Modelling Heavy Neutral Leptons in accelerator beamlines

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(based on arXiv: 2211.10210)

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WARWICK

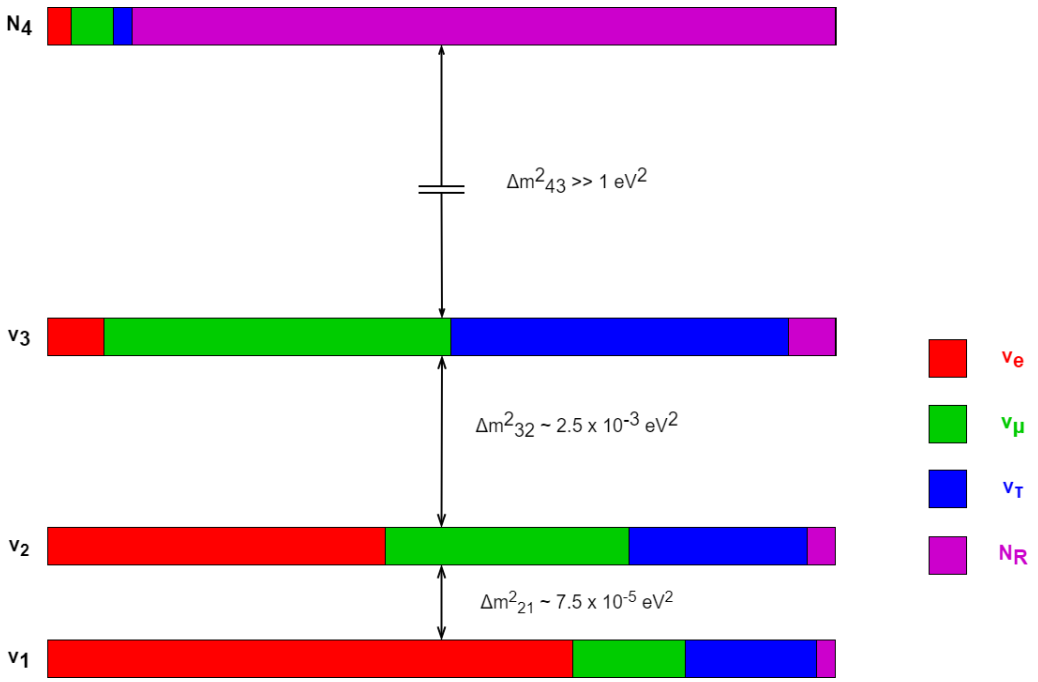
What are HNL?

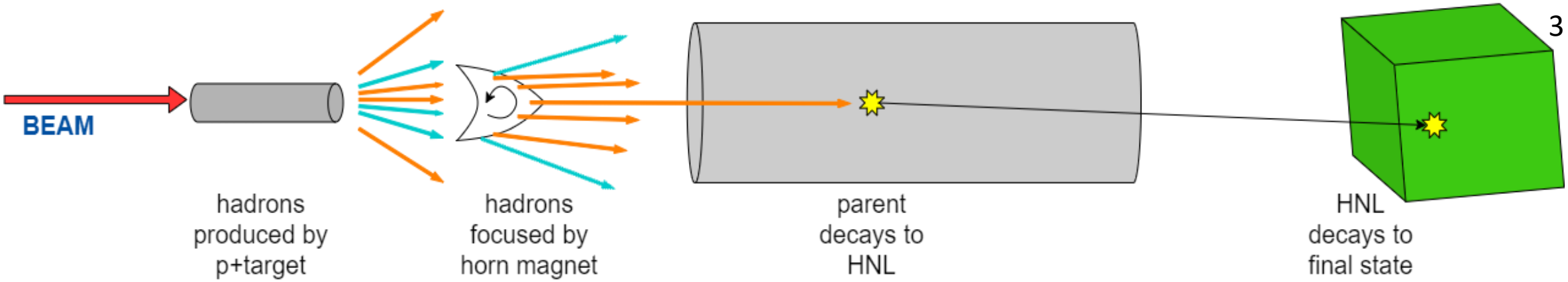
- Naturally motivated extension to Standard Model
  - Admixture with regular "flavour" eigenstates ν_α as $\nu_\alpha = \sum_{i=1,2,3} U_{\alpha i}\nu_i + \sum_{j\in J} U_{\alpha j}\, N_j$

- HNL: mass eigenstates of mass $\mathcal{O}(\leq \mathrm{TeV}/c^2)$
  - Can explain:
    - Active neutrino mass!
    - Dark matter candidate!
    - Matter-antimatter asymmetry!

    (see *Phys. Lett.* ***B*** **631** (2005) 4, *PPNP* ***104*** (2019) 1)

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





Click me!

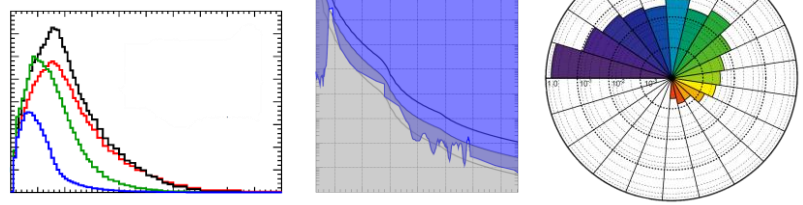
Popular event generator!
Versatile flux drivers +
ROOT infrastructure / utils
Embedded in simulation chain of many experiments

Click us!

Significant interest in HNL

Click us!

A generalized HNL GENIE model
(hep-ph/2211.10210)
(release coming soon)



