Modelling Heavy Neutral Leptons in GENIE: the BeamHNL module

Path to Dark Sector Discoveries at Neutrino Experiments

06/June/2023, Colorado State University, Fort Collins

John Plows

(Reference: K-J. Plows and Xianguo Lu, *Phys Rev D* **107** (2023) 055003)

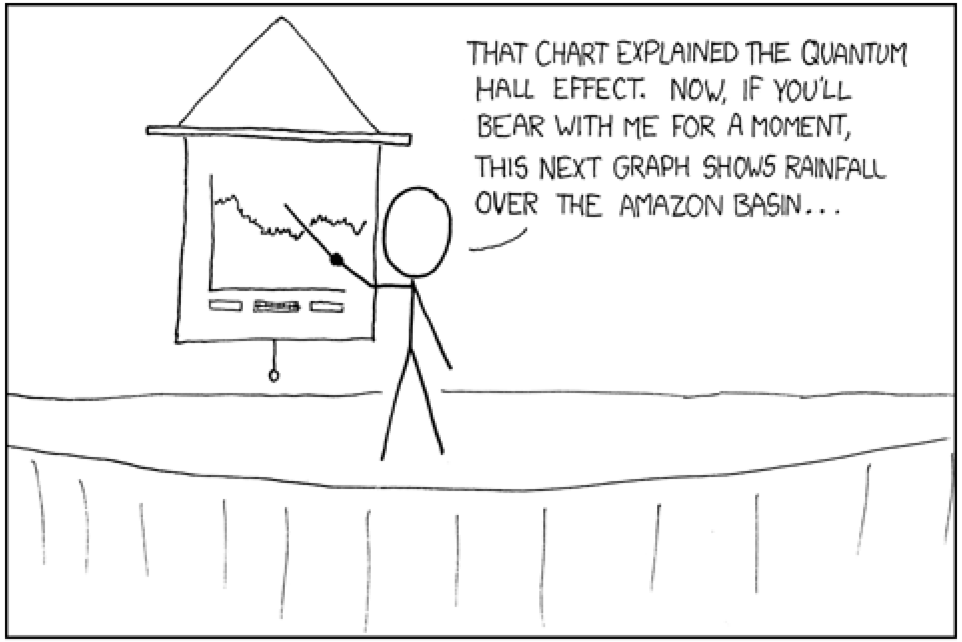
UNIVERSITY OF OXFORD

WARWICK

Outline

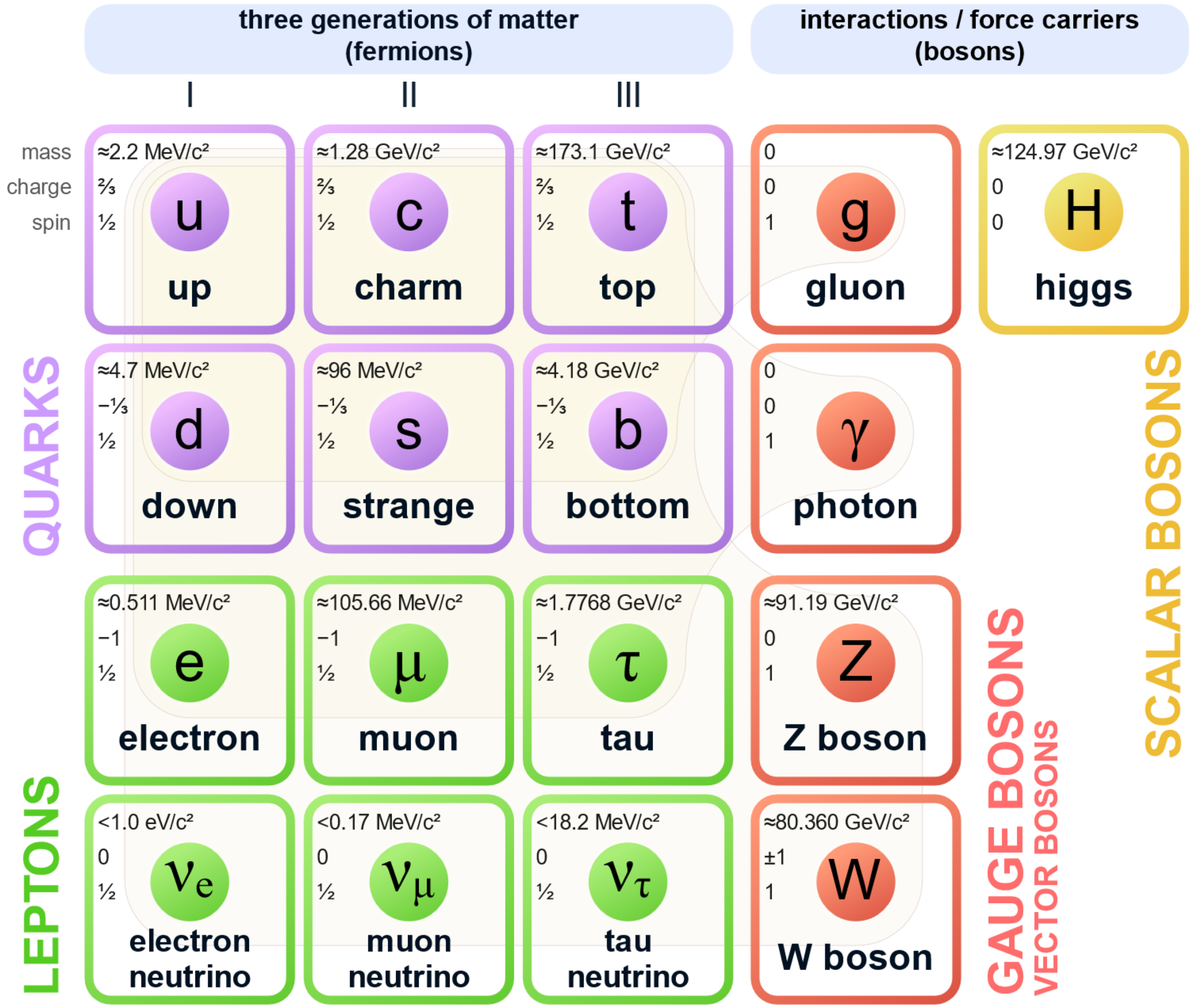
- What are HNL?
- The BeamHNL module
  - Overview
  - Inputs:
    - Beamline simulation
    - Detector location
    - Detector geometry
  - Configuring BeamHNL for physics
  - Modelling:
    - Flux prediction
    - Decay & polarisation
    - Vertex positioning & timing
    - POT estimation
  - Output: The GENIE event record
- Feature preview: theory input for BeamHNL

XKCD 365: Slides

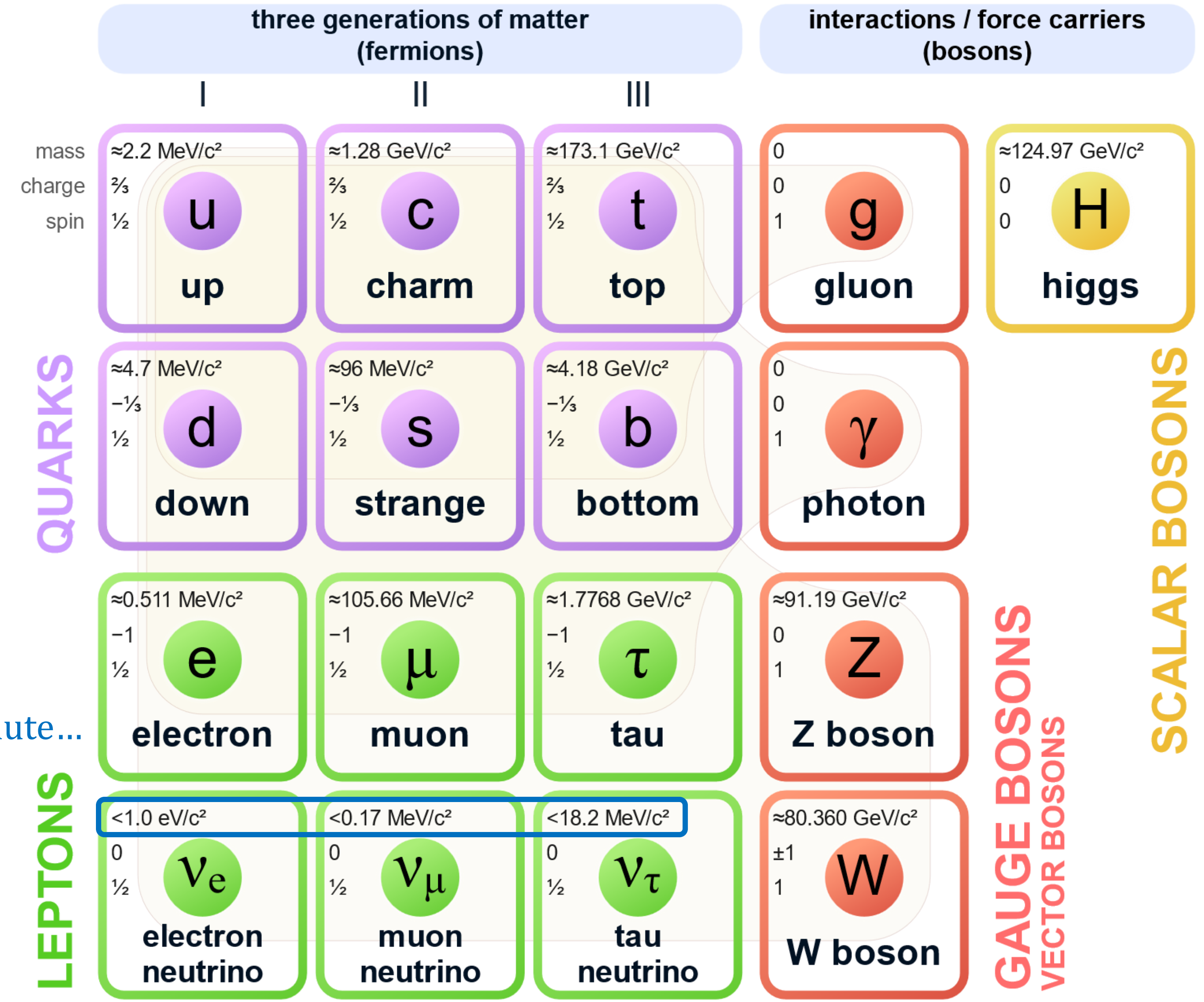


IF YOU KEEP SAYING "BEAR WITH ME FOR A MOMENT", PEOPLE TAKE A WHILE TO FIGURE OUT THAT YOU'RE JUST SHOWING THEM RANDOM SLIDES.

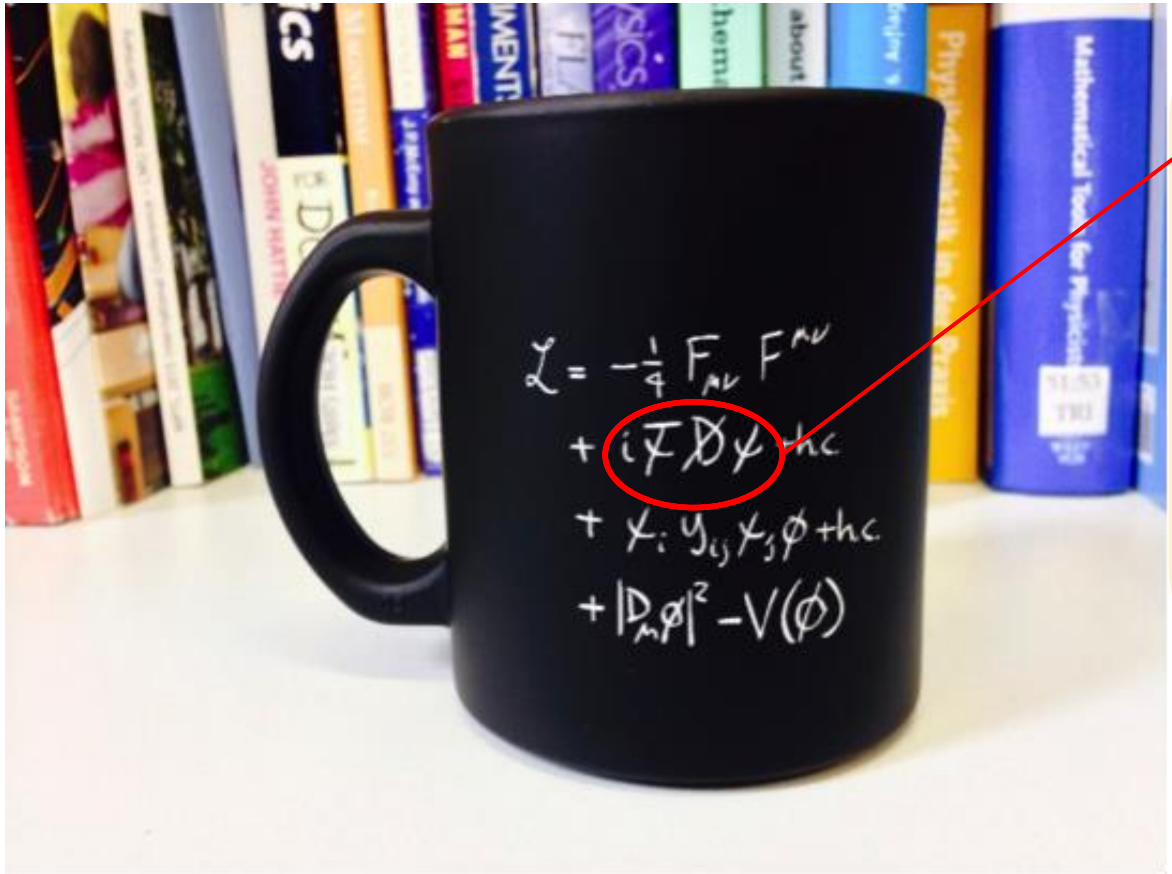
Standard Model of Elementary Particles



Standard Model of Elementary Particles



Wait a minute…



$\mathcal{L} \supset -\frac{1}{2}\bar{\psi}\gamma^\mu D_\mu \psi$, where ψ satisfies the Dirac equation:

$$(i\gamma^\mu D_\mu - m)\psi = 0$$

Weak force contains vector (V) and axial (A) currents:

$$j_V^\mu = \bar{\psi}\gamma^\mu\psi, j_A^\mu = \bar{\psi}\gamma^\mu\gamma^5\psi$$

(maximal parity violation + negative helicity $\Rightarrow V - A$)

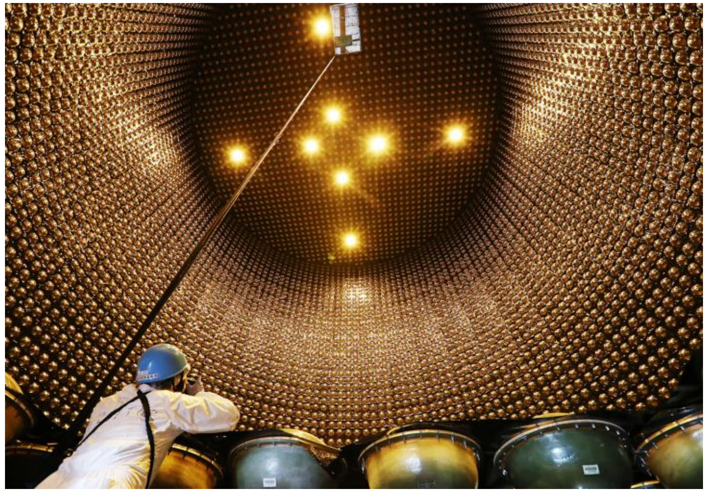
Continuity:

$$\partial_\mu j_V^\mu = 0 ✓$$

$$\partial_\mu j_A^\mu = 2im\bar{\psi}\gamma^5\psi = 0 \Rightarrow \boldsymbol{m = 0}$$

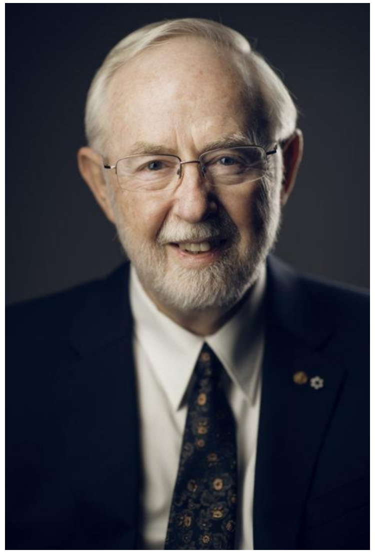
In the Standard Model, the neutrino is by construction massless.

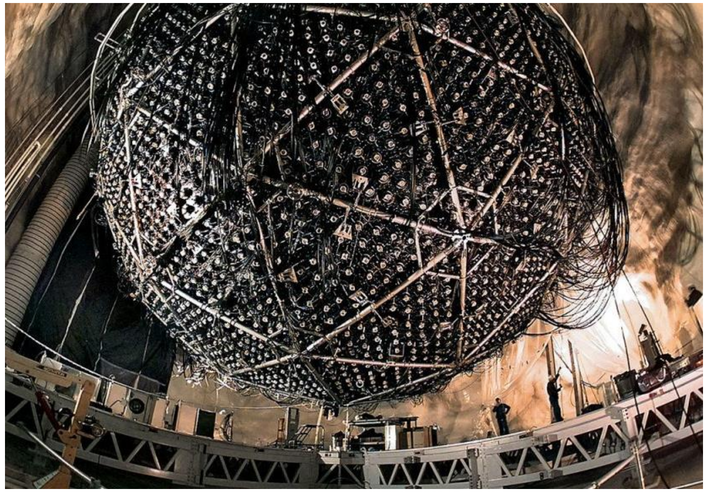
[Lee Grodzins holding the setup for the measurement of neutrino helicity, September 1958. Taken from *Nucl. Phys. B* **229** (2012) 5]



2015 Nobel Prize in Physics:

Neutrino oscillations

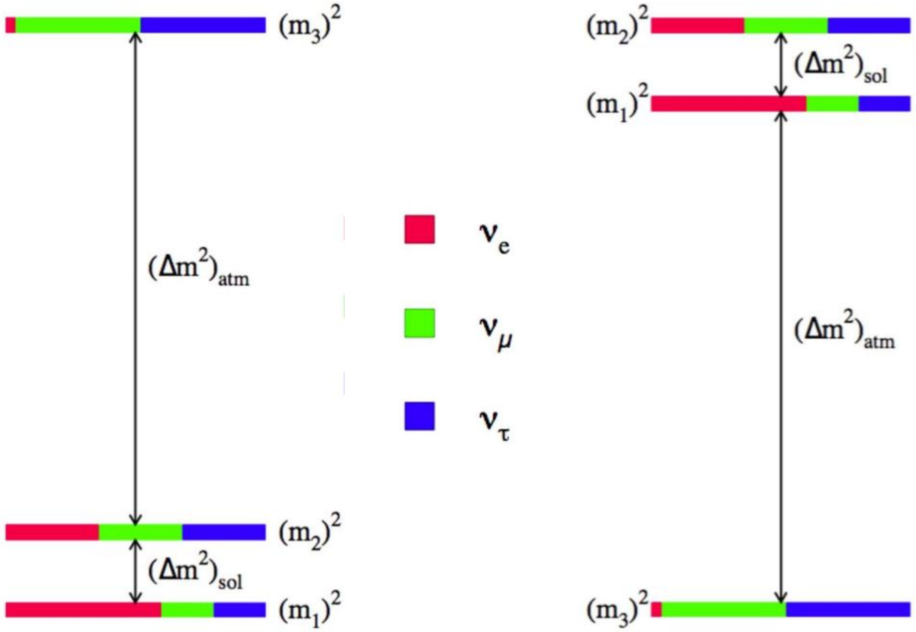


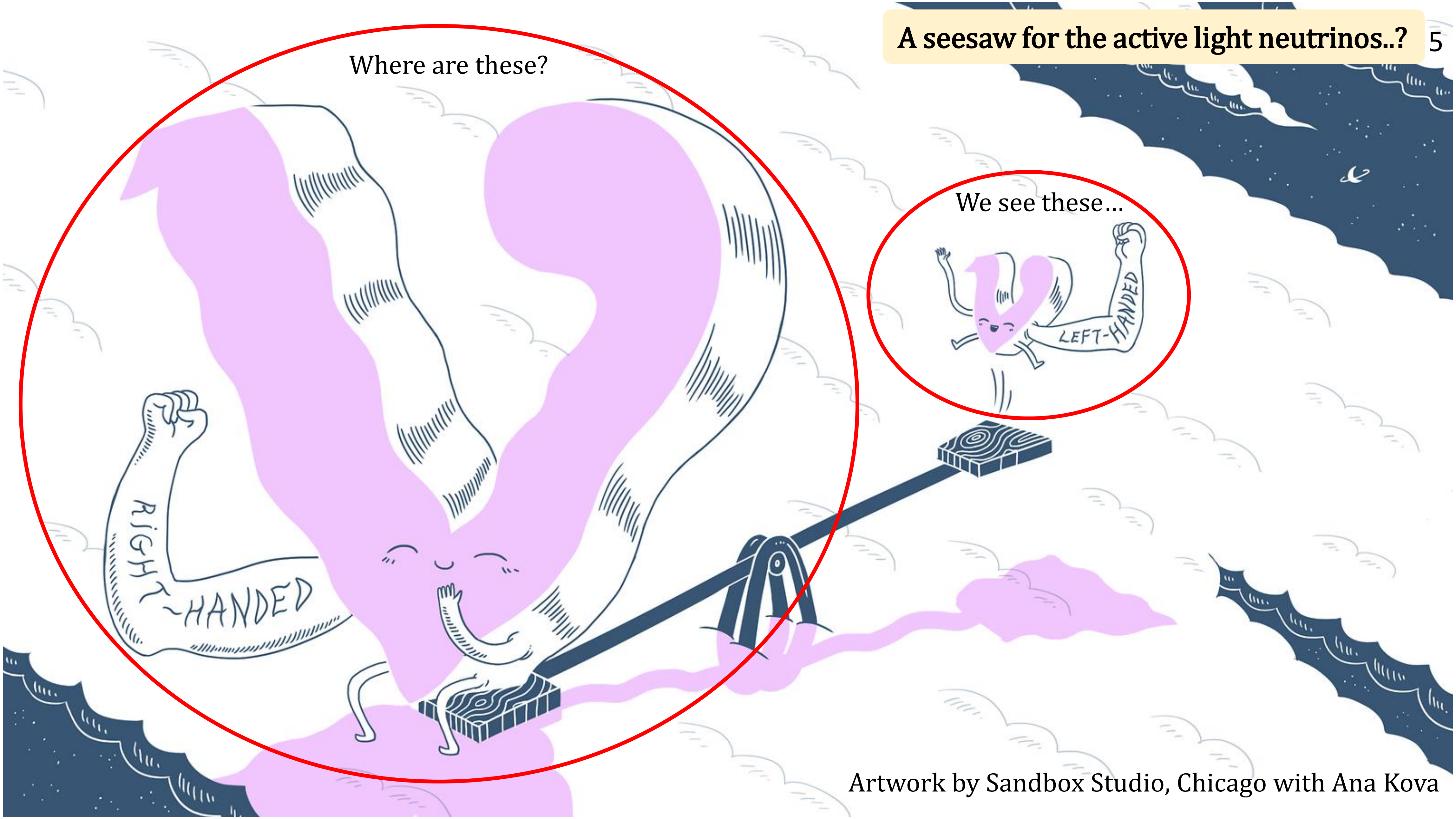


In the Standard Model, the neutrino is by construction massless.

