Displaced Vertex Search for Heavy Neutral Leptons using the ATLAS Detector

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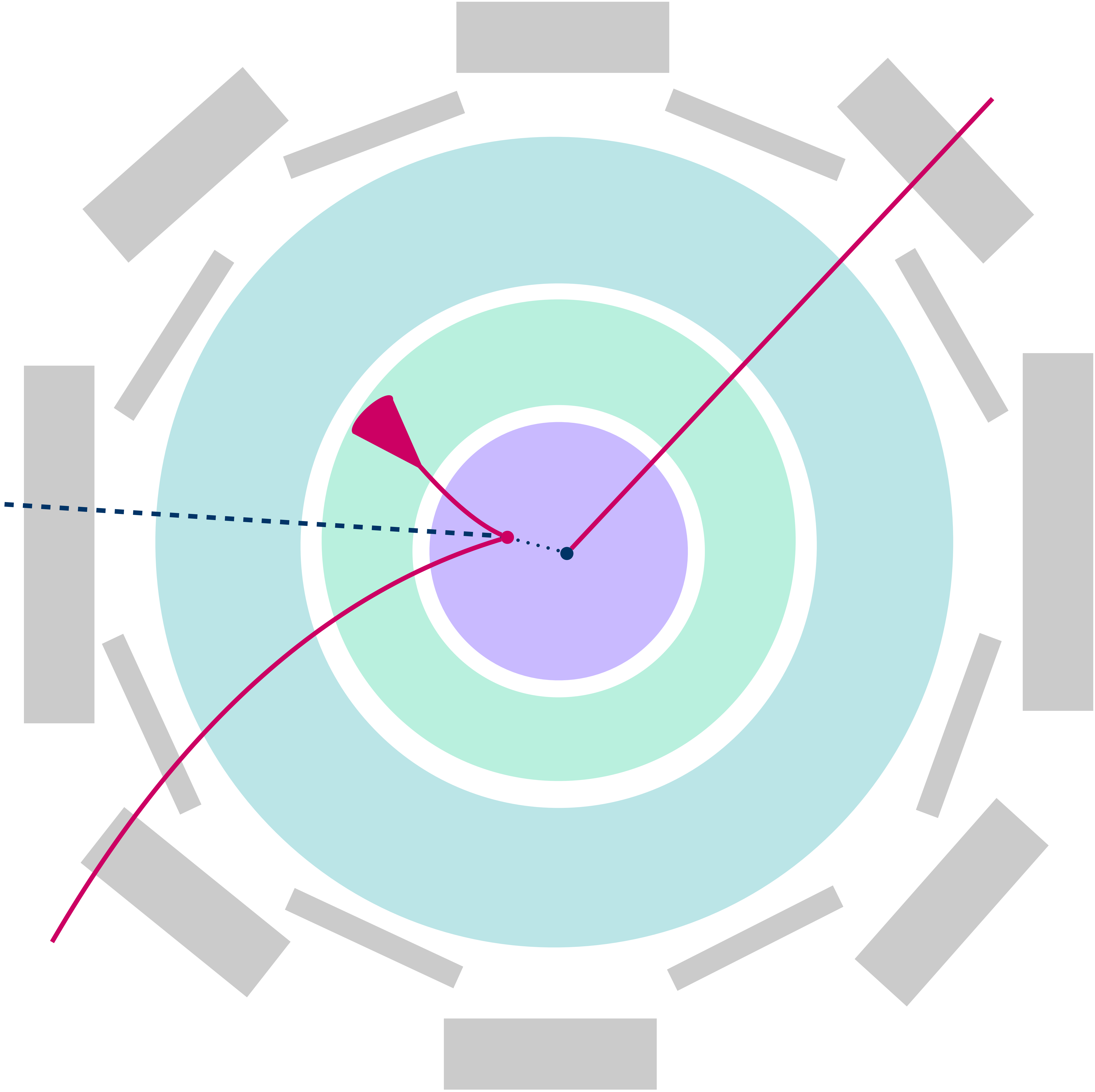
Brandeis University/ University of British Columbia

Canadian Association of Physicists
PPD Division Thesis Prize Talk
June 6, 2022



Acknowledgements — Thank you!

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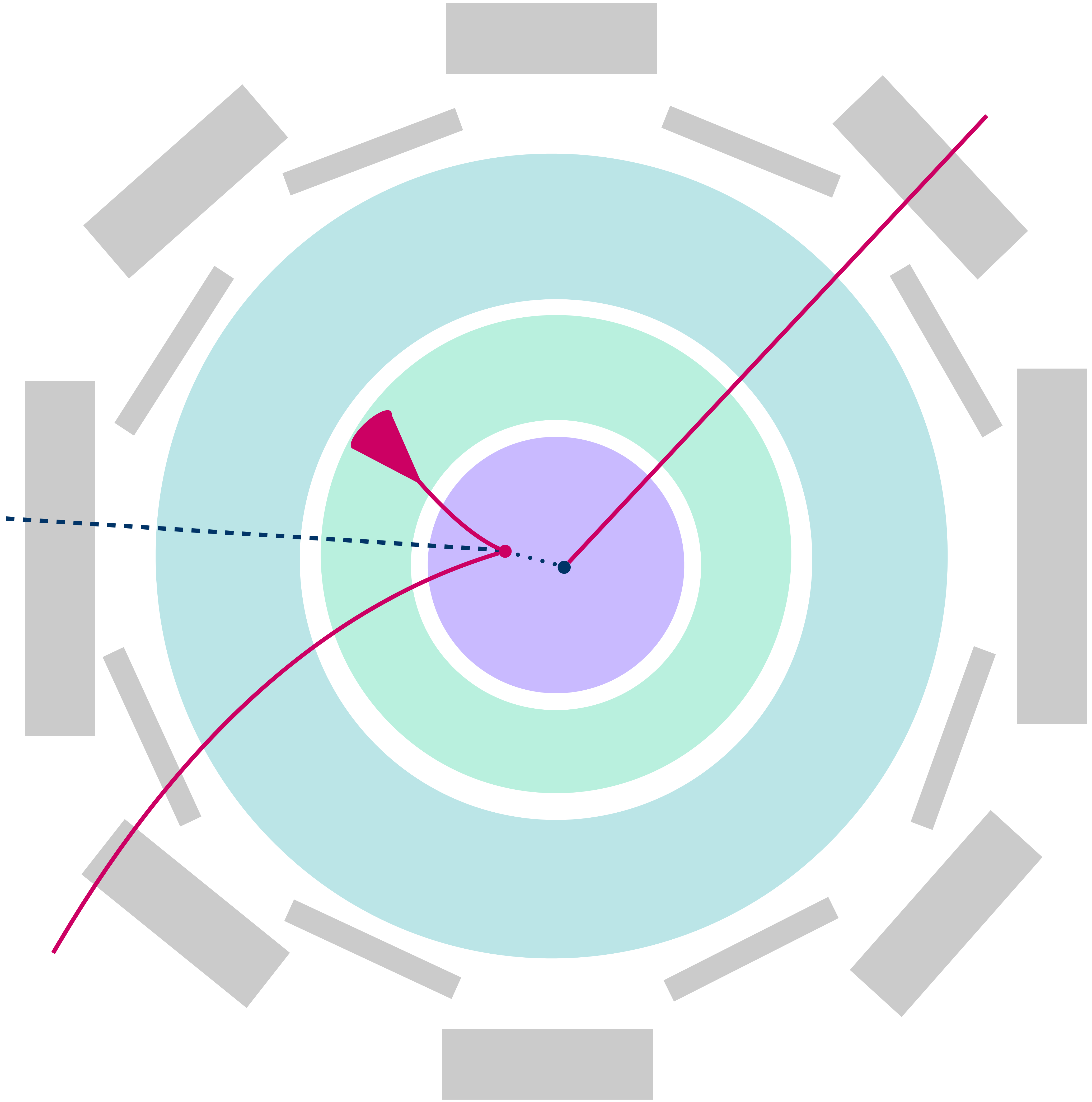
Outline

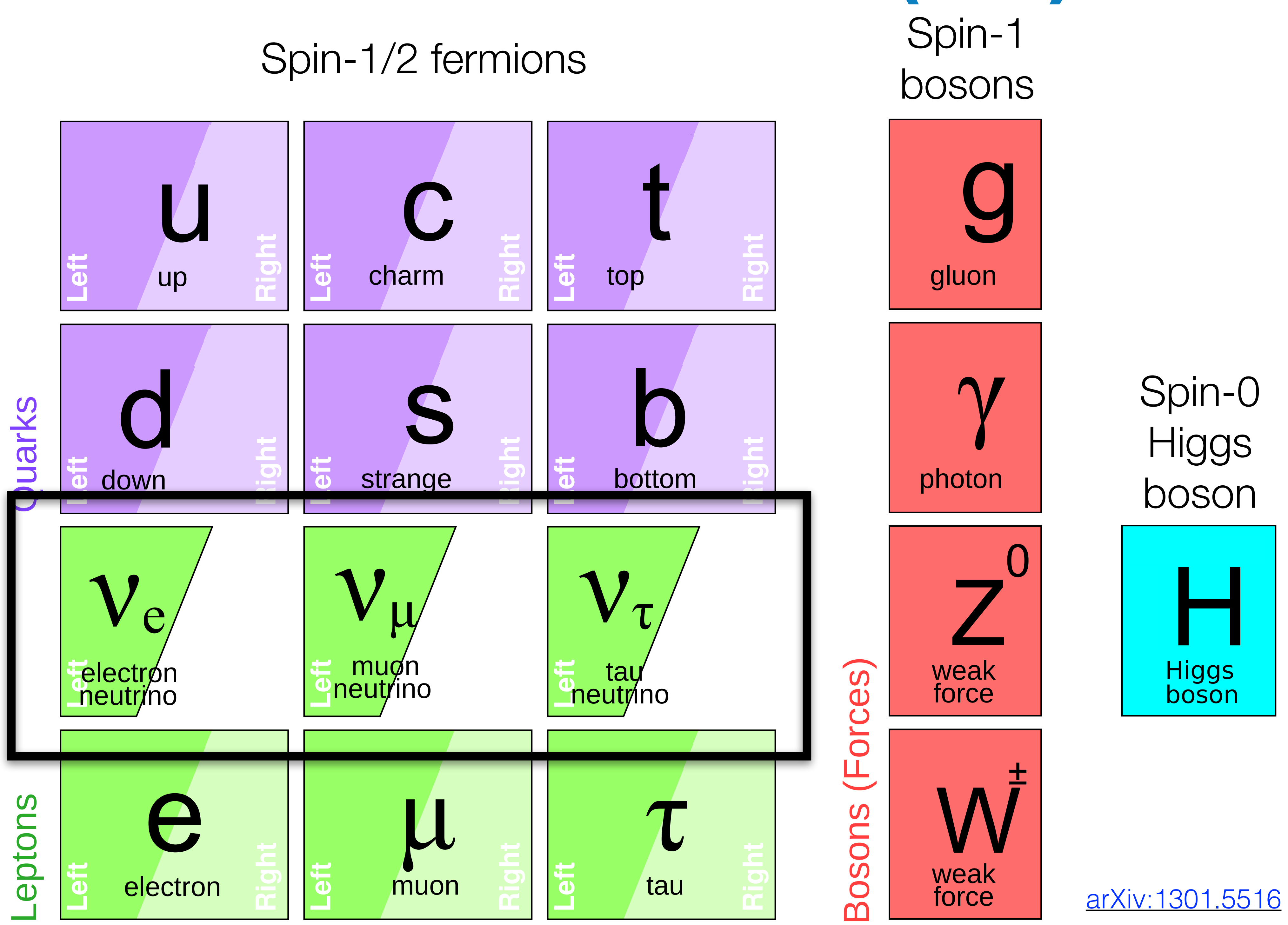


Displaced Vertex Search for Heavy Neutral Leptons

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

Heavy Neutral Leptons

The Standard Model (SM)

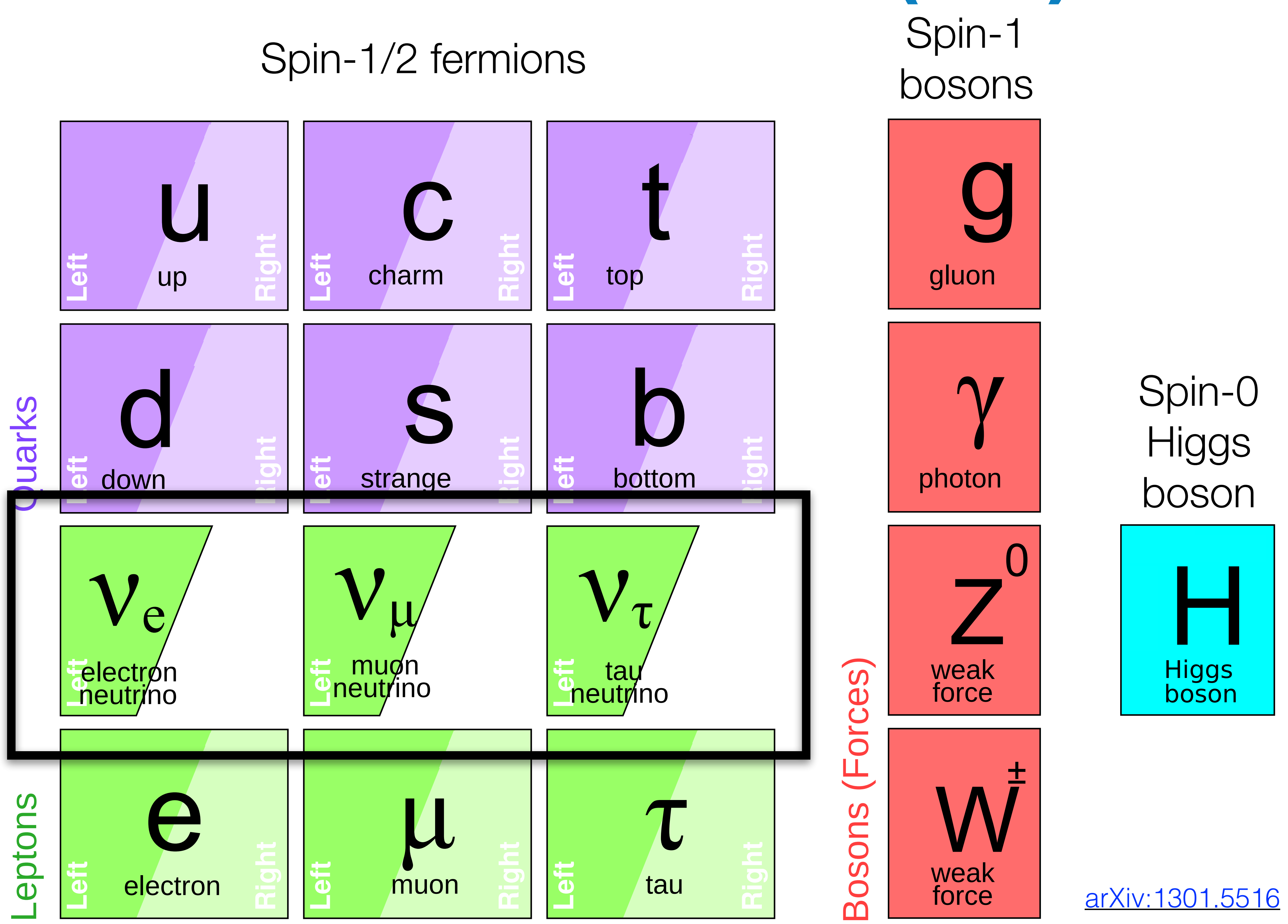


arXiv:1301.5516

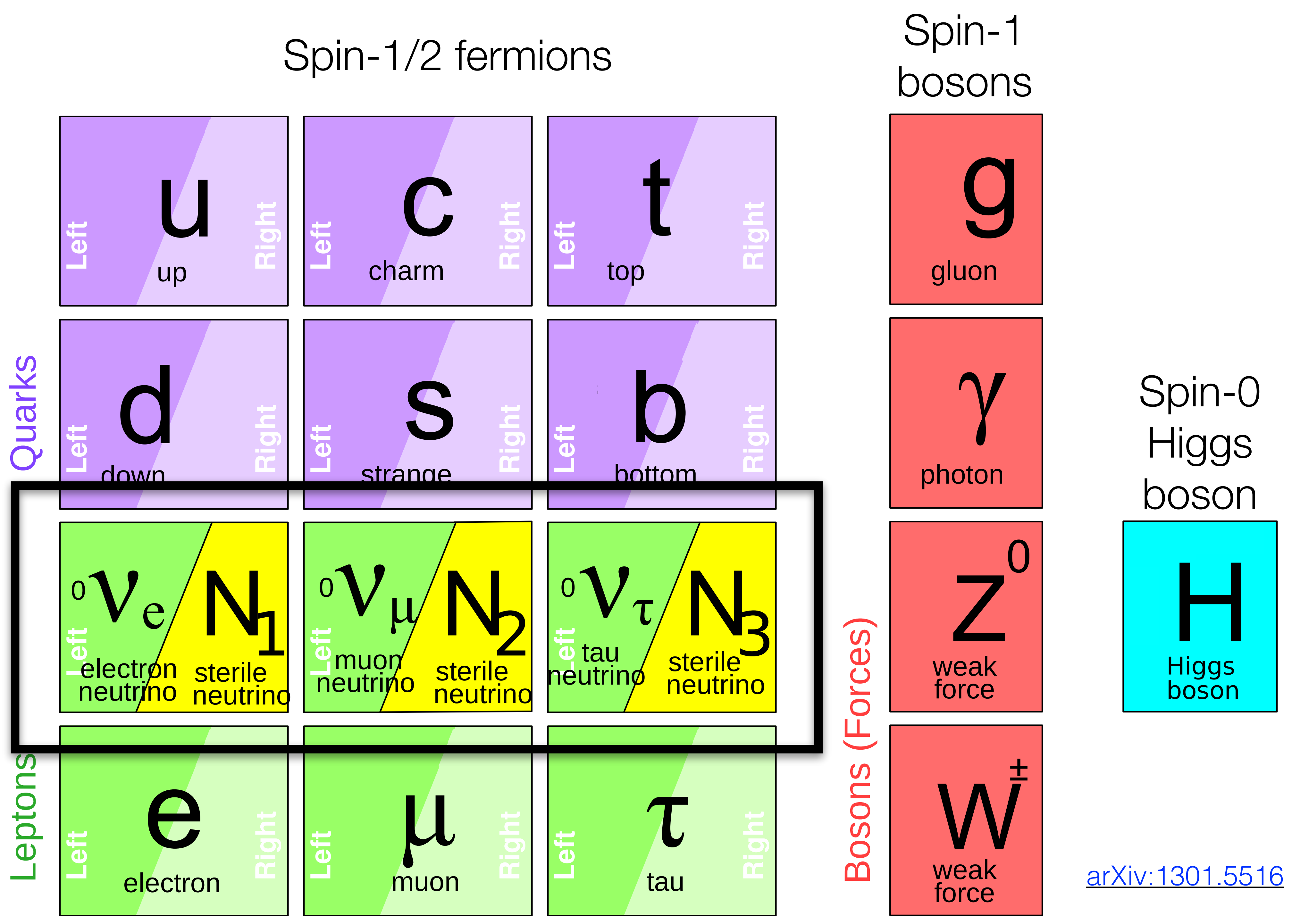
- Best-known description of fundamental particles and their interactions (except gravity)
- Neutrino oscillations suggest $m_\nu > 0$
- Non-zero m_ν is not included in SM

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 m_ν is not included in SM

- Introduce right-handed sterile neutrino states or **heavy neutral leptons (HNL)**

Motivation for HNLs

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

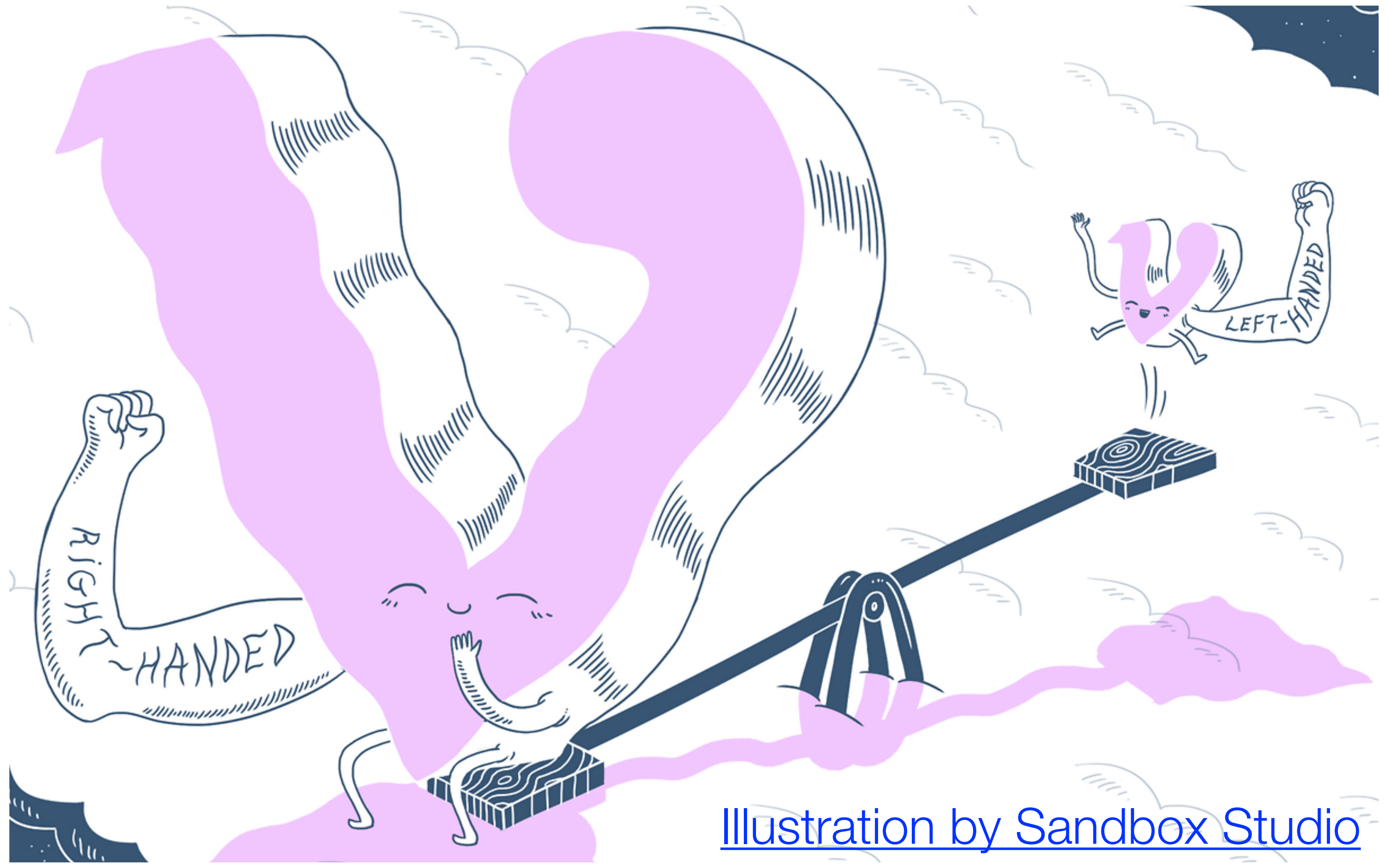
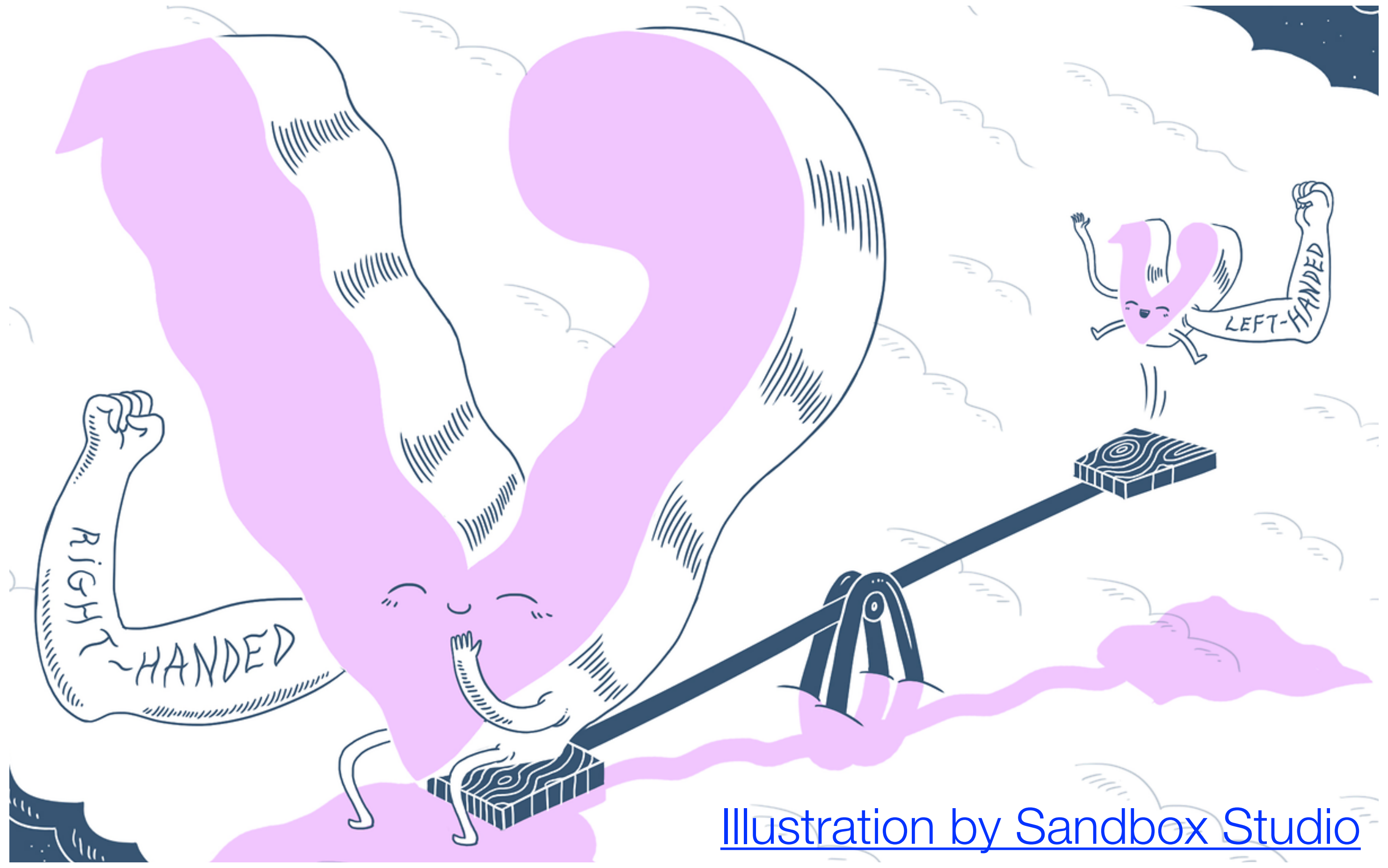


