HVAR, CROATIA

Lepton Number Violation at the LHC

Christos Leonidopoulos

THE UNIVERSITY of EDINBURGH

LNV@2024LHC-DAYS

2024 LHC DAYS IN SPLIT - HVAR, CROATIA - 1 OCTOBER 2024

Theoretical Motivation

Neutrino oscillations produce LNV

LNV has been **observed experimentally** and predicted by inequality of neutrino masses

Lepton Number Conservation:

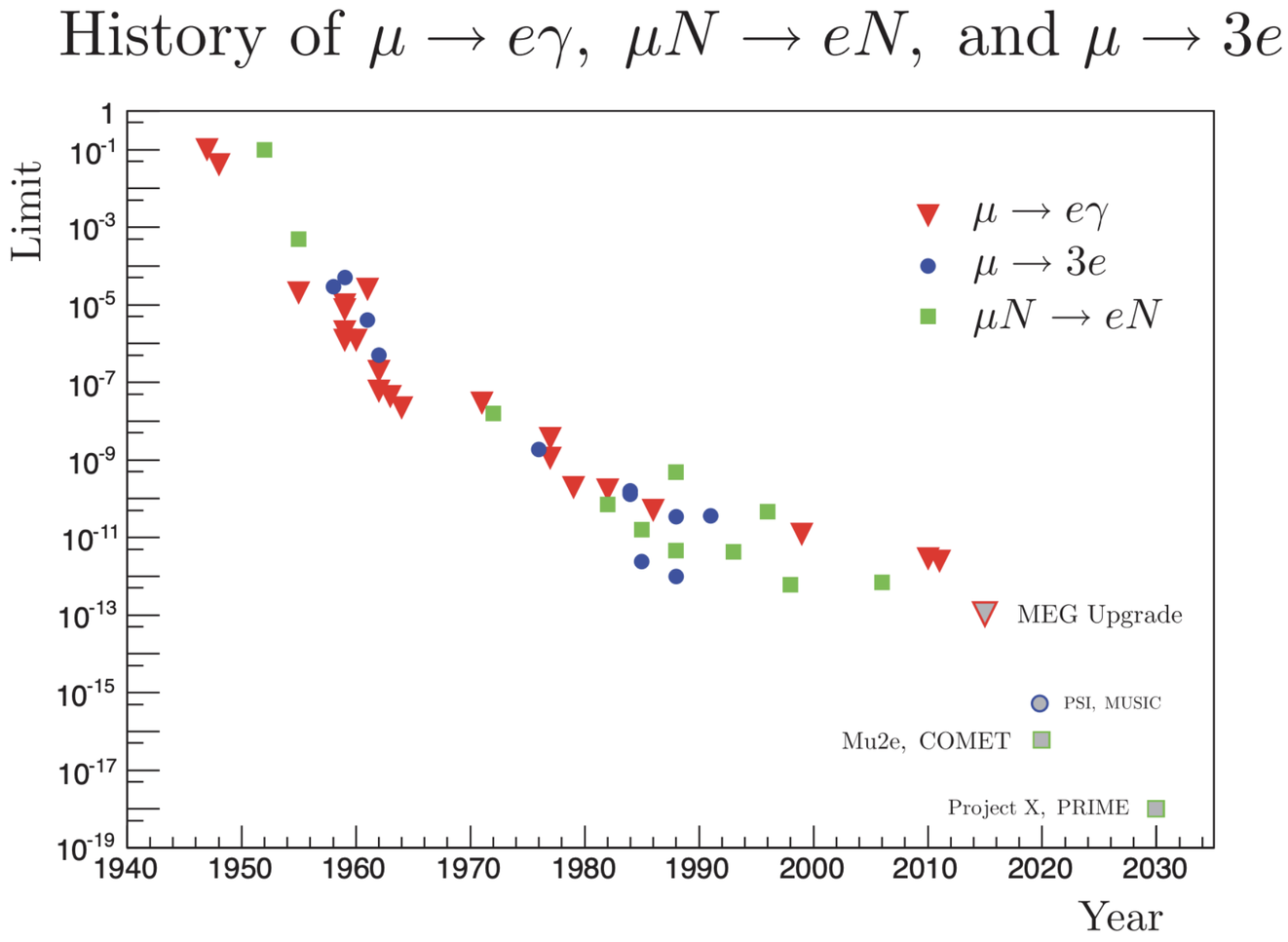
Not an **exact symmetry**

Not related to gauge symmetry, why should LN be conserved?

But SM-related LNV is very small, not detectable at LHC

Searches for LNV/LFV processes: free of SM background

Searches for charged LFV



arXiv:1307.5787

LNV/LFV searches at LHC

LHC offers probe to LFV processes involving heavy particles (Higgs, top, Z)

- ***Higgs decays***
- ***Heavy Neutrinos***
- ***Top decays***
- ***τ/B/Z decays***

Emphasis on searches of LFV in decays of SM particles

Many RVP SUSY searches targeting LNV (see backup)

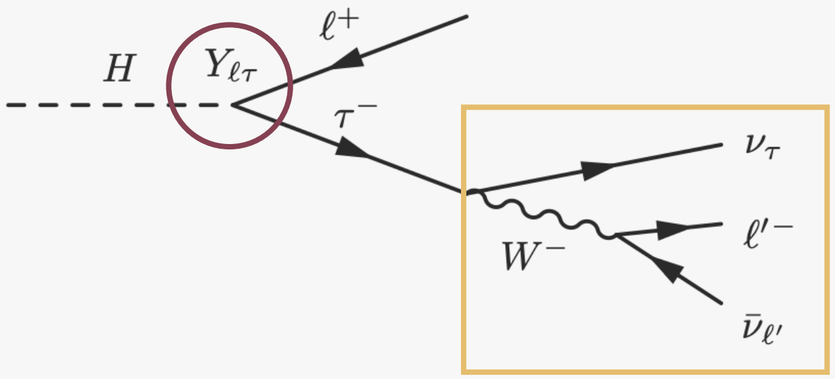
Higgs decays

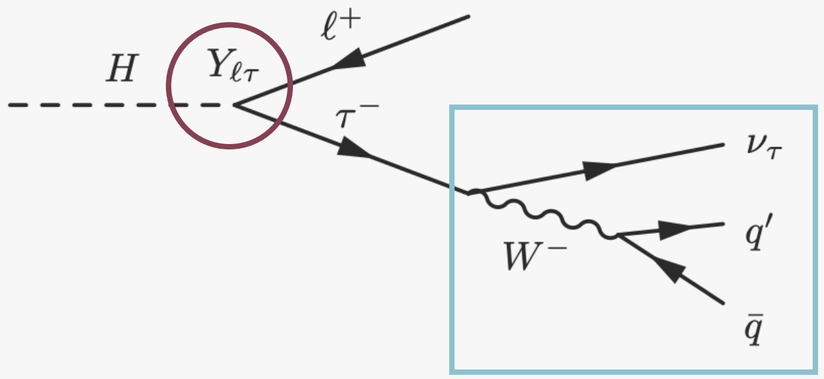
Higgs LFV decays

Forbidden at SM

Allowed via LFV Yukawa couplings in BSM models (SUSY, composite Higgs, Randall-Sundrum Extra Spatial Dimensions, etc)

Experimental signature: combination of e, μ, τ (with leptonic / hadronic tau reconstruction)





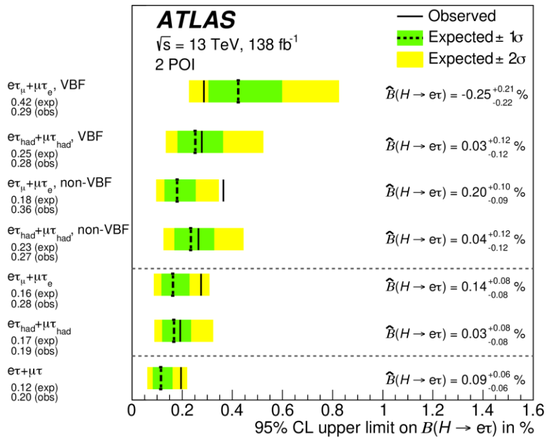
$H \to e\tau, H \to \mu\tau$

ATLAS (Run-2, 138 fb^{-1})
JHEP 07 (2023) 166
DOI: 10.1007/JHEP07(2023)166
$B(H \to e\tau) < 0.20\%$
$B(H \to \mu\tau) < 0.18\%$

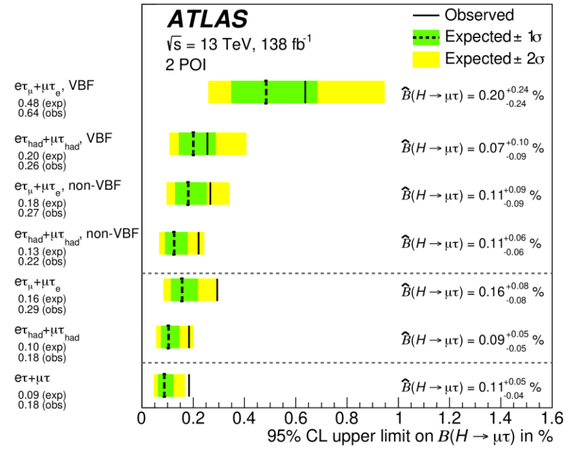
Small (but not significant) excesses observed by ATLAS & CMS

CMS (Run-2, 137 fb^{-1})
JHEP ***07*** (2023) 166
DOI: 10.1103/PhysRevD.104.032013
$B(H \to e\tau) < 0.22\%$
$B(H \to \mu\tau) < 0.15\%$