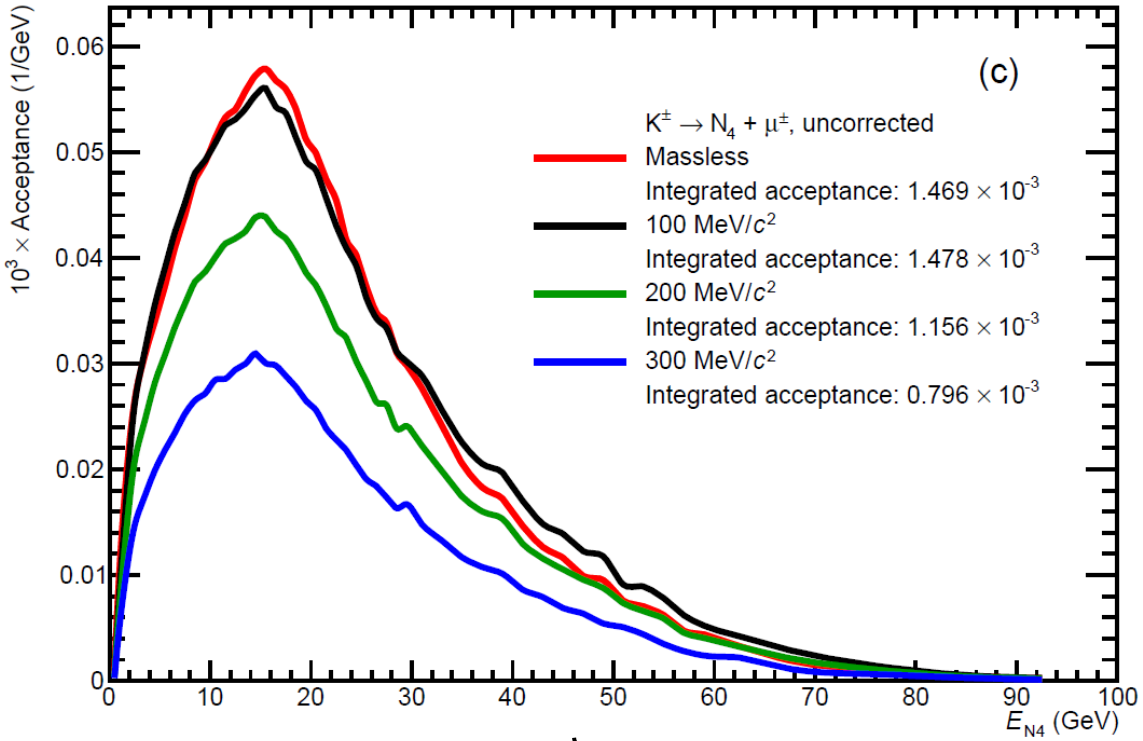
User gives us this

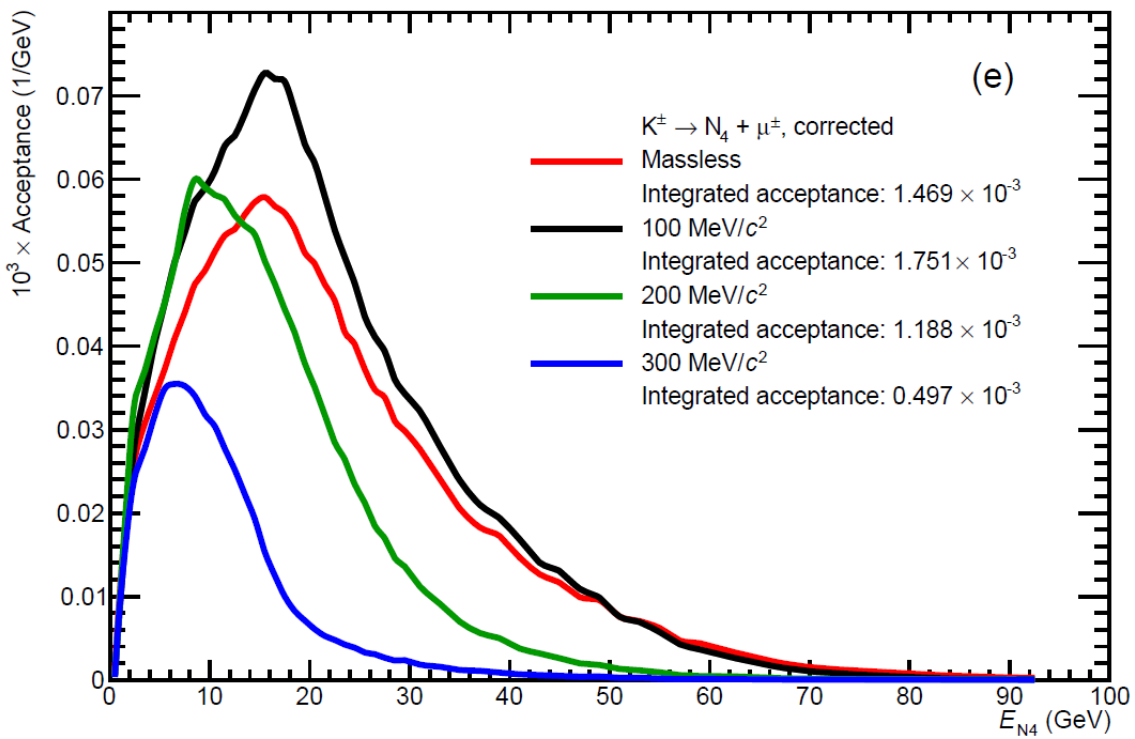
Beamline simulation = record of hadrons (decay to ν/N_4)

Massless ν:
- ✓ Always accepted
- ✓ Lightspeed travel

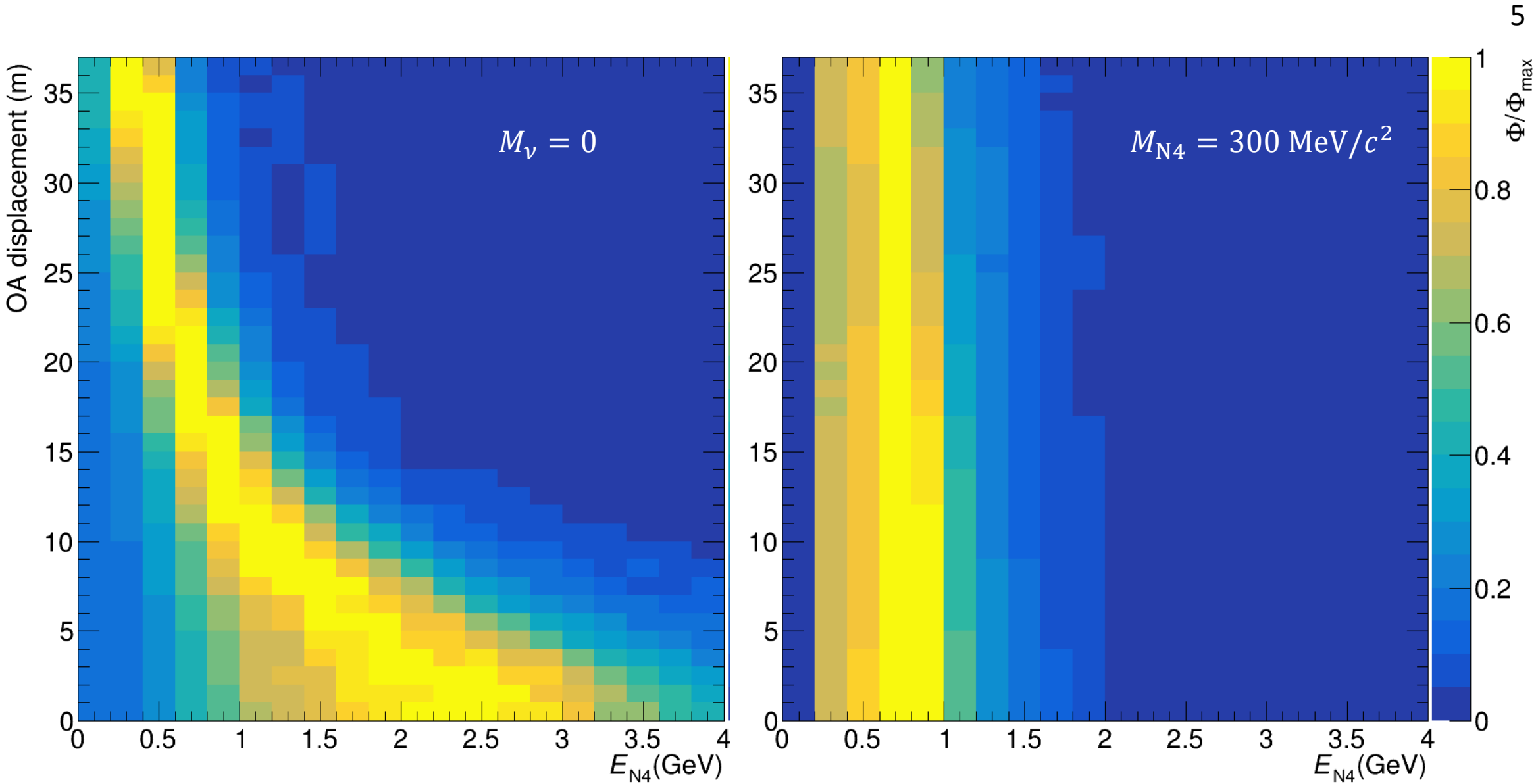
Massive N_4:
- × Not always accepted
- × Slower travel

