Characterizing long-lived HNLs at forward-physics experiments in the presence of a signal excess

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Anaheim CA , Mar 19th 2025

UCI Department of Physics & Astronomy

Heavy Neutral Leptons (HNLs)

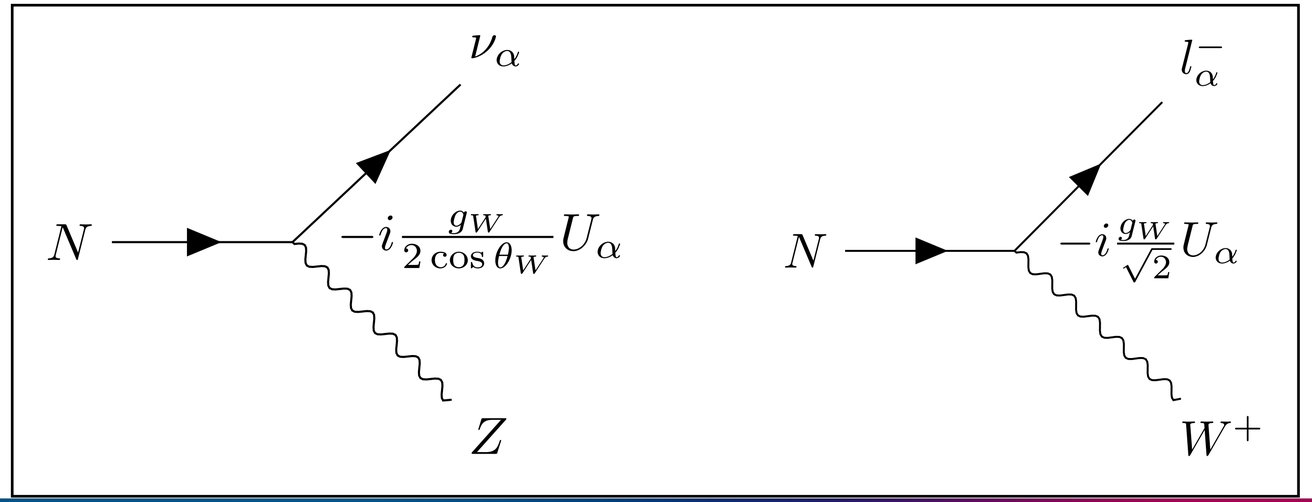
- A simple solution to the neutrino mass problem is the introduction of a **right-handed sterile neutrino** (**HNL** if referring to the mass eigenstate)
- After diagonalization, HNLs these give mass to active neutrinos
- This allows for the inclusion of a **Dirac mass** through a Yukawa interaction after electroweak symmetry breaking (EWSB)
- Additionally, one can incorporate **Majorana mass** terms which violate lepton number

$$\mathscr{L} \supset -\sum_{\alpha} Y_{\alpha}\bar{L}_{\alpha}\tilde{\phi}N' - M_R\overline{N'^{c}}N' - \sum_{\alpha\beta}\frac{C_5^{\alpha\beta}}{\Lambda}\bar{L}_{\alpha}\tilde{\phi}\tilde{\phi}^{T}L_{\beta}^{c} + \text{h.c.}$$

Dirac

Majorana

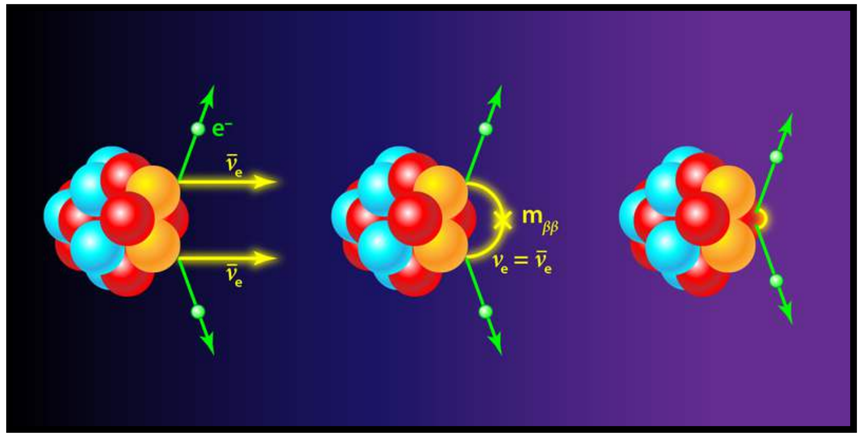
$$M_{\nu} = \begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix} \rightarrow \nu_{\alpha} = \sum_{i=1}^{3} V_{\alpha i}\nu_i + U_{\alpha}N^{c}$$



Dirac vs. Majorana

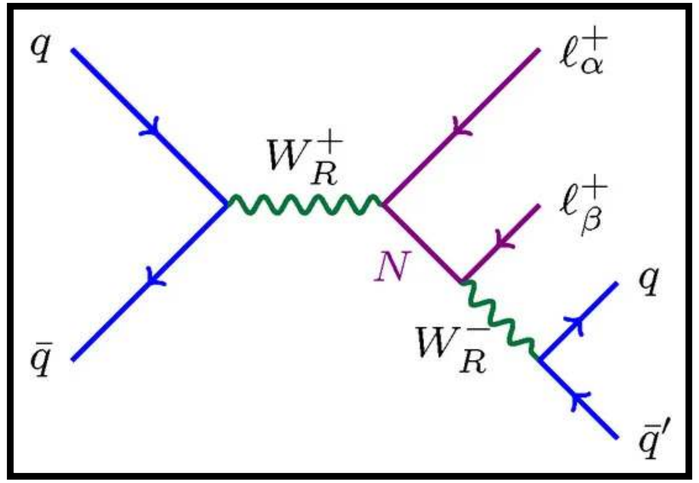
- An important questions:
  - are neutrinos Dirac or Majorana?
  - is lepton number violation (LNV) allowed in the SM?
- Direct tests of LNV have been carried out for decades in lab and collider based experiments:
  - $0\nu\beta\beta$ (Furry 1939)
  - $pp \to l^{\pm}l^{\pm}jj$ (Keung and Senjanović 1983)

Neutrinoless double beta decay



[https://physics.aps.org/articles/v11/30]

