Beam-produced Heavy Neutral Lepton simulation in GENIE

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International School of Nuclear Physics, 43rd Course: Neutrinos in Cosmology, in Astro-, Particle- and Nuclear Physics

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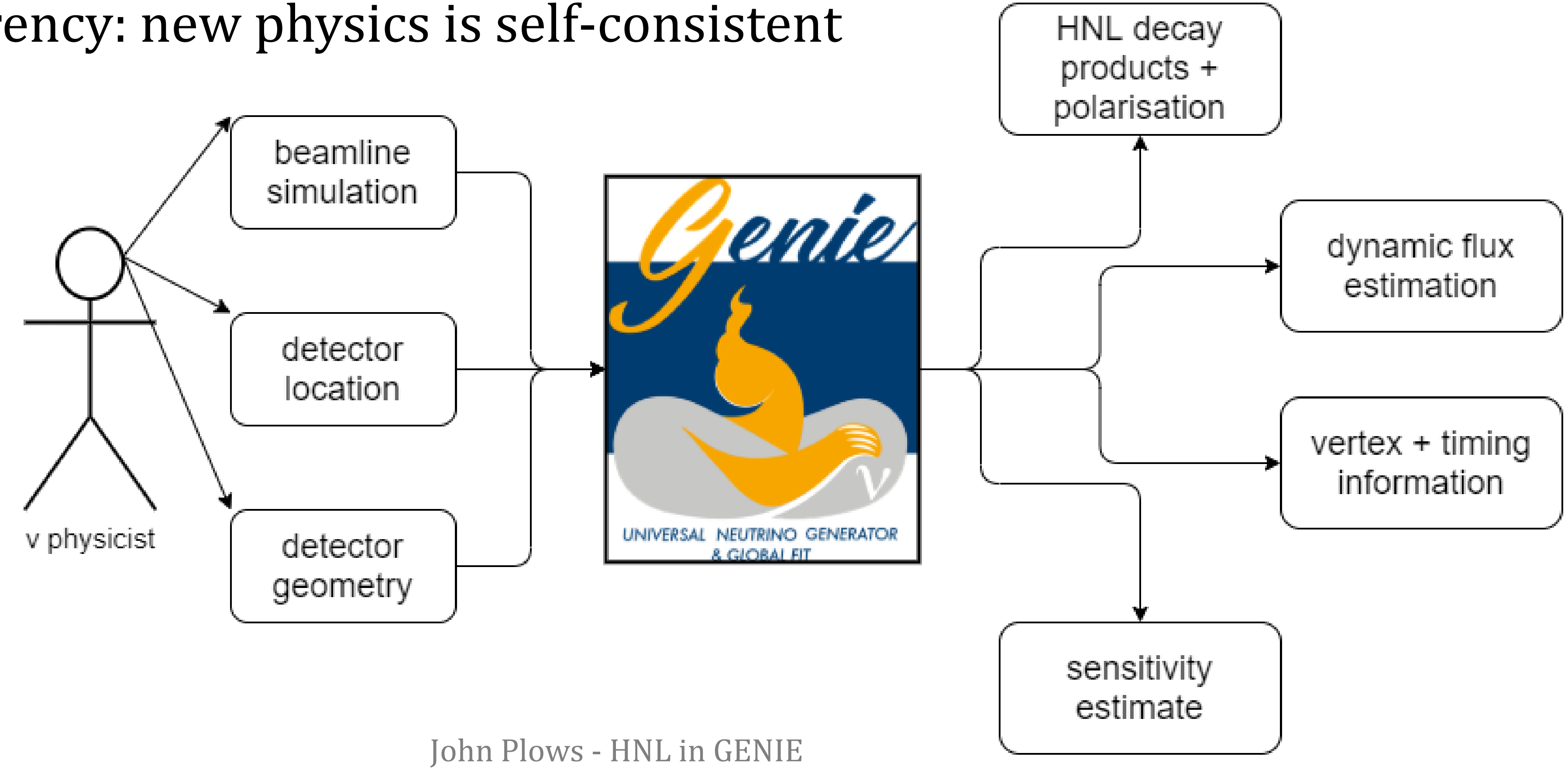
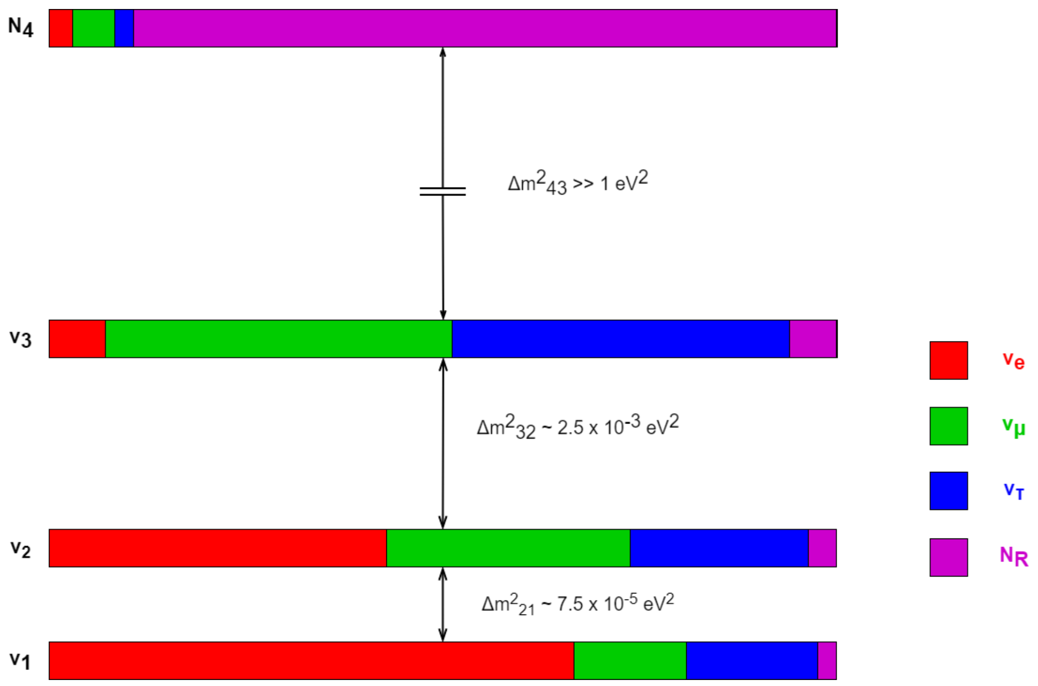
- Implement HNL into GENIE v3 event generator
- Goals:
  1. User flexibility: ease of use and integration with simulation
  2. Generality: for use with many beamlines, detectors
  3. Transparency: new physics is self-consistent



What are HNL?

also see talks by
Daniel Siegmann
Anatael Cabrera
Baha Balantekin
and others!

- Naturally motivated extension to Standard Model
  - Light neutrinos $\nu_{1,2,3}$ have at least 2 non-zero masses
  - 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: mass eigenstates of mass $\mathcal{O}(\leq \text{TeV}/c^2)$
  - Can explain:
    - Active neutrino mass!
    - Dark matter candidate!
    - Matter-antimatter asymmetry!

    (see *Phys. Lett.* ***B*** **631** (2005) 4, *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 *Phys. Rev. D* **100** (2019) 052006
  - Parameter space: $\left\{M_{N_4}, |U_{e4}|^2, |U_{\mu4}|^2, |U_{\tau4}|^2\right\} \equiv \{M_{N_4}, |U_{\alpha4}|^2\}$

