Displaced Vertex Search for Heavy Neutral Leptons with the ATLAS Detector

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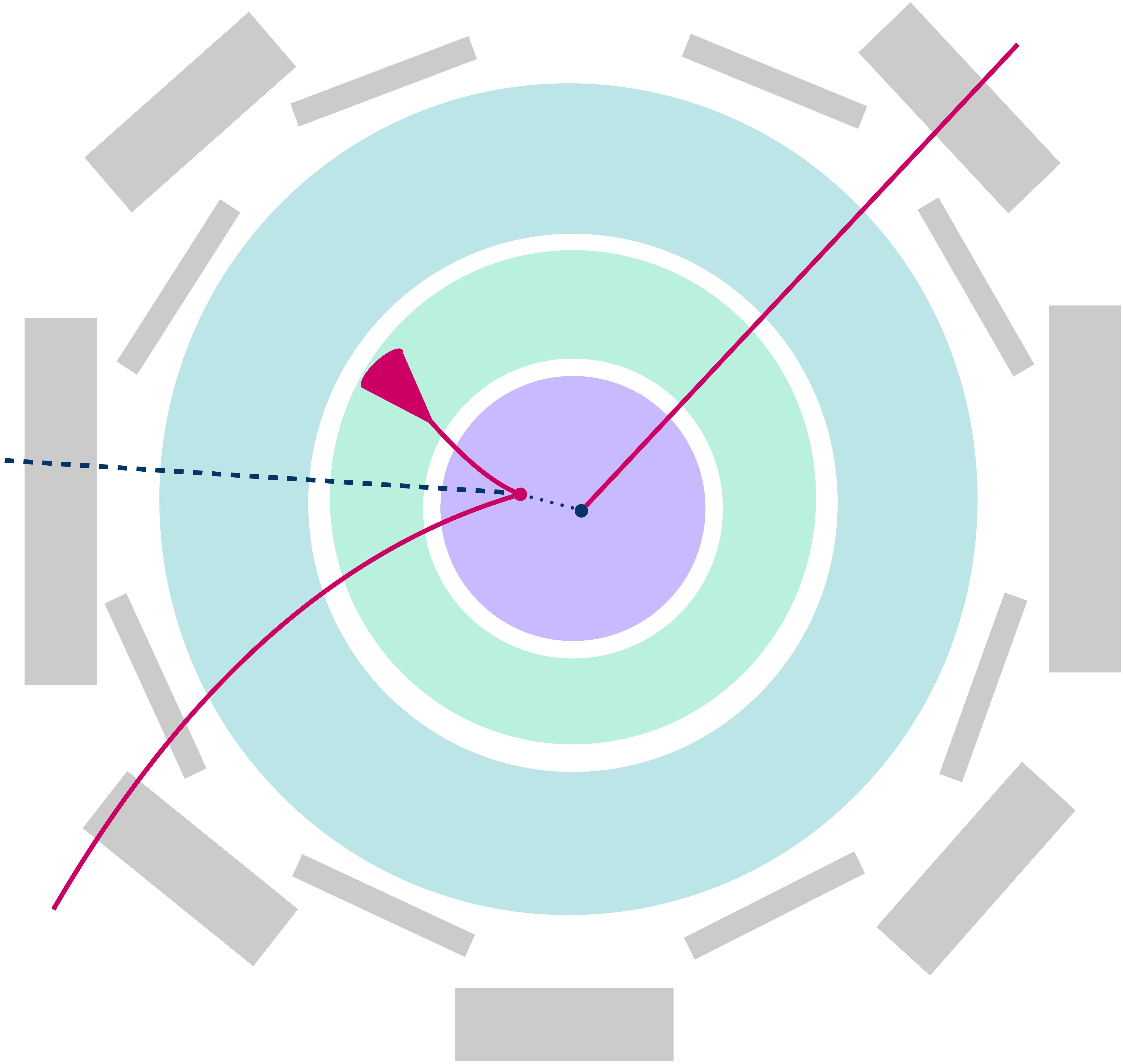
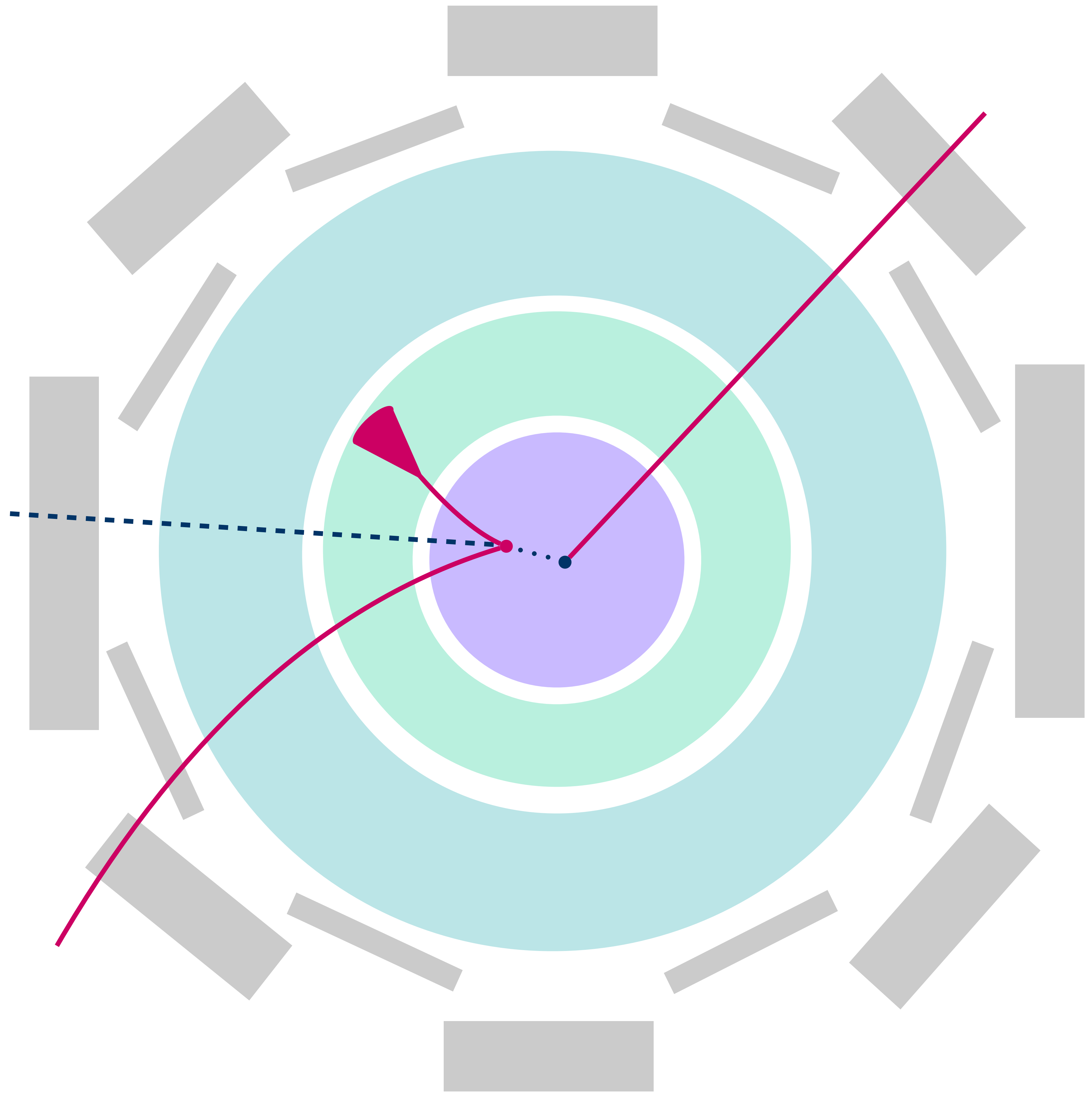


Outline

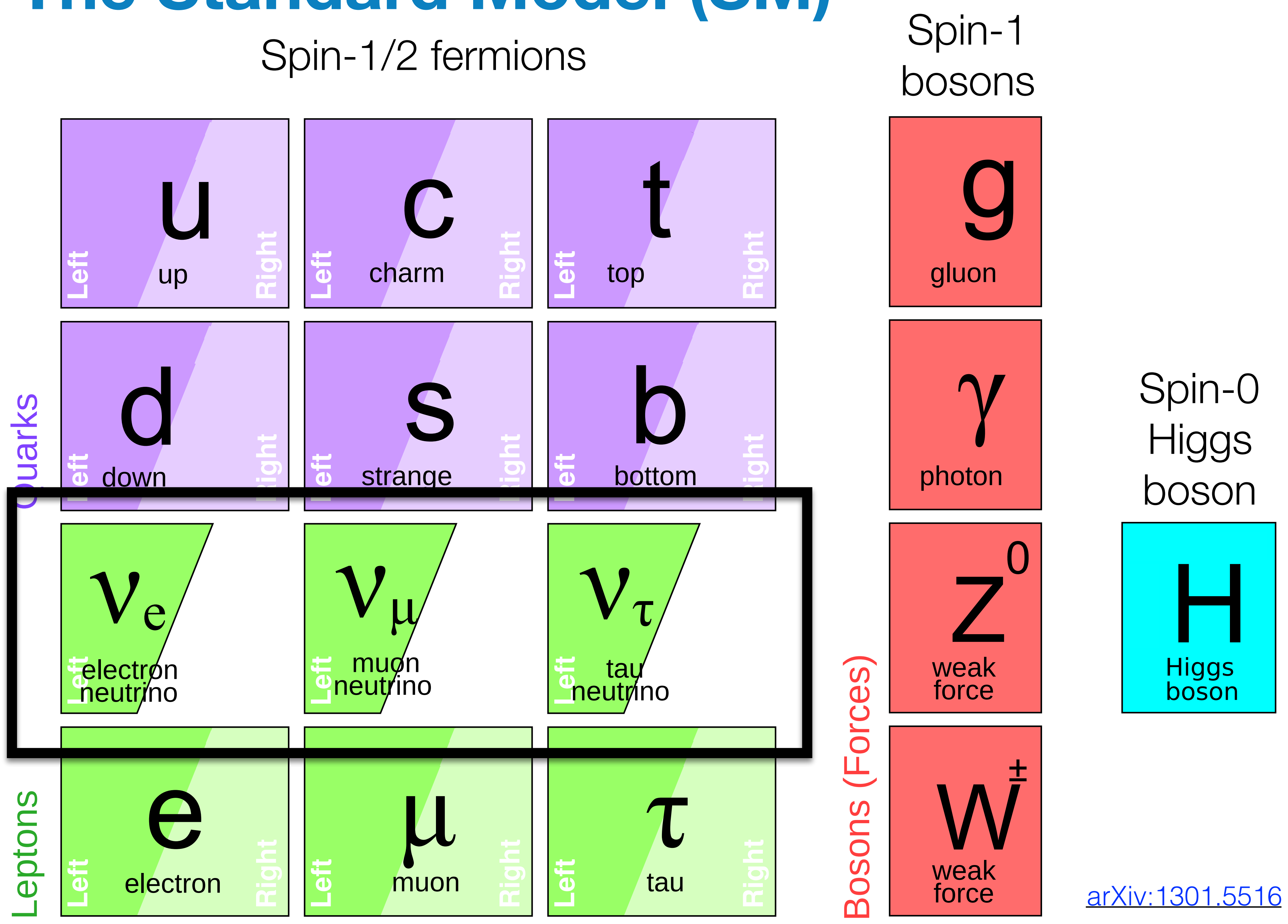


ATLAS Displaced Vertex
Search for Heavy Neutral Leptons (HNL)

- Signal model
- Discriminating variable: HNL mass
- Background estimation
- Results

Heavy Neutral Leptons

The Standard Model (SM)

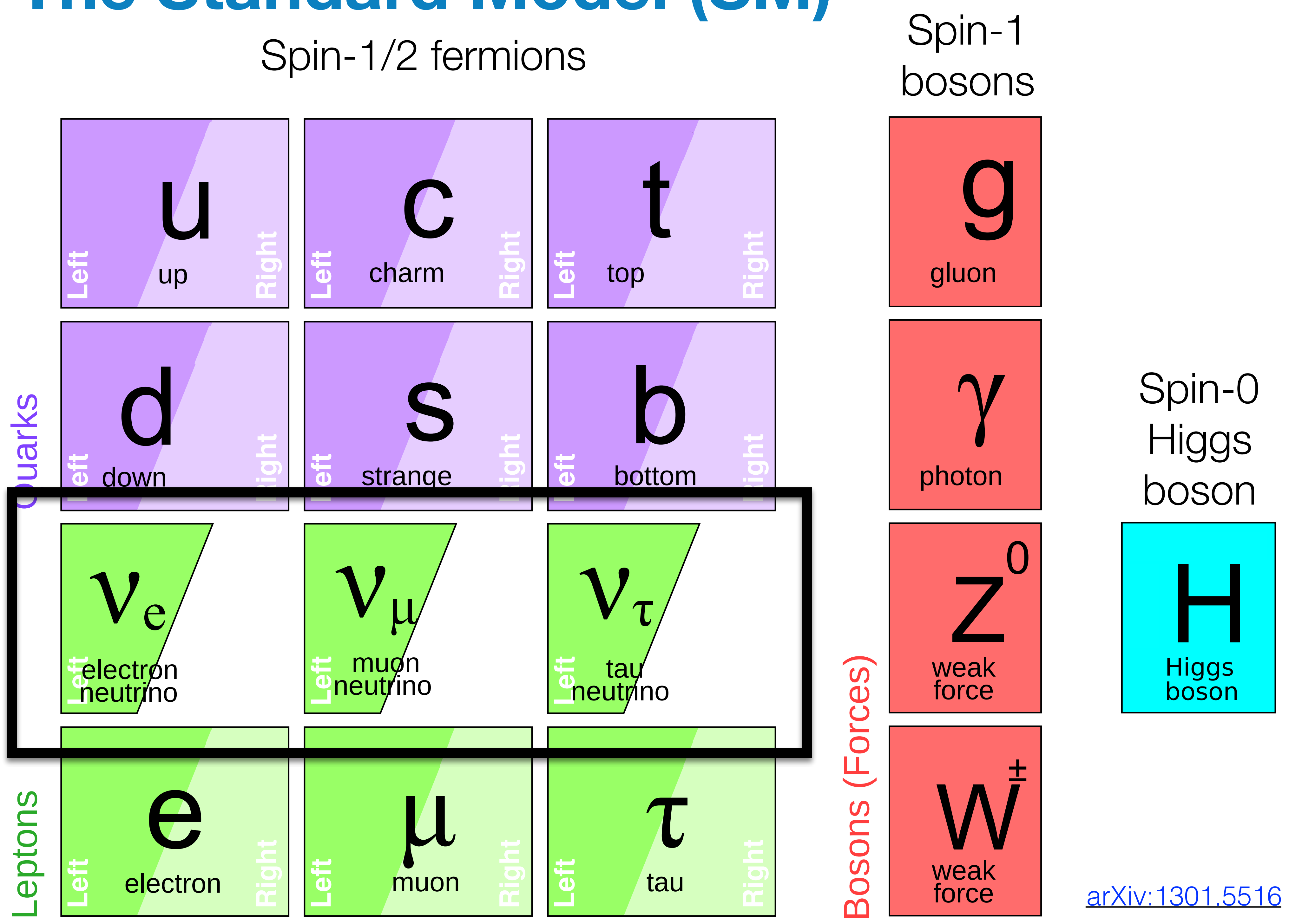


arXiv:1301.5516

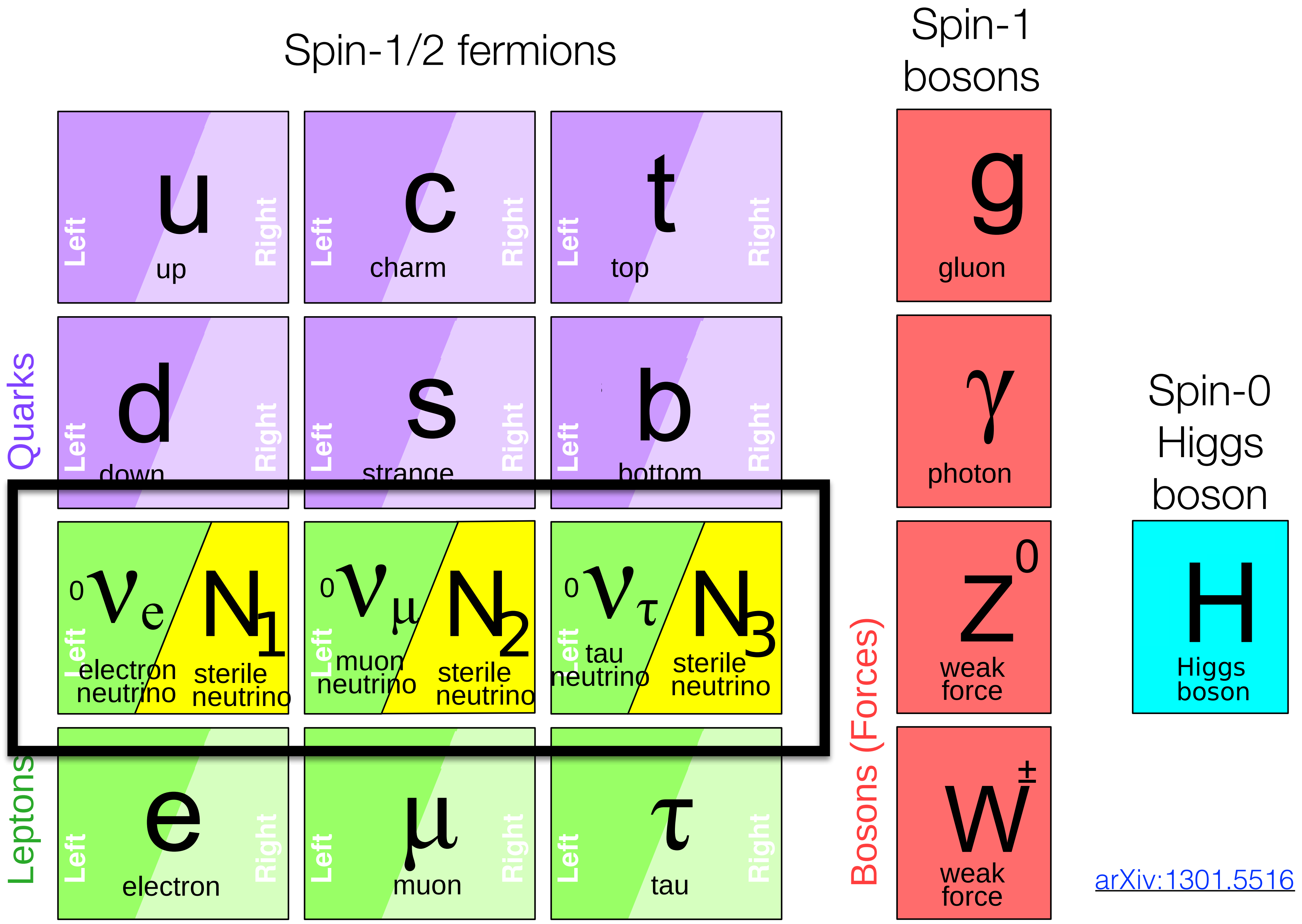
- Best-known description of fundamental particles and their interactions (except gravity)
- Neutrino oscillations suggest $m_\nu > 0$
- Non-zero neutrino mass is not included in SM

Heavy Neutral Leptons

The Standard Model (SM)



