More Realistic Sensitivity Estimates for the MATHUSLA Detector

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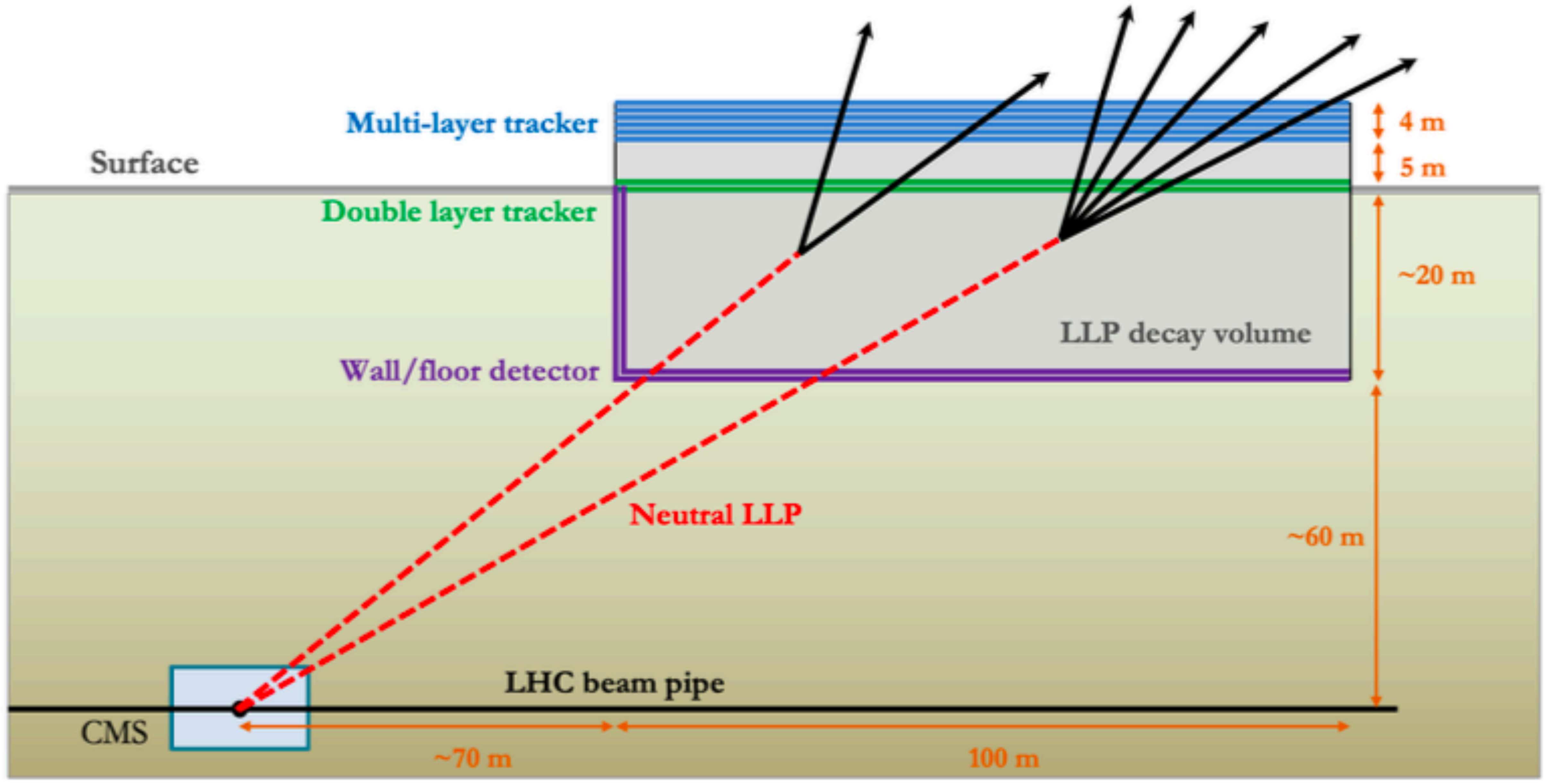
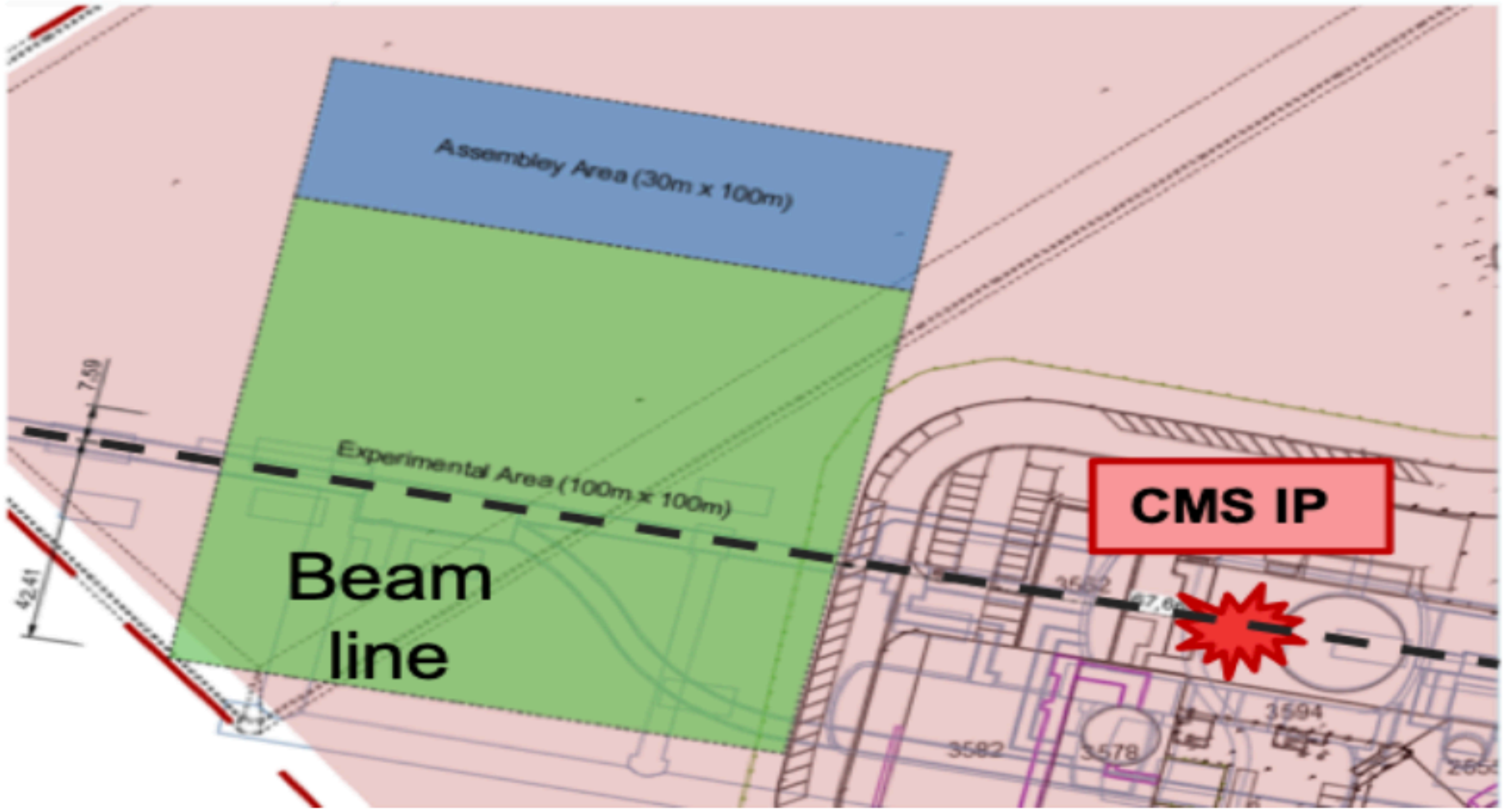
What is MATHUSLA?