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

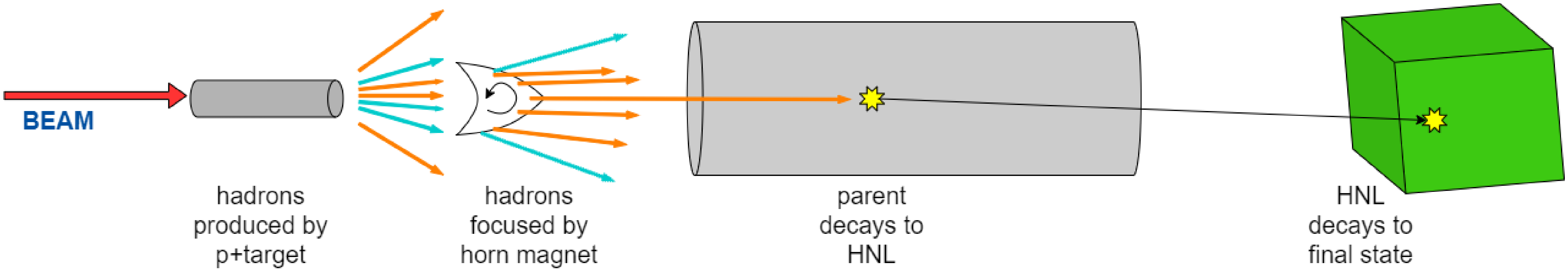
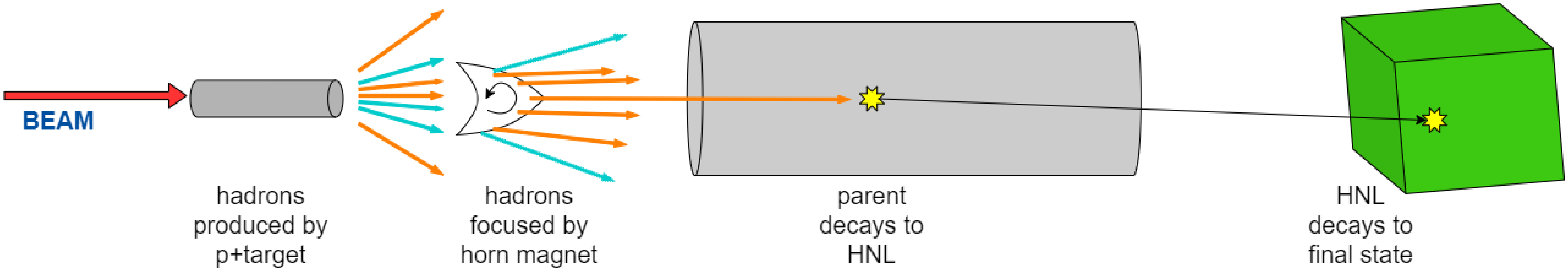
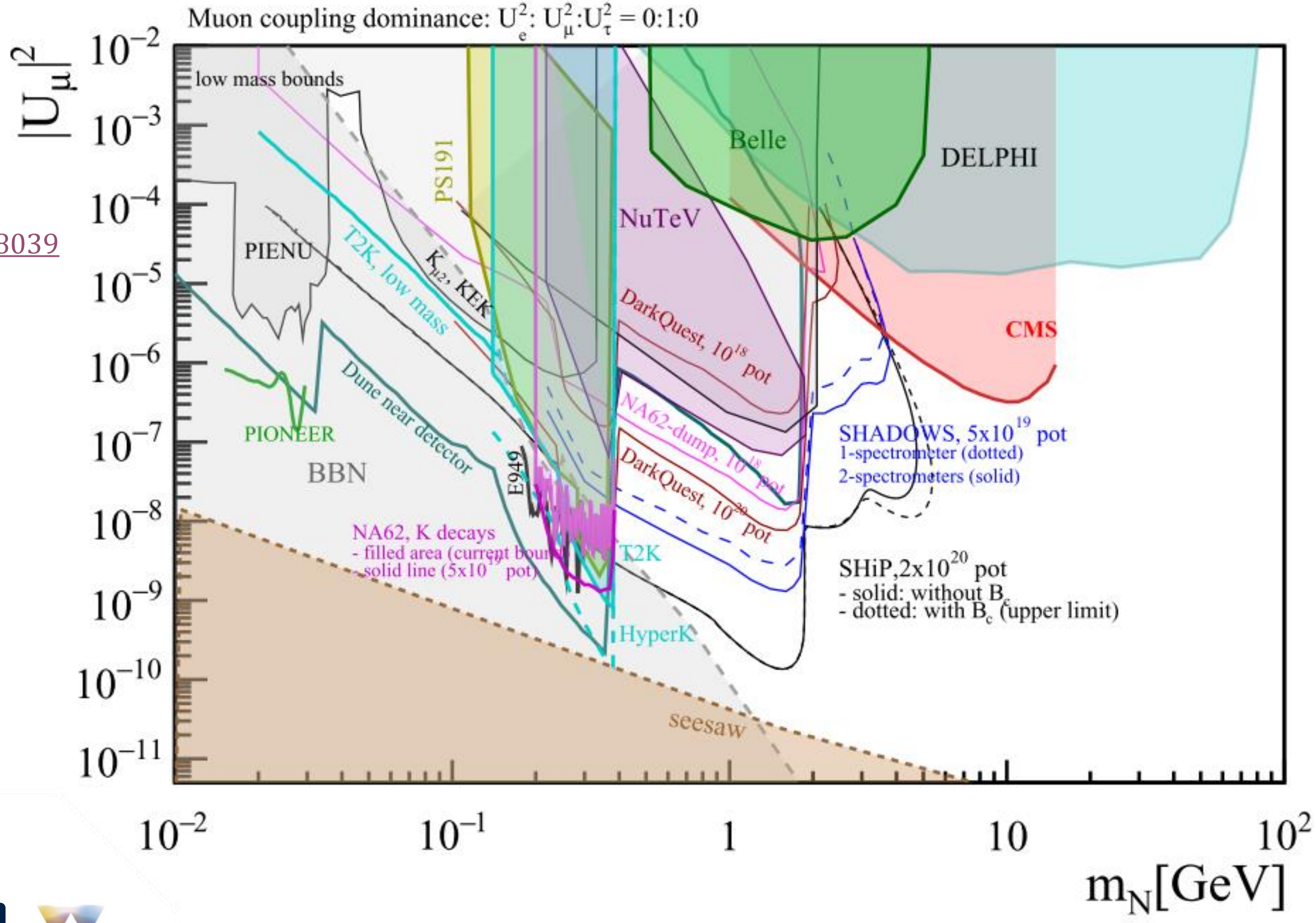


Table 1: Summary of the fixed-target searches for Heavy Neutral Leptons considered throughout Section 5.

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



arXiv: 2203.08039 [hep-ph]



```
|------------------------------------------------------------------------------------------------------------------|
|GENIE GHEP Event Record [print level:   3]                                                                         |
|------------------------------------------------------------------------------------------------------------------|
| Idx |          Name | Ist |        PDG |   Mother  | Daughter  |      Px |      Py |      Pz |       E |       m  |
|------------------------------------------------------------------------------------------------------------------|
|   0 |           HNL |   0 | 2000020000 |  -1 |  -1 |   2 |   1 |  -0.008 |  -0.294 |   4.931 |   4.949 |   0.300 |
|   1 |           pi+ |   1 |        211 |   0 |  -1 |  -1 |  -1 |  -0.089 |  -0.145 |   2.484 |   2.494 |   0.140 |
|   2 |           mu- |   1 |         13 |   0 |  -1 |  -1 |  -1 |   0.081 |  -0.149 |   2.448 |   2.456 |   0.106 |
|------------------------------------------------------------------------------------------------------------------|
|       Fin-Init:                                                  |  -0.000 |  -0.000 |   0.000 |   0.000 |           |
|------------------------------------------------------------------------------------------------------------------|
|       Vertex:            HNL @ (x =    -0.36245 m, y =    -0.42615 m, z =      5.54270 m, t =    3.689499e-09 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 =             0.00286 |
|------------------------------------------------------------------------------------------------------------------|
```

4 main physics points:

1. Production of initial state using dynamic flux prediction
2. Production of (signal) final state
3. Decay vertex assignment
4. Calculation of POT for signal event

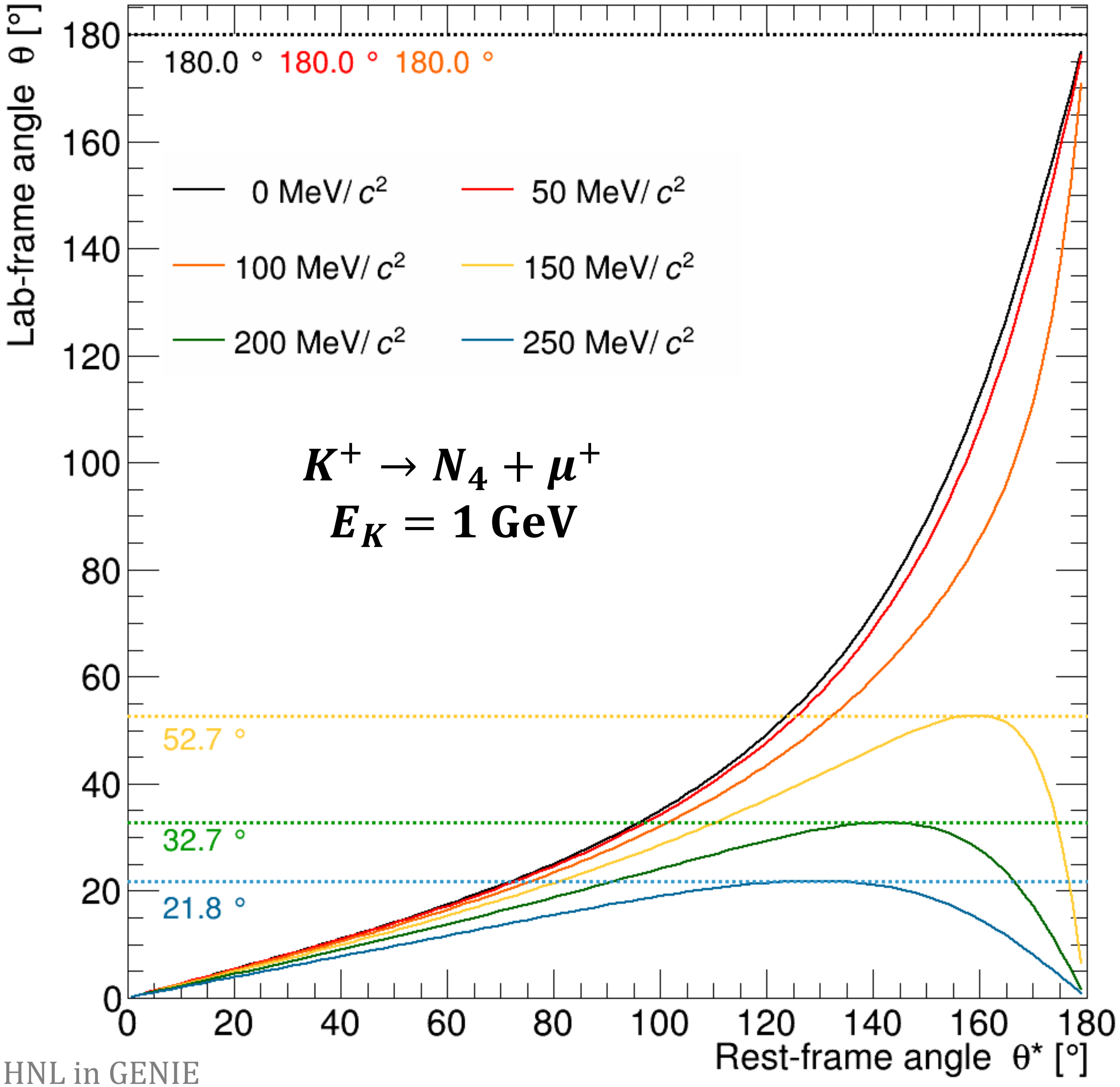
Production in beamline

- Assume all parents decay to HNL, $\sum_\alpha |U_{\alpha 4}|^2 = 1$

- Calculate kinematics under constraint: $\boldsymbol{p}_{N_4}$ intersects detector ⇒ probability of emission in suitable angular region: P_E

