Searches for Displaced Signatures

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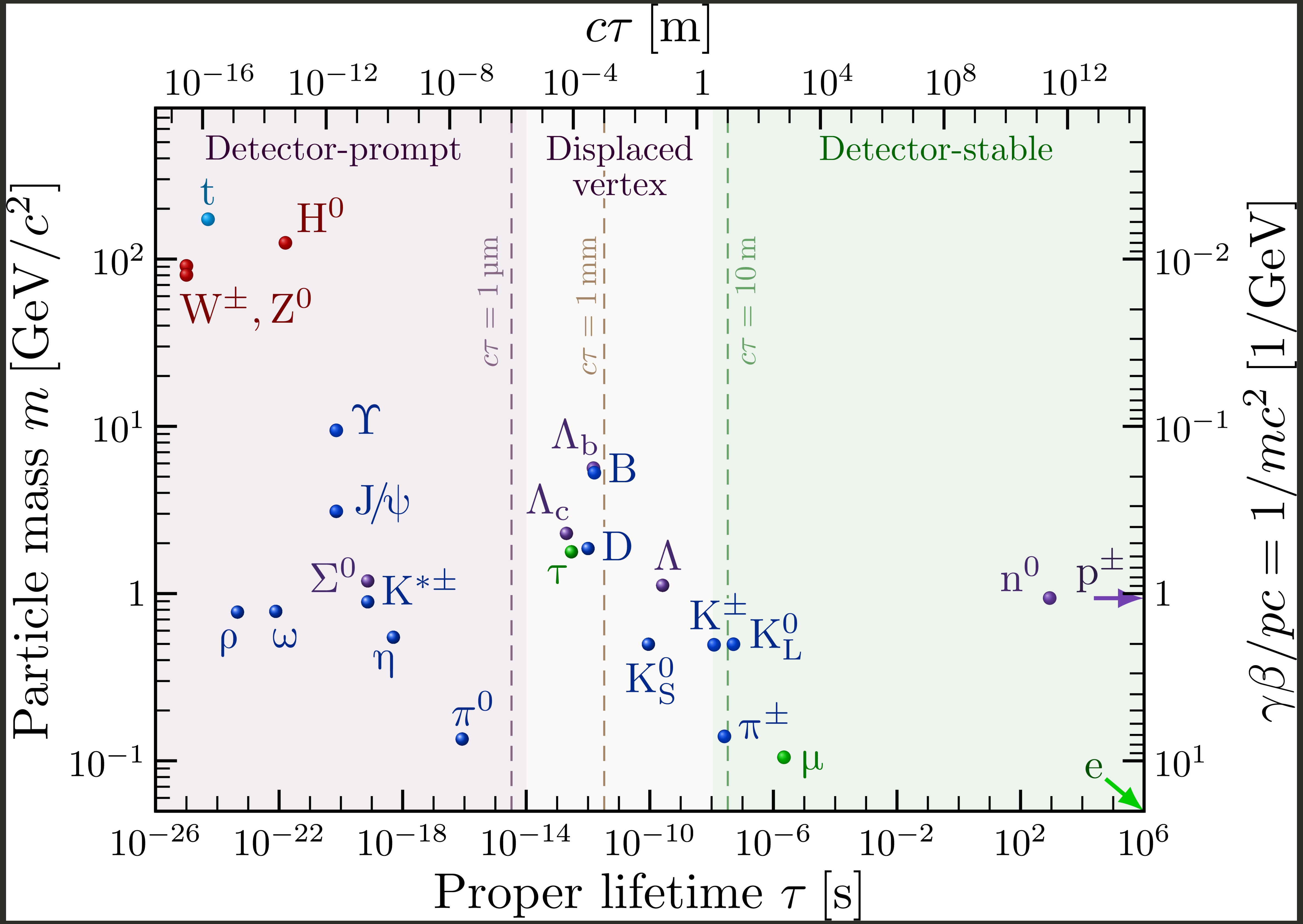
on behalf of ATLAS and CMS collaborations

Rencontres de Moriond Electroweak 2025

27th March 2025

Exploring the lifetime frontier

Long-Lived Particles (LLPs) are one of the most promising directions to expand searches at the LHC



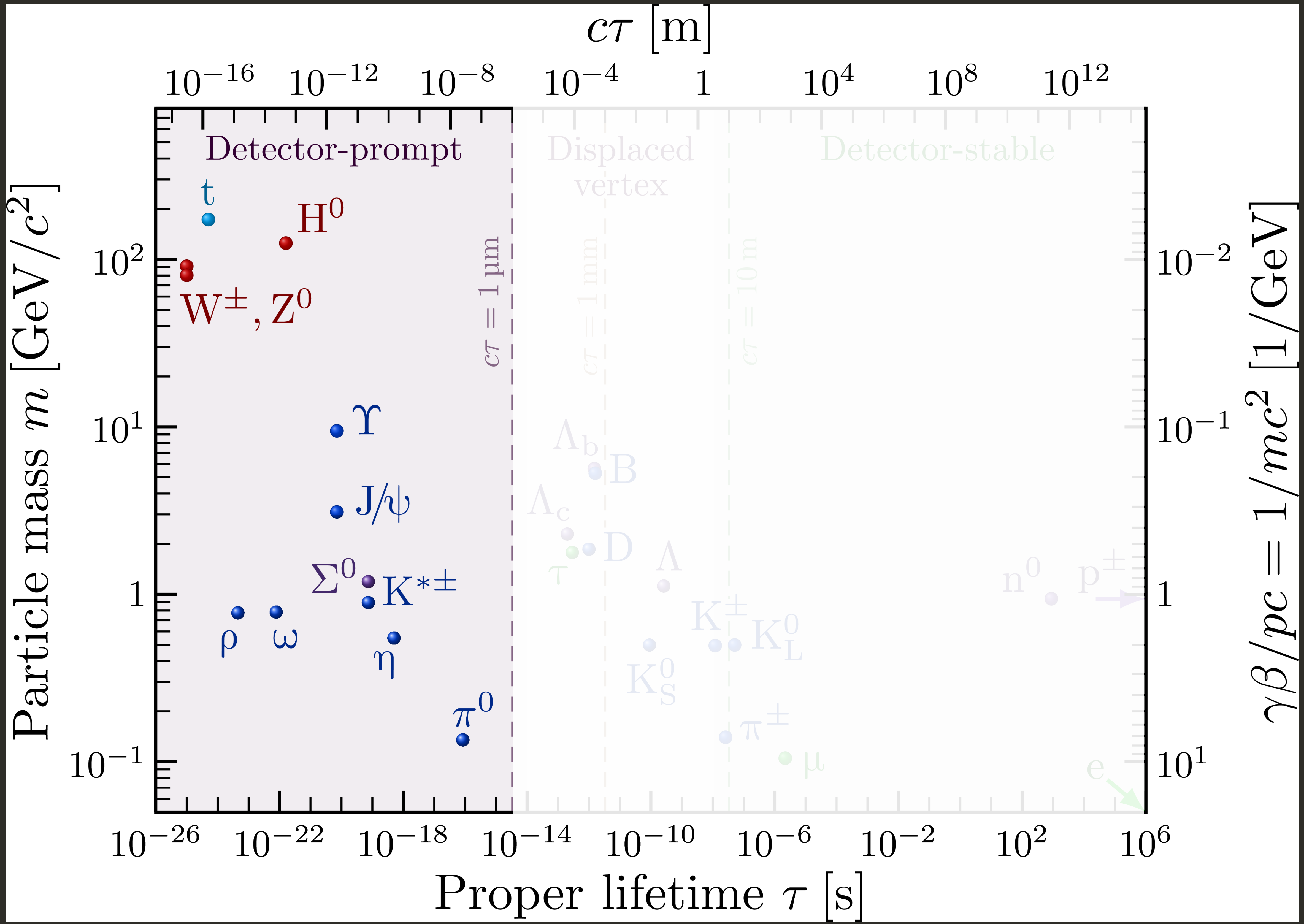
LLPs are abundant in the Standard Model

https://tikz.net/sm_particles_masses/

Simple theoretical motivations: ~ degenerate masses, small couplings, virtual intermediate states

Exploring the lifetime frontier

Probing the nature of prompt particles form the bulk of the LHC physics program

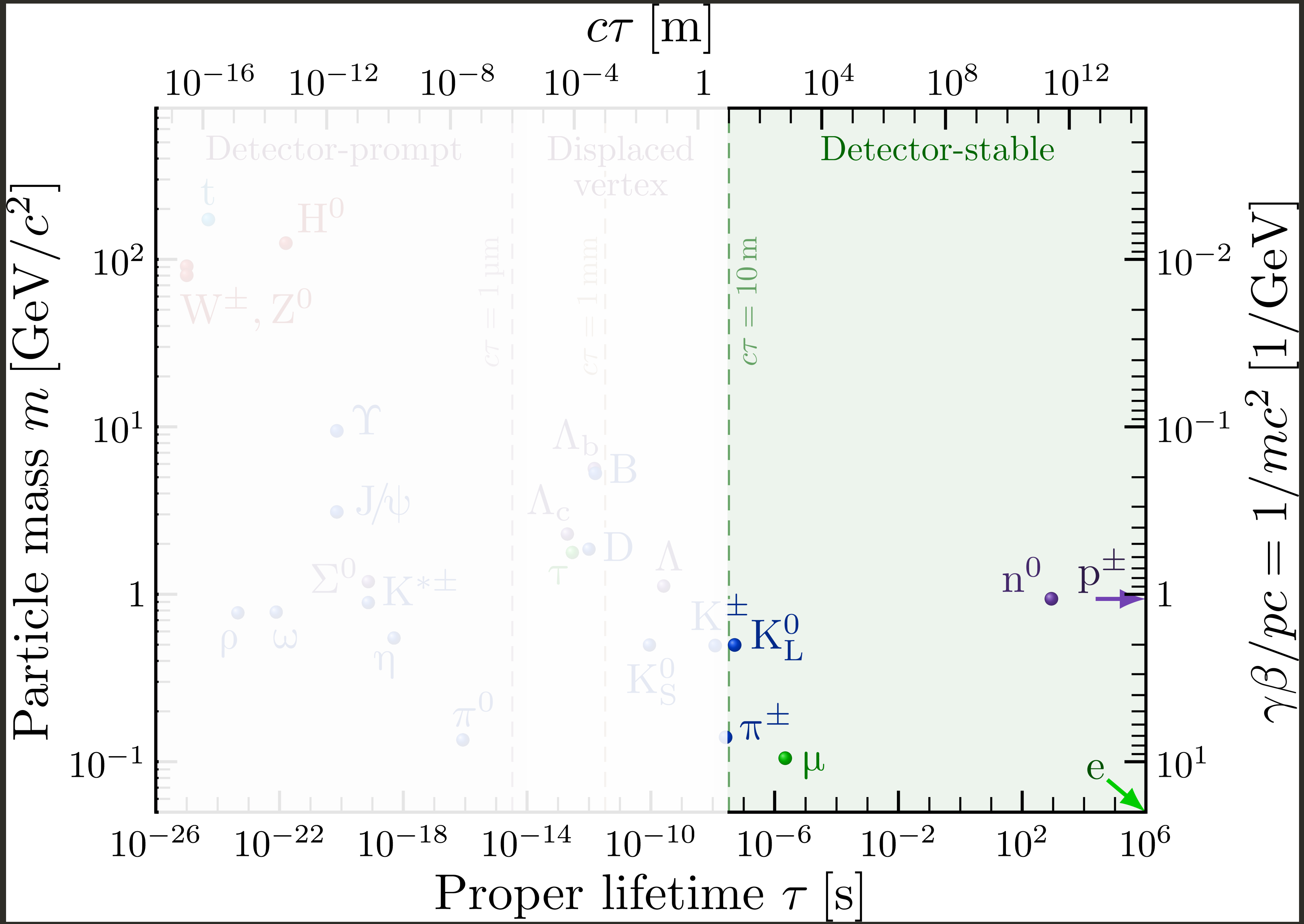


https://tikz.net/sm_particles_masses/

Well supported by standard reconstruction methods with the main challenges being analysis techniques

Exploring the lifetime frontier

LHC experiments are also sensitive to absence of activity from stable particles

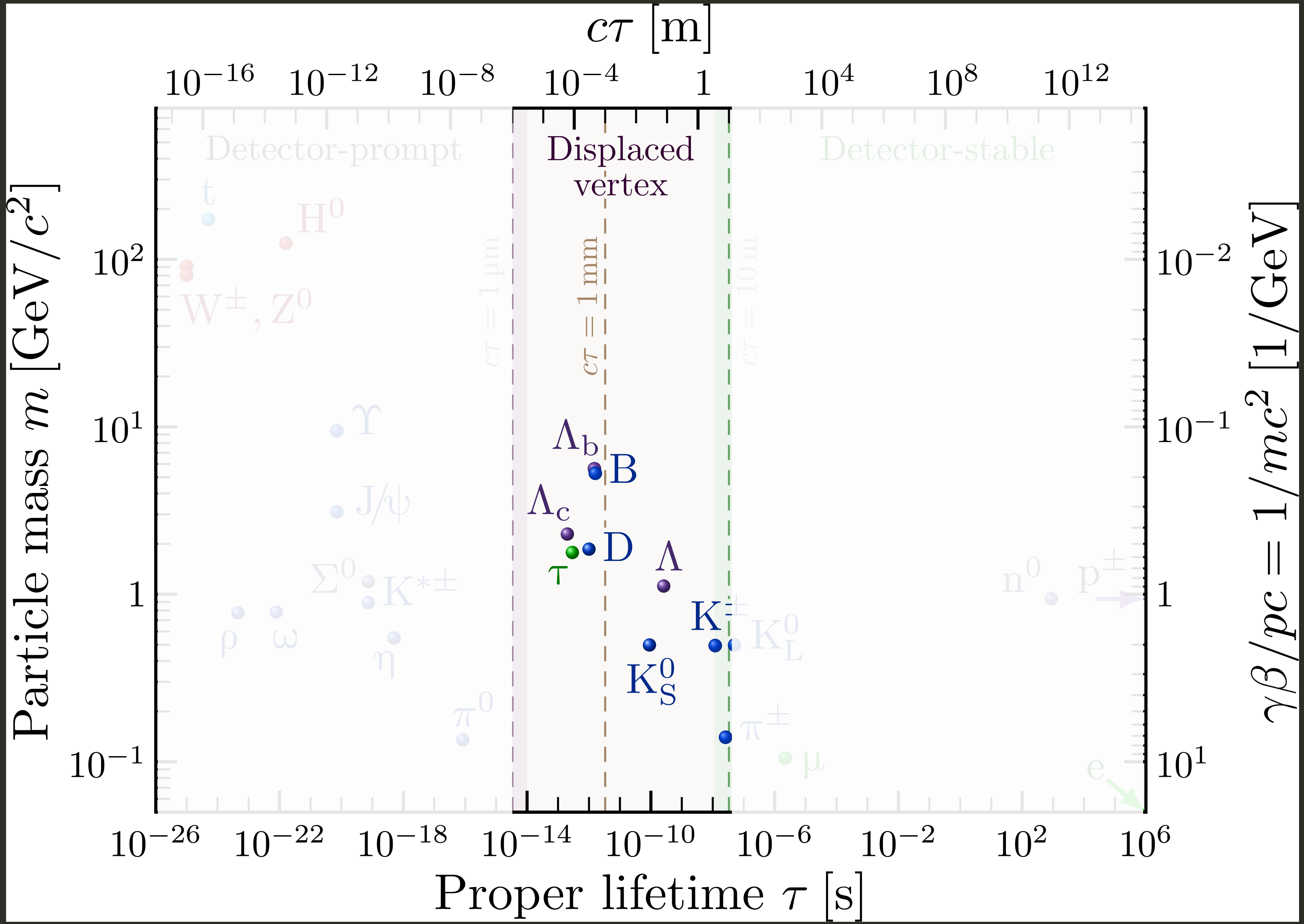


https://tikz.net/sm_particles_masses/

Searches such as mono-X or H→invisible allow strong constraints on new physics

Exploring the lifetime frontier

The detector size can capture physics signatures from particles that decay macroscopically



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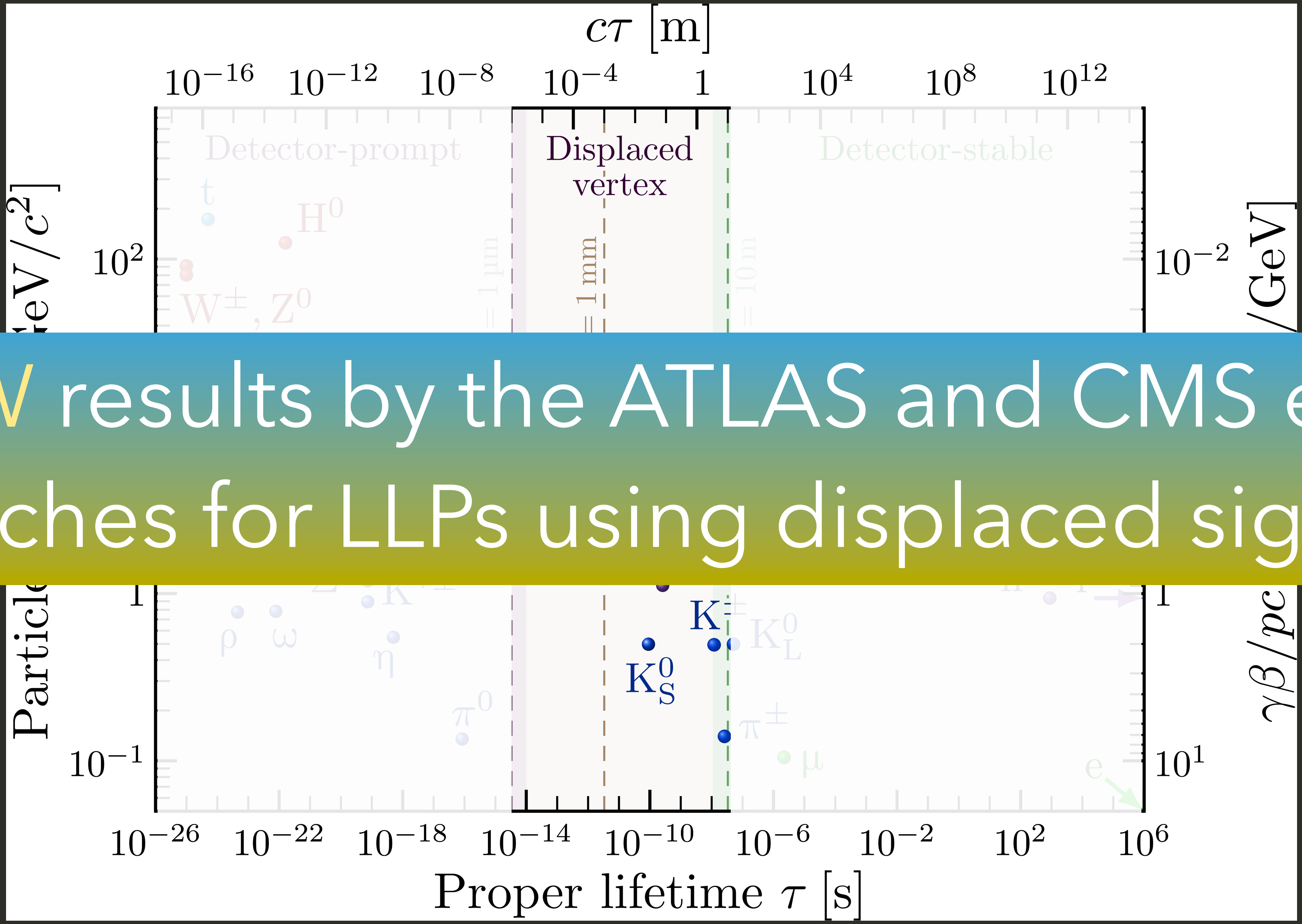
Such searches need specialized reconstruction and analysis techniques

Exploring the lifetime frontier

The detector size can capture physics signatures from particles that decay macroscopically

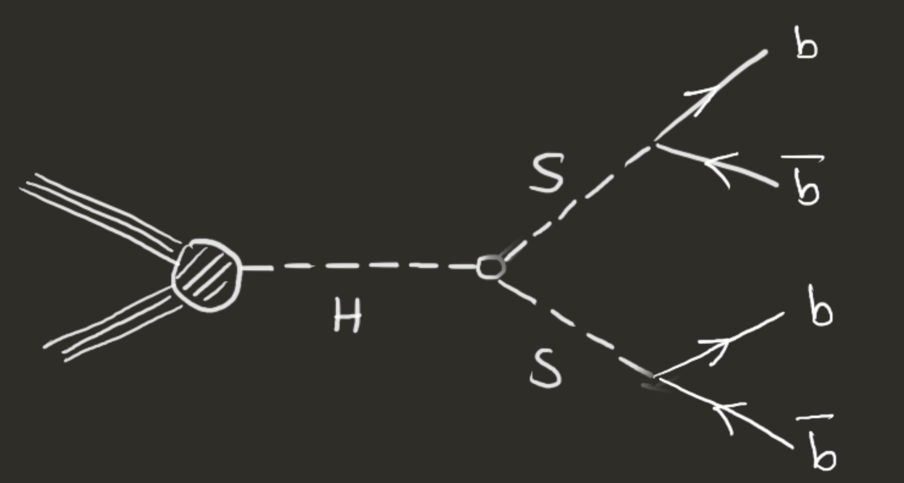


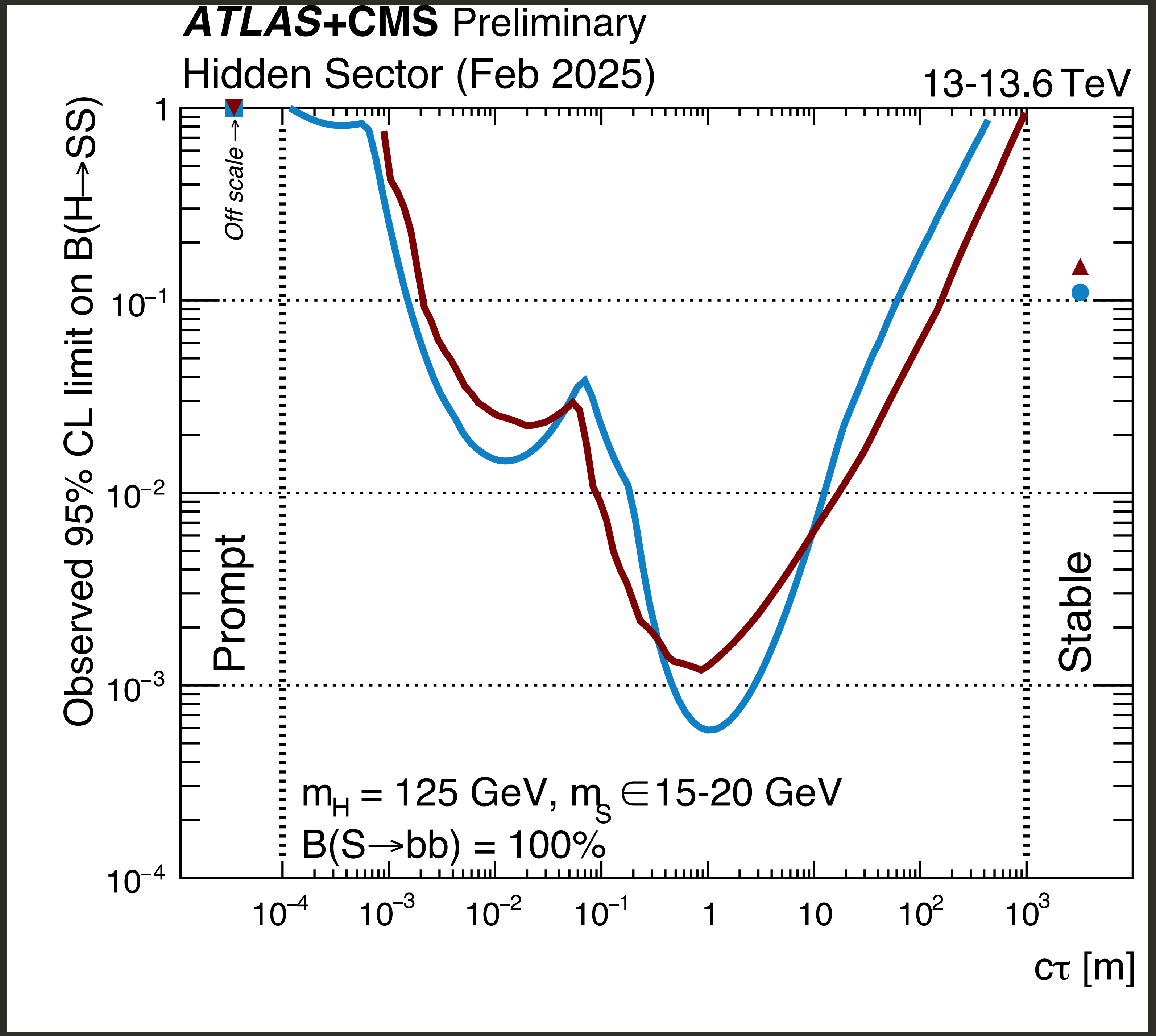
Today: NEW results by the ATLAS and CMS experiments on searches for LLPs using displaced signatures

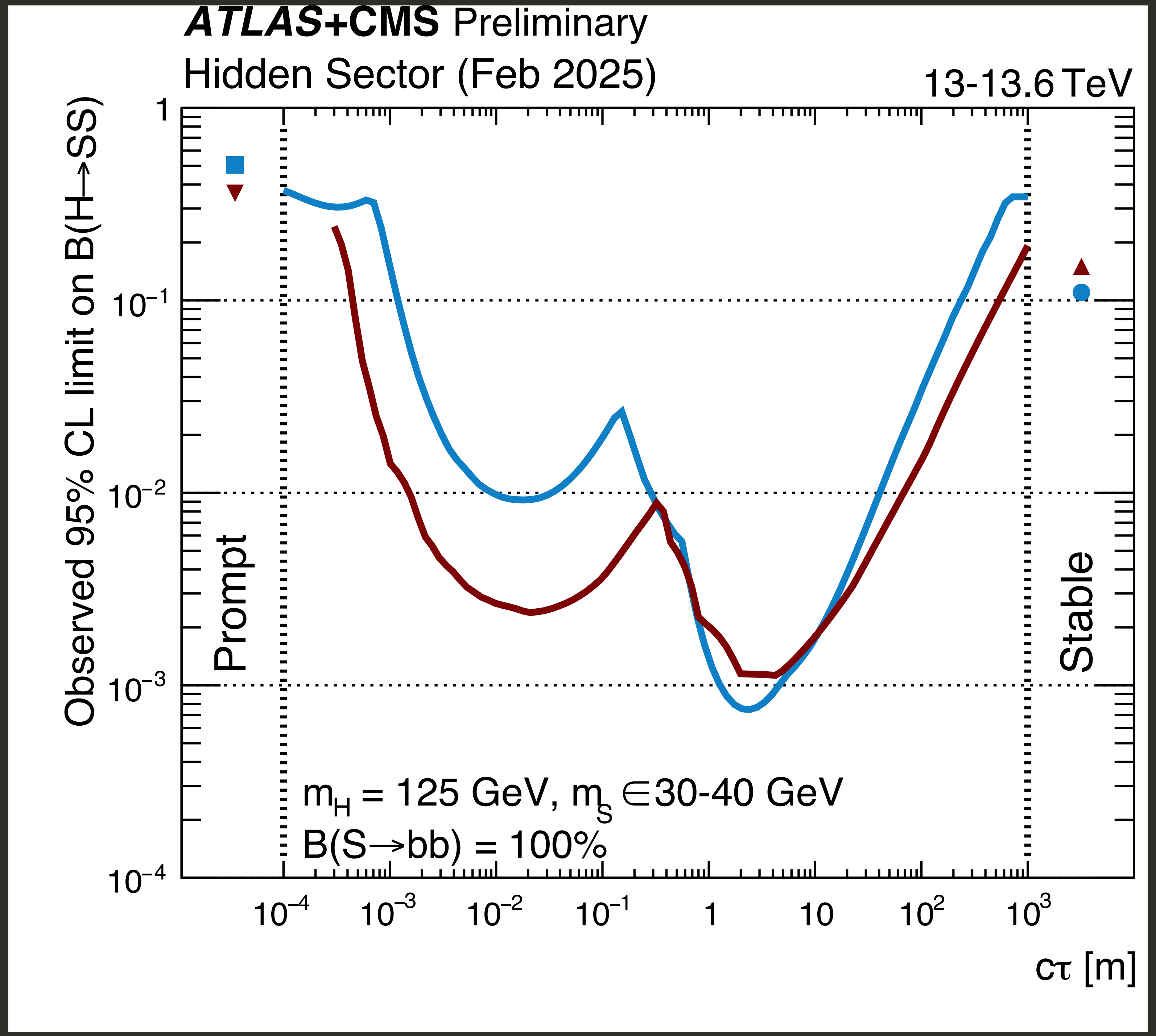
https://tikz.net/sm_particles_masses/

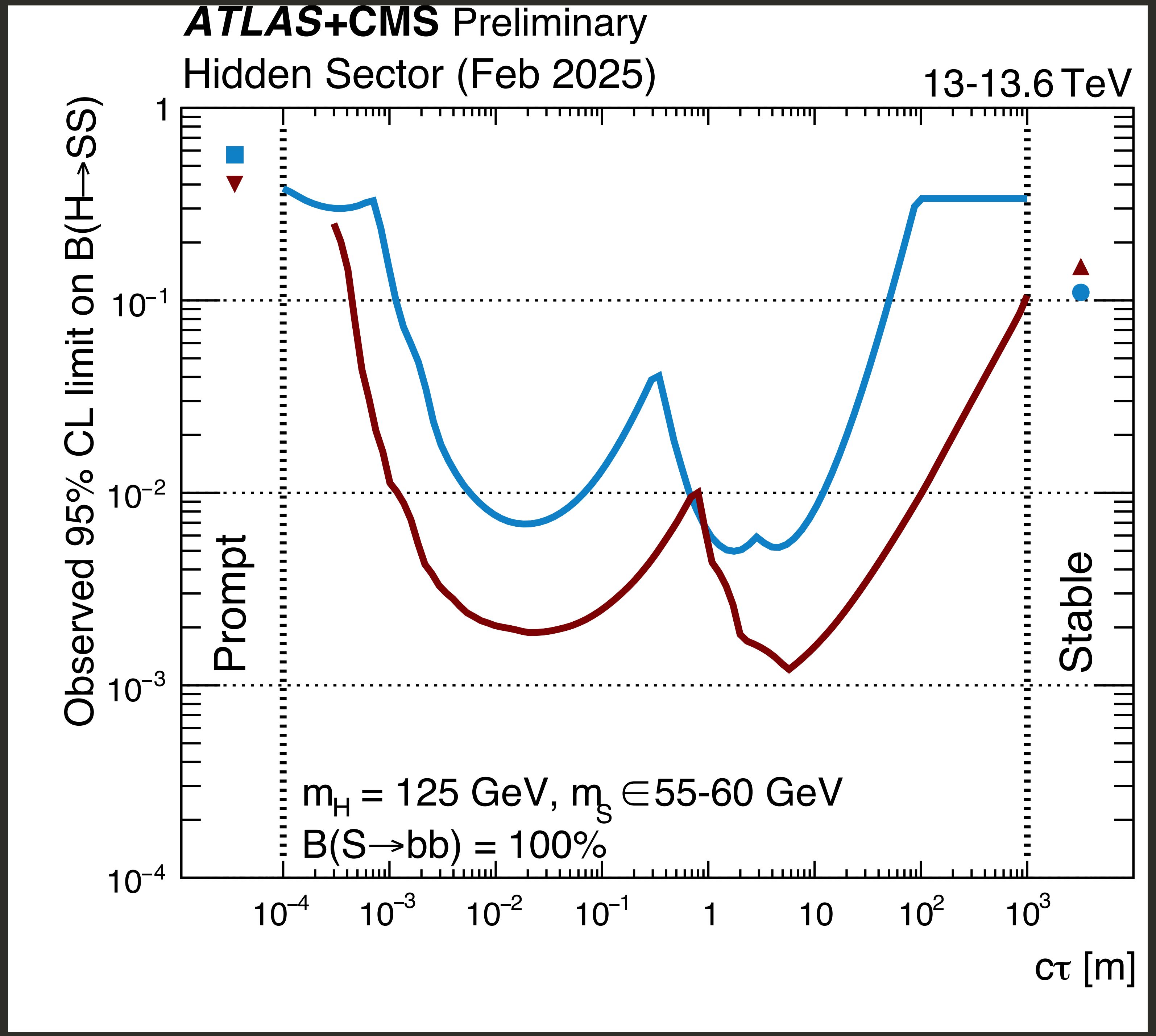
Such searches need specialized reconstruction and analysis techniques

Higgs boson mediated hidden sector summary





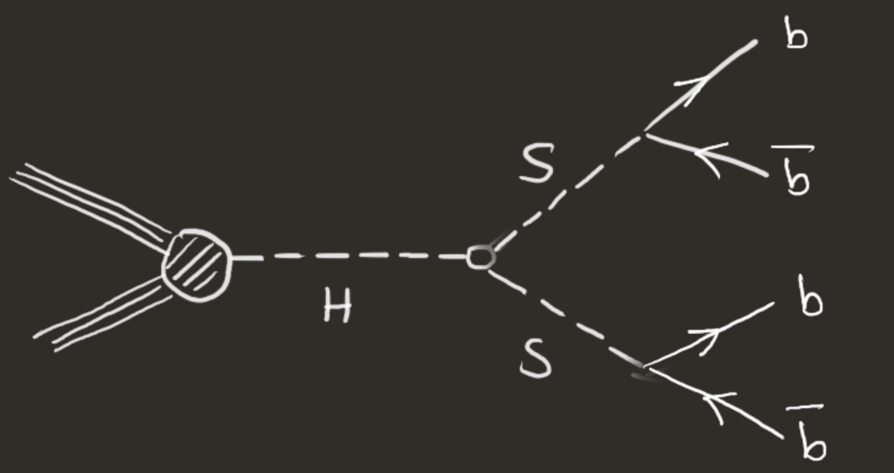




CMS **ATLAS**

ATL-PHYS-PUB-2025-002

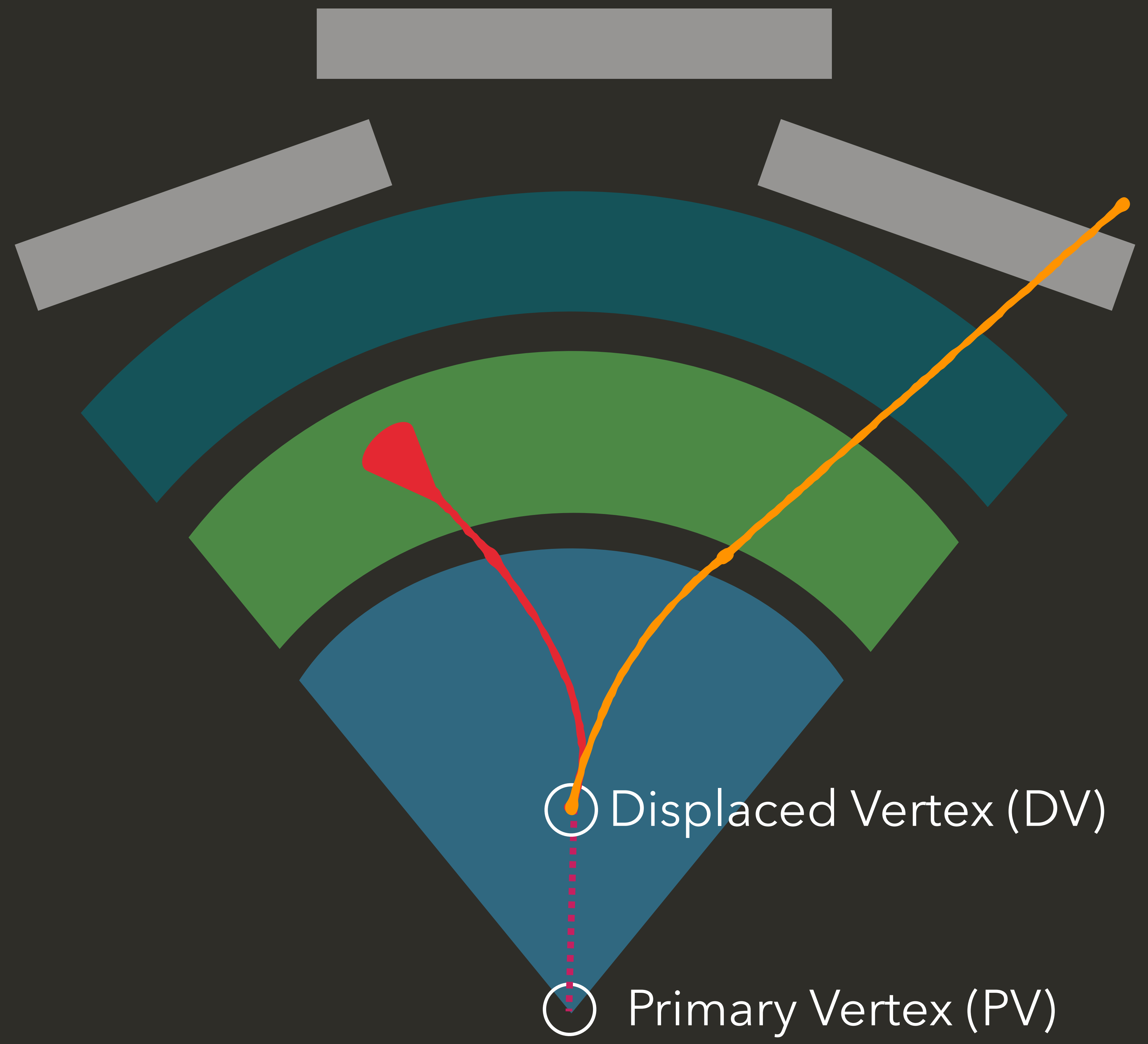
Higgs boson mediated hidden sector summary



Quite a few analyses contribute to an impressive level of excluded parameter space!

