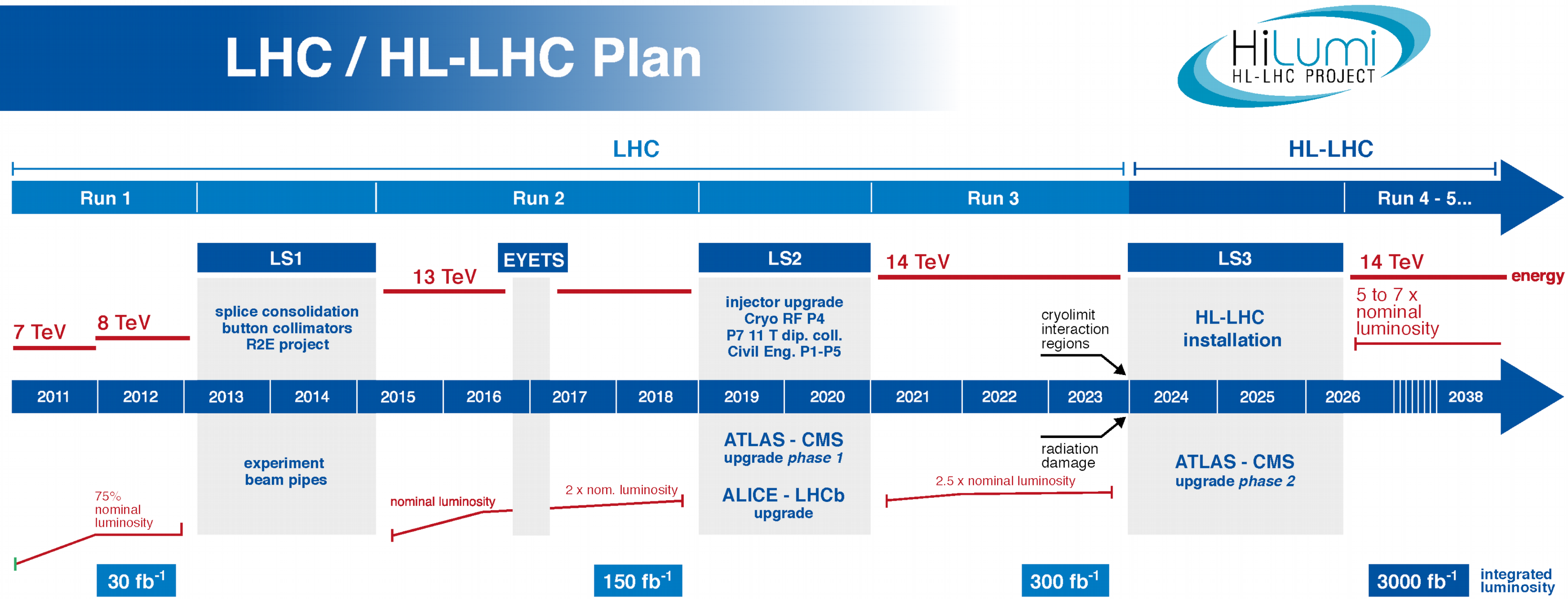
- Expression of interest 2013
- Technical proposal (TP) & physics proposal (PP) 2015
- SPSC and CERN research board recommended we continue to a comprehensive design study (CDS) phase → Re-optimisation of the entire experiment Now!
- Part of the CERN Physics beyond colliders (PBC) working group and will be an input to the European strategy meeting (ESPP) in 2019/2020



Slide from O. Lantwin @ EPS 2017

Looking into the future…

For context, the ShiP timescale is roughly the same as that for the High Luminosity LHC



Not that the LHC luminosity isn't already high…

Looking into the future...