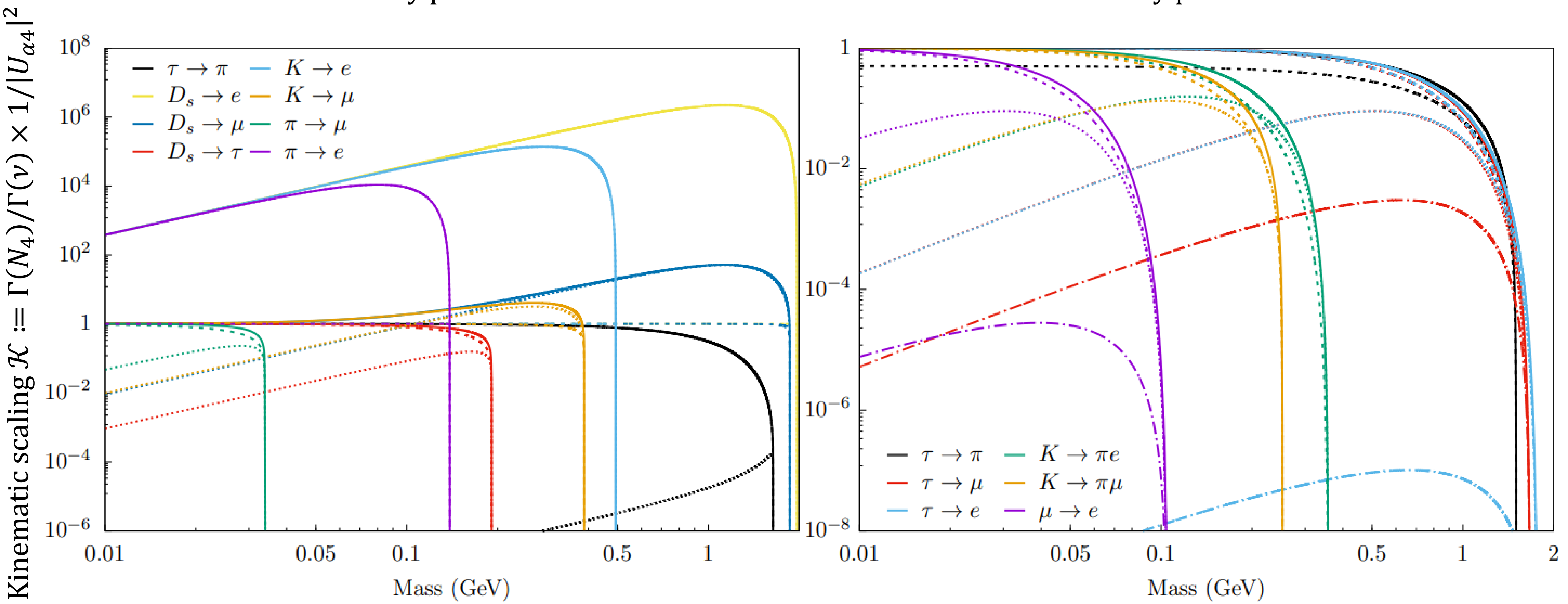
- Account for collimation effect:

  Lorentz boost more efficient



2-body production

3-body production



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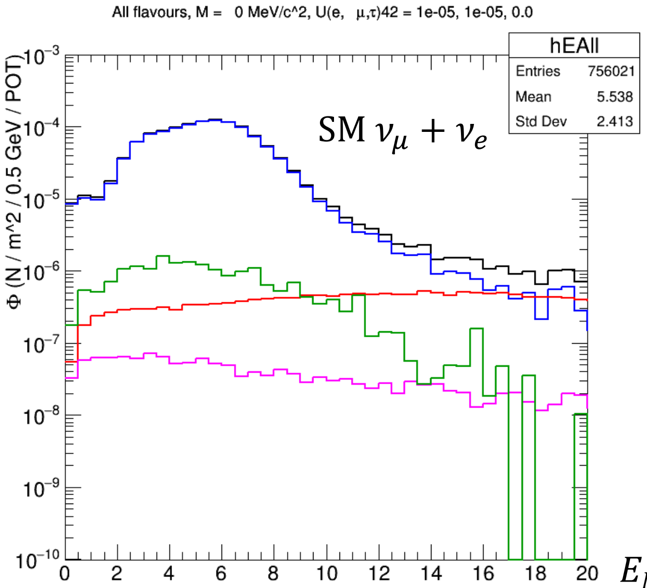
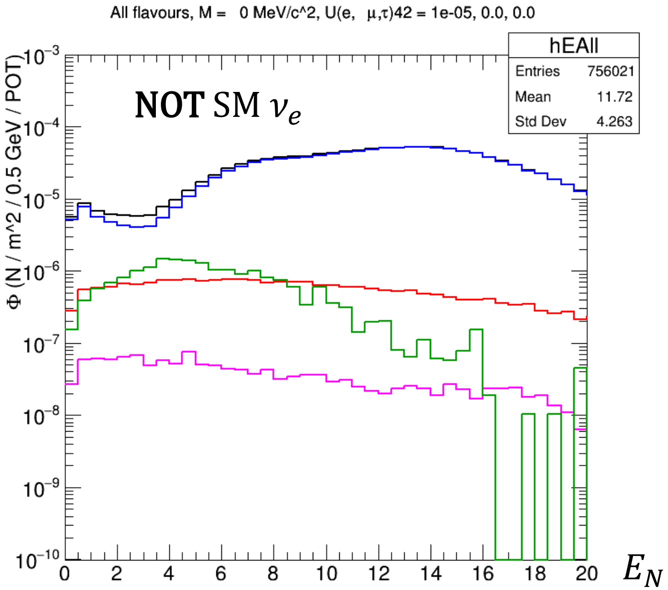
$$|U_{e4}|^2 : |U_{\mu 4}|^2 = 1:1$$

