BeamHNL, a GENIE-based general heavy neutral leptons generator

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On behalf of John Plows

The 4th Workshop on New Physics Opportunities at Neutrino Facilities

Daejeon, Korea, 4 Jun. 2024

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

Outline

- The BeamHNL module
  - Overview
  - Inputs:
    - Beamline simulation
    - Detector location
    - Detector geometry
  - Modelling:
    - Flux prediction
    - Decay & polarisation
    - Vertex positioning & timing
    - POT estimation
  - How to use it?

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:

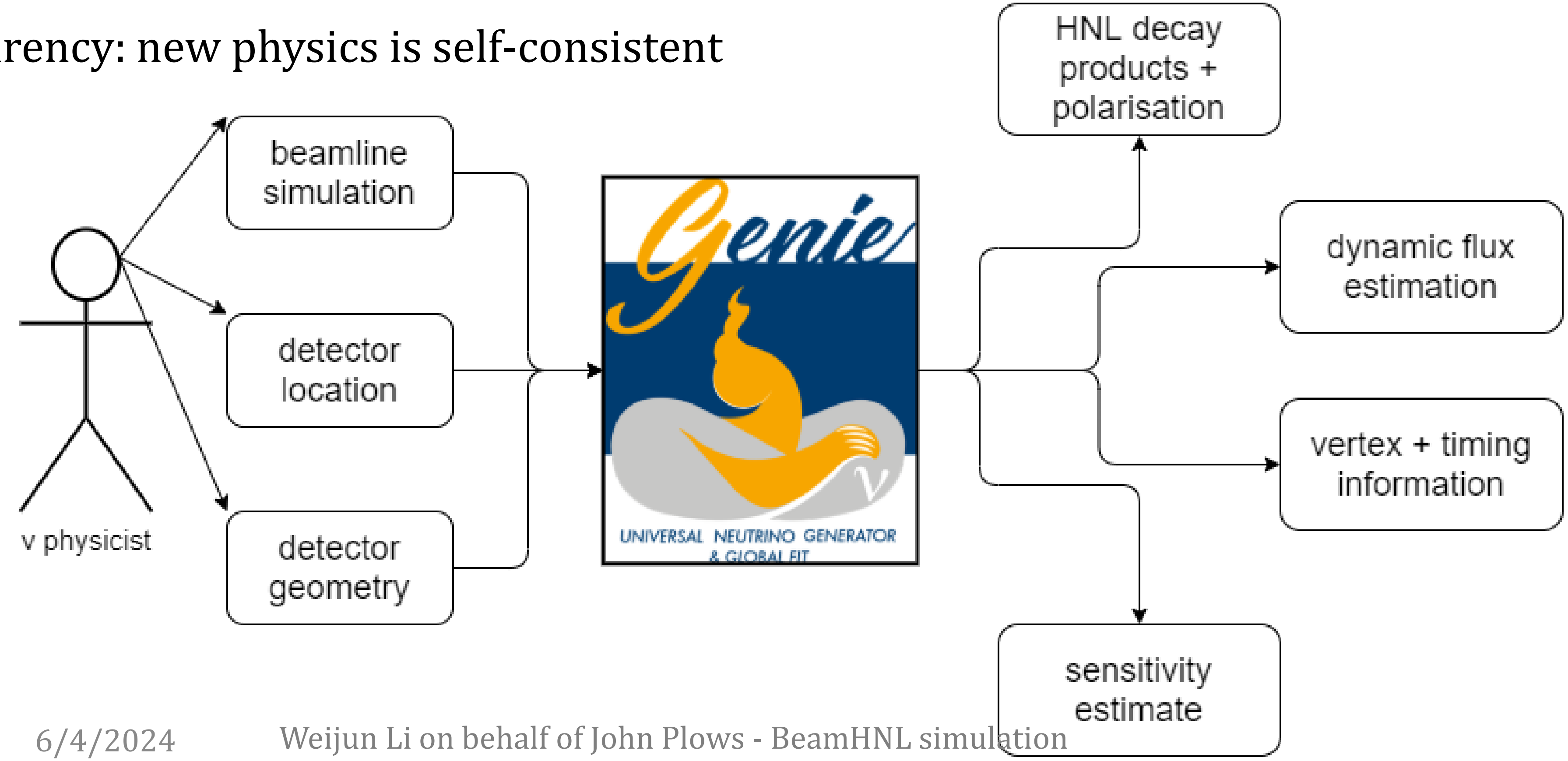
- Addition of Beam-produced Heavy Neutral Leptons. *Contribution by John Plows (Oxford)* . [GENIE pull request #223].

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].

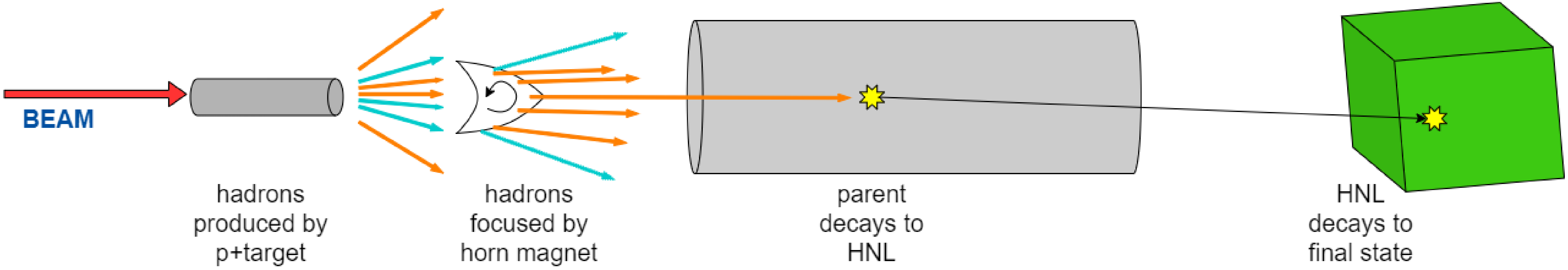
The BeamHNL module

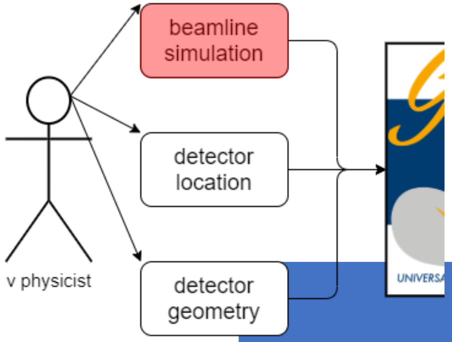
- An experiment-agnostic, configurable HNL generation application for accelerator neutrinos
- Goals:
  1. User flexibility: ease of use <u>and</u> integration with simulation
  2. Generality: for use with many beamlines, detectors
  3. Transparency: new physics is self-consistent



- Assume <u>one heavy neutrino</u> eigenstate N_4 as in K. Abe et al (T2K), *Phys. Rev. D* **100** (2019) 052006
  - Parameter space: $\left\{M_{N_4}, |U_{e4}|^2, \left|U_{\mu4}\right|^2, |U_{\tau4}|^2\right\} \equiv \{M_{N_4}, |U_{\alpha4}|^2\}$