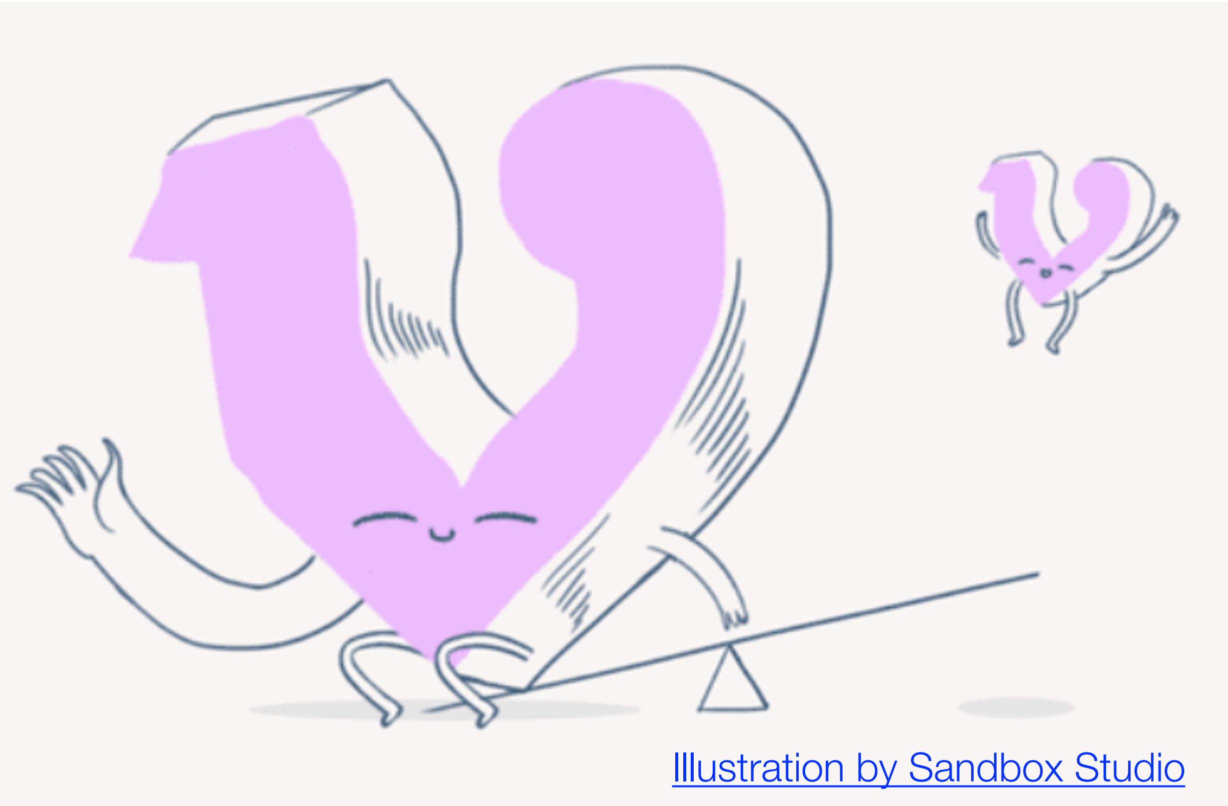
SM Extension with 3 HNLs



- Best-known description of fundamental particles and their interactions (except gravity)
- Neutrino oscillations suggest $m_\nu > 0$
- Non-zero neutrino mass is not included in SM

- Introduce right-handed states known as **heavy neutral leptons (HNL)**
- Type-I seesaw mechanism explains light neutrino masses

Motivation For HNLs



1. **Origin of neutrino masses**
   - Type-I seesaw mechanism: $m_\nu \simeq \frac{v^2}{2} Y m_N^{-1} Y^T$

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Illustration by Sandbox Studio

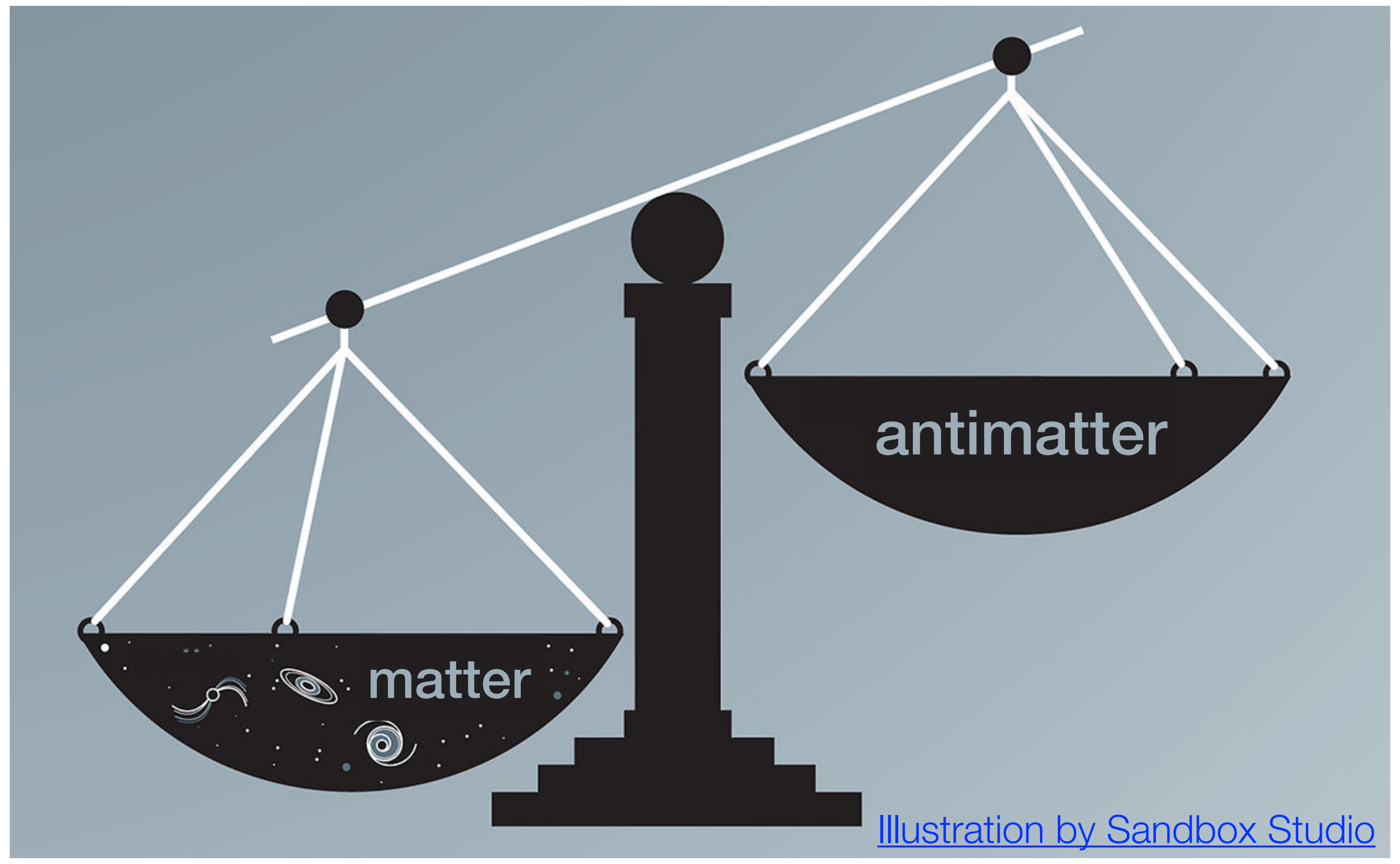

Illustration by Sandbox Studio

2. **Matter-antimatter asymmetry of the universe**
   - Increase in charge-parity violation as a result of neutrino oscillations in the early universe

Motivation For HNLs


Illustration by Sandbox Studio

1. Origin of neutrino masses

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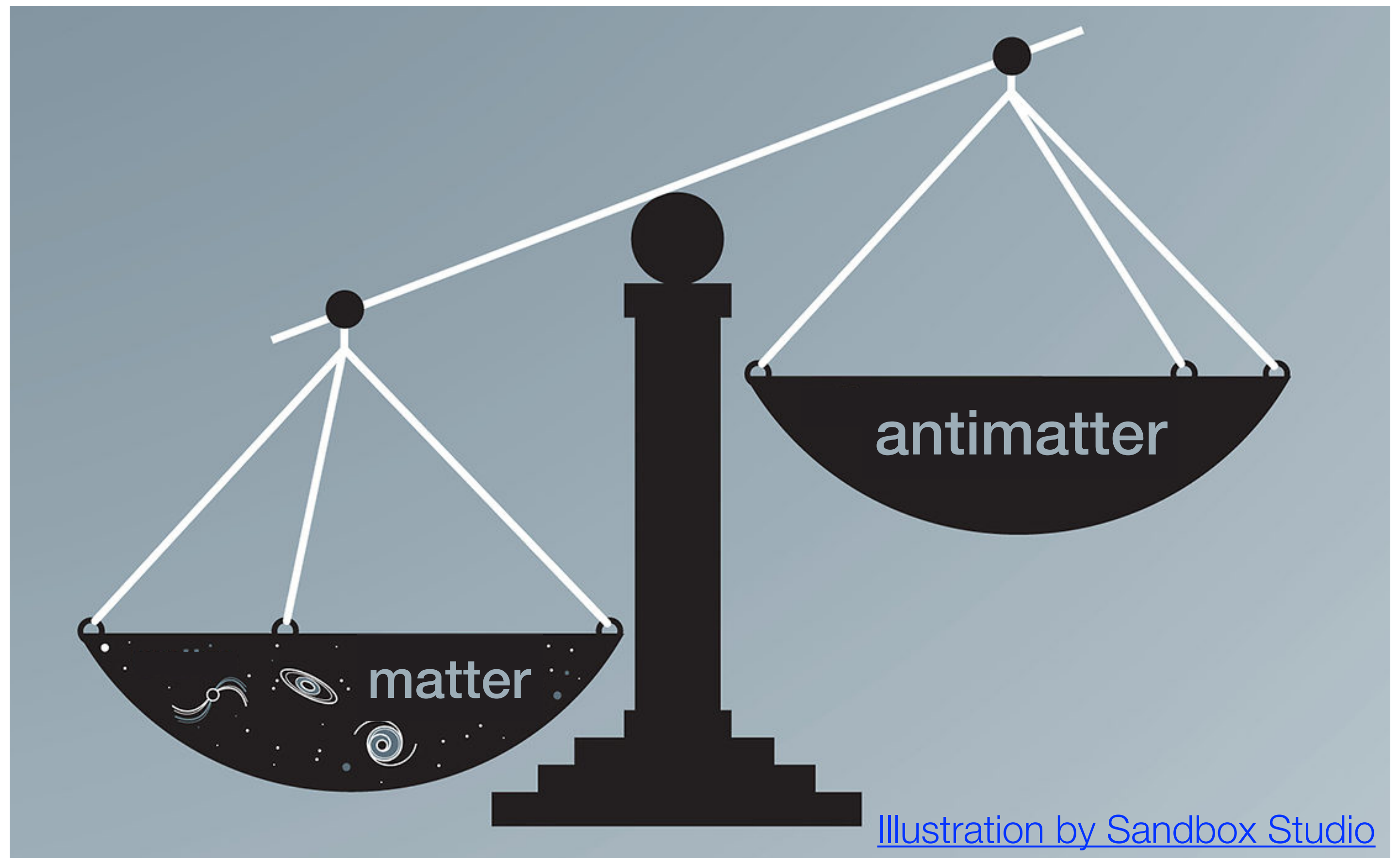


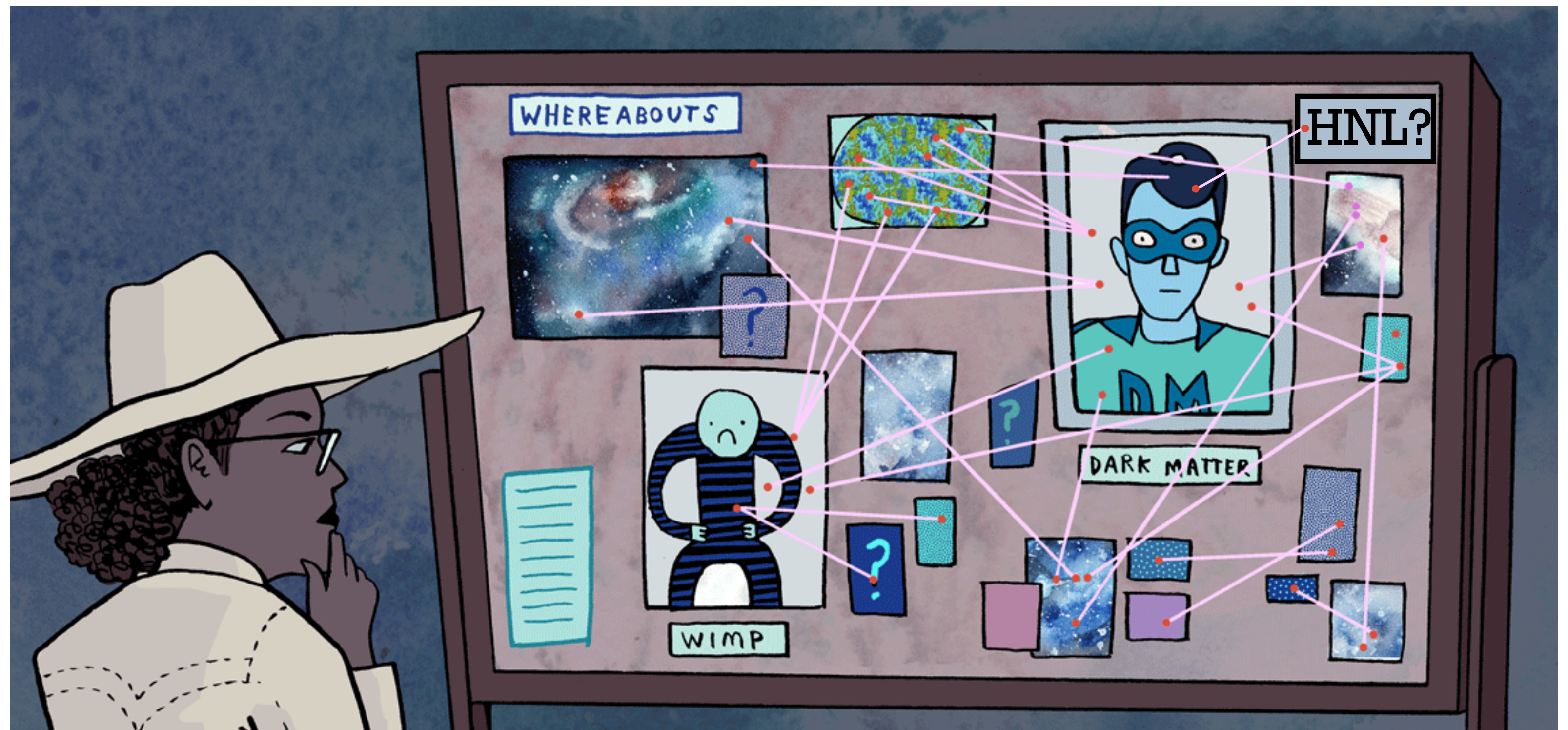
Illustration by Sandbox Studio

2. Matter-antimatter asymmetry of the universe

- Increase in charge-parity violation as a result of neutrino oscillations in the early universe

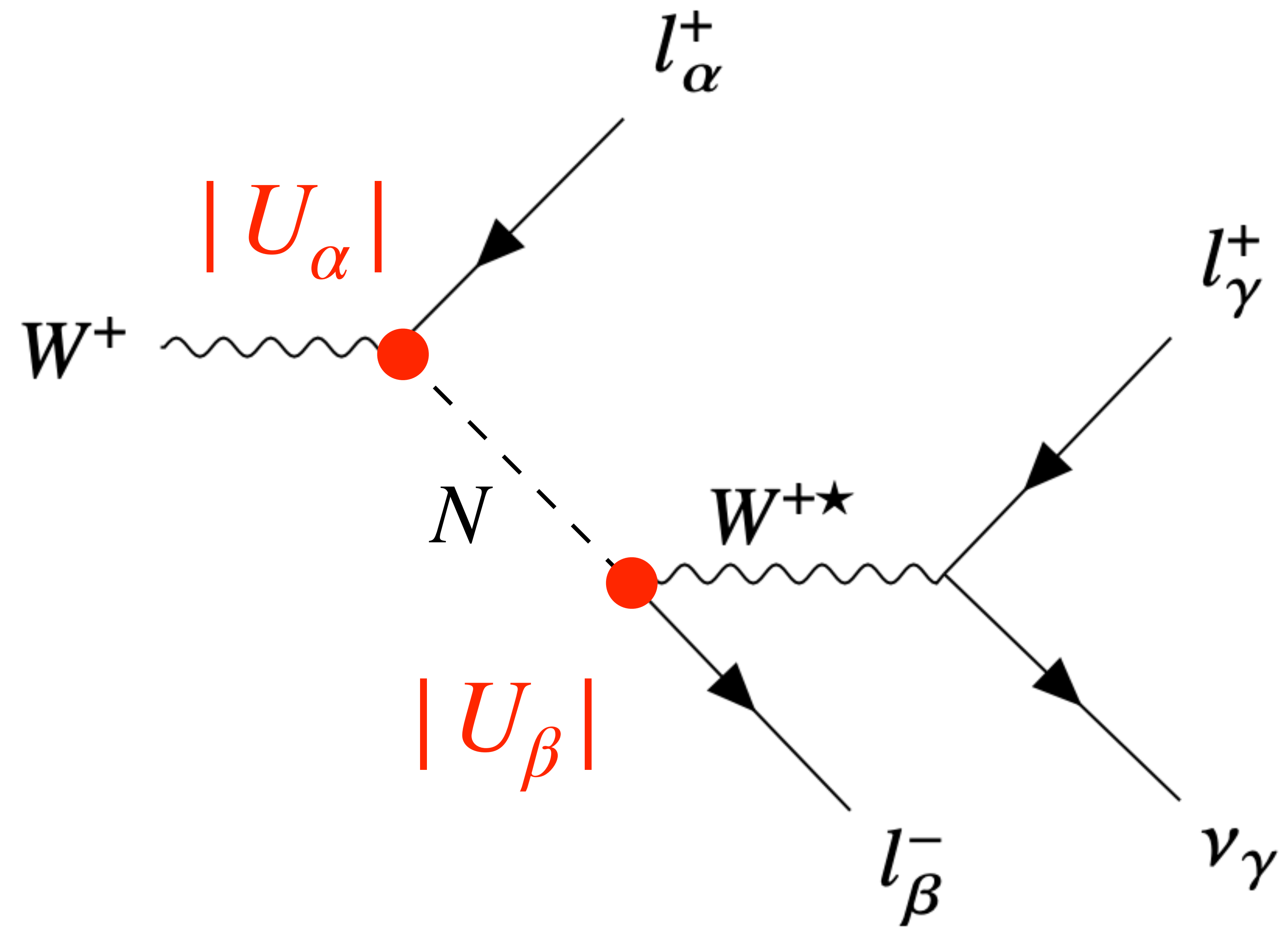
3. Dark matter candidate

- Models with at least three HNLs can incorporate a keV-scale sterile neutrino



Adapted from Illustration by Sandbox Studio

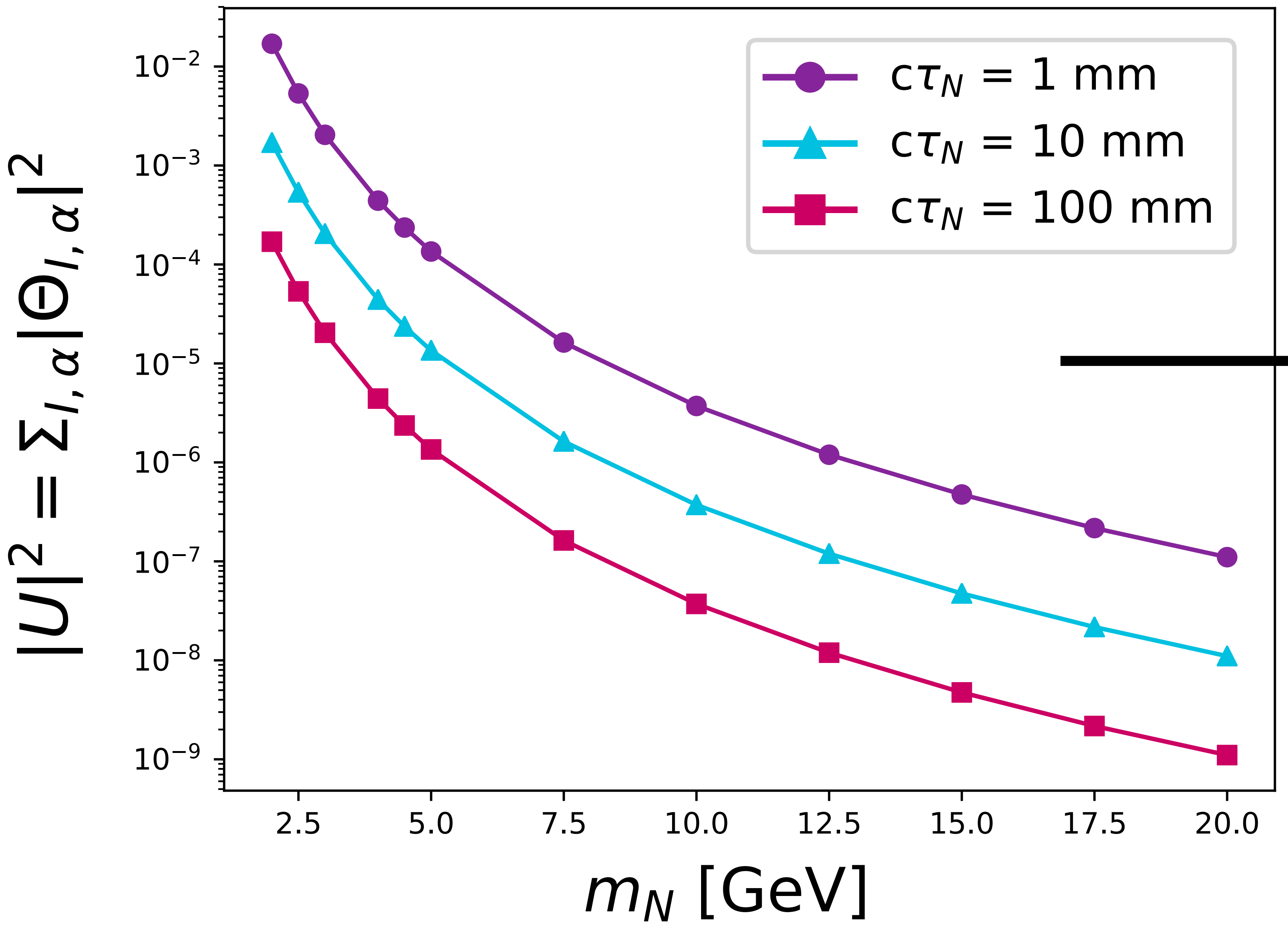
Experimentally Relevant Observables



- HNLs experience "weak-like" interactions controlled by dimensionless mixing angles ($|U_\alpha|^2$)
- m_N dictates kinematics of decay products
- HNL lifetime: $\tau_N \propto \frac{1}{m_N^5 |U_\alpha|^2}$

