

HNL experimental results from the LHC

Raffaella Tramontano - on behalf of the **ATLAS** and **CMS** collaborations

22-05-2023



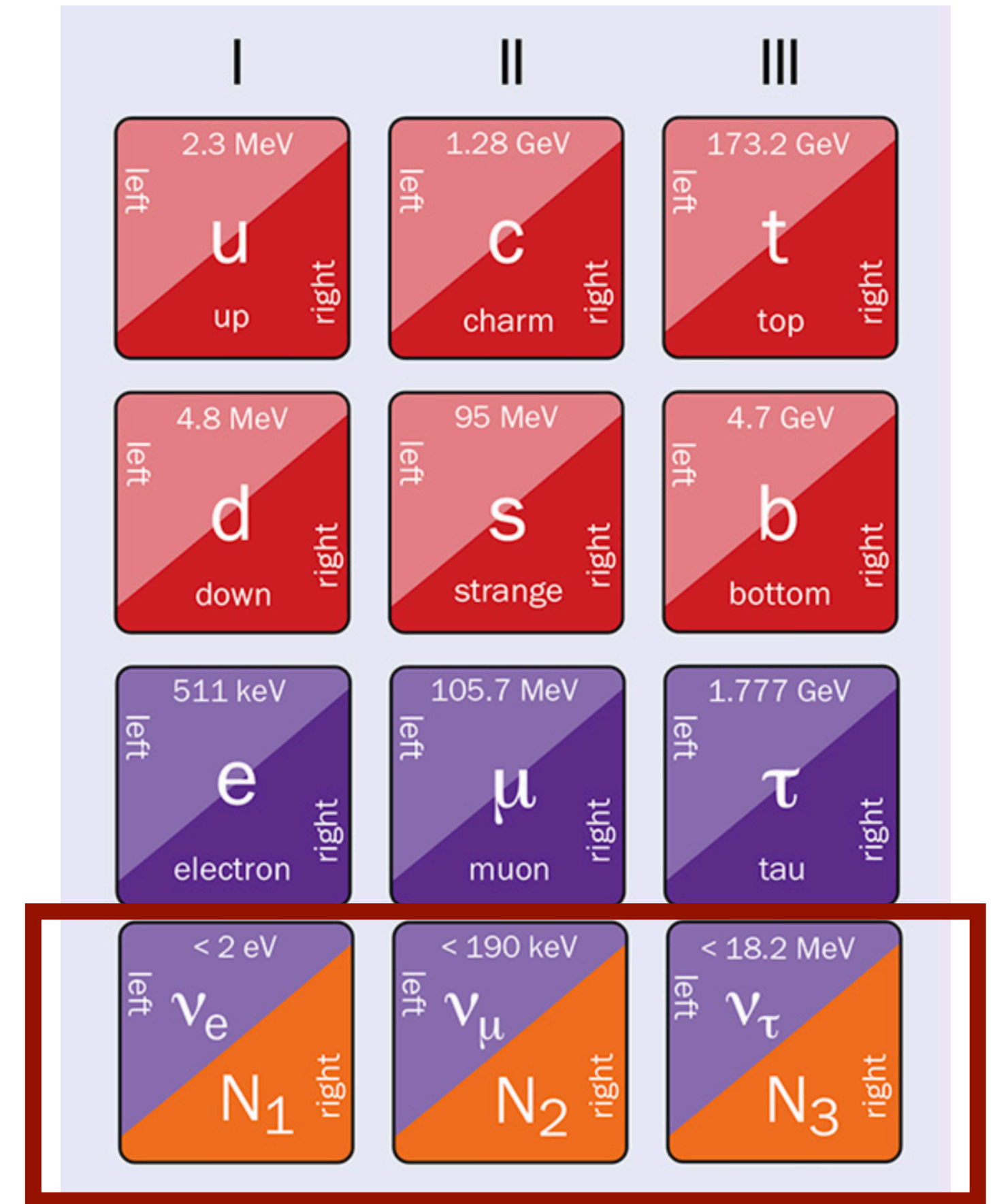
**Universität
Zürich^{UZH}**



Heavy Neutral Leptons: Why

- SM neutrinos have mass:
 - need right-handed neutrino for mass terms
- **SM + $n \geq 1$ sterile right handed neutrinos**
 - **Heavy Neutral Leptons (HNL)**
 - O(1-100) GeV sterile neutrino
 - **see-saw mechanism**
 - O(keV) sterile neutrino - **Dark matter candidate**
 - **Early universe CP violation enhancement**

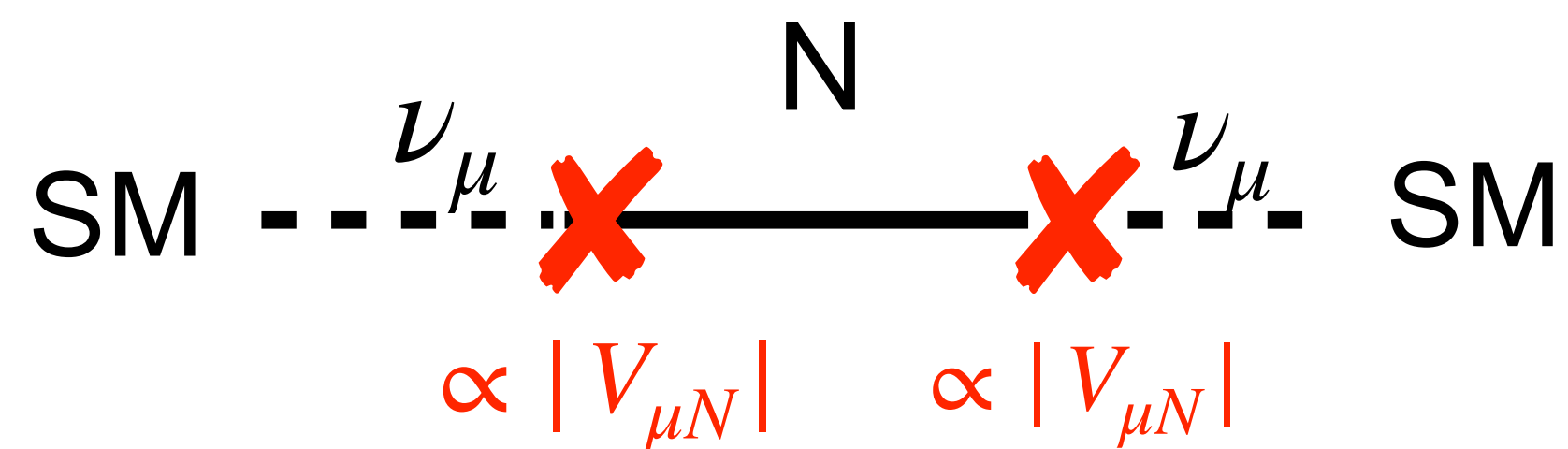
[CERN courier](#)



Majorana (particle = anti-particle)
or **Dirac**

State of the art

- Below EW bosons mass:

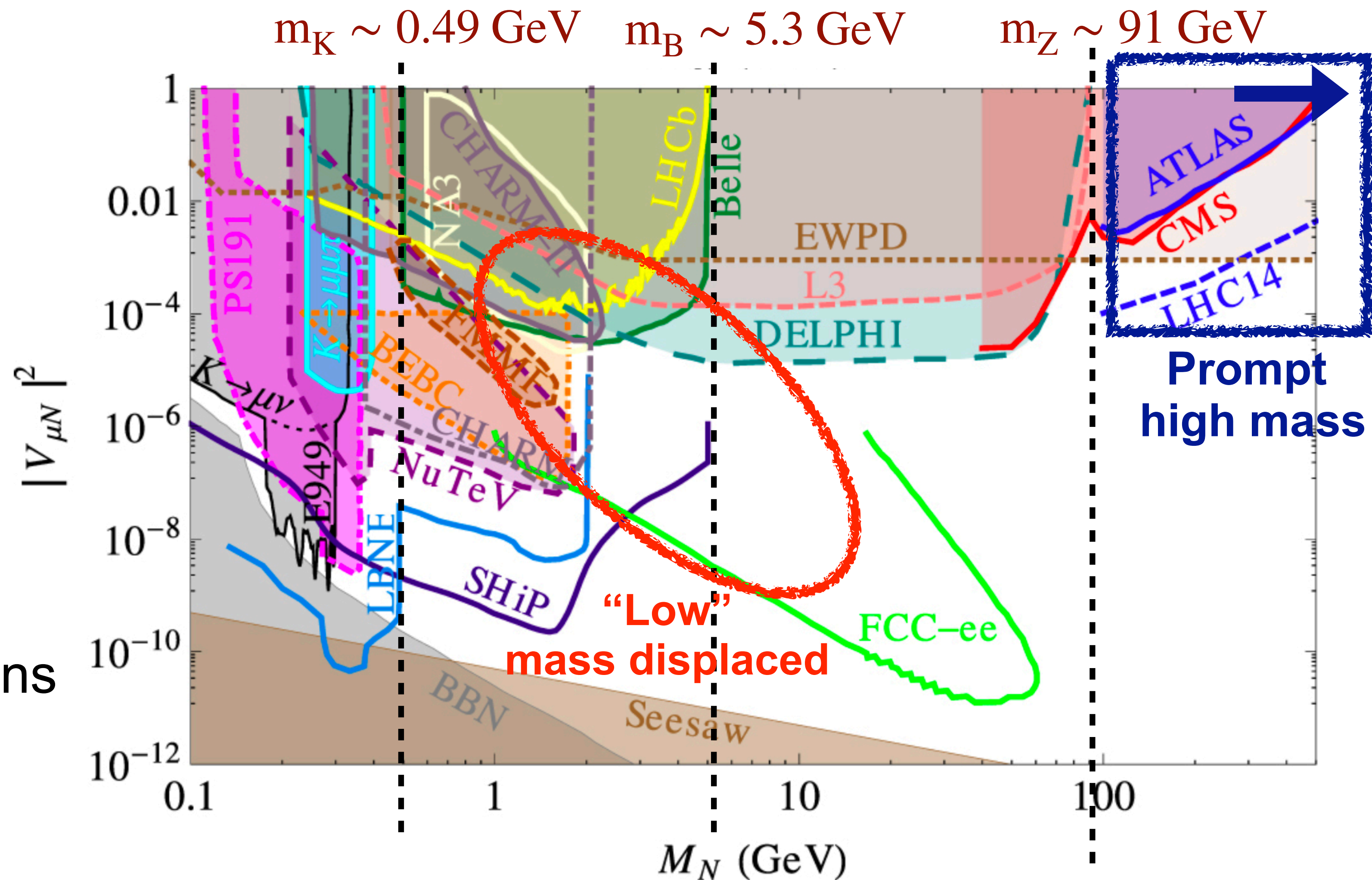


- Semileptonic decays** as HNL sources

- Above Z, W boson masses:

- Direct decay to on shell bosons**

Single flavor coupling searches



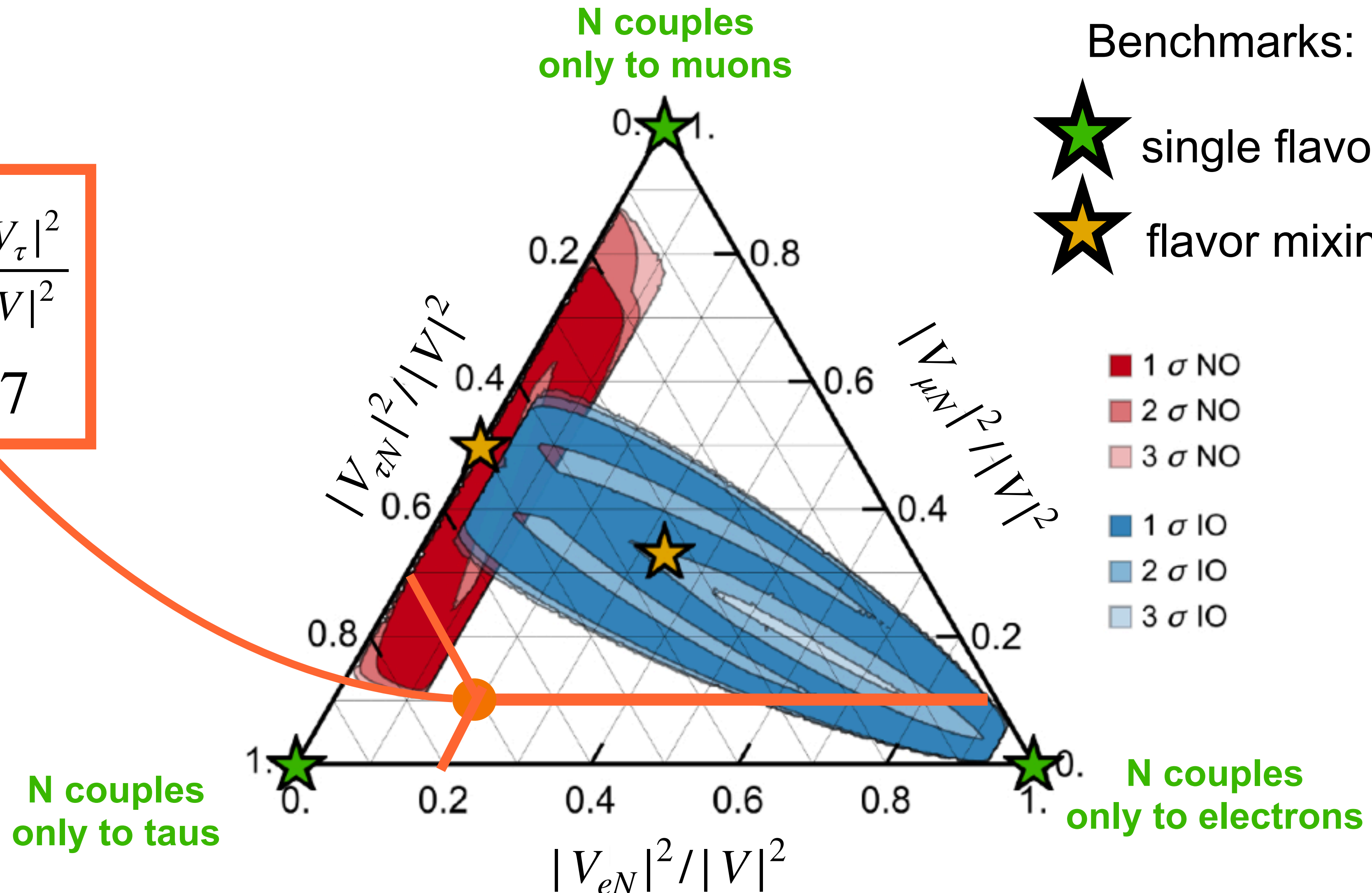
The multi-flavor frontier

Full fit neutrino oscillations measurements + ν MSM

Contours do not depend on m_N

$$\frac{|V_\mu|^2}{|V|^2} : \frac{|V_e|^2}{|V|^2} : \frac{|V_\tau|^2}{|V|^2}$$

$$0.1 : 0.2 : 0.7$$



LHC HNL searches spectrum

- **Run2 searches!**

- **Low mass displaced - SM + ν_R**

- **ATLAS:** HNL decays to displaced dilepton vertex search - [arXiv:2204.11988](https://arxiv.org/abs/2204.11988)
- **CMS:** HNL decays to displaced dilepton vertex - [arXiv:2201.05578](https://arxiv.org/abs/2201.05578)
HNL decays to displaced lepton + jets search - [CMS-PAS-EXO-21-013](https://arxiv.org/abs/2108.01301)

- **High mass - W_R and WW scattering**

- **ATLAS:** Search for heavy Majorana or Dirac neutrinos and right-handed W gauge bosons in final states with charged leptons and jets - [arXiv:1809.11105](https://arxiv.org/abs/1809.11105)
- **CMS:** Search for a right-handed W boson and a heavy neutrino - [arXiv:2112.03949](https://arxiv.org/abs/2112.03949)
- **ATLAS:** Search for Majorana neutrinos in same-sign WW scattering events - [EXOT-2020-06](https://arxiv.org/abs/2006.06006)
- **CMS:** heavy Majorana neutrinos and the Weinberg operator through vector boson fusion [arXiv:2206.08956](https://arxiv.org/abs/2206.08956)

Moriond 2023

NEW!

