Heavy Neutral Lepton search at MINERνA

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New Perspectives 2022

[SLIDES-22-045-ND]

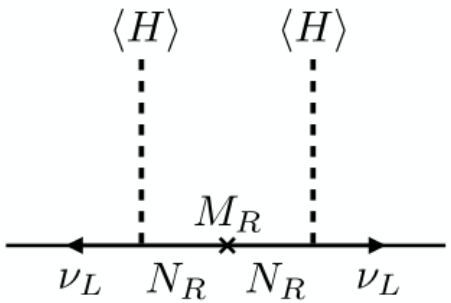
What are HNL?

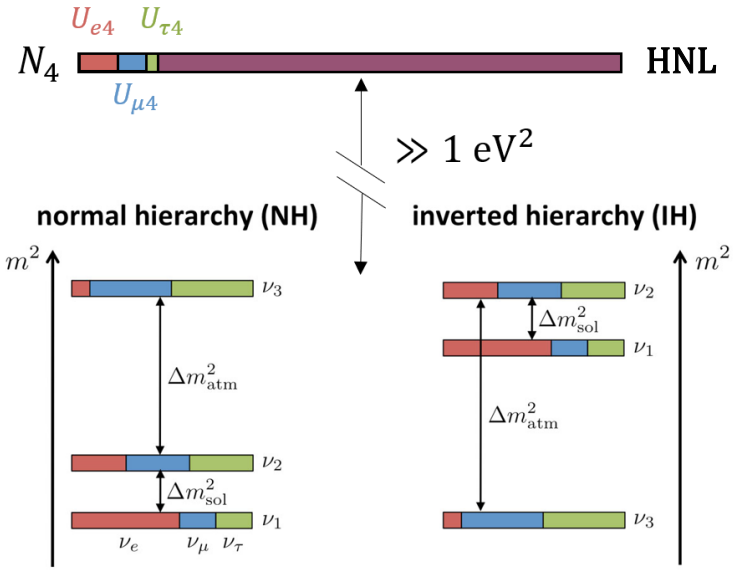
- Neutrino oscillations: $\Delta m^2_{21}, |\Delta m^2_{31}| > 0 \Rightarrow$ at least 2 massive neutrino states
- Problem: Standard Model predicts all neutrinos (always left-chiral in SM) are massless

New J. Phys. **6** (2004) 82; arXiv: 2203.08039 [hep-ph]

- Can explain masses through seesaw mechanism
  - Mix with LH in new mass eigenstates, HNL, via extended PMNS
  - Generally $\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i}\nu_i + \sum_I U_{\alpha I} N_I \,, \alpha = e, \mu, \tau$
  - For I = 1,

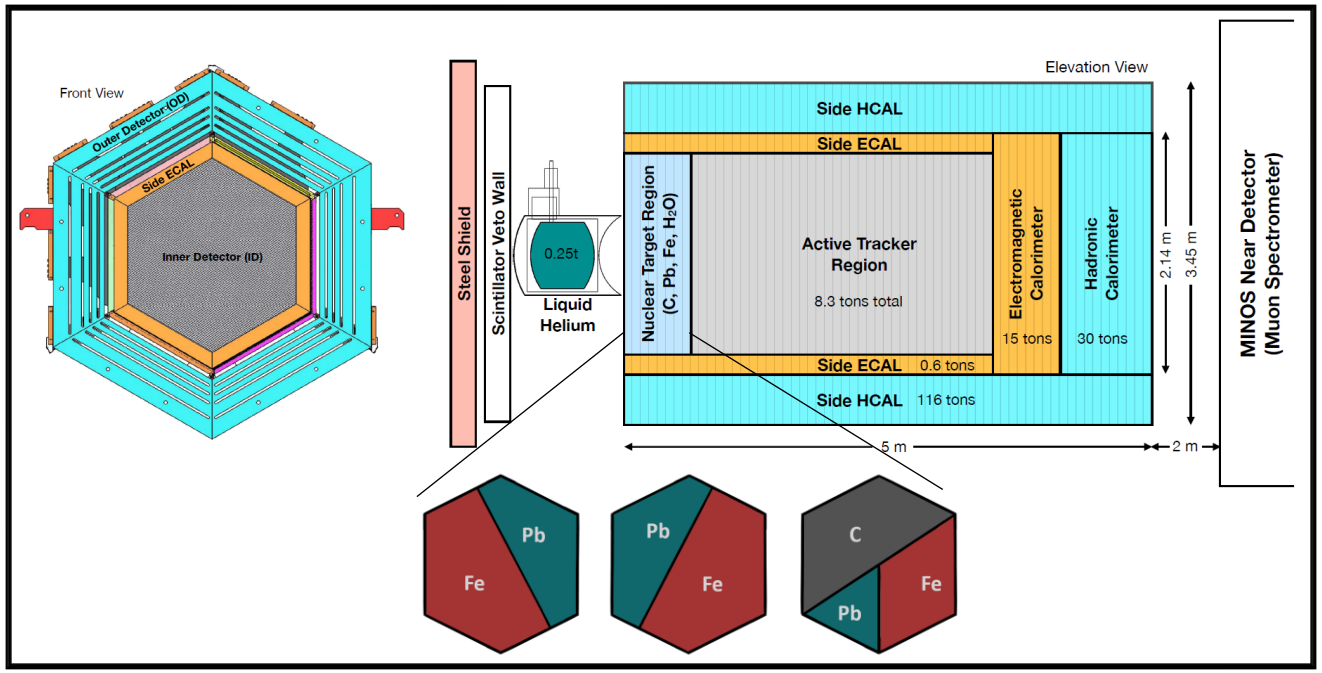
$$U = \begin{pmatrix} & U^{\text{PMNS}} & & U_{e4} \\ & & & U_{\mu 4} \\ & & & U_{\tau 4} \\ U^*_{e4} & U^*_{\mu 4} & U^*_{\tau 4} & U_{R4} \end{pmatrix}$$





The MINERvA detector

- Located on-axis in NuMI beamline
- 120 GeV $p + C \rightarrow$ hadrons $\rightarrow \nu, \bar{\nu}$
- Extruded plastic scintillator
- 1.2×10^{21} POT @ $\langle E_\nu \rangle = 6$ GeV



Why HNL?

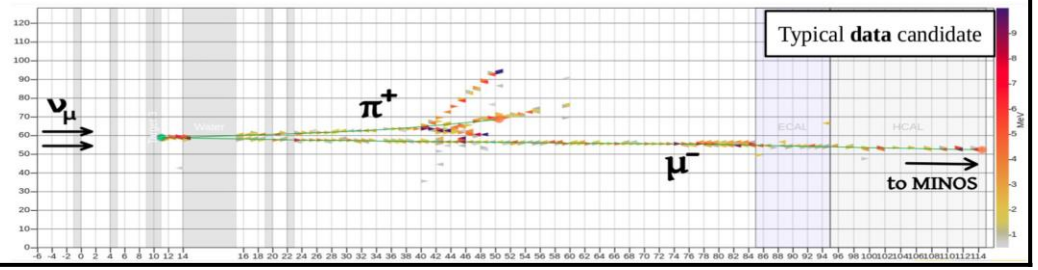
1. Exposure: HNL rates $\propto |U_{\alpha 4}|^4$ so need POT!
2. Reconstruction: resolutions $\sigma_t \sim 5$ns, $\sigma_x \sim 1$mm, $\sigma_\theta \sim 1$mrad + μ matching w/ MINOS
3. Background: irreducible SM bkg is
   i. CC coherent pion production
   ii. mis-ID'd CC ν_μ interactions

(see e.g. *JHEP* **2022** (2022) 48)

CC Coherent: $\nu_\ell + A \rightarrow \ell^\mp \pi^\pm A$

First measurement of coherent cross-section A-dependence!

Alejandro Ramírez Delgado, Joint Experimental-Theoretical Physics Seminar, 10/Jun/2022



What's the goal?