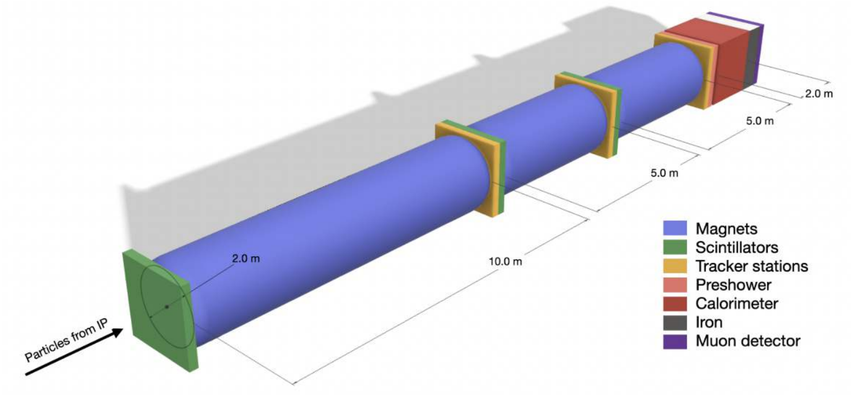
$$pp \to l^{\pm}l^{\pm}jj$$



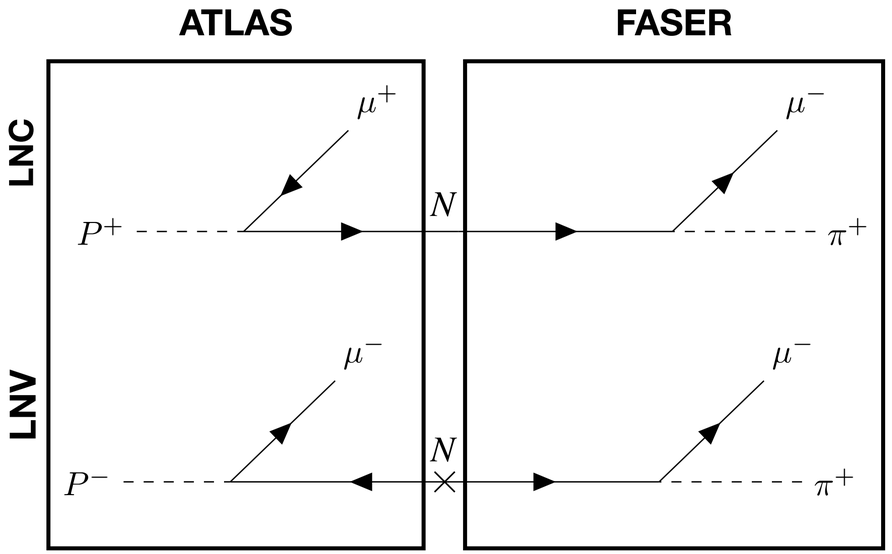
[https://www.mdpi.com/2218-1997/8/3/164]

Characterizing HNLs with FASER2

- Driving questions:
  - How well can FASER2 estimate the HNL model parameters in the event of signal detection?
  - Is it possible to discriminate between Dirac and Majorana HNLs using FASER2?
- FORward Experiment SEnsitivity Estimator (FORESEE):
  - MC event generator used to simulate forward physics LLP searches with customizable detector geometries
  - Recently updated to include HNL phenomenology
    - Feng J.L., Hewitt A., Kling F., **La Rocco D.** 2024 (2405.07330)
- Approaches to Model Discrimination:
  - Energy distributions as a probe of lifetime
  - FASER2 as a trigger for ATLAS

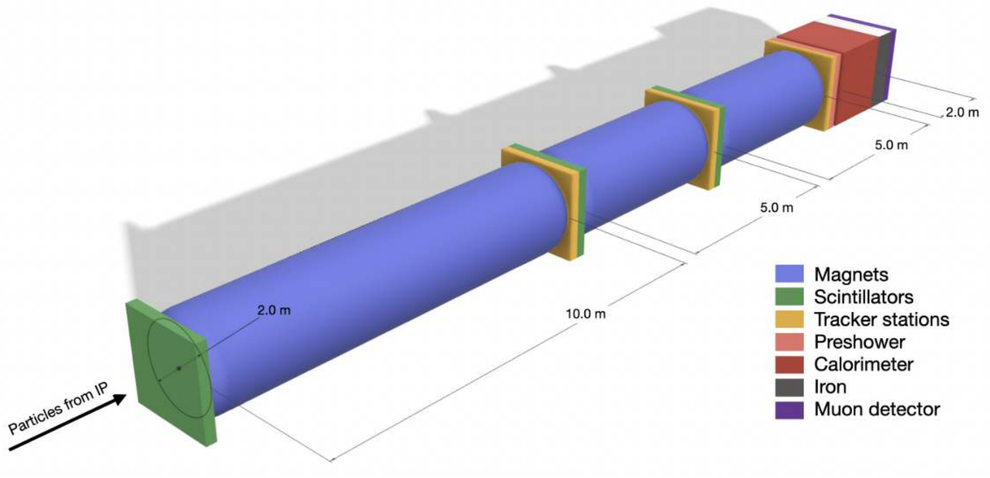


[Feng et al. 2203.05090]

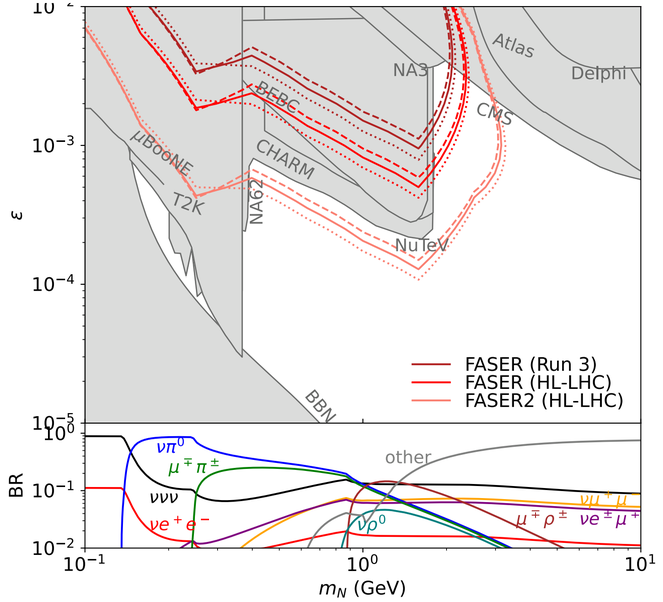


FPF: FASER2

- The Forward Physics Facility (FPF) is a proposed underground facility to house a suite of forward physics experiments during the High-Luminosity LHC era (HL-LHC)
- FASER2 is a proposed FPF experiment designed to detect forward boosted LLPs produced at the ATLAS interaction point
- Features an enlarged decay volume relative to FASER (ForwArd Search ExpeRiment)
- Located 650 meters down the beam axis, with a rectangular decay volume with cross-section $3\ \text{m} \times 1\ \text{m}$ and length $\Delta = 10\ \text{m}$.
- Angular coverage of $\theta \lesssim 2.4$ mrad ($\eta \gtrsim 6.7$)