But neutrinos oscillate: ⇒ they have mass!

… how?





Artwork by Sandbox Studio, Chicago with Ana Kova

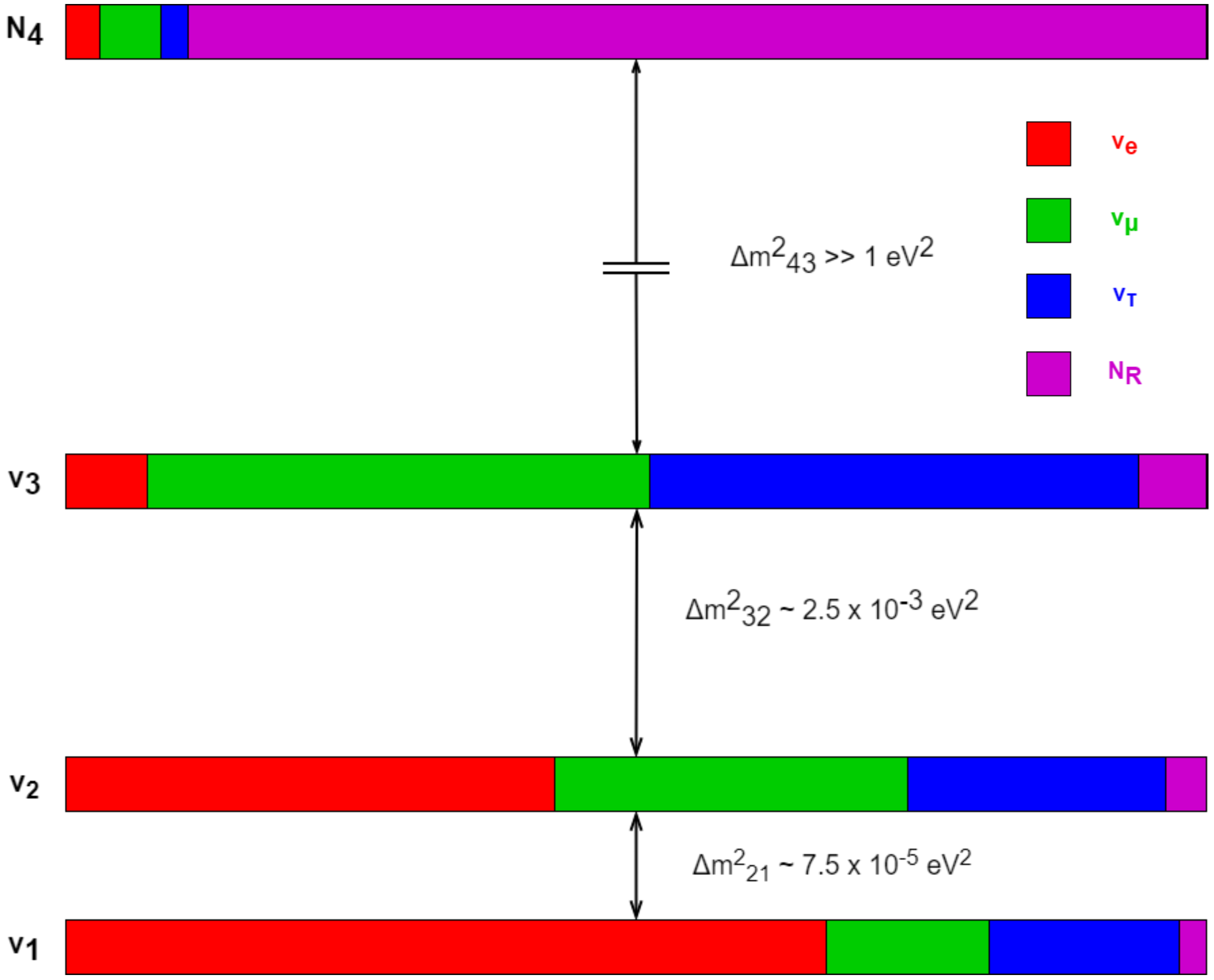
What are HNL?

- Naturally motivated extension to Standard Model
  - Light neutrinos $\nu_{1,2,3}$ have <u>at least 2 non-zero masses</u>
  - Admixture with regular "flavour" eigenstates ν_α as $\nu_\alpha = \sum_{i=1,2,3} U_{\alpha i}\nu_i + \sum_{j\in J} U_{\alpha j} N_j$

- HNL: **new mass eigenstates**
  - Mass $\mathcal{O}(\leq \text{TeV}/c^2)$ in νMSM "neutrino minimal SM"
  - Can explain:
    - Active neutrino mass!
    - Dark matter candidate!
    - Matter-antimatter asymmetry!

  (see T. Asaka et al, *Phys. Lett.* ***B*** **631** (2005) 4, A.Boyarsky et al, *PPNP* ***104*** (2019) 1)

  - $\mathcal{O}(100\ \text{MeV}/c^2 - \text{TeV}/c^2)$ HNL decay to visible signatures in detectors



- Assume one heavy neutrino eigenstate N_4 as in K. Abe et al (T2K), *Phys. Rev. D* **100** (2019) 052006
  - Parameter space: $\{M_{N_4}, |U_{e4}|^2, |U_{\mu 4}|^2, |U_{\tau 4}|^2\} \equiv \{M_{N_4}, |U_{\alpha 4}|^2\}$

- Effective field theory describing low-energy HNL (GeV range) as in P. Coloma et al, *EPJ C* **81** (2021) 78
  - HNL interact directly with mesons, valid up to ~ EW scale
  - Lagrangian available in FeynRules model database

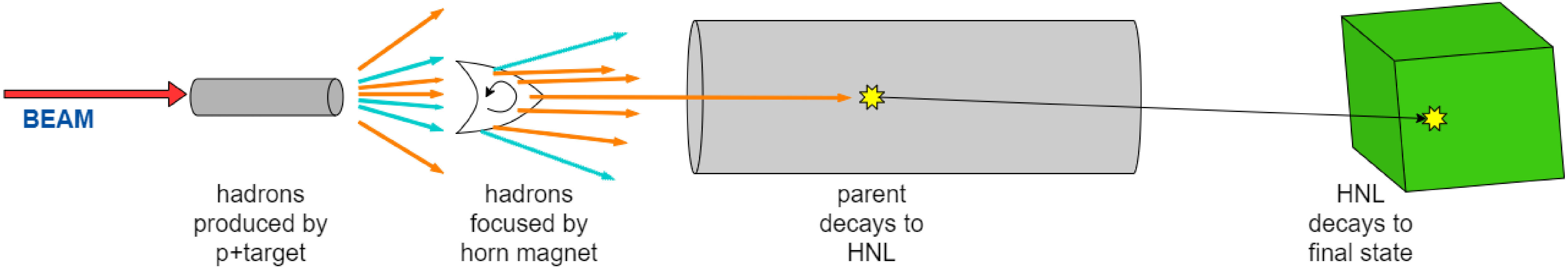
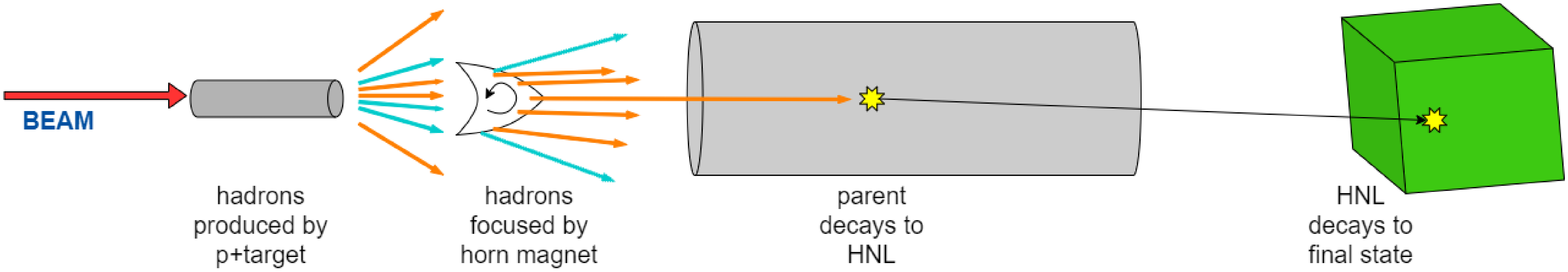


Table 1: Summary of the fixed-target searches for Heavy Neutral Leptons considered throughout Section 5.

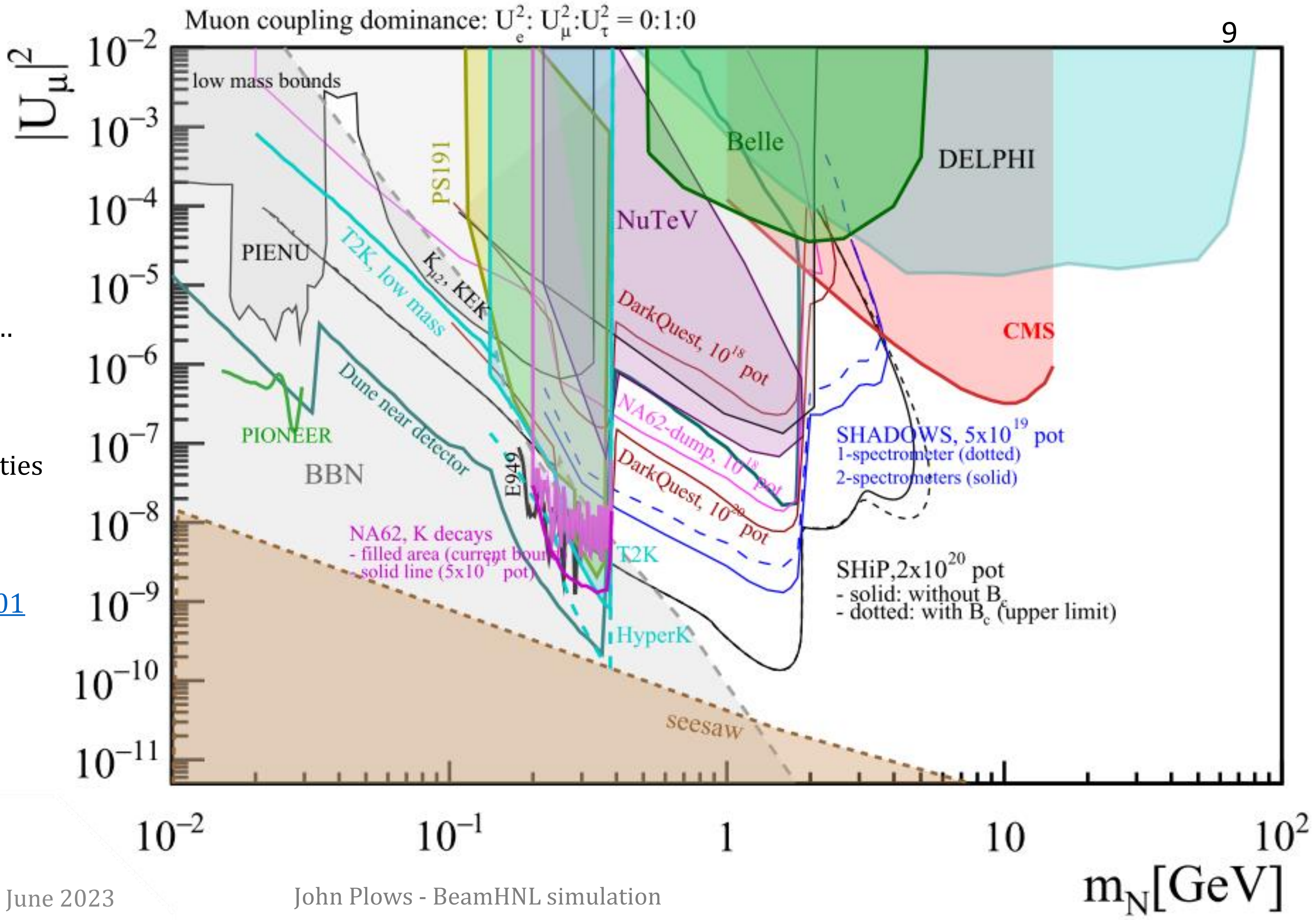
experiment/ proposal	lab	beam type	detector technology	detector transverse dimensions	detector decay volume length	distance from dump	N_{pot}	timescale
NA62-K	CERN	p, 400 GeV	spectrometer	$A = \pi r^2$, $r = 1$ m	~ 80 m	~100 m	$5 \cdot 10^{19}$	by (2032–2038)
NA62-dump	CERN	p, 400 GeV	spectrometer	$A = \pi r^2$, $r = 1$ m	~ 80 m	~100 m	$5 \cdot 10^{19}$	by (2032–2038)
SHADOWS	CERN	p, 400 GeV	spectrometer	2.5×2.5 m^2	~ 20 m	~ 10 m	$5 \cdot 10^{19}$	by (2032–2038)
SHiP	CERN	p, 400 GeV	spectrometer	5×10 m^2	~ 50 m	~ 45 m	$2 \cdot 10^{20}$	
T2K	J-PARC	p, 30 GeV	composite w/ GArTPC	~ 3.3 m^2	~ 1.7 m	280 m	$3.8 \cdot 10^{21}$	2010–2021
T2K-II	J-PARC	p, 30 GeV	composite w/ GArTPC	~ 3.3 m^2	~ 3.6 m	280 m	$+10 \cdot 10^{21}$	2022–2026
Hyper-K	J-PARC	p, 30 GeV	composite w/ GArTPC	~ 3.3 m^2	~ 3.6 m	280 m	$2.70 \cdot 10^{22}$	by 2038
SBND	FNAL	p, 8 GeV	LArTPC	16 m^2	5 m	110 m	$10 \cdot 10^{20}$	2023–2027
MicroBooNE	FNAL	p, 8/120 GeV	LArTPC	6 m^2	10.4 m	463 m/100 m	$1.5 \cdot 10^{21}/2.2 \cdot 10^{21}$	2015–2021
ArgoNeuT	FNAL	p, 120 GeV	LArTPC	0.2 m^2	0.9 m	318 m	$1.25 \cdot 10^{20}$	2009–2010
DUNE ND	FNAL	p, 120 GeV	LAr/GAr TPC	~12 m^2	~5 m	574 m	$\gtrsim 1.47 \cdot 10^{22}$	~2030–2040
DarkQuest	FNAL	p, 120 GeV	spectrometer	2×4 m^2	20 m	5 m	$1 \cdot 10^{18}$	2024-2025



No positive detection yet…

Shaded areas: published results
Unshaded areas: sensitivities of future analyses

A. M. Abdullahi et al, *J Phys G* **50** (2023) 020501



Genie Event Generator & Global Analysis of Neutrino Scattering Data

Version: 3.4.0
Tag: R-3_04_00, Released: 10 March 2023, Status: *pro*

Improvements over 3.2.2
(Important contributions by non-GENIE authors are especially acknowledged in the text below)

New and/or updated physics models:

- Addition of a spectral function-like approach for binding energies. *Contribution by Steven Dolan and Laura Munteanu* . [GENIE pull request #249].

New comprehensive model configurations and tunes:

- Added CMC desired by SBN and DUNE experiments: AR23_20i_00_000. [Readme file].

Beyond Standard model:

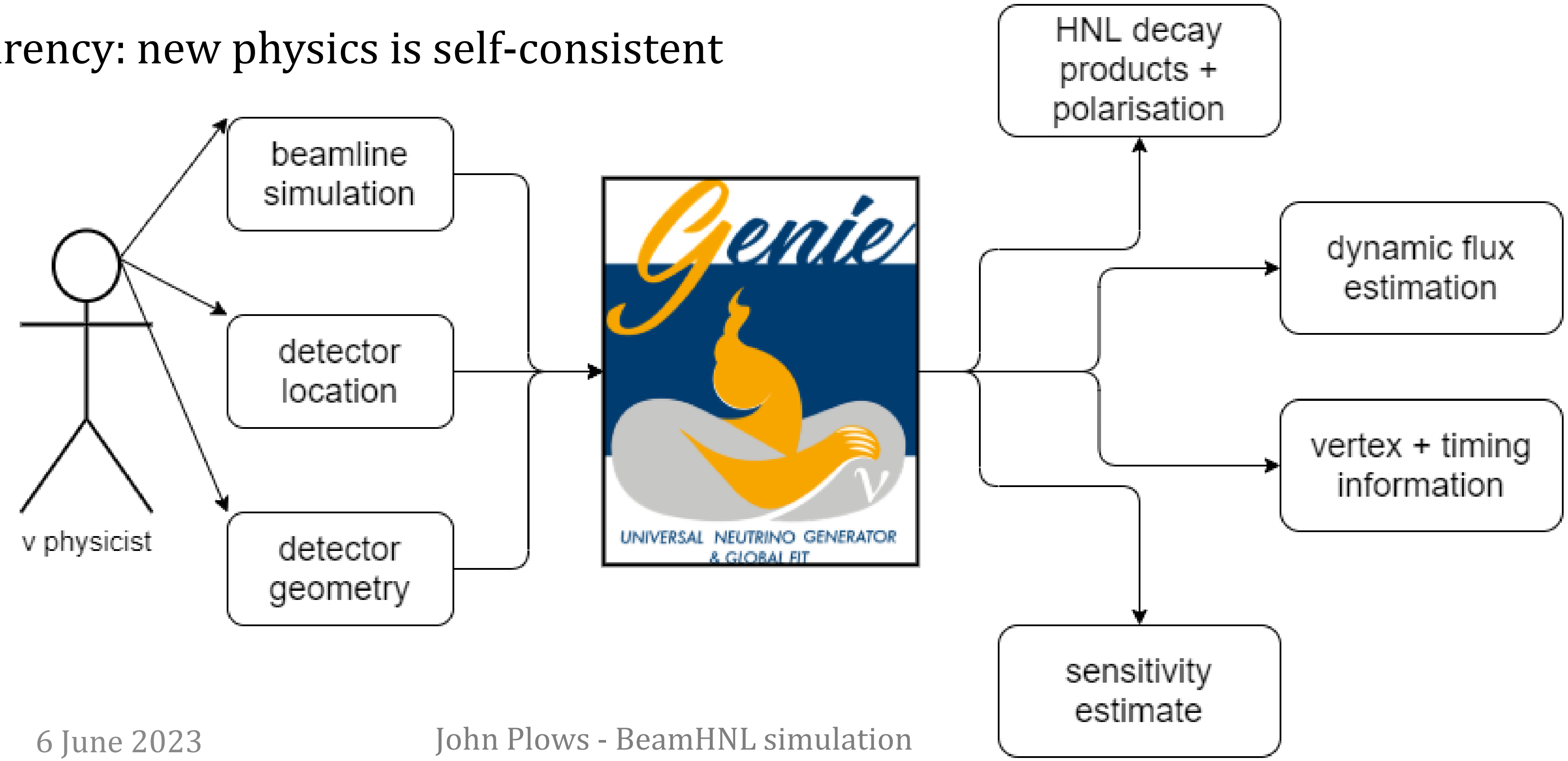
- Addition of Beam-produced Heavy Neutral Leptons. *Contribution by John Plows (Oxford)* . [GENIE pull request #223].