Today's results show improvements on top of these summary plots

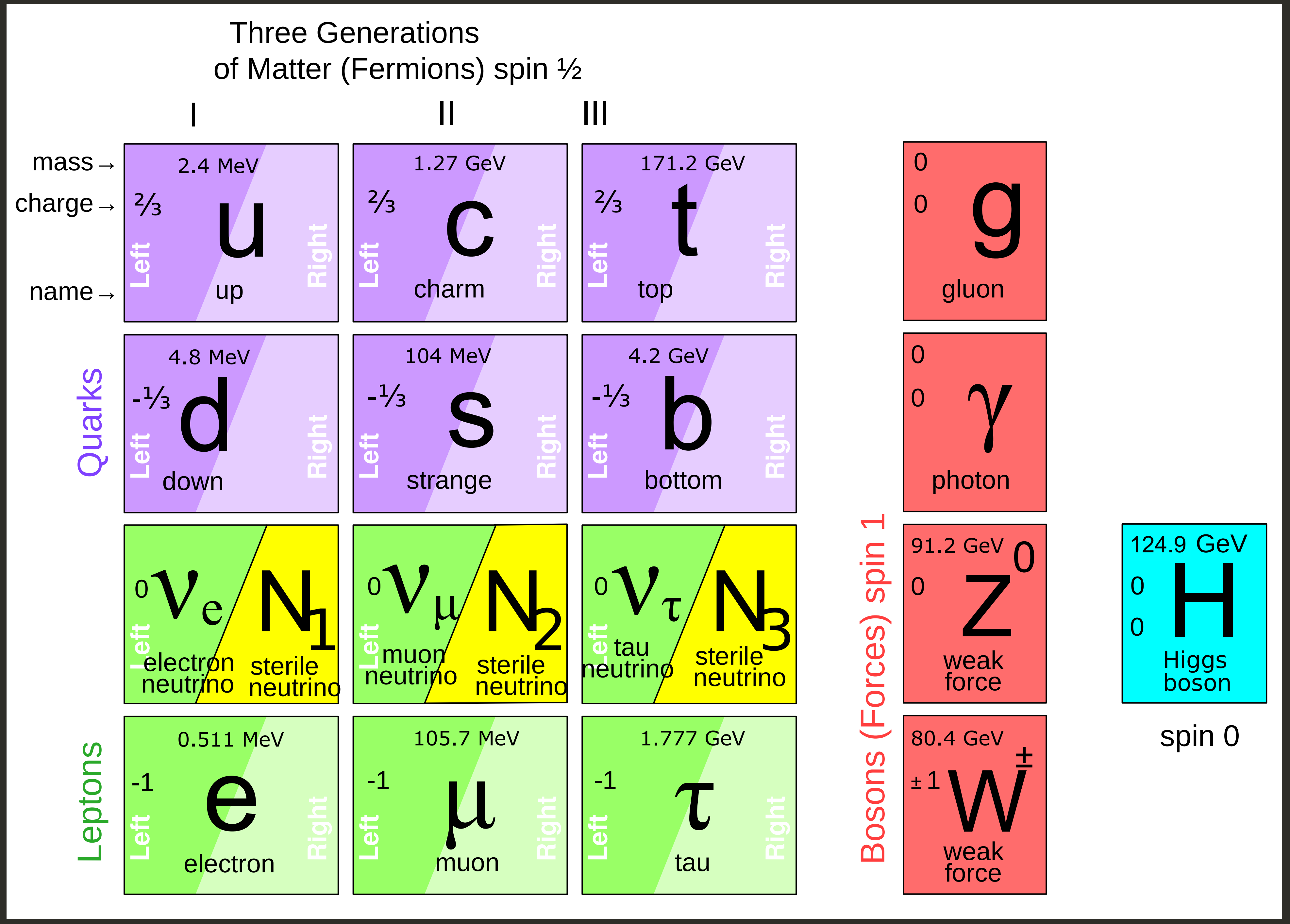
Displaced Vertices in the tracker



Heavy Neutral Leptons

Minimal Extension to the SM

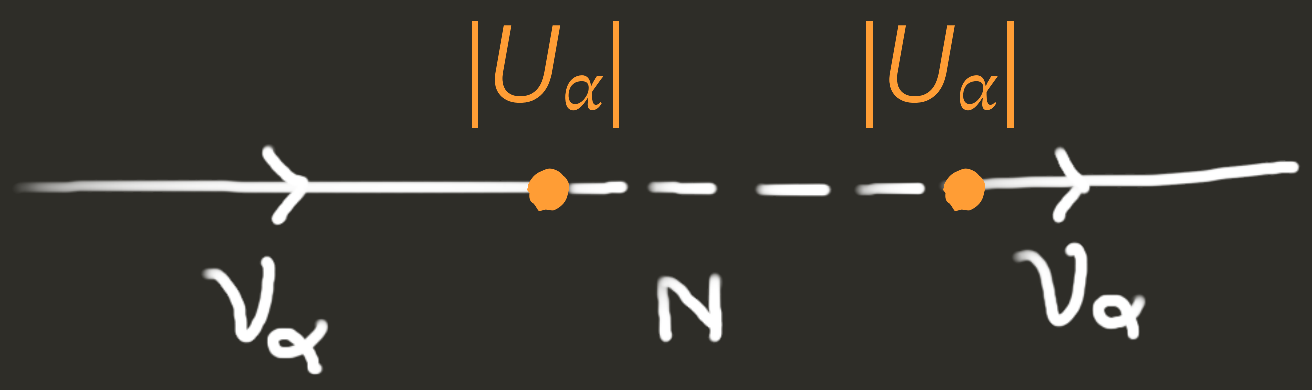
Heavy Neutral Leptons, or Sterile Neutrinos are massive right handed counterparts to Standard Model neutrinos



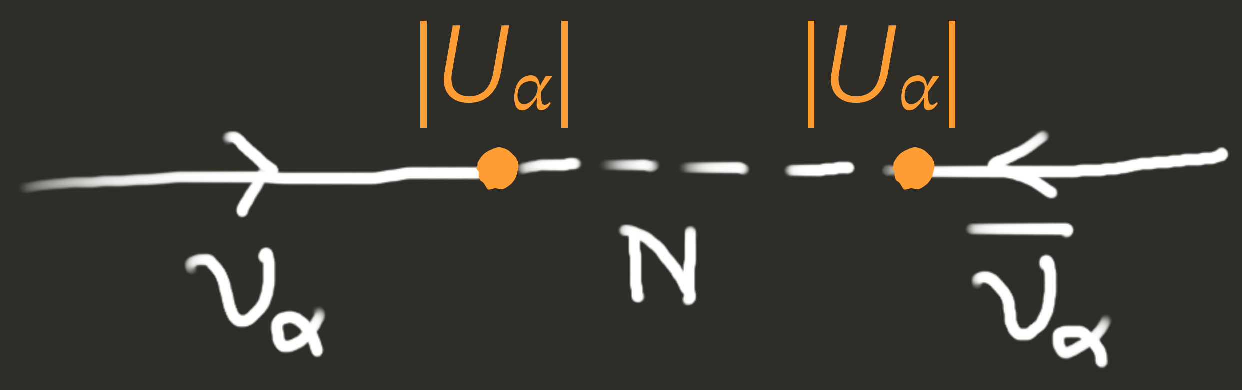
Three Generations of Matter (Fermions) spin ½

	I	II	III	Bosons (Forces) spin 1	spin 0
mass → charge → name →					
Quarks	2.4 MeV ⅔ u up	1.27 GeV ⅔ c charm	171.2 GeV ⅔ t top	0 0 g gluon	
Quarks	4.8 MeV -⅓ d down	104 MeV -⅓ s strange	4.2 GeV -⅓ b bottom	0 0 γ photon	
Leptons	0 ν_e electron neutrino N_1 sterile neutrino	0 ν_μ muon neutrino N_2 sterile neutrino	0 ν_τ tau neutrino N_3 sterile neutrino	91.2 GeV 0 Z^0 weak force	124.9 GeV 0 0 H Higgs boson
Leptons	0.511 MeV -1 e electron	105.7 MeV -1 μ muon	1.777 GeV -1 τ tau	80.4 GeV ±1 $W^\pm$ weak force	

$\mathscr{L} - \mathscr{L}_{SM} \supset$ Kinetic Term + Yukawa Coupling + Mass Term



Lepton Number Conserving



Lepton Number Violating

Model free parameters:

- HNL mass (m_N) – dictates the kinematics of the decay products
- Coupling strength ($|U_\alpha|^2$) – controls the proper lifetime of the HNL

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

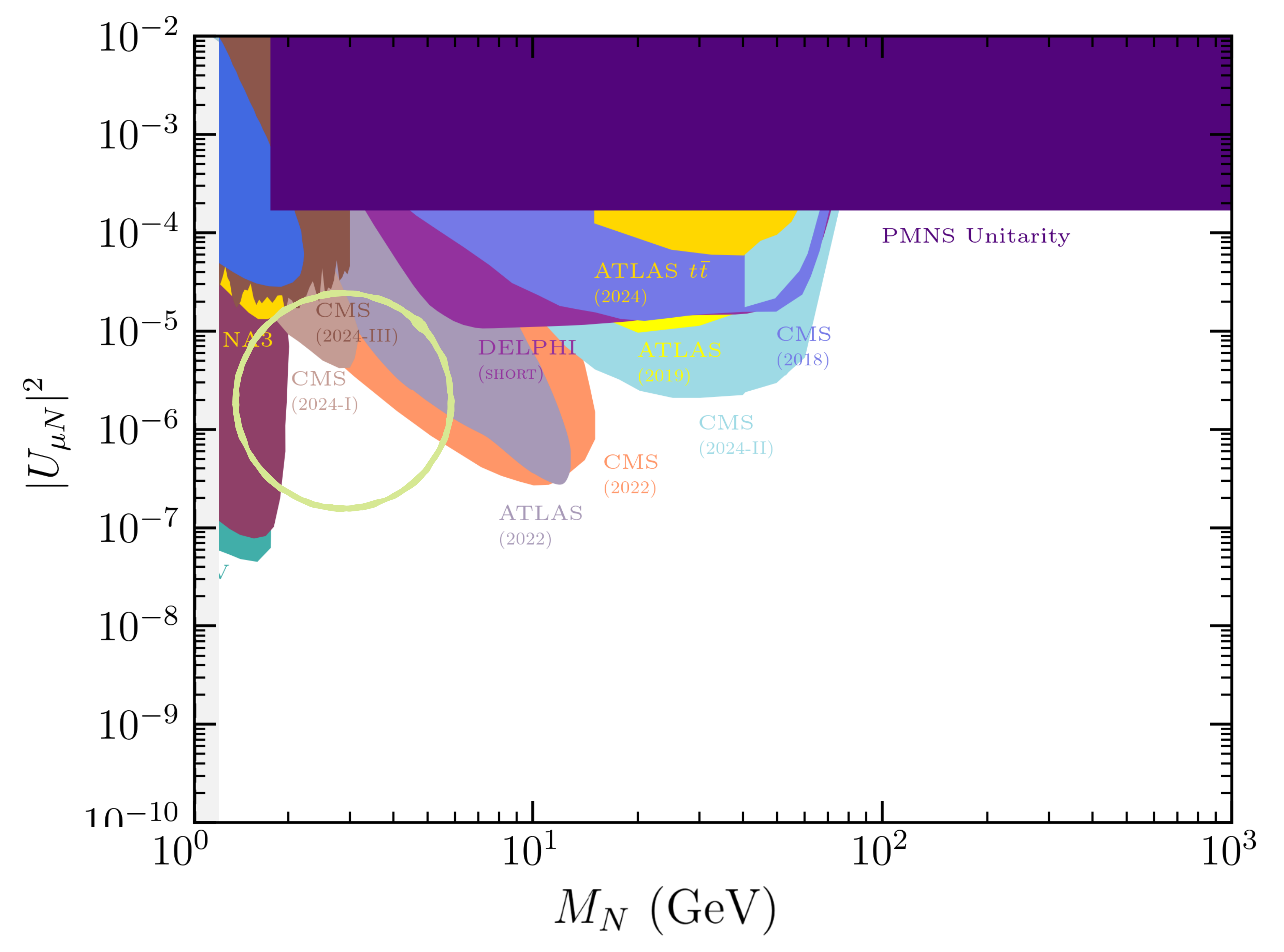
2503.16213

Heavy Neutral Leptons

Targeted Phase Space

A non-negligible gap in explored phase space remains

Typically left untouched for analysis convenience since the region is dominated by SM decays



arXiV:2304.06772

Heavy Neutral Leptons

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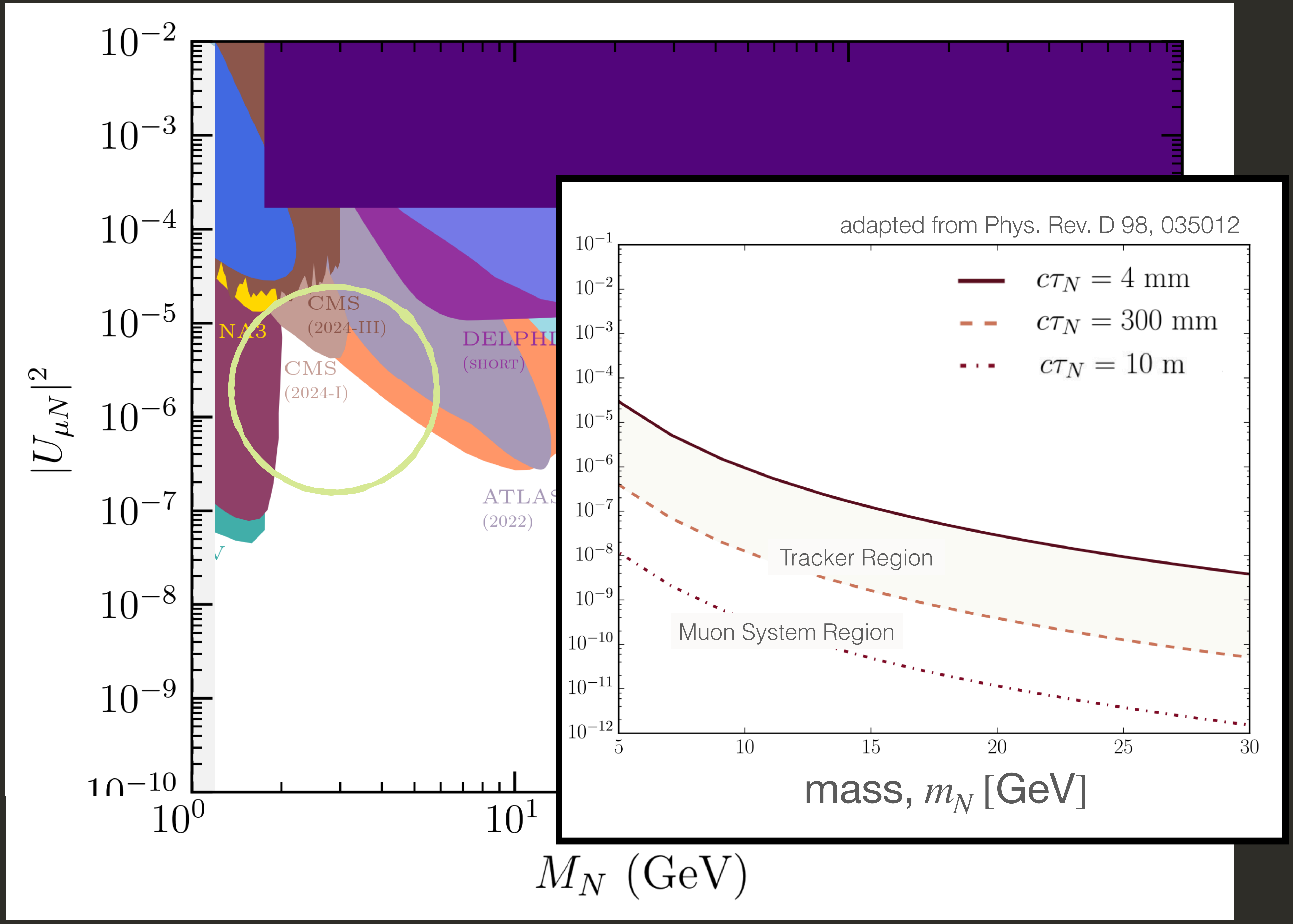

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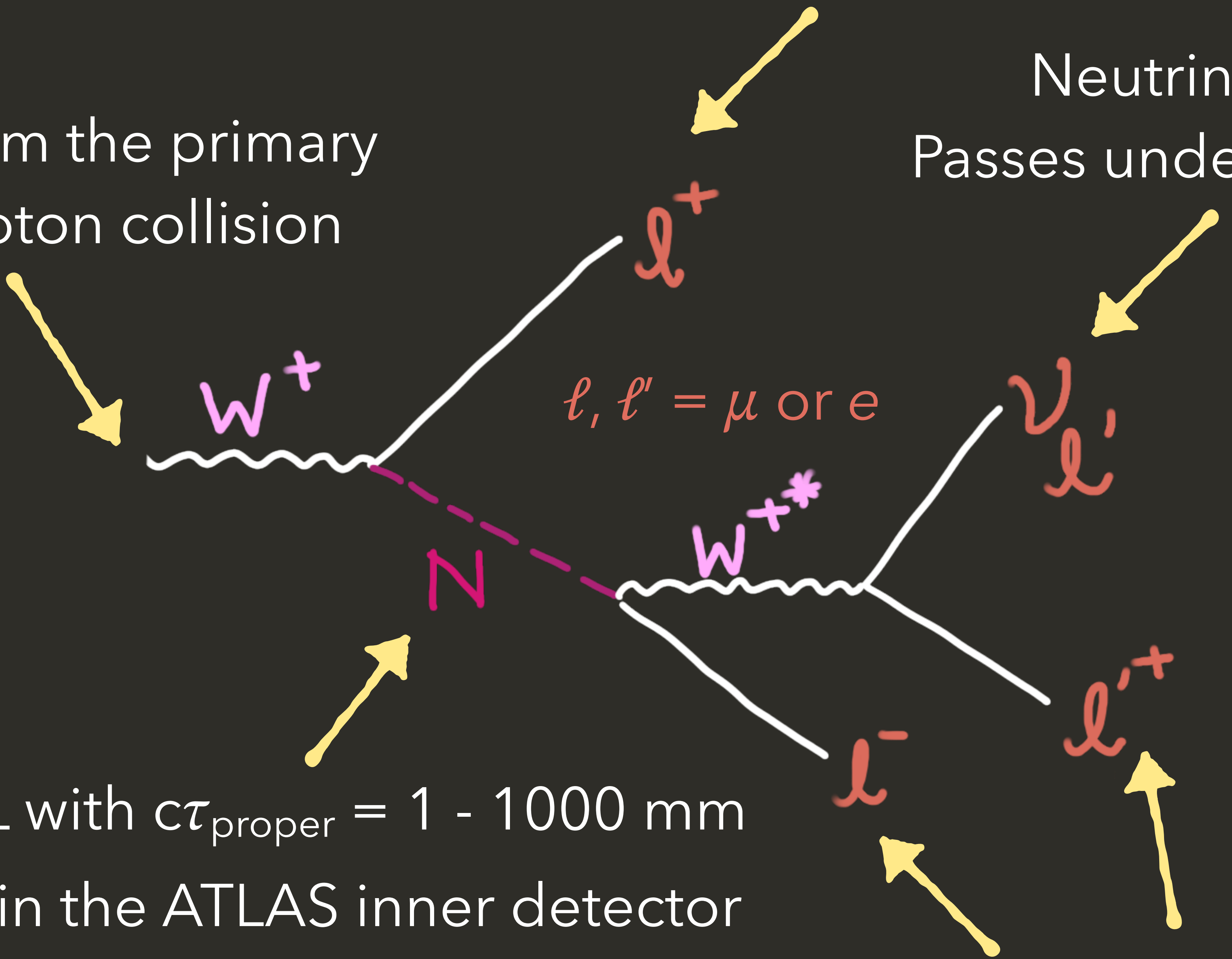
Heavy Neutral Leptons

Topology - Leptonic



Lepton from the primary p–p collision
Prompt and *isolated*

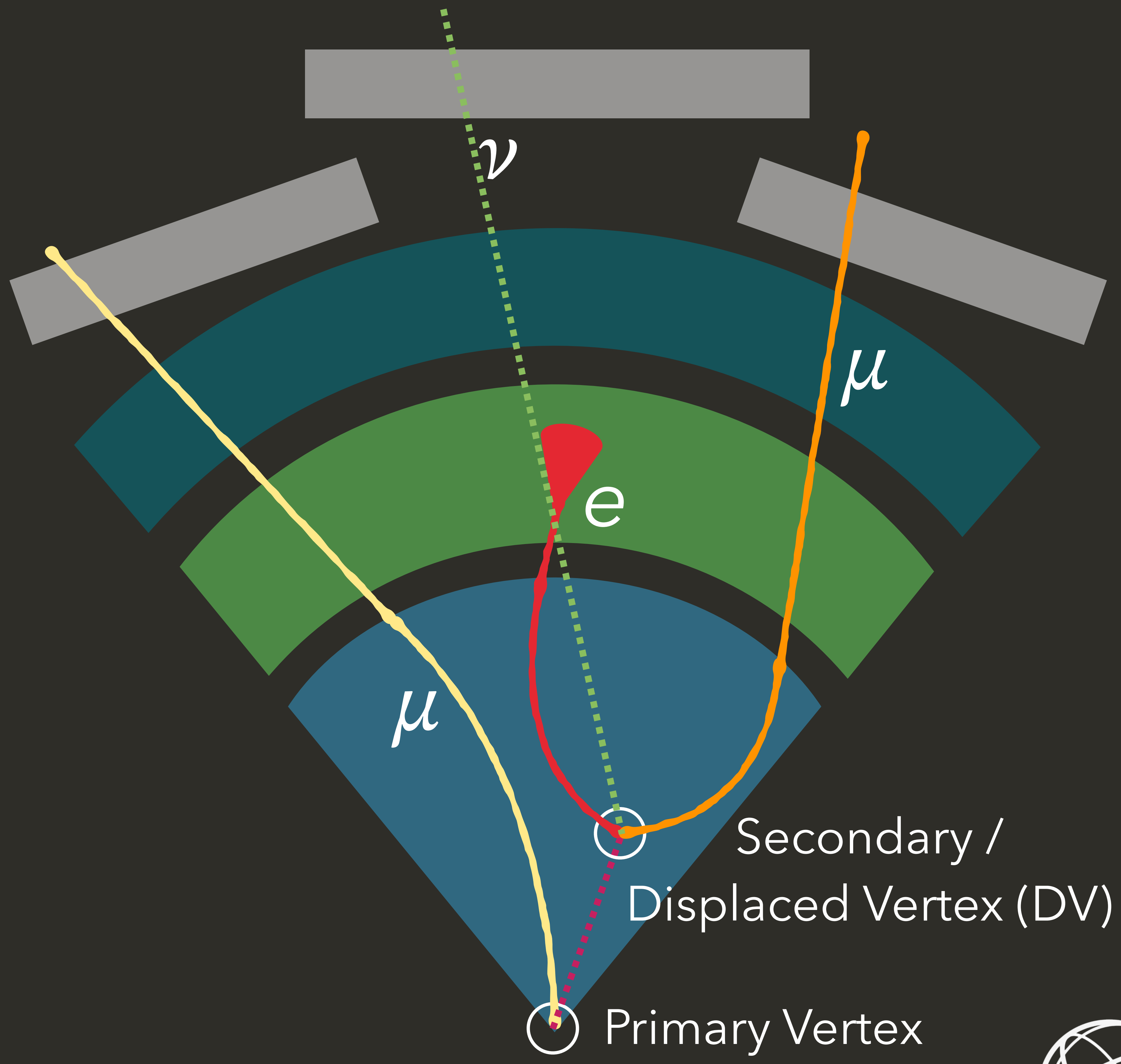
W boson from the primary
proton–proton collision

Neutrino from HNL decay
Passes undetected through ATLAS

O(GeV) HNL with $c\tau_{\text{proper}}$ = 1 - 1000 mm
decays within the ATLAS inner detector

$$\tau_{N,\text{proper}} \propto \frac{1}{m_N^5 |U_\alpha|^2}$$

Charged leptons from HNL decay
displaced and *isolated*



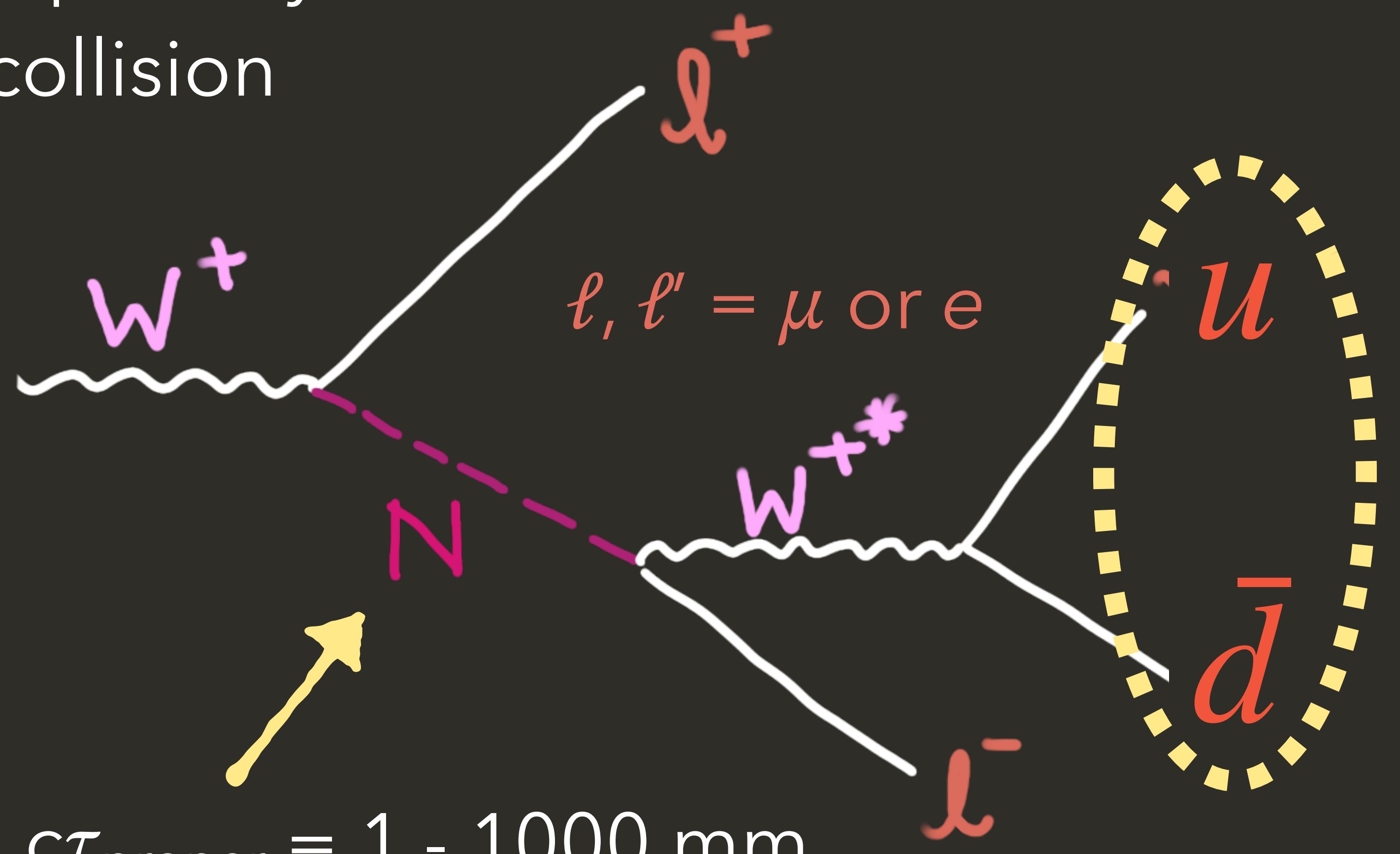
Heavy Neutral Leptons

Topology - Semi-leptonic

A new fully resonant channel adding useful contribution at low HNL masses.

Lepton from the primary p–p collision
Prompt and *isolated*

W boson from the primary
proton–proton collision



A pion i.e. a non-lepton
displaced track

O(GeV) HNL with $c\tau_{\text{proper}}$ = 1 - 1000 mm
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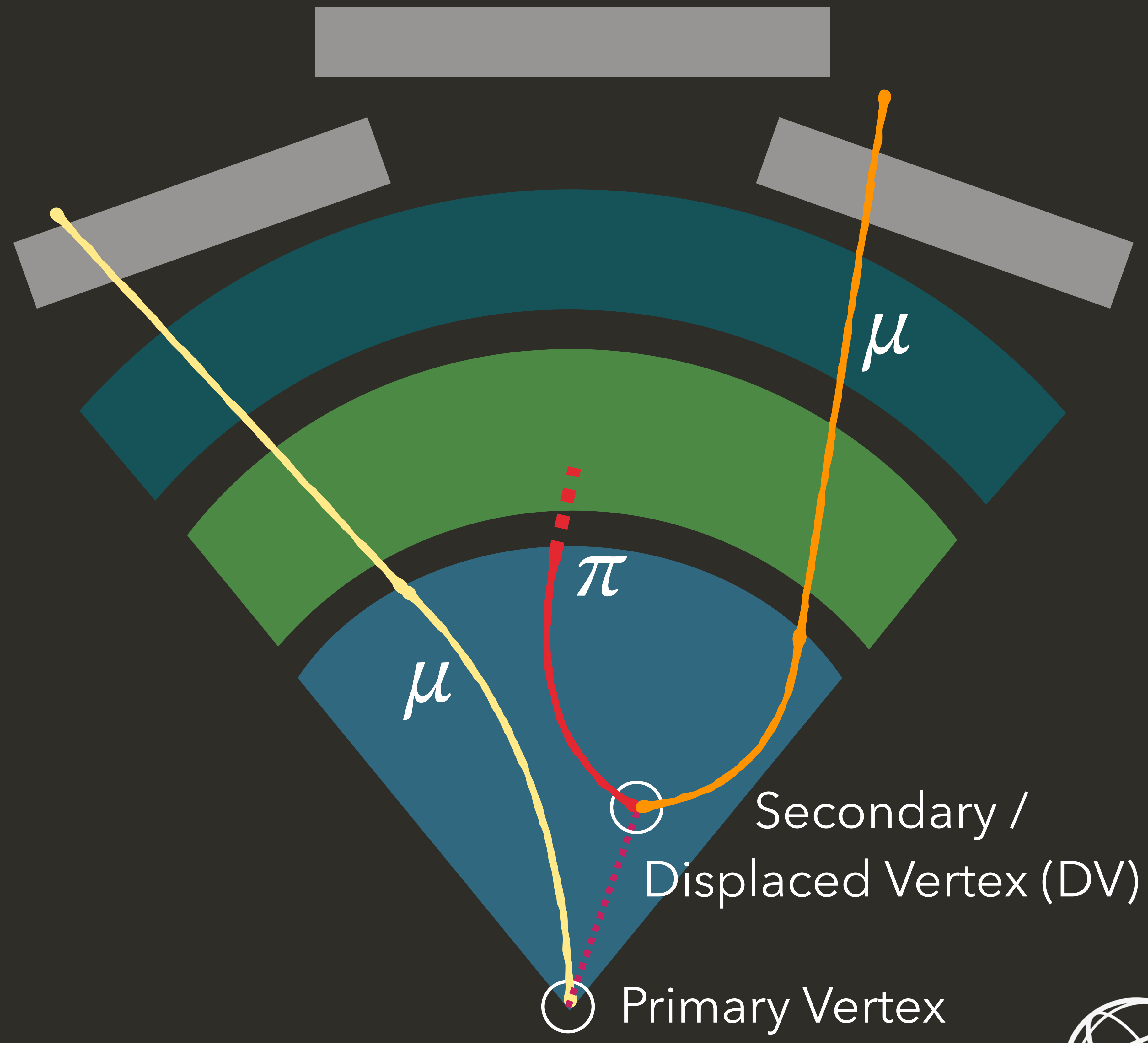
Charged lepton from HNL decay
displaced and *isolated*