Illustration by Sandbox Studio

Motivation for HNLs



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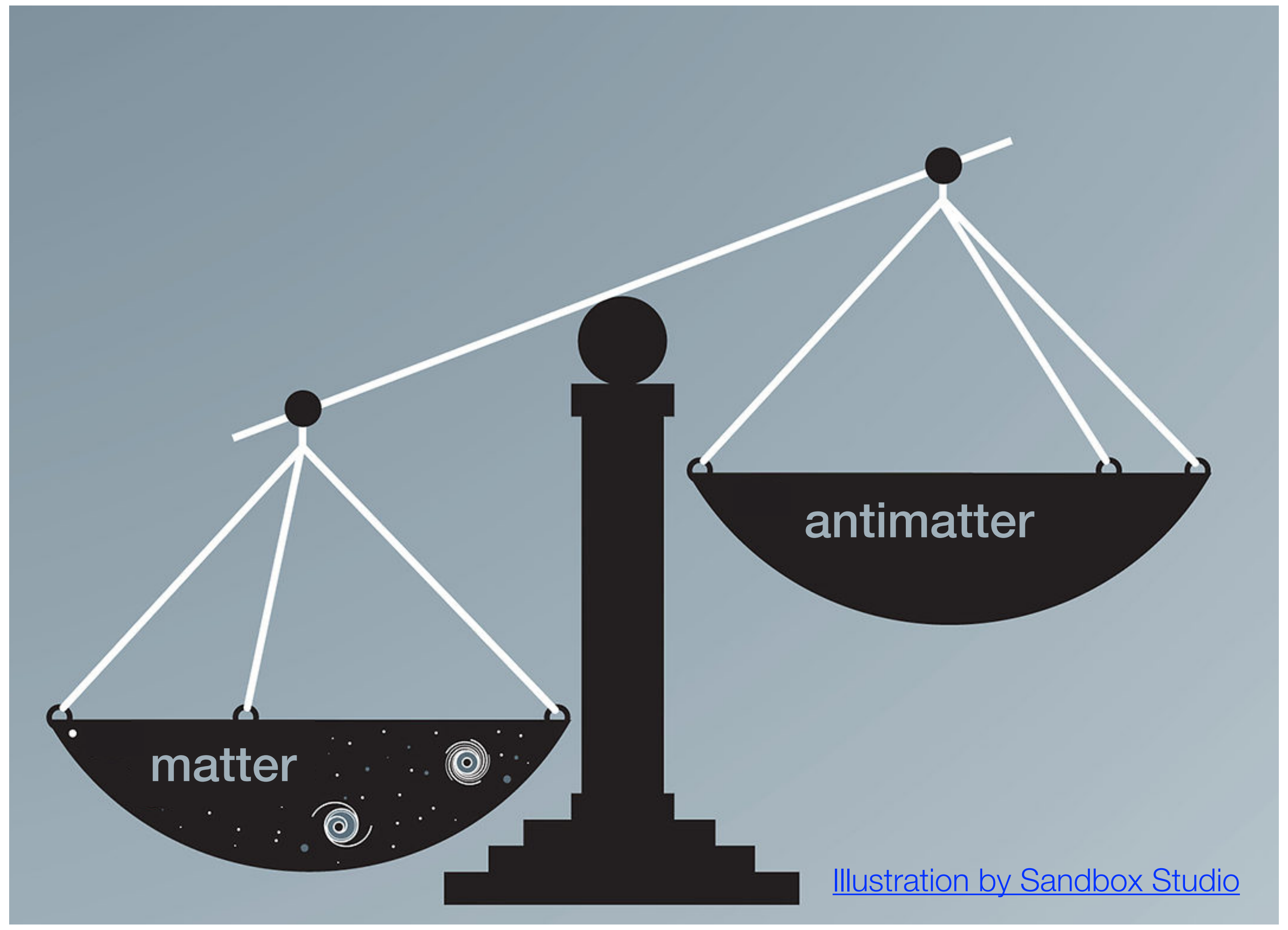


2. **Matter-antimatter asymmetry of the universe**

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

Motivation for HNLs

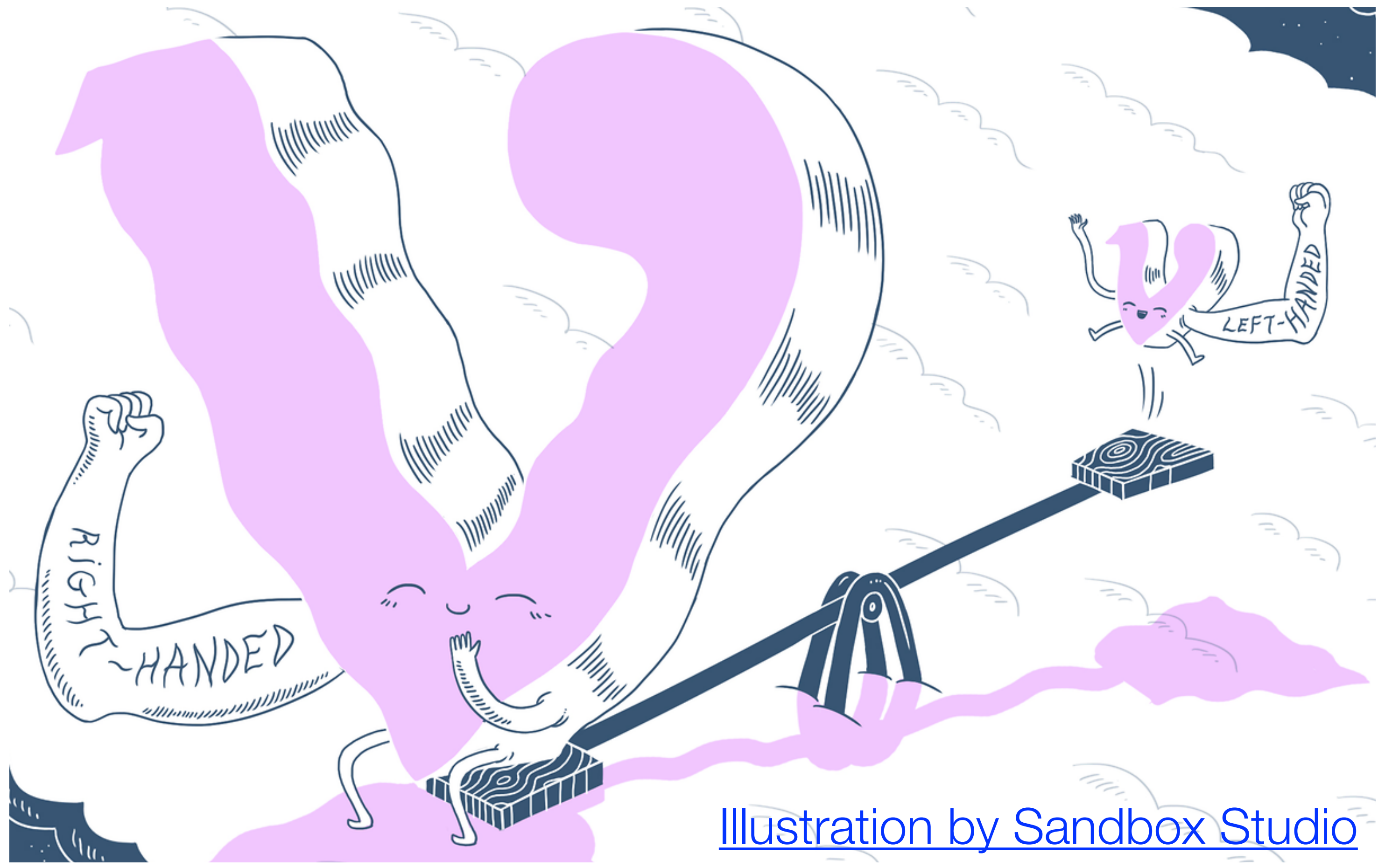


Illustration by Sandbox Studio

1. Origin of neutrino masses

- Type-I seesaw mechanism: $m_\nu \simeq \frac{v^2}{2} Y m_N^{-1} Y^T$

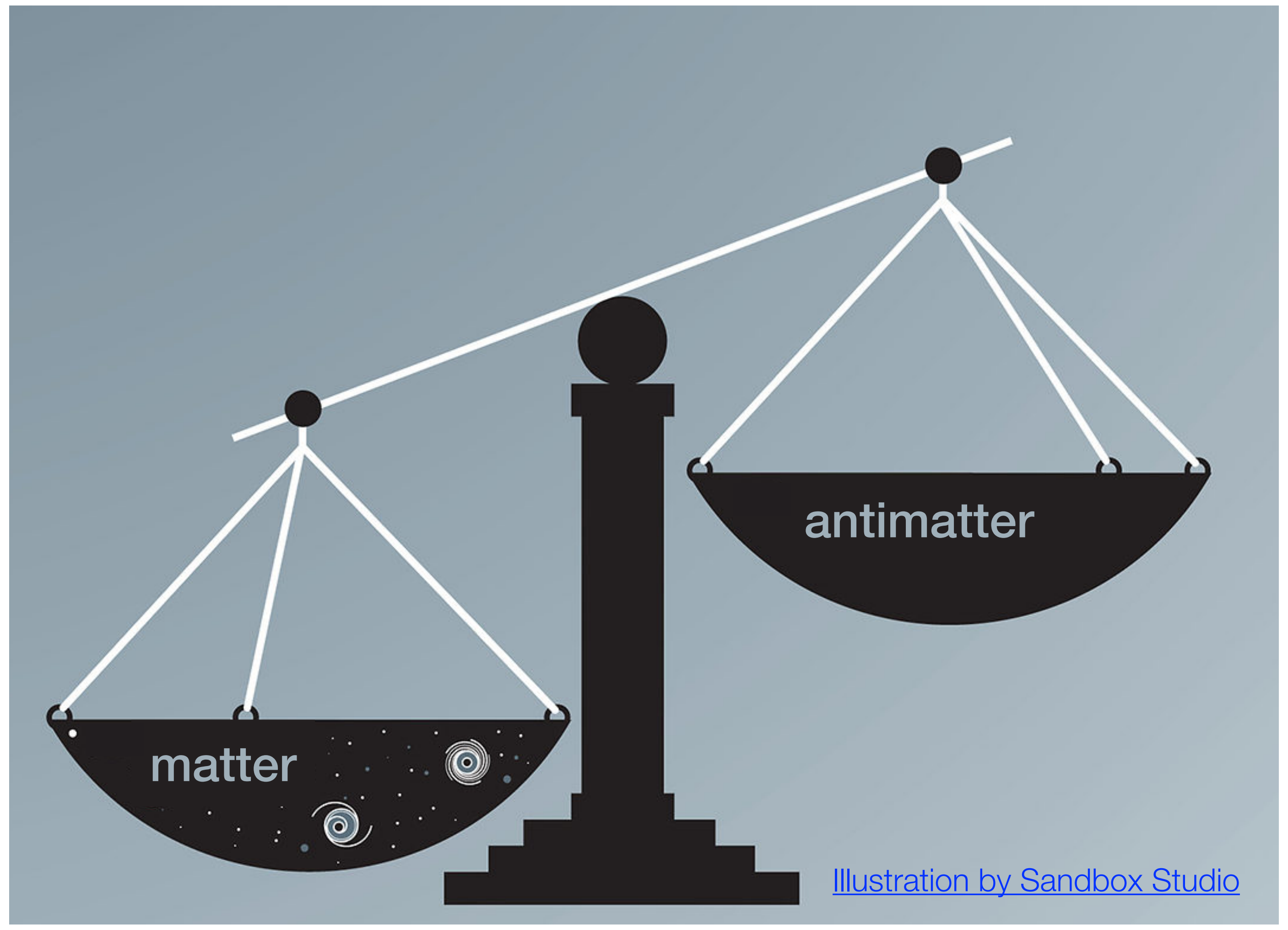


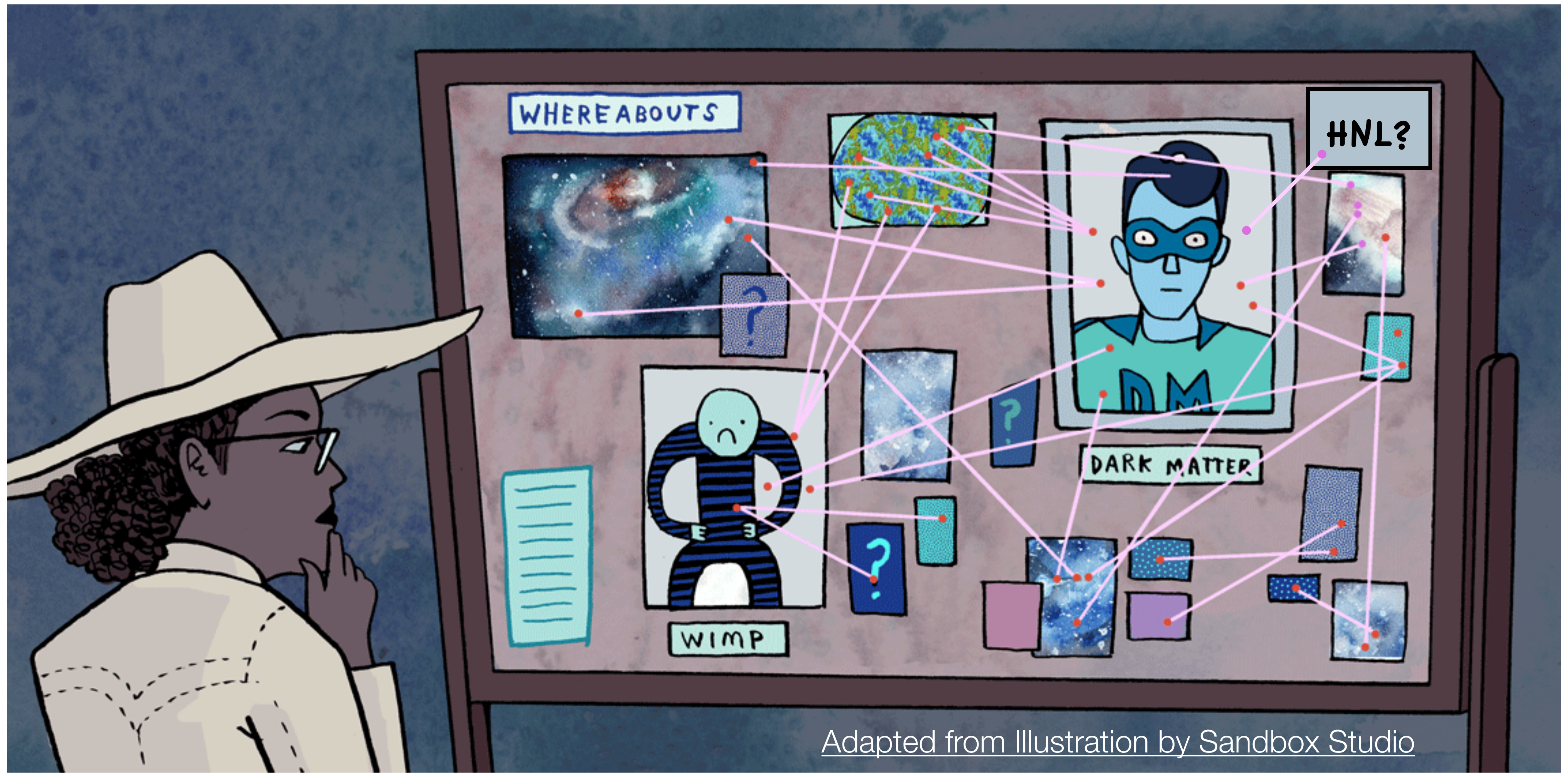
Illustration by Sandbox Studio

2. Matter-antimatter asymmetry of the universe

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

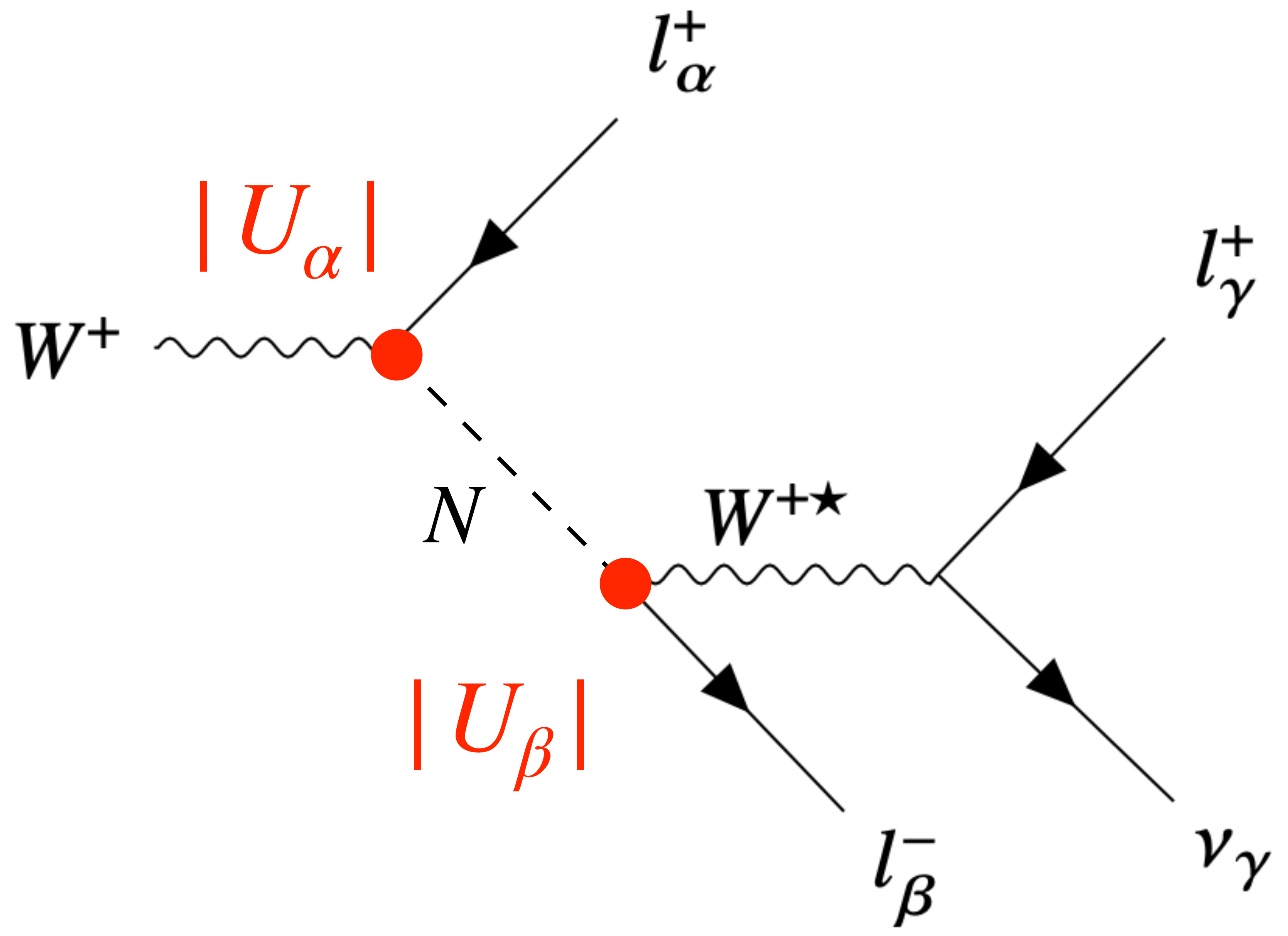
3. Dark matter candidate

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



Adapted from Illustration by Sandbox Studio

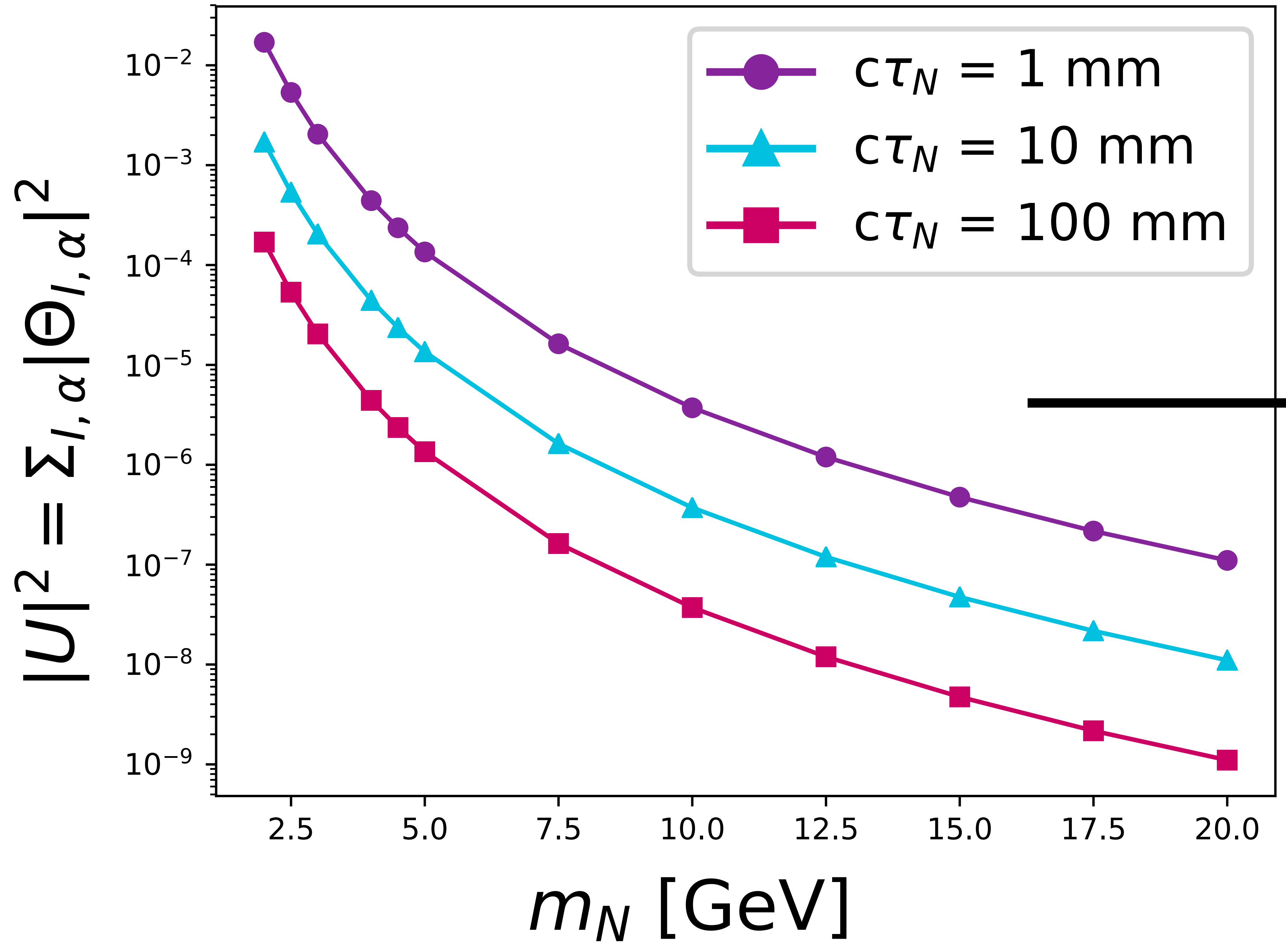
Experimentally Relevant Observables



- 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:

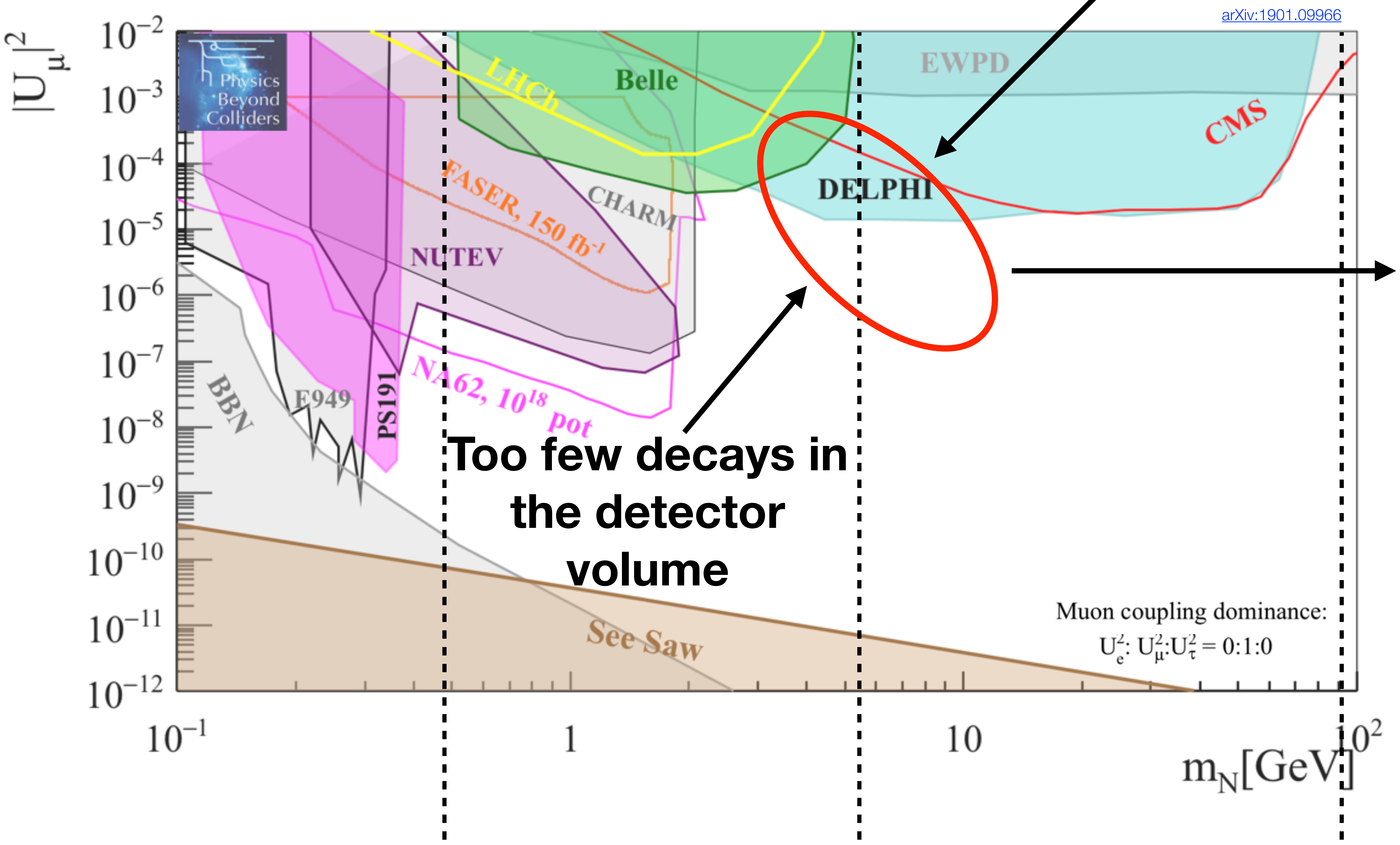
$\lvert U_\alpha \rvert^2$	Mixing angle between SM neutrino and HNL
m_N	HNL mass