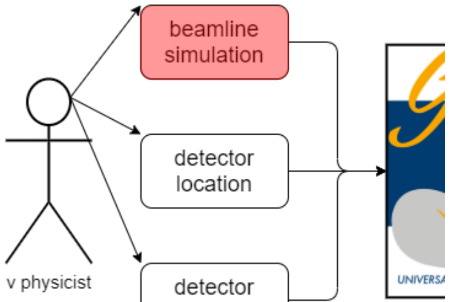
Other improvements / bug fixes:

- Fix in HAIntranuke about random number generation. [GENIE pull request #241].
- Fix in the hadronisation rotation. *Contribution by Qiyu Yan* . [GENIE pull request #264].

The BeamHNL module

- An experiment-agnostic, configurable HNL generation application for accelerator neutrinos
- Goals:
  1. User flexibility: ease of use <u>and</u> integration with simulation
  2. Generality: for use with many beamlines, detectors
  3. Transparency: new physics is self-consistent





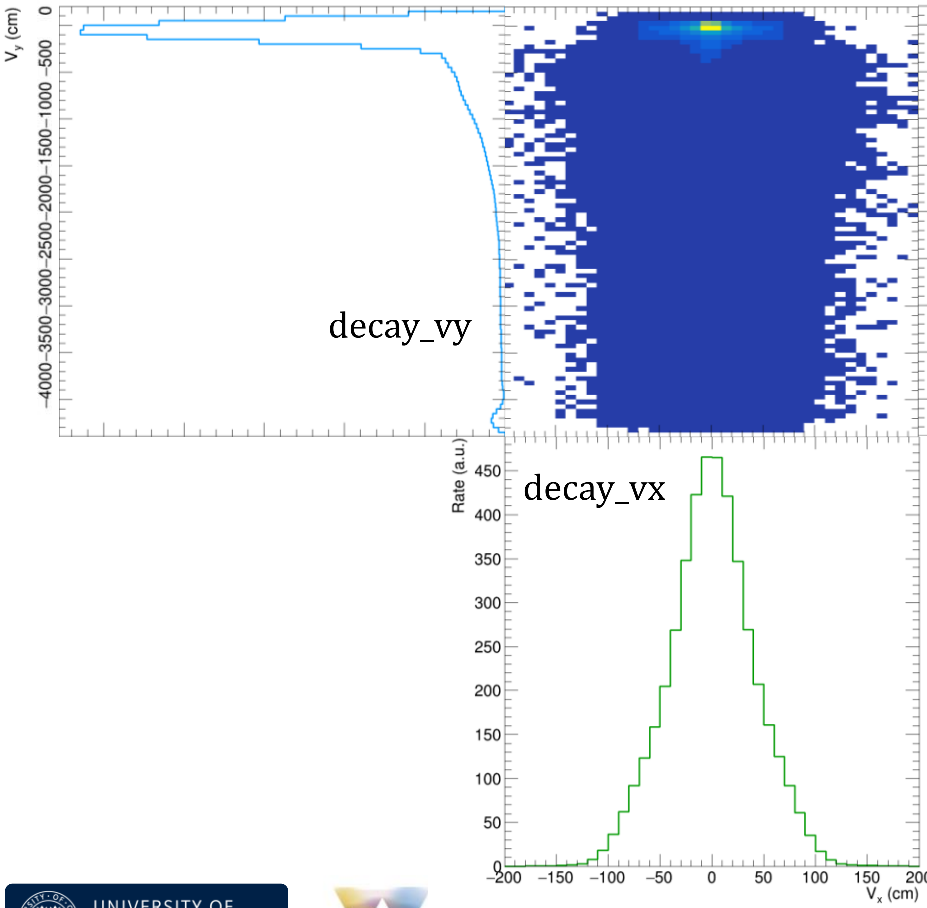

```
======> EVENT:25
 job              = 32
 potnum           = 98
 decay_vx         = -4.45755
 decay_vy         = -7.12057
 decay_vz         = 4097.12
 decay_pdpx       = -0.0012738
 decay_pdpy       = -0.0203605
 decay_pdpz       = 8.92705
 decay_ptype      = 321
 decay_necm       = 0.235532
 decay_nimpwt     = 3.33333
```

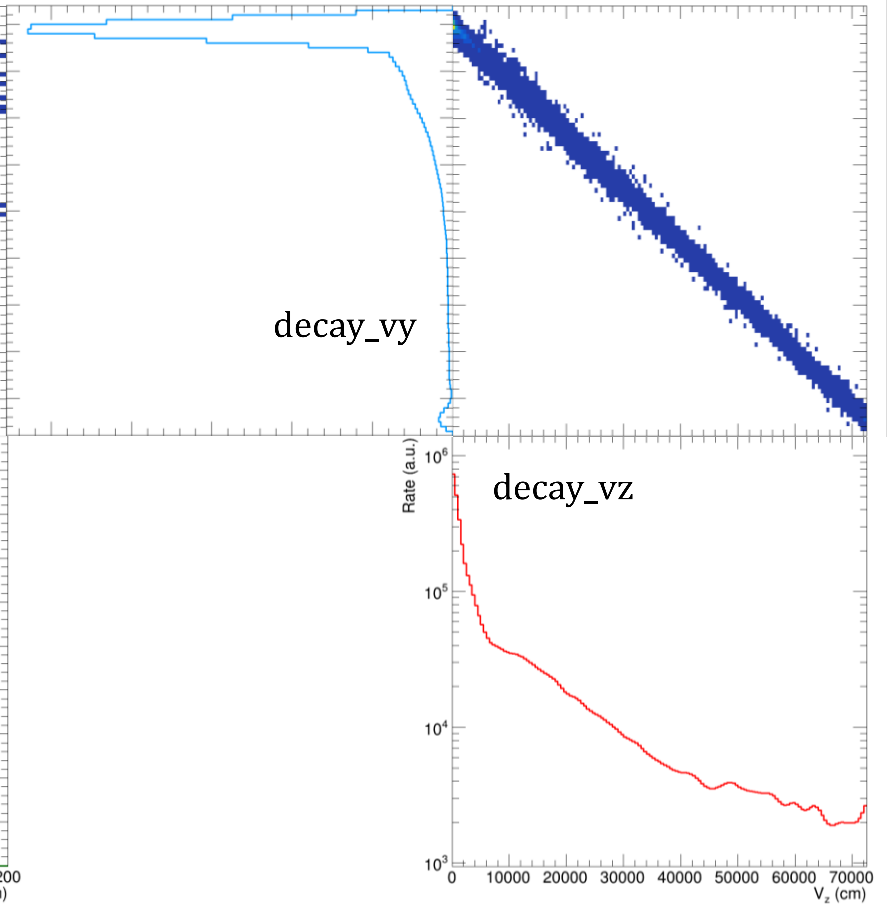
Parent decay coordinates (decay_vx, decay_vy, decay_vz)

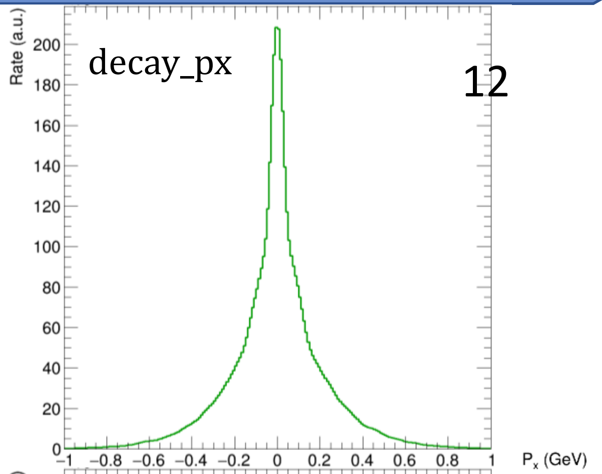
Parent decay momentum (decay_pdpx, decay_pdpy, decay_pdpz)

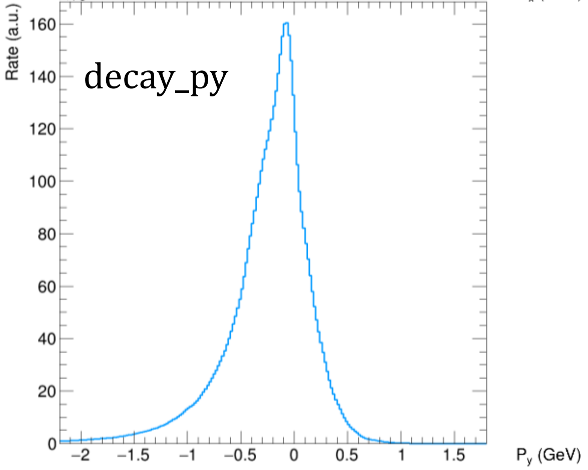
decay_necm → SM neutrino E

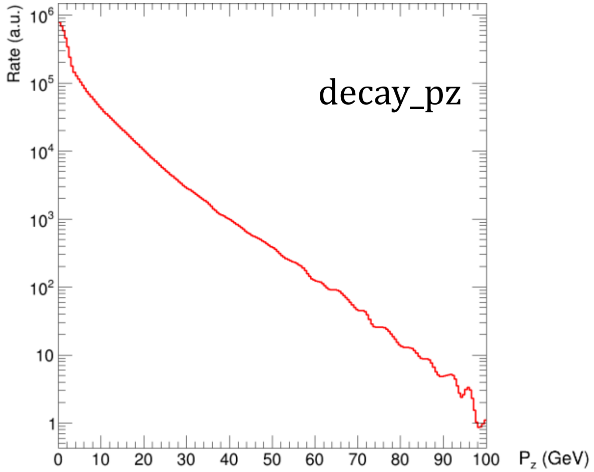
decay_nimpwt → Stat multiplier

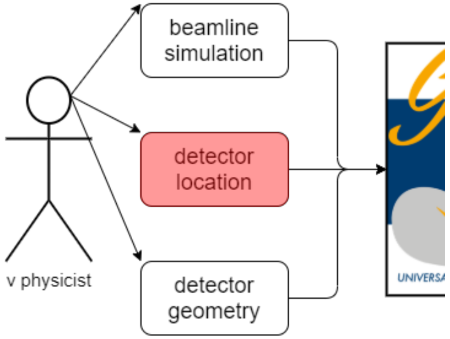








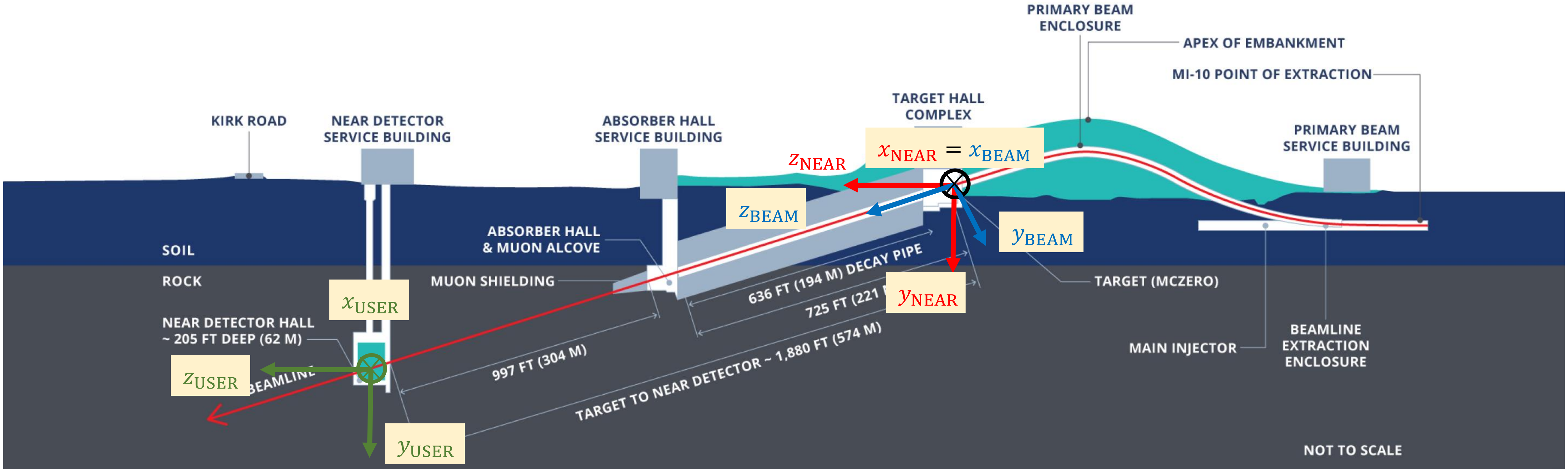


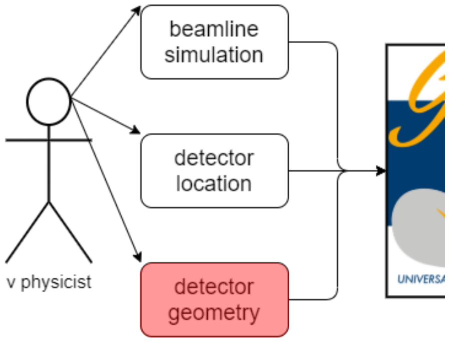


3 coordinate systems:

- NEAR (“global” system with *z* horizontal at target)
- BEAM (same origin as NEAR but rotated to match beamline)
- USER (the detector’s internal coordinate system)

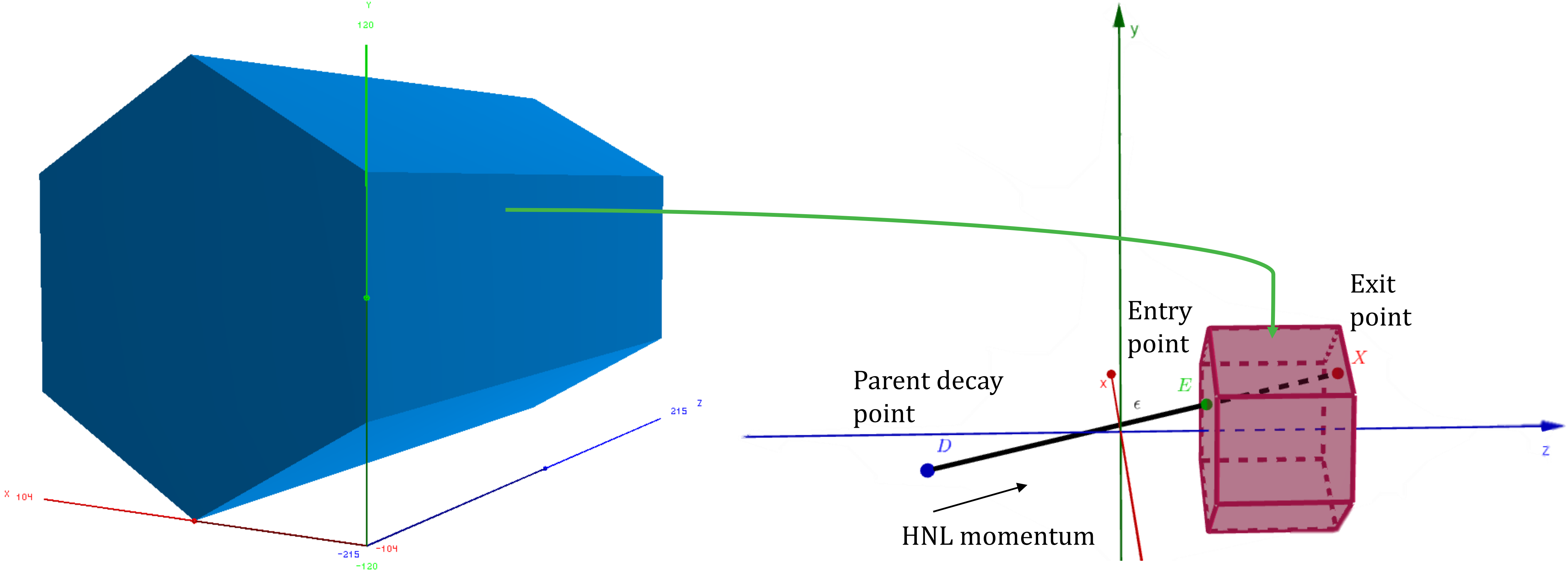
Can transform between two coordinate systems using **1 vector of translations** and **1 vector of rotations**





Arbitrarily complicated ROOT geometry file

BeamHNL calculates where a given HNL enters and exits the detector volume and assigns a vertex accordingly



Job runtime parameters controlled by single configuration file

- Script/batch friendly
- Storable for reproducibility
- Transparent

User passes arguments such as HNL mass, channels to simulate the decays of HNL into, detector location, flux-calculation switches…

An example can be found in

$GENIE/src/contrib/beamhnl/ CommonHNL_DEMO.xml

Descriptions of the entries can be found in $GENIE/config/BeamHNLGenerator.xml

```
<param_set name="ParameterSpace">
  <param type="double" name="HNL-Mass"> 0.200 </param> <!-- GeV -->
  <param type="vec-double" name="HNL-LeptonMixing" delim=";"> 1.0e-7 ; 1.0e-7 ; 0.0 </param>
  <param type="bool" name="HNL-Majorana"> false </param>

  <param type="bool" name="GetCMFrameInstead"> false </param>
</param_set>

<param_set name="Inte
  <!-- 2-body decays
  <param type="bool"
  <param type="bool"
  <param type="bool"
  <!-- 3-body decays -->
  <param type="bool" name="HNL-3B_nu_nu_nu"> true </param>
  <param type="bool" name="HNL-3B_nu_mu_mu"> false </param>
  <param type="bool" name="HNL-3B_nu_e_e"> false </param>
  <param type="bool" name="HNL-3B_nu_mu_e"> false </param>
  <param type="bool" name="HNL-3B_e_pi_pi0"> false </param>
  <param type="bool" name="HNL-3B_mu_pi_pi0"> false </param>
  <param type="bool" name="HNL-3B_nu_pi0_pi0"> false </param>
</param_set>

<param_set name="CoordinateXForm">
  <param type="vec-double" name="Near2Beam_R" delim=";"> 0.0 ; 0.0 ; -0.05830 </param> <!-- rad -->
  <!-- Euler angles, extrinsic x-z-x = 1-2-3, RM * BEAM = USER, RM = Rx(1) * Rz(2) * Rx(3). -->
  <!-- Describes rotation of BEAM wrt NEAR frame -->
  <param type="vec-double" name="Near2User_T" delim=";"> 0.0 ; -60.0 ; 1000.0 </param> <!-- m -->
  <!-- USER origin in NEAR coordinates -->
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  <!-- Position of detector centre in USER frame, in case it is not at USER origin -->
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```

ParameterSpace block: specify what HNL mass / mixings / nature you want

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</param_set>
```

InterestingChannels block: specify which channels you want to simulate.

```
<param_set name="InterestingChannels">
  <!-- 2-body decays -->
  <param type="bool" name="HNL-2B_mu_pi"> true </param>
  <param type="bool" name="HNL-2B_e_pi"> true </param>
  <param type="bool" name="HNL-2B_nu_pi0"> false </param>
  <!-- 3-body decays -->
  <param type="bool" name="HNL-3B_nu_nu_nu"> true </param>
  <param type="bool" name="HNL-3B_nu_mu_mu"> false </param>
  <param type="bool" name="HNL-3B_nu_e_e"> false </param>
  <param type="bool" name="HNL-3B_nu_mu_e"> false </param>
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```

(in this example: $N_4 \to \ell^{\mp}\pi^{\pm}, N_4 \to \nu\nu\nu$ events will be kept in the event record)

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  <param type="bool"
  <param type="bool"
  <param type="bool"
  <param type="bool"
  <param type="bool"
  <param type="bool"
</param_set>
```

CoordinateXForm block: Provide vectors describing detector location.