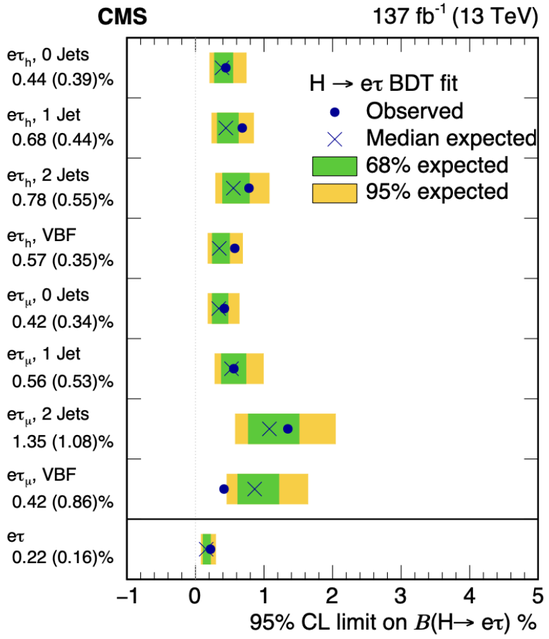
$H \to e\tau$



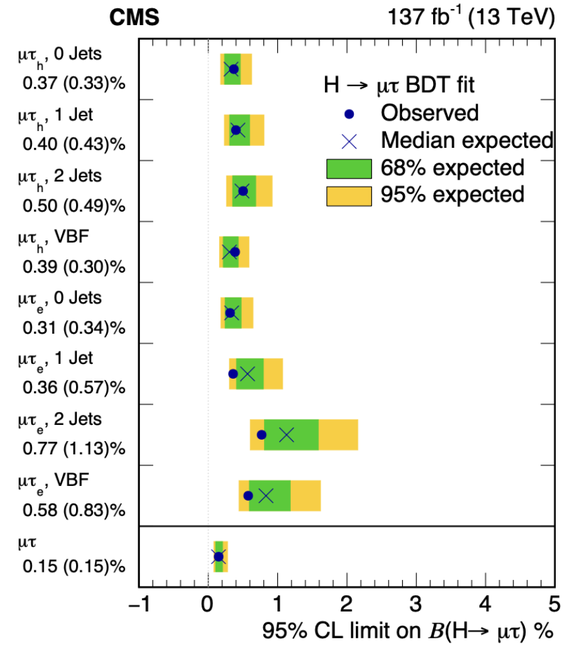
$H \to \mu\tau$



$H \to e\tau$

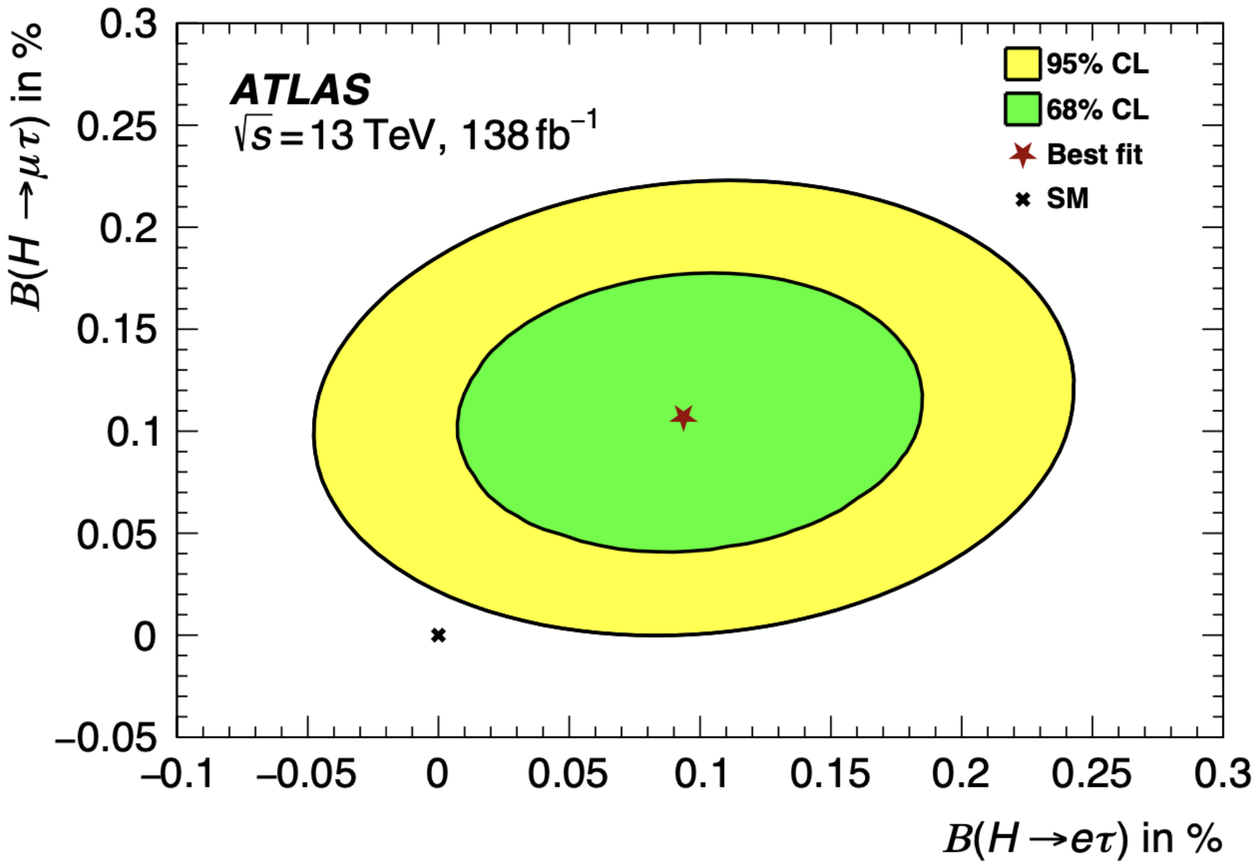


$H \to \mu\tau$



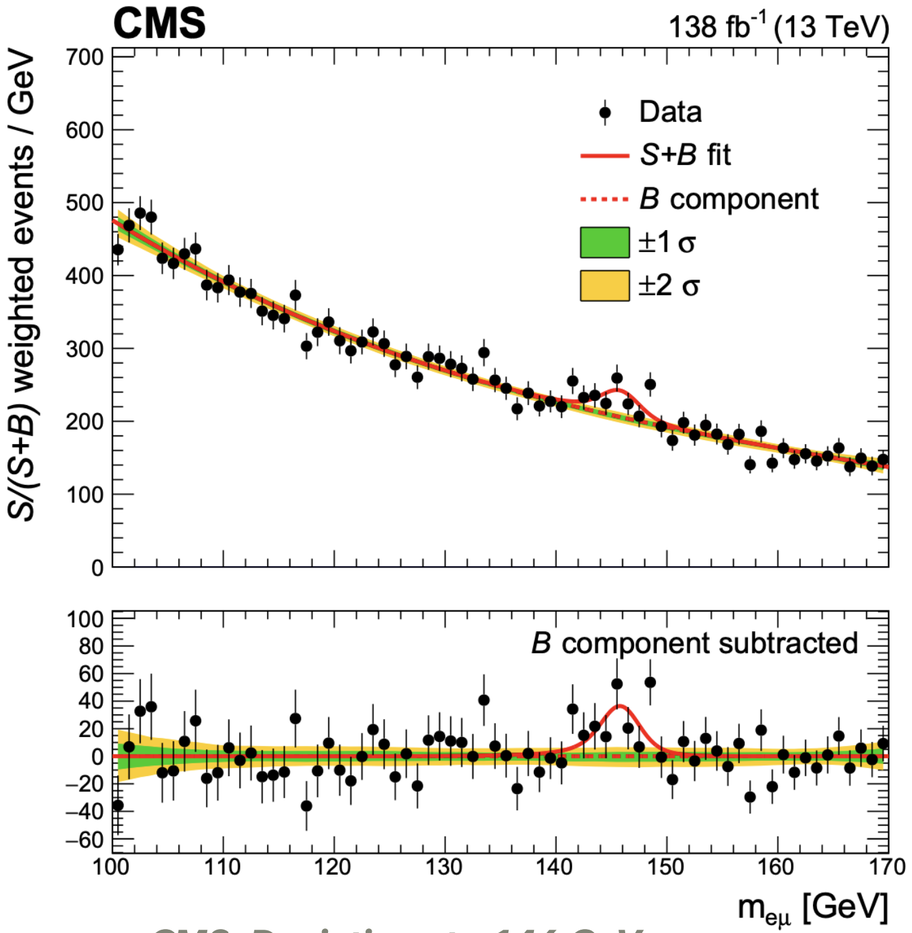
$H \to e\tau, H \to \mu\tau$

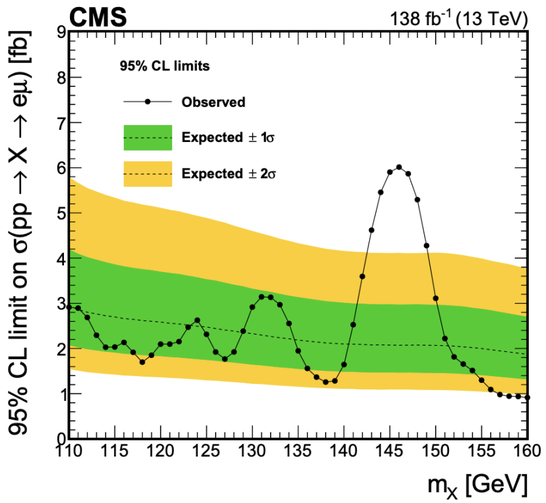
ATLAS (Run-2, 138 fb^{-1})
JHEP 07 (2023) 166
DOI: 10.1007/JHEP07(2023)166
$B(H \to e\tau) < 0.20\%$
$B(H \to \mu\tau) < 0.18\%$

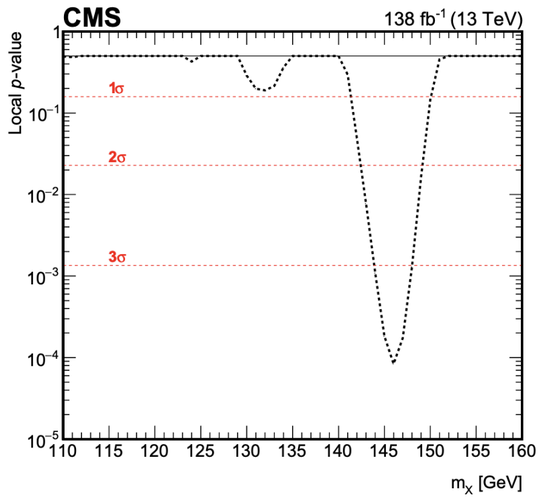


Small (but not significant) excesses observed by ATLAS & CMS
results consistent with SM within 2.5σ

$H \to e\mu$ (and $X \to e\mu$)



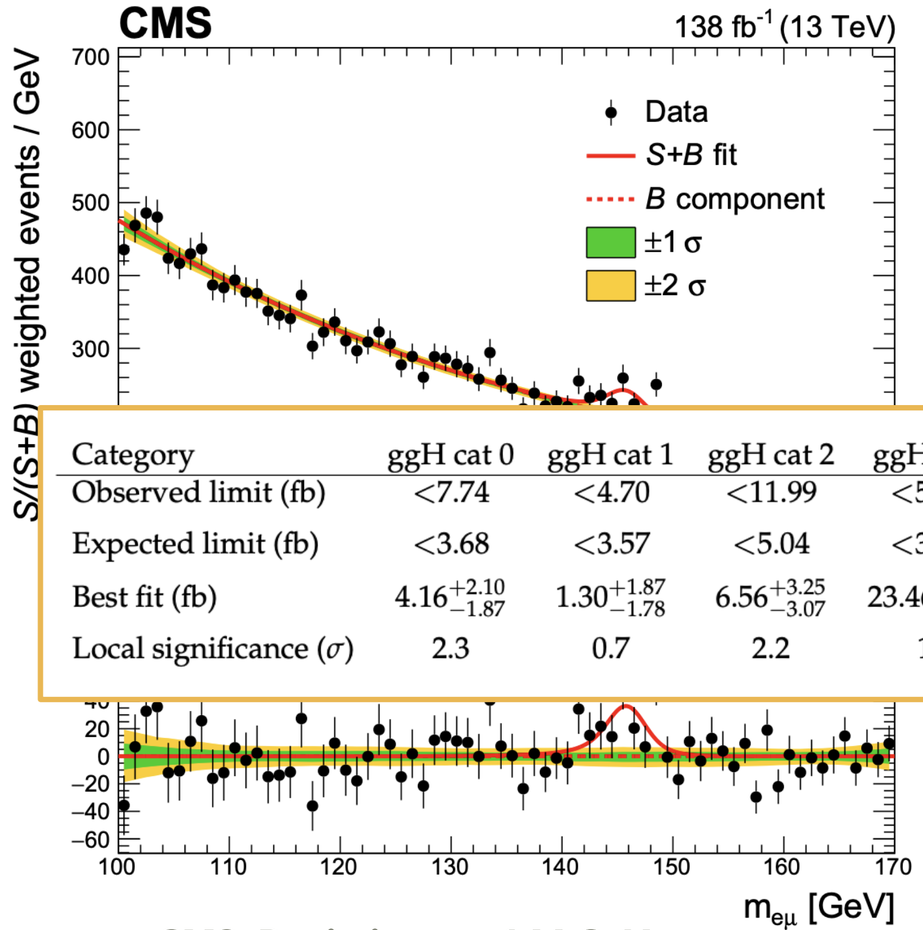


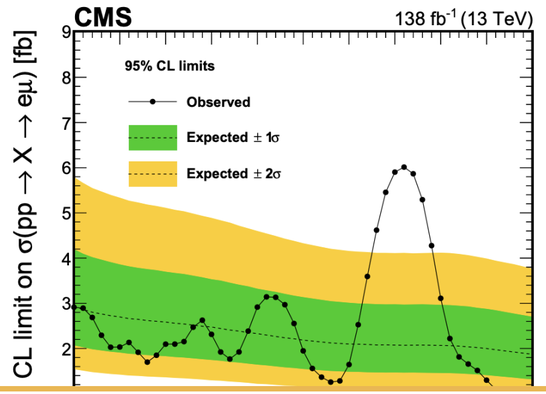


CMS: Deviation at ~146 GeV
Local (global) significance
3.8σ (2.8σ)