- 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

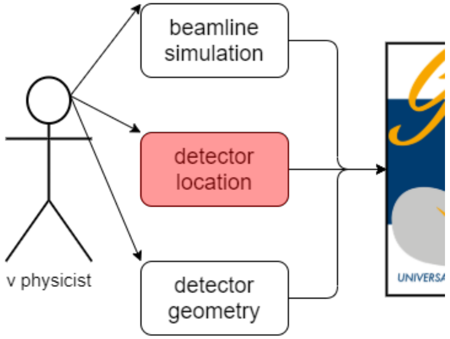





```
======> EVENT:25
 job              = 32
 potnum           = 98
 decay_vx         = -4.45755
 decay_vy         = -7.12057
 decay_vz         = 4097.12
 decay_pdpx       = -0.0012738
 decay_pdpy       = -0.0203605
 decay_pdpz       = 8.92705
 decay_ptype      = 321
 decay_necm       = 0.235532
 decay_nimpwt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

Flux Input Example

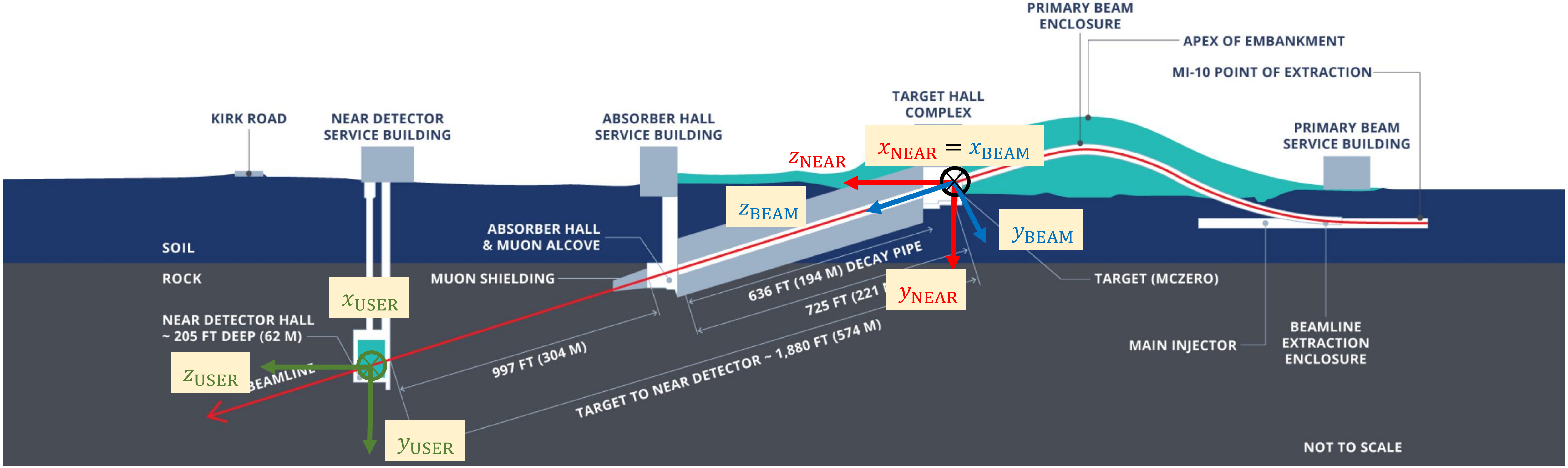
	GENIE(dk2nu)	T2K
parent pdg	decay_ptype	ppid
nu parent decay coordinates in [cm]	decay_vx,vy,vz	Xpi[0],xpi[1],xpi[2] (in [cm])
parent momentum in lap frame in [GeV/c] (?)	decay_pdpx,py,pz	ppi*(npi[0],npi[1],npi[2])
E_nu in C.O.M frame of the nu parent [GeV]	decay_necm	calculated
relative weight of each event entry, default=1	decay_nimpwt	Norm->more complicated

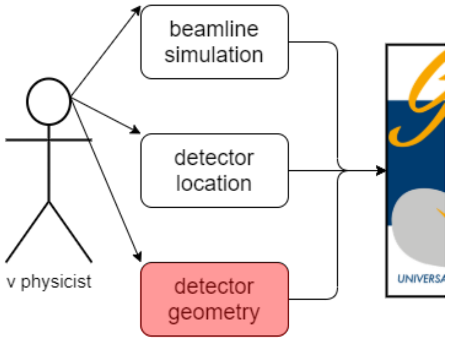


3 coordinate systems:

- 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)

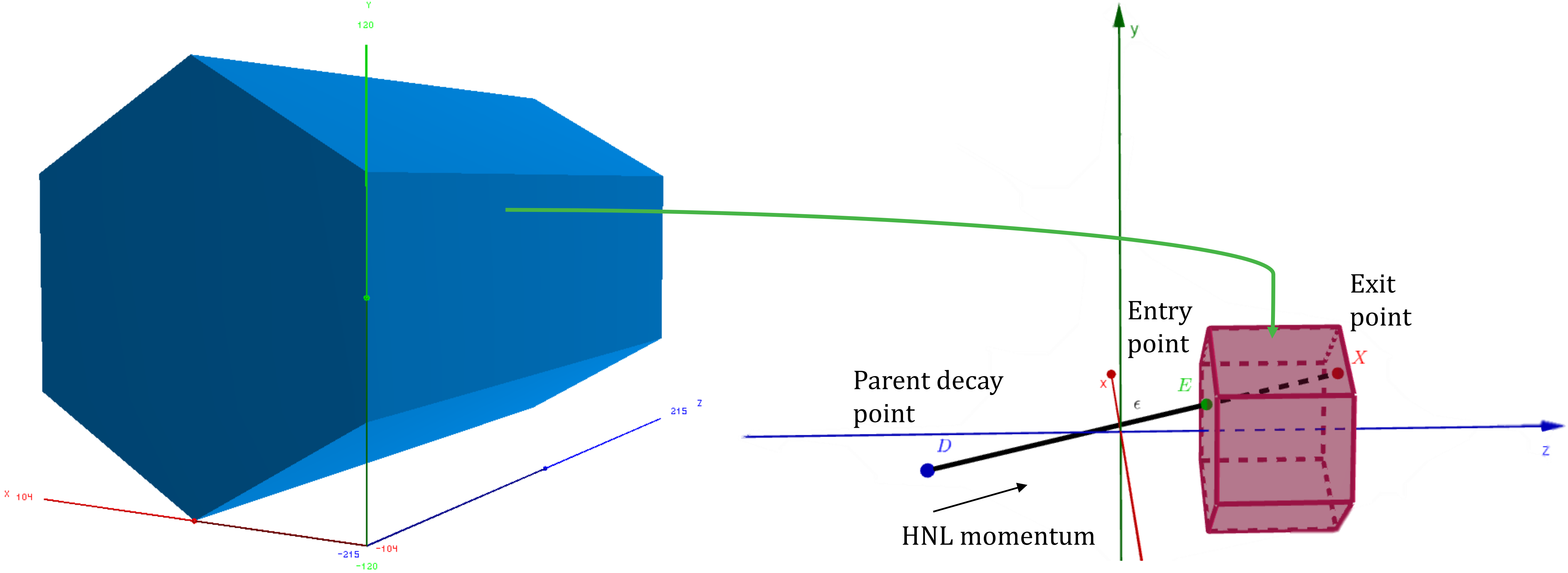
Can transform between two coordinate systems using **1 vector of translations** and **1 vector of rotations**

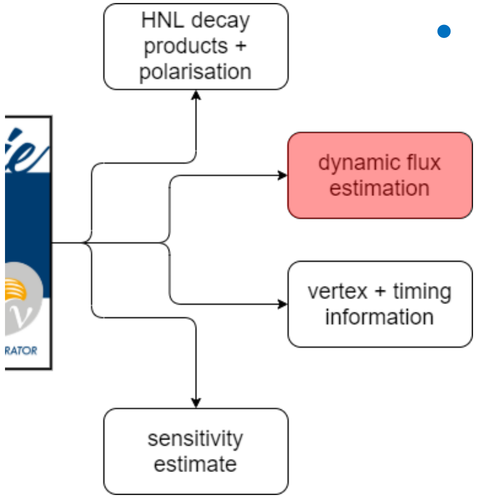




Arbitrarily complicated ROOT geometry file

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





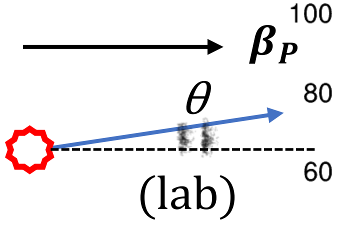
- Pseudoscalar meson decay $P \to N_4 + \ell$ (+ pseudoscalar D)
  - Lorentz boost from parent-rest frame into lab frame dominant factor
  - For a massive neutrino

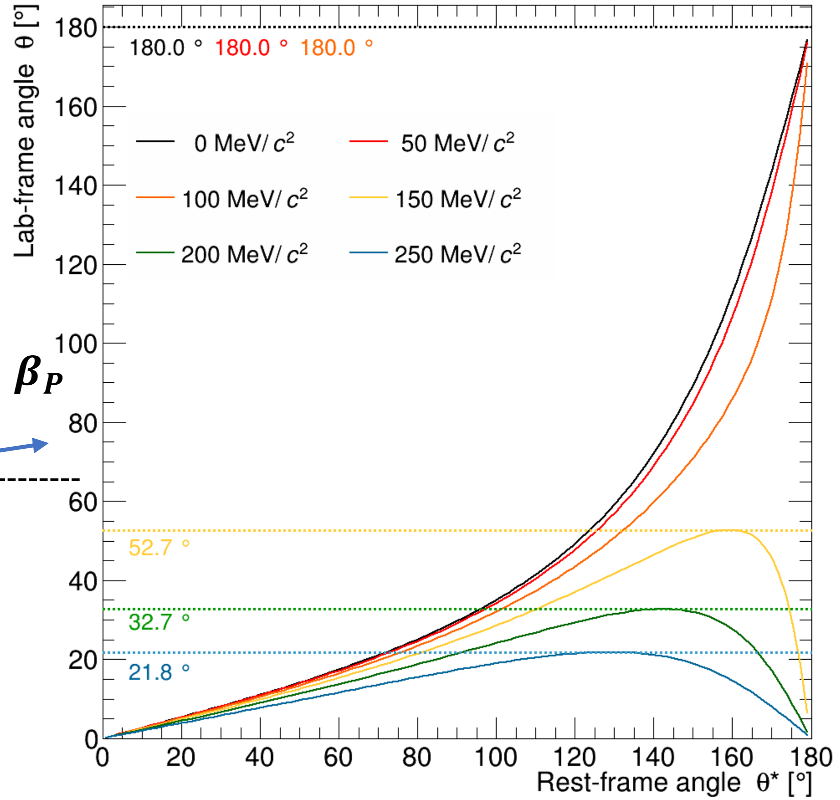
$$\mathcal{B} = \frac{E_{\mathrm{N4}}}{E_{\mathrm{N4}}^{(\mathrm{CM})}} = \frac{1}{\gamma_P(1 - \beta_P \beta_{\mathrm{N4}} \cos\theta_{\mathrm{det}})} \text{ (1)}, \beta_{\mathrm{N4}} \text{ lab} - \text{frame}$$