In this example, detector centre at:

$(x_{\mathrm{NEAR}}, y_{\mathrm{NEAR}}, z_{\mathrm{NEAR}}) = (0, -60, 1000)$ m

$(x_{\mathrm{USER}}, y_{\mathrm{USER}}, z_{\mathrm{USER}}) = \mathbf{0}$

Beam rotated by 58.3 mrad down in (y_{NEAR}, z_{NEAR}) plane

```
<param_set name="CoordinateXForm">
  <param type="vec-double" name="Near2Beam_R" delim=";"> 0.0 ; 0.0 ; -0.05830 </param> <!-- rad -->
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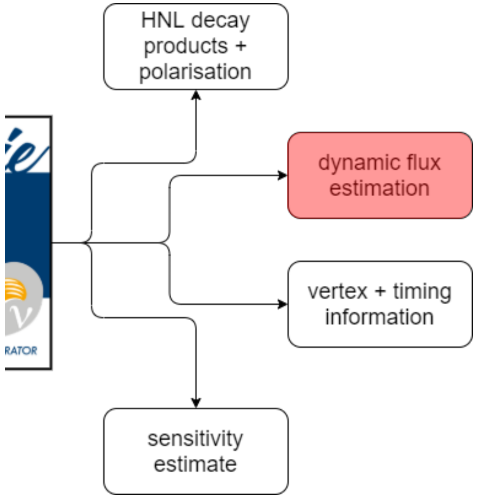


- Pseudoscalar meson decay $P \to N_4 + \ell$ (+ pseudoscalar D)
  - Lorentz boost from parent-rest frame into lab frame dominant factor
  - For a massive neutrino

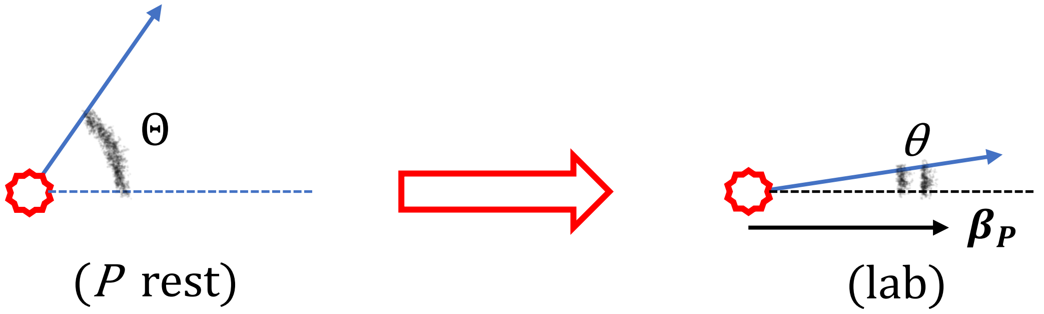
$$\mathcal{B} = \frac{E_{\mathrm{N4}}}{E_{\mathrm{N4}}^{(\mathrm{CM})}} = \frac{1}{\gamma_P(1 - \beta_P \beta_{\mathrm{N4}} \cos\theta_{\mathrm{det}})} \text{ (1)}, \beta_{\mathrm{N4}} \text{ lab} - \text{frame}$$

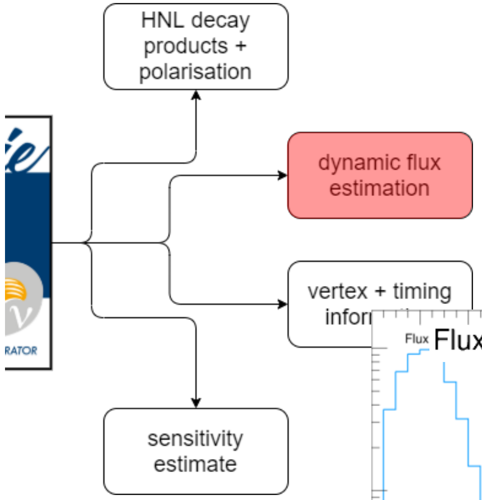
$$(\text{cf.}\, \beta_{\mathrm{N4}} = 1 \text{ for SM})$$

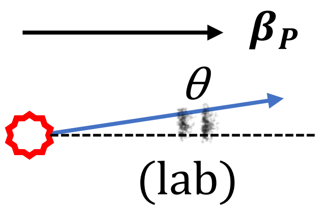
  - Collimation effect:

$$\tan\theta = \frac{q_{\mathrm{N4}} \sin\Theta}{\gamma_P \left(\beta_P E_{\mathrm{N4}}^{(\mathrm{CM})} + q_{\mathrm{N4}} \cos\Theta\right)} \text{ (2)}$$

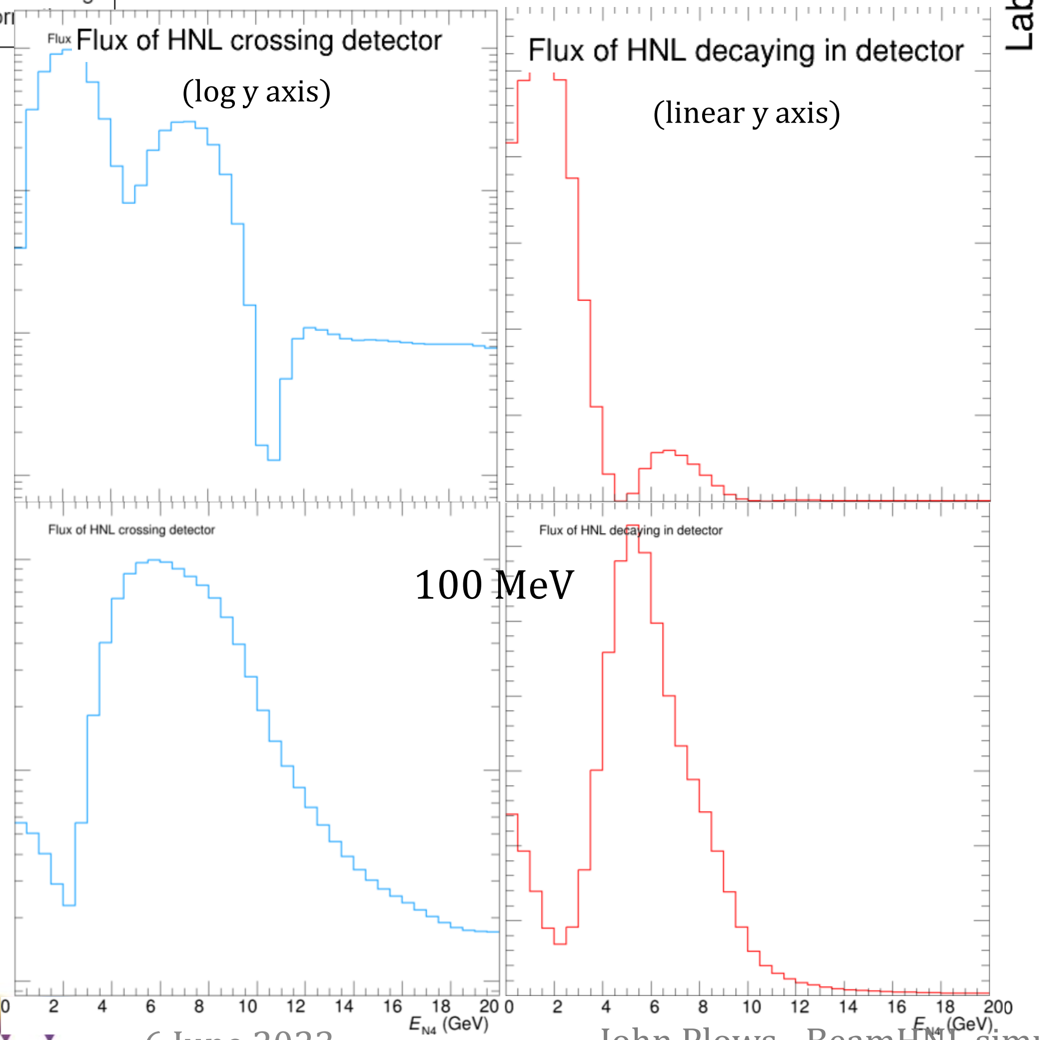
HNL are more collimated with their parents than SM neutrinos.
The flux depends much more strongly on parent kinematics!



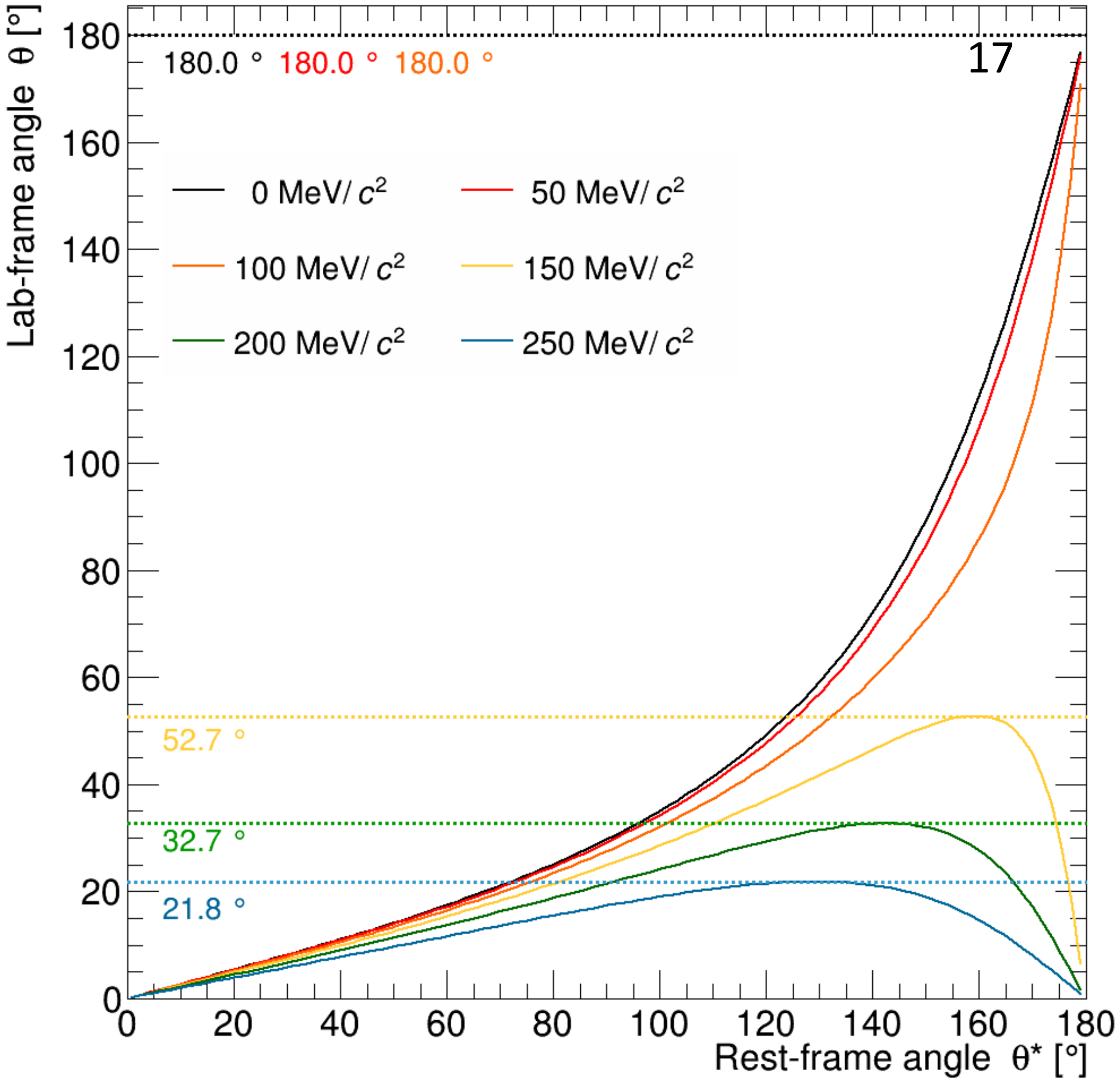


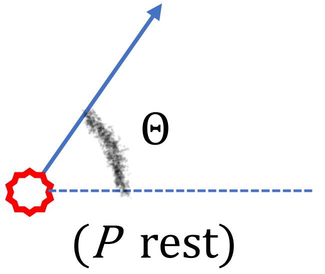


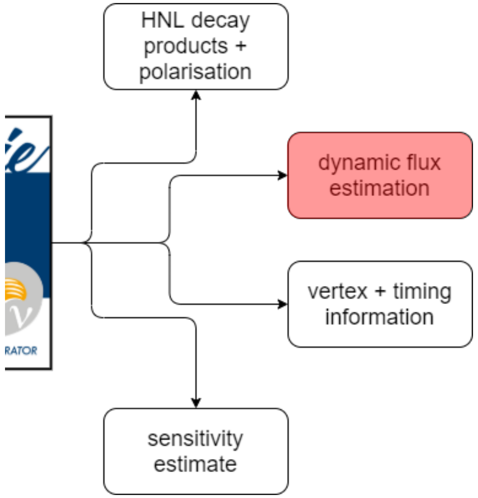
30 MeV

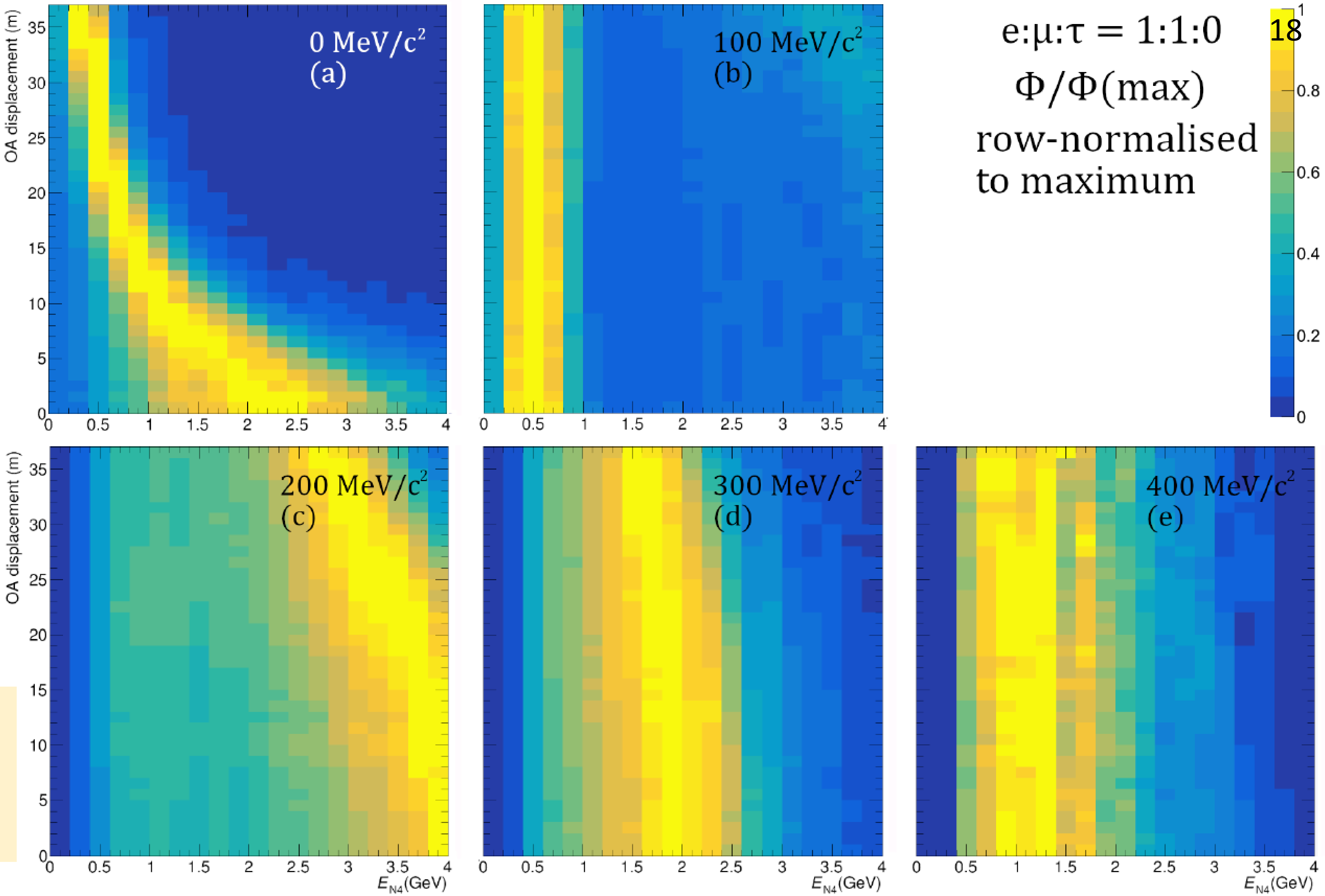


100 MeV

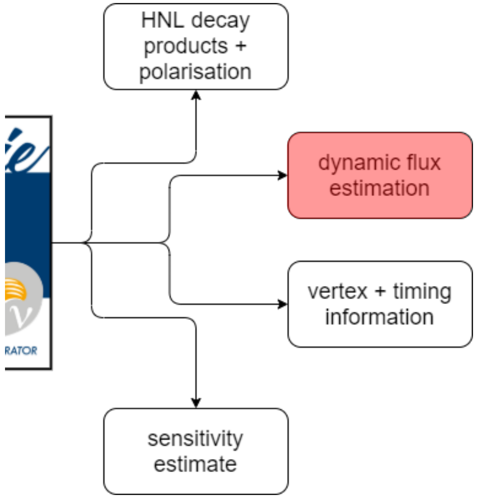


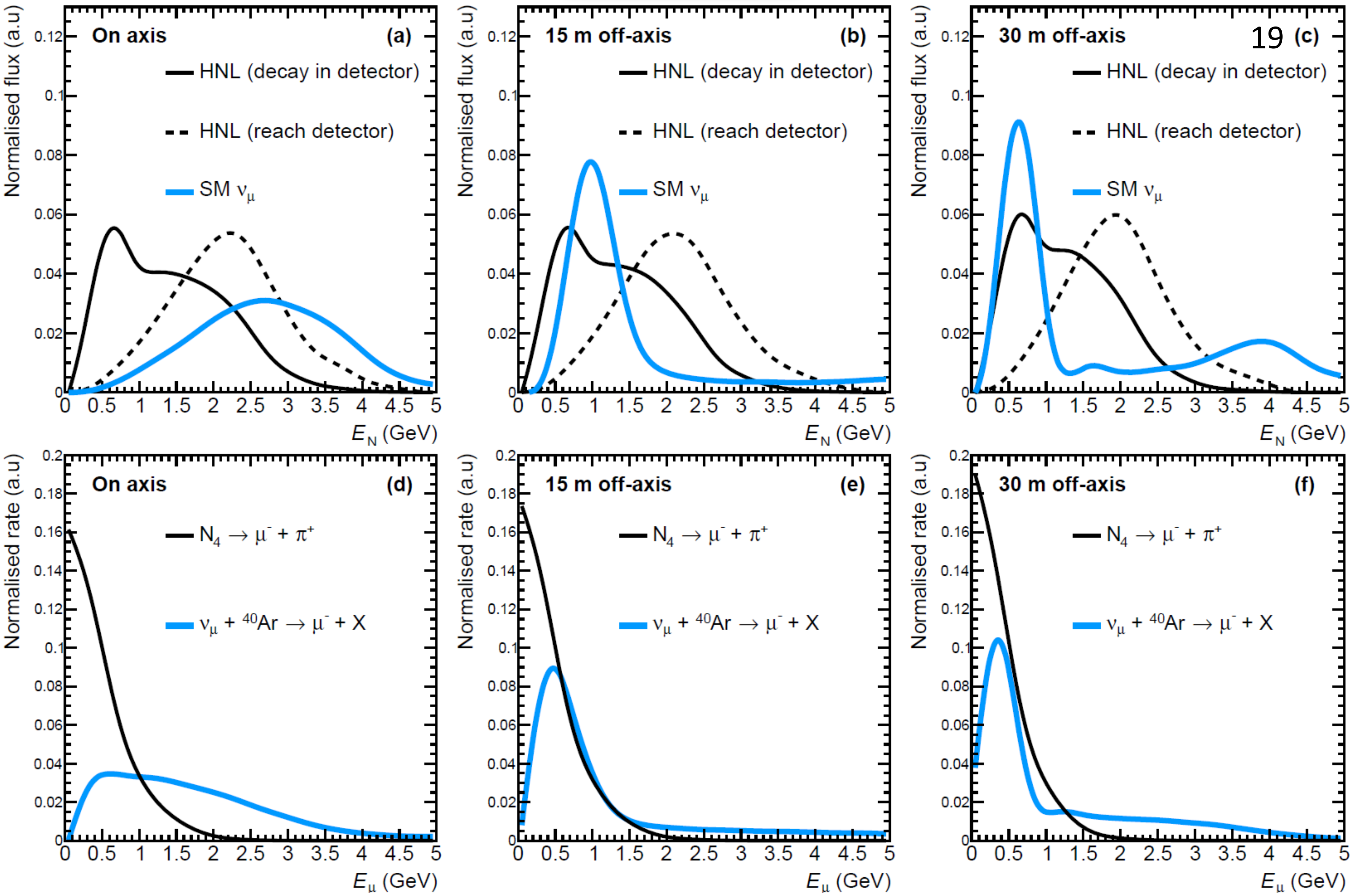