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

Experimental Picture

Decays too quickly

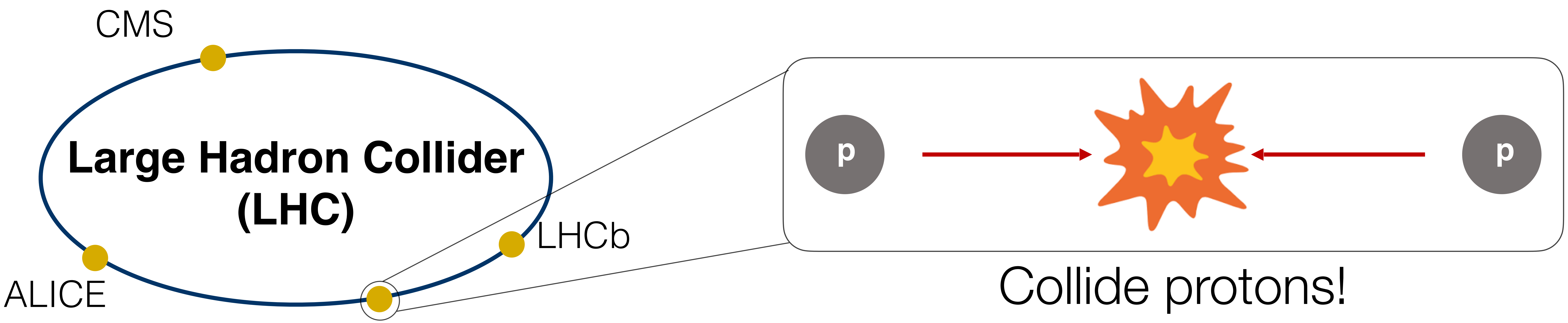


$m_K = 0.49$ GeV $m_B = 5.3$ GeV $m_Z = 91$ GeV

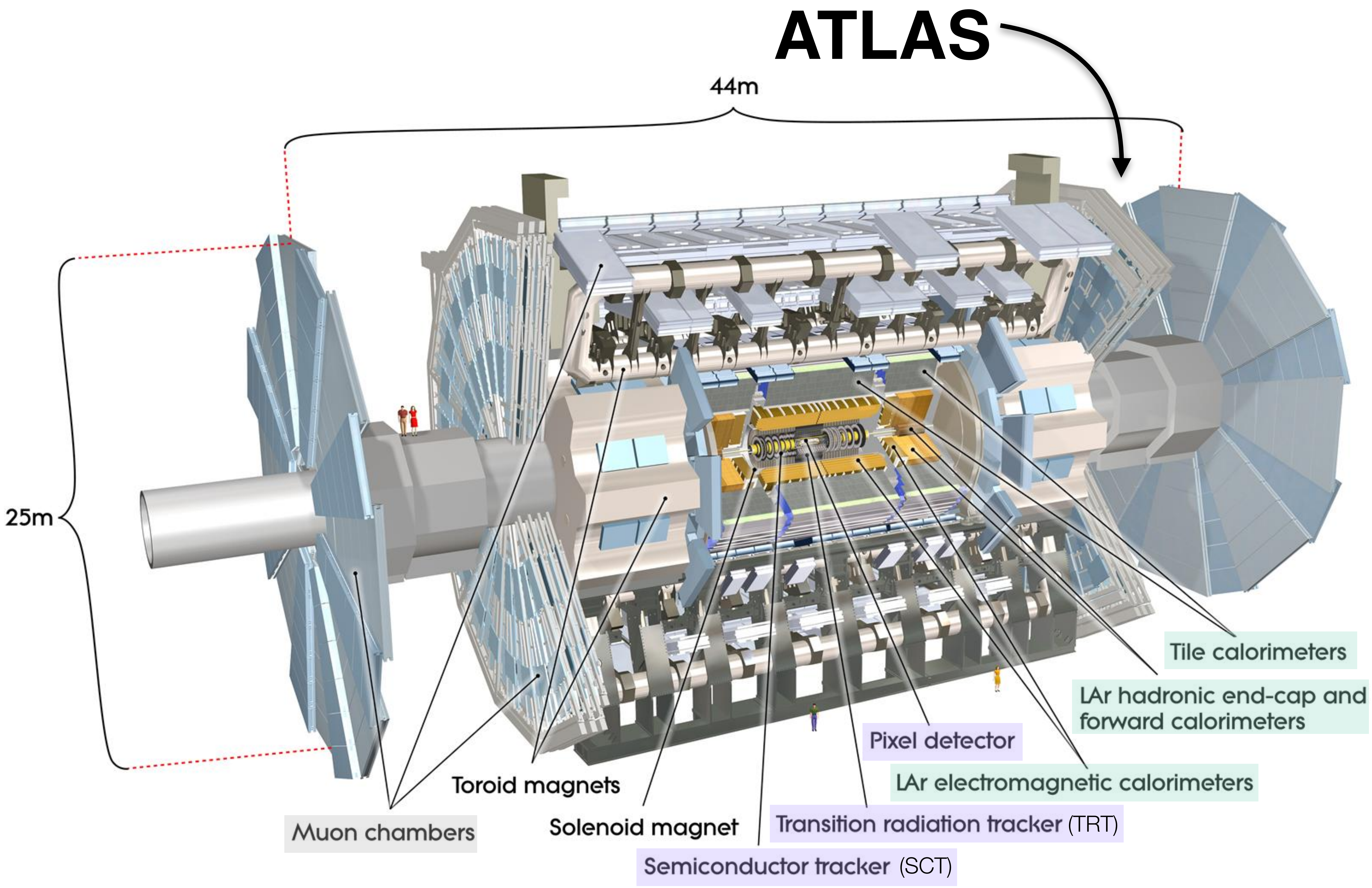
Target the **long-lived region** of phase space accessible at collider experiments!

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

The LHC and the ATLAS Experiment



Collide protons!

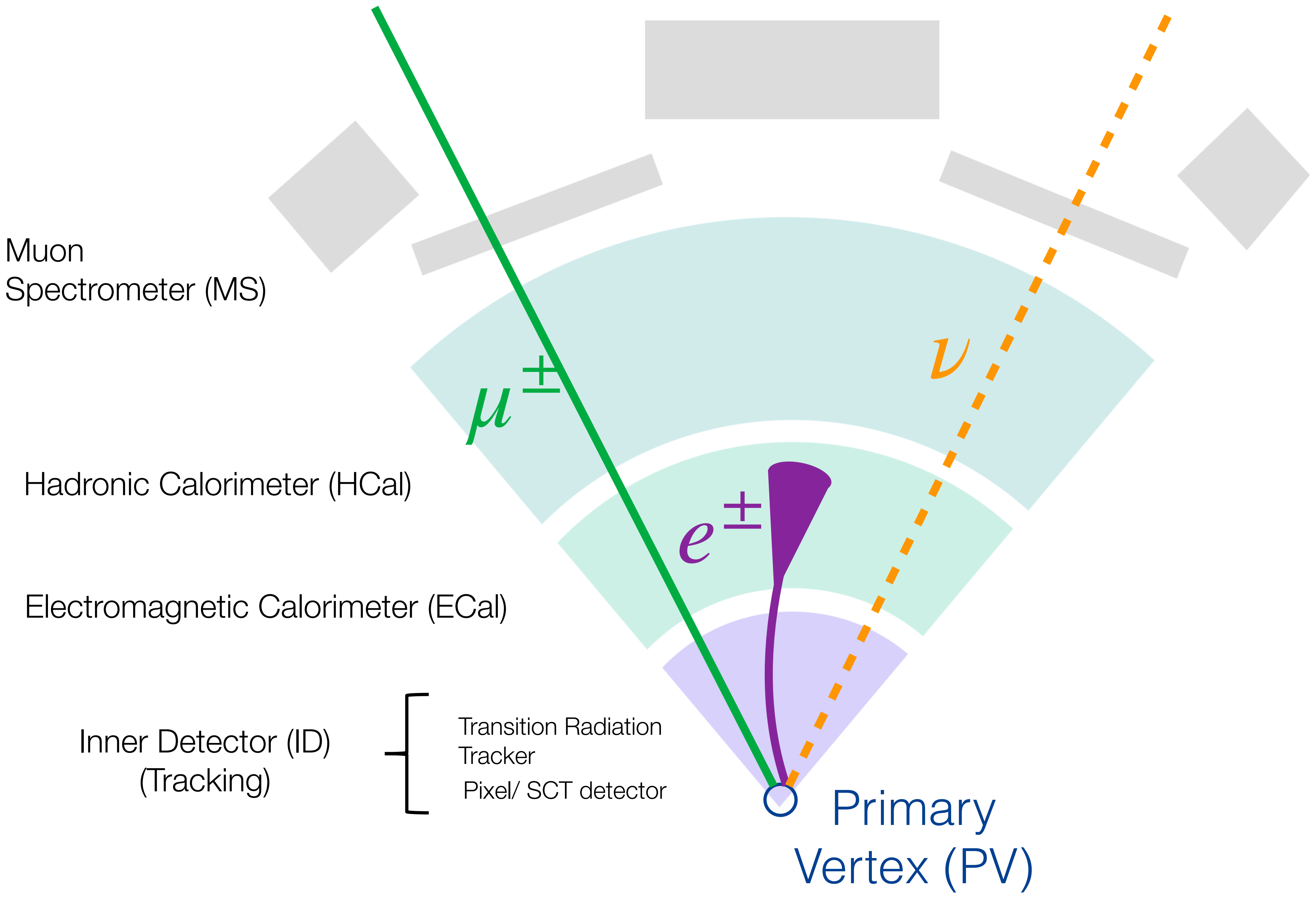


- **ATLAS** = general purpose particle detector
  - **Inner detector**
  - **Calorimeter** (electromagnetic & hadronic)
  - **Muon spectrometer**

Object Reconstruction

Standard:

(Constrained to originate from primary collision vertex)

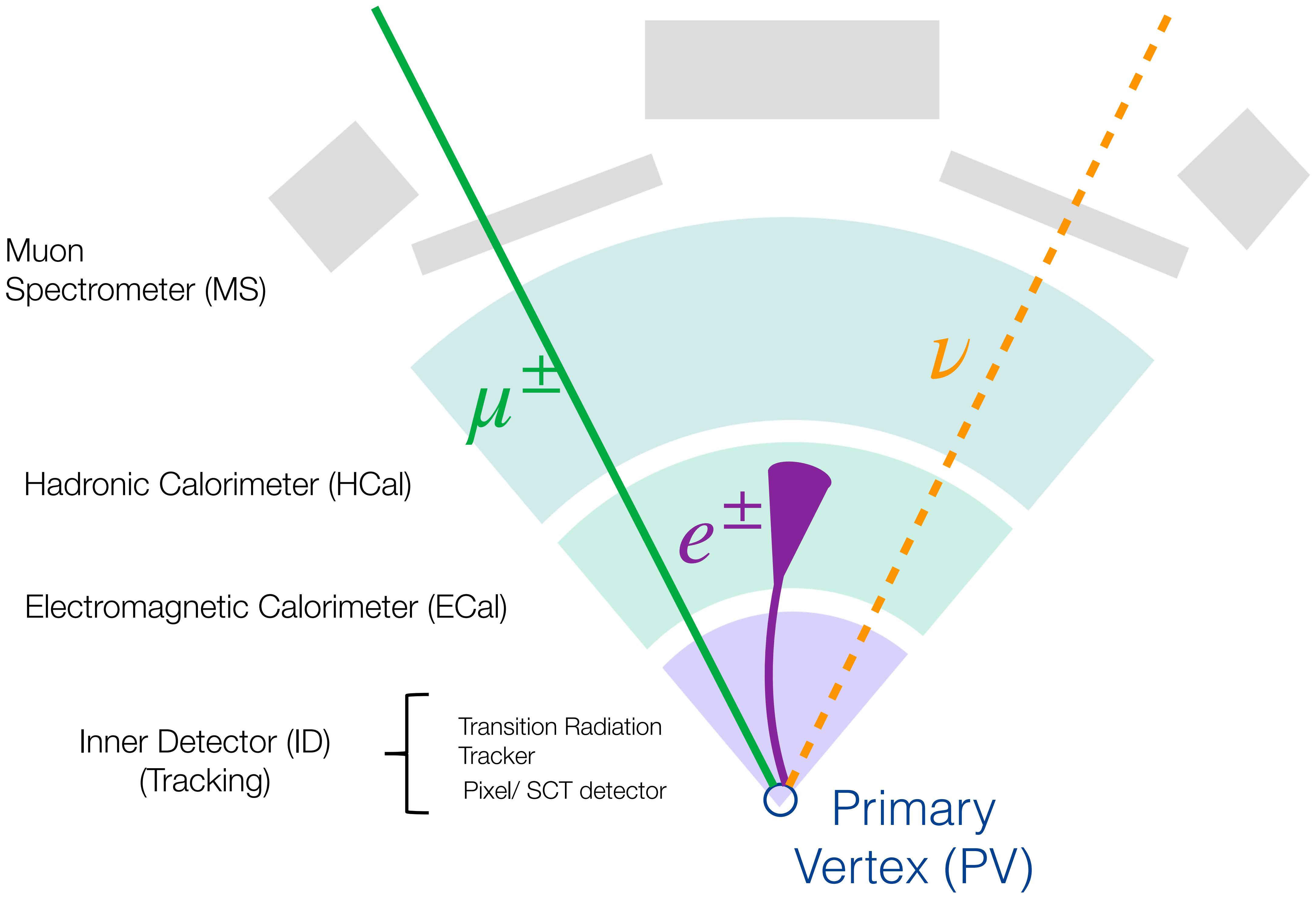


1. **Muons** (μ): ID track + MS track
2. **Electrons** (e): ID track + ECal deposit
3. **Neutrinos** (ν): invisible to the detector

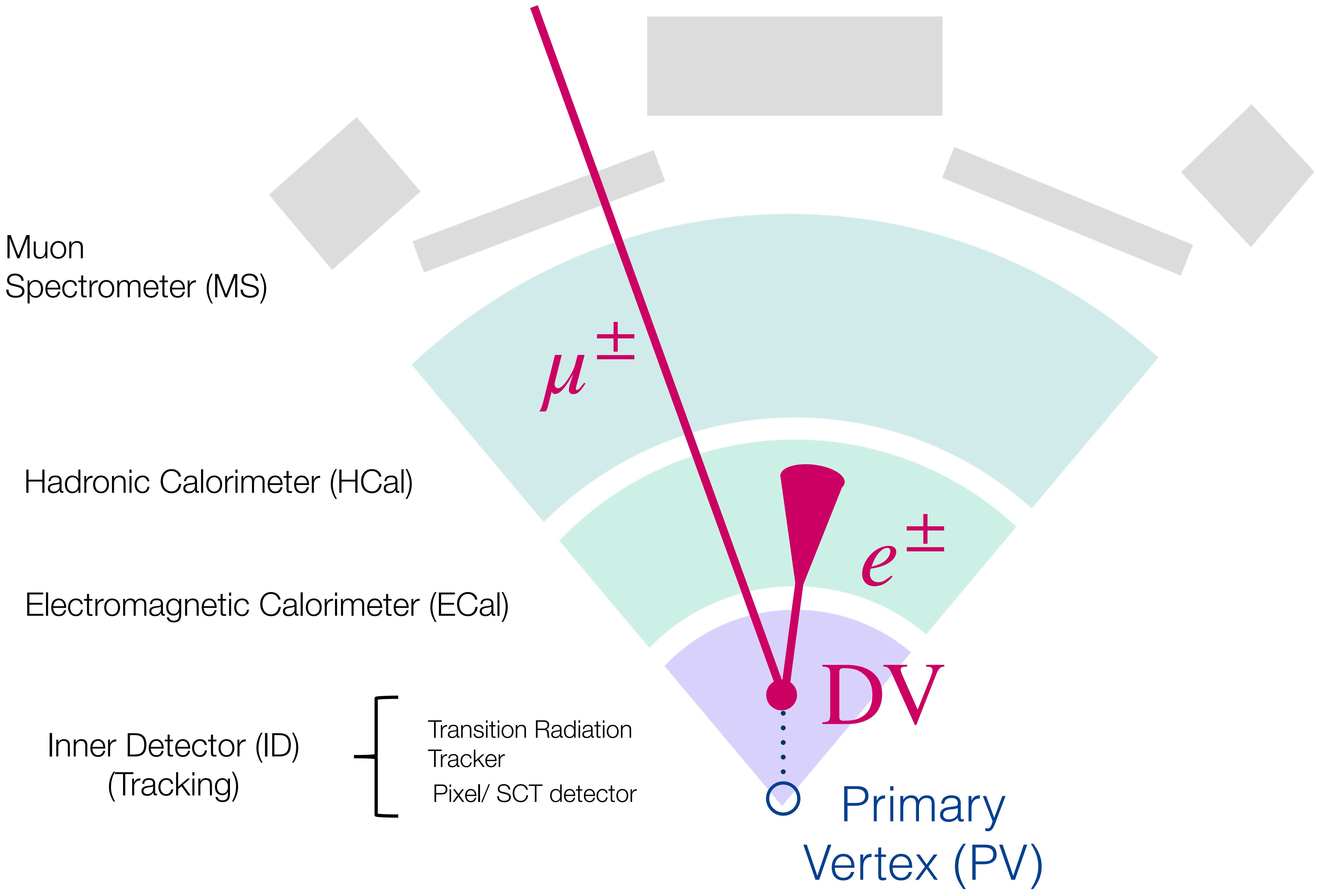
Object Reconstruction

Standard:

(Constrained to originate from primary collision vertex)



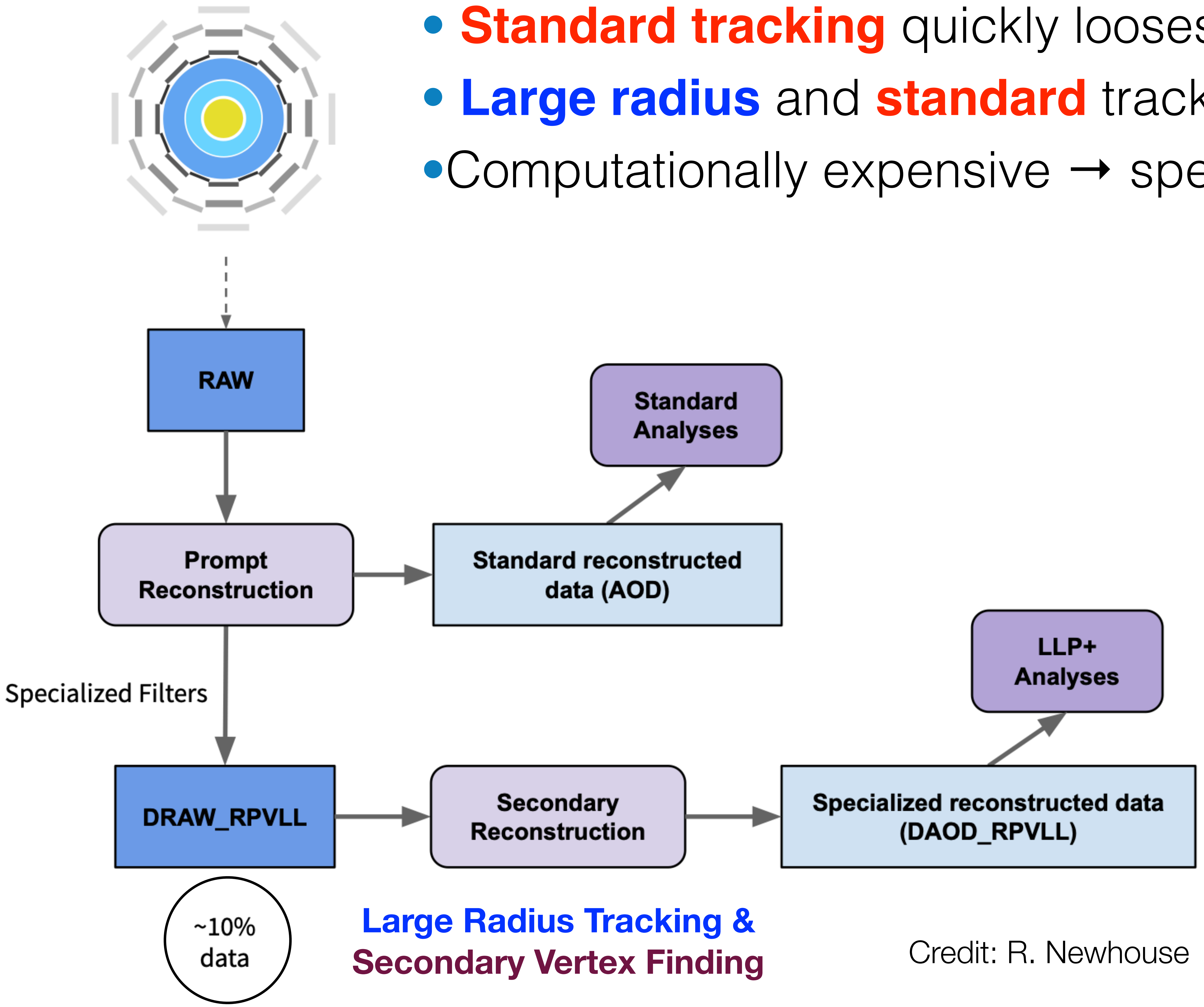
Non-Standard:



1. **Muons** (μ): ID track + MS track
2. **Electrons** (e): ID track + ECal deposit
3. **Neutrinos** (ν): invisible to the detector
4. **Displaced Vertex (DV)**: Common origin point for ≥ 2 tracks that is displaced with respect to PV
   ↳ Requires **special displaced track reconstruction**

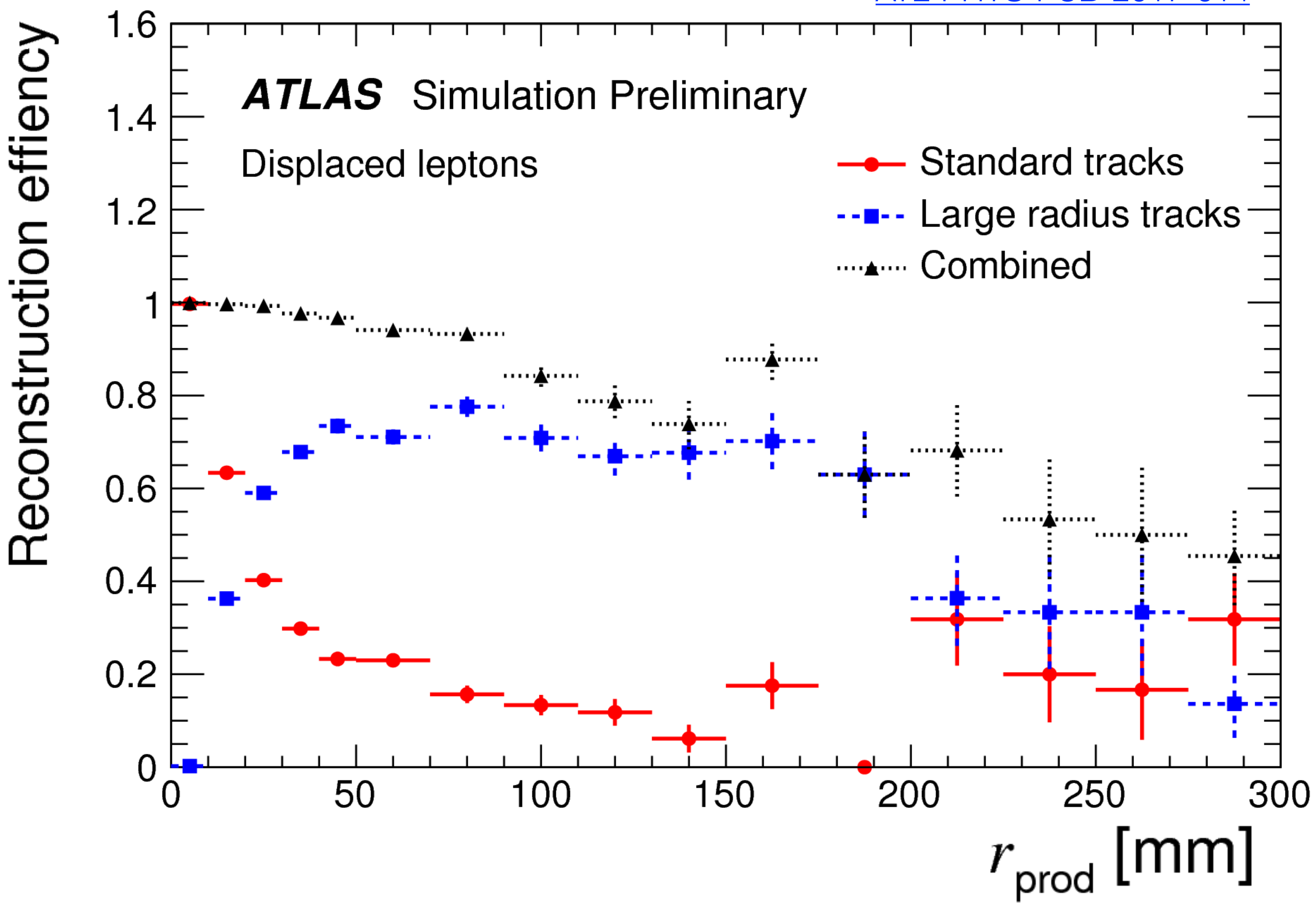
Displaced Track Reconstruction

- **Standard tracking** quickly looses efficiency for displaced tracks
- **Large radius** and **standard** tracks both used for displaced vertex finding
- Computationally expensive → special reprocessing required; **limited to ~10% of data**