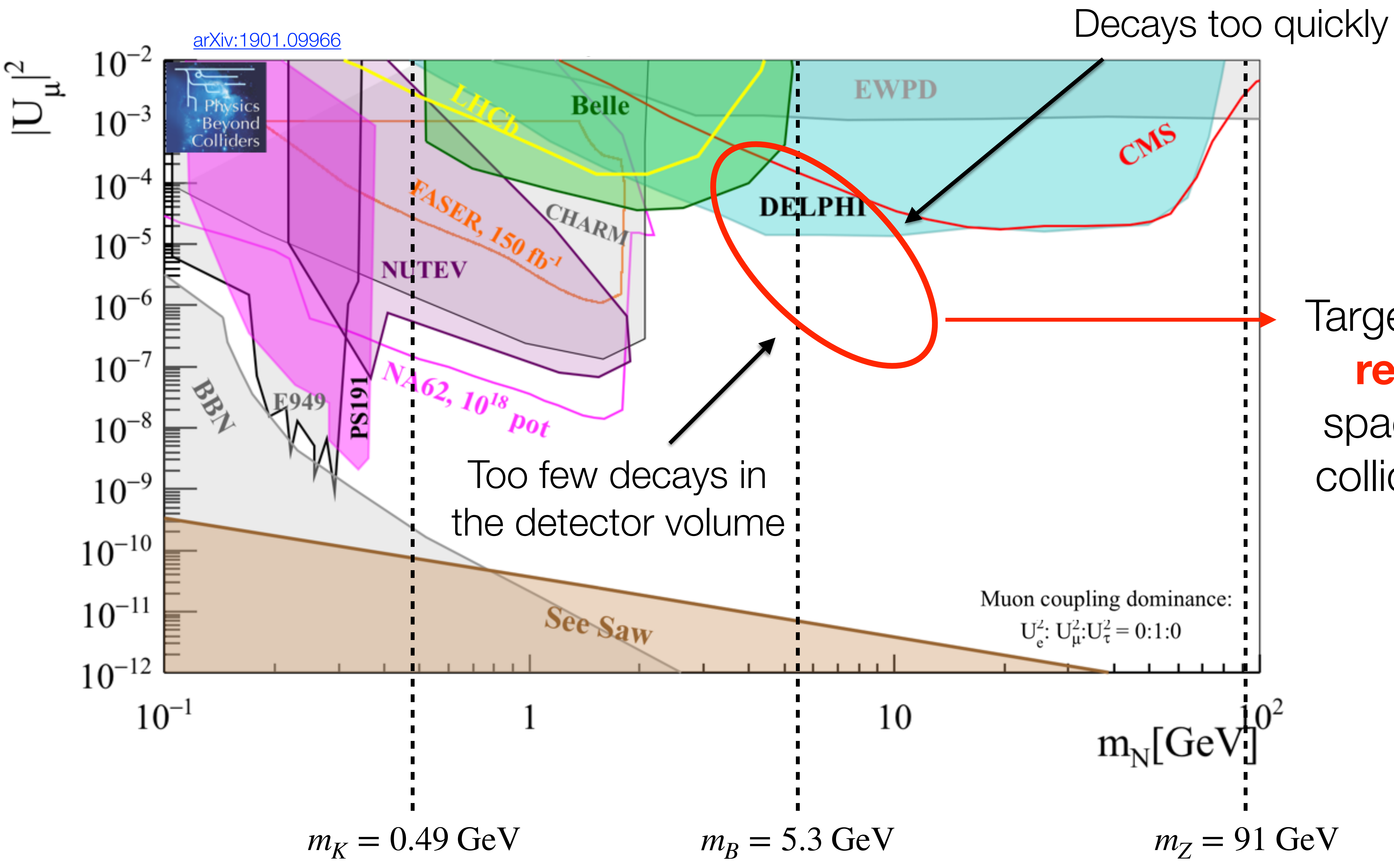
Relevant Observables:

$\lvert U_\alpha\rvert^2$	Mixing angle between SM neutrino and HNL
m_N	HNL mass



Can lead to interesting experimental signatures from long-lived HNLs!

Experimental Picture



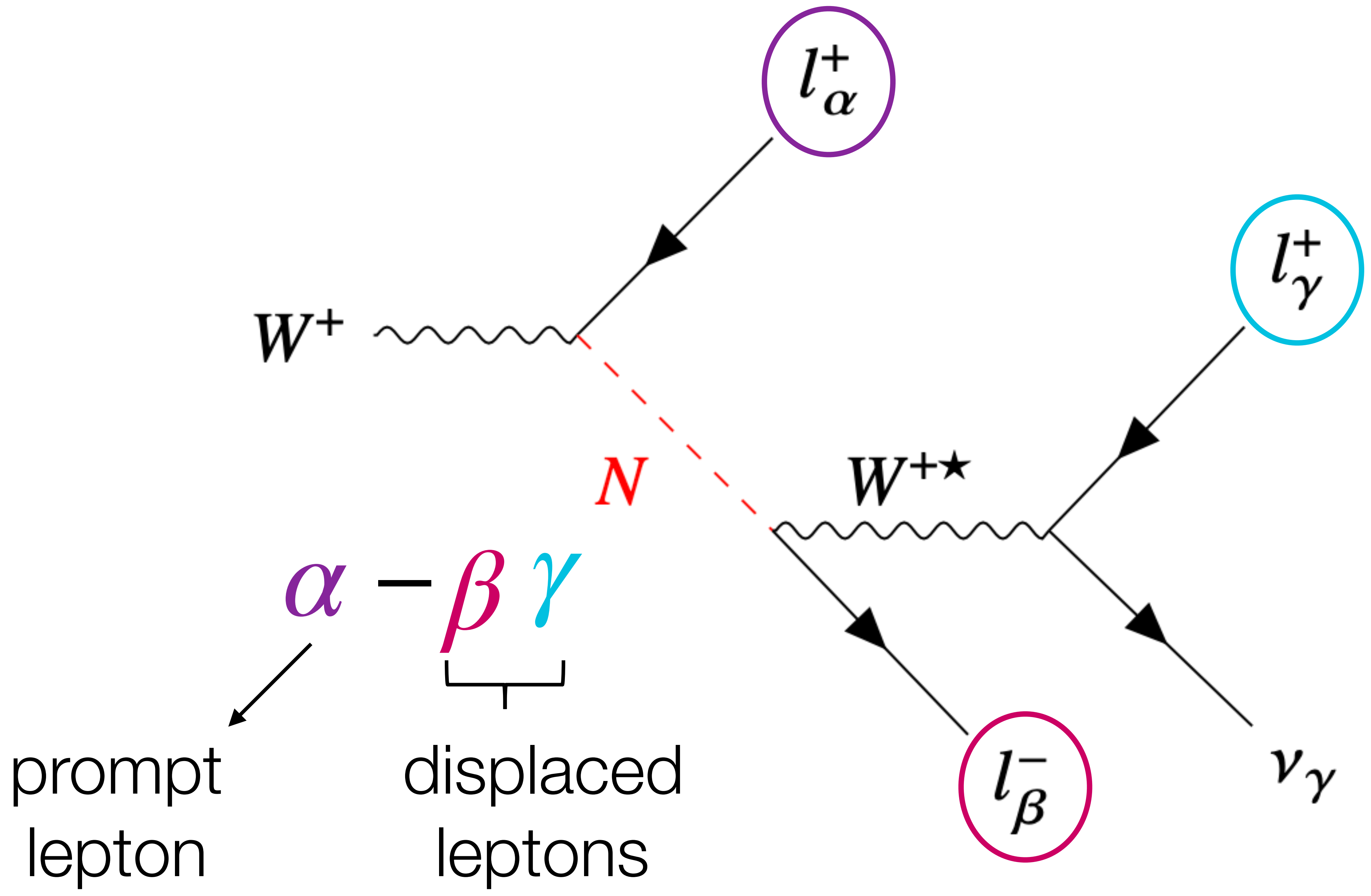
Target the **long-lived region** of phase space accessible at collider experiments!

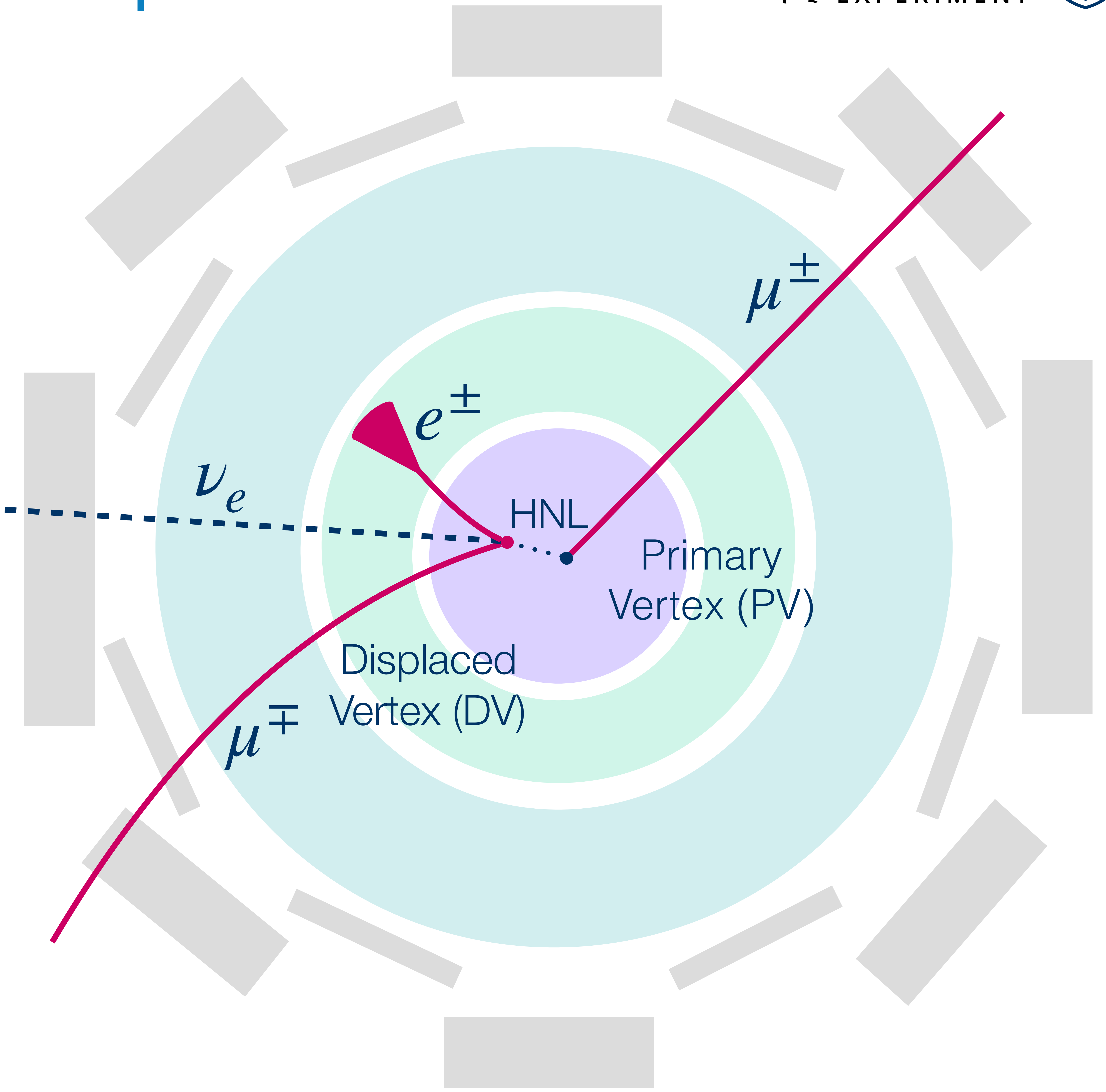
Displaced Heavy Neutral Leptons

Experimental HNL Signature:

— Prompt lepton (used for trigger)

— Displaced vertex (DV) with 2 opposite charge leptons





Six signal regions (SR):

μ-μμ, μ-μe, μ-ee, e-ee, e-eμ, e-μμ

HNL Mixing Scenarios

Mixing scenario benchmarks:

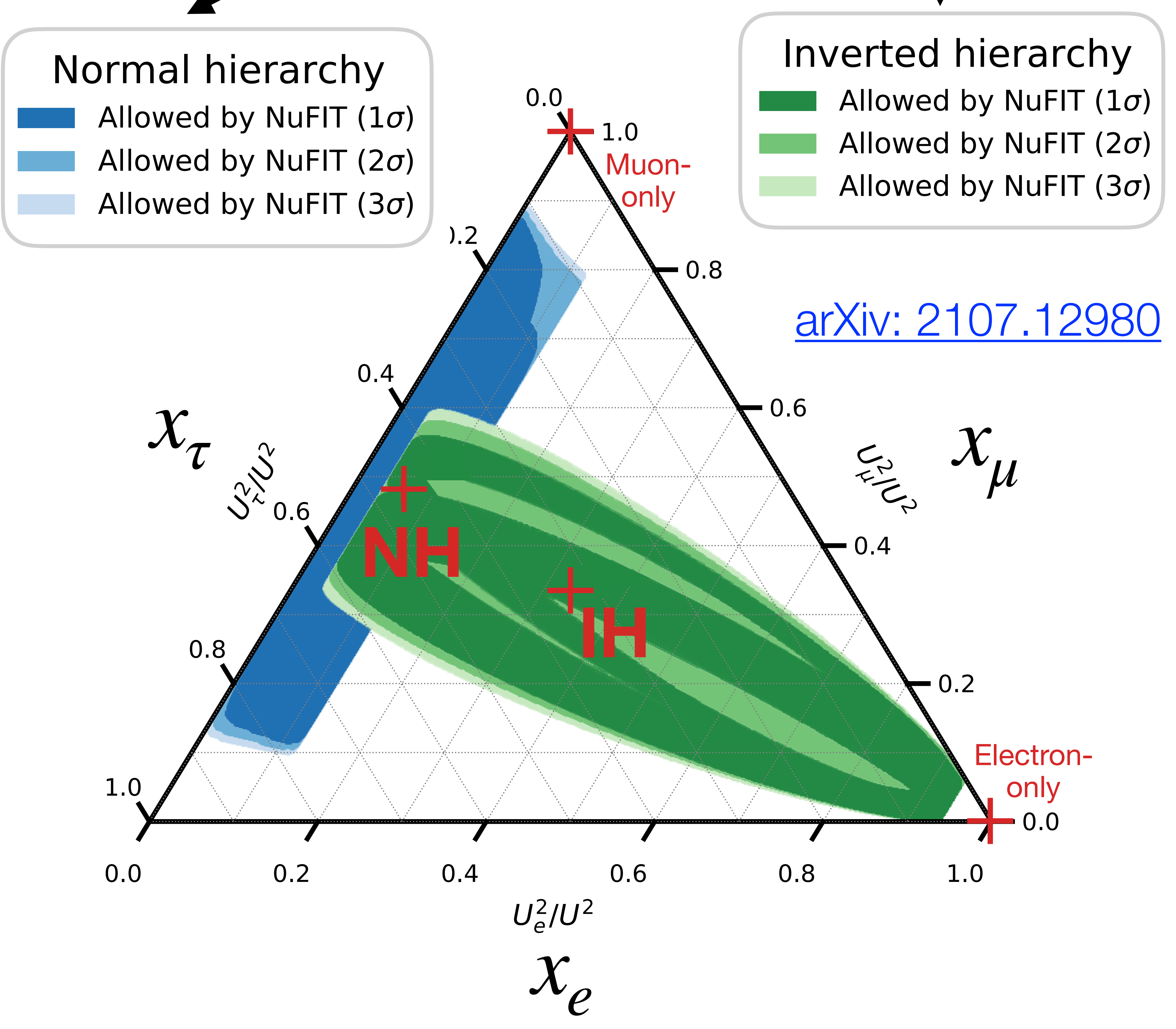
- Simple model: One HNL with single-flavour mixing (1SFH)
  1. **Muon-only** mixing ($|U_\mu|^2$) More data!
  2. **Electron-only** mixing ($|U_e|^2$) New!
- Realistic scenario: Two quasi-degenerate HNLs (2QDH)
  3. **Inverted hierarchy (IH)** mixing ($|U|^2$) New!
  4. **Normal hierarchy (NH)** mixing ($|U|^2$) New!