[Feng et al. 2203.05090]



Generated in FORESEE

$|U_\mu| = \varepsilon$

Asymptotic Maximum Likelihood Fit

- First we need a **test statistic**, q, which determines the level of agreement between pseudo-data and the fitted model
  - Small $q \implies$ Large $L(m_N, U_\mu)$
- We perform a binned **profiled maximum likelihood (ML)** fit
  - $\vec{d} = (d_1, \ldots, d_N)$
  - α : Correlated Uncertainty ($\sigma_{flux} = 35\,\%$)
    - Driven by uncertainties in forward hadron production
  - γ_i : Uncorrelated Uncertainty ($\sigma_{MC} = 10\,\%$)

Test Statistic

$$q(\vec{d}\,; m, U) := -2 \ln \frac{L(\vec{d}\,; m, U, \vec{\theta}_{min})}{L(\vec{d}\,; \hat{m}, \hat{U}, \hat{\vec{\theta}}_{min})}$$

Profiled Likelihood

$$L(\vec{d}\,; m, U, \vec{\theta} = \{\vec{\gamma}, \alpha\}) = \prod_i f_P\left(d_i\,; \alpha\gamma_i\mu_i^{mc}\right) G\left(1; \gamma_i, \sigma_{mc}\right) G\left(1; \alpha, \sigma_{flux}\right)$$

$$f_P(d;\mu) = \frac{\mu^d}{d!}e^{-\mu} \qquad G(d;\mu,\sigma) = \frac{1}{\sqrt{2\pi\sigma}}e^{-(d-\mu)^2/2\sigma^2}$$

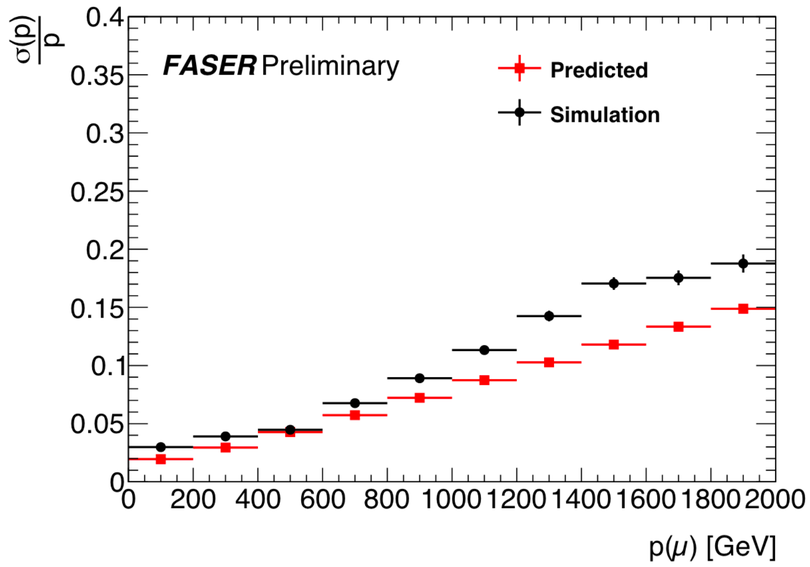
$$p = \int_{q_{min}}^{\infty} f_q(\vec{d}; q')dq'$$

Signal & Measurement Uncertainty

- In this work, we restrict ourselves to the case of a Majorana HNL that only mixes with ν_μ.
- Signal: $N \to \mu\pi$
- True Parameters: $m_N = 2.0$ GeV, $|U_\mu| = 0.002$
- Kinematic Data: $E_{\mu\pi}, m_{\mu\pi}$
- We assume that $m_{\mu\pi}$ can be reconstructed via the muon and pion energies, $E_{\mu(\pi)}$ and their opening angle, $\theta_{\mu\pi}$.

$$\frac{\delta E_\mu}{E_\mu} = \frac{\delta p_\mu}{p_\mu} \qquad \frac{\delta E_\pi}{E_\pi} = \frac{50\,\%}{\sqrt{E_\pi}} \qquad \frac{\delta \theta_{\mu\pi}}{\theta_{\mu\pi}} = 0.4 \text{ mrad}$$