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

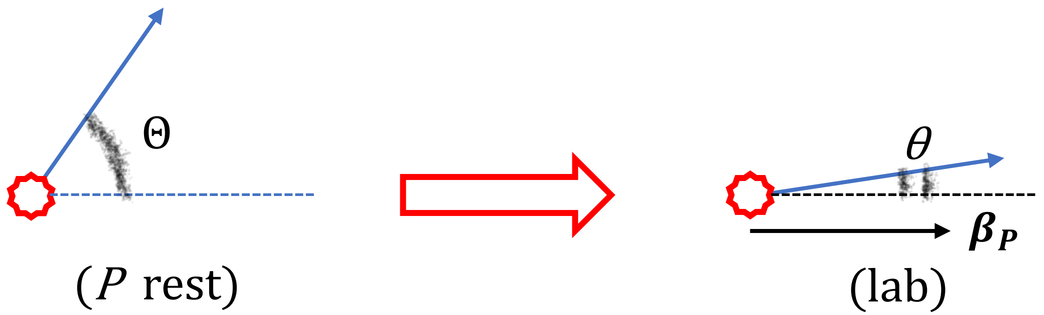
  - Collimation effect:

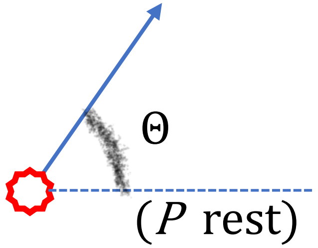
$$\tan\theta = \frac{q_{\mathrm{N4}} \sin\Theta}{\gamma_P \left(\beta_P E_{\mathrm{N4}}^{(\mathrm{CM})} + q_{\mathrm{N4}} \cos\Theta\right)} \text{ (2)}$$

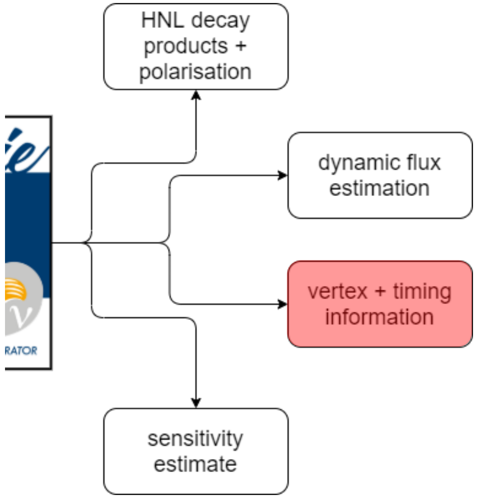


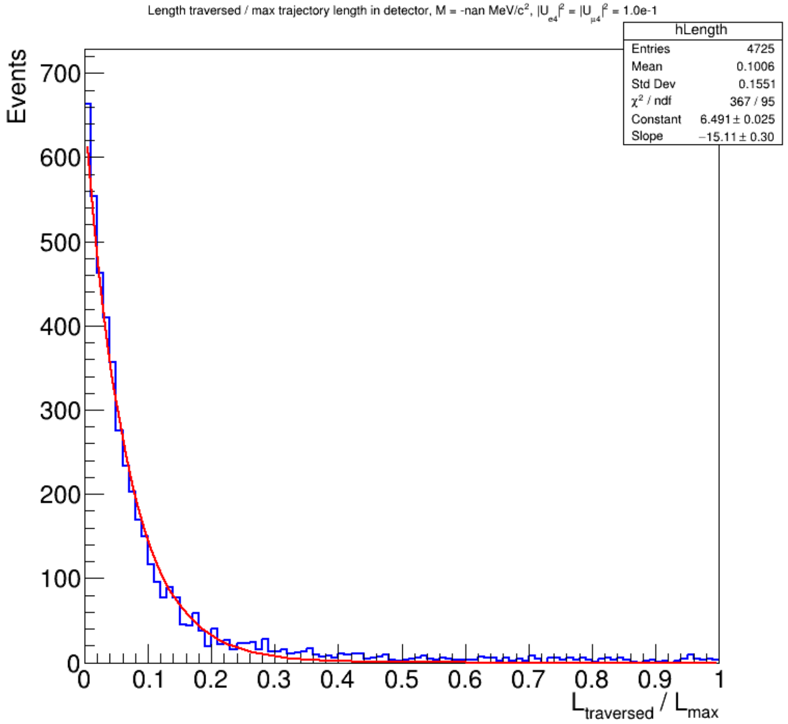


HNL are more collimated with their parents than SM neutrinos. The flux depends much more strongly on parent kinematics!



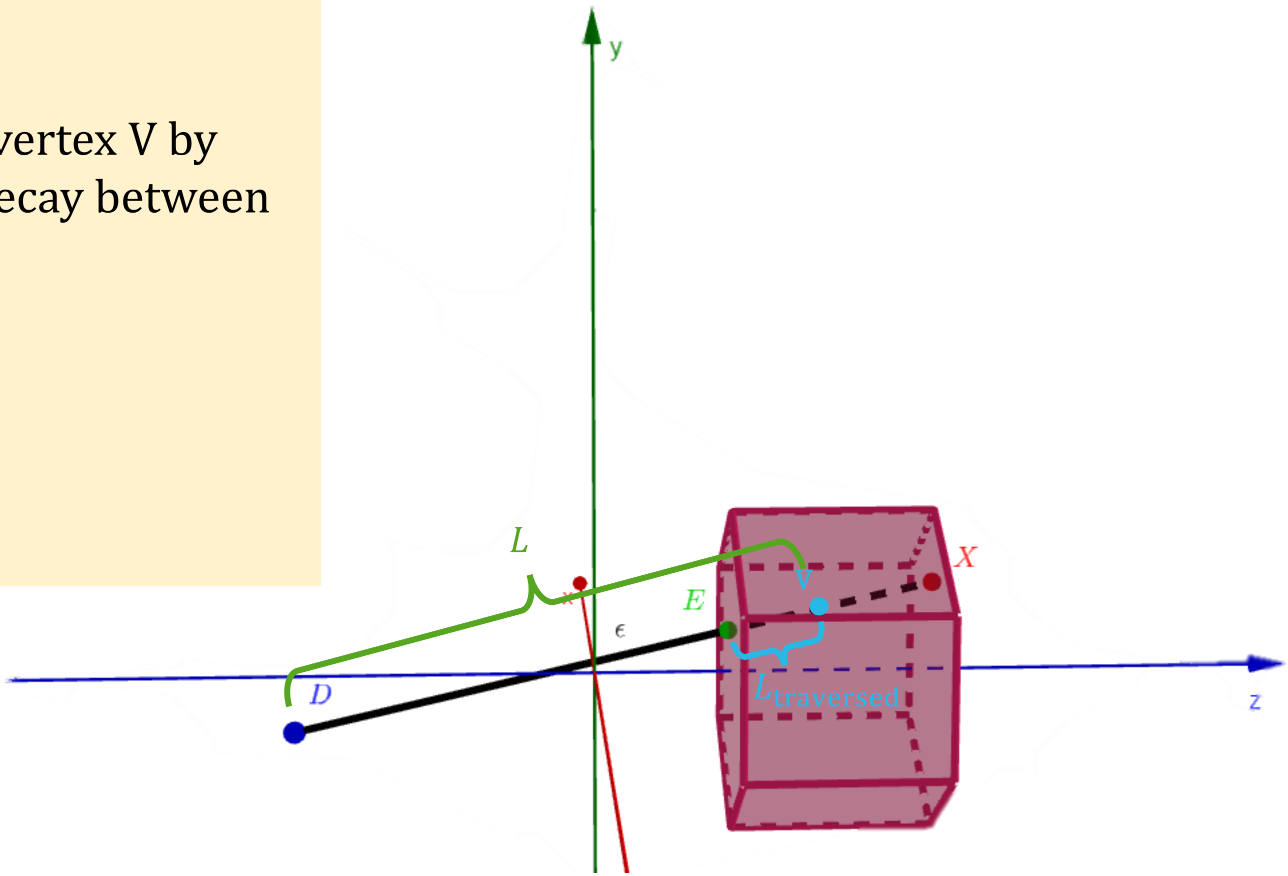


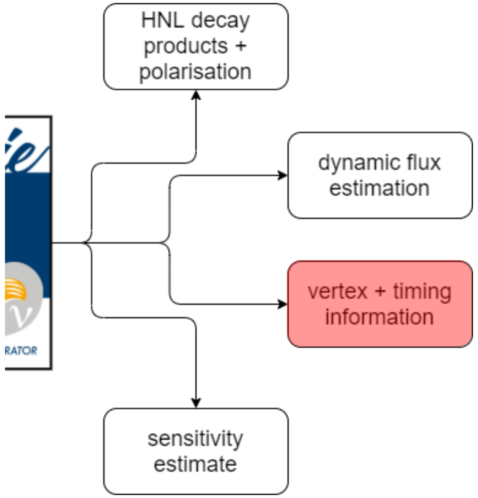




∀ HNL know production point D and momentum $\boldsymbol{p}$ ⇒ Calculate entry, exit points E, X

Assign decay vertex V by exponential decay between E and X

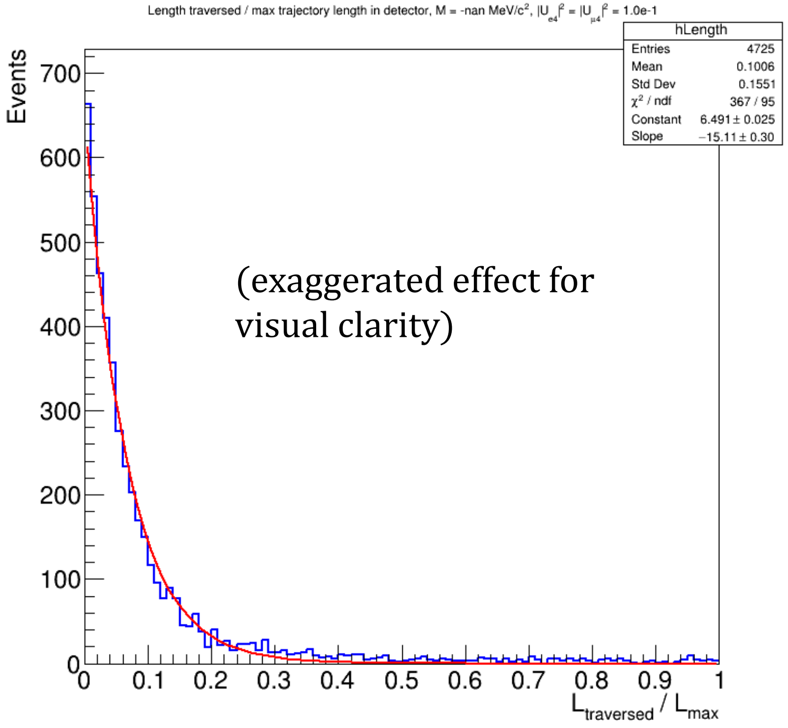




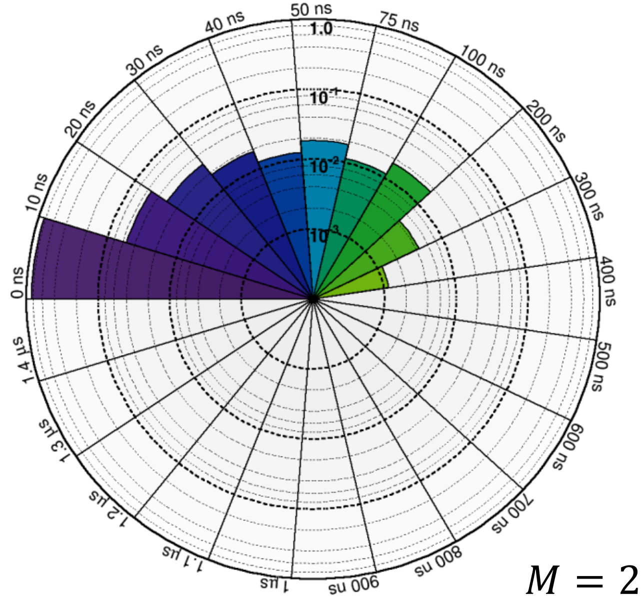
∀ HNL know production point D and momentum $\boldsymbol{p}$ ⇒ Calculate entry, exit points E, X

Assign decay vertex V by exponential decay between E and X

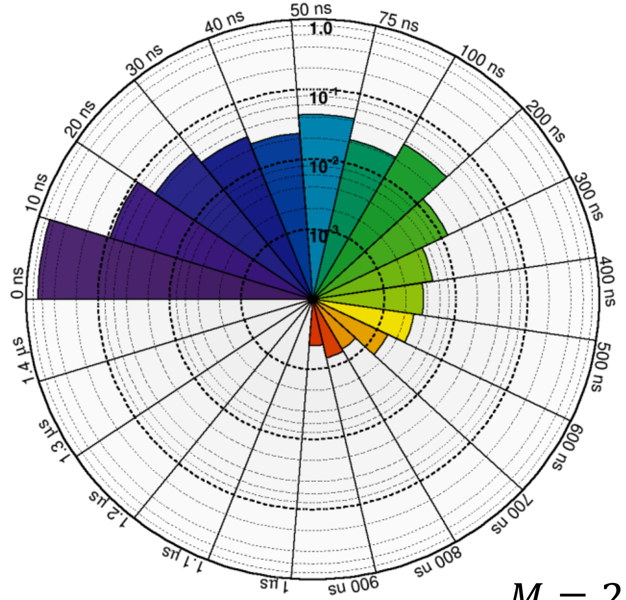
Total travel distance L and velocity $\boldsymbol{\beta}$ known ⇒ calculate delay wrt SM neutrino



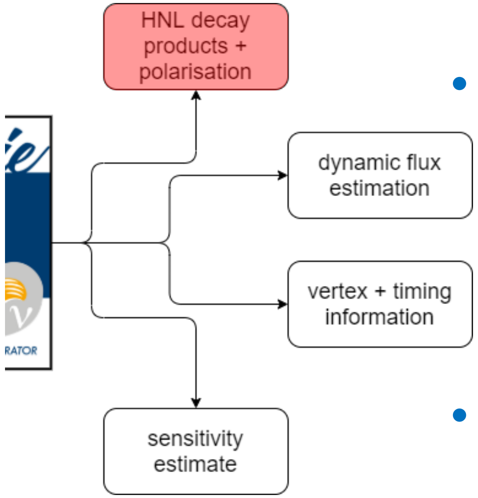
(exaggerated effect for visual clarity)



$M = 25$ MeV



$M = 250$ MeV



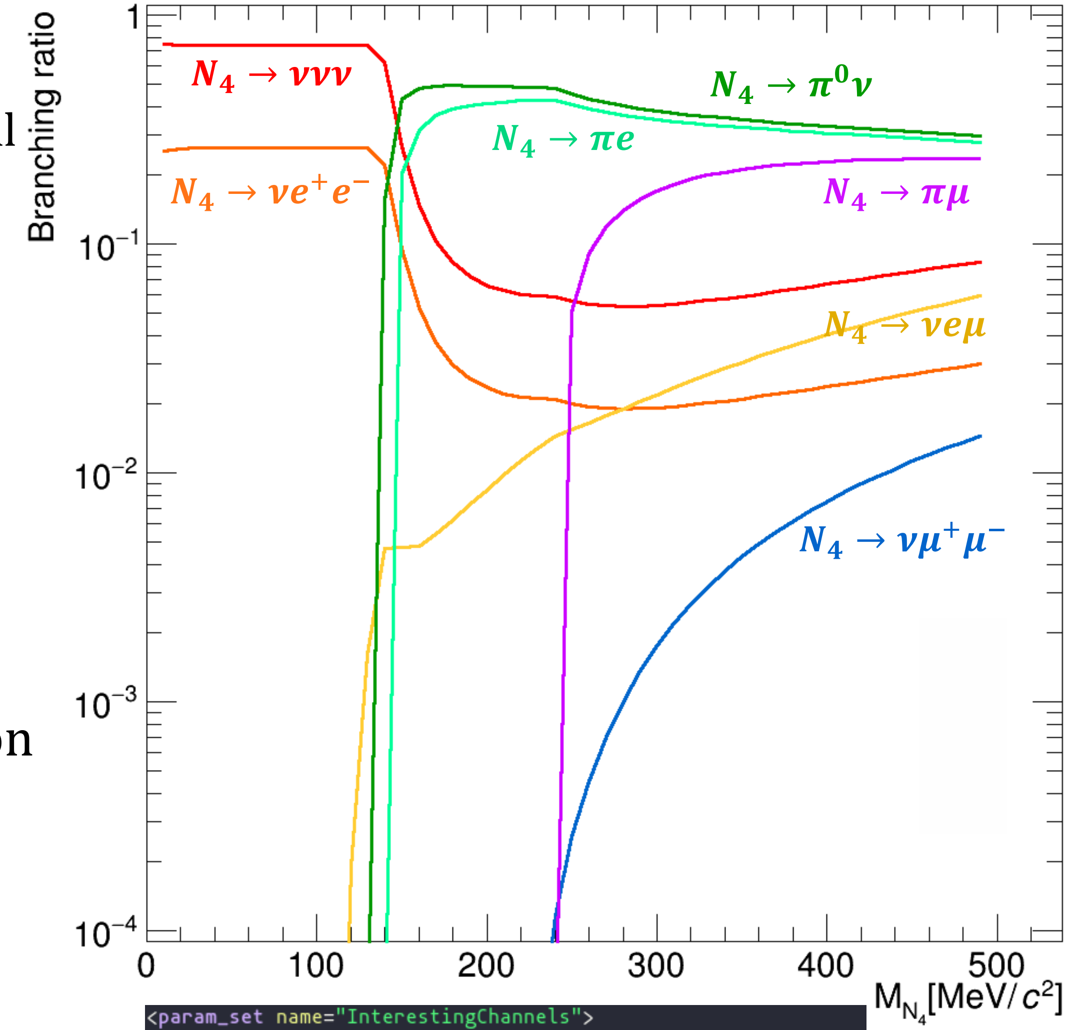
- Choose signal channel(s)
  - Module keeps track of total and individual decay widths for calculations

- Polarisation reweighting: by spin conservation

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

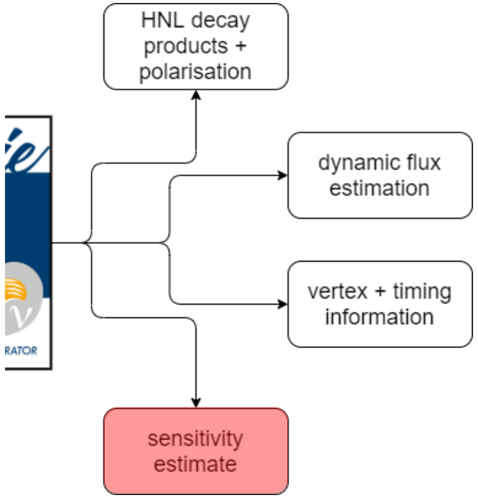
$$\frac{d\Gamma}{d\cos\theta_{\boldsymbol{P}}} \propto 1 \pm \hbar \cdot \cos\theta_{\boldsymbol{P}}$$

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>
```