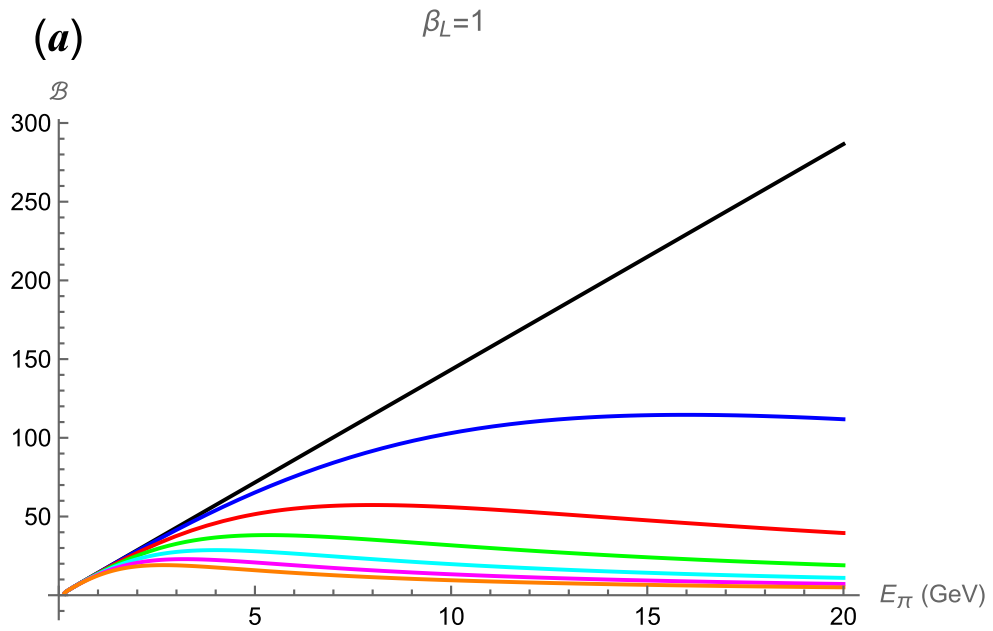
And this:
$(M_{N4}, |U_{\alpha 4}|^2)$

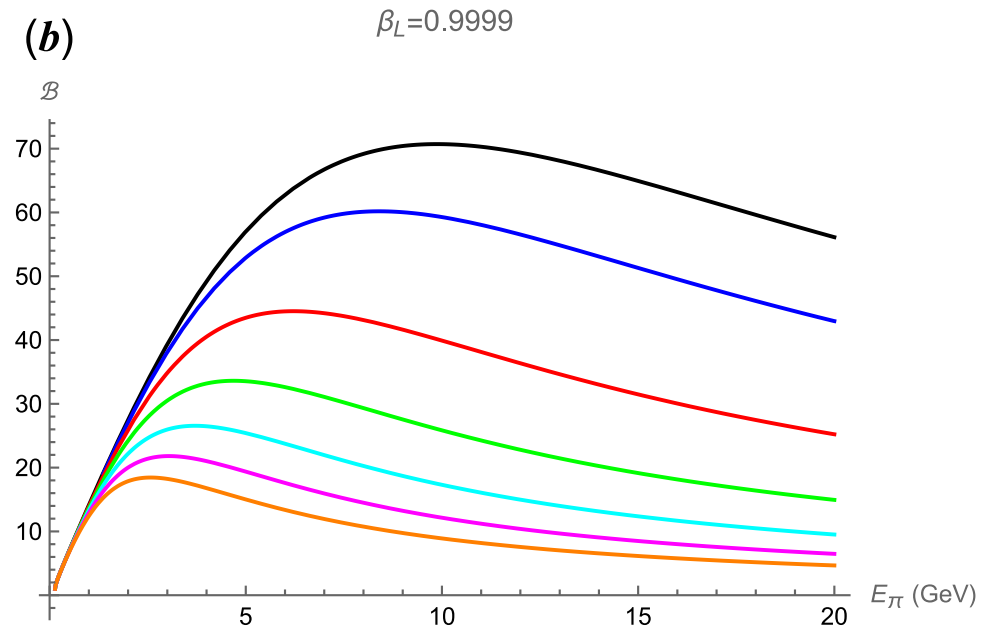


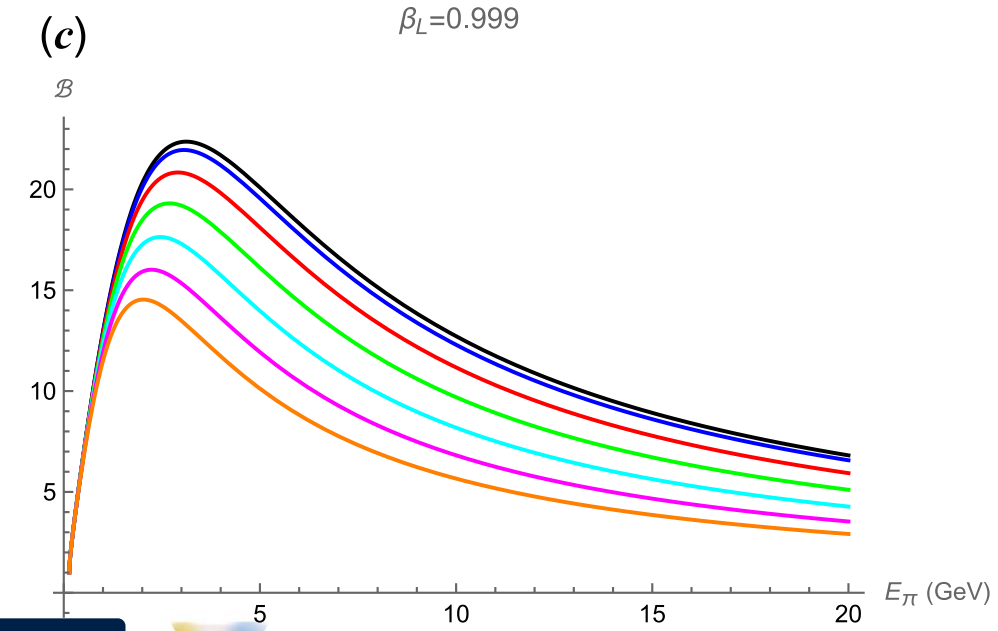


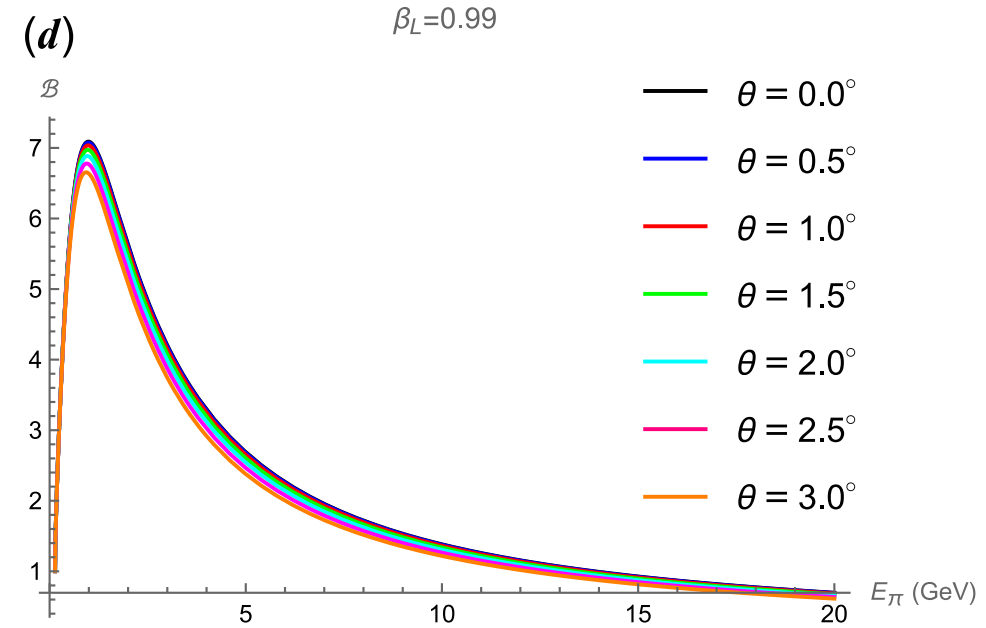
correction due to collimation effect (backup)