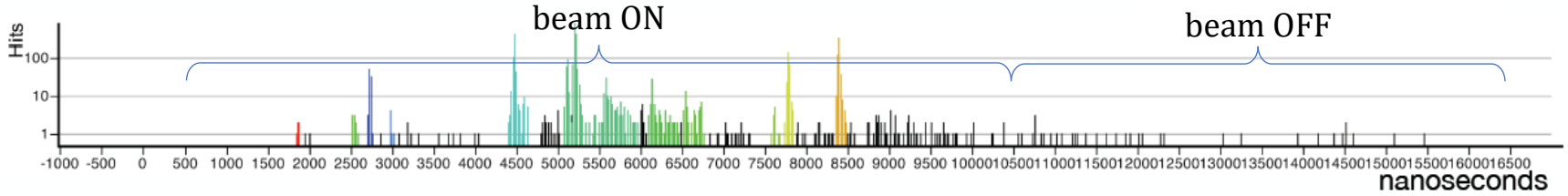
- Either <u>detect HNL</u> or <u>update limit plots</u>
- Counting analysis: find <u>excess over SM background after reduction</u>
- Using cuts on topology and kinematics to reduce backgrounds
  - <u>Coherent-like topology</u>: $\sim \mathcal{O}(100\text{k})$ events in tracker before cuts
  - <u>Trident-like topology</u>: $\sim \mathcal{O}(10)$ events in tracker

(1.2×10^{21} POT)

JHEP **2019** (2019) 119

Interaction	vs	Decay
$\nu_\mu + A \rightarrow \mu^- \pi^+ A$	$\leftrightarrow$	$N \rightarrow \mu^- \pi^+$
$\nu_\mu + A \rightarrow \mu^- \mu^+ \nu_\mu A$	$\leftrightarrow$	$N \rightarrow \mu^- \mu^+ \nu_\mu$

- Other channels considered but hard to reconstruct sufficiently well in MINERvA
  - Can differentiate μ from π because of outer calorimetry + MINOS matching *NIM A* **743** (2014) 130-159
- Timing information: Sufficiently slow HNL can appear past NuMI beam spill



Recent Fermilab searches:
ArgoNEUT: *Phys. Rev. Lett.* **127** (2021) 12
MicroBooNE (BNB): *Phys. Rev. D* **101** (2020) 5

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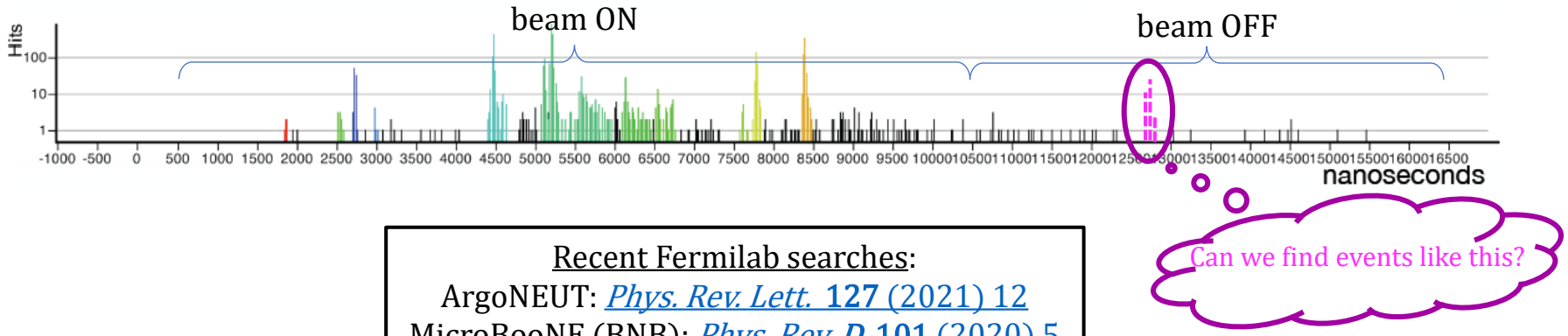

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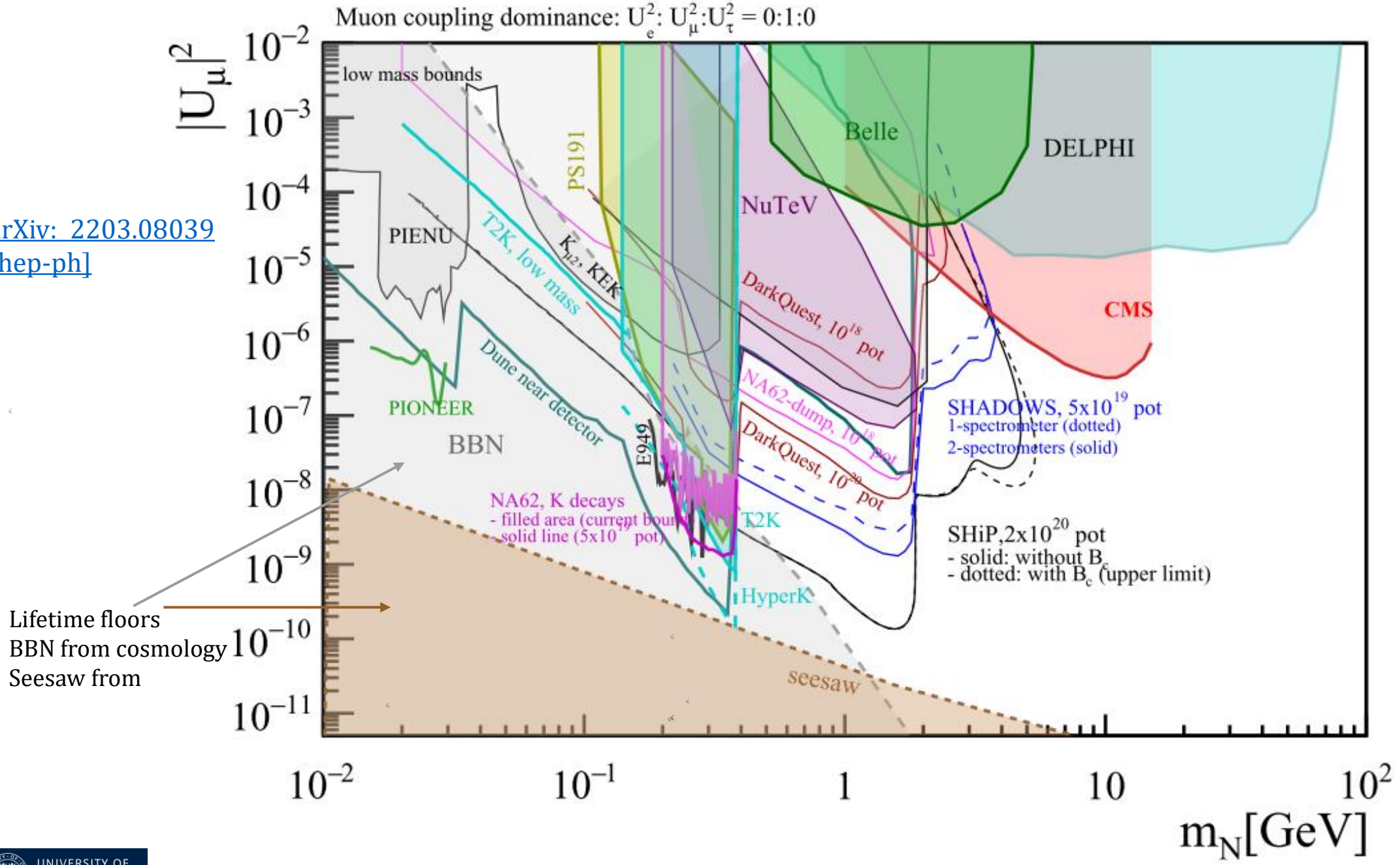