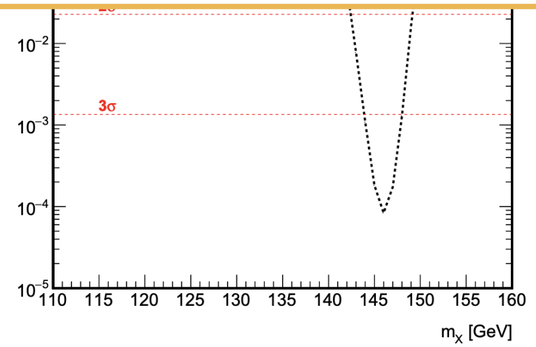
CMS (Run-2, 138 fb⁻¹)
Phys. Rev. D 108, 072004
DOI: 10.1103/PhysRevD.108.072004

$H \to e\mu$ (and $X \to e\mu$)





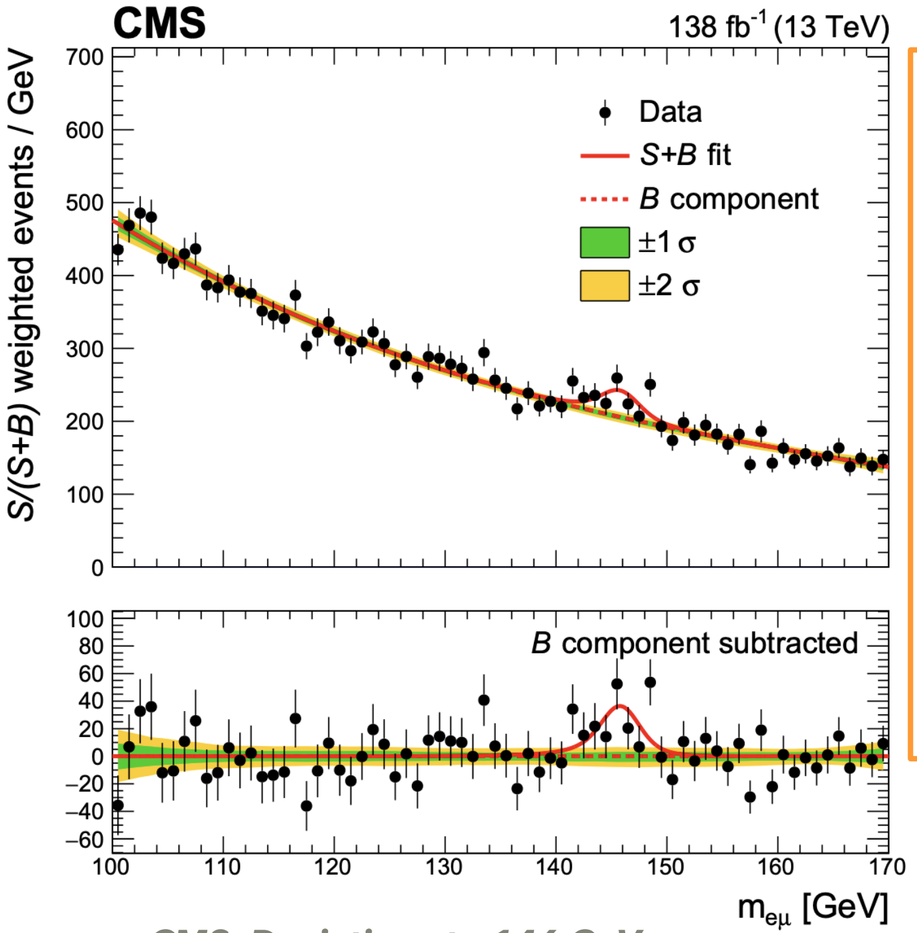
Category	ggH cat 0	ggH cat 1	ggH cat 2	ggH cat 3	VBF cat 0	VBF cat 1	Combined
Observed limit (fb)	<7.74	<4.70	<11.99	<54.87	<12.56	<22.46	<6.01
Expected limit (fb)	<3.68	<3.57	<5.04	<34.56	<6.56	<12.58	<2.07
Best fit (fb)	$4.16^{+2.10}_{-1.87}$	$1.30^{+1.87}_{-1.78}$	$6.56^{+3.25}_{-3.07}$	$23.46^{+18.17}_{-17.31}$	$5.35^{+3.92}_{-2.96}$	$9.00^{+7.46}_{-6.30}$	$3.89^{+1.25}_{-1.13}$
Local significance (σ)	2.3	0.7	2.2	1.4	2.1	1.5	3.8

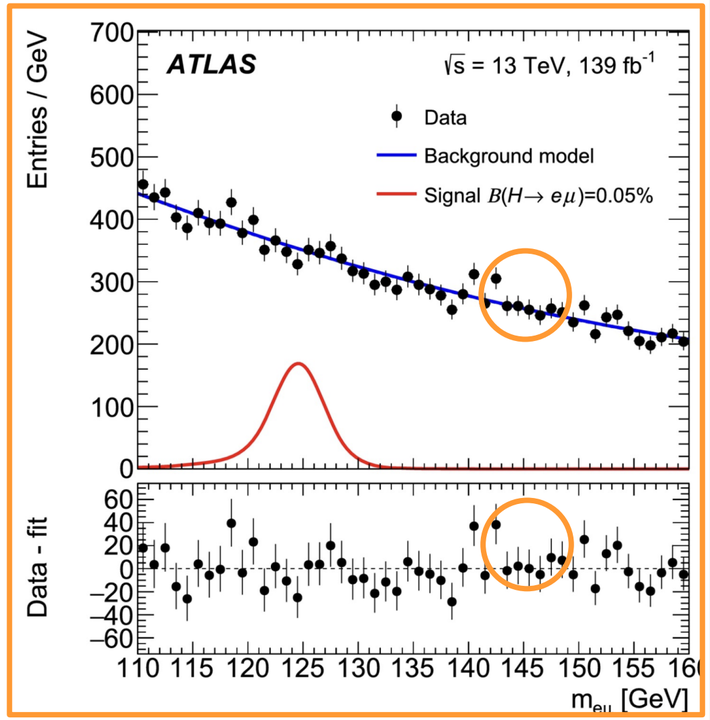


CMS: Deviation at ~146 GeV
Local (global) significance
3.8σ (2.8σ)

CMS (Run-2, 138 fb^{-1})
Phys. Rev. D 108, 072004
DOI: 10.1103/PhysRevD.108.072004

$H \to e\mu$ (and $X \to e\mu$)



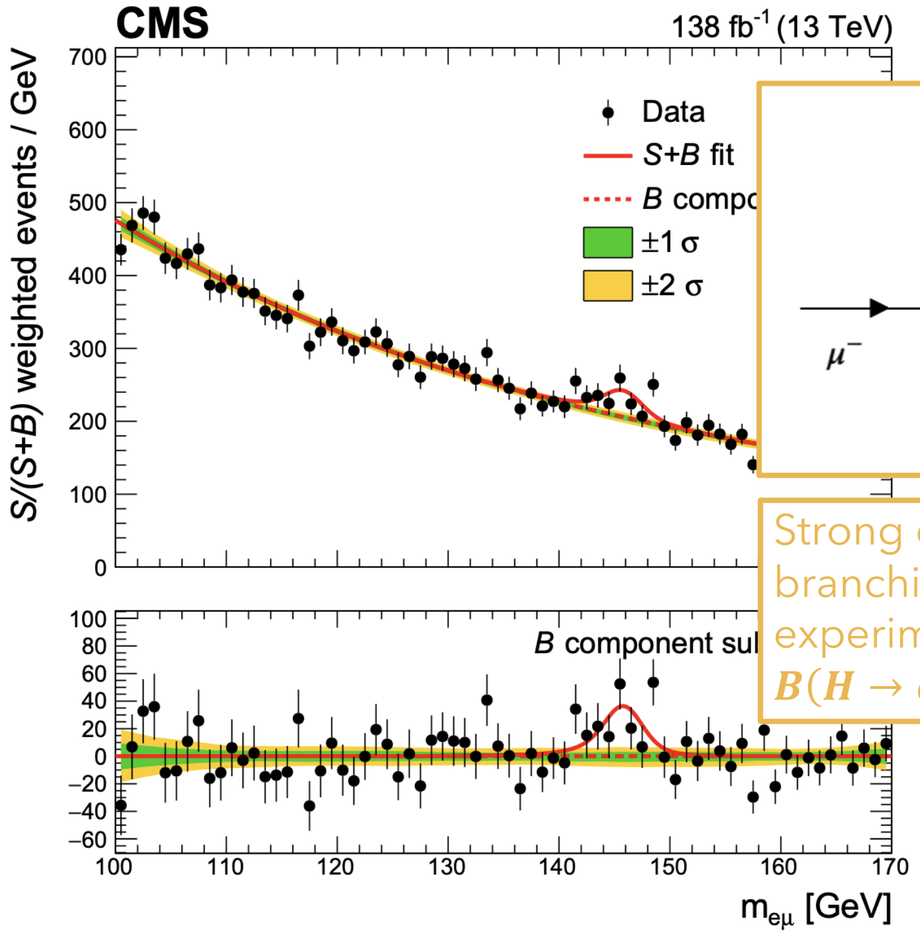


CMS: Deviation at ~146 GeV
Local (global) significance
3.8σ (2.8σ)

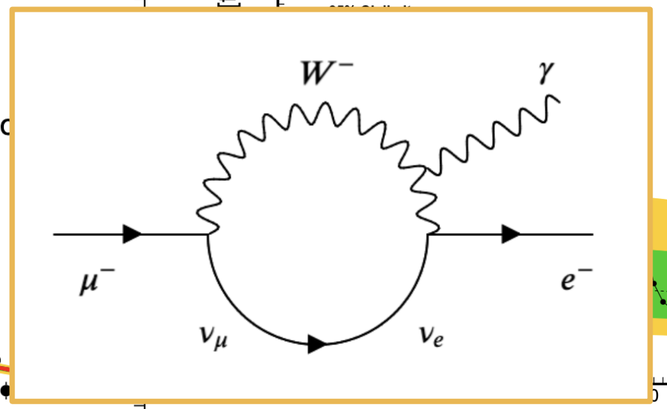
ATLAS (Run-2, 139 fb^{-1})
Phys. Lett. B 801 (2020) 135148
DOI:10.1016/j.physletb.2019.135148