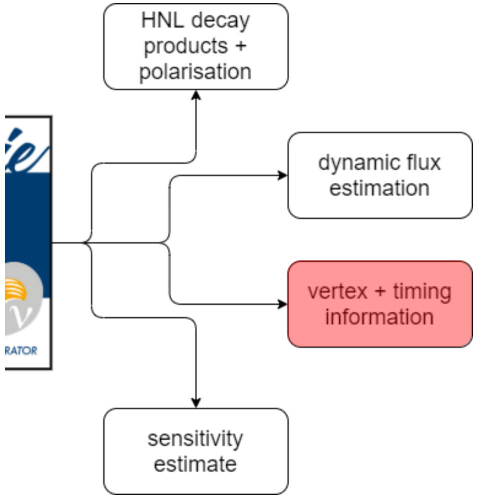
OA effect weakens most close to threshold (panels b, e): **heavier HNL are slower.**

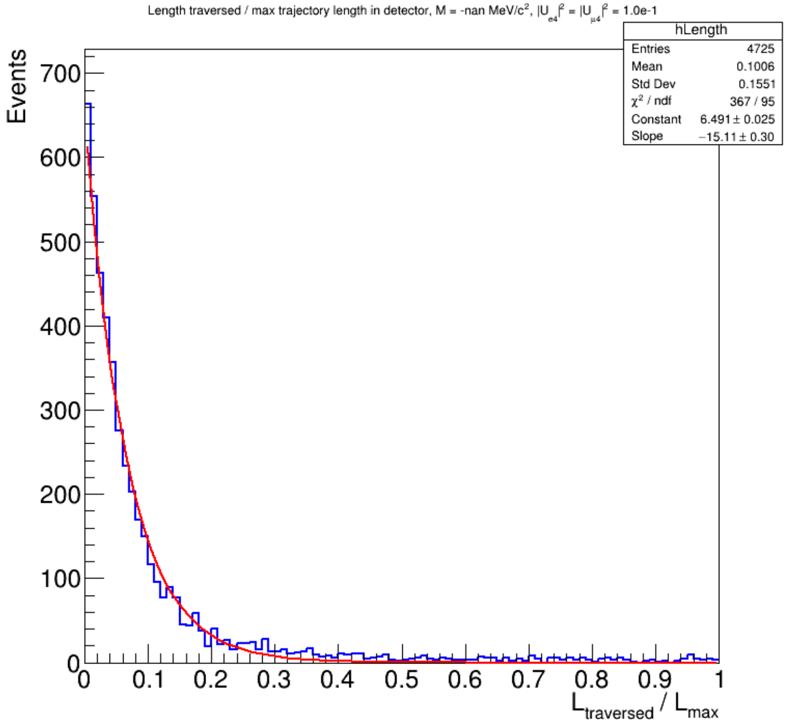




$$M_{N4} = 300\ \mathrm{MeV}/c^2$$

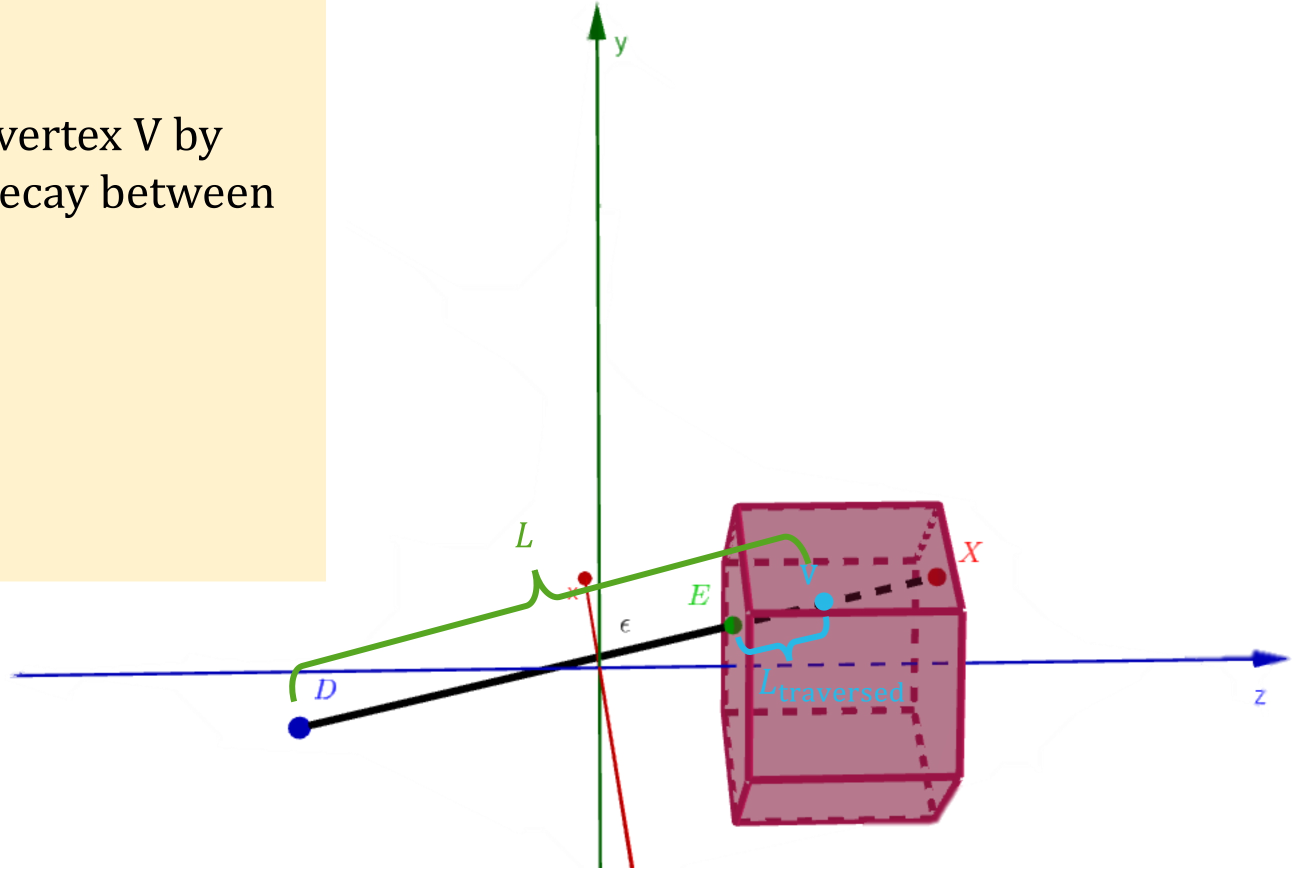
Bkg: GENIE v3.02.00
tune G18_02a_00_000

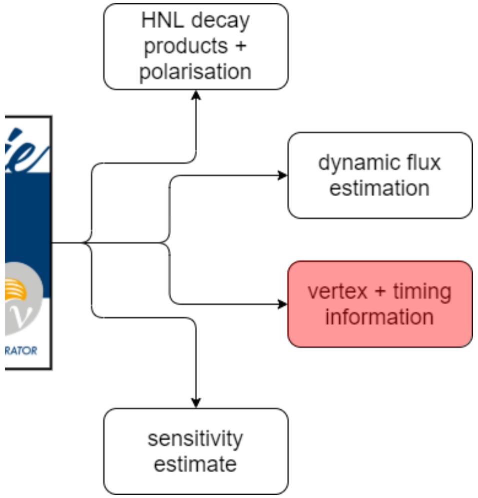


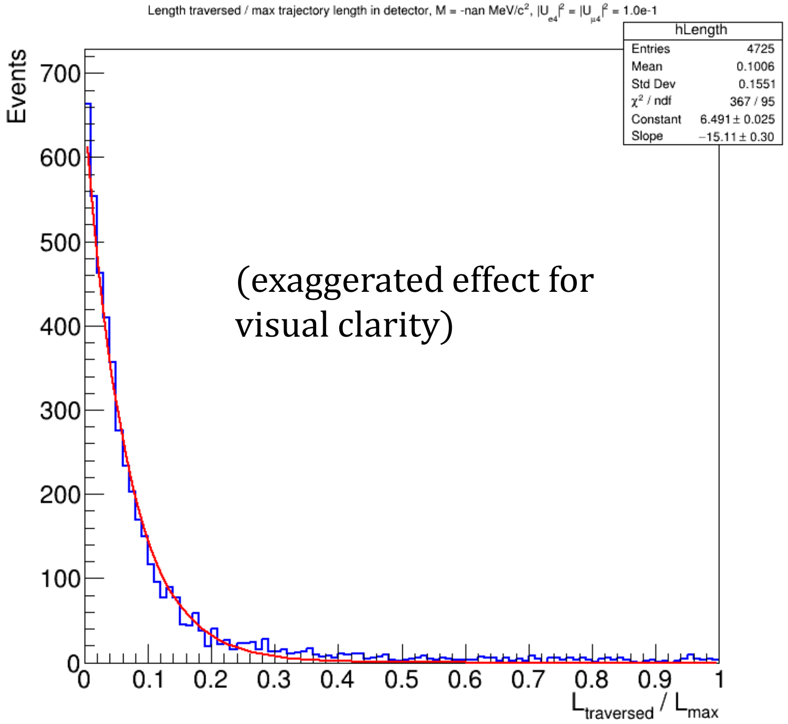


∀ HNL know production point D and momentum $\boldsymbol{p}$ ⇒ Calculate entry, exit points E, X

Assign decay vertex V by exponential decay between E and X



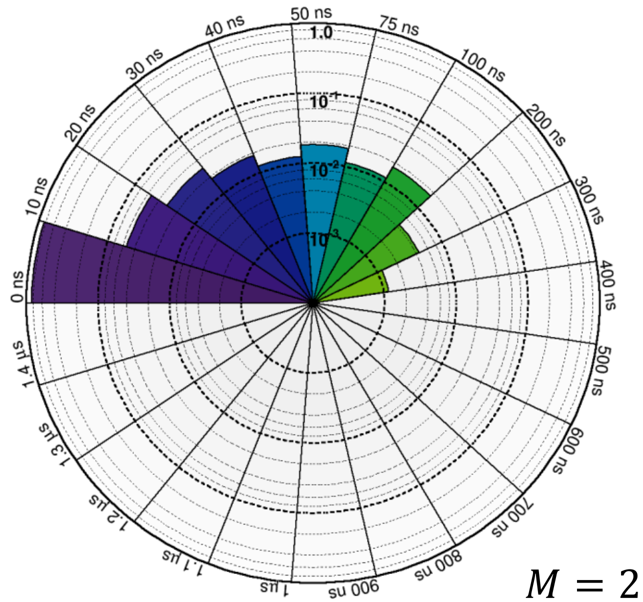




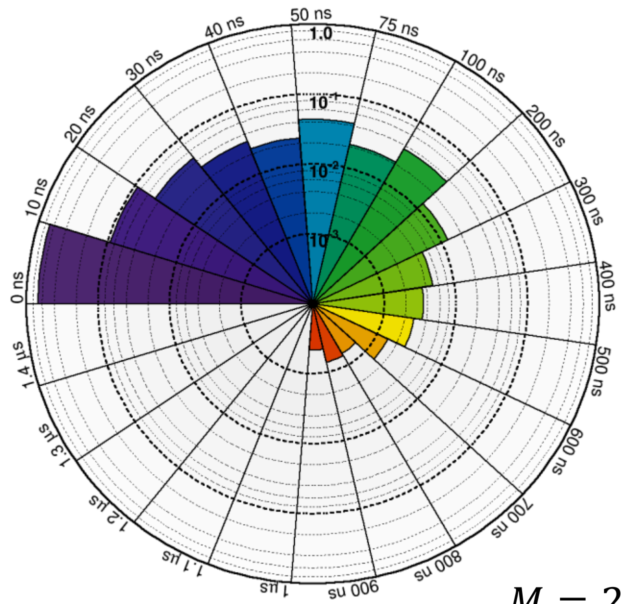
∀ HNL know production point D and momentum $\boldsymbol{p}$ ⇒ Calculate entry, exit points E, X

Assign decay vertex V by exponential decay between E and X

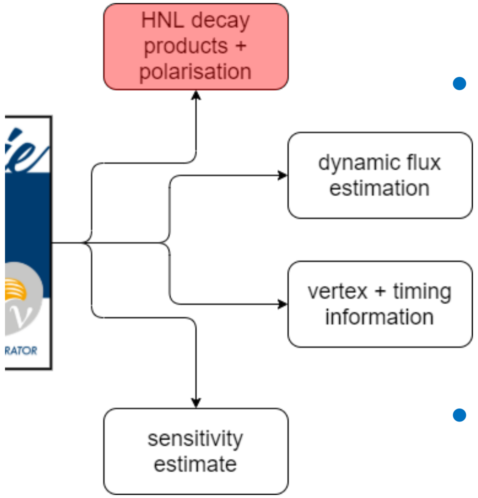
Total travel distance L and velocity $\boldsymbol{\beta}$ known ⇒ calculate delay wrt SM neutrino



$M = 25$ MeV



$M = 250$ MeV



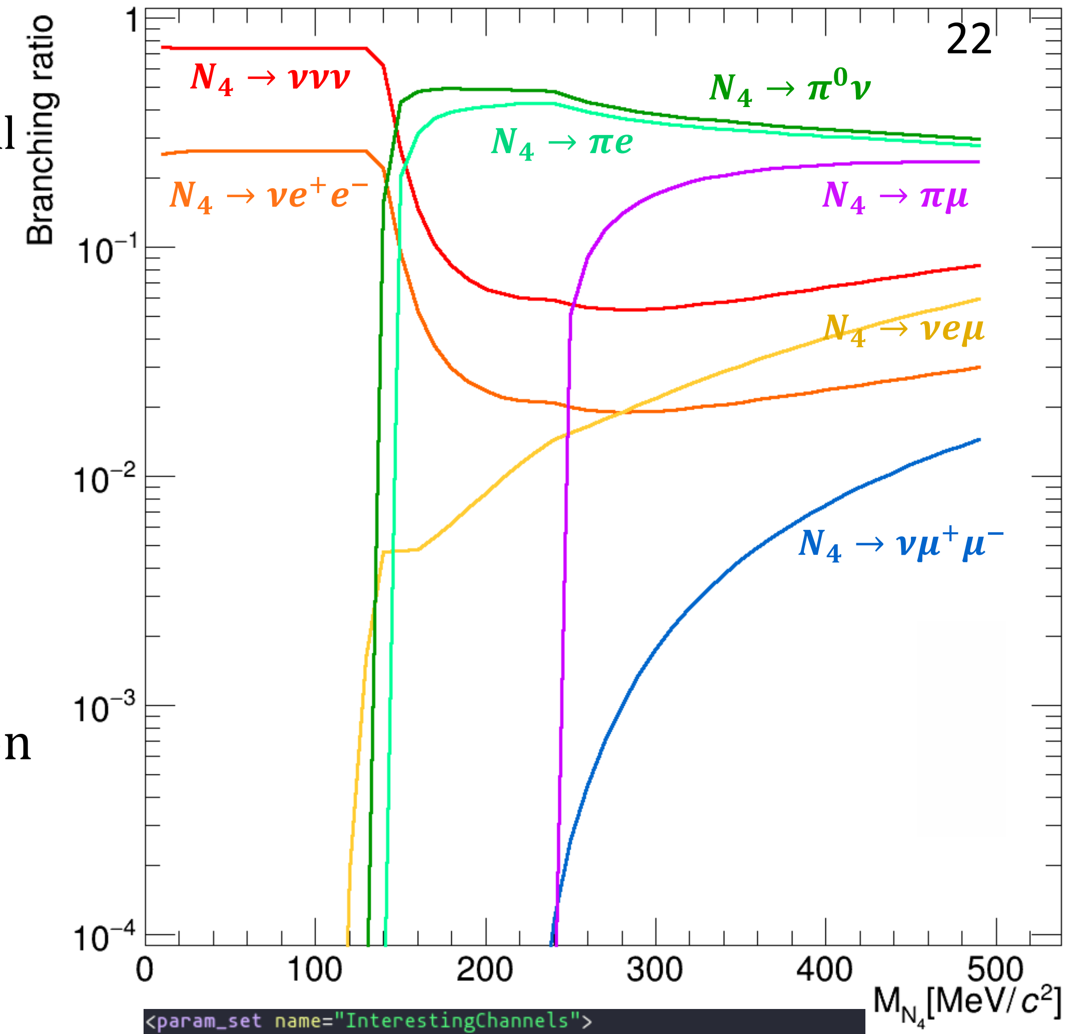
- Choose signal channel(s)
  - Module keeps track of total and individual decay widths for calculations

- Polarisation reweighting: by spin conservation

$+: N_4, -: \bar{N}_4$. Cancels out for Majorana HNL

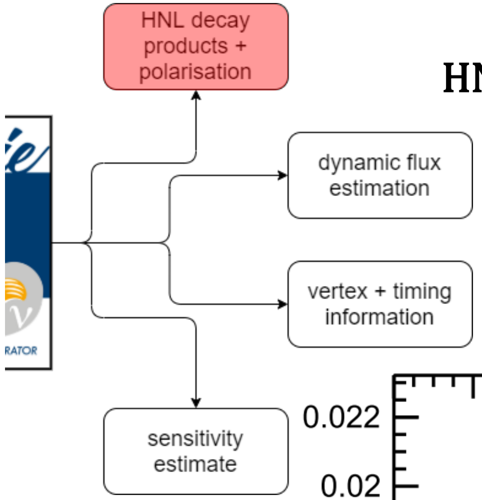
$$\frac{d\Gamma}{d\cos\theta_{\boldsymbol{P}}} \propto 1 \pm \hbar \cdot \cos\theta_{\boldsymbol{P}}$$

where $\boldsymbol{P}$ is the direction of the polarisation vector in HNL rest frame and $\hbar$ the polarisation modulus (see [arXiv: 1805.06419 [hep-ph]])

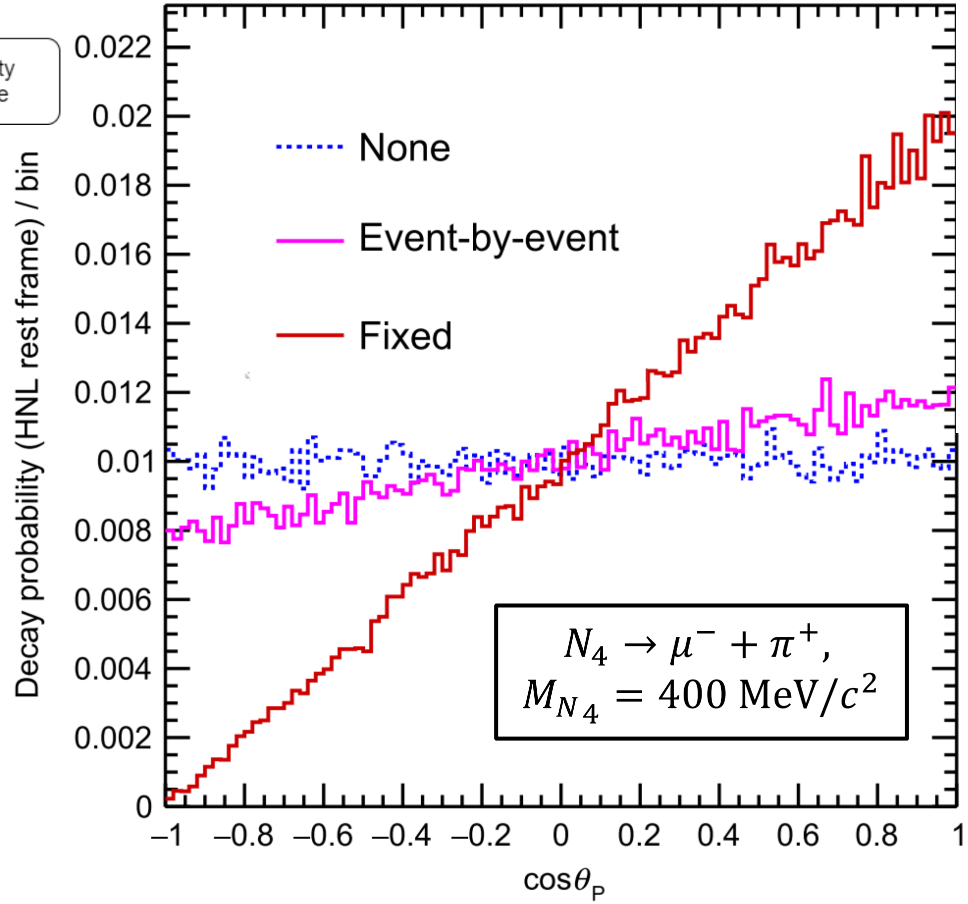


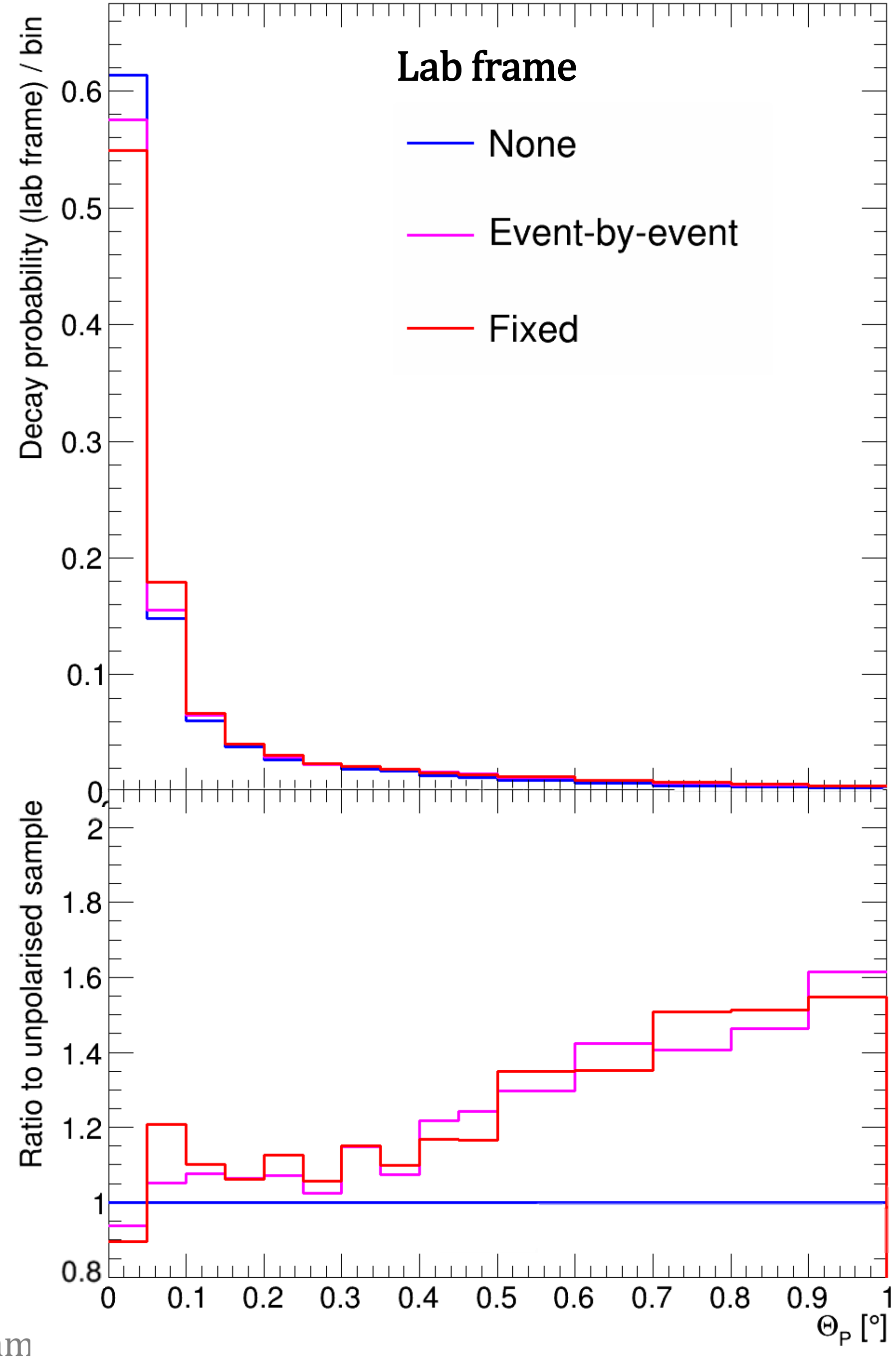
E.g. only simulate $N_4 \to \pi + \mu$