Lifetime floors
BBN from cosmology
Seesaw from

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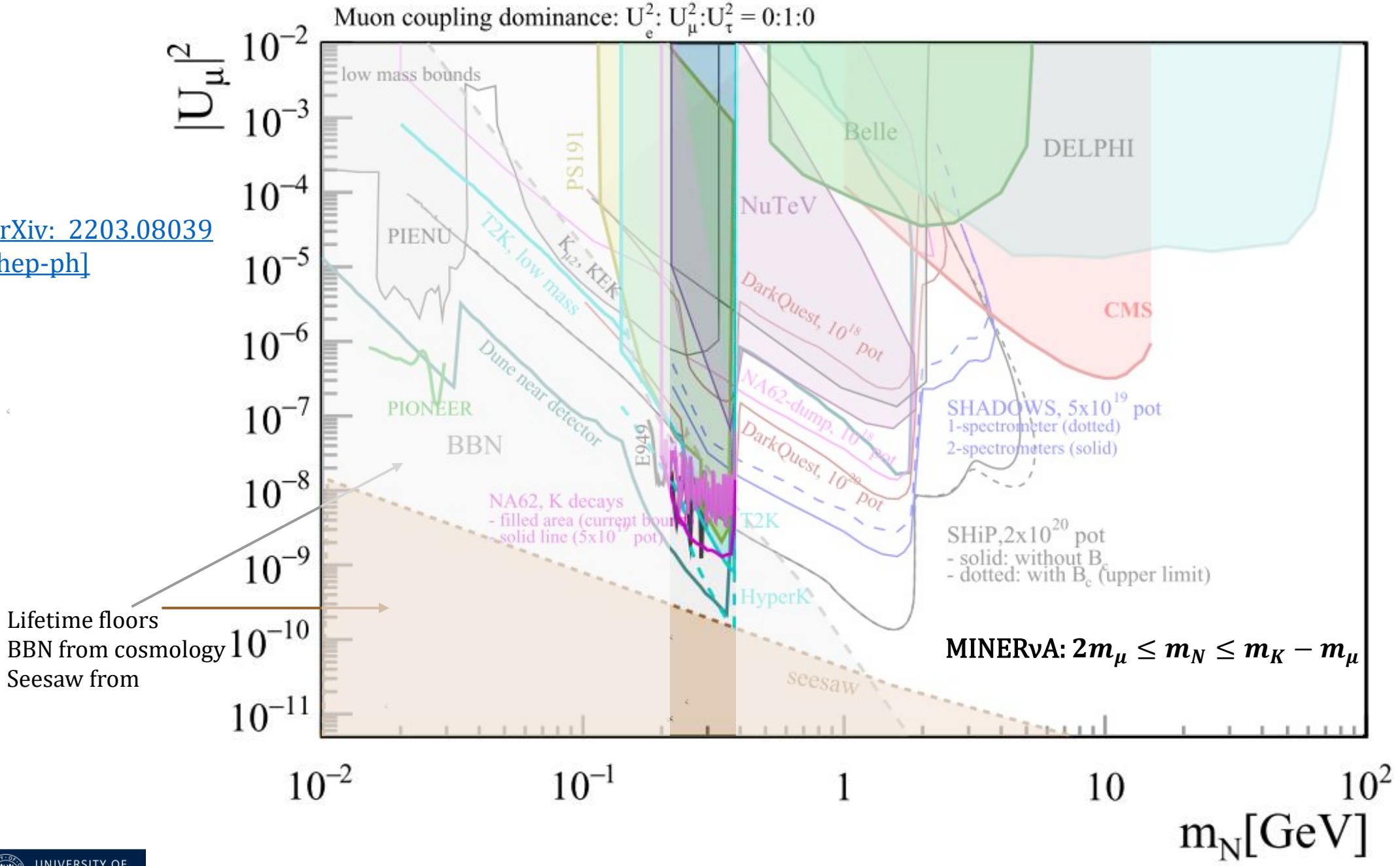
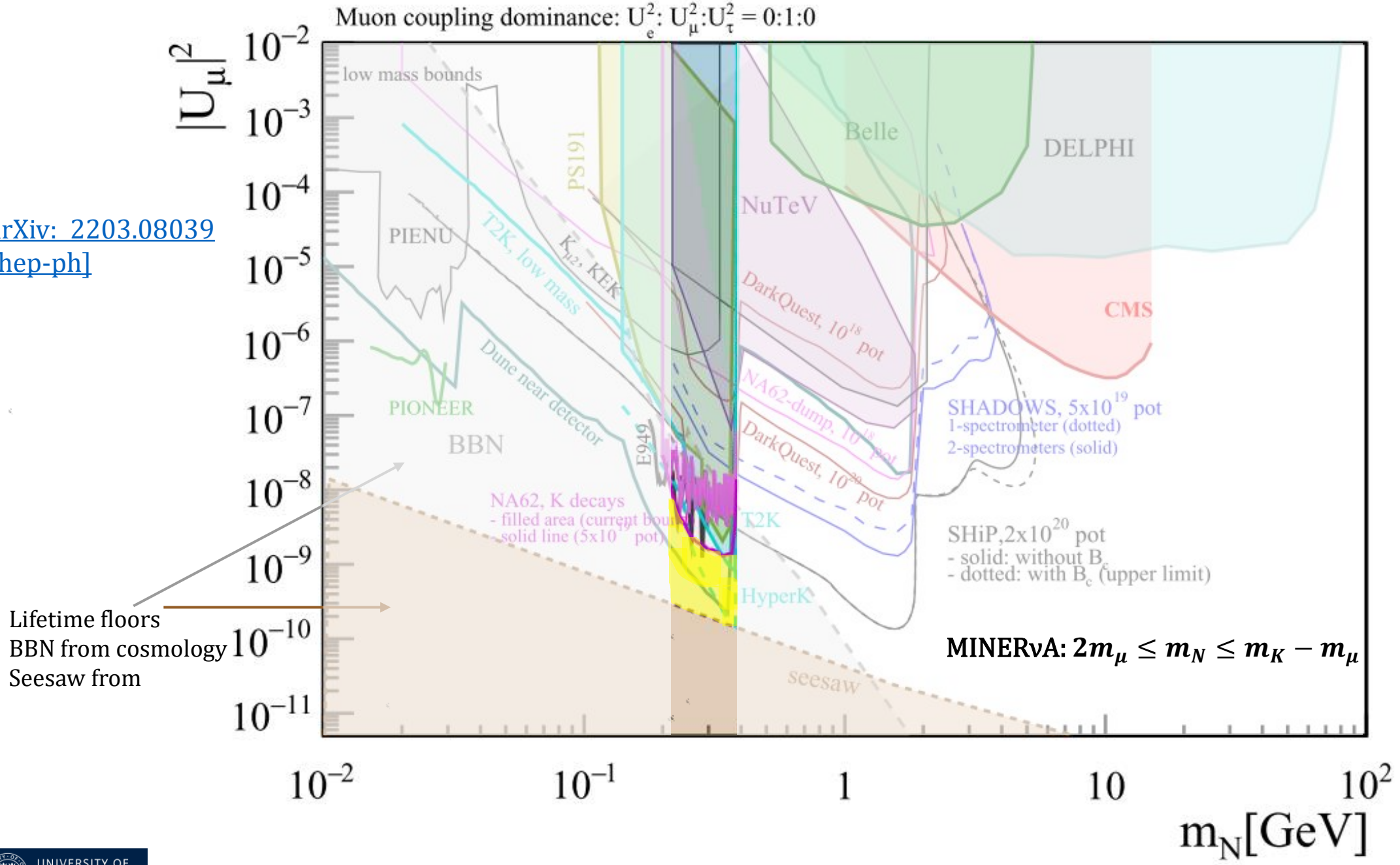


Lifetime floors
BBN from cosmology
Seesaw from

MINERvA: $2m_\mu \leq m_N \leq m_K - m_\mu$

arXiv: 2203.08039 [hep-ph]



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HNL implementation: GENIEv3

- Need to generate HNL events in MINERvA using appropriate Lagrangian
- Implementing long-lived HNL module
- Major deliverables:

Phys. Rev. D **94** (2014) 9

1. Flux prediction from NuMI flux ("dk2nu") files

   Depending on HNL parameter space

   and location of detector

2. Decay selection routines with correct event rates

   Generate available final states in map: <Gamma, FS>

   Using simple phase-space decay & boost to lab frame

3. Detector geometry routines

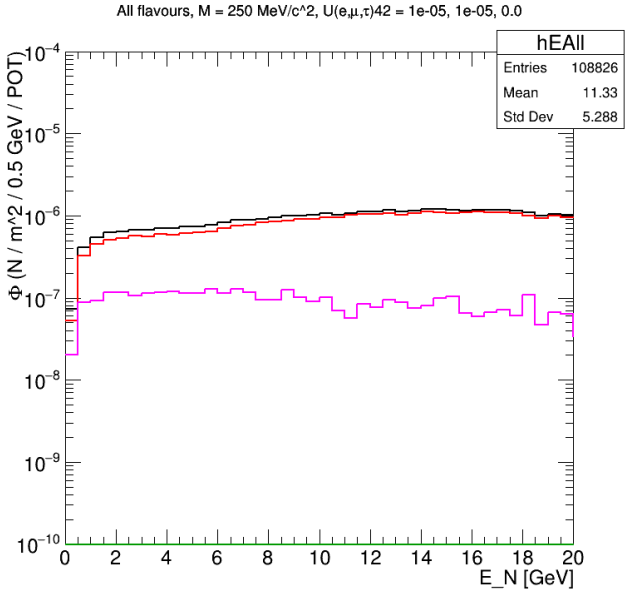
   Used to update effective POT as:

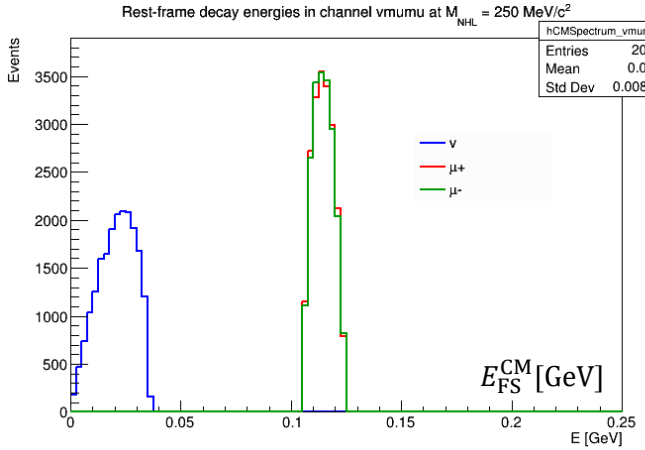
$$n_{\mathrm{POT}} = n^{\mathrm{SM}}_{\mathrm{POT}}(P_{surv}P_{dec})^{-1}(\sum_{\alpha}|U_{\alpha 4}|^2)^{-1}$$

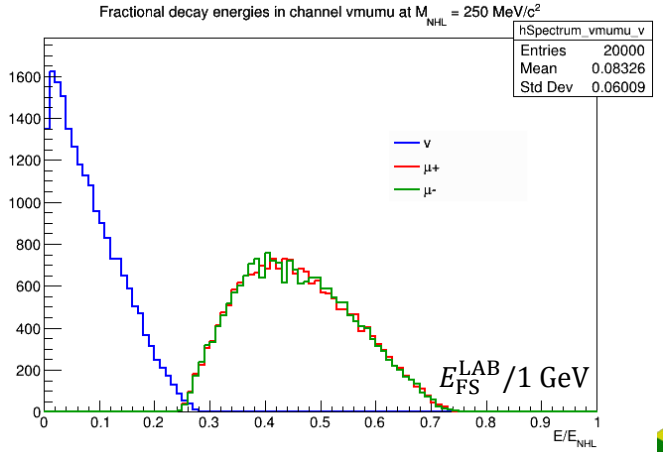
$$P_{surv} = \exp\left(-\frac{L}{c\beta_{\mathrm{HNL}}\gamma_{\mathrm{HNL}}}\Gamma_{\mathrm{tot}}\right)$$

$$P_{dec} = 1 - \exp\left(-\frac{\ell}{c\beta_{\mathrm{HNL}}\gamma_{\mathrm{HNL}}}\Gamma_{tot}\right)$$

L: prod to det entry, ℓ: det entry to det exit





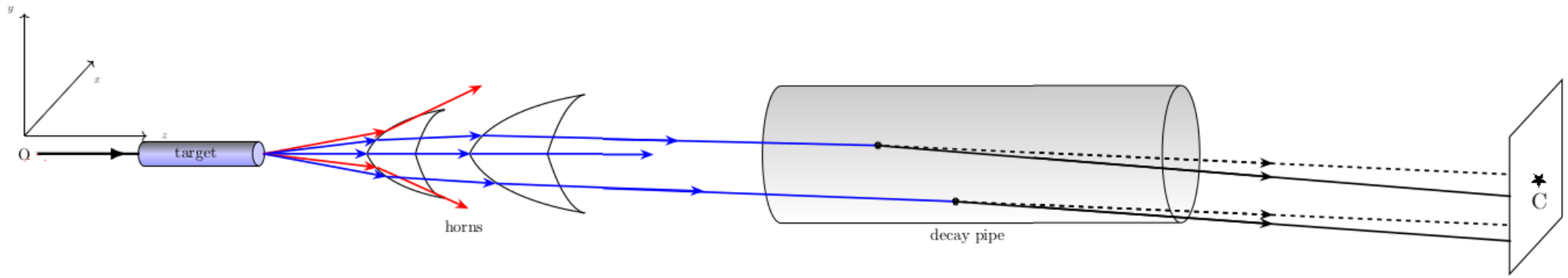


UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

Project wiki page
Generator fork

Flux prediction

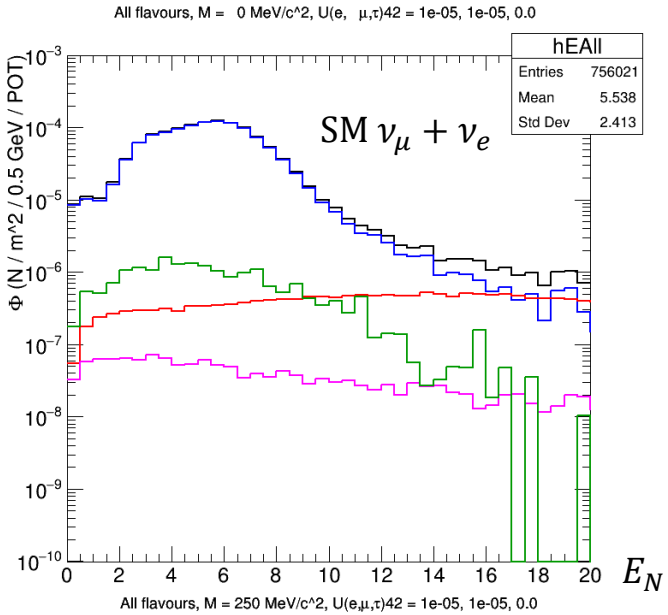
- Using dk2nu files: ignore all neutrino information
- Use parent $(\pi^{\pm}, K^{\pm}, \mu^{\mp}, K_L^0)$ information and n_{POT}
- Re-calculate parent decay rates under pseudo-unitarity constraint $\sum_\alpha |U_{\alpha 4}|^2 = 1$
  - (i.e. no SM ν are made in this simulation)
- Re-calculate neutrino energy & geometrical acceptance in "dk2nu-like" manner
  - Boost correction: $B = \left(\gamma(1 - \beta\beta_{\mathrm{HNL}}^{\mathrm{BEAM}}\cos\theta)\right)^{-1}$
  - $E_{\mathrm{HNL}}^{\mathrm{BEAM}} = E_{\mathrm{HNL}}^{\mathrm{CM}} \times B$
  - $A = \frac{\Omega}{4\pi} \times B^2$
- Also add correction due to backwards-emitted HNL reaching detector