  ↳ two mixing benchmarks proposed by the LLP community

$$|U|^2 = \sum_{\alpha=\mu,e,\tau} |U_\alpha|^2$$

$$x_\alpha = |U_\alpha|^2 / |U|^2$$

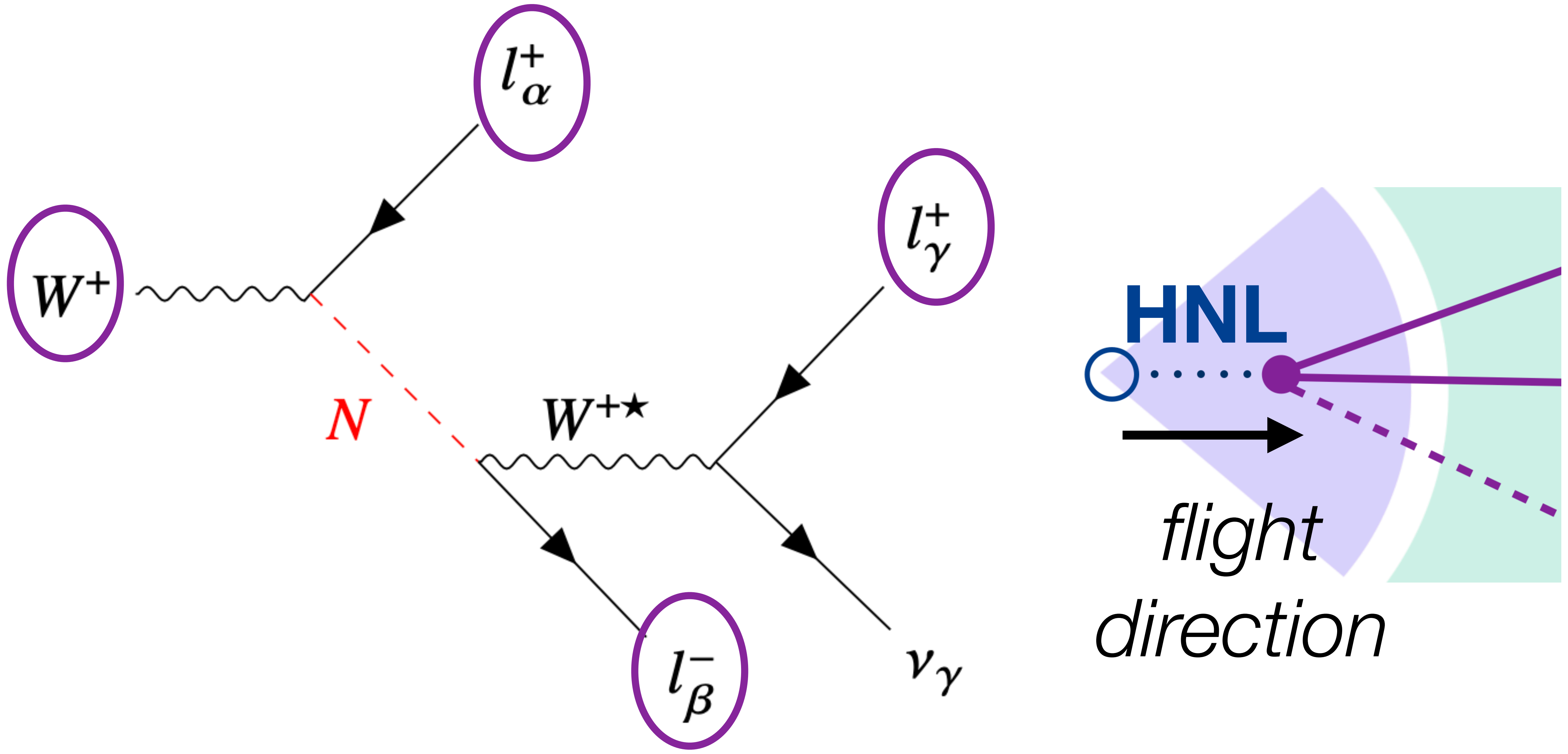
"Realistic" **multi-flavour mixing** models consistent with neutrino oscillations data



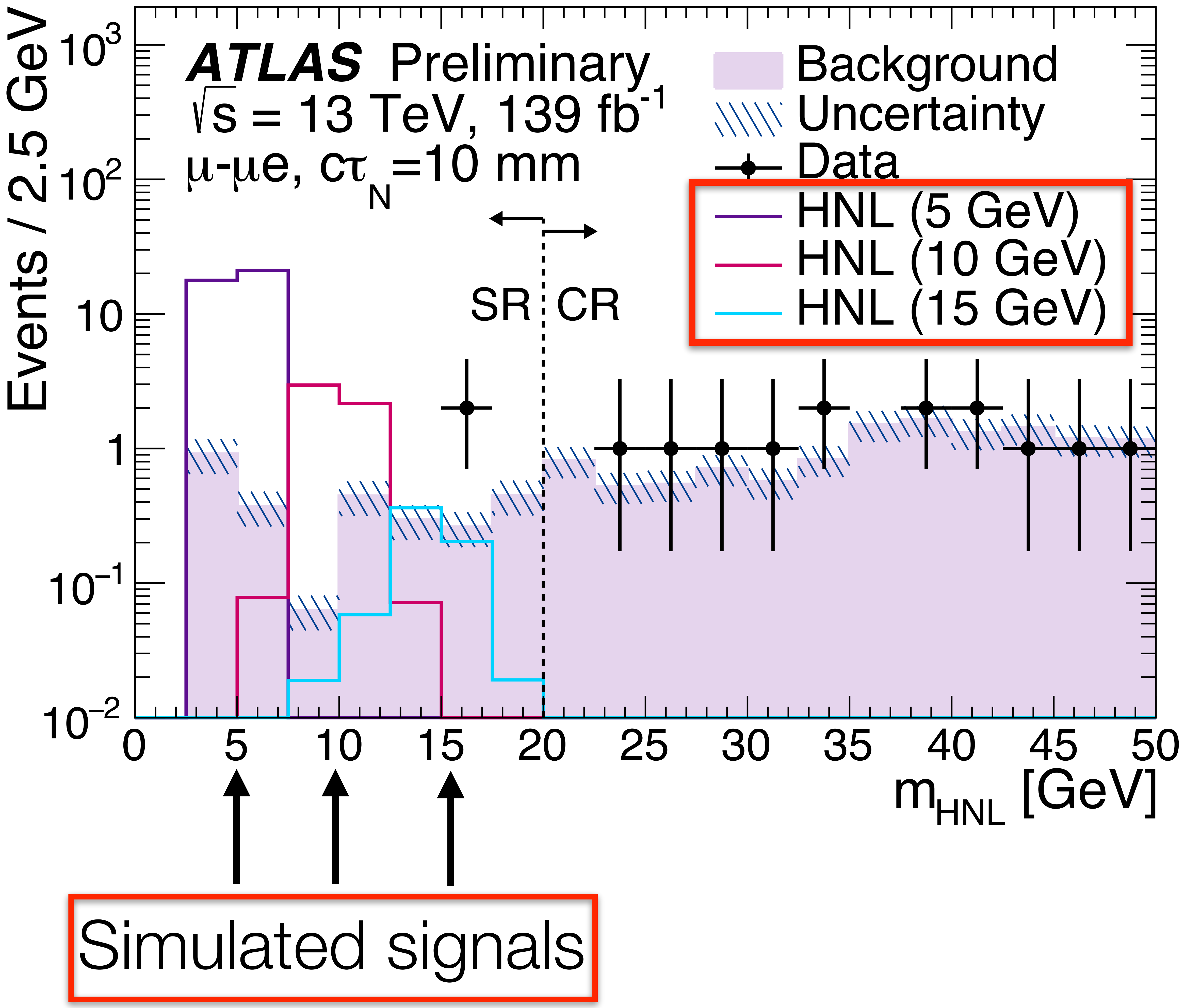
arXiv: 2107.12980

Discriminating Variable: HNL mass

- **Energy-momentum conservation** is used to reconstruct the HNL mass (m_{HNL})
- Uses kinematics of charged leptons, W mass and the flight direction of the HNL

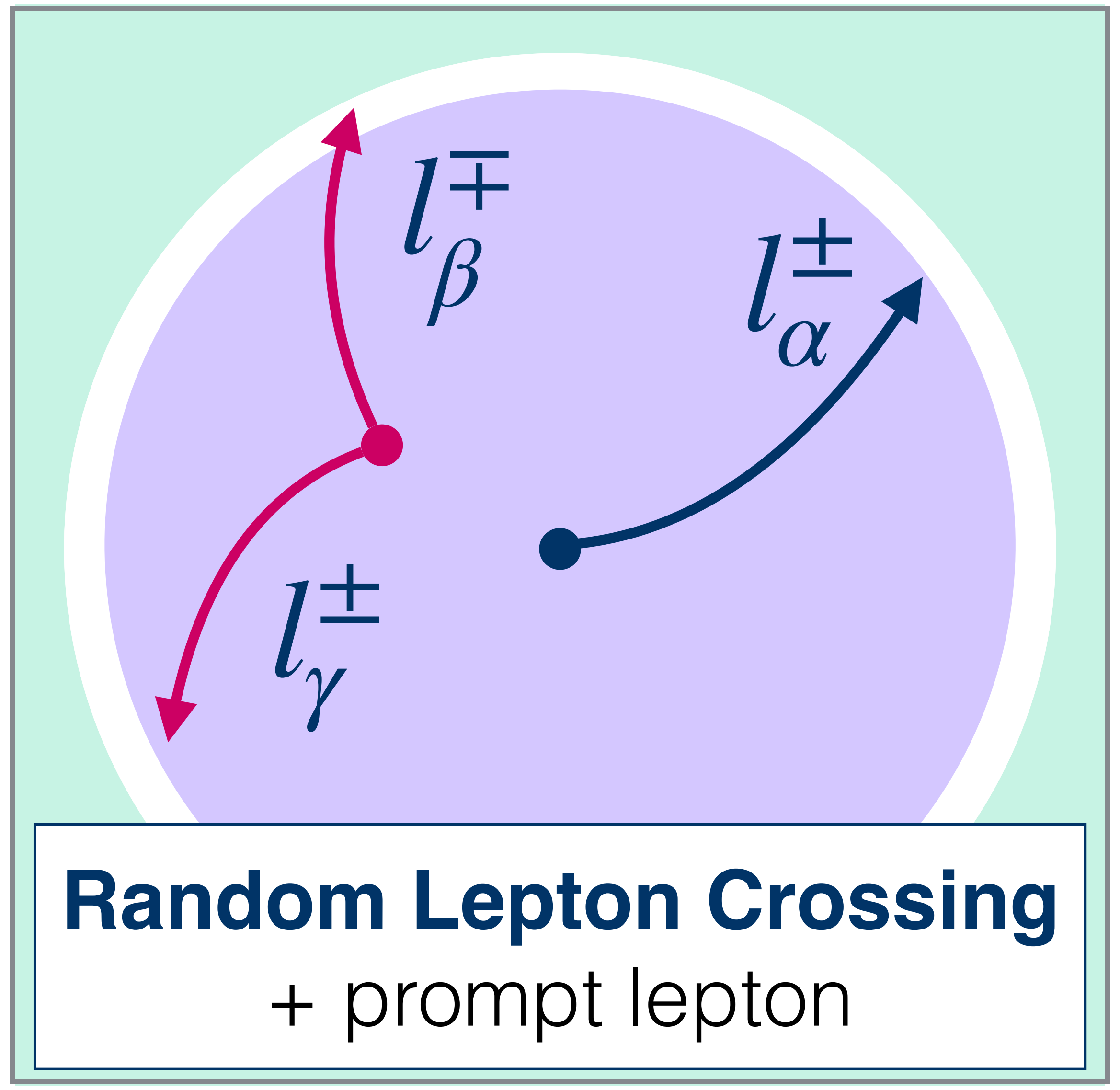


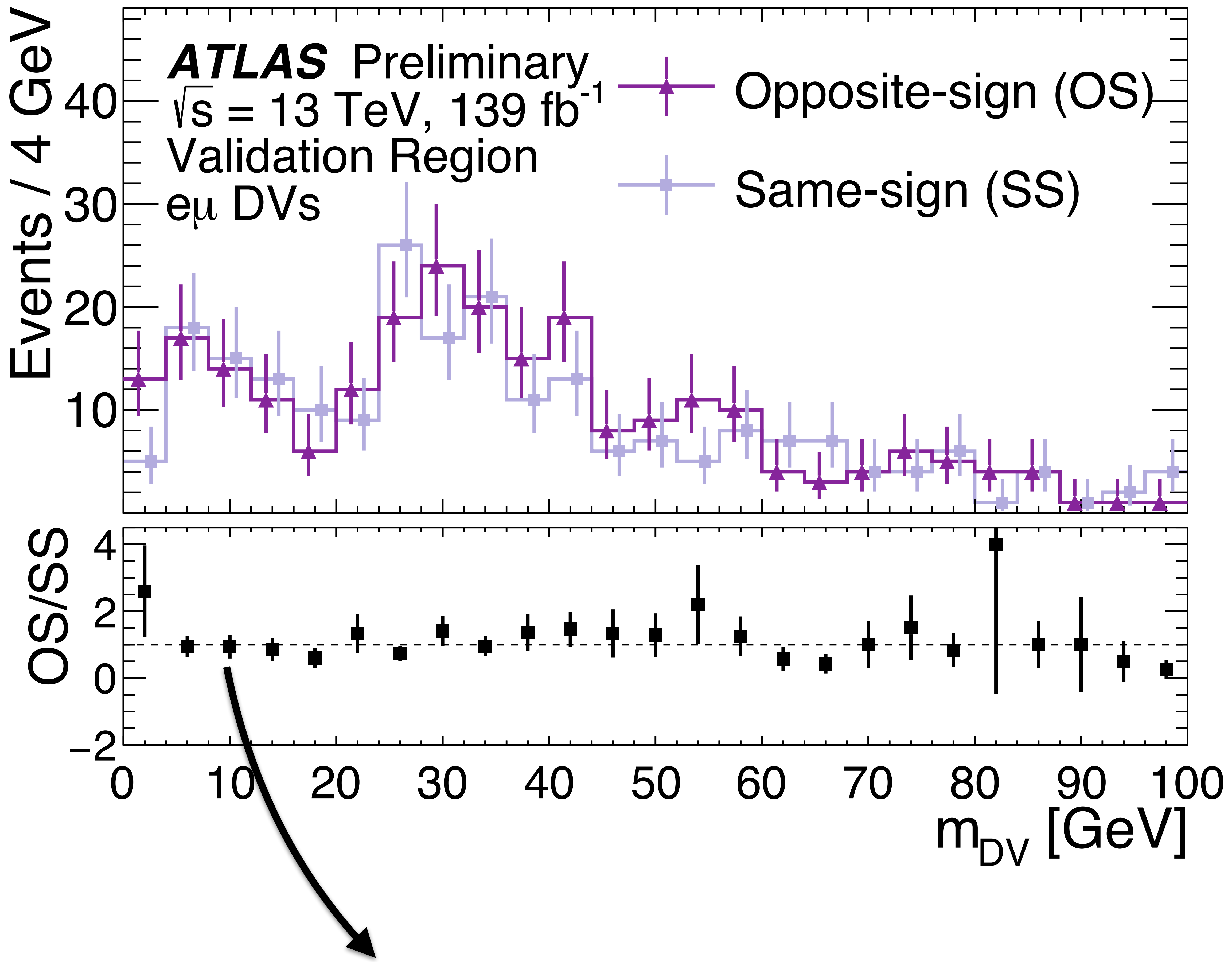
HNL mass: $m^2_{\text{HNL}} = (\, p^\mu_{l_\beta} + p^\mu_{l_\gamma} + p^\mu_{\nu_\gamma})^2$



Backgrounds

- Dedicated event selections used to remove non-random backgrounds (e.g. heavy-flavour decays)
- Dominant background: **random lepton crossings**
  - Random crossing probability is independent of the lepton charge
- Study data events in validation region (VR) that contains events with no prompt leptons

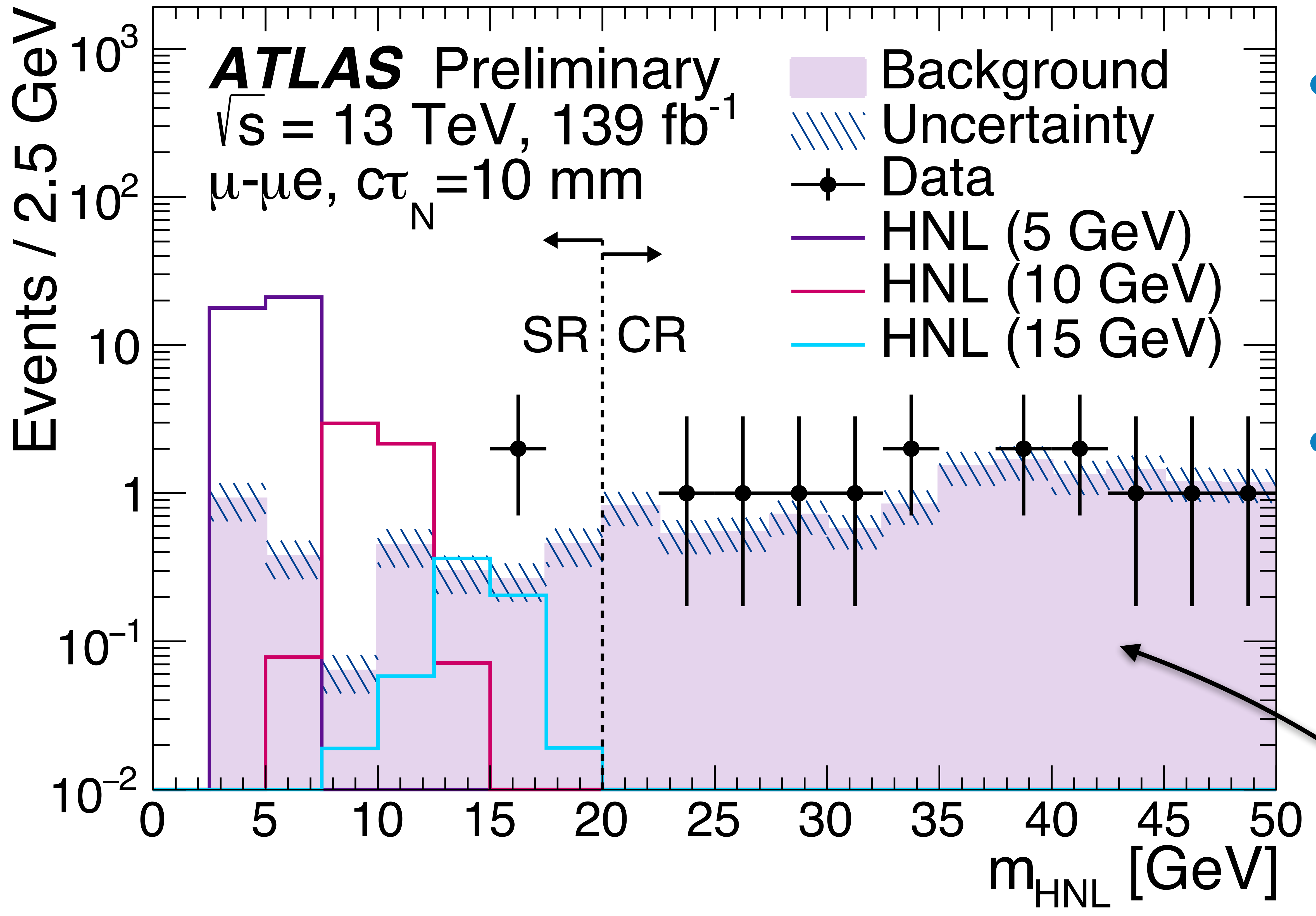




Good agreement between vertices with two charged leptons with the opposite-sign (OS) and same-sign (SS) indicates **random crossings dominate the background.**

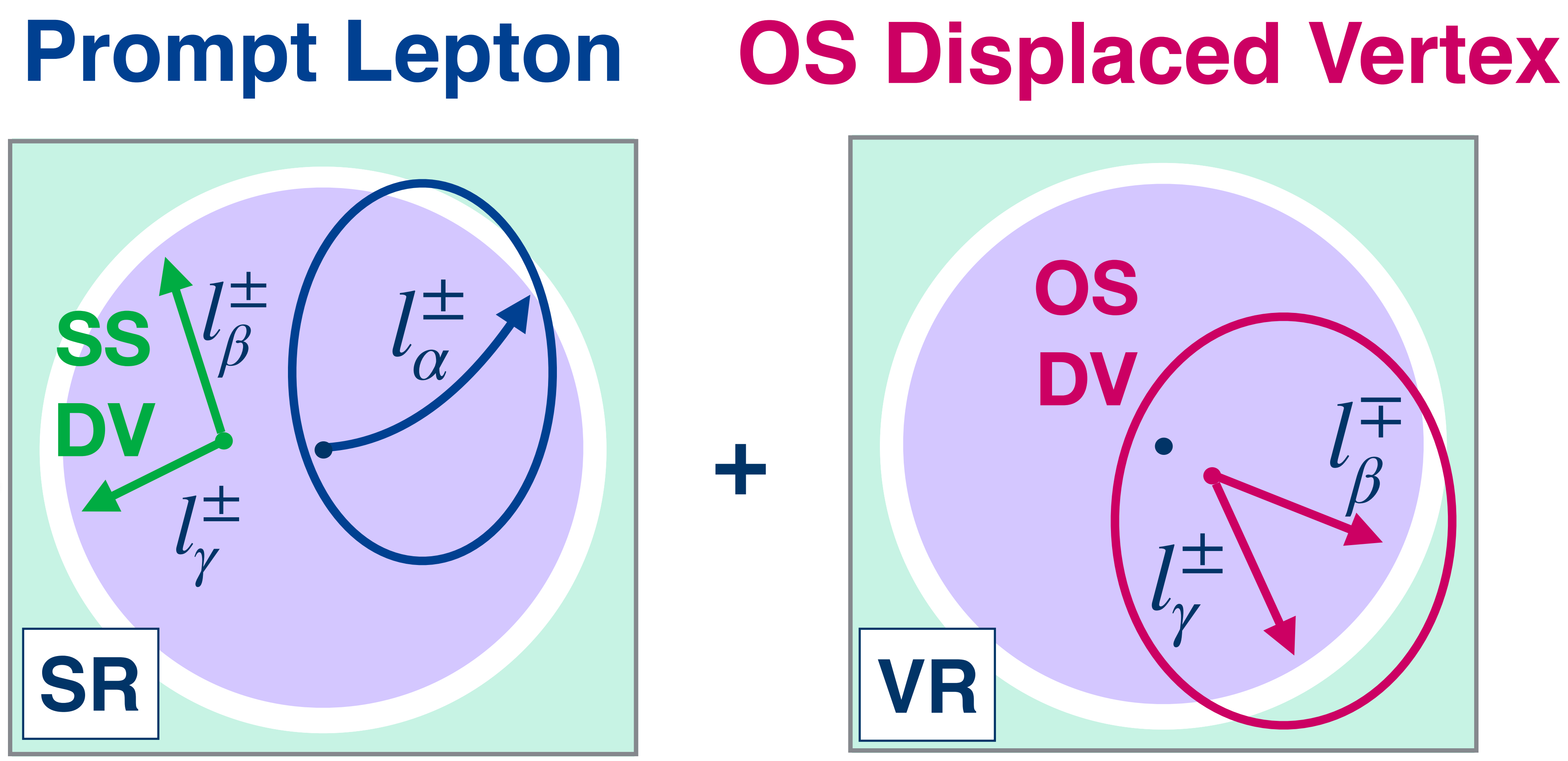
Background Estimate

- Data-driven **object shuffling method** is used to estimate the background from random lepton crossings