LHC HNL searches spectrum

- **Run2 searches!**

- **Low mass displaced - SM + ν_R**

- **ATLAS:** HNL decays to displaced dilepton vertex search
- **CMS:** HNL decays to displaced dilepton vertex - [arXiv:2103.04515](#)
HNL decays to displaced lepton + jets search - [arXiv:2103.04515](#)

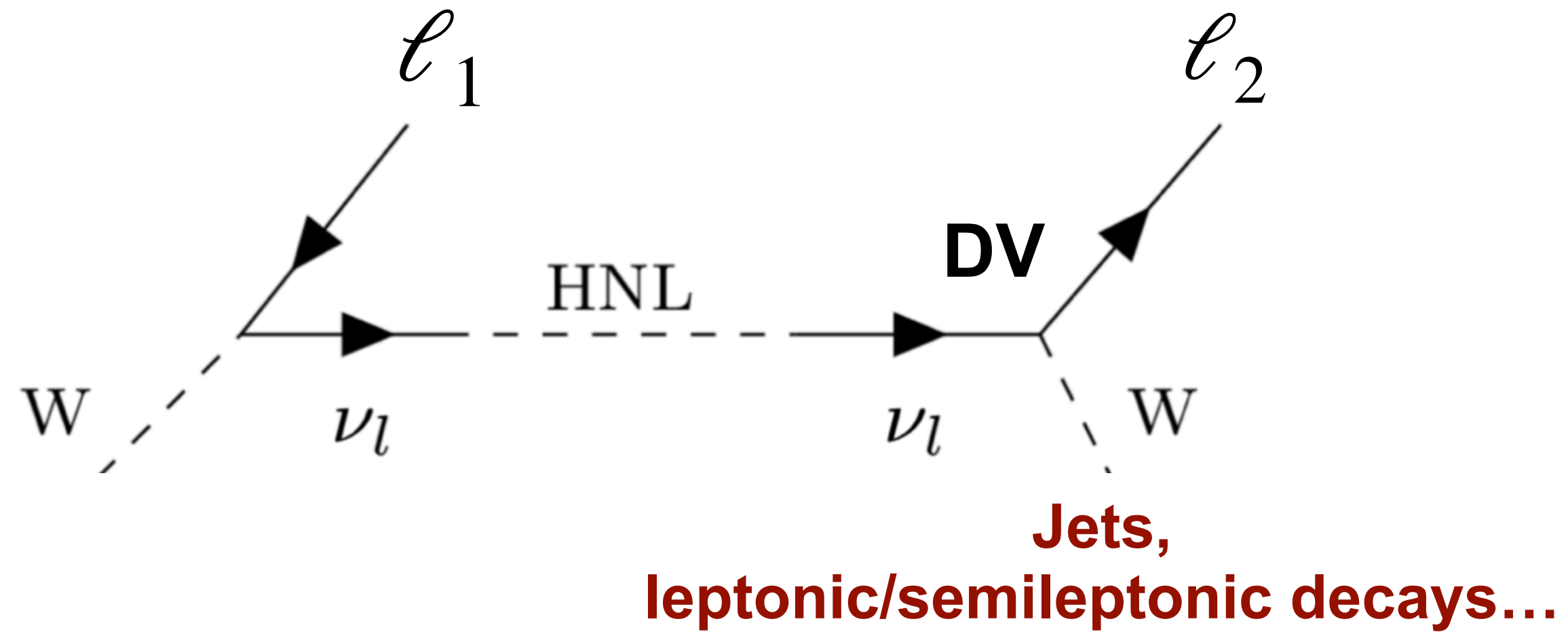
- **High mass - W_R and WW scattering**

- **ATLAS:** Search for heavy Majorana or Dirac neutrinos and right-handed W gauge bosons in final states with charged leptons and jets - [arXiv:2204.11988](#)
- **CMS:** Search for a right-handed W boson and a heavy neutrino - [arXiv:2112.03949](#)
- **ATLAS:** Search for Majorana neutrinos in same-sign WW scattering events - [EXOT-2020-06](#)
- **CMS:** heavy Majorana neutrinos and the Weinberg operator through vector boson fusion [arXiv:2206.08956](#)

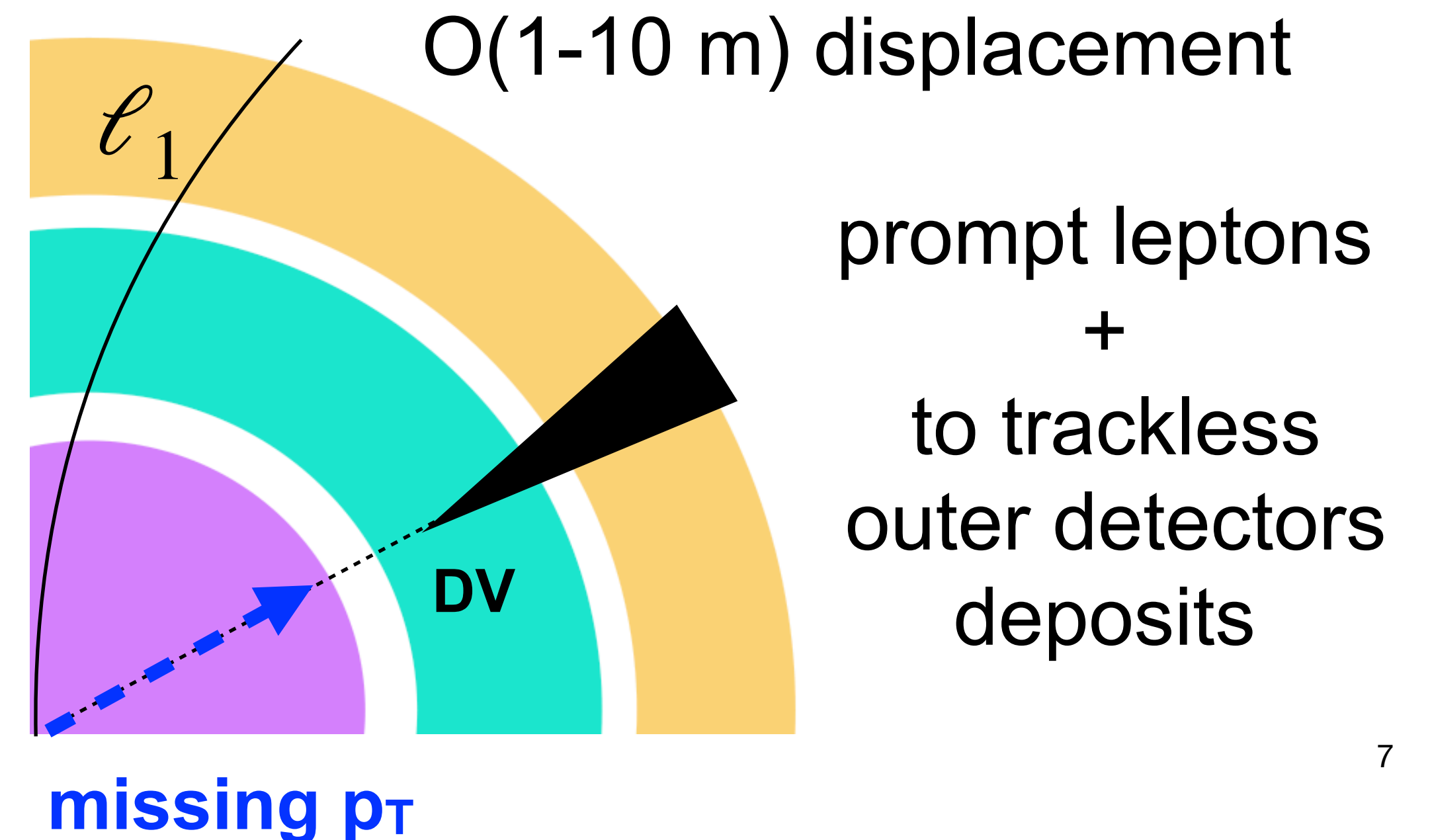
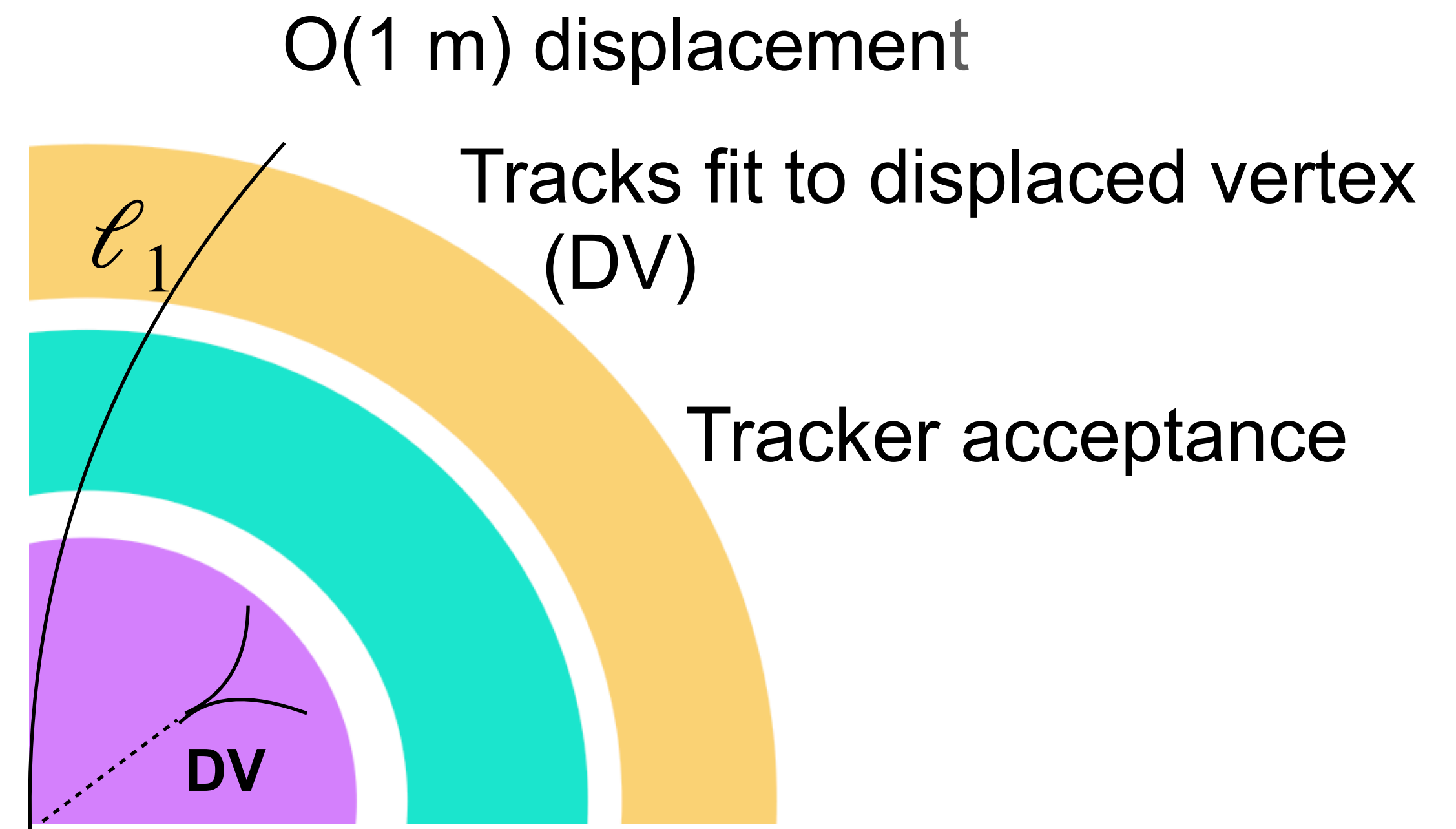
Note
Mostly public well established results
(Full HNL @ LHC literature available here)
No excesses observed up to now

Today's focus
ATLAS and CMS "parallel" searches
New results

Displaced HNLs



- $BR \propto |V_{\ell_1 N} \cdot V_{N \ell_2}|$
- $m_{HNL} \leq 20 \text{ GeV}$: Long Living HNL
- Lifetime $c\tau \propto \frac{1}{|V|^2 \cdot m_N^5}$



Tracker DV searches - ATLAS & CMS

$$\ell_{prompt} + (DV \rightarrow)\ell'\ell''$$

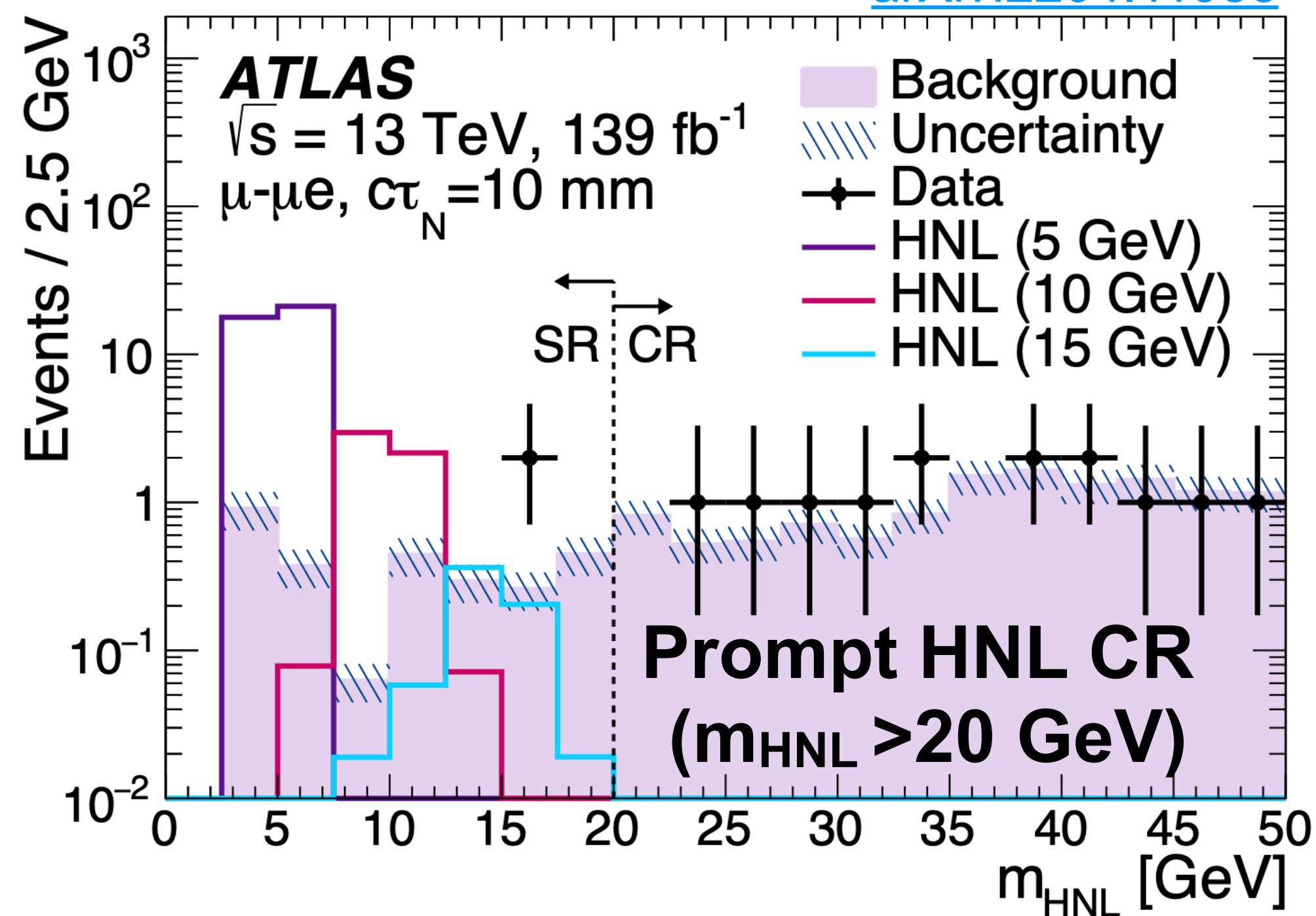
ATLAS

Large radius tracking:

Dedicated DV algorithm, sequential Kalman filter

- Background: Prompt ℓ + DV uncorrelated pairs

[arXiv:2204.11988](https://arxiv.org/abs/2204.11988)



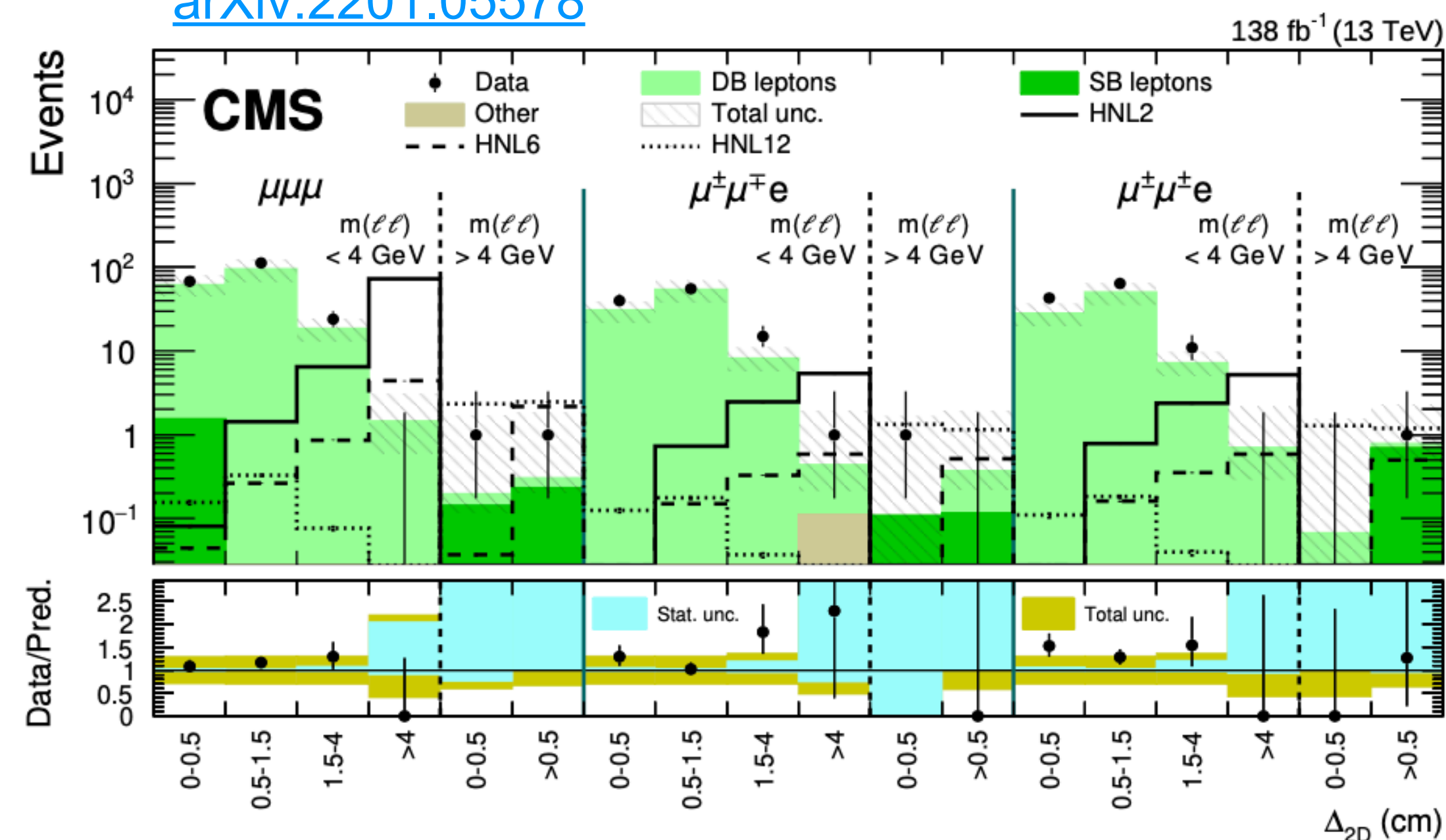
CMS

- $m_{\ell'\ell''} \times \Delta_{2D}^{\ell'\ell''}$ categories:

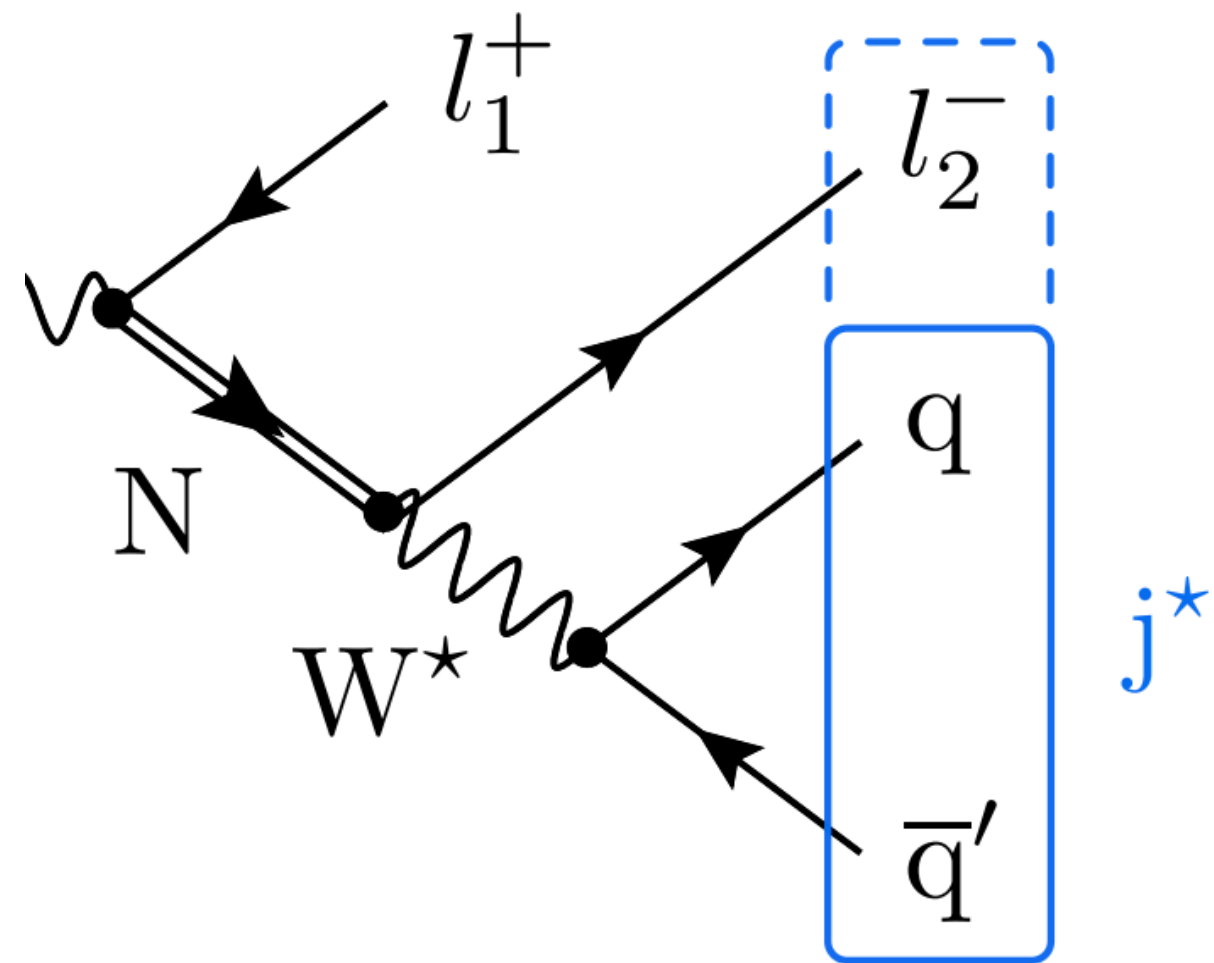
- Kinematics x lifetime signal enhancements

- Δ_{2D} is DV transverse displacement

[arXiv:2201.05578](https://arxiv.org/abs/2201.05578)

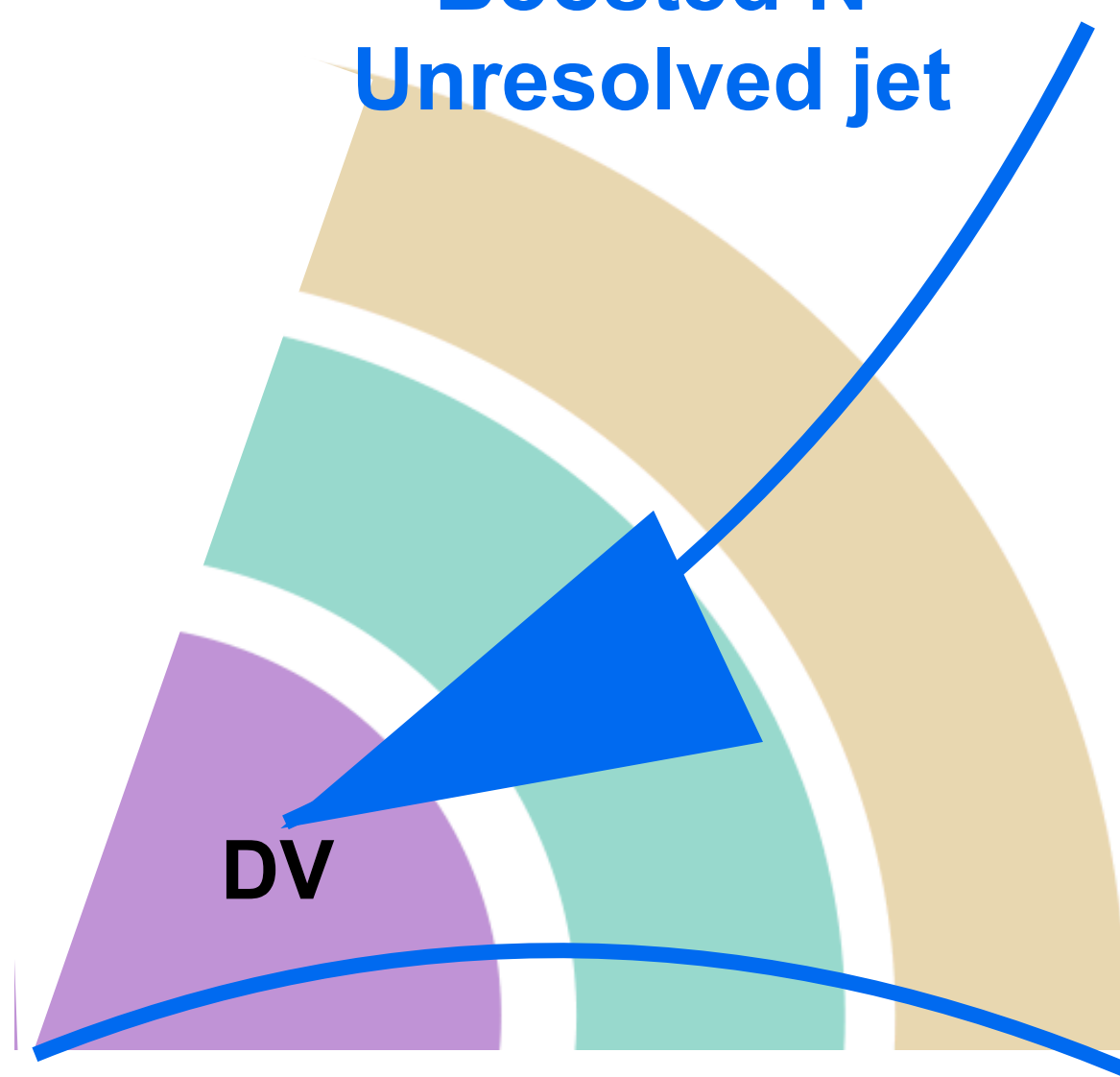
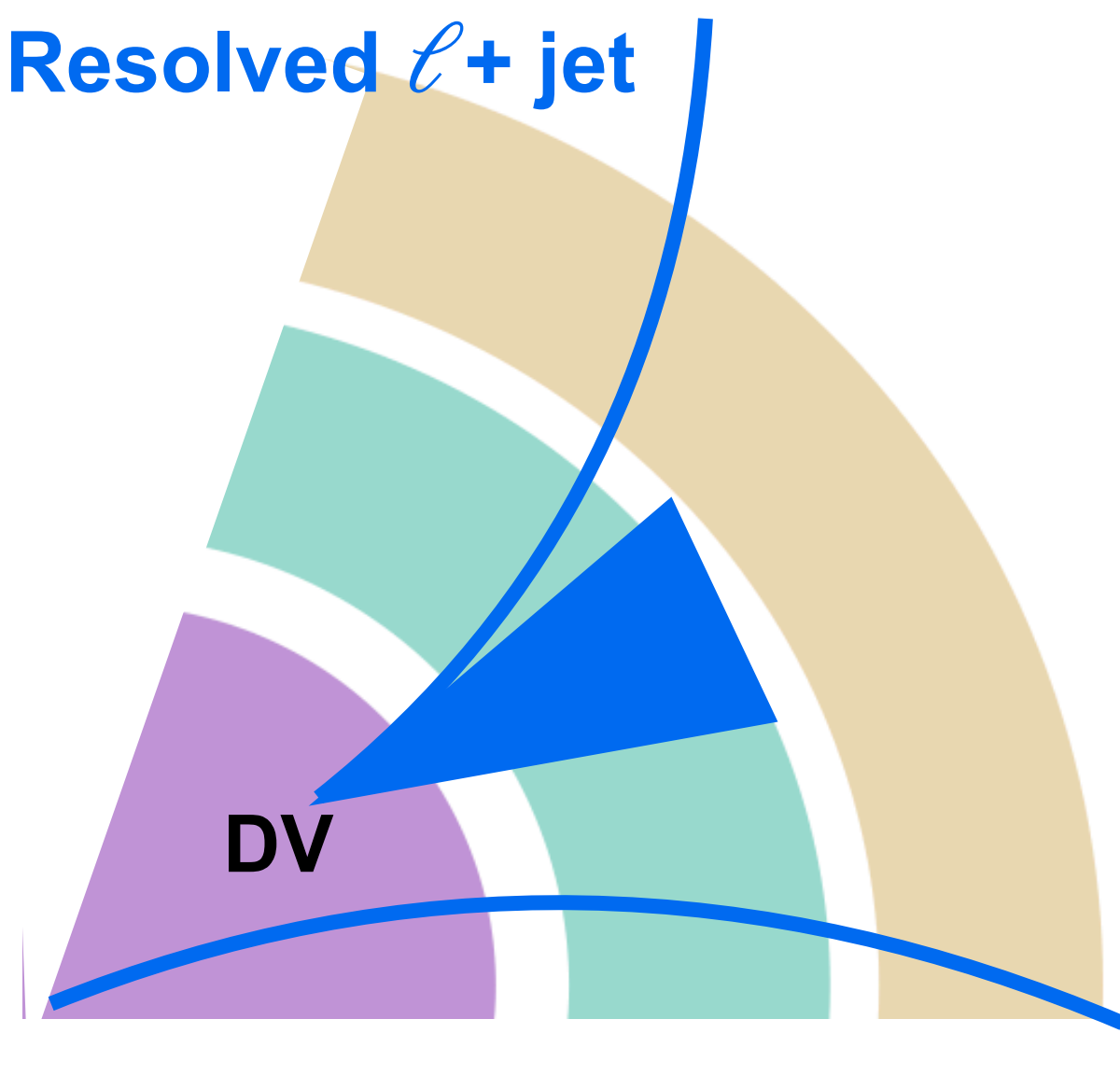


ℓ + jet searches - CMS

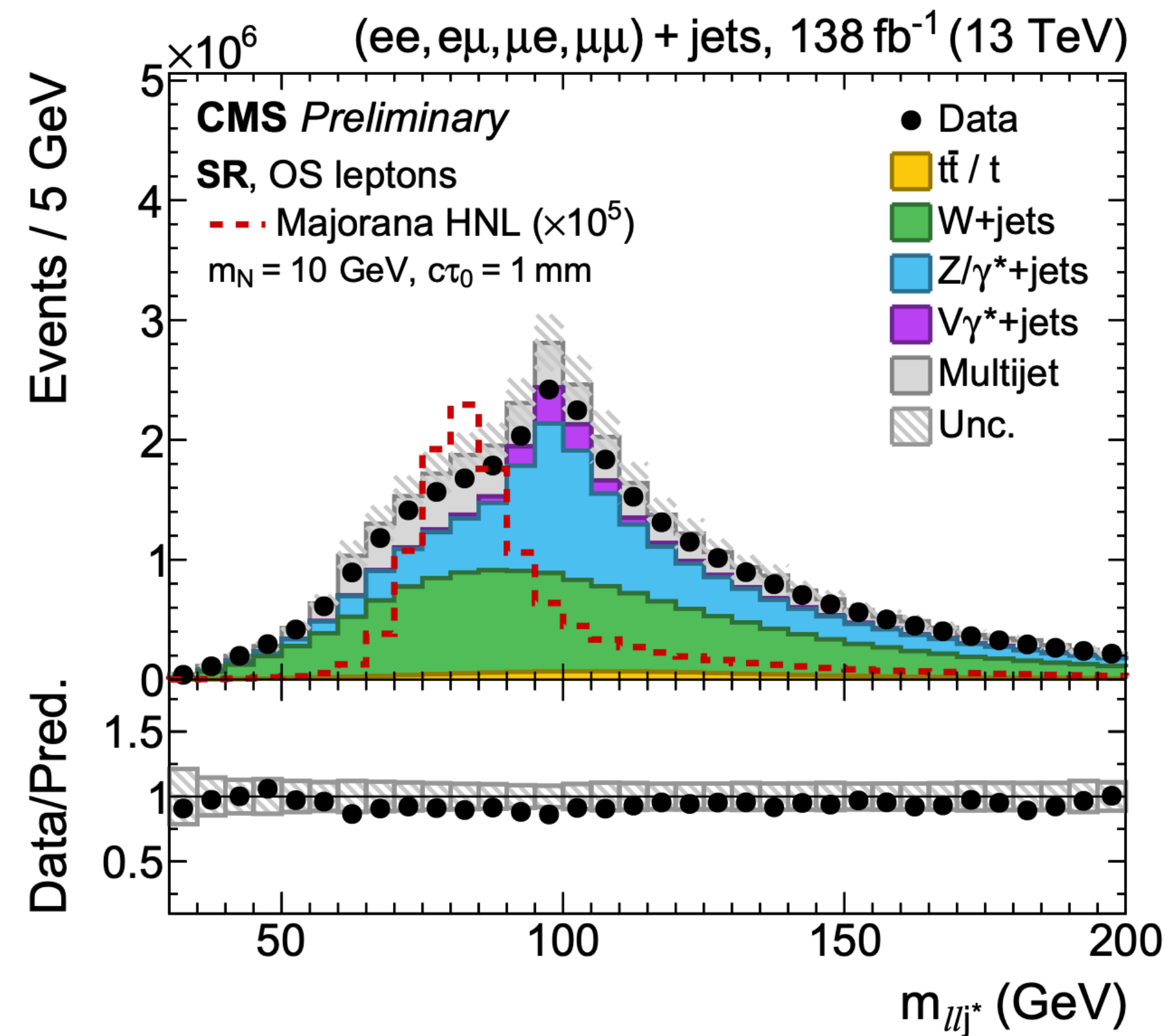


Low boost N
Resolved ℓ + jet

Boosted N
Unresolved jet



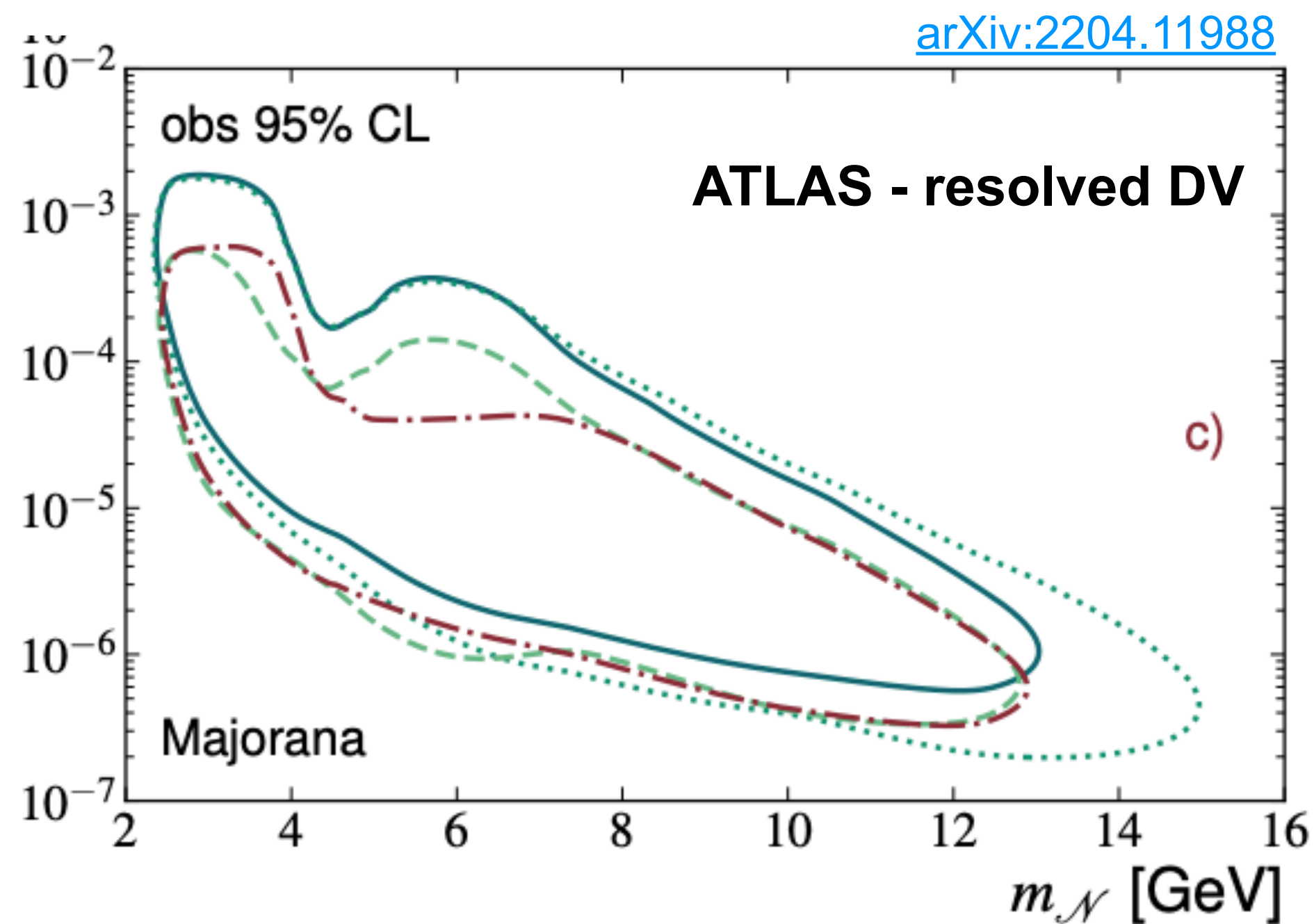
- NN displaced jet tagger
- No DV needed



