Heavy neutrinos at the LHC - results and prospects

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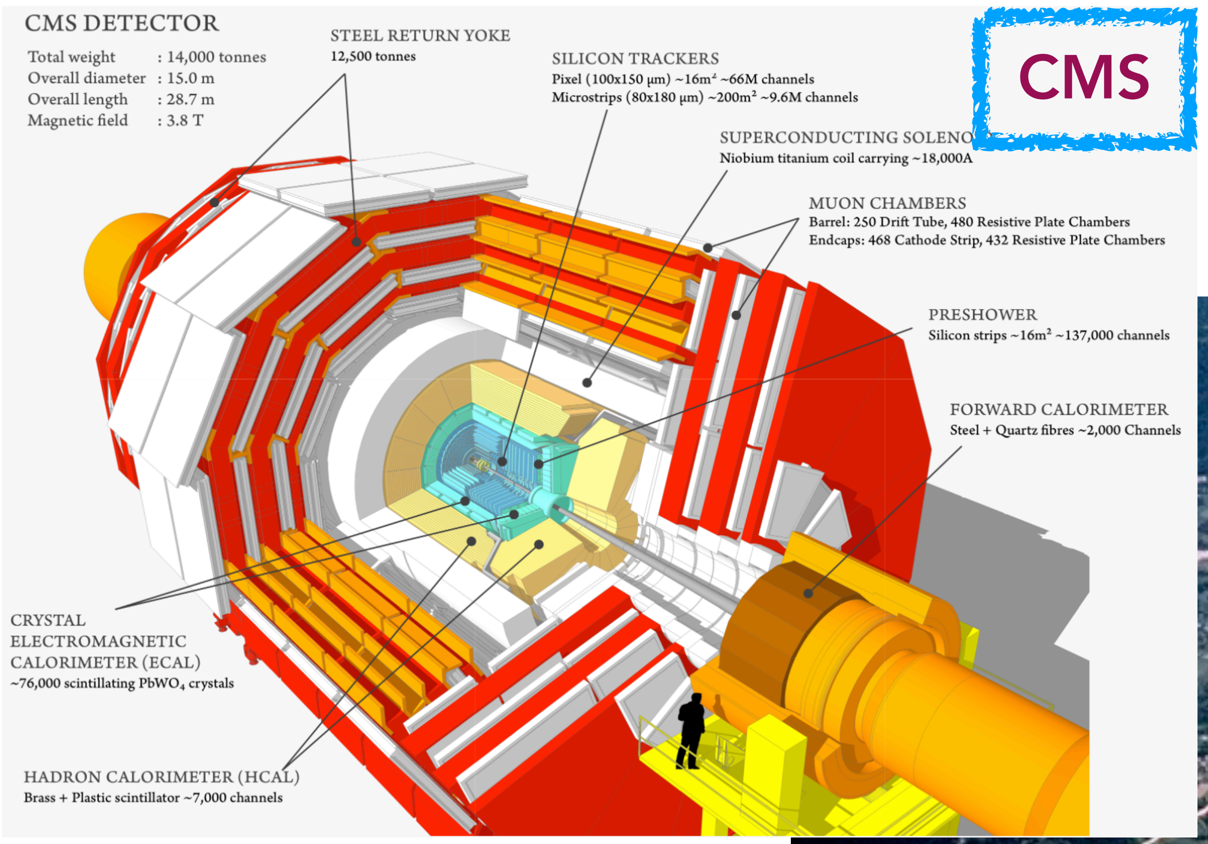
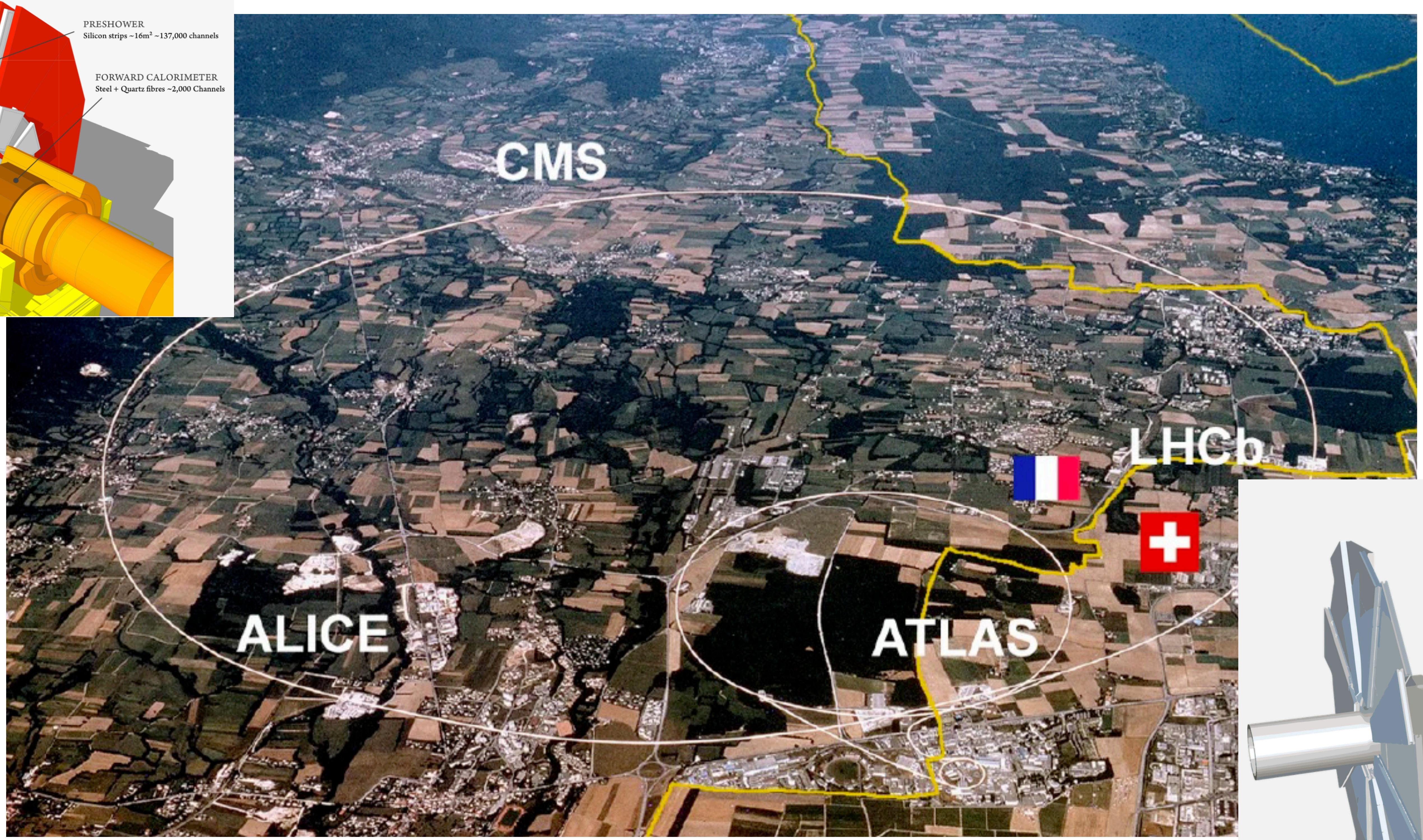
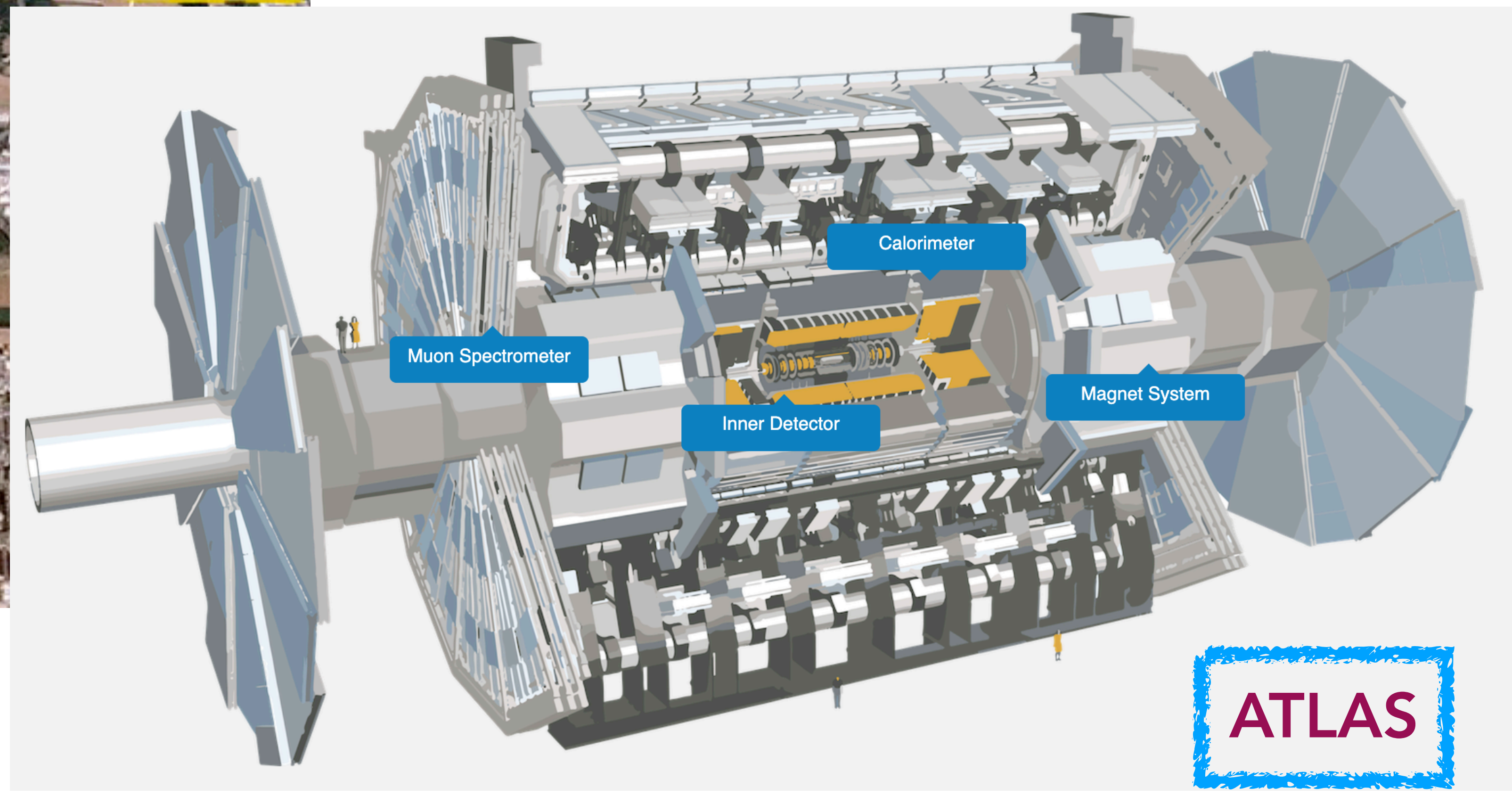
03-June-2022

The Large Hadron Collider Run-2

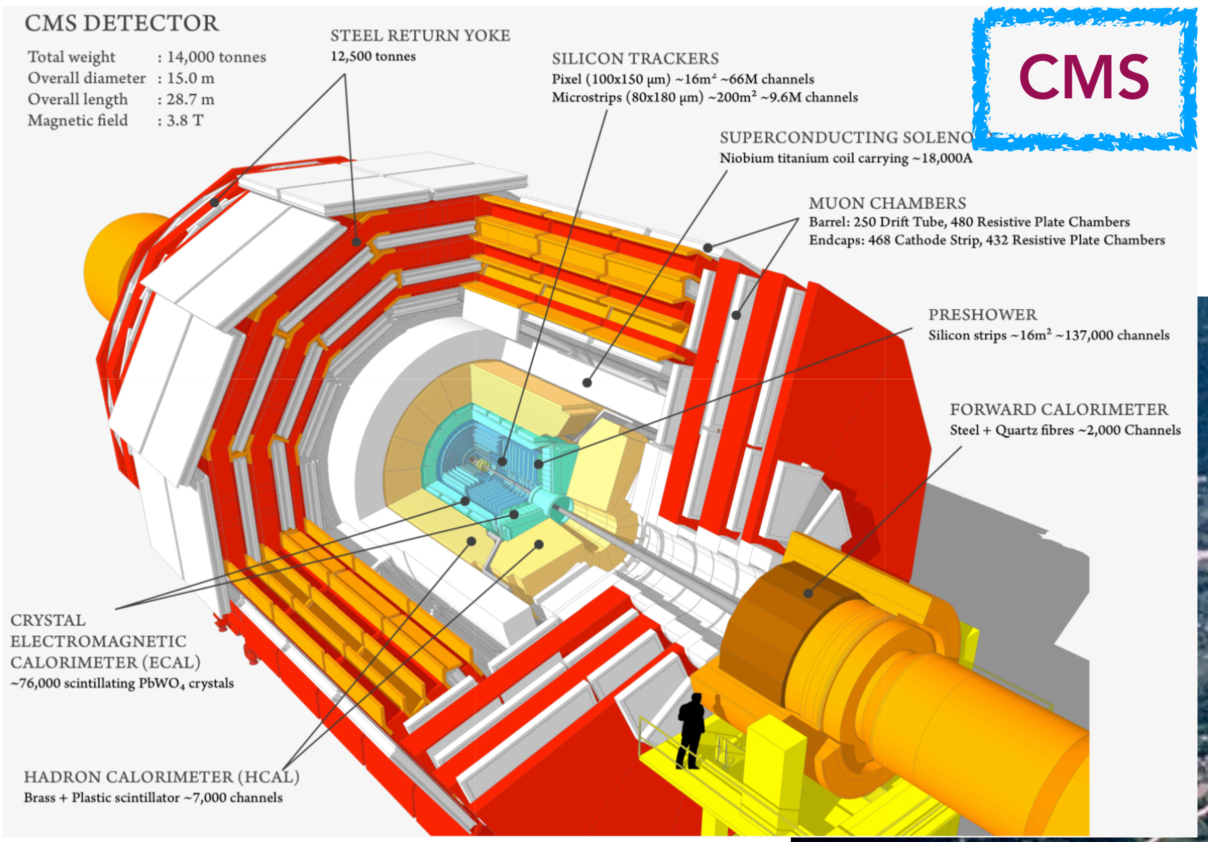


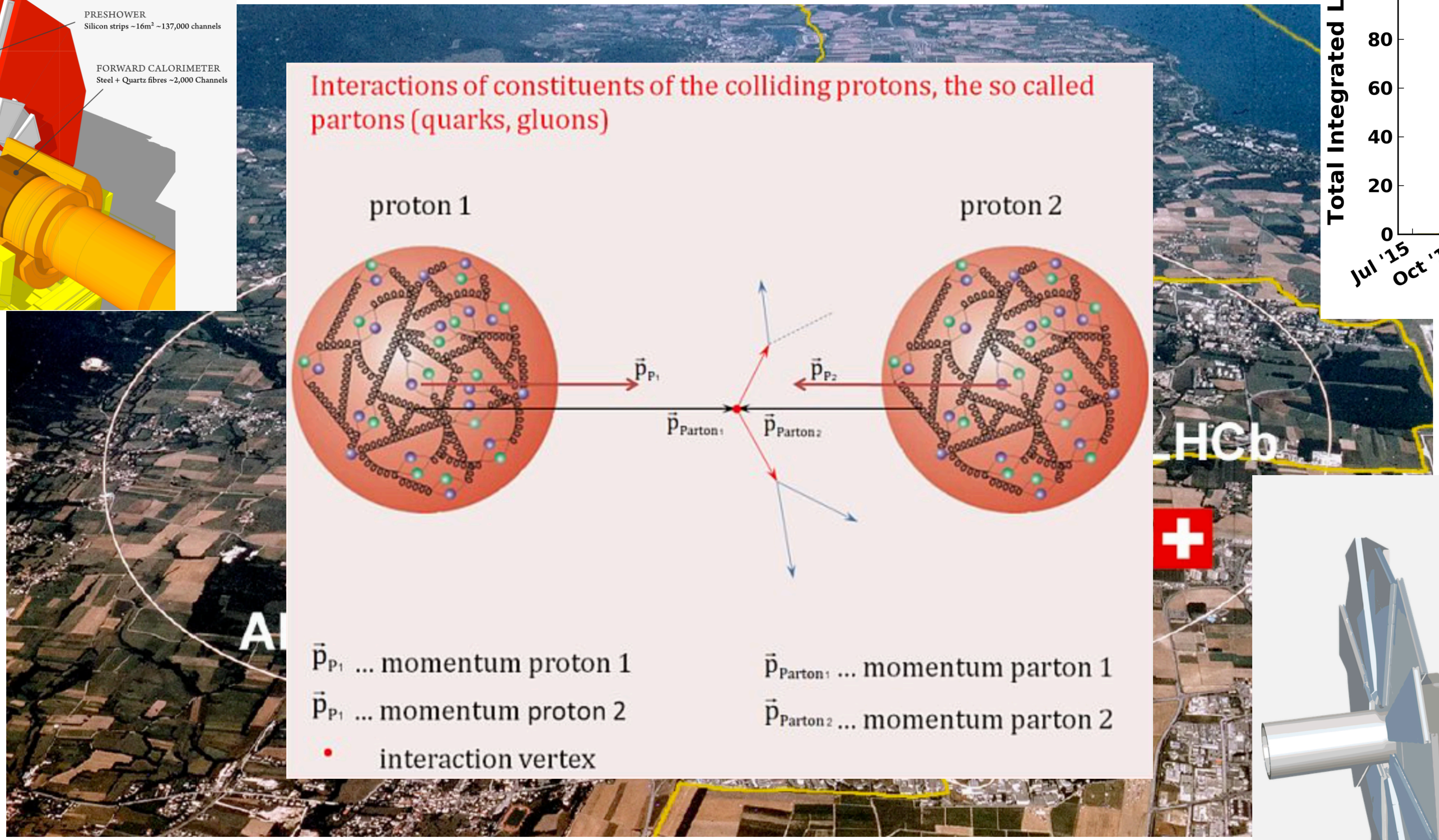


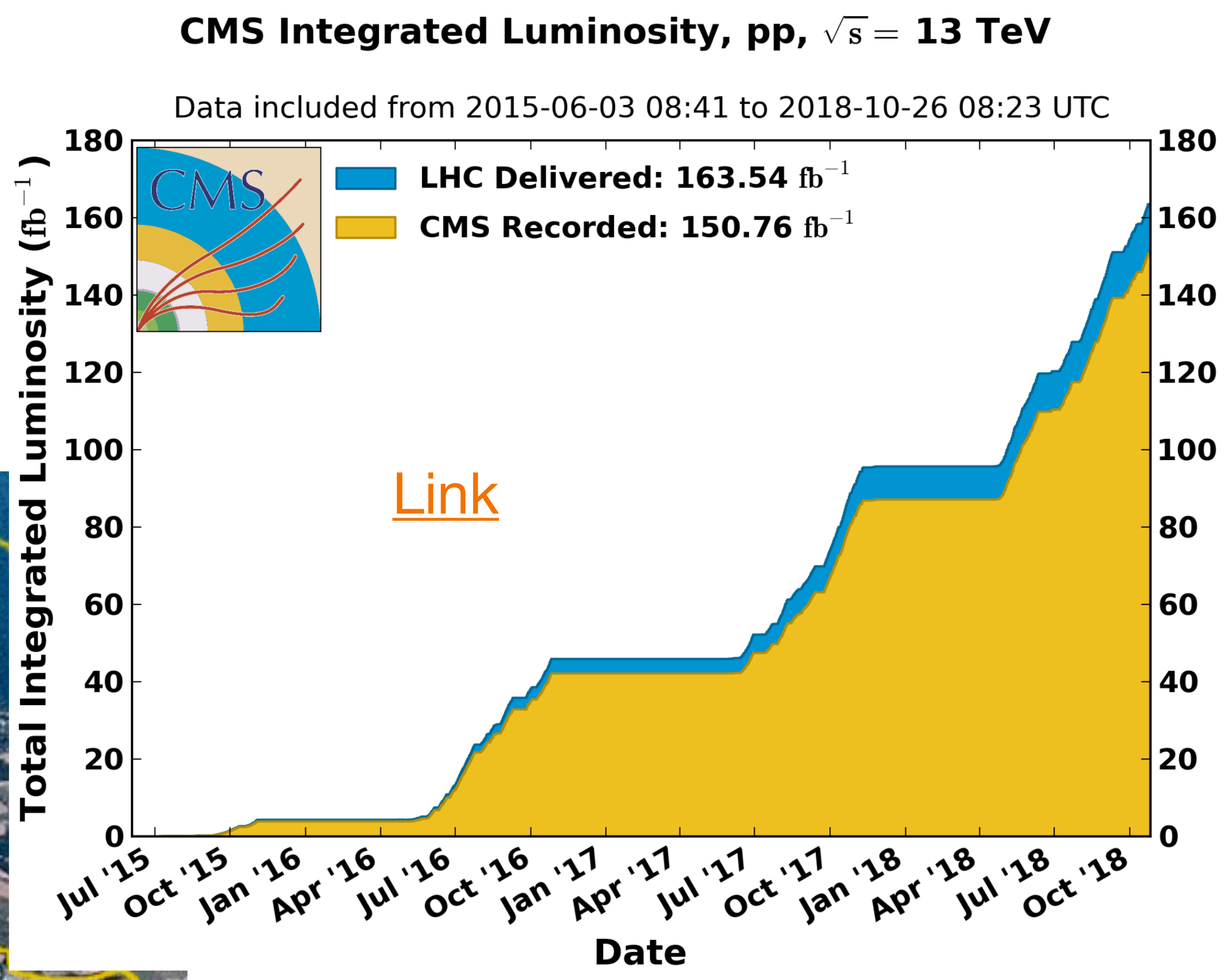


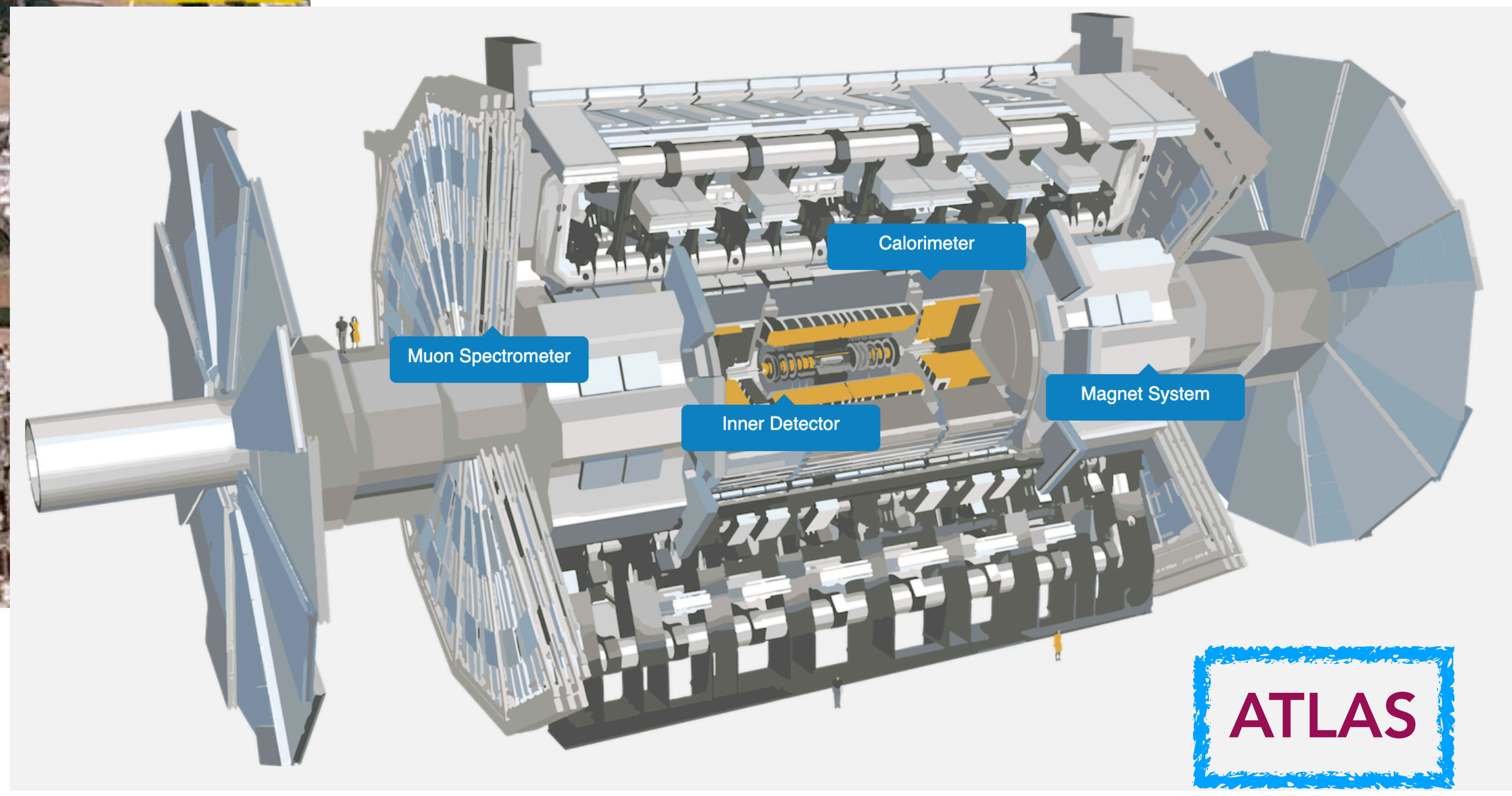
- Multi-purpose detectors at LHC: **ATLAS** & **CMS**