MAssive Timing Hodoscope for Ultra-Stable neutraL pArticles

- Proposed detector above CMS @ CERN to find Long Lived Particles (LLPs)
- Aims to reconstruct signals using Displaced Vertices (DVs)
- Addresses main LHC detector issues for LLP searches - trigger limitations and complex backgrounds (BG)
- Location at surface shields from QCD BG

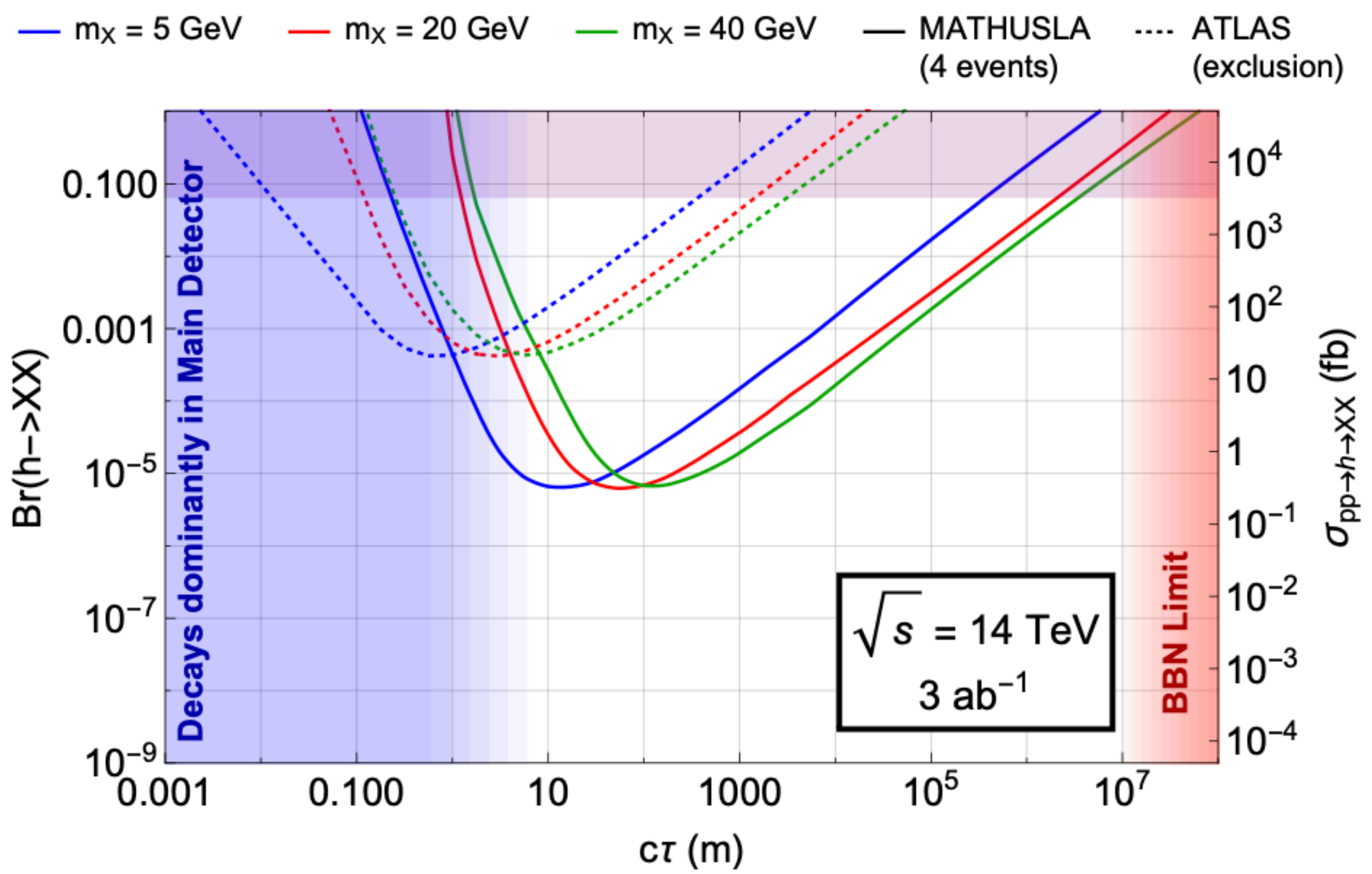




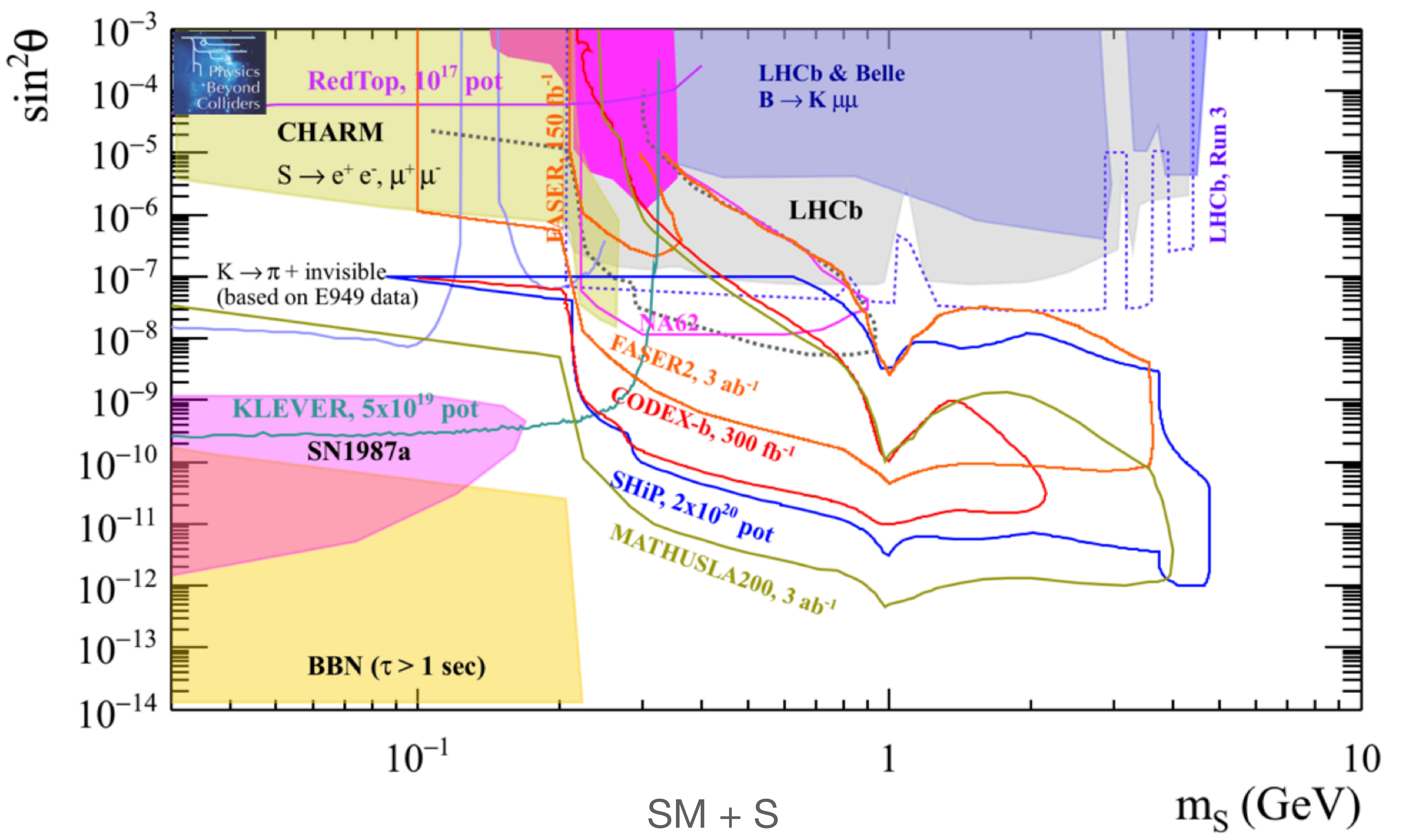
see 1606.06298, 1806.07396 , 1811.00927, 2009.01693, 2203.08126