```
<param_set name="InterestingChannels">
  <!-- 2-body decays -->
  <param type="bool" name="HNL-2B_mu_pi"> true </param>
  <param type="bool" name="HNL-2B_e_pi"> false </param>
  <param type="bool" name="HNL-2B_nu_pi0"> false </param>
  <!-- 3-body decays -->
  <param type="bool" name="HNL-3B_nu_nu_nu"> false </param>
  <param type="bool" name="HNL-3B_nu_mu_mu"> false </param>
  <param type="bool" name="HNL-3B_nu_e_e"> false </param>
  <param type="bool" name="HNL-3B_nu_mu_e"> false </param>
  <param type="bool" name="HNL-3B_e_pi_pi0"> false </param>
  <param type="bool" name="HNL-3B_mu_pi_pi0"> false </param>
  <param type="bool" name="HNL-3B_nu_pi0_pi0"> false </param>
</param_set>
```

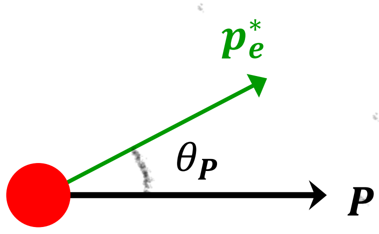


HNL rest frame

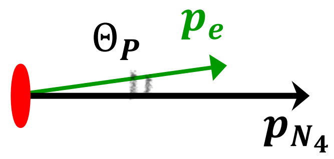




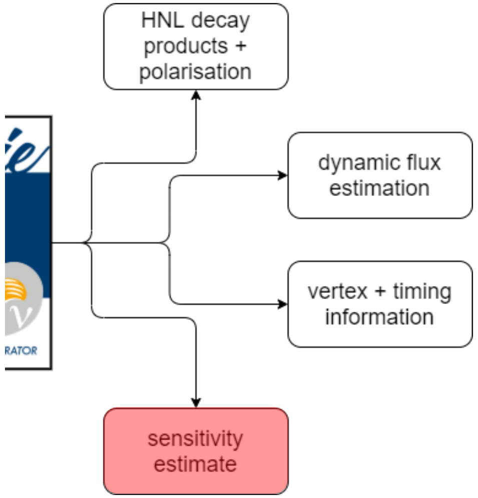
HNL rest frame



Lab frame



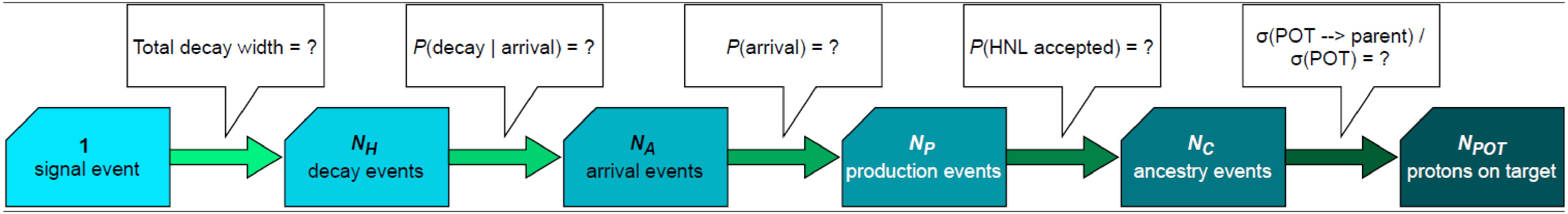
How do we calculate rates?



Rates (in POT equivalent) depend on many factors:

- Directly on HNL mass / mixing
- Flux simulation (parent collimation)
- Geometry file (detector size effect) + detector location
- Physics assumptions (Dirac vs Majorana nature of neutrino)

Solution: Let user simulate as many events as they want and account for the POT it would take to make them!
Pass the expected NPOT per event as a weight in GENIE



```
Current Event Number: 8000
Approximate total processing time: 15.11 s
Approximate processing time/event: 0.00188851 s
```

Assuming Dirac HNL, M = 100 MeV, $e:\mu:\tau = 1:1:0$, $|U_{\alpha 4}|^2 = 10^{-8}$

```
|----------------------------------------------------------------------------------------------------|
|GENIE GHEP Event Record [print level:   3]                                                          |
|----------------------------------------------------------------------------------------------------|
| Idx |           Name | Ist |        PDG |   Mother  | Daughter  |      Px |      Py |      Pz |       E |       m |
|----------------------------------------------------------------------------------------------------|
|   0 |         HNLBar |   0 | -2000020000 |  -1 |  -1 |  -1 |   3 |  -0.000 |  -0.029 |   0.471 |   0.483 |   0.100 |
|   1 |       nu_e_bar |   1 |        -12 |   0 |  -1 |  -1 |  -1 |  -0.017 |  -0.008 |   0.047 |   0.051 |   0.000 |
|   2 |      nu_mu_bar |   1 |        -14 |   0 |  -1 |  -1 |  -1 |  -0.019 |  -0.034 |   0.293 |   0.296 |   0.000 |
|   3 |     nu_tau_bar |   1 |        -16 |   0 |  -1 |  -1 |  -1 |   0.035 |   0.013 |   0.131 |   0.136 |   0.000 |
|----------------------------------------------------------------------------------------------------|
|       Fin-Init:                                               |  -0.000 |   0.000 |  -0.000 |  -0.000 |         |
|----------------------------------------------------------------------------------------------------|
|       Vertex:         HNLBar @ (x =    -0.37425 m, y =    -0.34240 m, z =    -0.37426 m, t =    7.393239e-08 s) |
|----------------------------------------------------------------------------------------------------|
| Err flag [bits:15->0] : 0000000000000000    |  1st set:                                    none |
| Err mask [bits:15->0] : 1111111111111111    |  Is unphysical:    NO |   Accepted:   YES         |
|----------------------------------------------------------------------------------------------------|
| sig(Ev) =       0.00000e+00 cm^2  | dsig(Ev;{K_s})/dK   =     0.00000e+00 cm^2/{K} | Weight =        51.56644 |
|----------------------------------------------------------------------------------------------------|
```

Delay wrt SM neutrino

This signal event took
51.6e+20 POT

Coming soon to BeamHNL…

5.4 Discrepancies with previous literature

P. Coloma et al, *EPJ C* **81** (2021) 78

The decay widths of a HNL into mesons, neutrinos and leptons have been derived several times in previous literature; for an incomplete list see e.g. Refs. [28,39,49,53,66,73]. Here we summarize the main discrepancies and differences found between our results and some of these works:

Implementing a "tune system" for BeamHNL : accept theory input for:
- HNL production kinematic scaling factors
- HNL decay widths to channels

Goals:
- User-friendly
- Storable and persistent
- Easily modifiable

Theory input handled through xml files in dedicated HNL tune directory

- GHNL20_00a
  - Rates
    - decay.xml
    - production.xml
  - ModelConfiguration.xml
  - TuneGeneratorList.xml


```
<param_set name="Default">

  <!-- Who did the calculations? -->
  <param type="string" name="Calculation"> ColomaEtAl_EFT </param>
  <param type="string" name="Reference"> Coloma et al, EPJ C 81 (2021) 78 </param>

  <!-- Define knots for HNL masses here -->
  <param type="vec-double" name="Masses" delim=";">
  0.000 ; 0.005 ; 0.010 ; 0.015 ; 0.020 ; 0.025 ; 0.030 ; 0.035 ; 0.040 ; 0.045 ;
  0.050 ; 0.055 ; 0.060 ; 0.065 ; 0.070 ; 0.075 ; 0.080 ; 0.085 ; 0.090 ; 0.095 ;
  0.100 ; 0.105 ; 0.110 ; 0.115 ; 0.120 ; 0.125 ; 0.130 ; 0.135 ; 0.140 ; 0.145 ;
  0.150 ; 0.155 ; 0.160 ; 0.165 ; 0.170 ; 0.175 ; 0.180 ; 0.185 ; 0.190 ; 0.195 ;
  0.200 ; 0.205 ; 0.210 ; 0.215 ; 0.220 ; 0.225 ; 0.230 ; 0.235 ; 0.240 ; 0.245 ;
  0.250 ; 0.255 ; 0.260 ; 0.265 ; 0.270 ; 0.275 ; 0.280 ; 0.285 ; 0.290 ; 0.295 ;
  0.300 ; 0.305 ; 0.310 ; 0.315 ; 0.320 ; 0.325 ; 0.330 ; 0.335 ; 0.340 ; 0.345 ;
  0.350 ; 0.355 ; 0.360 ; 0.365 ; 0.370 ; 0.375 ; 0.380 ; 0.385 ; 0.390 ; 0.395 ;
  0.400 ; 0.405 ; 0.410 ; 0.415 ; 0.420 ; 0.425 ; 0.430 ; 0.435 ; 0.440 ; 0.445 ;
  0.450 ; 0.455 ; 0.460 ; 0.465 ; 0.470 ; 0.475 ; 0.480 ; 0.485 ; 0.490
  </param>
```

```
<!-- N4 -> v v v -->
<decayChannel name="nu_nu_nu">
  <param type="vec-double" name="Rates_0" delim=";">
    0.000       ; 2.14224e-25 ; 6.8558e-24  ; 5.20612e-23 ; 2.19386e-22 ; <!-- 0 - 20 -->
    6.69511e-22 ; 1.66596e-21 ; 3.60079e-21 ; 7.02034e-21 ; 1.26509e-20 ;
    2.14224e-20 ; 3.45042e-20 ; 5.33107e-20 ; 7.95472e-20 ; 1.15225e-19 ;
    1.62691e-19 ; 2.24651e-19 ; 3.04195e-19 ; 4.04828e-19 ; 5.30489e-19 ;
    6.8558e-19  ; 8.74993e-19 ; 1.10413e-18 ; 1.37895e-18 ; 1.70594e-18 ; <!-- 100 - 120 -->
    2.09222e-18 ; 2.54551e-18 ; 3.07416e-18 ; 3.68721e-18 ; 4.39438e-18 ;
    5.20612e-18 ; 6.13361e-18 ; 7.18882e-18 ; 8.38451e-18 ; 9.73425e-18 ;
    1.12525e-17 ; 1.29545e-17 ; 1.48565e-17 ; 1.69756e-17 ; 1.933e-17   ;
    2.19386e-17 ; 2.48215e-17 ; 2.79998e-17 ; 3.14956e-17 ; 3.53323e-17 ; <!-- 200 - 220 -->
    3.9534e-17  ; 4.41263e-17 ; 4.91357e-17 ; 5.45901e-17 ; 6.05185e-17 ;
    6.69511e-17 ; 7.39195e-17 ; 8.14563e-17 ; 8.95957e-17 ; 9.83832e-17 ;
    1.07825e-16 ; 1.17991e-16 ; 1.28909e-16 ; 1.4062e-16  ; 1.53168e-16 ;
    1.66596e-16 ; 1.80949e-16 ; 1.96276e-16 ; 2.12623e-16 ; 2.30042e-16 ; <!-- 300 - 320 -->
    2.48585e-16 ; 2.68304e-16 ; 2.89256e-16 ; 3.11496e-16 ; 3.35084e-16 ;
    3.60079e-16 ; 3.8654e-16  ; 4.14544e-16 ; 4.44142e-16 ; 4.75408e-16 ;
    5.0841e-16  ; 5.4322e-16  ; 5.79911e-16 ; 6.18559e-16 ; 6.5924e-16  ;
    7.02034e-16 ; 7.47021e-16 ; 7.94287e-16 ; 8.43915e-16 ; 8.95993e-16 ; <!-- 400 - 420 -->
    9.50611e-16 ; 1.00786e-15 ; 1.06784e-15 ; 1.13063e-15 ; 1.19632e-15 ;
    1.26509e-15 ; 1.33695e-15 ; 1.41204e-15 ; 1.49047e-15 ; 1.57234e-15 ;
    1.65778e-15 ; 1.74688e-15 ; 1.83978e-15 ; 1.93659e-15
  </param>
  <param type="string" name="Scaling_Dirac_0 "> (x[0]+x[1]+x[2])/3.0 </param>
  <param type="string" name="Scaling_Majorana_0"> 2.0*(x[0]+x[1]+x[2])/3.0 </param>

</decayChannel>
```

```
GHNL20_00a
  Rates
    decay.xml
    production.xml
  ModelConfiguration.xml
  TuneGeneratorList.xml
```

Theory input handled through xml files in dedicated HNL tune directory

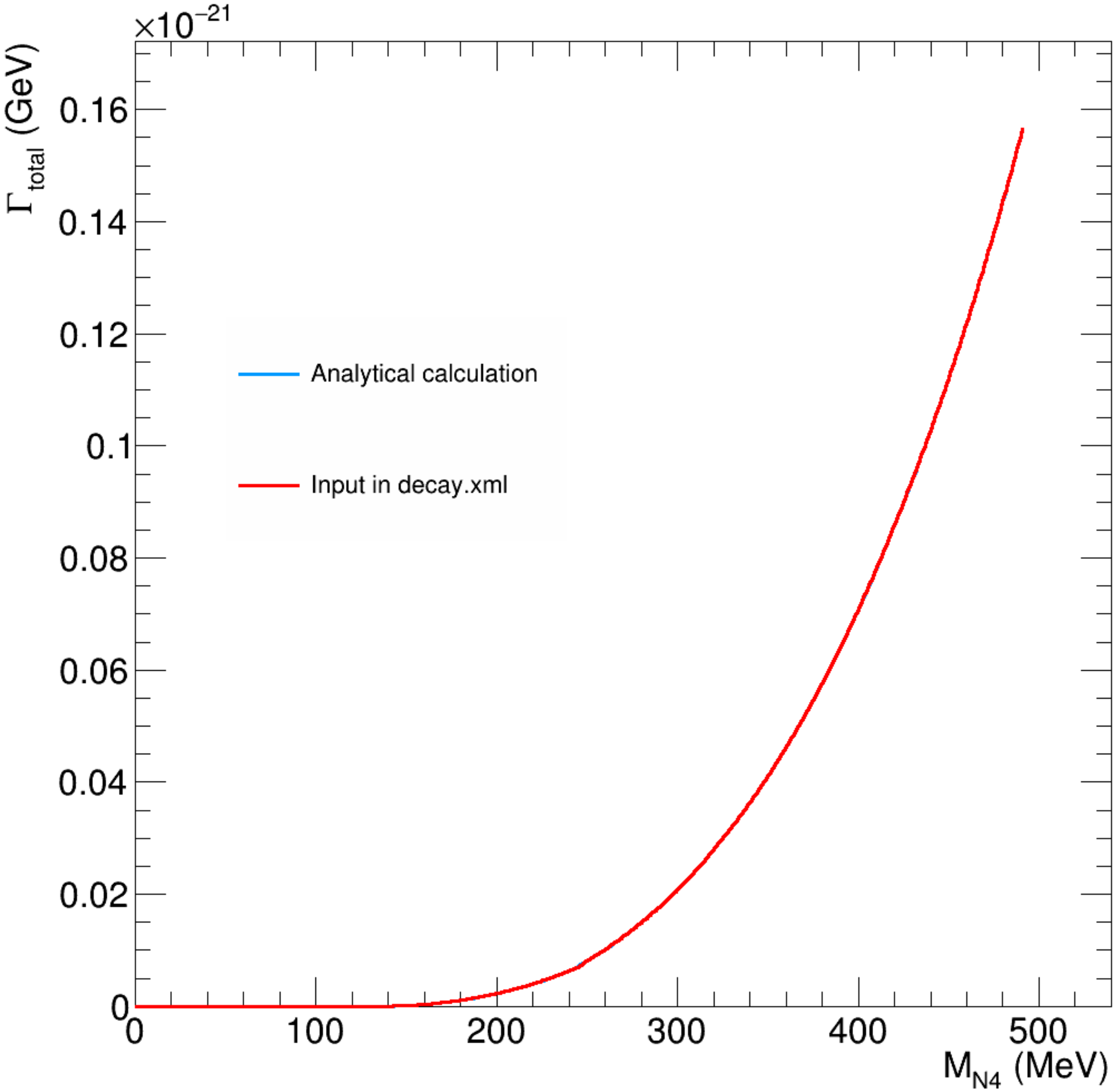
For each channel, identify component **with definite scaling behaviour**
e.g. $\propto (\Sigma_\alpha |U_{\alpha 4}|^2)^2, |U_{\ell 4}|^2$

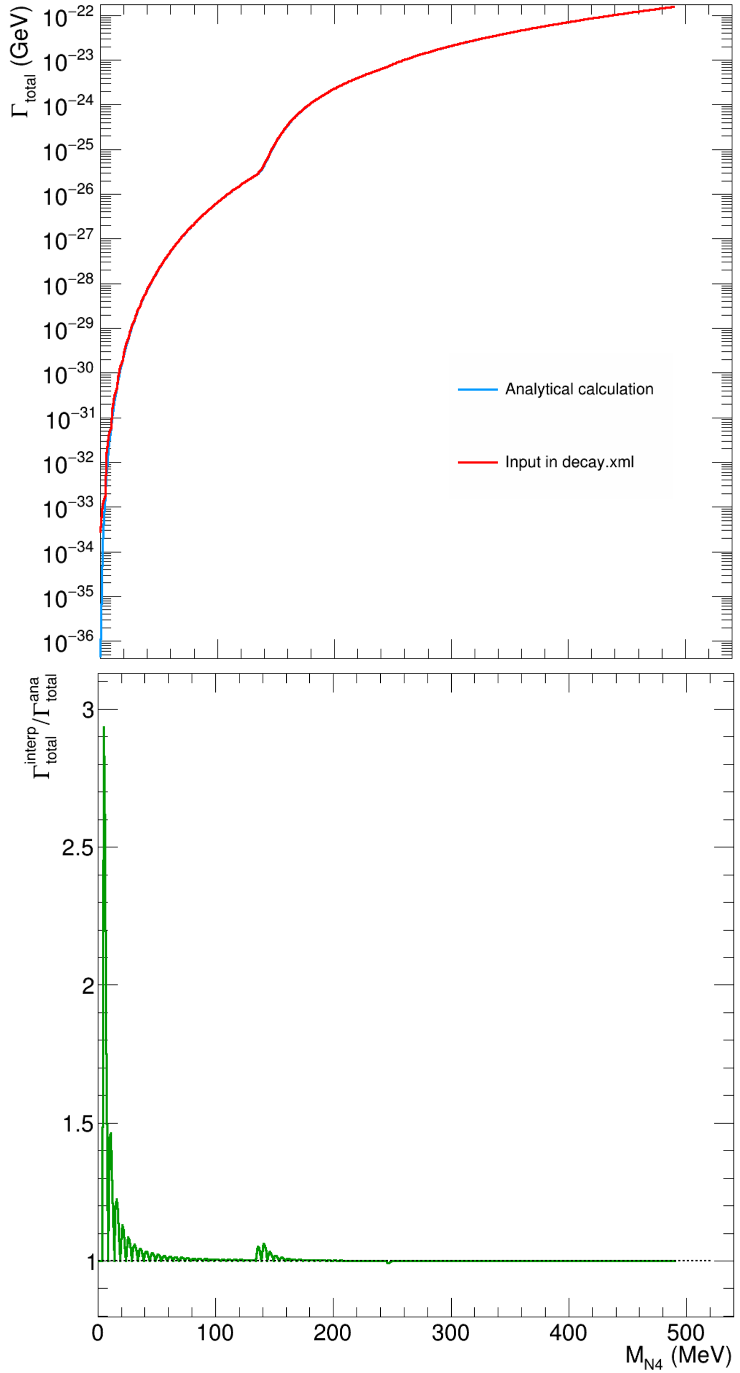
Specify a desired mass partition and the decay width of each component at $|U_{\ell 4}|^2 = 1, \ell = e, \mu, \tau$
Specify scaling behaviour as a TFormula

Group components into \`decayChannel\` objects in xml file