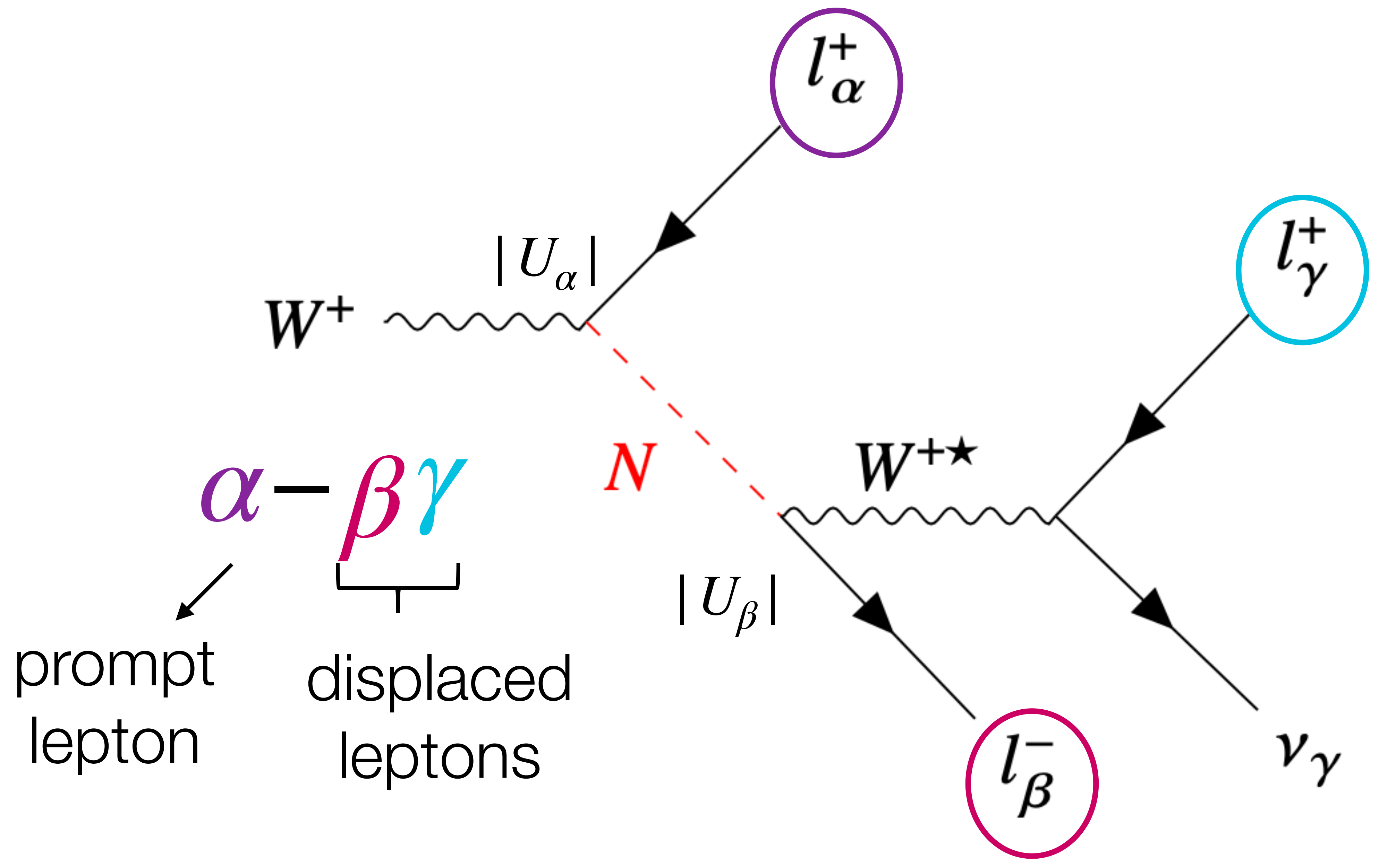
Credit: R. Newhouse

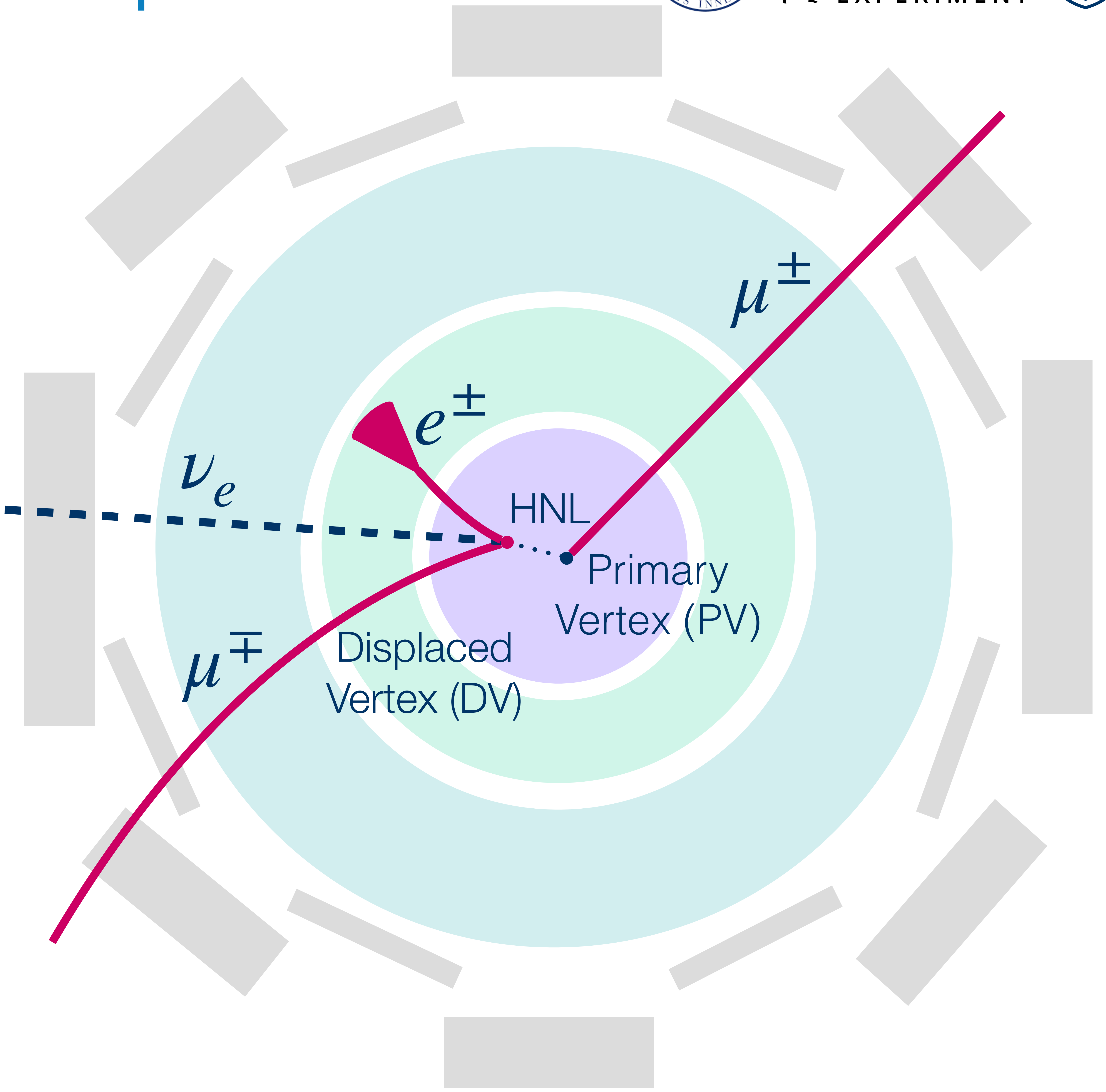
ATL-PHYS-PUB-2017-014



Displaced Heavy Neutral Leptons

Experimental HNL Signature:
— Prompt lepton (used for trigger)
— 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

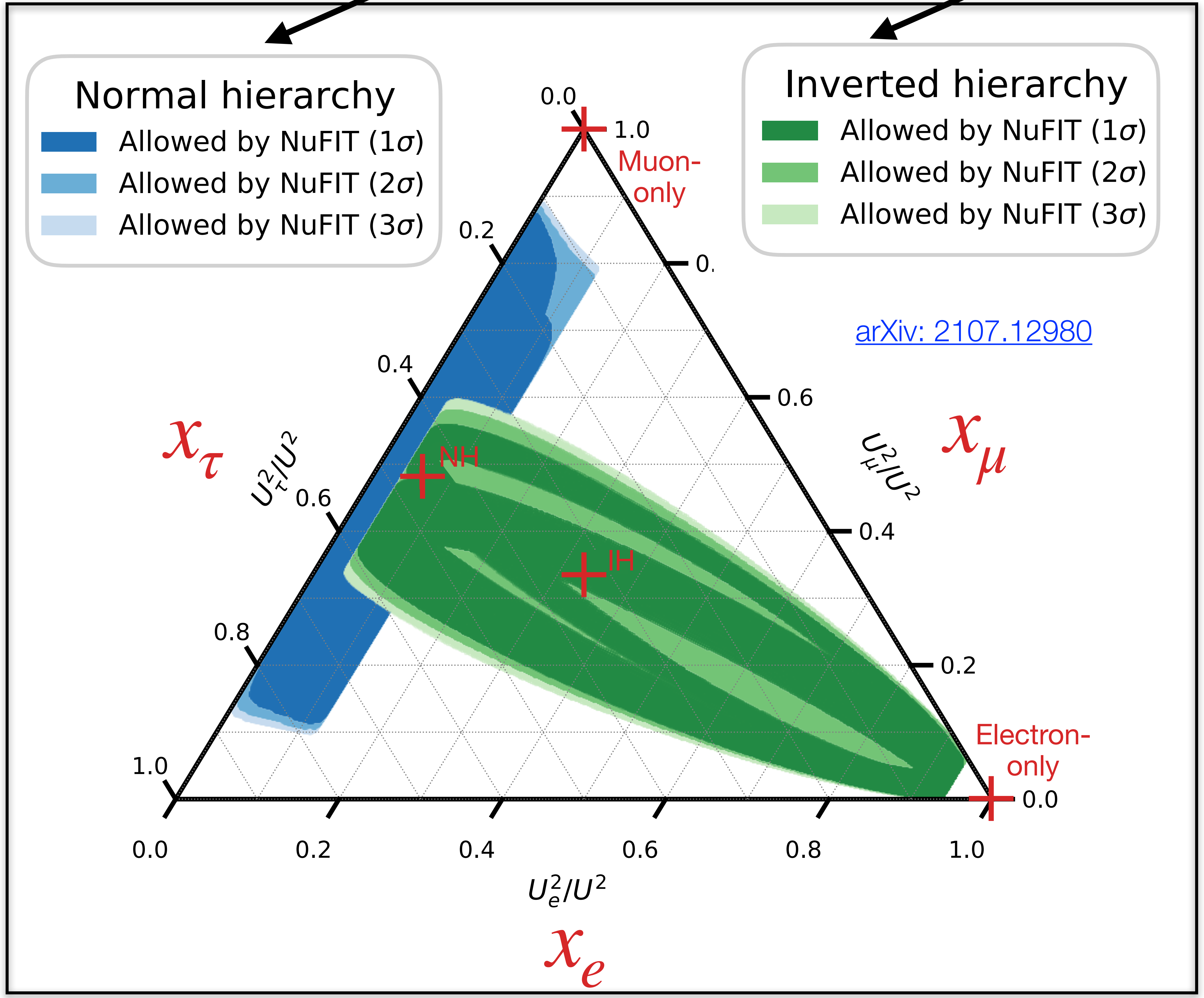
Mixing scenario benchmarks:

- Simple model: One HNL with single-flavour mixing (1SFH)
  - **Muon-only** mixing ($|U_\mu|^2$) More data!
  - **Electron-only** mixing ($|U_e|^2$) New!
- Realistic scenario: Two quasi-degenerate HNLs with m1~m2 (2QDH)
  - **Inverted hierarchy (IH)** mixing ($|U|^2$) New!
  - **Normal hierarchy (NH)** mixing ($|U|^2$) New!

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

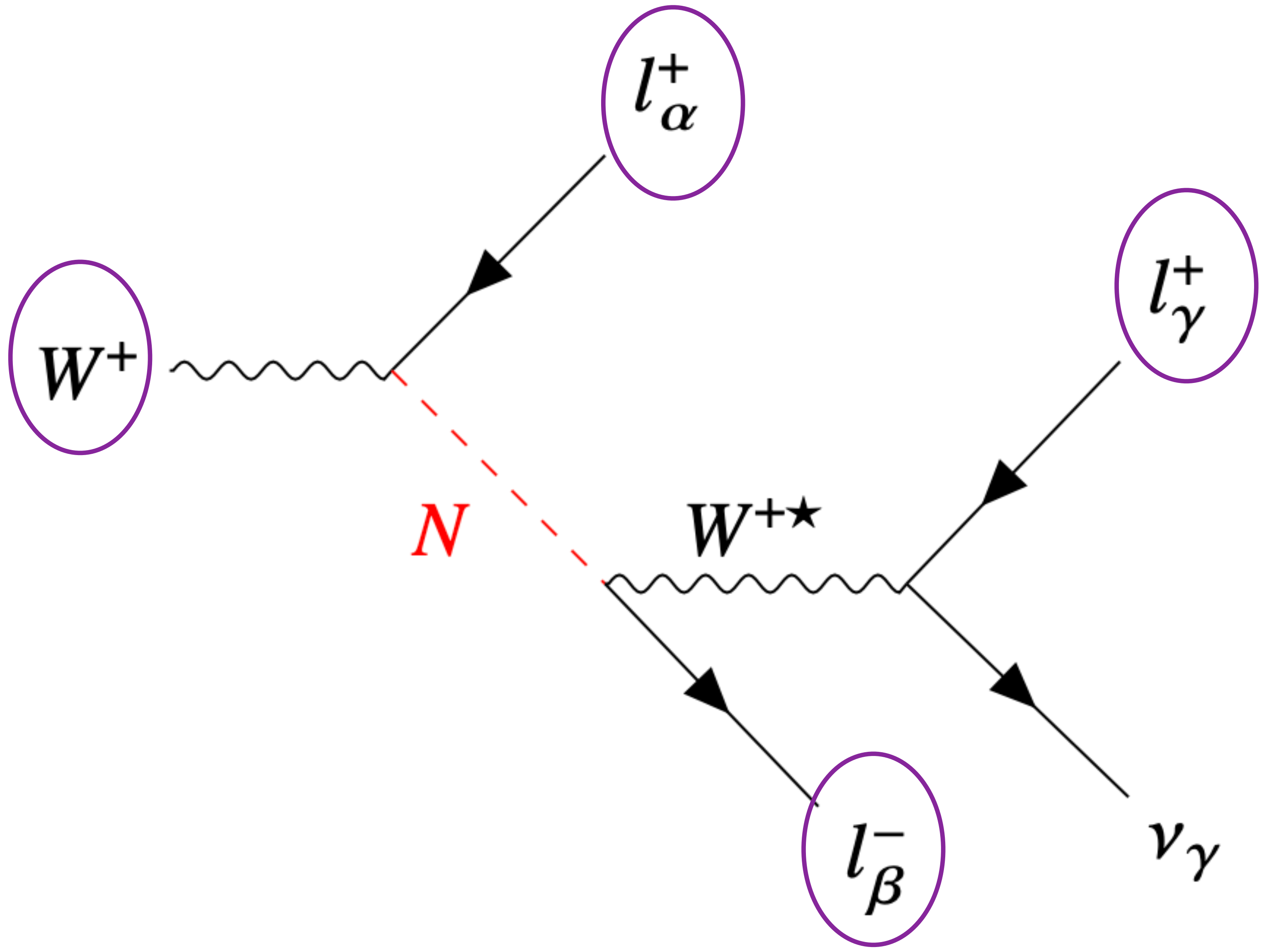
$$x_\alpha = |U_\alpha|^2/|U|^2$$

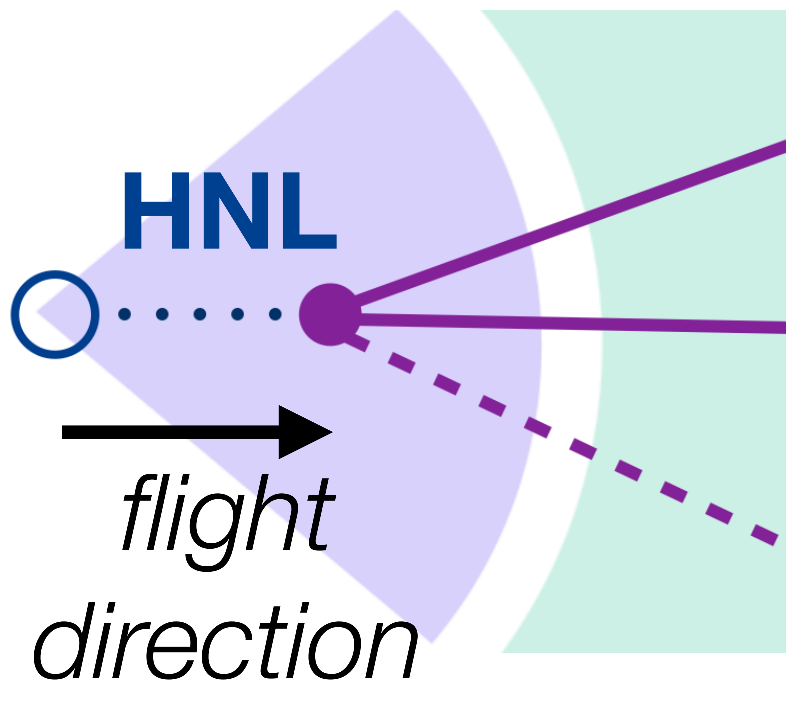
"Realistic" multi-flavour mixing models consistent with neutrino oscillations data



Discriminating Variable: HNL mass

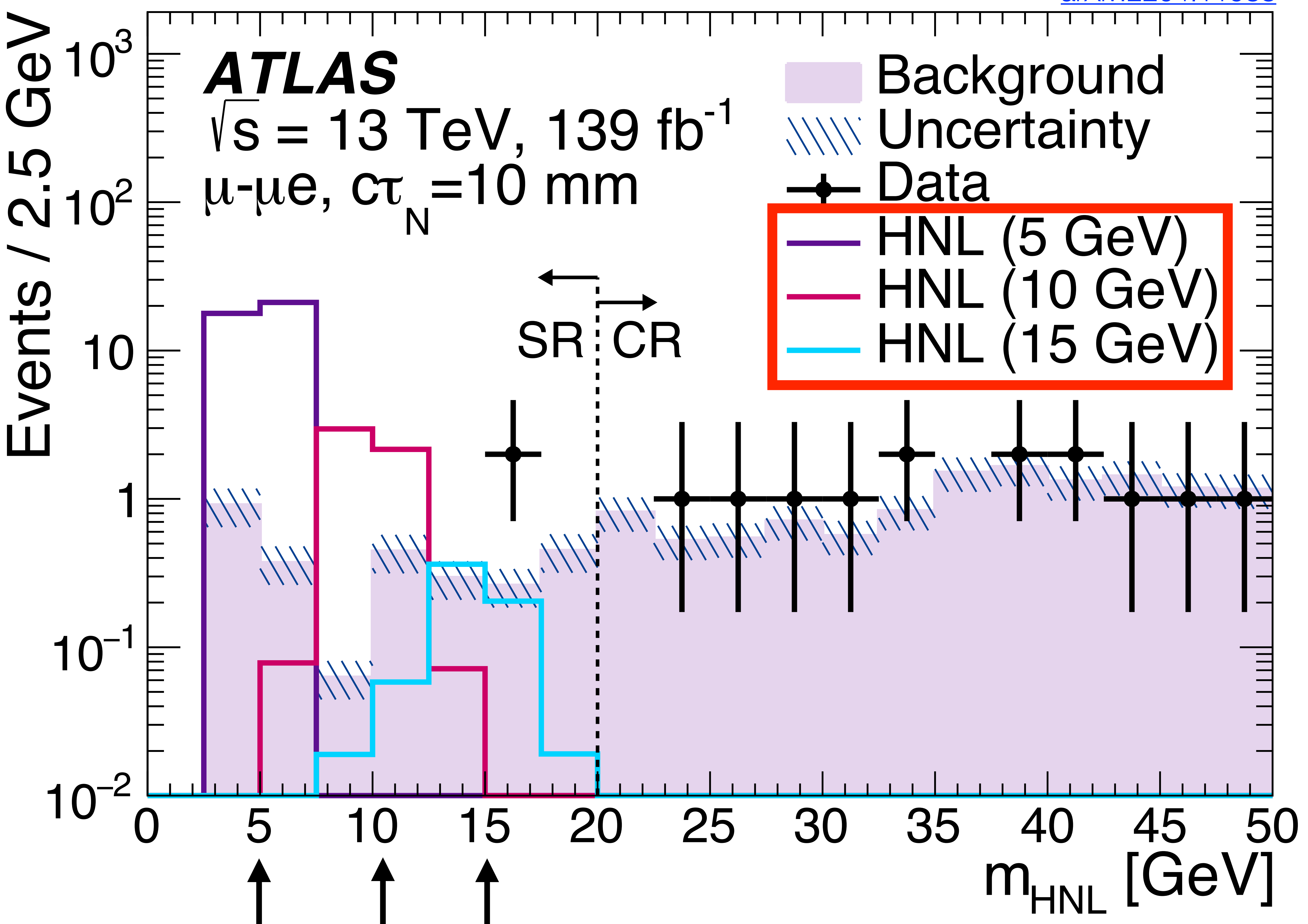
- **Energy-momentum conservation** is used to reconstruct the HNL mass (m_{HNL})
- Uses kinematics of charged leptons, W mass and the flight direction of the HNL to completely constrain the neutrino momentum





HNL mass: $m_{\mathrm{HNL}}^2 = (P_{l_\beta} + P_{l_\gamma} + P_{\nu_\gamma})^2$

arXiv:2204.11988

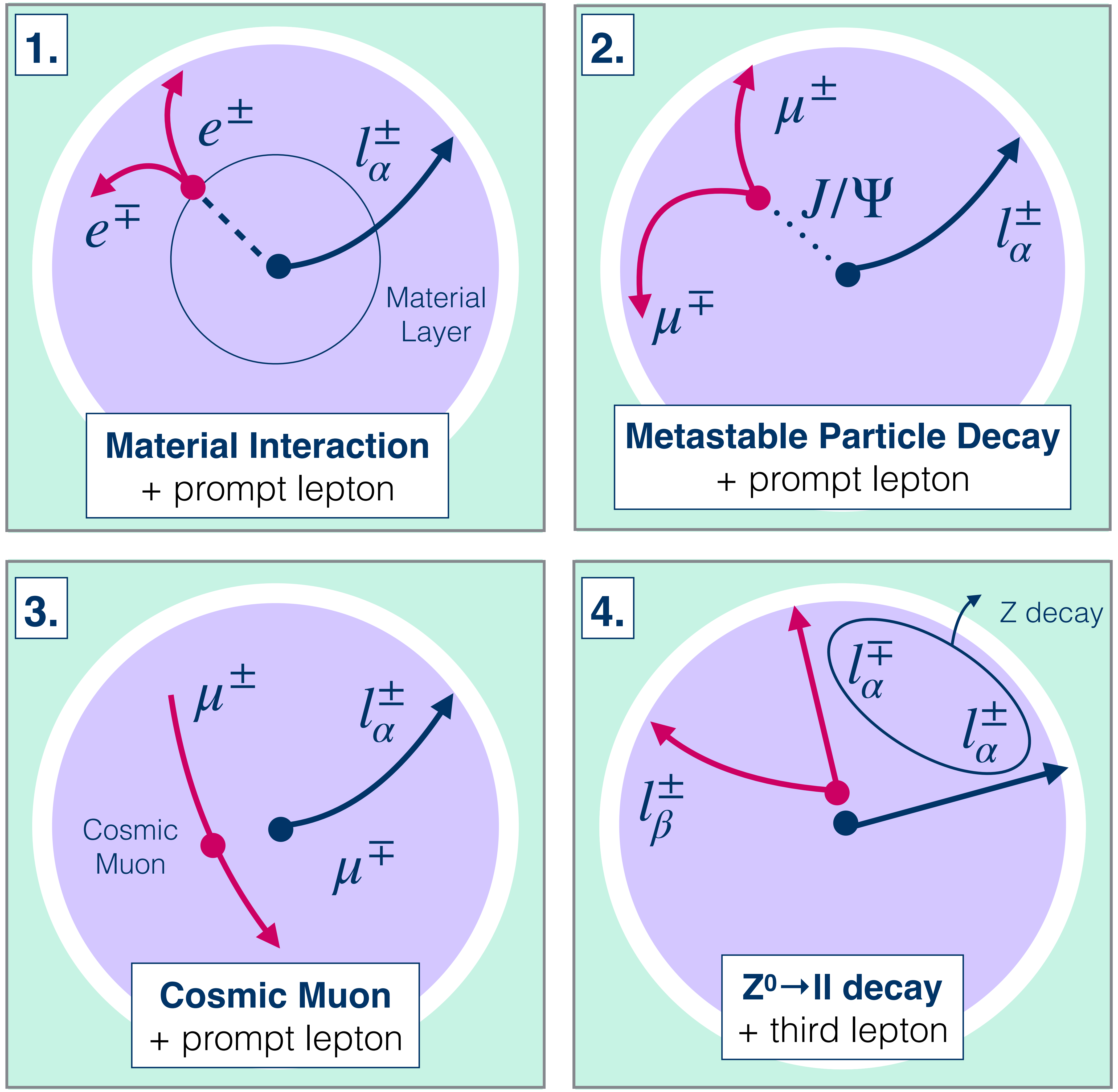


Simulated Signals

Main Backgrounds

- Five main backgrounds that produce **opposite-charge DV** + **prompt lepton**:

Non-random Backgrounds

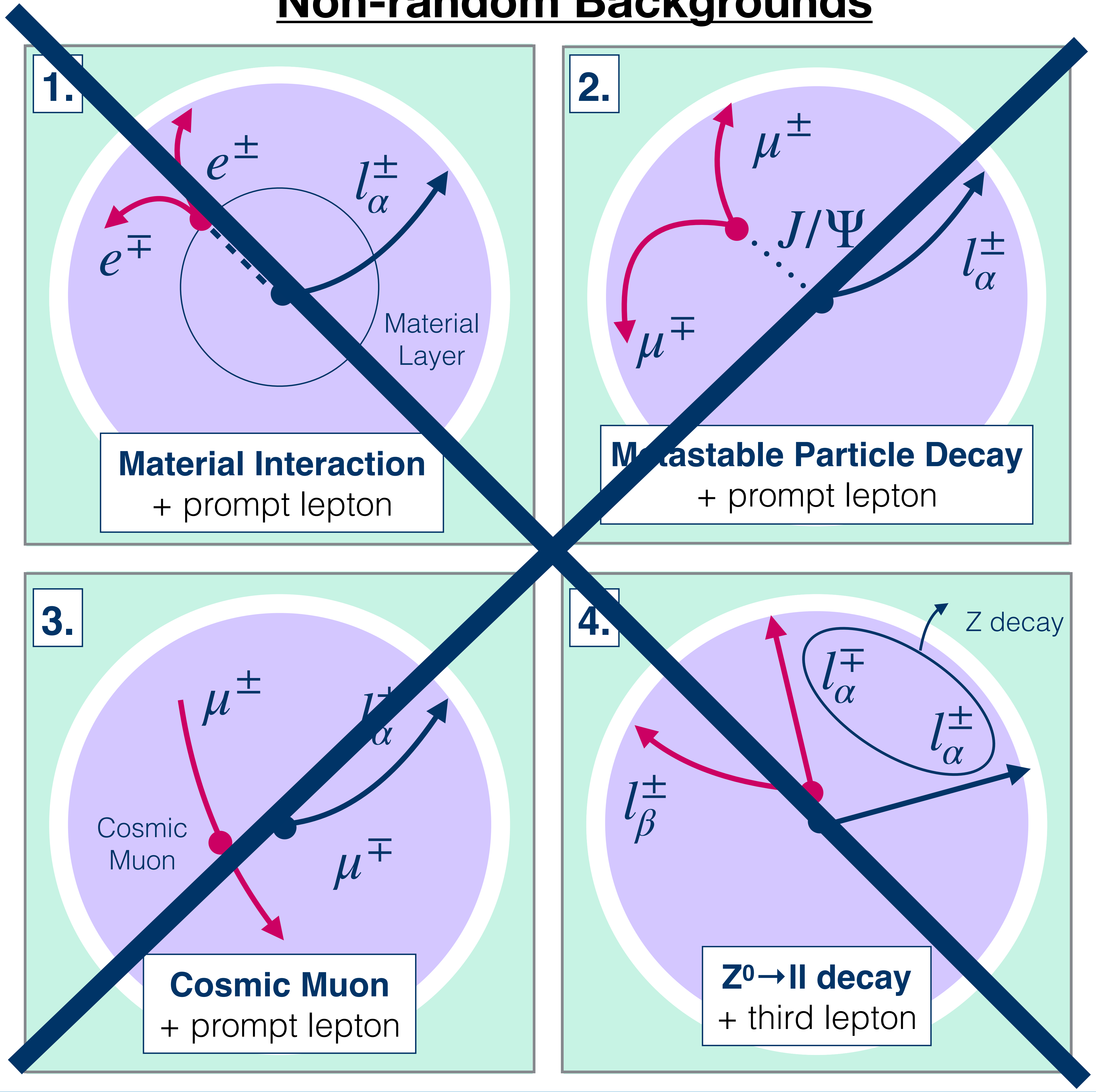


- Dedicated selections to remove non-random backgrounds:
  1. Material veto for ee DVs
  2. DV mass (m_{DV}) and radius (r_{DV}) cuts to remove metastable decays
  3. Veto cosmic muons with track separation cut (no back-to-back tracks)
  4. Z mass veto for same flavour opposite charge pairs