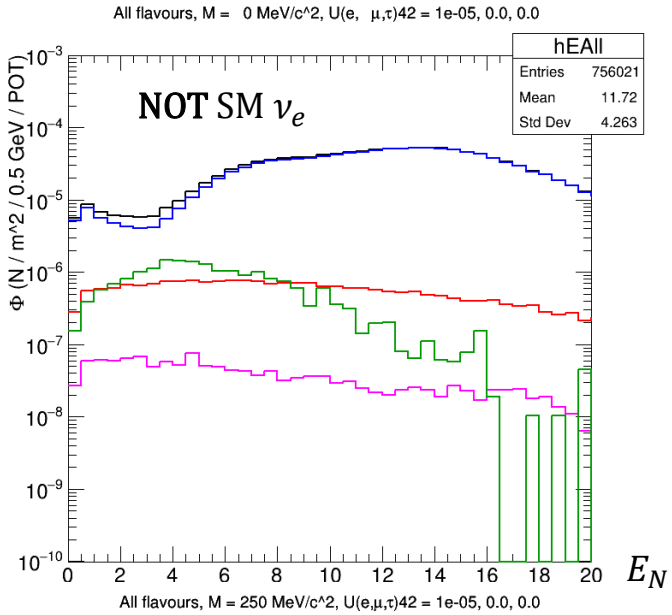


$|U_{e4}|^2 : |U_{\mu 4}|^2 = 1:1$

$|U_{e4}|^2 : |U_{\mu 4}|^2 = 1:0$

$M_N = 0$ MeV/c^2



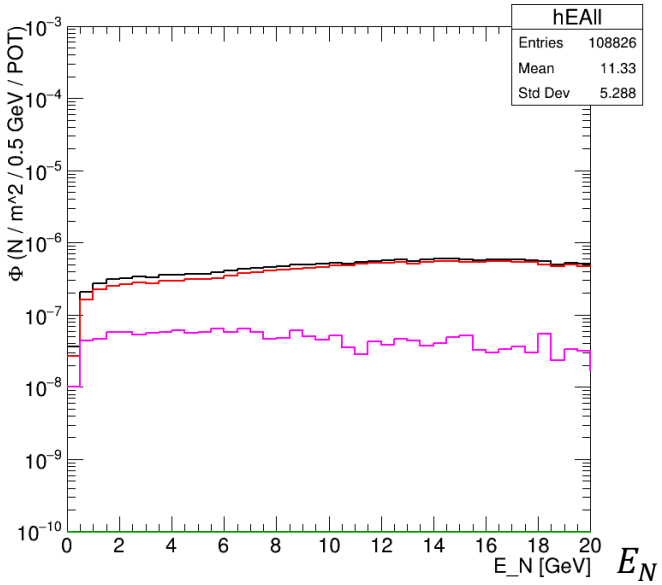


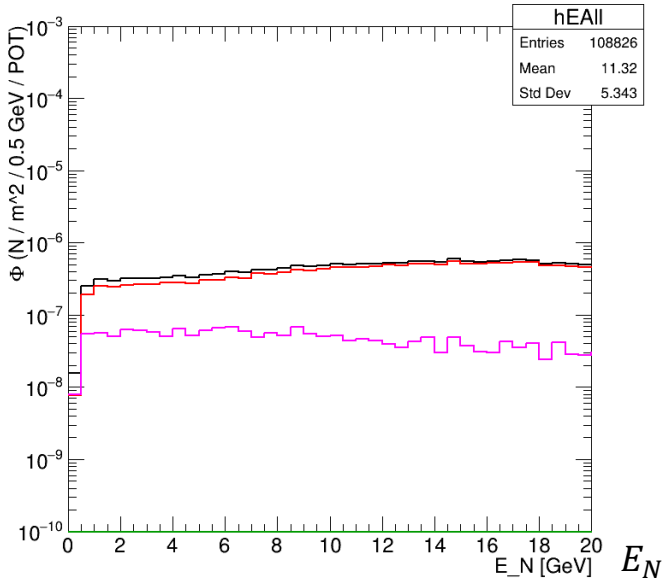
Flux spectra at MINERvA

4 parents $\{M_N\} \otimes \{U_{\alpha 4}\}$

$\sum_\alpha |U_{\alpha 4}|^2 = 1$

$M_N = 250$ MeV/c^2





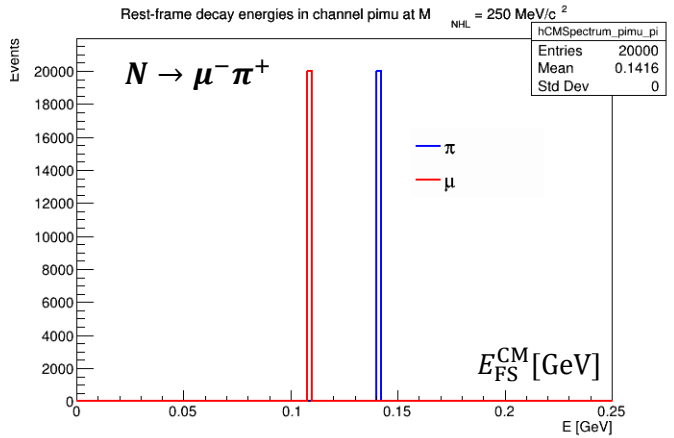
Parents

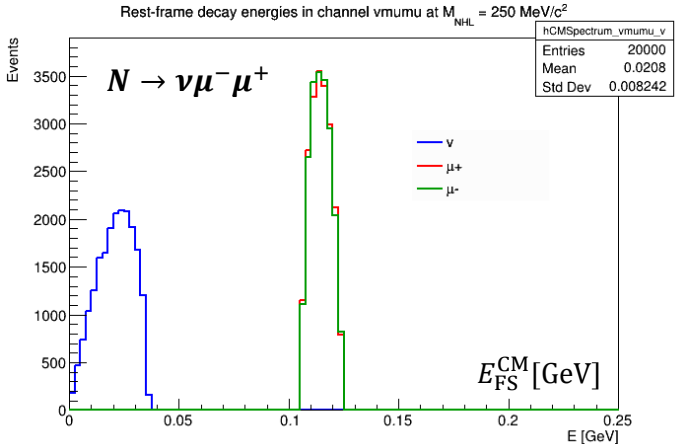
- : all
- : pion
- : kaon
- : muon
- : K0

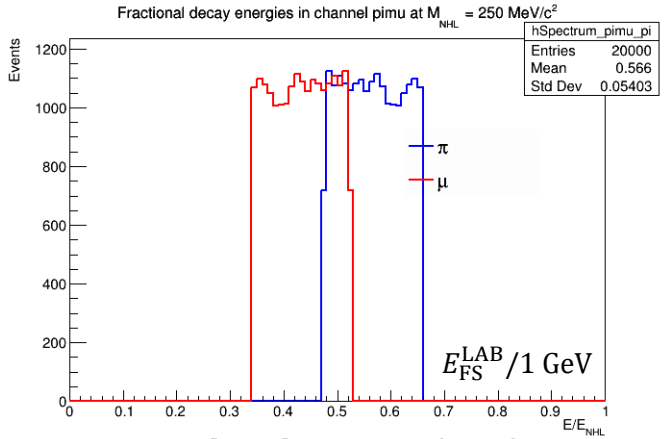
Decay

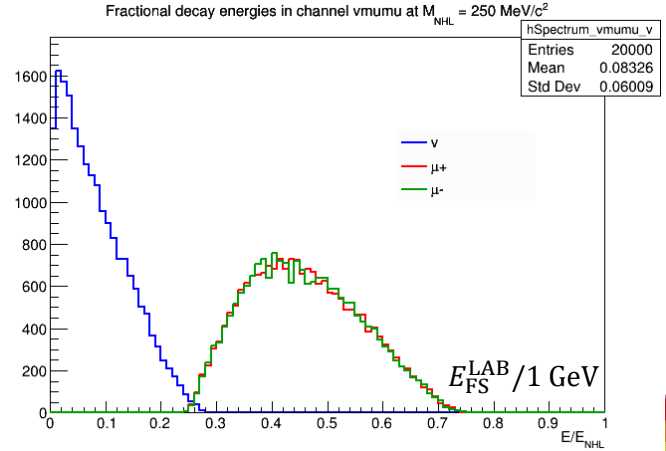
- First evaluate decay rates given $M_{\mathrm{HNL}}, |U_{\alpha 4}|^2$
- Construct map of allowed decay modes (check threshold) & associate w/ decay rate
- Select appropriate decay mode using transformation method
- Construct kinematics: do phase space decay with appropriate FS particles
- Read off boost vector of HNL in lab frame and boost FS particles into lab

Decay channels for HNL with mass = 250 MeV and $\|U_{e4}\|^2 : \|U_{\mu 4}\|^2 = 1:1$	
Channel (threshold mass)	**Allowed?**
$N \to \nu\nu\nu$ (0 MeV)	YES
$N \to \nu ee$ (1 MeV)	YES
$N \to \nu e\mu$ (106 MeV)	YES
$N \to \pi^0\nu$ (135 MeV)	YES
$N \to \pi e$ (140 MeV)	YES
$N \to \nu\mu\mu$ (211 MeV)	YES
$N \to \pi\mu$ (245 MeV)	YES
$N \to \pi^0\pi^0\nu$ (270 MeV)	NO
$N \to \pi\pi^0 e$ (275 MeV)	NO
$N \to \pi\pi^0\mu$ (380 MeV)	NO