```
<!-- N4 -> v v v -->
<decayChannel name="nu_nu_nu">
  <param type="vec-double" name="Rates_0" delim=";">
    0.000       ; 2.14224e-25 ; 6.8558e-24  ; 5.20612e-23 ; 2.19386e-22 ; <!-- 0 - 20 -->
    6.69511e-22 ; 1.66596e-21 ; 3.60079e-21 ; 7.02034e-21 ; 1.26509e-20 ;
    2.14224e-20 ; 3.45042e-20 ; 5.33107e-20 ; 7.95472e-20 ; 1.15225e-19 ;
    1.62691e-19 ; 2.24651e-19 ; 3.04195e-19 ; 4.04828e-19 ; 5.30489e-19 ;
    6.8558e-19  ; 8.74993e-19 ; 1.10413e-18 ; 1.37895e-18 ; 1.70594e-18 ; <!-- 100 - 120 -->
    2.09222e-18 ; 2.54551e-18 ; 3.07416e-18 ; 3.68721e-18 ; 4.39438e-18 ;
    5.20612e-18 ; 6.13361e-18 ; 7.18882e-18 ; 8.38451e-18 ; 9.73425e-18 ;
    1.12525e-17 ; 1.29545e-17 ; 1.48565e-17 ; 1.69756e-17 ; 1.933e-17   ;
    2.19386e-17 ; 2.48215e-17 ; 2.79998e-17 ; 3.14956e-17 ; 3.53323e-17 ; <!-- 200 - 220 -->
    3.9534e-17  ; 4.41263e-17 ; 4.91357e-17 ; 5.45901e-17 ; 6.05185e-17 ;
    6.69511e-17 ; 7.39195e-17 ; 8.14563e-17 ; 8.95957e-17 ; 9.83832e-17 ;
    1.07825e-16 ; 1.17991e-16 ; 1.28909e-16 ; 1.4062e-16  ; 1.53168e-16 ;
    1.66596e-16 ; 1.80949e-16 ; 1.96276e-16 ; 2.12623e-16 ; 2.30042e-16 ; <!-- 300 - 320 -->
    2.48585e-16 ; 2.68304e-16 ; 2.89256e-16 ; 3.11496e-16 ; 3.35084e-16 ;
    3.60079e-16 ; 3.8654e-16  ; 4.14544e-16 ; 4.44142e-16 ; 4.75408e-16 ;
    5.0841e-16  ; 5.4322e-16  ; 5.79911e-16 ; 6.18559e-16 ; 6.5924e-16  ;
    7.02034e-16 ; 7.47021e-16 ; 7.94287e-16 ; 8.43915e-16 ; 8.95993e-16 ; <!-- 400 - 420 -->
    9.50611e-16 ; 1.00786e-15 ; 1.06784e-15 ; 1.13063e-15 ; 1.19632e-15 ;
    1.26509e-15 ; 1.33695e-15 ; 1.41204e-15 ; 1.49047e-15 ; 1.57234e-15 ;
    1.65778e-15 ; 1.74688e-15 ; 1.83978e-15 ; 1.93659e-15
  </param>
  <param type="string" name="Scaling_Dirac_0 "> (x[0]+x[1]+x[2])/3.0 </param>
  <param type="string" name="Scaling_Majorana_0"> 2.0*(x[0]+x[1]+x[2])/3.0 </param>