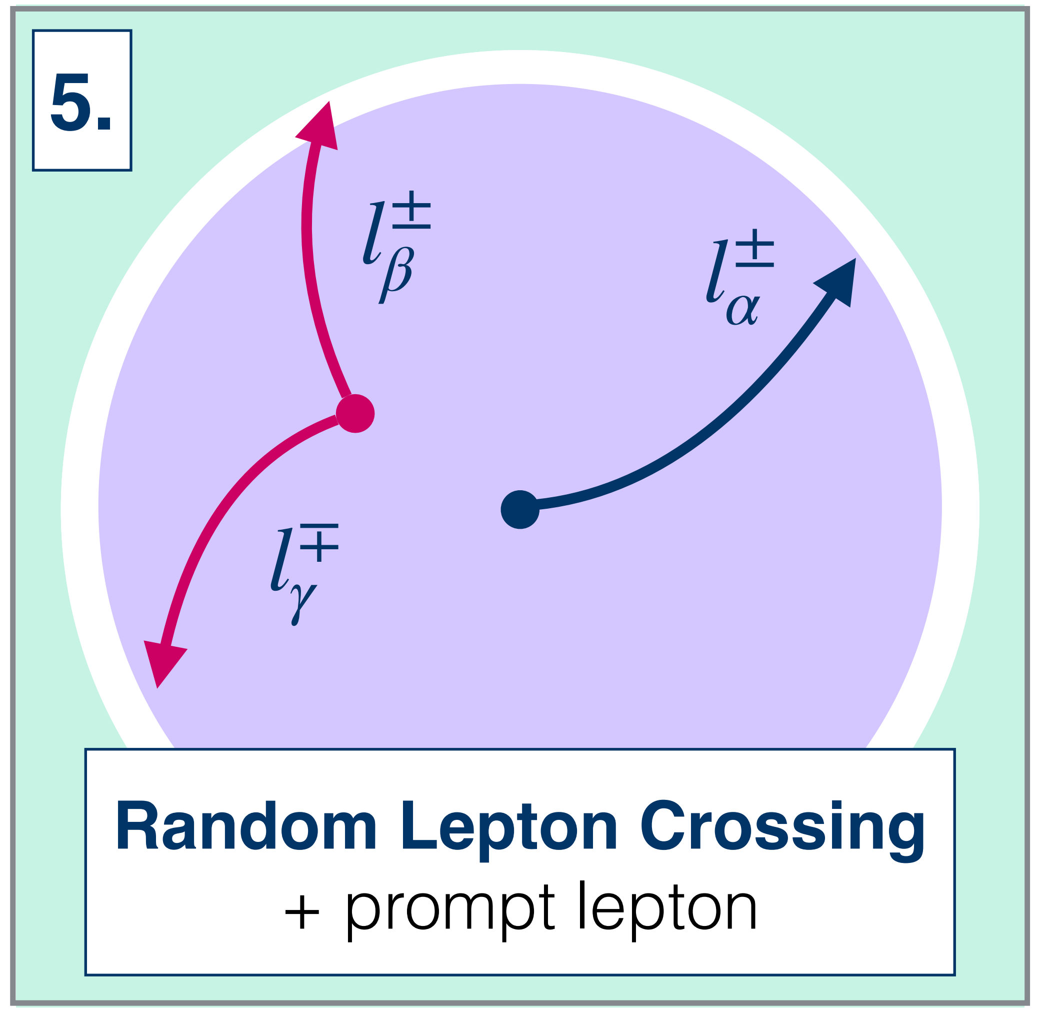
Main Backgrounds

- Five main backgrounds that produce **opposite-charge DV** + **prompt lepton**:

Non-random Backgrounds



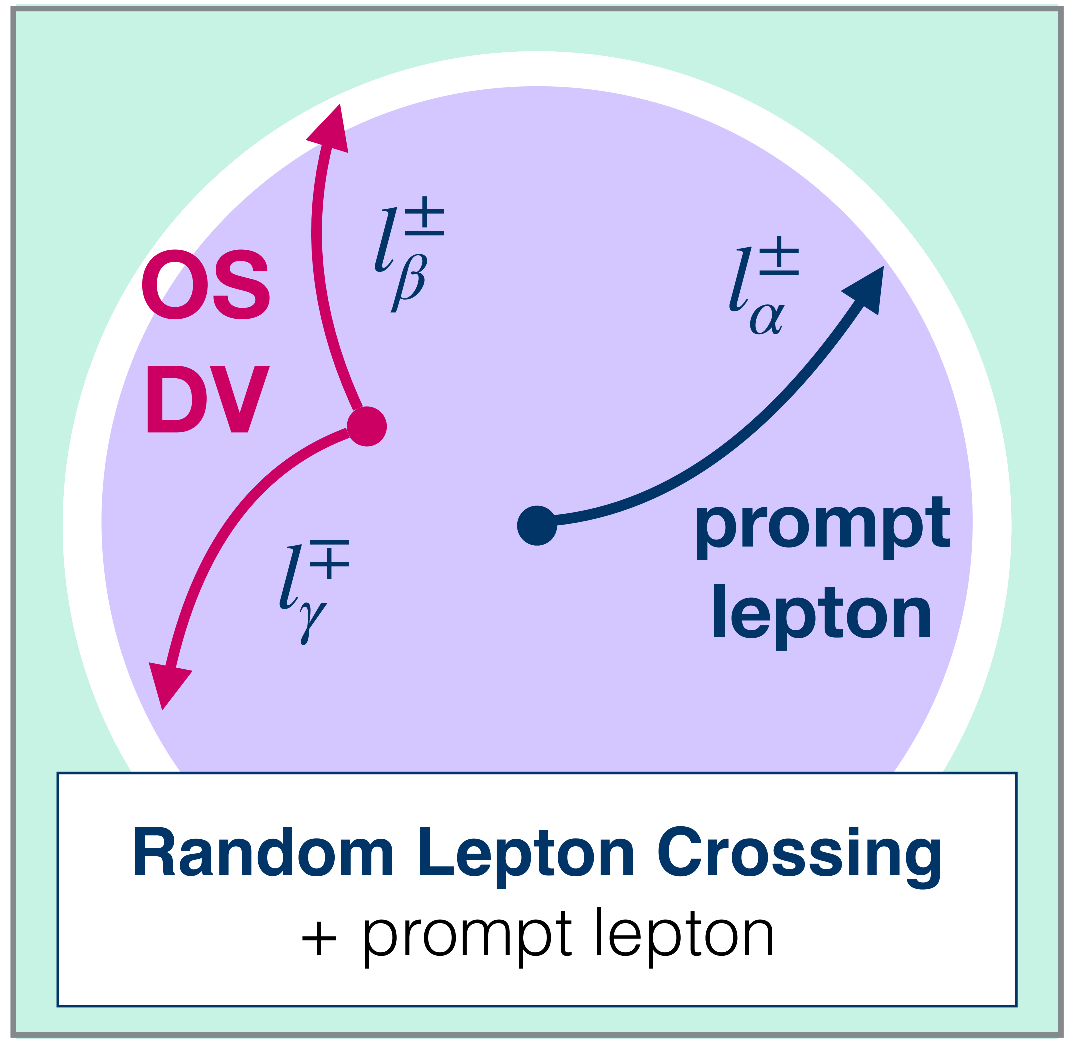
Random Background



Dominant Background!

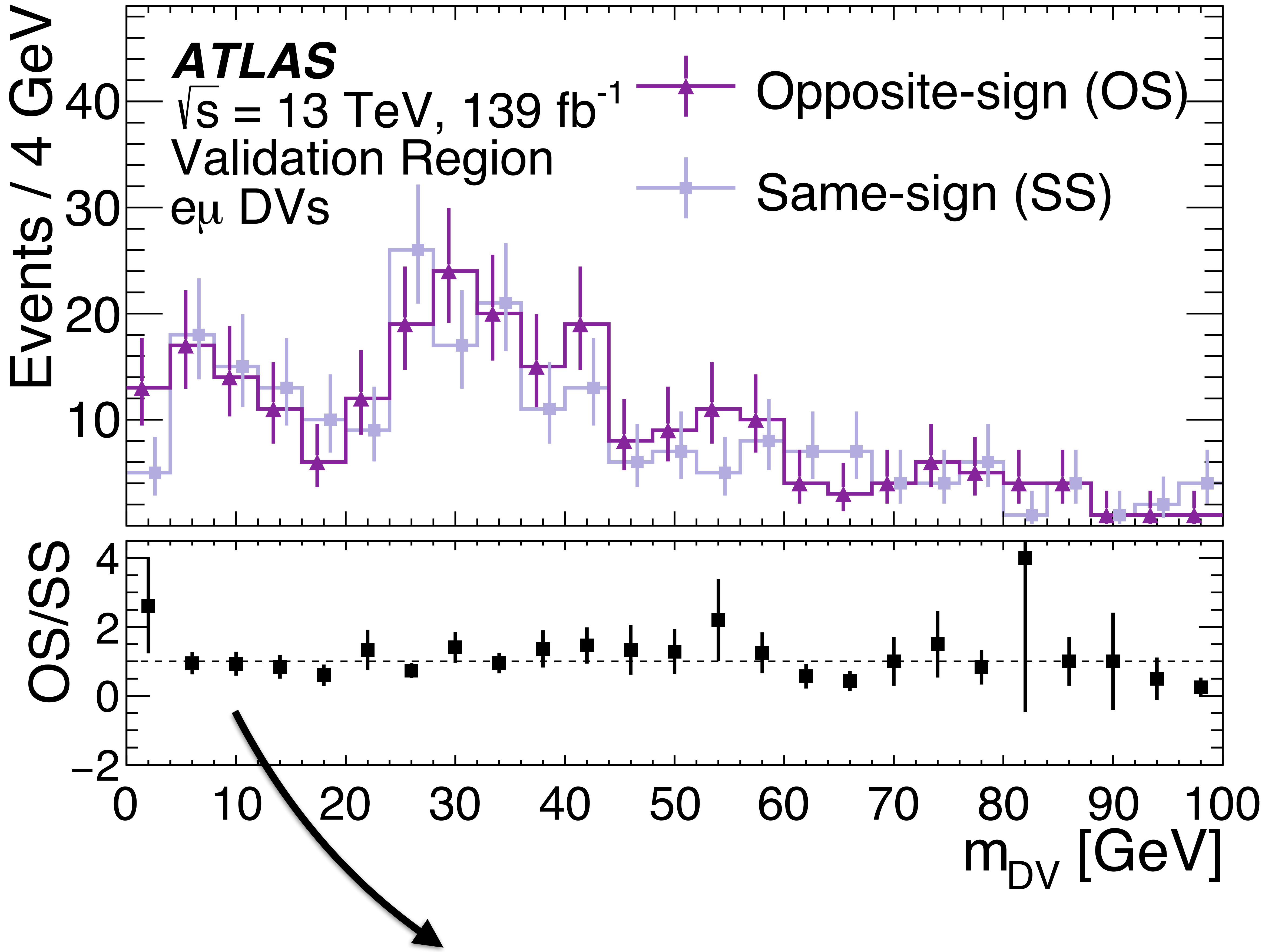
Background Validation

Dominant background:



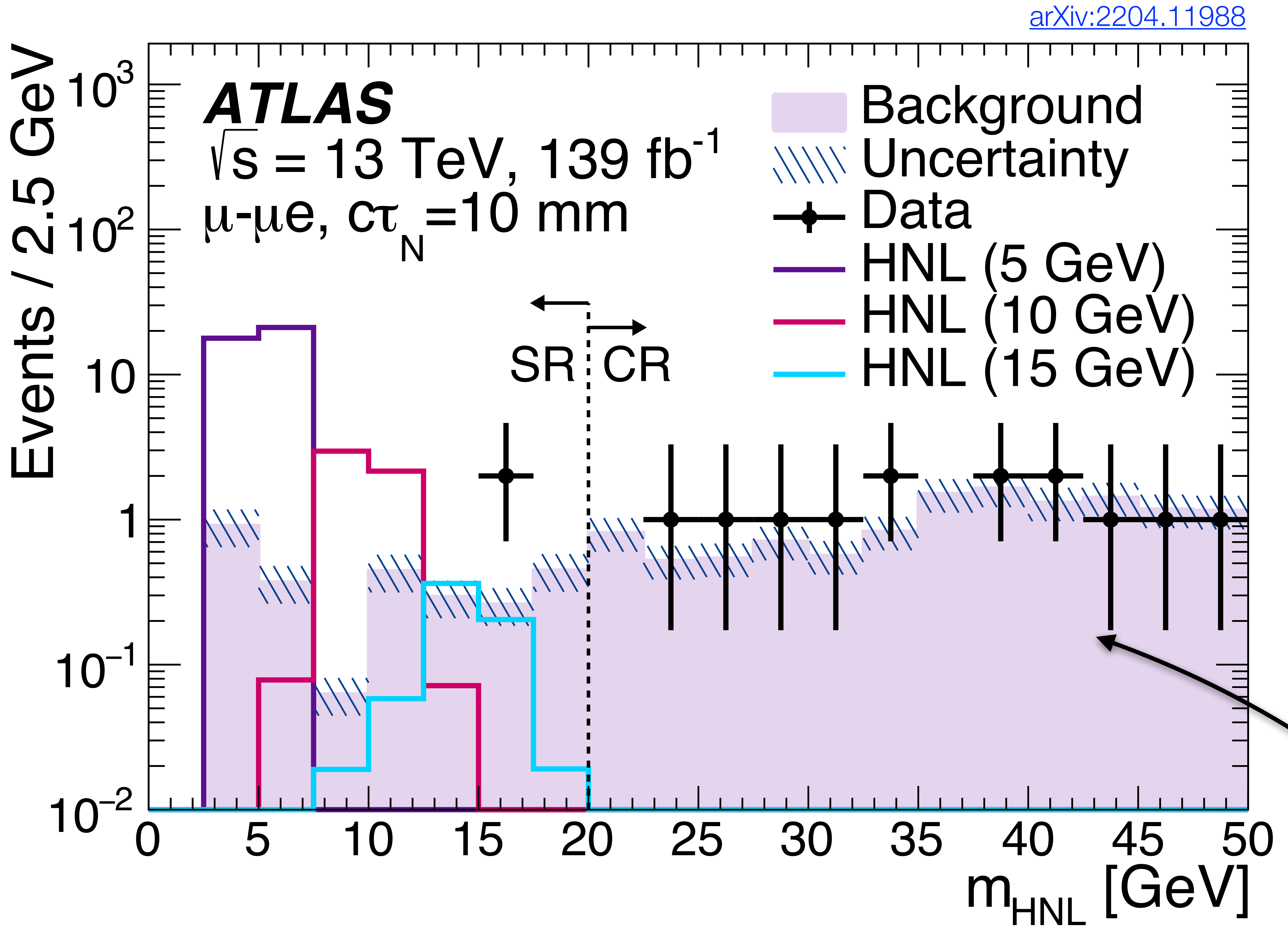
- Use that probability for accidental crossing is independent of the charges of the displaced tracks
  - Study events in validation region (VR) that contains events with no prompt leptons

arXiv:2204.11988

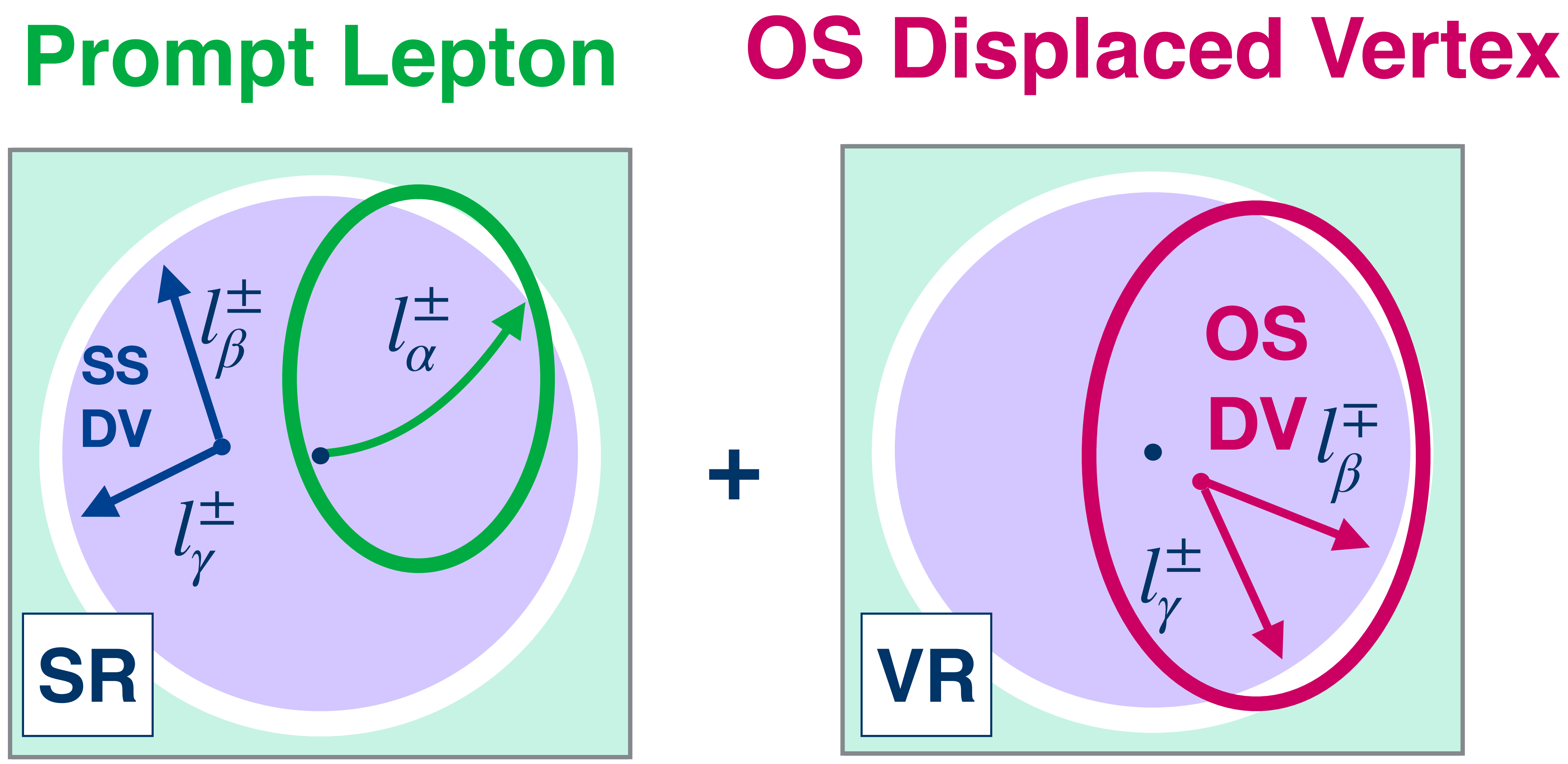


Good agreement between vertices with two charged leptons with the same-sign (SS) and opposite-sign (OS) indicates **random crossings are the dominant background.**

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)
  - Mix randomly with **OS DVs** from validation region (VR)

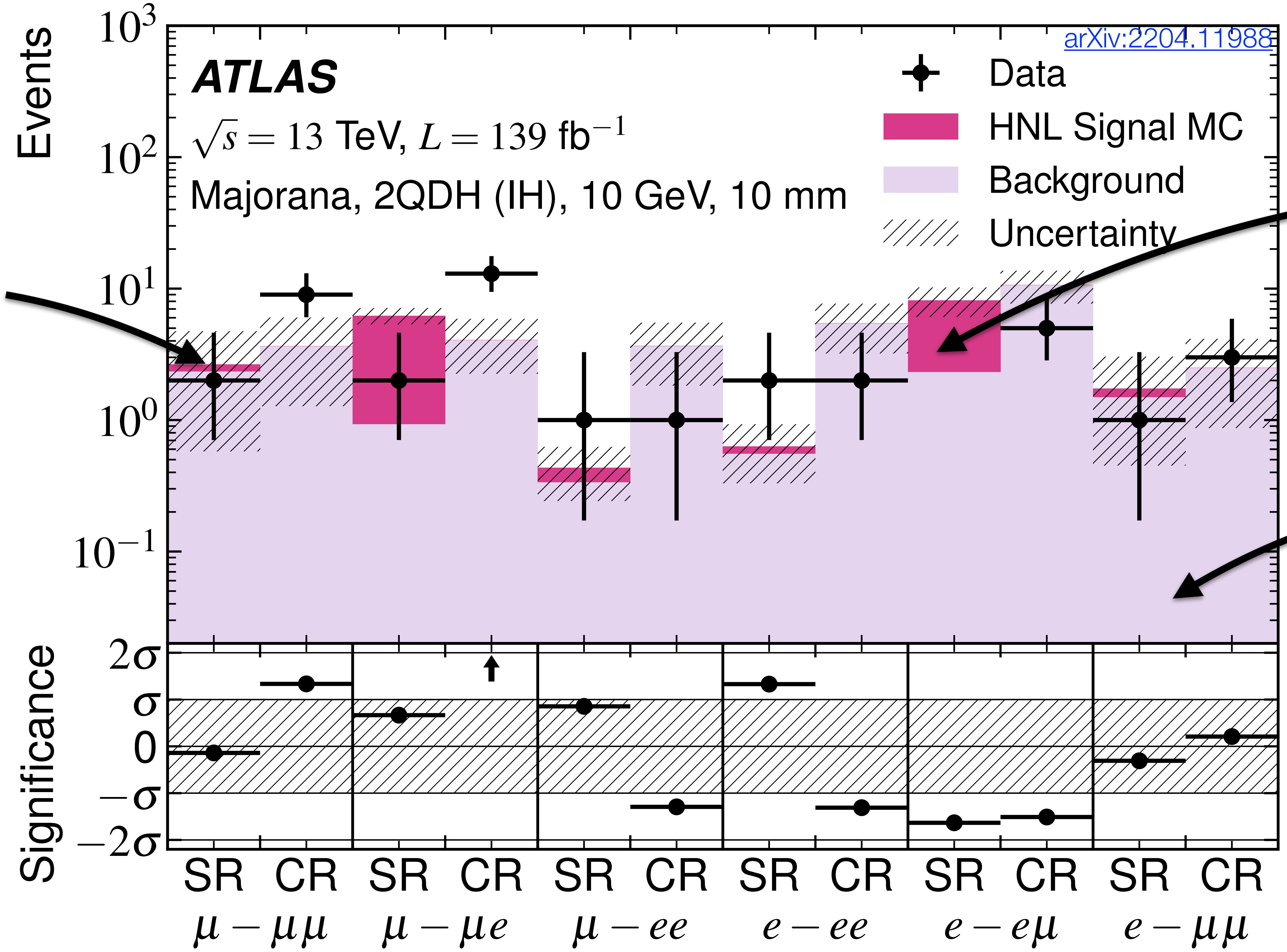


- This method increases the available statistics (~x2,000) and creates a smooth distribution as a function of m_{HNL}

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)

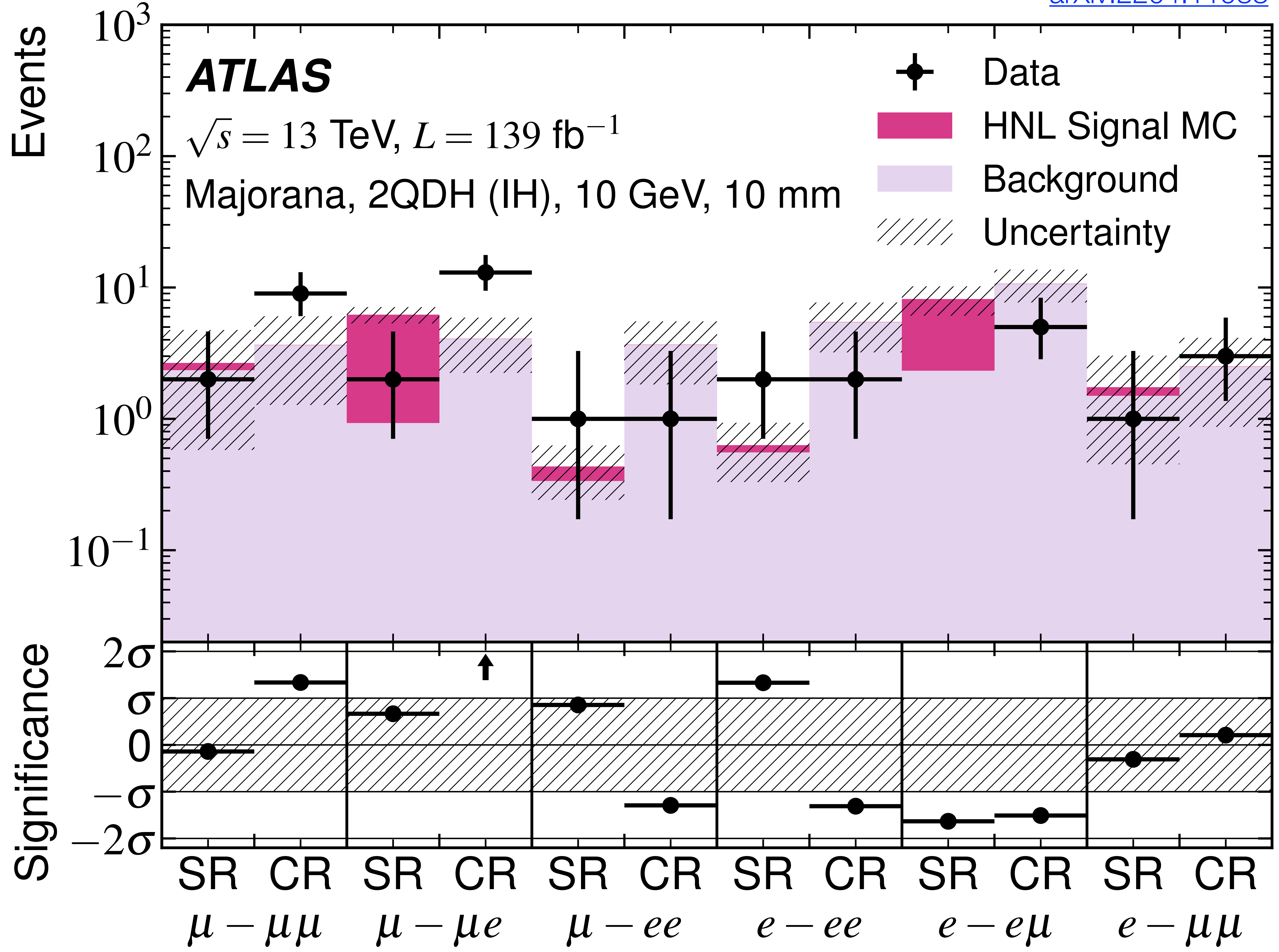
Signal Region (SR): m_{HNL} < 20 GeV
Control Region (CR): 20 GeV < m_{HNL} < 50 GeV → Used to constrain the background in the SR!