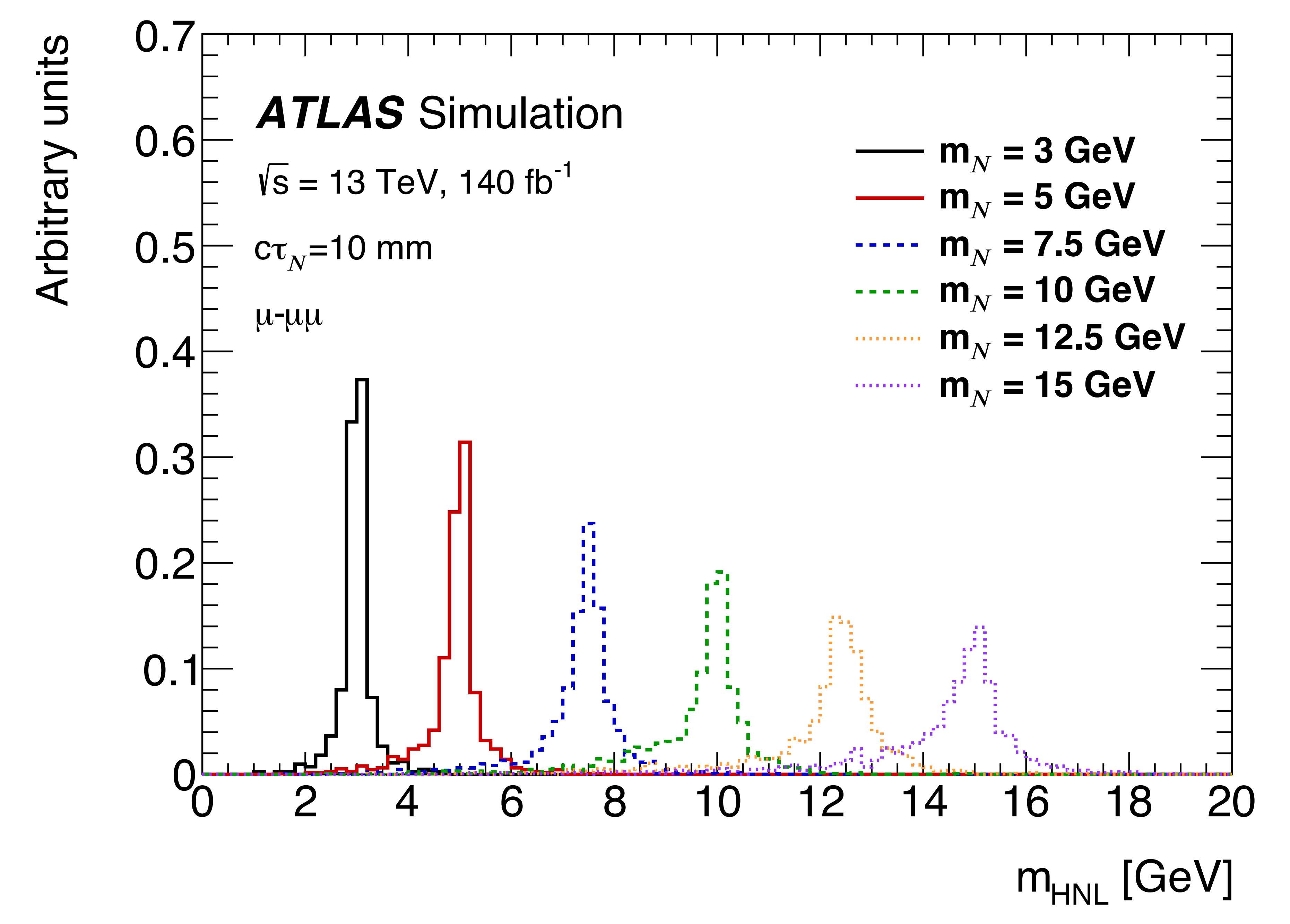


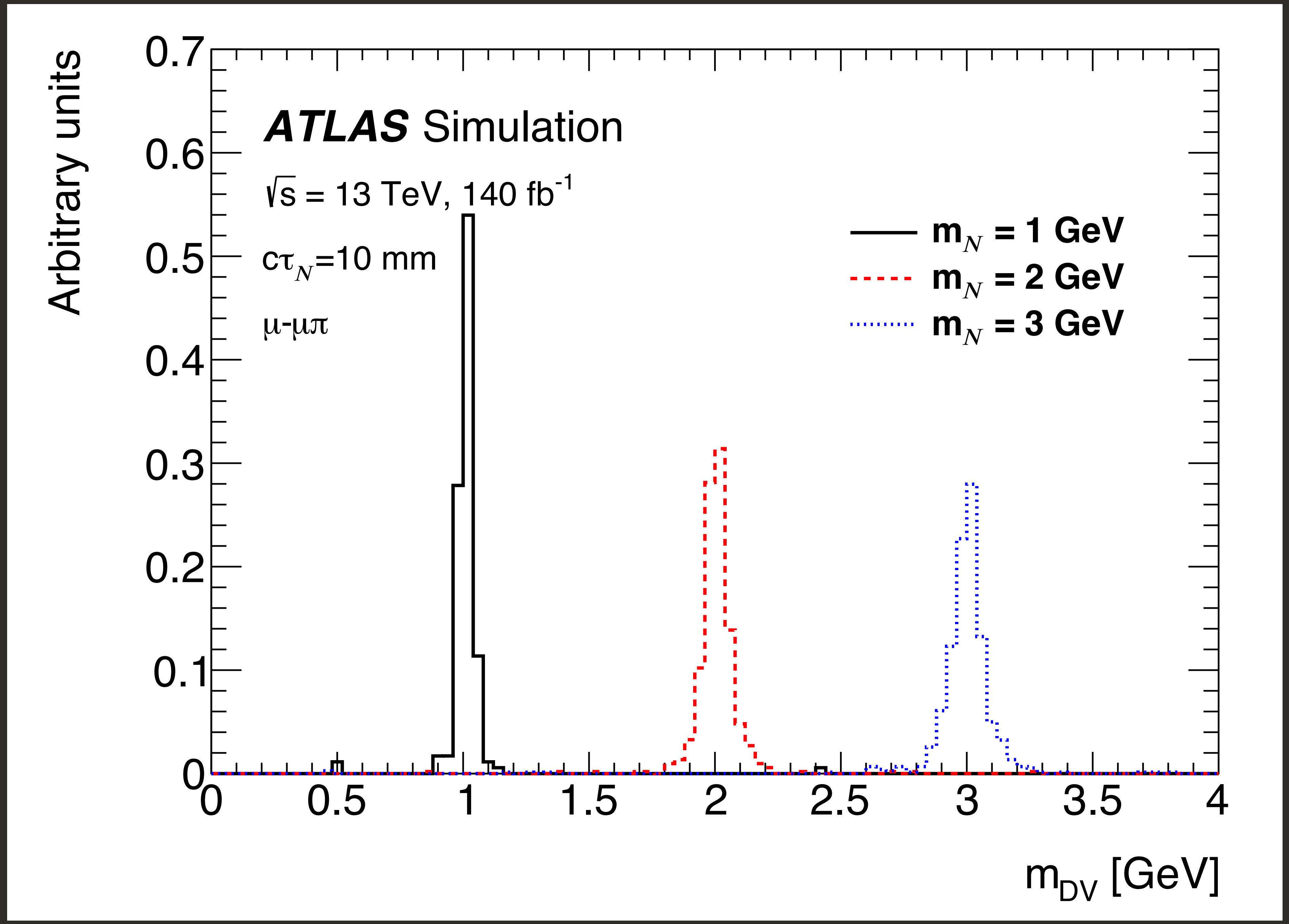
Simplest extension from a two-lepton to a lepton-track DV tagged search

Heavy Neutral Leptons

Discriminant

Using the reconstructed HNL mass as the signal discriminant





Leptonic Channels:

The HNL mass can be reconstructed using the PV-DV direction and a W mass constraint to fill-in for neutrino p_4 degrees of freedom

Semi-leptonic Channels:

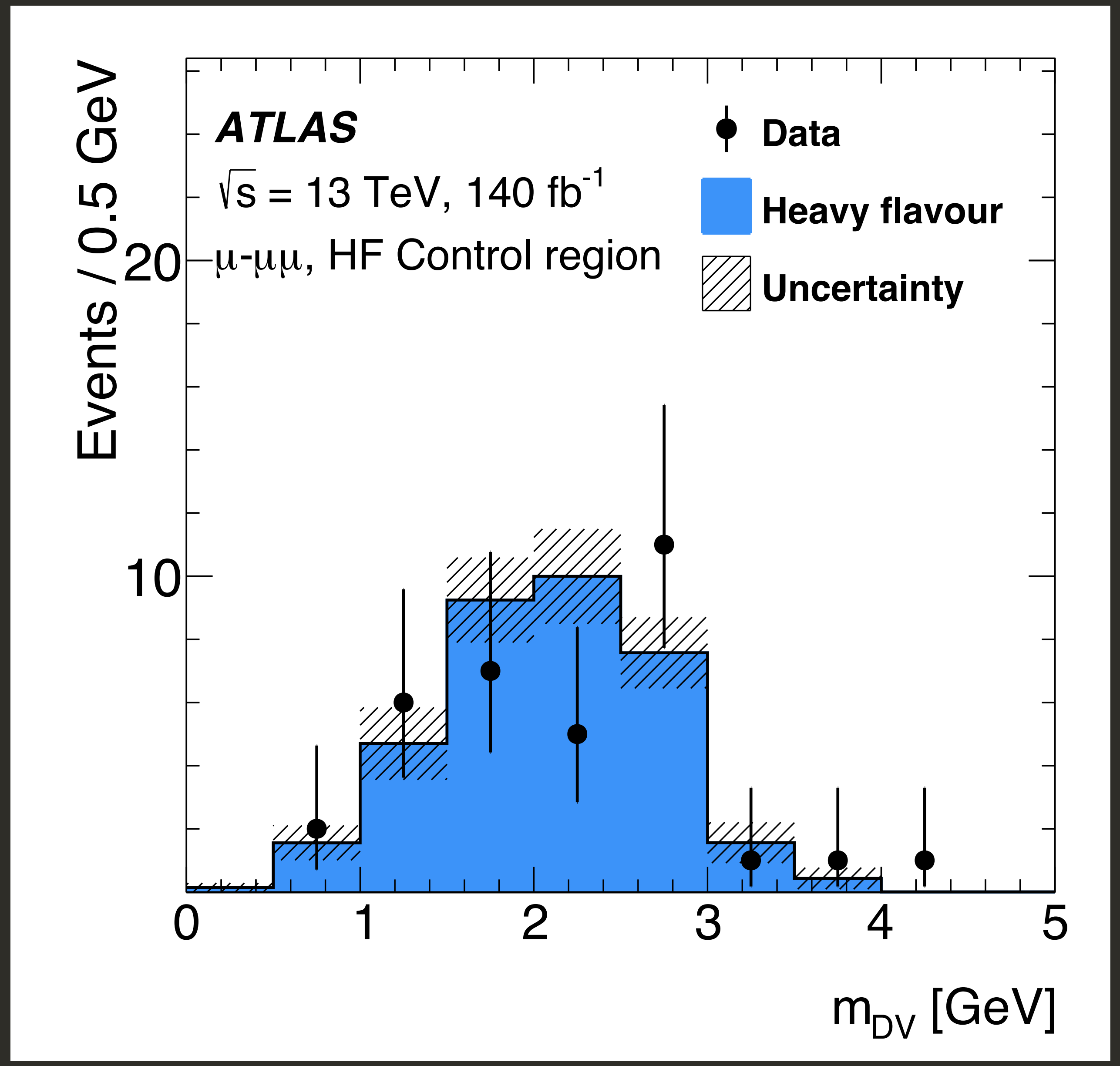
The HNL mass is just the reconstructed m_{DV}

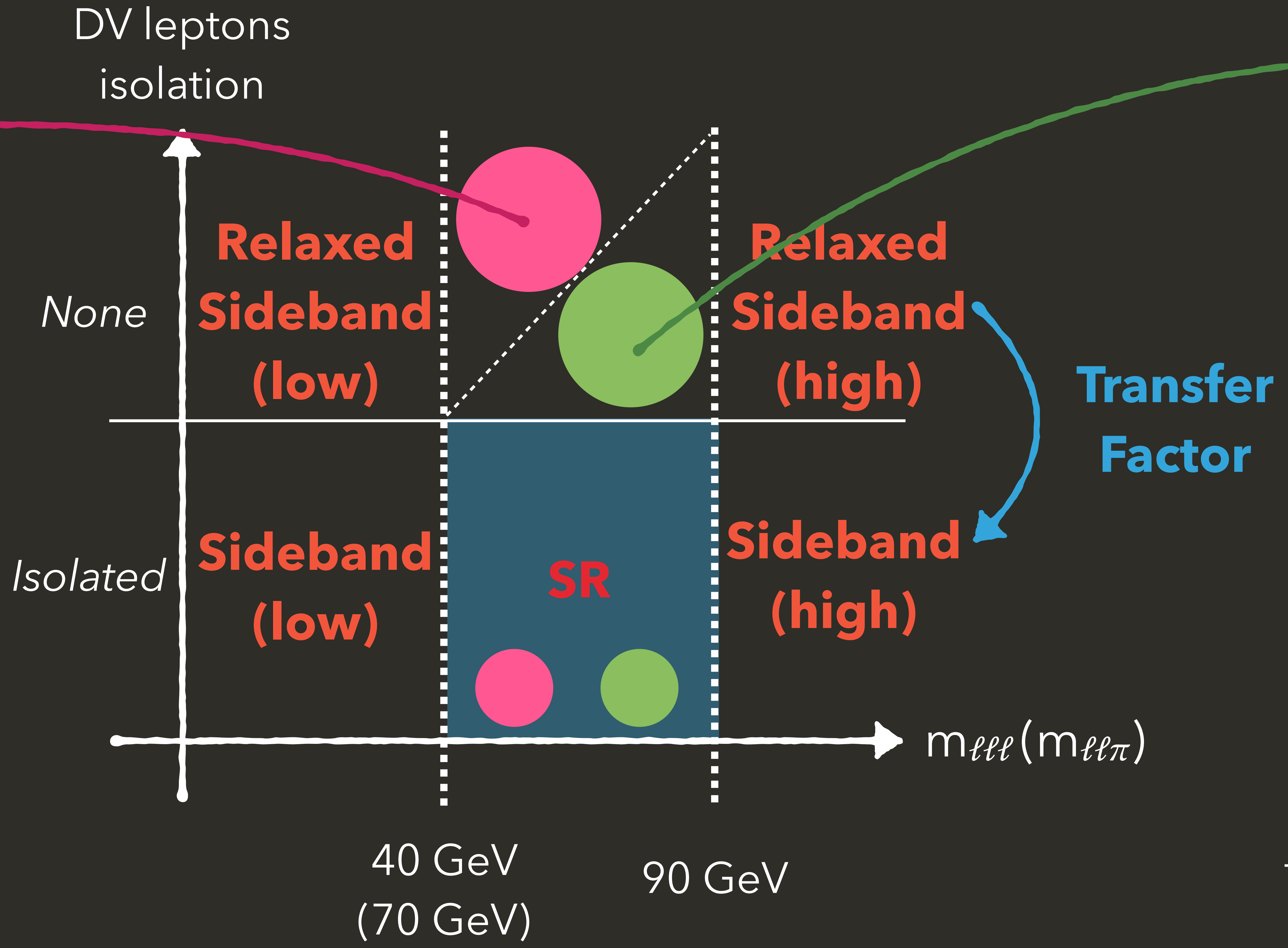
Heavy Neutral Leptons

Background Estimation

Heavy flavor hadrons (from MC)

Inverted Isolation + b-tag
10 Control Regions





Fake leptons (not modeled in MC)

①

Build *high* and *low* templates using the sidebands

②

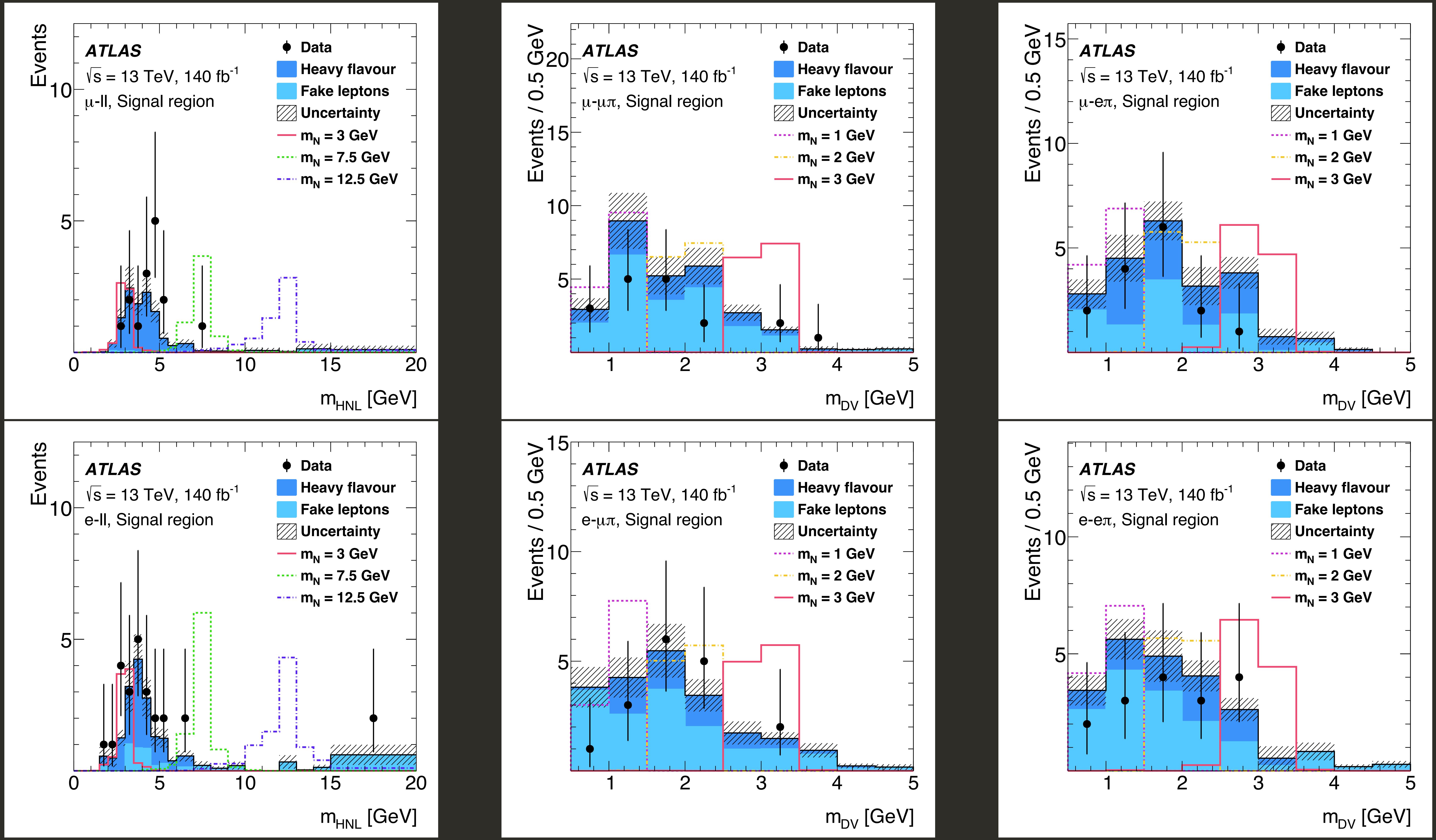
$$\mathrm{TF} = \frac{(\text{data-MC})_{\mathrm{SB}}}{(\text{data-MC})_{\text{relaxed-SB}}}$$

③

Scale side-band templates with the transfer factor and average to get the prediction in the SR

Heavy Neutral Leptons

Results

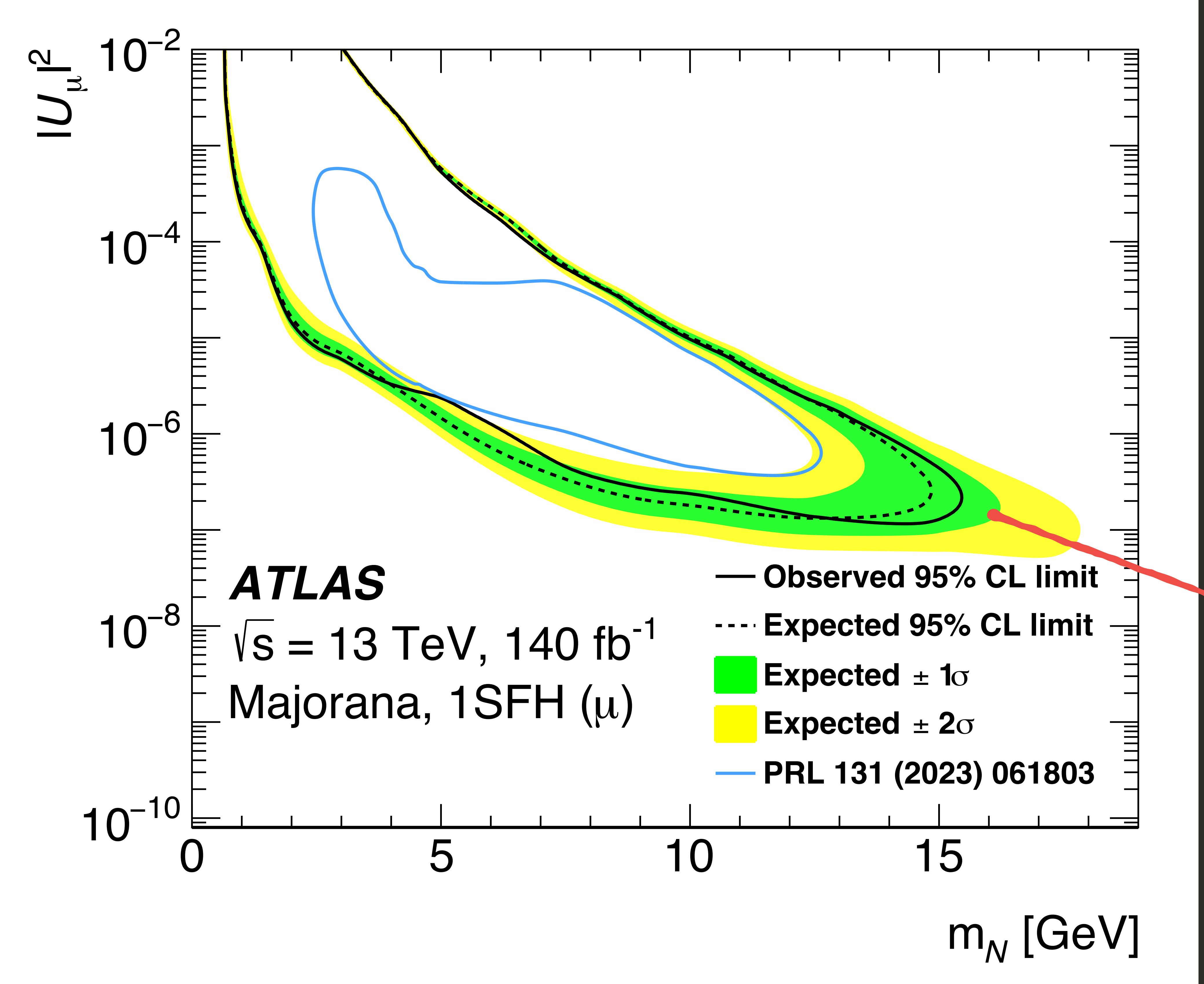


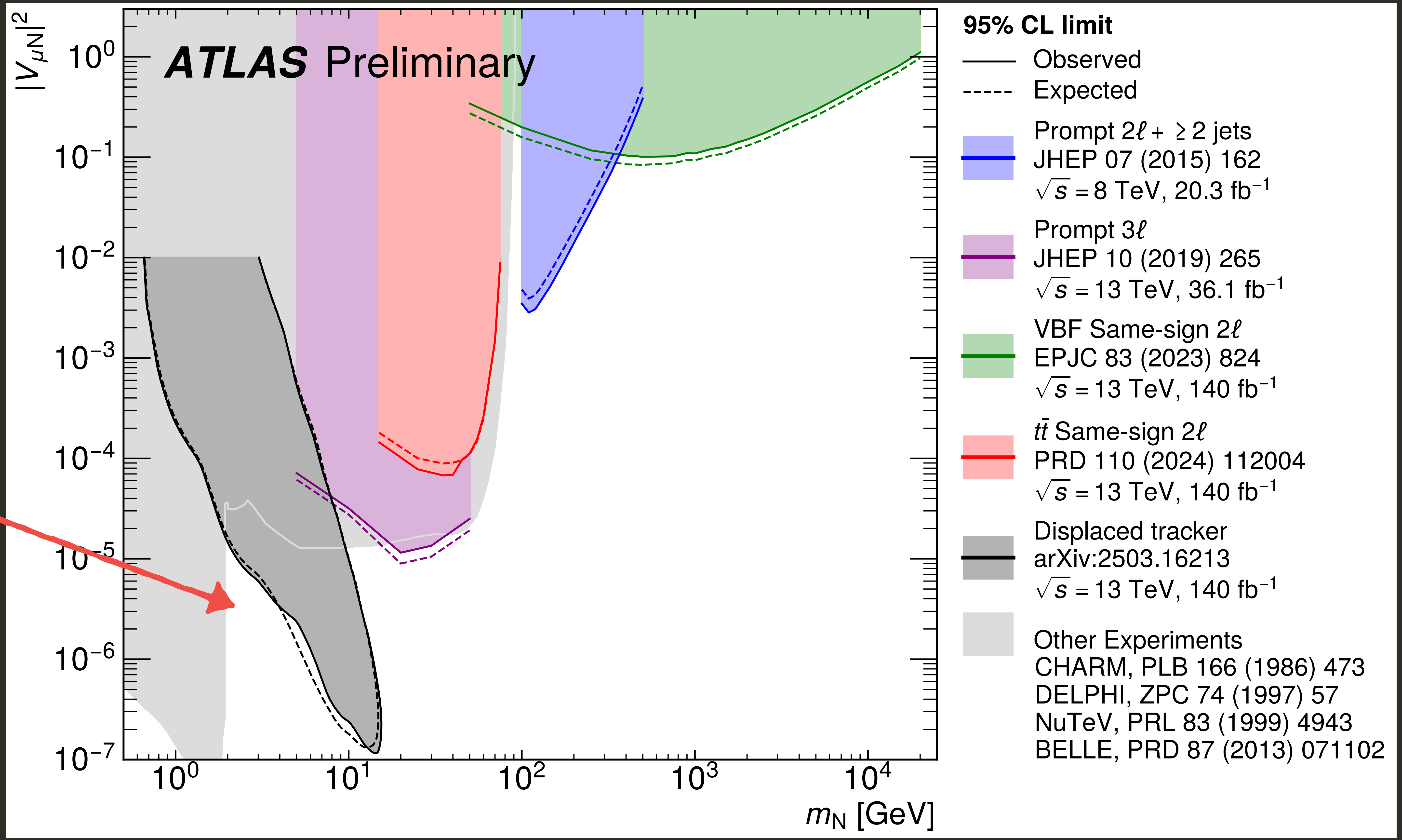
No excesses found compatible with the signal hypothesis; Statistical fluctuations in low-stats channels

Heavy Neutral Leptons

Majorana HNL μ-only Mixing

Other models in the backup

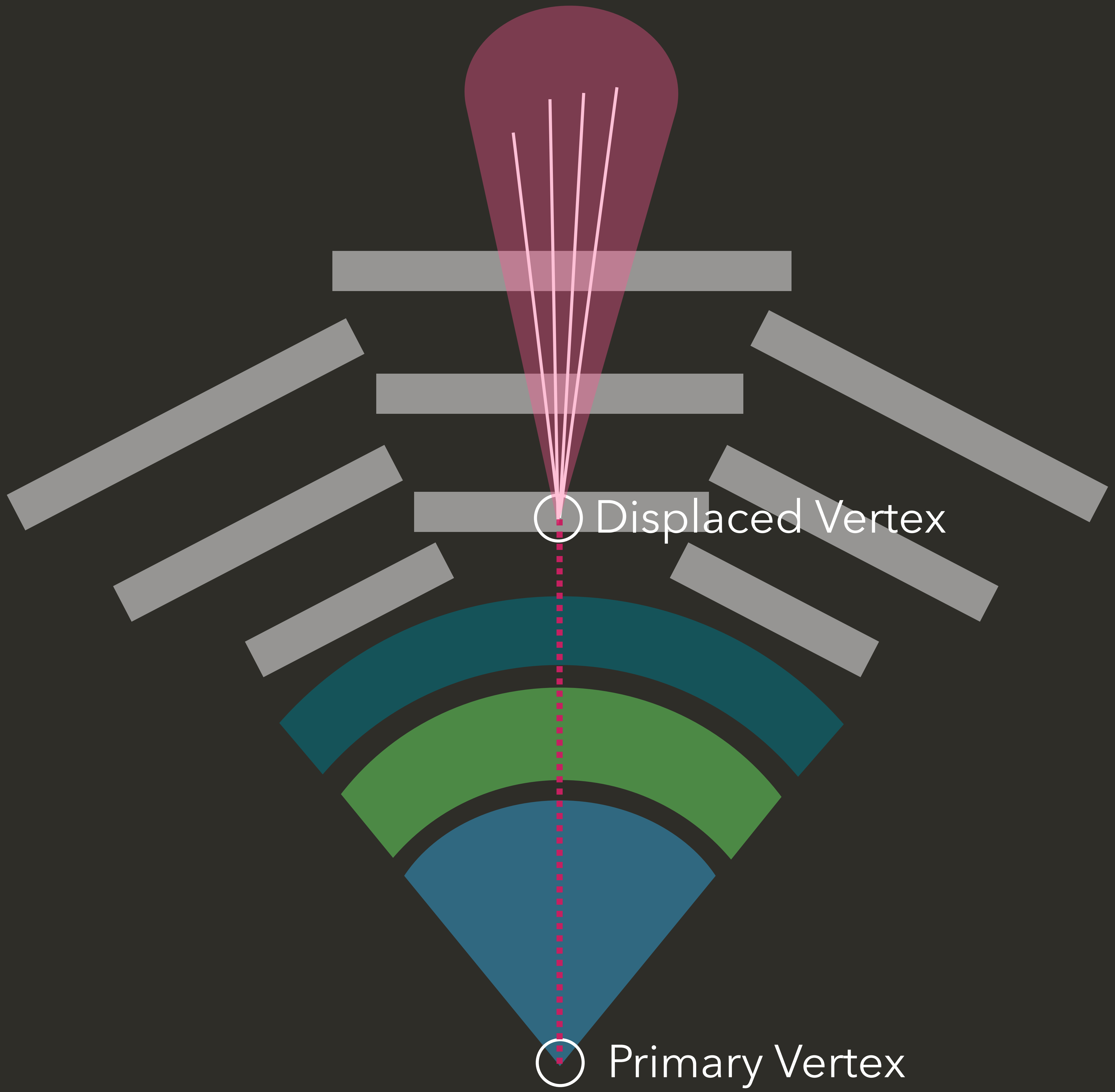




Large improvements wrt the previous analysis using the same dataset but improved reconstruction + analysis techniques; results largely statistics limited

ATL-PHYS-PUB-2025-008

Displaced Vertices in the muon system

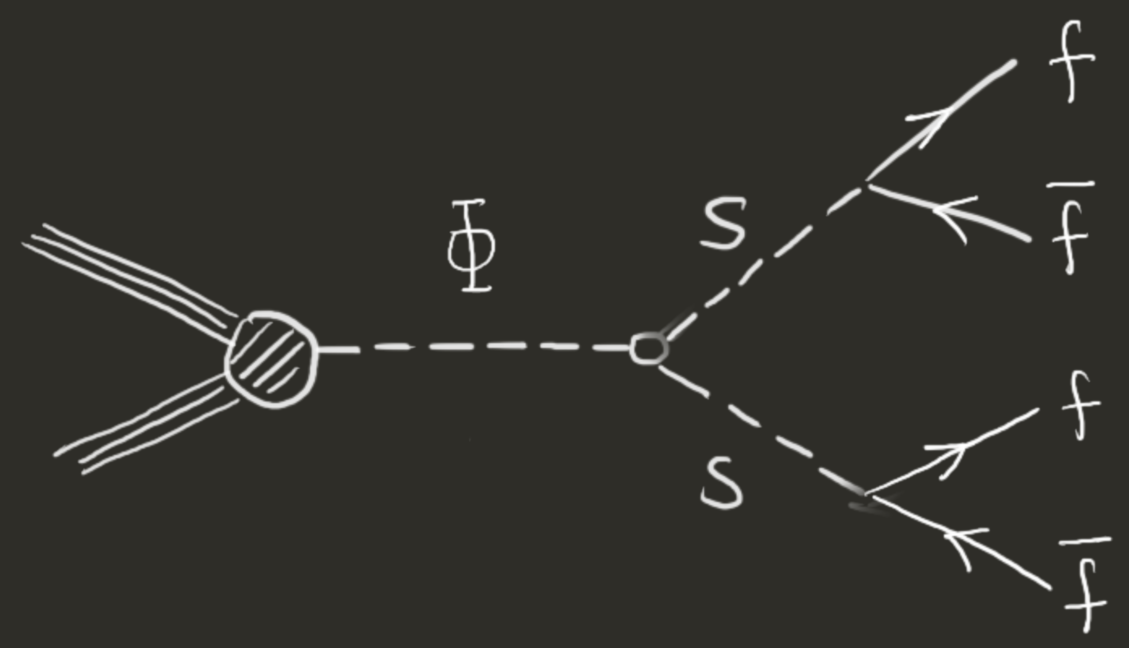


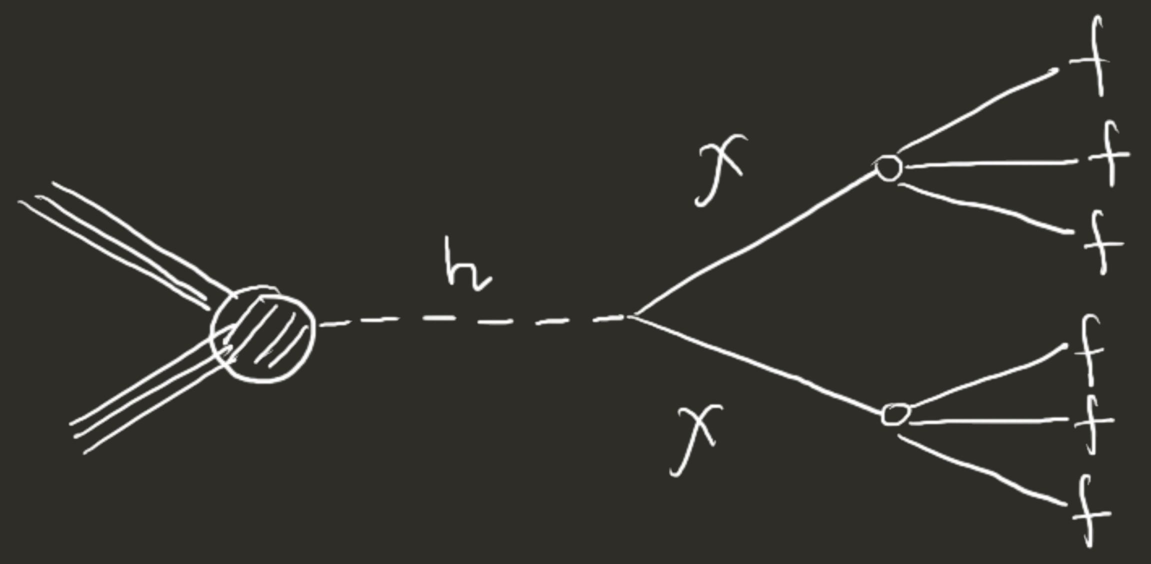
Jets in the Muon System

Introduction

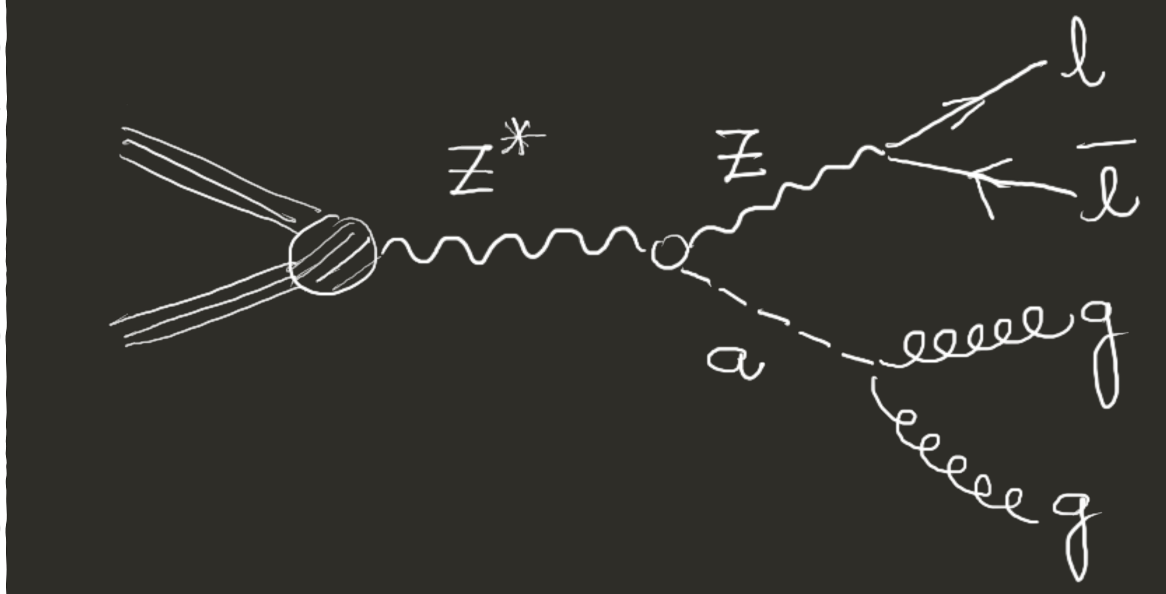
Model agnostic search probing hadronic clusters in the MS