The Large Hadron Collider Run-2







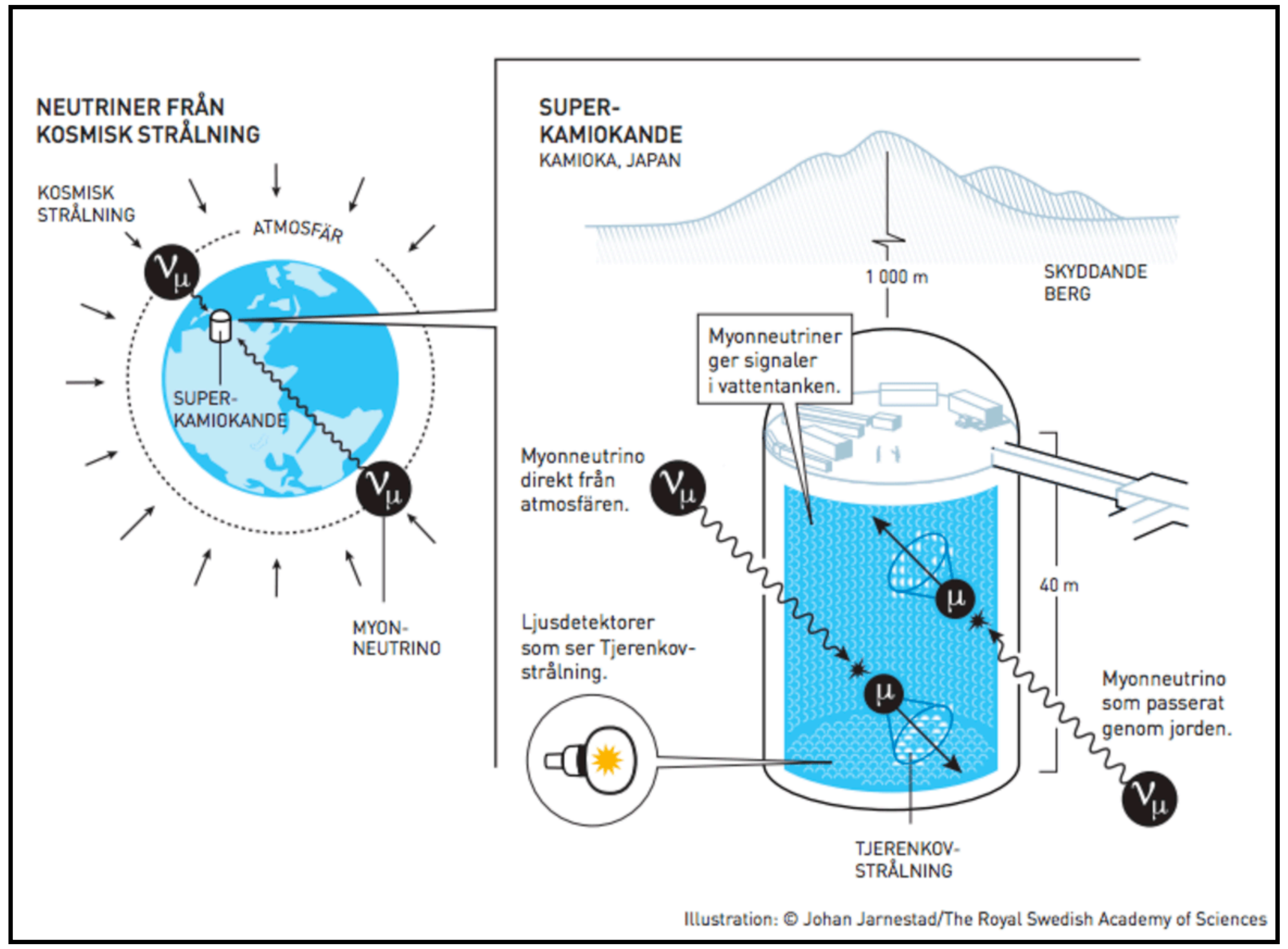


- Multi-purpose detectors at LHC: **ATLAS** & **CMS**
- Run-2 collected proton-proton collisions data at $\sqrt{s} = 13$ TeV: ~140/fb

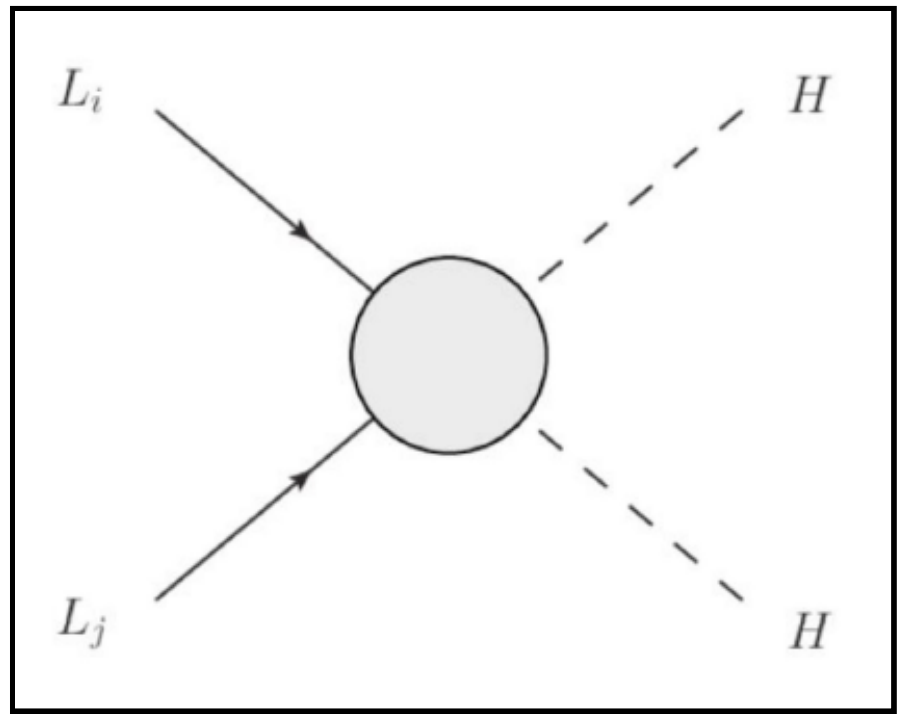
Recent heavy neutrino analyses at the LHC

- Probing heavy Majorana neutrinos & Weinberg operator via pp→$\mu^{\pm}\mu^{\pm}$jj
  - EXO-21-003
- Search for type-III seesaw heavy leptons
  - **arXiv:**2202.02039, **arXiv:**2202.08676
- Heavy Composite Majorana Neutrino
  - EXO-20-011
- Left-Right Symmetry model
  - JHEP 04 (2022) 047, EXO-20-006
- Long-lived heavy neutral leptons with displaced vertices
  - **arXiv:**2204.11988, **arXiv:**2201.05578

The dim-5 Weinberg operator



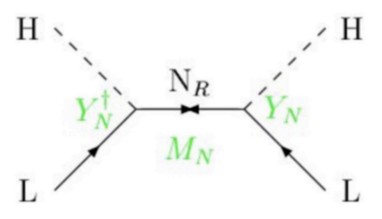
- The Standard Model neutrino masses are non-zero
- Why are neutrinos massless in the SM?
  - Renormalizability requires all SM operators with dimension = 4
  - $SU(2)_L \times U(1)_Y$ ElectroWeak symmetry
    - Only left-handed neutrino → No Dirac mass term
    - Only one neutral Higgs doublet → No Majorana mass term
    - Masses of SM neutrinos call for an extension to the SM lagrangian
- What if we give up renormalizabilty and introduce a higher dimension operator?
  - An **Effective Field Theory (EFT)** solution: the dimension-5 Weinberg Operator Weinberg ('79)
    - Adding this operator will give SM neutrinos Majorana masses
    - EFT doesn't describe the new physics in detail. Need to open the black box and check new physics wherein



Seesaw Model

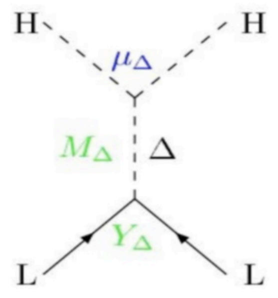
- Opening the black box of Weinberg Operator requires a "**seesaw**"
  - Only three different kinds of realization at Born-level are allowed

Right-handed singlet:
(type-I seesaw)

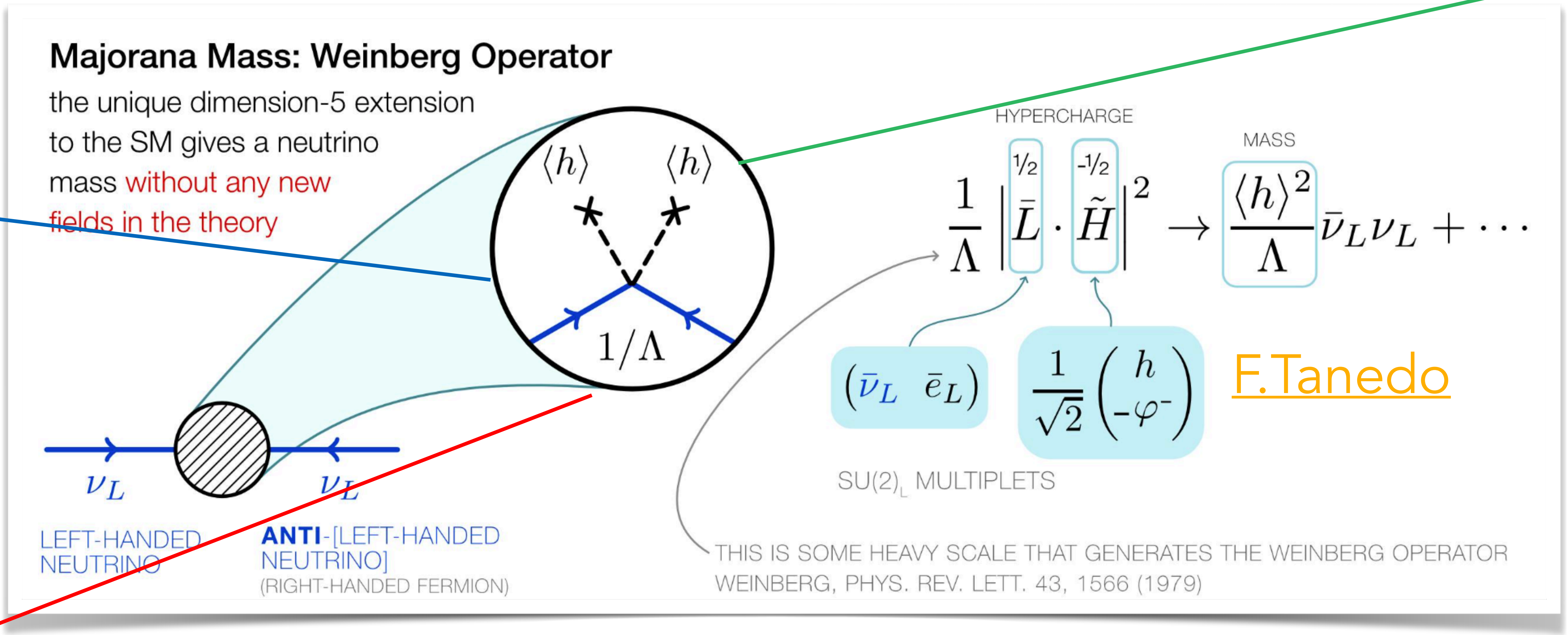


$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$

Scalar triplet:
(type-II seesaw)



$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$



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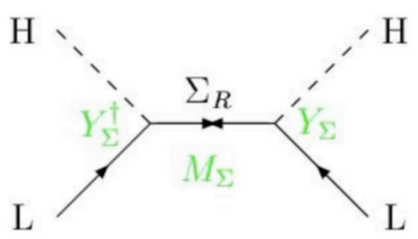
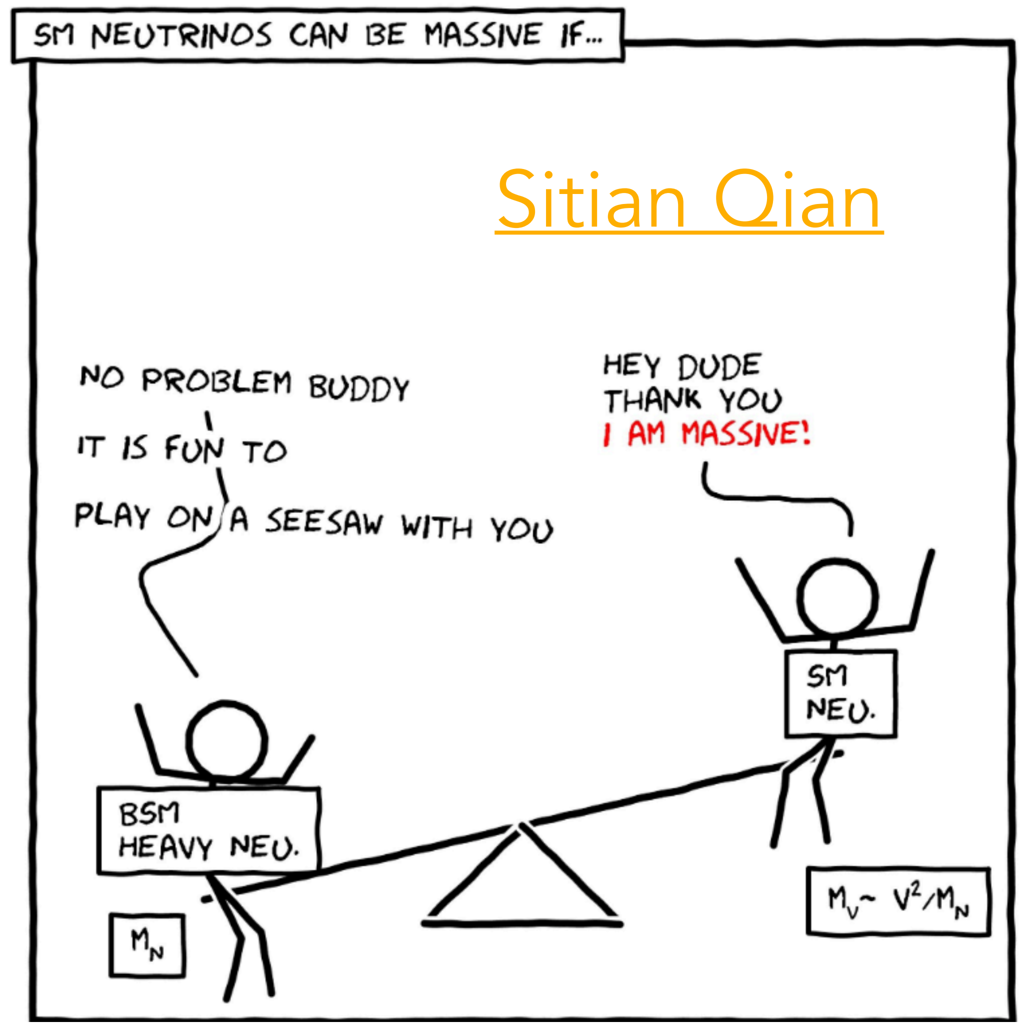
Fermion triplet:
(type-III seesaw)



$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$



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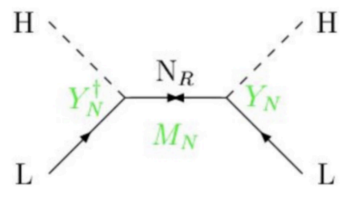
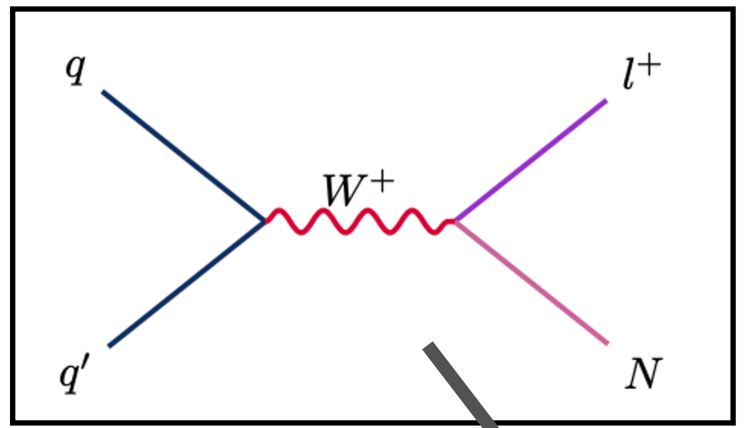
- Heavier BSM particles lead to lighter SM neutrinos

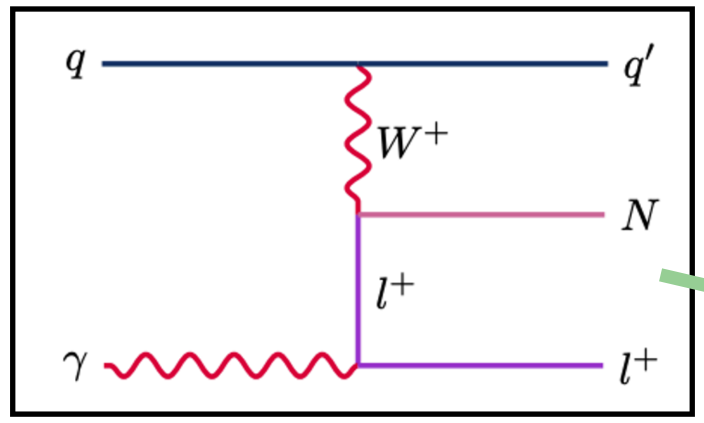
Probing heavy Majorana neutrinos & Weinberg op. via pp→μ±μ±jj

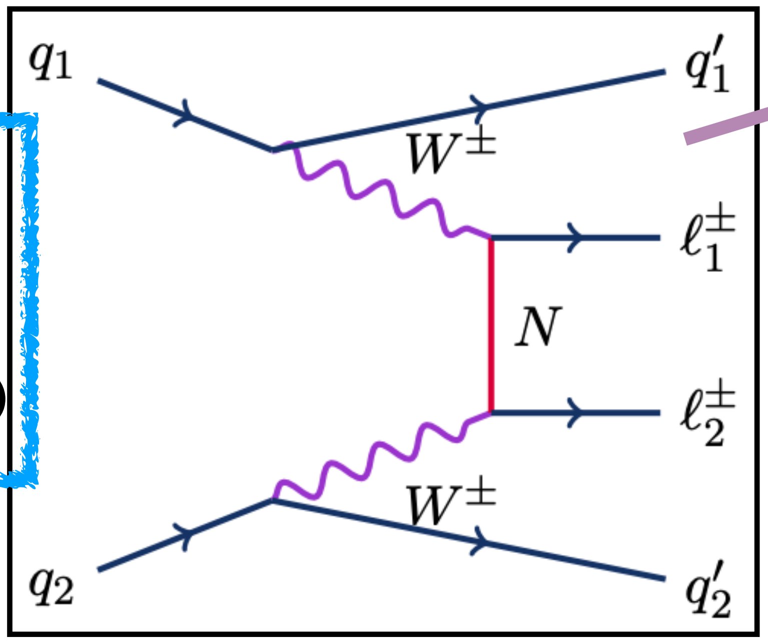
Right-handed singlet:
(type-I seesaw)

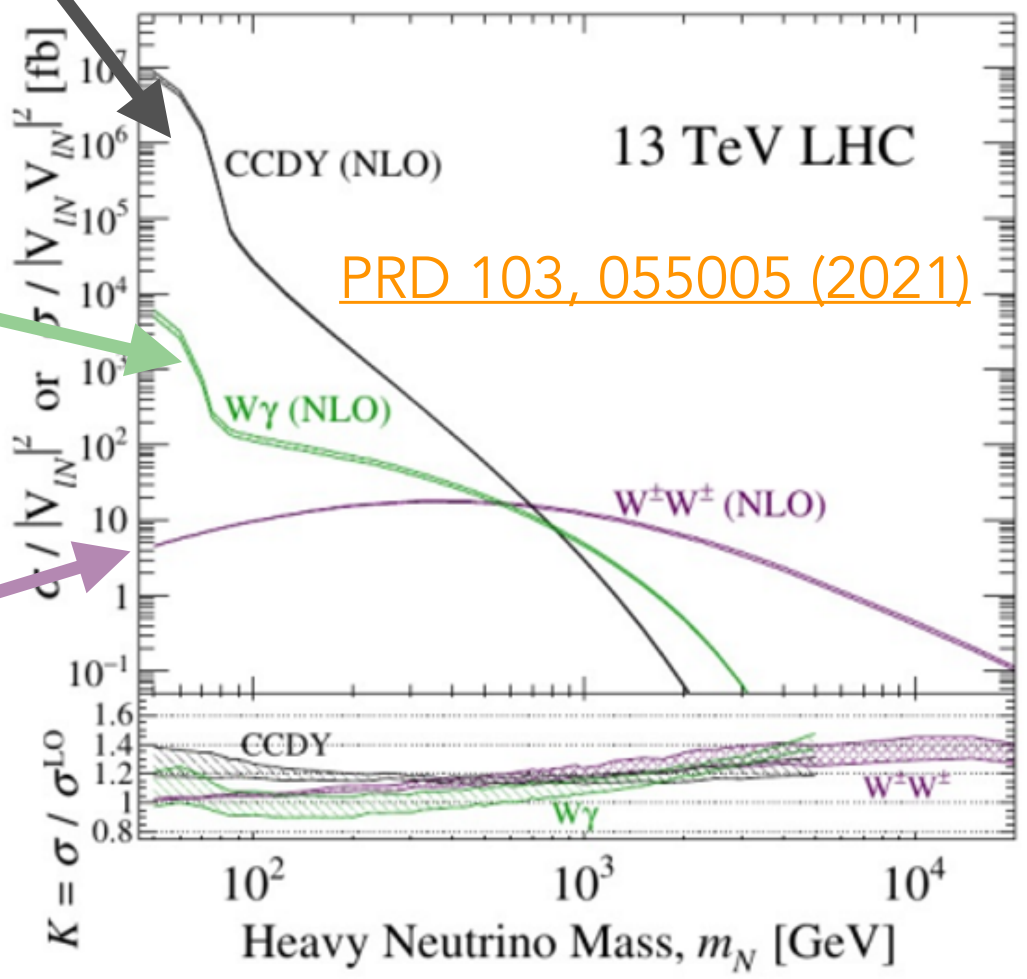


$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$







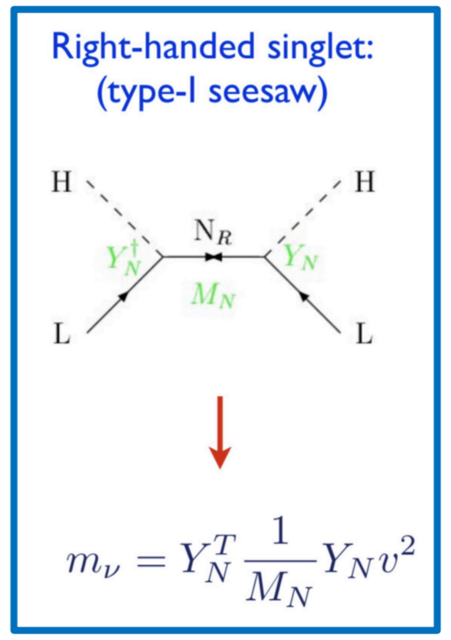


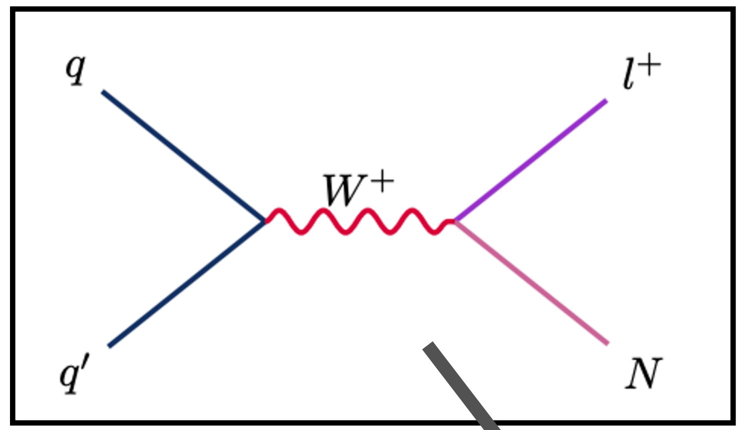
Type-I Seesaw Heavy Majorana neutrino (HMN)

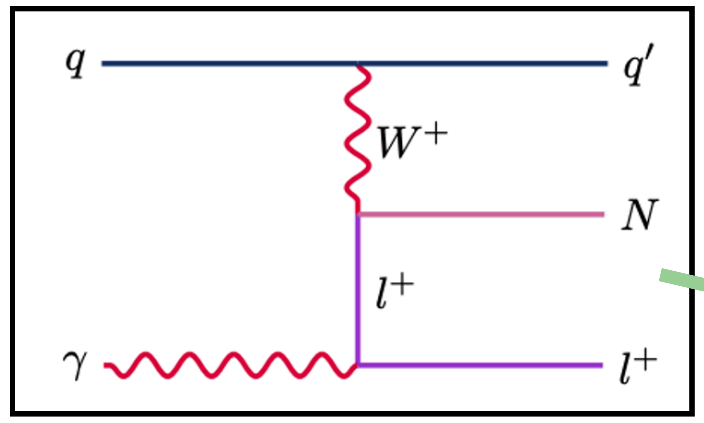
$$\sigma^{\ell\ell'}(s) \equiv \left|V_{\ell N} V^*_{\ell' N}\right|^2 \times \sigma_0^{\ell\ell'}(s)$$