FASER muon momentum resolution

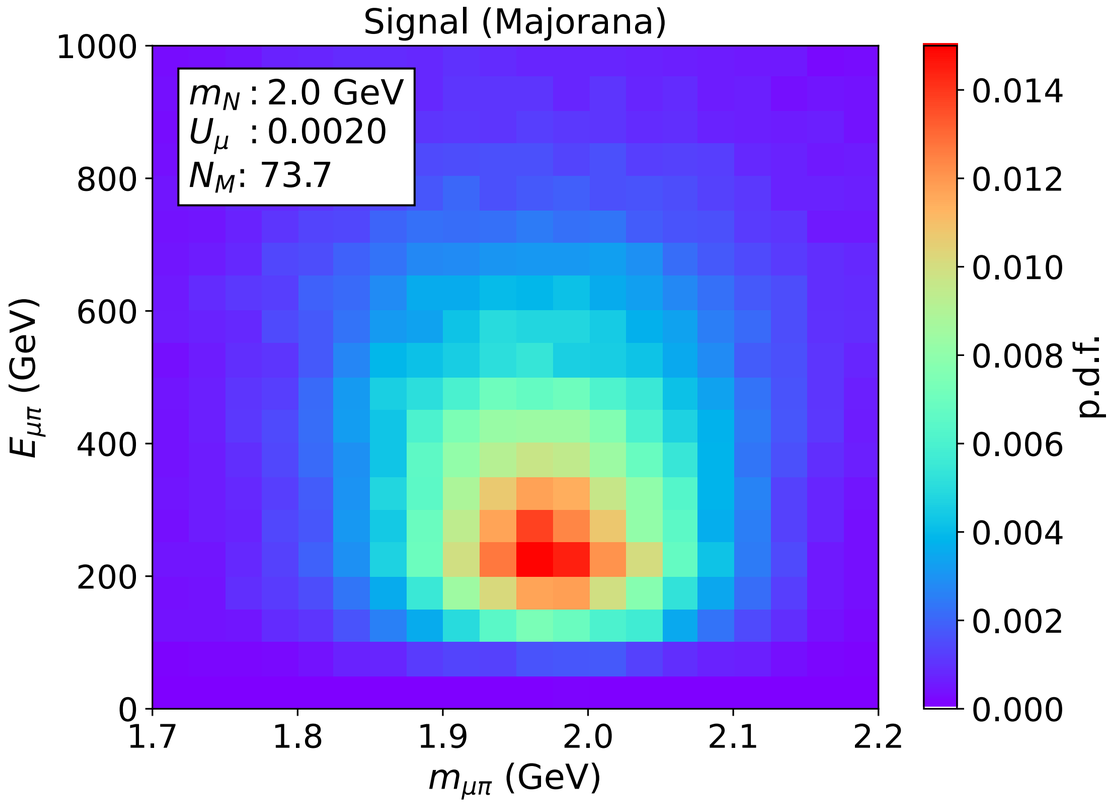


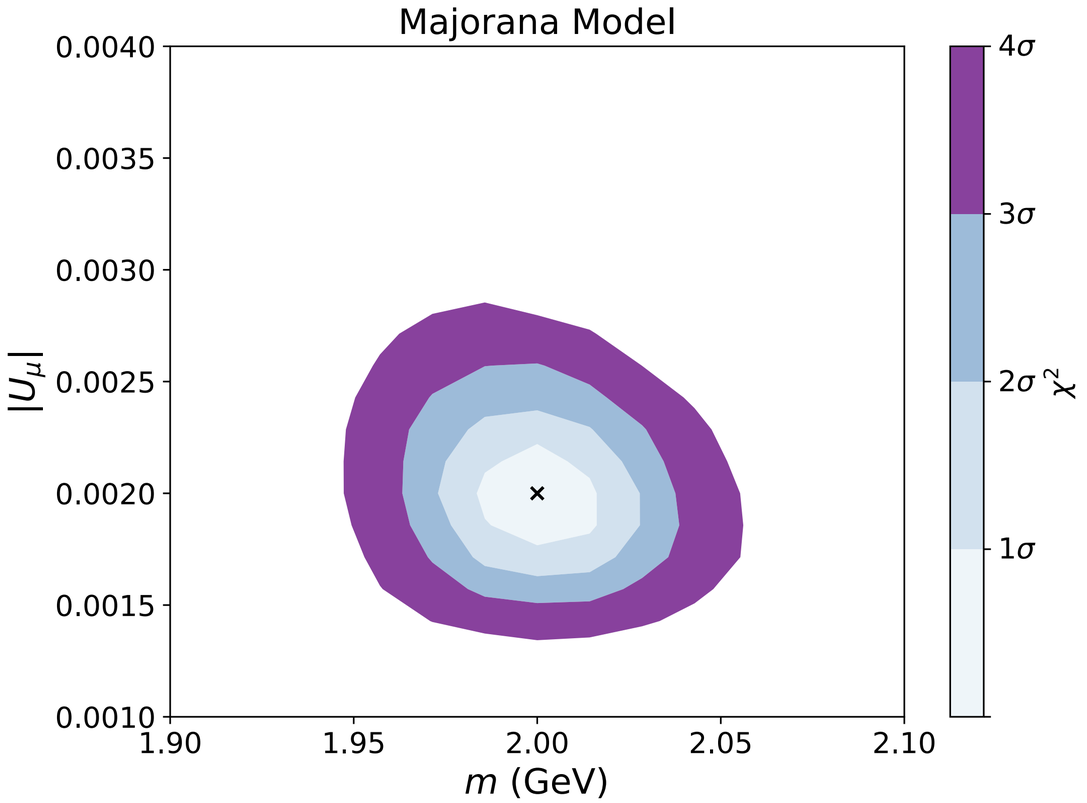
[FASER Collaboration 2018]

Invariant Mass

$$m_{\mu\pi} = \sqrt{2E_\mu E_\pi (1 - \cos\theta_{\mu\pi})}$$

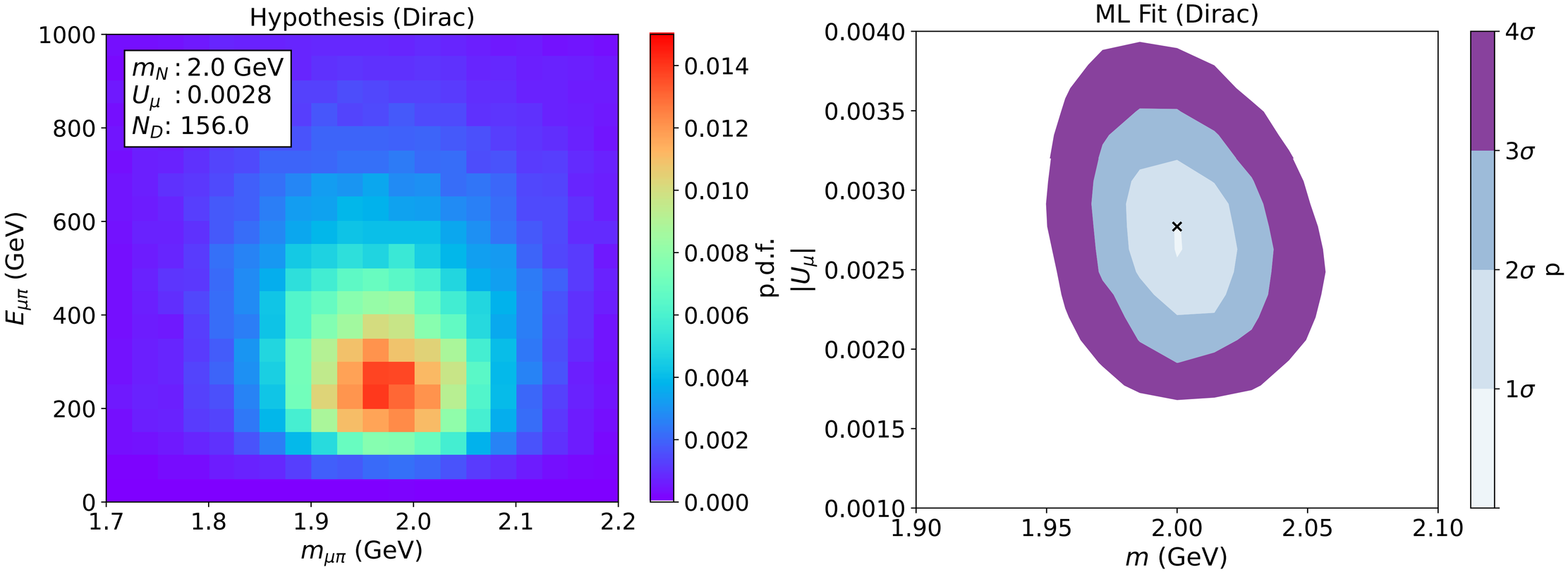
Parameter Estimation





$$\frac{\delta m}{m} \approx 5\,\% \qquad \frac{\delta U}{U} \approx 30\,\%\ (2\sigma)$$