CMS (Run-2, 138 fb^{-1})
Phys. Rev. D 108, 072004
DOI: 10.1103/PhysRevD.108.072004

$H \to e\mu$ (and $X \to e\mu$)



$B(H \to e\mu) < 4.4 \times 10^{-5}$



Strong constraints on branching fraction by μ→eγ experimental limits:
$B(H \to e\mu) < 10^{-9}$

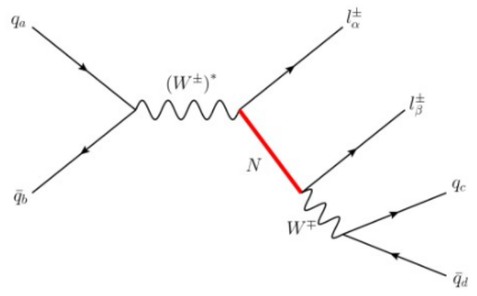
CMS (Run-2, 138 fb^{-1})
Phys. Rev. D 108, 072004
DOI: 10.1103/PhysRevD.108.072004

Heavy Neutrinos

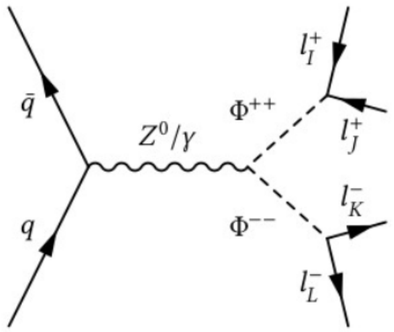
Heavy Neutrinos at LHC

- SeeSaw mechanism: a natural way to produce light (SM) neutrino masses through heavy right-handed neutrinos
- If neutrino is ***Majorana particle*** → ***Lepton Number Violation***

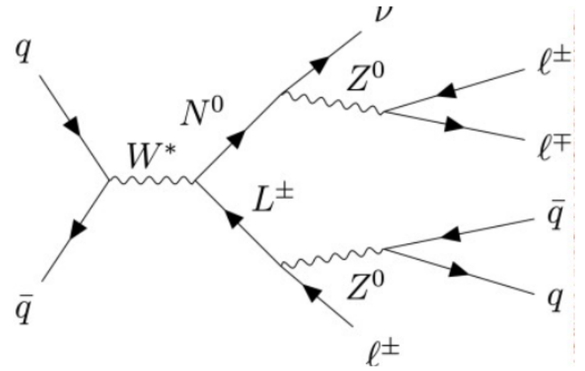
Type-I: right-handed neutrinos (via W/W_R)



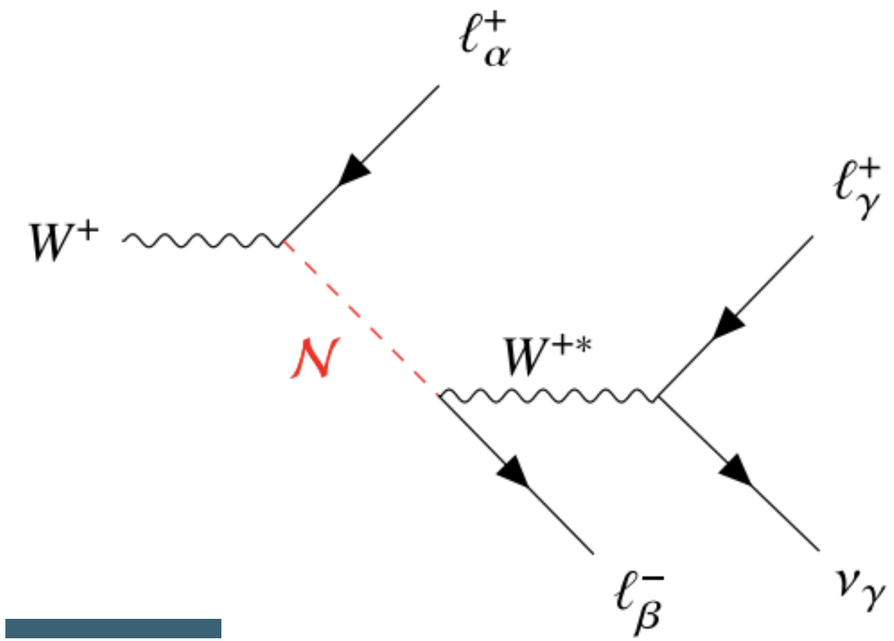
Type-II: scalar triplets

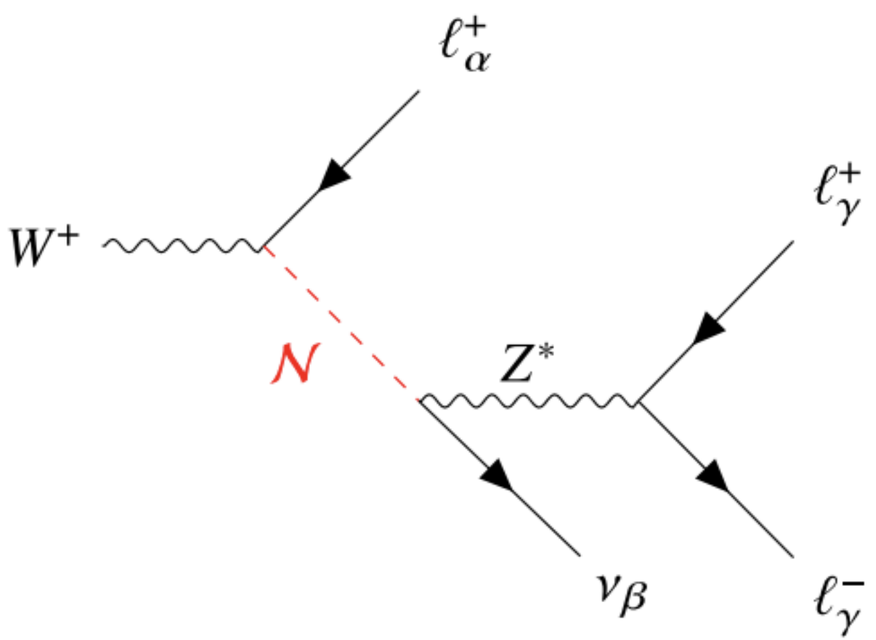


Type-III: at least two fermion triplets



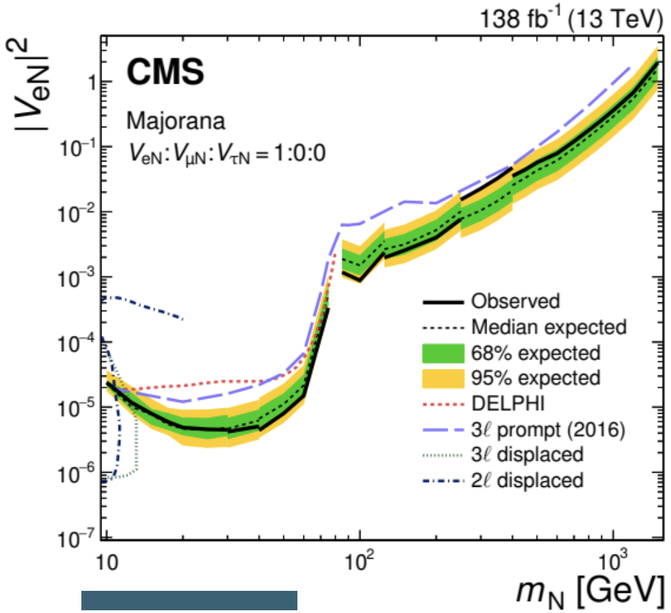
Type-I & Type-II: further embedded into Left-Right Symmetric Model (LRSM)

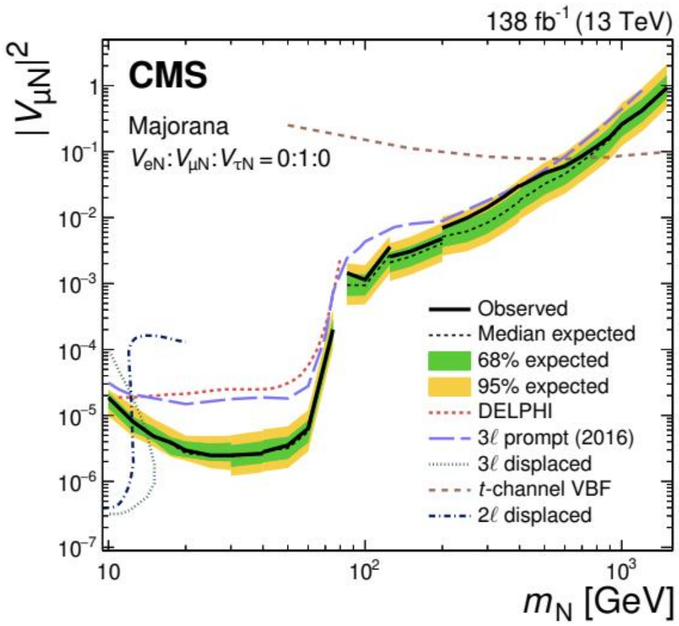


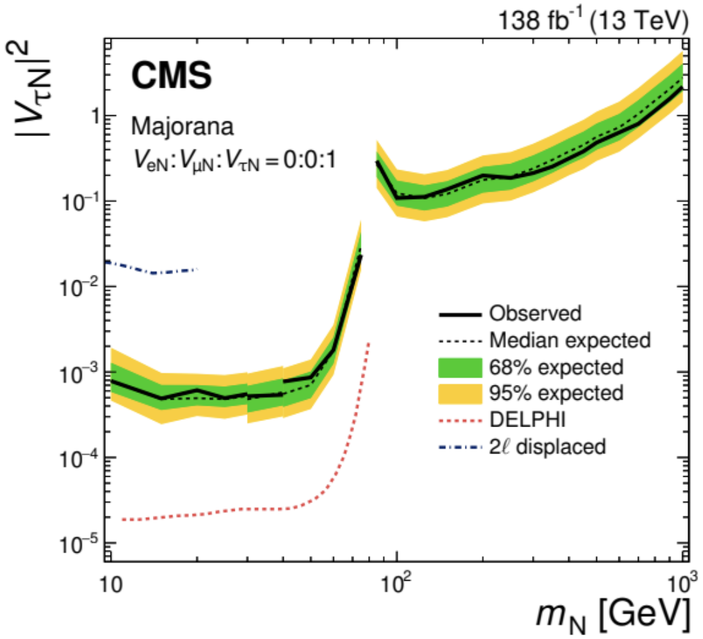


Type-I Heavy Neutrinos

- Type-I simplest form: final state with charged leptons (and escaping neutrino)
- If interaction mediated by ***Majorana neutrino***: same-charge leptons originating from $W^{\pm}$ and N_R