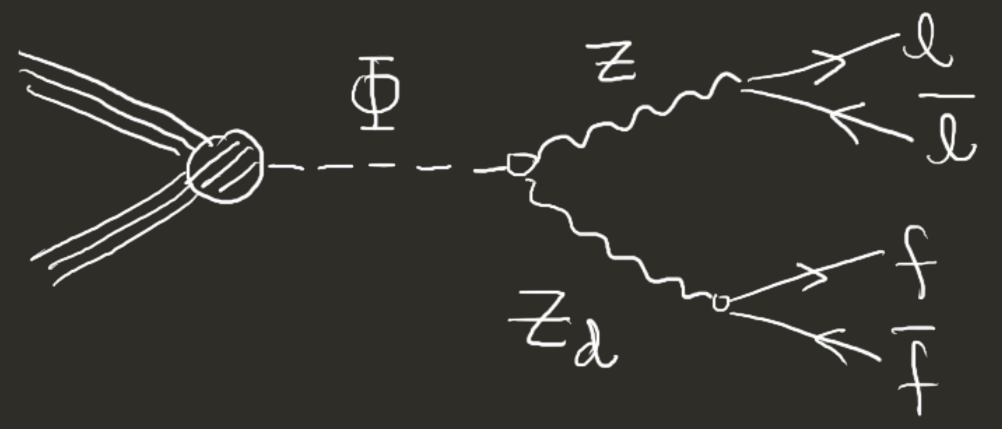
Isolated Clusters





Associated Production





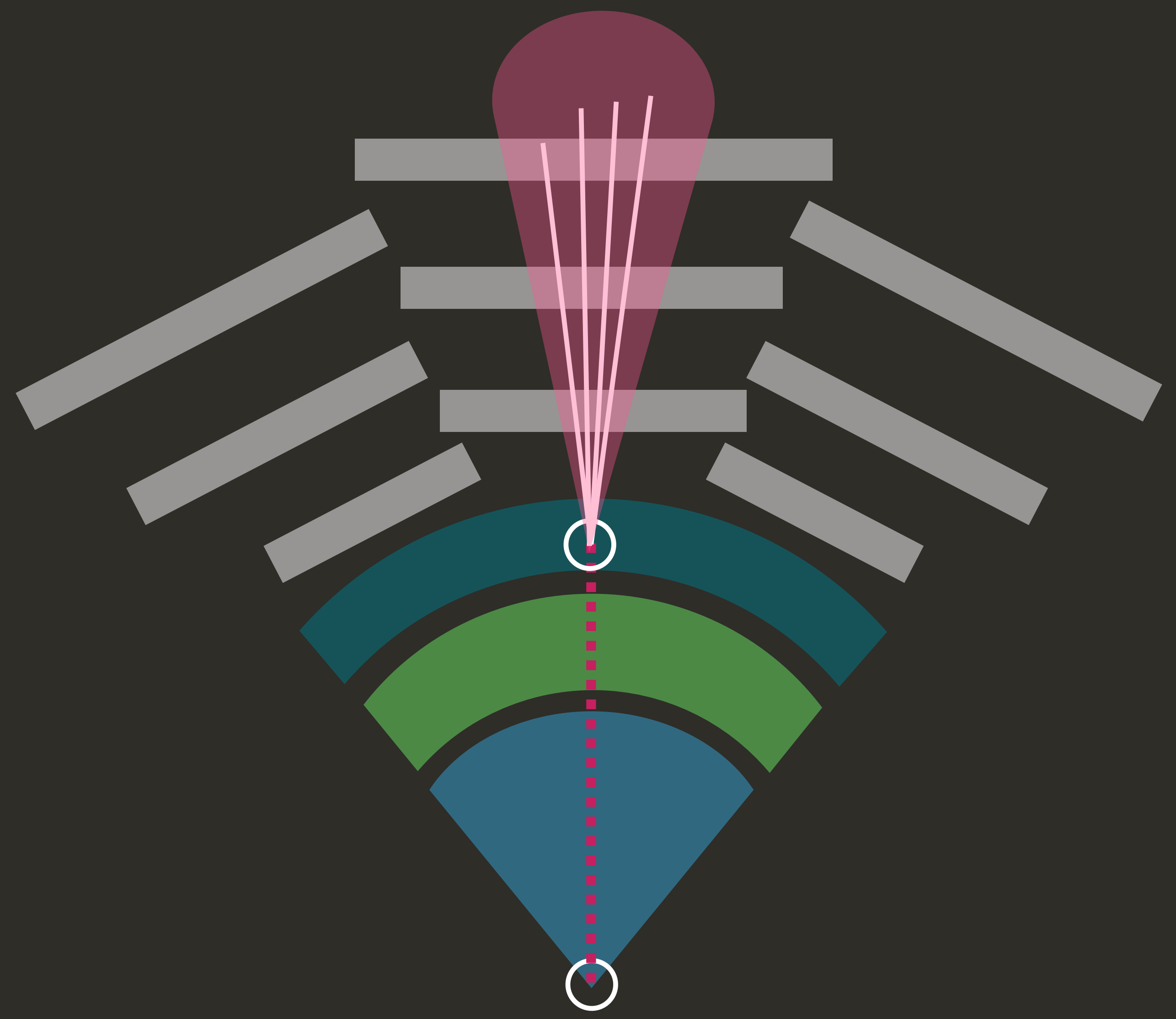
CERN-EP-2025-062

Jets in the Muon System

Channels

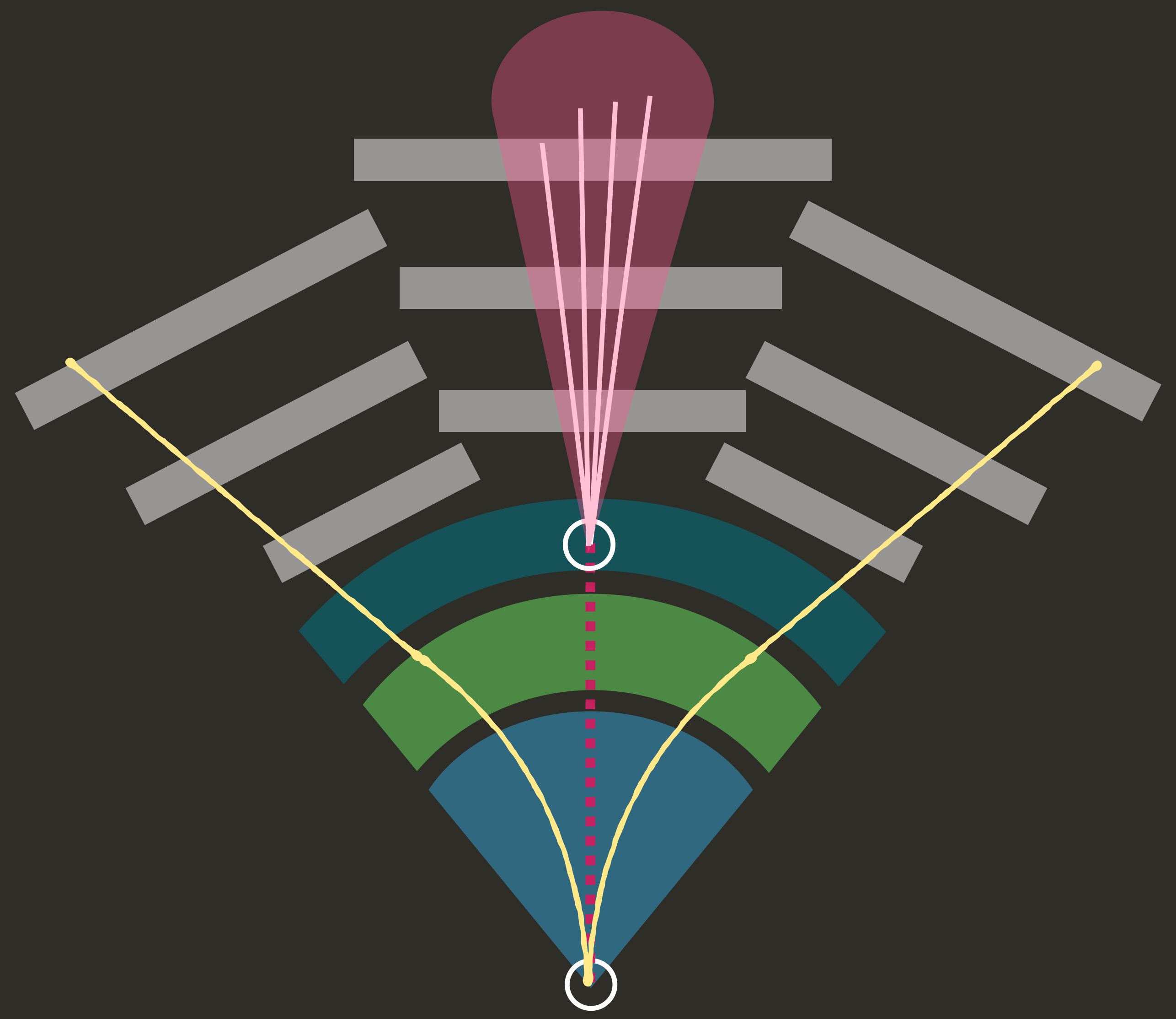
Model agnostic search probing hadronic clusters in the MS

Isolated Clusters



Uses a specialized muon cluster ROI trigger with online DV reconstruction which is then matched to the offline DV

Associated Production

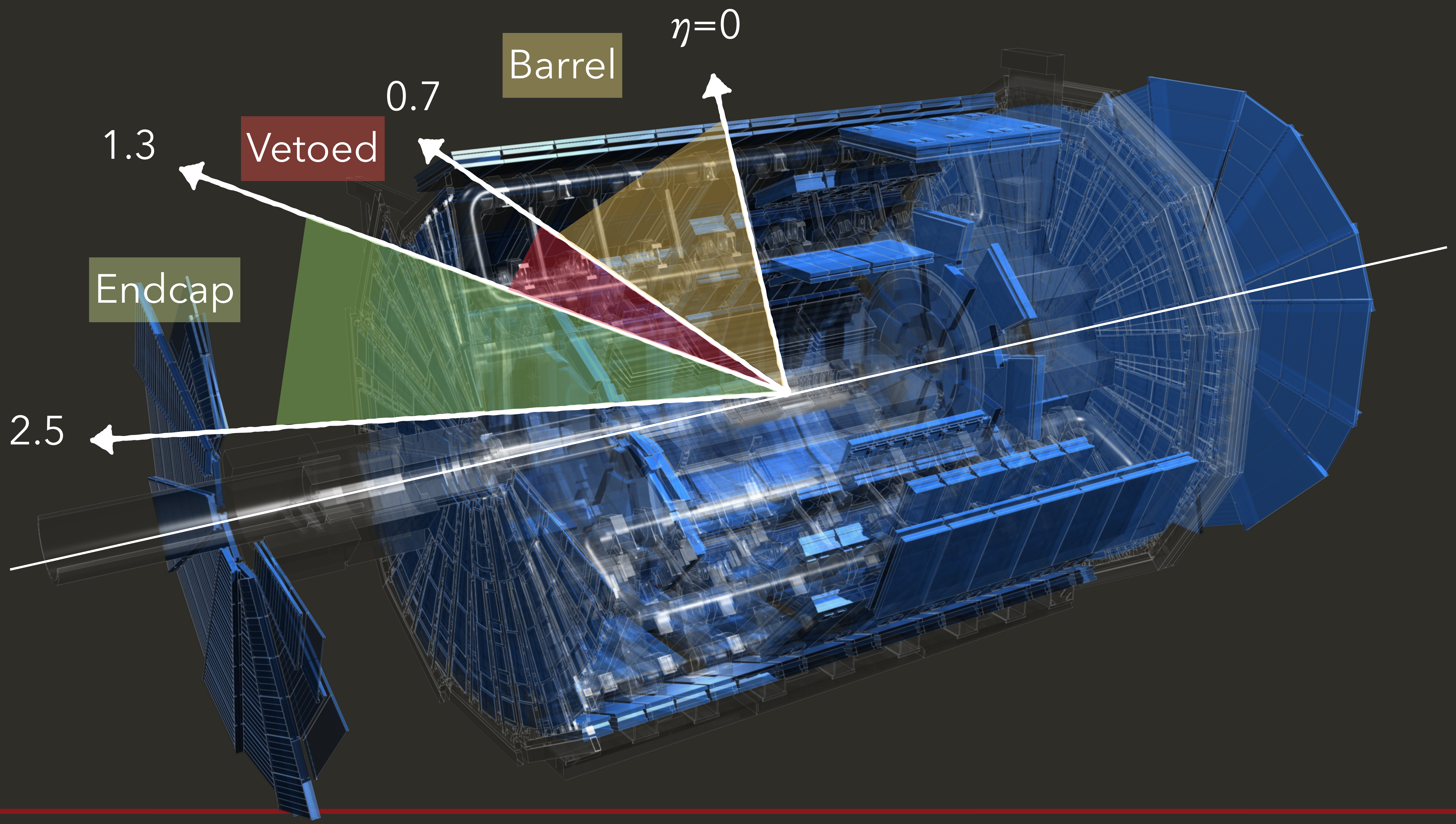


Uses standard lepton triggers and requires exactly one pair of opposite-sign same-flavor leptons with mass around the Z peak

Jets in the Muon System

Regions

Phase space geometrically split based on the MS geometry

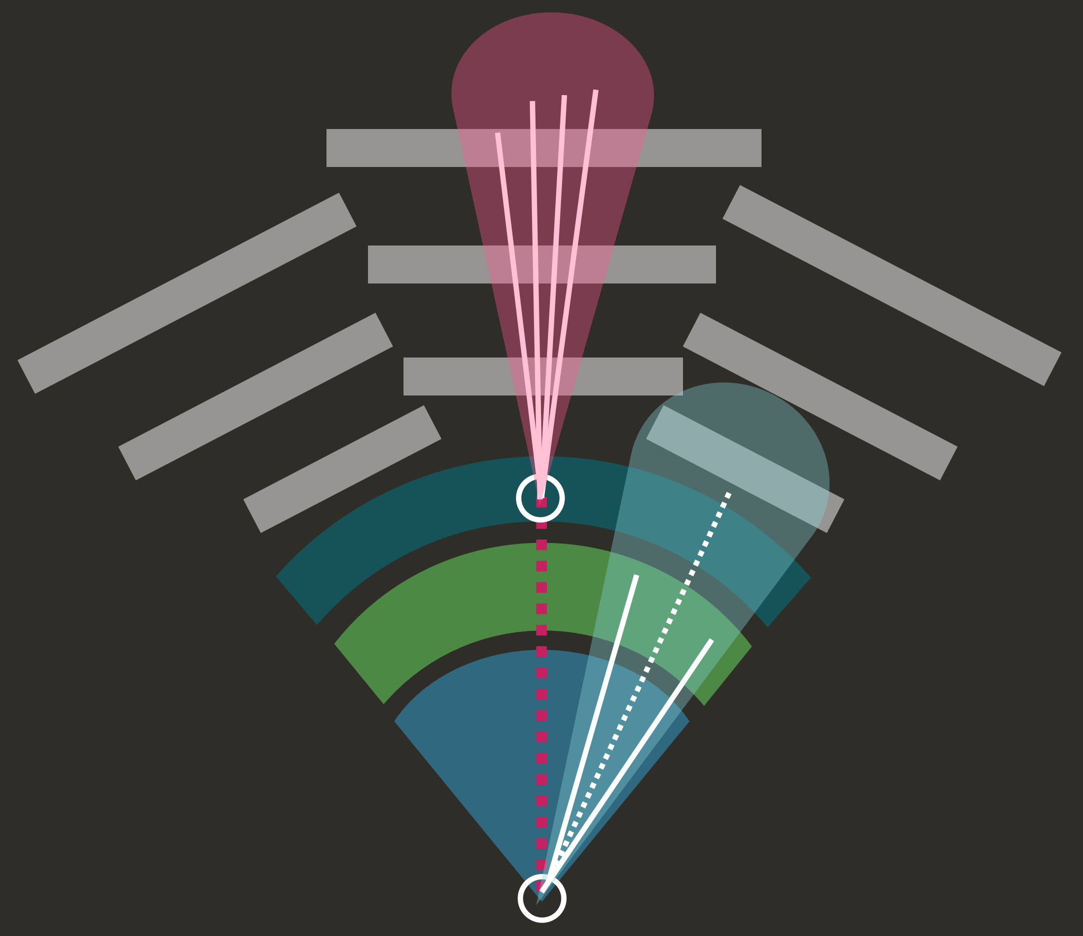


Jets in the Muon System

Background Suppression

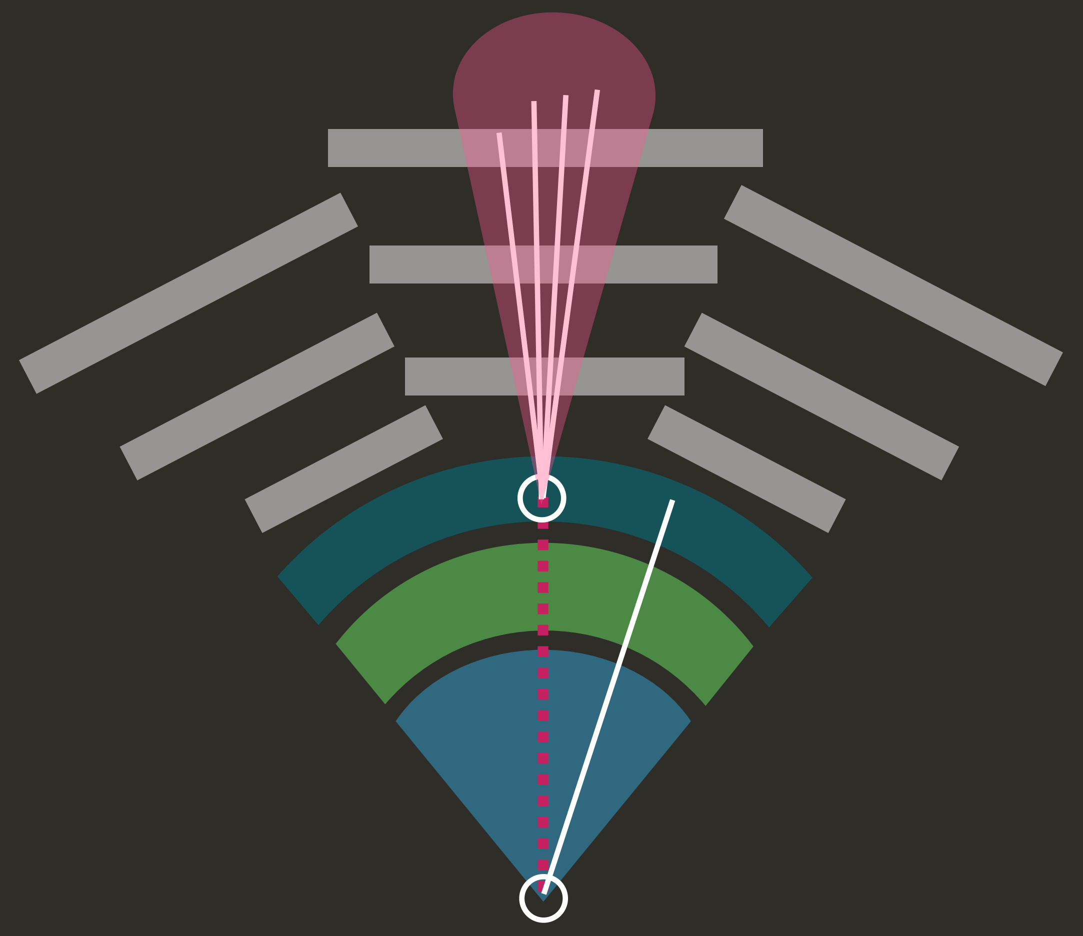
Residual hadronic interactions from prompt production, or “punch-through jets” forms the biggest background

Jets



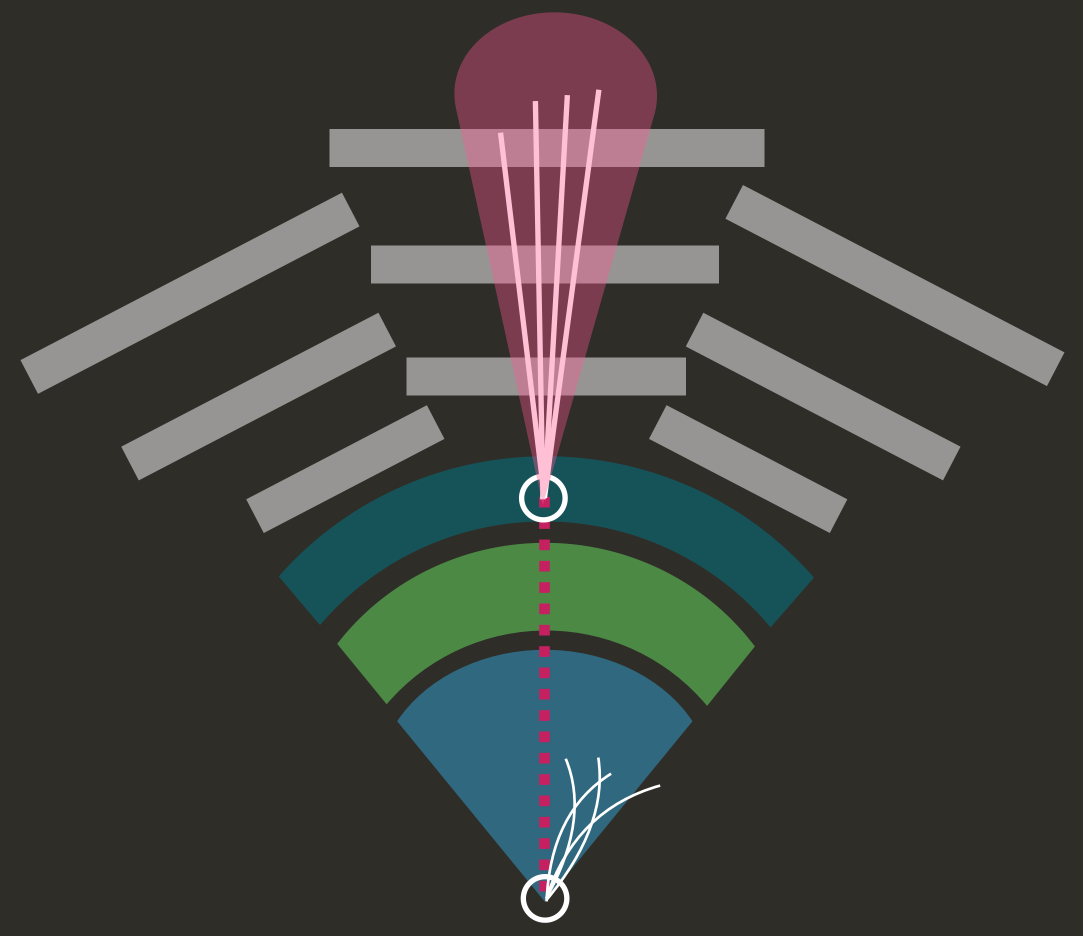
ΔR(DV, jet)

Hard Tracks



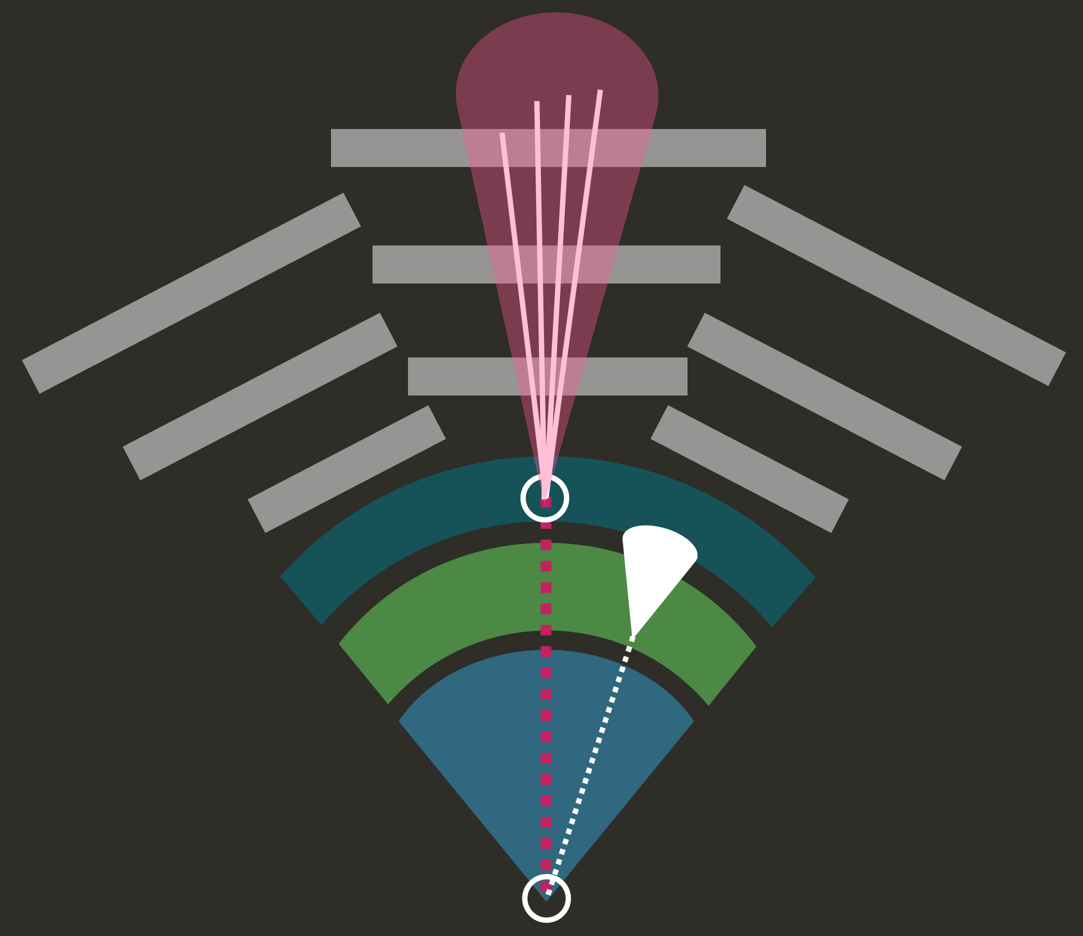
ΔR(DV, track)

Soft Tracks



Σp_T tracks close to DV

Hadrons



E_T^{miss}, H_T^{miss}

Jets in the Muon System

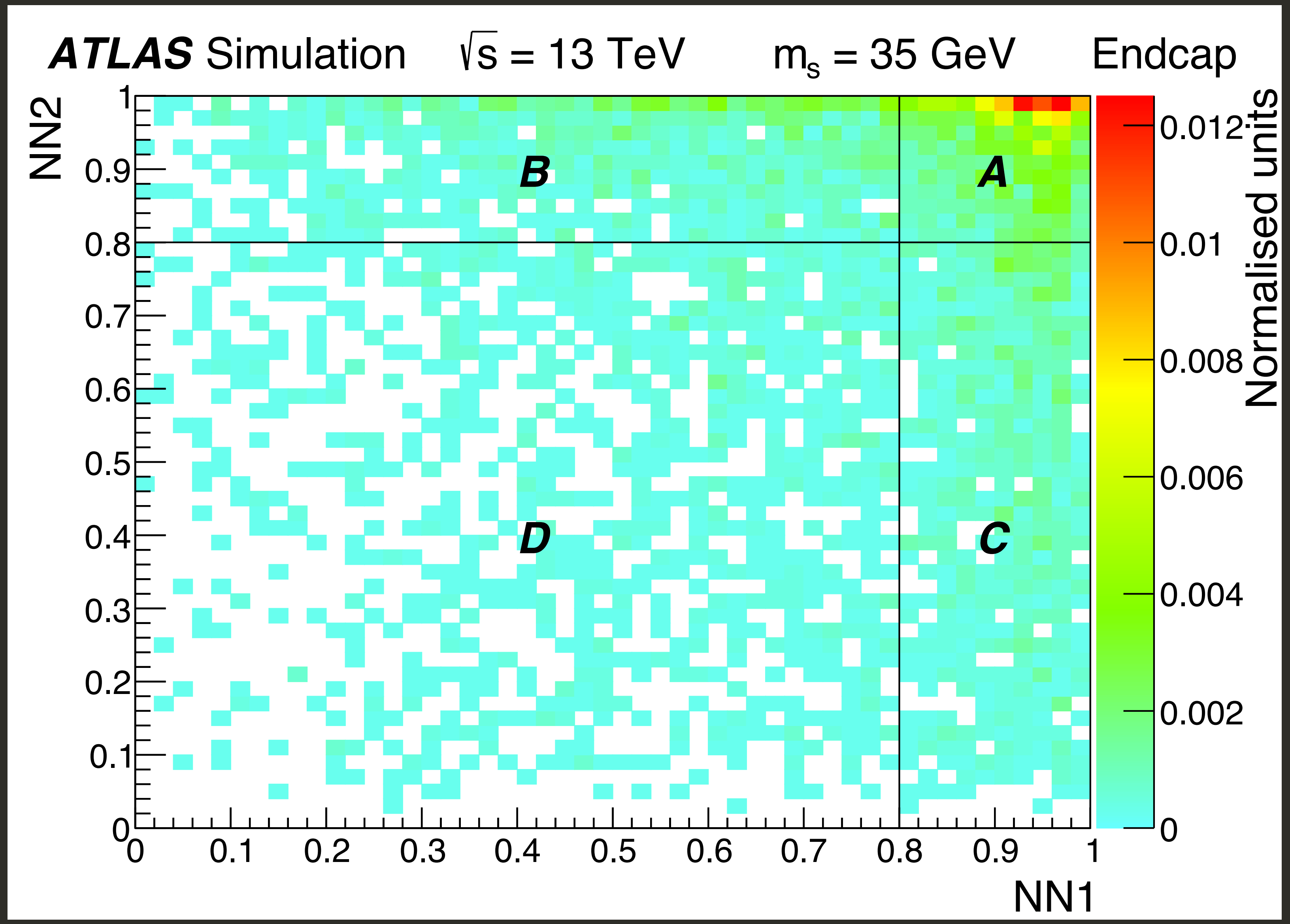
Background Estimation

Two neural networks (with uncorrelated inputs) are trained to further distinguish signal from background

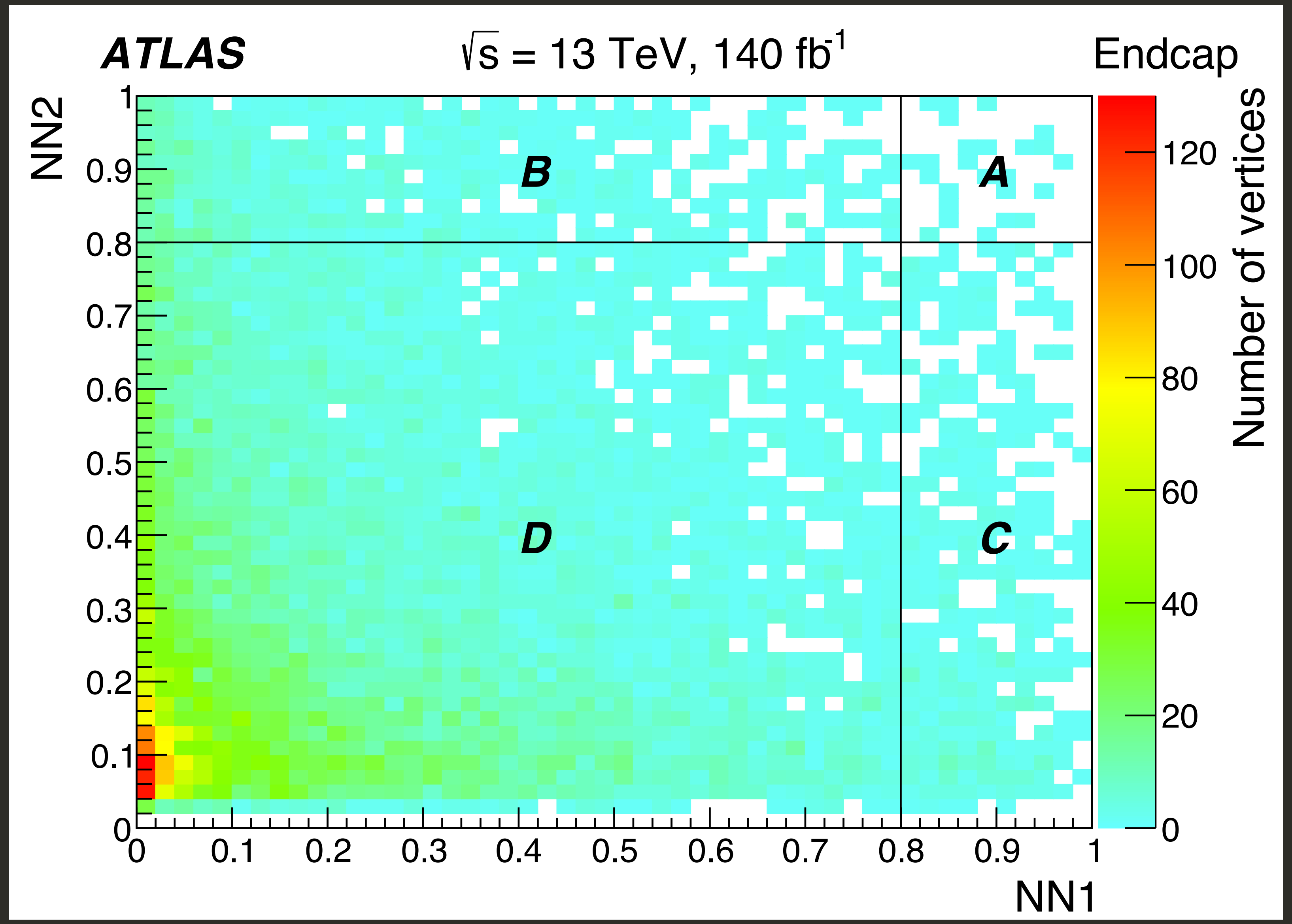
NN outputs are used to defined ABCD planes giving a background estimate