Physics Objectives

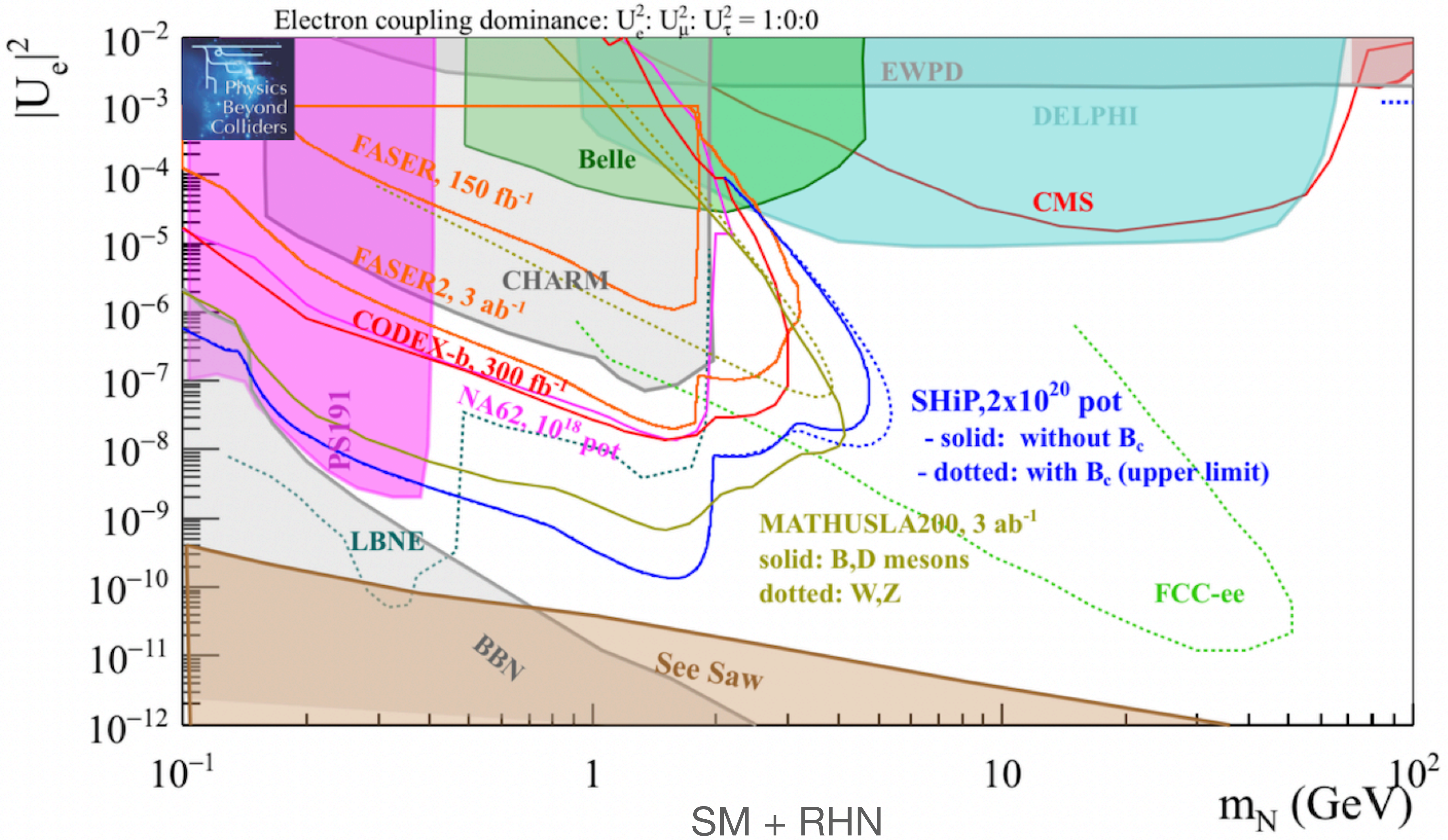
- **Primary** - O(10-100) GeV LLPs decaying hadronically e.g. $h \rightarrow XX$
- **Secondary** - Low mass LLPs (includes all decays) e.g. SM+S, RHN
- **Goal of our project:** Previous sensitivity estimates (shown for $N_{obs} = 4$) were done assuming perfect decay reconstruction efficiency - we present **updated plots taking into account the geometric acceptance of the detector for LLP decay final states.**