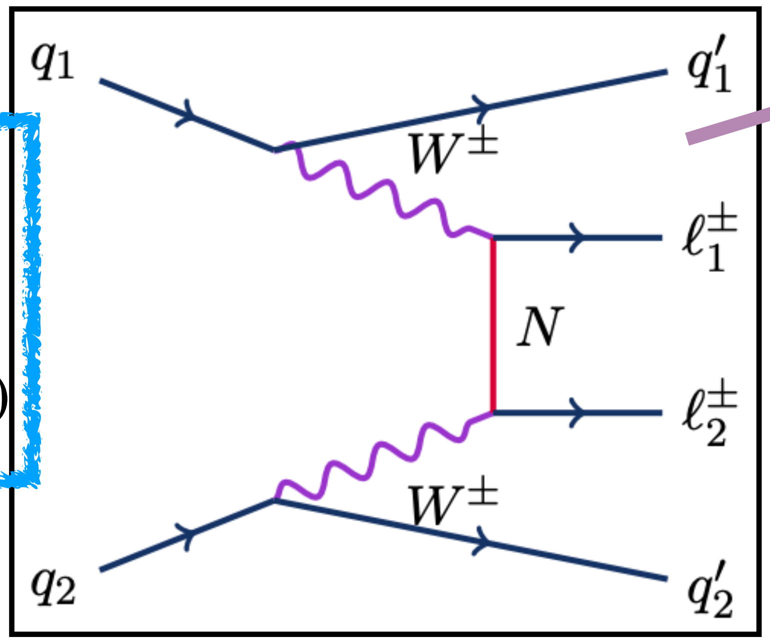
- The "neutrinoless double-β decay" version of the LHC
- Signal topology: two **same-sign muons** + **two jets**

Probing heavy Majorana neutrinos & Weinberg op. via pp→μ±μ±jj









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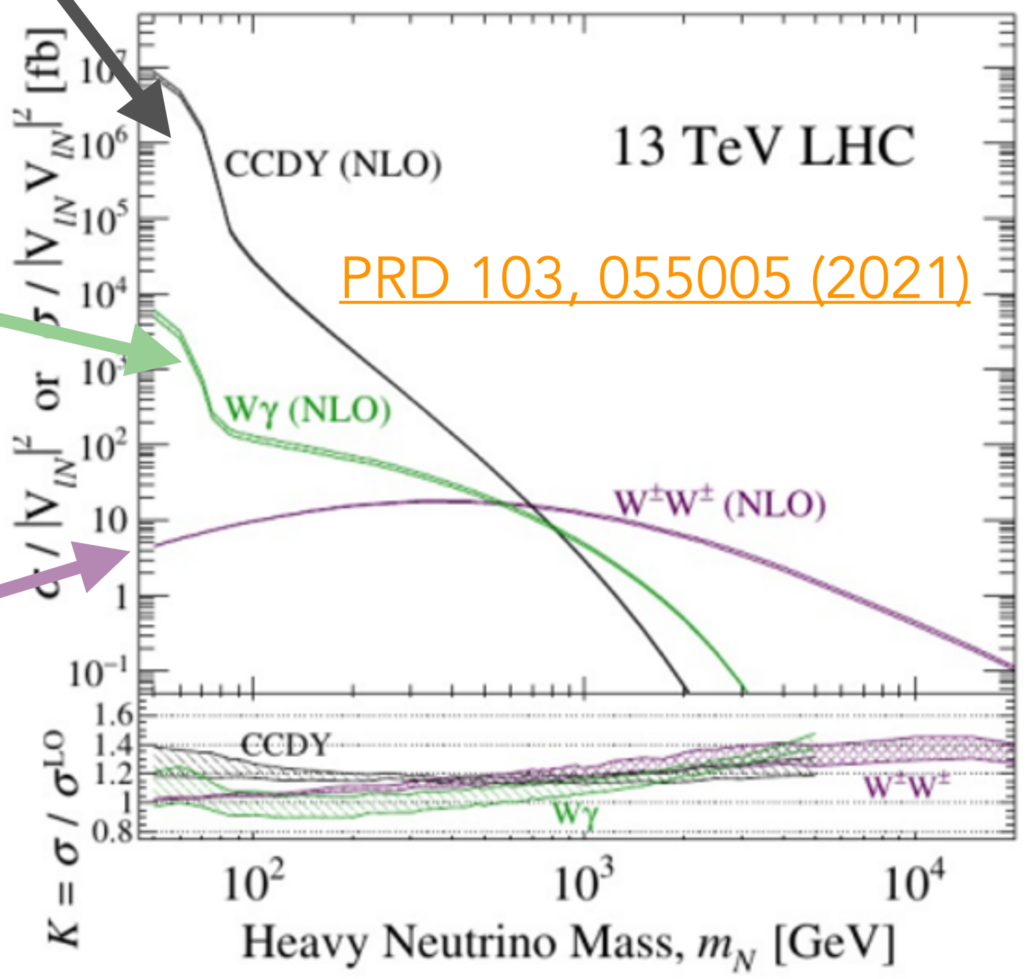
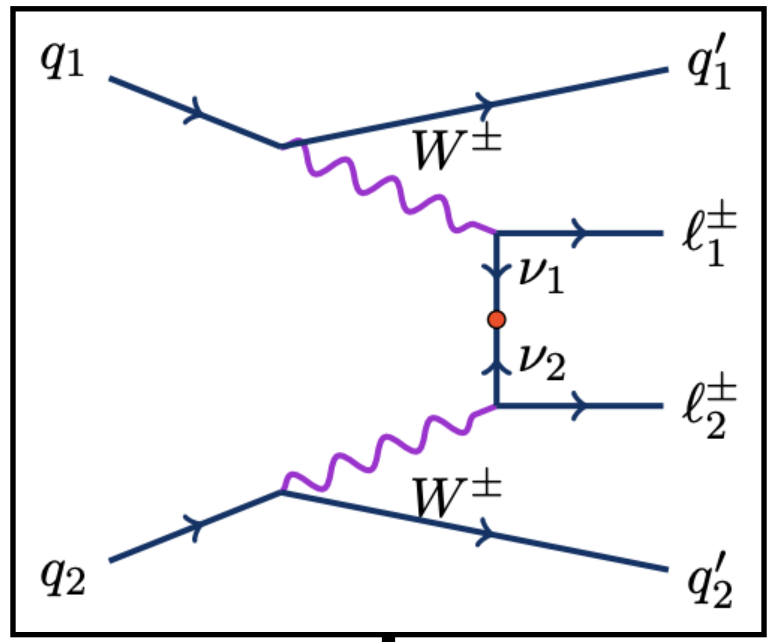


PRD 103, 055005 (2021)

Dim-5 Weinbreg Operator (WO)



Wilson Coefficients

$$\mathcal{L}_5 = \frac{C_5^{\ell\ell'}}{\Lambda}\left[\Phi\cdot \overline{L}_\ell^c\right]\left[L_{\ell'}\cdot\Phi\right] + \text{H.c.}$$

EFT Scale

$$v = \sqrt{2}\langle\Phi\rangle \approx 246\ \text{GeV}$$

$$m_{\ell\ell'} = C_5^{\ell\ell'} v^2/\Lambda$$

Effective Majorana Mass

$$\nu_\ell(p)\ \ \nu_{\ell'}^c(-p) = \frac{i\not{p}}{p^2}\frac{-iC_5^{\ell\ell'}v^2}{\Lambda}\frac{i\not{p}}{p^2} = \frac{i m_{\ell\ell'}}{p^2}$$

Phys. Rev. D 103, 115014

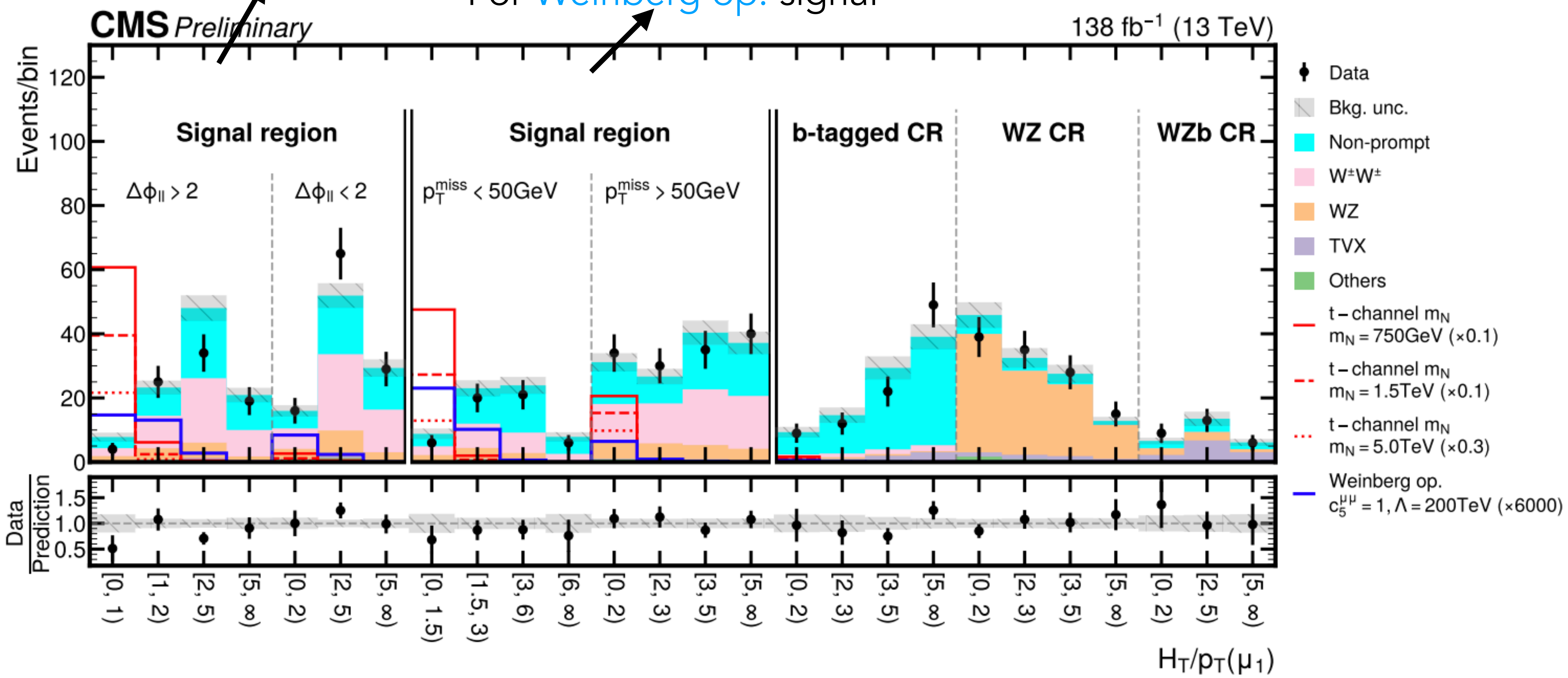
$$\sigma \sim \left|m_{\ell\ell'}\right|^2 \propto \left|C_5^{\ell\ell'}/\Lambda\right|^2$$

- The "neutrinoless double-β decay" version of the LHC
- Signal topology: two **same-sign muons** + **two jets**

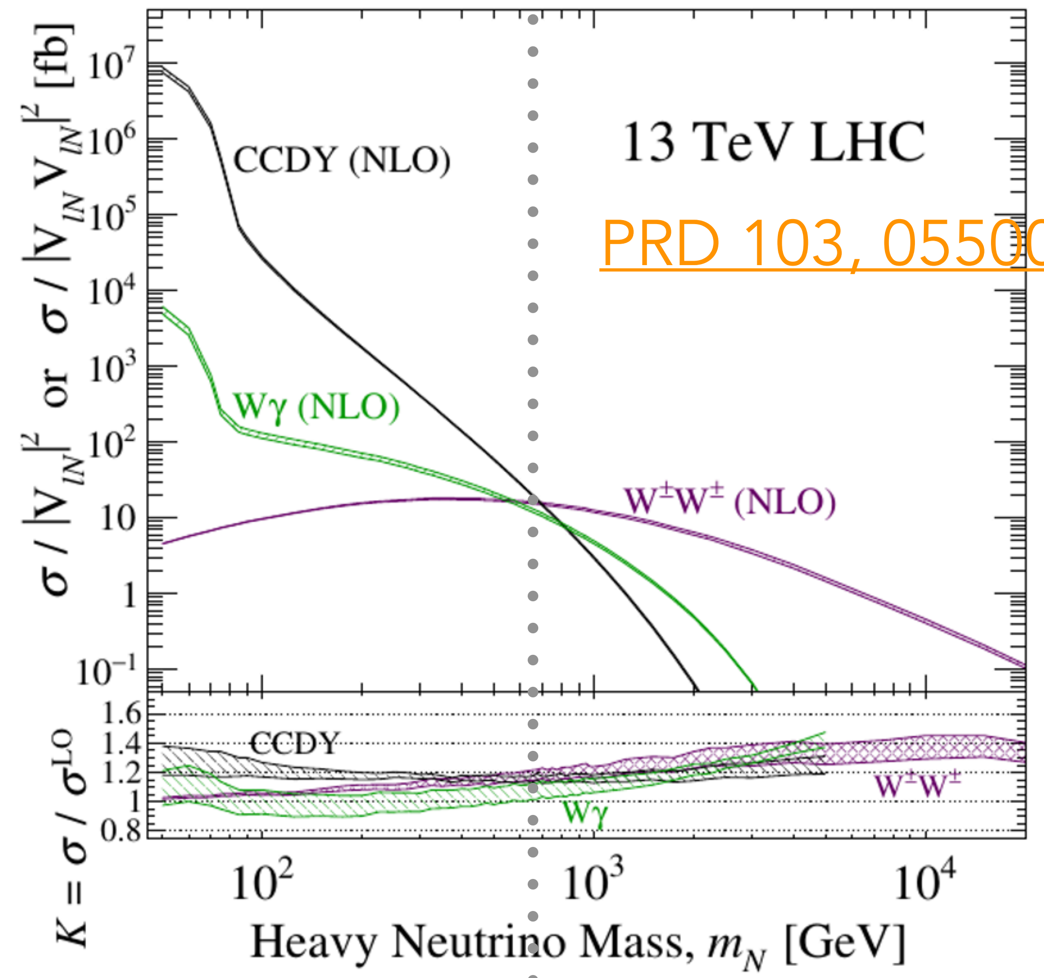
Probing heavy Majorana neutrinos & Weinberg op. via pp→μ±μ±jj

For HMN signals

For Weinberg op. signal



$qq \to W \to \ell N$ ← → VBF t-channel



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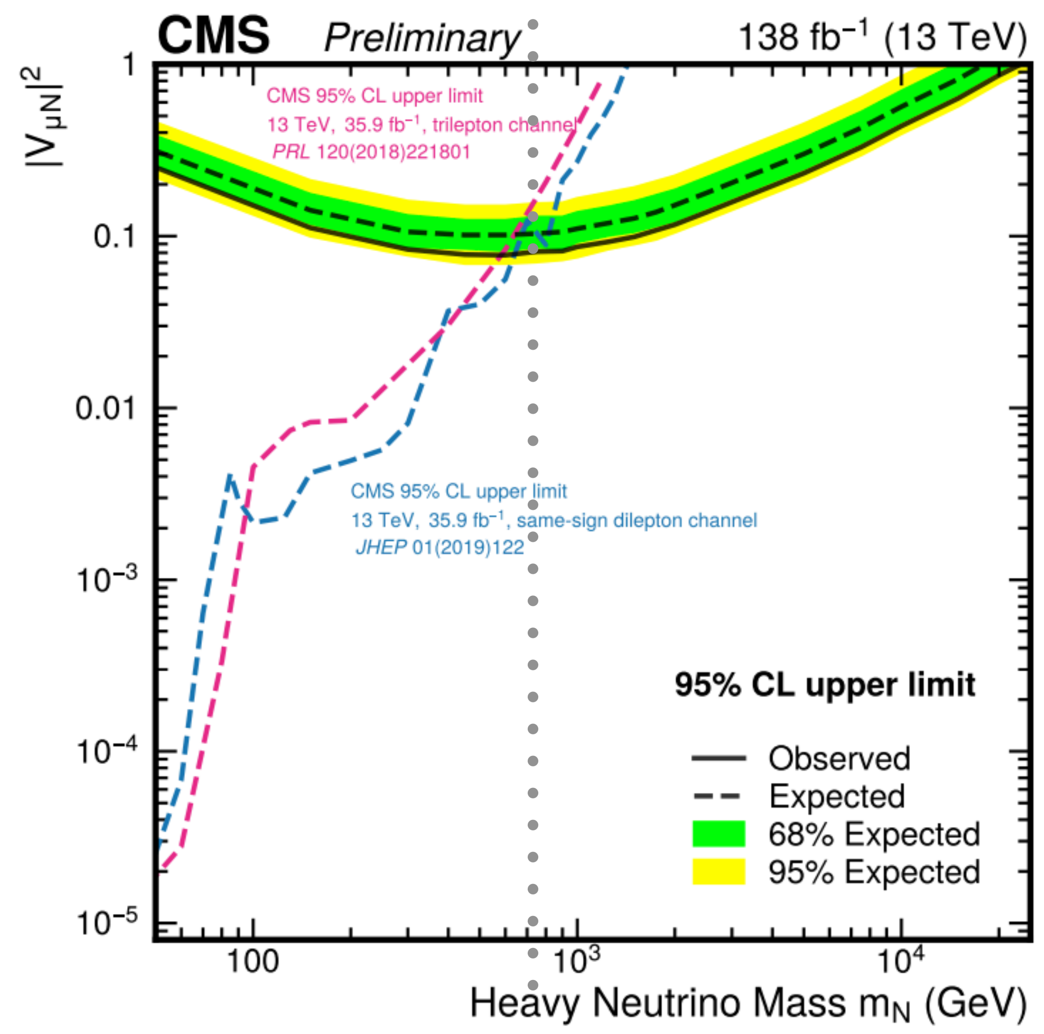
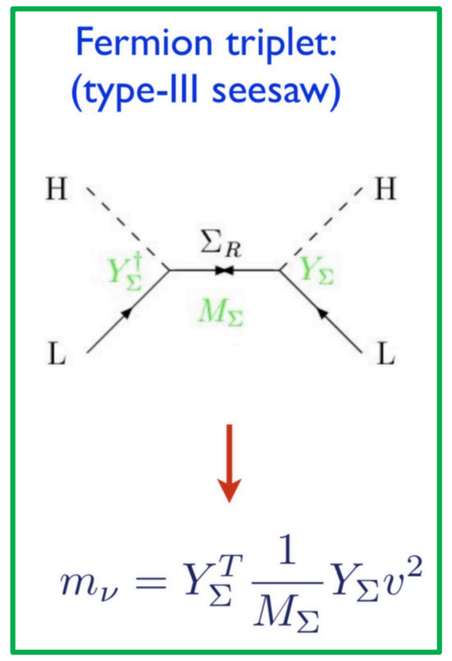


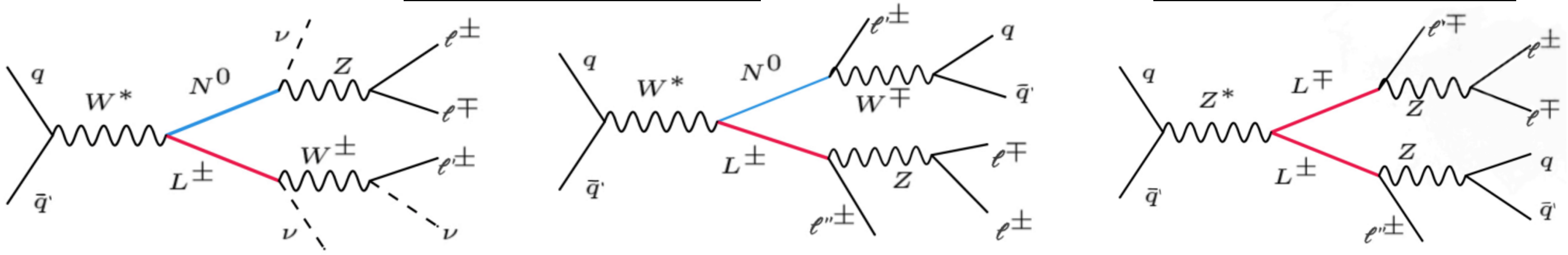
- **HMN**: m_N excluded up to ~ 23 TeV → Best limits $\gtrsim 650$ GeV
- **WO**: obs. (exp.) upper limit on effective mass $|m_{\mu\mu}|$: 10.8 (12.8) GeV

Search for type-III seesaw heavy leptons



- Introduce $SU(2)_L$ fermion triplet
  - Neutral Majorana (N^0) and charged ($L^\pm$) heavy leptons
  - Usually assuming to be degenerate in mass in analysis

$\boxed{pp \to W^* \to N^0 L^\pm}$ $\boxed{pp \to Z^* \to L^\pm L^\mp}$



$\boxed{L^\pm \to H\ell^\pm, Z\ell^\pm, W^\pm\nu}$

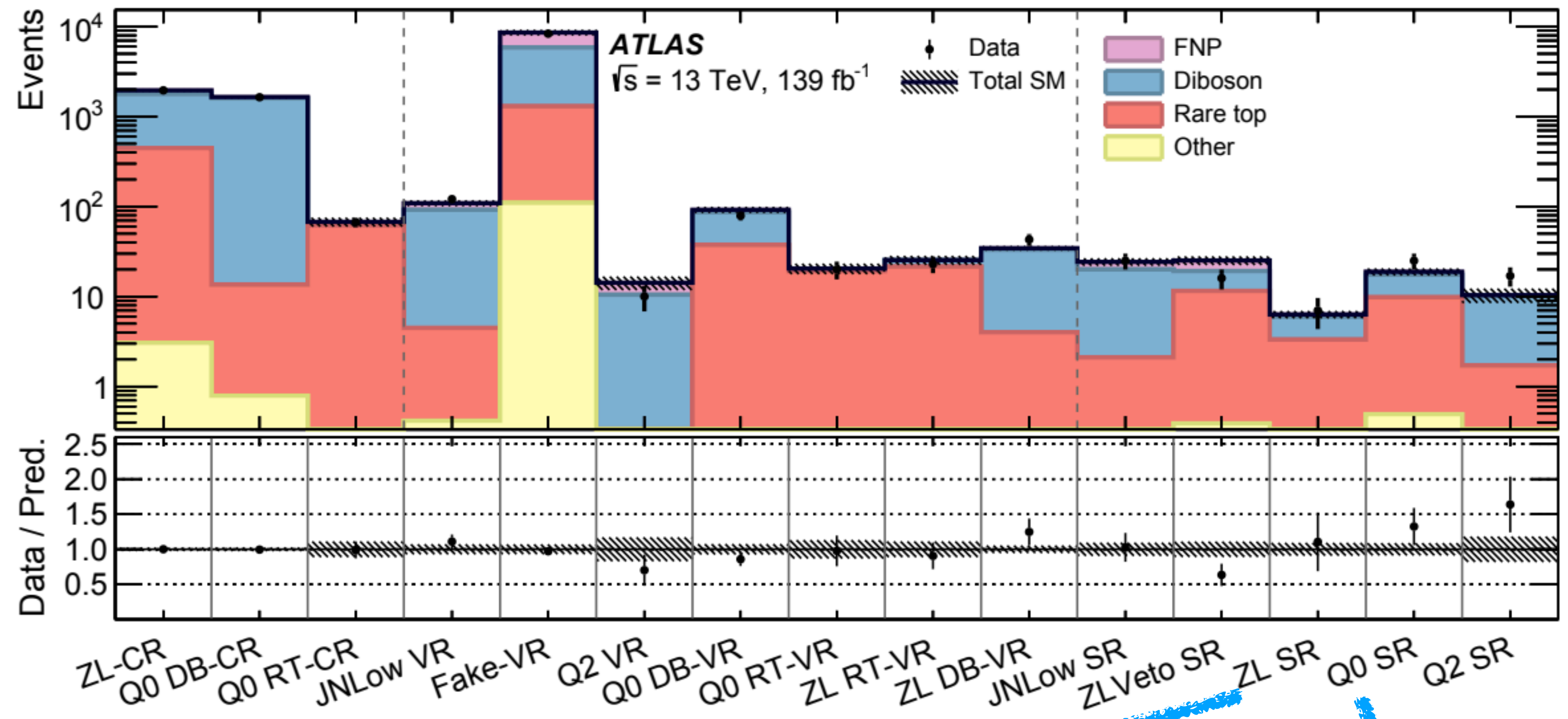
$\boxed{N^0 \to Z\nu, H\nu, W^\pm\ell^\mp}$