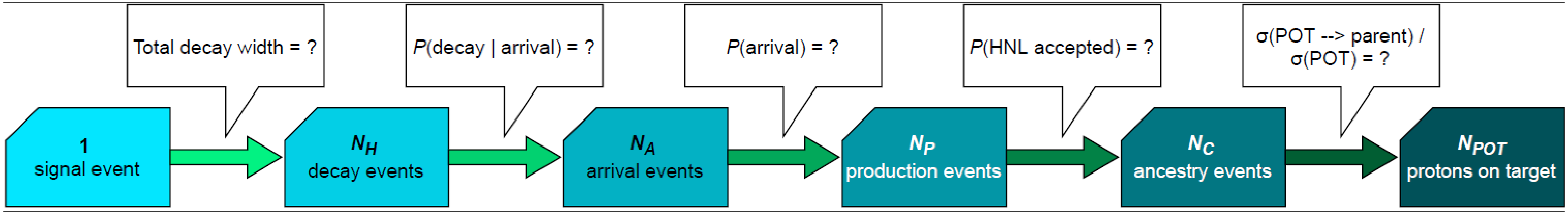


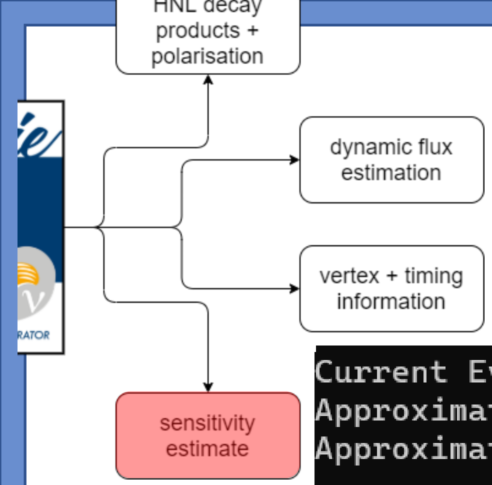
How do we calculate rates?

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, $e:\mu:\tau = 1:1:0$, $|U_{\alpha 4}|^2 = 10^{-8}$

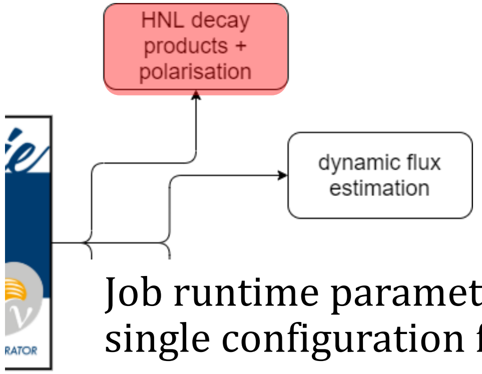
```
|------------------------------------------------------------------------------------------------------------------|
|GENIE GHEP Event Record [print level:   3]                                                                        |
|------------------------------------------------------------------------------------------------------------------|
| 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

How to use BeamHNL?

```
#!/usr/bin/env bash
echo "Running configuration script generated by the Lamp..."
./configure \
  --with-optimiz-level=O2 \
  --enable-debug \
  --enable-test \
  --enable-heavy-neutral-lepton \
  --enable-hnl-validation \
  --with-compiler=gcc \
  >& log this build.config
```



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>
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</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 -->
  <param type="vec-double" name="Near2User_R" delim=";"> 0.0 ; 0.0 ; 0.0 </param>
  <!-- Euler angles, extrinsic x-z-x -->
  <!-- Describes rotation of USER wrt NEAR frame -->
  <param type="vec-double" name="DetCentre_User" delim=";"> 0.0 ; 0.0 ; 0.0 </param> <!-- m -->
  <!-- Position of detector centre in USER frame, in case it is not at USER origin -->
</param_set>
```
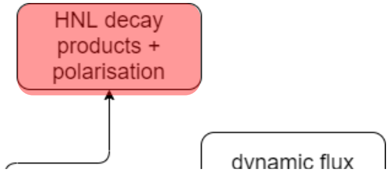

ParameterSpace block: specify what HNL mass / mixings / nature you want



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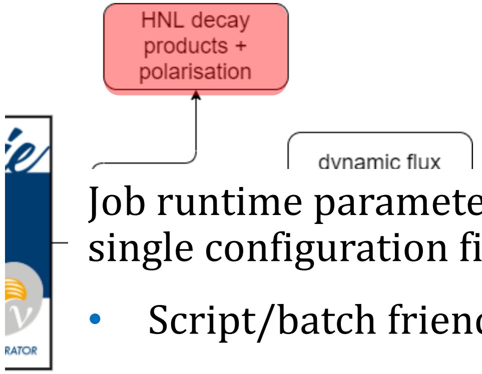
```

Interesting Channels block: specify which channels you want to simulate.

(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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  <!-- Position of detector centre in USER frame, in case it is not at USER origin -->
</param_set>
```

CoordinateXForm block: Provide vectors describing detector location.

In this example, detector centre at:
$(x_{\text{NEAR}}, y_{\text{NEAR}}, z_{\text{NEAR}}) = (0, -60, 1000)$ m
$(x_{\text{USER}}, y_{\text{USER}}, z_{\text{USER}}) = \mathbf{0}$
Beam rotated by 58.3 mrad down in (y_{NEAR}, z_{NEAR}) plane

Thank you!

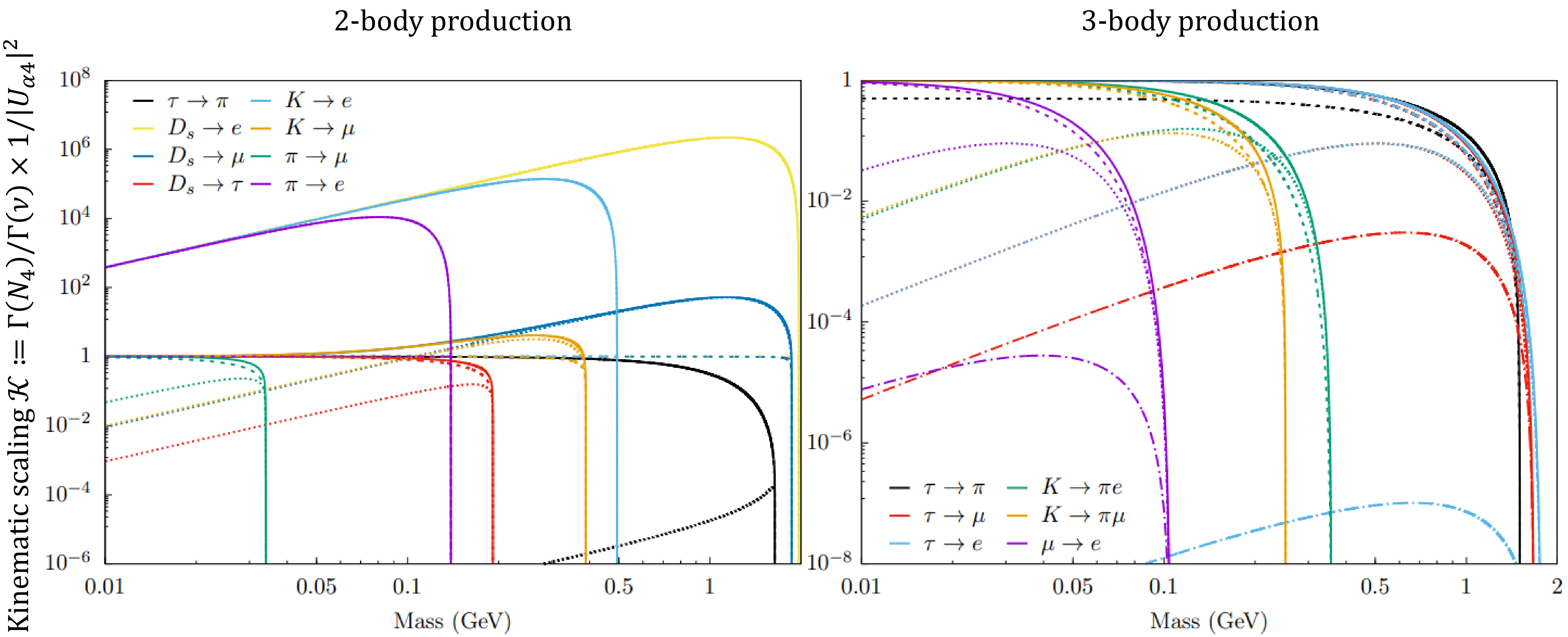
Some useful links:

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

BeamHNL principal branch:
kjplows/Generator

Preview branch with theory input:
kjplows/Generator at multiLagrangian

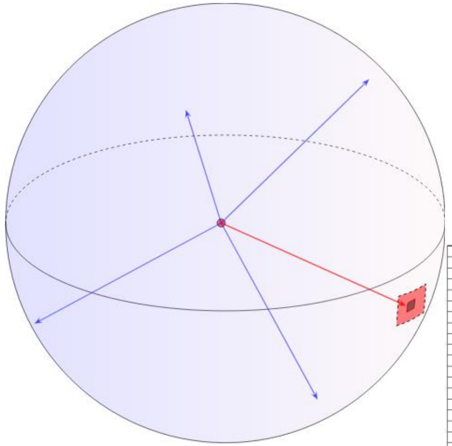
Backup

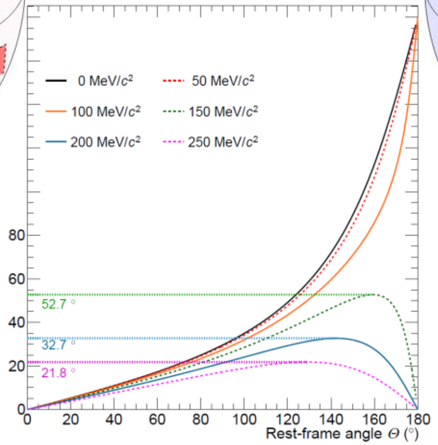


P. Ballett et al, *JHEP* **2020** (2020) 111

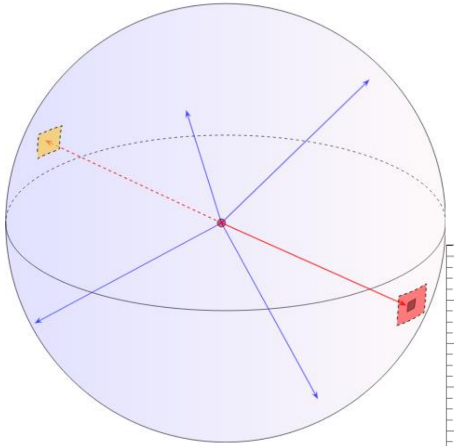
Acceptance correction

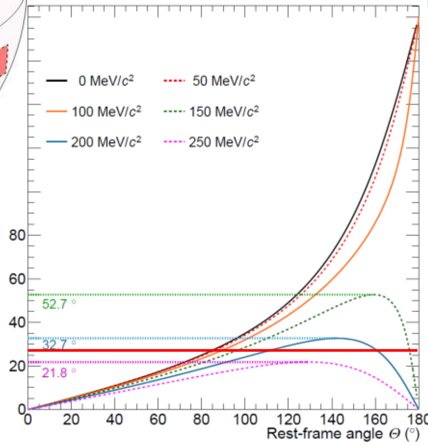
- Collimation effect ⇒ <u>HNL not guaranteed to hit detector</u>
- Parents have to be well-focused or HNL cannot "correct course" enough to reach a point
- Back-emitted HNL may also hit detector if parent focused enough!