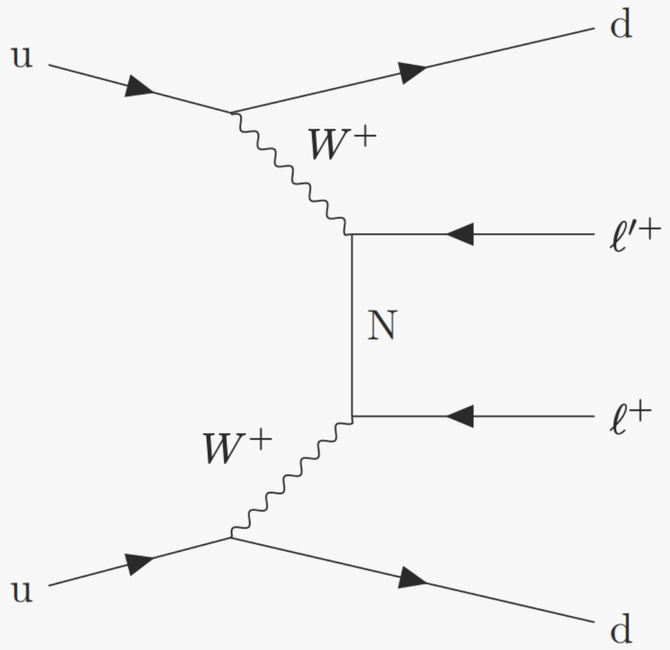




Type-I Heavy Neutrinos

- Large mass range explored
- No flavour mixing
- Shape of exclusion limits curve: caused by $W^{\pm}$ and N_R mass hierarchy
- Better than LEP for electrons/muons

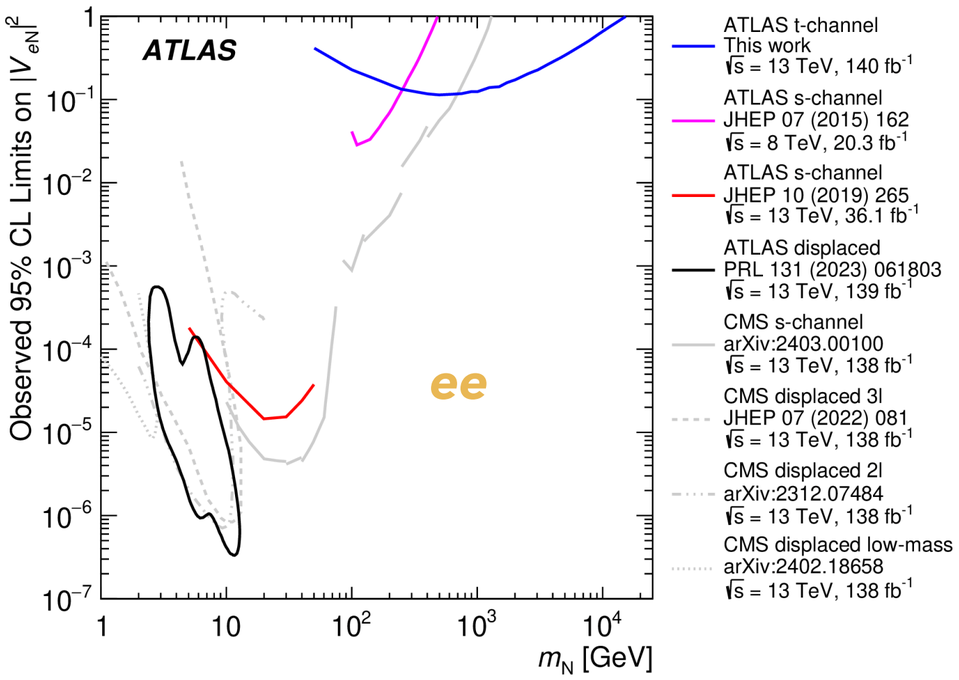
CMS (Run-2, 138 fb^{-1})
JHEP 06 (2024) 123
DOI: 10.1007/JHEP06%282024%29123

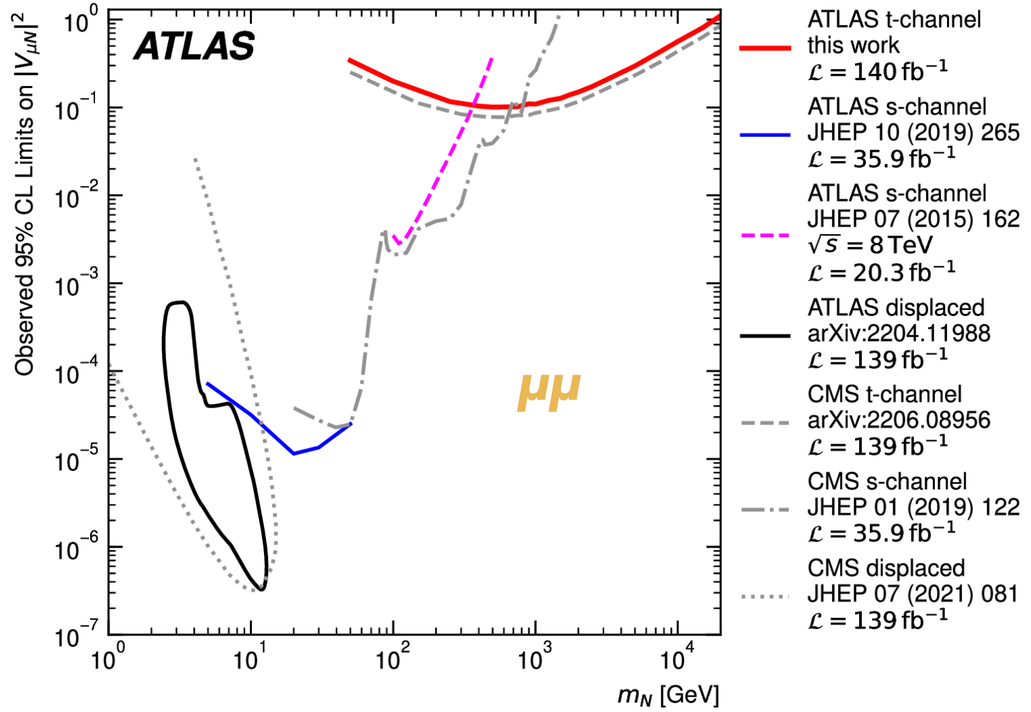


- High-energy W boson scattering (analogous to neutrinoless double-β decay)
- Interaction mediated by ***Majorana neutrino*** (EFT: d=5 Weinberg operator)
- Experimental signature: Same-sign pairs of electrons & muons (ee, μμ, eμ)

Heavy Neutrinos & WW scattering

Heavy Neutrinos & WW scattering: ee/μμ





ATLAS (Run-2, 140 fb^{-1}):
Phys.Lett.B 856 (2024) 138865
DOI:10.1016/j.physletb.2024.138865

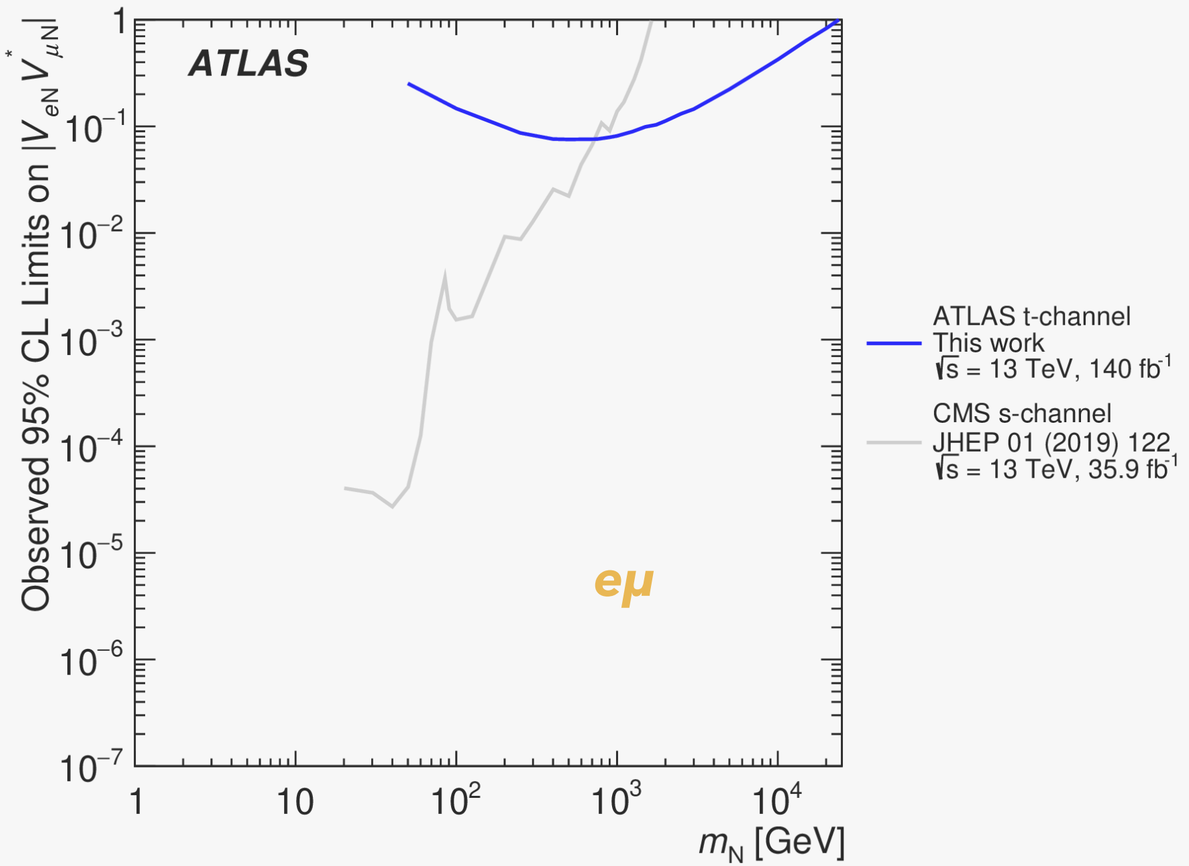
ATLAS (Run-2, 140 fb^{-1}):
Eur. Phys. J. C 83 (2023) 824
DOI:10.1140/epjc/s10052-023-11915-y