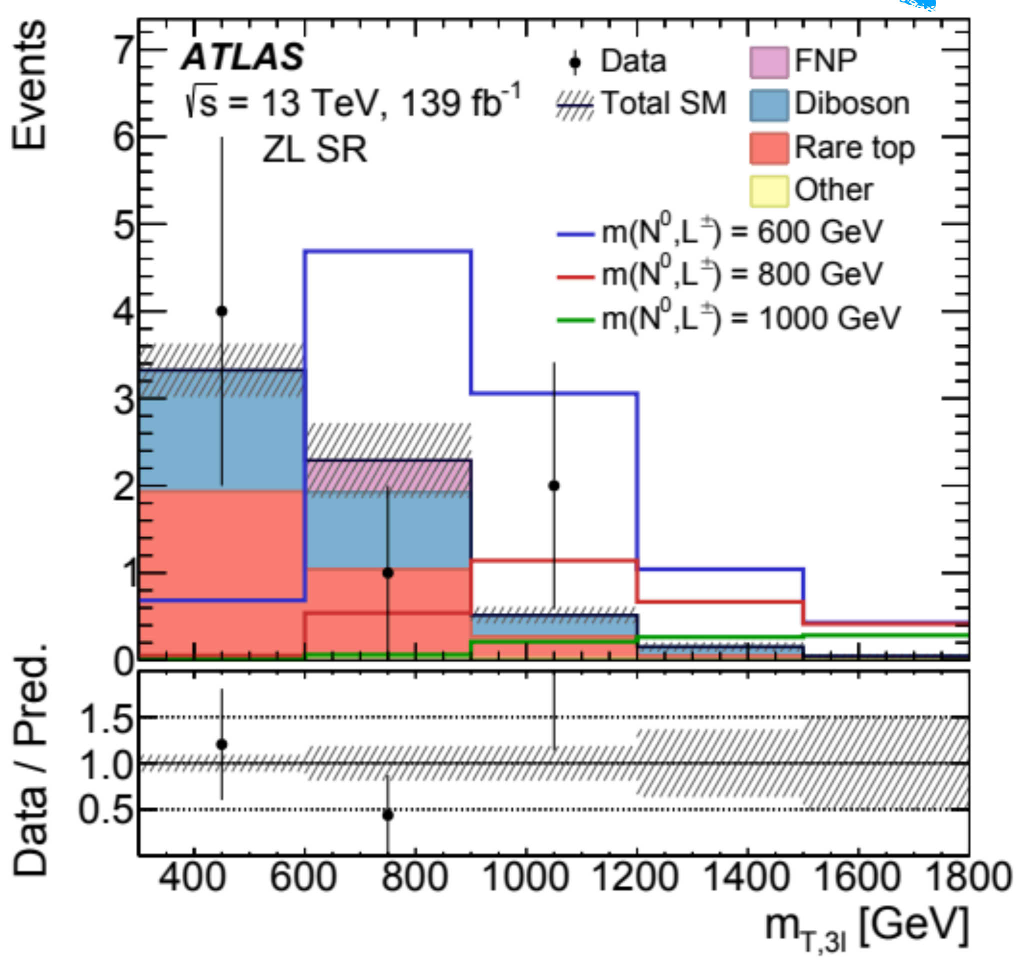
- Signal topology

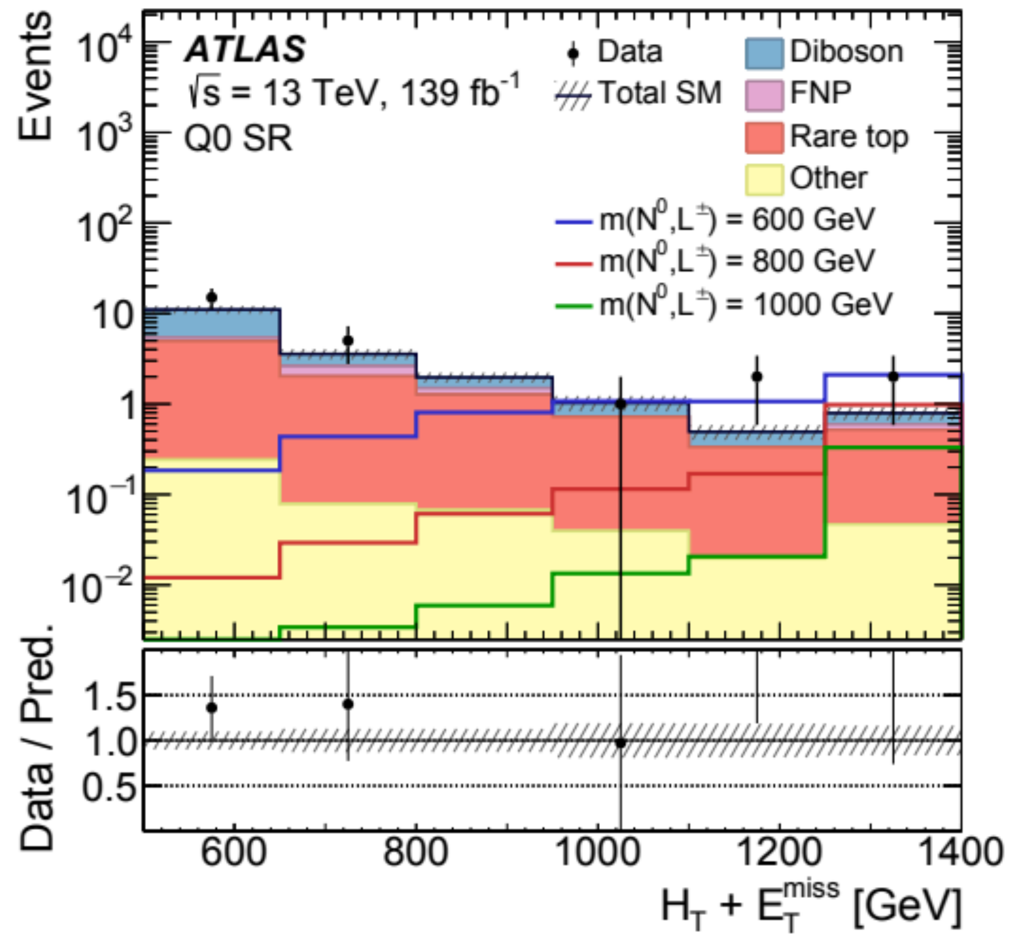
Three-lepton signal regions			Four-lepton signal regions	
ZL SR	ZLveto SR	JNLow SR	Q0 SR	Q2 SR
Z boson	Z boson veto	NJet <=1	$\sum q_\ell = 0$ and $\left|\sum q_\ell\right| = 2$ identify the zero charge (Q0) and double charge (Q2)	

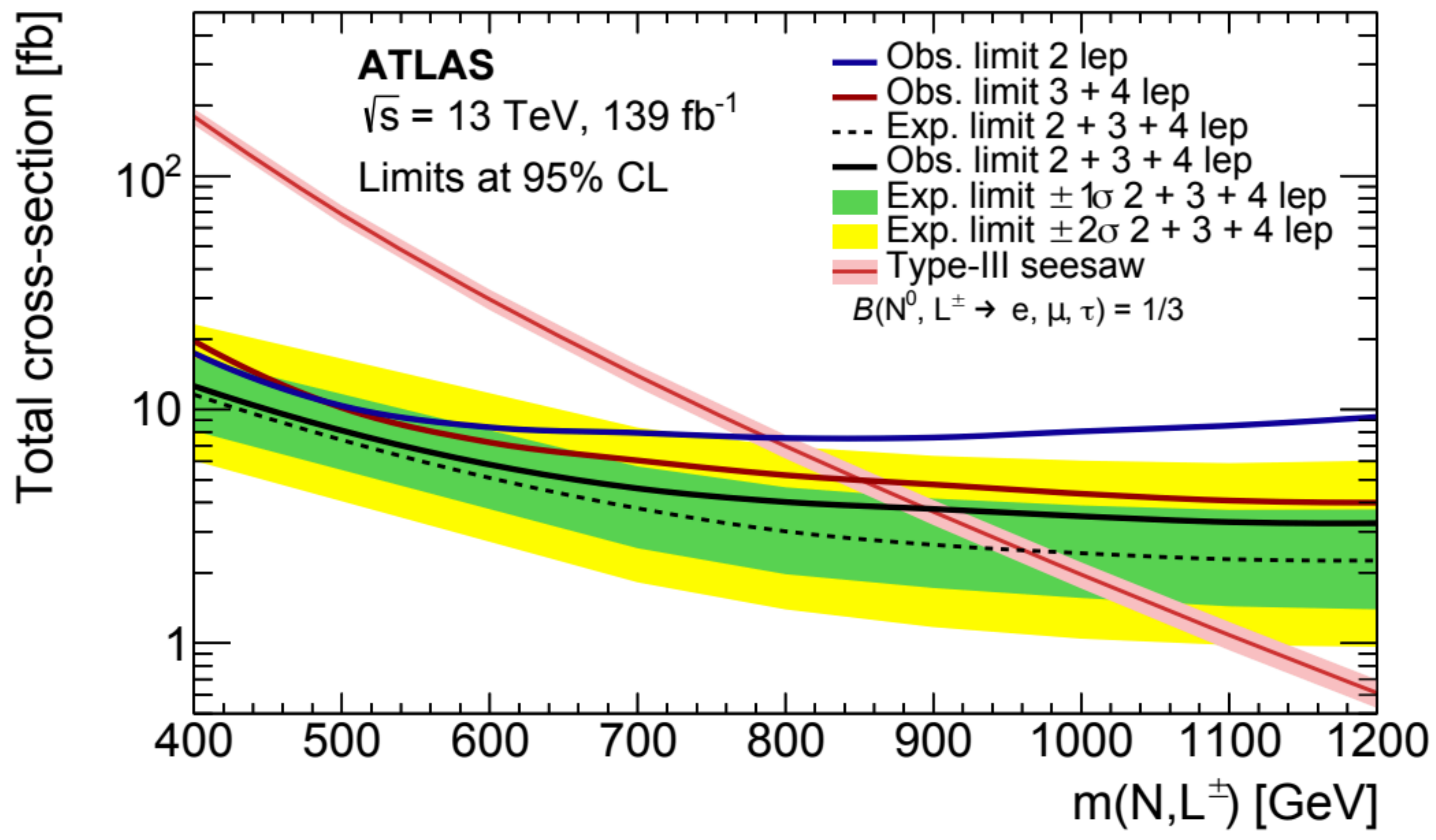
Leptons
- Electrons
- Muons

Search for type-III seesaw heavy leptons









Exclusion Limits at 95% CL

- Assuming the **flavor-democratic** scenario
- 3+4 lep: **870 GeV**
- 2+3+4 lep (combined with previous 2 lep results): **910 GeV**

Search for type-III seesaw heavy leptons

- A multi-bin, inclusive, model-independent multilepton analysis with full Run2 data
- Covering light leptons, hadronic **taus**
- Results will be interpreted in the context of three signal models:
  - **Type-III Seesaw**
  - Vector-like leptons (singlet and doublet)
  - Leptoquarks (coupling to top quark and a charged lepton)

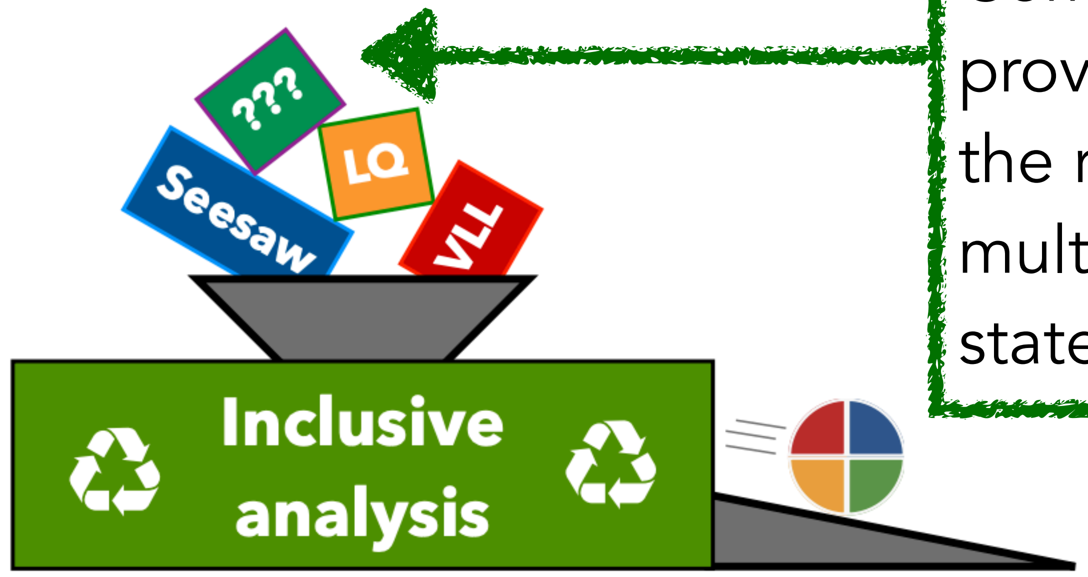
Trilepton channels

- **3L**: 3 light leptons, 0 had. taus
- **2L1T**: 2 light leptons, 1 had. tau
- **1L2T**: 1 light lepton, 2 had. taus

Quadlepton channels*

- **4L**: 4 light leptons, 0 had. tau
- **3L1T**: 3 light leptons, 1 had. tau
- **2L2T**: 2 light lepton, 2 had. taus
- **1L3T**: 2 light lepton, 2 had. taus

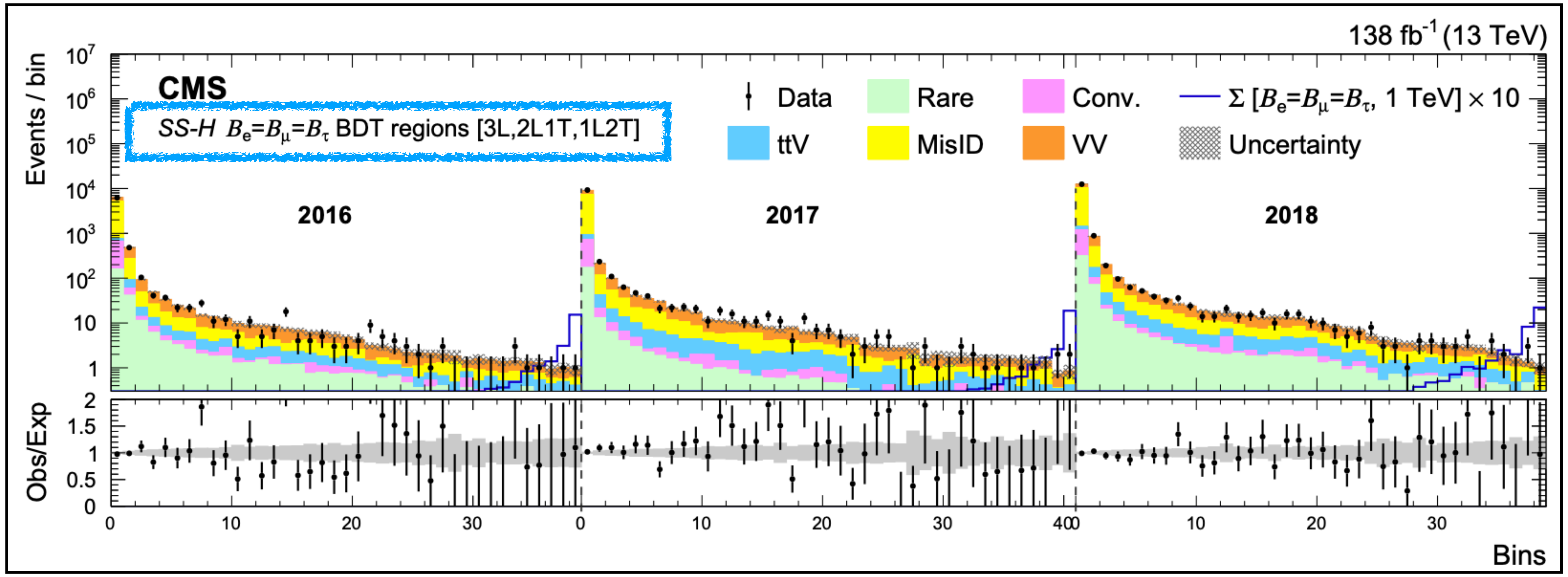
** No veto on additional leptons → only lead. four objects are considered*

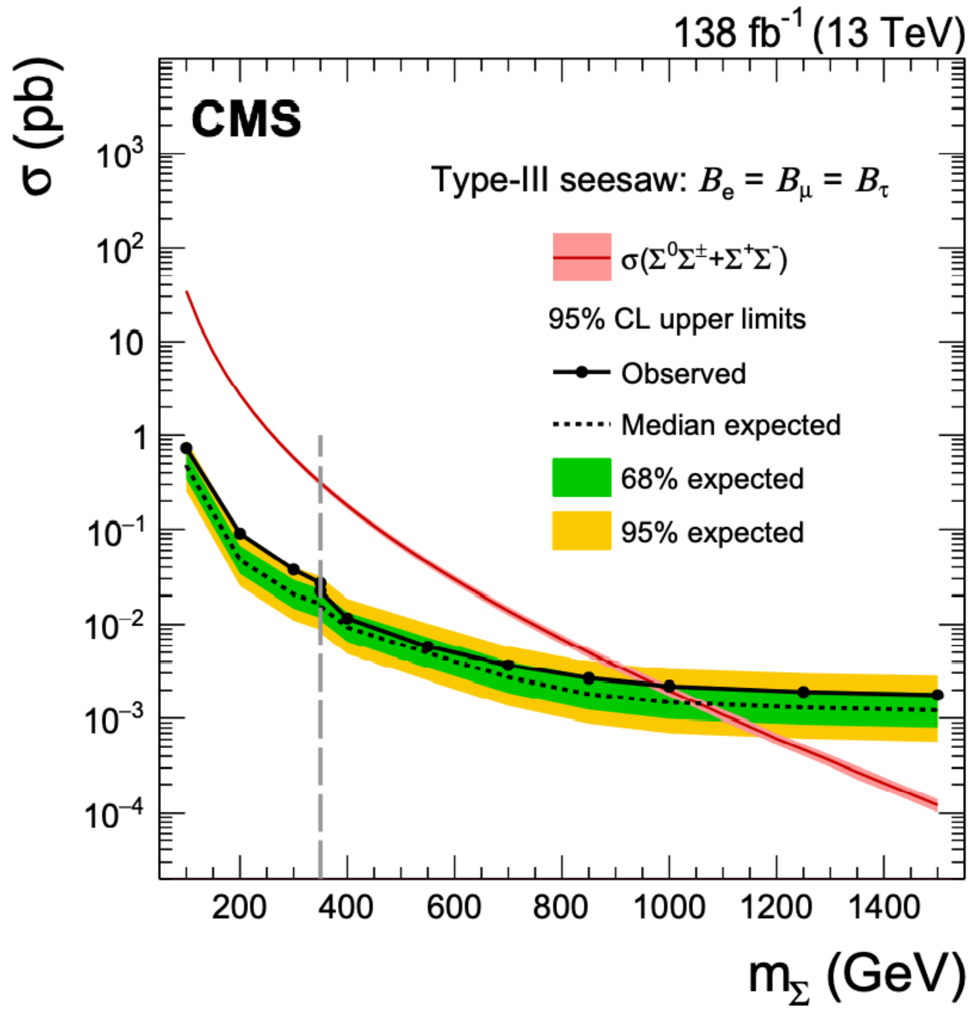


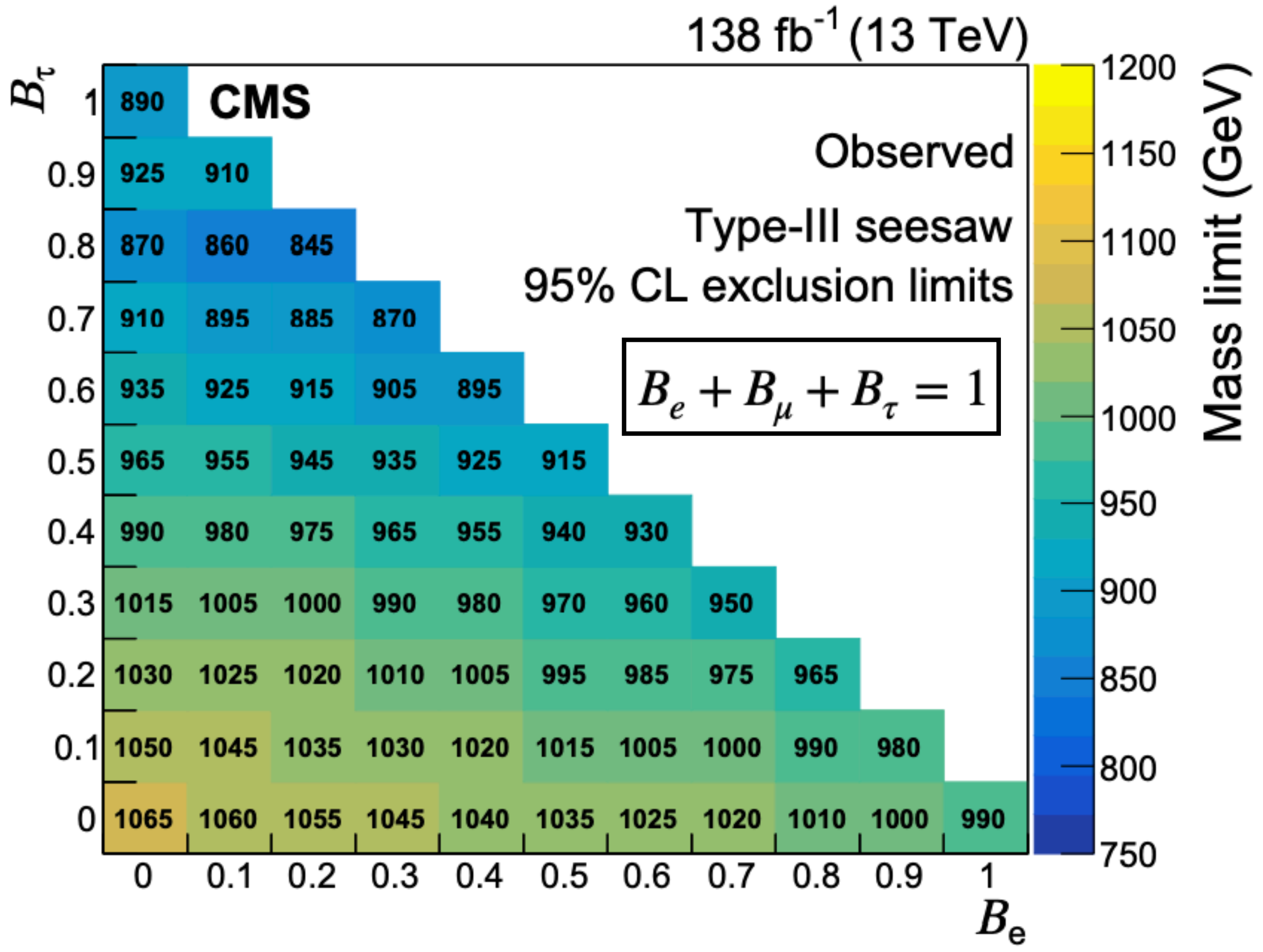
Complete set of HEPData will be provided to allow reinterpretation of the results for many other models with multilepton signatures in the final state.

Search for type-III seesaw heavy leptons

- Boosted Decision Tree (**BDT**) is used for **specific signal**



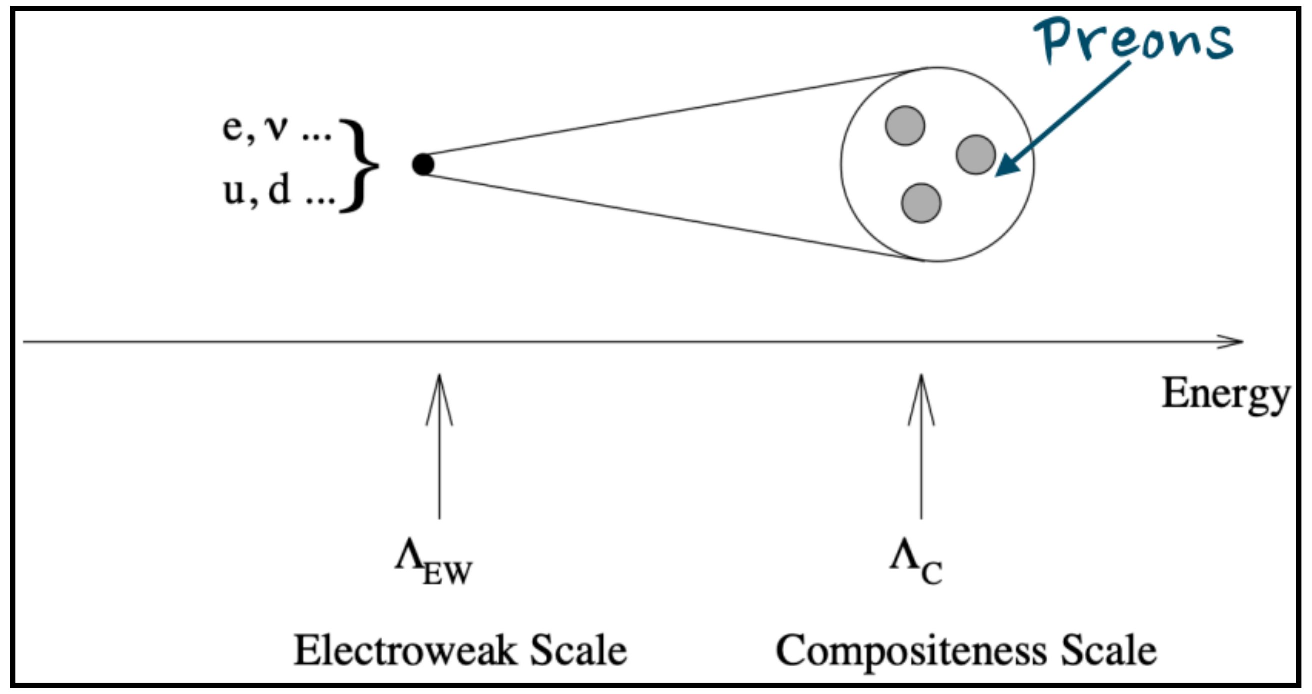




Upper observed mass limits

- **980** GeV assuming the flavor-democratic scenario
- **990** GeV assuming the $B_e = 1$ scenario
- **1065** GeV assuming the $B_\mu = 1$ scenario
- **890** GeV assuming the $B_\tau = 1$ scenario