Model Discrimination



Results:

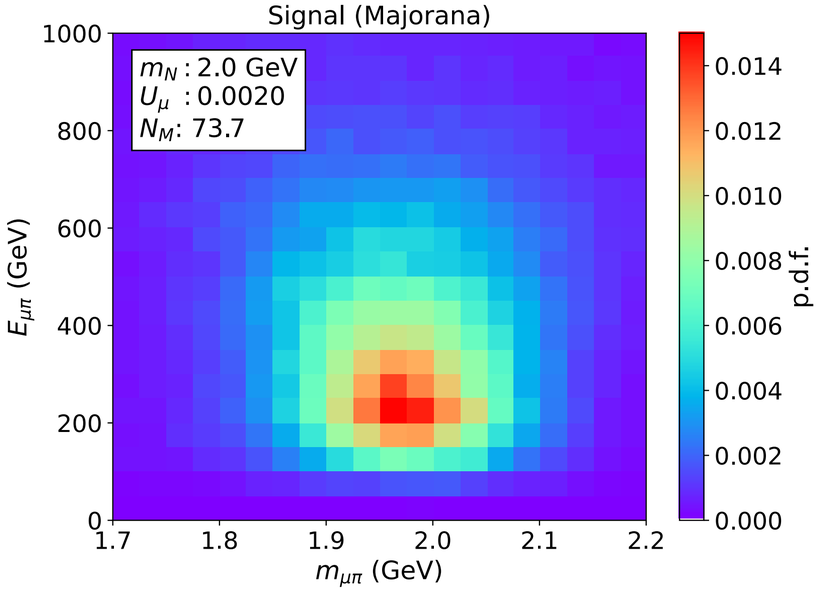
The Majorana model is favored over the Dirac model at $\sim 1\sigma$

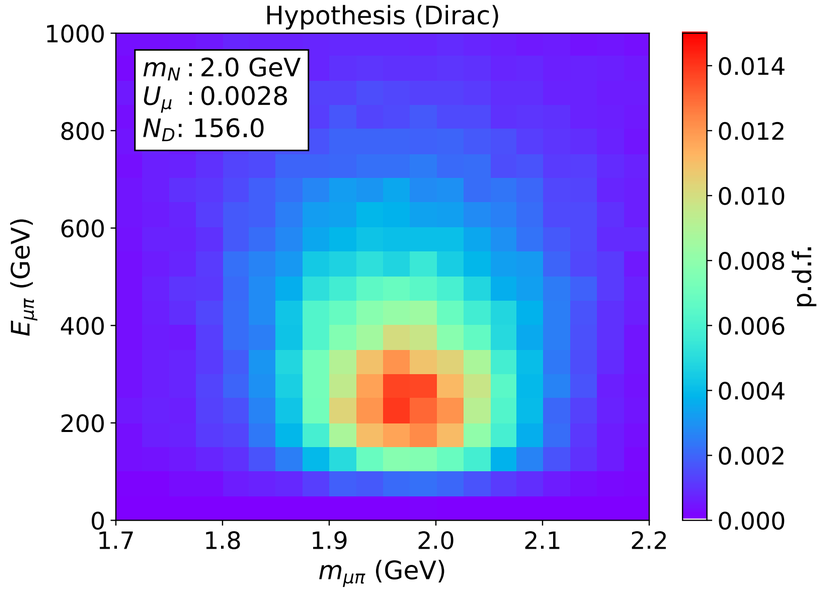
Energy as a probe of lifetime

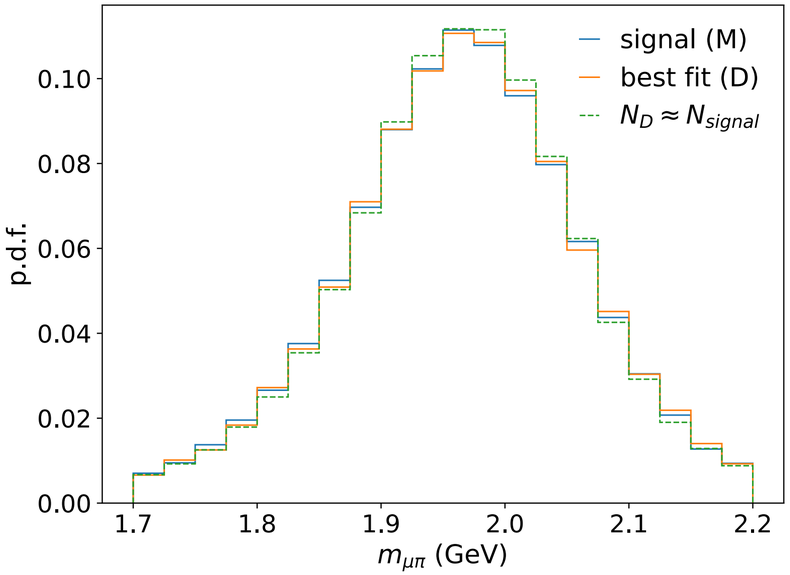
- Due to the presence of lepton-number-violating decays, **Majorana HNLs generally have a shorter lifetime**
- For a fixed event rate, the models differ by exactly a factor of 2

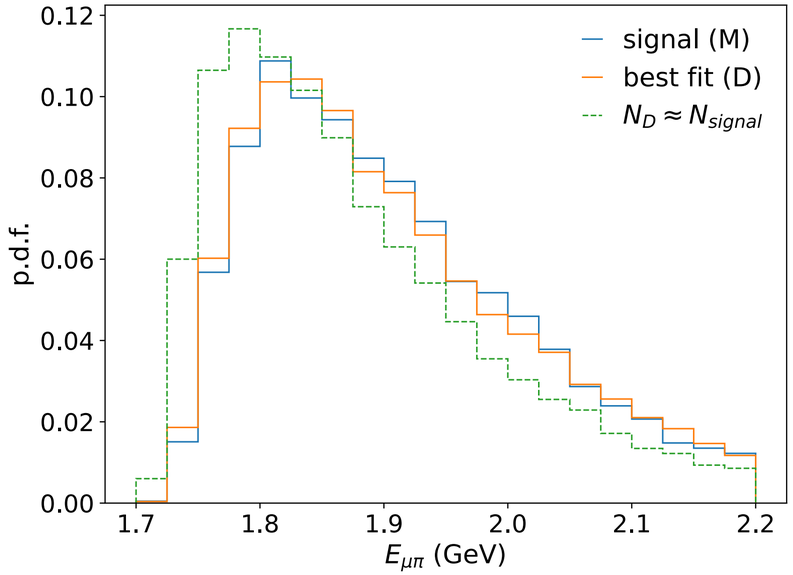
$$\tau_M = \frac{\tau_D}{2}$$

- However, our analysis is limited by the large flux uncertainties from our MC generators