Muon ROI Triggered - Endcap

H→SS Signal



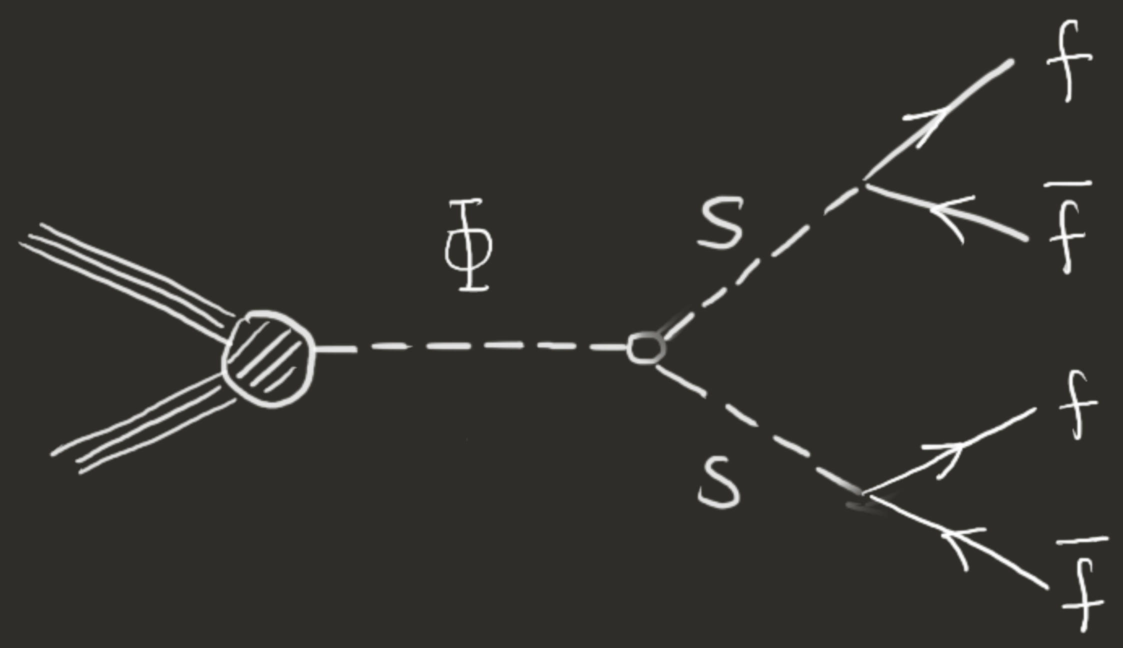
Data

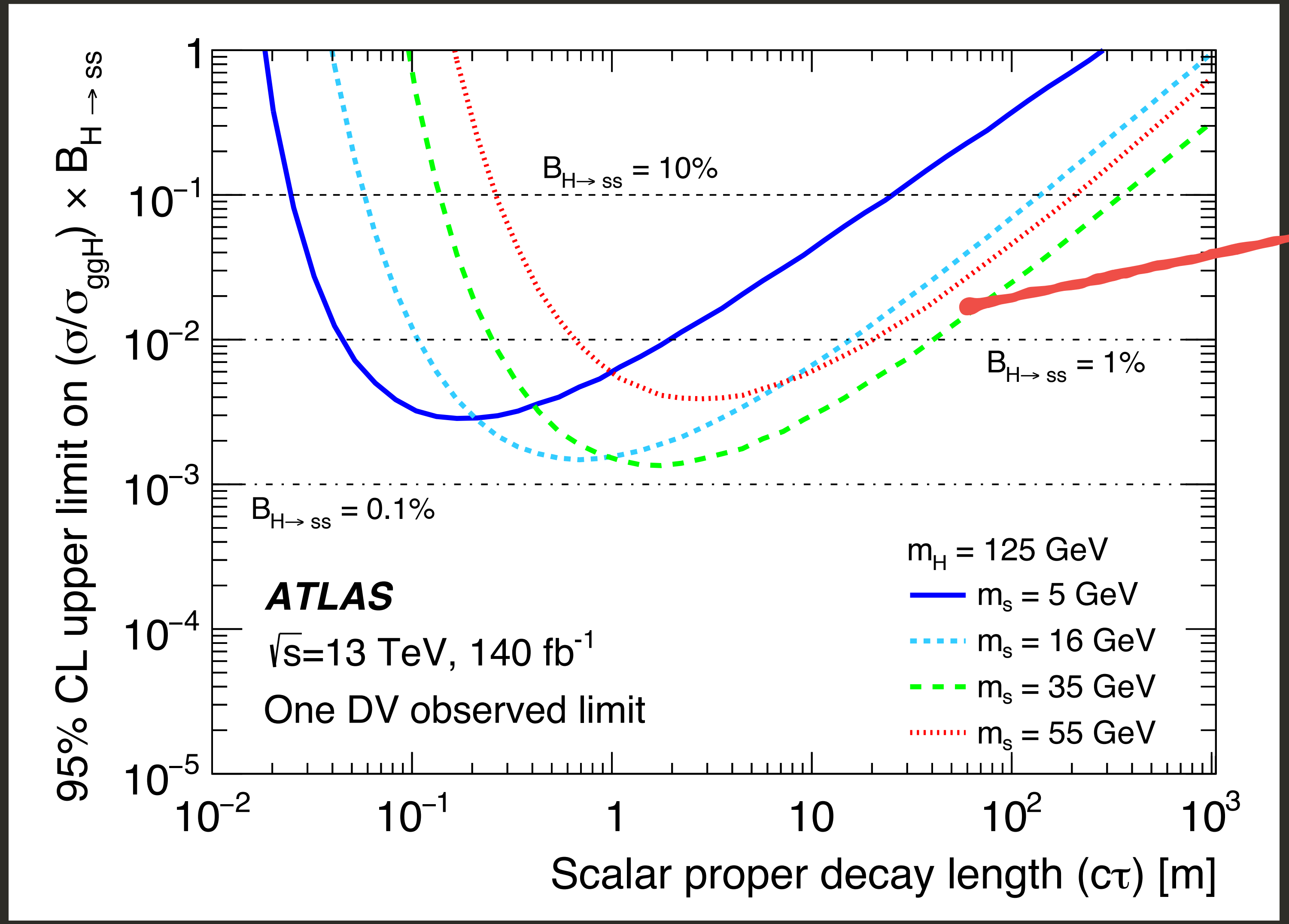


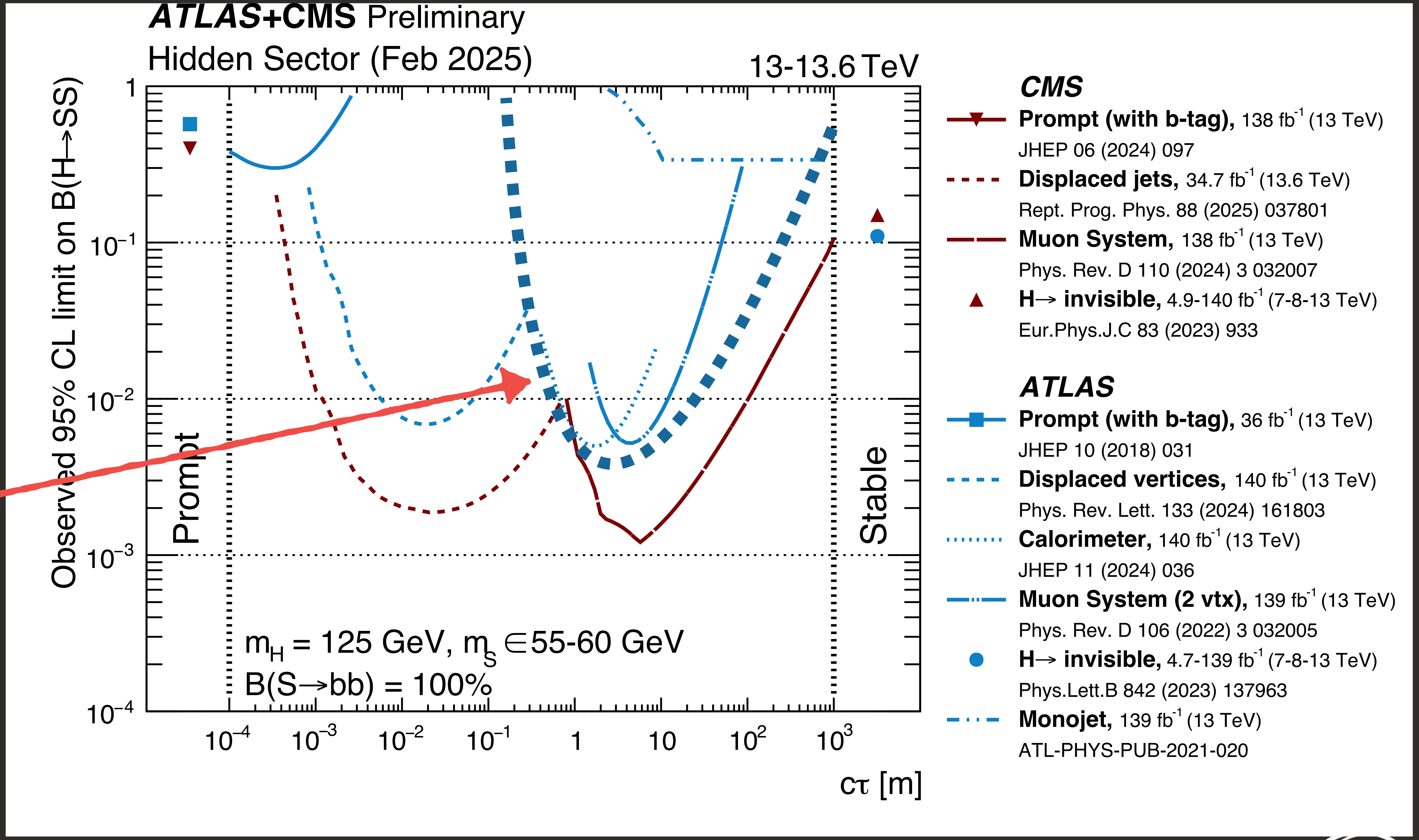
Jets in the Muon System

Results - Higgs mediated sector

Events in **A** for all channels and regions found to be compatible with the background prediction





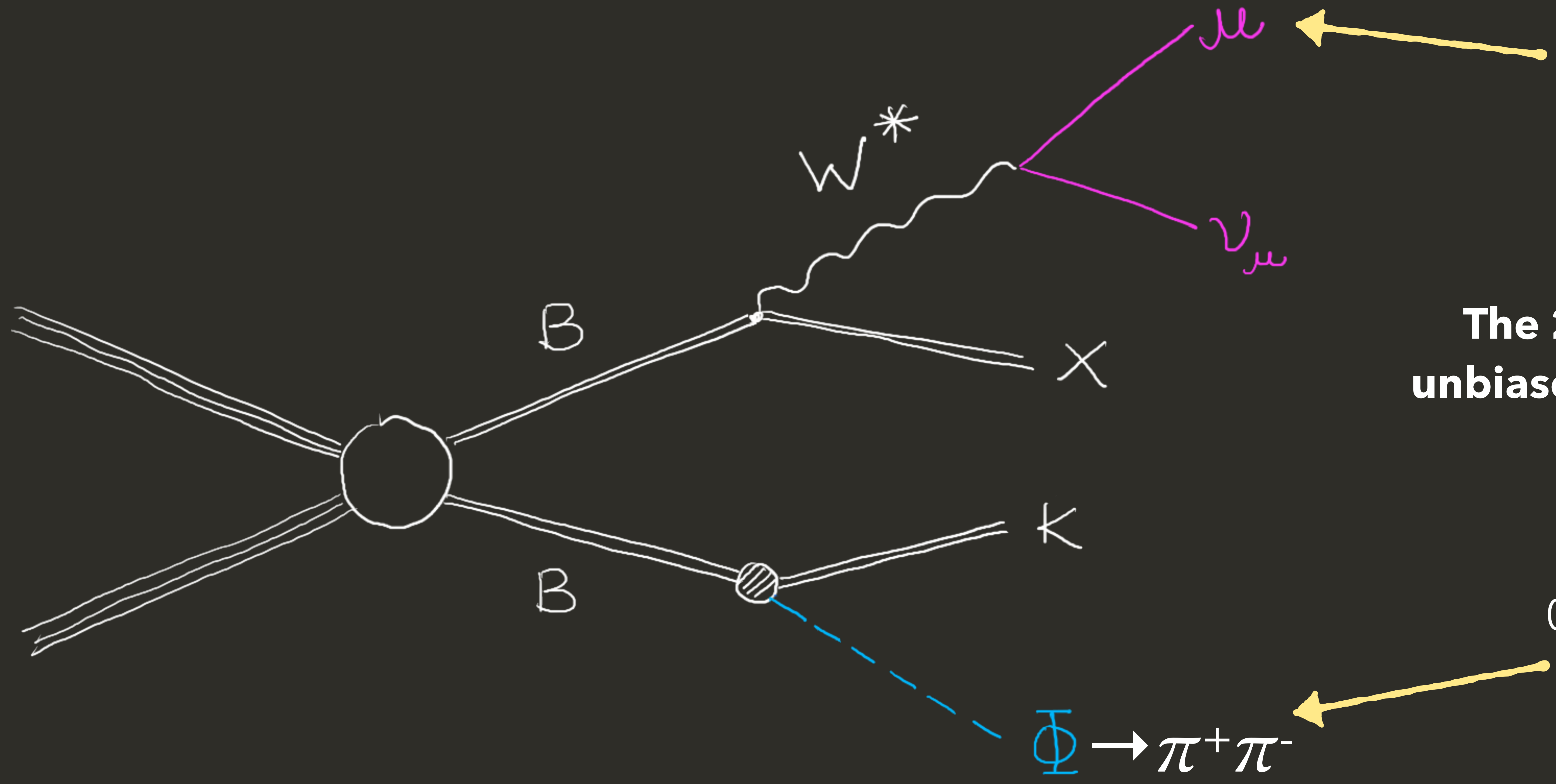


More limits in the paper

Clusters in the Muon System

Introduction

A simplified model search looking for pion pairs in the MS



Triggering signature with non-zero position significance wrt the *pp* interaction

The 2018 CMS b-parking dataset gives a pure unbiased collection of ~10 billion b hadron decays

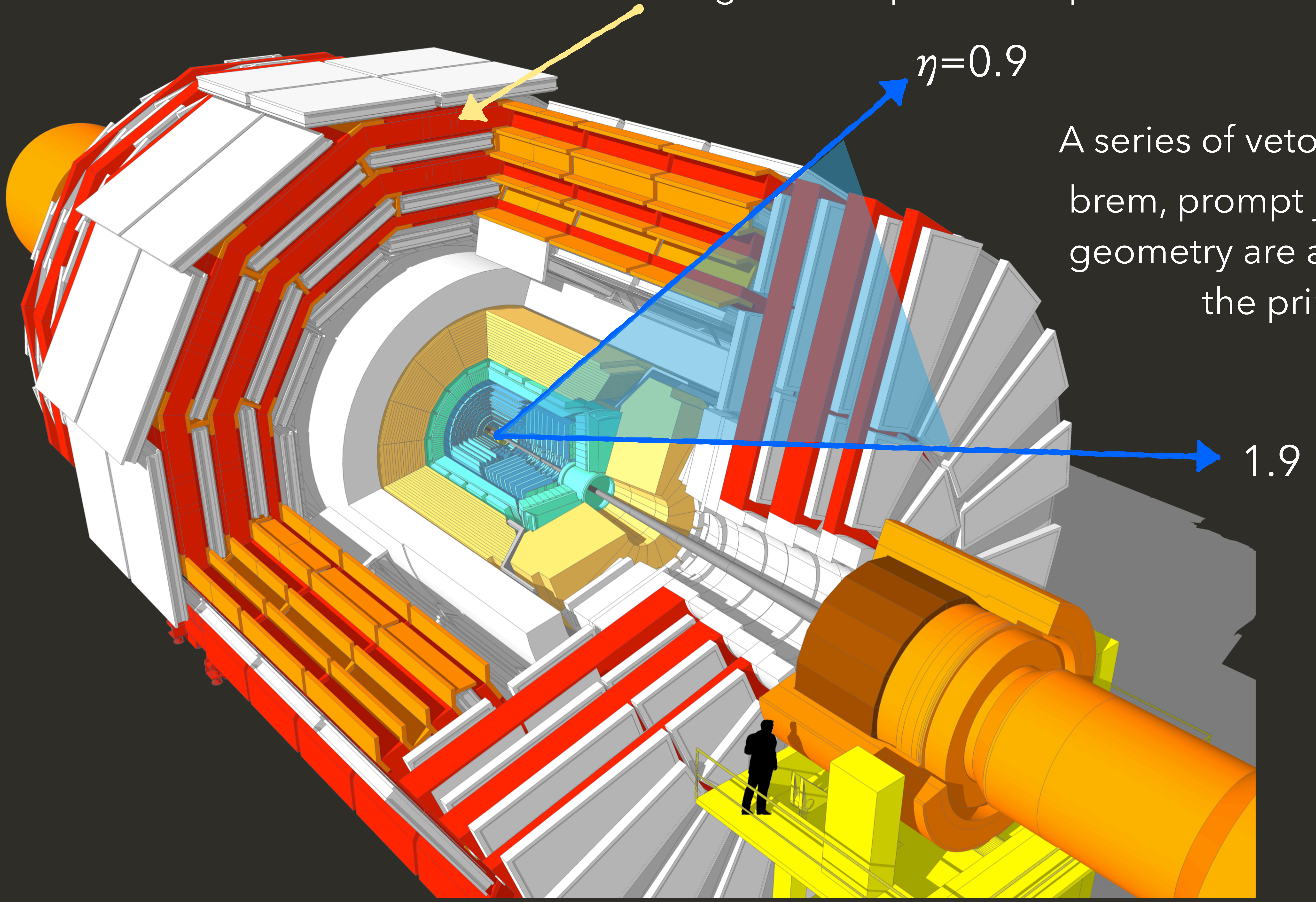
0.3-3.0 GeV scalar with $c\tau_{proper}$ = 10 - 5000 mm decaying within the CMS muon system

CMS-PAS-EXO-24-004

Clusters in the Muon System

Background Shielding

The CMS steel return yoke provides a natural shielding against SM processes produced in the detector bulk

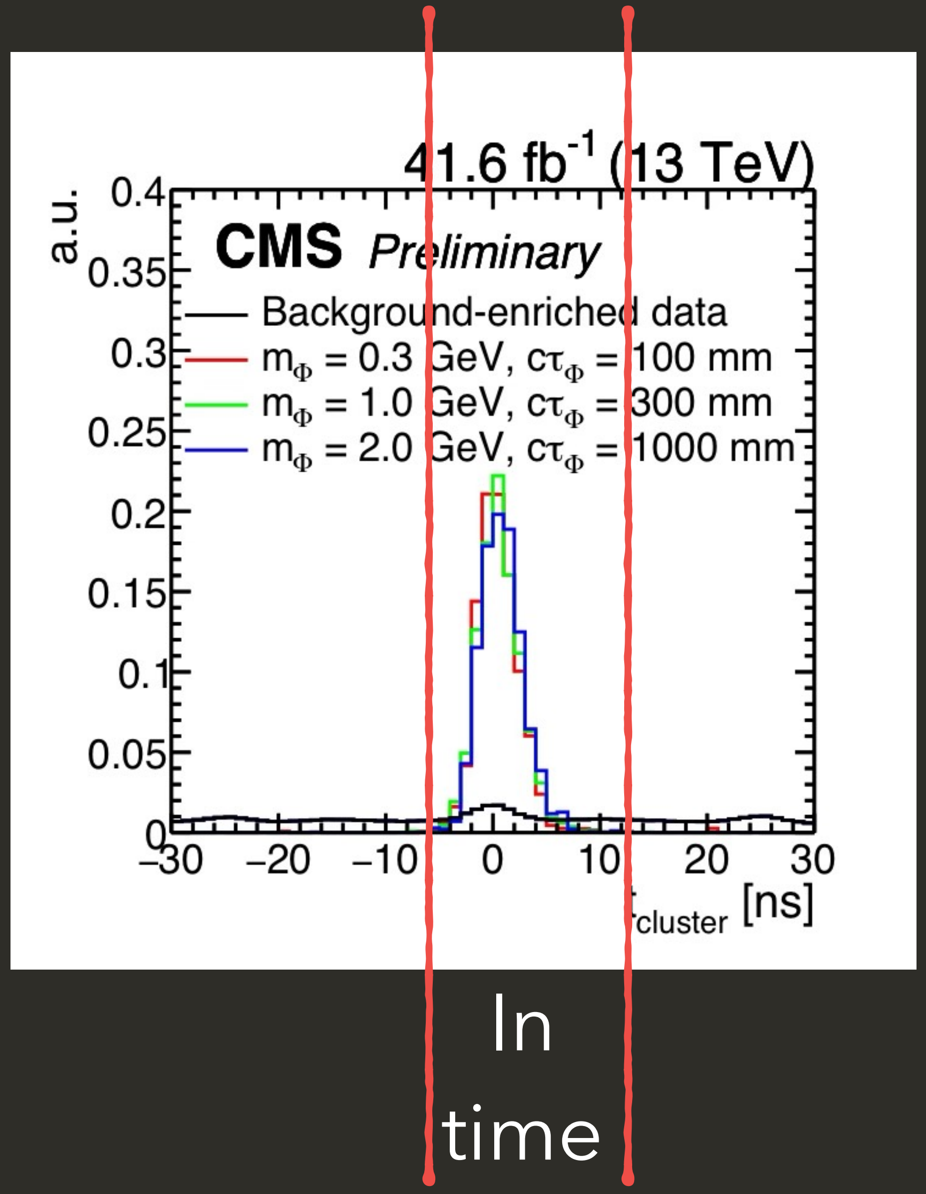


A series of vetos to suppress uncorrelated backgrounds (μ brem, prompt jets punch-through) based on the detector geometry are applied. **Cathode Strip Chambers** used as the primary cluster reconstructing system

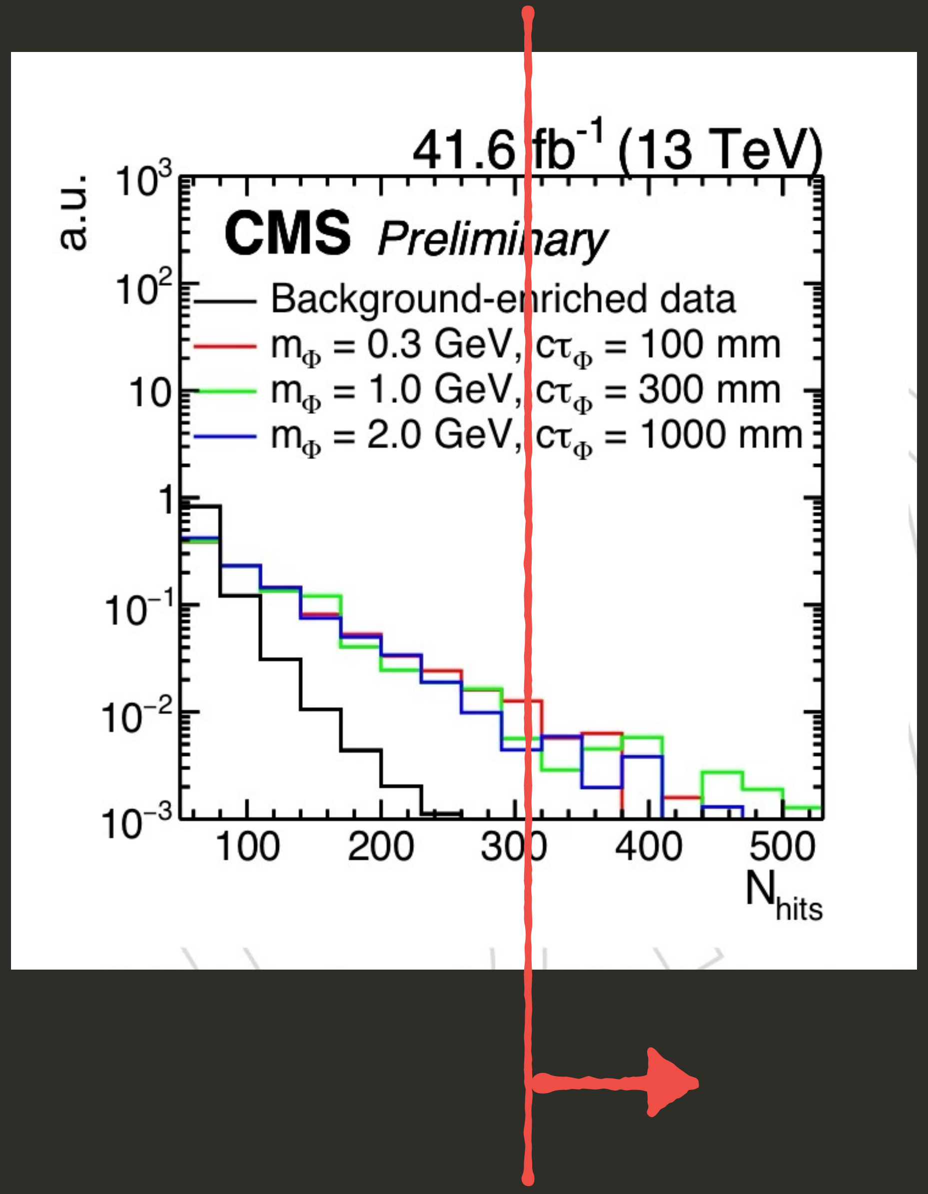
Clusters in the Muon System

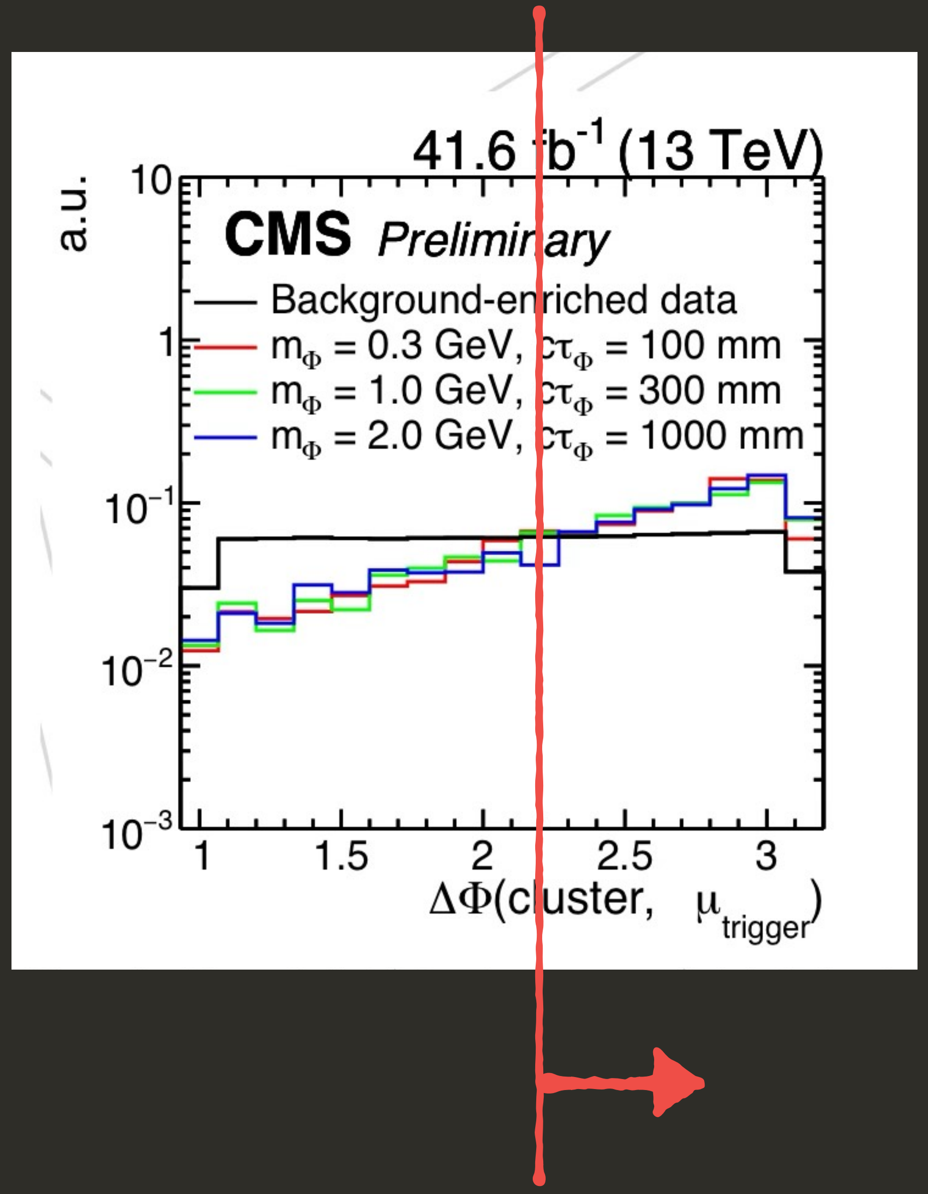
Background Estimation

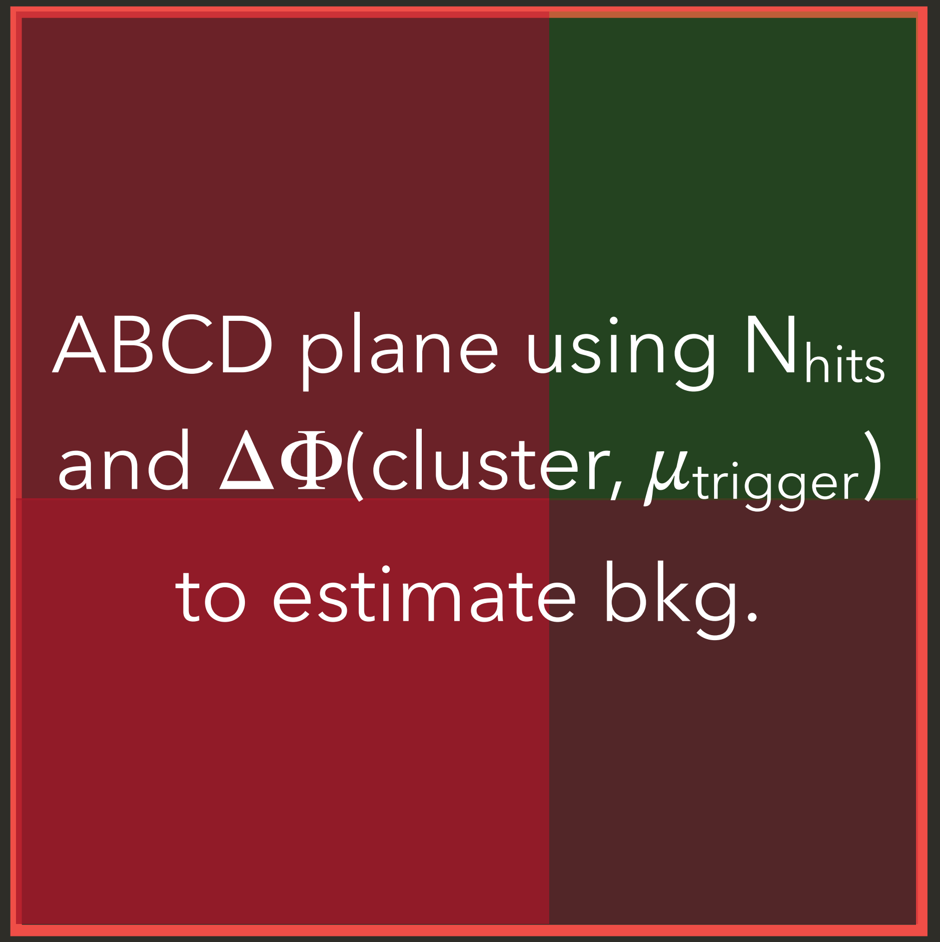
- **Uncorrelated Background**: Residual background estimated by using the cluster timing, hits, and position



In time





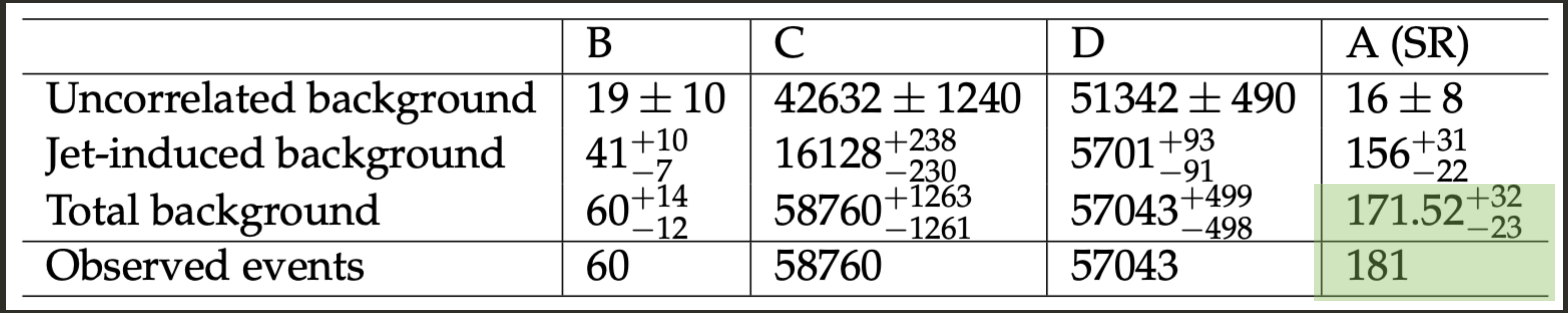


ABCD plane using N_{hits} and $\Delta\Phi$(cluster, $\mu_{trigger}$) to estimate bkg.

- **Correlated Background**: Irreducible background from SM LLP decays estimated in an independent dataset using *W*+jets events and applied as a per-jet fake factor to the b-parking dataset

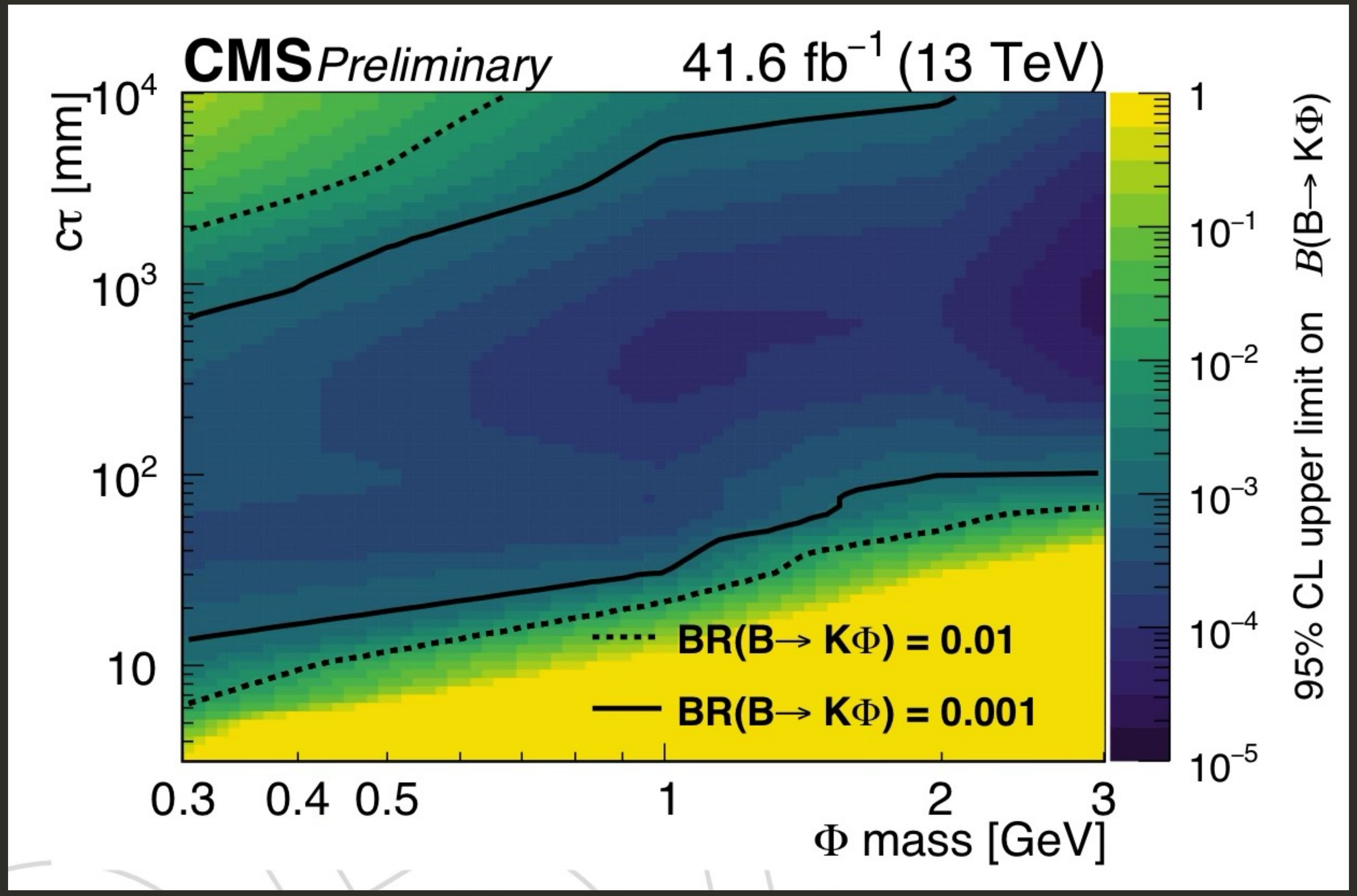
Clusters in the Muon System

Results



	B	C	D	A (SR)
Uncorrelated background	19 ± 10	42632 ± 1240	51342 ± 490	16 ± 8
Jet-induced background	41^{+10}_{-7}	16128^{+238}_{-230}	5701^{+93}_{-91}	156^{+31}_{-22}
Total background	60^{+14}_{-12}	58760^{+1263}_{-1261}	57043^{+499}_{-498}	171.52^{+32}_{-23}
Observed events	60	58760	57043	181

Observed events found to be compatible with the background prediction in the signal region



95% CL limits on Br(B→KΦ) constrained down to 10^{-5}. First search ever for B decays to LLP scalars!