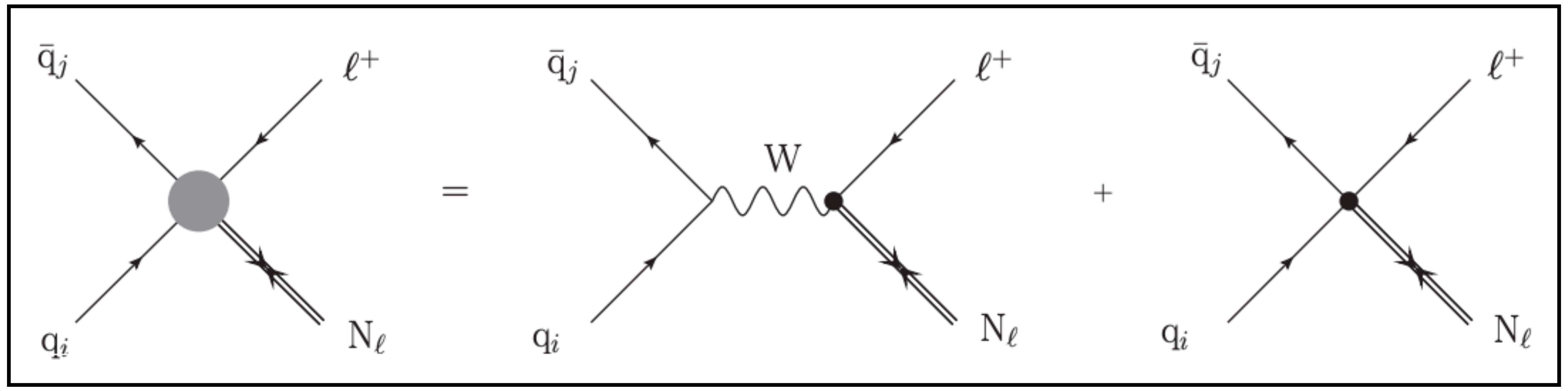
Heavy Composite Majorana Neutrino (HCMN)

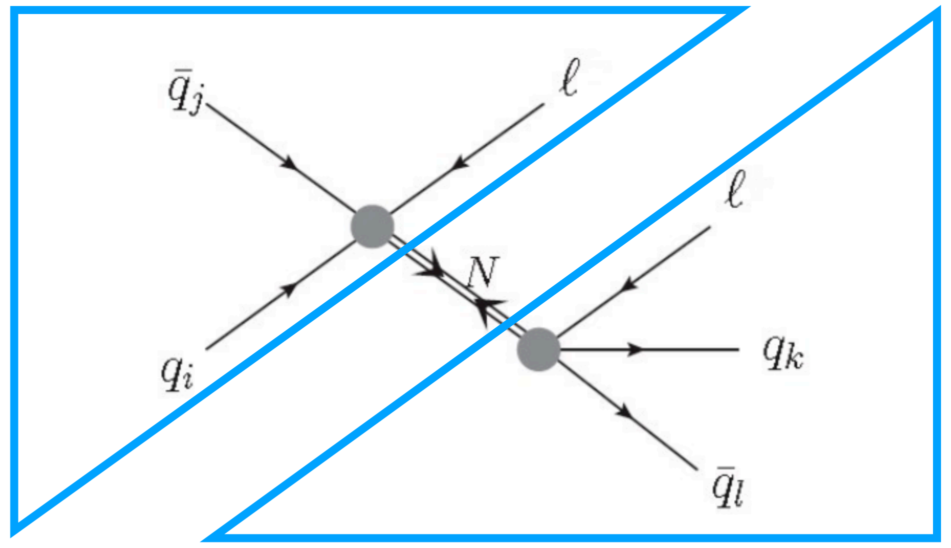


Excited states is a heavy composite Majorana neutrino (**HCMN**, $N_\ell, \ell = e, \mu, \tau$)

Gauge interaction

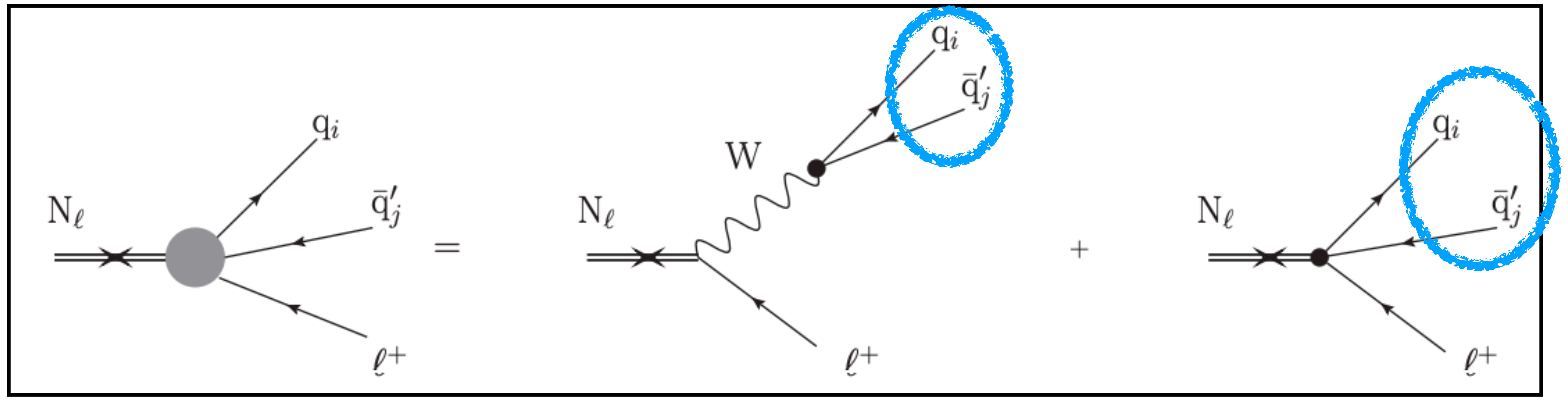
Contact interaction





Signal topology

- Di-electron or di-muon
- One **Fatjet**



Gauge interaction

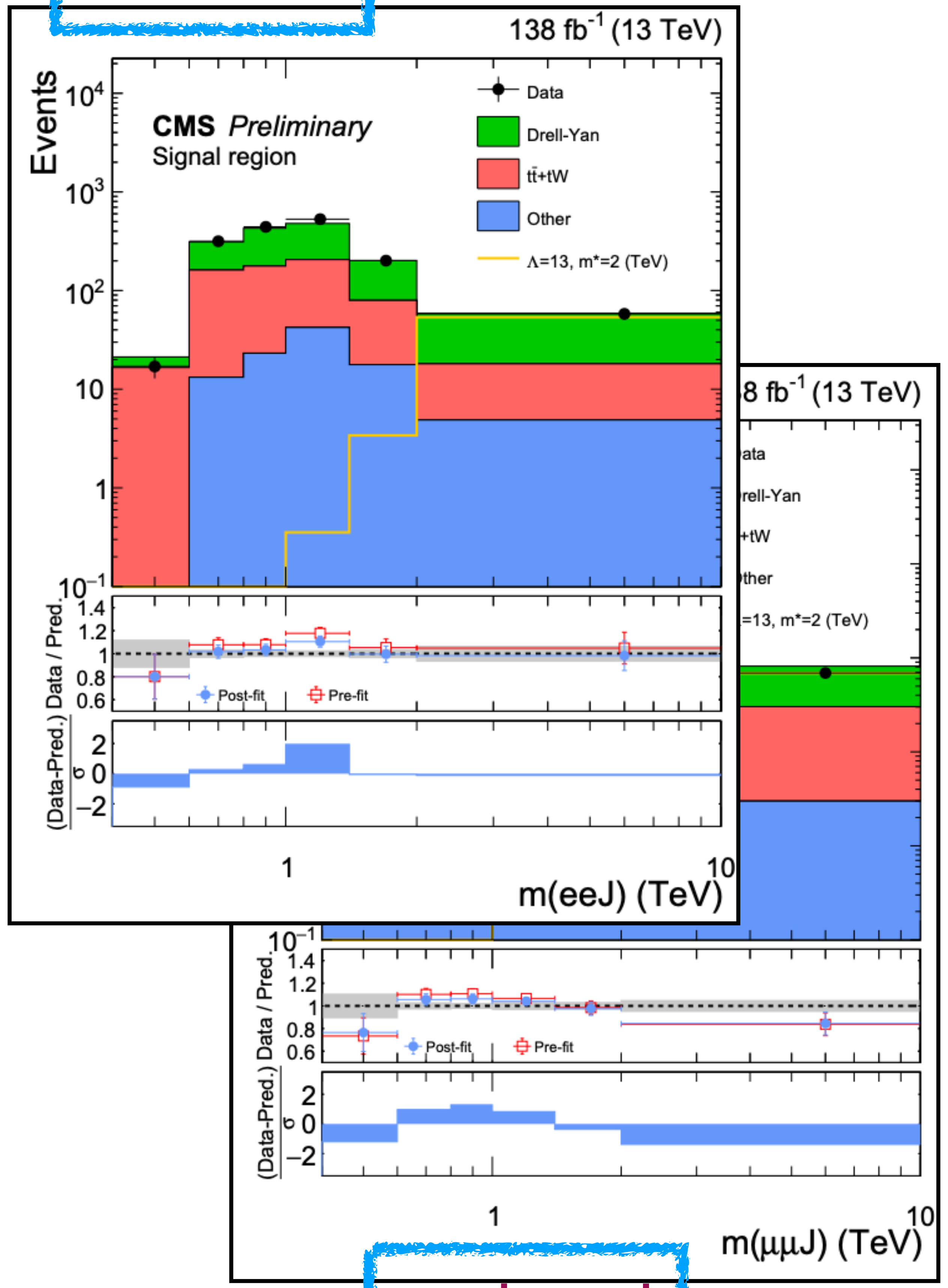
Contact interaction

Heavy Composite Majorana Neutrino (HCMN)

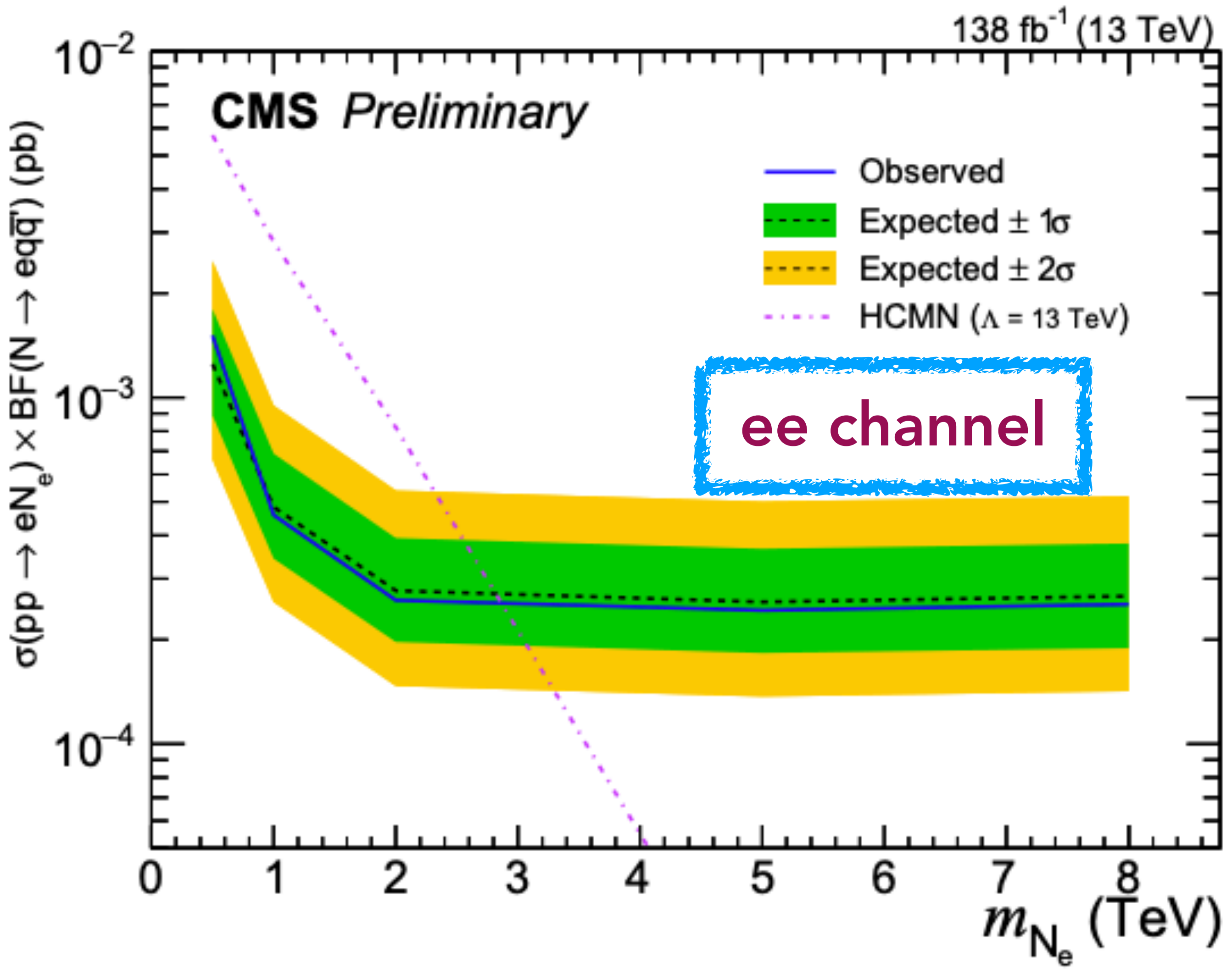
Unitarity constraints (link): Focus on a valid EFT expansion region

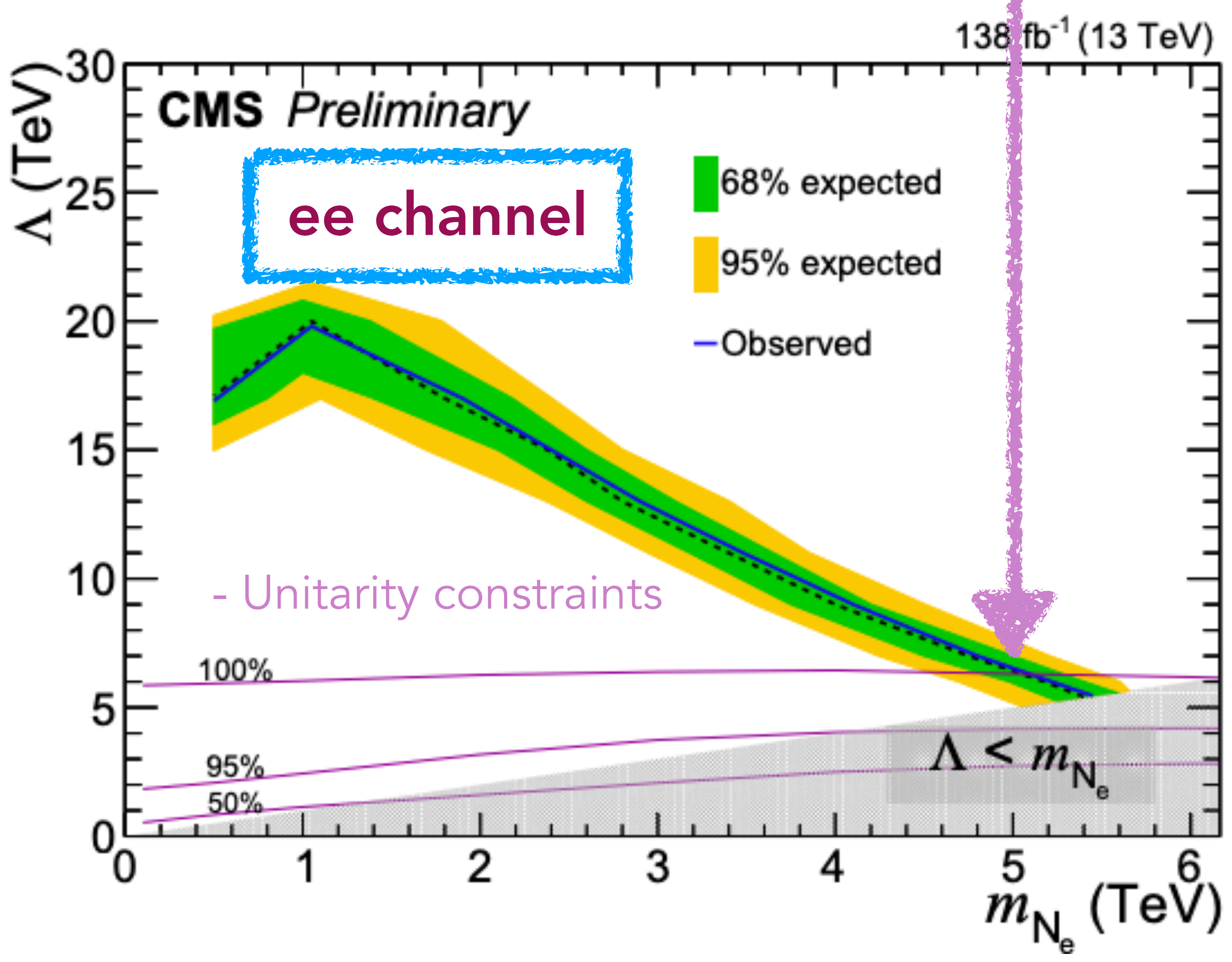
- For $\Lambda = 6$ TeV, N_e (N_μ) is excluded for masses up to 5.2 (5.4) TeV

ee channel



$\mu\mu$ channel





1D limits:

For $\Lambda = 13$ TeV

- N_e (N_μ) is excluded for masses up to ~3.0 (3.4) TeV

$\Lambda - m_{N_\ell}$ 2D plane:

For $\Lambda = m_{N_\ell}$

- N_e (N_μ) is excluded for masses up to 5.5 (5.7) TeV

Left-Right Symmetry model (LRSM)

- Left-Right Symmetry model (LRSM)

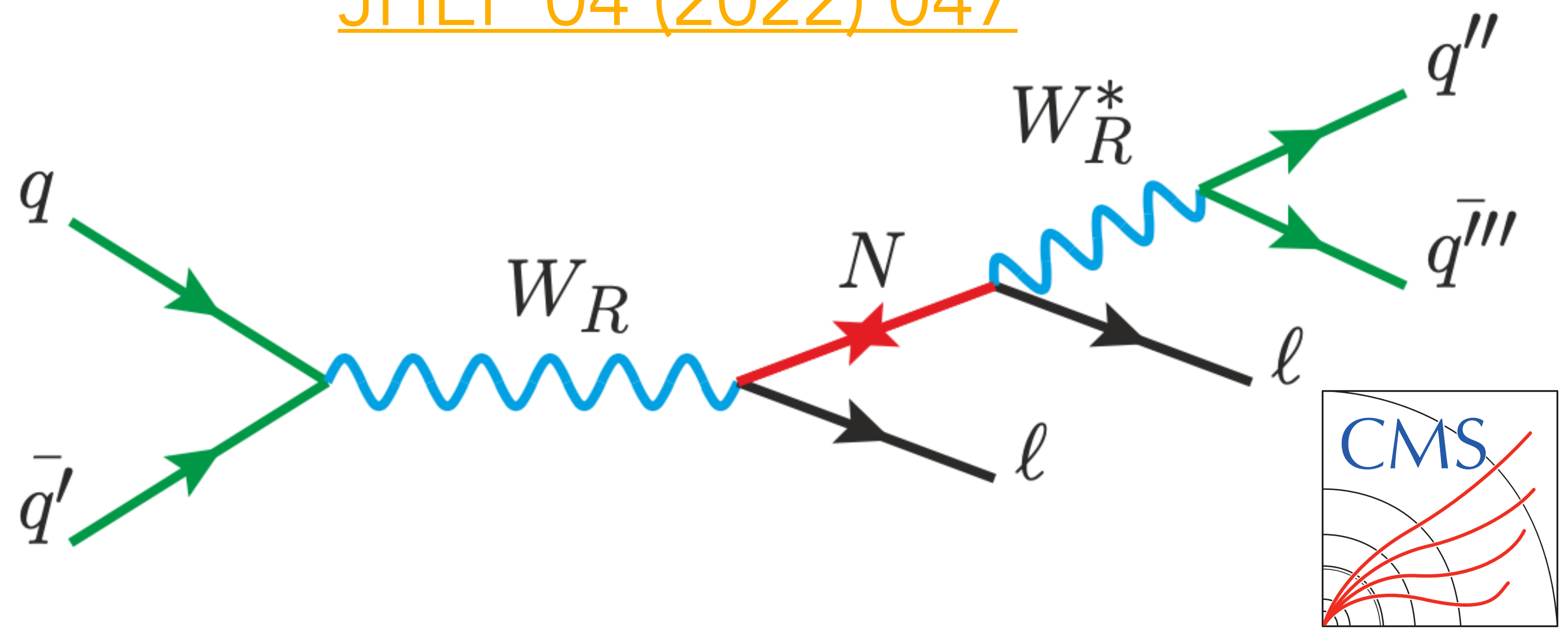
$$\mathrm{SU}(3)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes \mathrm{U}(1)_{B-L}$$

The symmetry between left and right SU(2) groups

- LRSM offers the Seesaw scale and **heavy neutral lepton (HNL)**
  - Three additional gauge bosons $W_R^{\pm}$, and Z'
  - Three right-handed neutrinos $\mathrm{N}_e, \mathrm{N}_\mu,$ and N_τ
- Search for extra gauge bosons and heavy Majorana neutrinos