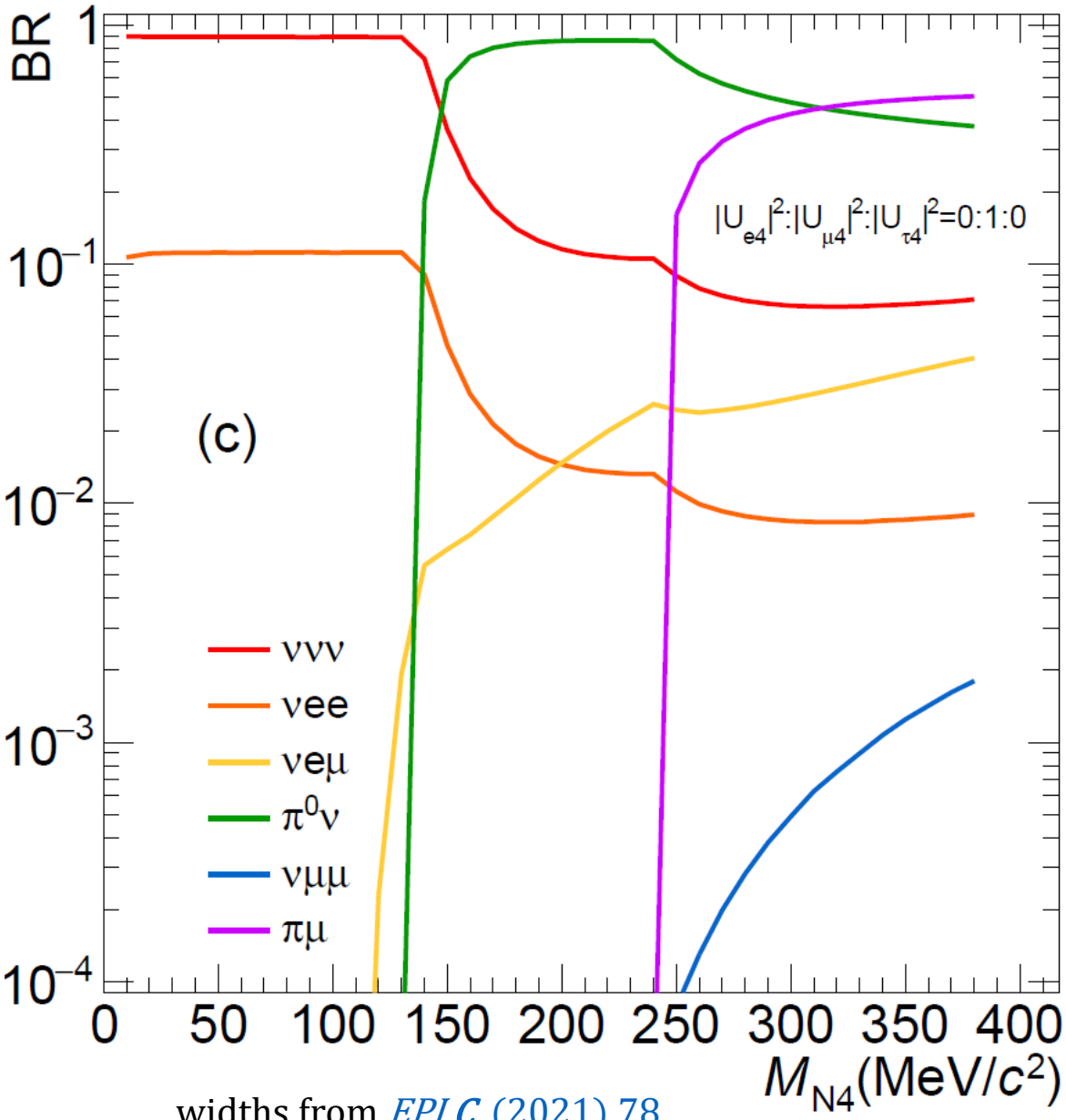

$M_\nu = 0$
$M_{\mathrm{N4}} = 300\ \mathrm{MeV}/c^2$
OA displacement (m)
E_{N4}(GeV)
Φ/Φ_{max}


(a)
β_L=1
$\mathcal{B}$
300
250
200
150
100
50
5
10
15
20
E_π (GeV)