Experimental sensitivity & results extended to larger-mass region

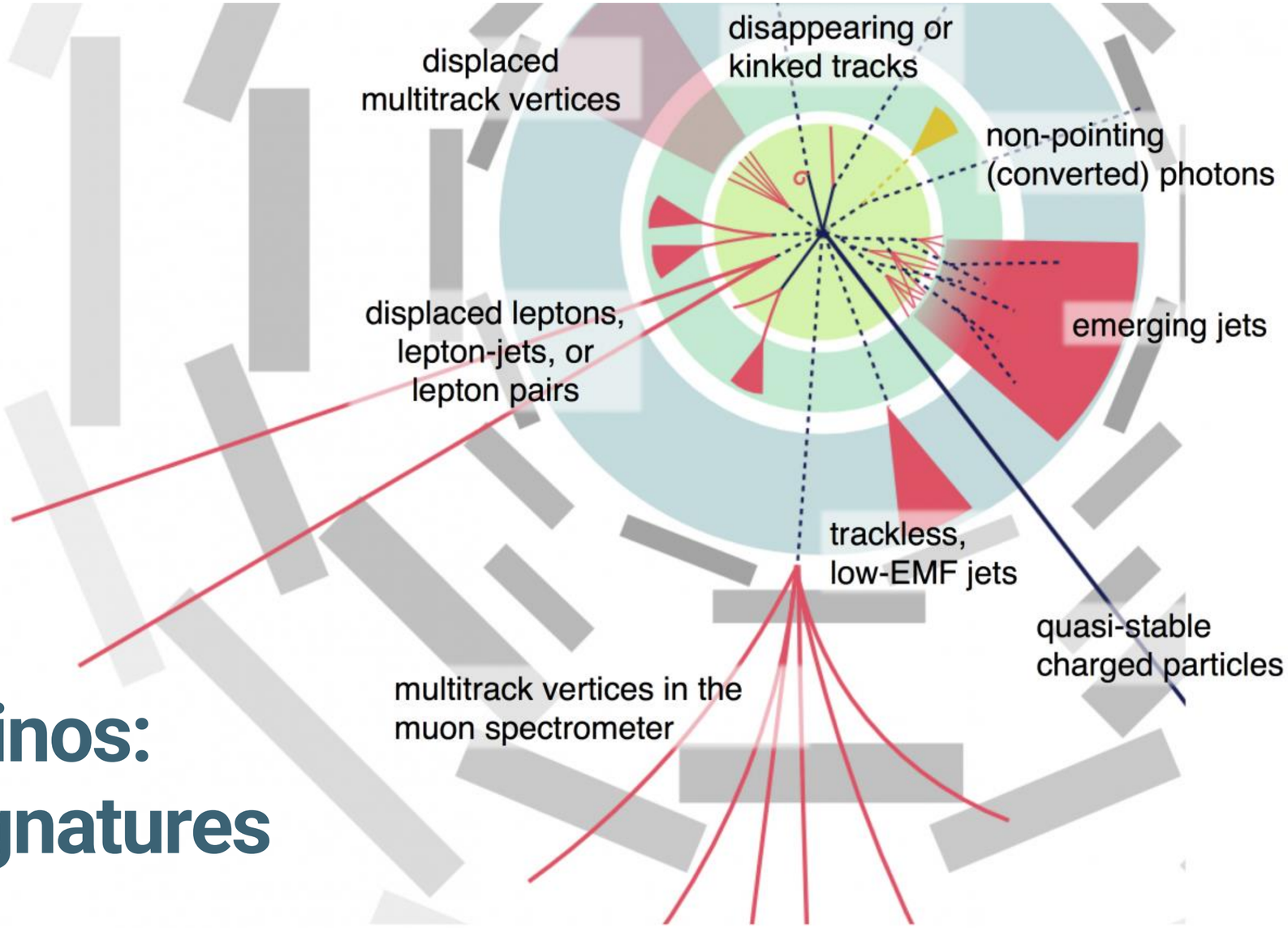
ATLAS (Run-2, 140 fb^{-1}):
Phys.Lett.B 856 (2024) 138865
DOI:10.1016/j.physletb.2024.138865

Experimental sensitivity & results extended to larger-mass region (LFV case)

Heavy Neutrinos & WW scattering: eμ

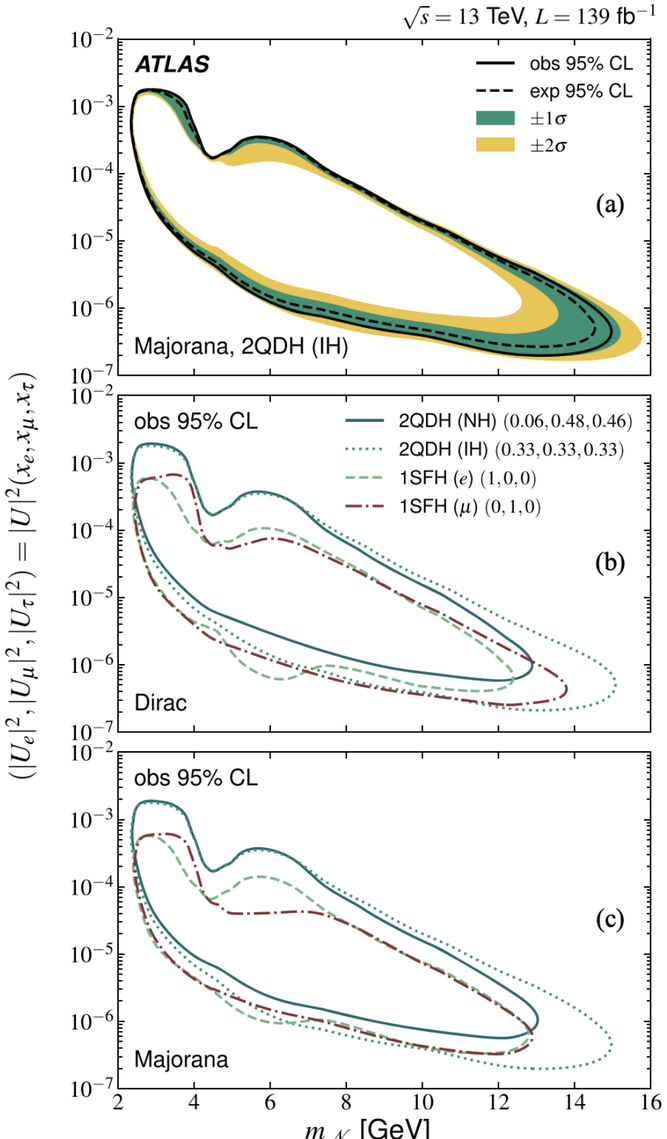


Heavy Neutrinos: displaced signatures

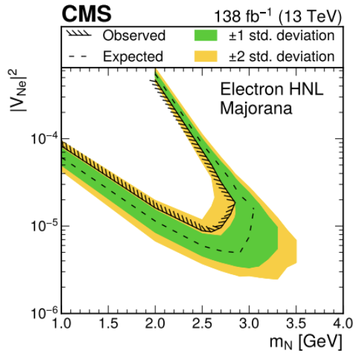


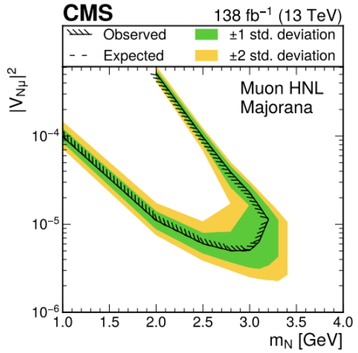
Credit: Heather Russell (LLP White Paper)

Heavy Neutrino: displaced signatures

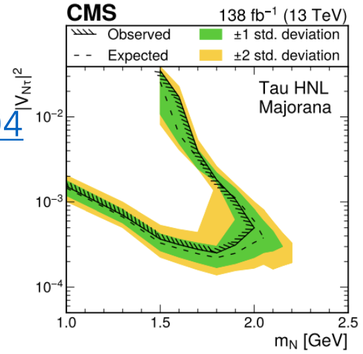


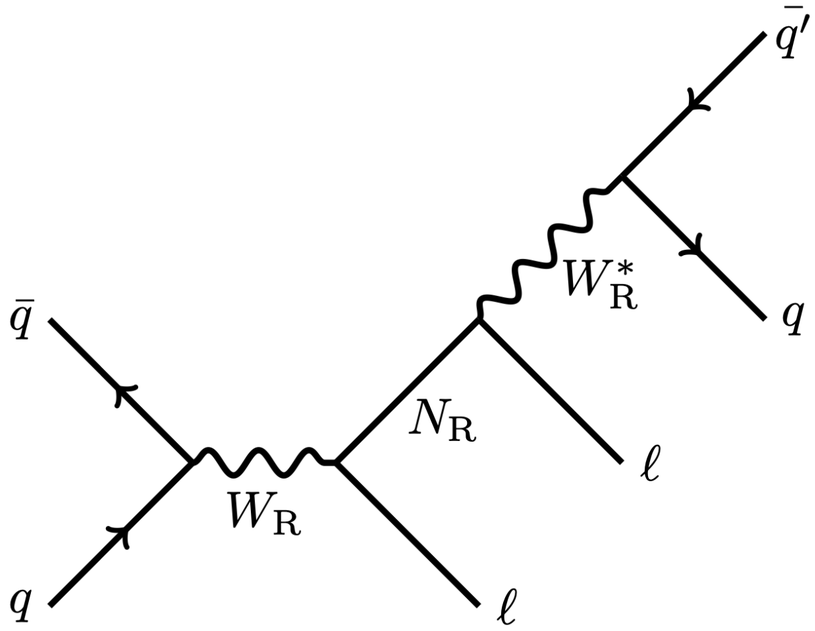
ATLAS (Run-2, 139 fb^{-1})
Phys. Rev. Lett. 131, 061803
DOI: 10.1103/PhysRevLett.131.061803





CMS (Run-2, 138 fb^{-1})
Phys. Rev. D 110 (2024) 012004
DOI: 10.1103/PhysRevD.110.012004





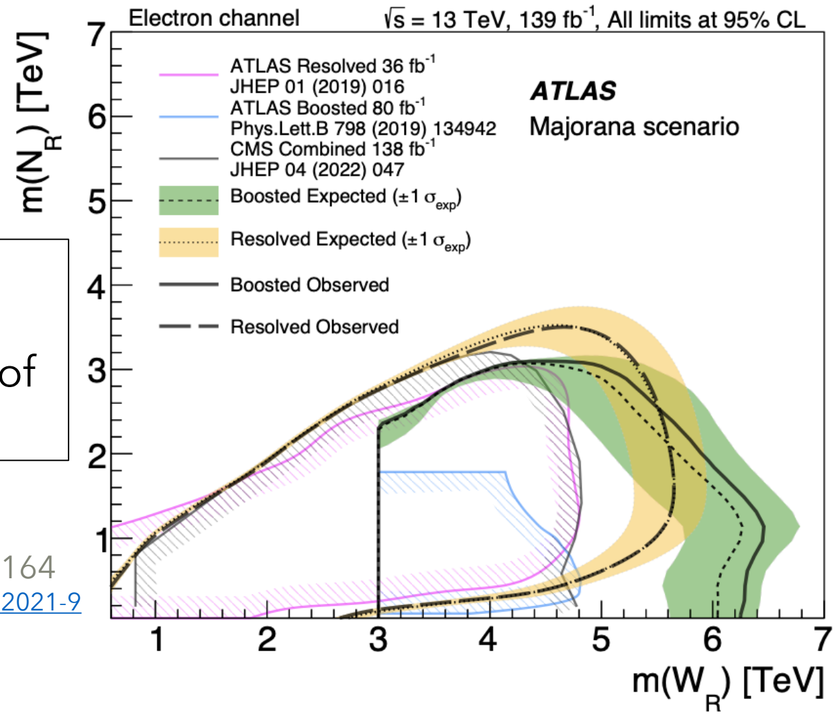
G. Senjanović and R. N. Mohapatra, *Exact left-right symmetry and spontaneous violation of parity*, Phys. Rev. D **12** (1975) 1502.