Summary

- LLPs form an important part of the LHC physics program despite the challenges in their identification, opening up an opportunity to innovate various steps of the analysis chain

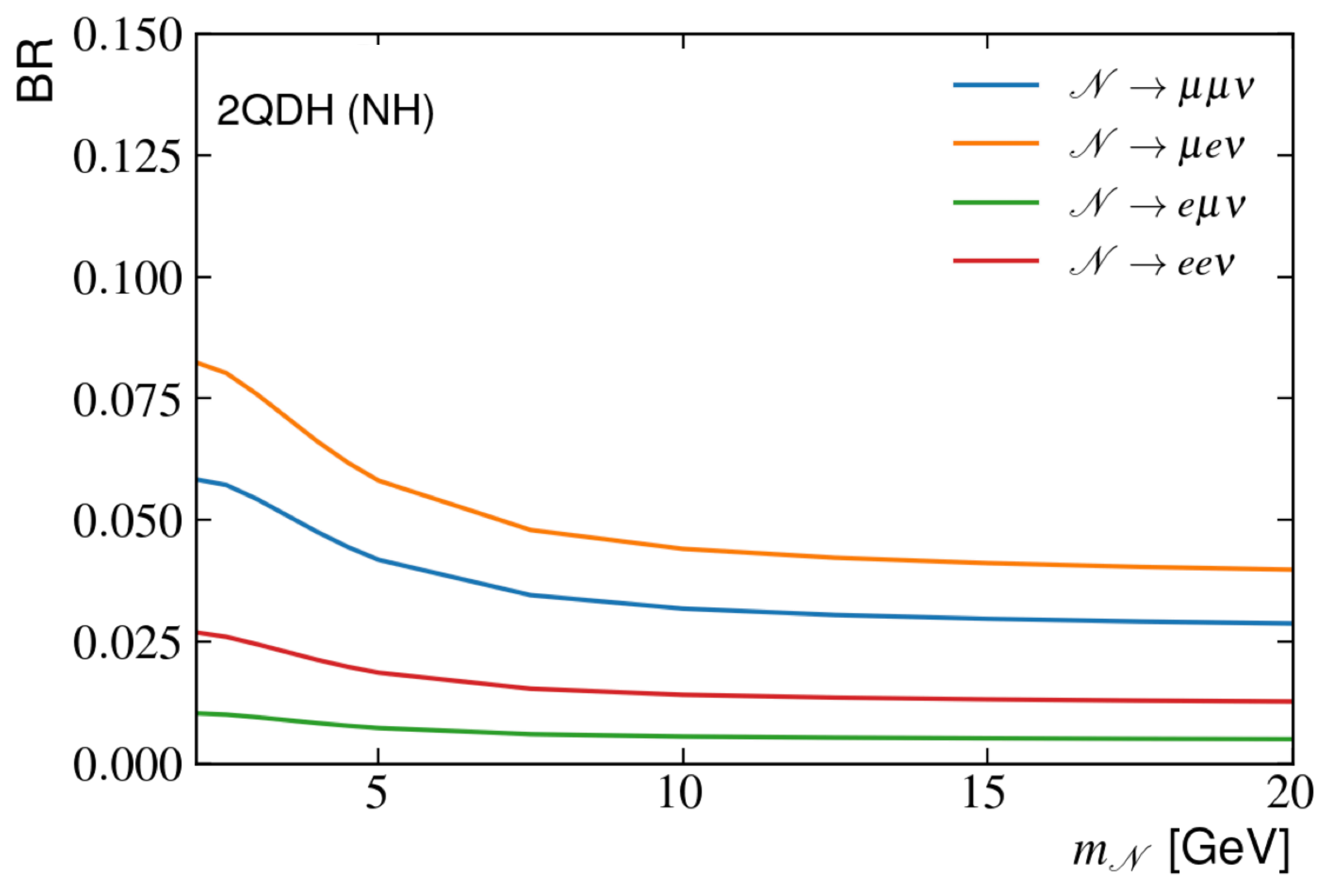
- Many all new searches with displaced signatures are presented
  - ATLAS+CMS Feb. 2025 summary of LLPs in the Higgs boson mediated hidden sector: ATL-PHYS-PUB-2025-002
  - Displaced vertices in the tracker -
    - Search for heavy neutral leptons by ATLAS: 2503.16213
  - Displaced vertices in the muon system -
    - Model agnostic search using displaced jets in the MS by ATLAS: CERN-EP-2025-062
    - Search for long-lived scalars from b hadron decays in the 2018 b-parking data by CMS: CMS-PAS-EXO-24-004

ADDITIONAL MATERIAL

Heavy Neutral Leptons

Analysis Channels

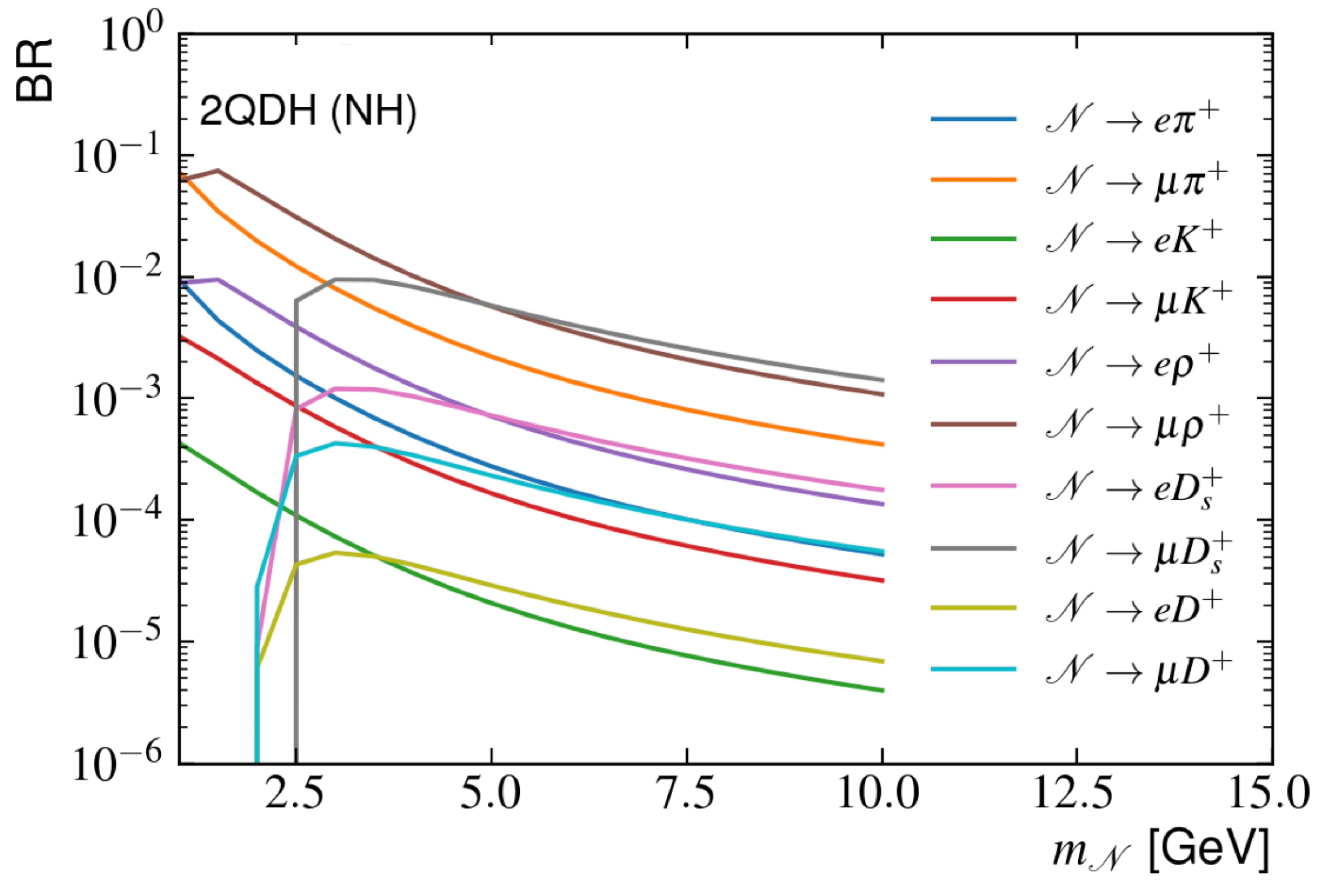
*The Branching Ratio depends on the HNL model considered



Six signal channels: $\ell_{\text{prompt}} - \ell_{\text{DV}}^1\ \ell_{\text{DV}}^2$

μ–$\mu\mu$, μ–μe, μ–ee, e–$\mu\mu$, e–μe, e–ee

τ decays were found to have negligible acceptance in our analysis phase space



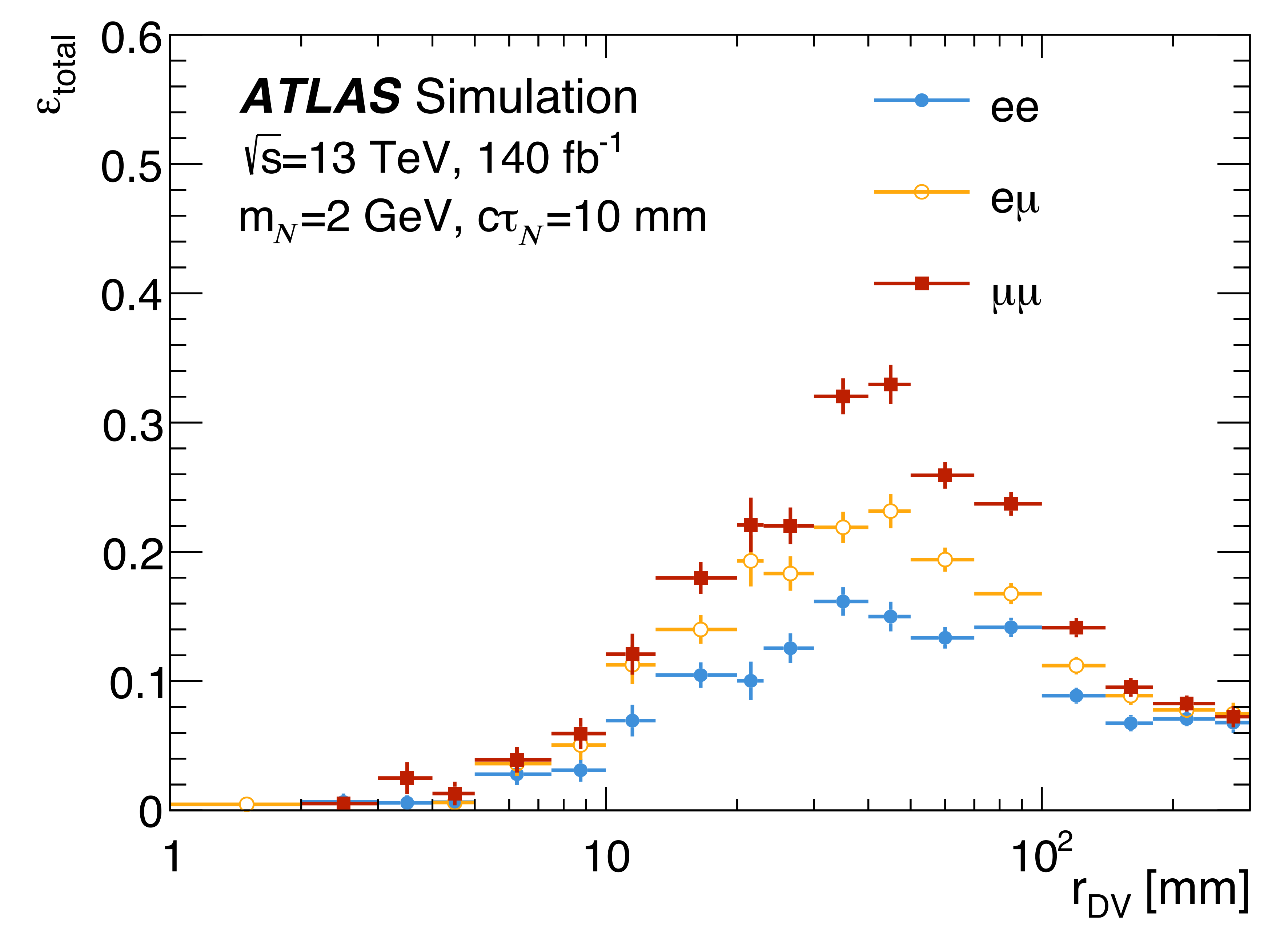
Four signal channels: $\ell_{\text{prompt}} - \ell_{\text{DV}}\pi$

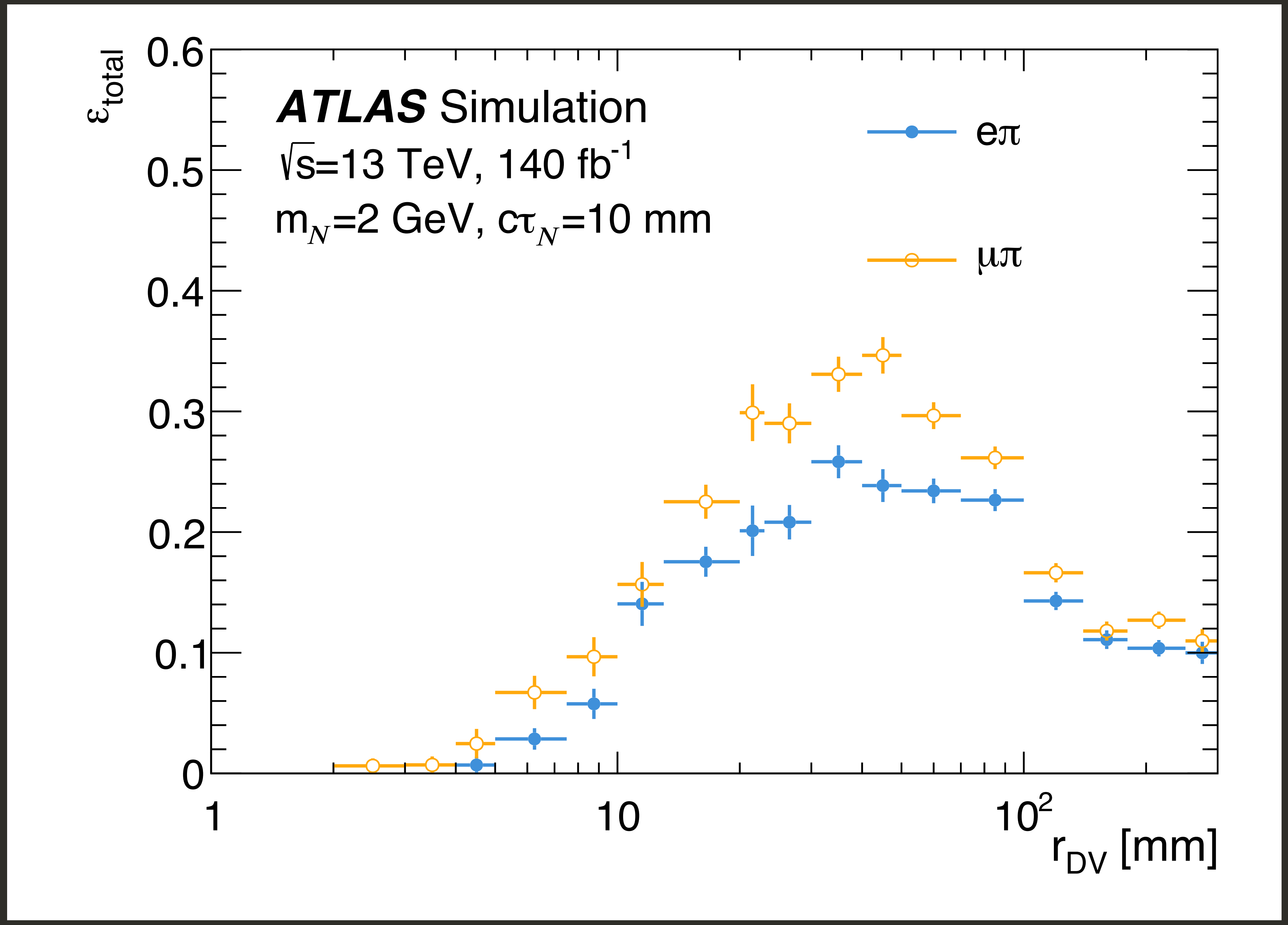
μ–$\mu\pi$, μ–$e\pi$, e–$\mu\pi$, e–$e\pi$

Mesons heavier than pions decay rapidly and did not have large acceptance in the analysis

Heavy Neutral Leptons

DV Reconstruction





Finding and fitting the displaced vertex is the biggest strength of this analysis!
Significant reduction in all backgrounds even for a not highly efficient DV reconstruction

Note that this is not a technical efficiency but the **total** efficiency – doesn’t account for acceptance effects

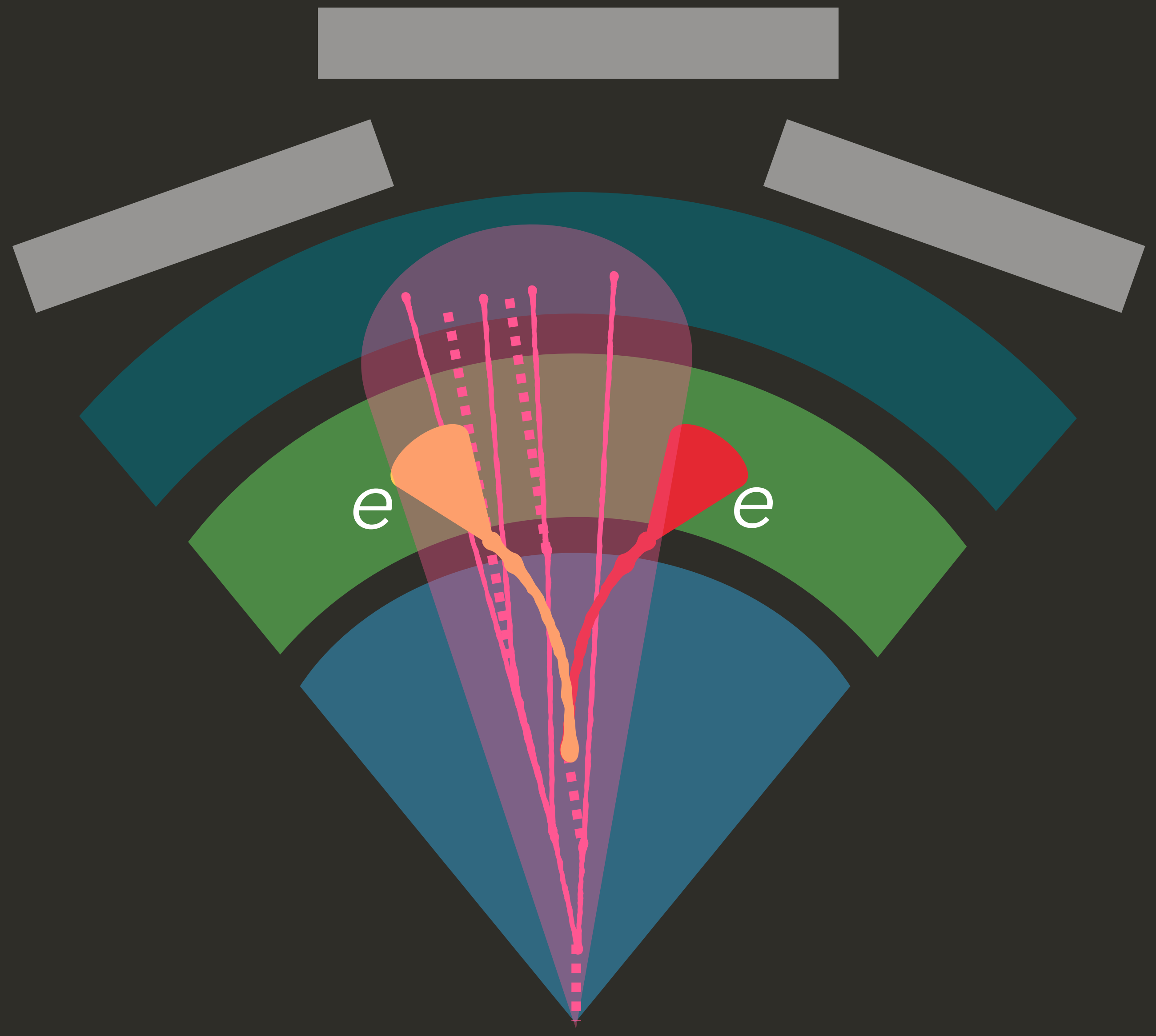
Heavy Neutral Leptons

Metastable Hadrons

- By far the biggest background, and hence many suppression cuts

- Lead (sub-lead) track $p_T > 10$ (5) GeV to suppress soft decays
- Fiducial selection:
  - Leptonic channels: $4 < r_{DV} < 300$ mm; Material map veto for *ee* DVs
  - Semi-leptonic channels: $20 < r_{DV} < 300$ mm; Material map veto

- $\Delta R(\mathrm{DV}, \mathrm{jet}) > 0.4$
- DV 3D position significance
  - $\mathcal{S}^2 = \boldsymbol{\Delta}_{3D}(\mathrm{PV},\mathrm{DV})^T \cdot \mathrm{Cov}(\boldsymbol{\Delta}_{3D}(\mathrm{PV},\mathrm{DV}))^{-1} \cdot \boldsymbol{\Delta}_{3D}(\mathrm{PV},\mathrm{DV})$
  - $\mathcal{S} > 100$ if $m_{DV} < 5$ GeV

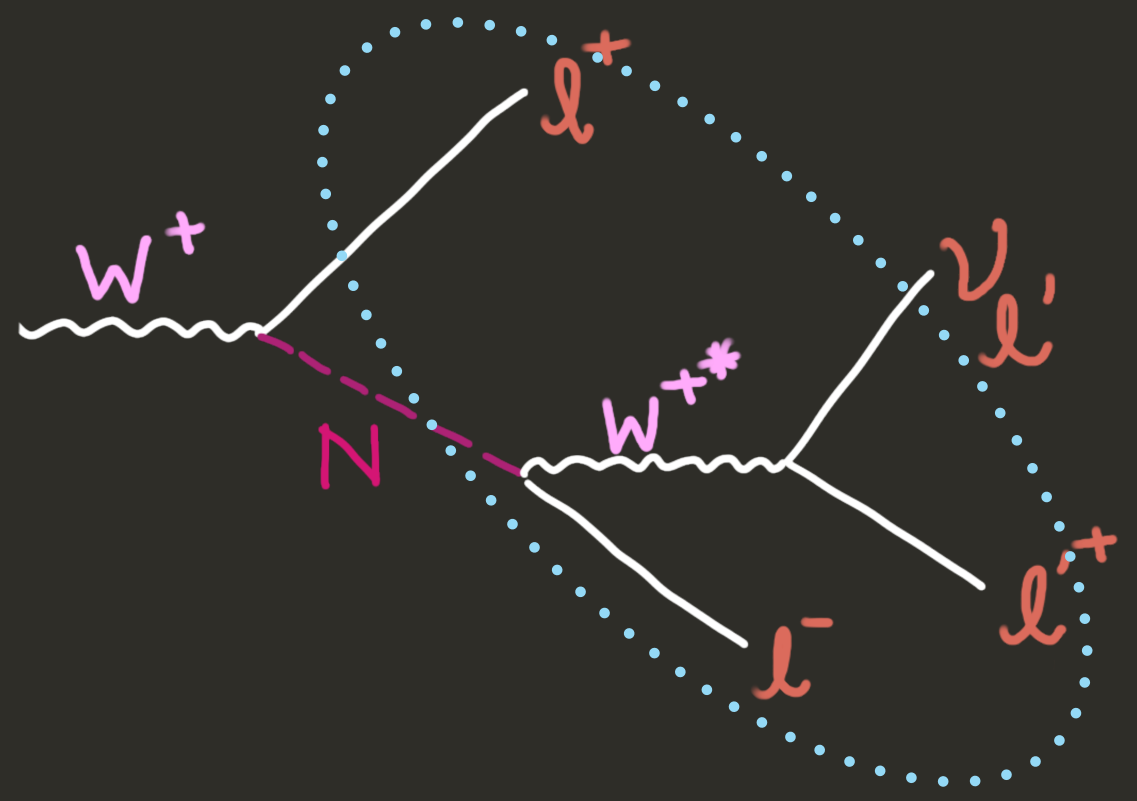


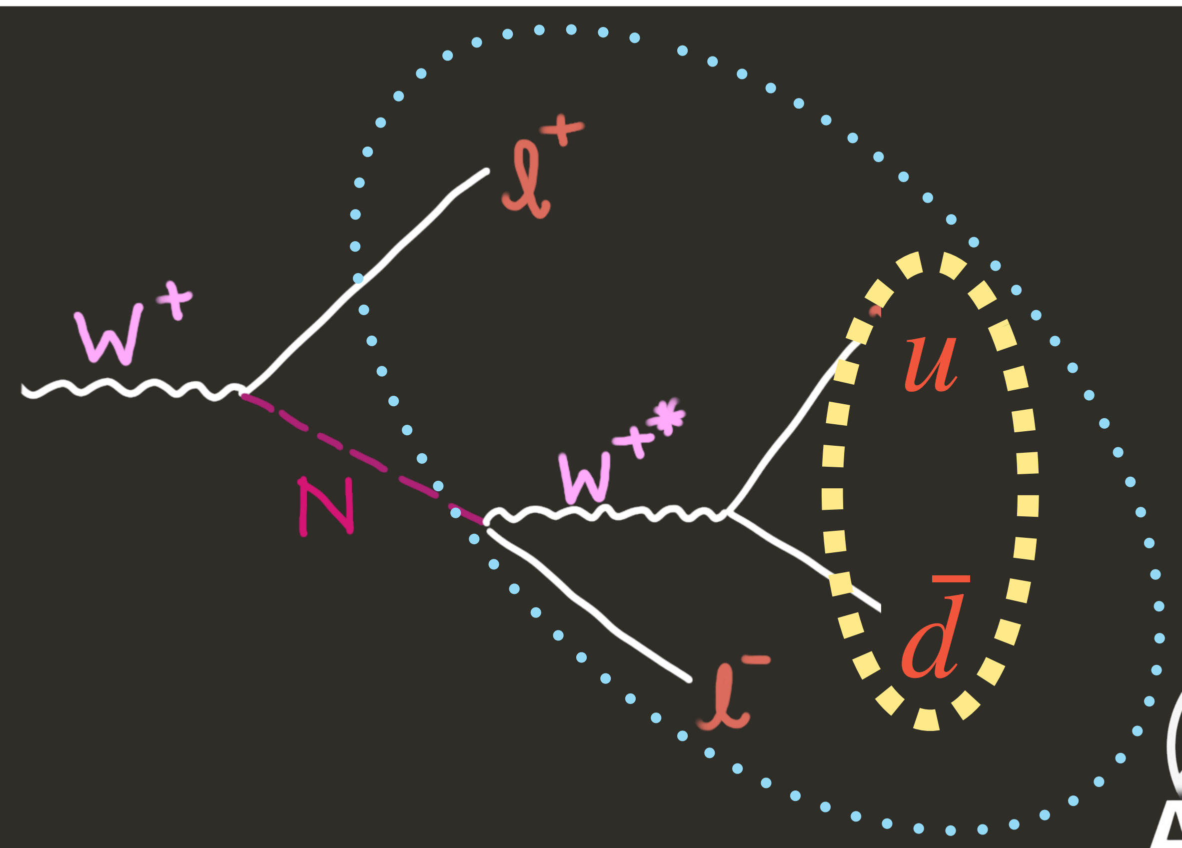
Leptons inside jets

Heavy Neutral Leptons

Heavy Flavor Decay Background

	Leptonic Channels	**Semi-Leptonic Channels**
Signal Region (SR)	$40 < m_{\ell\ell\ell} < 90$ GeV 2 isolated displaced leptons b-jet veto	$70 < m_{\ell\ell\pi} < 90$ GeV 1 isolated displaced lepton b-jet veto
Heavy Flavor (HF) Control Region (CR)	$40 < m_{\ell\ell\ell} < 90$ GeV >=1 non-isolated displaced lepton >=1 b-tagged jet	$70 < m_{\ell\ell\pi} < 90$ GeV >=1 non-isolated displaced lepton >=1 b-tagged jet

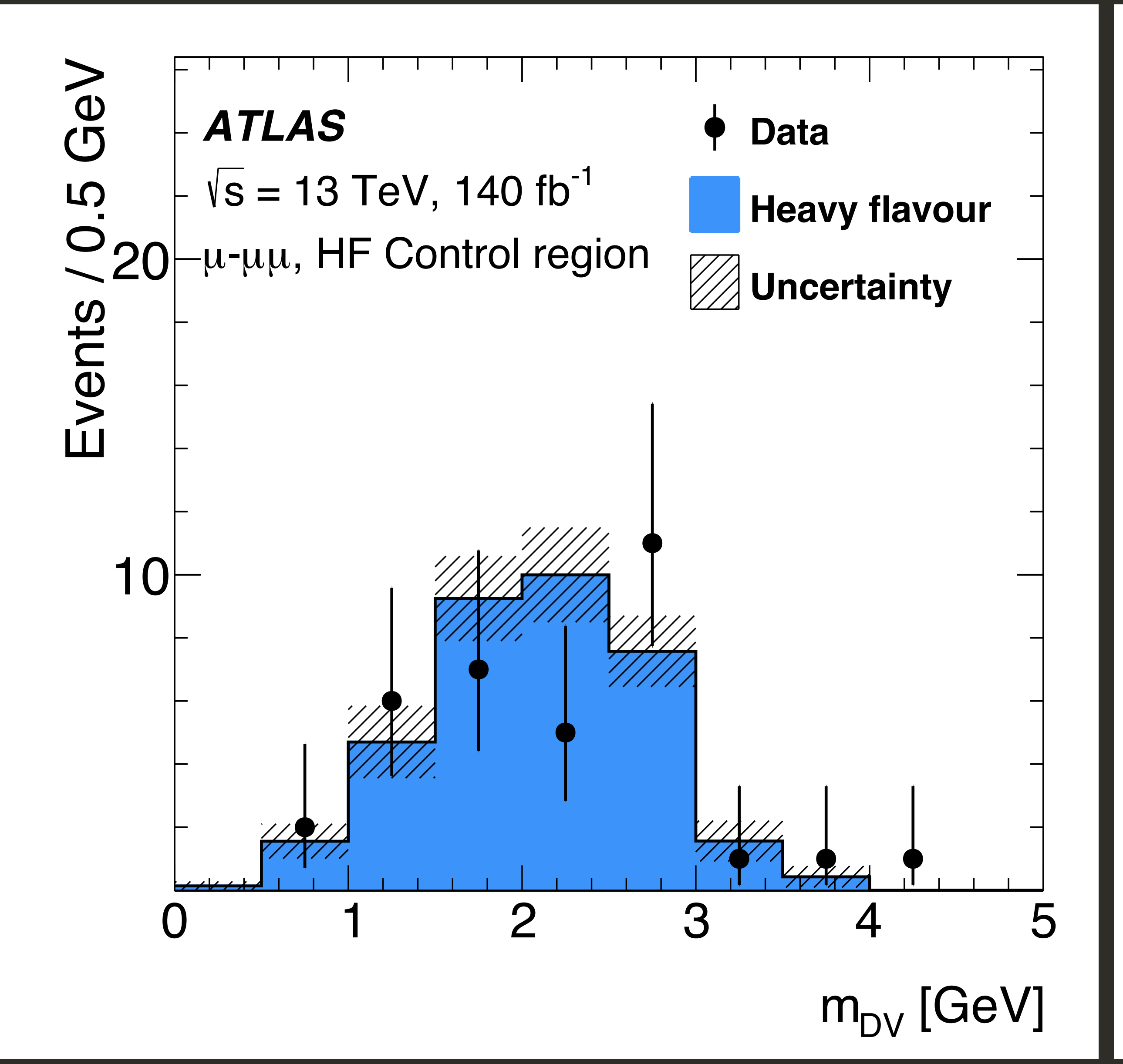


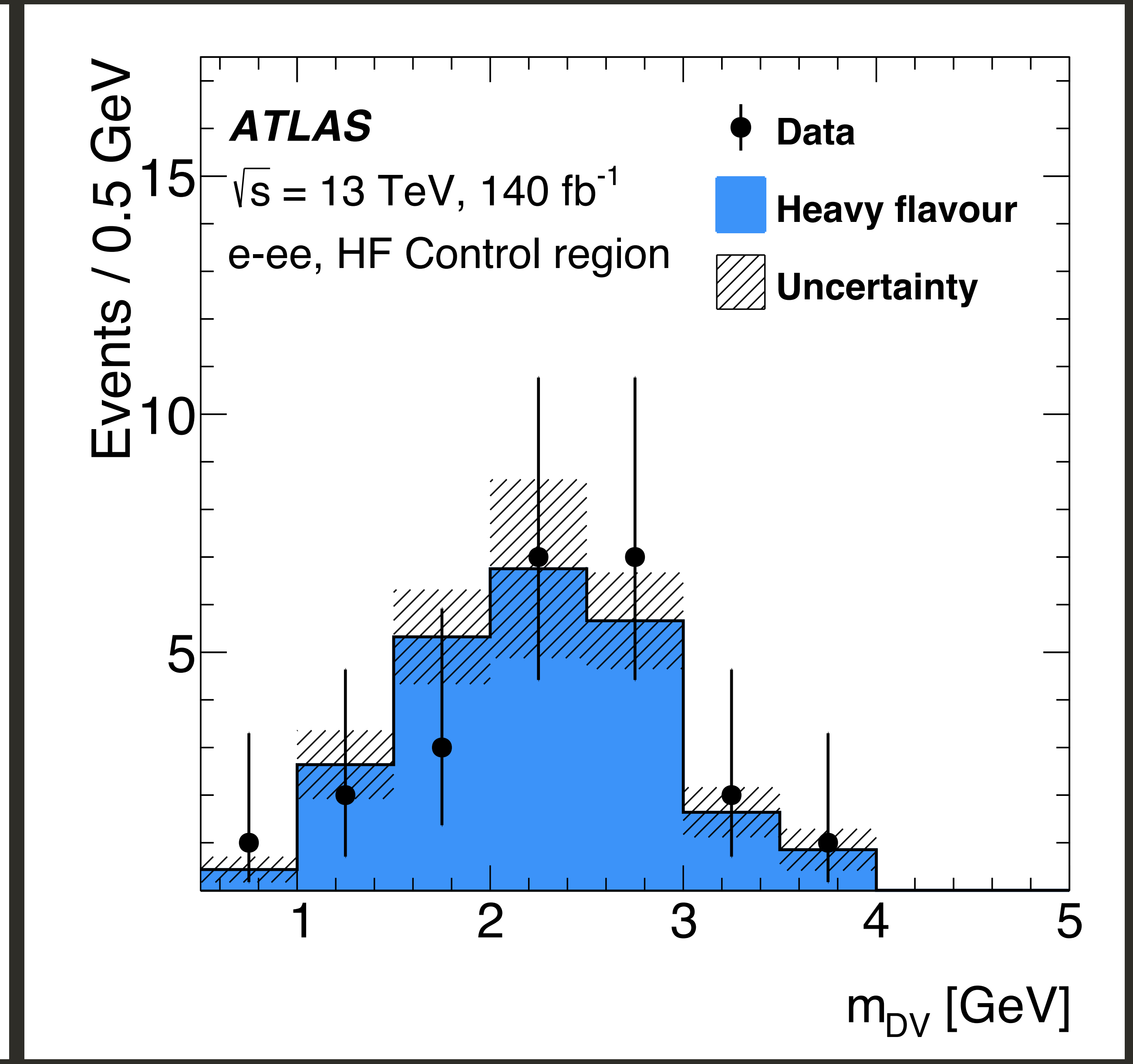


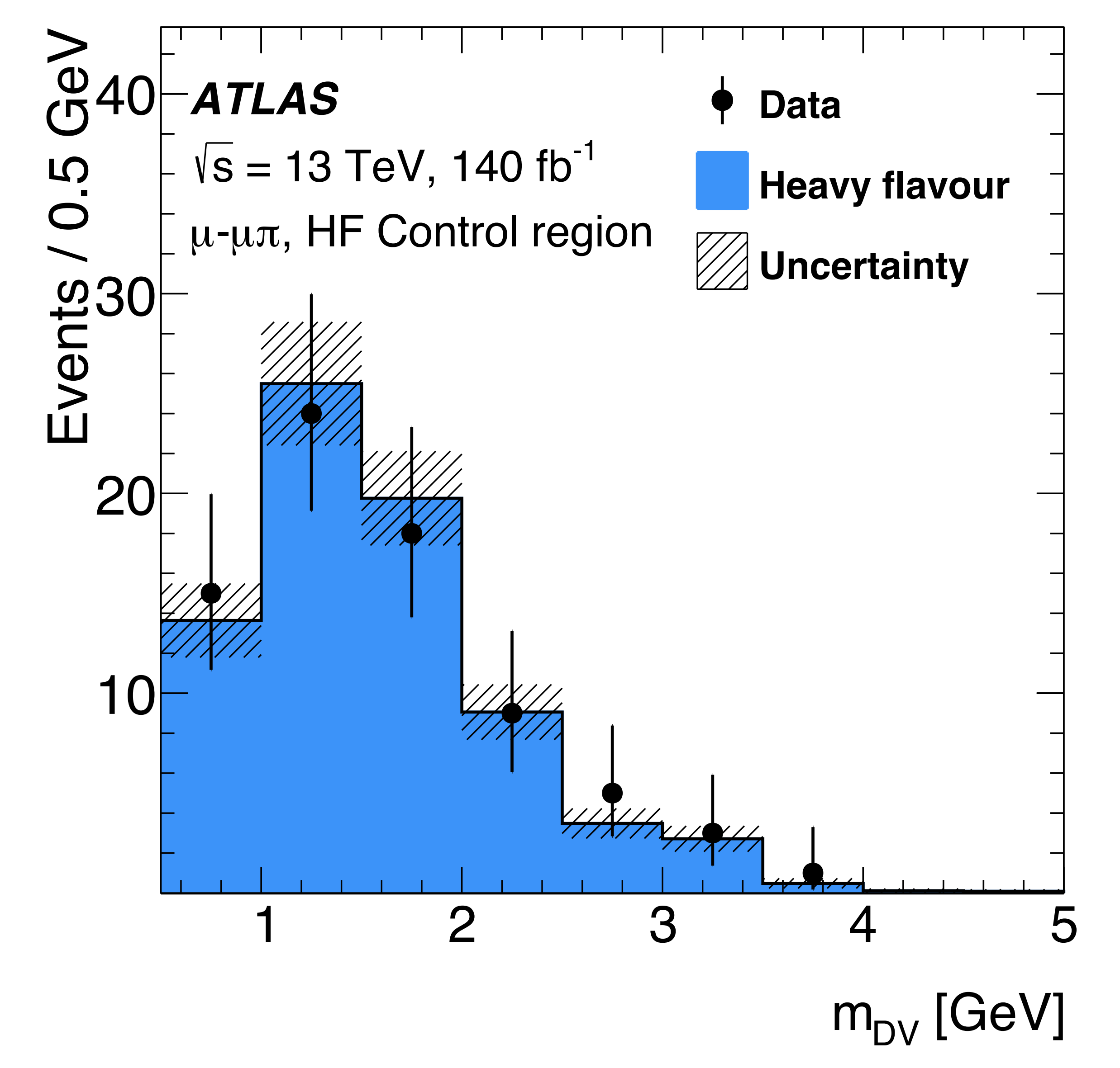
Heavy Neutral Leptons

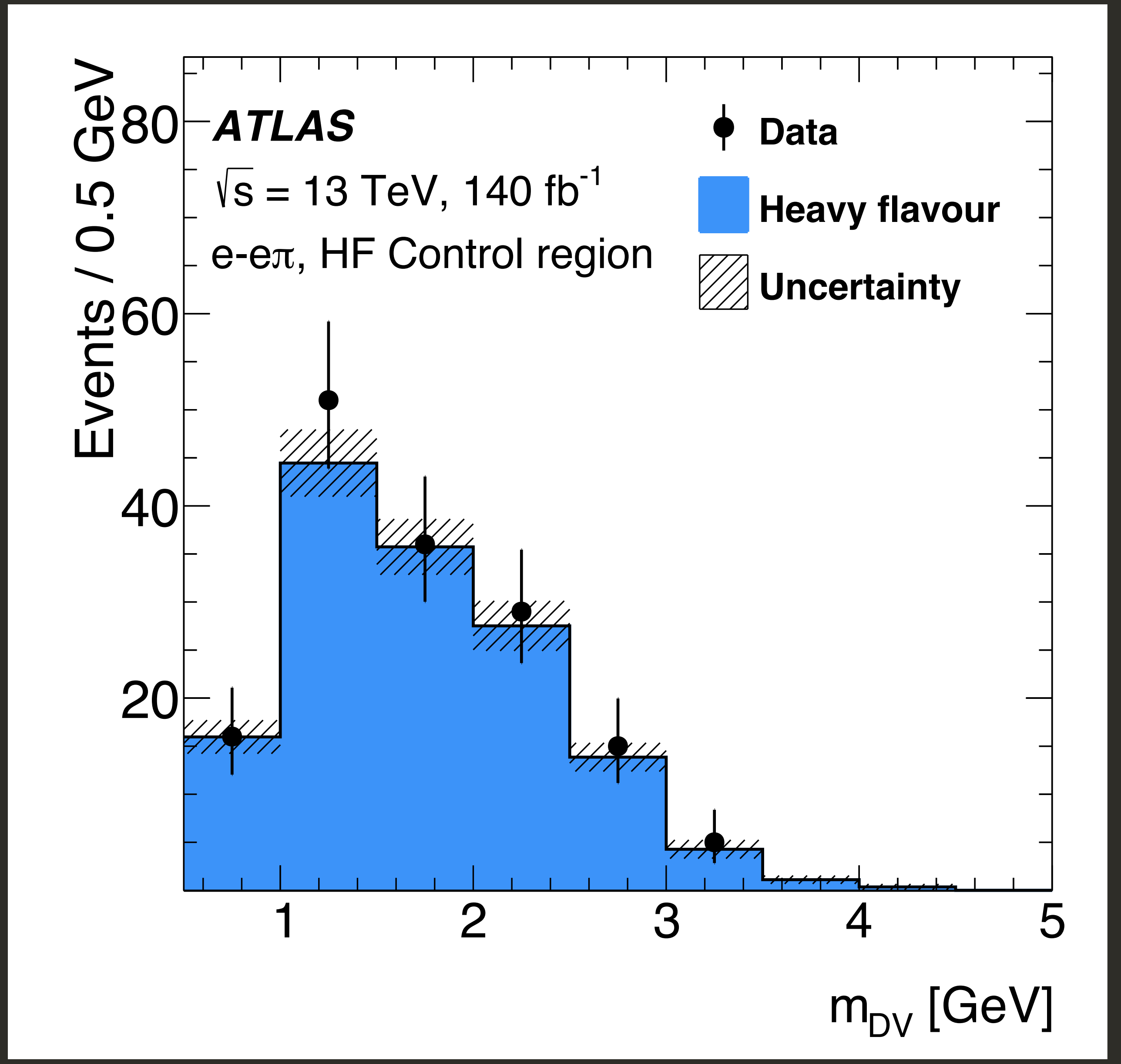
Control Regions

Background modeled using templates from SM MC ($t\bar{t}$ and V+jets) predictions.