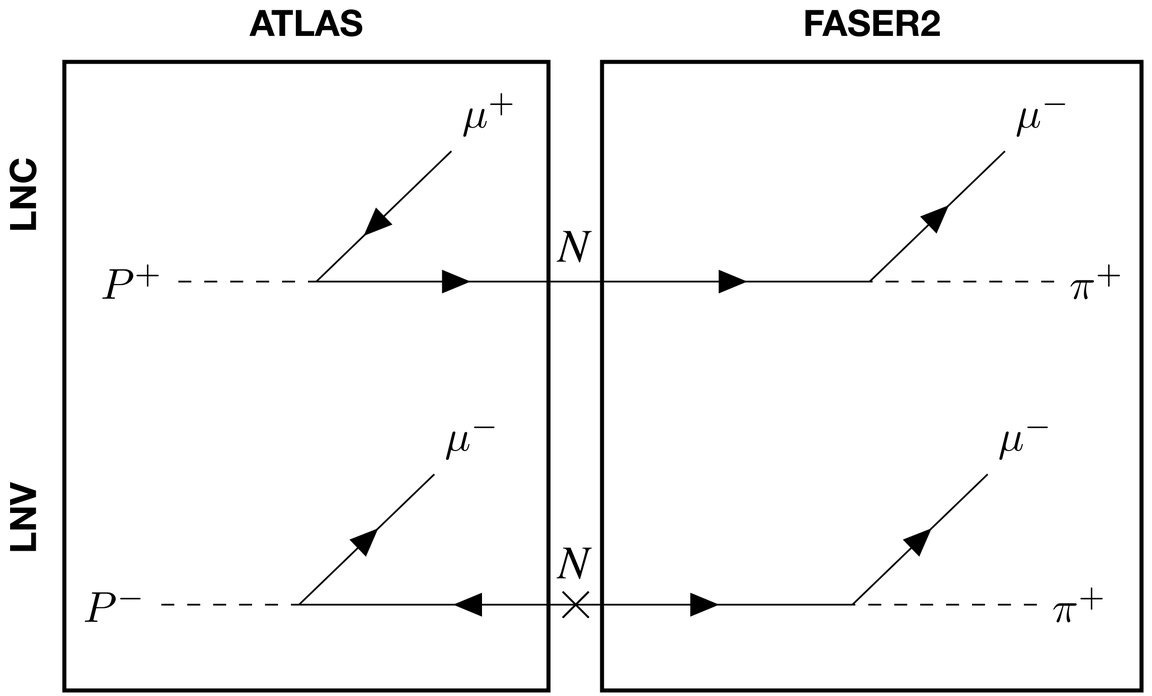






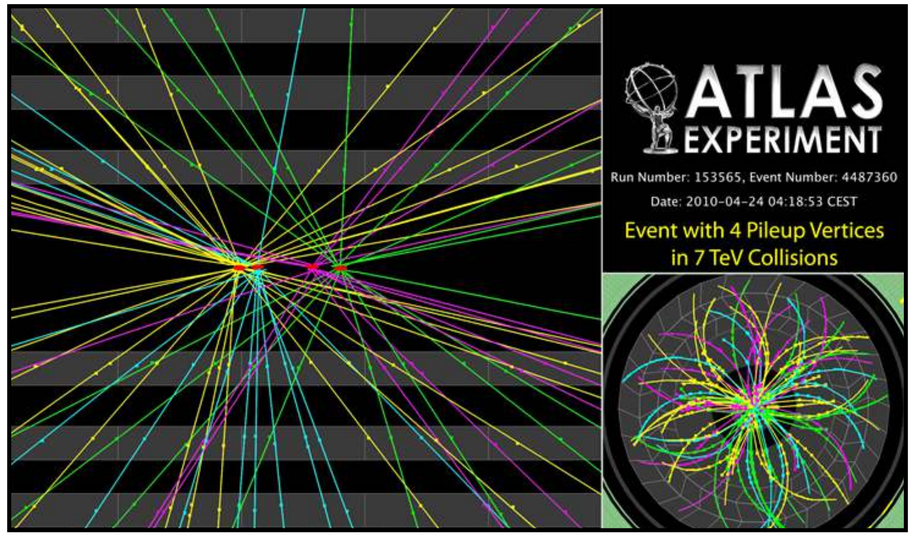
FASER2 as a Trigger for ATLAS

- When Majorana HNLs are produced on-shell, LNC and LNV events occur with equal rates.
- Correlating the charge of the muon produced in ATLAS and the muon in FASER, we could classify these event as either lepton-number-conserving (LNC) or lepton-number-violating (LNV)
- These leptons are low p_T (forward boosted), so they won't pass ATLAS triggers, therefore we propose to use FASER2 as a trigger for ATLAS
  - Proposed Triggering Time: $5.4\,\mu$s
  - ATLAS Buffer: $6\,\mu$s
- However this is not in the absence of background!