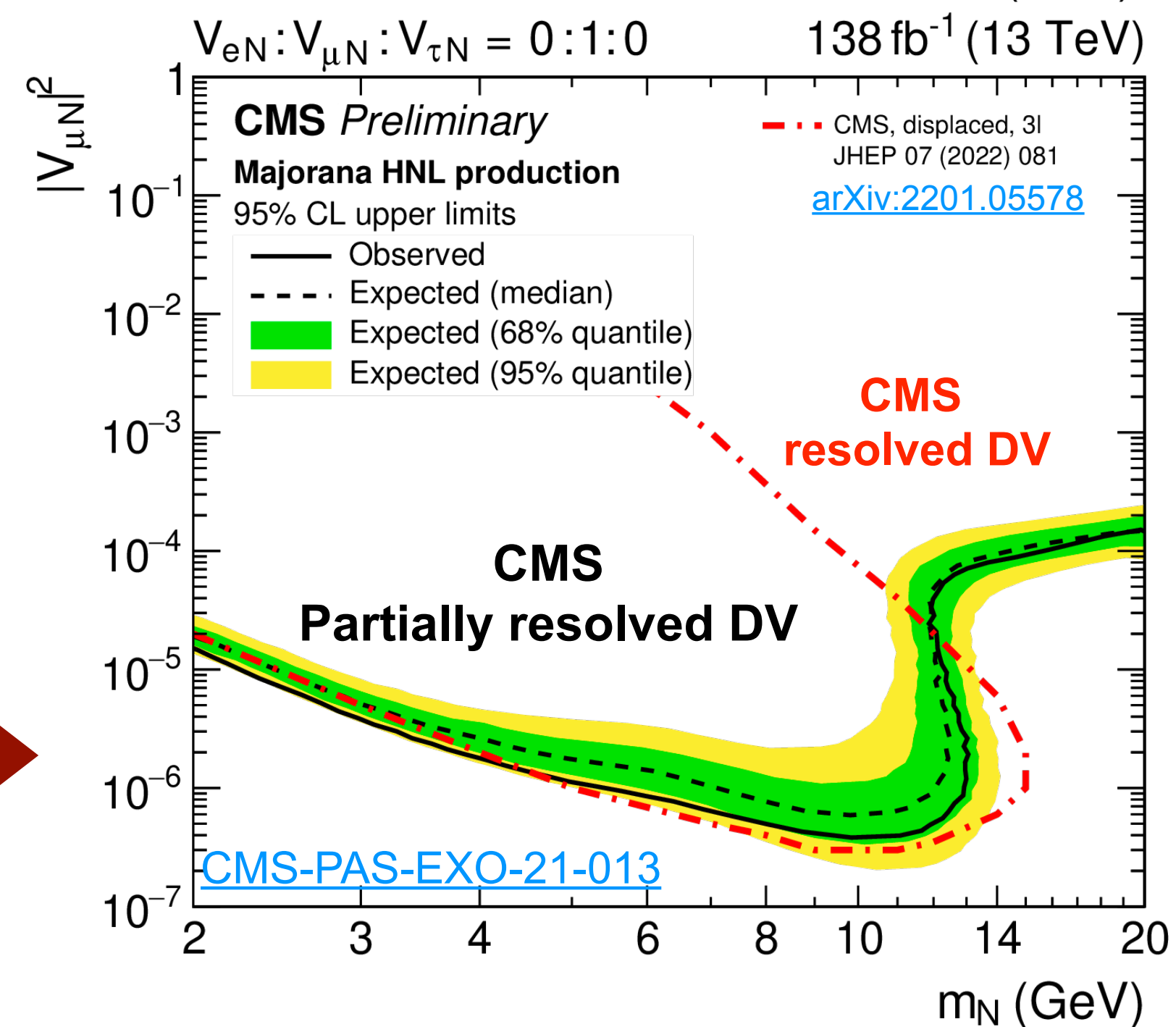
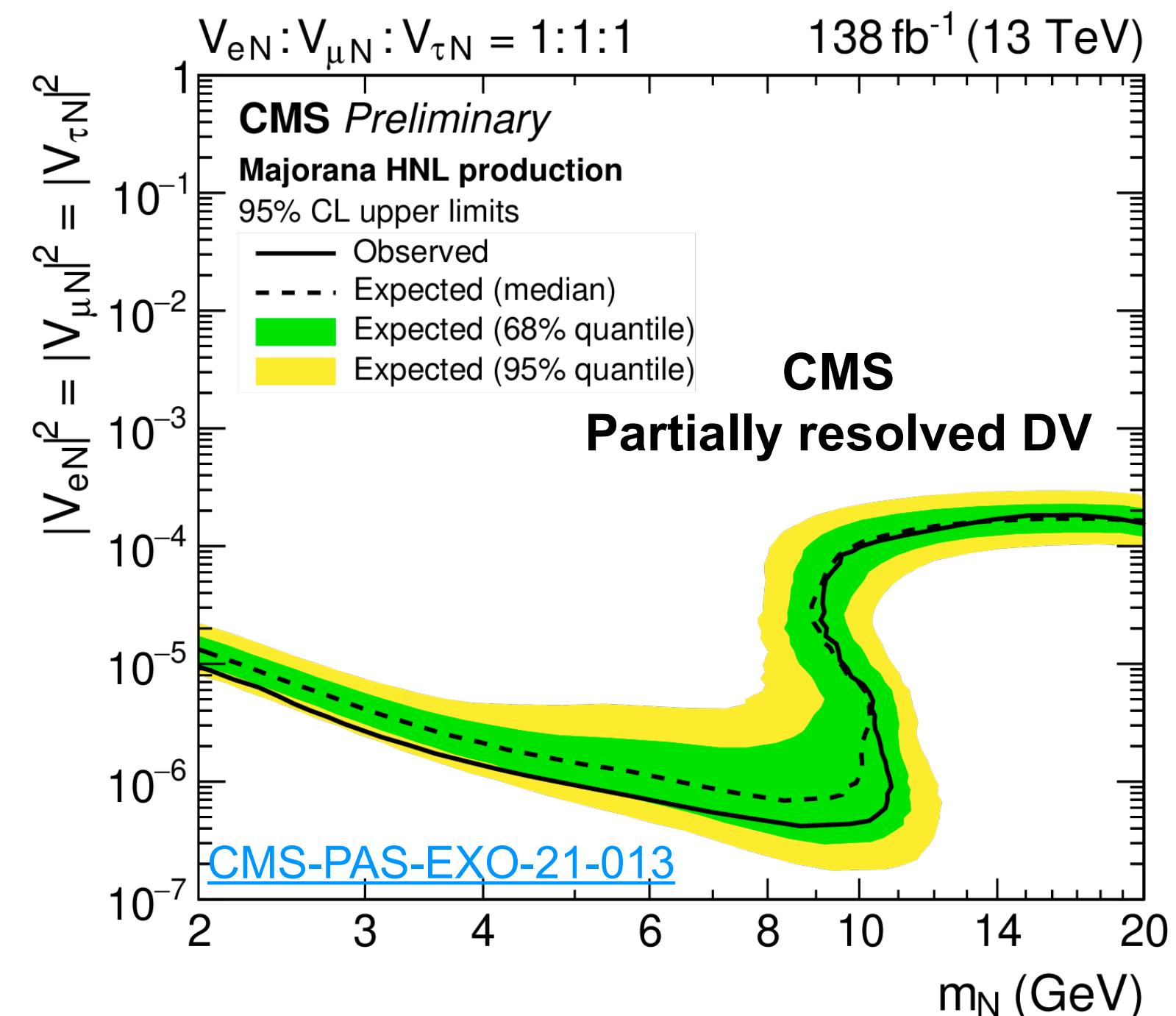
Results - $m_{\text{HNL}} [2-20] \text{ GeV}$

$$(|U_e|^2, |U_\mu|^2, |U_\tau|^2)$$

- 2QDH (NH) (0.06, 0.48, 0.46)
- ⋯ 2QDH (IH) (0.33, 0.33, 0.33)



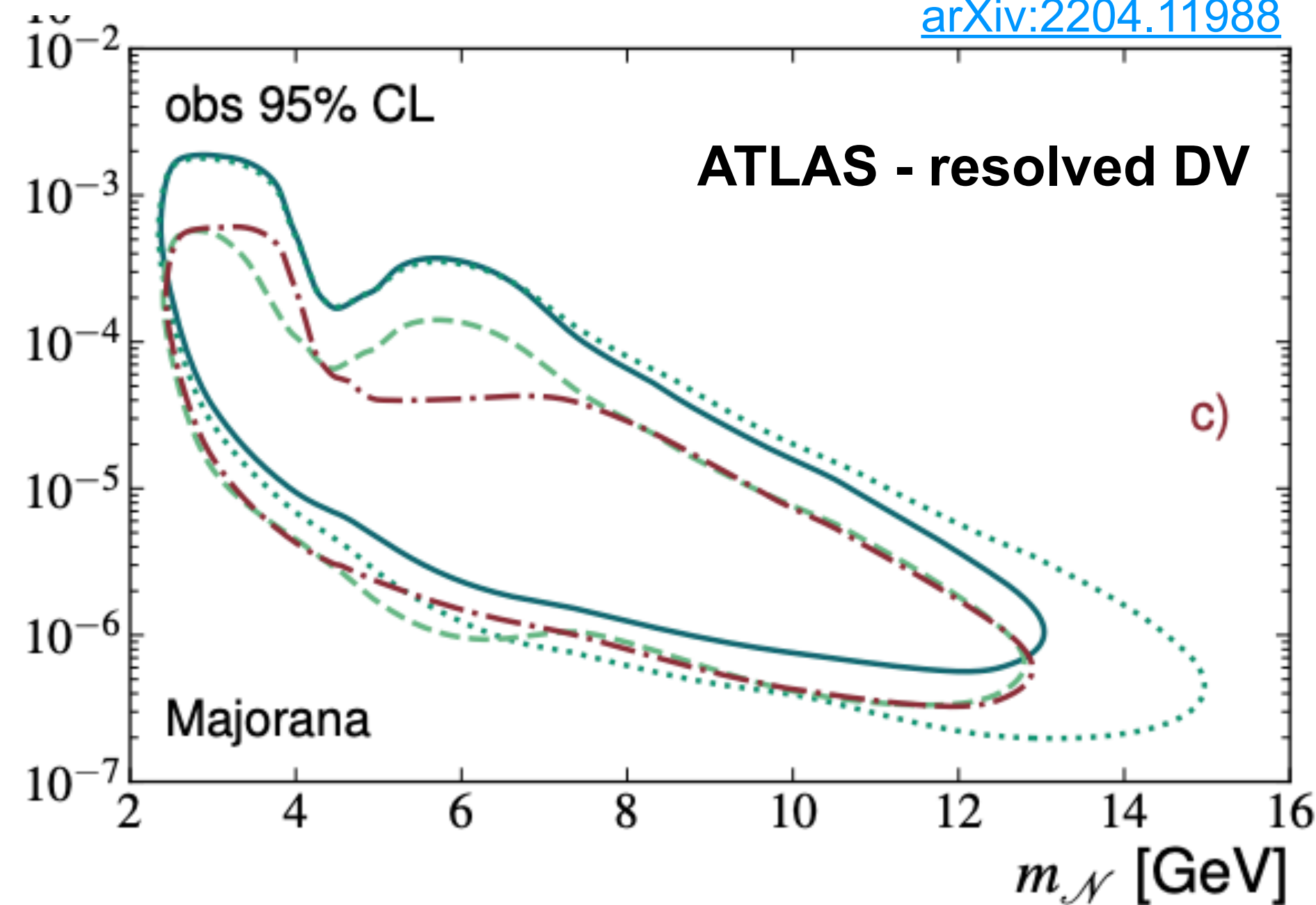
- - - 1SFH (e) (1,0,0)
- · - 1SFH (μ) (0,1,0)



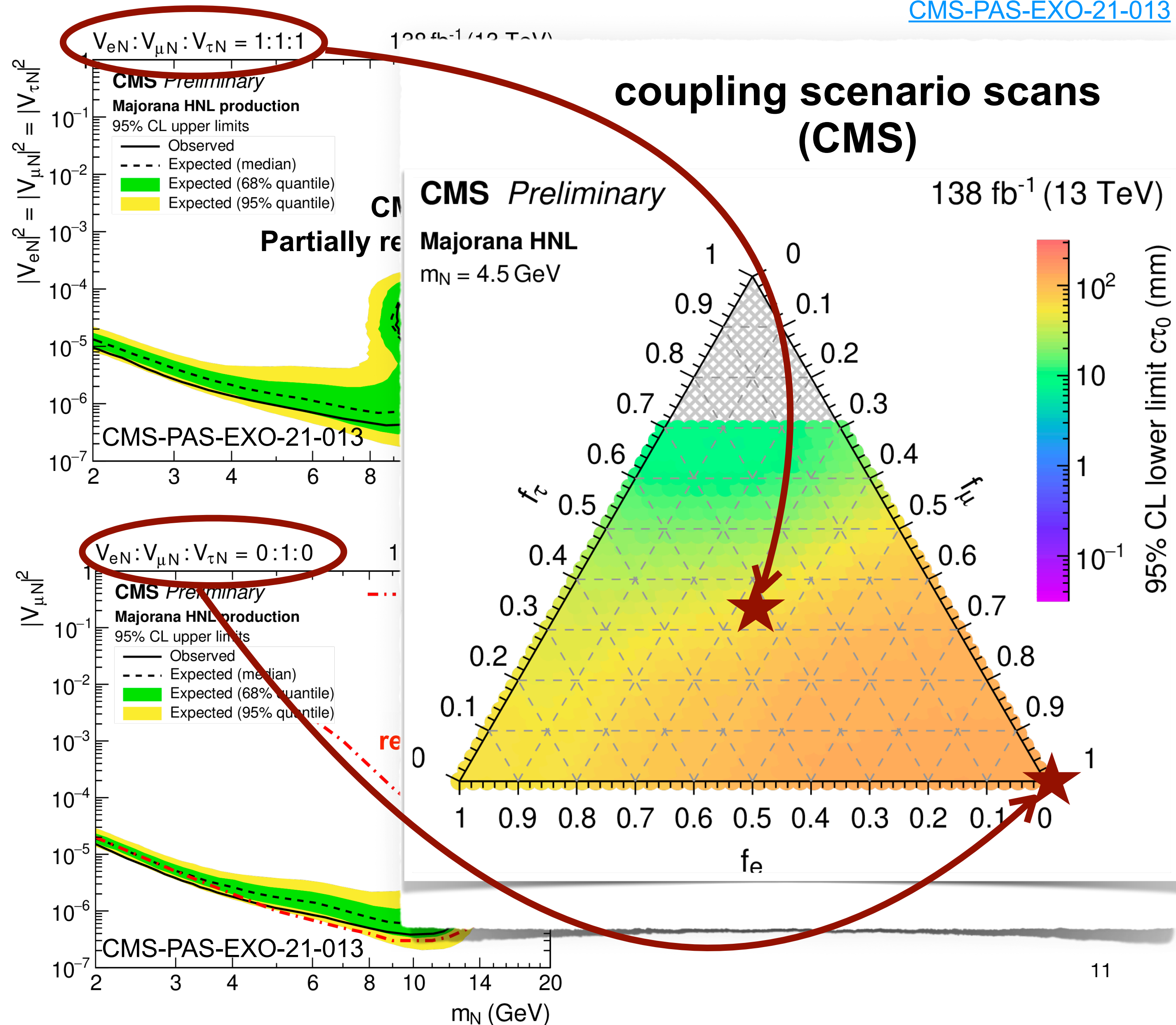
Results - $m_{\text{HNL}} [2-20]$ GeV

$$(|U_e|^2, |U_\mu|^2, |U_\tau|^2)$$

- 2QDH (NH) (0.06, 0.48, 0.46)
- ⋯ 2QDH (IH) (0.33, 0.33, 0.33)



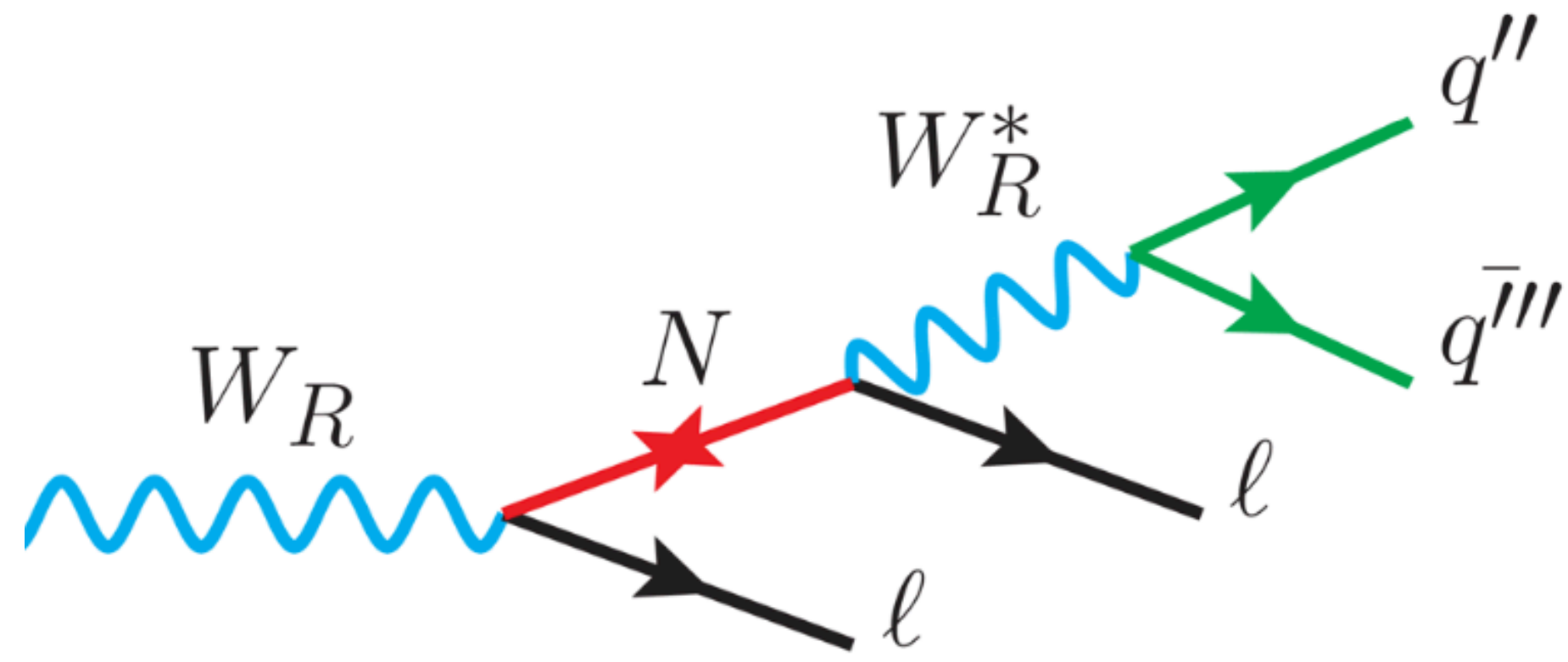
- - - 1SFH (e) (1,0,0)
- · - 1SFH (μ) (0,1,0)