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

$M_N = 0\ \mathrm{MeV}/c^2$



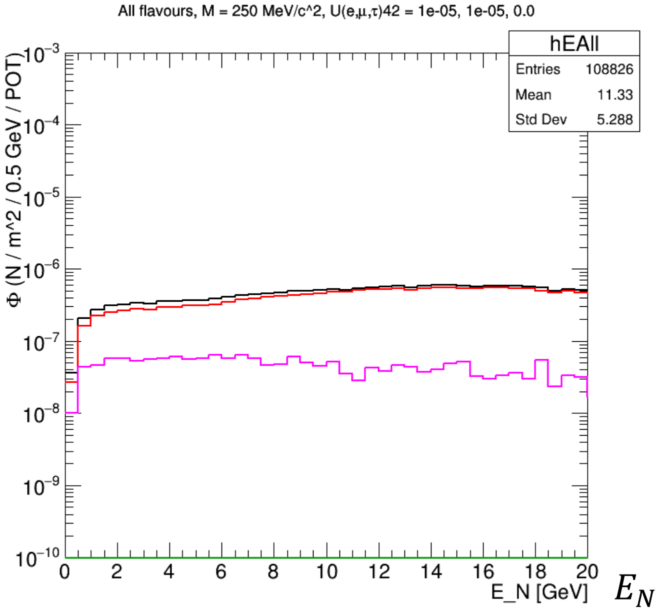


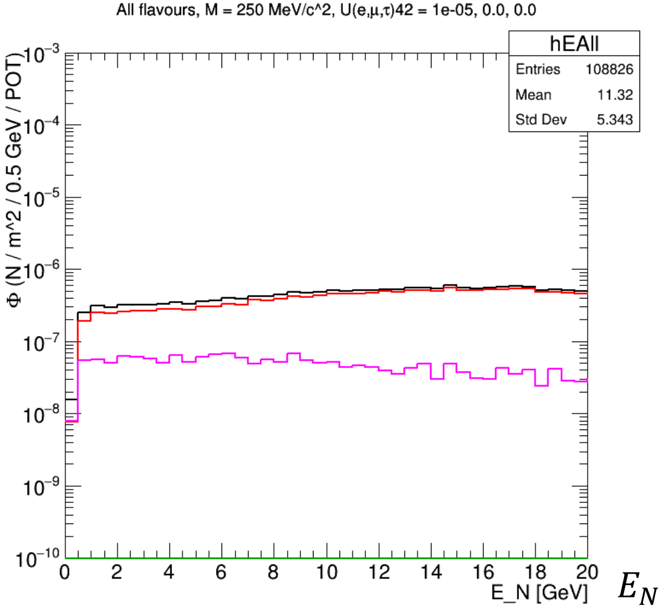
Flux spectra at MINERvA

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

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

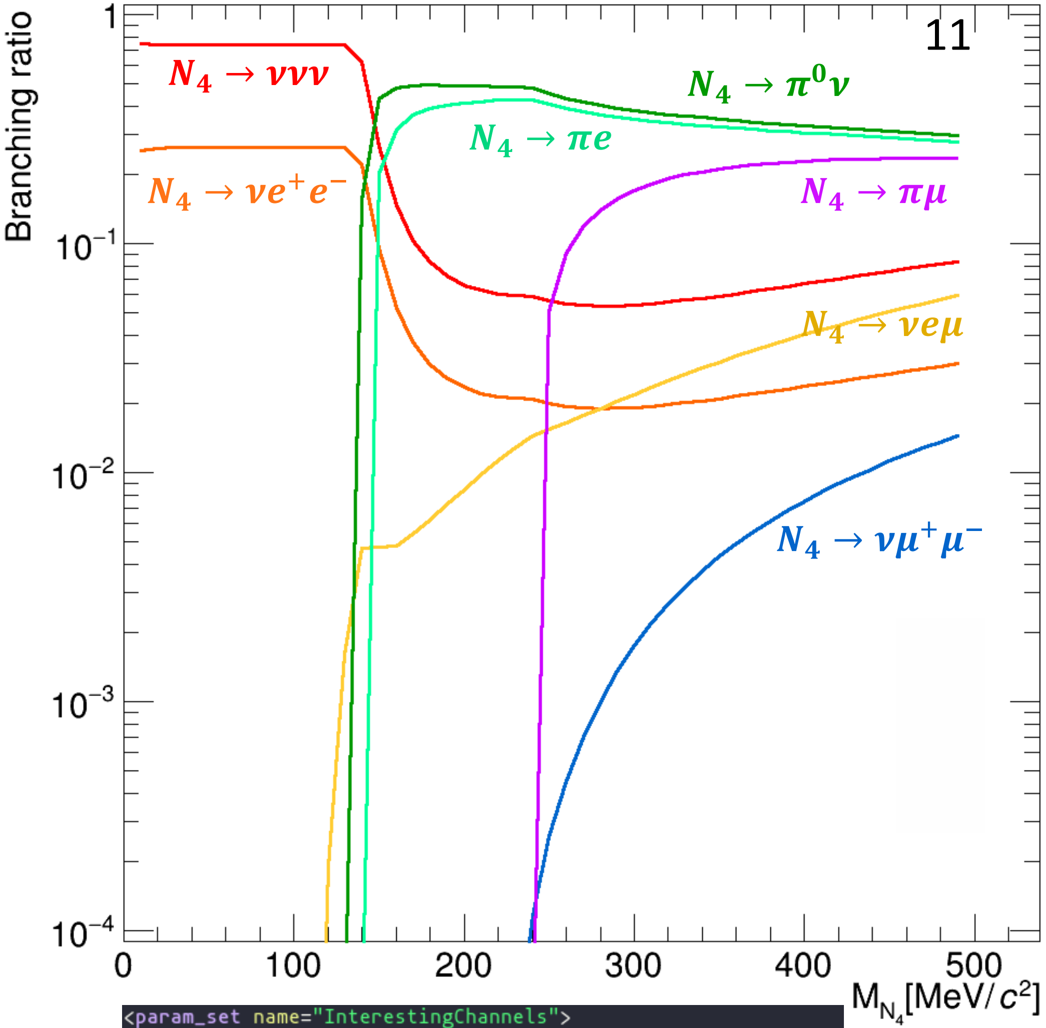
$M_N = 250\ \mathrm{MeV}/c^2$





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

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



- Polarisation reweighting: by spin conservation

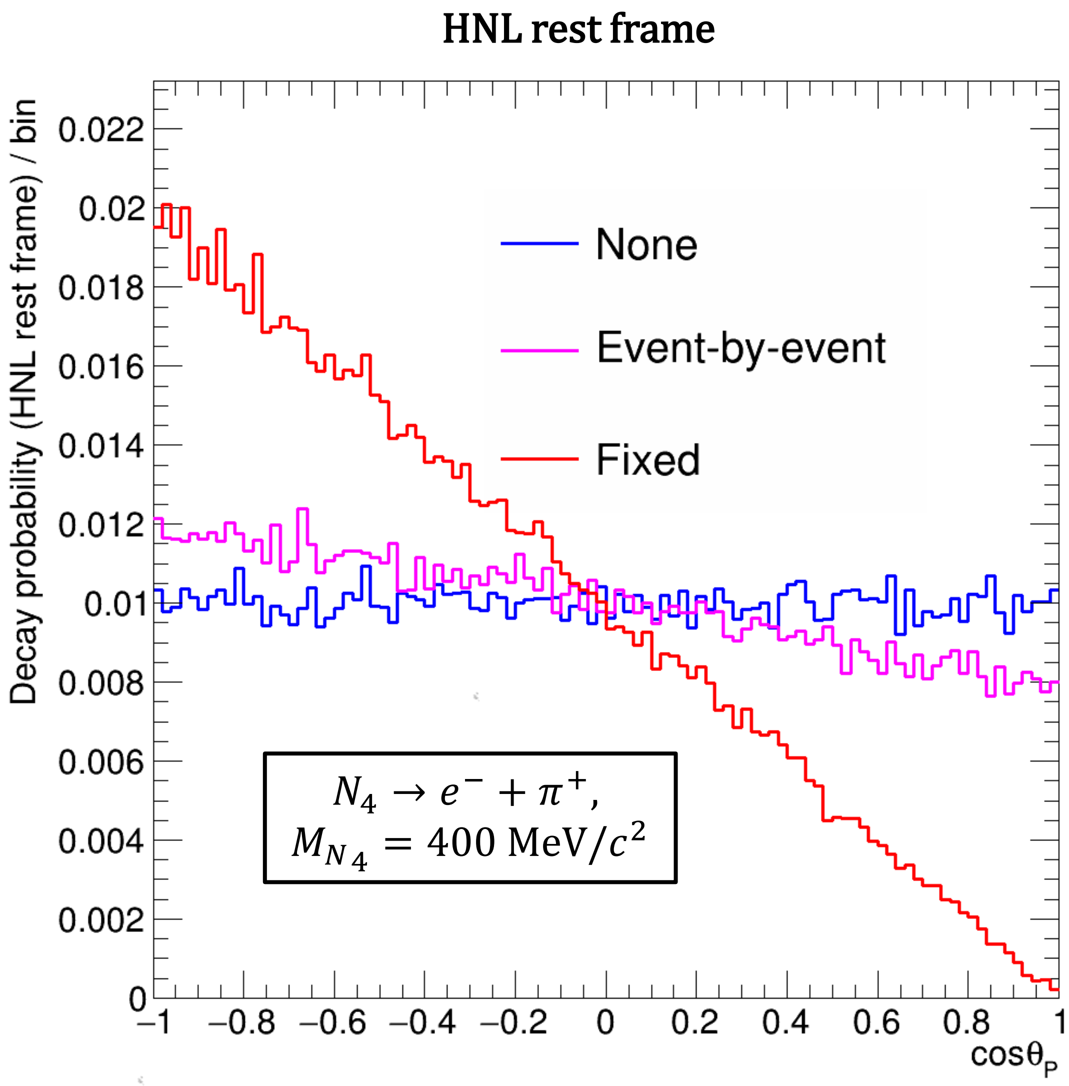
$-$: N_4, $+$: $\bar{N}_4$. Cancels out for Majorana HNL

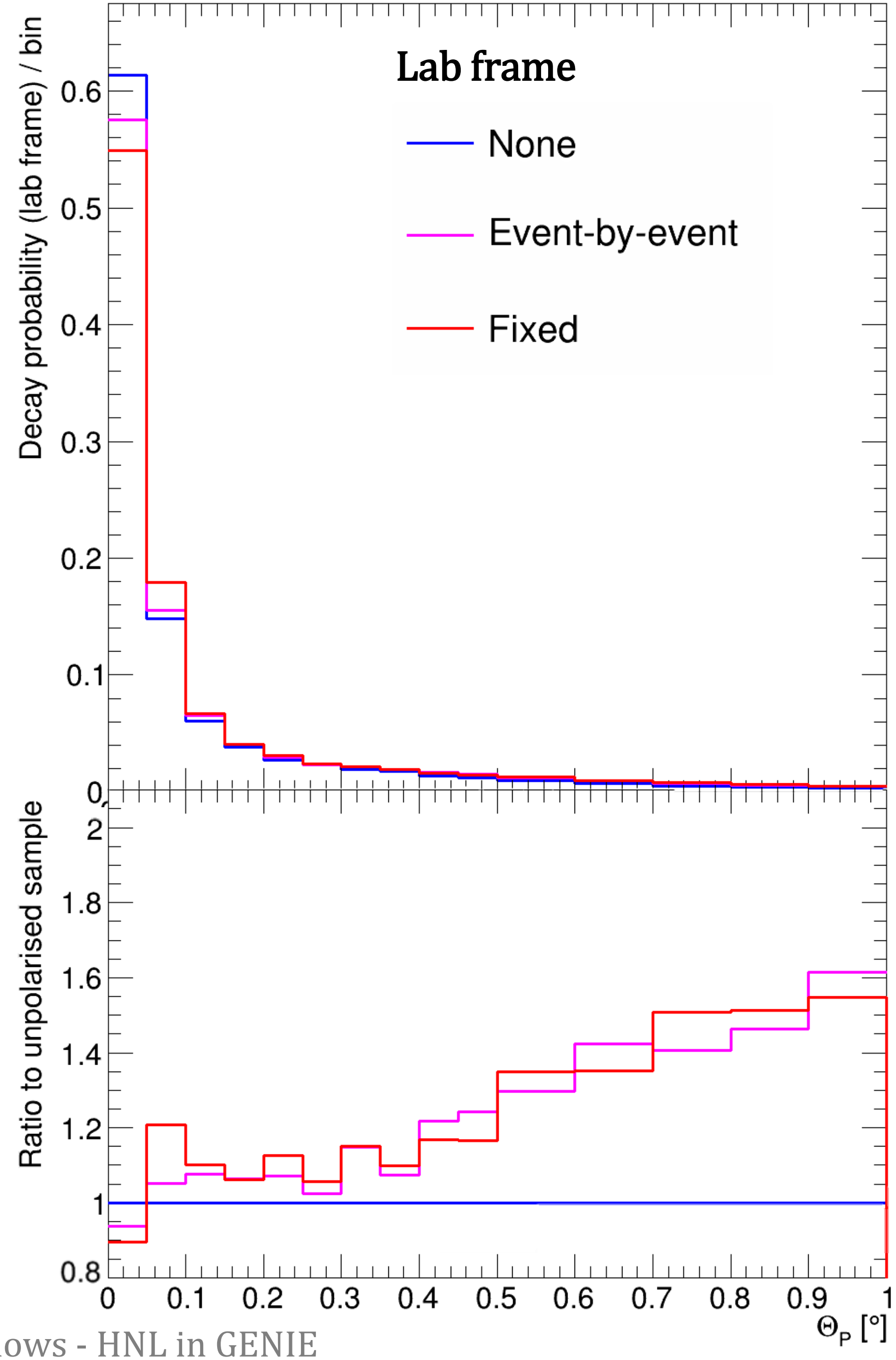
$$\frac{d\Gamma}{d\cos\theta_{\boldsymbol{P}}} \propto 1 \mp \hbar \cdot \cos\theta_{\boldsymbol{P}}$$