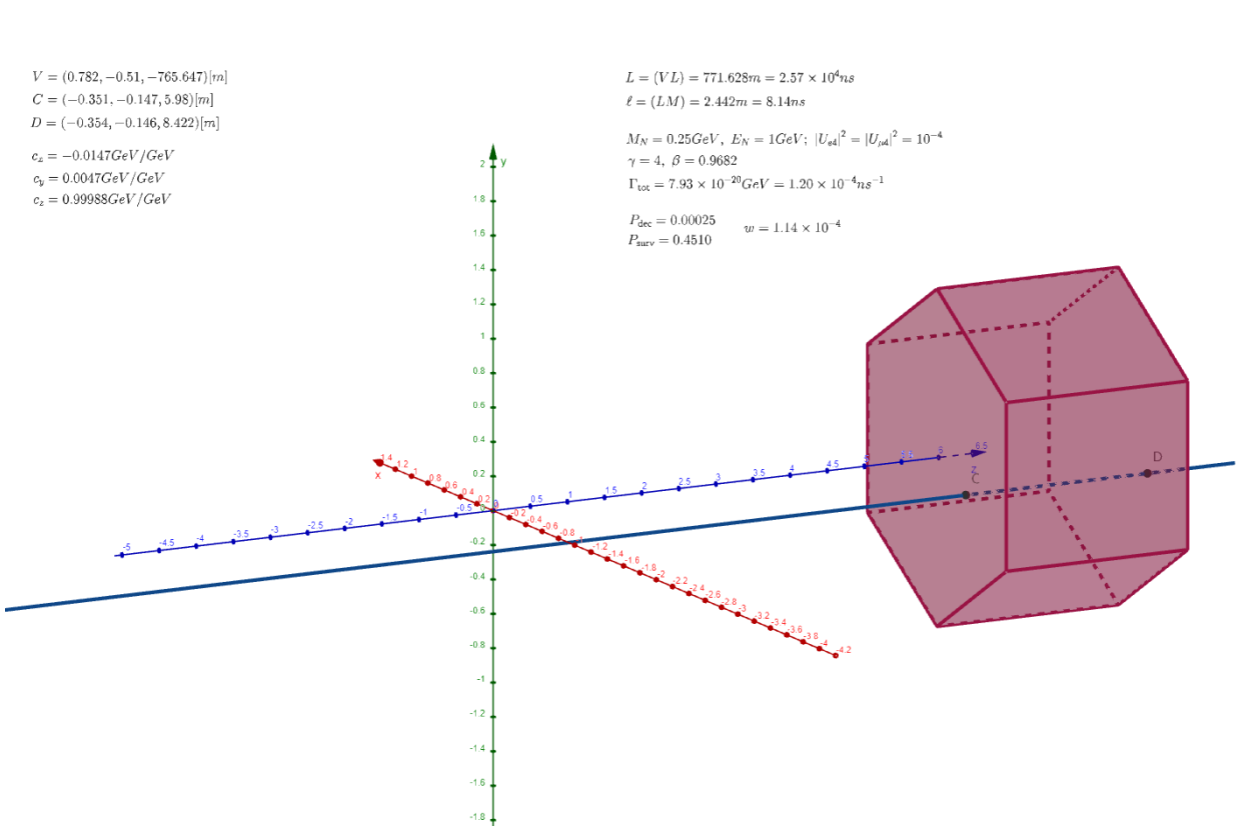


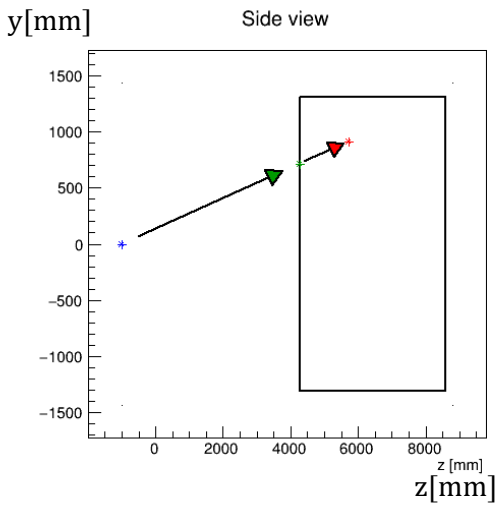


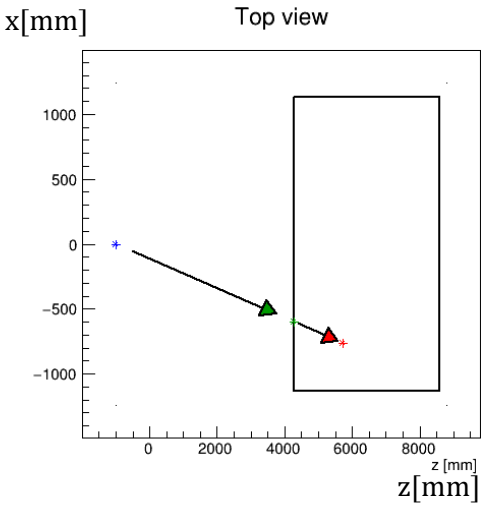


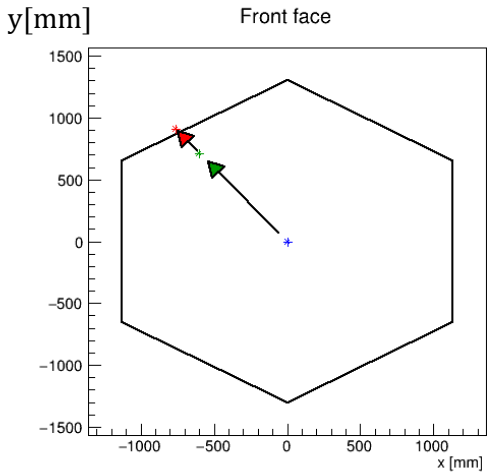
Geometry

- Using ROOT geometry to calculate entry and exit points
- Get trajectory: HNL production calculated from flux step, intersection w/line given by **p**









ientry = 0

(θ, ϕ) = (-10, -50.0)

Start [mm] : (0.0, 0.0, -1000.0)

Entry [mm] : (-598.9, 713.7, 4283.7)

Exit [mm] : (-762.6, 908.9, 5728.5)

Finally…

- We get an event record that can be piped into the MINERvA detector simulation!
- Use MINERvA Analysis Toolkit for analysis of tuples

- Exciting variables for $N \rightarrow \pi\mu$ channel:
- Vertex energy: sum of E(non-muon clusters) | cluster is within 250mm of vertex
  - Removes most "messy" events such as DIS
- 4-momentum transfer to nucleus: $|t| \coloneqq \sqrt{\left(p_\nu^{\text{reco}} - (p_\mu + p_\pi)\right)^2}$
- Muon-pion opening angle [WIP]
- Muon-pion invariant mass $M_{\mu\pi} \coloneqq \sqrt{E_\mu E_\pi - (\boldsymbol{p}_\mu \cdot \boldsymbol{p}_\pi)}$ [WIP]

Outlook

- HNL search has technical requirements necessitating custom MC
- Robust implementation in GENIEv3
  - Validating + standardizing this simulation
- Flexible for masses + mixings + custom geometry for MINERvA