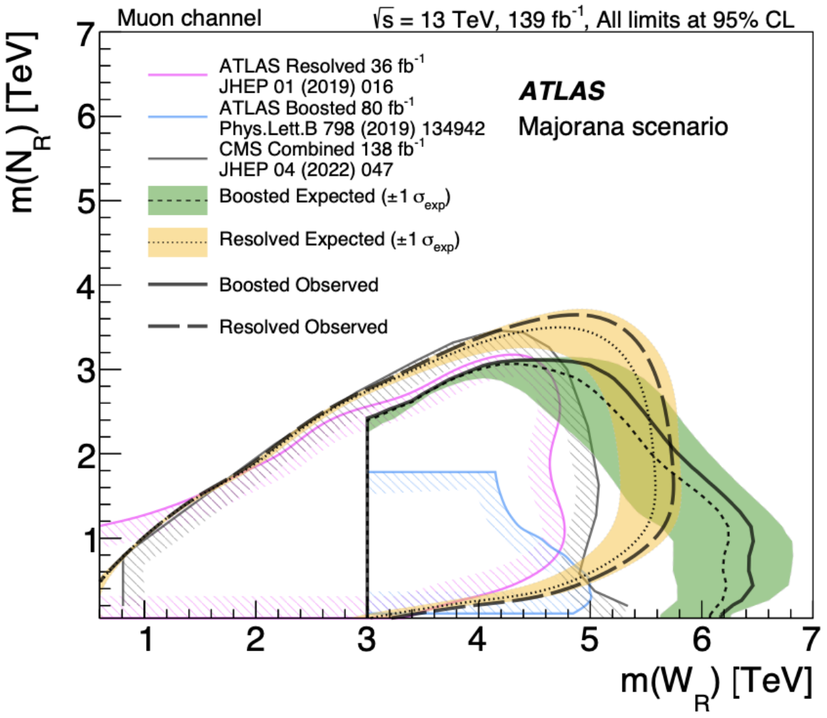
LRSM

- L-R symmetric model: restores parity at high-energy by introducing new heavy charged bosons (W_R)
- Parity violation explained by $W - W_R$ mass difference
- Two particles to be found : N_R and W_R
- Mixed flavour of leptons: LFV
- Experimental signature: two charged leptons & two jets
- Opposite- or same-sign dileptons: Dirac vs Majorana

Newly added
boosted region
extends sensitivity of
resolved region

ATLAS (Run-2, 138 fb^{-1}):
Eur. Phys. J. C 83 (2023) 1164
DOI: 10.1140/epjc/s10052-023-12021-9





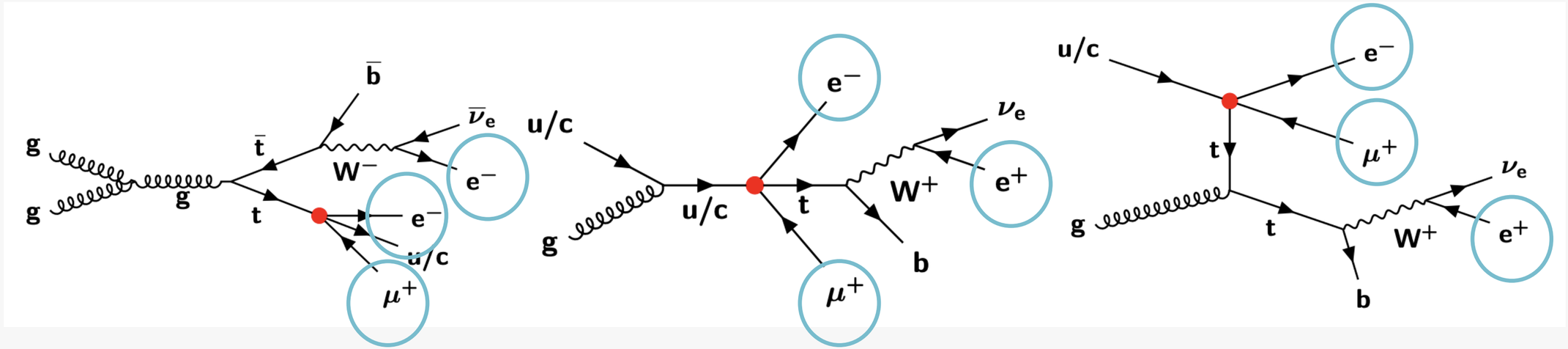
LRSM

- L-R symmetric model: restores parity at high-energy by introducing new heavy charged bosons (W_R)
- Parity violation explained by $W - W_R$ mass difference
- Two particles to be found : N_R and W_R
- Mixed flavour of leptons: LFV
- Experimental signature: two charged leptons & two jets
- Opposite- or same-sign dileptons: Dirac vs Majorana

Top decays

Top decays with eeμ

- Complex analysis with three charged leptons in final state



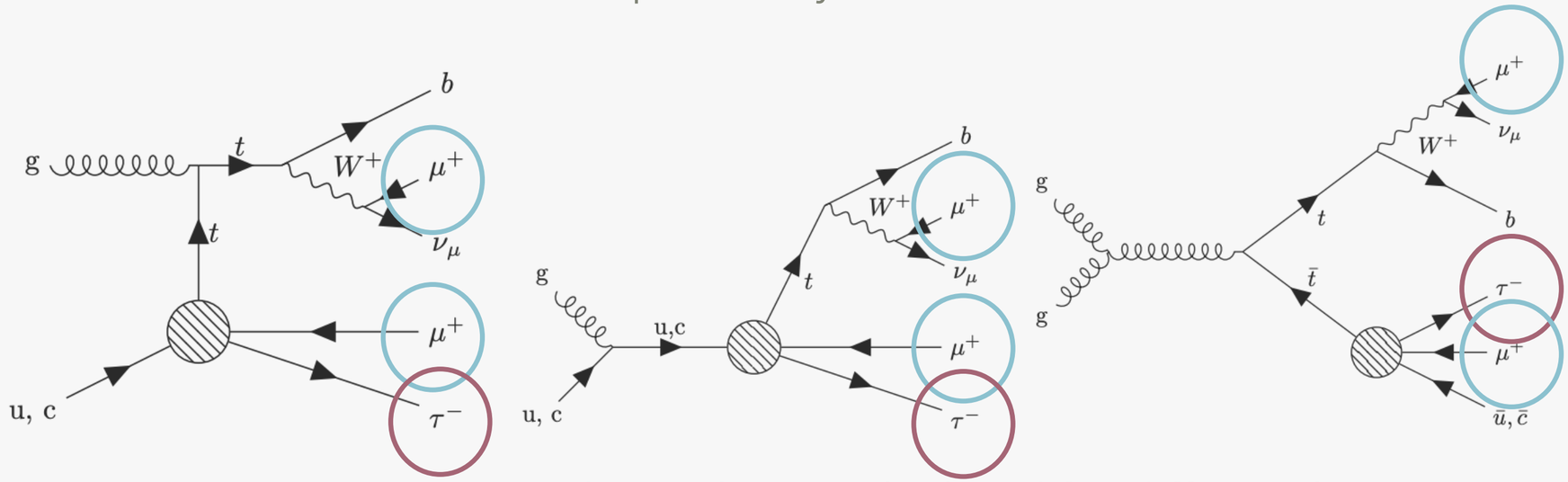
- Exclusion limits calculated for tensor-like, vector-like and scalar-like interactions for eμtu & eμtc vertices

CLFV coupling	Lorentz structure	$C_{e\mu tq}/\Lambda^2$ (TeV^{-2}) Exp. (68% CL range)	Obs.	$\mathcal{B}(t \to e\mu q) \times 10^{-6}$ Exp. (68% CL range)	Obs.
eμtu	Tensor	0.022 (0.018–0.026)	0.024	0.027 (0.018–0.040)	0.032
	Vector	0.044 (0.036–0.054)	0.048	0.019 (0.013–0.028)	0.022
	Scalar	0.093 (0.077–0.114)	0.101	0.010 (0.007–0.016)	0.012
eμtc	Tensor	0.084 (0.069–0.102)	0.094	0.396 (0.272–0.585)	0.498
	Vector	0.175 (0.145–0.214)	0.196	0.296 (0.203–0.440)	0.369
	Scalar	0.385 (0.318–0.471)	0.424	0.178 (0.122–0.266)	0.216

CMS (Run-2, 138 fb^{-1}): CMS-TOP-22-005, CERN-EP-2023-258 arXiv:2312.03199

Top decays with μμτ

- Complex analysis with two muons & one tau in final state



- Exclusion limits calculated for different lepton/quark generations for μττu & μττc vertices

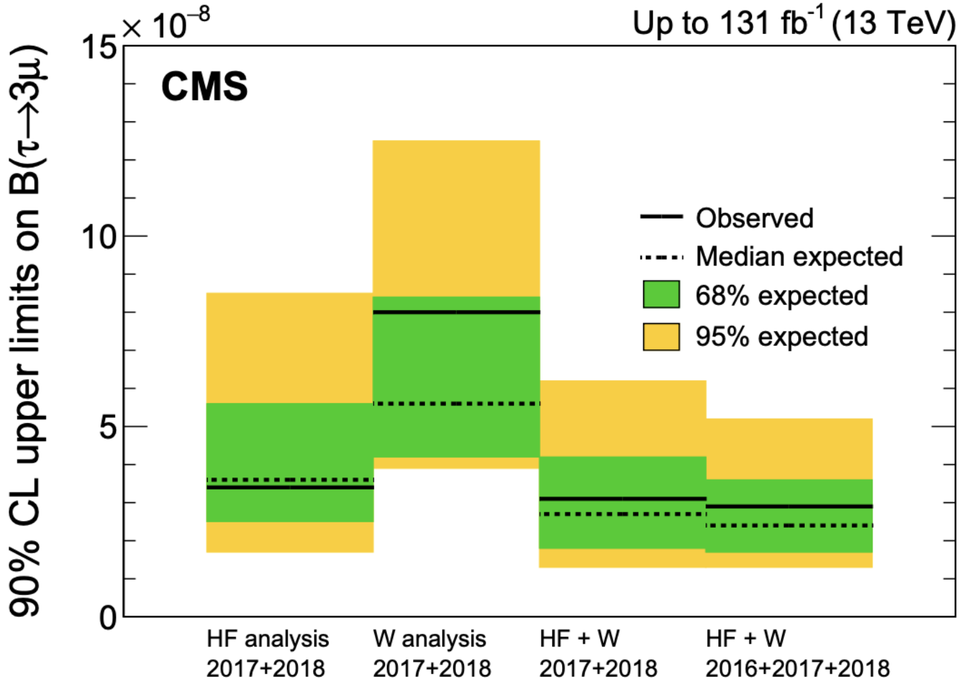
	95% CL upper limits on $\mathcal{B}(t \to \mu\tau q)$ $(\times 10^{-7})$					
	$c_{lq}^{-(ijk3)}$	$c_{eq}^{(ijk3)}$	$c_{lu}^{(ijk3)}$	$c_{eu}^{(ijk3)}$	$c_{lequ}^{1(ijk3)}$	$c_{lequ}^{3(ijk3)}$
Expected (u)	2.3	2.0	1.9	2.2	1.2	3.0
Observed (u)	4.0	3.6	3.3	3.8	2.0	5.2
Expected (c)	33	32	32	33	20	41
Observed (c)	56	54	53	54	34	67

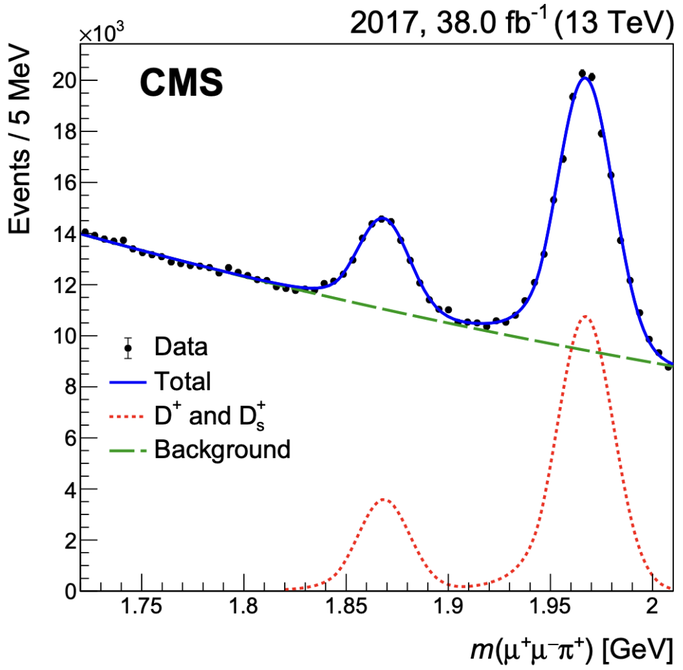
ATLAS (Run-2, 140 fb^{-1}): Phys. Rev. D 110 (2024) 012014 DOI: 10.1103/PhysRevD.110.012014