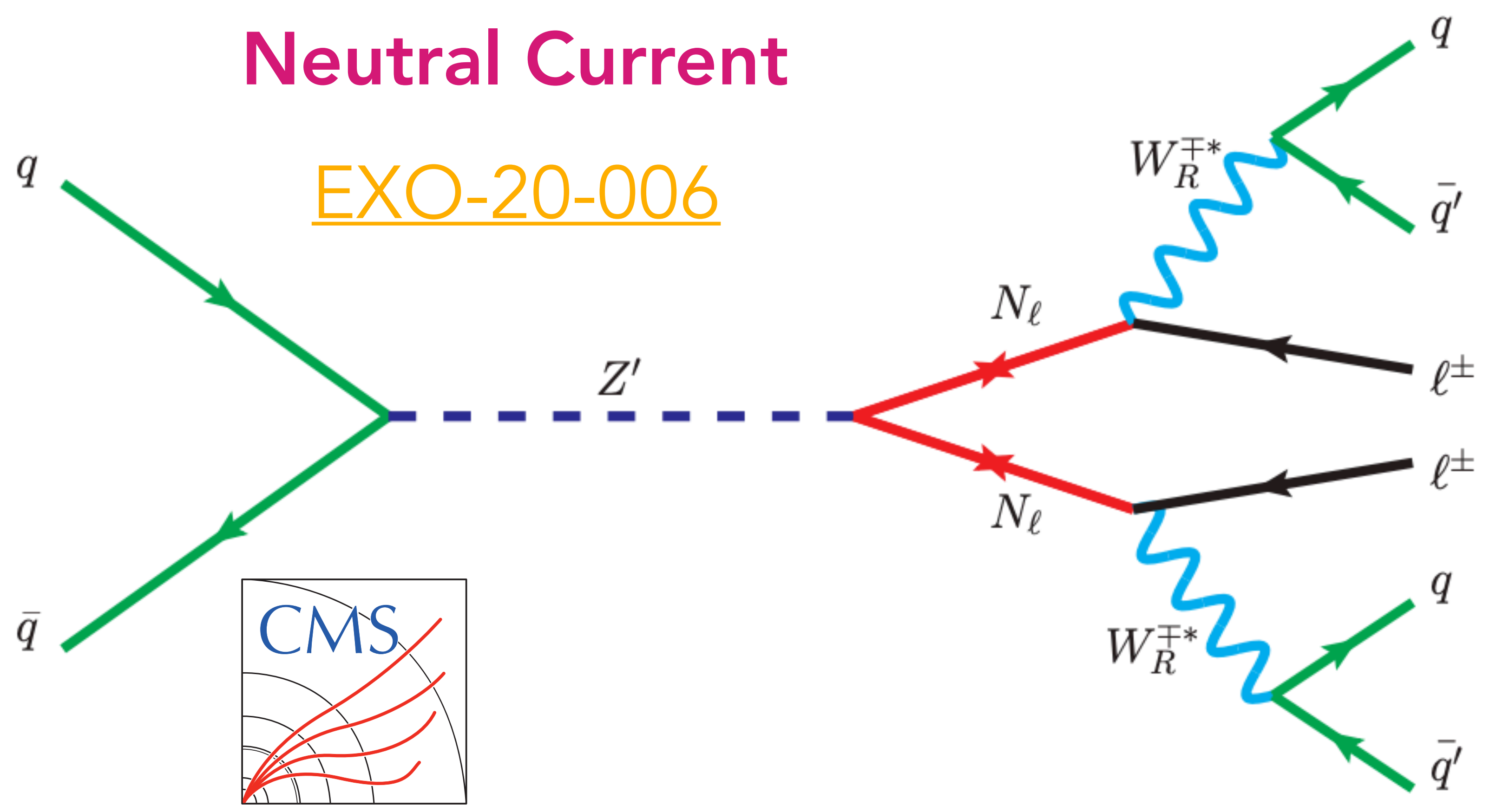
Charged Current

JHEP 04 (2022) 047



Neutral Current

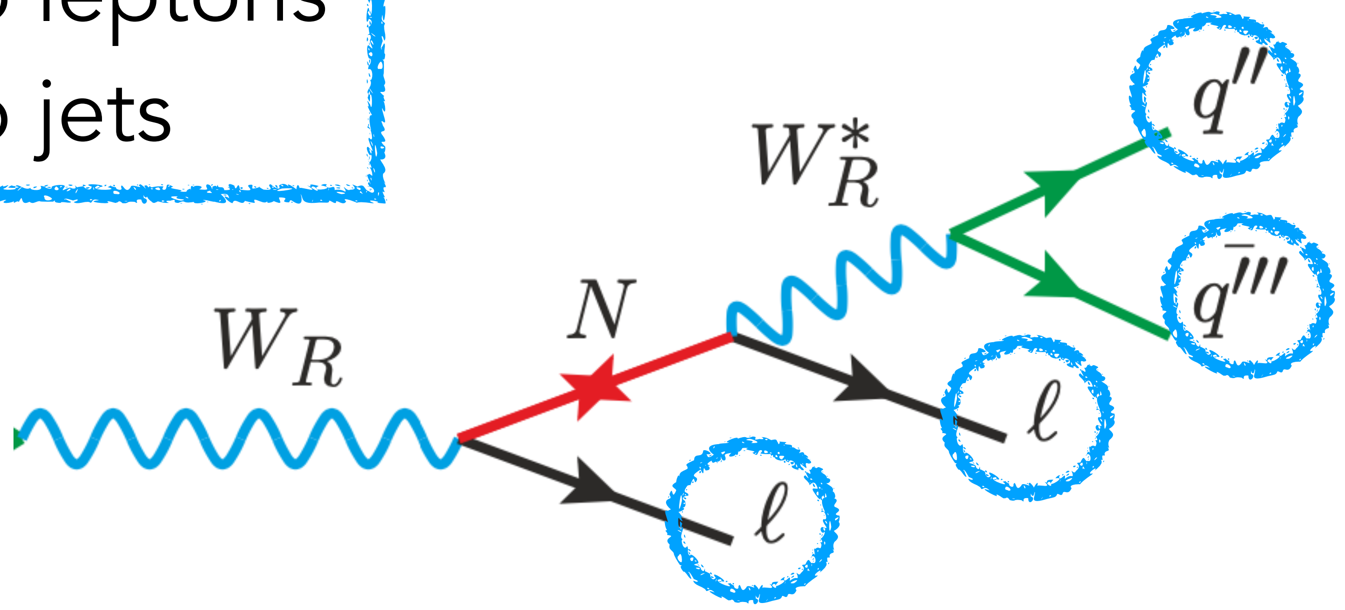
EXO-20-006



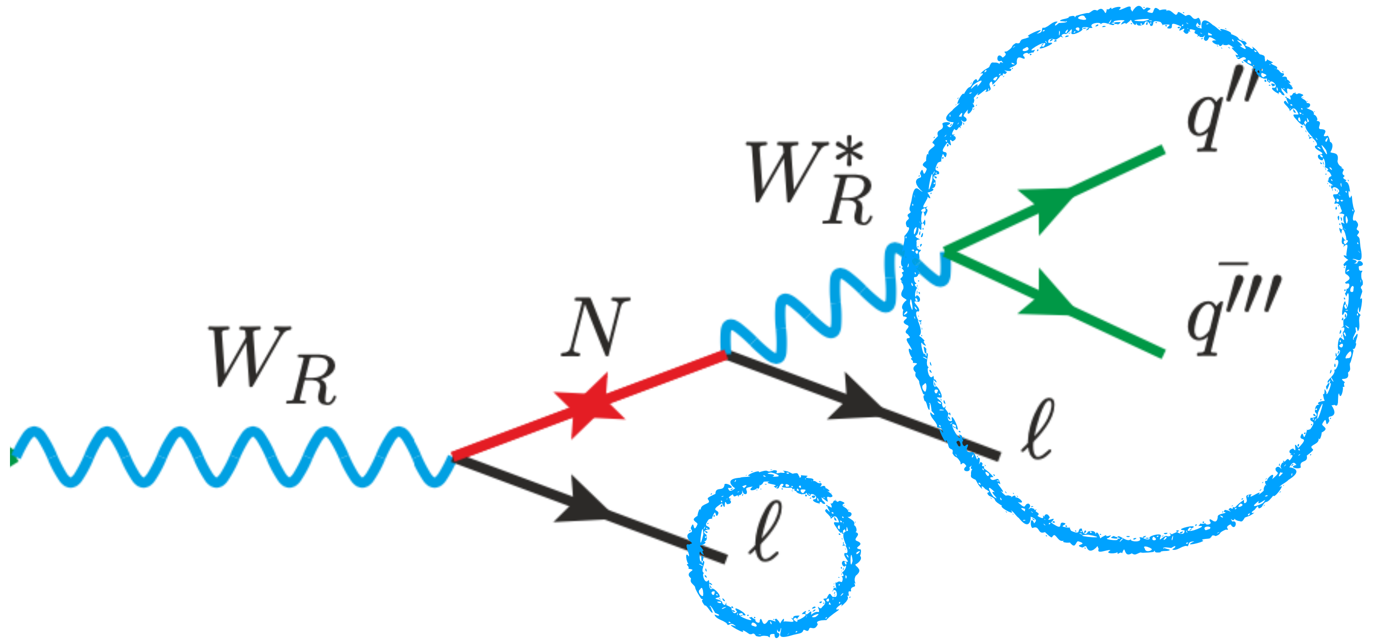
Search for W_R and N

- Considering **dielectron** and **dimuon** channels
- Signal topology: **Resolved** + **Boosted**

Resolved
- Two leptons
- Two jets



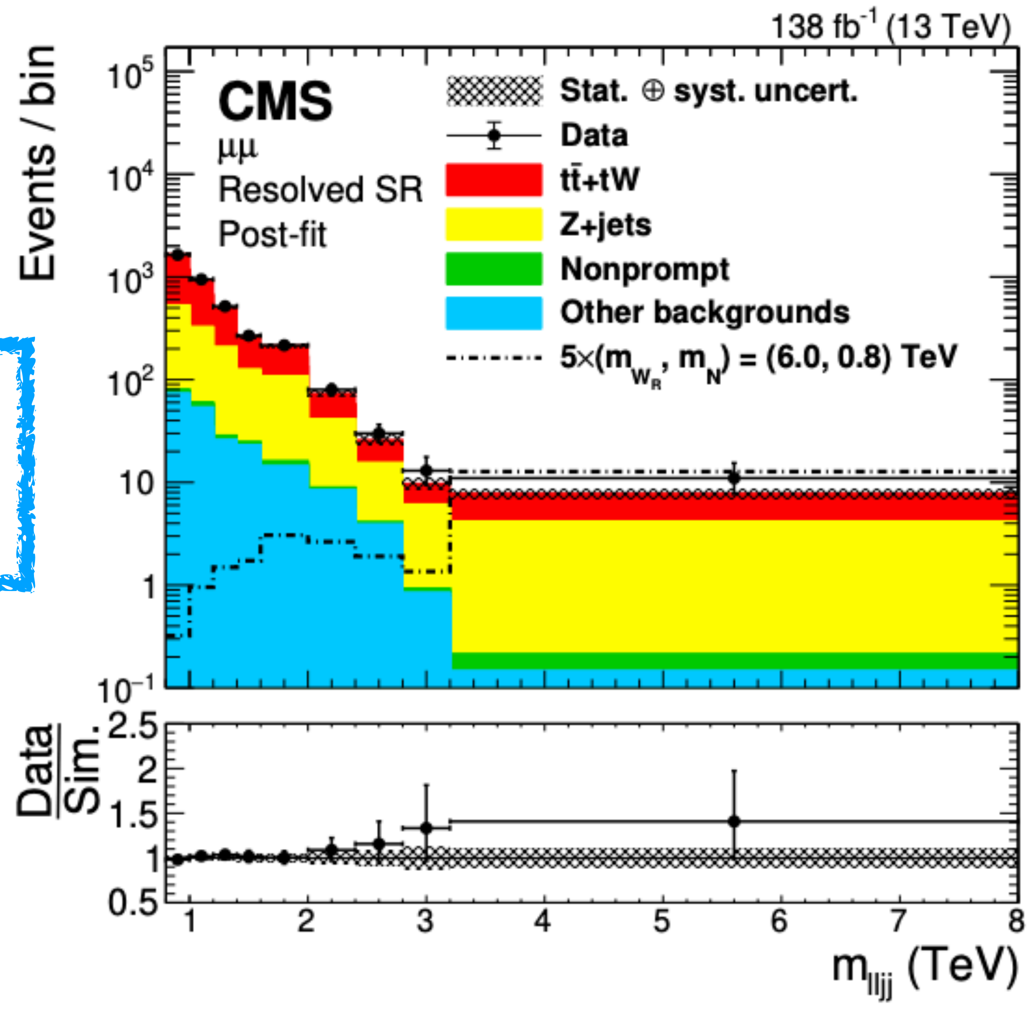
Boosted
- One leptons
- One fatjet with one lepton inside



Search for W_R and N

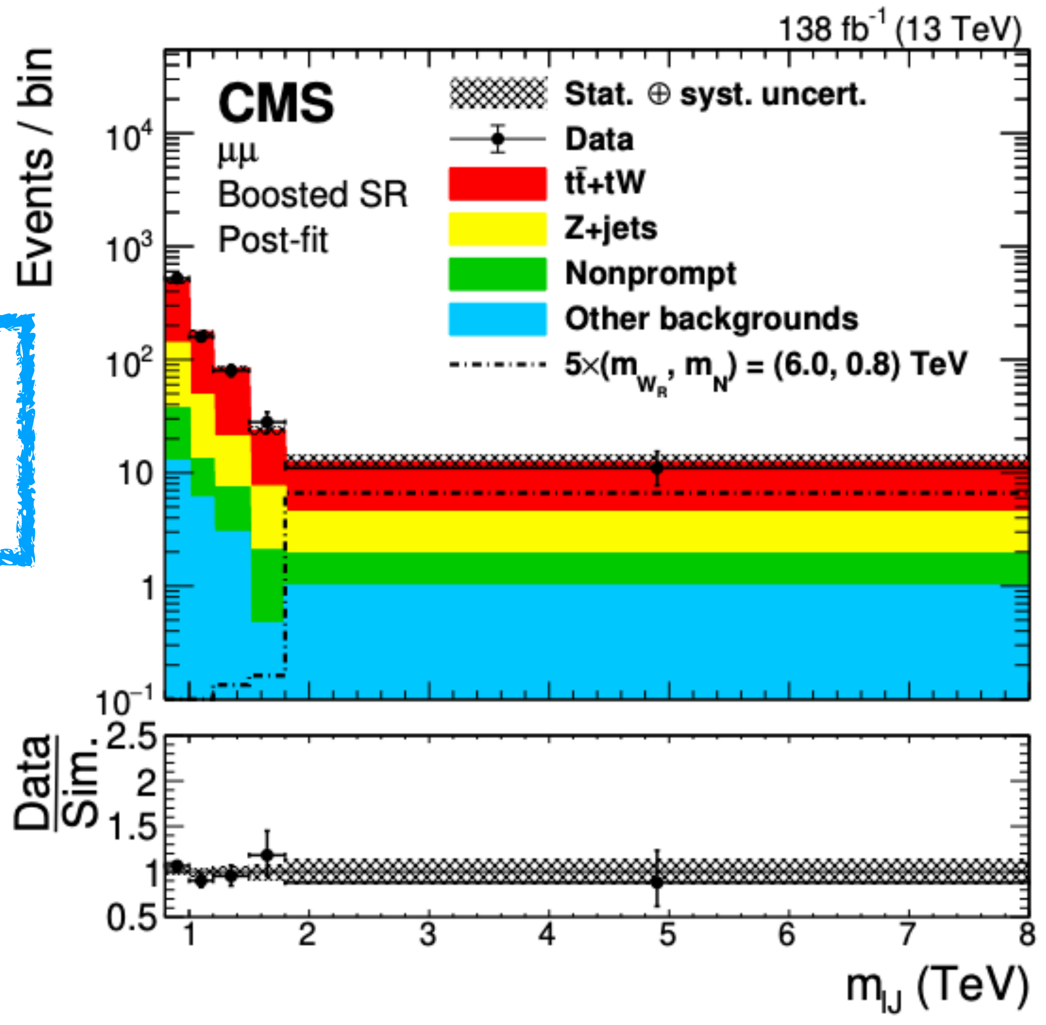
Resolved:

Invariant mass m_{lljj}



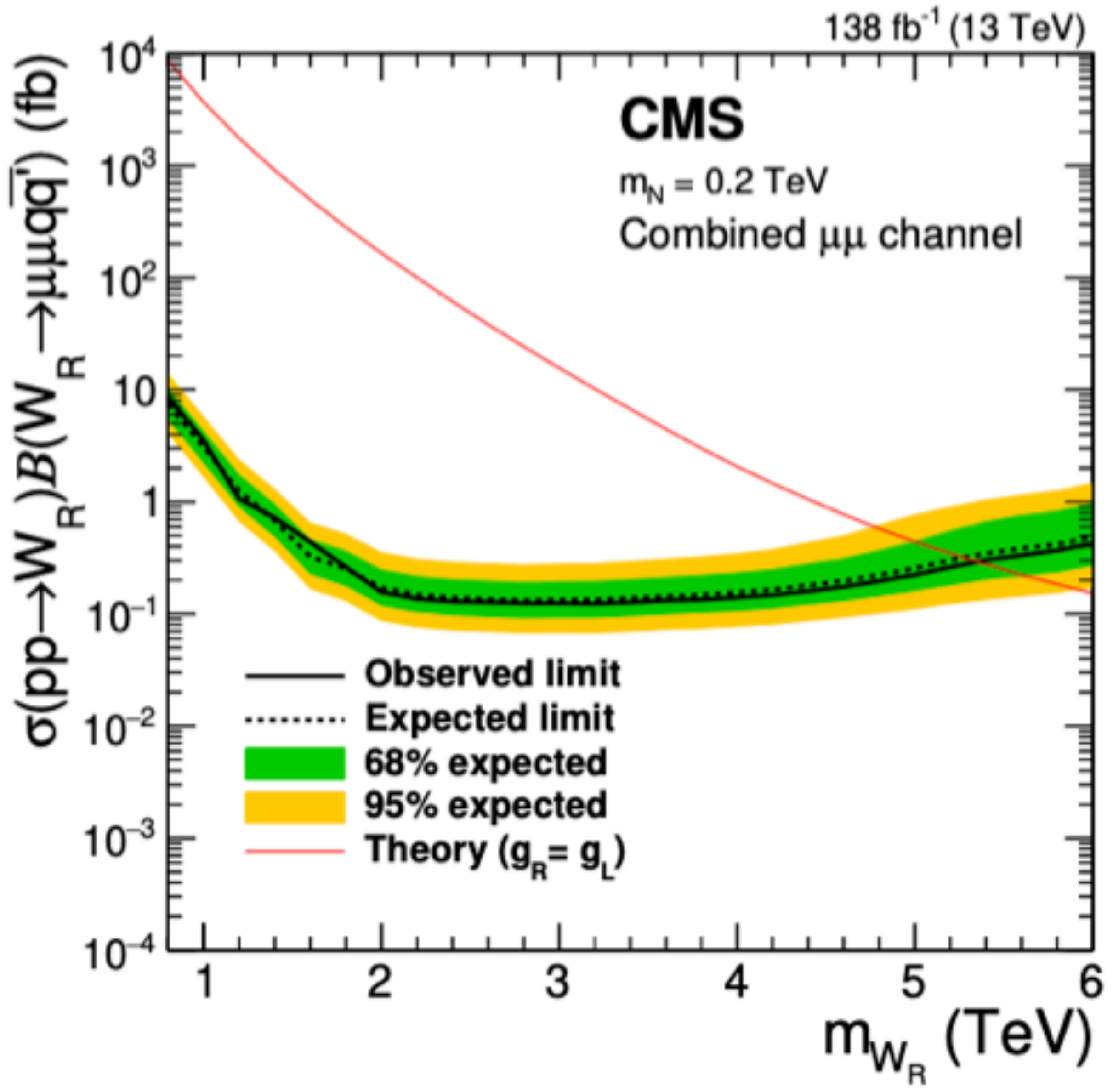
Boosted:

Invariant mass m_{lJ}



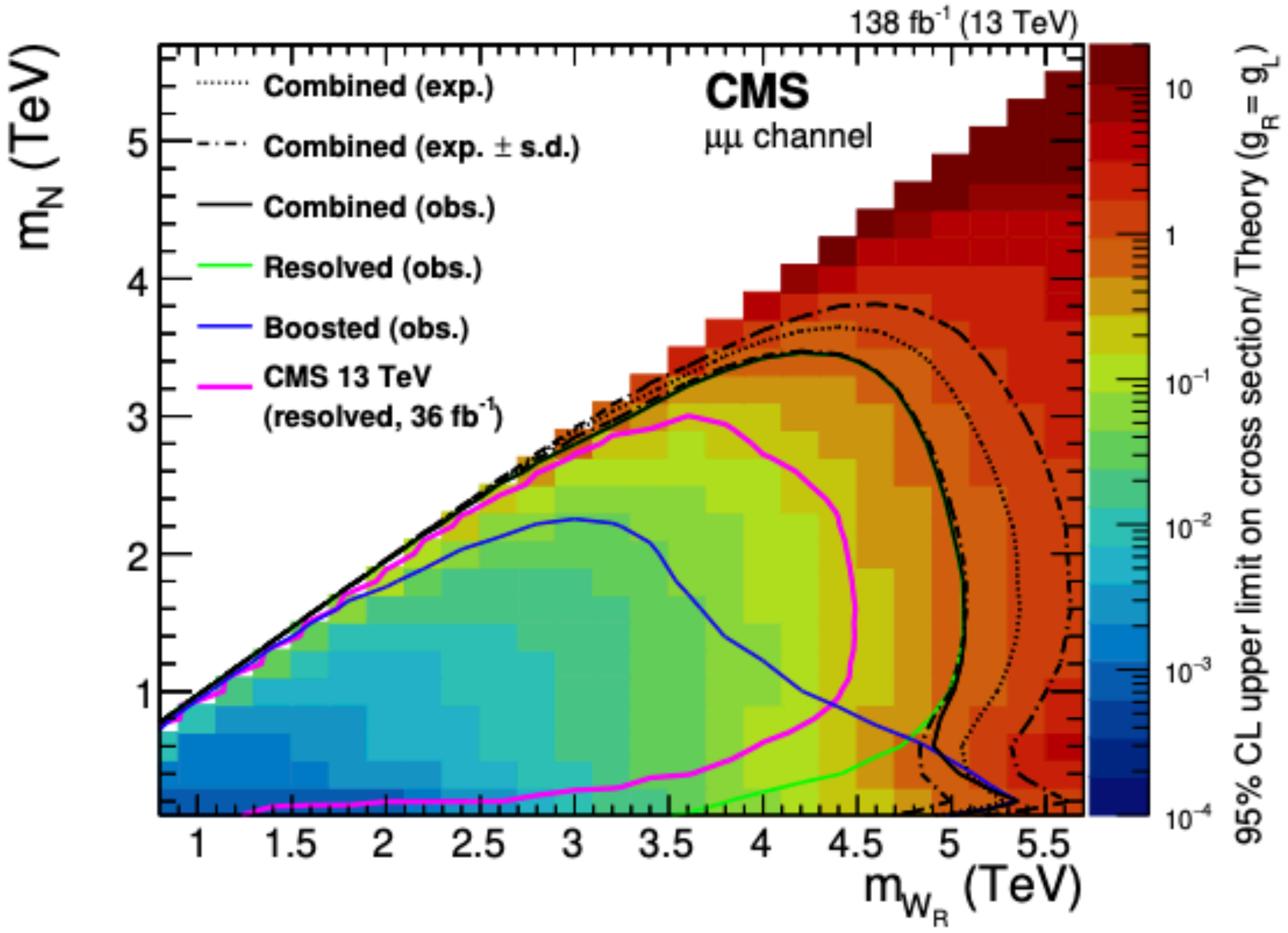
1D limits:

- Muon channel example
- m_N = 0.2 TeV



2D limits:

- Muon channel example



Exclude the phase space up to

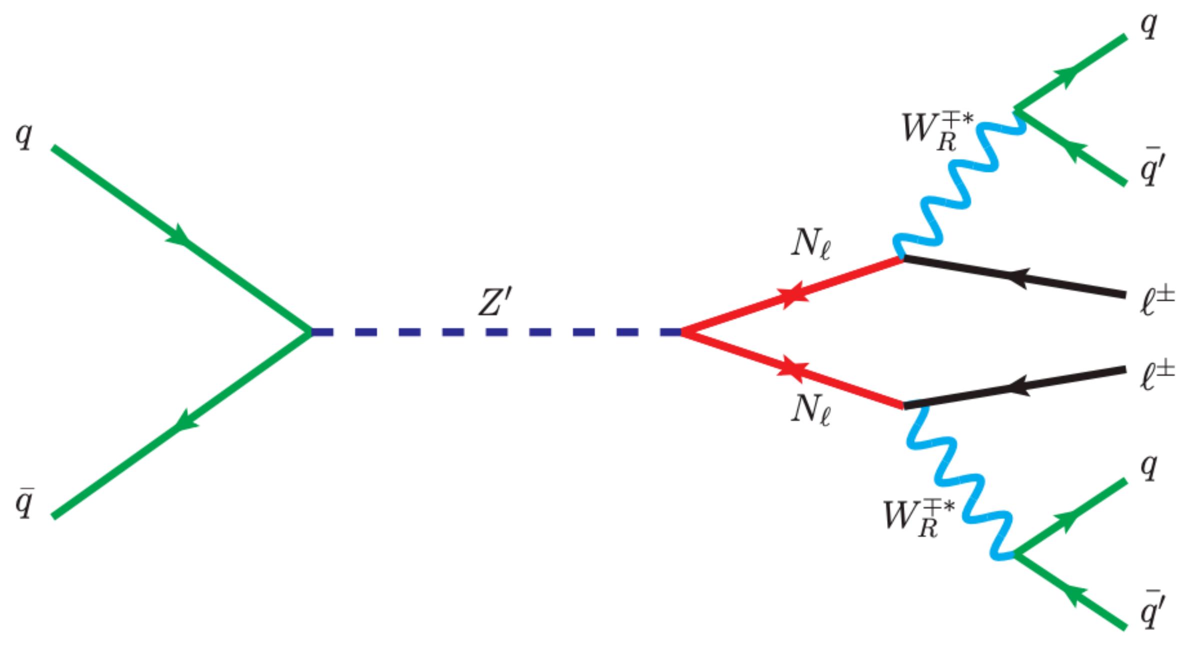
- m_{W_R} = 4.8 (5.0) TeV for the electron channel
- m_{W_R} = 5.4 (5.3) TeV for the muon channel

Significant improvement in boosted channel

- For $m_N = 200 GeV, ee(\mu\mu) : m_{W_R}$ 4600 (5400) GeV excluded

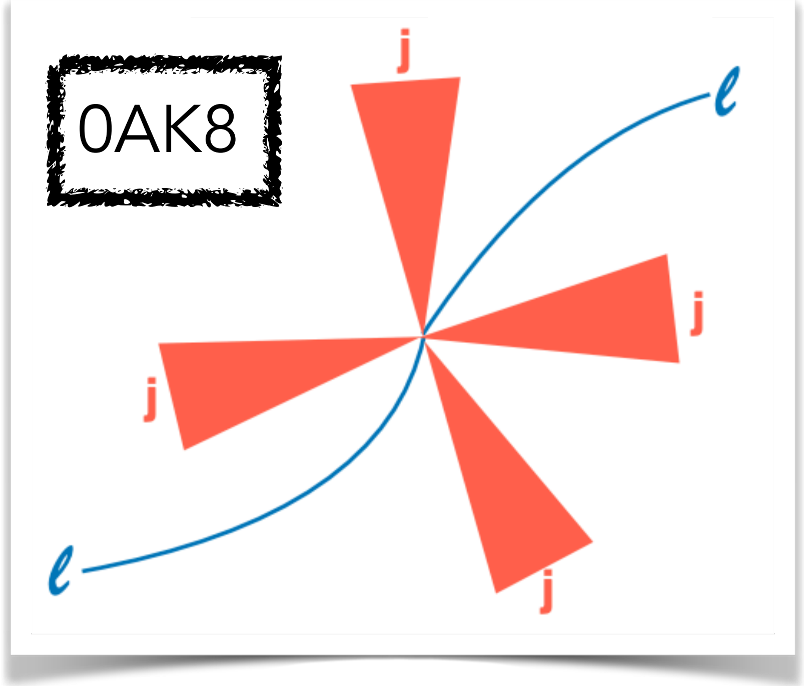
Search for Z' and N

- Considering **dielectron** and **dimuon** channels
- Signal topology:

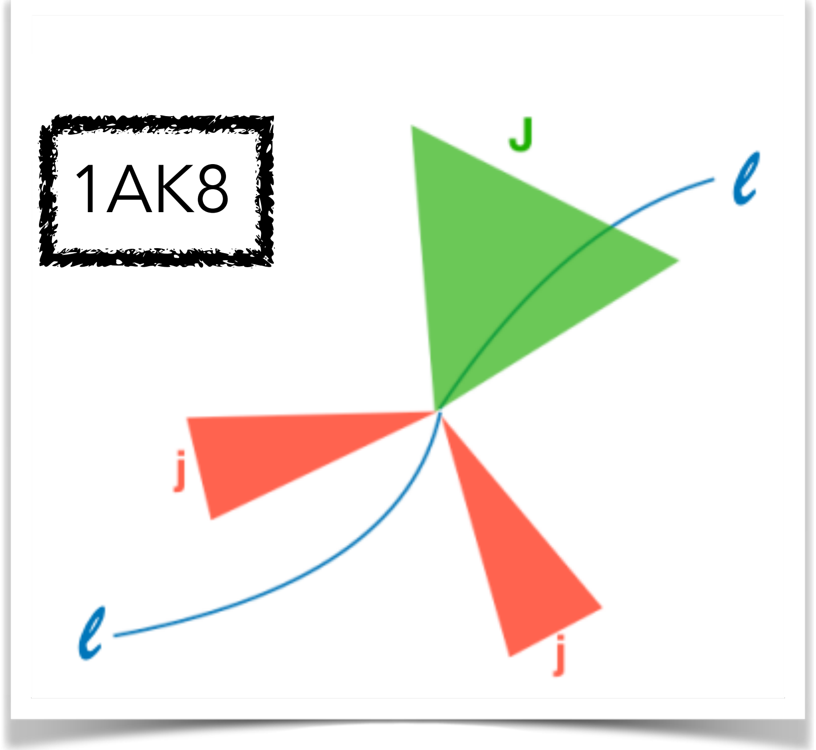


SR	N(AK8 jet)	N(tight leptons)	N(AK4 jet)
SR1 (0AK8)	=0	=2	≥4
SR2 (1AK8)	=1	≥1	≥2
SR3 (2AK8)	≥2	—	—