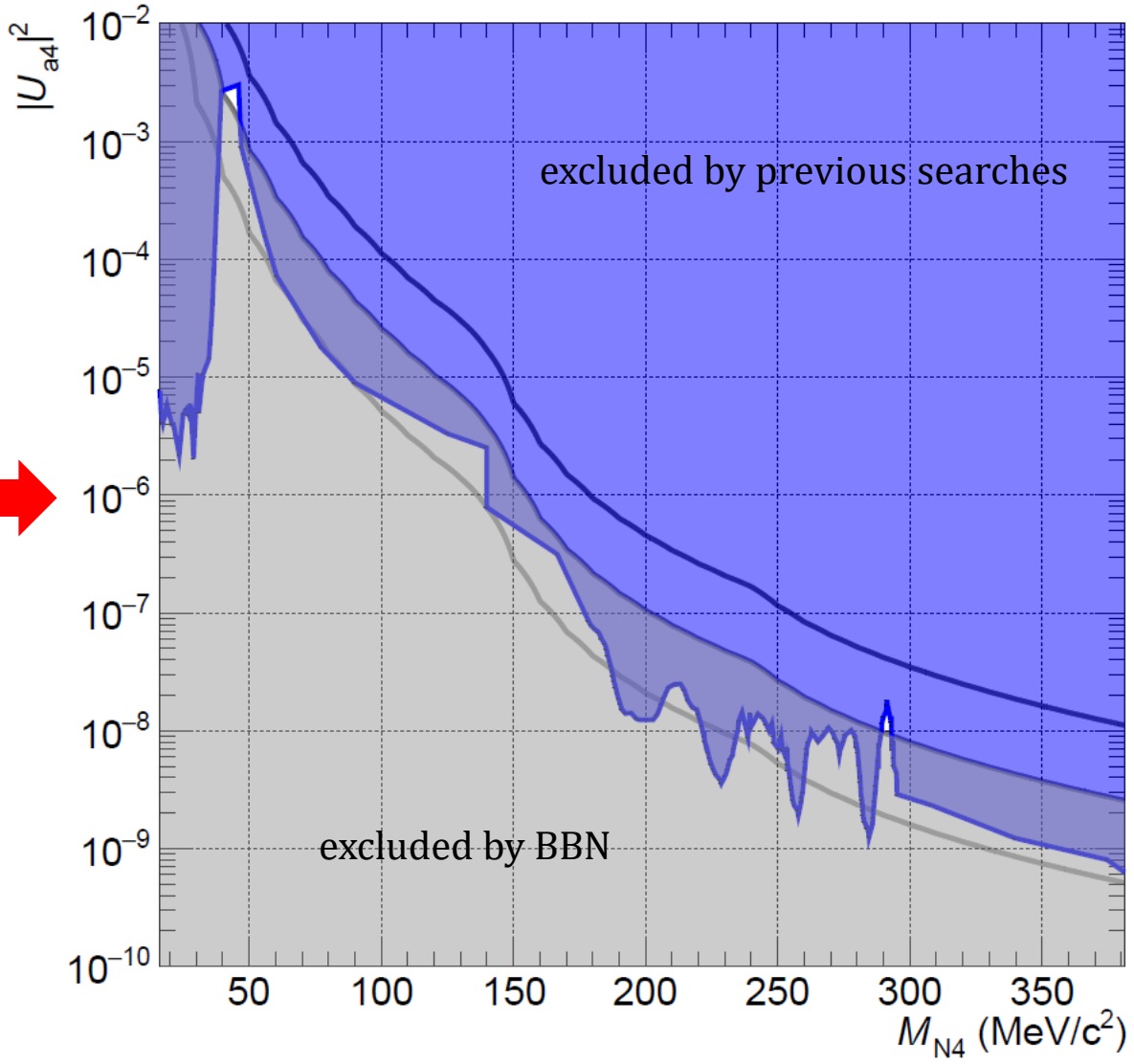

(b)
β_L=0.9999
$\mathcal{B}$
70
60
50
40
30
20
10
5
10
15
20
E_π (GeV)


(c)
β_L=0.999
$\mathcal{B}$
20
15
10
5
5
10
15
20
E_π (GeV)