$h \rightarrow XX$



SM + S



SM + RHN

LLP Signal calculation

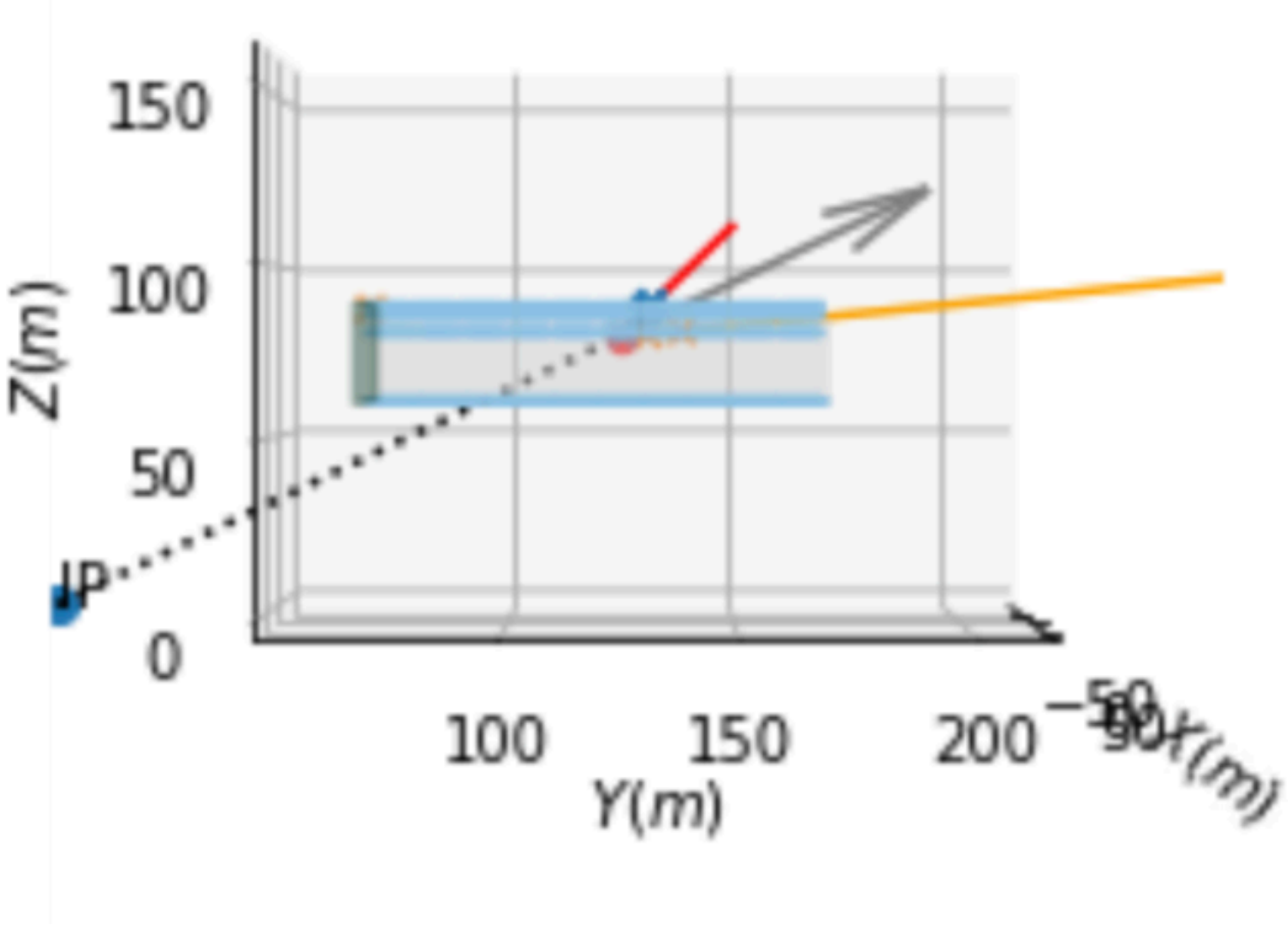
Number of reconstructible decays for an LLP is given by

$$N_{obs} = (\mathscr{L}\sigma_{LLP}n_{LLP}) \otimes \xi^{geo}_{LLP} \otimes \bar{P}_{decay} \otimes \xi^{geo}_{decay} \otimes \epsilon_{recon}$$