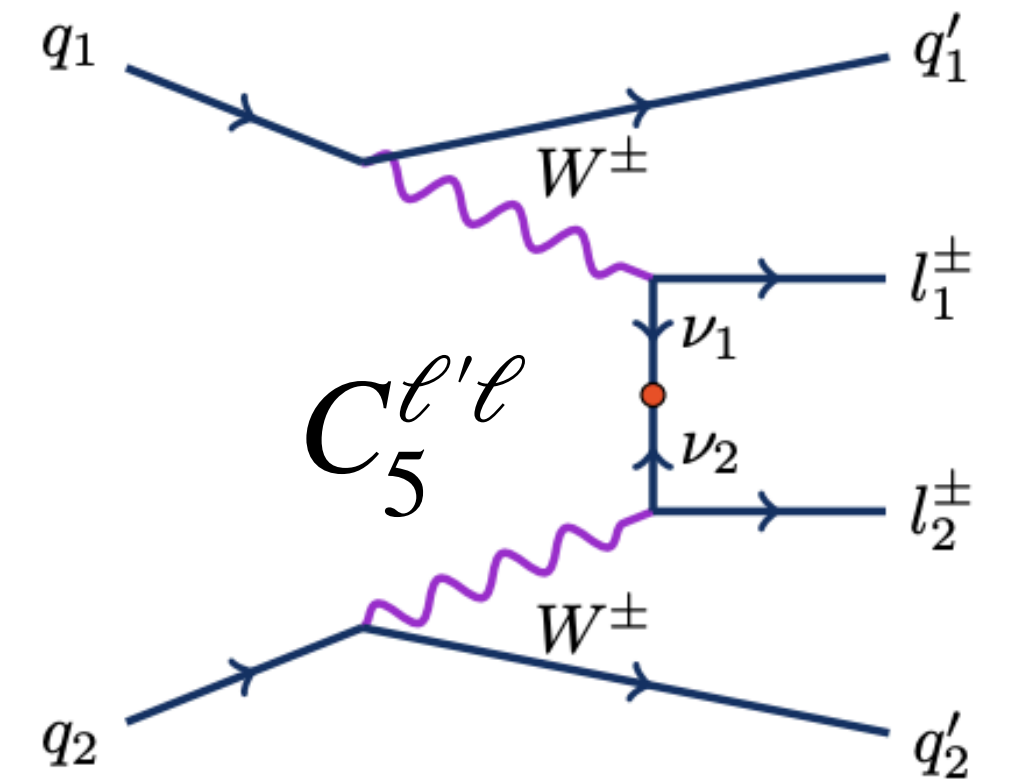
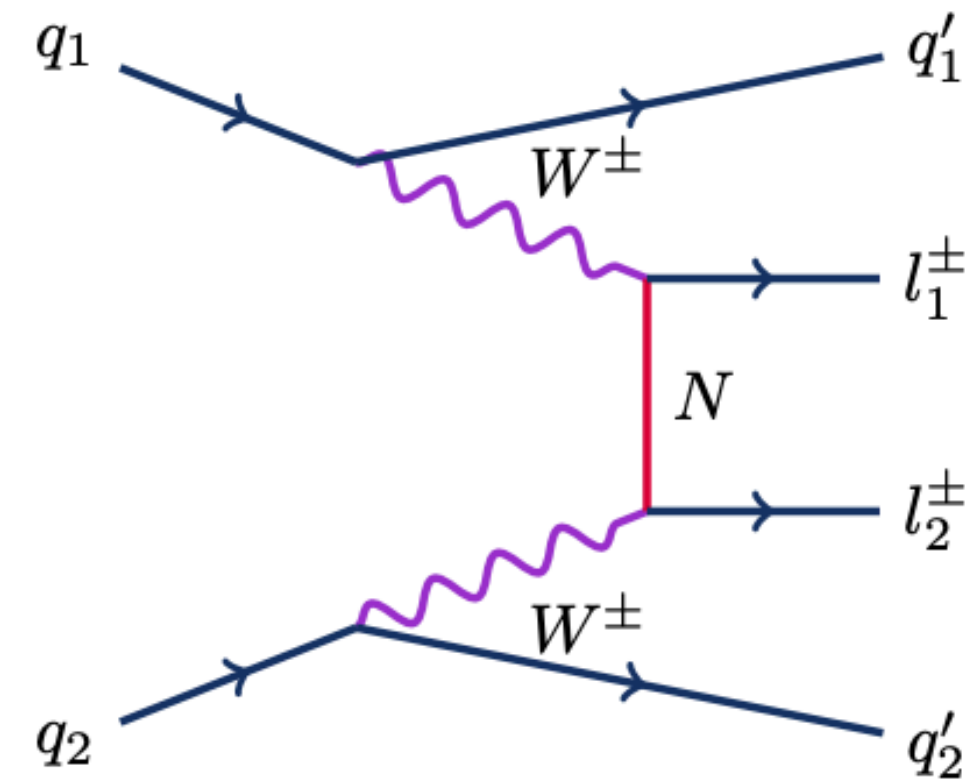
W_R bosons + HNL & $W^\pm W^\pm$ scattering

m_{HNL} in multi-TeV scale

- **SM + $SU(2)_R$** : $W_R \rightarrow N + \ell$



- **SMEFT - N OR Weinberg $C_5^{\ell'\ell}$**



complementary final states

If $M_{W_R} \gg m_N$ - Boosted regime:

lepton(s) + 1 jet

2 leptons + 2 jets

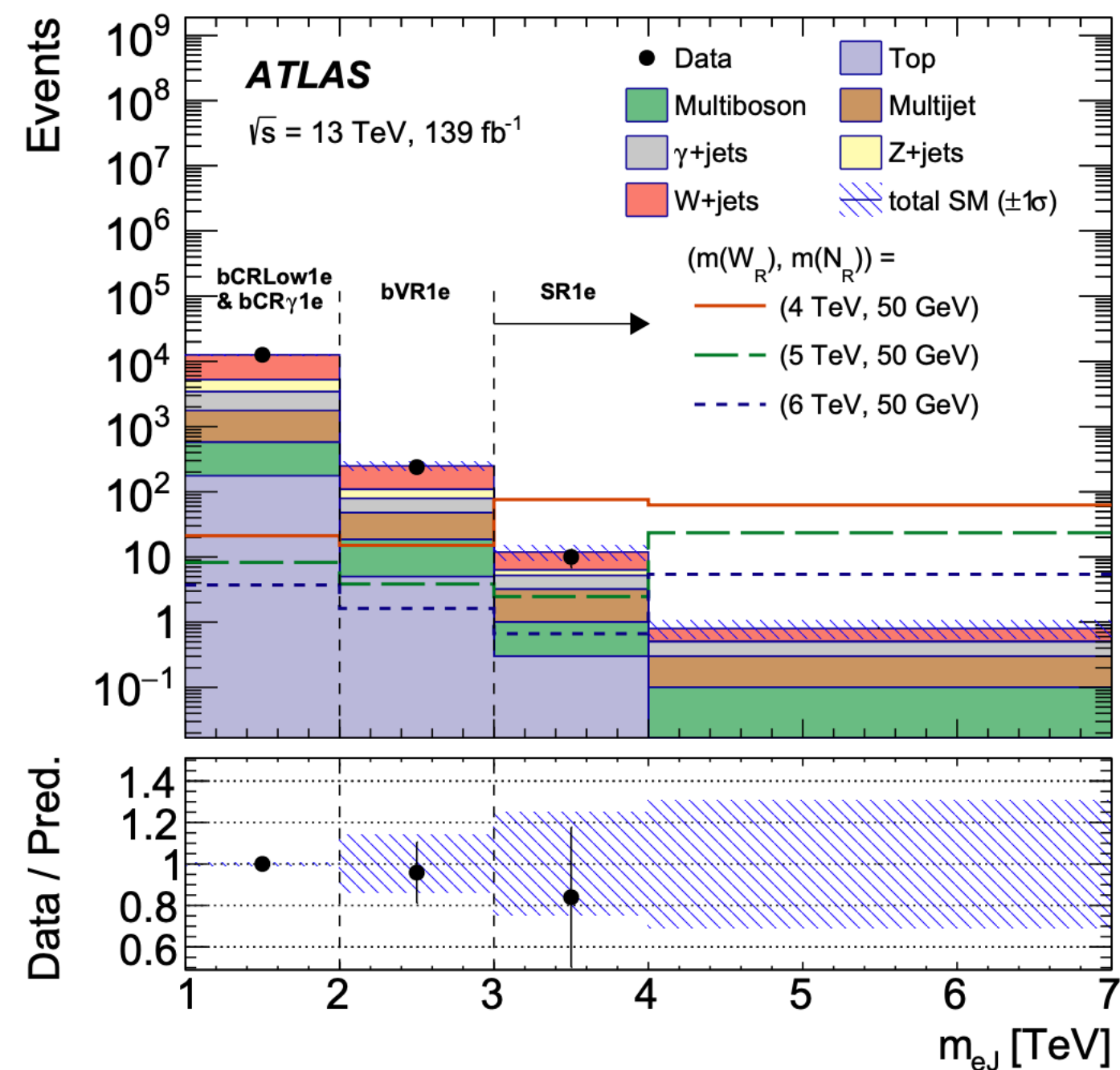
High $\Delta\eta$ jets separation

μ signatures only

$W_R \rightarrow N + \ell$ analysis strategy

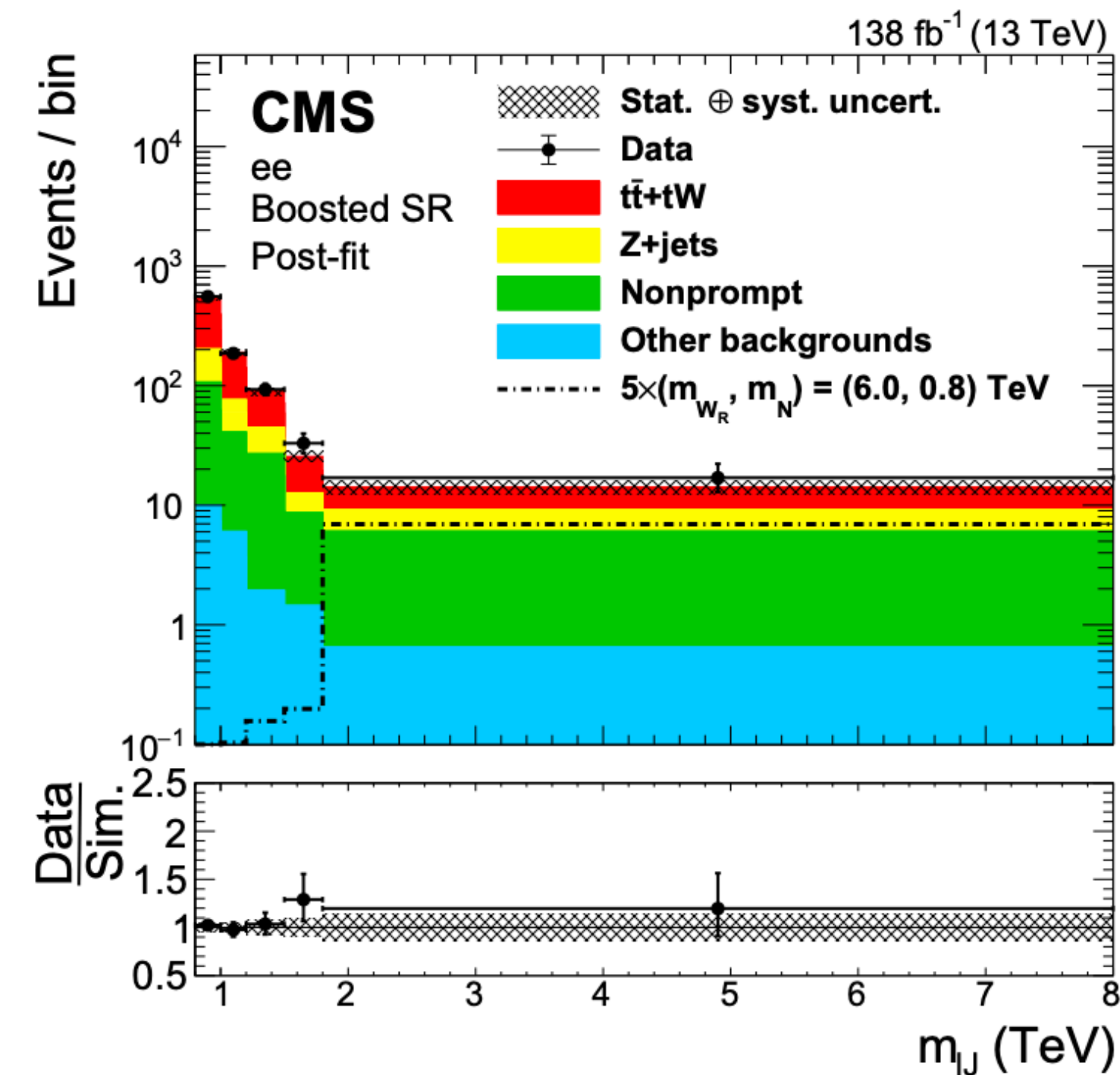
ATLAS [arXiv:1809.11105](https://arxiv.org/abs/1809.11105)

- Resolved + boosted ($\Delta M > 4$ TeV)
- Boosted: 2 leptons + 1 jet
- + (electron + monojet)



CMS [arXiv:2112.03949](https://arxiv.org/abs/2112.03949)

- Resolved + boosted ($m_{W_R}/m_{HNL} > 10$)
- Boosted = 1 isolated lepton + 1 jet (+ lepton)

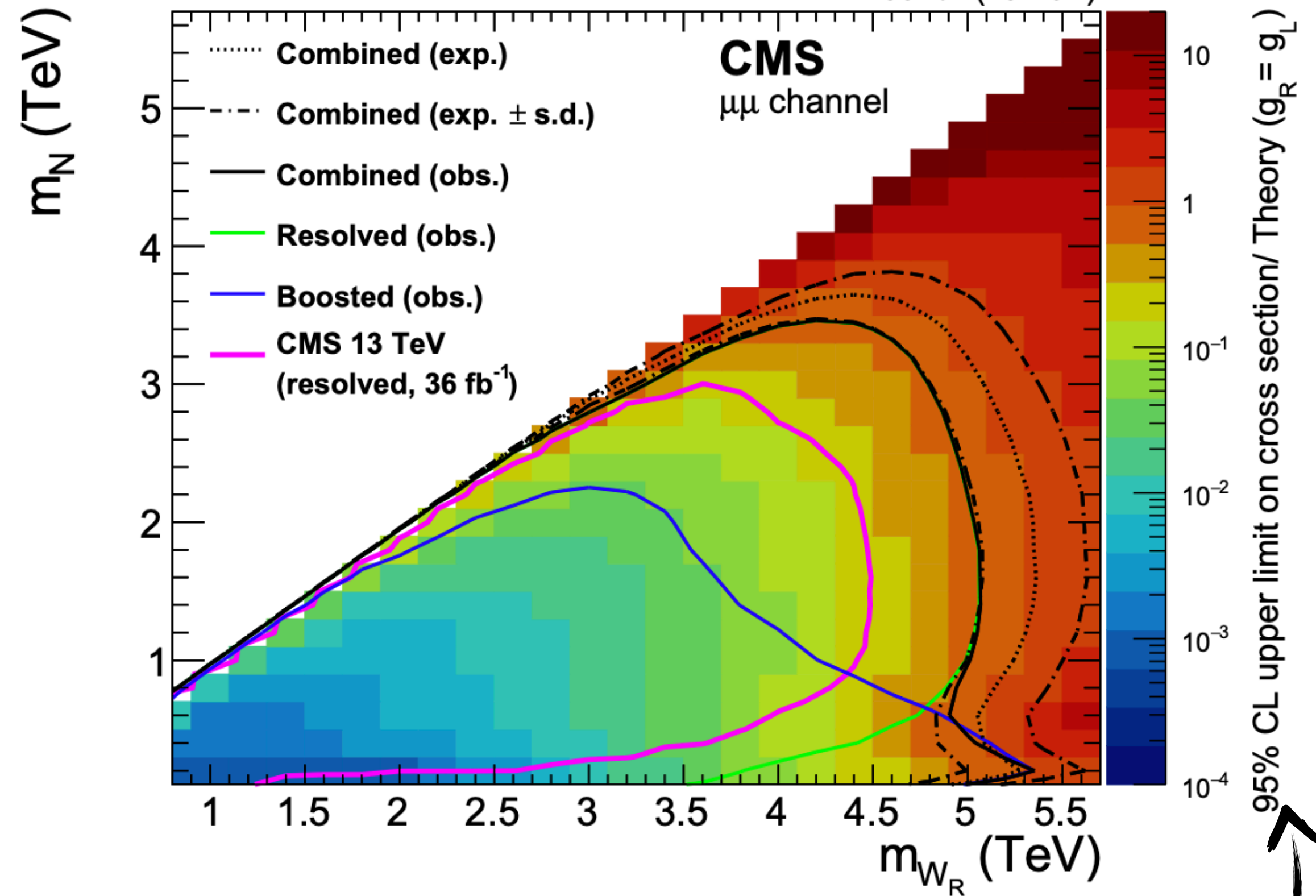
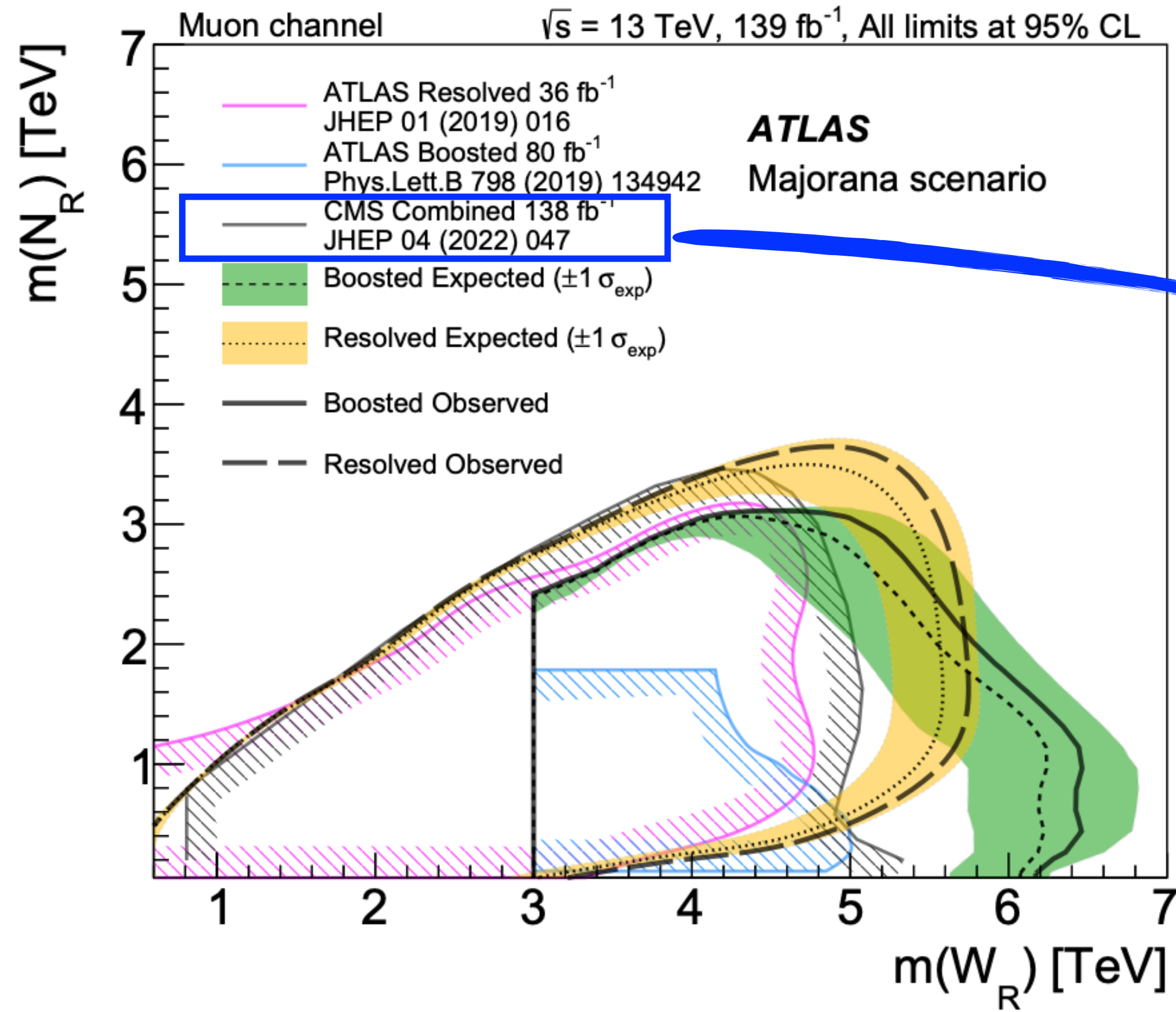