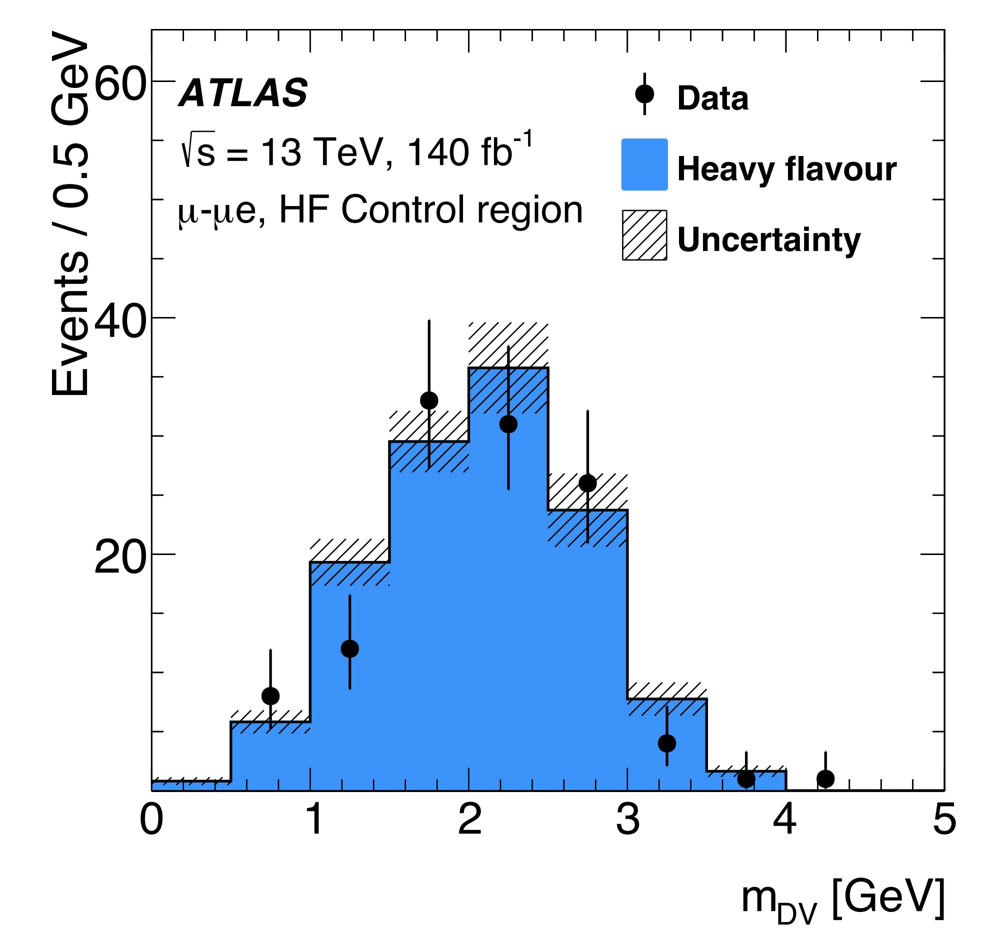


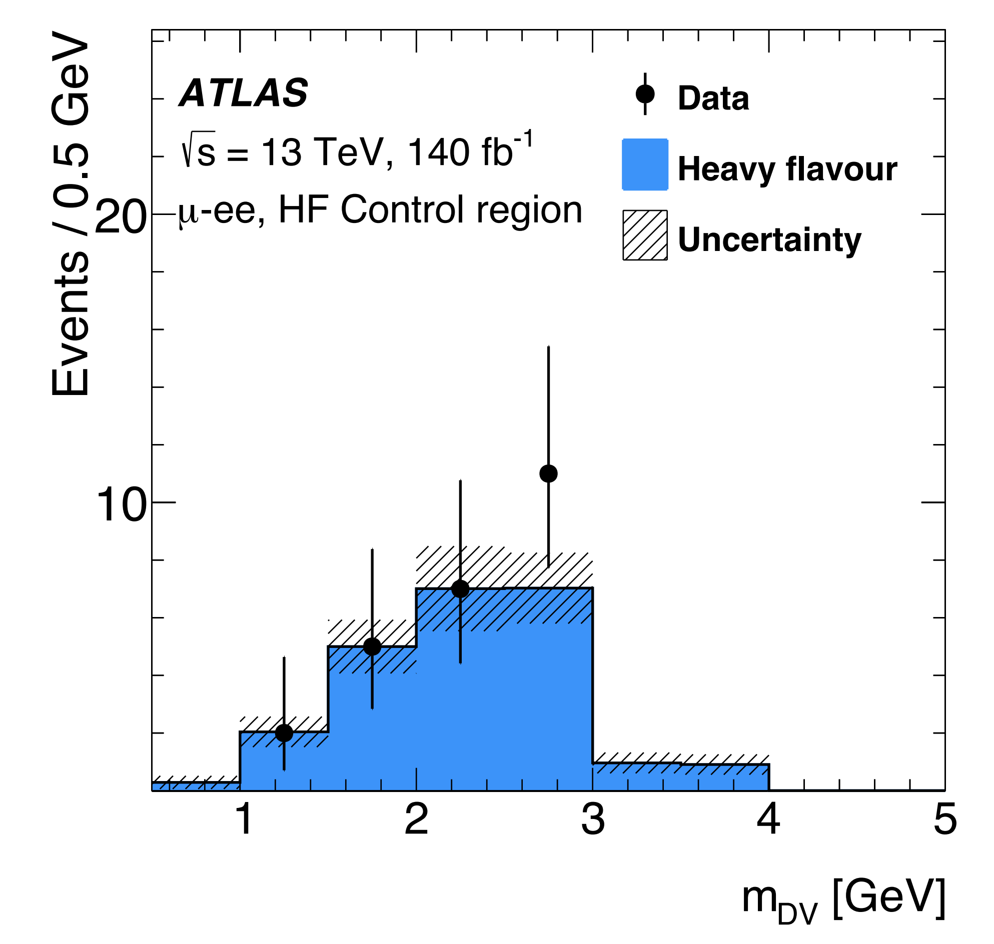


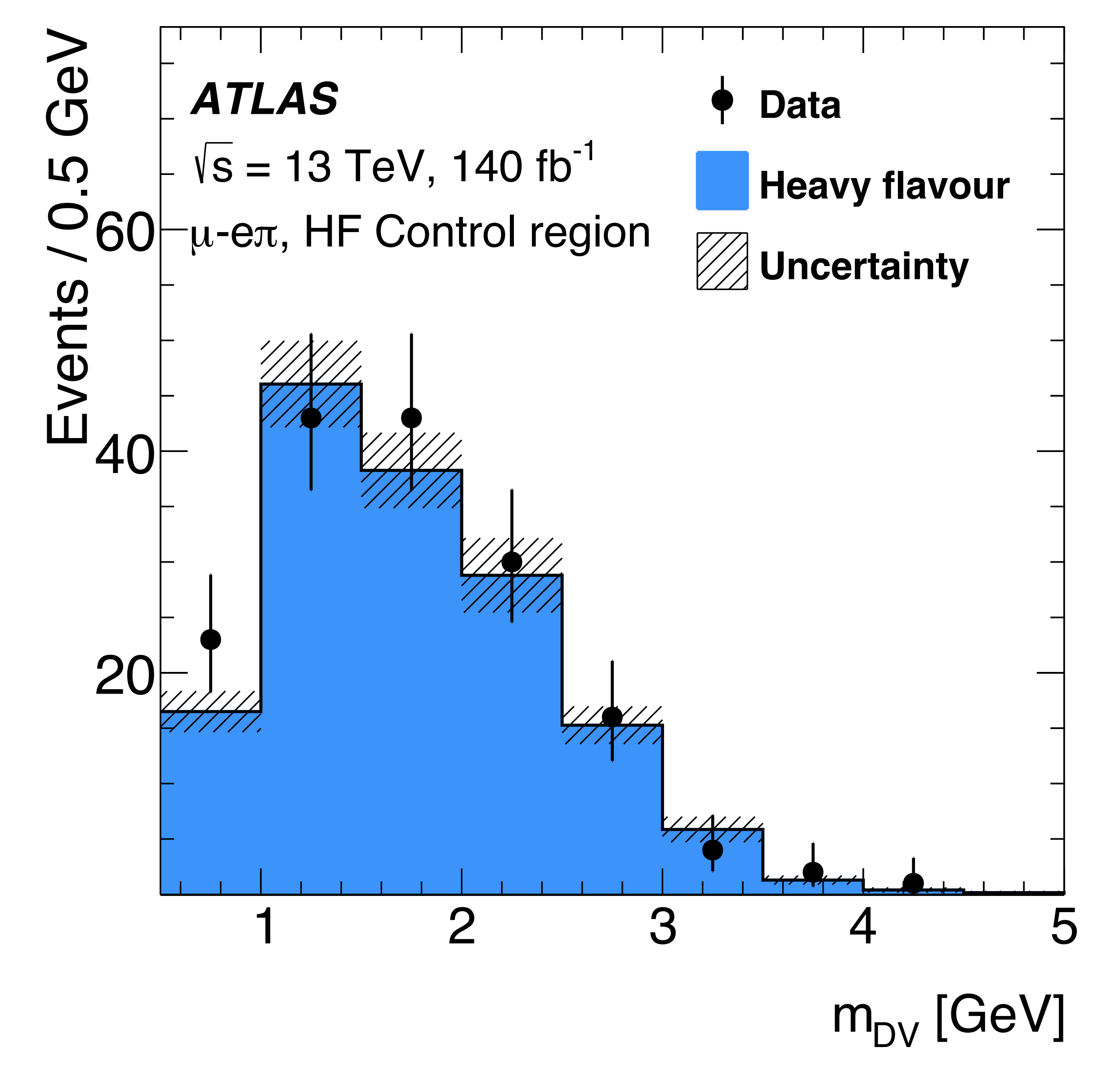
10 independent HF CRs with m_{DV} as the discriminant

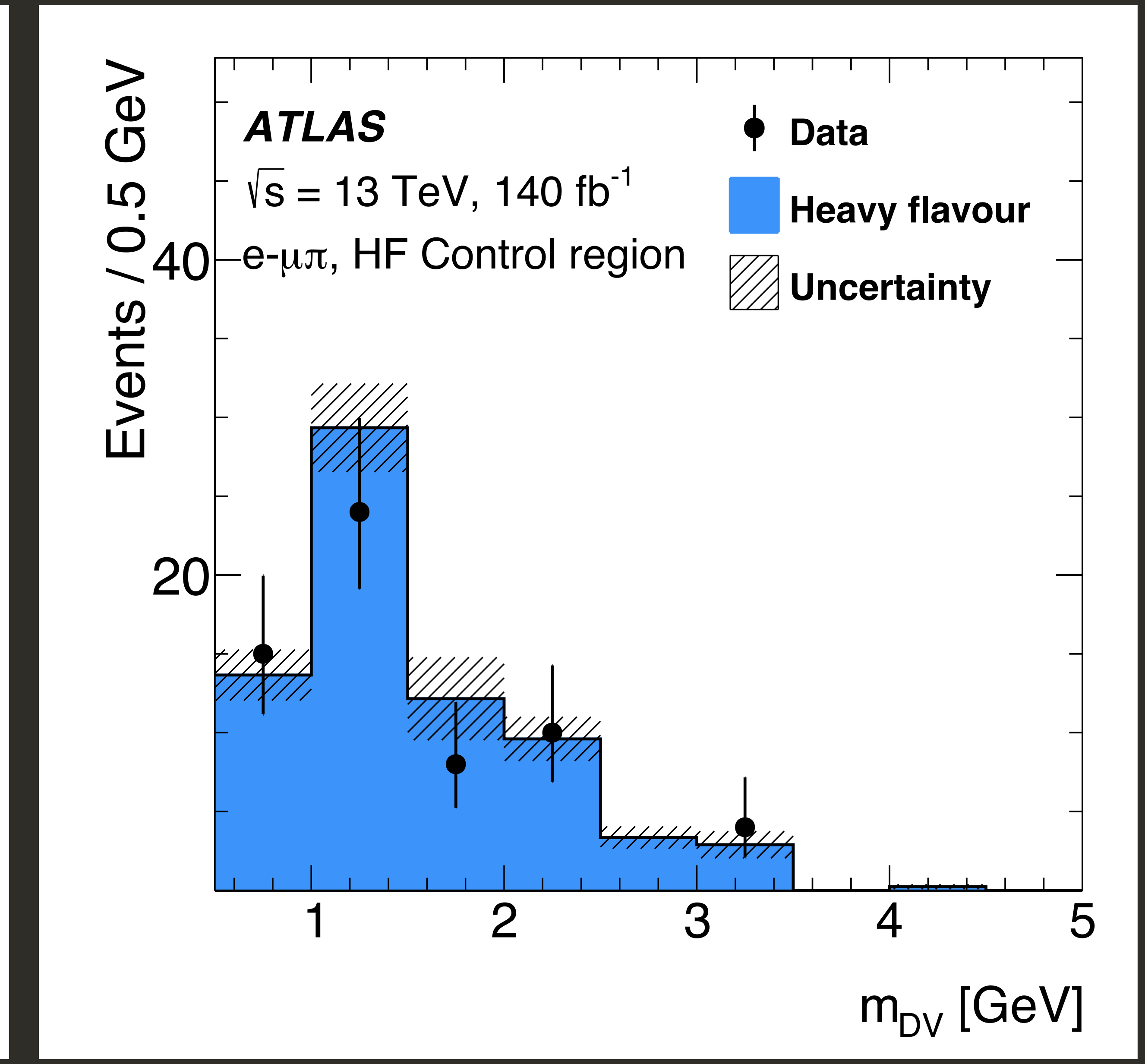
Heavy Neutral Leptons

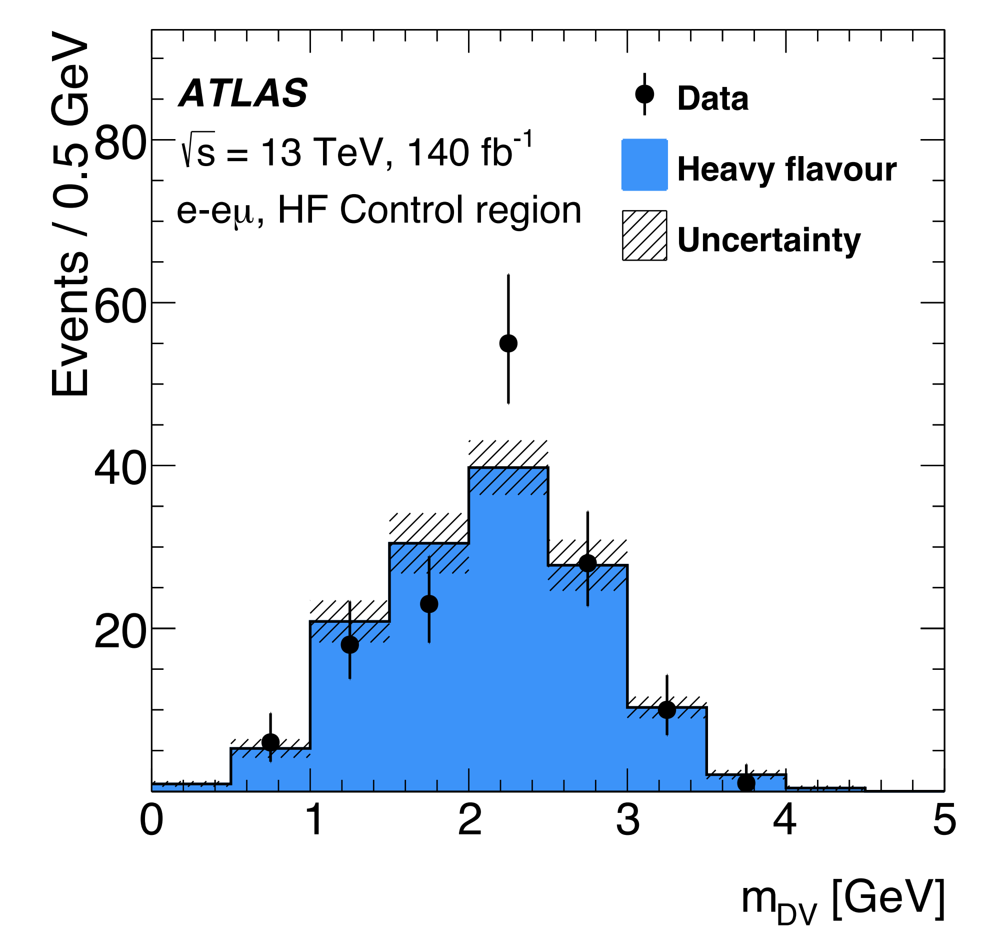
Control Regions

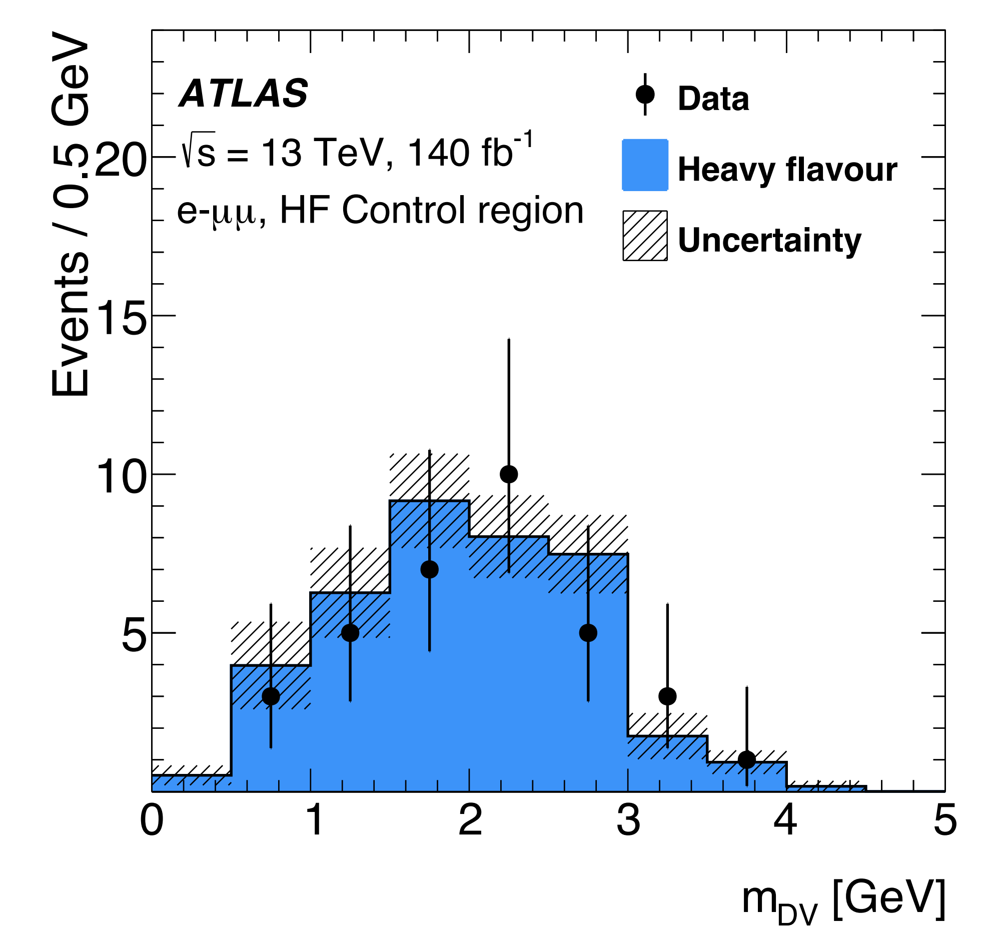












Heavy Neutral Leptons

Leptons from soft jets (or fakes)

	Leptonic Channels	**Semi-Leptonic Channels**
Signal Region (SR)	$40 < m_{\ell\ell\ell} < 90$ GeV 2 isolated displaced leptons b-jet veto	$70 < m_{\ell\ell\pi} < 90$ GeV 1 isolated displaced lepton b-jet veto
Heavy Flavor (HF) Control Region (CR)	$40 < m_{\ell\ell\ell} < 90$ GeV >=1 non-isolated displaced lepton >=1 b-tagged jet	$70 < m_{\ell\ell\pi} < 90$ GeV >=1 non-isolated displaced lepton >=1 b-tagged jet
Sideband CR	low $m_{\ell\ell\ell}$: $m_{\ell\ell\ell} < 40$ GeV high $m_{\ell\ell\ell}$: $m_{\ell\ell\ell} > 90$ GeV 2 isolated displaced leptons	low $m_{\ell\ell\pi}$: $m_{\ell\ell\pi} < 70$ GeV high $m_{\ell\ell\pi}$: $m_{\ell\ell\pi} > 90$ GeV 1 isolated displaced lepton
Isolation Relaxed Sideband CR	low $m_{\ell\ell\ell}$: $m_{\ell\ell\ell} < 40$ GeV high $m_{\ell\ell\ell}$: $m_{\ell\ell\ell} > 90$ GeV no isolation requirement	low $m_{\ell\ell\pi}$: $m_{\ell\ell\pi} < 70$ GeV high $m_{\ell\ell\pi}$: $m_{\ell\ell\pi} > 90$ GeV no isolation requirement

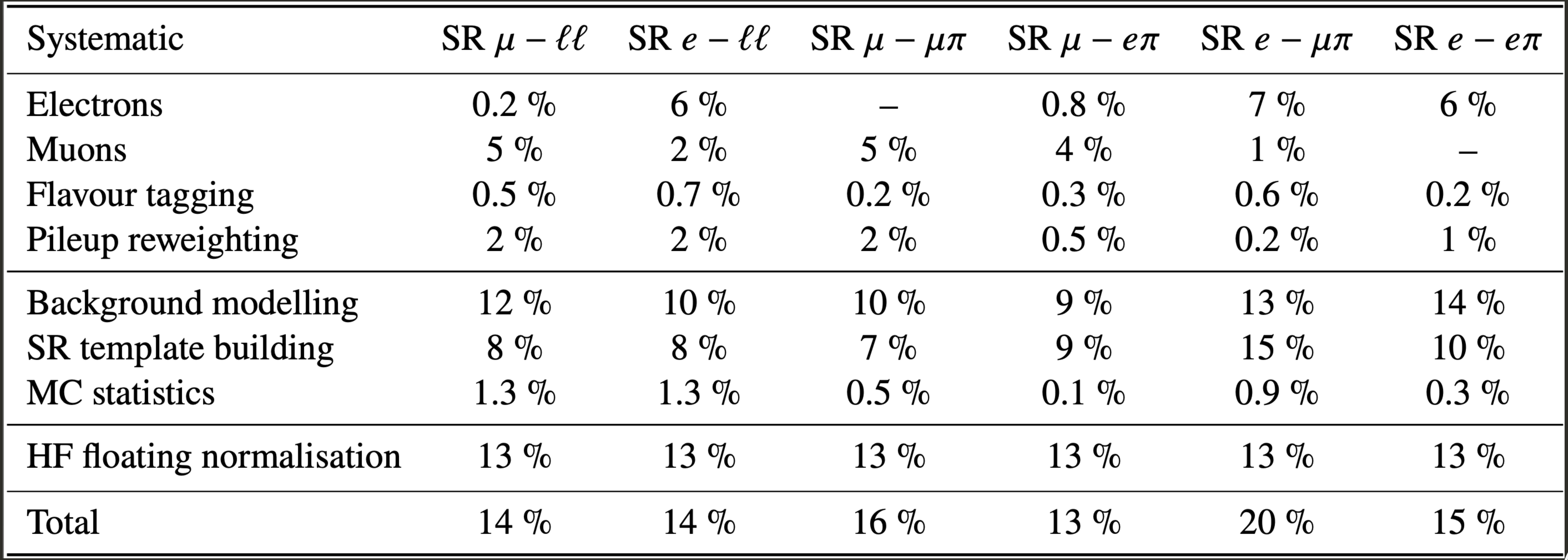
Heavy Neutral Leptons

Simultaneous Fit Structure

	μ–$\mu\mu$	μ–μe	μ–ee	μ–$\mu\pi$	μ–$e\pi$
μ	SR			SR	SR
	CR	CR	CR	CR	CR
e	e–$\mu\mu$	e–μe	e–ee	e–$\mu\pi$	e–$e\pi$
	SR			SR	SR
	CR	CR	CR	CR	CR

Heavy Neutral Leptons

Systematic Uncertainties

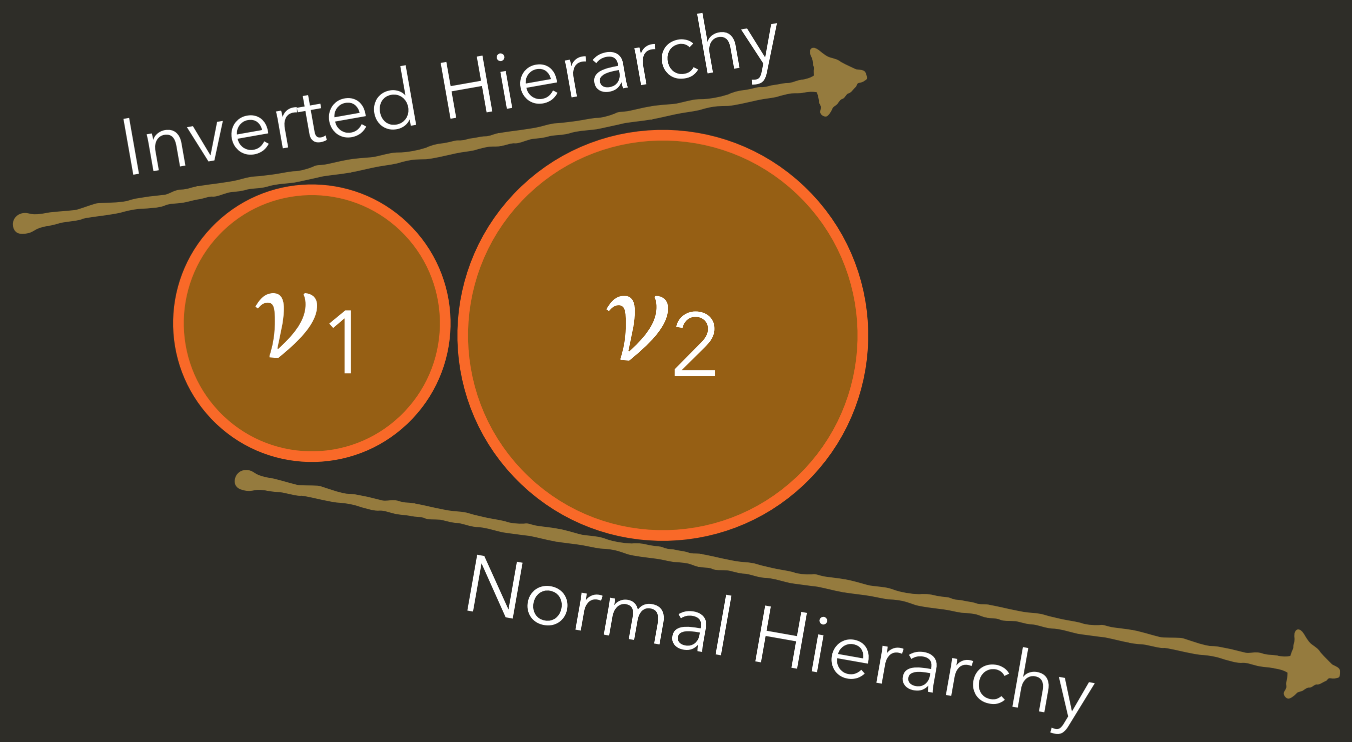


Systematic	SR $\mu-\ell\ell$	SR $e-\ell\ell$	SR $\mu-\mu\pi$	SR $\mu-e\pi$	SR $e-\mu\pi$	SR $e-e\pi$
Electrons	0.2 %	6 %	–	0.8 %	7 %	6 %
Muons	5 %	2 %	5 %	4 %	1 %	–
Flavour tagging	0.5 %	0.7 %	0.2 %	0.3 %	0.6 %	0.2 %
Pileup reweighting	2 %	2 %	2 %	0.5 %	0.2 %	1 %
Background modelling	12 %	10 %	10 %	9 %	13 %	14 %
SR template building	8 %	8 %	7 %	9 %	15 %	10 %
MC statistics	1.3 %	1.3 %	0.5 %	0.1 %	0.9 %	0.3 %
HF floating normalisation	13 %	13 %	13 %	13 %	13 %	13 %
Total	14 %	14 %	16 %	13 %	20 %	15 %

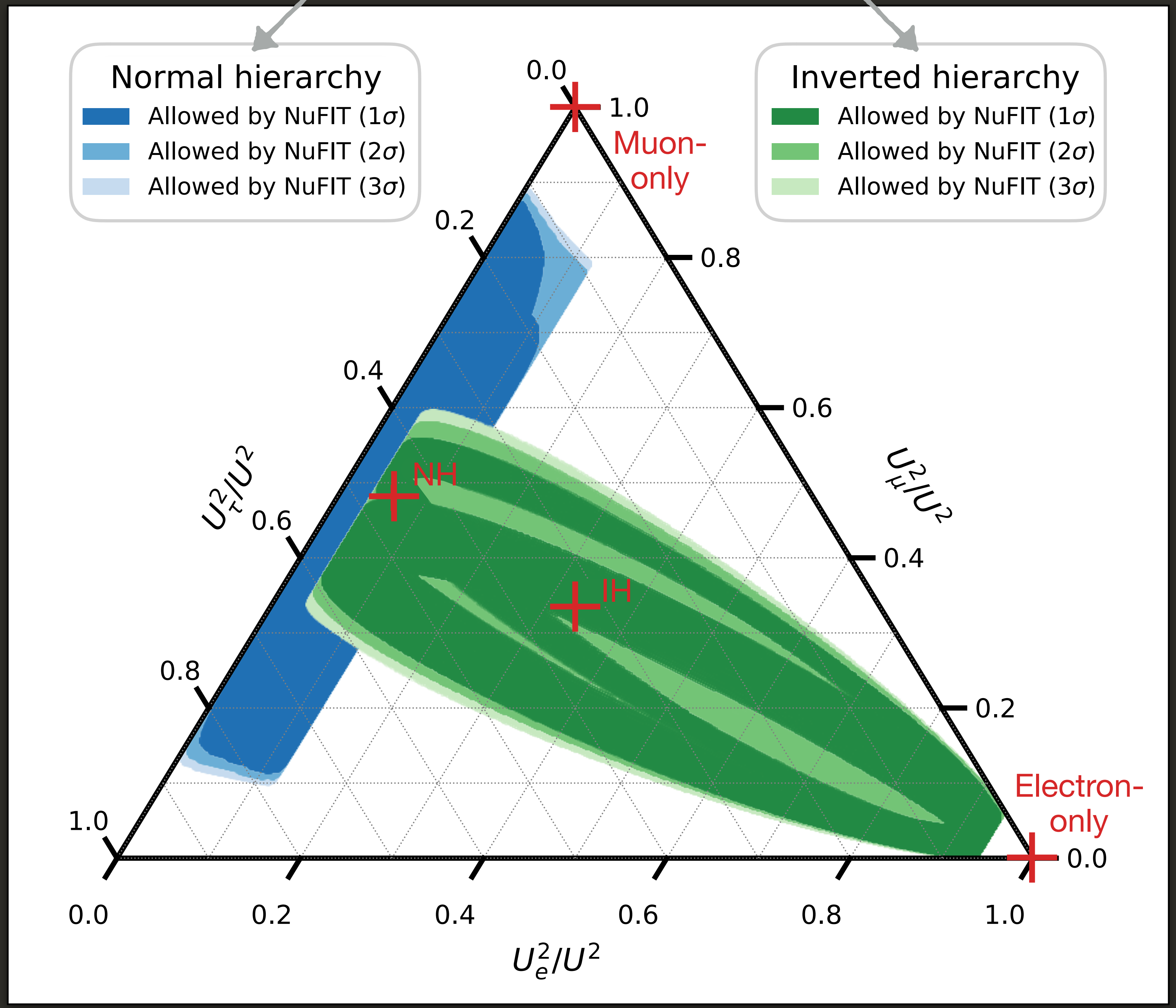
Heavy Neutral Leptons

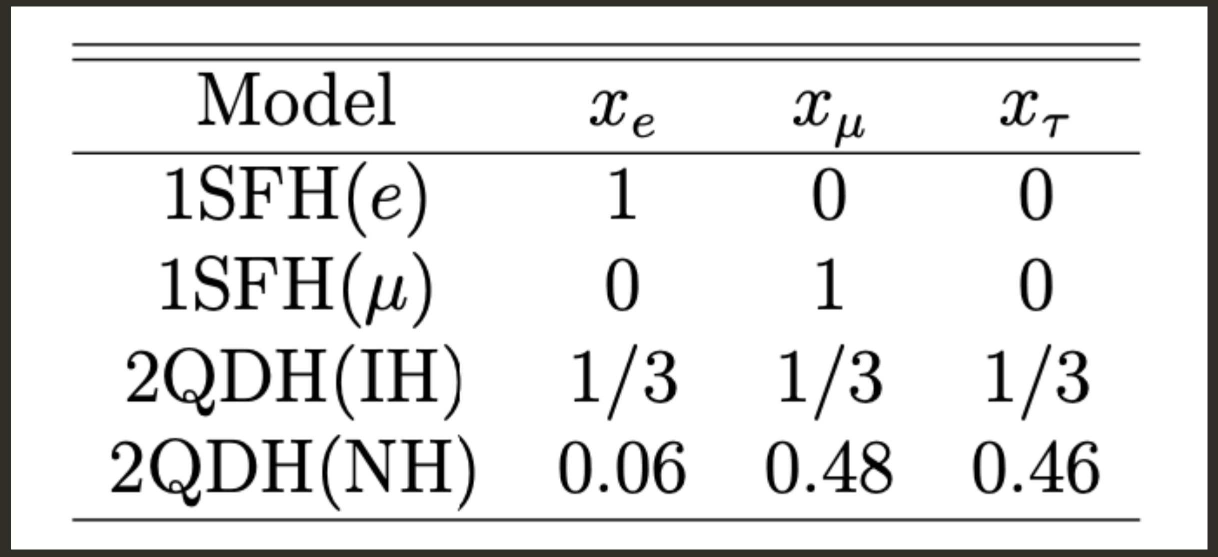
Benchmark Models

- Models with one or two HNLs:
  - One HNL with single-flavour mixing (1SFH)
  - Two quasi-degenerate HNLs (2QDH) with $m_1 \sim m_2$
- Four different mixing scenarios:
  - Muon-only mixing
  - Electron-only mixing
  - Inverted hierarchy (IH) multi-flavor mixing
  - Normal hierarchy (NH) multi-flavor mixing