- Basic idea:
  - Take a **prompt lepton** from event with **SS DV** in signal region (SR)
  - Shuffle with **OS DVs** from validation region (VR)

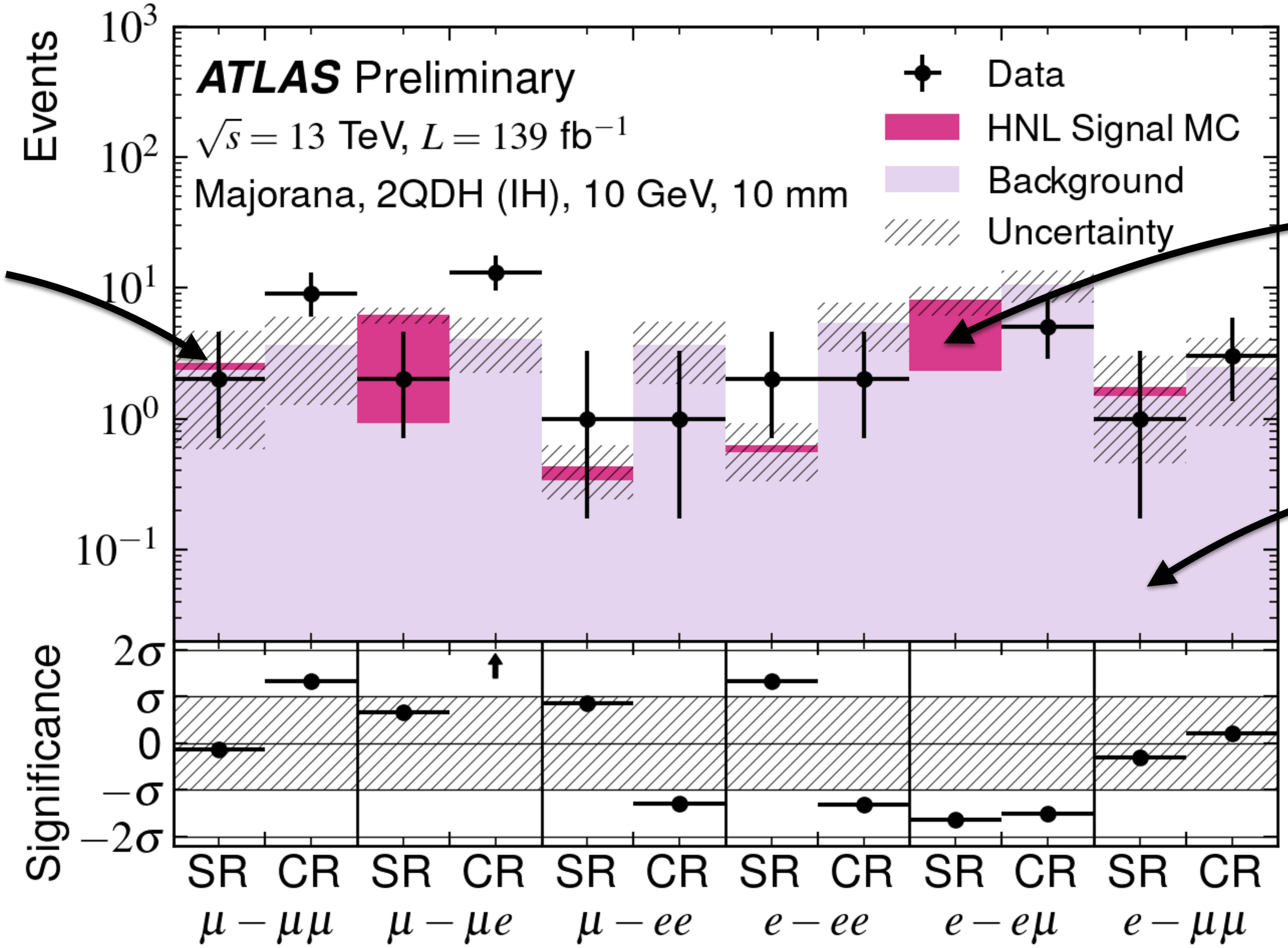
- Significantly increases the available statistics (~x2,000)



Fit Model

- Global fit for the signal strength, background yields and nuisance parameters is performed

data events
(OS DVs)



simulated signal samples

shuffled background model
↳ *free-floating normalization*
(6 separate factors; one for each channel)

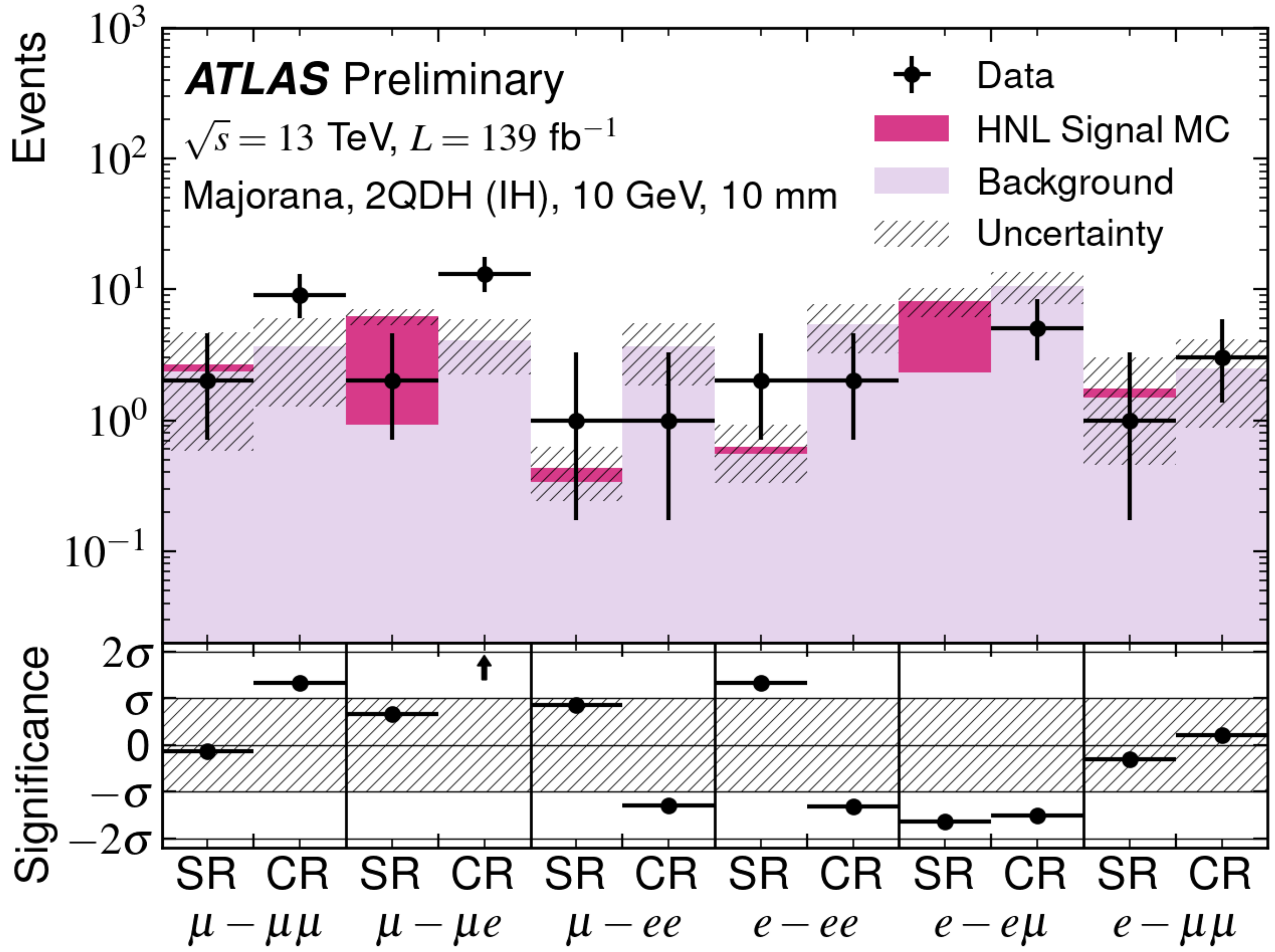
Signal Region (SR): $m_{HNL} < 20$ GeV
Control Region (CR): 20 GeV $< m_{HNL} < 50$ GeV

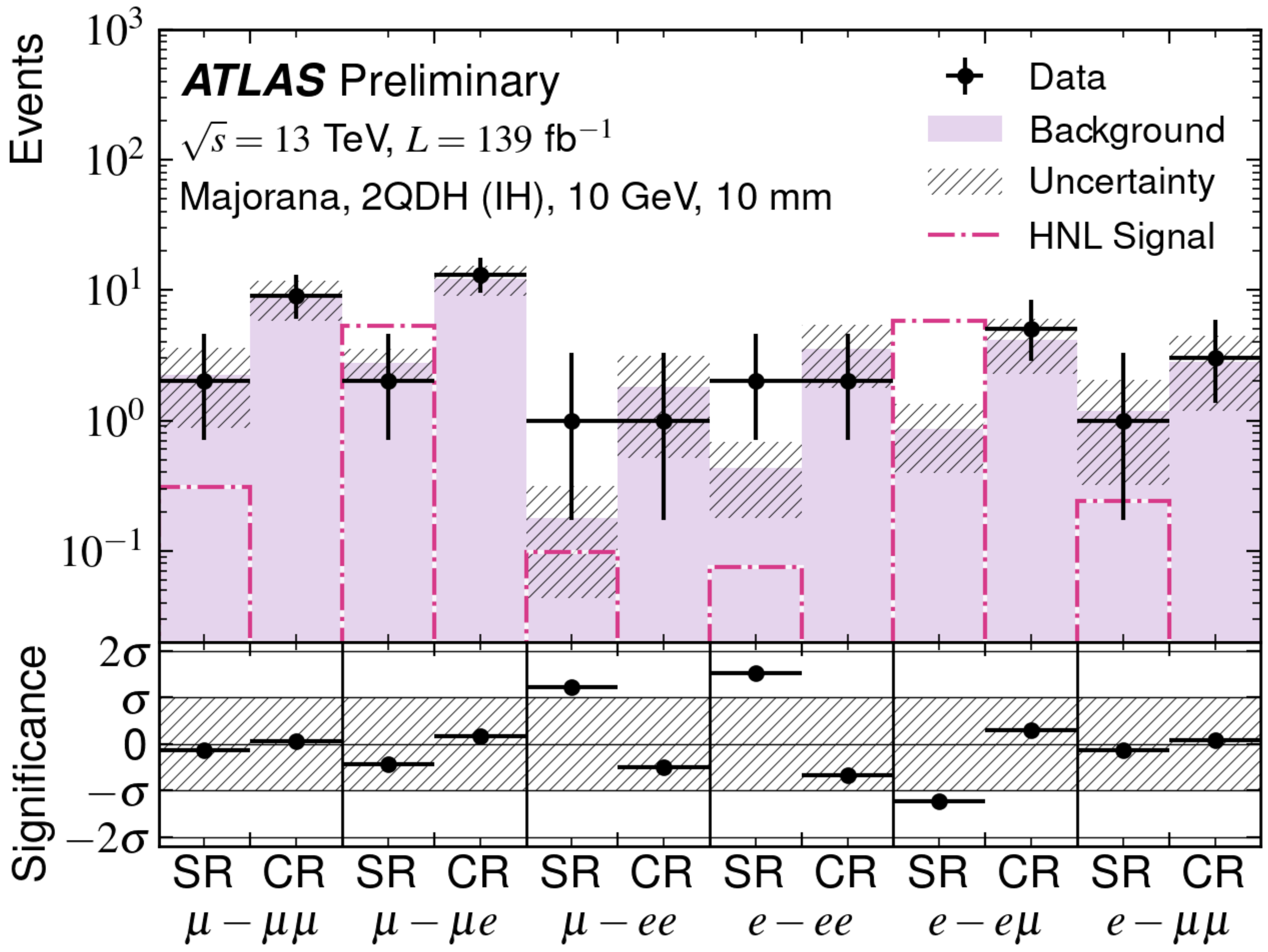
Used to constrain the background in the SR!

Results

- Fit results are consistent with **no significant excesses** in any of the six channels
  - ↳ **No new physics!** 🙁

Run fit →



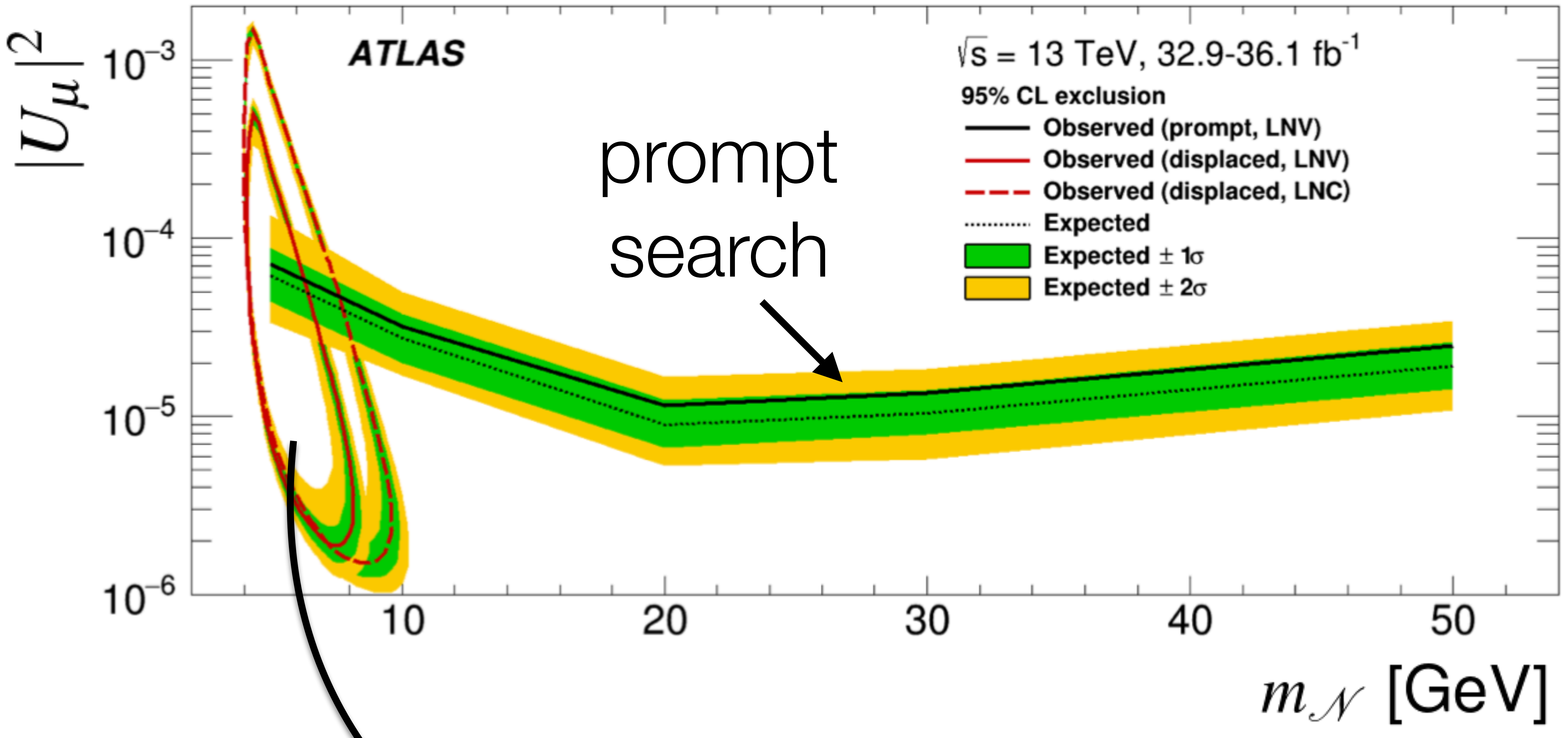


Limits For Muon-Only Mixing

muon-only mixing

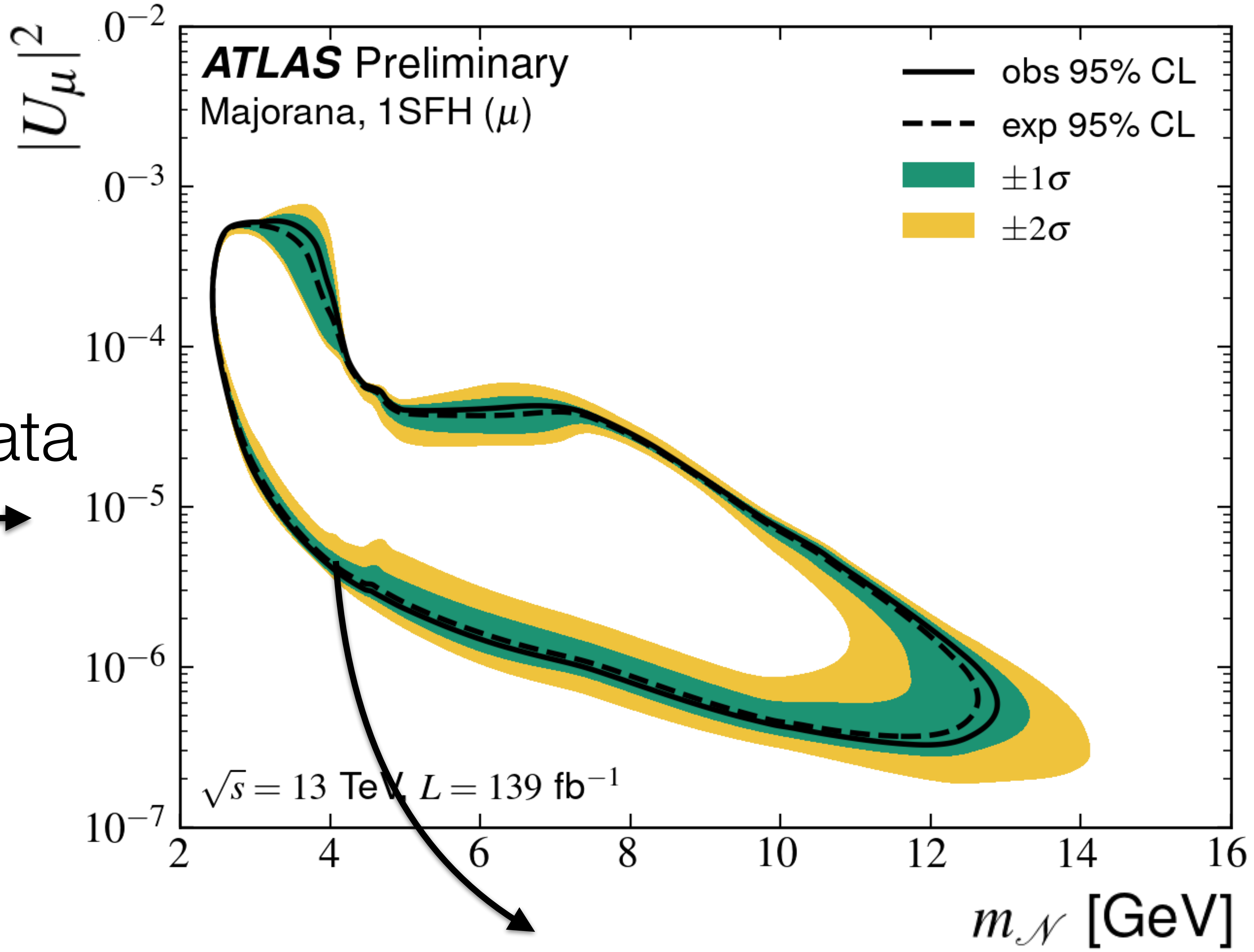
$U_e^2 : U_\mu^2 : U_\tau^2 = 0:1:0$

[arXiv:1905.09787](https://arxiv.org/abs/1905.09787)