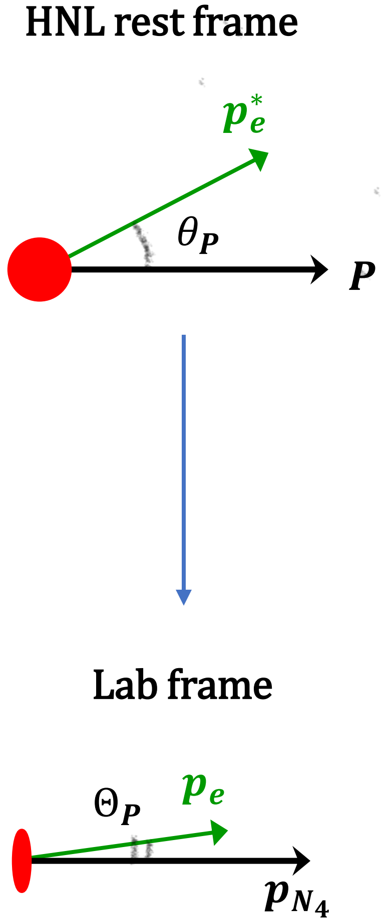
where $\boldsymbol{P}$ is the direction of the polarisation vector in HNL rest frame and $\hbar$ the polarisation modulus (see arXiv: 1805.06419 [hep-ph])

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
Decay probability (HNL rest frame) / bin
None
Event-by-event
Fixed
$N_4 \to e^- + \pi^+$,
$M_{N_4} = 400$ MeV/c^2
cosθ_P

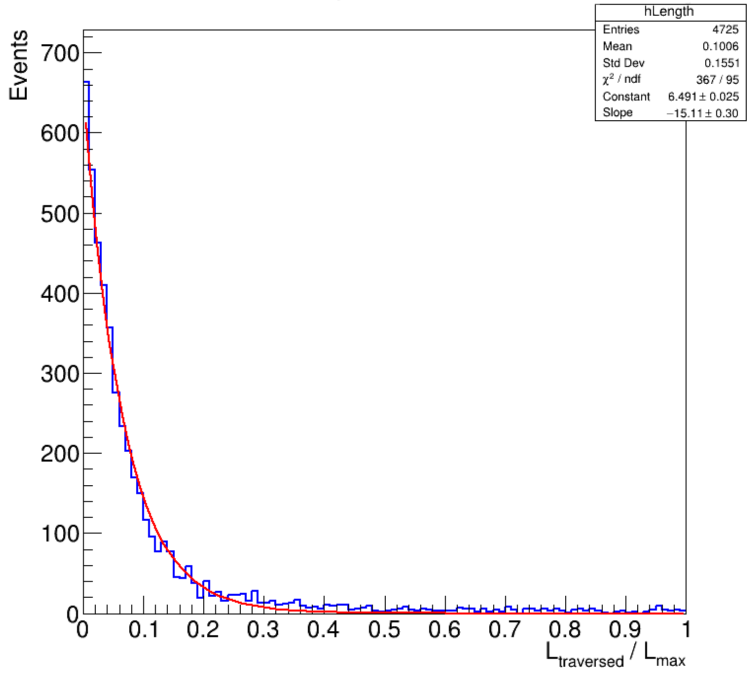

Lab frame
Decay probability (lab frame) / bin
None
Event-by-event
Fixed
Ratio to unpolarised sample
Θ_P [°]

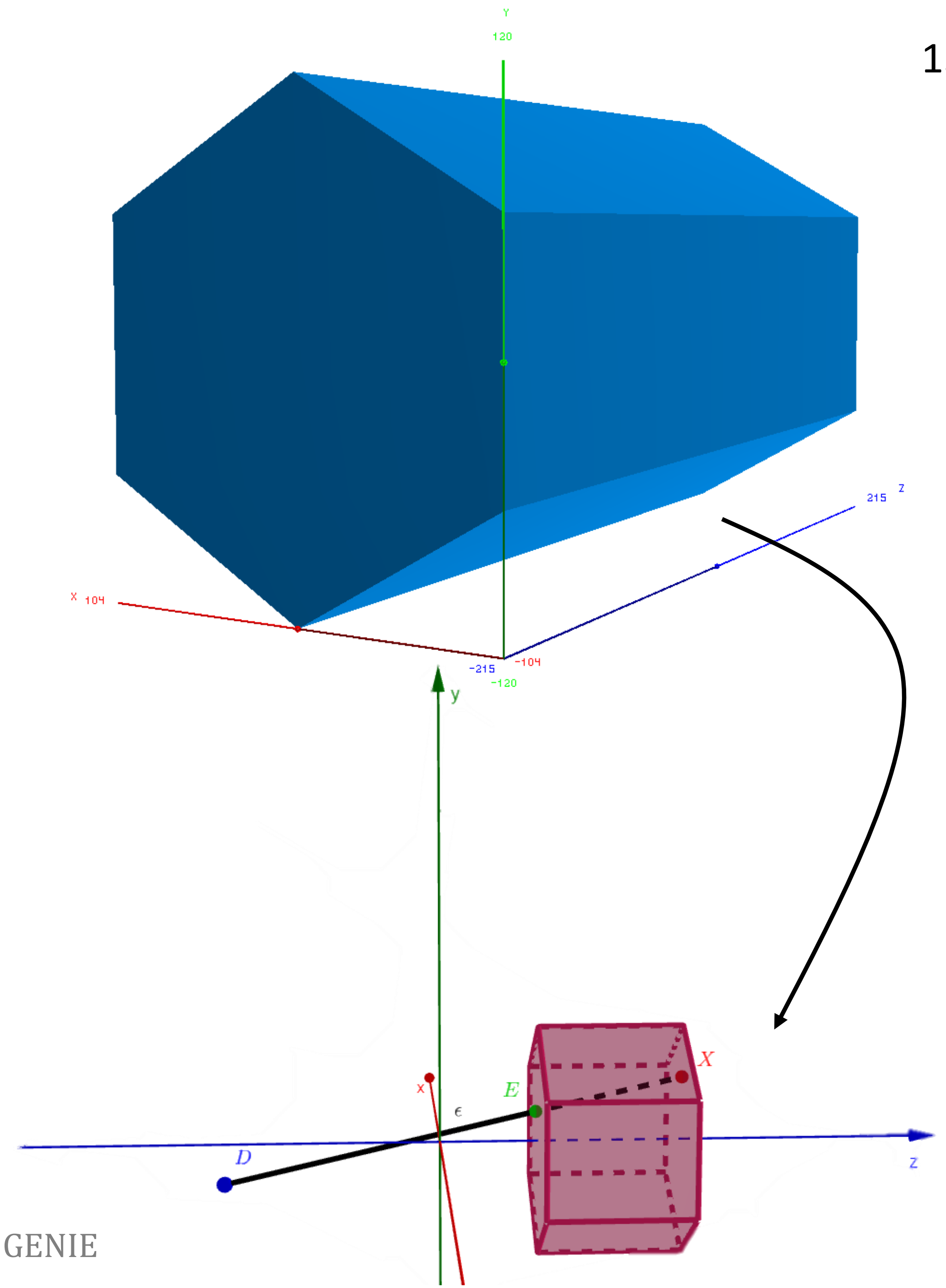

HNL rest frame
p_e^*
θ_P
P
Lab frame
Θ_P
p_e
p_{N_4}

- HNL is produced at point D with momentum $\boldsymbol{p}_{N_4}$ defining a 3D trajectory