“Realistic” multi-flavour mixing models consistent with neutrino oscillations data

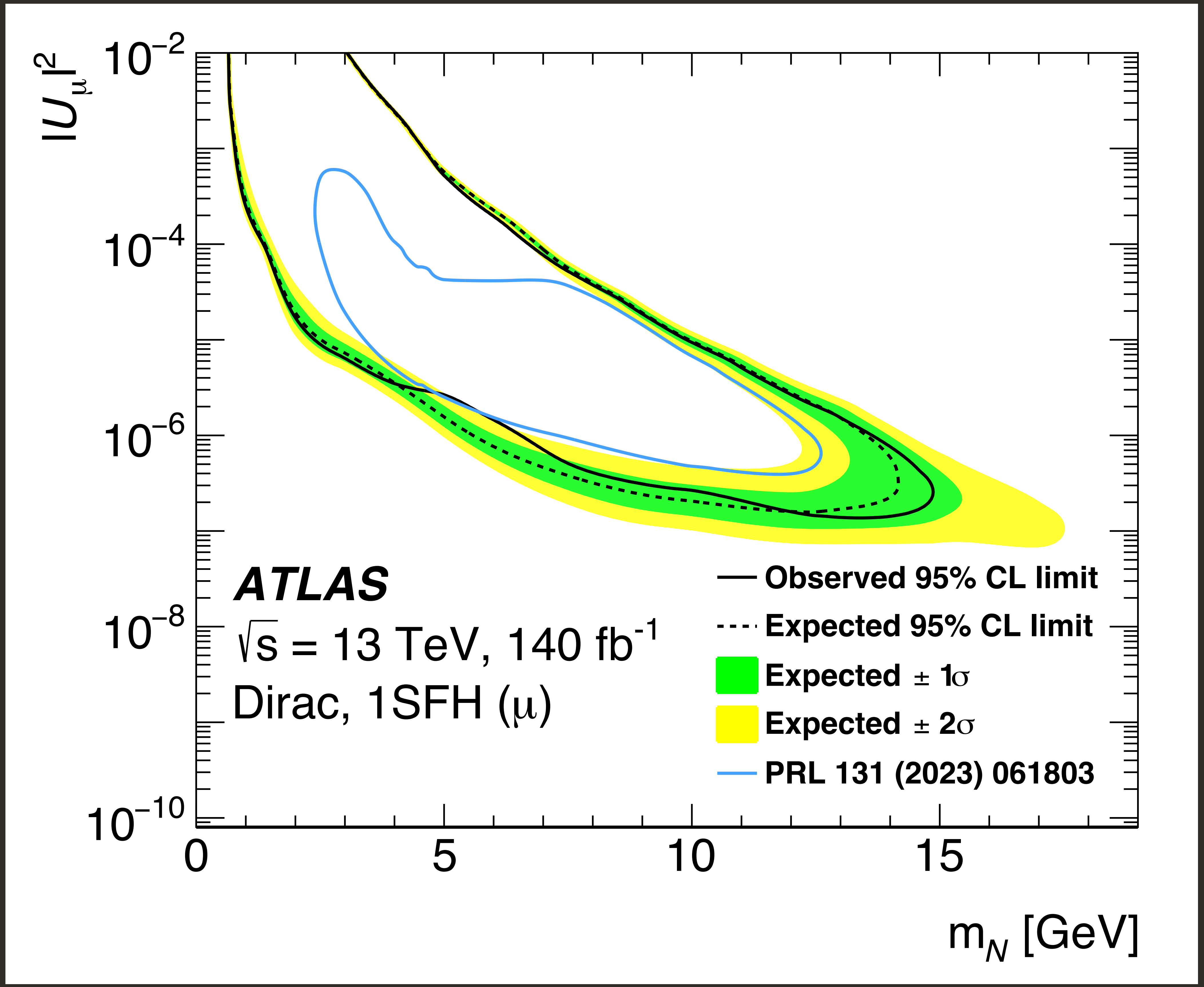


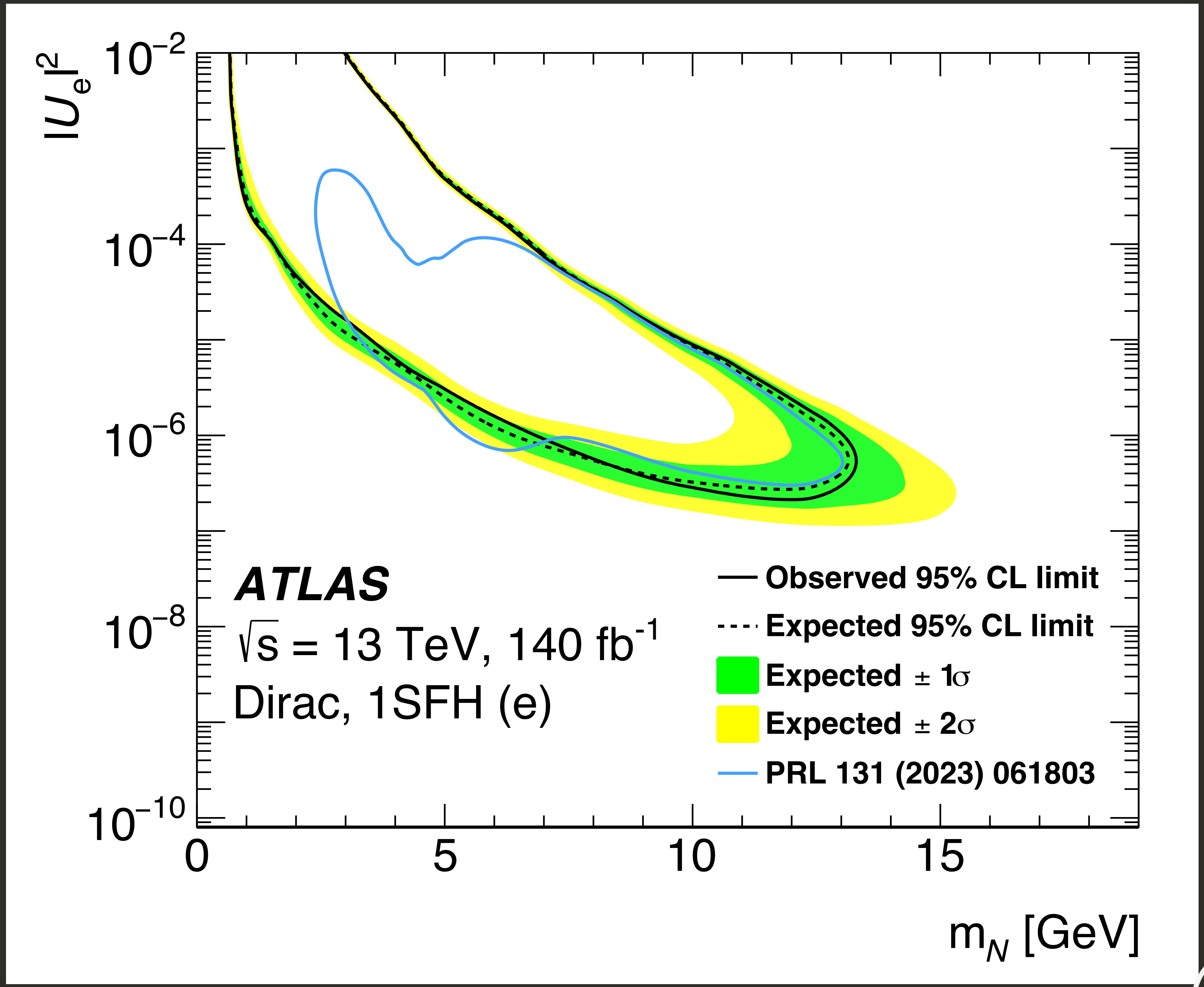


Model	x_e	x_μ	x_τ
1SFH(e)	1	0	0
1SFH(μ)	0	1	0
2QDH(IH)	1/3	1/3	1/3
2QDH(NH)	0.06	0.48	0.46

Heavy Neutral Leptons

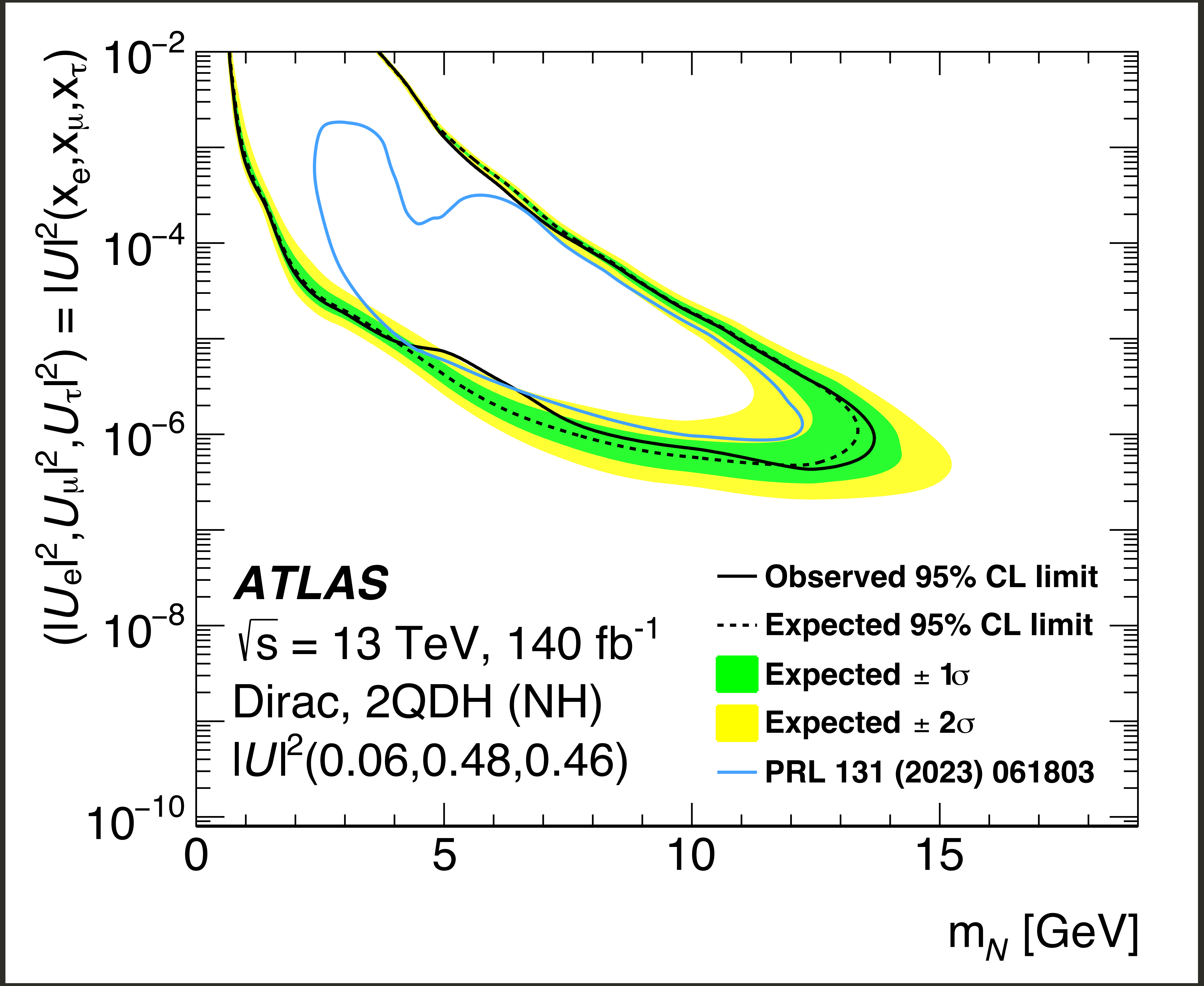
Dirac HNL Single Flavor Mixing

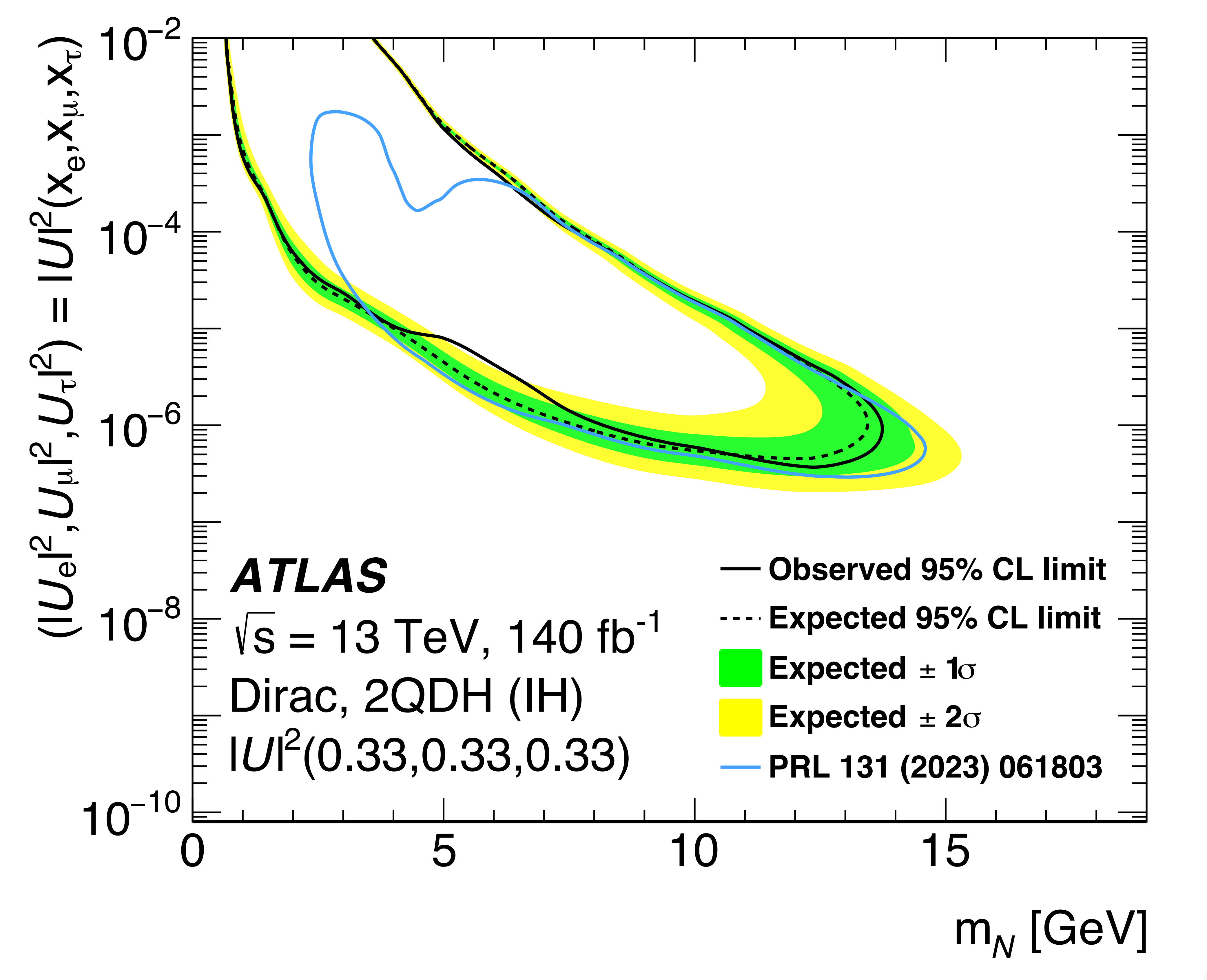




Heavy Neutral Leptons

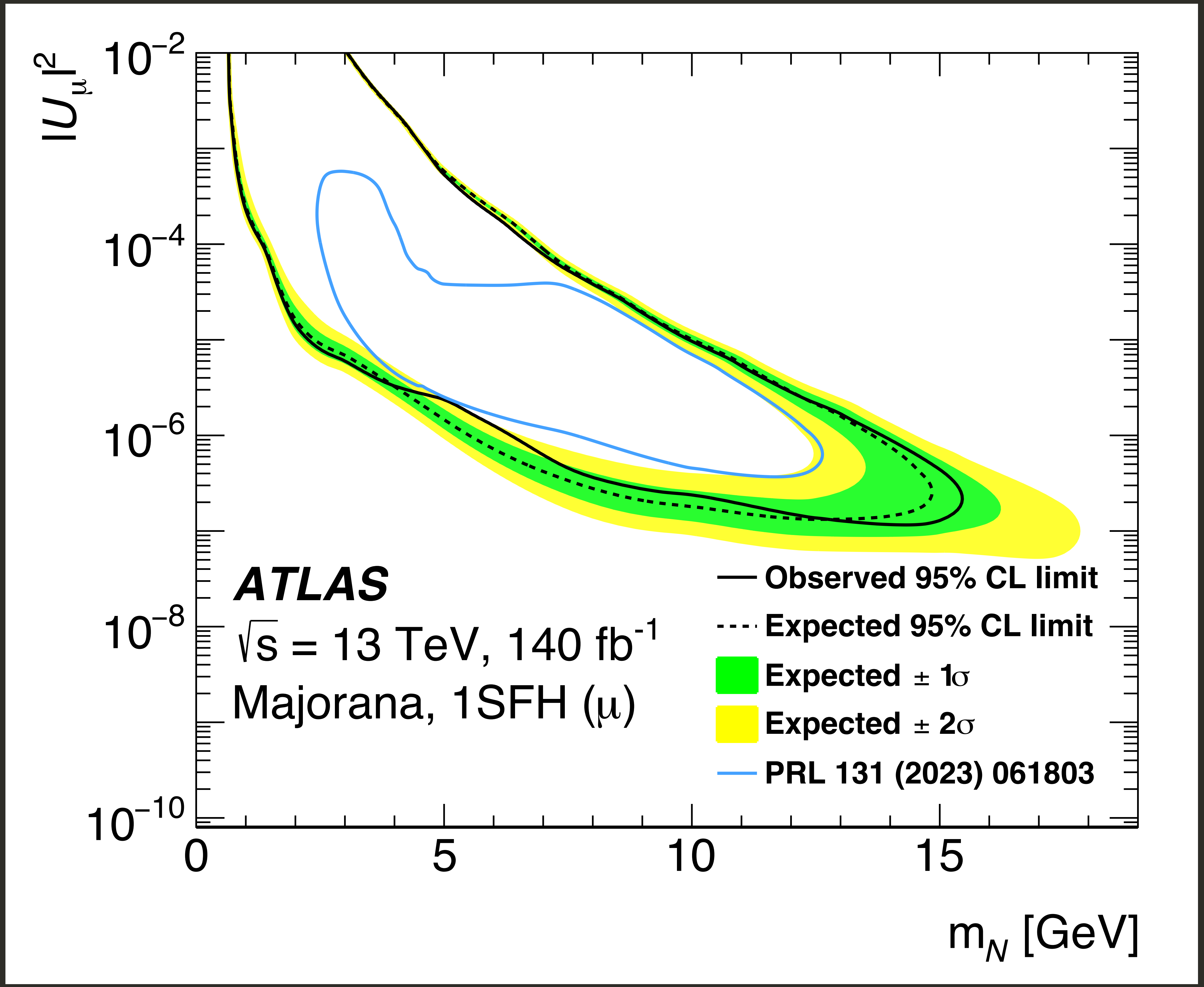
Dirac HNL Multi-Flavor Mixing

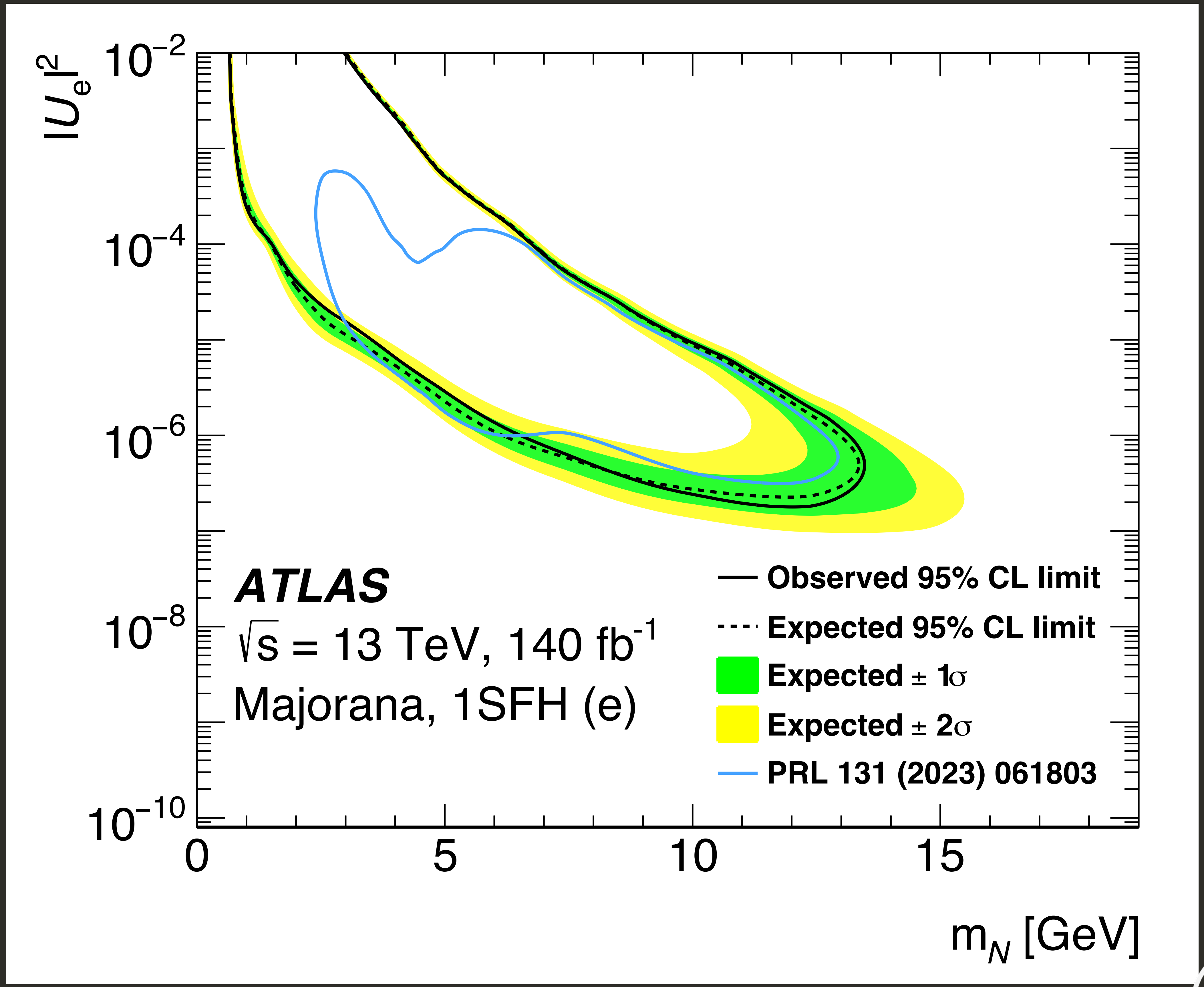




Heavy Neutral Leptons

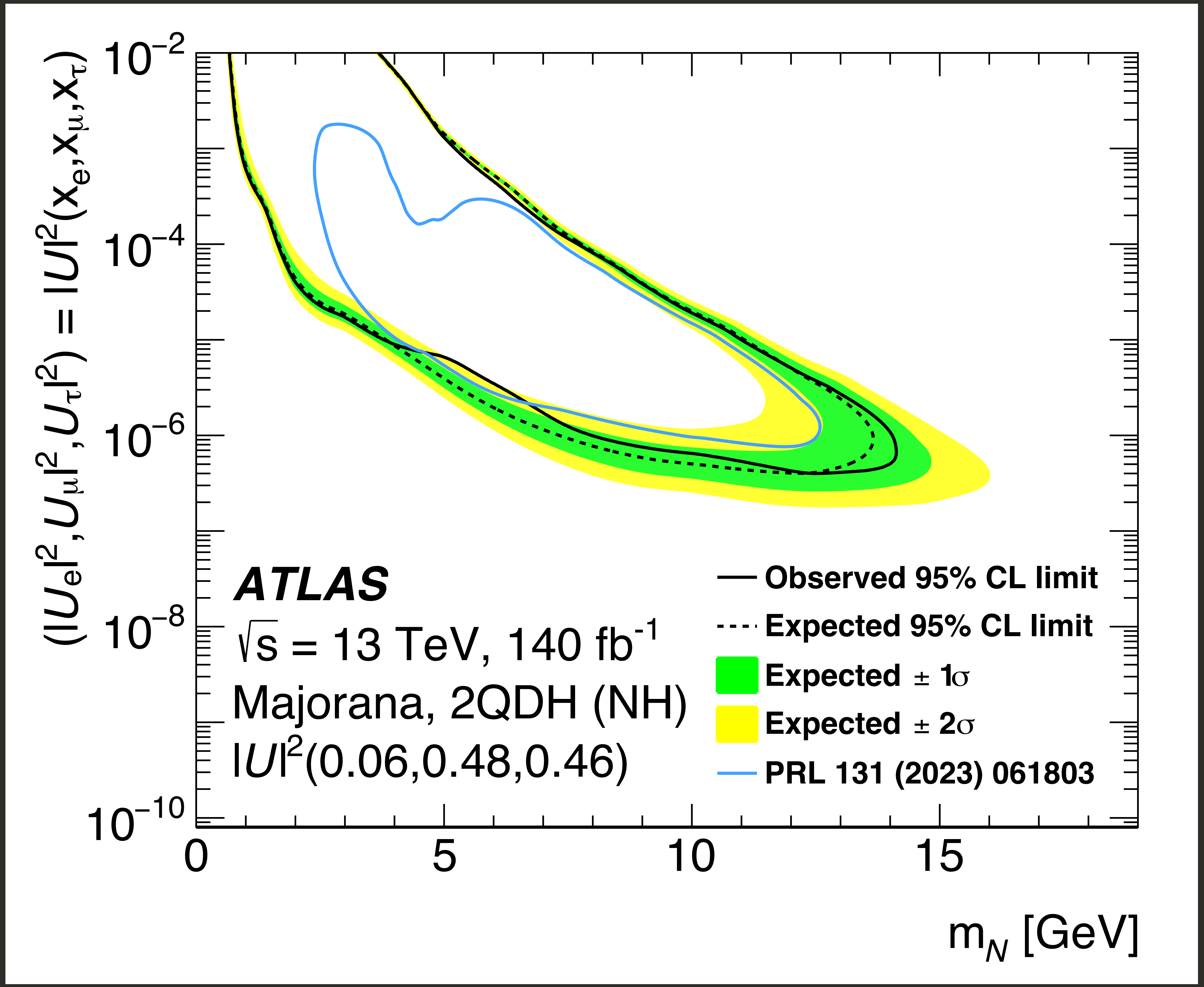
Majorana HNL Single Flavor Mixing

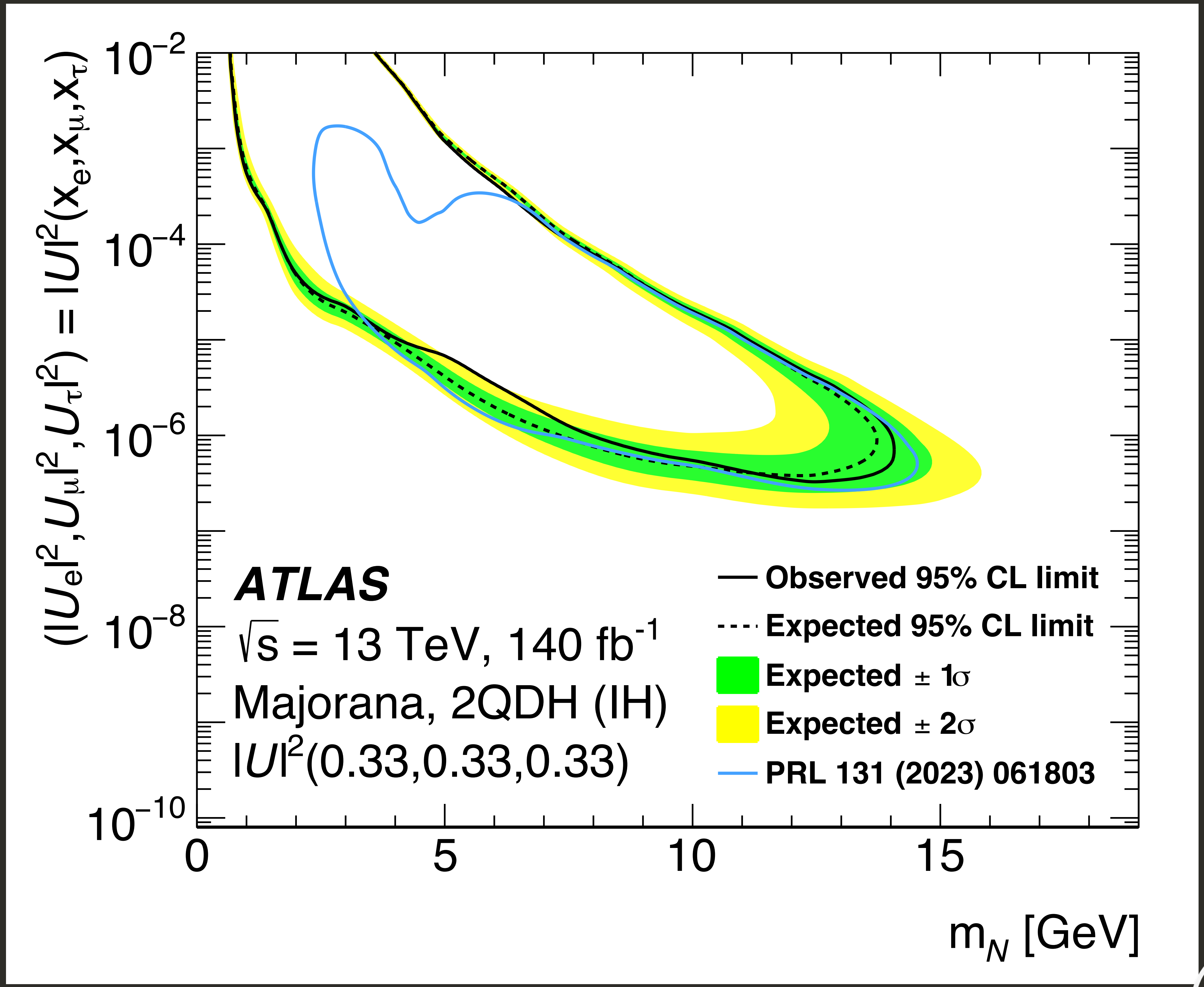




Heavy Neutral Leptons

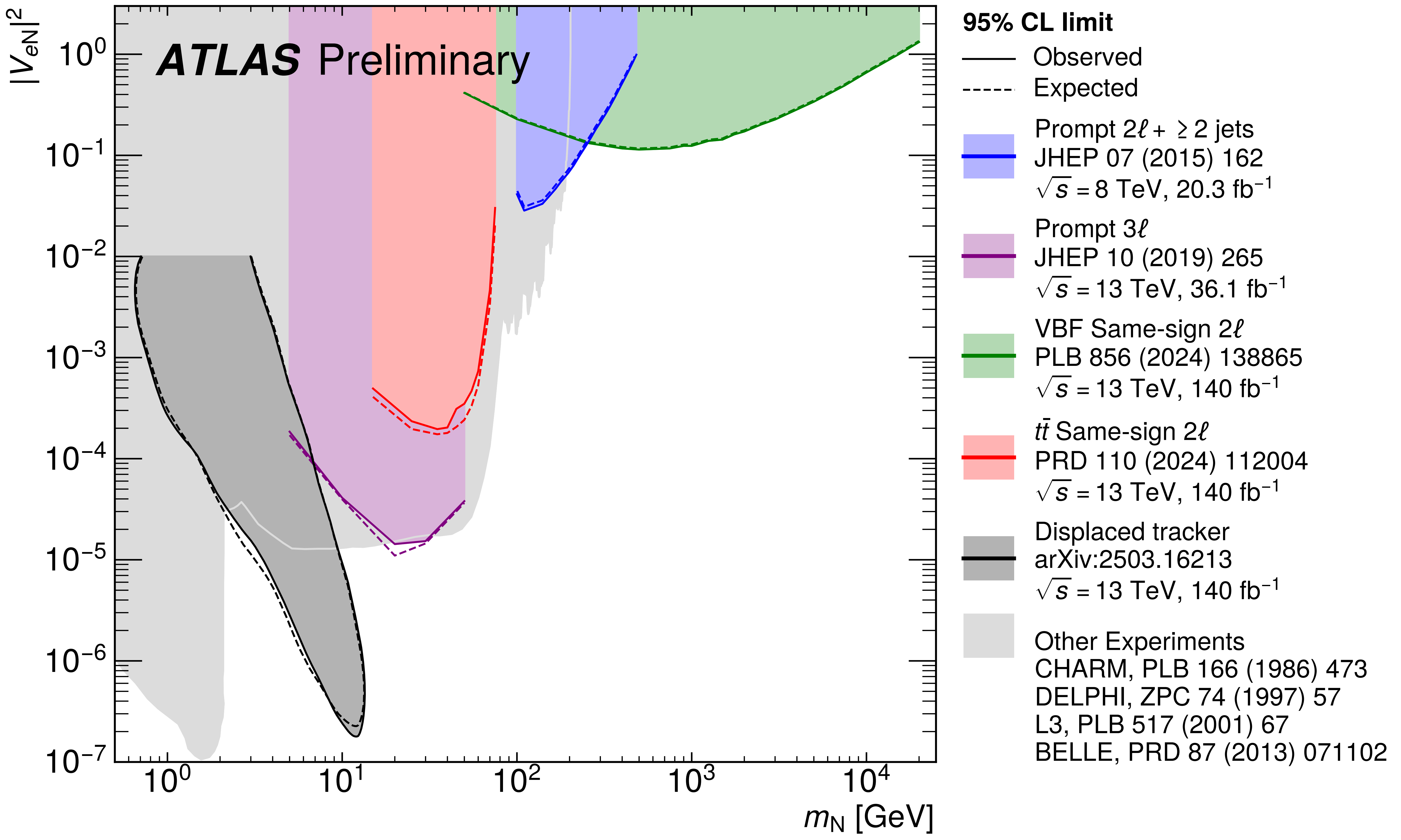
Majorana HNL Multi-Flavor Mixing





Heavy Neutral Leptons

Majorana HNL e-only Mixing Summary



Jets in the Muon System

DV Reconstruction Efficiency