τ/B/Z decays

$\tau \to 3\mu$

- Perhaps the cleanest LFV search at the LHC
- Using taus from heavy-flavour ($D_S^{\pm}$, $B^{\pm}$, B^0) and W-boson decays
- Using $D_S^{\pm} \to \varphi(\mu^+\mu^-)\pi^{\pm}$ channel for normalisation





$B(\tau \to 3\mu) < 2.9 \times 10^{-8}$ (CMS & best LHC result)
$B(\tau \to 3\mu) < 1.9 \times 10^{-8}$ (Belle)

Projections:
$B(\tau \to 3\mu) \sim 10^{-9}$ (CMS with 3 ab^{-1} at HL-LHC)
$B(\tau \to 3\mu) < 10^{-9}$ (Belle II)

CMS (Run-2, 131 fb^{-1}):
Phys. Lett. B 853 (2024) 138633
DOI: 10.1103/PhysRevD.110.012014

Decay mode	Limit at 90% CL	Dataset (fb^{-1})
$B^0 \to K^{*0}\mu^{\pm}e^{\mp}$	9.9×10^{-9}	9
$B_S \to \varphi\mu^{\pm}e^{\mp}$	15.9×10^{-9}	9
$B^+ \to K^+\mu^-e^+$	7.0×10^{-9}	3
$B^+ \to K^+\mu^+e^-$	6.4×10^{-9}	3
$B^+ \to K^+\mu^-\tau^+$	3.9×10^{-5}	9
$B_S \to \mu^{\pm}\tau^{\mp}$	3.9×10^{-5}	3
$B^0 \to \mu^{\pm}\tau^{\mp}$	1.2×10^{-5}	3
$B_S \to \mu^{\pm}e^{\mp}$	5.4×10^{-9}	3
$B^0 \to \mu^{\pm}e^{\mp}$	1.0×10^{-9}	3
$\tau \to 3\mu$	4.6×10^{-8}	3

LFV in B-meson decays

LHCb (Run-1&2, 3-9 fb^{-1}):
Eur. Phys. J. Spec. Top. 233, 225–240 (2024)
DOI: 10.1140/epjs/s11734-023-01010-4

LFV in B-meson decays

Decay mode	Limit at 90% CL	Dataset (fb^{-1})
$B^0 \to K^{*0}\mu^{\pm}e^{\mp}$	9.9×10^{-9}	9
$B_S \to \varphi\mu^{\pm}e^{\mp}$	15.9×10^{-9}	9
$B^+ \to K^+\mu^-e^+$	7.0×10^{-9}	3
$B^+ \to K^+\mu^+e^-$	6.4×10^{-9}	3
$B^+ \to K^+\mu^-\tau^+$	3.9×10^{-5}	9
$B_S \to \mu^{\pm}\tau^{\mp}$	3.9×10^{-5}	3
$B^0 \to \mu^{\pm}\tau^{\mp}$	1.2×10^{-5}	3
$B_S \to \mu^{\pm}e^{\mp}$	5.4×10^{-9}	3
$B^0 \to \mu^{\pm}e^{\mp}$	1.0×10^{-9}	3
$\tau \to 3\mu$	4.6×10^{-8}	3

Phys. Rev. Lett.123 (2019) 241802

Update with full 2011- 2018 data in progress

LHCb (Run-1&2, 3-9 fb^{-1}):
Eur. Phys. J. Spec. Top. 233, 225–240 (2024)
DOI: 10.1140/epjs/s11734-023-01010-4

Decay mode	Limit at 90% CL	Dataset (fb^{-1})
$B^0 \to K^{*0}\mu^{\pm}e^{\mp}$	9.9×10^{-9}	9
$B_S \to \varphi\mu^{\pm}e^{\mp}$	15.9×10^{-9}	9
$B^+ \to K^+\mu^-e^+$	7.0×10^{-9}	3
$B^+ \to K^+\mu^+e^-$	6.4×10^{-9}	3
$B^+ \to K^+\mu^-\tau^+$	3.9×10^{-5}	9
$B_S \to \mu^{\pm}\tau^{\mp}$	3.9×10^{-5}	3
$B^0 \to \mu^{\pm}\tau^{\mp}$	1.2×10^{-5}	3
$B_S \to \mu^{\pm}e^{\mp}$	5.4×10^{-9}	3
$B^0 \to \mu^{\pm}e^{\mp}$	1.0×10^{-9}	3
$\tau \to 3\mu$	4.6×10^{-8}	3

Phys. Rev. Lett.123 (2019) 211801

Factor of x2 improvement wrt to BaBar results

LFV in B-meson decays

LHCb (Run-1&2, 3-9 fb^{-1}):
Eur. Phys. J. Spec. Top. 233, 225–240 (2024)
DOI: 10.1140/epjs/s11734-023-01010-4

Decay mode	Limit at 90% CL	Dataset (fb^{-1})
$B^0 \to K^{*0}\mu^{\pm}e^{\mp}$	9.9×10^{-9}	9
$B_S \to \varphi\mu^{\pm}e^{\mp}$	15.9×10^{-9}	9
$B^+ \to K^+\mu^-e^+$	7.0×10^{-9}	3
$B^+ \to K^+\mu^+e^-$	6.4×10^{-9}	3
$B^+ \to K^+\mu^-\tau^+$	3.9×10^{-5}	9
$B_S \to \mu^{\pm}\tau^{\mp}$	3.9×10^{-5}	3
$B^0 \to \mu^{\pm}\tau^{\mp}$	1.2×10^{-5}	3
$B_S \to \mu^{\pm}e^{\mp}$	5.4×10^{-9}	3
$B^0 \to \mu^{\pm}e^{\mp}$	1.0×10^{-9}	3
$\tau \to 3\mu$	4.6×10^{-8}	3

JHEP 03 (2018) 078

Strongest limits in the world

LFV in B-meson decays

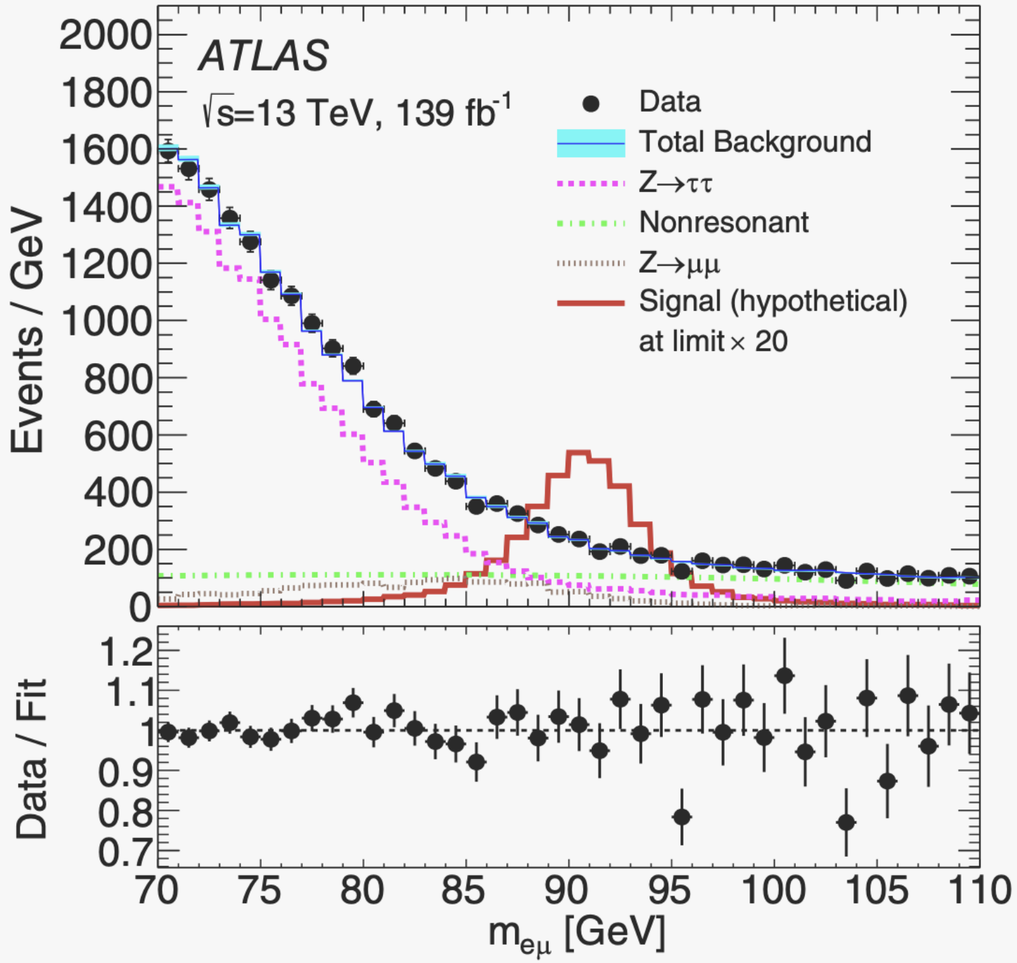
LHCb (Run-1&2, 3-9 fb^{-1}):
Eur. Phys. J. Spec. Top. 233, 225–240 (2024)
DOI: 10.1140/epjs/s11734-023-01010-4

LFV in Z decays

ATLAS (Run-2, 139 fb^{-1}):
Phys. Rev. D 108 (2023) 032015
DOI: 10.1103/PhysRevD.108.032015

Decay	LEP limit on *BR*	ATLAS limit on *BR*
$Z \to e\mu$	1.7 × 10^{-6}	2.6 × 10^{-7}
$Z \to e\tau$	9.8 × 10^{-6}	7.0 × 10^{-6}
$Z \to \mu\tau$	1.2 × 10^{-5}	7.2 × 10^{-6}

ATLAS (Run-2, 139 fb^{-1}):
Phys. Rev. Lett. 127 (2021) 271801
DOI: 10.1103/PhysRevLett.127.271801



LHC now outperforms LEP
in LFV decays of Z-bosons

Summary

LHC offers new perspectives into possible LNV/LFV processes involving heavy particles (Higgs, top, Z)

Summary

New results from LHC extend our LNV/LFV reach in

- Higgs decays
- Heavy Neutrino searches
- Top decays

New analyses show improved sensitivity compared to LEP for

- τ/B/Z decays

More datasets to analyse & new ideas under implementation

HVAR, CROATIA

LNV@2024LHC-DAYS

Lepton Number Violation at the LHC

Christos Leonidopoulos

LHC DAYS 2024 HVAR, CROATIA - 1 OCTOBER 2024

Backup

LNV in RPV SUSY

- 1 lepton https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2019-04/
- 2 same-sign or 3 leptons
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2019-22/
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2020-27/
- Tri-lepton res https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2018-36/
- 4 leptons https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2018-02/
- Stop b-l https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2018-37
- eμ asymmetry https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2018-29/
- RPC-RPV with taus https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2024-007/