Displaced HNL result with **2016 data only**

~ x4 data



2015-2018 Data Result

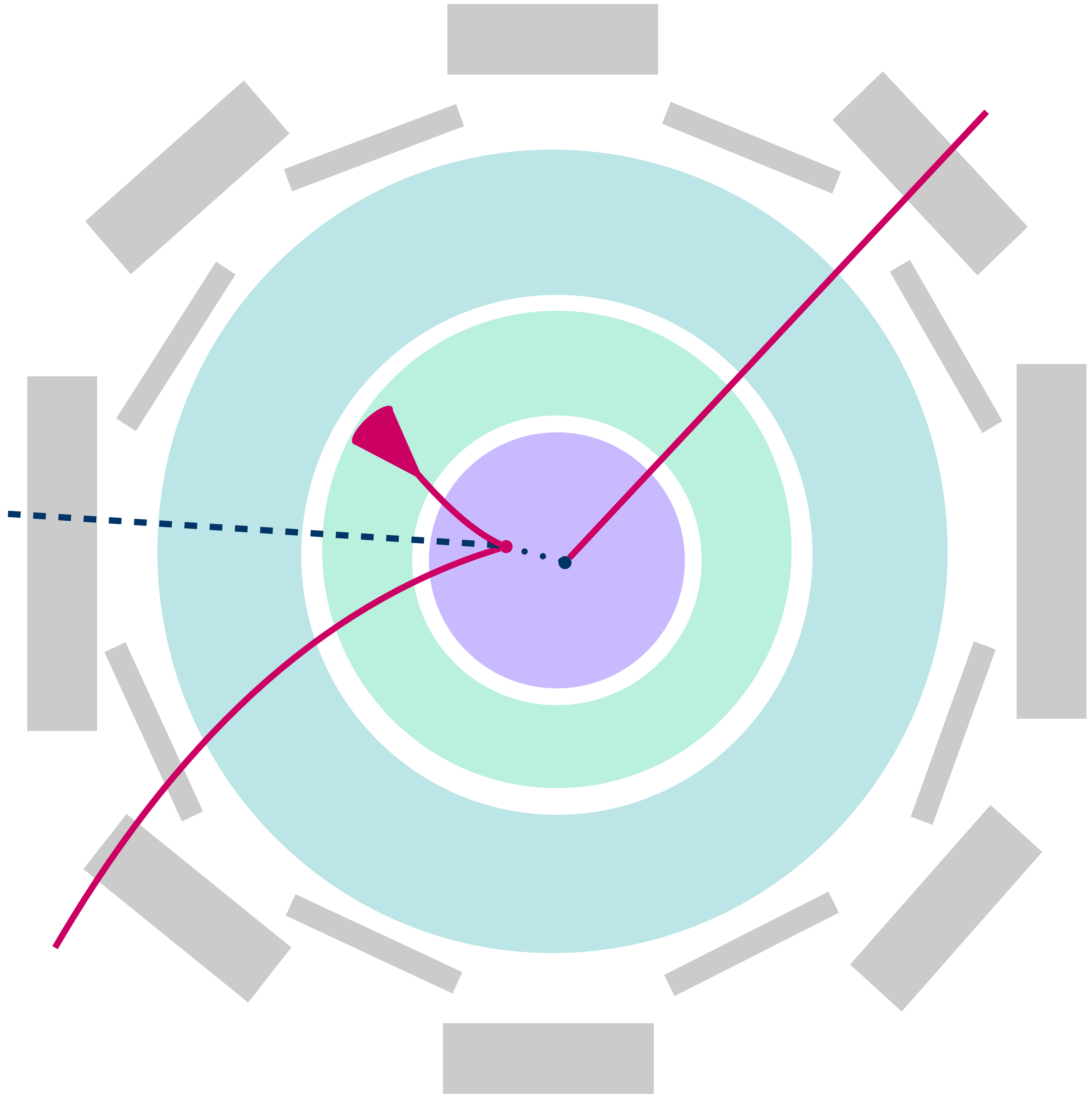
low-mass: ~1 GeV improvement
high-mass: ~4 GeV improvement

~x3 stronger limit on $|U_\mu|^2$

Exclusion Limits Summary

- Limits span a challenging long-lived region of phase space
- Interpretations assuming various mixing scenarios provide constraints for theoretical predictions

Summary

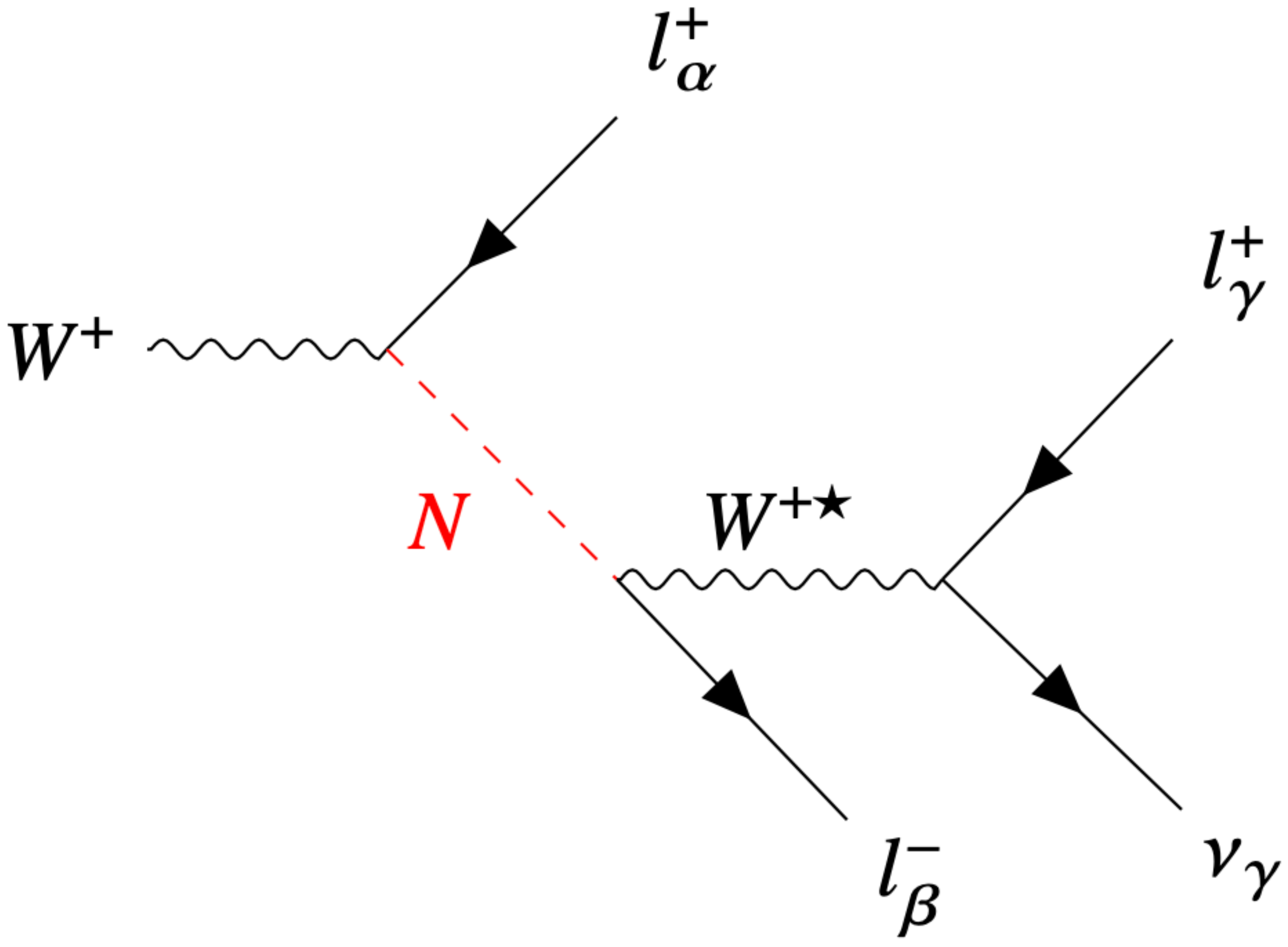


ATLAS Displaced Vertex Search for Heavy Neutral Leptons

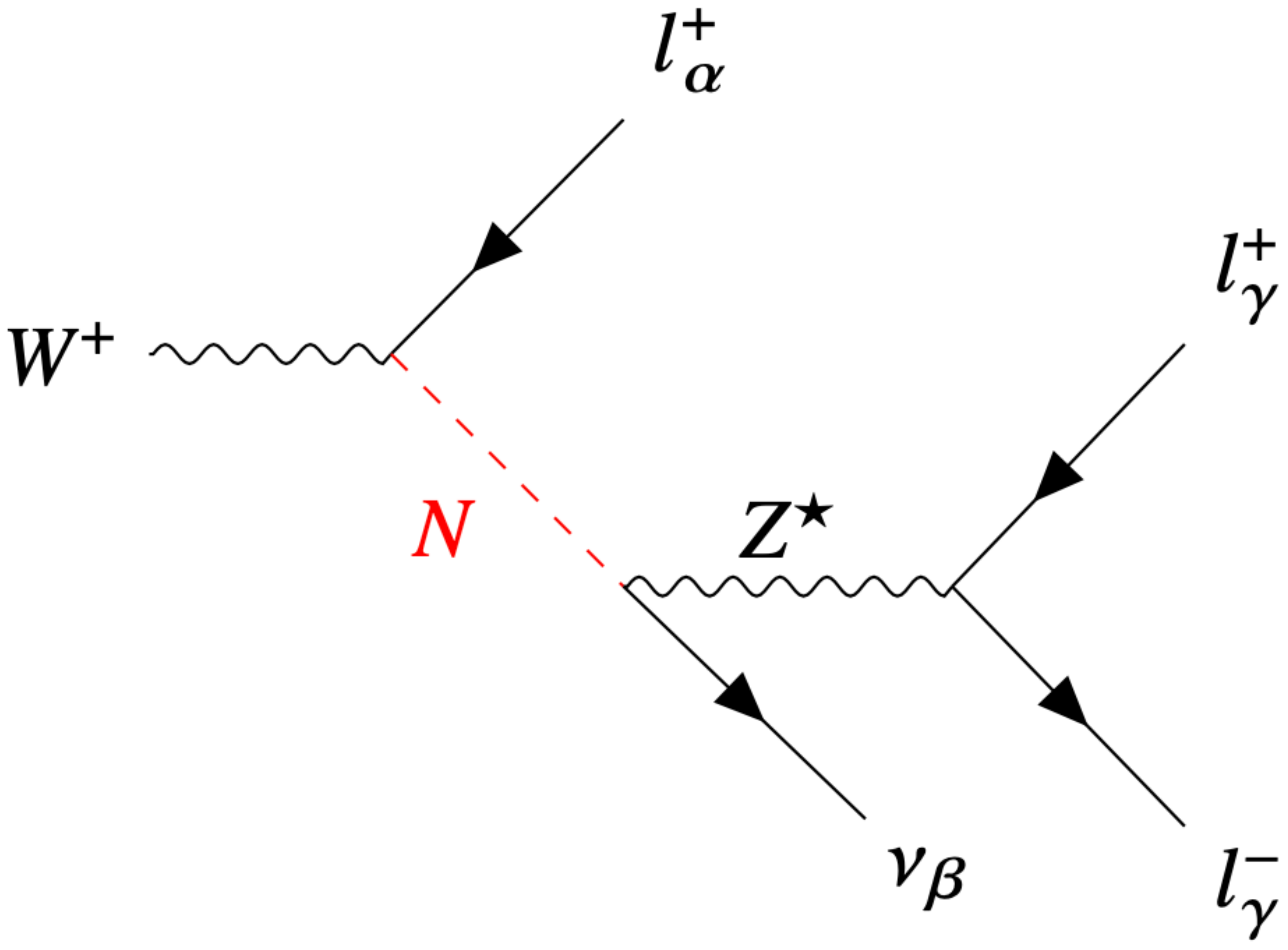
- No evidence for new physics
- Brand new results for electron-only and multi-flavour mixing scenarios
- Improved limits in muon-only mixing scenarios

Backups

HNL Production and Decay



(a) Charged current decay ($\alpha - \beta\gamma$)

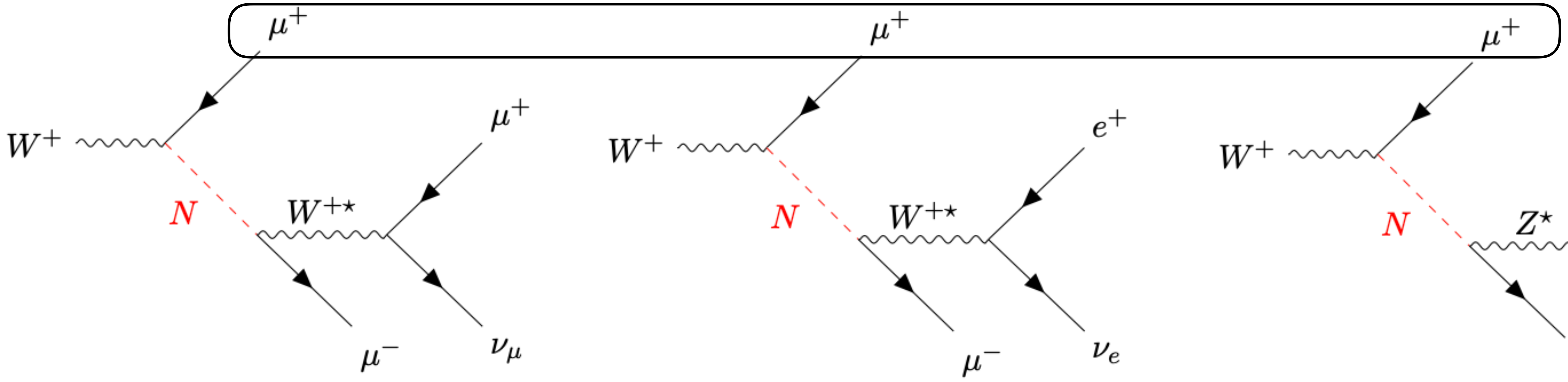


(b) Neutral current decay ($\alpha - \gamma\gamma$)