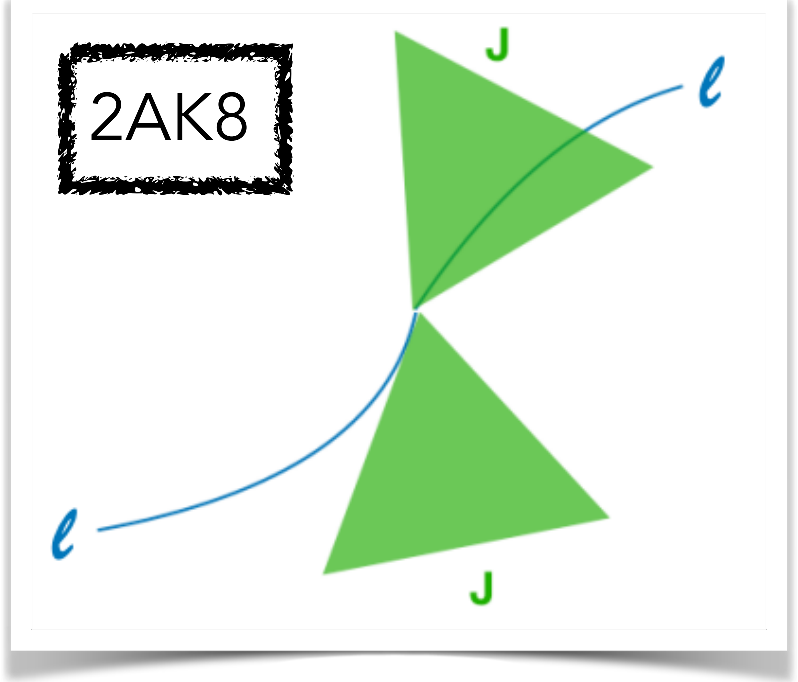
AK4 jet AK8 jet



- Two N(= one ℓ + two j)
- Z' = N1 + N2



- N (two j and the tight lepton)
- The other N(J)
- Z' = N1 + N2



- N(tight lepton and the closest J)
- The other N(remaining J)
- Z' = N1 + N2

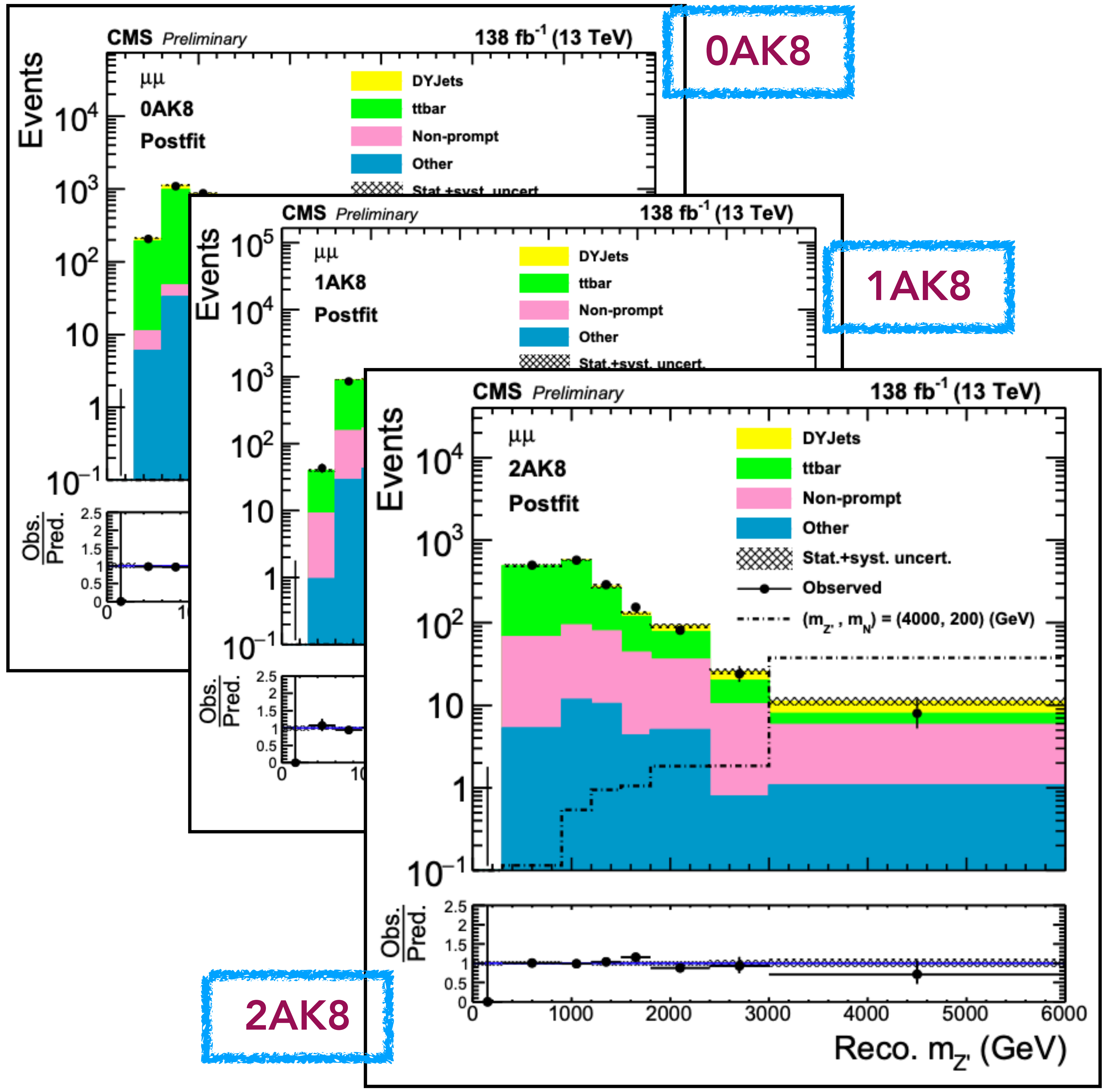
Search for Z' and N

Reconstruct $m_{Z'}$

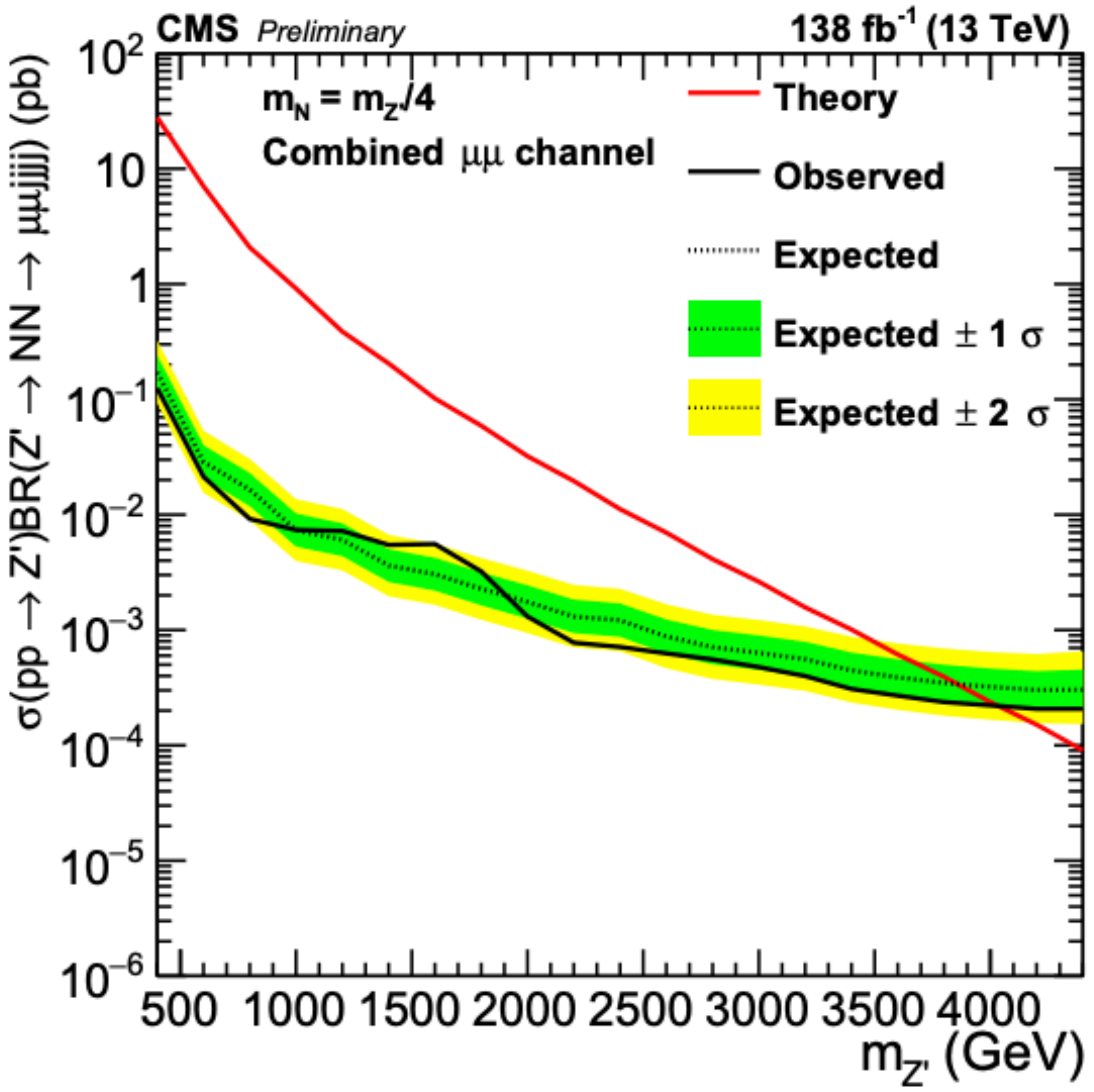
0AK8

1AK8

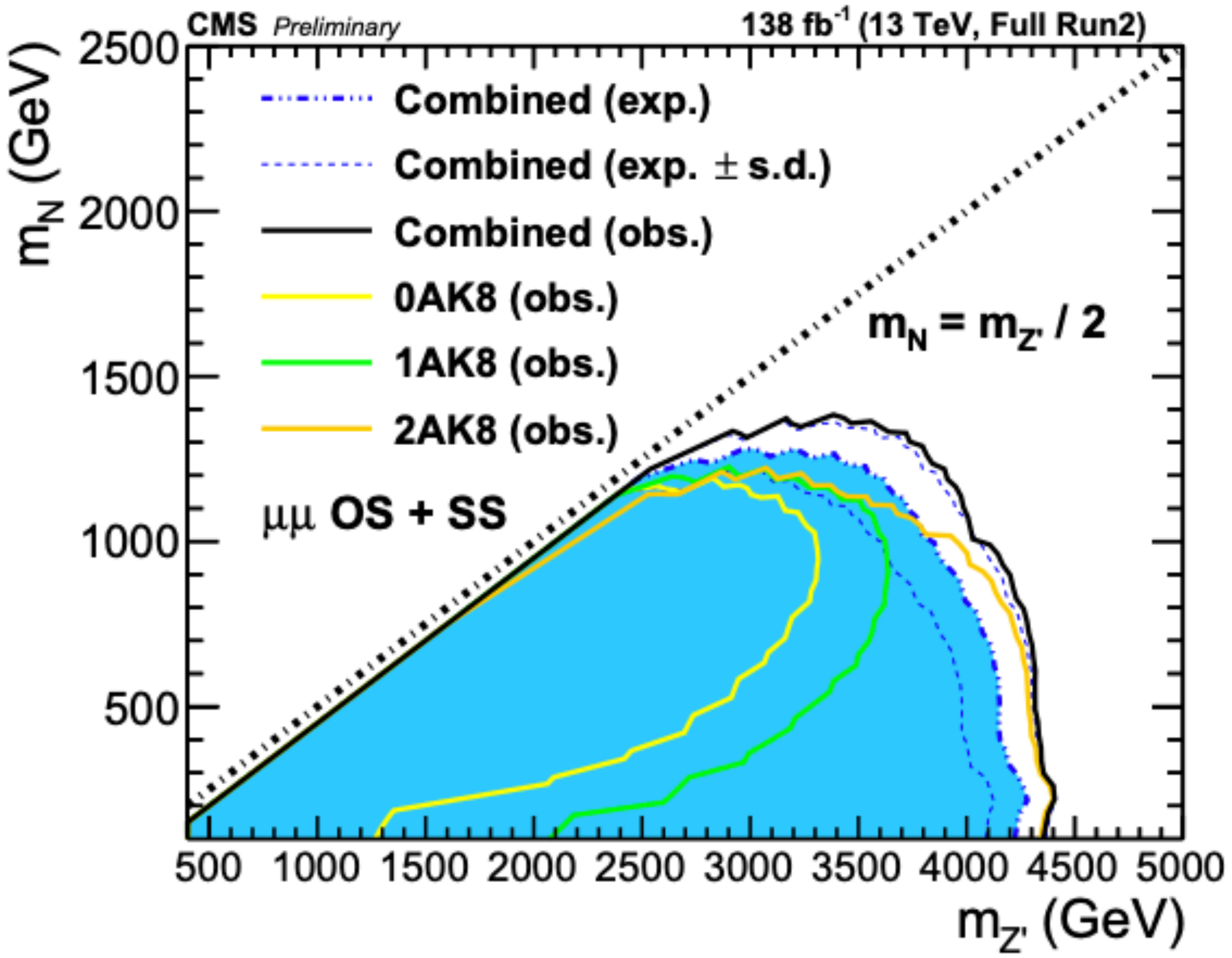
2AK8



1D limits:
- Muon channel example
- $m_N = m_{Z'}/4$



2D limits:
- Muon channel example



Exclude the phase space up to
- $m_{Z'}$ = 3.60(3.87) TeV for the electron channel
- $m_{Z'}$ = 4.04(3.87) TeV for the muon channel

Significant improvement
- 0AK8 SR: $m_{Z'}$ = 1 to 2 TeV and m_N = 0.5 to 1 TeV
- 1AK8 SR: higher $m_{Z'}$ with resolved Ns
- 2AK8 SR: dominant where Ns are boosted

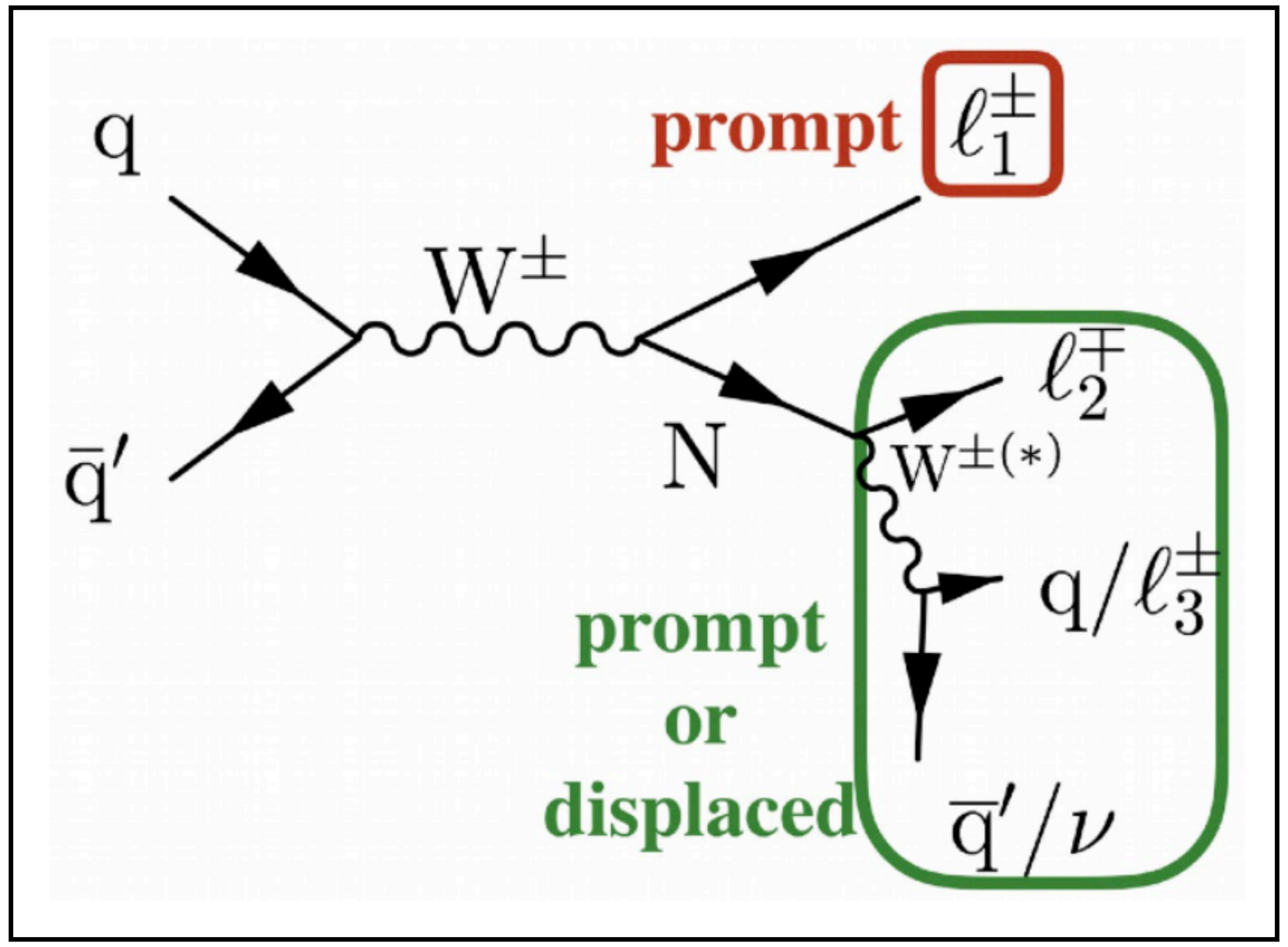
Long-lived heavy neutral leptons with displaced vertices

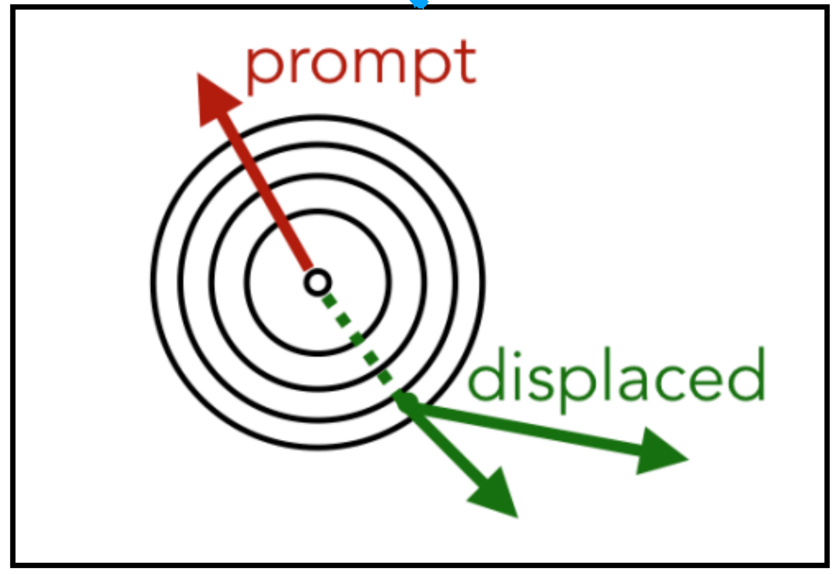
- HNLs are sterile which means they only interact with ν_{SM} through mixing $\nu_{\mathrm{SM}} \to N$.
  - HNL **lifetime (**τ**)**: smaller is the mass or the N-mixing — longer N lives

$$\tau \propto \sum_i \left|V_{i\,\mathrm{N}}\right|^{-2} m_{\mathrm{N}}^{-5}$$

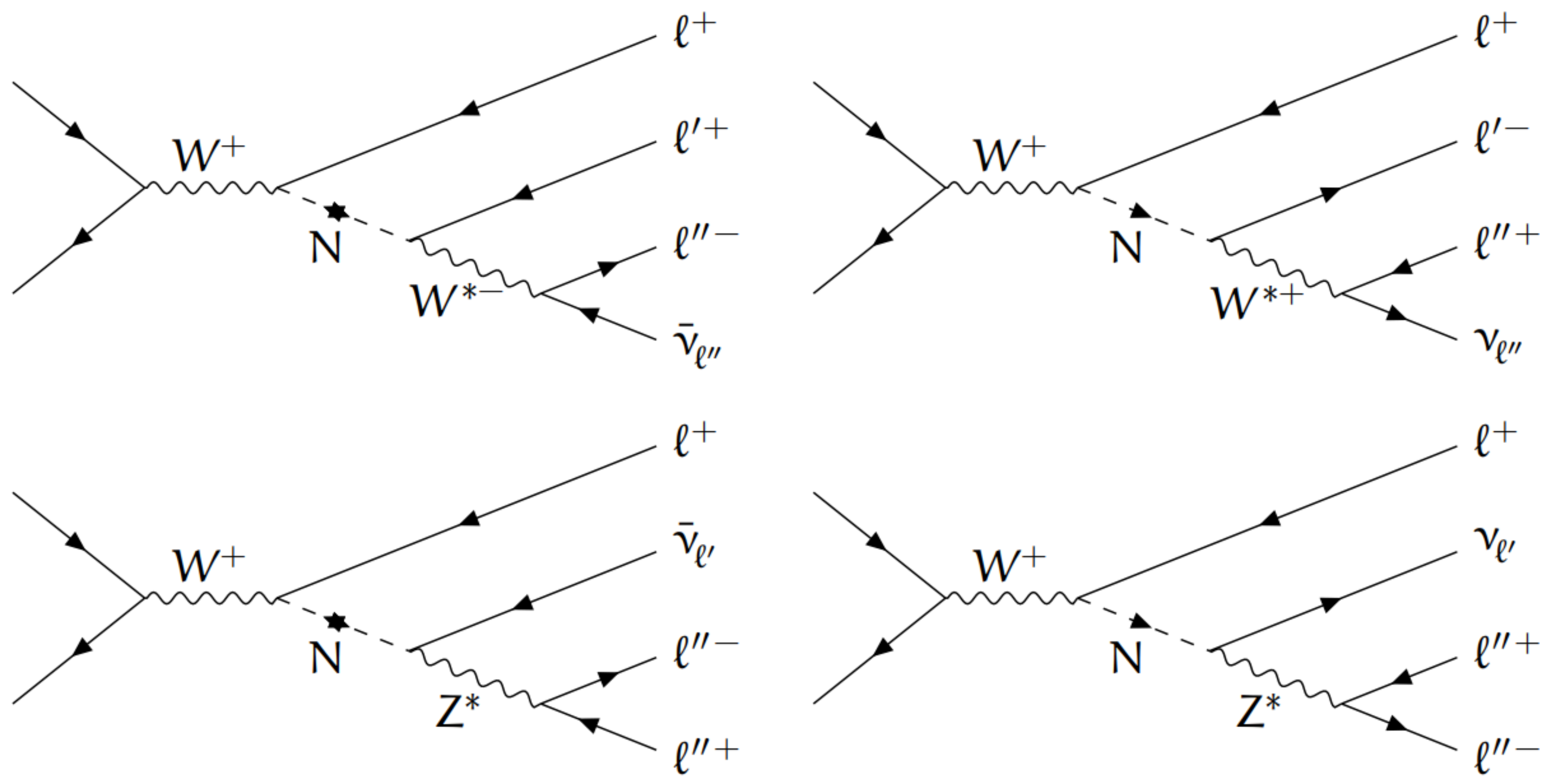
From very small (prompt decays) to macroscopic distances from production vertex (**displaced decays**) at **very low mass and couplings.**

Pioneering signatures: **displaced objects**



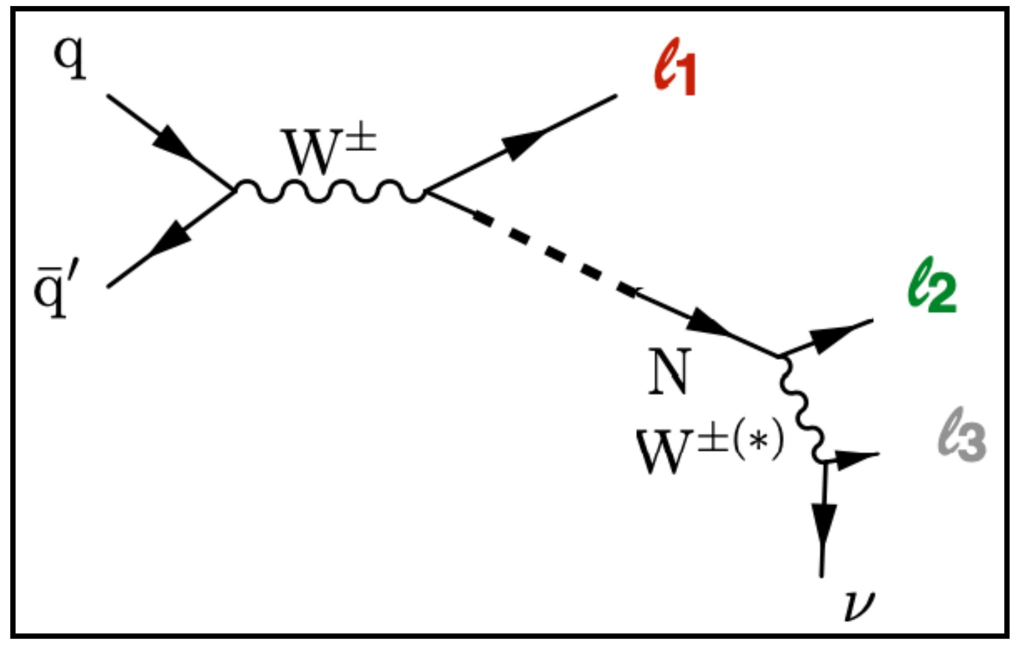


Long-lived heavy neutral leptons with displaced vertices



Majorana and Dirac models

- **Dirac**: lepton number conserved (**LNC**)
- **Majorana**: lepton number conserved (**LNC**) or violated (**LNV**) (LNV/LNC = 1 (ratio is model dependent)