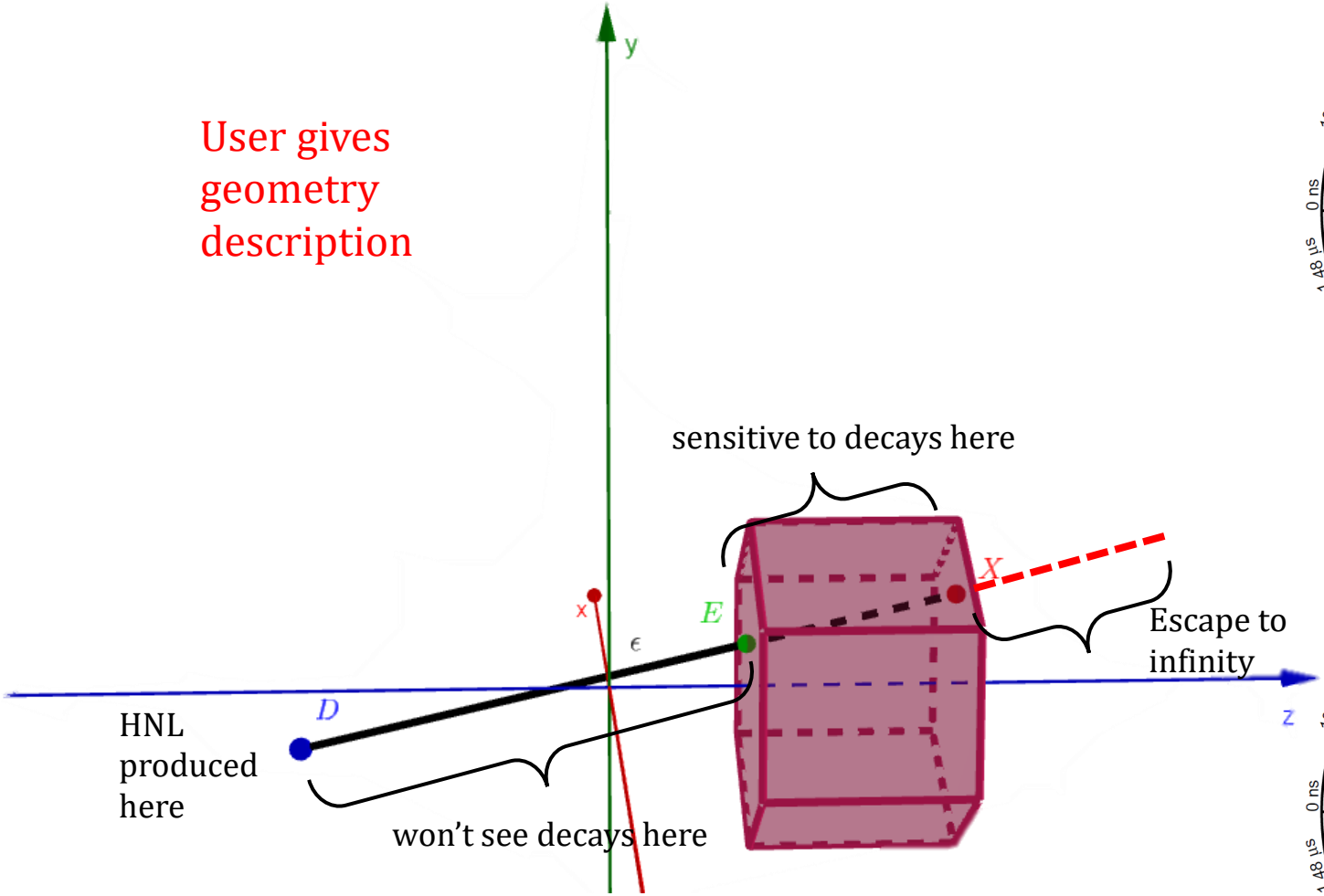

(d)
β_L=0.99
$\mathcal{B}$
7
6
5
4
3
2
1
5
10
15
20
E_π (GeV)
$\theta = 0.0^\circ$
$\theta = 0.5^\circ$
$\theta = 1.0^\circ$
$\theta = 1.5^\circ$
$\theta = 2.0^\circ$
$\theta = 2.5^\circ$
$\theta = 3.0^\circ$