Signal Channels

prompt muon

Muon-only mixing



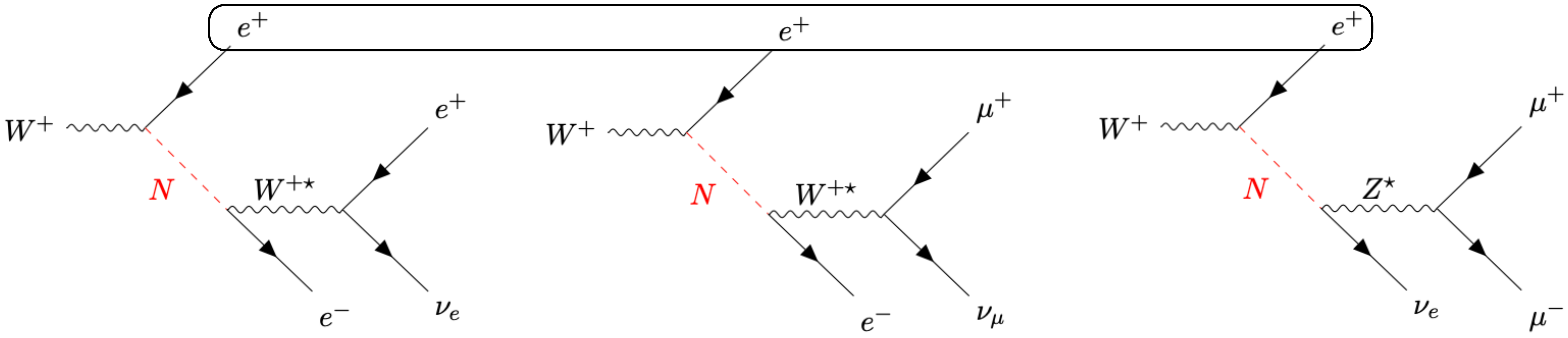
(a) μ−$\mu\mu$ μμ DV

(c) μ−μe eμ DV

(e) μ−ee ee DV

prompt electron

Electron-only mixing



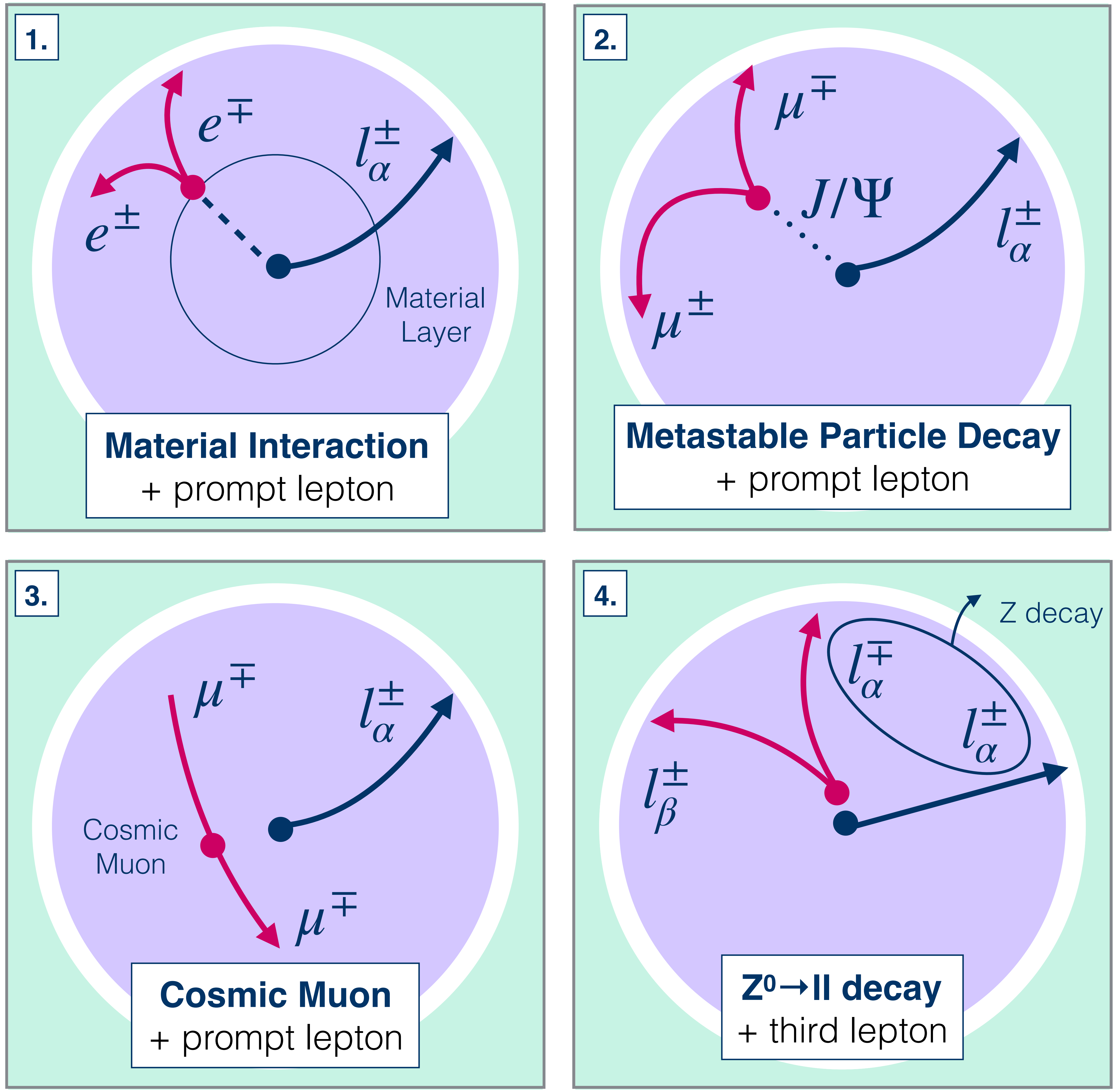
(b) e−ee ee DV

(d) e−$e\mu$ eμ DV

(f) e−$\mu\mu$ μμ DV

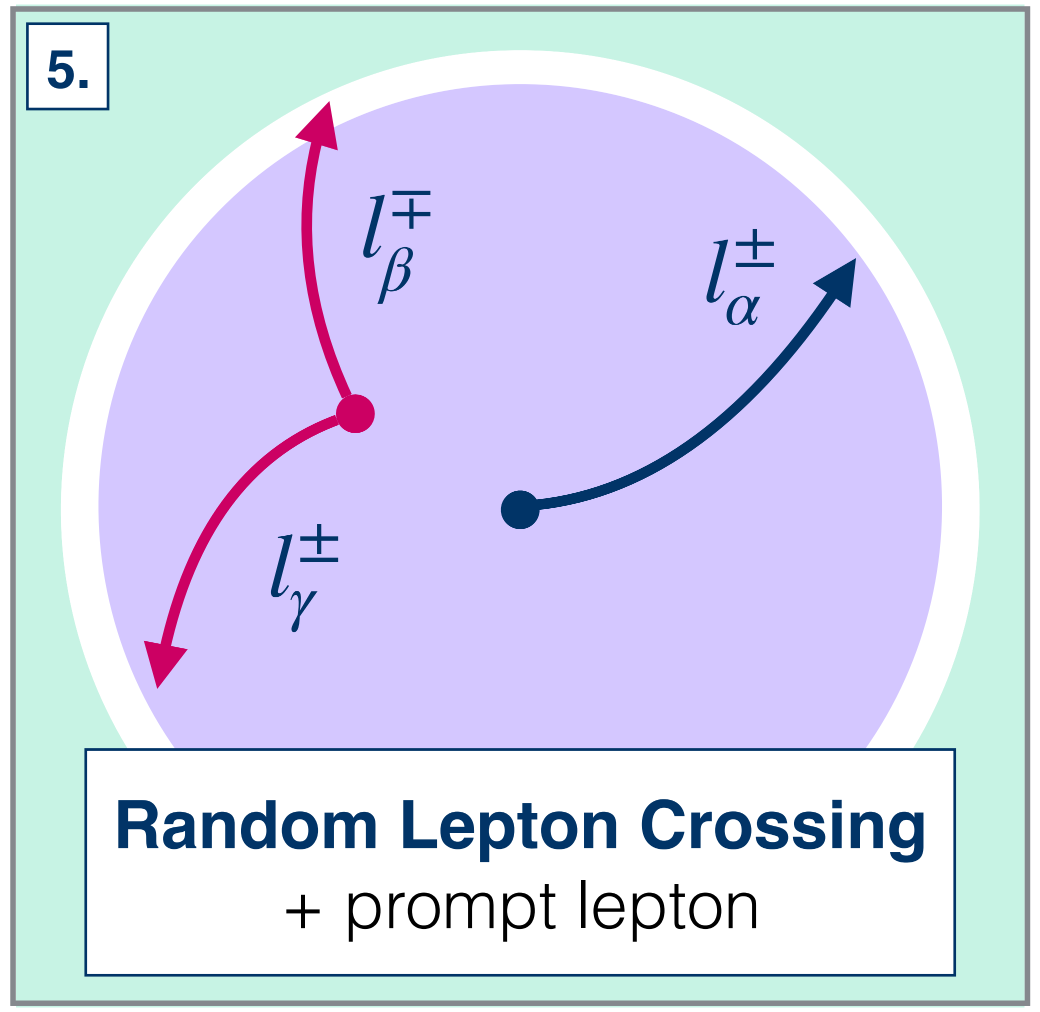
Backgrounds

Non-random Backgrounds

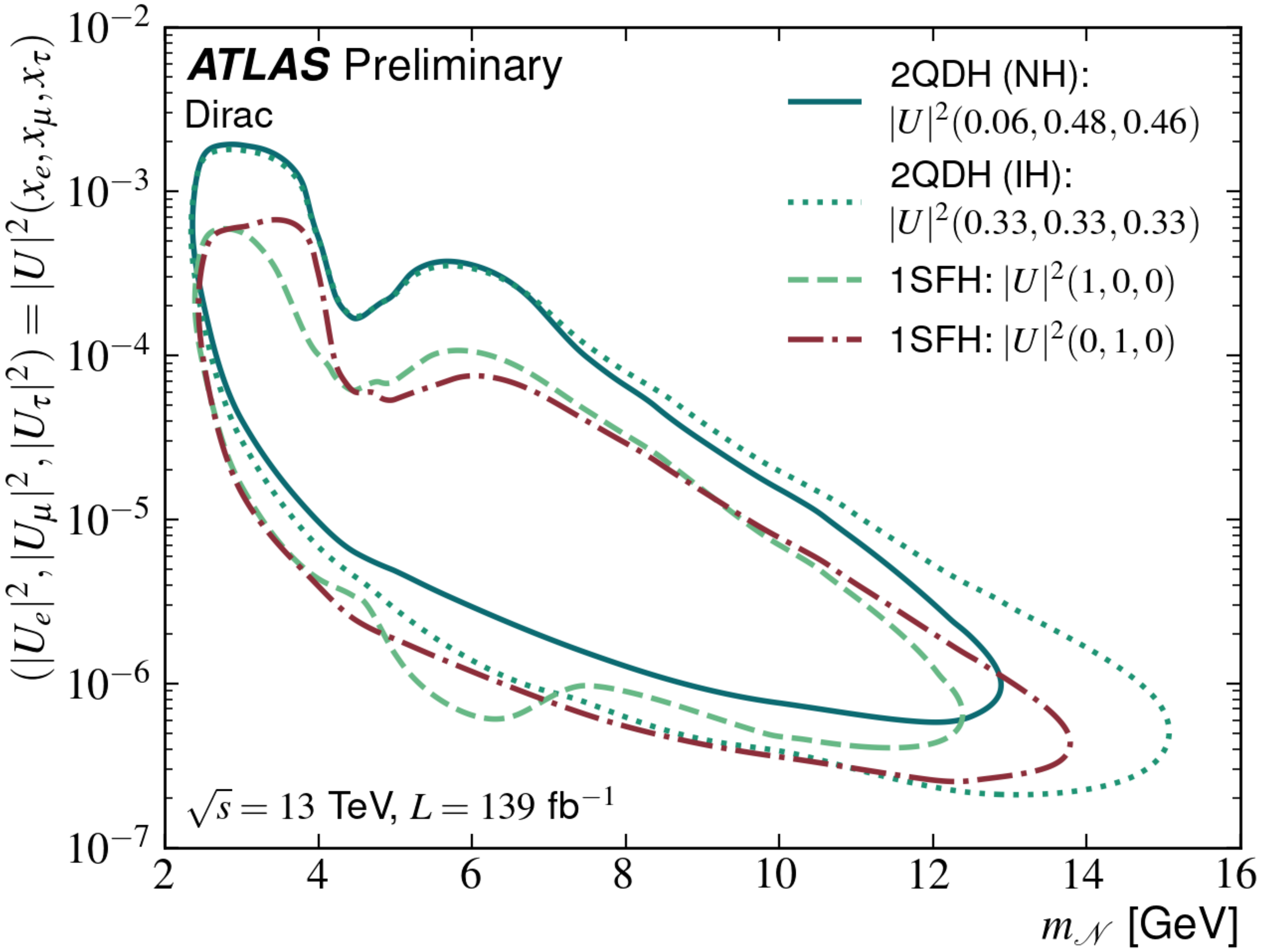


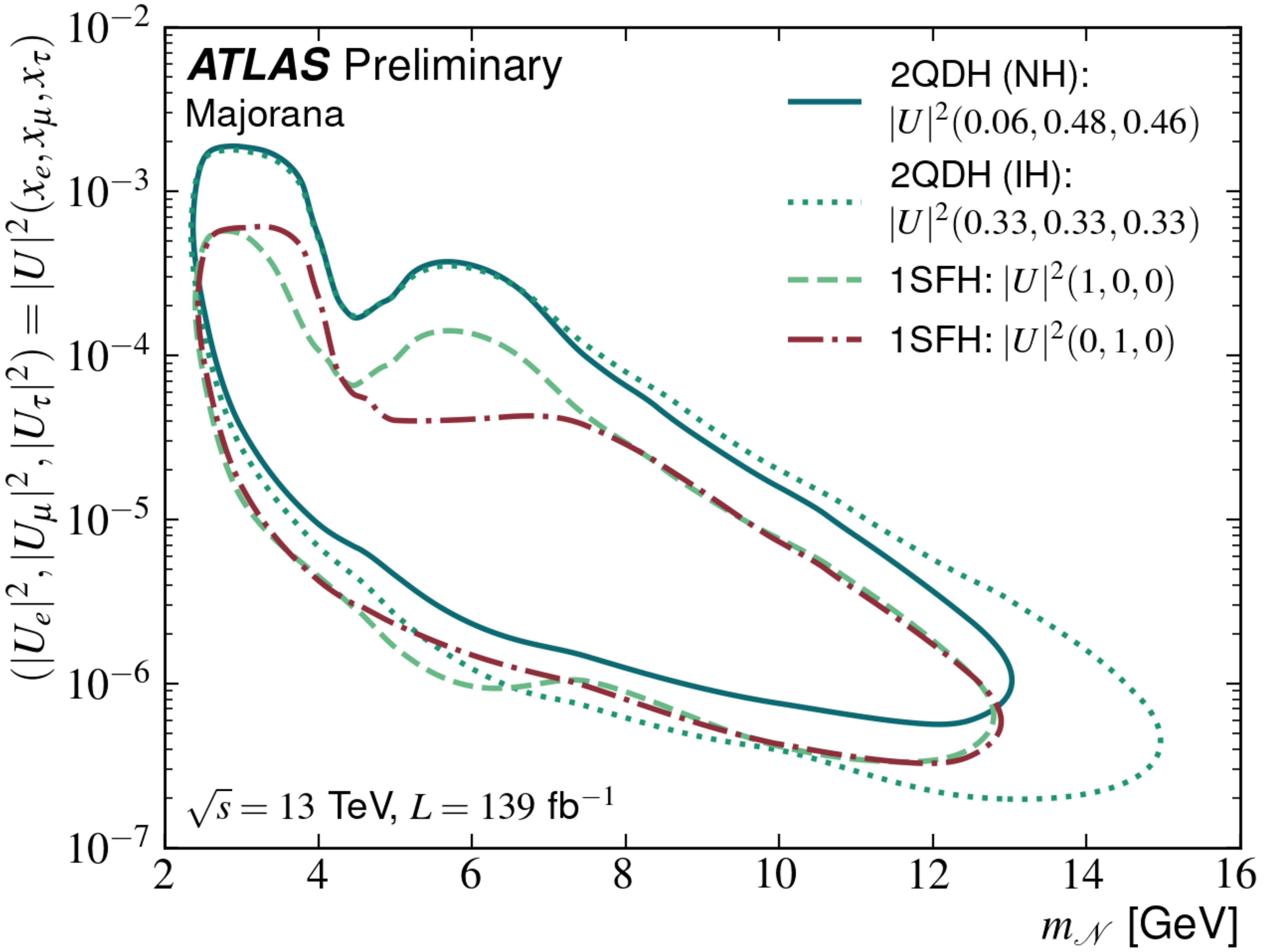
- Dedicated selections use to remove non-random backgrounds
  - e.g. minimum requirements on the invariant mass of the DV (m_{DV}) to reject heavy-flavour decays
- Dominant background: **random lepton crossings**

Random Background



Limit Summary Plots





Dirac-limit: 100% lepton number conserving (LNC)

Majorana-limit: 50% LNC / 50% lepton number violating (LNV)

Single-Flavour Mixing Limits

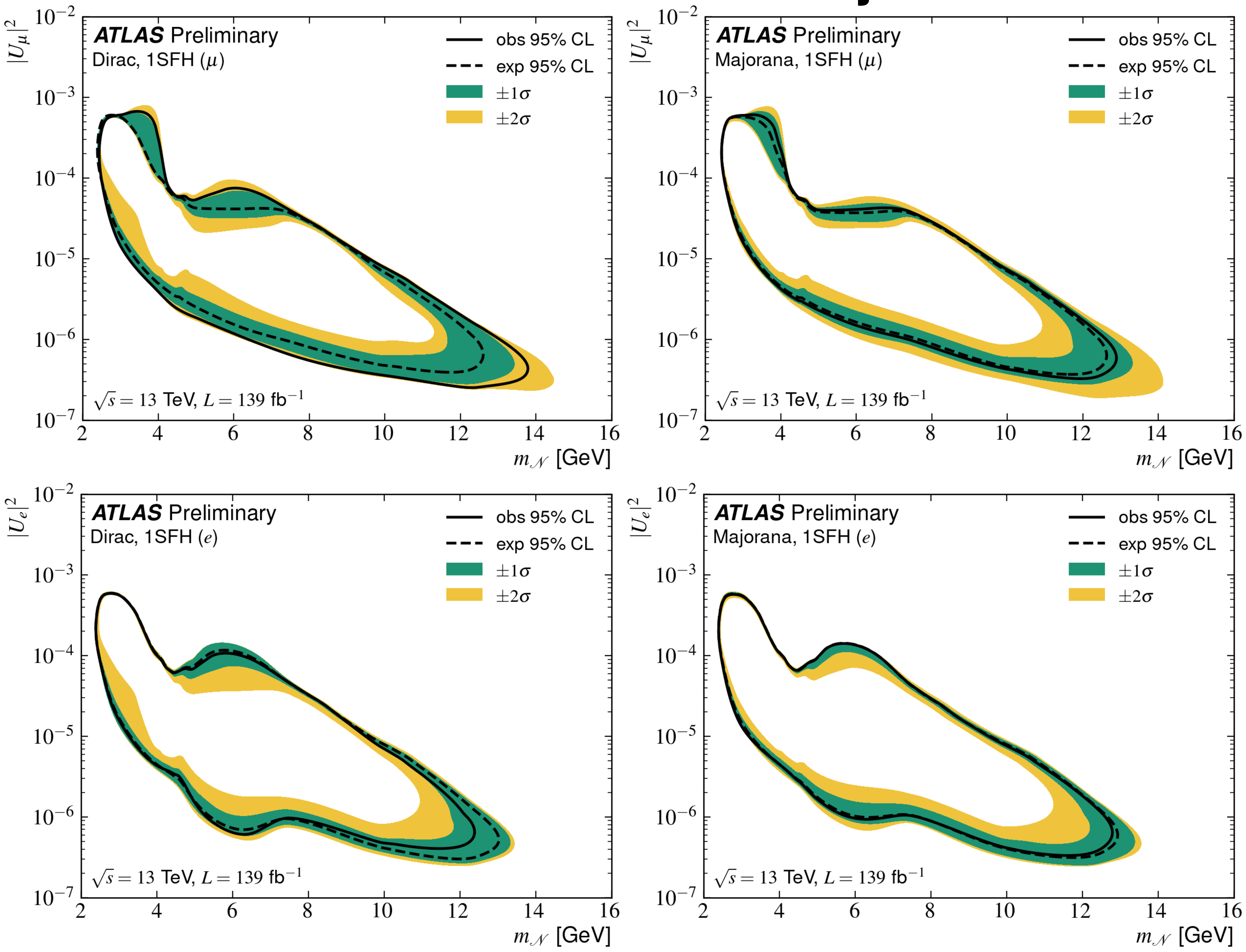
Dirac-limit | Majorana-limit

Muon-only mixing

$|U_e|^2 : |U_\mu|^2 : |U_\tau|^2 = 0 : 1 : 0$

Electron-only mixing

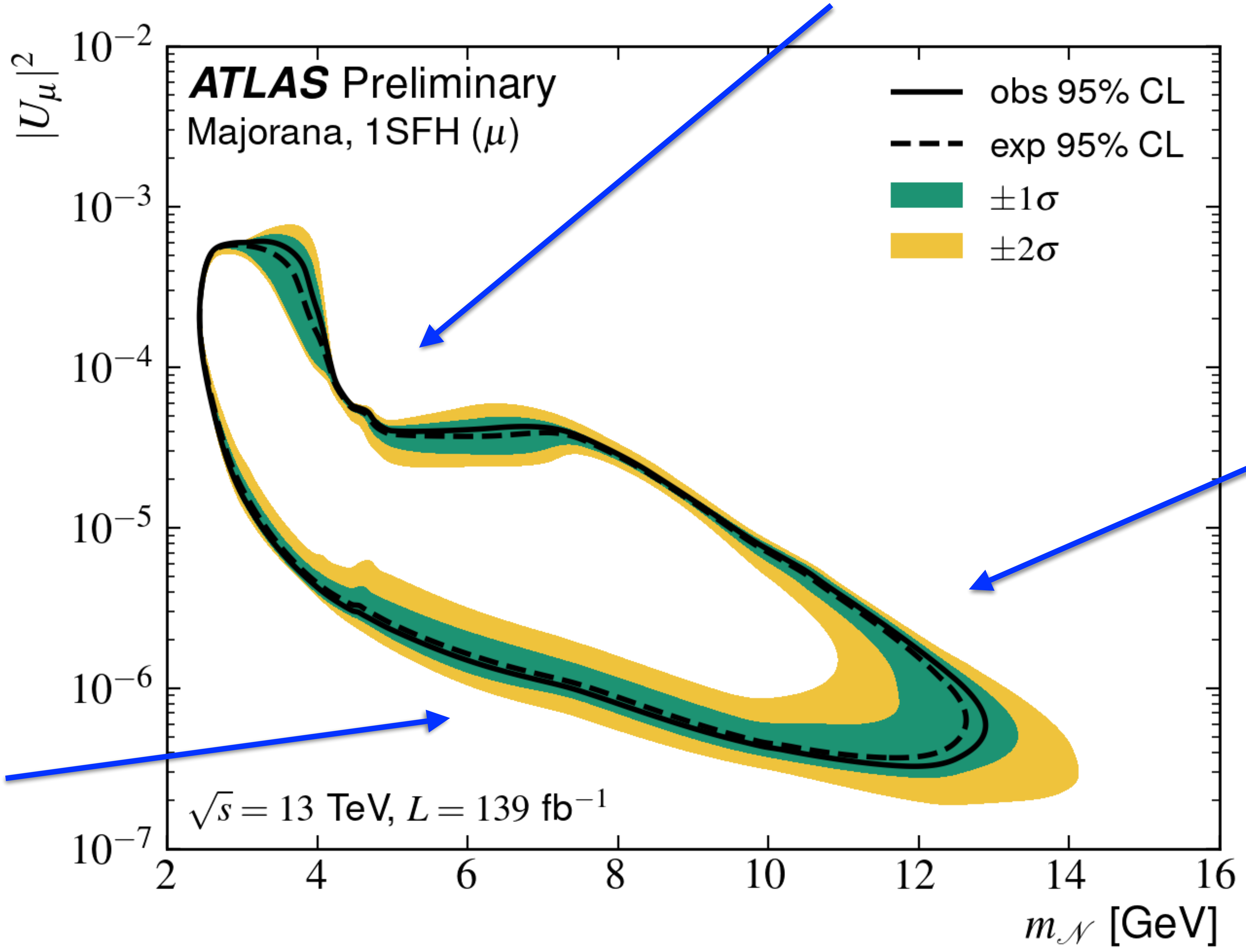
$|U_e|^2 : |U_\mu|^2 : |U_\tau|^2 = 1 : 0 : 0$