$W_R \rightarrow N + \ell$ results

[arXiv:1809.11105](https://arxiv.org/abs/1809.11105)

Moriond 2023

[arXiv:2112.03949](https://arxiv.org/abs/2112.03949)

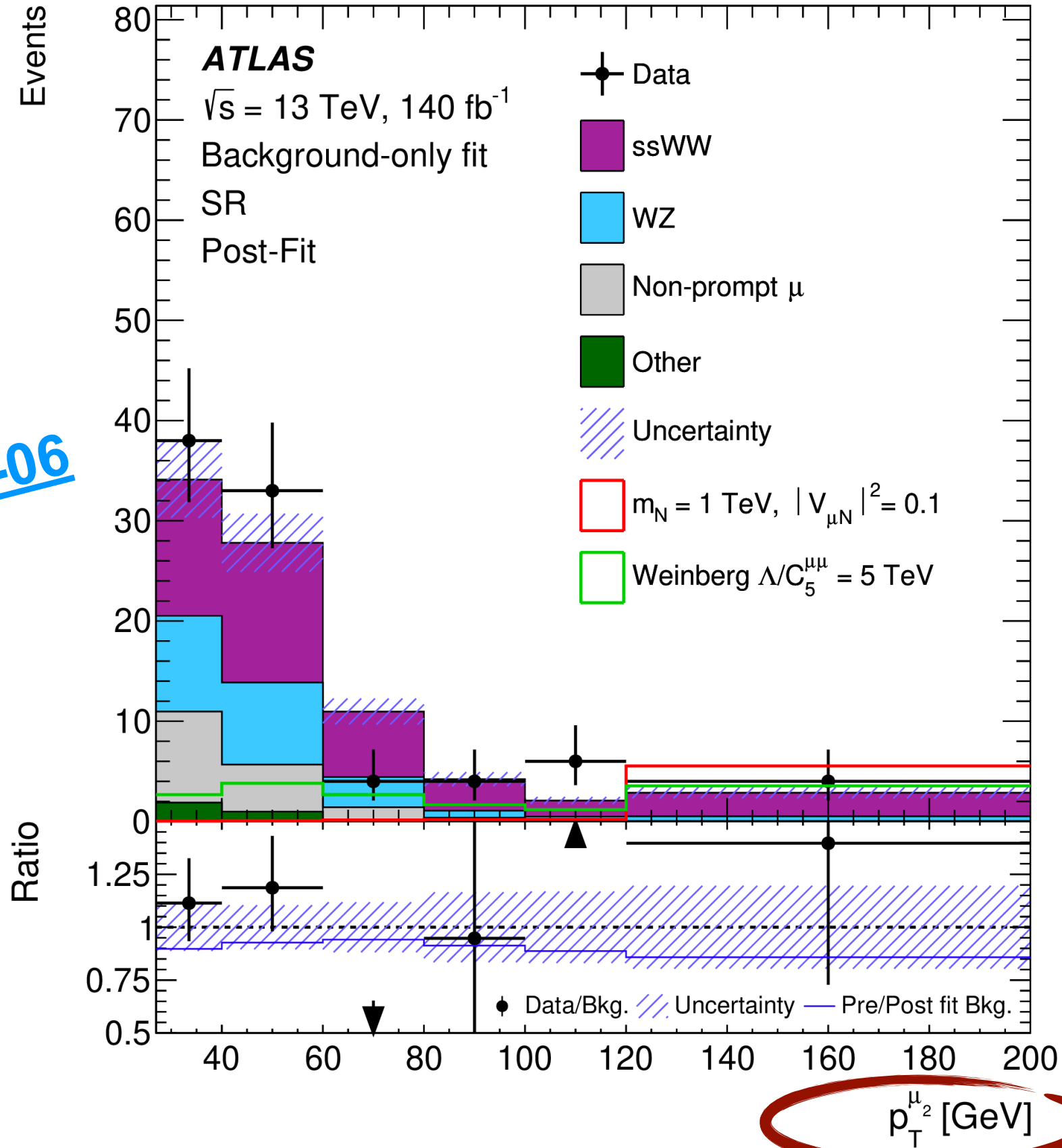


Most stringent limit to date to W_R N events

$\sigma_{95\%C.L.} / \sigma_{SM}$ scan

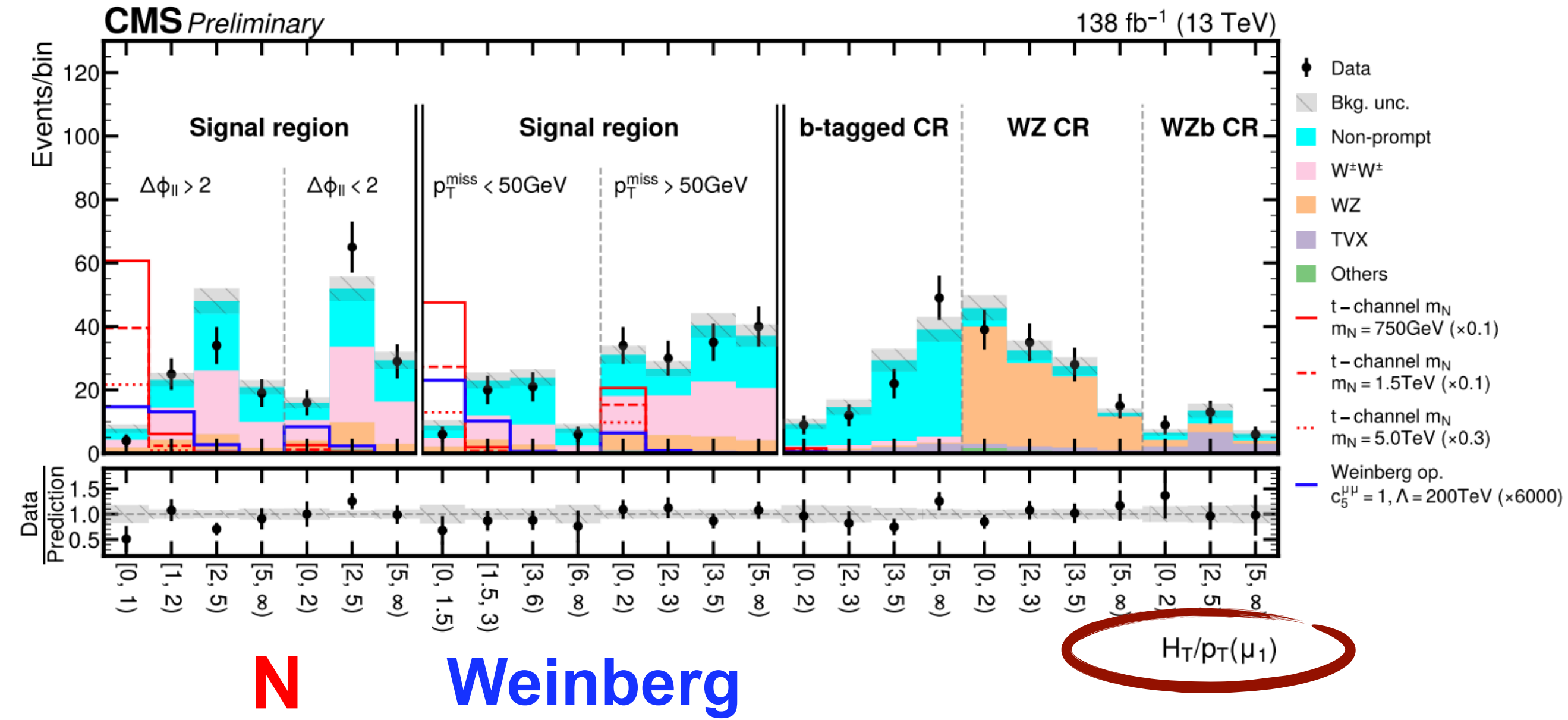
$W^\pm W^\pm$ scattering - analysis strategy

ATLAS



NEW!
 EXOT-2020-06

CMS [arXiv:2206.08956](https://arxiv.org/abs/2206.08956)



N **Weinberg**

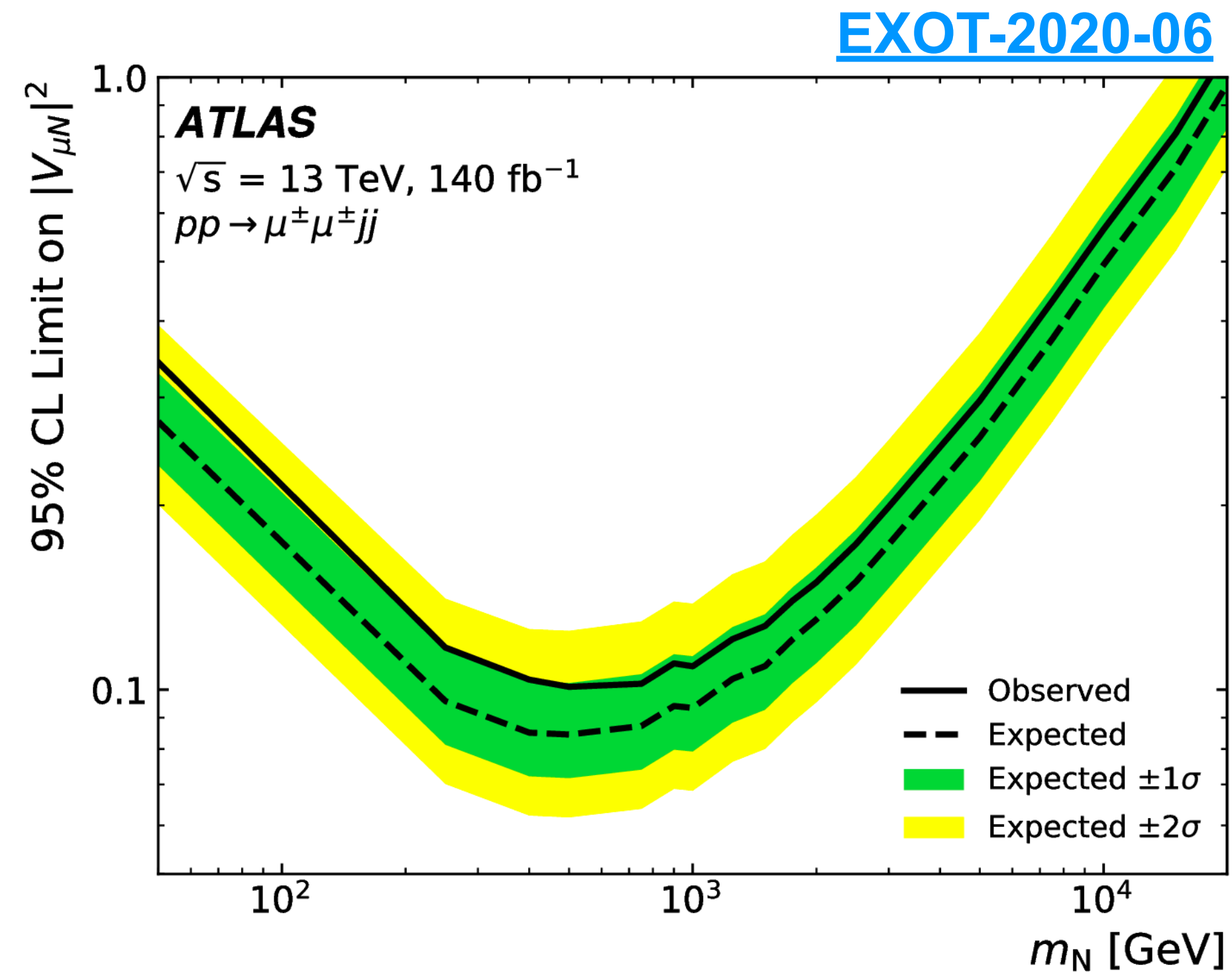
$H_T/p_T(\mu_1)$
 H_T : sum of the jets p_T

- $p_T^{\mu_2}$ most discriminating variable
- SR optimised for **N with $m_N > 1 \text{ TeV}$**

- $H_T/p_T^{\mu_1}$ most discriminating variable
- Two SRs for **N** vs **Weinberg** hypotheses

$W^\pm W^\pm$ scattering - results

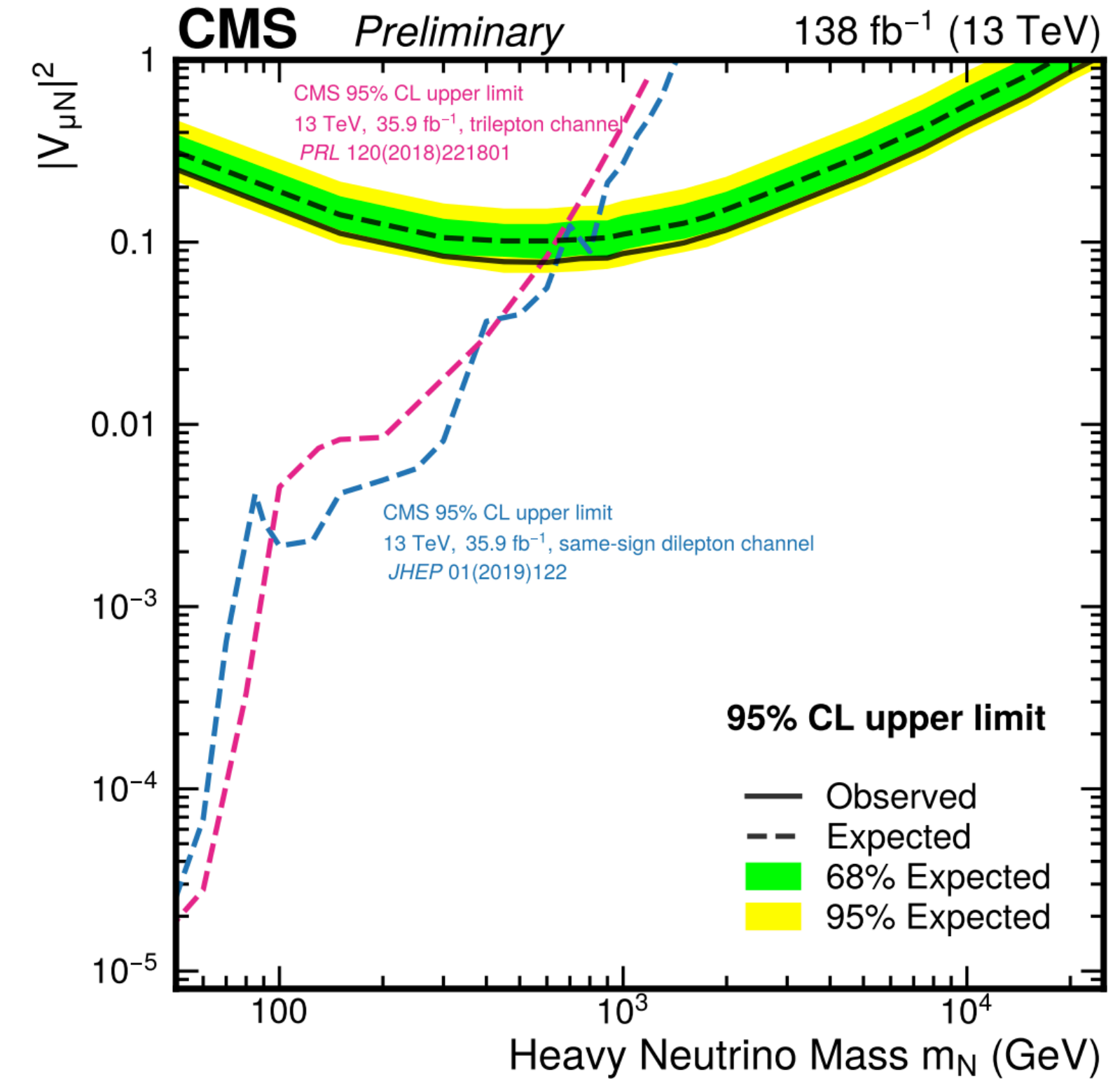
ATLAS



**Competitive exclusions
for multi-TeV scale**

$m_{\mu\mu}^{\text{EFT}}$ (observed) upper limit **16.7 GeV**

CMS [arXiv:2206.08956](#)