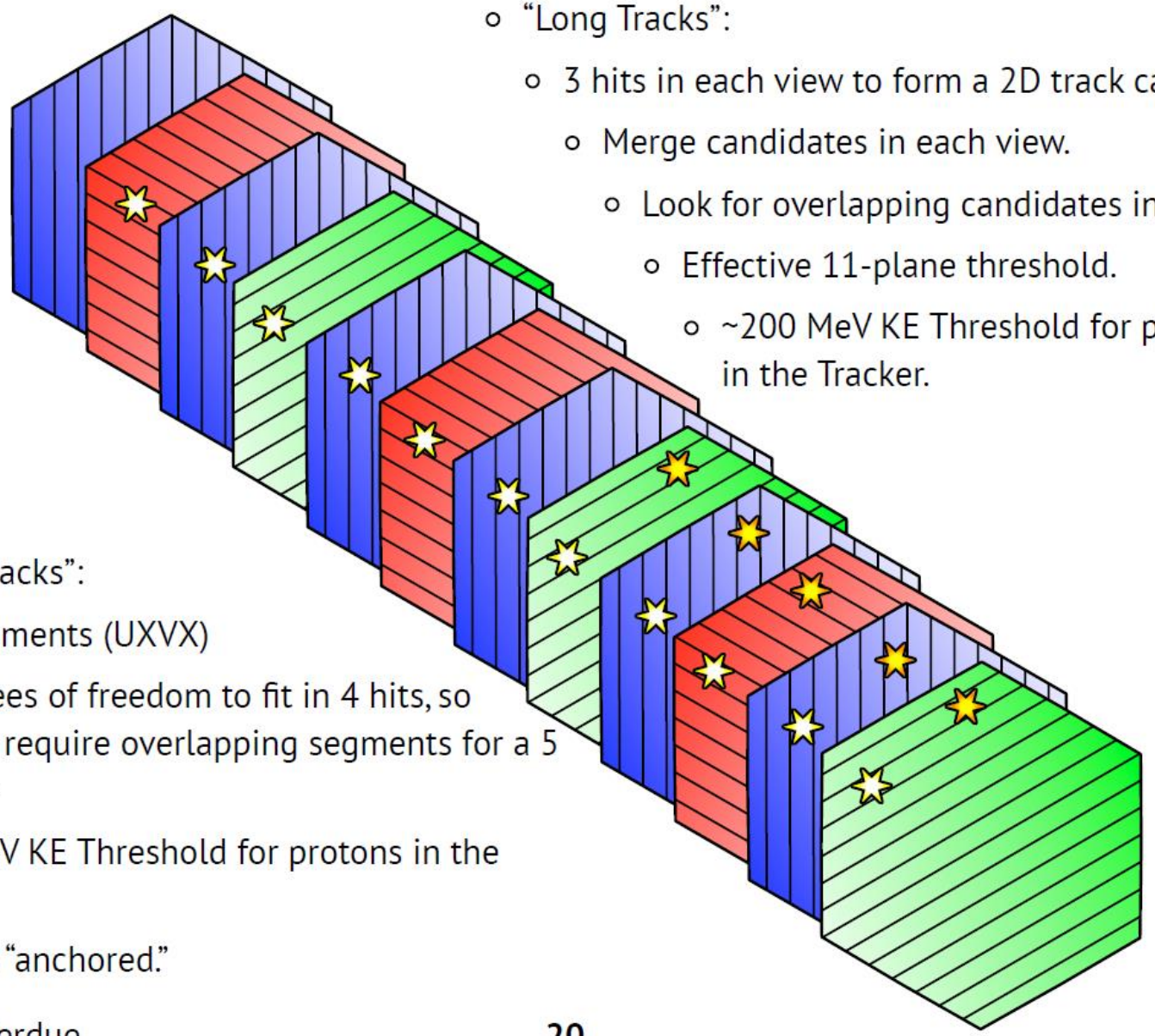
- $N \rightarrow \pi\mu$ channel's coherent background requires cuts
- $N \rightarrow \nu\mu\mu$ channel is rare, easier to ID

- Todo: Come up with phase-space cuts on HNL using special signal sample
- Todo: Apply systematic errors on the various stages
- Todo: Standardise limit test for extracting parameter space contours

There's plenty of work ahead, but so are exciting results!

Backup

- "Long Tracks":
  - 3 hits in each view to form a 2D track candidate.
    - Merge candidates in each view.
      - Look for overlapping candidates in 3D.
        - Effective 11-plane threshold.
          - ~200 MeV KE Threshold for protons in the Tracker.



- "Short Tracks":
- 4 hit-segments (UXVX)
- No degrees of freedom to fit in 4 hits, so typically require overlapping segments for a 5 hit track.
- ~100 MeV KE Threshold for protons in the Tracker.
- Typically "anchored."

Gabriel N. Perdue **20** Fermilab

Event loop overview

Flux prediction

User inputs flux tuples (for full flux prediction) or energy spectra (must correspond to hardcoded masses for now, will change in future)

Calculates p^{μ} of HNL under constraint that it reaches the detector
Detector centre (beam coordinates) given by user

Construct HNL with p^{μ}

Decay process

Given HNL with p^{μ}, selects a decay channel and performs a phase space decay (no polarisation effects for now)

Decay rates calculated once outside event loop, using parameter space input by user and event rates from *EPJ C* 81 (2020) 78 *

Saves 4-momenta of FS particles and populates event record

Construct decay product list

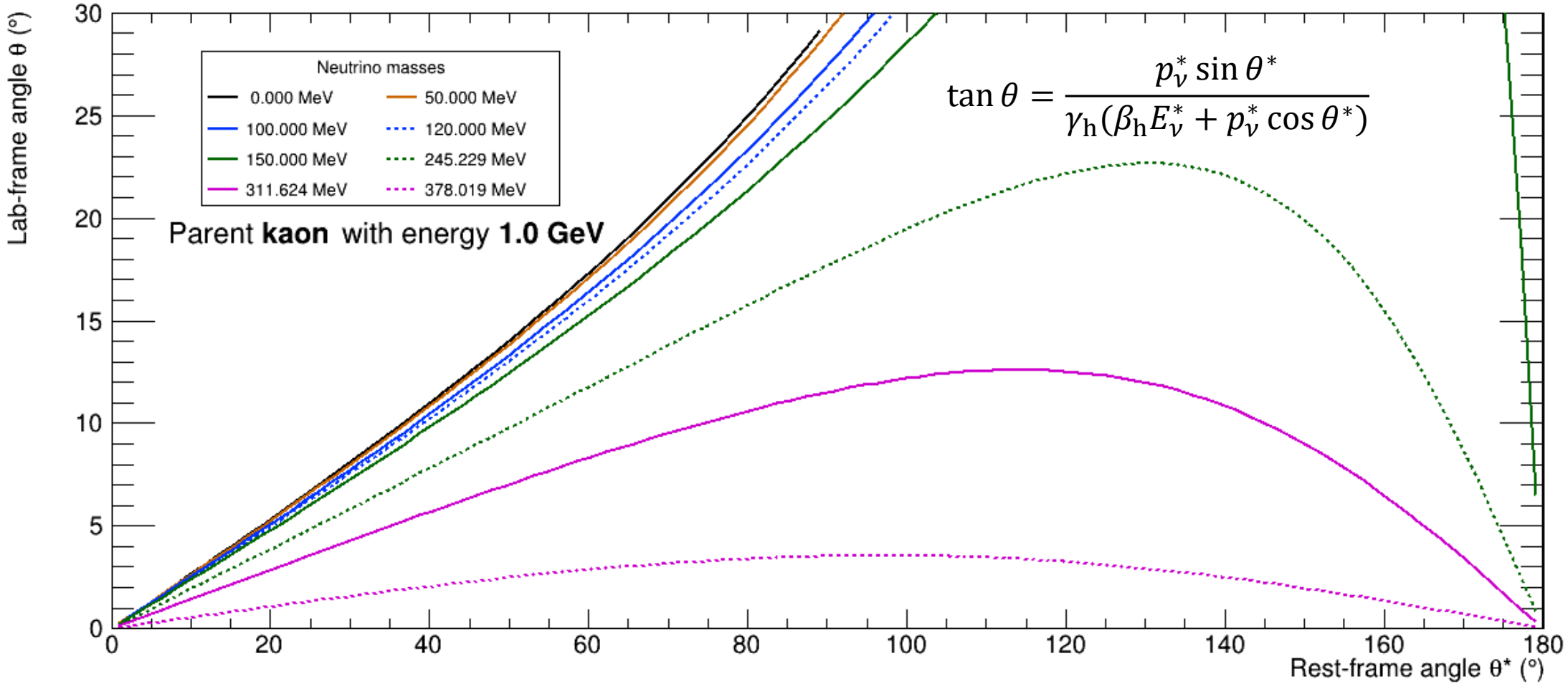
Weight calculation

Calculates geometric weight of HNL trajectory and decay vertex position

User inputs ROOT geometry containing full detector description
Finds trajectory entry and exit into detector, calculates
$P(\text{decay in det} \,|\text{survival}) = P(\text{survival})P(\text{decay in det})$