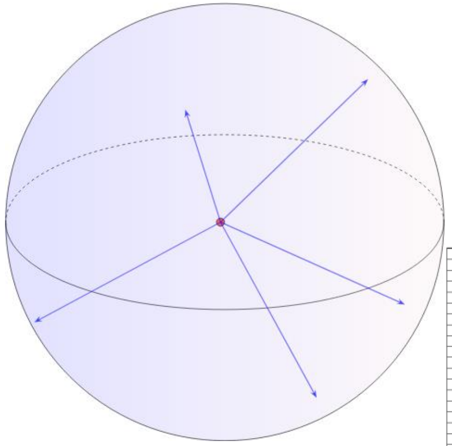


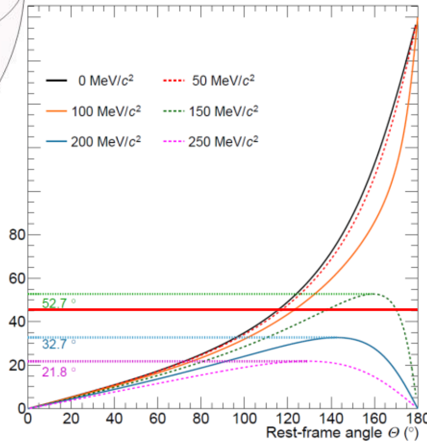
1 preimage
(SM ν)



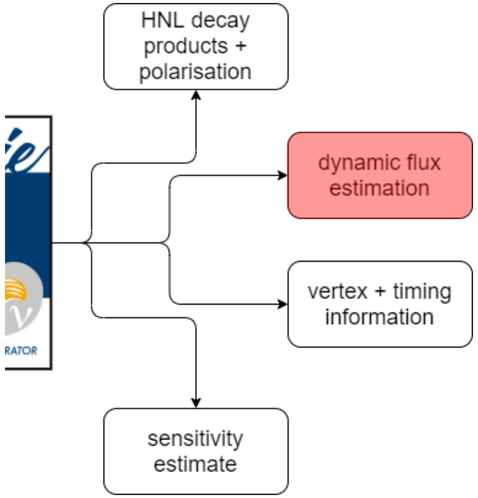


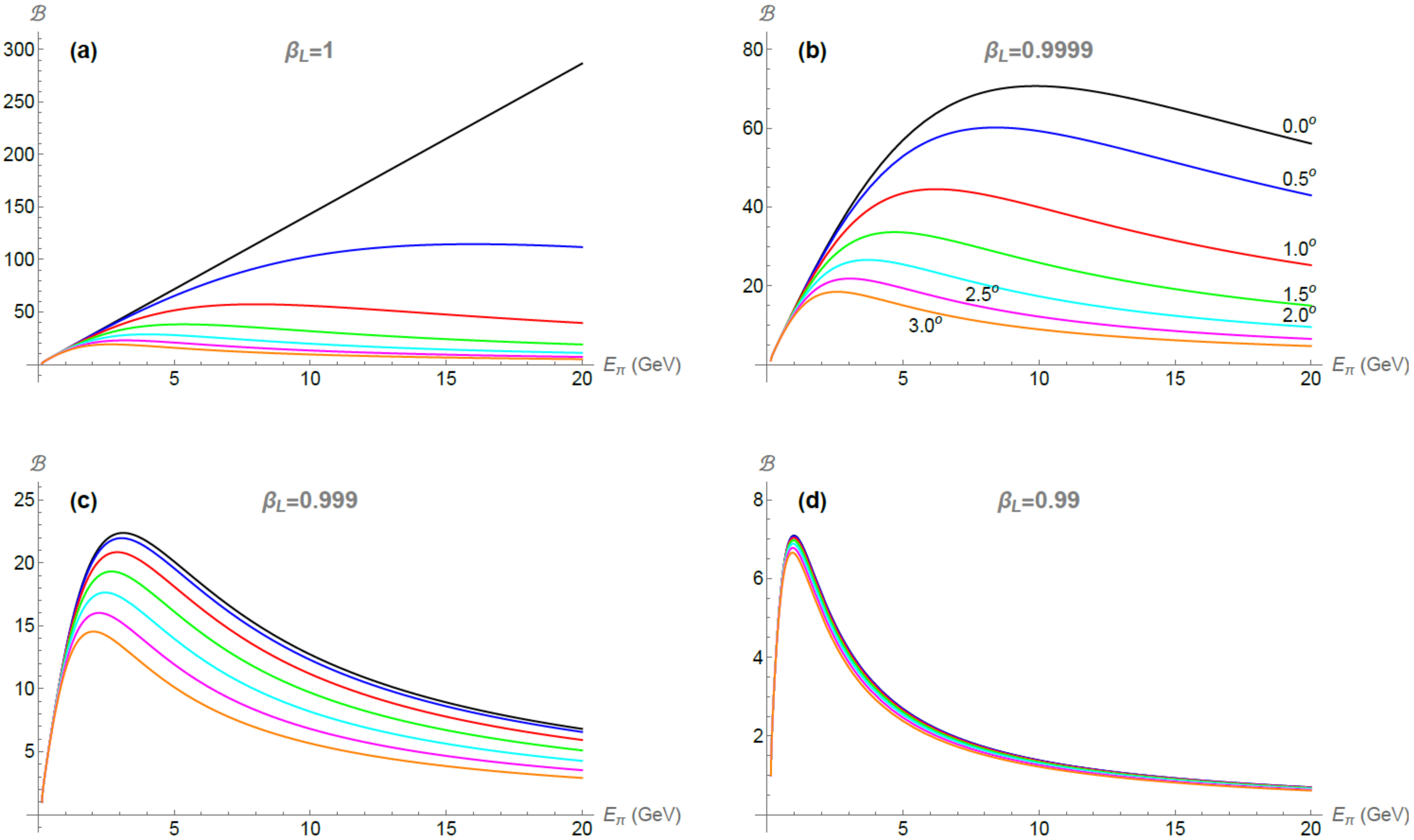
2 preimages
($M_N = 200$ MeV,
$\theta < 32.7°$)





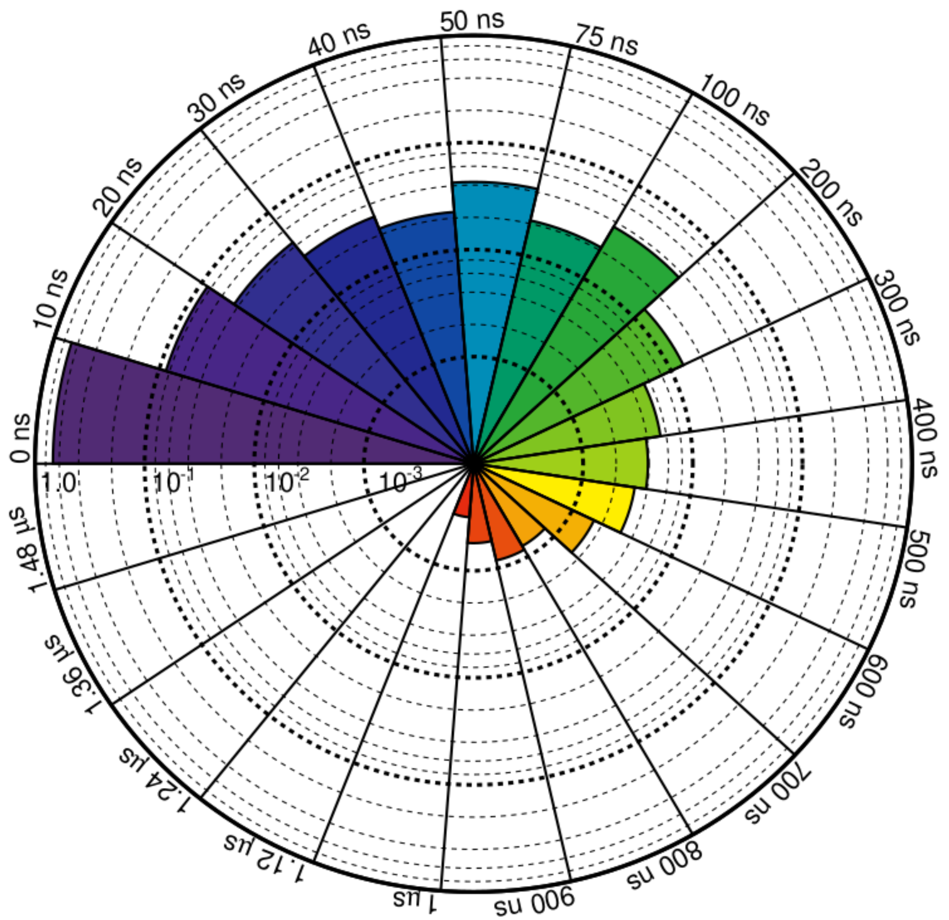
0 preimages
($M_N = 200$ MeV,
$\theta \geq 32.7°$)

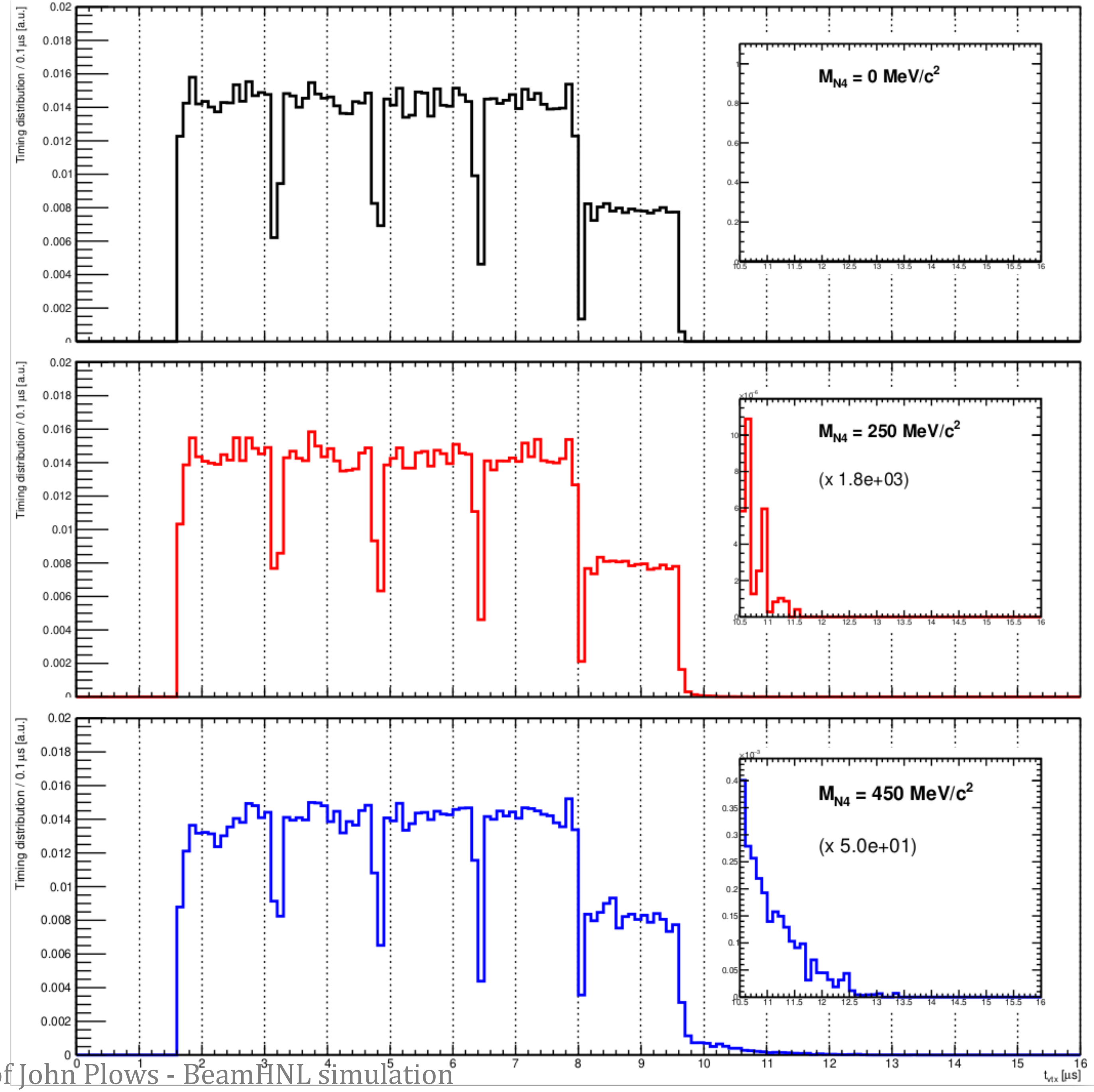




Presence of β_{N4} term in (1) weakens off axis effect compared to SM

Delay time distribution at MINERvA, 250 MeV

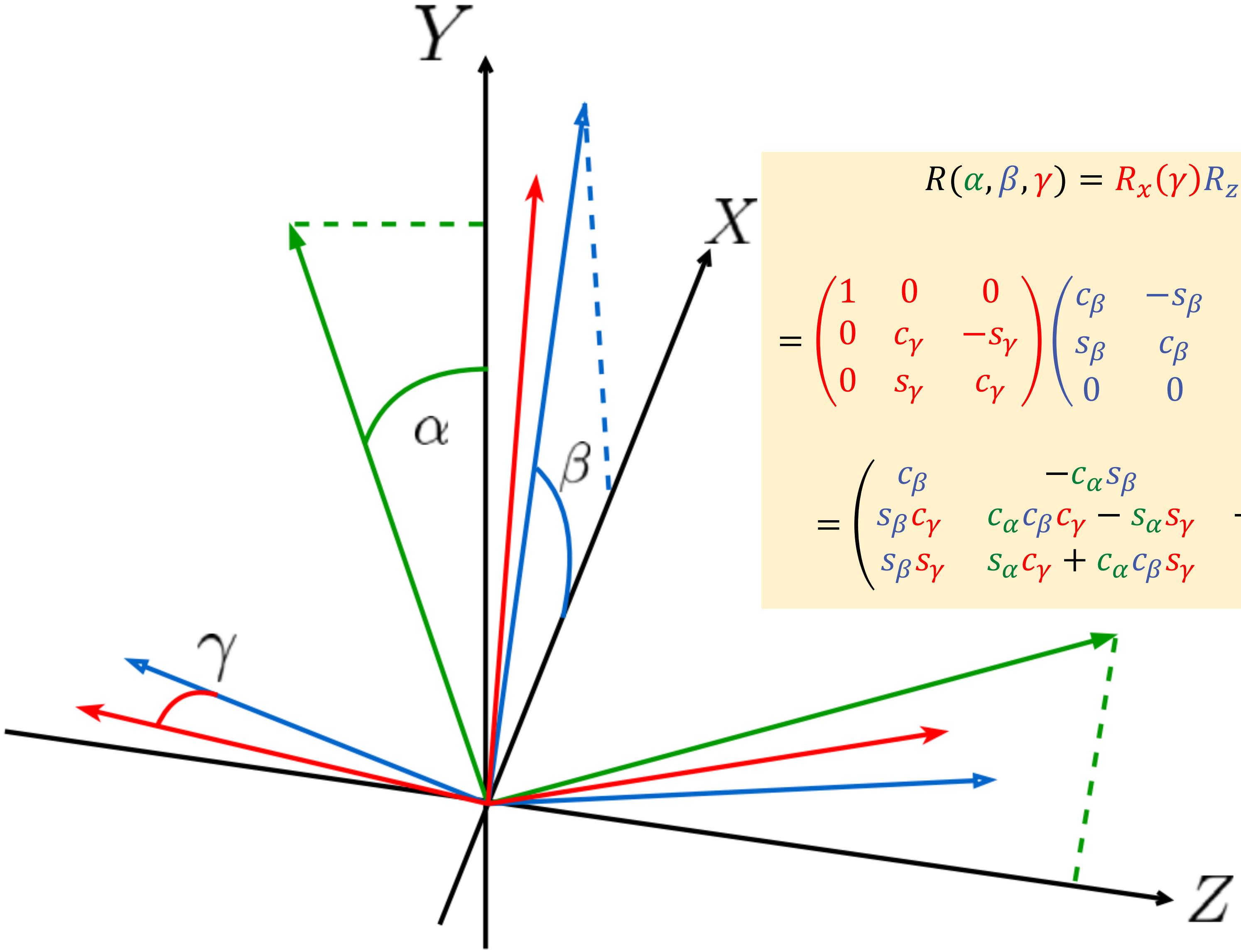




$$\begin{pmatrix}X\\Y\\Z\end{pmatrix} \overset{R_X(\alpha)}{\mapsto} \begin{pmatrix}X_1\\Y_1\\Z_1\end{pmatrix}$$