$m_{\mu\mu}^{\text{EFT}}$ (observed) upper limit **10.84 GeV**

Conclusions

- **HNL searches: fast evolving sector in LHC**
 - Multiple models to probe (see-saw type I and III, prompt heavy HNLs)
 - Large energy and lifetimes reach
- **Push detectors reconstruction potential:**
 - Displaced soft signatures
 - Merged boosted high energy signatures
- **New algorithms and innovative signatures** crucial for maximal data exploitation:
 - Large Radius Tracking (ATLAS)
 - Outer detector signatures for very displaced signals (CMS)

Backup

More LHC Run2 HNL literature

- **ATLAS:** HNL decays to displaced dilepton vertex search - arXiv:2204.11988
- **CMS:** HNL decays to displaced dilepton vertex - arXiv:2201.05578
HNL decays to displaced lepton + jets search - CMS-PAS-EXO-21-013
- **LHCb:** Search for heavy neutral leptons in $W^+ \rightarrow \mu^+\mu^\pm$ jet decays Eur. Phys. J. C 81 (2021) 248 (LHCb)

- **ATLAS:** Search for type-III seesaw heavy leptons in leptonic final states - arXiv:2202.02039
- **CMS:** Inclusive nonresonant multilepton probes of new phenomena - arXiv:2202.08676

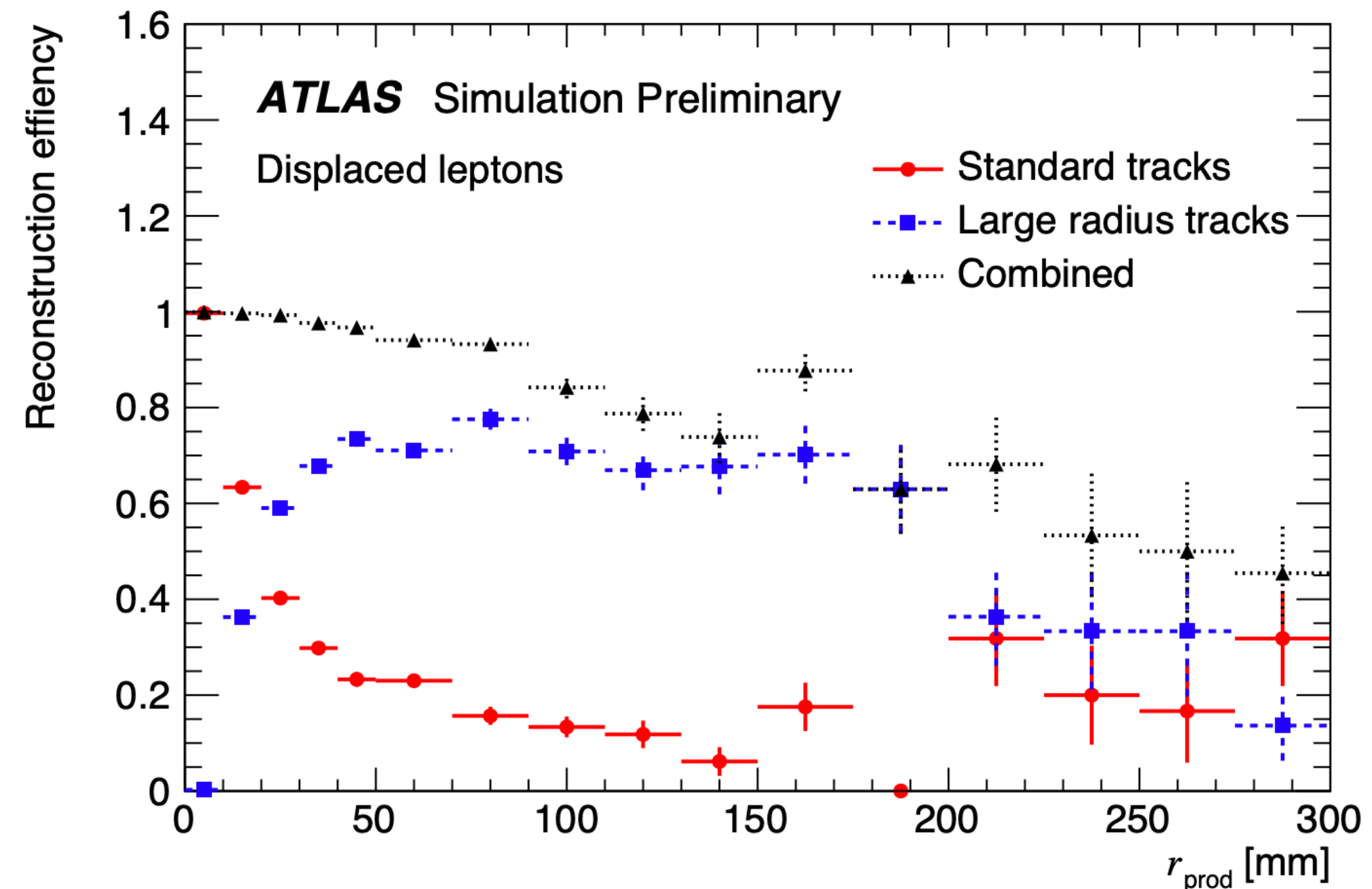
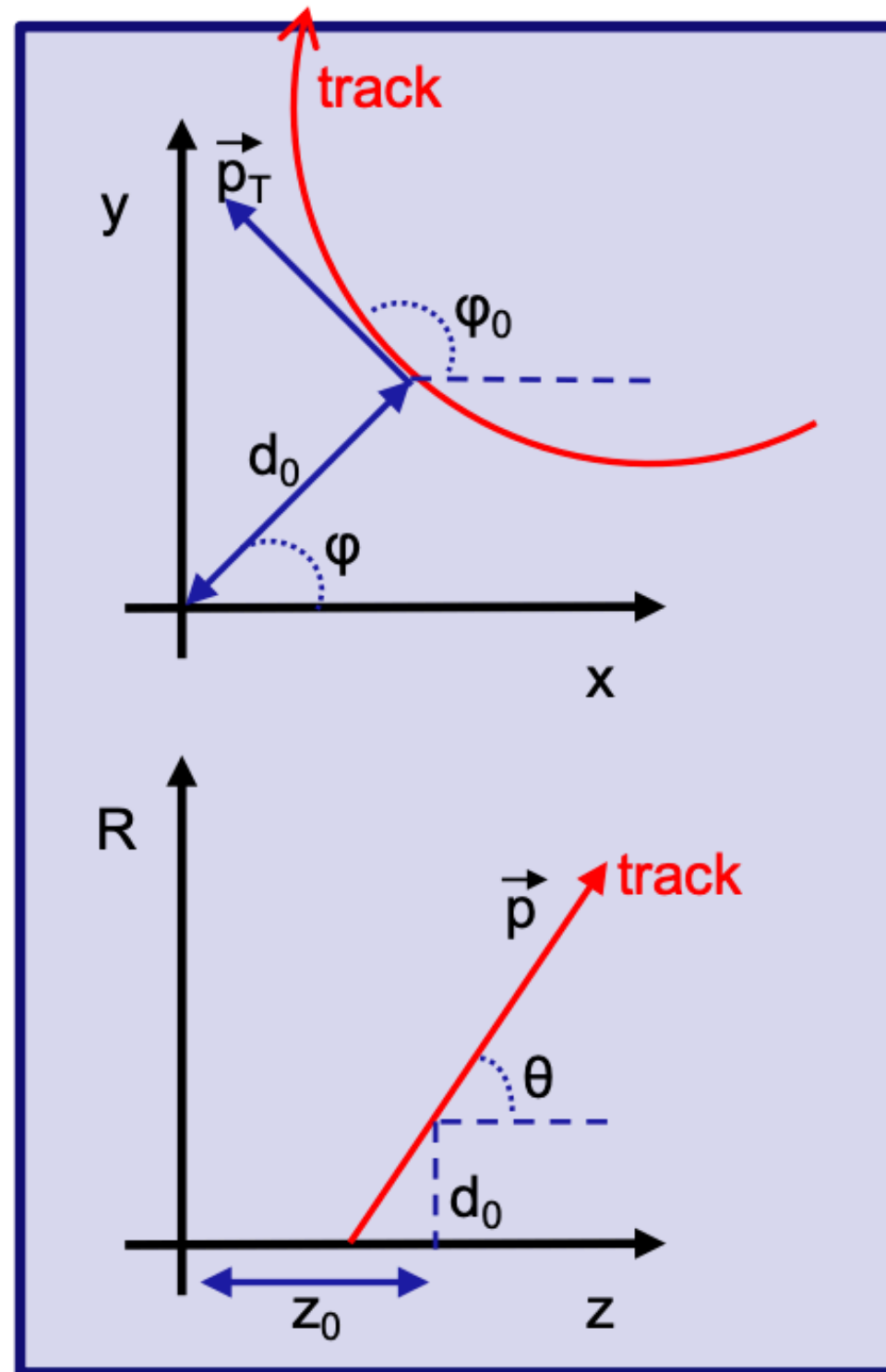
- **ATLAS:** Search for heavy Majorana or Dirac neutrinos and right-handed W gauge bosons in final states with charged leptons and jets - **arXiv:2204.11988**
- **CMS:** Search for a right-handed W boson and a heavy neutrino - **arXiv:2112.03949**

- **ATLAS:** Search for Majorana neutrinos in same-sign WW scattering events -
- **CMS:** heavy Majorana neutrinos and the Weinberg operator through vector boson fusion **arXiv:2206.08956**
- **CMS:** Search for a heavy composite Majorana neutrino **arXiv:2210.03082 (CMS)**
- **CMS:** Search for Z' bosons decaying to pairs of heavy Majorana neutrinos in proton-proton collisions at $\sqrt{s}=13$ TeV **CMS-PAS-EXO-20-006 (CMS)**

ATLAS Large Radius Tracking

Left over hits after standard tracking

- **Sequential Kalman Filter**
- Seeds tracks in the silicon subdetectors and extended in TRT
- track quality parameters loosened



NN displaced jet tagger

[CMS-PAS-EXO-21-013](#)

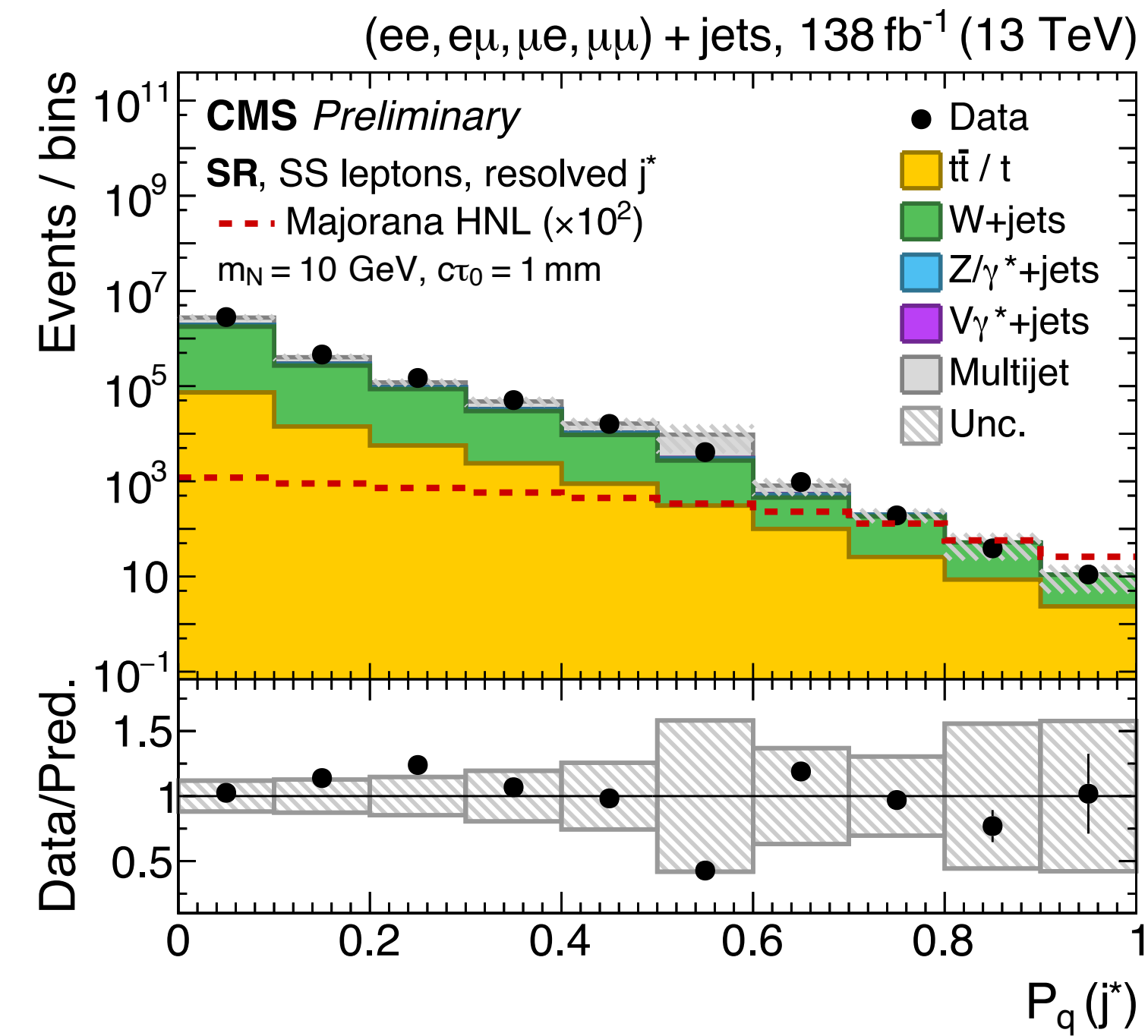
parametrised on transverse displacement L_{xy}

Multi-class discrimination:

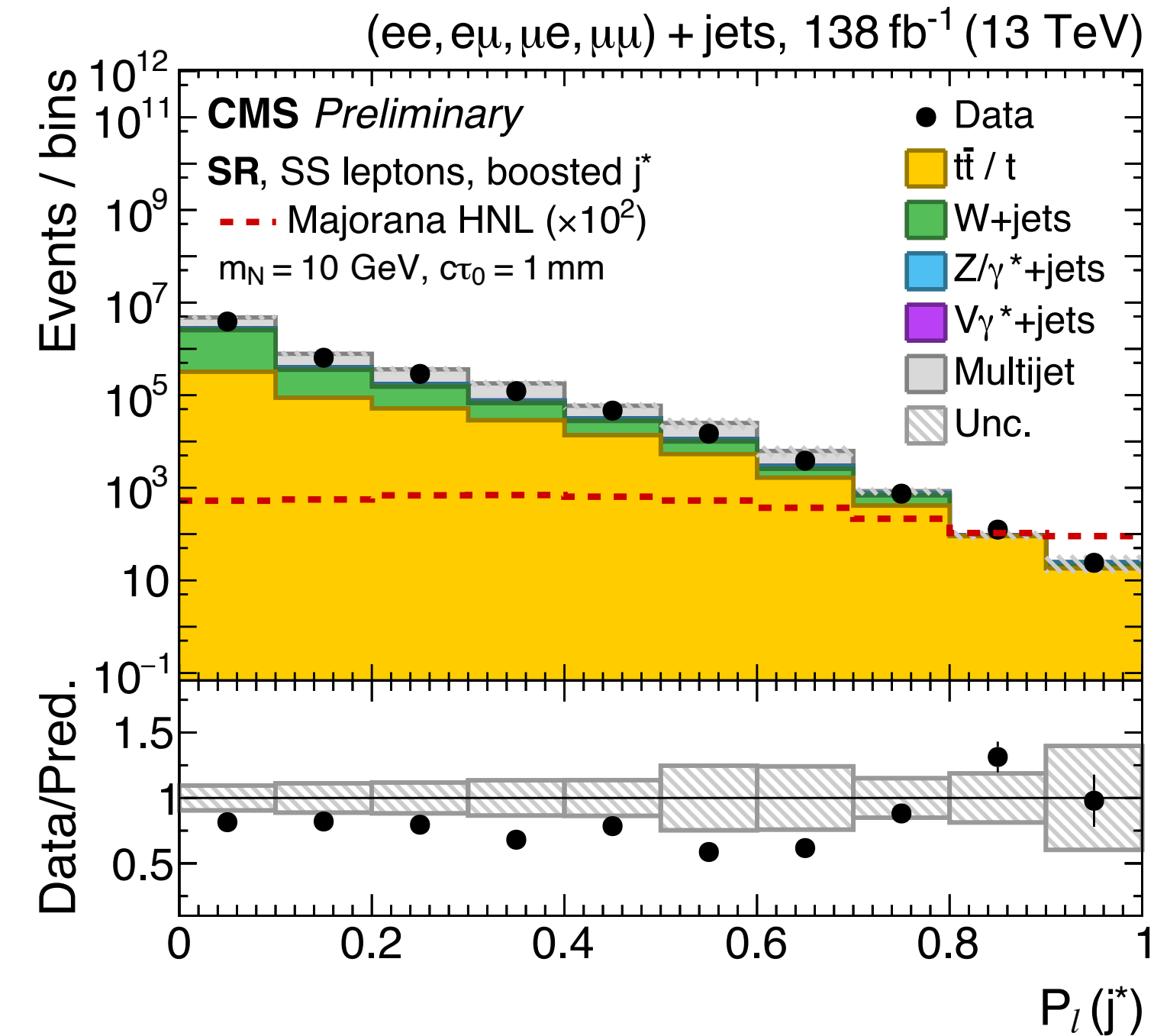
- Quark/gluon hadronization prompt jets
- **Quark/gluon hadronization displaced jets**
- Jets + prompt leptons
- **Jets+ displaced leptons**
- PU jets

Large set of features:

- Kinematics
- Jet shape and composition
- subjettiness



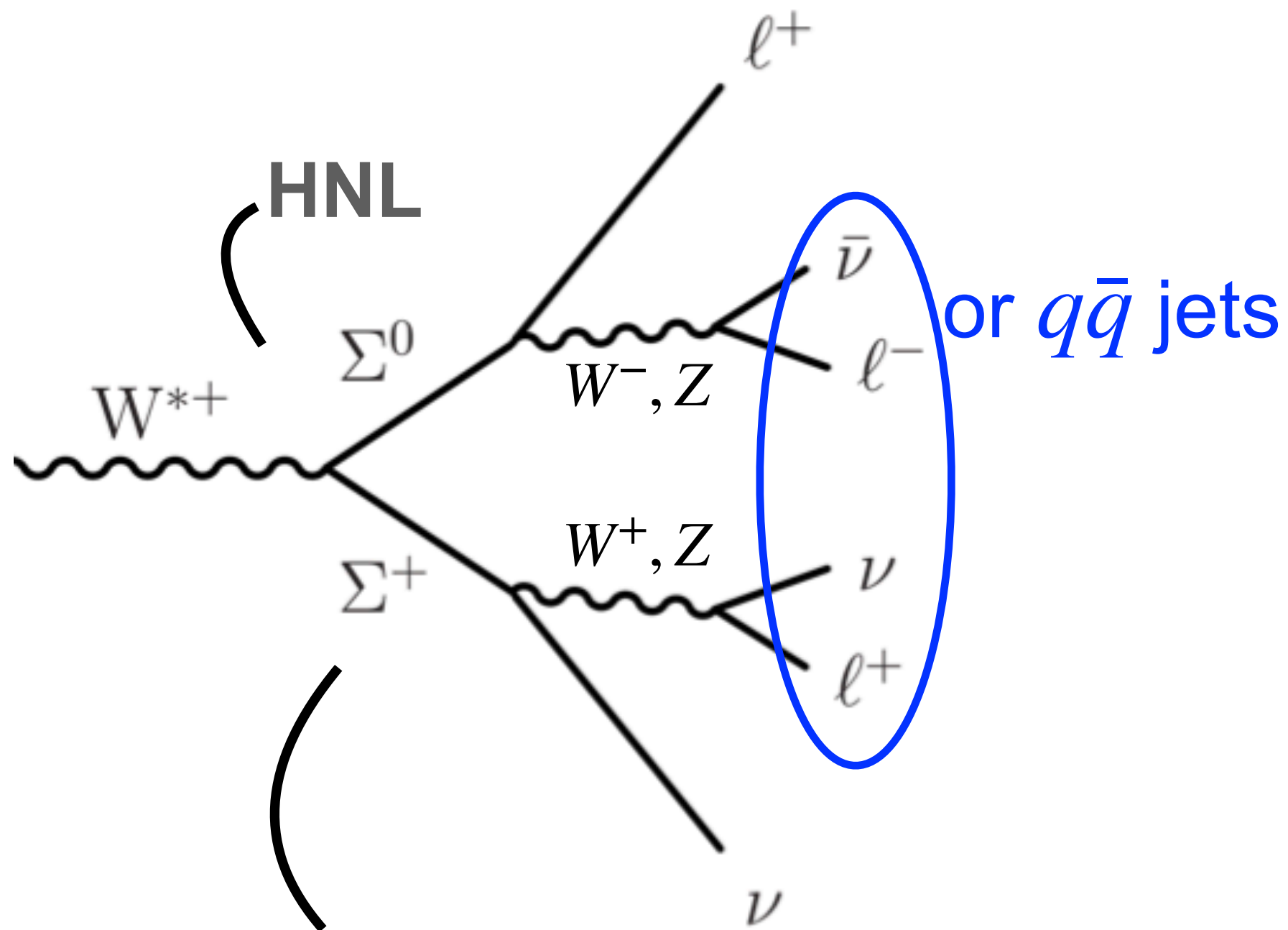
Resolved



Boosted

Type III see-saw

SM + $SU(2)_L$ triplet



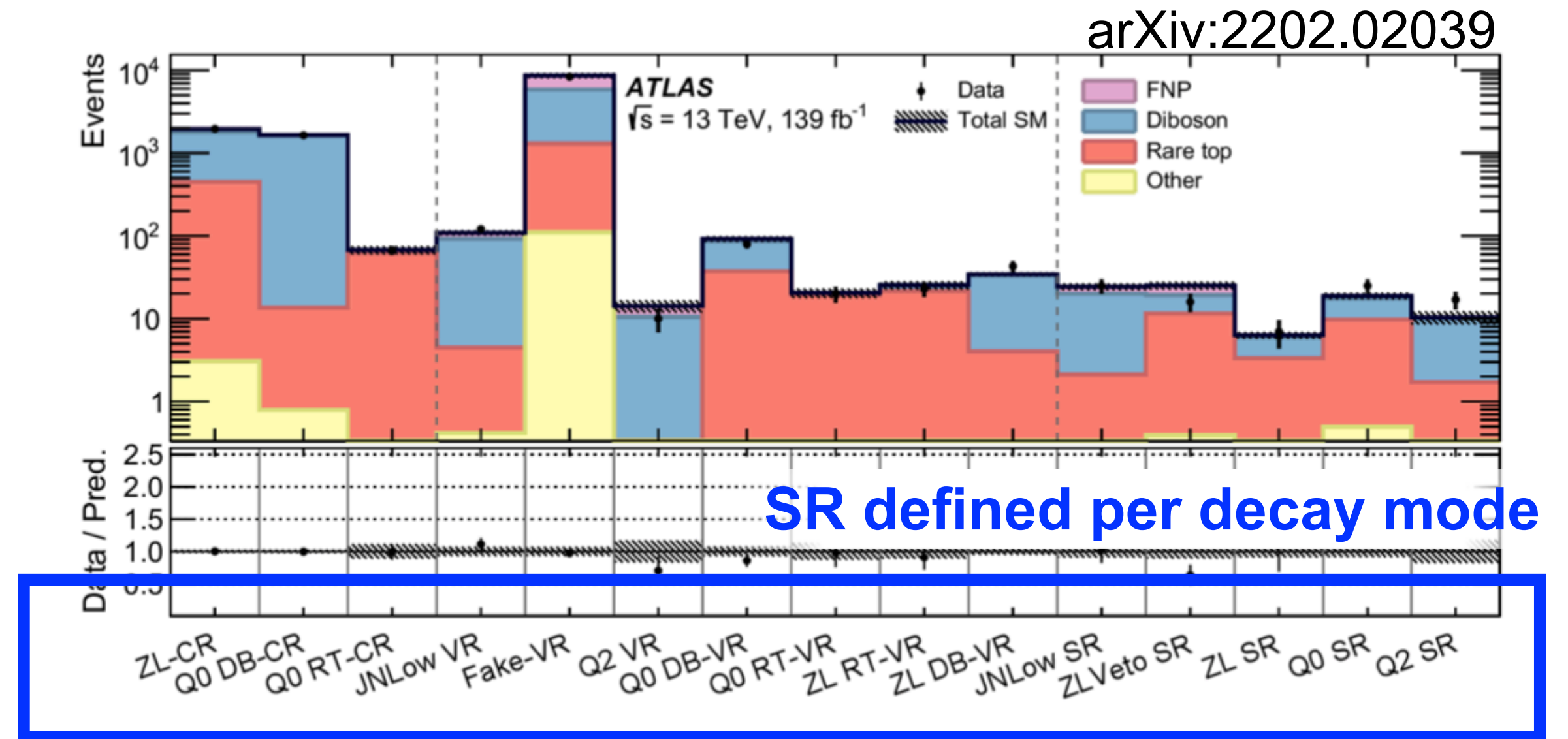
Heavy Charged Leptons

High complexity

27 distinct signatures

Raffaella Tramontano

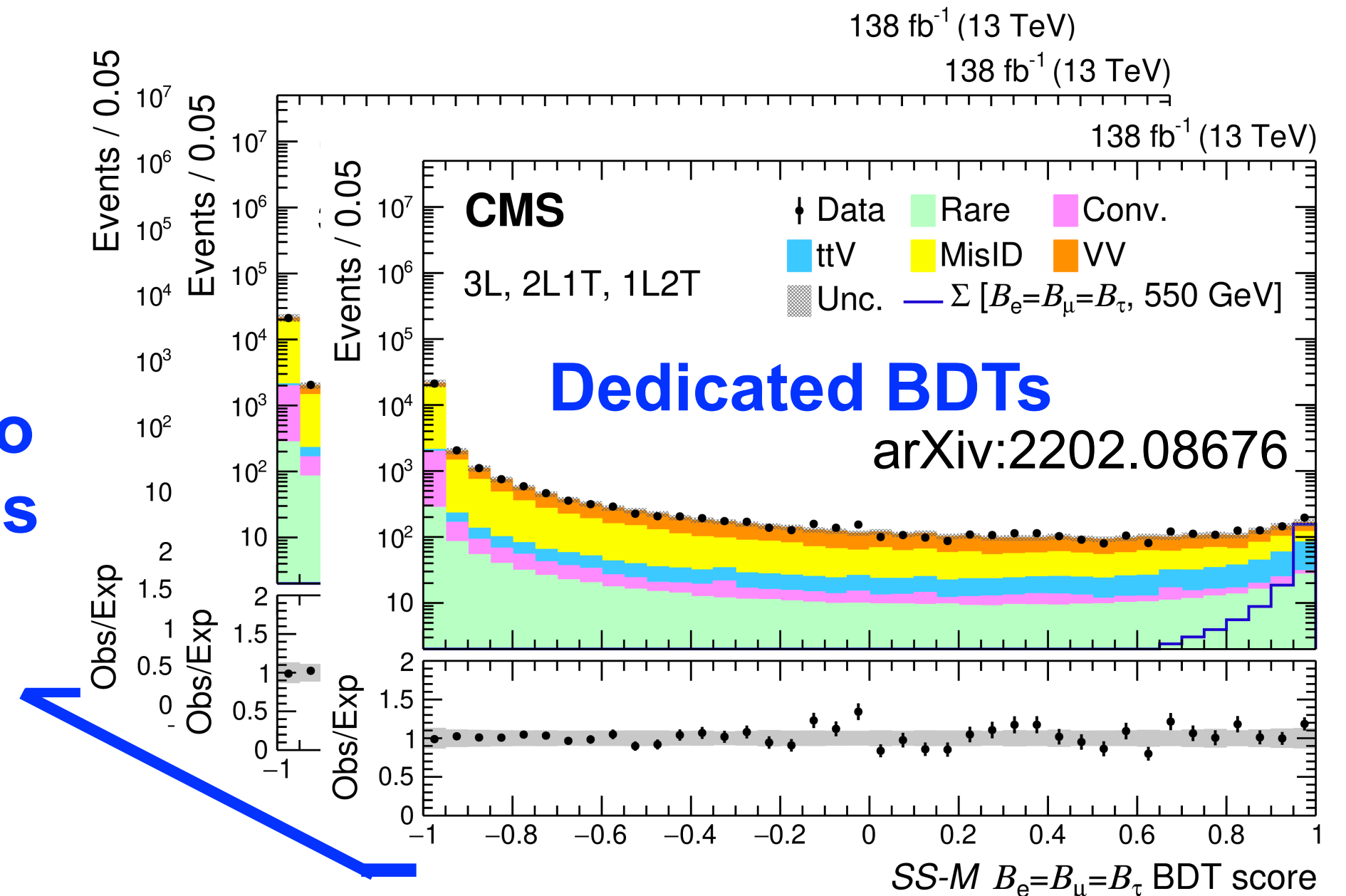
ATLAS: 3-4 ℓ + jets topology



CMS: 7 channels x 257 (SR + CR) regions

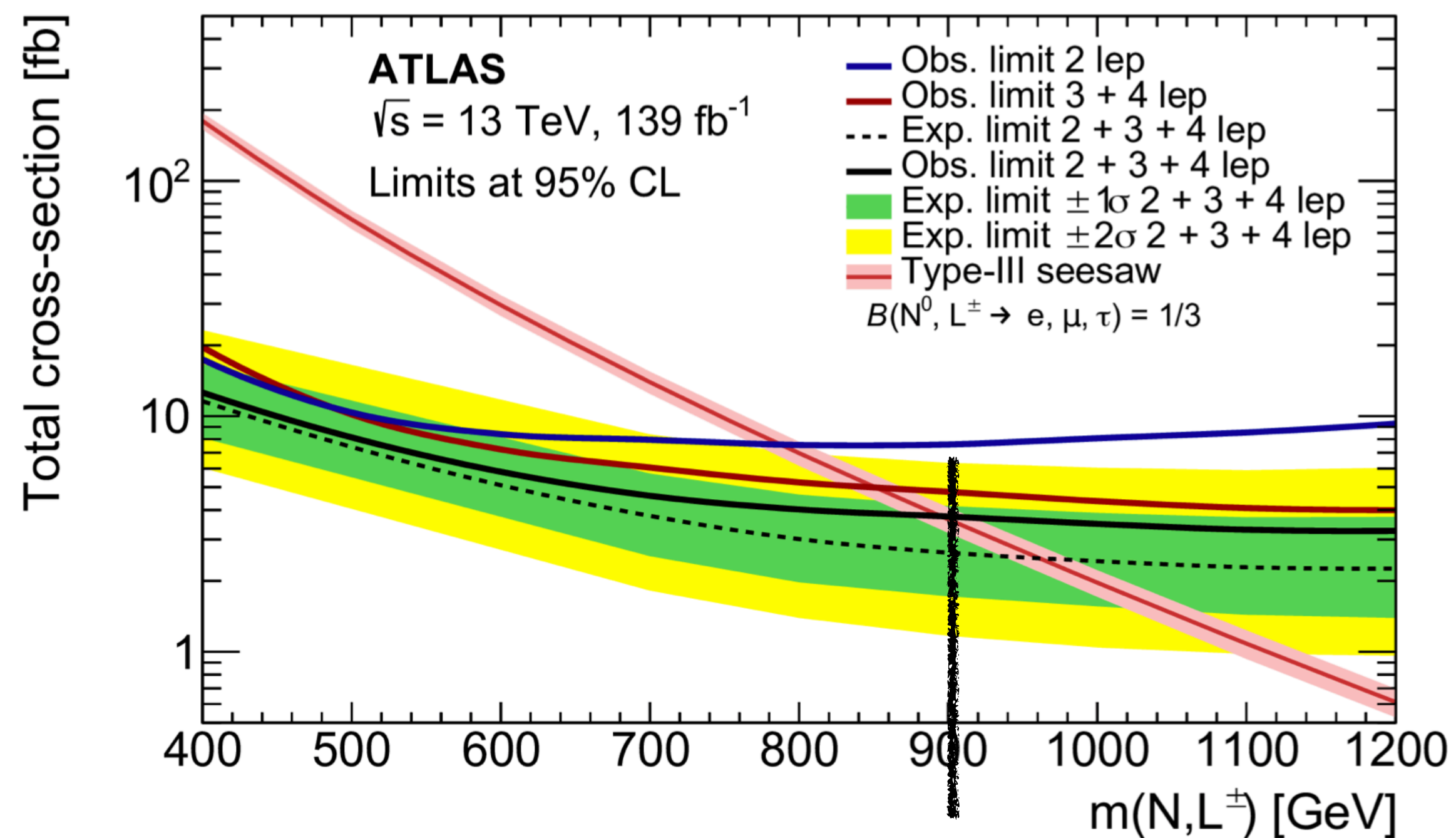
3 mass ranges

2 coupling scenario dependent trainings



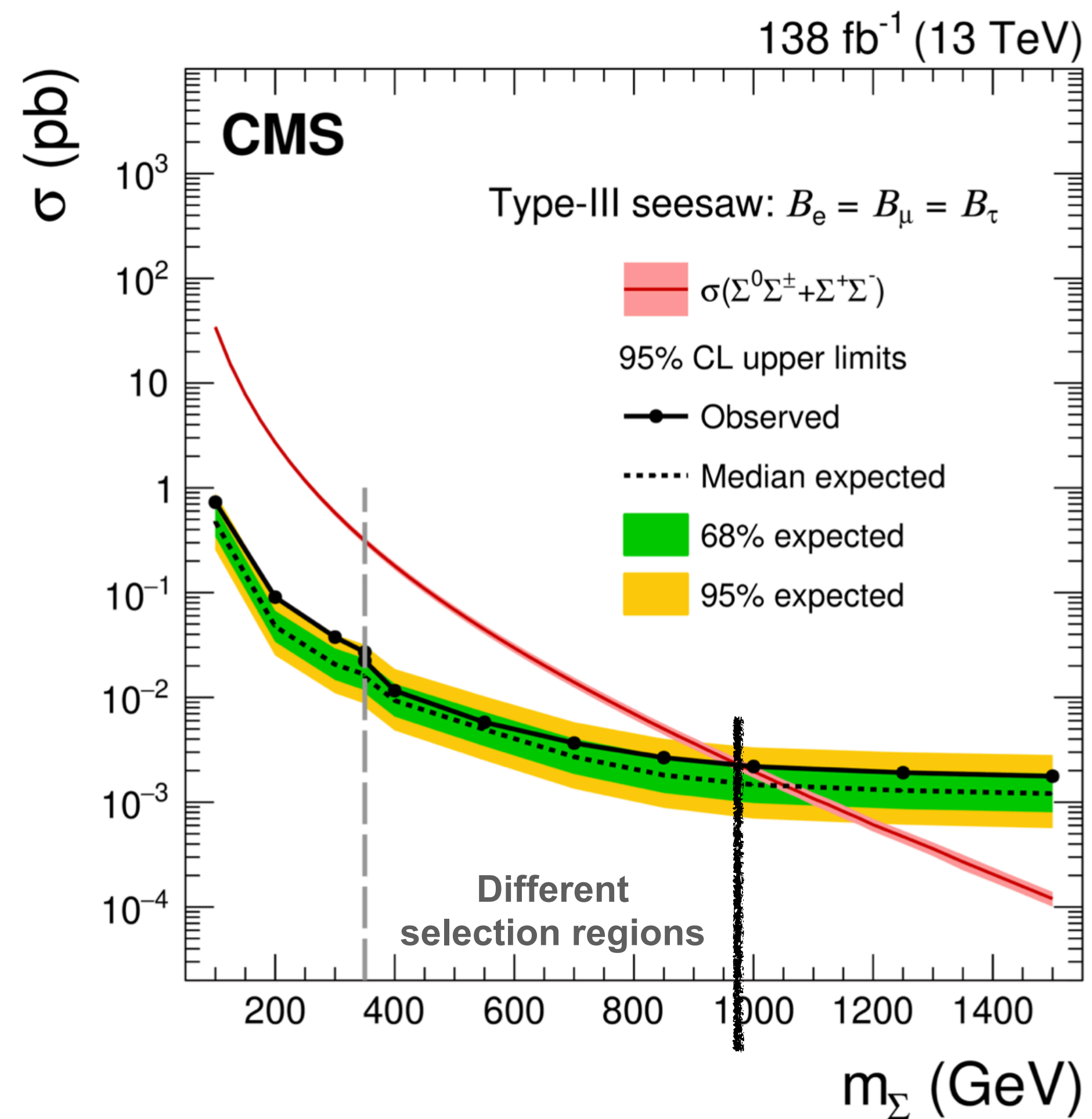
Type III see-saw - $m_{\text{HNL}} < 1 \text{ TeV}$

ATLAS arXiv:2202.02039



$m_{\text{HNL}} < 910 \text{ GeV}$ excluded

CMS arXiv:2202.08676



+ BRs scan

$m_{\text{HNL}} < 980 \text{ GeV}$ excluded