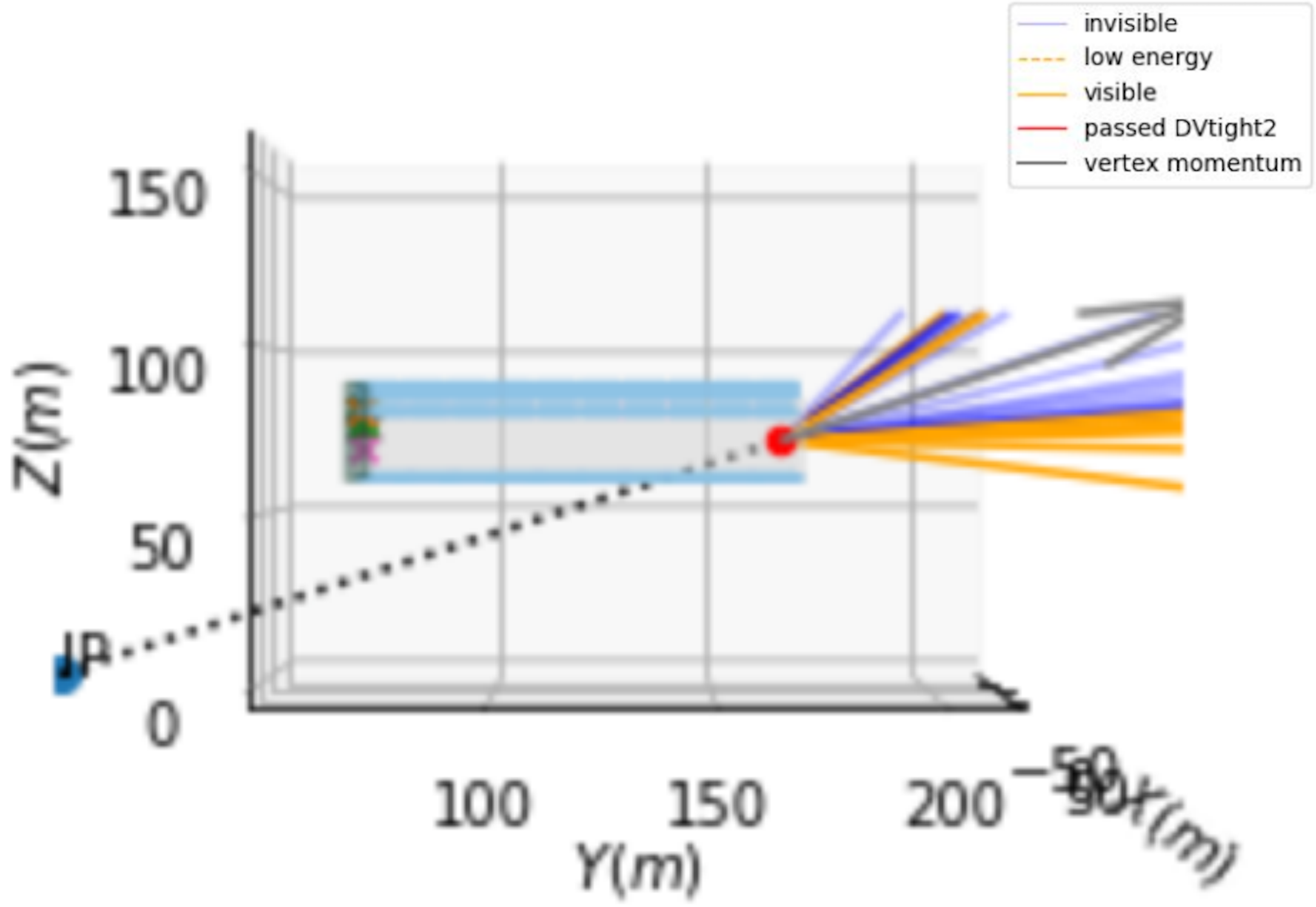
- $\mathscr{L}\sigma_{LLP}n_{LLP}$: number of LLPs produced
- ξ^{geo}_{LLP} : fraction of **those** LLPs that pass through MATHUSLA
- $\bar{P}_{decay}$: **average** probability for **those** LLPs to decay within MATHUSLA
- ξ^{geo}_{decay} : average geometric acceptance for final states of **those LLP decays** to hit sufficient sensor panes to be reconstructed as tracks and displaced vertices. **This could be a bottleneck for sensitivity if many charged decay products escape undetected through the wall, floor or detector gaps.**
- ϵ_{recon} : reconstruction efficiency for LLPs that pass those geometric criteria (close to 1)

Previous estimates assumed ξ^{geo}_{decay} = 1. We run more detailed simulations to obtain ξ^{geo}_{decay} for various LLP models.