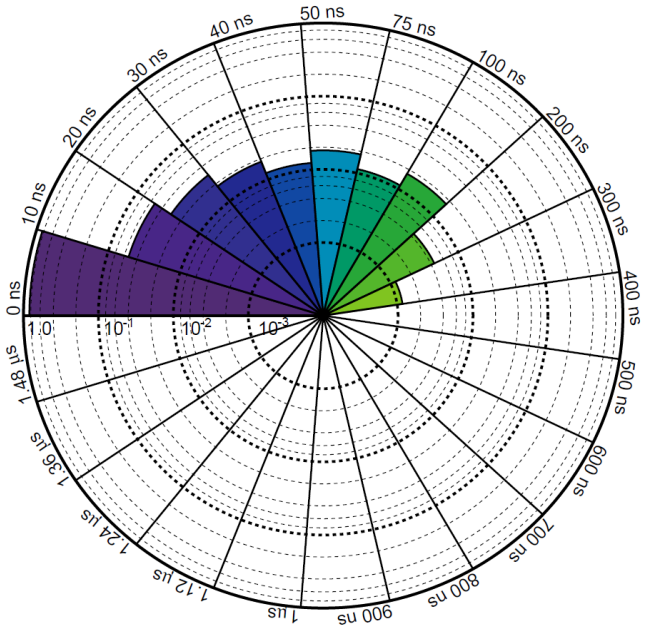


widths from *EPJ C* (2021) 78

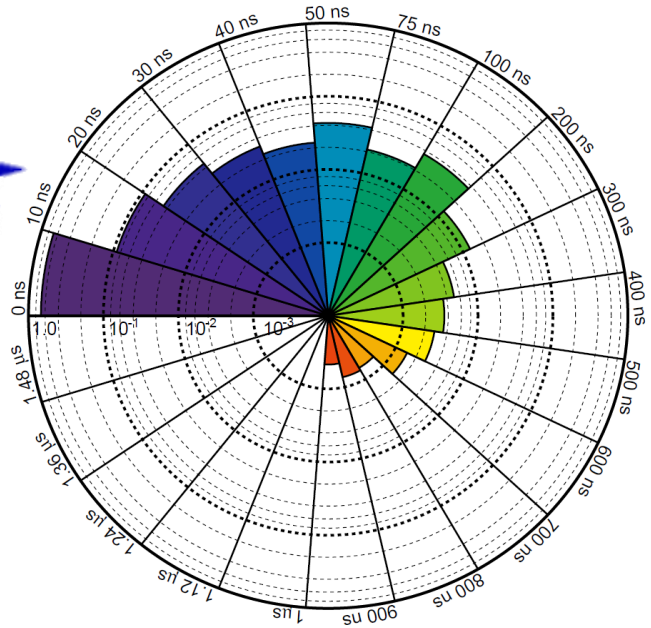


User gives geometry description



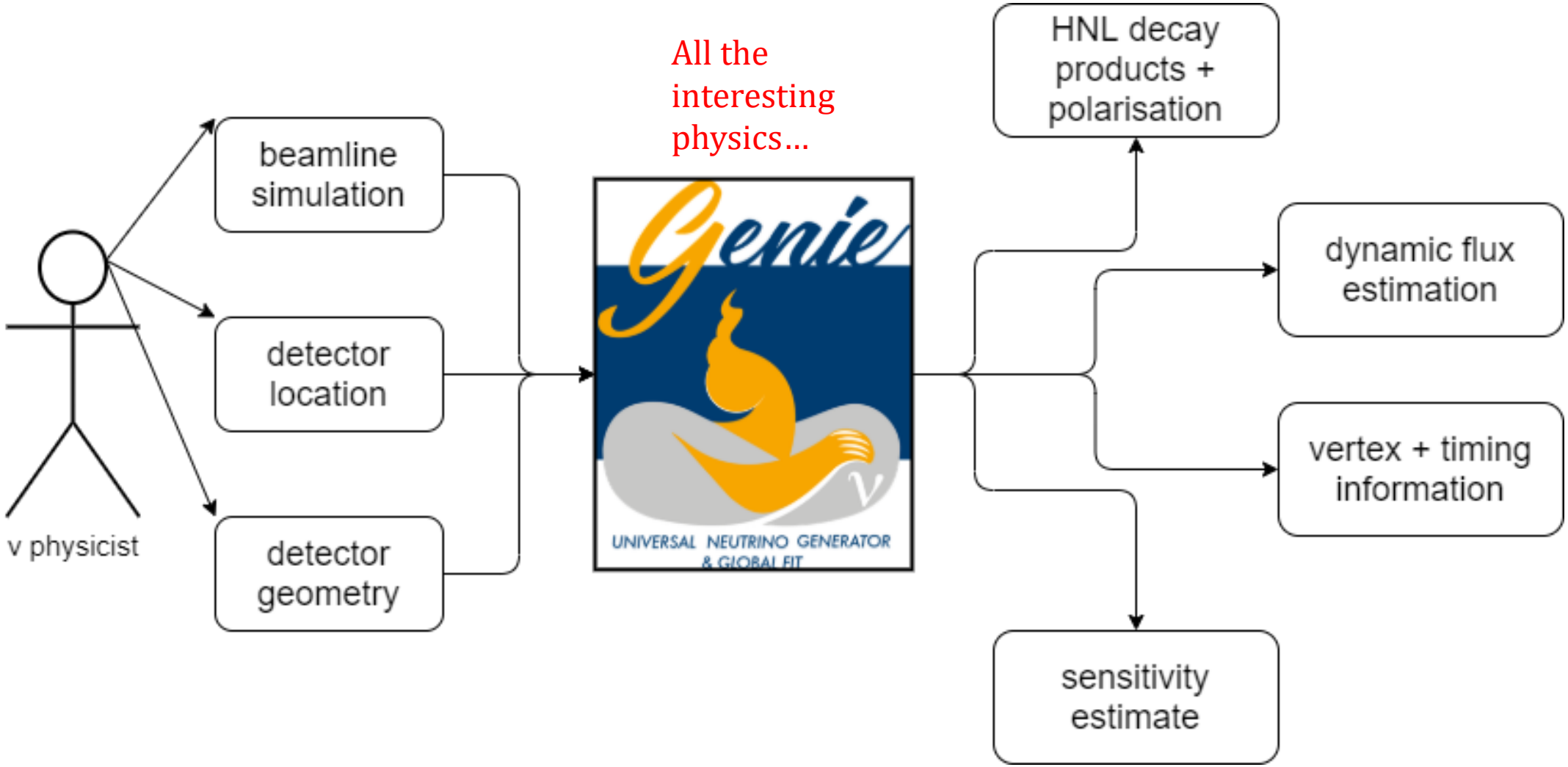


$M_{N4} = 25\ MeV/c^2$

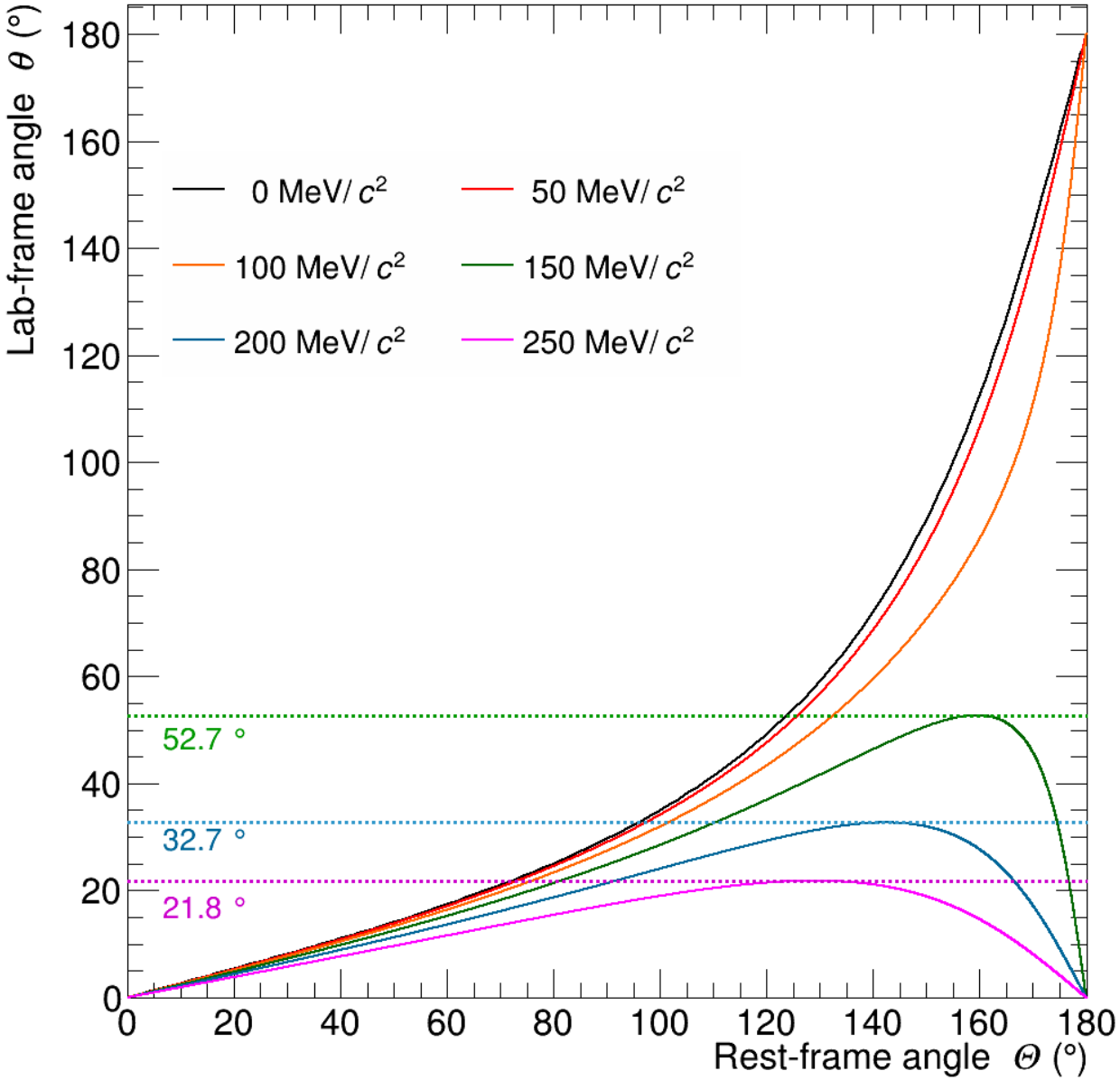


$M_{N4} = 250\ MeV/c^2$

Backup

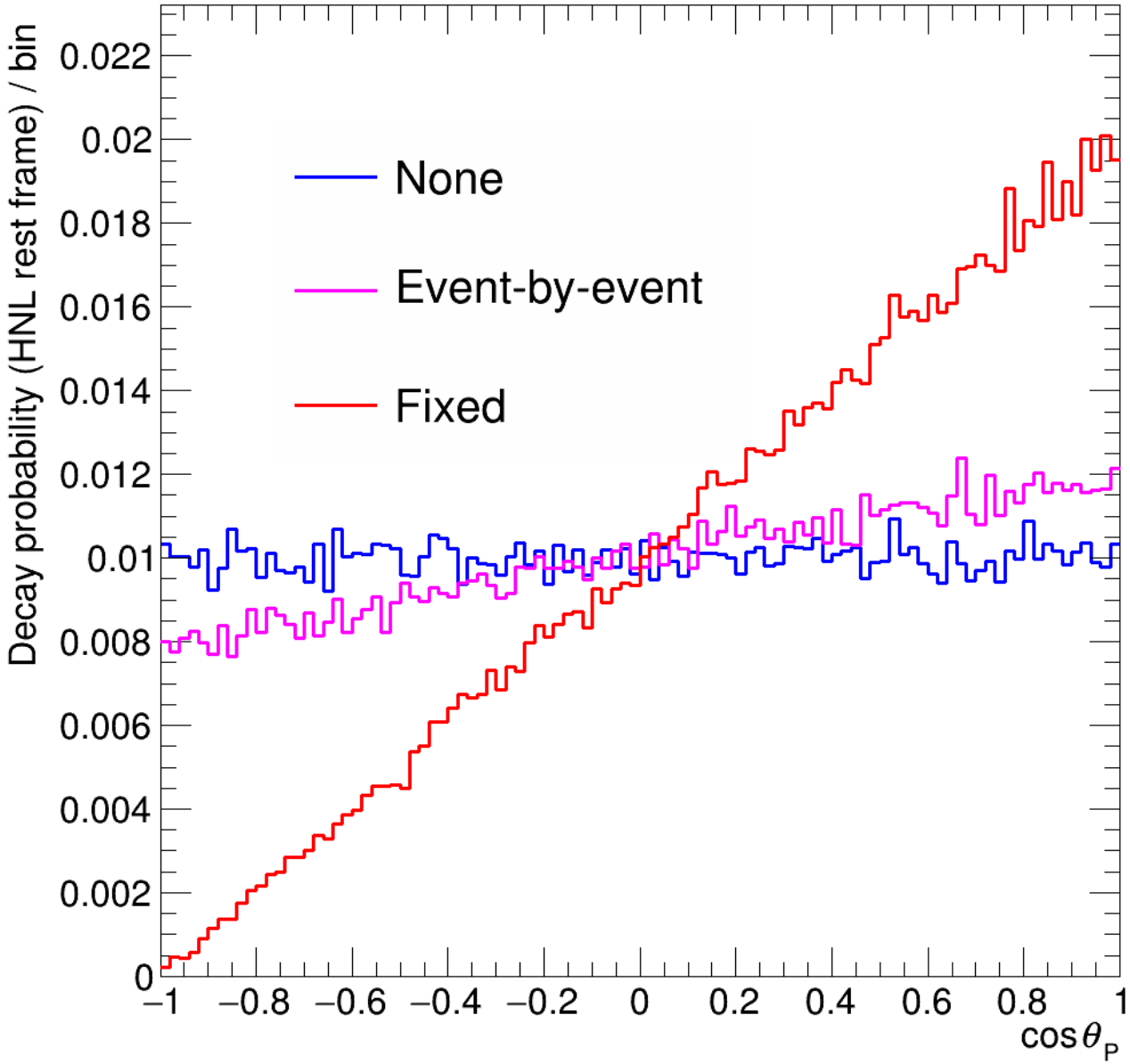


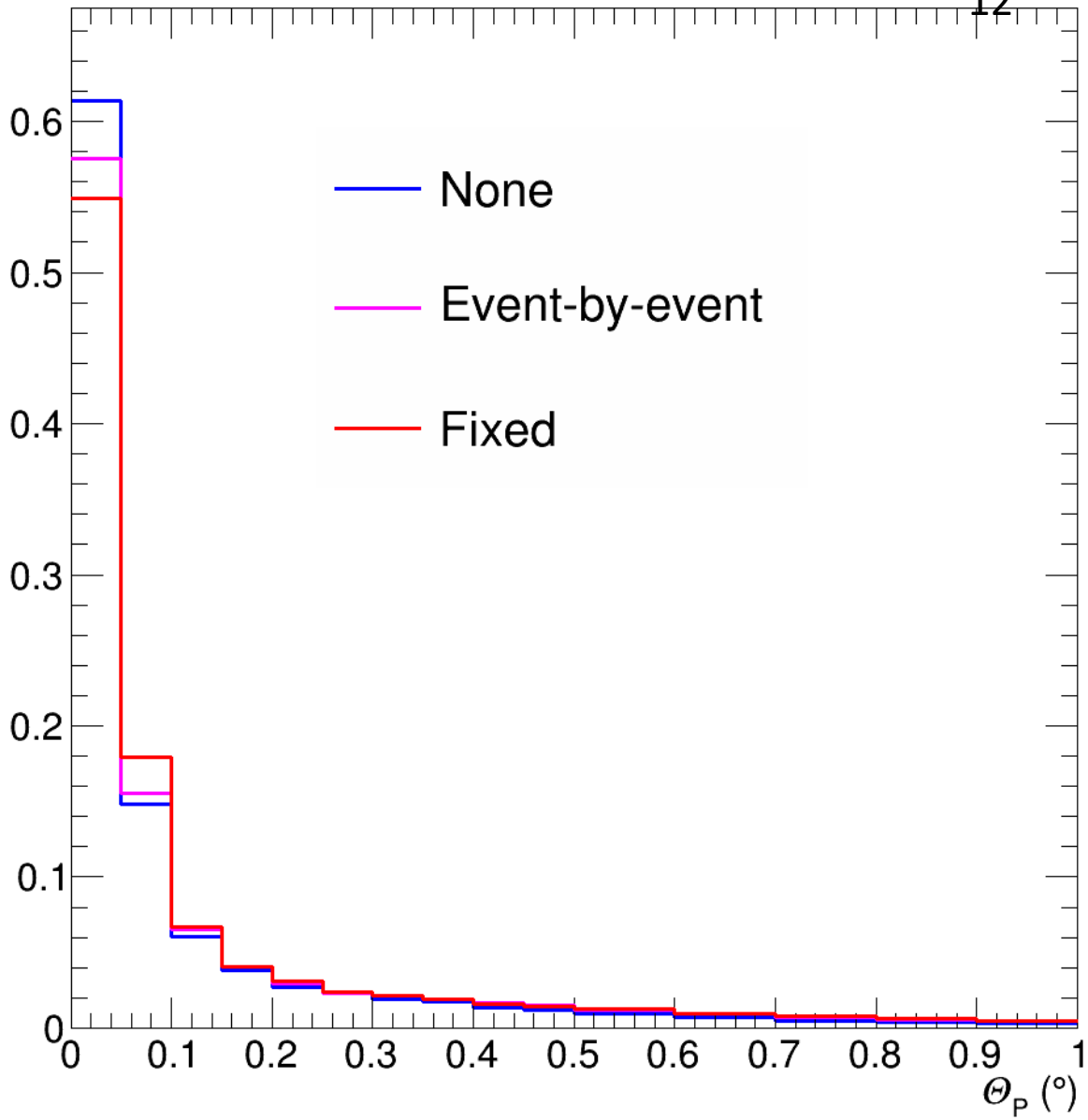
One single interface for massive neutrinos and <u>arbitrary experimental setups!</u>



Collimation effect:

Backwards emitted HNL that are heavy enough will be swept forwards instead!


Decay probability (HNL rest frame) / bin
0.022
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
None
Event-by-event
Fixed
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
cos θP


0.6
0.5
0.4
0.3
0.2
0.1
0
None
Event-by-event
Fixed
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
ΘP (°)

```
<common_HNL_list>

 <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>
```

Choose $M_{\mathrm{N4}} = 200\ \mathrm{MeV}/c^2$
$|U_{e4}|^2 = |U_{\mu 4}|^2 = 10^{-7}$
Dirac HNL

```
 <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>
```

Enable decay modes
$N_4 \to \pi^+ \ell^-, N_4 \to \nu\nu\nu$

```
 <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>
```

Place a detector at ~ 1km from beamline origin
Beam rotated on yz plane by ~ 3.34° downwards