Results

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

Run fit →

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



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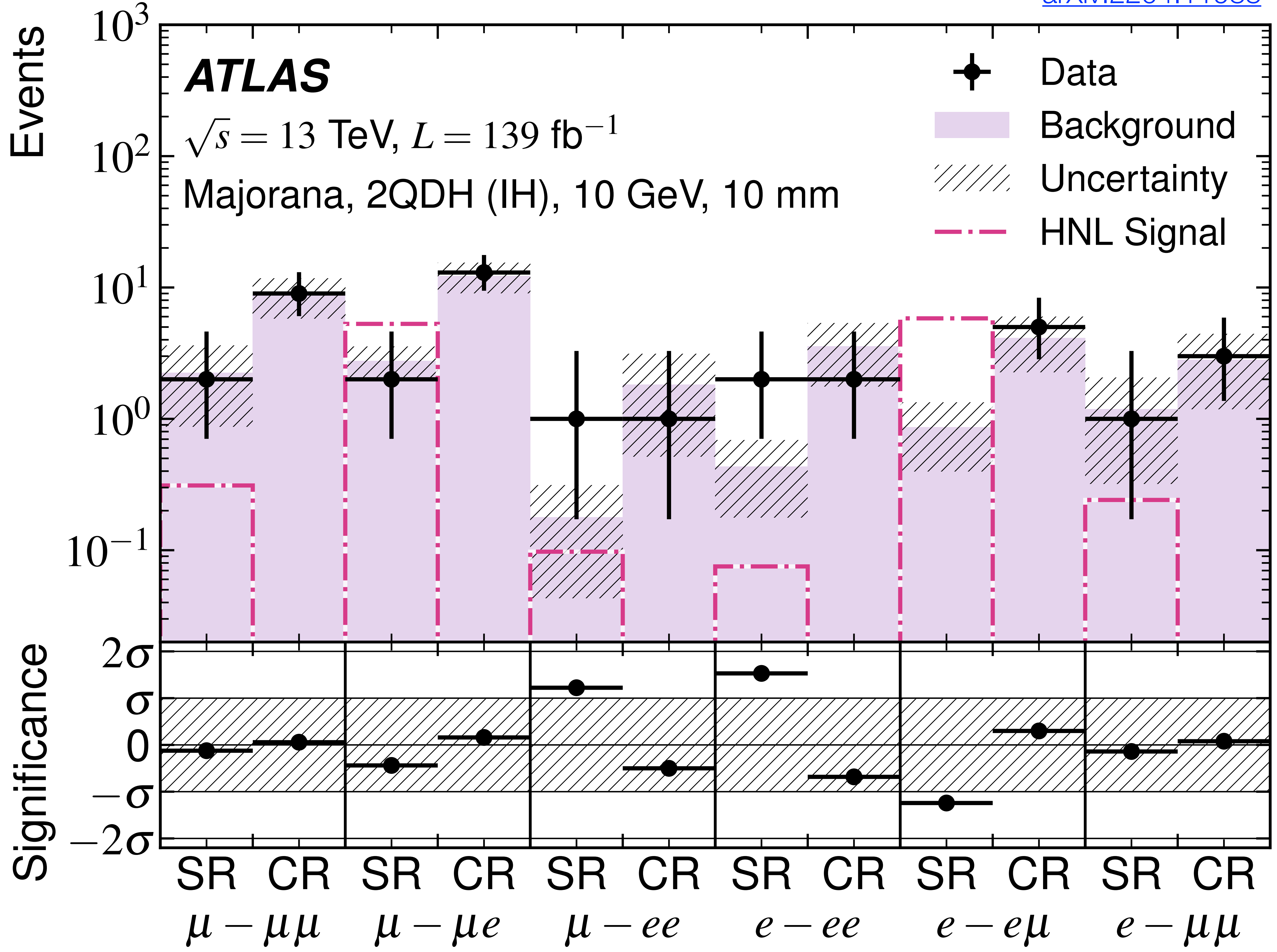
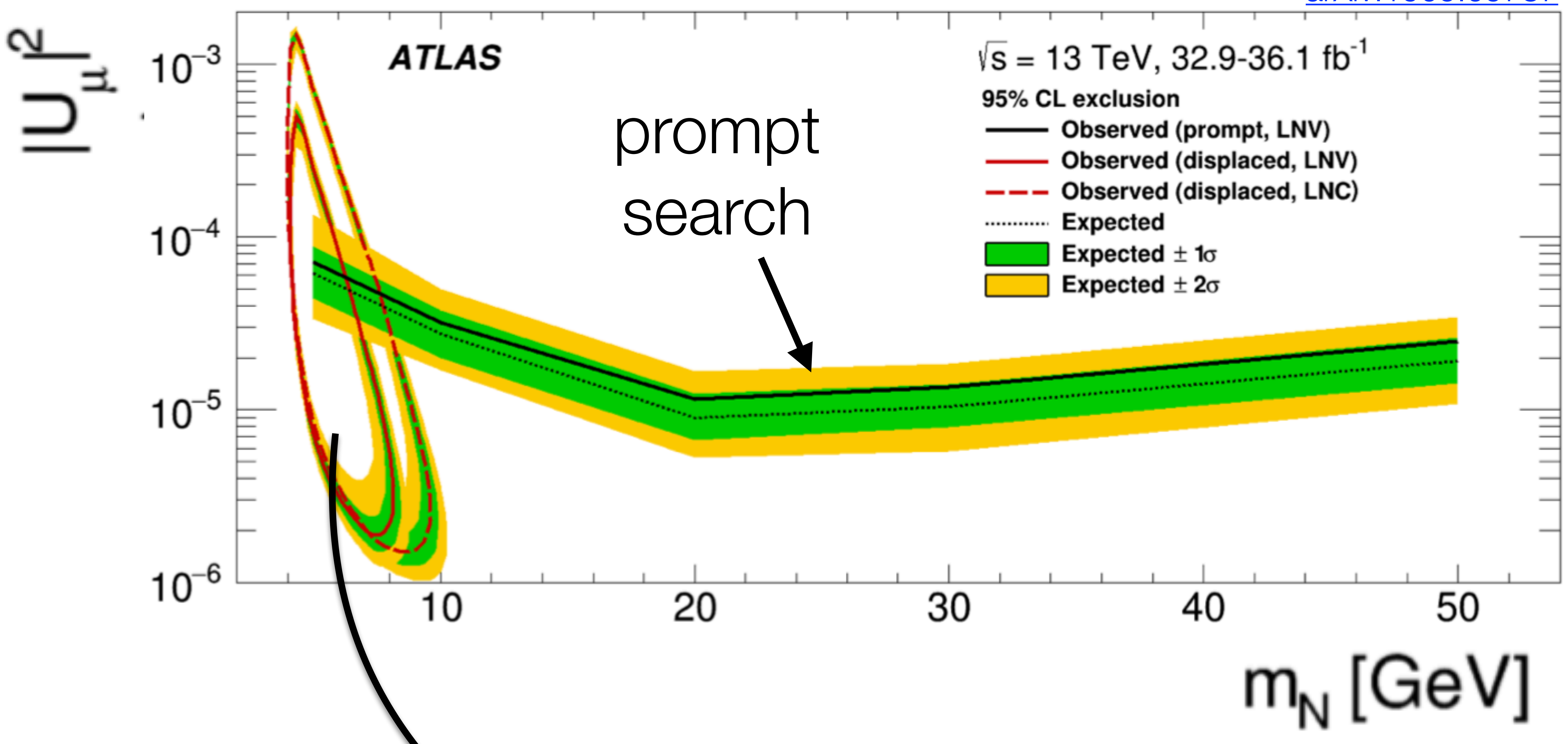


Limits For Muon-Only Mixing

Muon-only mixing

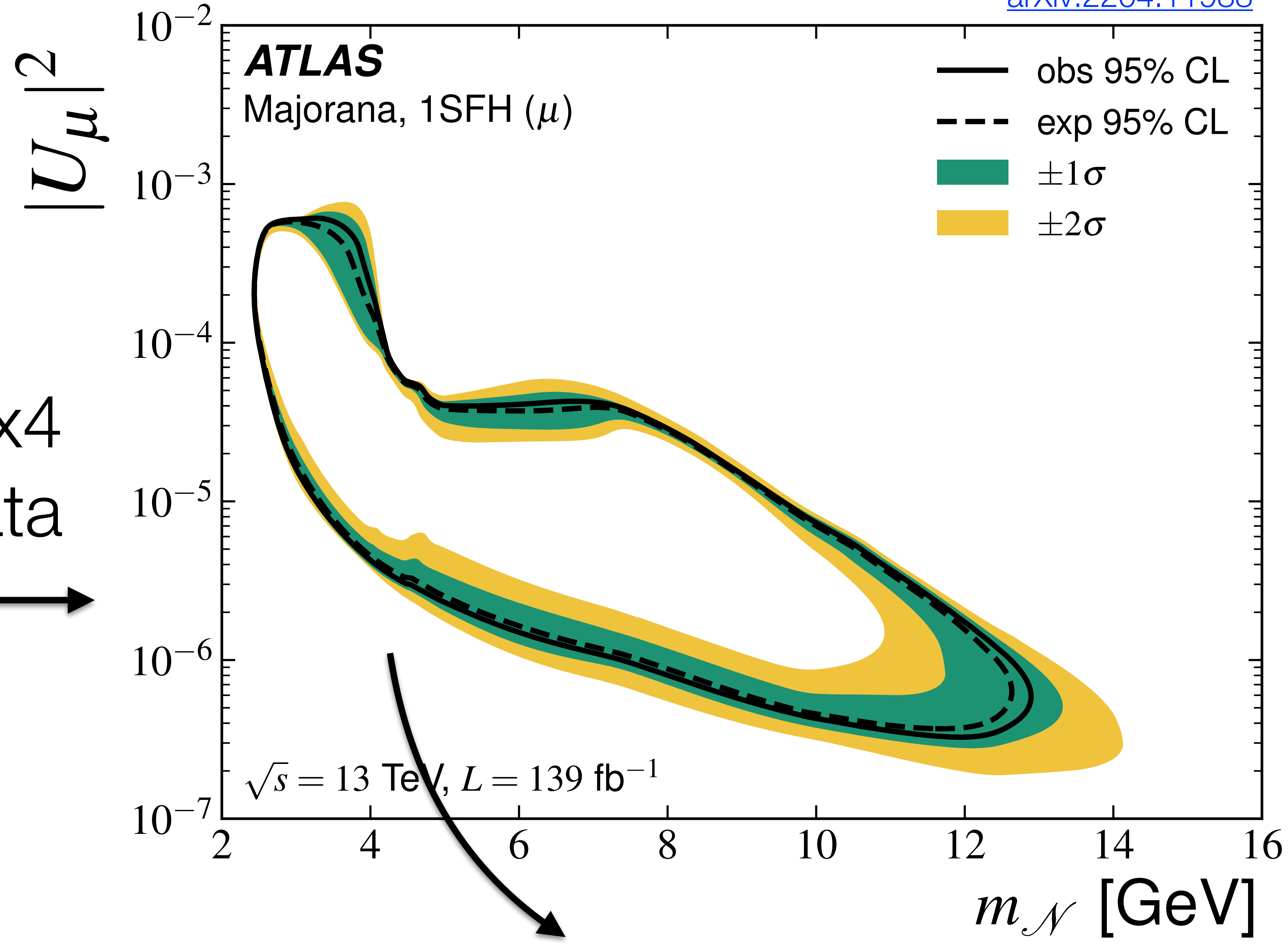
$U_e^2 : U_\mu^2 : U_\tau^2 = 0:1:0$

arXiv:1905.09787



~ x4 data

arXiv:2204.11988



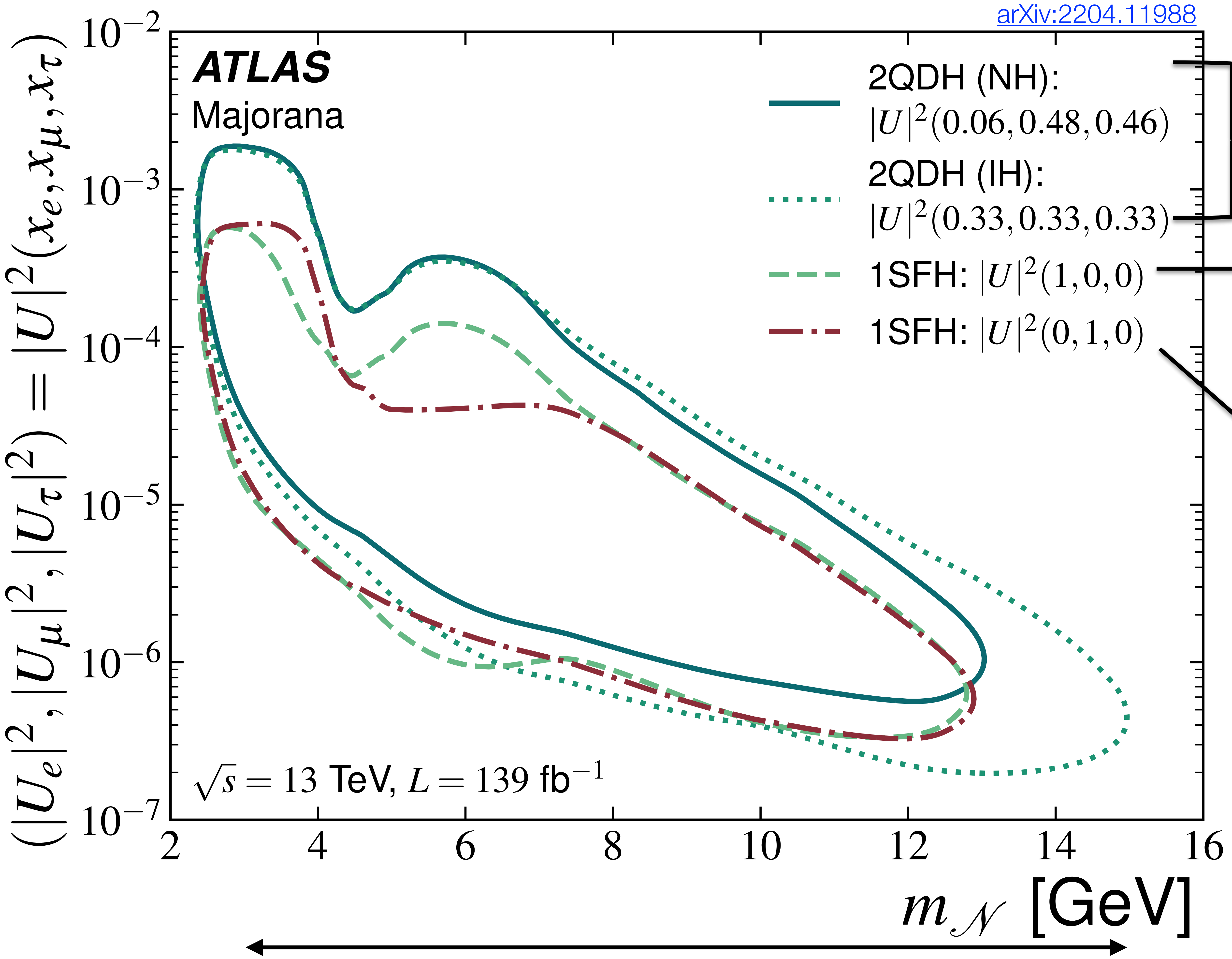
Displaced HNL result with **2016 data only**

2015-2018 Data Result:

low-mass: ~1 GeV improvement
high-mass: ~3 GeV improvement

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

Exclusion Limits Summary



$10^{-3} < |U|^2 < 10^{-7}$

$3 < m_N < 15$ GeV

Multi-flavour mixing — New!

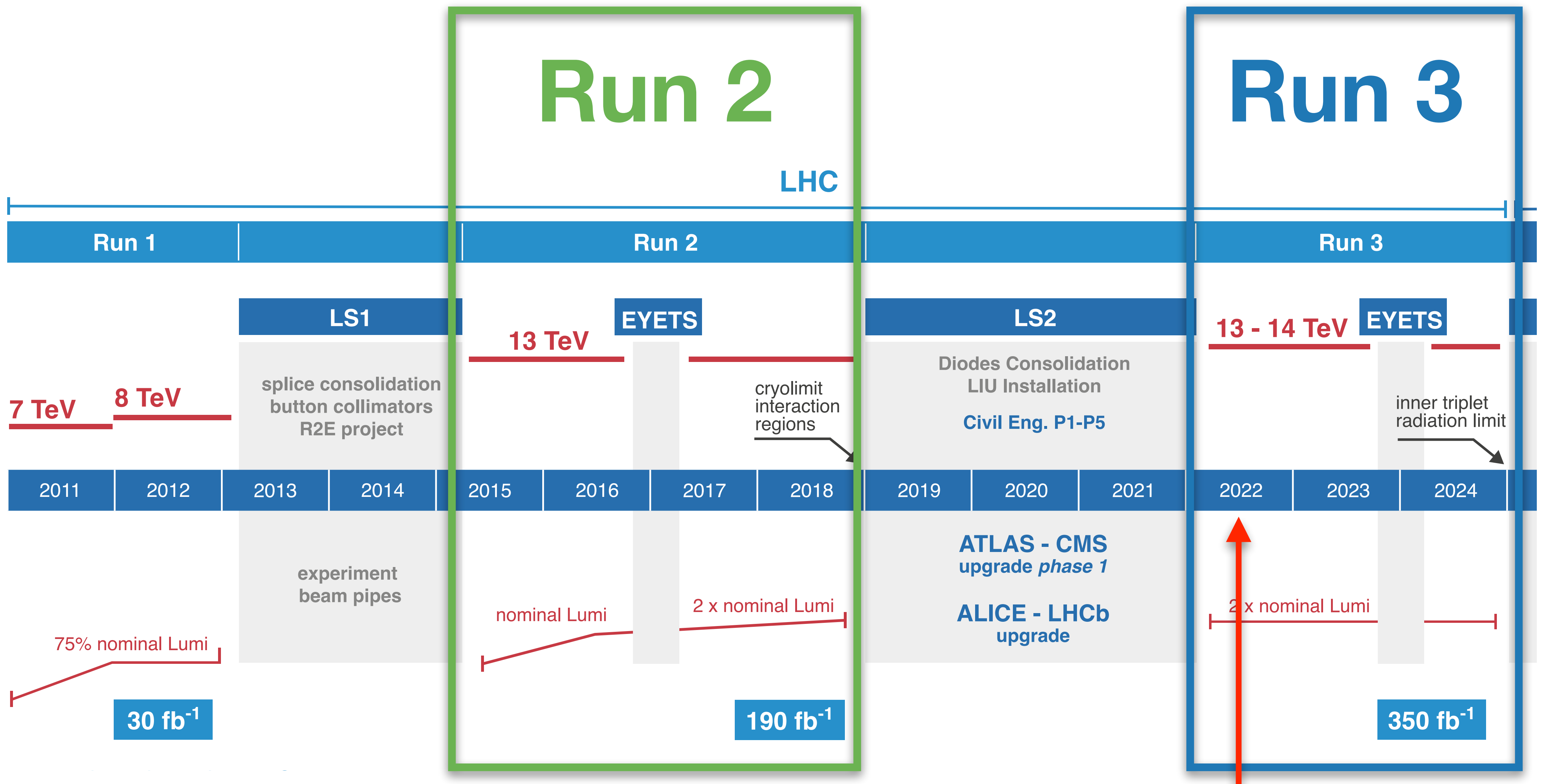
Electron-only mixing — New!

Muon-only mixing — More data!

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

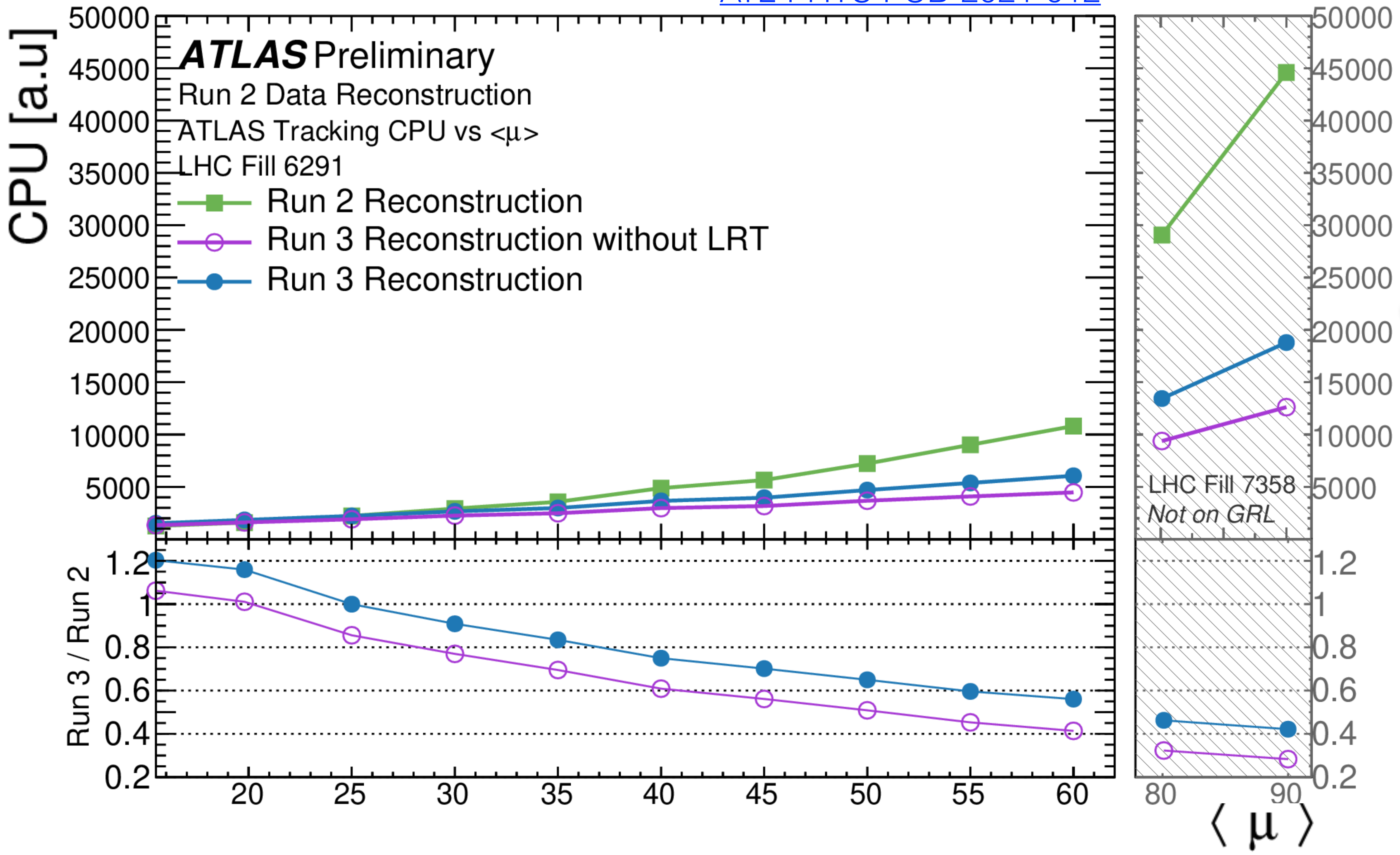
Future of Long-Lived Particle Searches

LHC timeline:



Today!

ATL-PHYS-PUB-2021-012



Reduced required CPU resources by a factor of ~2.