Unreconstructible LLP Decays



Leptonic 2-Body



Hadronic

MATHUSLA FastSIM

(extending work by Wentao Cui, Lillian Luo)

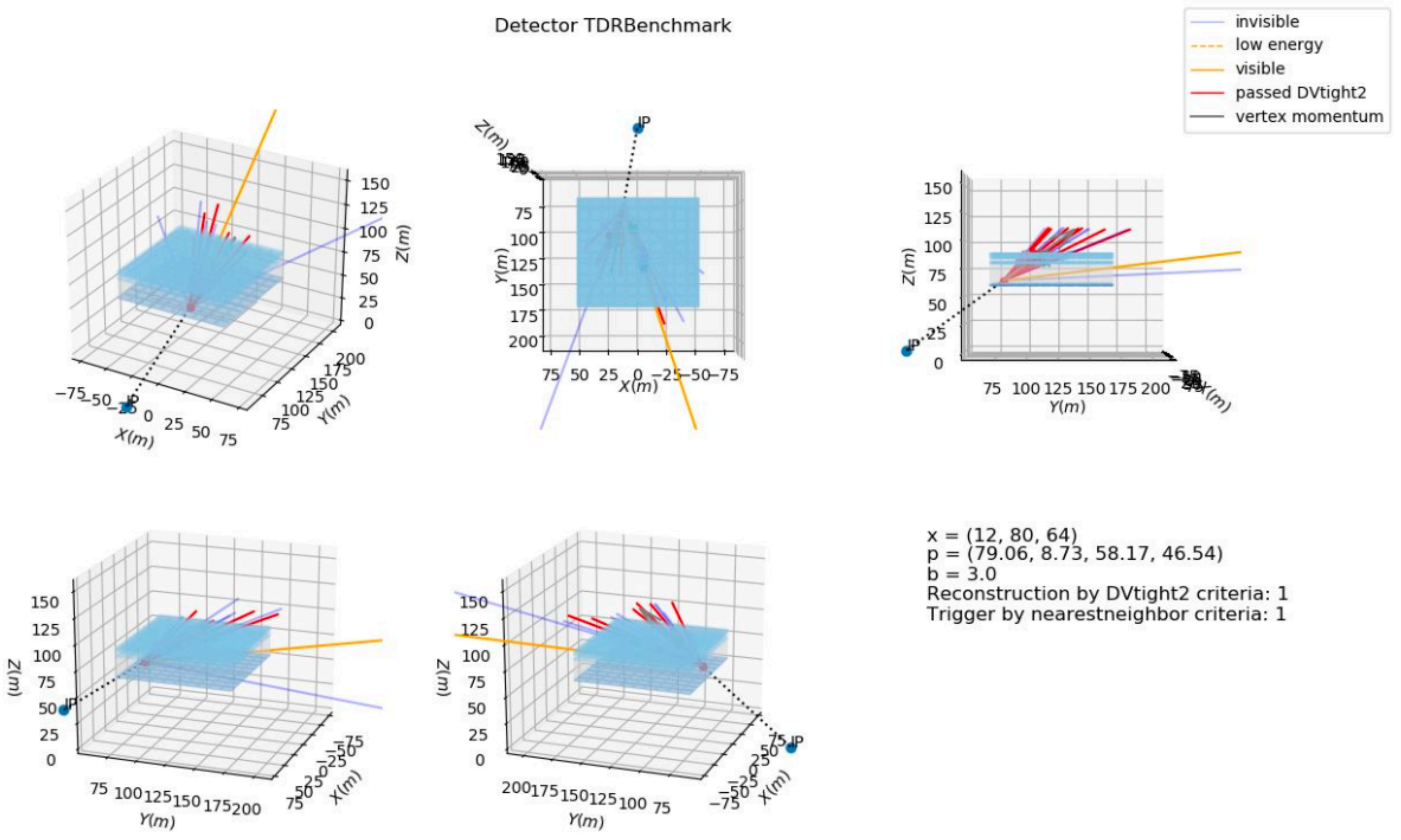
- highly customizable Python code that simulates the geometry of MATHUSLA sensor layers
- Very flexible: define a “param card” with any geometry, recon or trigger criteria
- Takes in LLP 4-vectors and returns ξ^{geo}_{decay} based on defined criteria, which can be used to get N_{obs} (assuming ϵ_{recon} = 1)
- Can also enable scintillator/spatial track resolution (if needed)

```
#Single track reconstruction criteria: TIGHT, LOOSE, TIGHT_UPWARDS, etc.
#track_recon_criteria = name min_num_hits tracker_planes(start indexing at 0)
#first one is default
track_recon_criteria = tight 5 0,1,2,3,4,5,6,7,8
#subsequent ones
track_recon_criteria = medium 4 0,1,2,3,4,5,6,7,8
track_recon_criteria = loose 3 0,1,2,3,4,5,6,7,8
track_recon_criteria = floor 1 0,1

#Single track trigger criteria: #TIGHT, LOOSE, etc.
#track_trigger_criteria = name min_num_hits tracker_planes(start indexing at 0) neighbourhood
track_trigger_criteria = nearestneighbor 5 4,5,6,7,8 1

#Vertex reconstruction criteria #TIGHT, LOOSE, etc.
#vertex_recon_criteria = name min_num_tracks1 track_recon_name1 min_num_tracks2 track_recon_name2 ...
vertex_recon_criteria = DVtight2 2 tight
vertex_recon_criteria = DVtight1medium1 1 tight 1 medium
vertex_recon_criteria = DVtight1loose1 1 tight 1 loose
vertex_recon_criteria = DVtight3 3 tight
vertex_recon_criteria = DVtight2medium1 2 tight 1 medium
vertex_recon_criteria = DVtight1medium2 1 tight 2 medium
vertex_recon_criteria = DVtight1loose2 1 tight 2 loose
vertex_recon_criteria = DVmedium3 3 medium

#Minimum particle momenta (MeV)
#min_particle_momenta = PID1,momentum1 PID2,momentum2 ... PIDn,momentumn
min_particle_momenta = 2212,600 211,200 321,400 11,200 13,200
```