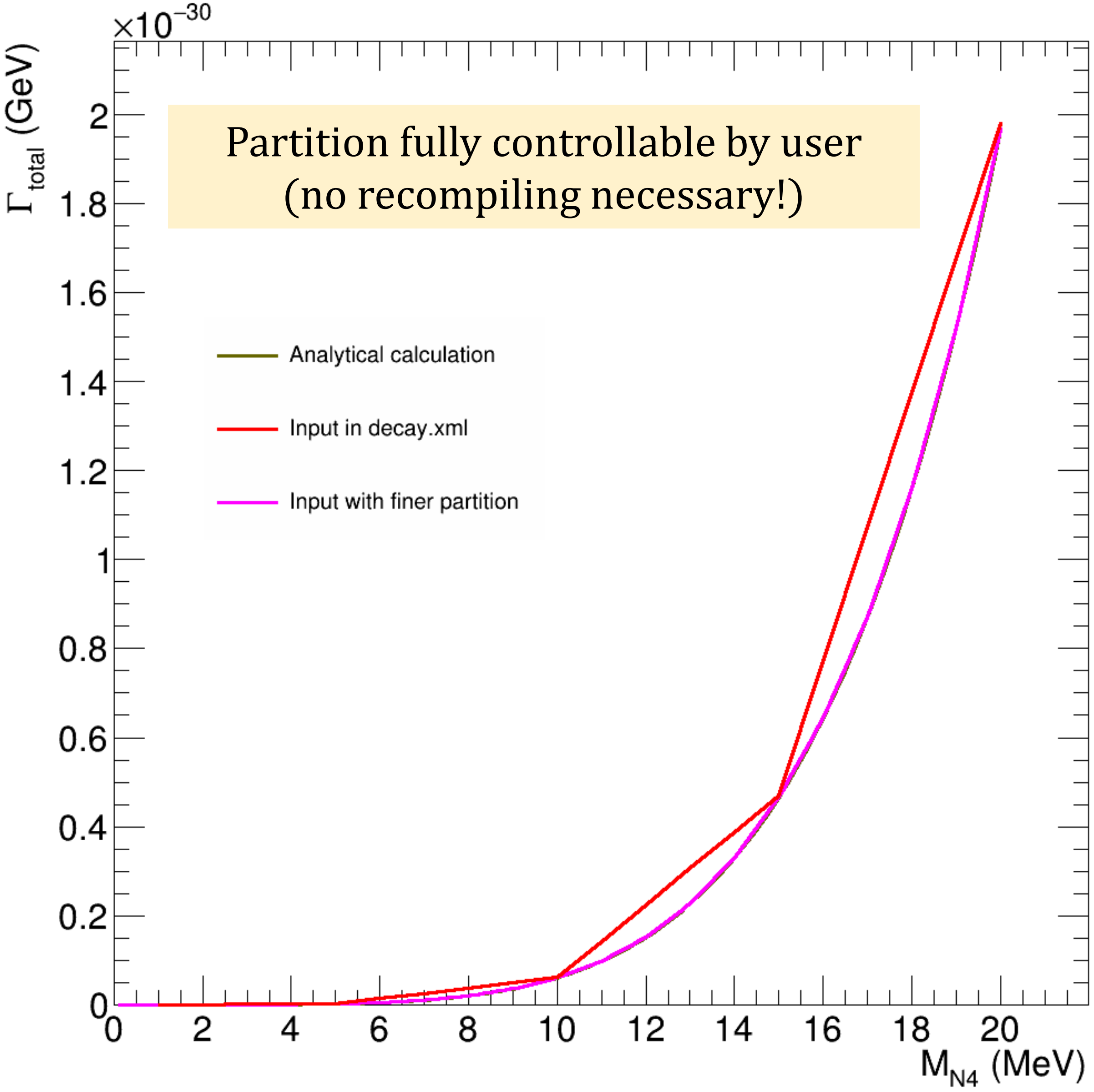
</decayChannel>
```

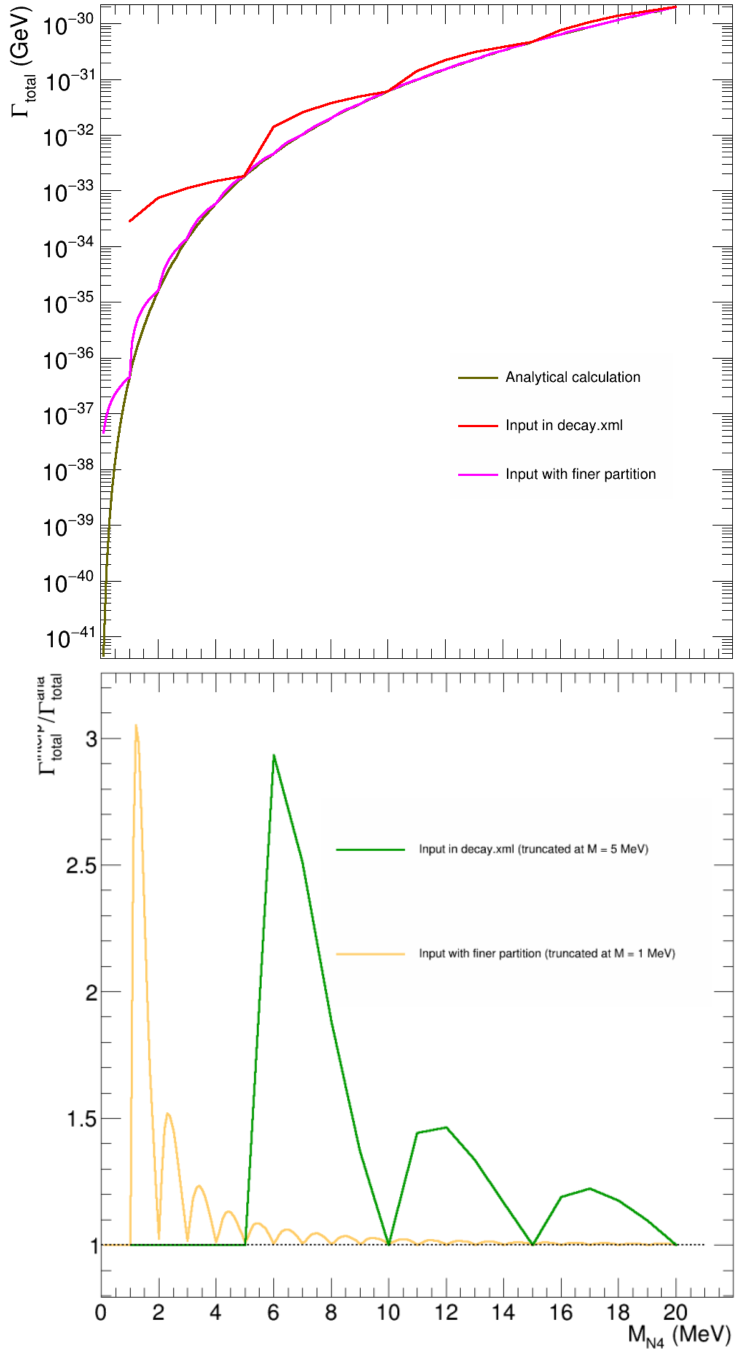




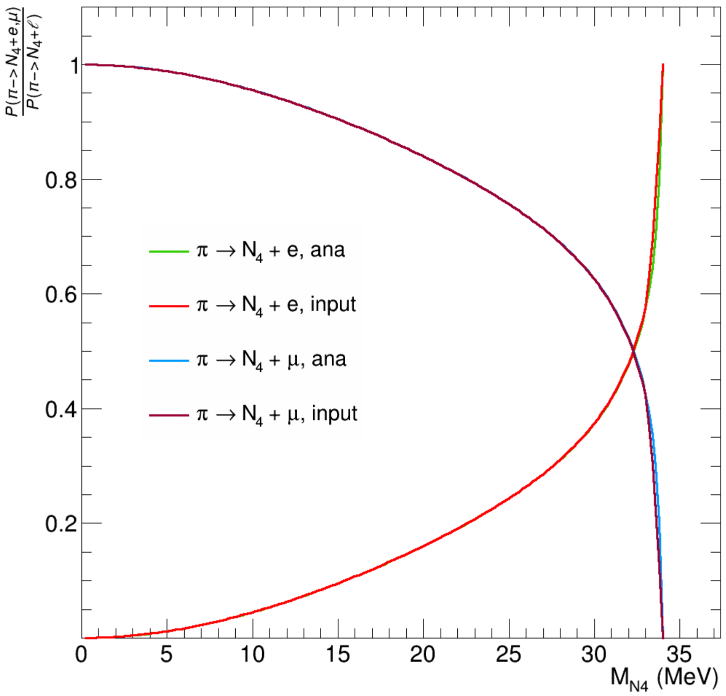
Reference model: [*EPJ C* **81** (2021) 78]

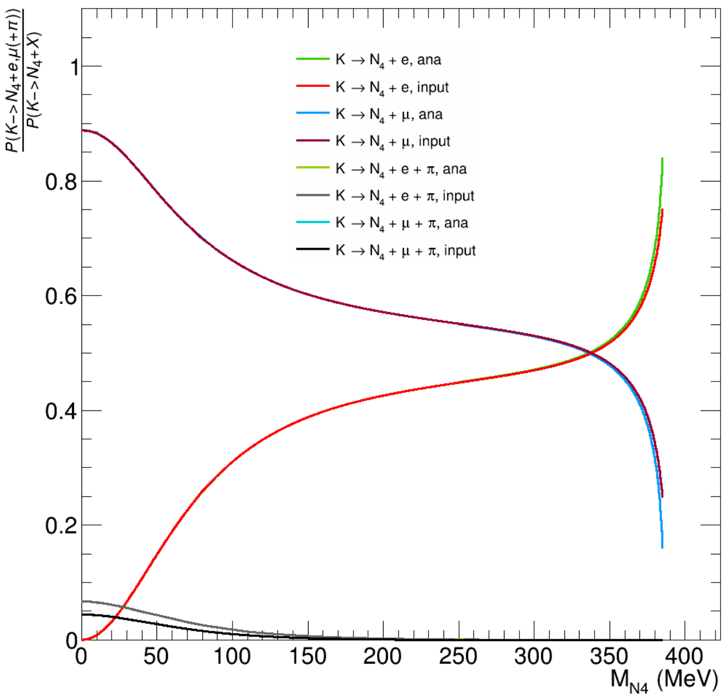
Partition fully controllable by user (no recompiling necessary!)

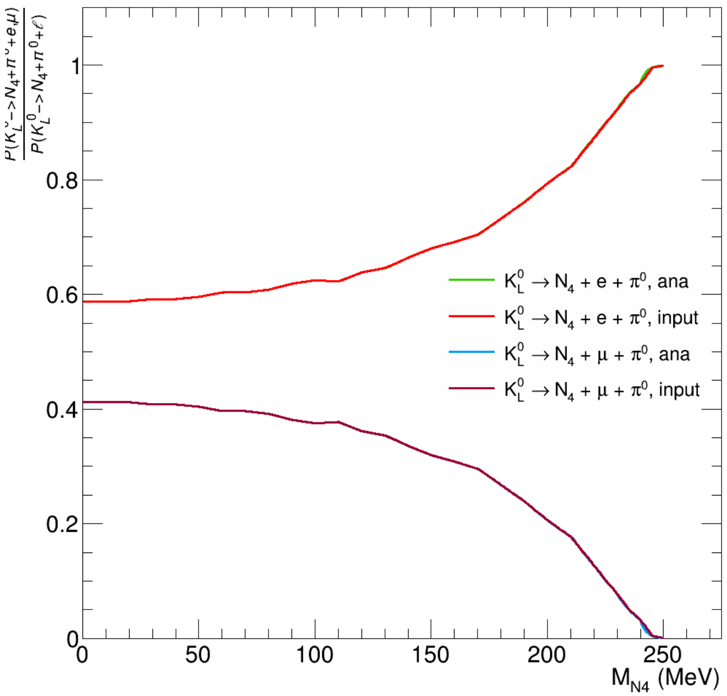




Reference model: [*EPJ C* **81** (2021) 78]







For production channels, specify kinematic scaling factors for each parent, and the masses to evaluate for each parent.

$$\Gamma(M, |U_{\alpha 4}|^2) = \mathcal{K}(M) \cdot |U_{\alpha 4}|^2$$

Reference model: *EPJ C* **81** (2021) 78

Thank you!

Some useful links:

BeamHNL paper (PRD):
Phys Rev D **107** (2023) 055003

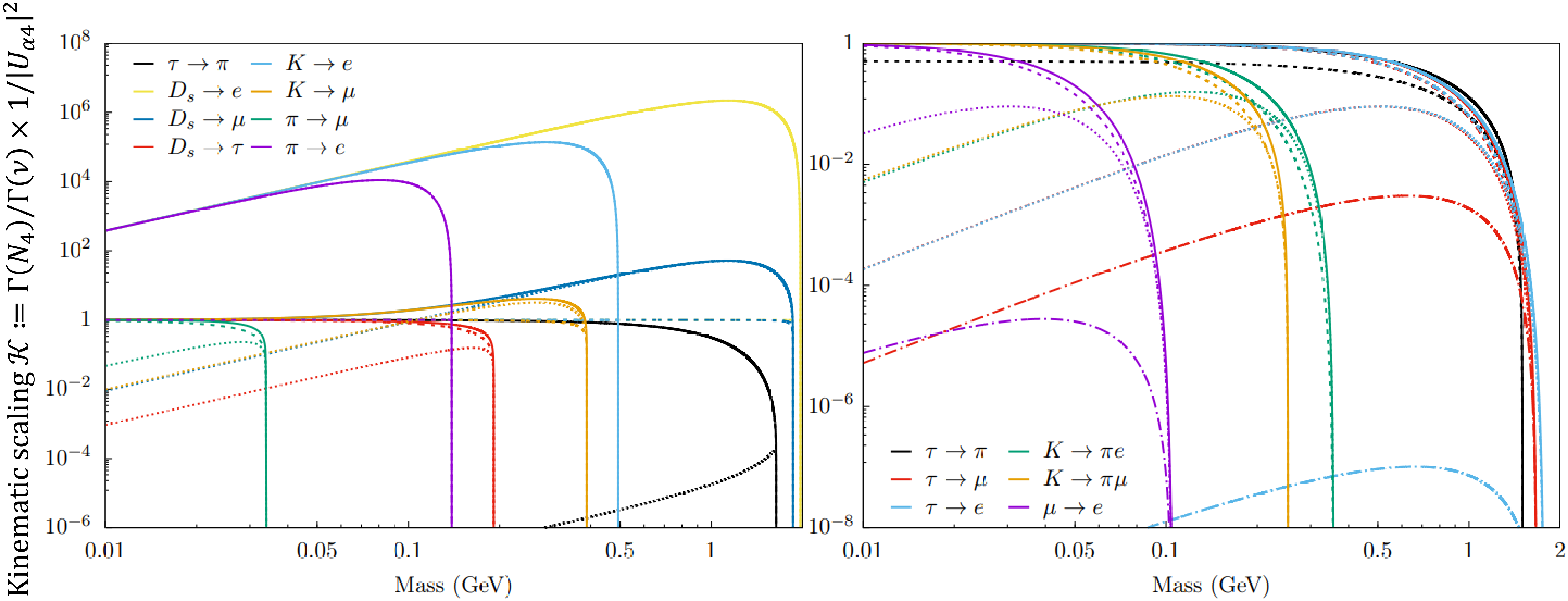
BeamHNL principal branch:
kjplows/Generator

Preview branch with theory input:
kjplows/Generator at multiLagrangian

Backup

2-body production

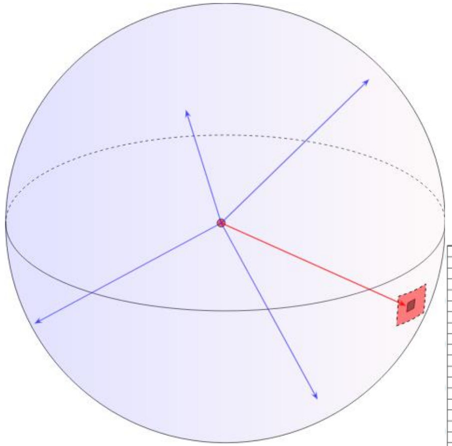
3-body production

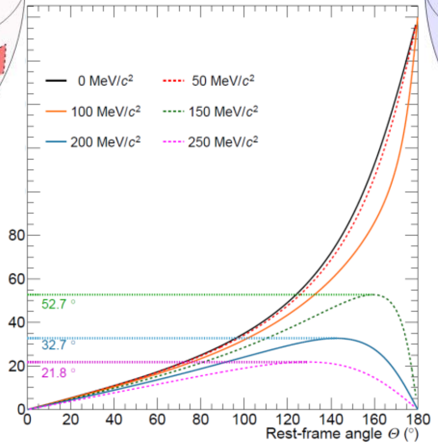


P. Ballett et al, [*JHEP* **2020** (2020) 111]

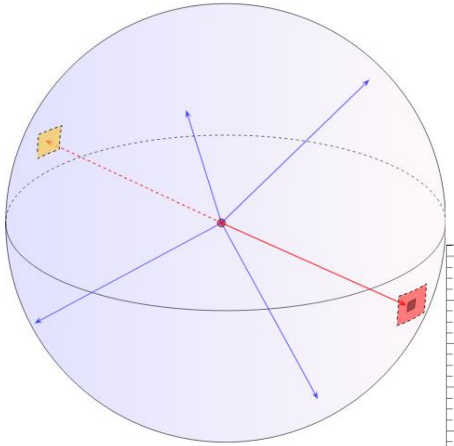
Acceptance correction

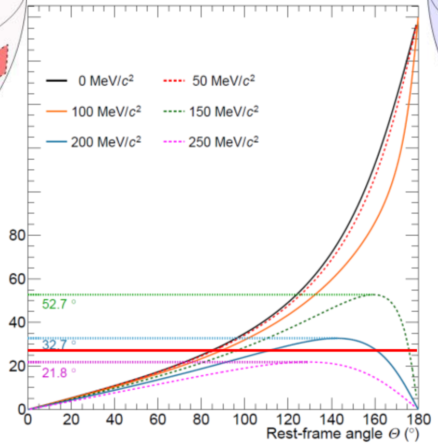
- Collimation effect ⇒ <u>HNL not guaranteed to hit detector</u>
- Parents have to be well-focused or HNL cannot “correct course” enough to reach a point
- Back-emitted HNL may also hit detector if parent focused enough!



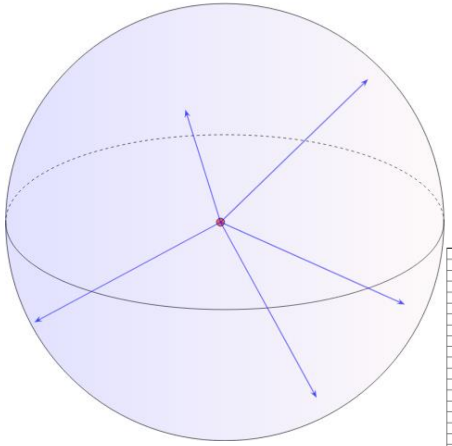


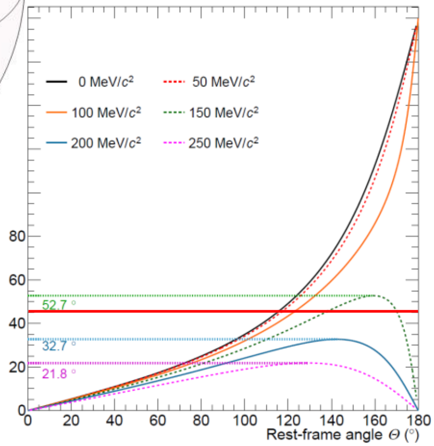
1 preimage
(SM ν)



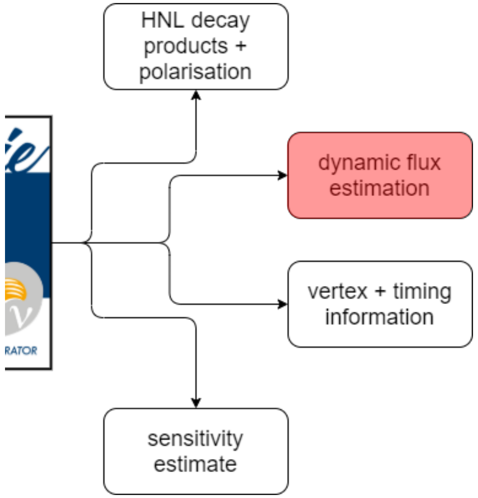


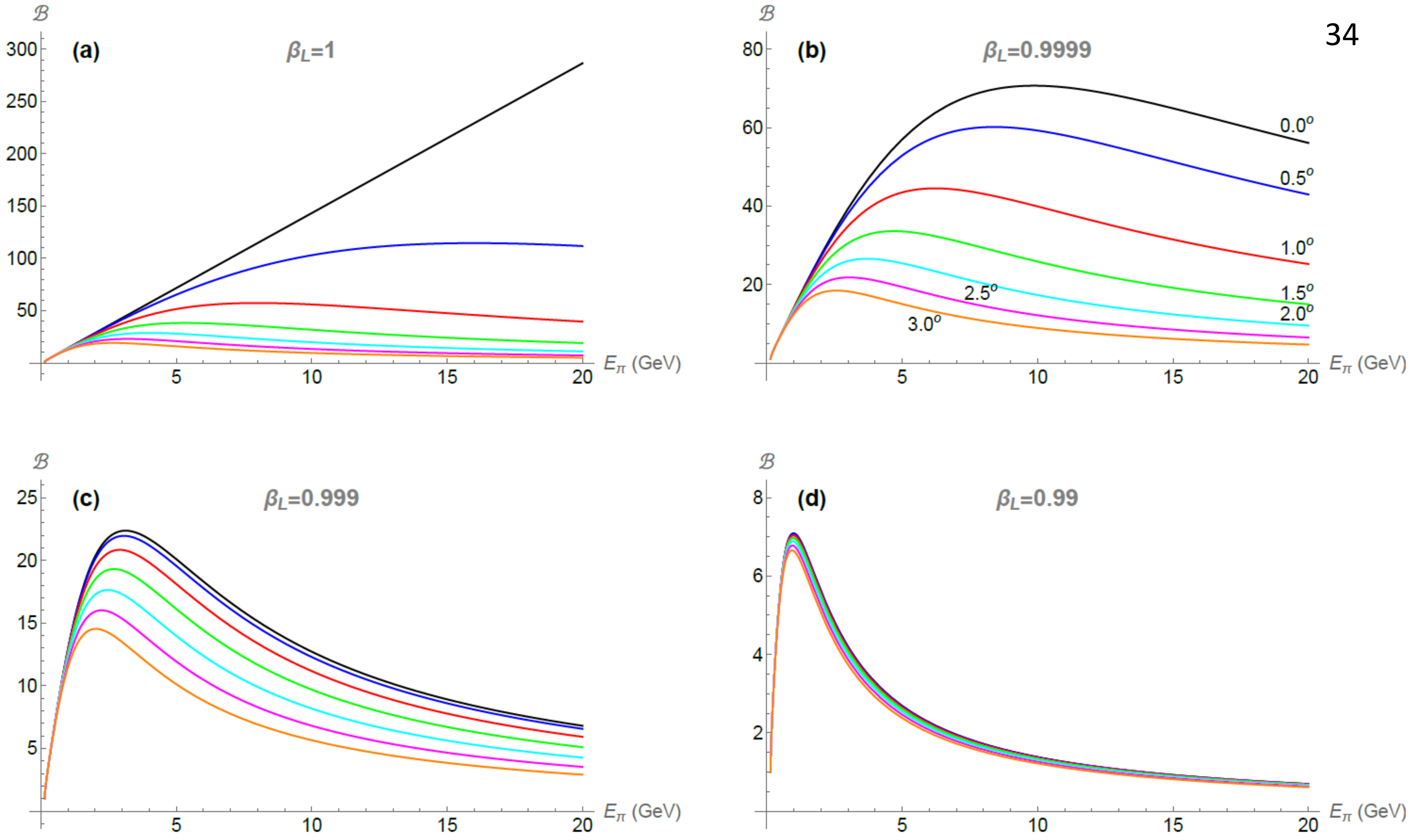
2 preimages
($M_N = 200$ MeV, $\theta < 32.7°$)





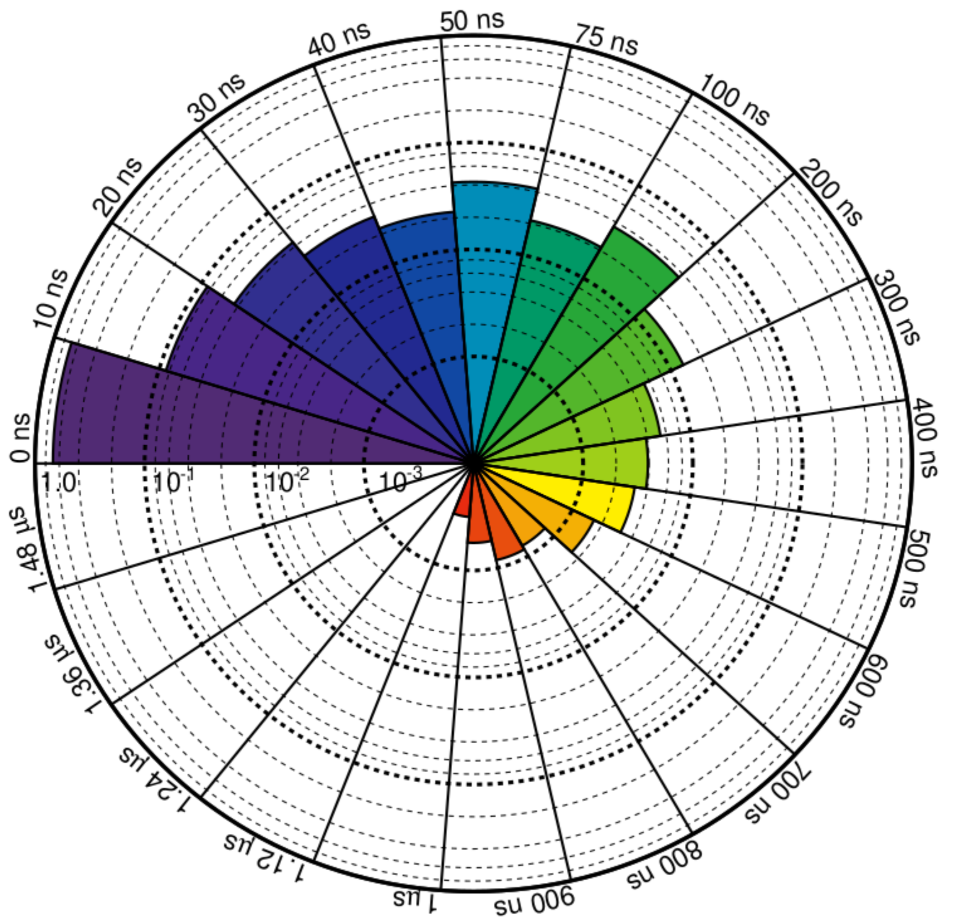
0 preimages
($M_N = 200$ MeV, $\theta \geq 32.7°$)

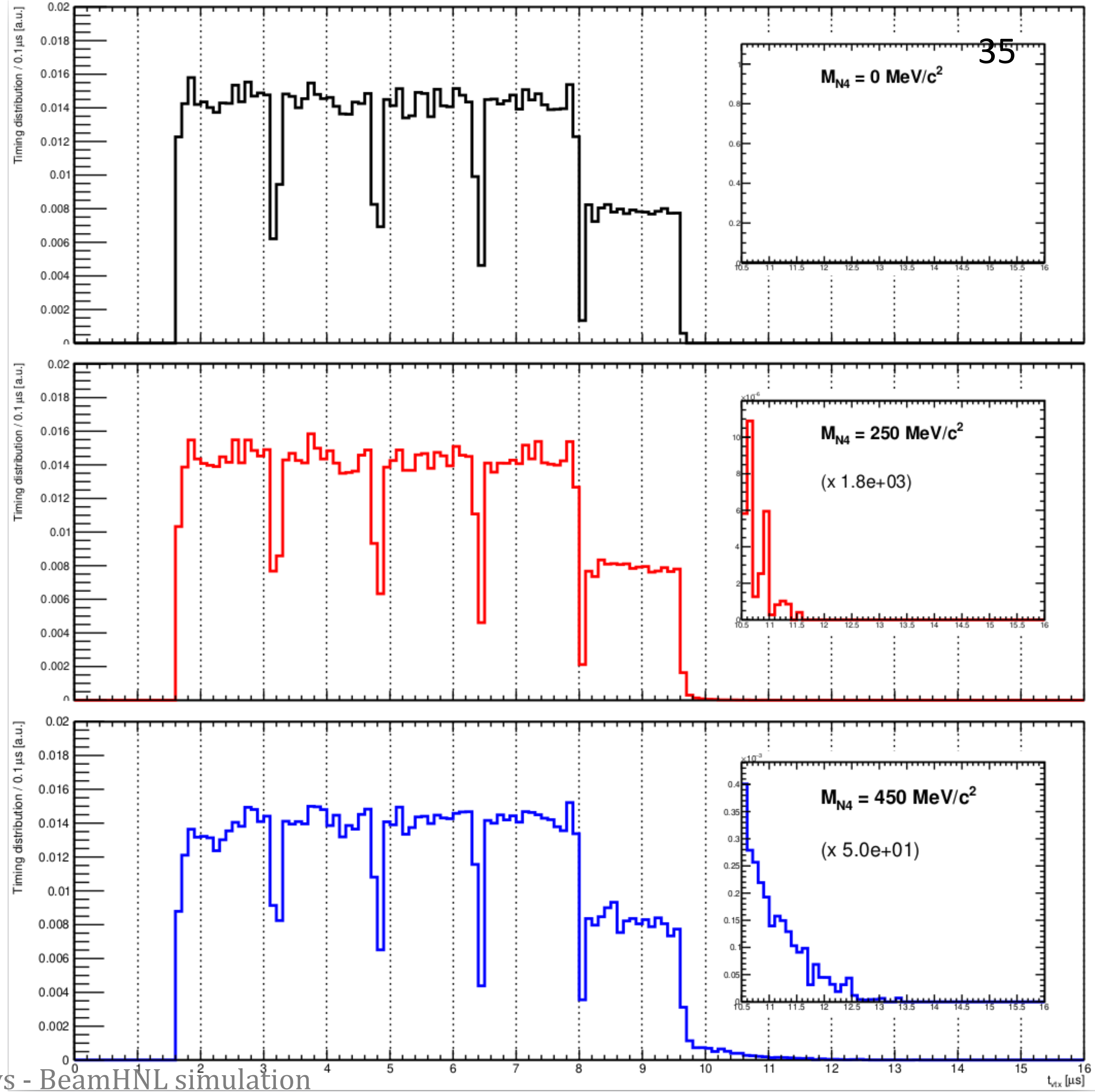




Presence of β_{N4} term in (1) <u>weakens off axis effect</u> compared to SM

Delay time distribution at MINERvA, 250 MeV

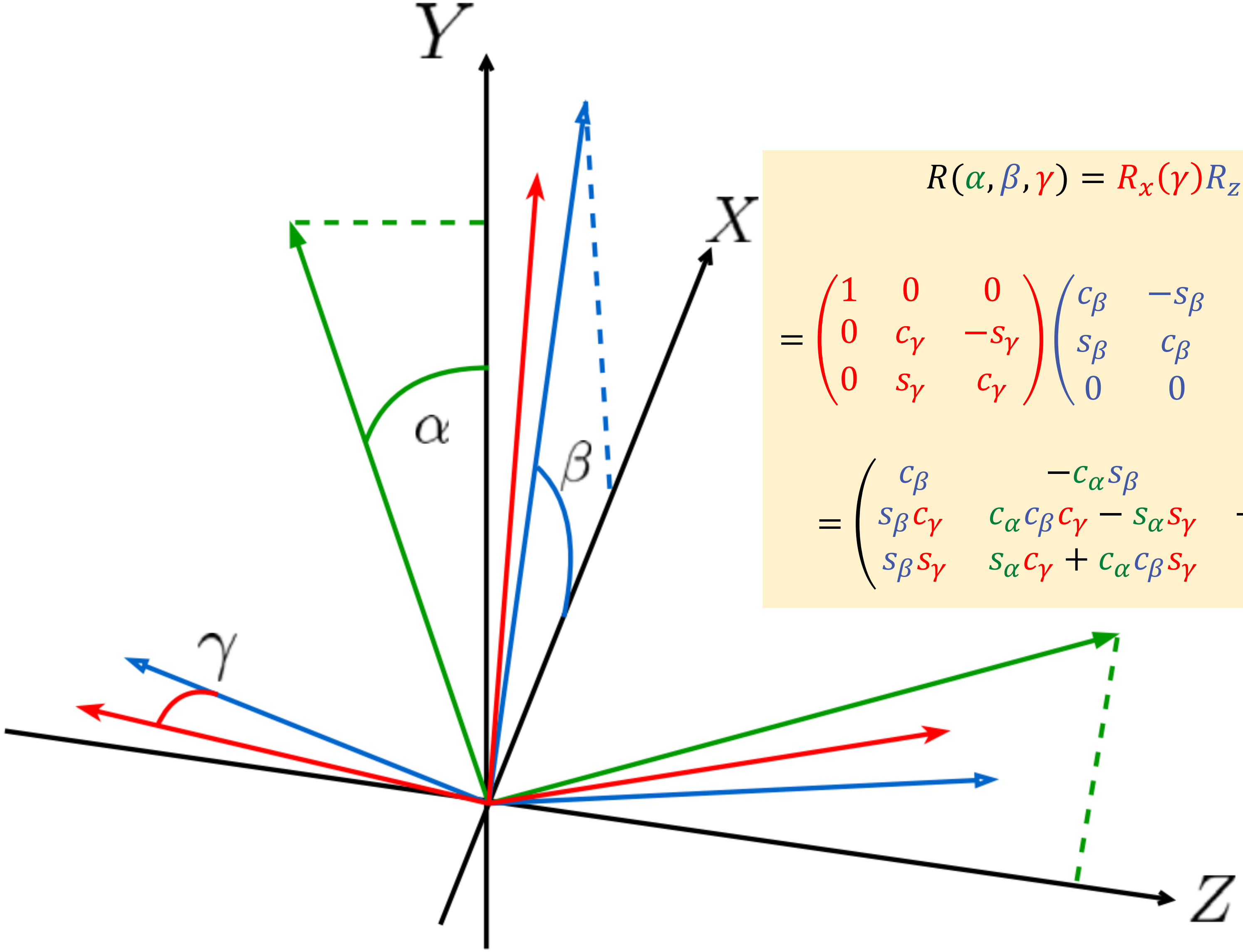




$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \overset{R_X(\alpha)}{\mapsto} \begin{pmatrix} X_1 \\ Y_1 \\ Z_1 \end{pmatrix}$$

$$\begin{pmatrix} X_1 \\ Y_1 \\ Z_1 \end{pmatrix} \overset{R_Z(\beta)}{\mapsto} \begin{pmatrix} X_2 \\ Y_2 \\ Z_2 \end{pmatrix}$$

$$\begin{pmatrix} X_2 \\ Y_2 \\ Z_2 \end{pmatrix} \overset{R_X(\gamma)}{\mapsto} \begin{pmatrix} X_U \\ Y_U \\ Z_U \end{pmatrix}$$



$$R(\alpha,\beta,\gamma) = R_x(\gamma)R_z(\beta)R_x(\alpha)$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_\gamma & -s_\gamma \\ 0 & s_\gamma & c_\gamma \end{pmatrix} \begin{pmatrix} c_\beta & -s_\beta & 0 \\ s_\beta & c_\beta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_\alpha & -s_\alpha \\ 0 & s_\alpha & c_\alpha \end{pmatrix}$$

$$= \begin{pmatrix} c_\beta & -c_\alpha s_\beta & s_\alpha s_\beta \\ s_\beta c_\gamma & c_\alpha c_\beta c_\gamma - s_\alpha s_\gamma & -s_\alpha c_\beta c_\gamma - c_\alpha s_\gamma \\ s_\beta s_\gamma & s_\alpha c_\gamma + c_\alpha c_\beta s_\gamma & c_\alpha c_\gamma - s_\alpha c_\beta s_\gamma \end{pmatrix}$$