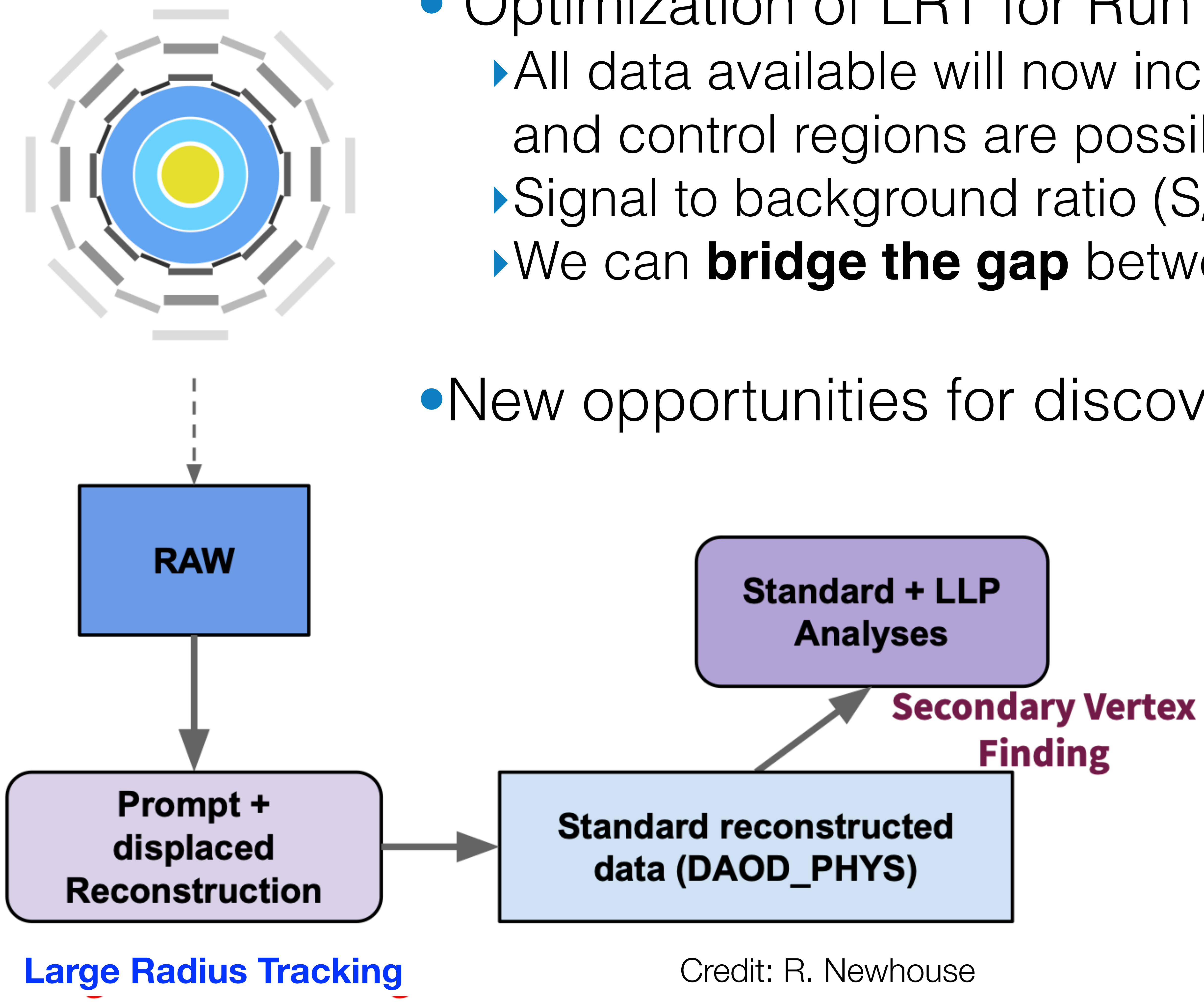
Avg. number of proton interactions per bunch-crossing

- Exciting prospects for next LHC data taking period (Run 3)
  - Optimization of large radius tracking (LRT)
  - Lots of room for improvements in long-lived particle (LLP) searches with displaced tracks

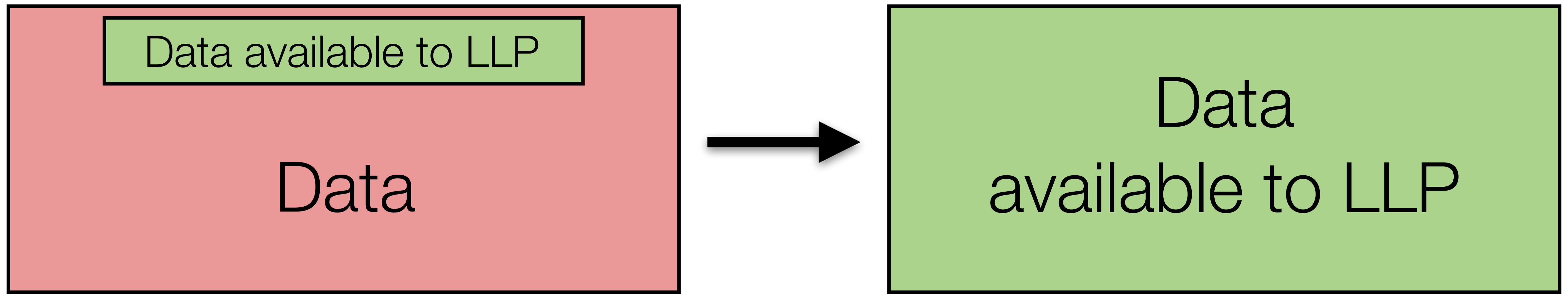
Future of Long-Lived Particle Searches

- Optimization of LRT for Run 3 will mean:
  - All data available will now include displaced reconstruction → better validation and control regions are possible
  - Signal to background ratio (S/B) improves dramatically (fewer fake tracks!)
  - We can **bridge the gap** between **prompt** and **long-lived** searches

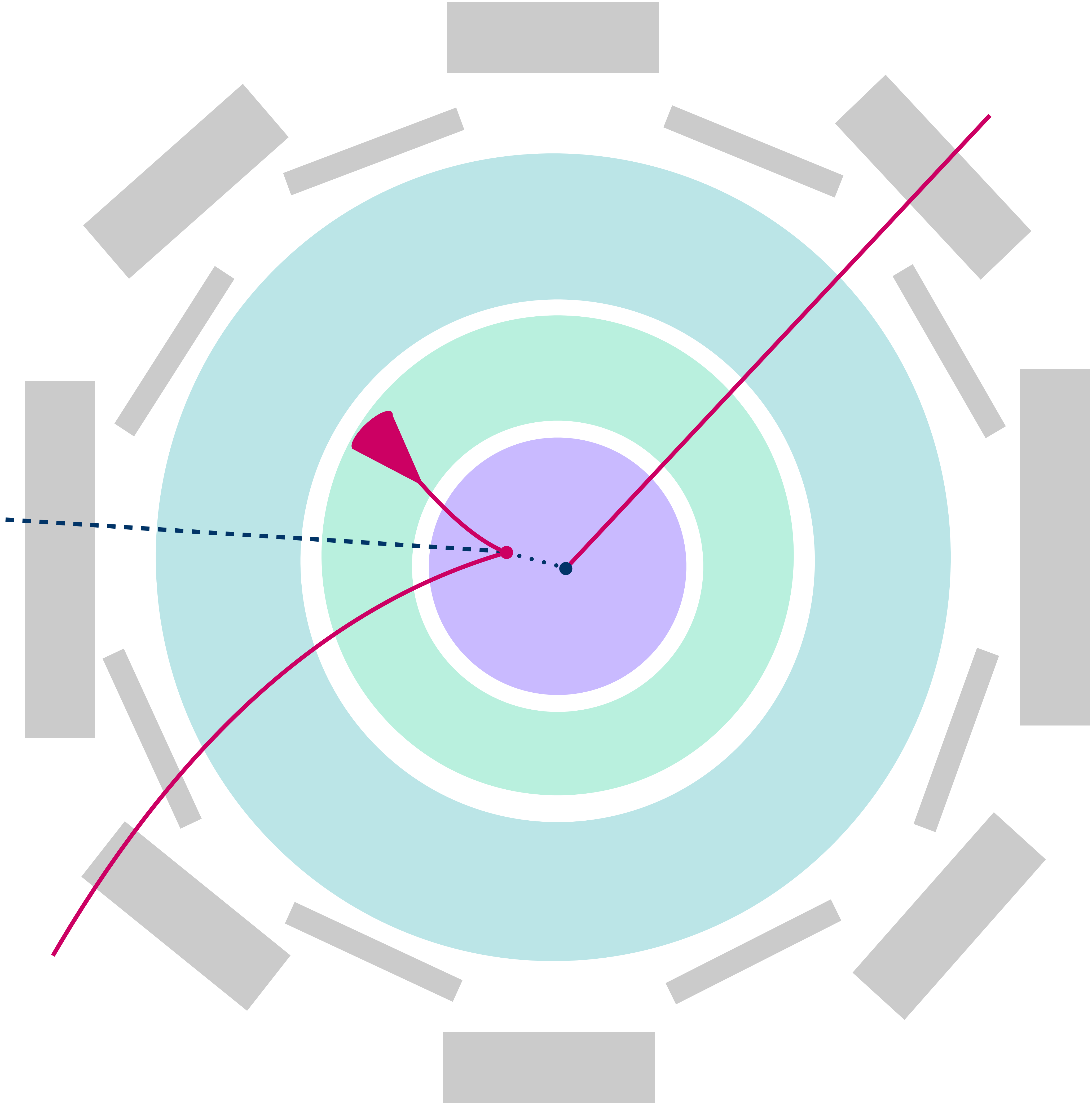
- New opportunities for discovery!



Credit: R. Newhouse



Summary



Displaced Vertex Search for Heavy Neutral Leptons

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

Acknowledgements — Thank you!

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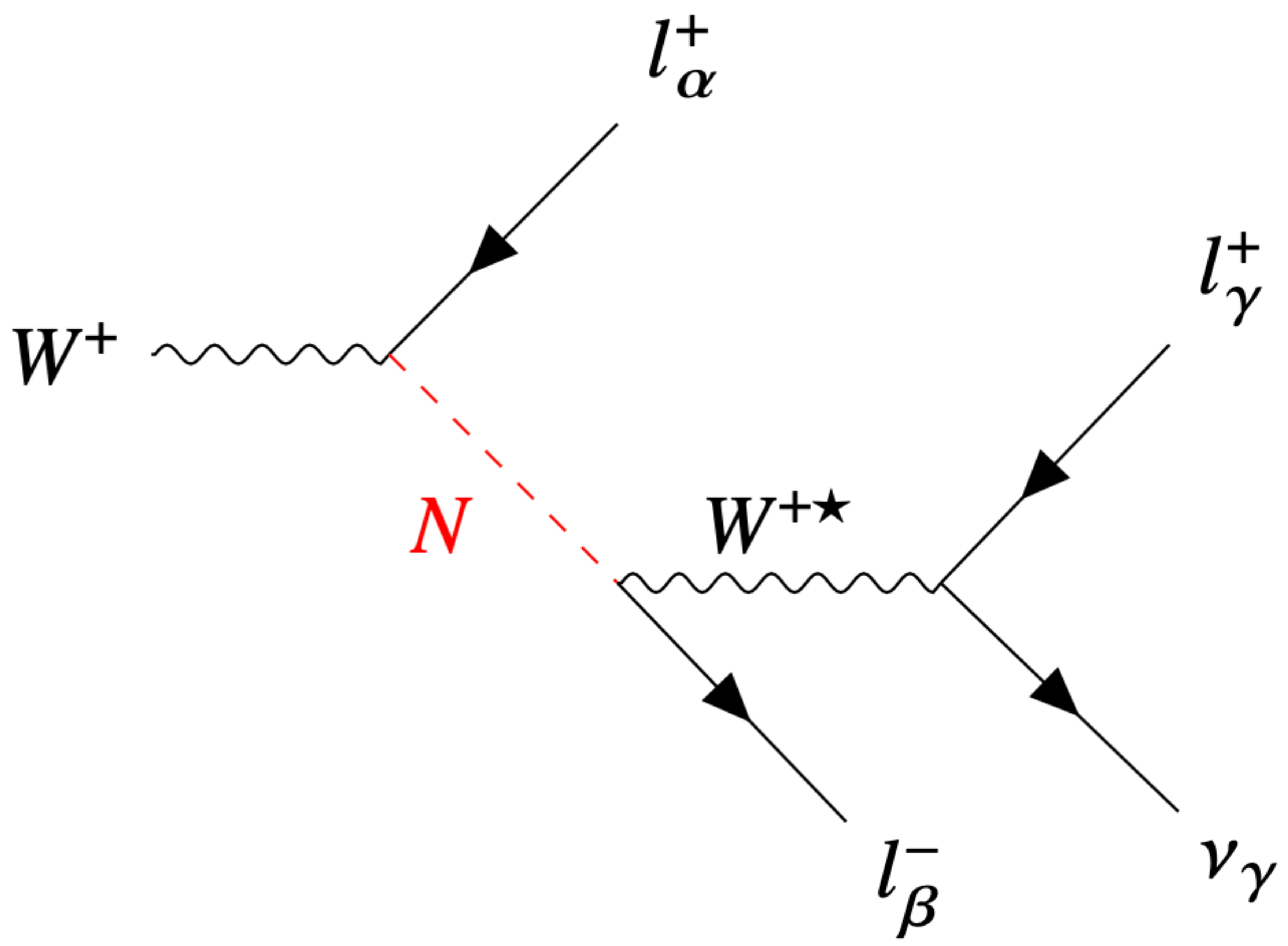
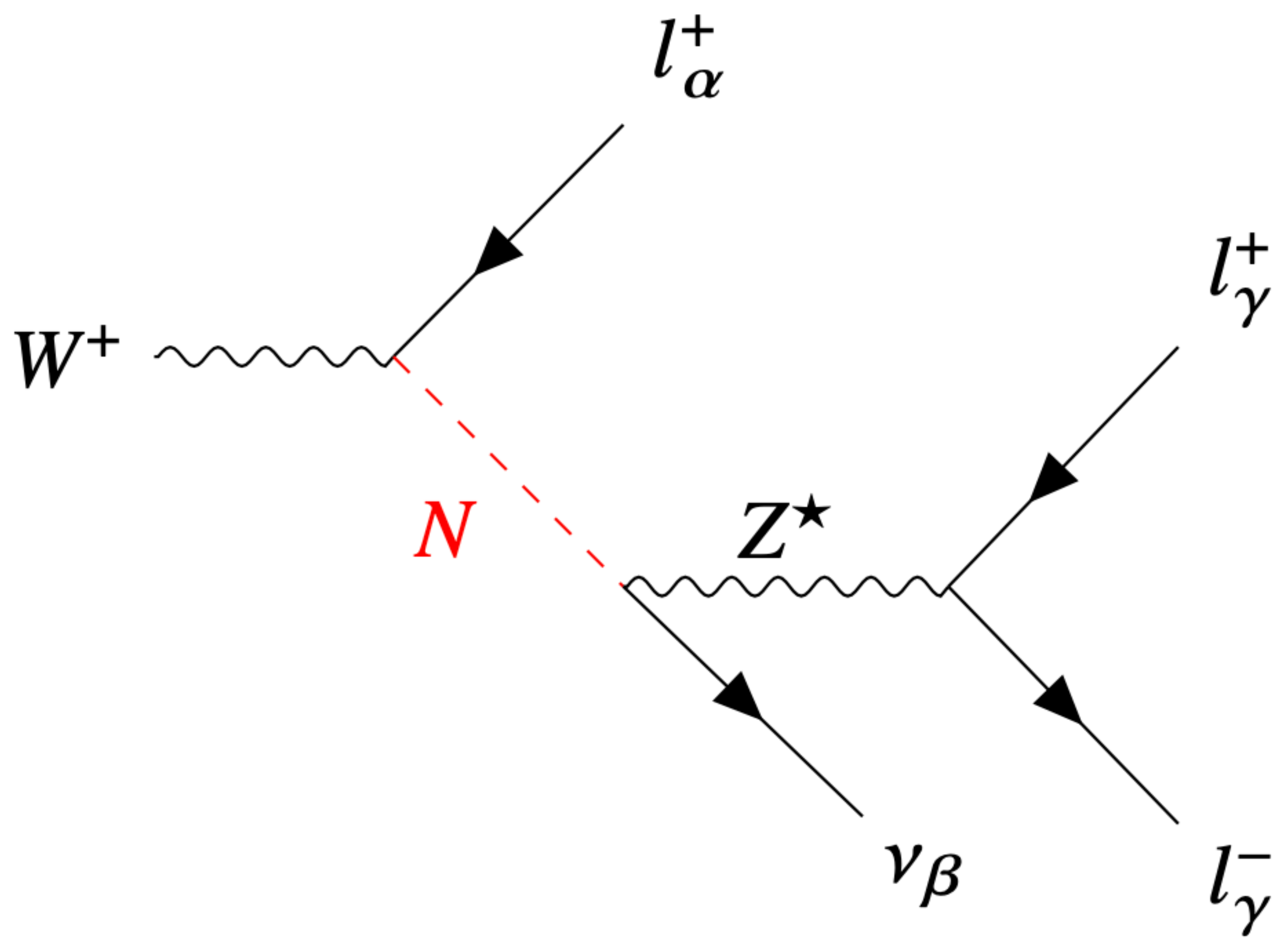
Backups

HNL Production and Decay



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



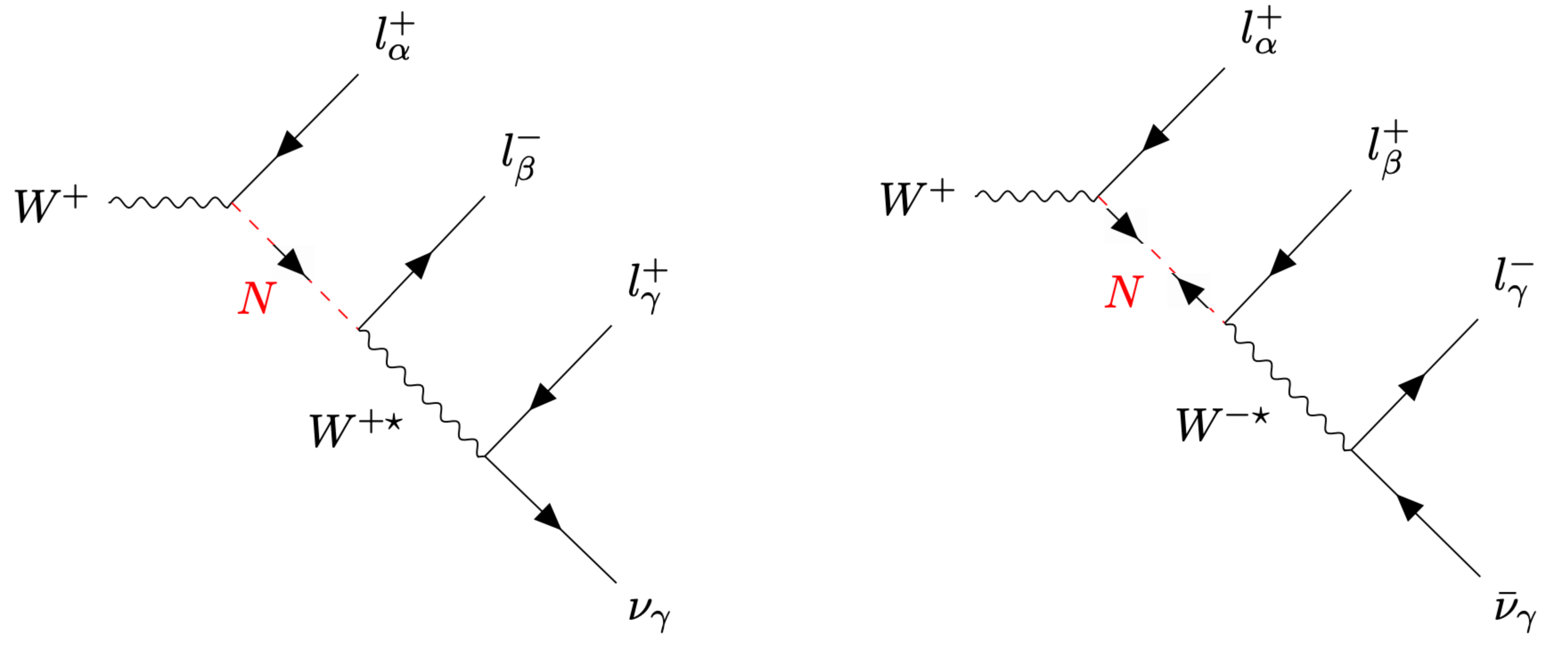
(b) Neutral current decay ($\alpha - \gamma\gamma$)

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)



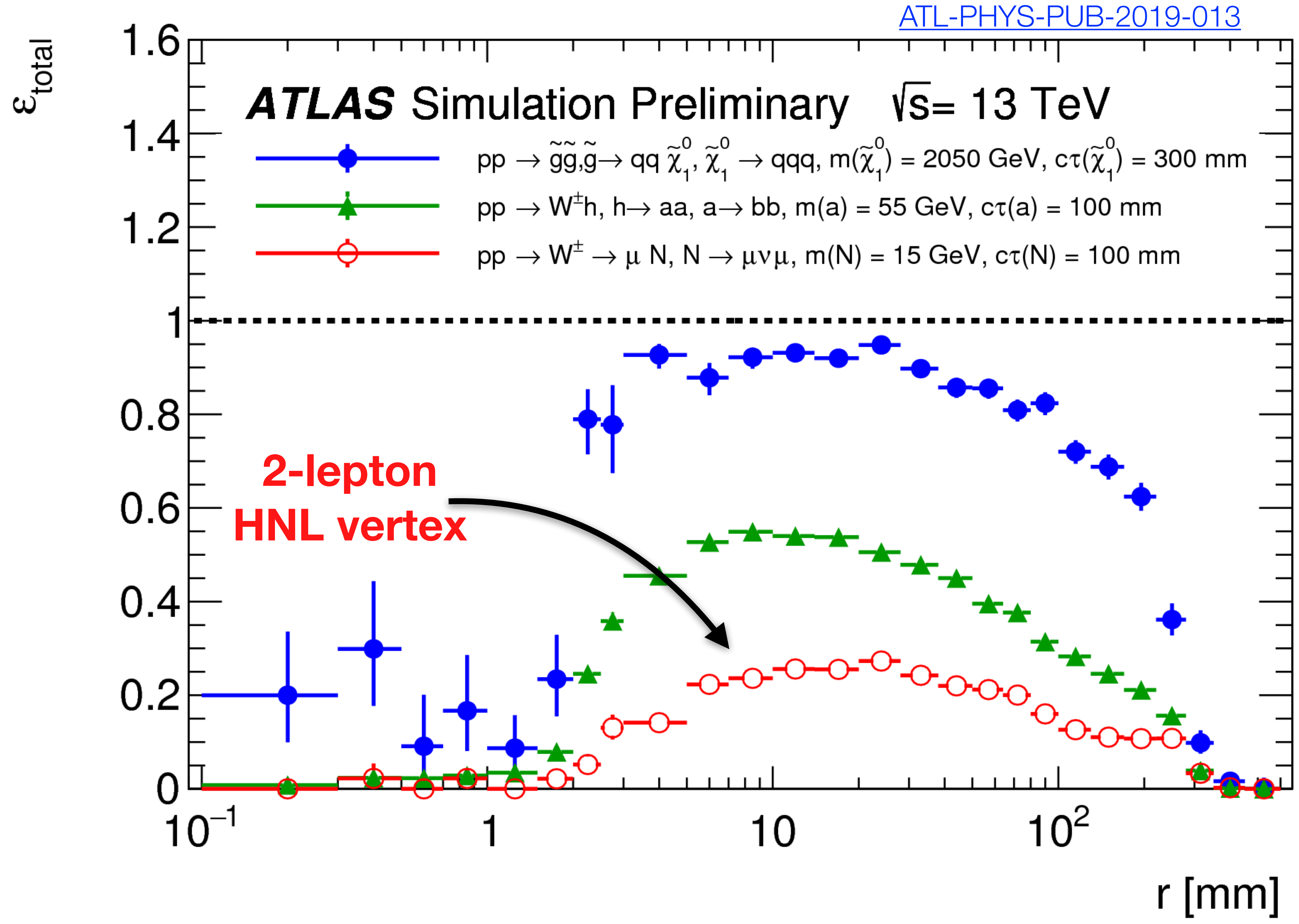
(a) LNC (b) LNV

Different angular distributions!

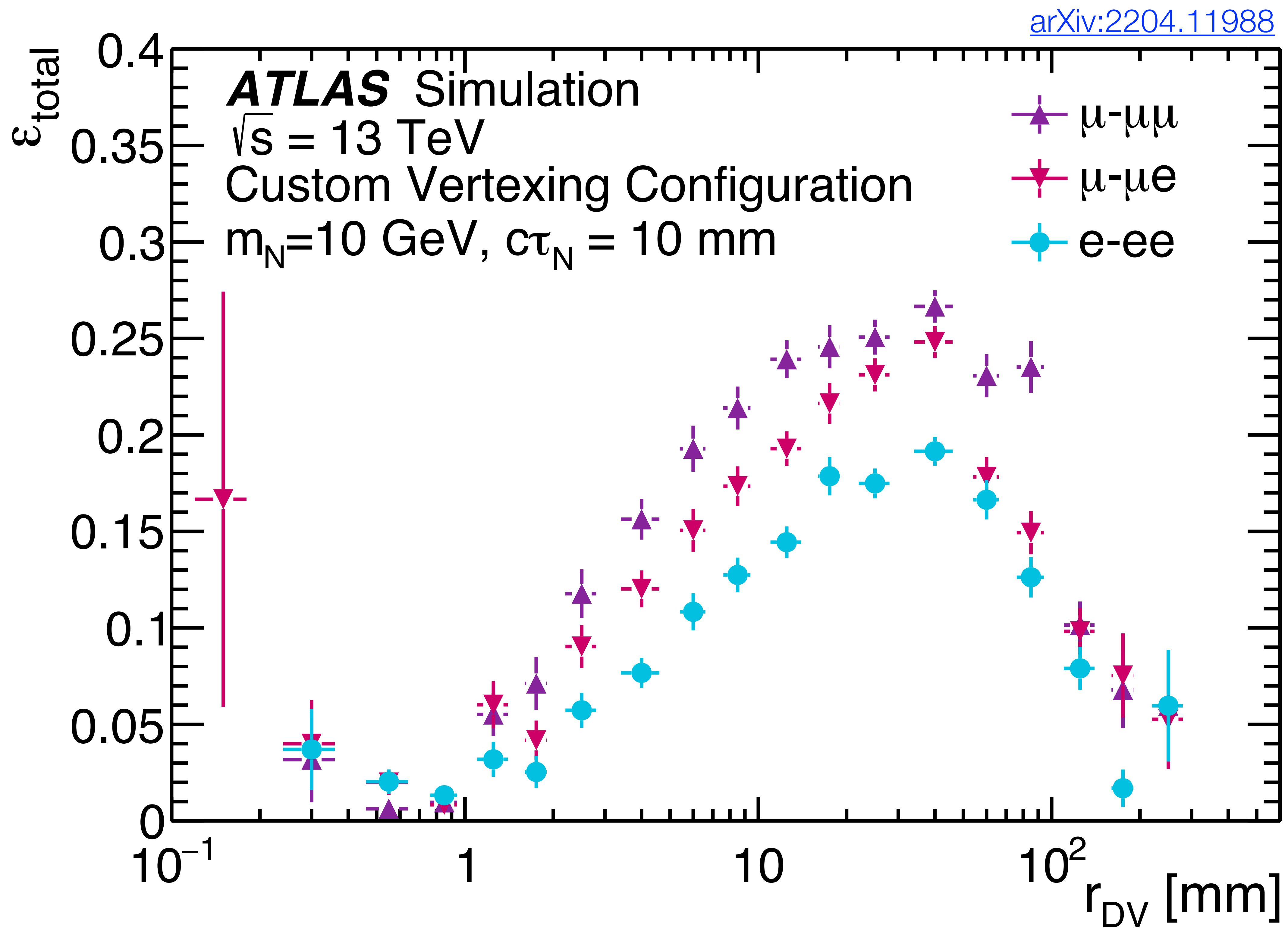
Analysis Selections

Level	Selection	Value
Pre-selection	Event cleaning	Standard ATLAS event cleaning
	Trigger	Pass at least one single muon or electron trigger
	Trigger matched lepton	At least one lepton with *Medium* (or *LHMedium*) quality
	Primary Vertex	At least one (standard ATLAS selection)
	DRAW Filter	Pass any HNL filter
	Prompt lepton quality	*Medium* (muons) or *LHMedium* (electrons)
	Prompt lepton impact parameters	$d_0 < 3$ mm and $\|z_0 \sin\theta\| < 0.5$ mm
	Trigger matched lepton	At least one
	Cosmic veto	$\sqrt{(\Sigma\eta)^2 + (\pi - \Delta\phi)^2} > 0.05$
	Displaced lepton-only vertex	At least one
	Number of tracks in DV	2
	Fiducial volume	$4 < L_{xy} < 300$ mm
SR selection	DV charge	Opposite-sign tracks
	Prompt+ disp. l charge	Opposite-sign leptons (one Dirac HNL single-flavour mixing model only)
	DV type	ee, $e\mu$ or $\mu\mu$ vertex
	Displaced lepton quality	*Medium* (muons), *VeryVeryLoose* (electrons)
	Material veto	Applied for ee DVs only
	B-hadron veto	$m_{DV} > 5.5$ GeV ($\mu\mu$ DVs) or Diagonal m_{DV}-L_{xy} cut (ee or $e\mu$ DVs)
	Z mass veto	$m_{prompt+disp.lep.} < 80$ or $m_{prompt+disp.lep.} > 100$ GeV if prompt and displaced leptons have same flavour and OS
	Tri-lepton mass	$40 < m_{lll} < 90$ GeV
	HNL mass	$m_{\text{HNL}} < 20$ GeV

Long-Lived Non-Standard Reconstruction



Standard Vertexing



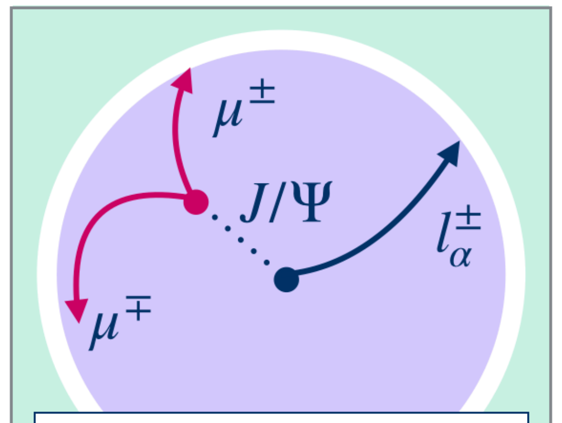
Custom Lepton-Only Vertexing

Metastable Particle Decays

- DV mass and radius selections used to remove OS backgrounds
  - Study data events in validation region (VR)
- Regain sensitivity to low DV mass HNLs using DV mass and radius cut
  - Selection is sufficient to remove J/ψ→μμ decays, so a flat DV mass only cut is used.