Limits For Muon-Only Mixing

- Limits on $|U|^2$ as a function of m_N extracted at the 95% confidence level:

m_{DV} and r_{DV} cuts to remove metastable decays also removes sensitivity to short-lived low mass HNLs

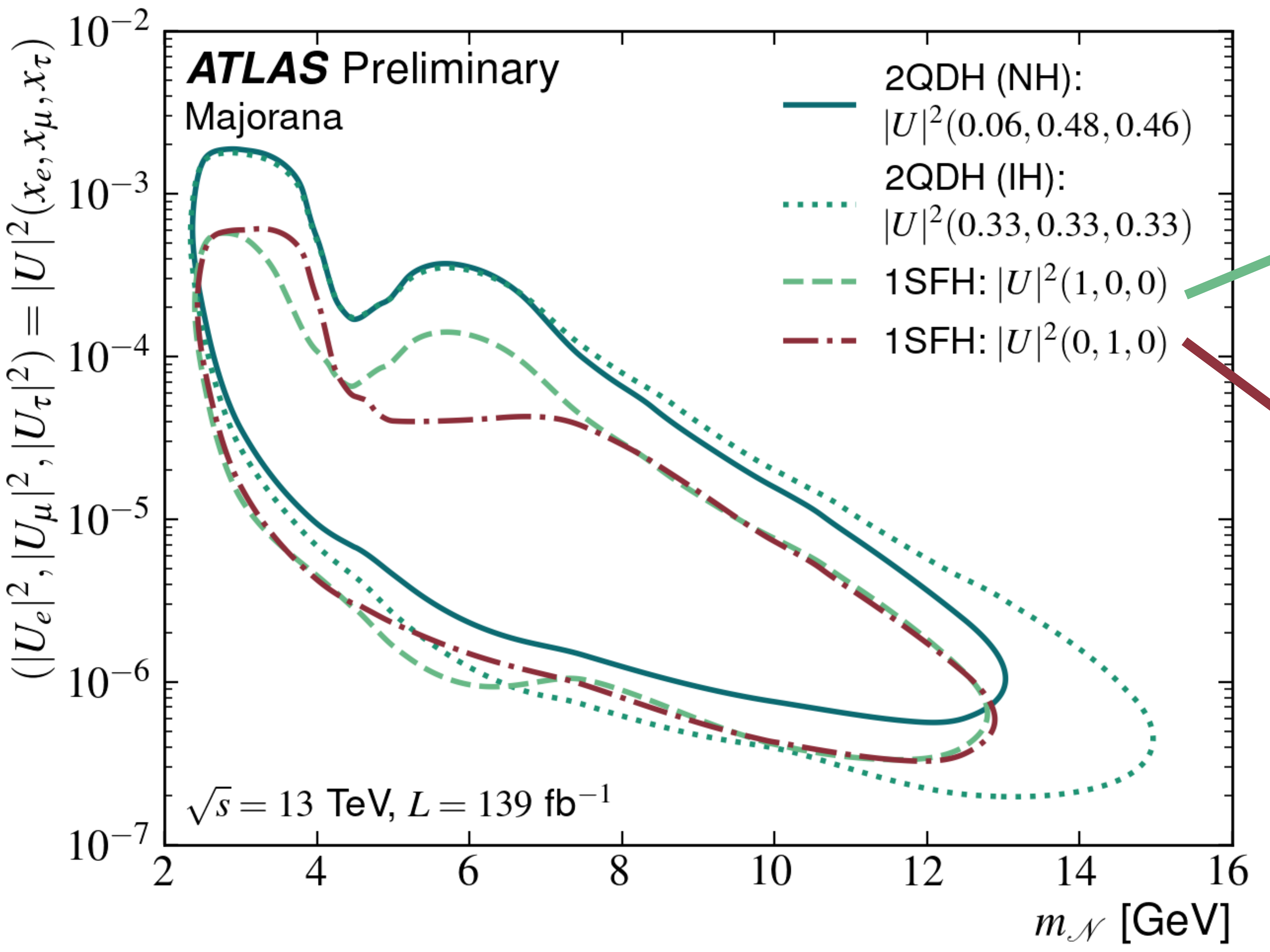


Decays too quickly

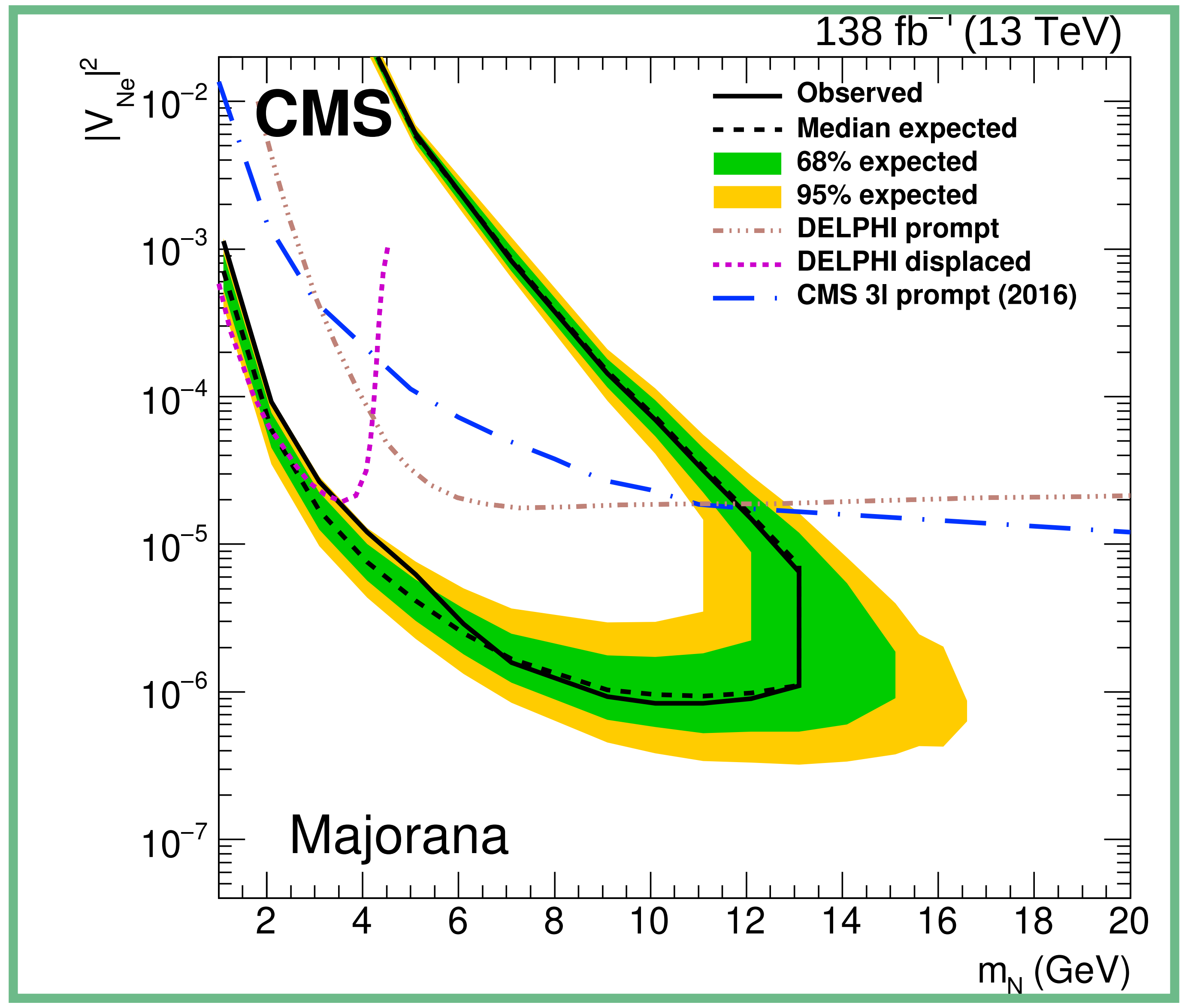
Too few decays in the detector volume

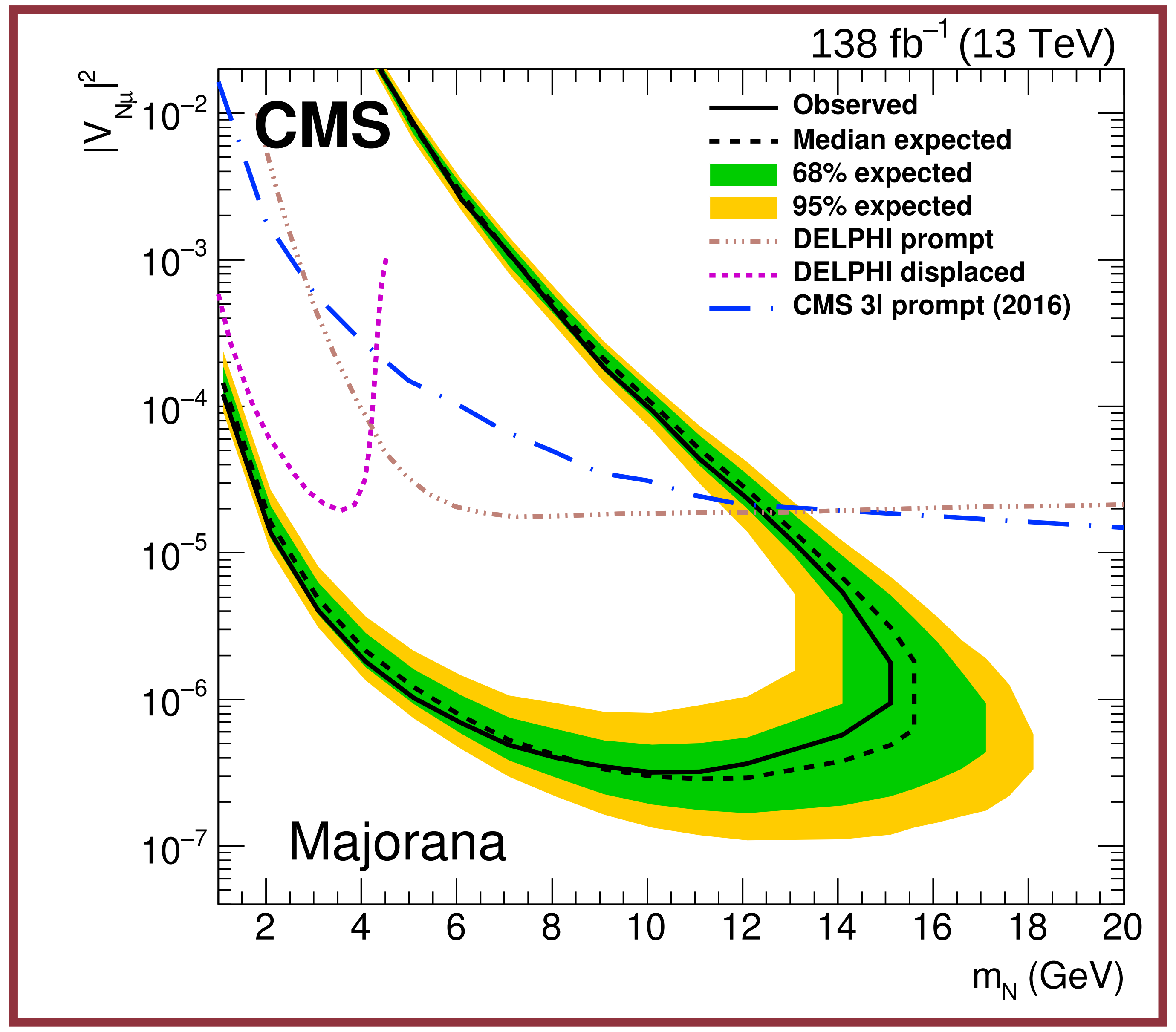
$$\tau_N \propto \frac{1}{m_N^5 |U_\alpha|^2}$$

Comparison with CMS Limits



CMS-EXO-20-009





Similar story for Dirac models.

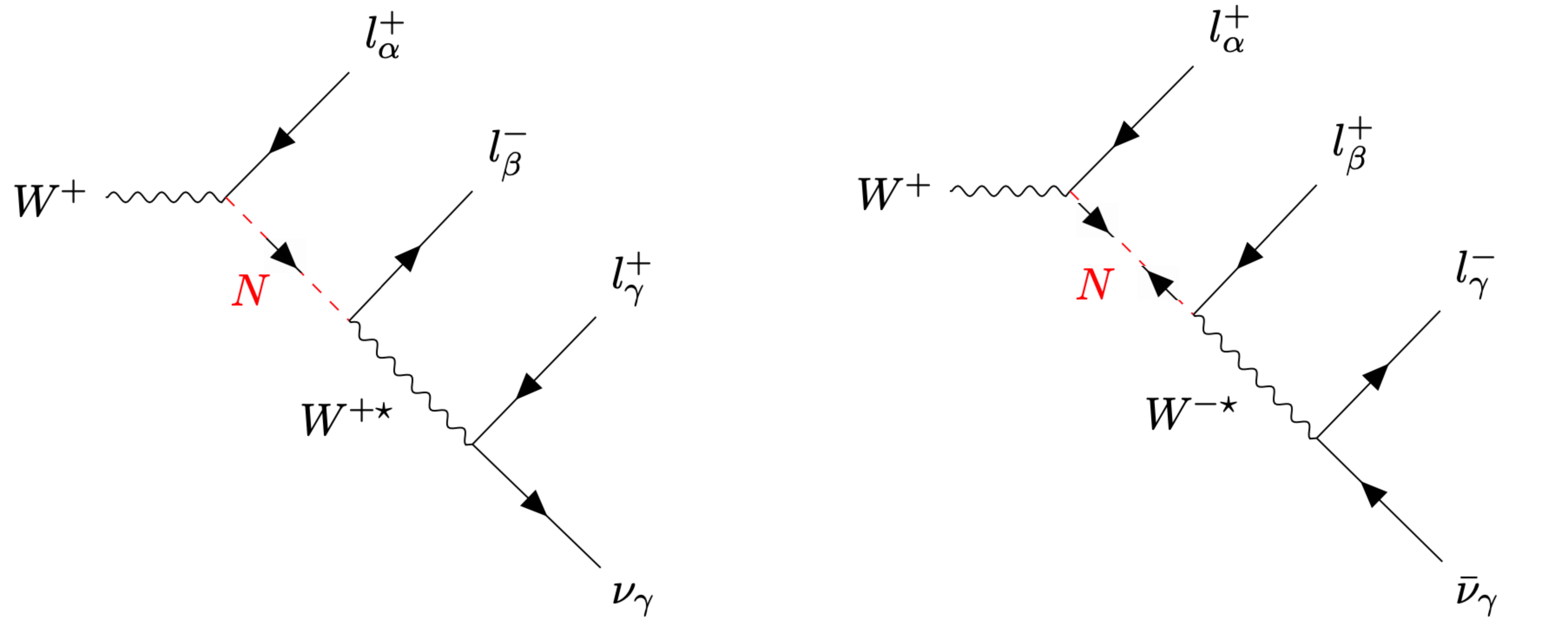
HNL Decays

- Depending on the nature of the HNL, lepton number violating decays are possible

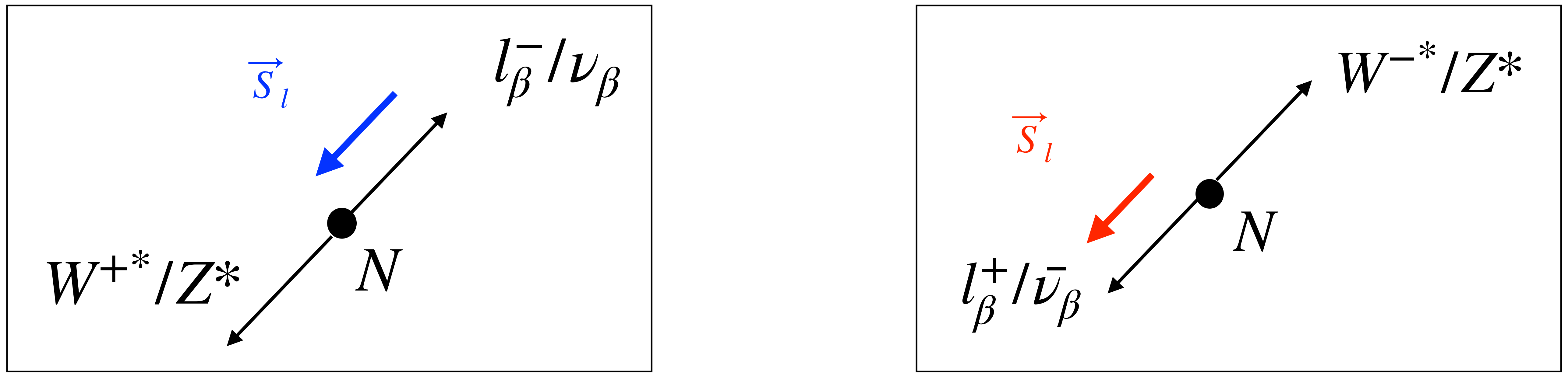
- ATLAS search considers both:
  - “Dirac-limit”: 100% LNC
  - “Majorana-limit” 50% LNC / 50% LNV

Limits are provided for both scenarios.

Lepton number conserving (LNC) | Lepton number conserving (LNV)



(a) LNC (b) LNV



Different angular distributions!

Analysis Selections

Level	Selection	Value
Pre-selection	Event cleaning	Standard ATLAS event cleaning
	Primary vertex	At least one with $p_{\mathrm{T}} > 500$ MeV
	Trigger	At least one single muon or electron trigger
	Trigger-matched lepton	At least one *Medium* (μ) or *LHMedium* (e) lepton with $p_{\mathrm{T}} > 27$ GeV
	Filter	At least one HNL filter
	Prompt lepton	At least one
	Trigger matched lepton	At least one
	Displaced lepton-only vertex	At least one
	Number of tracks in DV	2
	Fiducial volume	4 mm $< L_{xy} <$ 300 mm
SR selection	DV charge	Opposite-sign tracks
	Prompt + disp. l charge	Opposite-sign leptons (For 1SFH models with only LNC decays)
	DV type	ee, $e\mu$ or $\mu\mu$ vertex
	Tri-lepton mass	40 GeV $< m_{lll} <$ 90 GeV
	HNL mass	$m_{\mathrm{HNL}} <$ 20 GeV
	Cosmic muon veto	$\sqrt{(\Sigma\eta)^2 + (\pi - \Delta\phi)^2} > 0.05$
	Material veto	Applied for ee DVs only
	Heavy-flavour decay veto	$m_{\mathrm{DV}} > 5.5$ GeV ($\mu\mu$ DVs) or m_{DV}-L_{xy} cut (ee or $e\mu$ DVs)
	Z mass veto	$m_{ll} <$ 80 GeV or $m_{ll} >$ 100 GeV, for same-flavour opposite-sign leptons

Heavy-Flavour Decay Background Veto

- Exploit DV mass (m_{DV}) and DV radius (r_{DV}) correlations
  - Data events studied in the validation region (VR)
- Re-gain sensitivity to low DV mass HNLs
  - **eμ** and **ee** decays removed using $m_{\mathrm{DV}} - r_{\mathrm{DV}}$ correlation selection
  - Larger reconstruction efficiency for **μμ** DVs means that the $m_{\mathrm{DV}} - r_{\mathrm{DV}}$ correlation selection is not sufficient to remove remove heavy-flavour μμ decays

Heavy-flavour veto

- **μμ DVs :**
  - $m_{\mathrm{DV}} > 5.5\ \mathrm{GeV}$
- **eμ and ee DVs:**
  - $m_{\mathrm{DV}} > 5.5\ \mathrm{GeV}$, if $r_{\mathrm{DV}} < 32\ \mathrm{mm}$
  - $m_{\mathrm{DV}} > -\dfrac{7\ \mathrm{GeV}}{150\ \mathrm{mm}} r_{\mathrm{DV}} + 7\ \mathrm{GeV}$, if $32\ \mathrm{mm} < r_{\mathrm{DV}} < 107\ \mathrm{mm}$
  - $m_{\mathrm{DV}} > 2\ \mathrm{GeV}$, if $r_{\mathrm{DV}} > 107\ \mathrm{mm}$