* *Caveat*: Not used for decay channels involving 3-body π^0 production

Lorentz boost relations for massive neutrinos

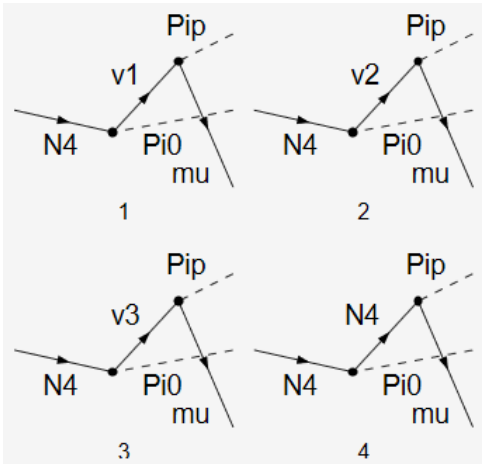


Decay channels for HNL with mass = 250 MeV and $|U_{e4}|^2 : |U_{\mu 4}|^2 = 1:1$

Channel (threshold mass)	Allowed?	Score interval
$N \to \nu\nu\nu$ (0 MeV)	YES	[0.0000, 0.0563]
$N \to \nu ee$ (1 MeV)	YES	[0.0563, 0.0763]
$N \to \nu e\mu$ (106 MeV)	YES	[0.0763, 0.0918]
$N \to \pi^0\nu$ (135 MeV)	YES	[0.0918, 0.5441]
$N \to \pi e$ (140 MeV)	YES	[0.5441, 0.9491]
$N \to \nu\mu\mu$ (211 MeV)	YES	[0.9491,0.9494]
$N \to \pi\mu$ (245 MeV)	YES	[0.9494,1.0000]
$N \to \pi^0\pi^0\nu$ (270 MeV)	NO	N/A
$N \to \pi\pi^0 e$ (275 MeV)	NO	N/A
$N \to \pi\pi^0\mu$ (380 MeV)	NO	N/A

$$s_{i+1} = s_i + \frac{\Gamma_i}{\Gamma_{\text{tot}}}, \qquad s_0 = 0$$

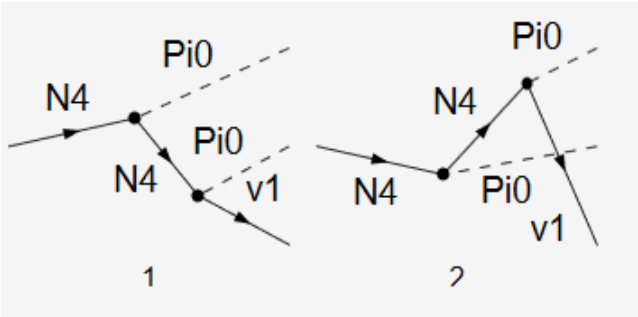
About π^0 and event rates



- Generic $N \to \pi^{\pm}\pi^0\ell^{\mp}, \pi^0\pi^0\nu$ mediated by on-shell ρ
- Low $m_N \leq m_K$: decay channel accessible but ρ not accessible!

- Solution: Calculate matrix element → decay rate
  using EFT Lagrangian described in *EPJ C* **81** (2020) 78
  and uploaded to FeynRules database

Comput. Phys. Commun. **64** (1991) 345-359
Comput. Phys. Commun. **207** (2016) 432-444
2001.04407 [hep-ph]

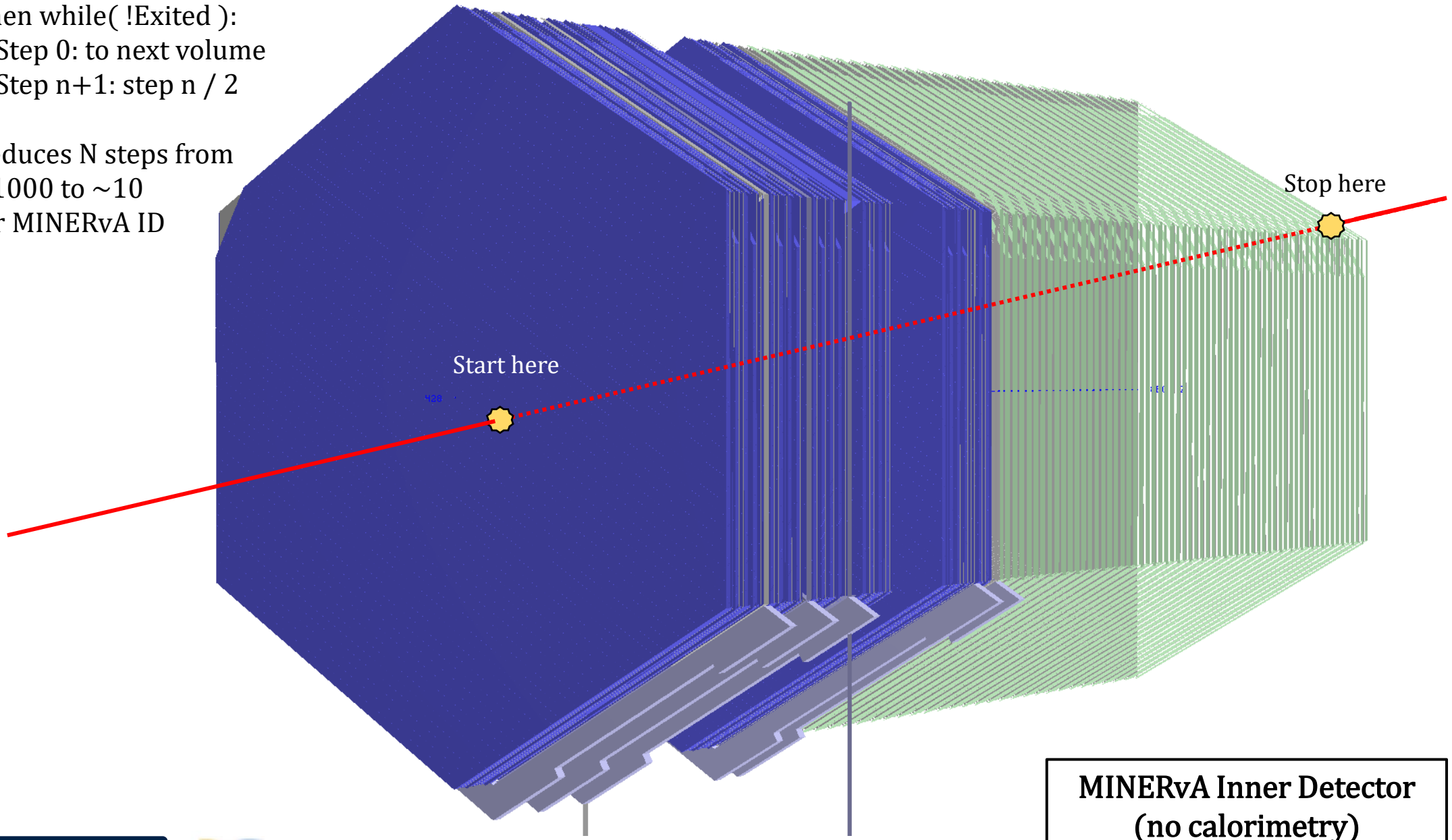


  - Uses FeynArts and FeynCalc Mathematica packages
  - Input FeynRules model and desired topology (1 → 3 legs, 0 loops) then insert particles (e.g. $N \to \pi^0\pi^0\nu$): generates matrix element
  - Calculate $\overline{|\mathcal{M}|^2}$ and decay rate "by hand", step-by-step using automated trace technology

  - $N \to \pi^0\pi^0\nu$ heavily suppressed as $|U_{\alpha 4}|^4$
  - $N \to \pi^{\pm}\pi^0\ell^{\mp}$ suppressed by phase space

Step 1: min(half max BBox side, 50 cm)
Then while(!Exited):
  Step 0: to next volume
  Step n+1: step n / 2

Reduces N steps from
~1000 to ~10
for MINERvA ID



MINERvA Inner Detector (no calorimetry)