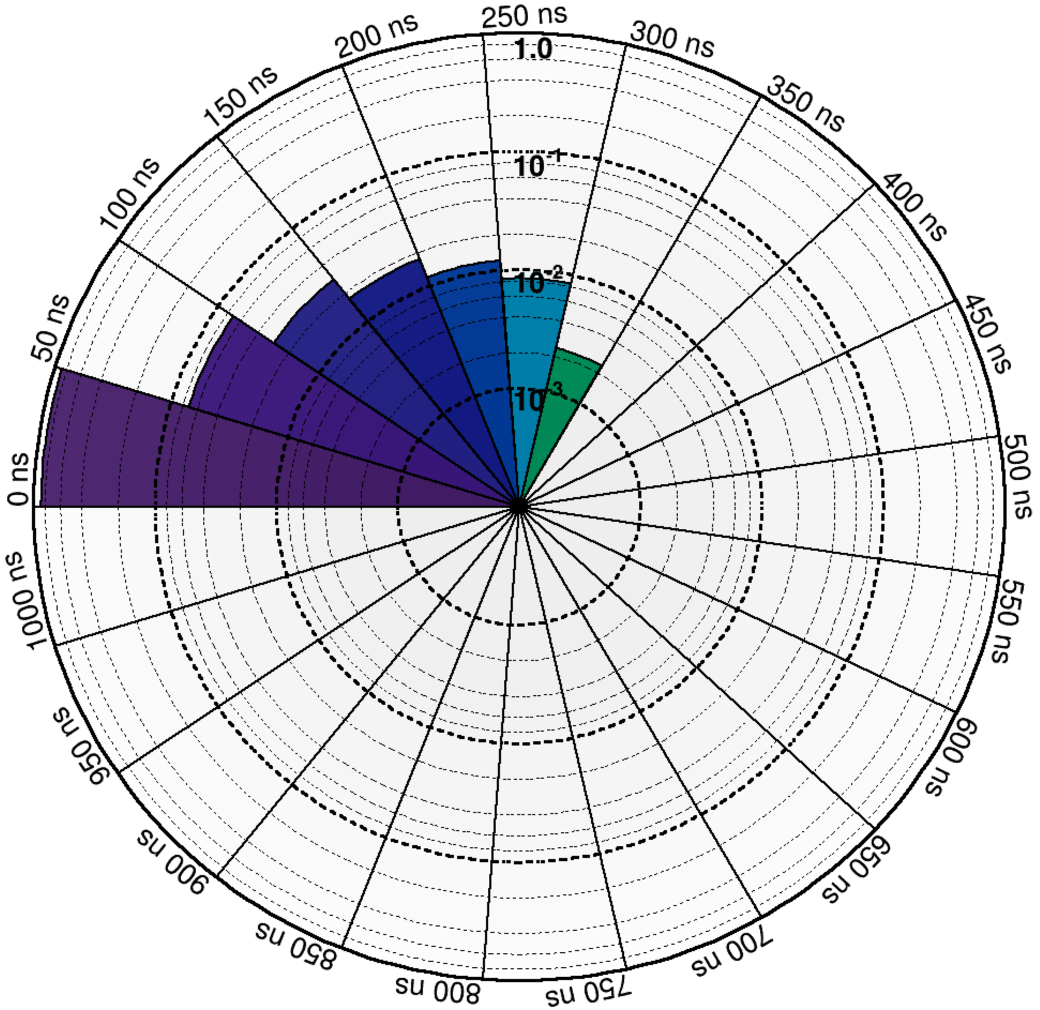
$$\epsilon: \boldsymbol{r}(u) = \boldsymbol{r}_D + u \cdot \boldsymbol{p}_{N_4}$$

- Exponentially decaying distribution in $\ell_{\text{elapsed}} / \ell_{\max}$

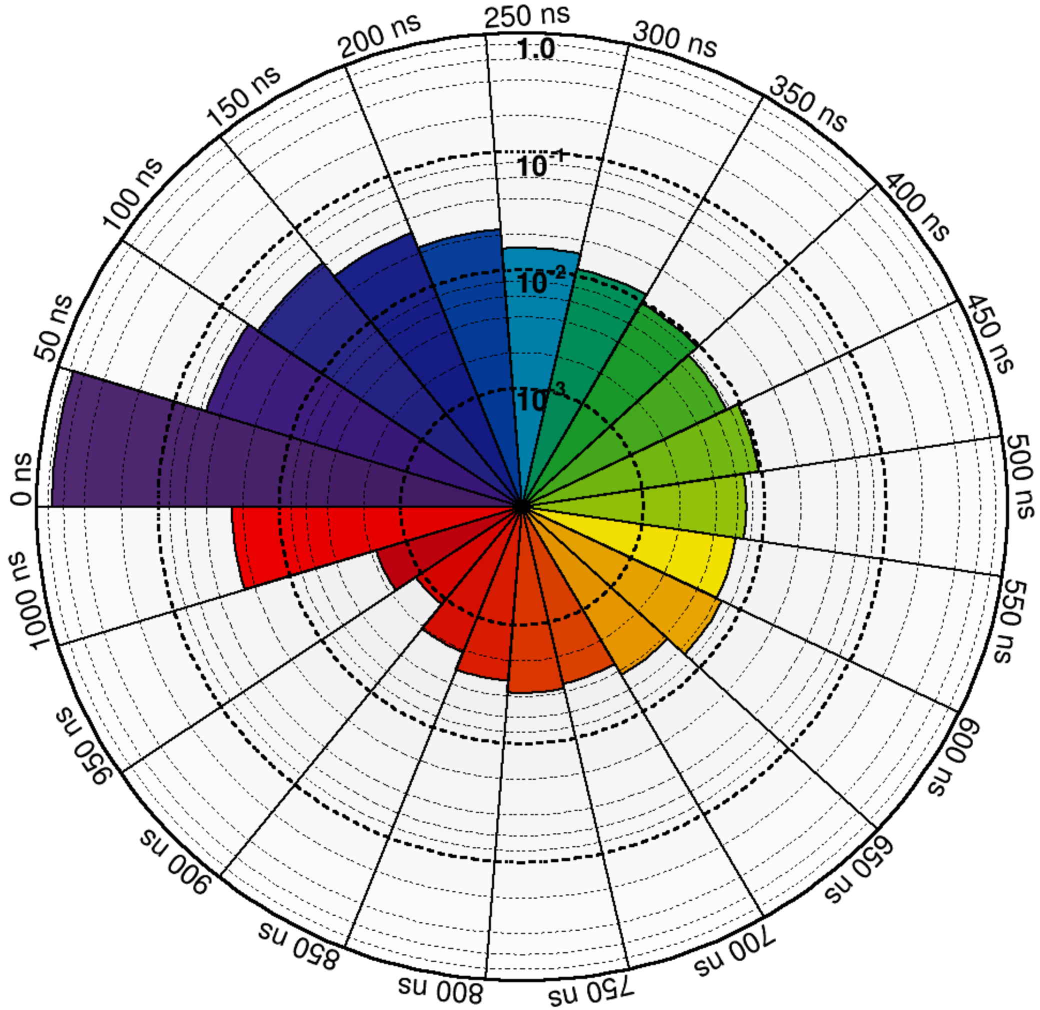




$\Delta t := t_{N_4} - t_\nu$ at MINERνA



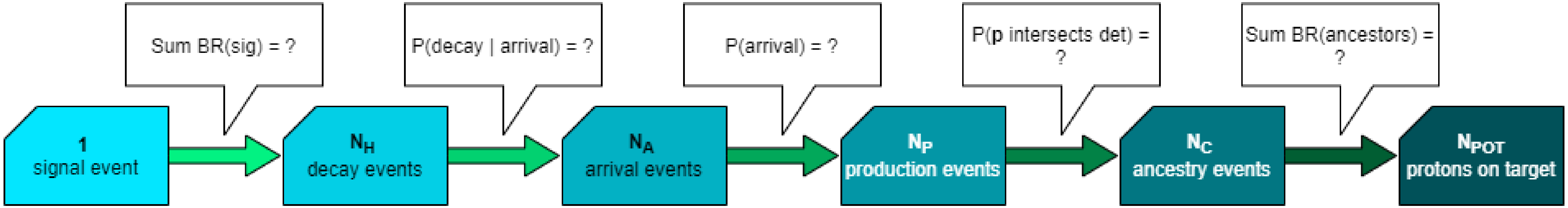
$M_{N_4} = 25\ \mathrm{MeV}/c^2$



$M_{N_4} = 350\ \mathrm{MeV}/c^2$

POT calculation

- A central question: **how many signal events does a detector expect to see?**
  - Cannot calculate *a priori* a $N_{\mathrm{POT}} \mapsto N_{\mathrm{signal}}$ map
- Solution: work our way backwards!




```
|----------------------------------------------------------------------------------------------------------|
|GENIE GHEP Event Record [print level:   3]                                                                |
|----------------------------------------------------------------------------------------------------------|
| Idx |          Name | Ist |        PDG |   Mother  | Daughter  |      Px |      Py |      Pz |       E |      m  |
|----------------------------------------------------------------------------------------------------------|
|   0 |           HNL |   0 | 2000020000 |  -1 |  -1 |   2 |   1 |  -0.008 |  -0.294 |   4.931 |   4.949 |   0.300 |
|   1 |           pi+ |   1 |        211 |   0 |  -1 |  -1 |  -1 |  -0.089 |  -0.145 |   2.484 |   2.494 |   0.140 |
|   2 |           mu- |   1 |         13 |   0 |  -1 |  -1 |  -1 |   0.081 |  -0.149 |   2.448 |   2.456 |   0.106 |
|----------------------------------------------------------------------------------------------------------|
|       Fin-Init:                                                 |  -0.000 |  -0.000 |   0.000 |   0.000 |         |
|----------------------------------------------------------------------------------------------------------|
|       Vertex:             HNL @ (x =    -0.36245 m, y =    -0.42615 m, z =     5.54270 m, t =    3.689499e-09 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 =          0.00286 |
|----------------------------------------------------------------------------------------------------------|
```

e.g. this 300 MeV/c^2 HNL with $|U_{e4}|^2 = |U_{\mu 4}|^2 = 10^{-7}$ took 2.86×10^{17} POT to make

Future directions

- The module is quite general, built for wide variety of use cases
- Pull request already open on Github

Publication in preparation!

- Can still expand utility of module!
  1. Include heavier parents (such as D, D_s) and decay channels $\Rightarrow$ increase valid mass range
  2. Polarisation for 3-body decays (see for example *Phys. Rev. D* **105** (2022) 015019)
  3. Support for multiple Lagrangians? (user-input decay widths?)
- + always open to suggestions and comments! :-)

Backup

How are HNL made?