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

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



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

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

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

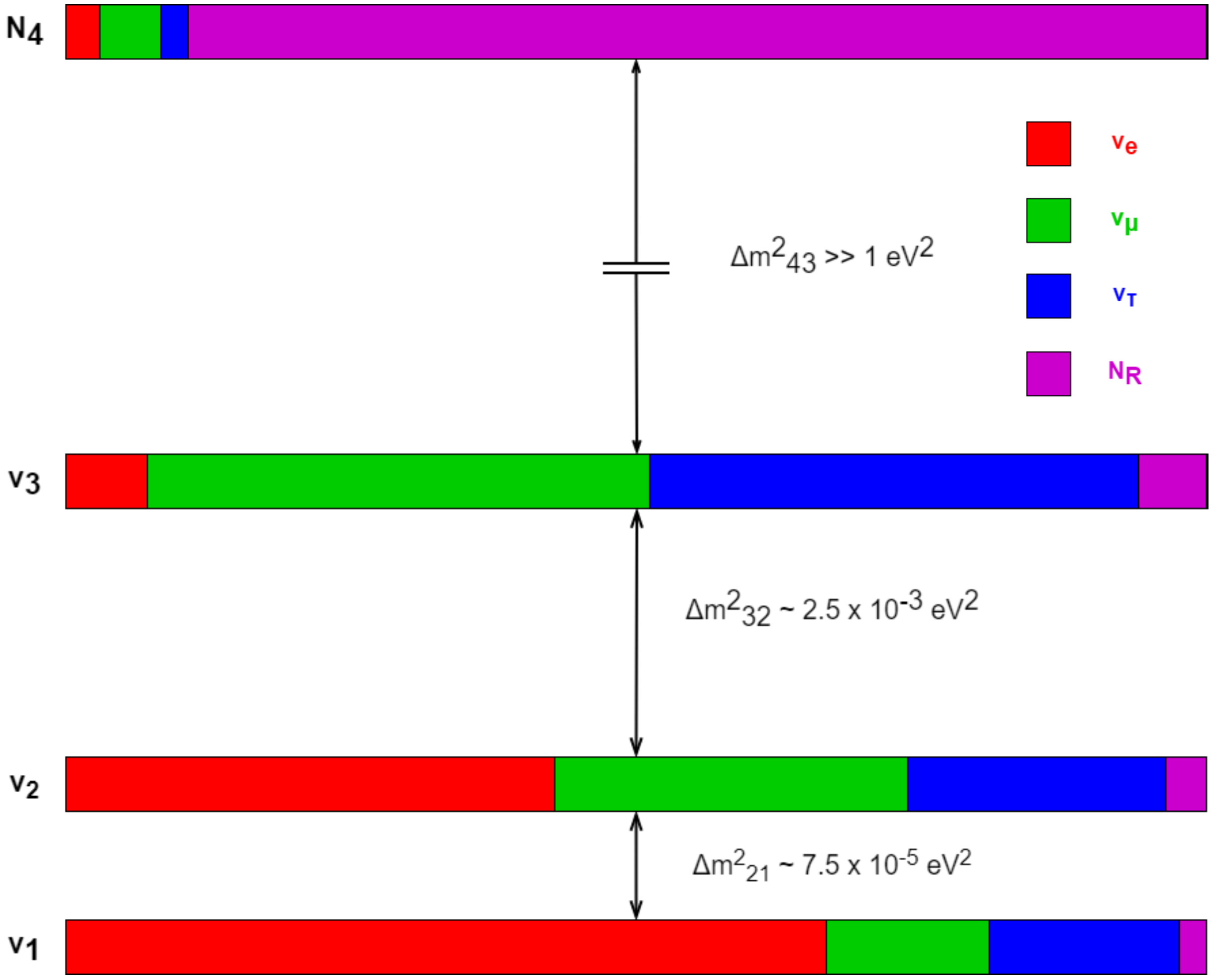
What are HNL?

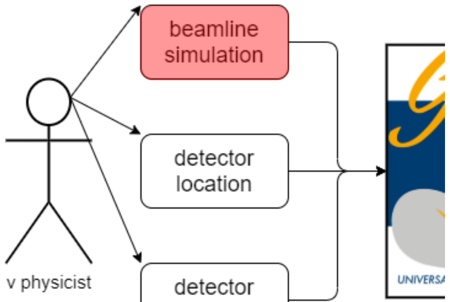
- Naturally motivated extension to Standard Model
  - Light neutrinos $\nu_{1,2,3}$ have <u>at least 2 non-zero masses</u>
  - Admixture with regular "flavour" eigenstates ν_α as $\nu_\alpha = \sum_{i=1,2,3} U_{\alpha i} \nu_i + \sum_{j \in J} U_{\alpha j} N_j$

- HNL: **new mass eigenstates**
  - Mass $\mathcal{O}(\leq \mathrm{TeV}/c^2)$ 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]())

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





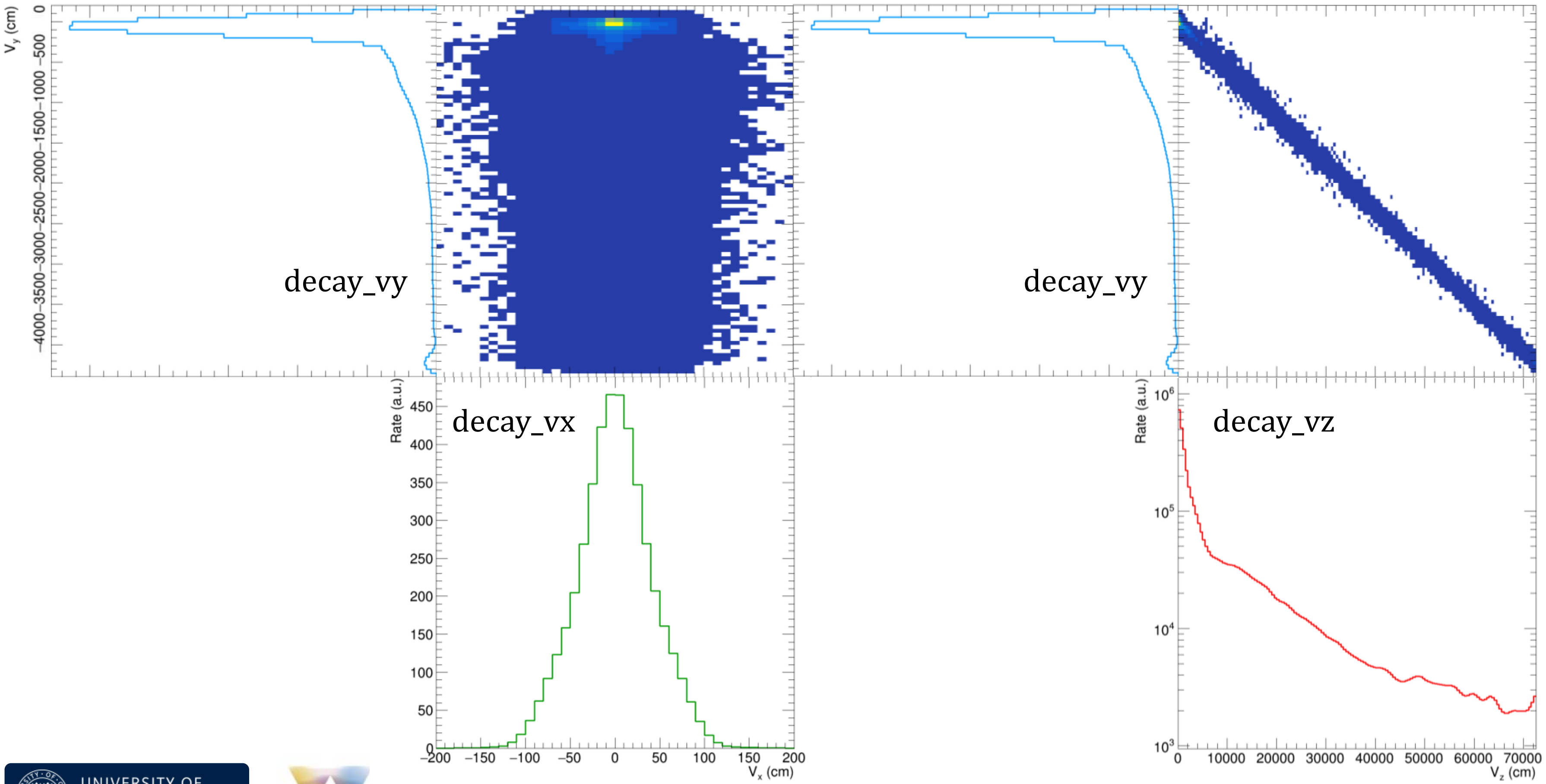

```
======> EVENT:25
 job              = 32
 potnum           = 98
 decay_vx         = -4.45755
 decay_vy         = -7.12057
 decay_vz         = 4097.12
 decay_pdpx       = -0.0012738
 decay_pdpy       = -0.0203605
 decay_pdpz       = 8.92705
 decay_ptype      = 321
 decay_necm       = 0.235532
 decay_nimpwt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

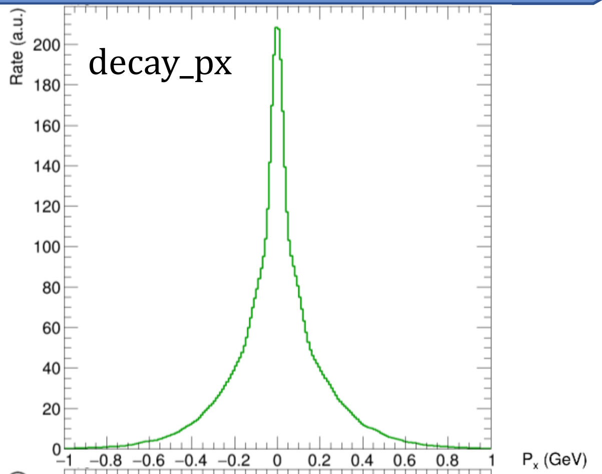
Parent decay coordinates

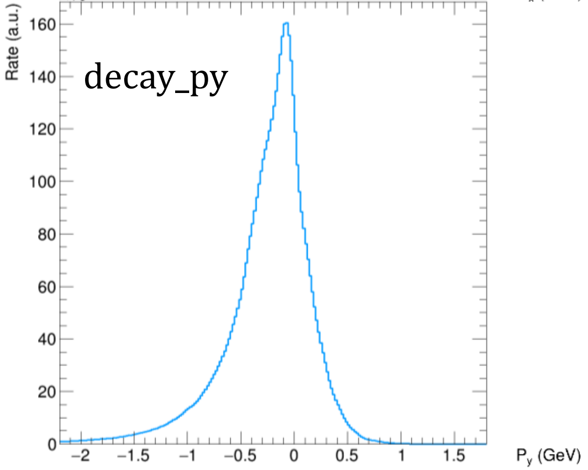
Parent decay momentum

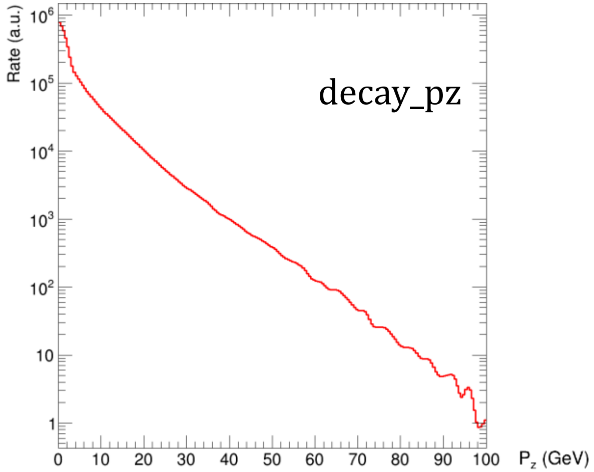
→ SM neutrino E

→ Stat multiplier



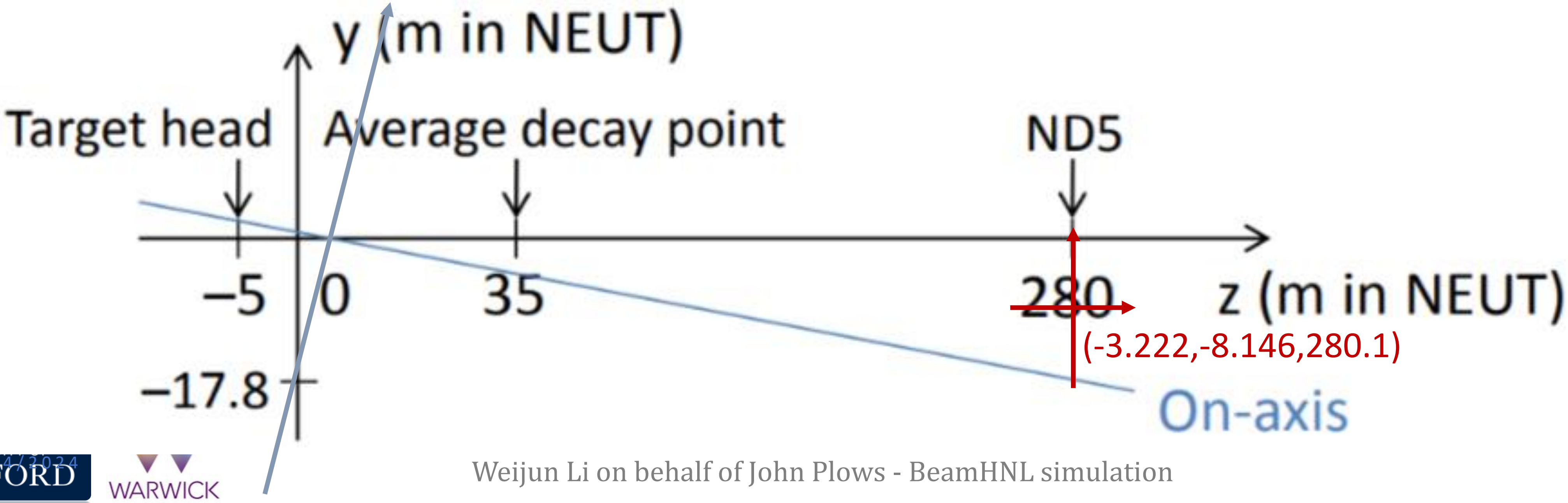






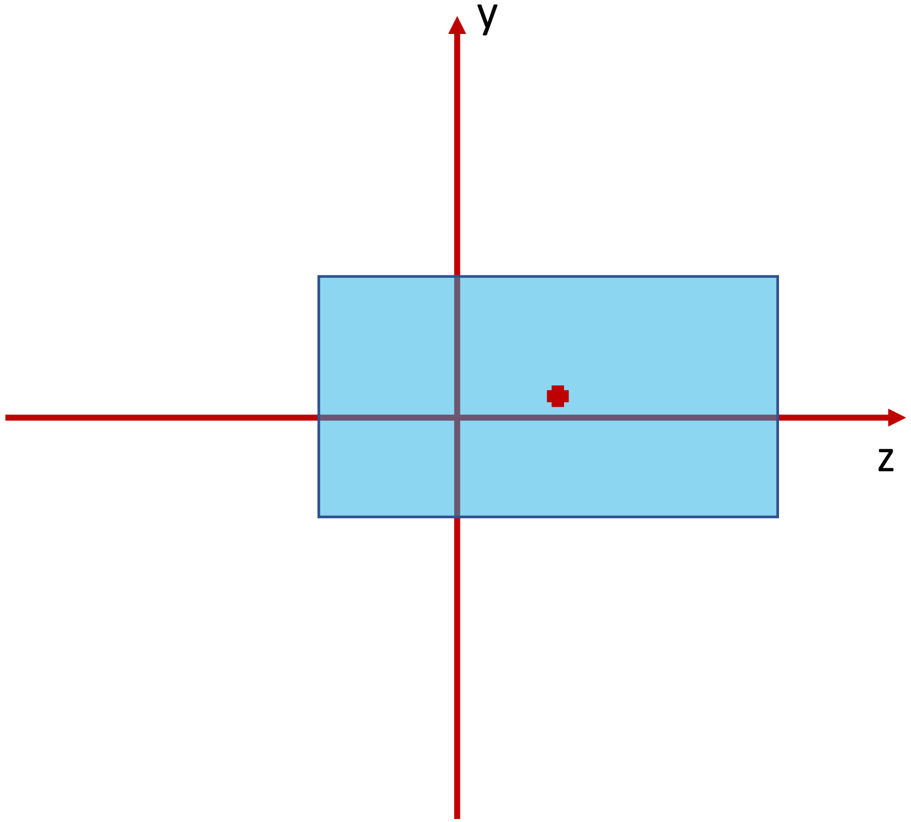
BeamHNL Geometry

- It uses 3 coordinate systems,
  - NEAR – origin in the target, NEUT Coordinate
  - BEAM – z-axis is the beam direction, i.e. t2k on-axis
    - The transformation from NEAR to BEAM is by a rotation around the x-axis downwards by 63.44 mrad.
  - USER – origin is at the centre of ND280, (-3.222,-8.146,280.1) w.r.t NEAR origin



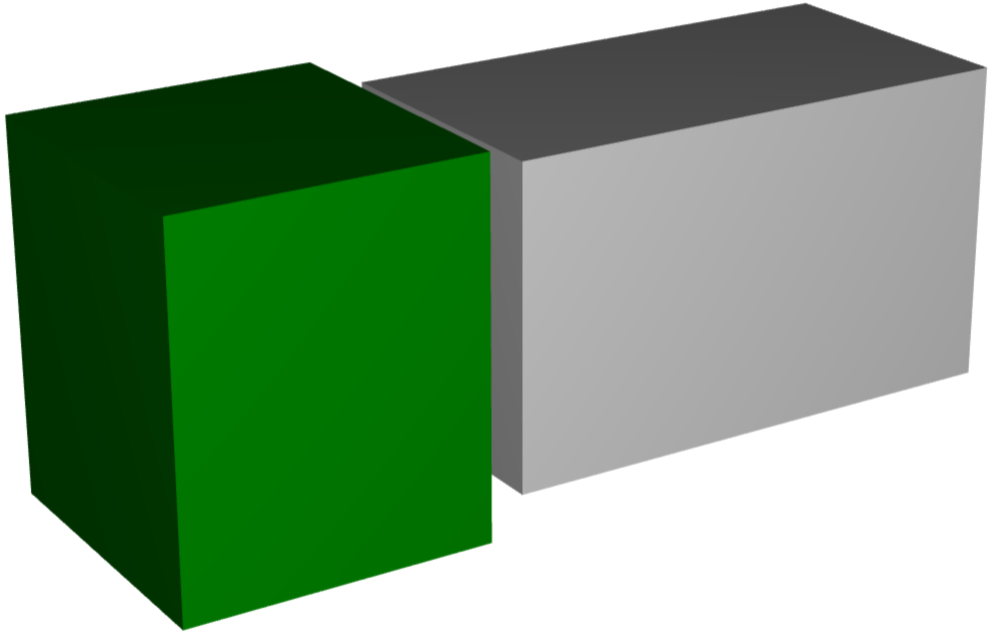
Detector Geometry

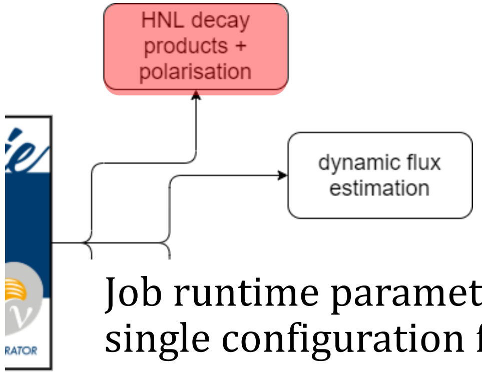
- Looking at a box [(1740,1960,3281) mm in size] just large enough to contain all TPC segments, centred at (0,50,915.5)
- The three sides are from
- (-870,-930,-725) to (870,1030,2556)



Simplified Geometry Input

- For test purposes, a simplified geometry file, containing one big box enclosing SFGD&HATPC and another enclosing all three TPCs are used.





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…

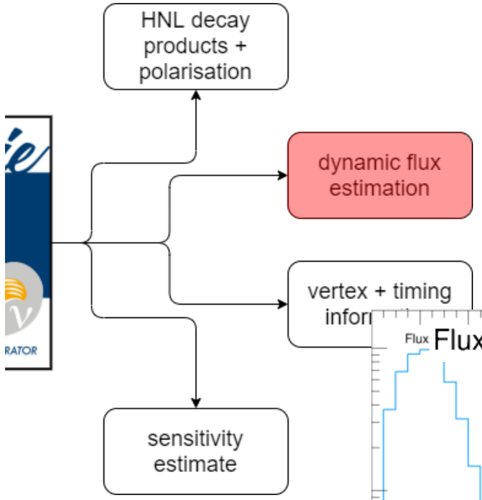
An example can be found in

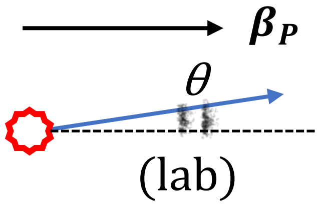
$GENIE/src/contrib/beamhnl/CommonHNL_DEMO.xml

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

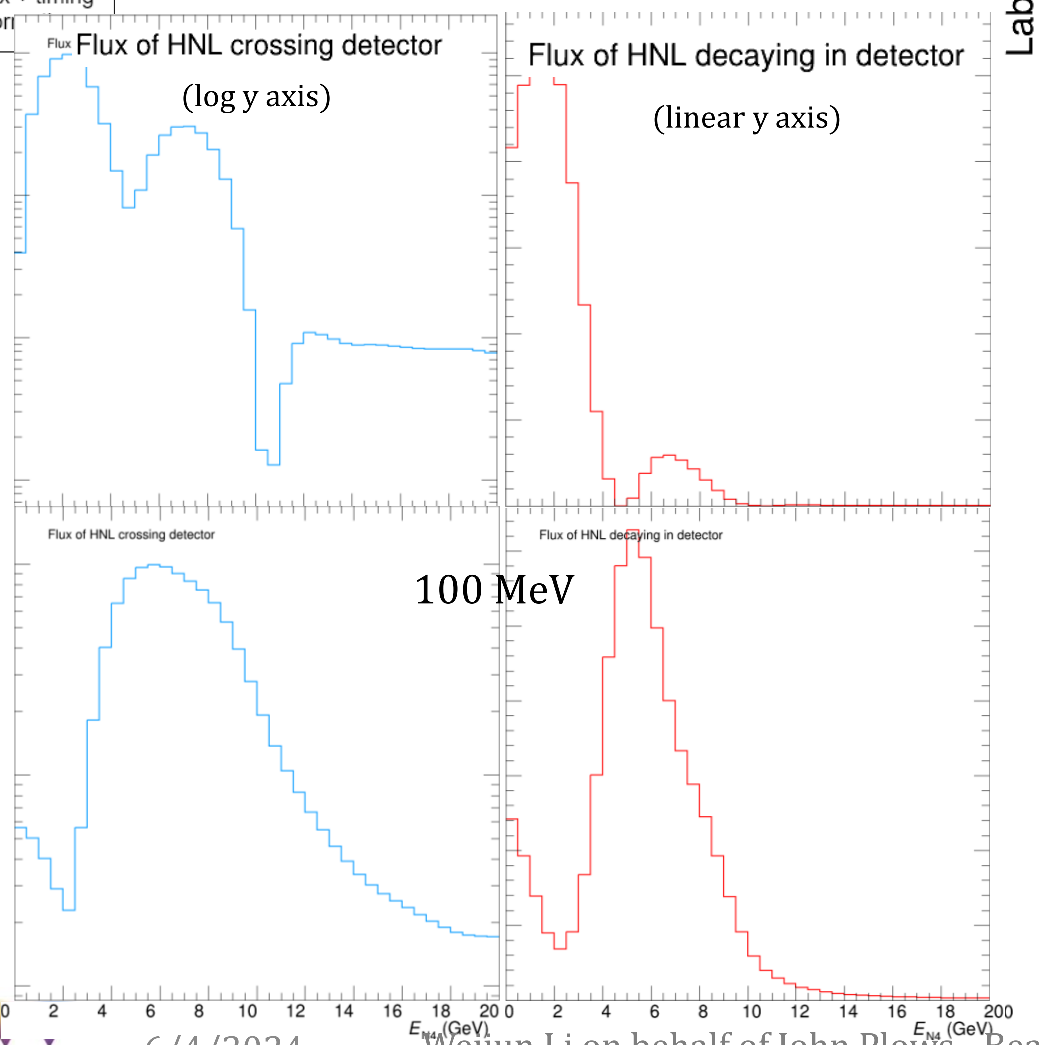
```
<param_set name="ParameterSpace">
  <param type="double" name="HNL-Mass"> 0.200 </param> <!-- GeV -->
  <param type="vec-double" name="HNL-LeptonMixing" delim=";"> 1.0e-7 ; 1.0e-7 ; 0.0 </param>
  <param type="bool" name="HNL-Majorana"> false </param>