3 leptons in the final state

$q\bar{q}' \to W \to \ell N \to \ell\ell' W^* \to \ell\ell'\ell''\nu_{\ell''}$

$q\bar{q}' \to W \to \ell N \to \ell\nu_{\ell'} Z^* \to \ell\nu_{\ell'}\ell''\ell''$

3 leptons final state:

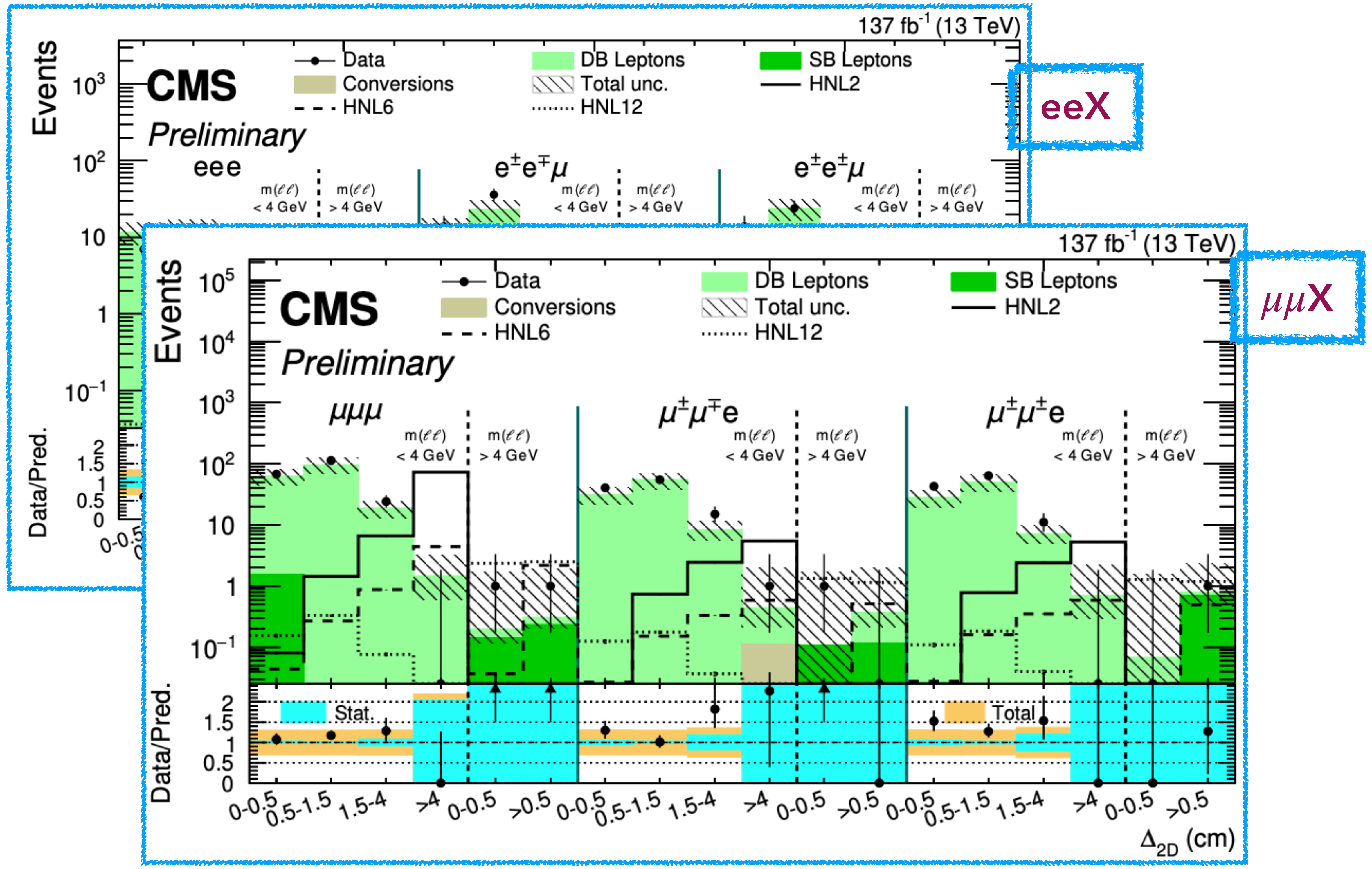
- 1 prompt lepton (ℓ_1)
- 2 displaced leptons (ℓ_2 — ℓ_3)

Features and requirements of the HNL-displaced signature:

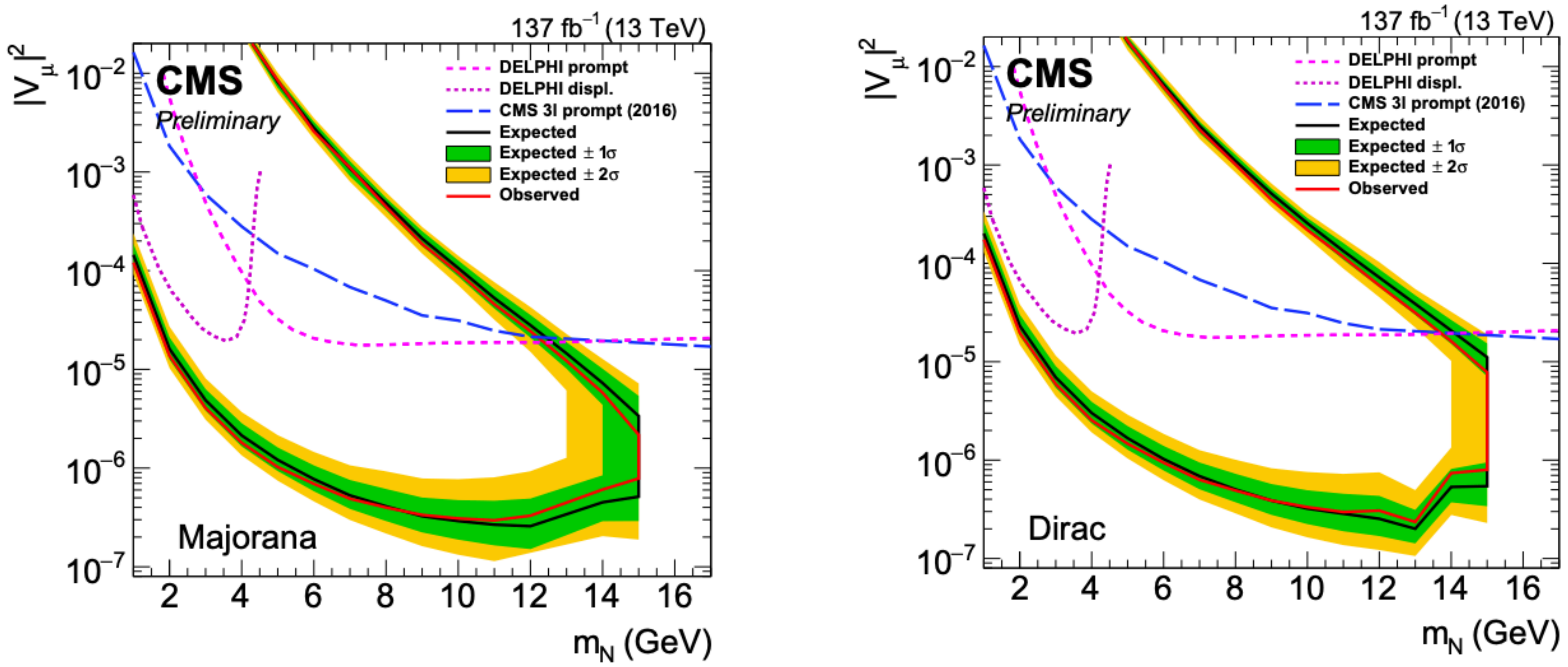
- **Low dilepton mass** $M_{\ell_2\ell_3}$
- **Soft** leptons, ℓ_2 — ℓ_3 → trigger on ℓ_1
- **Collimated** leptons, ℓ_2 — ℓ_3
- **Displaced** leptons, ℓ_2 — ℓ_3 → loose impact parameters

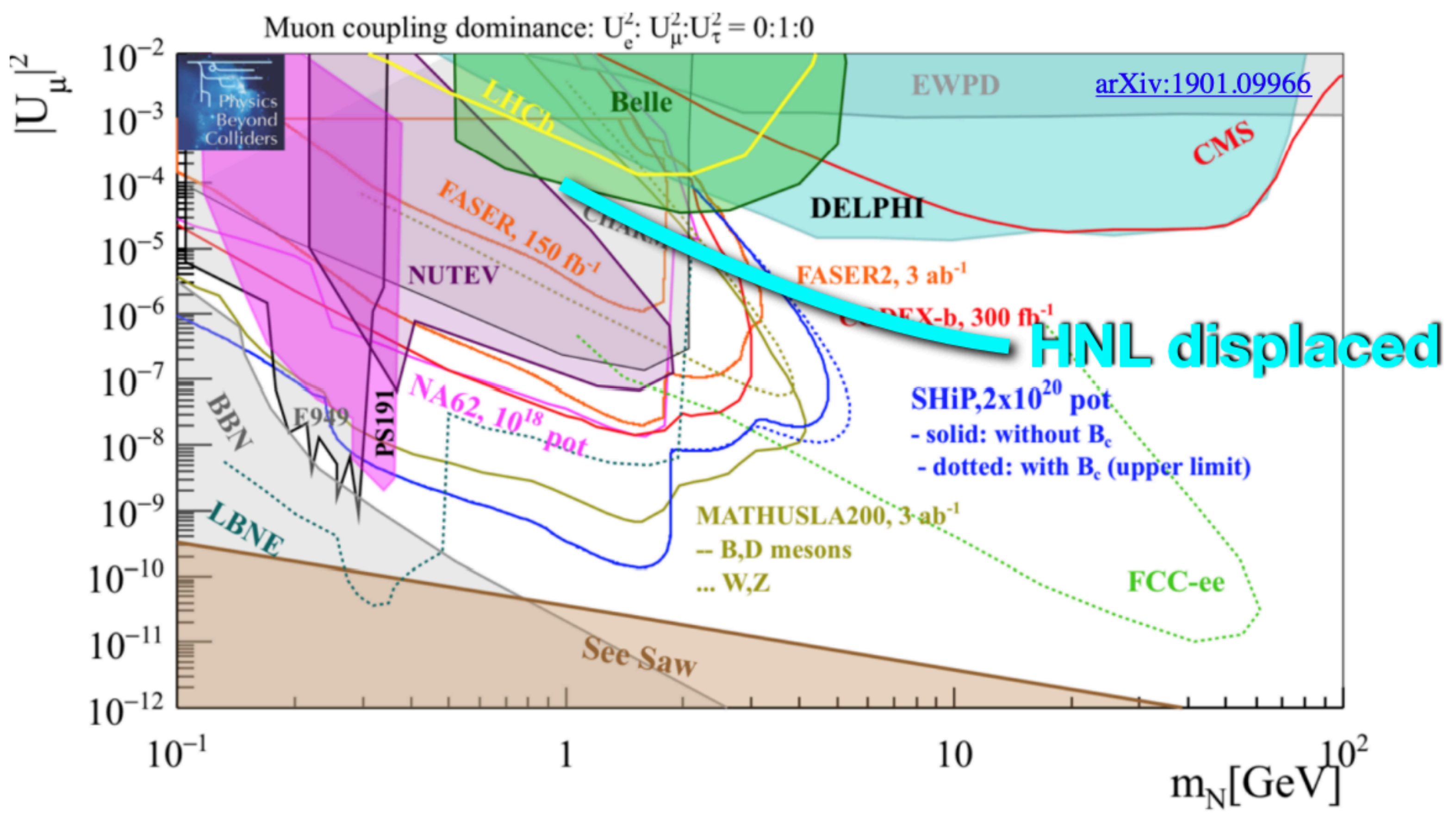
Long-lived heavy neutral leptons with displaced vertices

- The CMS analysis only considers the HNL mixes with a single neutrino flavor (**1SFH**)



Distances between the PV and the SV in the transverse plane (Δ_{2D})

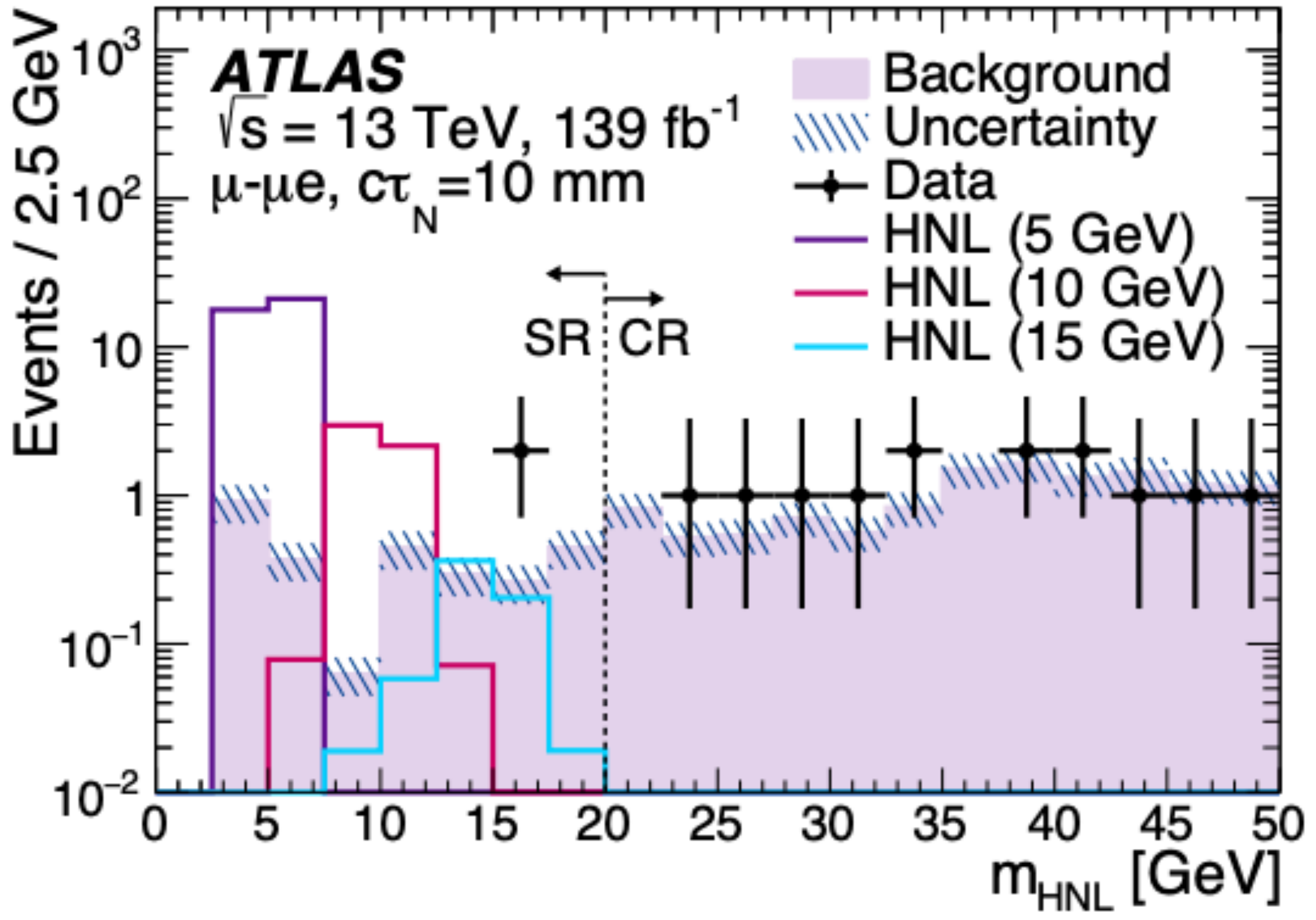




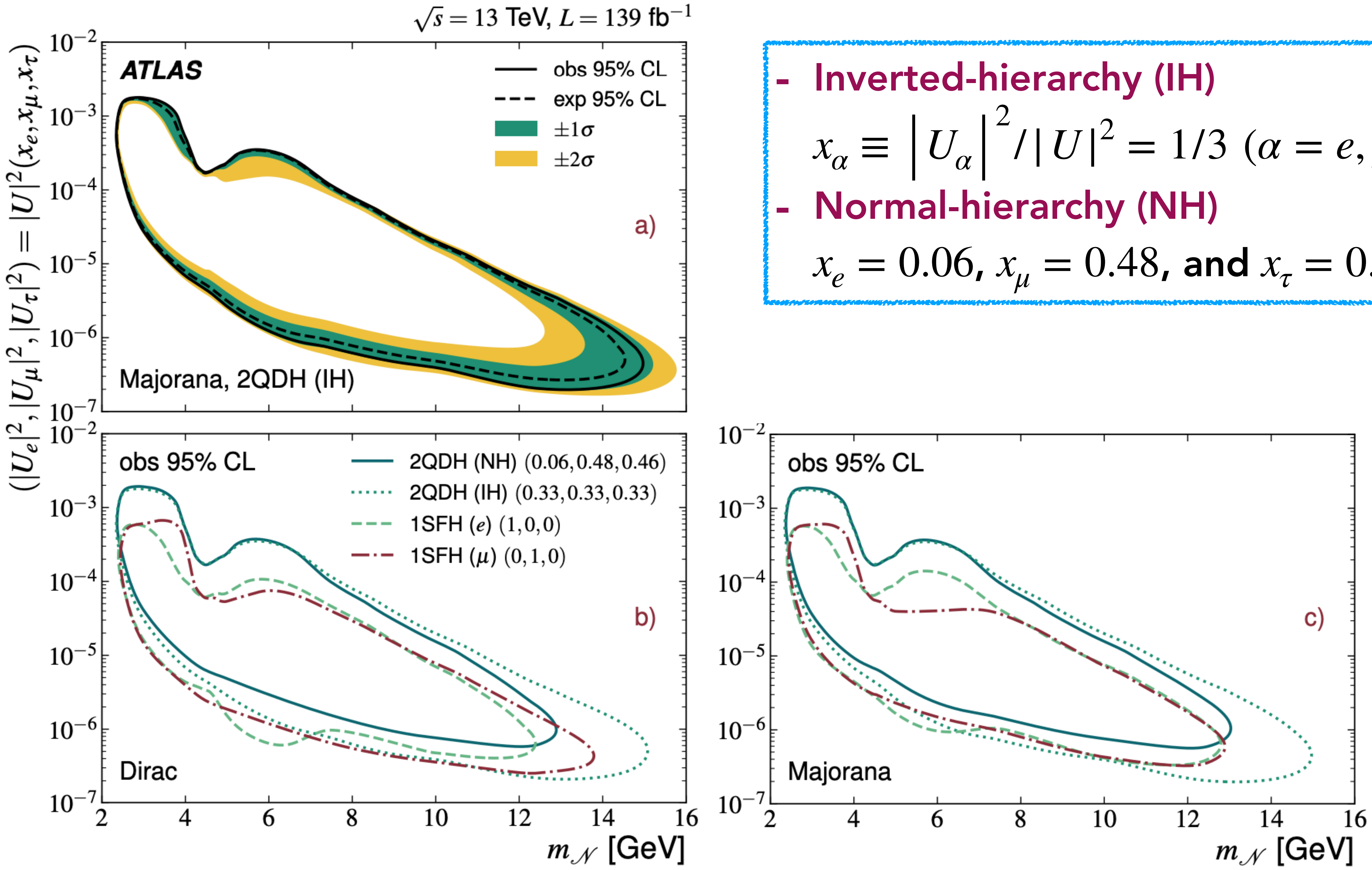
Clear improvement wrt DELPHI results in the displaced regime

Long-lived heavy neutral leptons with displaced vertices

- The ATLAS analysis considers both **1SFH** and two quasi-degenerate HNLs (**2QDH**) scenarios



Channel	Signal region		Control region	
	Background	Observed	Background	Observed
$e{-}ee$	0.4 ± 0.3	2	3.6 ± 1.8	2
$\mu{-}ee$	0.2 ± 0.1	1	1.8 ± 1.3	1
$e{-}e\mu$	0.9 ± 0.4	0	4.1 ± 1.9	5
$\mu{-}\mu e$	2.8 ± 0.8	2	12.2 ± 3.2	13
$e{-}\mu\mu$	1.2 ± 0.9	1	2.8 ± 1.6	3
$\mu{-}\mu\mu$	2.2 ± 1.4	2	8.7 ± 2.9	9
$e^{\pm}{-}e^{\mp}\mu^{\pm}$	0.6 ± 0.3	0	2.4 ± 1.4	3
$\mu^{\pm}{-}\mu^{\mp}e^{\pm}$	1.9 ± 0.6	0	8.1 ± 2.6	10



- **Inverted-hierarchy (IH)**

  $x_\alpha \equiv \left| U_\alpha \right|^2 / |U|^2 = 1/3 \ (\alpha = e, \mu, \tau)$

- **Normal-hierarchy (NH)**

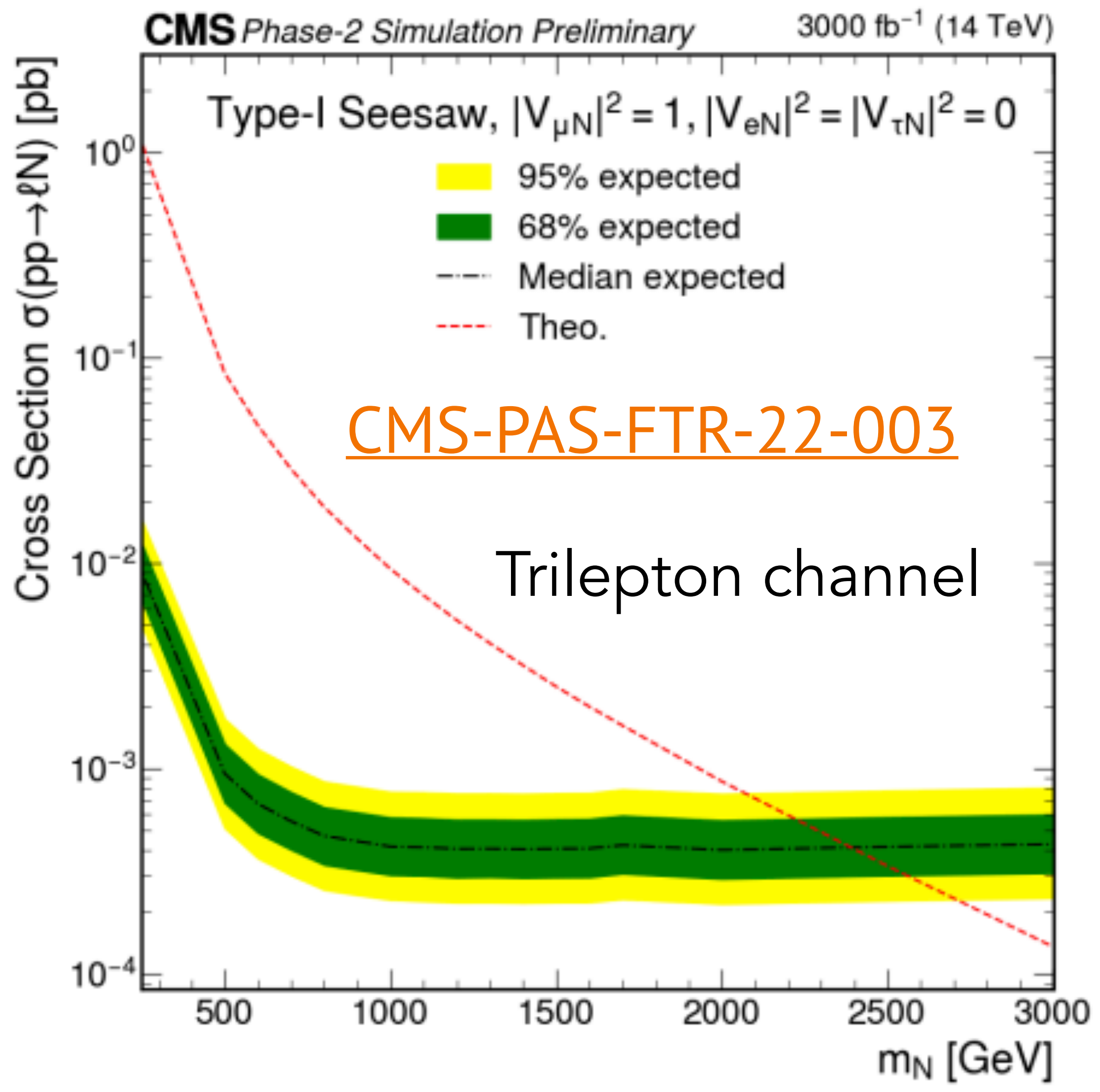
  $x_e = 0.06$, $x_\mu = 0.48$, and $x_\tau = 0.46$

Summary and Prospect

- Heavy neutrinos with mass from a few GeV to ~20 TeV are probed in various models:

  Type-I seesaw, Type-III seesaw, Heavy Composite Majorana Neutrino, Left-Right Symmetry model, …

  The exclusion mass increase and the limits are more stringent on the model parameters. But no significant deviations from the SM were detected.



- Prospect
  - Run-3 is approaching, and then is HL-LHC
  - Other sectors can be tested, e.g., Top, Tau, …
  - More models could be studied.
    In particular, analyses provide a wider range of reinterpretation materials, e.g., HEPData