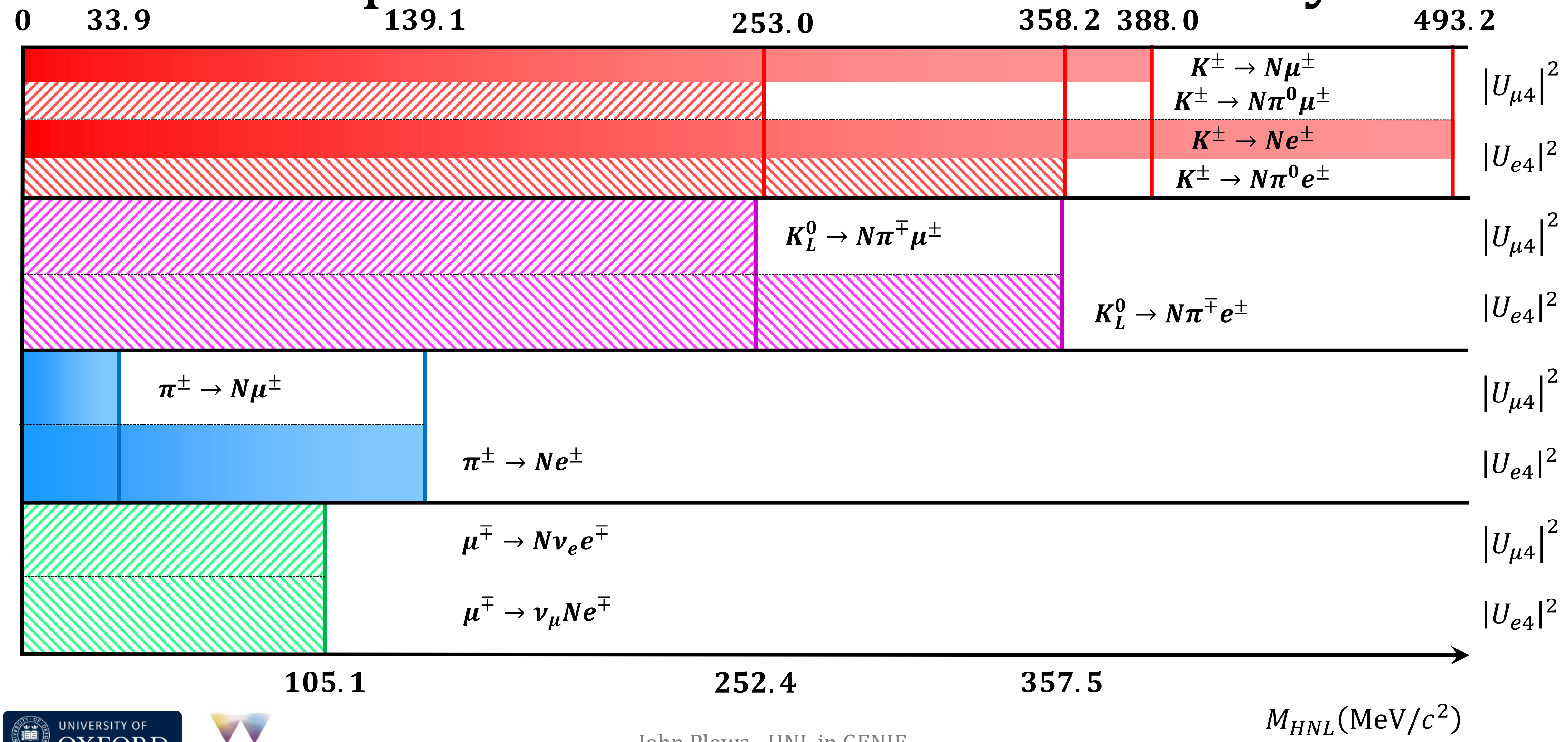
- $M > M_{EW}$: Drell-Yan, $g + g$ fusion, $W + \gamma$ or $W + W$ fusion (e.g. at colliders)
- $M_P < M < M_{EW}$: Decays of particle (lepton, meson) P (at colliders, neutrino beams, atmospheric production…)
- $0 < M$: Production by upscattering (from SM neutrino - nuclear interactions through mixing alone or including transition "ν-N dipole")
- $0 < M$: Oscillations: SM --> HNL

- In this implementation, we consider production from meson decay in neutrino beams, through mixing alone
  - GENIE also handles HNL production through neutrino upscattering + decay via new "dark boson" Z_D (`DarkNeutrino` module, available in GENIE v3.2.0)

dk2nu flux input

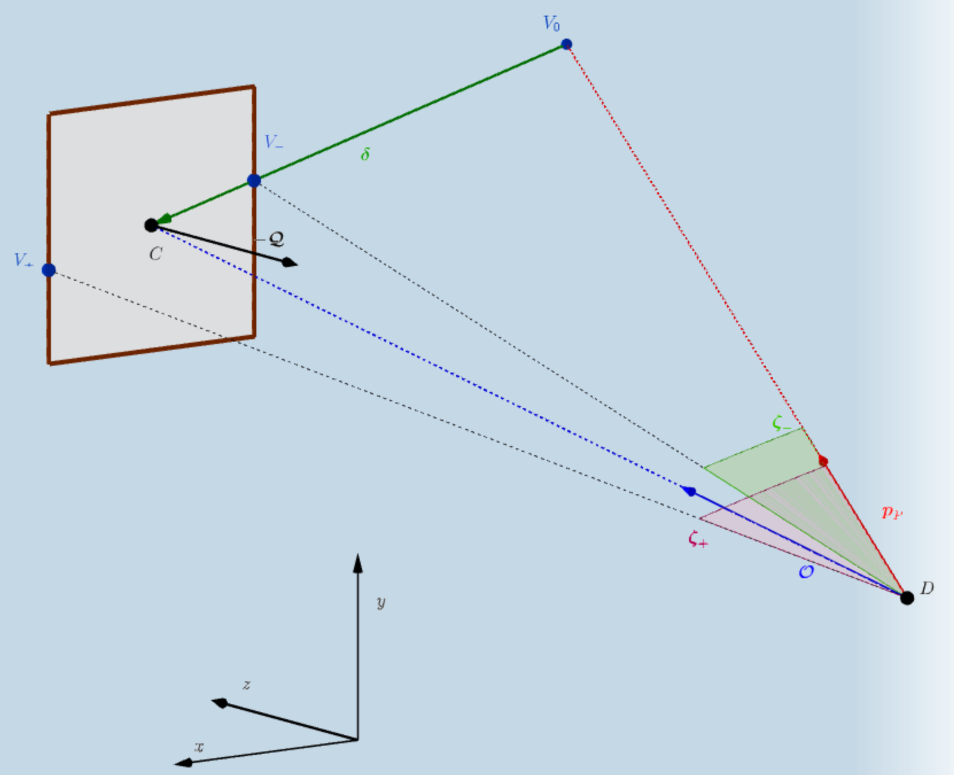
- Fermilab-wide common format: see related document
- User supplies "flat" trees containing:
  - HNL production vertex in NEAR coordinates
  - Parent 3-momentum in NEAR coordinates
  - Parent PDG
  - SM neutrino energy in parent rest frame
  - "Importance weight" (≡ multiplier for very similar hadron kinematics, used to reduce simulation events in g4numi)
- See also `$GENIE/src/contrib/beamhnl` for details how to make these trees

HNL production channels: summary



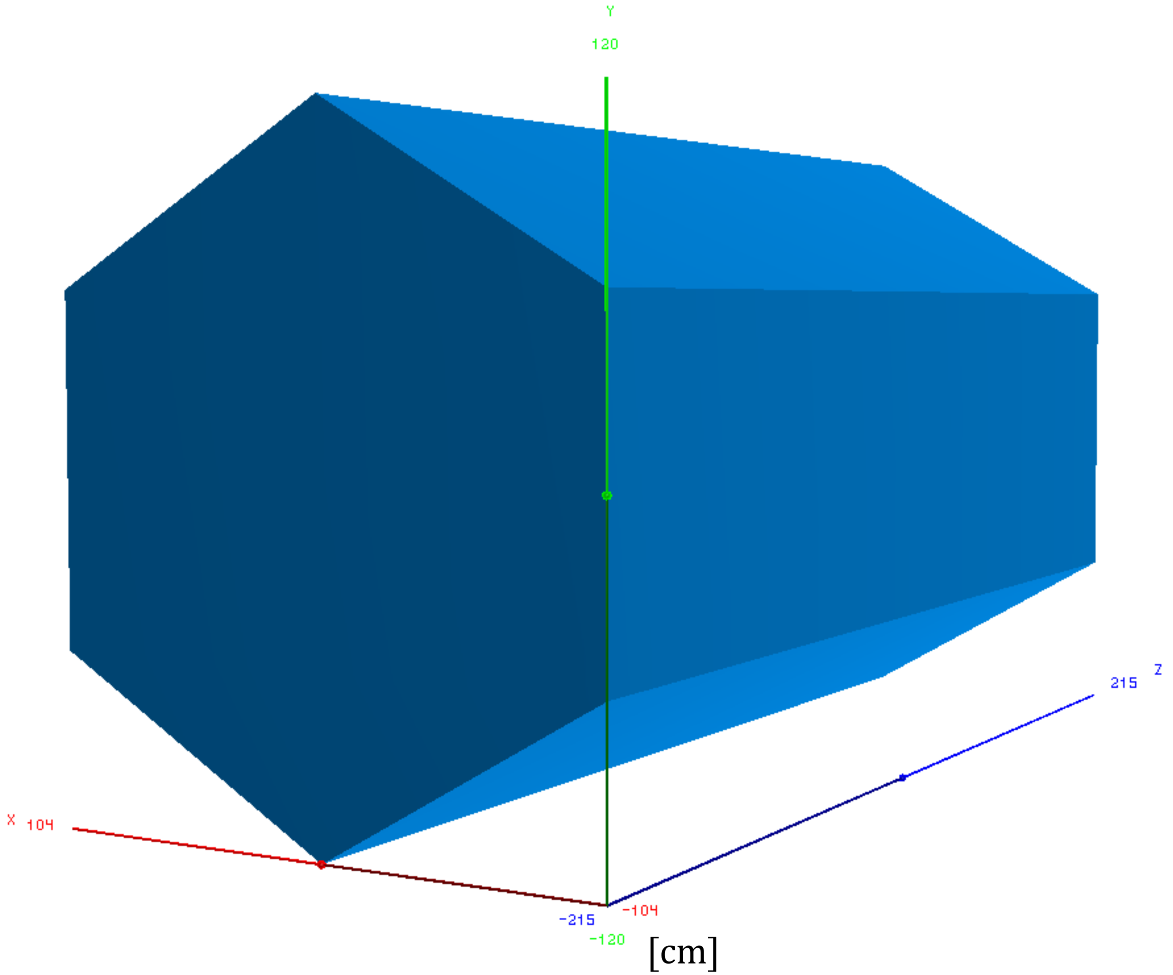
Geometry description + location of decay vertex + knowledge of $\boldsymbol{p}_{\text{parent}} \Rightarrow$ constraint on deviation (emission) angle θ