  <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 -->
  <param type="vec-double" name="Near2User_R" delim=";"> 0.0 ; 0.0 ; 0.0 </param>
  <!-- Euler angles, extrinsic x-z-x -->
  <!-- Describes rotation of USER wrt NEAR frame -->
  <param type="vec-double" name="DetCentre_User" delim=";"> 0.0 ; 0.0 ; 0.0 </param> <!-- m -->
  <!-- Position of detector centre in USER frame, in case it is not at USER origin -->
</param_set>
```

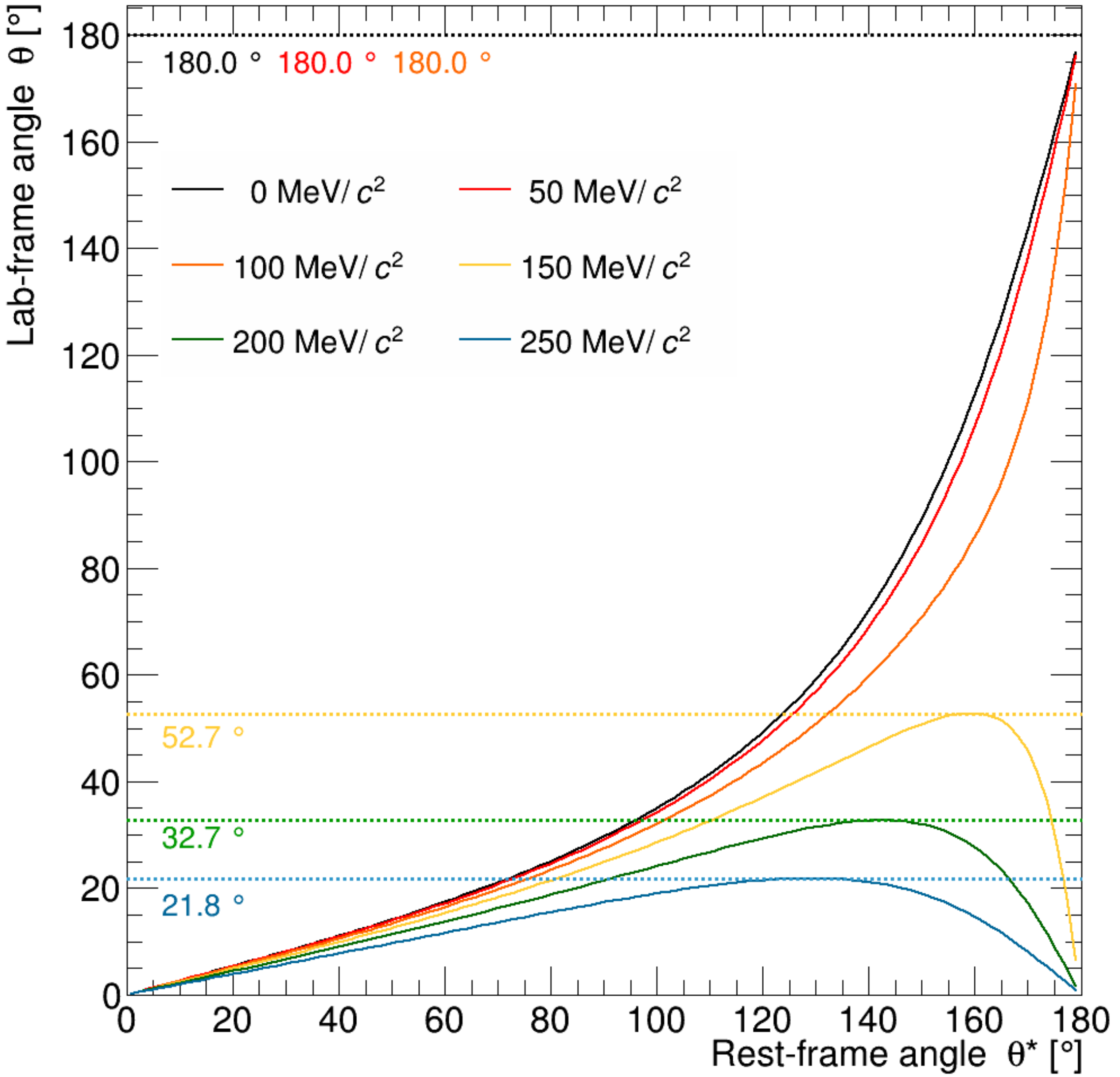
ParameterSpace block: specify what HNL mass / mixings / nature you want

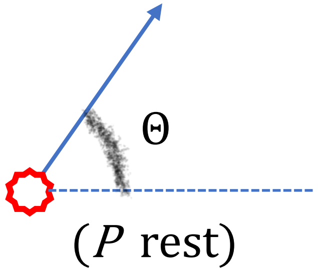

HNL decay products + polarisation
dynamic flux estimation
vertex + timing infor
sensitivity estimate

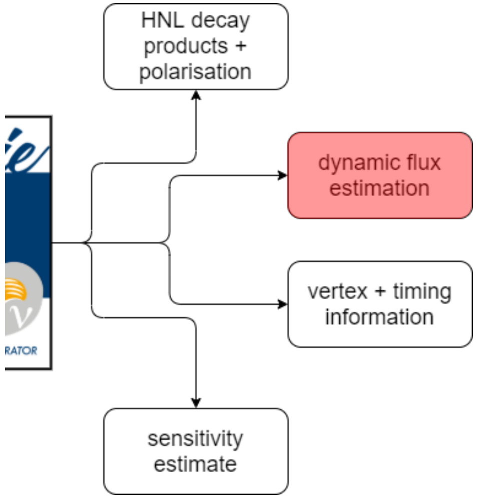

β_P
θ
(lab)

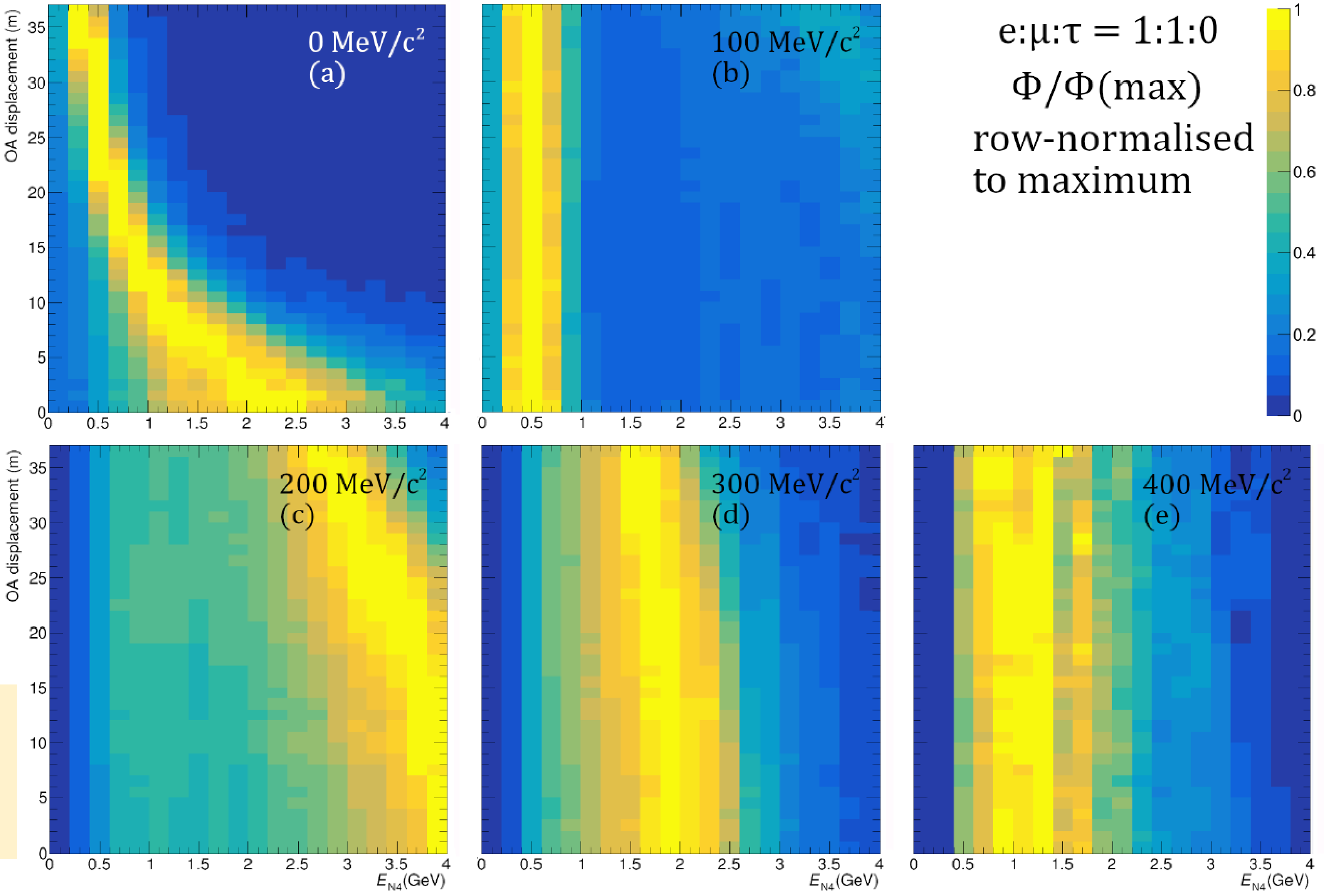
30 MeV


Flux
Flux of HNL crossing detector
(log y axis)
Flux of HNL decaying in detector
(linear y axis)
Flux of HNL crossing detector
Flux of HNL decaying in detector
100 MeV
0 2 4 6 8 10 12 14 16 18 20
E_{N4} (GeV)

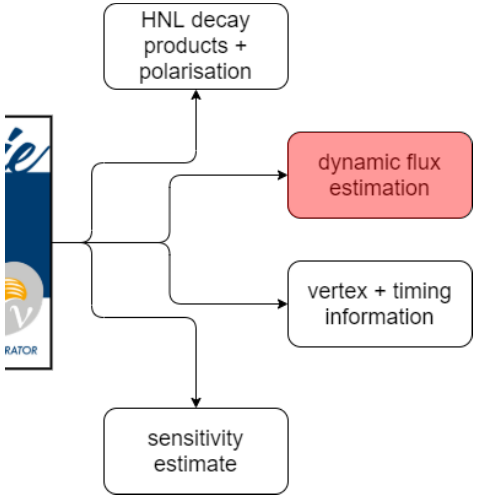

Lab-frame angle θ [°]
180.0 ° 180.0 ° 180.0 °
0 MeV/ c^2
50 MeV/ c^2
100 MeV/ c^2
150 MeV/ c^2
200 MeV/ c^2
250 MeV/ c^2
52.7 °
32.7 °
21.8 °
Rest-frame angle θ* [°]

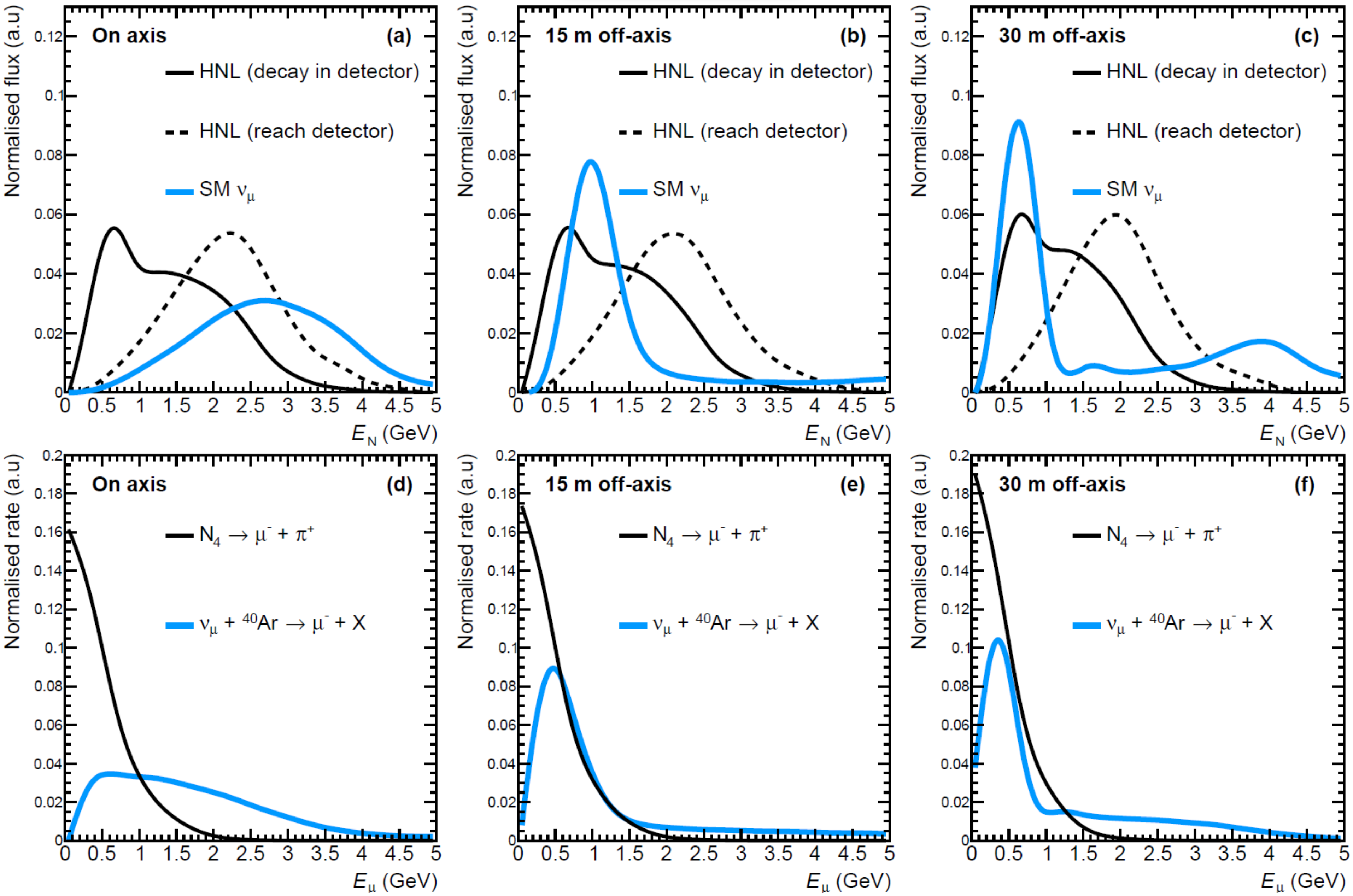

Θ
(P rest)





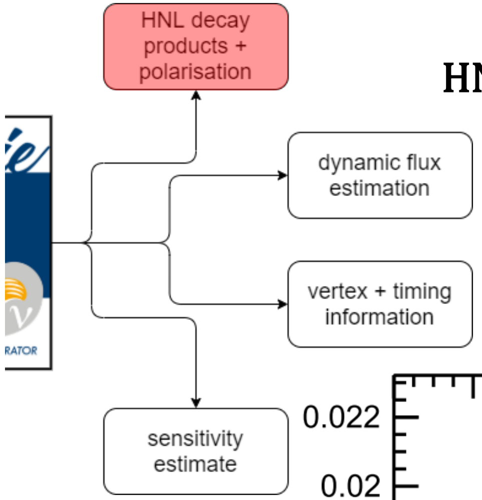
OA effect weakens most close to threshold (panels b, e): **heavier HNL are slower.**



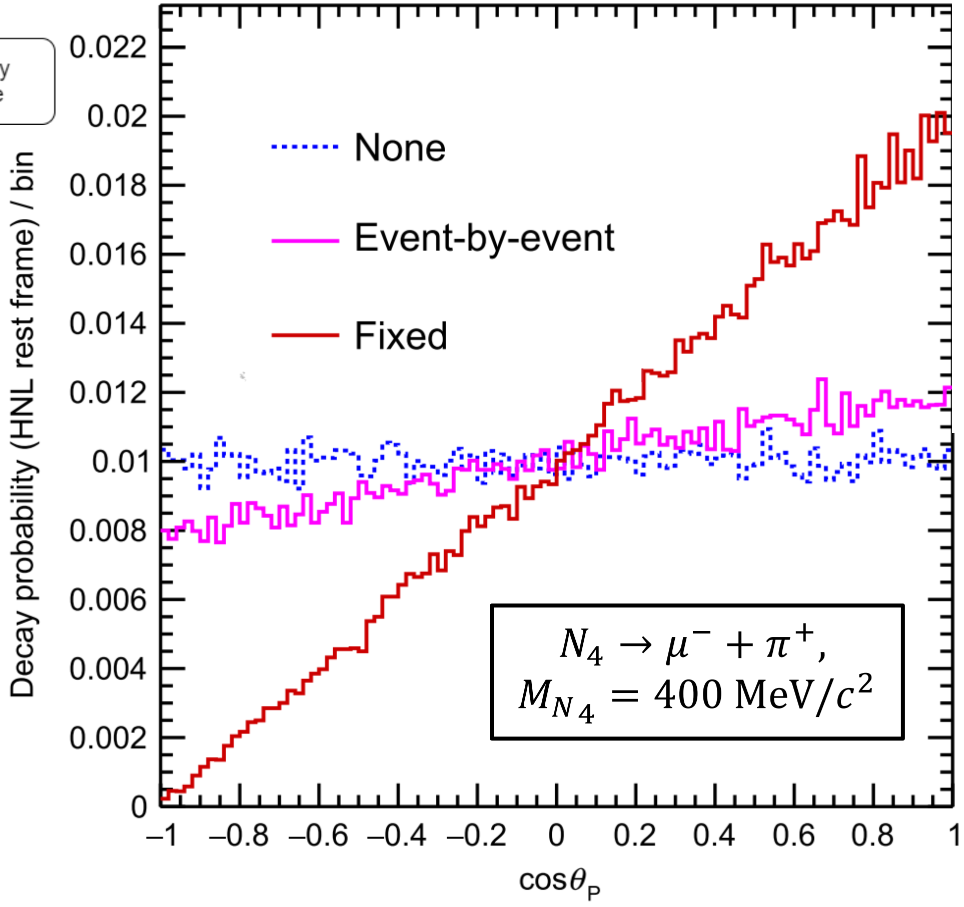


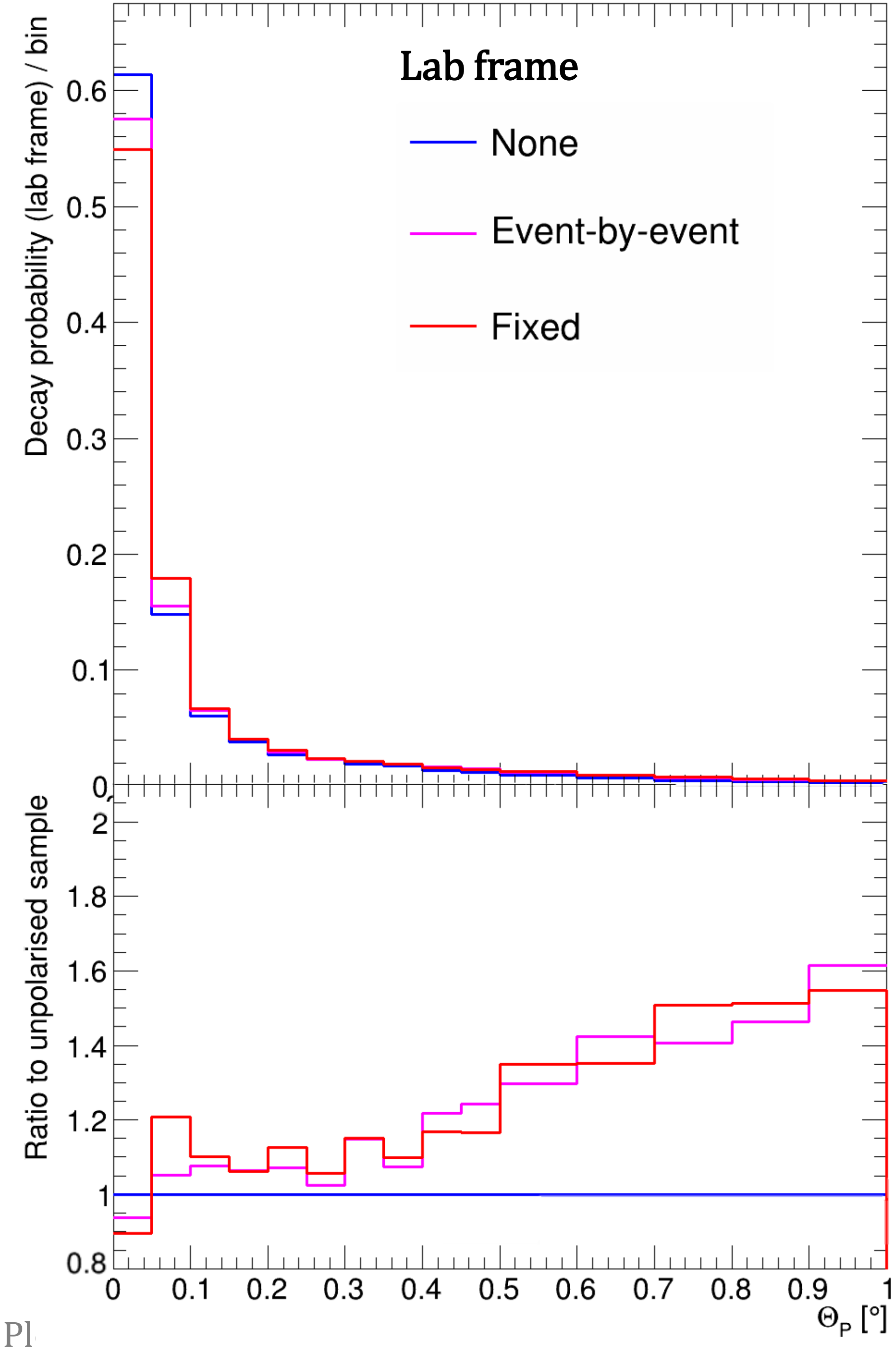
$M_{N4} = 300\ \mathrm{MeV}/c^2$

Bkg: GENIE v3.02.00
tune G18_02a_00_000

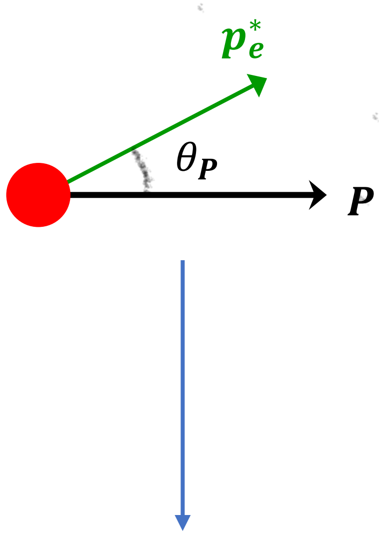


HNL rest frame

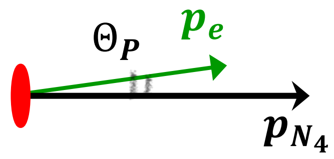




HNL rest frame



Lab frame



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

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

Theory input handled through xml files in dedicated HNL tune directory