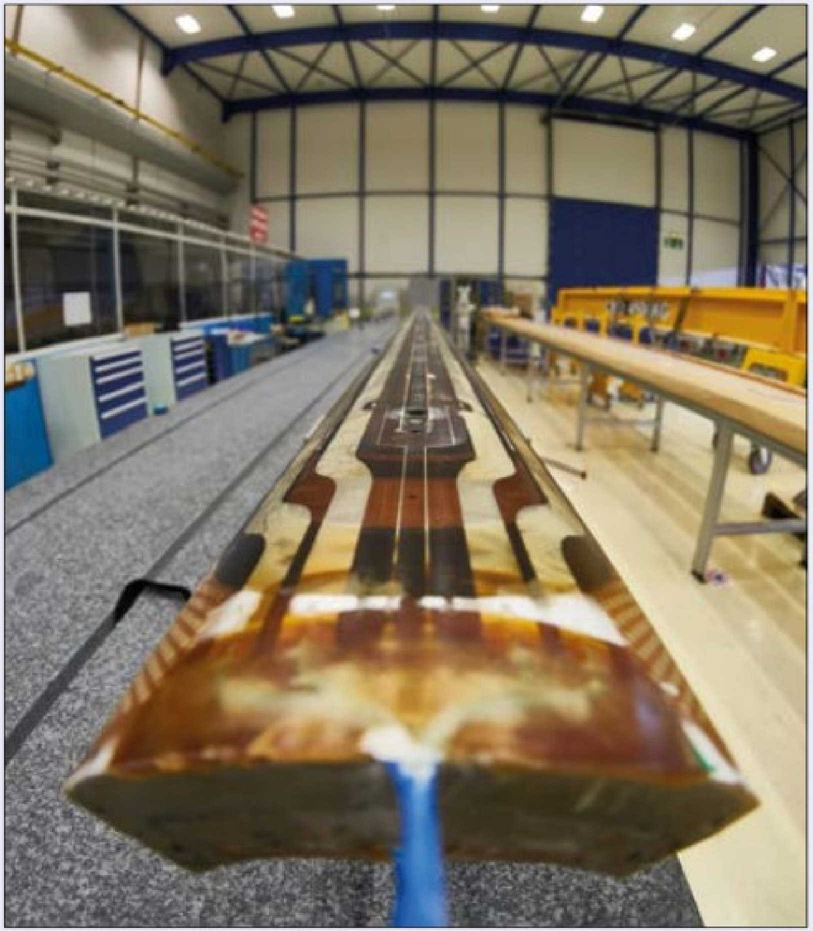
The CERN courier devoted its September issue to superconductivity, and it looks like magnet technology is keeping up with us for now

CERN breaks records with high-field magnets for High-Luminosity LHC

To keep the protons on a circular track at the record-breaking luminosities planned for the LHC upgrade (the HL-LHC) and achieve higher collision energies in future circular colliders, particle physicists need to design and demonstrate the most powerful accelerator magnets ever. The development of the niobium-titatnium LHC magnets, currently the highest-field dipole magnets used in a particle accelerator, followed a long road that offered valuable lessons. The HL-LHC is about to change this landscape by relying on niobium tin (Nb_3Sn) to build new high-field magnets for the interaction regions of the ATLAS and CMS experiments. New quadrupoles (called MQFX) and two-in-one dipoles with fields of 11 T will replace the LHC's existing 8 T dipoles in these regions. The main challenge that has prevented the use of Nb_3Sn in accelerator magnets is its brittleness, which can cause permanent degradation under very low intrinsic strain. The tremendous progress of this technology in the past decade led to the successful tests of a full-length 4.5 m-long coil that reached a record nominal field value of 13.4 T at BNL. Meanwhile at CERN, the winding of 7.15 m-long coils has begun.

Several challenges are still to be faced, however, and the next few years will be decisive for declaring production readiness of the MQFX and 11 T magnets. R&D is also ongoing for the development of a Nb_3Sn wire with an improved performance that would allow fields beyond 11 T. It is foreseen that a 14–15 T magnet with real physical aperture will be tested in the US, and this could drive technology for a 16 T magnet for a future circular collider. Based on current experience from the LHC and HL-LHC, we know that the performance requirements for Nb_3Sn for a future circular collider require a large industrial effort to make very large-scale production viable.

● *Panagiotis Charitos, CERN.*



New long coils for the Nb_3Sn quadrupoles for the HL-LHC.

A little further still...

If you really want to probe the energy and intensity frontiers, you're going to need something big...