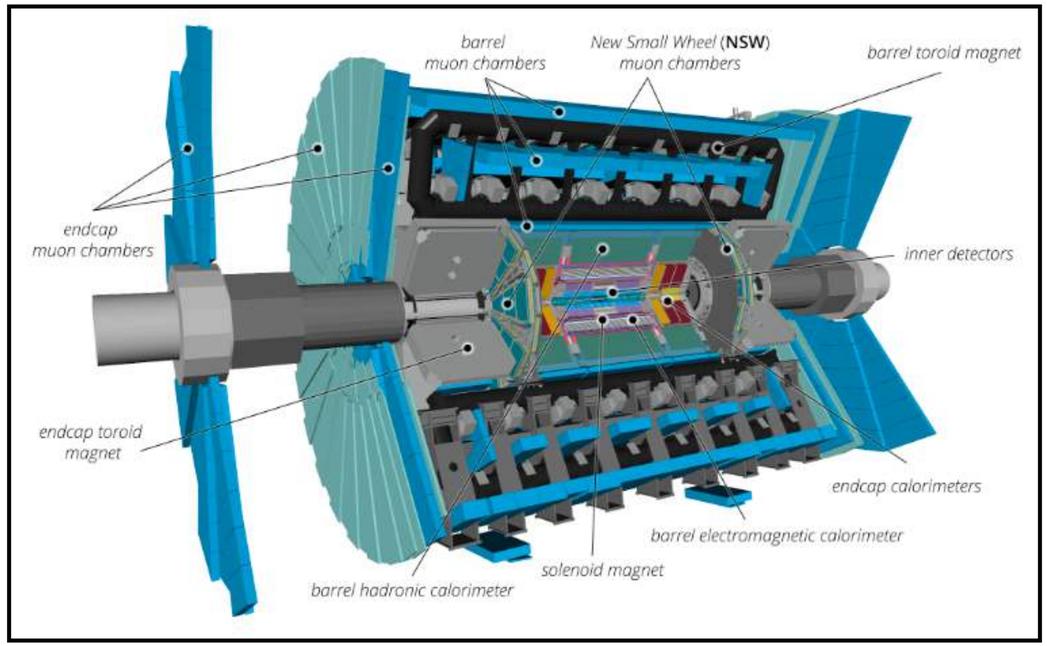


Pile-up Background

- At the HL-LHC, there are $\sim 10^{11}$ protons per bunch, resulting in $\langle \mu \rangle = 200$ pile-up events per crossing.
- We use Pythia8 to overlay 200 pp collisions to generate an estimate for the number of background tracks per bunch crossing, b
- A high-η muon tagger is required to reduce background from charged tracks
  - Proposed in ATLAS Phase-II upgrade (ATLAS Collaboration 2015)
- We find roughly **b ~ 1 bkg muon per bunch crossing**



[https://lhc-closer.es/taking_a_closer_look_at_lhc/0.pile_up]



[ATLAS Collaboration 2023]

FASER2 + ATLAS

- Kinematic data is binned into two categories based on the sign of the muons produced at ATLAS and detected at FASER
- In order to obtain sufficient signal to background ratios, we find that tracking coverage must be extended to $|\eta| \leq 5$. Additionally, we will apply the cut $3.5 \leq |\eta| \leq 5$
- This improves FASER2's discrimination, however its still once again limited by forward hadron production uncertainties

Dirac

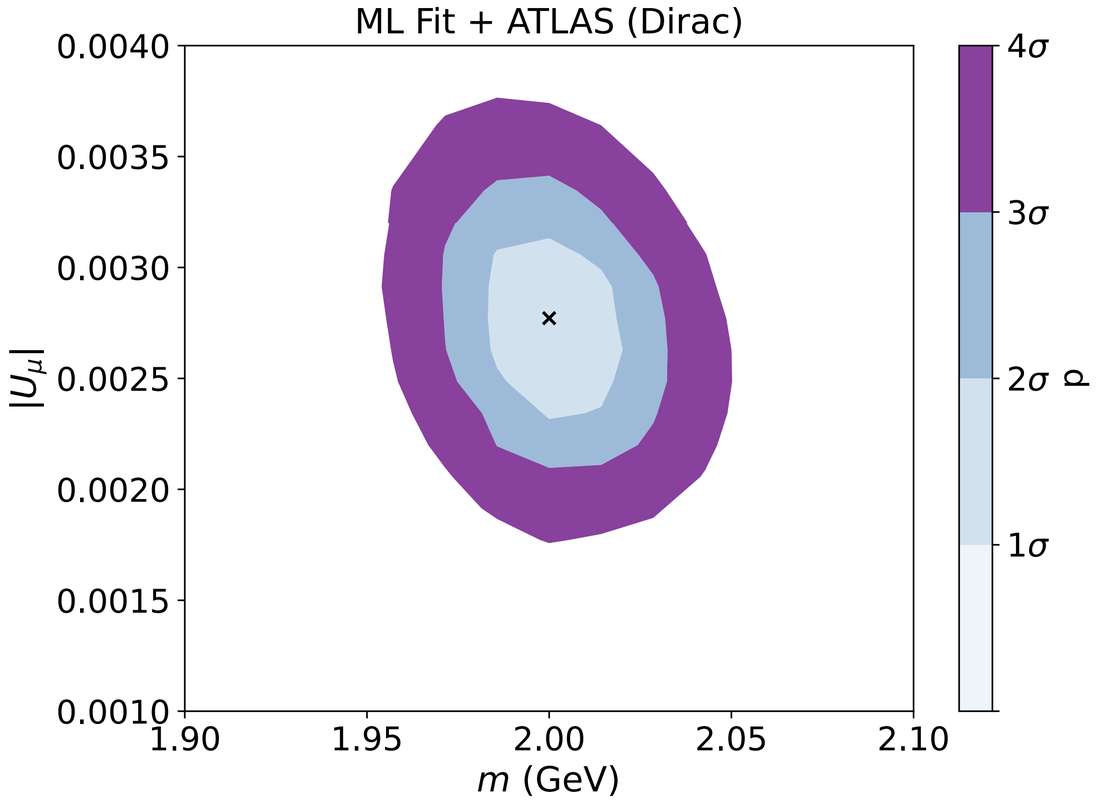
$$n_i^{OS} = \frac{1}{2} b \cdot n_i^{FASER} + n_i^{ATLAS}$$