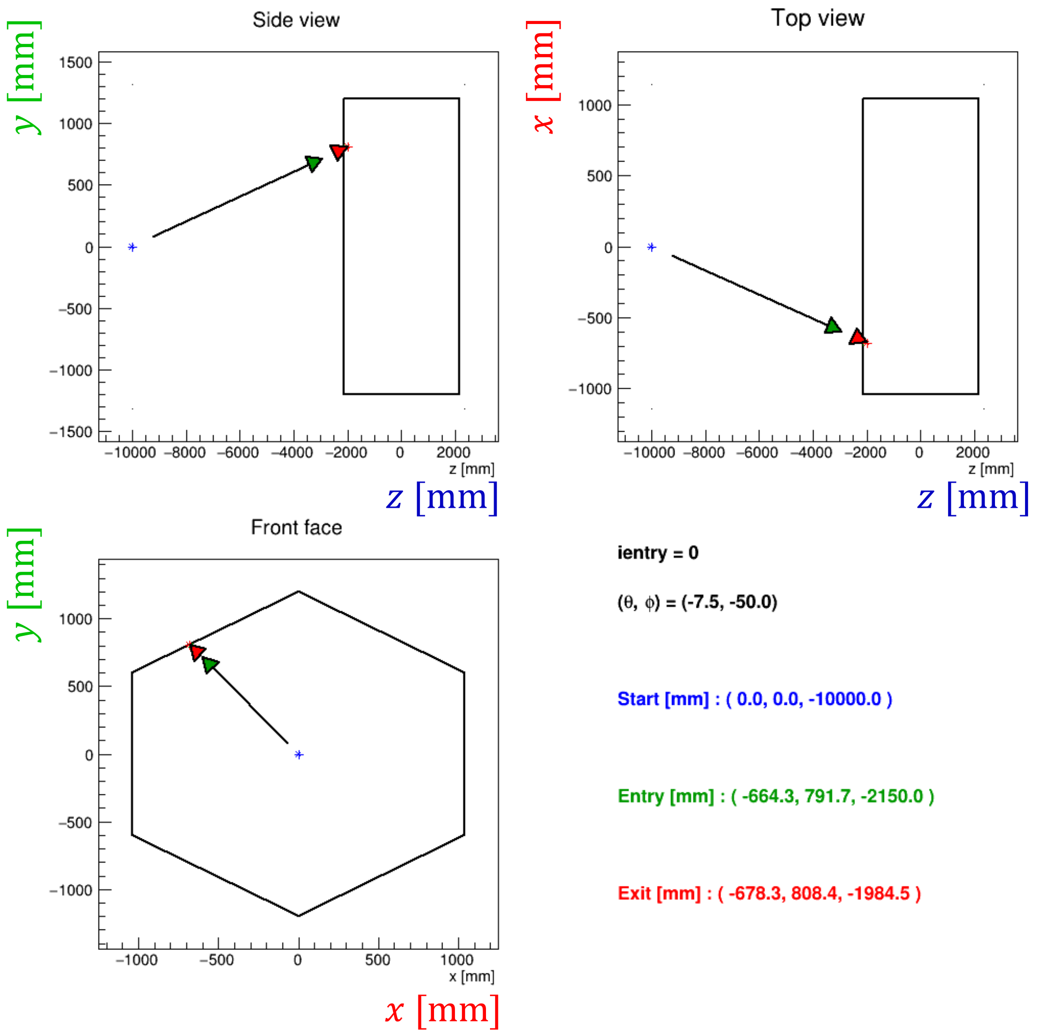
Estimate acceptance correction due to collimation effect by calculating min/max deviation $\zeta_{\mp}$ and mapping back to rest-frame emission angle θ^*

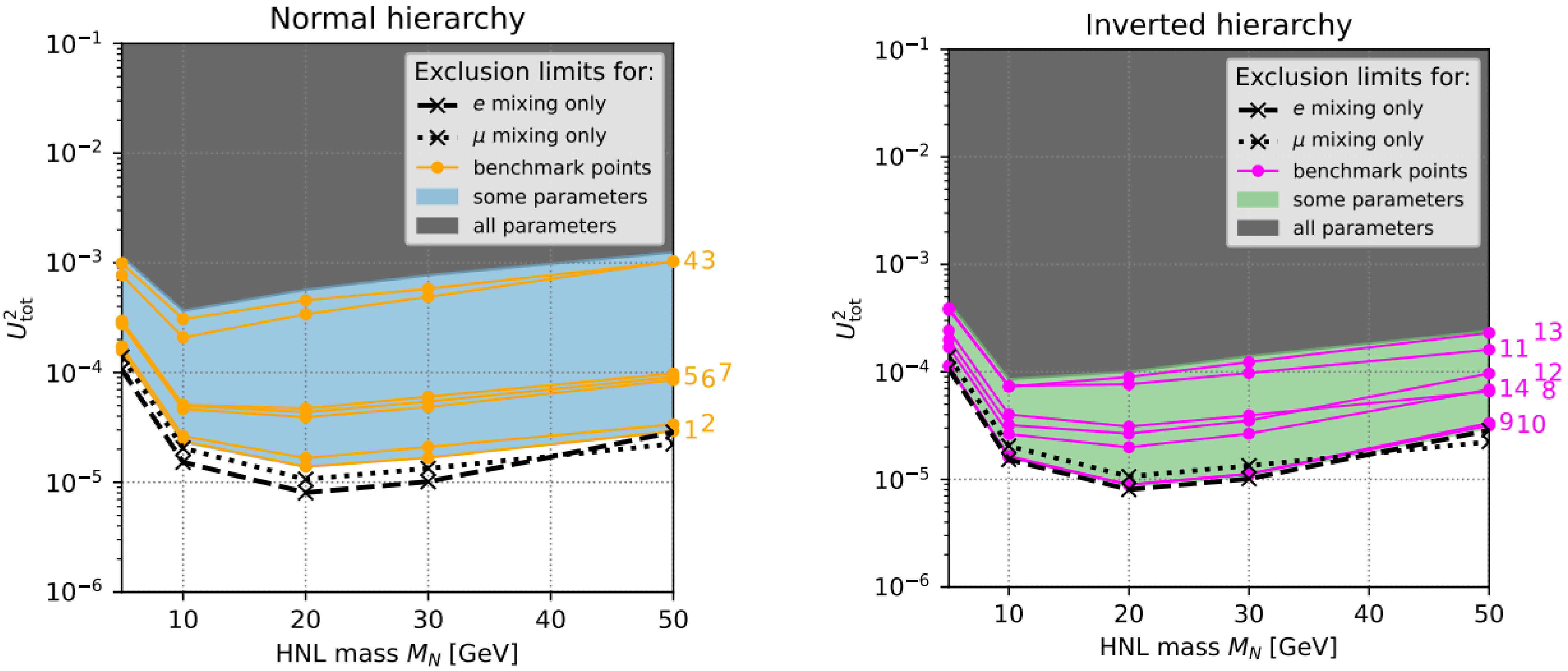


Intersection points

- ROOT’s TGeoManager handles the intersection calculations







[*JHEP* **2021** (2021) 182](https://doi.org/10.1007/JHEP03(2021)182)

```
<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_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>
  <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>
```

User configuration (abridged)

Relevant physics assumptions and needs (which decay channels to simulate, where the detector is, HNL mass + couplings, etc) are accessible from a single configuration file

User may change these in between runs without recompiling code ⇒ build once, run for lots of different physics! (different detector setups, sizes, signal channel combinations, Dirac or Majorana neutrinos, ...)

```
<param_set name="FluxCalc">
  <param type="vec-double" name="ParentPOTScalings" delim=";"> 1.0 ; 1.005 ; 9.353 ; 10.458 </param>
  <param type="bool" name="IsParentOnAxis"> true </param>
  <param type="bool" name="IncludePolarisation"> false </param>
  <param type="bool" name="FixPolarisationDirection"> false </param>
  <param type="vec-double" name="HNL-PolDir" delim=";"> 0.0 ; 0.0 ; 1.0 </param>
</param_set>
```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