```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>
```

```xml
<!-- 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

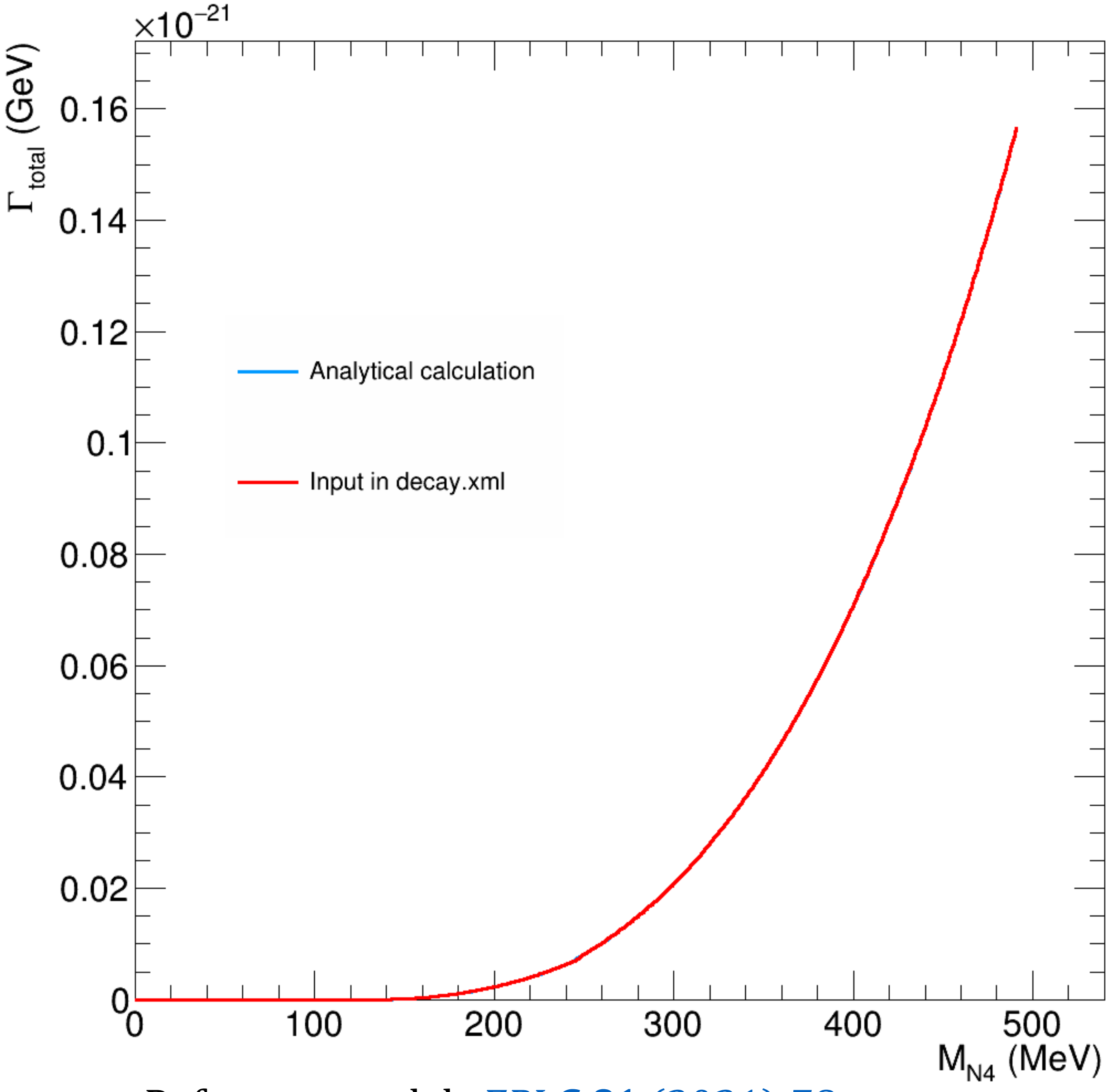
Theory input handled through xml files in dedicated HNL tune directory

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

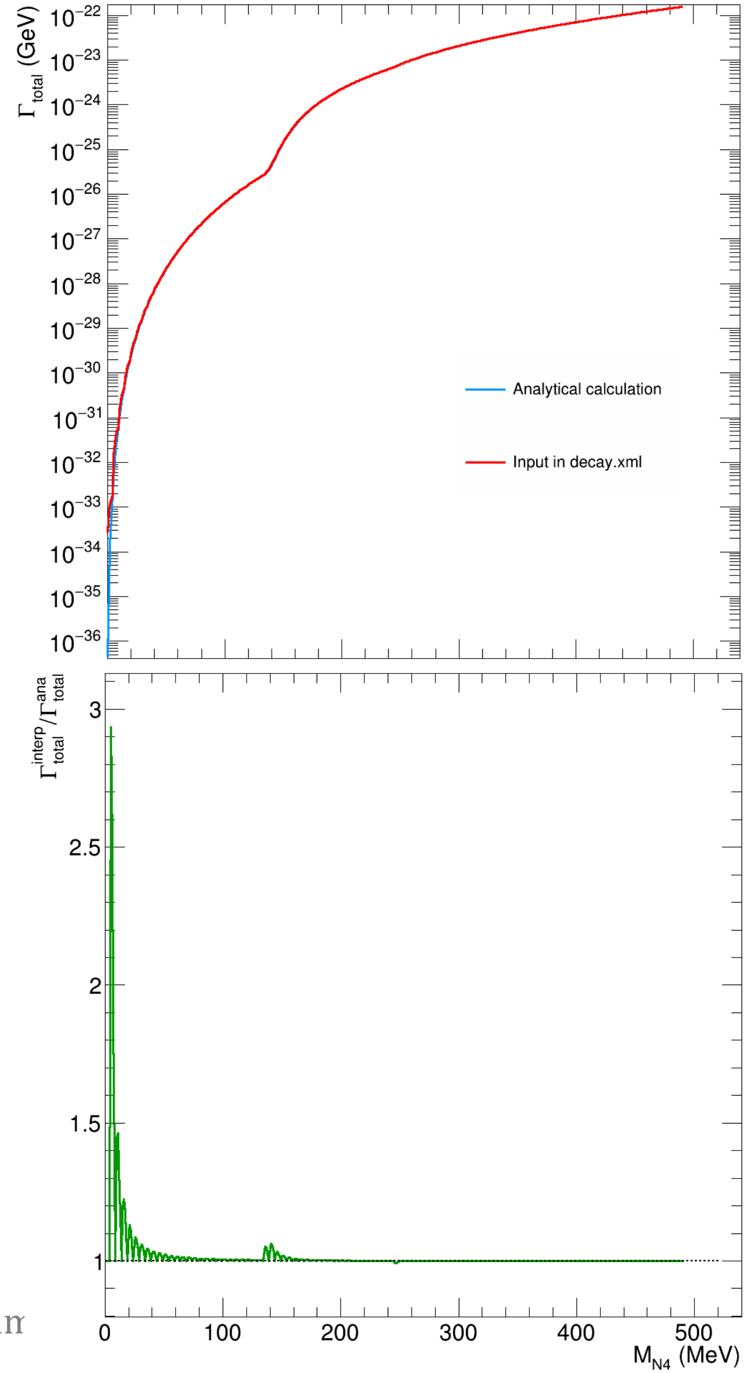
Specify a desired mass partition and the decay width of each component at $|U_{\ell 4}|^2 = 1, \ell = e, \mu, \tau$
Specify scaling behaviour as a TFormula

Group components into `decayChannel` objects in xml file

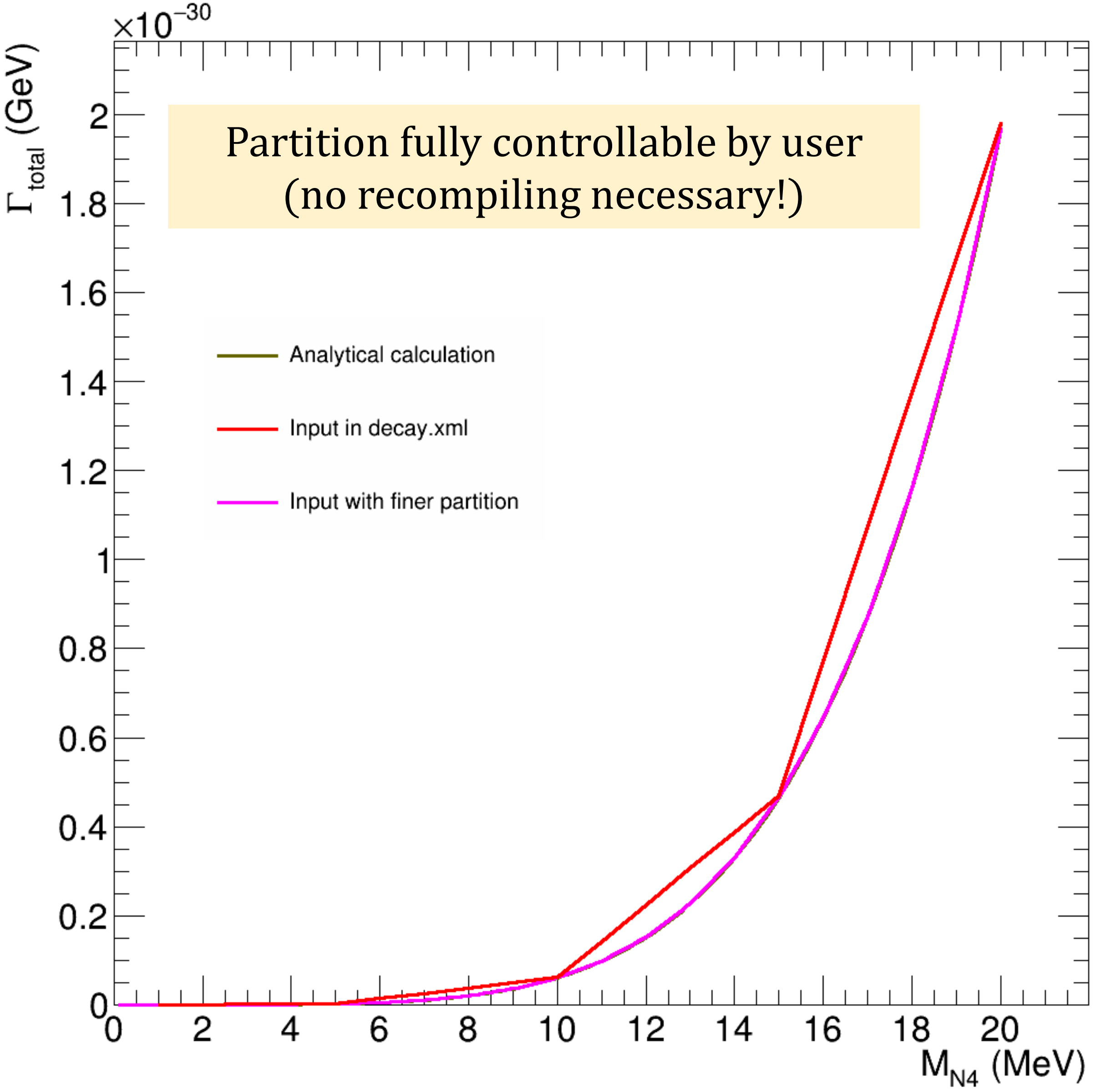
```
<!-- N4 -> v v v -->
<decayChannel name="nu_nu_nu">
  <param type="vec-double" name="Rates_0" delim=";">
    0.000       ; 2.14224e-25 ; 6.8558e-24  ; 5.20612e-23 ; 2.19386e-22 ; <!-- 0 - 20 -->
    6.69511e-22 ; 1.66596e-21 ; 3.60079e-21 ; 7.02034e-21 ; 1.26509e-20 ;
    2.14224e-20 ; 3.45042e-20 ; 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>
```

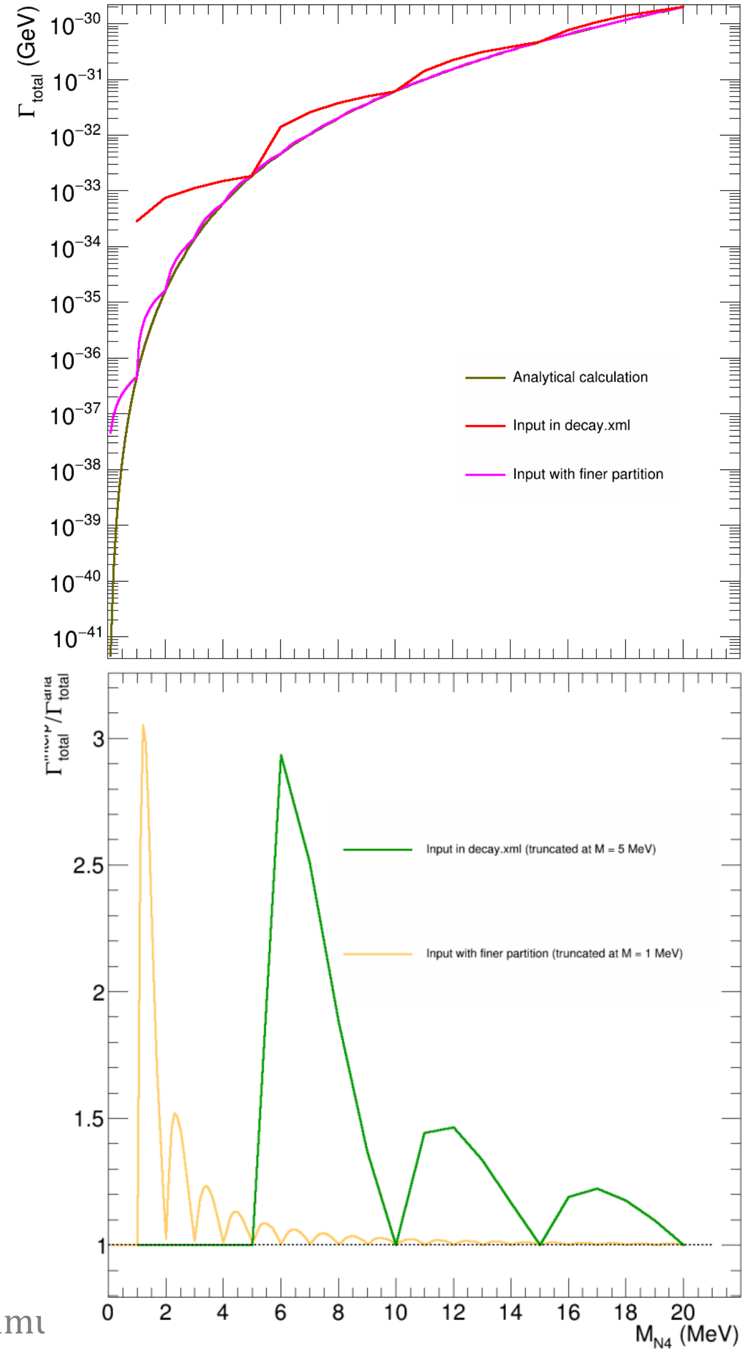


Reference model: [*EPJ C* **81** (2021) 78](https://doi.org/)

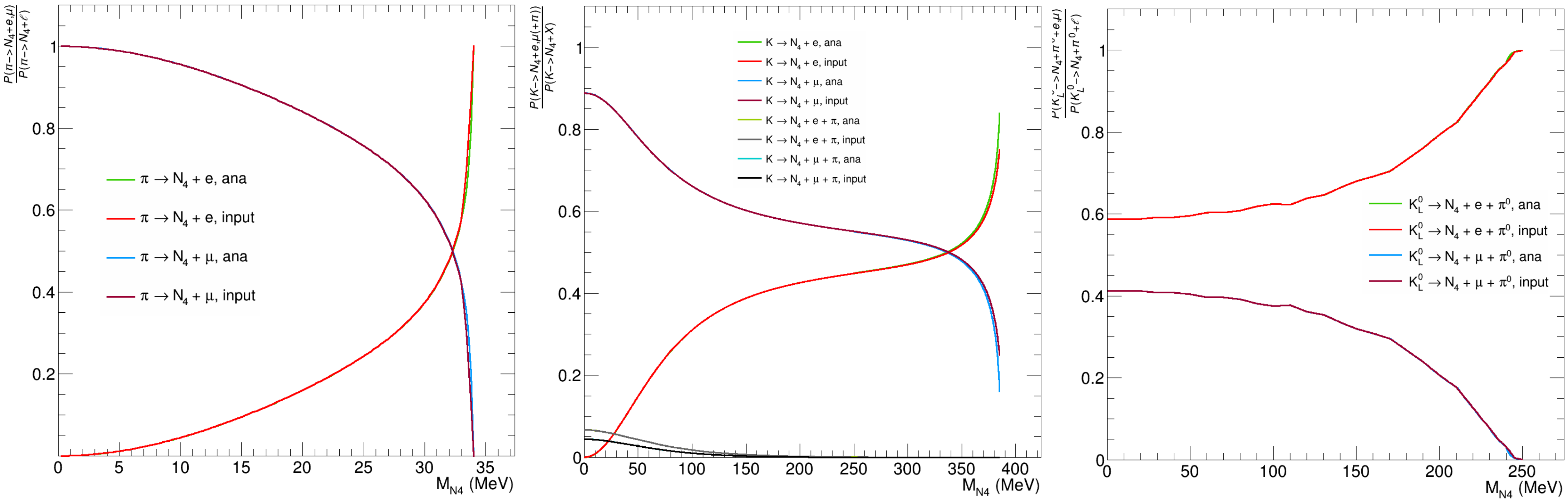


Partition fully controllable by user
(no recompiling necessary!)





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