Metastable particle veto:

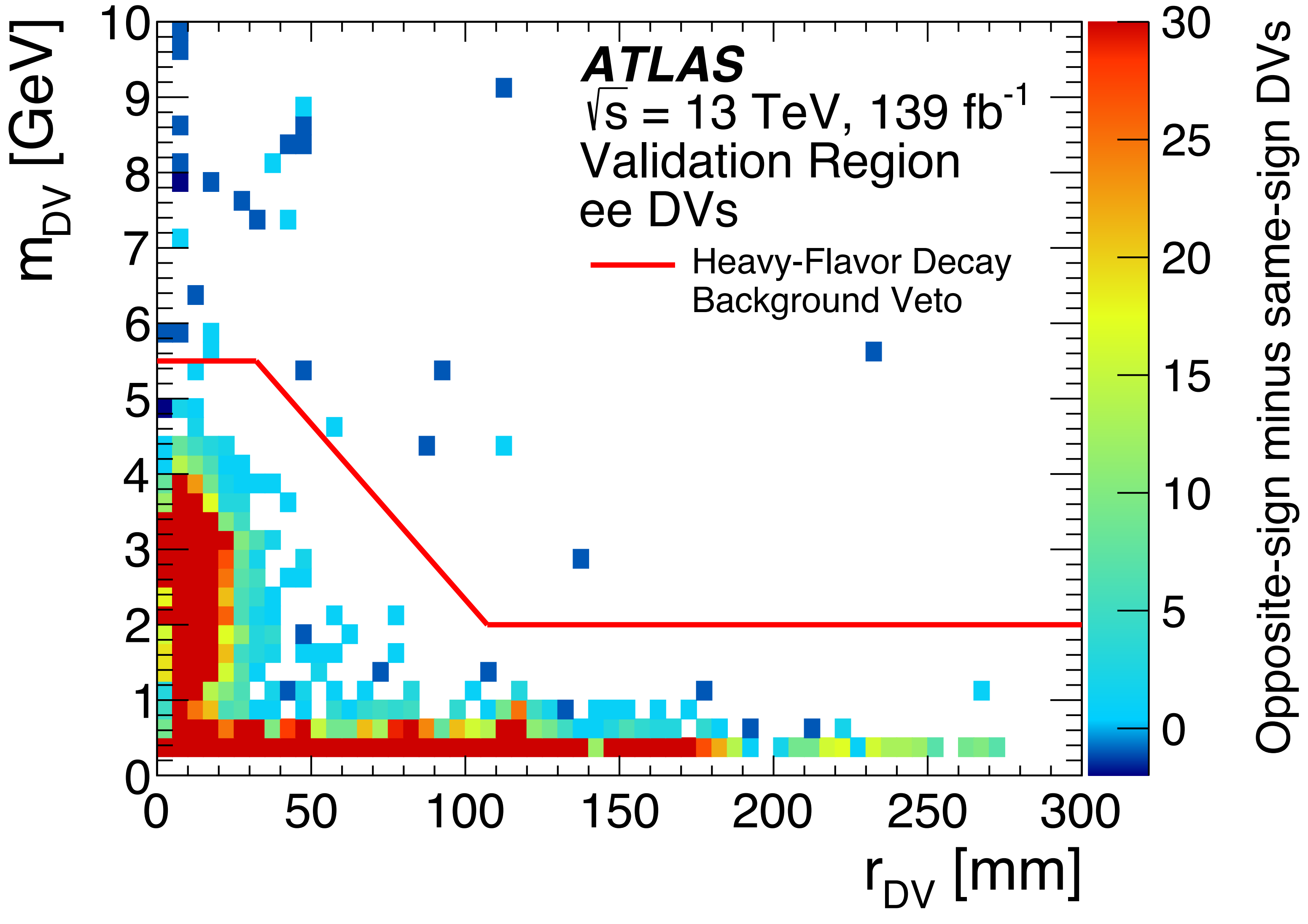
- DV Mass Cut (e-μμ and μ-μμ) : $m_{DV} > 5.5$ GeV
- Diagonal Cut (e-eμ, μ-μe, e-ee and μ-ee):
  - $m_{DV} > 5.5$ GeV , if $r_{DV} < 32$ mm
  - $m_{DV} > -\frac{7\ \mathrm{GeV}}{150\ \mathrm{mm}} r_{DV} + 7$ GeV, if $32\ \mathrm{mm} < r_{DV} < 107$ mm
  - $m_{DV} > 2$ GeV , if $r_{DV} > 107$ mm



Metastable Particle Decay
+ prompt lepton

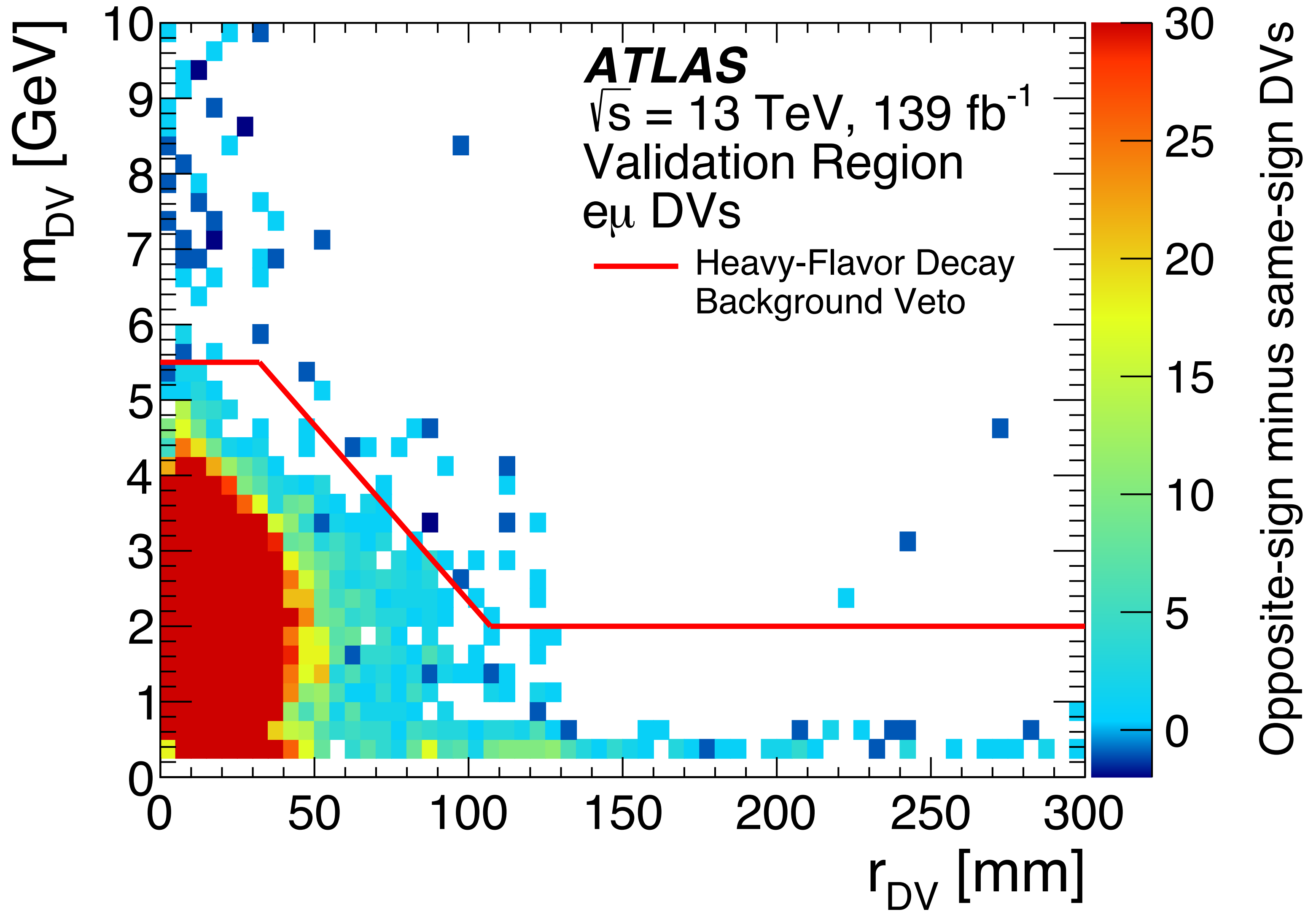
ee DVs

arXiv:2204.11988



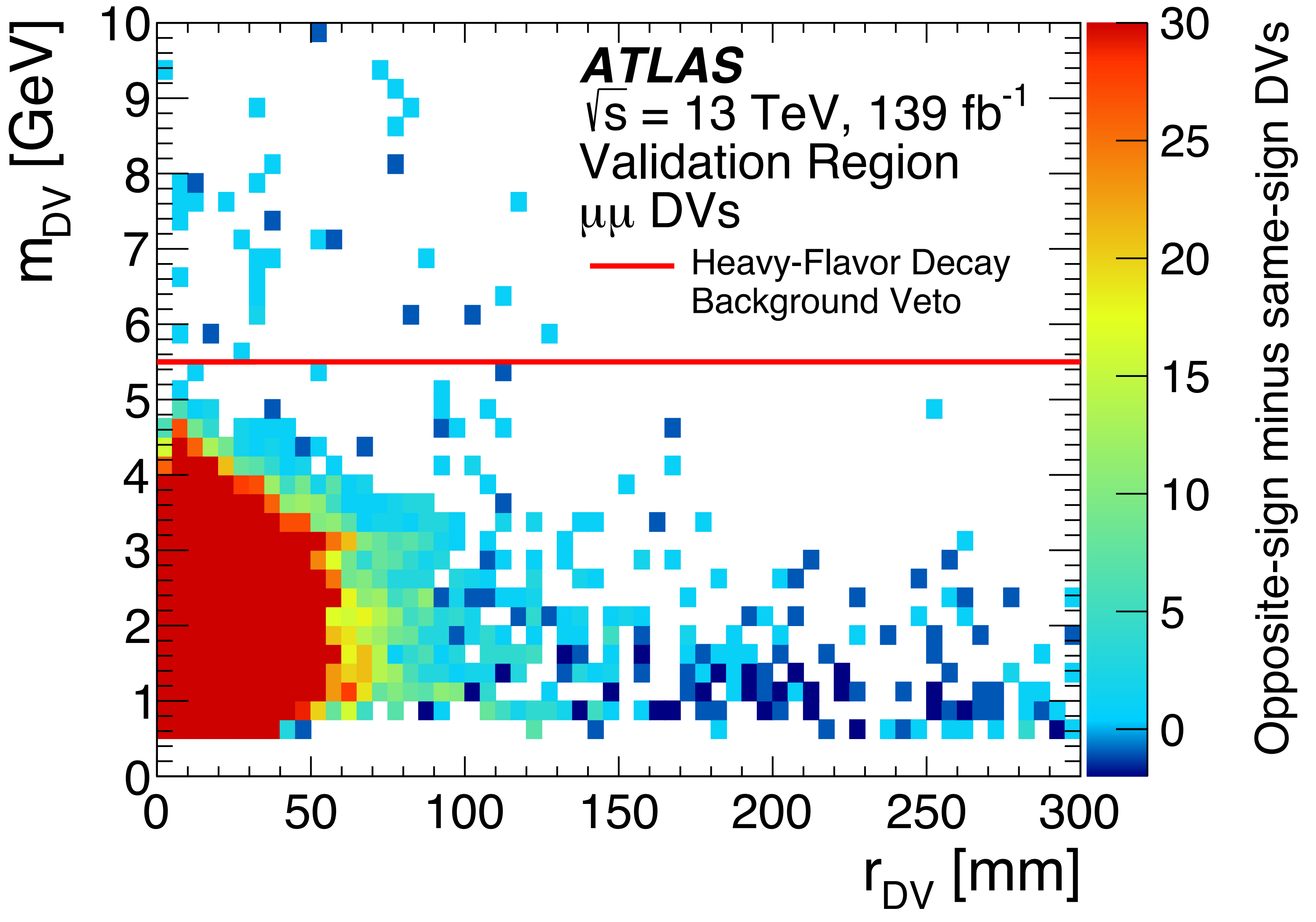
eμ DVs

arXiv:2204.11988



μμ DVs

arXiv:2204.11988



Displaced Vertex Systematic

EXOT-2019-29

Uncertainty Source Channel	Maximum Selection Efficiency Uncertainty [%] $\mu-\mu\mu$	 $\mu-\mu e$	 $\mu-ee$	 $e-ee$	 $e-e\mu$	 $e-\mu\mu$
Integrated luminosity	2					
Pileup	3					
Filter discrepancy	3					
Tracking	3					
Displaced vertexing	11	21	19	20	28	9
Lepton d_0 extrapolation	5	7	7	7	6	4
Trigger efficiency	< 1	1	< 1	< 1	< 1	< 1
Lepton reconstruction and identification	4	9	12	17	15	2
W cross section and modeling	3					
HNL branching fractions and decay	5					
Total	8 – 33					

- Largest contribution to the signal efficiency uncertainty is due to the **reconstruction of displaced vertices**
- This uncertainty is evaluated with $K_s^0 \rightarrow \pi^+\pi^-$ decays selected in **dijet simulations** and **data** in the validation region with zero prompt leptons
- The vertexing uncertainty is parametrized as a function of p_T and r_{DV}

Cross Section Systematics

EXOT-2019-29

Uncertainty Source Channel	Maximum Selection Efficiency Uncertainty [%] μ–$\mu\mu$	 μ–μe	 μ–ee	 e–ee	 e–$e\mu$	 e–$\mu\mu$
Integrated luminosity	2					
Pileup	3					
Filter discrepancy	3					
Tracking	3					
Displaced vertexing	11	21	19	20	28	9
Lepton d_0 extrapolation	5	7	7	7	6	4
Trigger efficiency	< 1	1	< 1	< 1	< 1	< 1
Lepton reconstruction and identification	4	9	12	17	15	2
W cross section and modeling	3					
HNL branching fractions and decay	5					
Total	8 – 33					

Cross section uncertainties:

- **W cross section** uncertainty is taken from ATLAS measurement of $\sigma(pp \to W) \cdot BR(W \to l_\alpha \nu)$
  - This 3% is also sufficient to cover and systematic from the W p_T modelling
- The uncertainty on the **HNL branching ratio** calculations are conservatively estimated by taking into account perturbative QCD corrections

HNL cross section:

$$\sigma_N = \sigma(pp \to W) \cdot BR(W \to l_\alpha \nu) \cdot x_\alpha \cdot |\Theta_{\text{tot}}|^2 \cdot \left(1 - \frac{m_N^2}{m_W^2}\right)^2 \left(1 + \frac{m_N^2}{2m_W^2}\right) \cdot BR(N \to l_\beta l_\gamma \nu)$$

3% (experiment)

5% (theory)

Other Signal Systematics

EXOT-2019-29

Uncertainty Source	Maximum Selection Efficiency Uncertainty [%]					
Channel	$\mu\!-\!\mu\mu$	$\mu\!-\!\mu e$	$\mu\!-\!ee$	$e\!-\!ee$	$e\!-\!e\mu$	$e\!-\!\mu\mu$
Integrated luminosity	2					
Pileup	3					
Filter discrepancy	3					
Tracking	3					
Displaced vertexing	11	21	19	20	28	9
Lepton d_0 extrapolation	5	7	7	7	6	4
Trigger efficiency	< 1	1	< 1	< 1	< 1	< 1
Lepton reconstruction and identification	4	9	12	17	15	2
W cross section and modeling	3					
HNL branching fractions and decay	5					
Total	8 – 33					

- Standard **luminosity**, **pile-up** uncertainties
- **Filter discrepancy** accounts for the difference between the objects selected in data and MC due to an event filter use to run displaced tracking
- **Track reconstruction** uncertainty is calculated with a central tool that randomly removes tracks with a probability parameterized in p_T and η
- **Displaced lepton d_0 extrapolation** accounts for the differences in lepton identification between data and MC when the leptons have a large d_0
- Standard **lepton calibration, identification, reconstruction and trigger** uncertainties

Fit Model

- A global fit for the signal strength ($\hat{\mu}$) performed using a profile likelihood ($\mathscr{L}$)

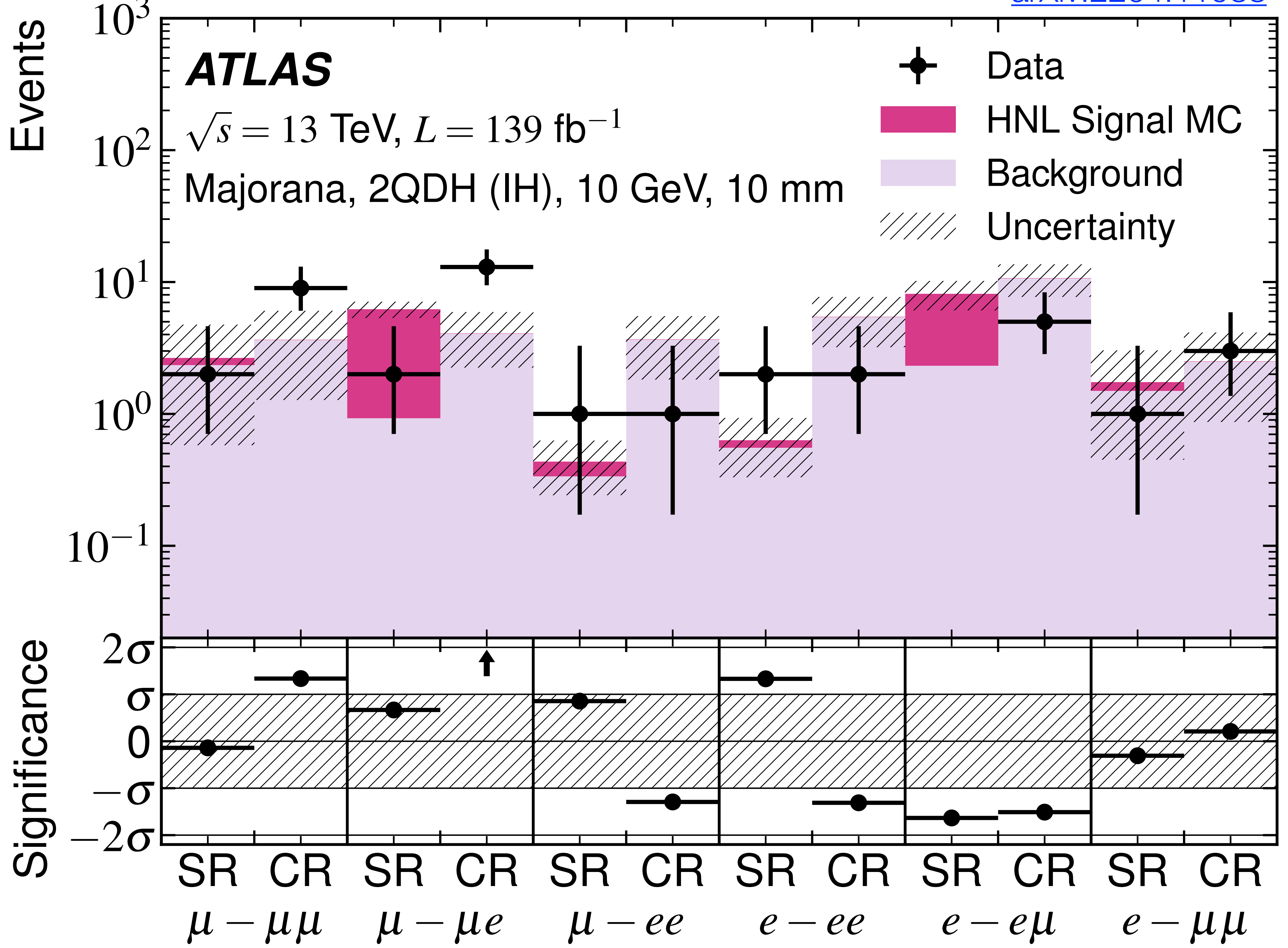
- Fit model inputs:
  1. Event yields from **data events** (OS DVs)
  2. Event yields from **simulated signal samples**
  3. Event yields from **shuffled background model**
     ↳ *free-floating normalization (6 separate factors; one for each channel)*

- Systematic uncertainties are included as nuisance parameters (θ)

- Inclusion of the **control region (CR)** in the fit **directly constrains** the predicted number of background events in the SR

$$\mathscr{L}(n\,|\,\mu, \mu_b, \vec{\theta}) = \prod_{i \in \text{bins}} P\left(n_i \,\middle|\, \mu S(\vec{\theta}) + \mu_b B(\vec{\theta})\right) \cdot \underbrace{\prod_{j \in \text{NP}} G(\theta_j)}_{\text{systematics}}$$

arXiv:2204.11988



Highlight of Changes to LRT in Run 3

See ATL-PHYS-PUB-2021-012 for more details!

Tightening of cuts which are applied at several stages of track reconstruction

The earlier the cuts can be applied, the less CPU time is wasted processing fake tracks in later steps

Only SCT is used for seeding as opposed to SCT or Pixel seeds

Changes in the seed ranking decides the order in which tracks are processed

3-space-point seeds must be confirmed by a fourth

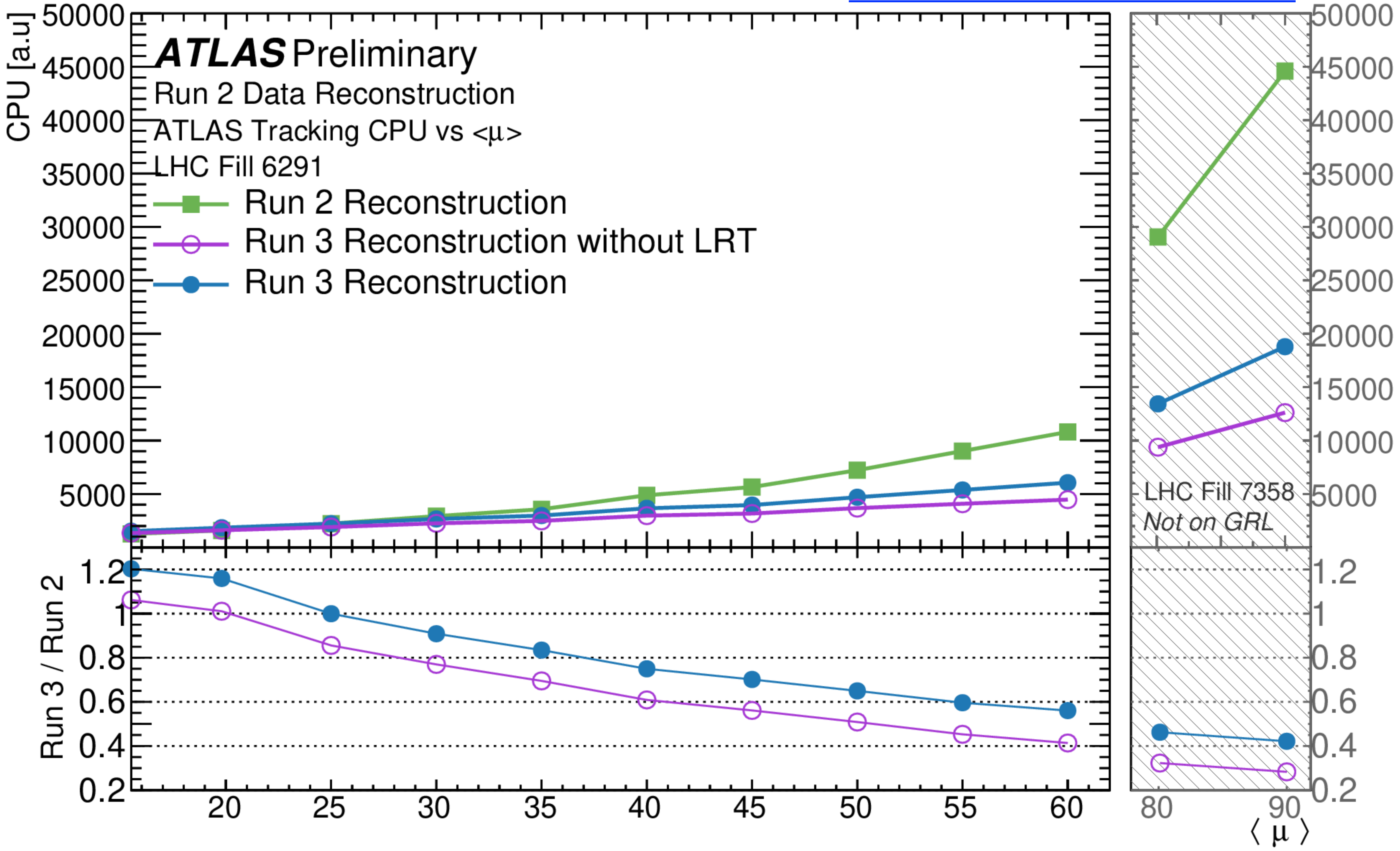
CPU dominated by *track finding* and *ambiguity resolution* steps

Credit: R. Newhouse

LRT in Run 3

CPU

ATL-PHYS-PUB-2021-012



Disk Space

ATL-PHYS-PUB-2021-012