$$n_i^{LS} = \frac{1}{2} b \cdot n_i^{FASER}$$

Majorana

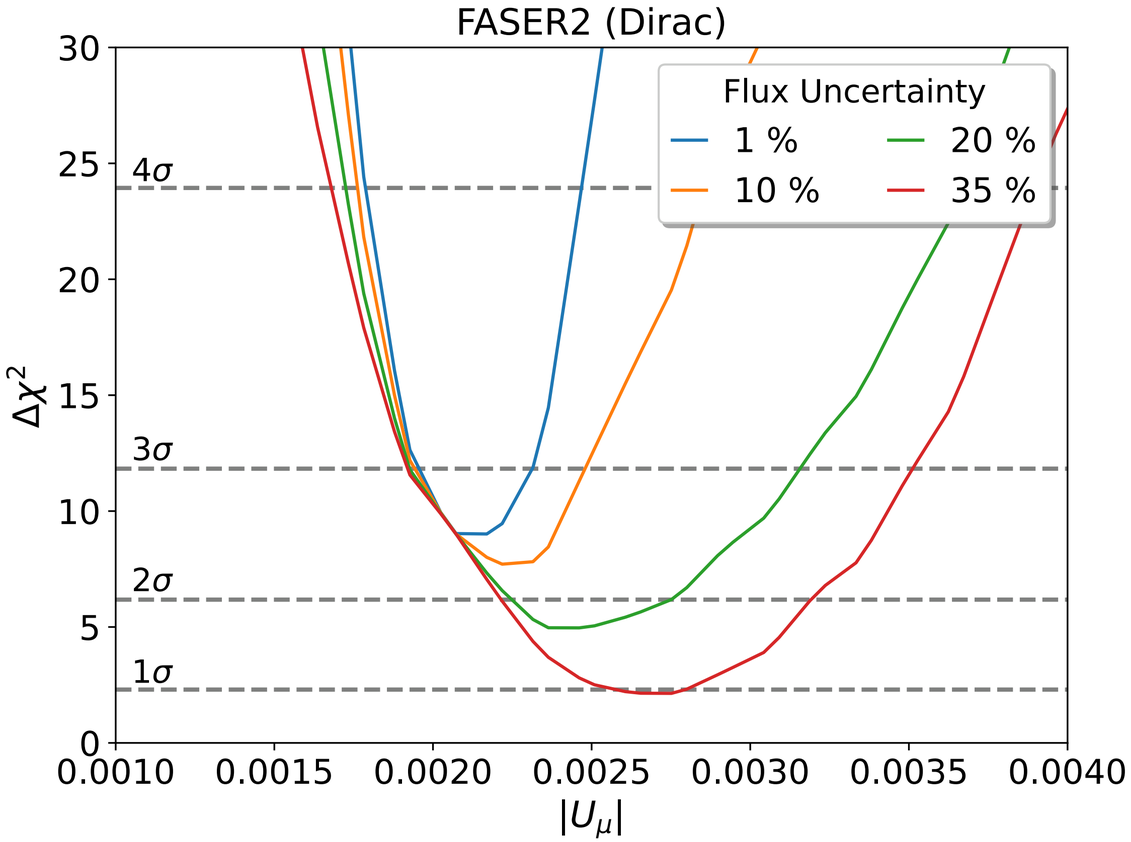
$$n_i^{OS} = \frac{1}{2} b \cdot n_i^{FASER} + \frac{1}{2} n_i^{ATLAS}$$

$$n_i^{LS} = \frac{1}{2} b \cdot n_i^{FASER} + \frac{1}{2} n_i^{ATLAS}$$



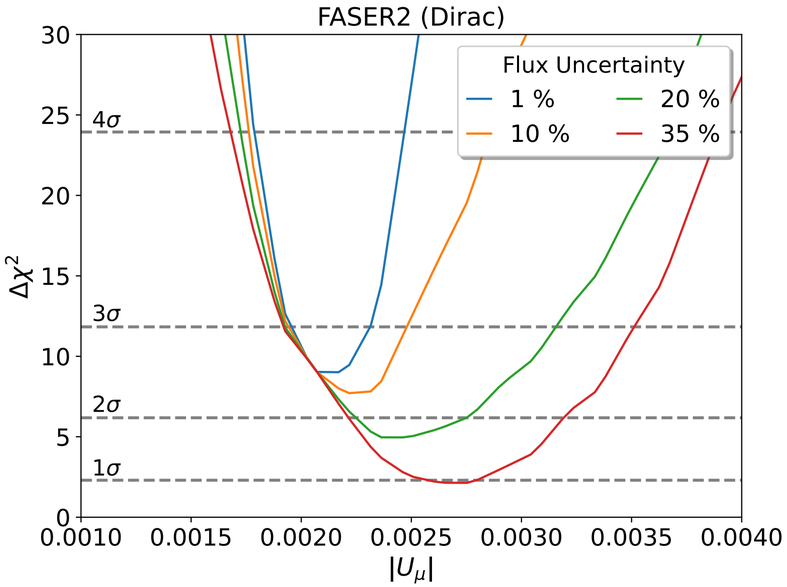
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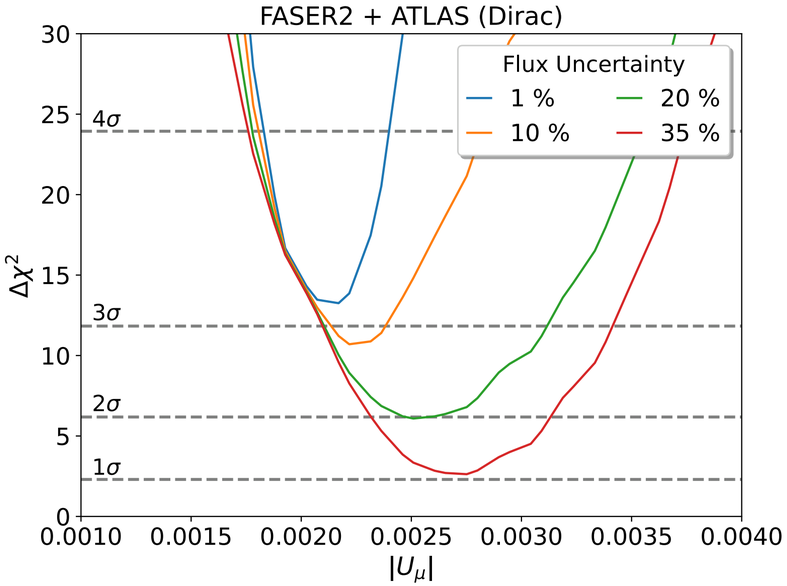
- Fortunately, forward hadron production estimates are likely to improve as FASERν continues to measure forward neutrino fluxes (and eventually FASERν2 @ FPF):
  - "First Measurement of the Muon Neutrino Interaction Cross Section and Flux as a Function of Energy at the LHC with FASER" (FASER Collaboration 2024)



Improving Flux Uncertainties

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Summary

- Heavy Neutral Leptons are a simple, well-motivated extension to the SM which have a rich phenomenology to be studied at colliders
- We have studied the capability of FASER2 to measure and constrain the mass and coupling of an HNL, in the event of a signal detection
- Additionally, we have presented the capability to differentiate Majorana and Dirac HNL's by studying the impact of their lifetimes their energy distributions
- Lastly, we have showed how FASER2 can be used as a trigger for ATLAS to improve discrimination between Dirac and Majorana by studying the correlation of muons produced at ATLAS and detected at FASER2

Paper is currently in progress, stay tuned!

Anaheim CA , Mar 19th 2025

UCI Department of Physics & Astronomy

Backup Slides: Pileup

Meson	Muons Produced
prompt	$20/300 \approx 0.07$
211	$13/300 \approx 0.04$
321	$7/300 \approx 0.023$
130	$0/300$

TABLE III. Summary after final cut of $4 < \eta < 4.5$, 0.6 GeV$< p_T <$2 GeV are placed. This results in a background of $42/300 \approx 0.14$ with roughly half coming from the prompt decays and half coming from the light meson decays.