Default track reconstruction criteria: **tight**
5 hits in any tracker planes

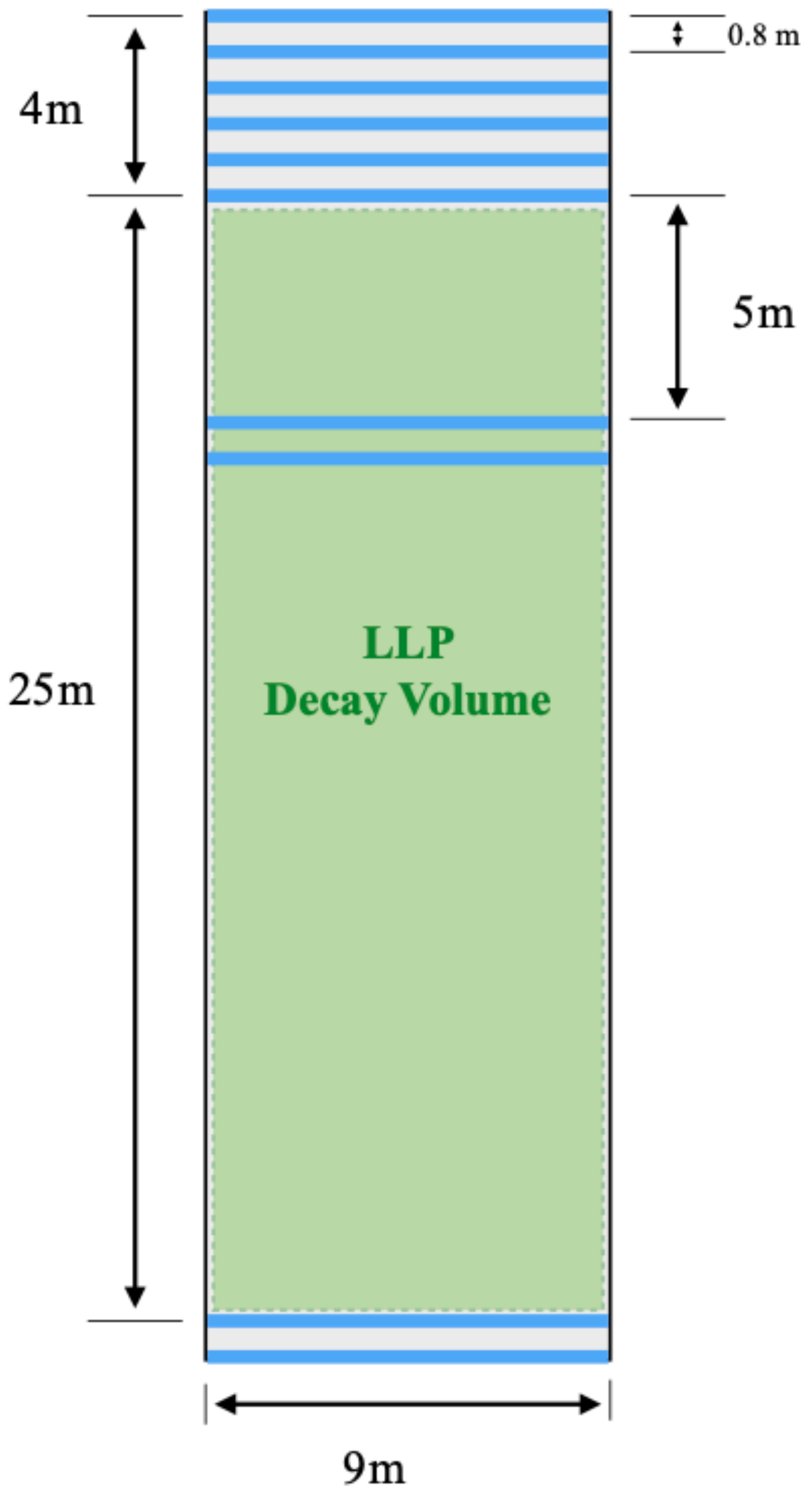
Default trigger criteria: **nearestneighbor**
5 hits among ceiling trackers (4, 5, 6, 7, 8), within 3x3 tracker modules

Default vertex reconstruction criteria: **DVtight2**
2 tracks passing **tight** reconstruction criteria



Detector Geometry Details

- Modular construction - 100m x 100m footprint with 100 9m x 9m detector units
- Detector units made up of 10 + 2 sensor planes (2 floor, 2 intermediate, 6 top and 2 front layers) - provide position and timing coordinates of charged decays
- Floor and front layers help veto background from LHC
- Particle needs 4+ hits for reconstruction and 4+ hits within 3x3 module group for trigger



Geometry & Recon Criteria

used for obtaining updated estimates

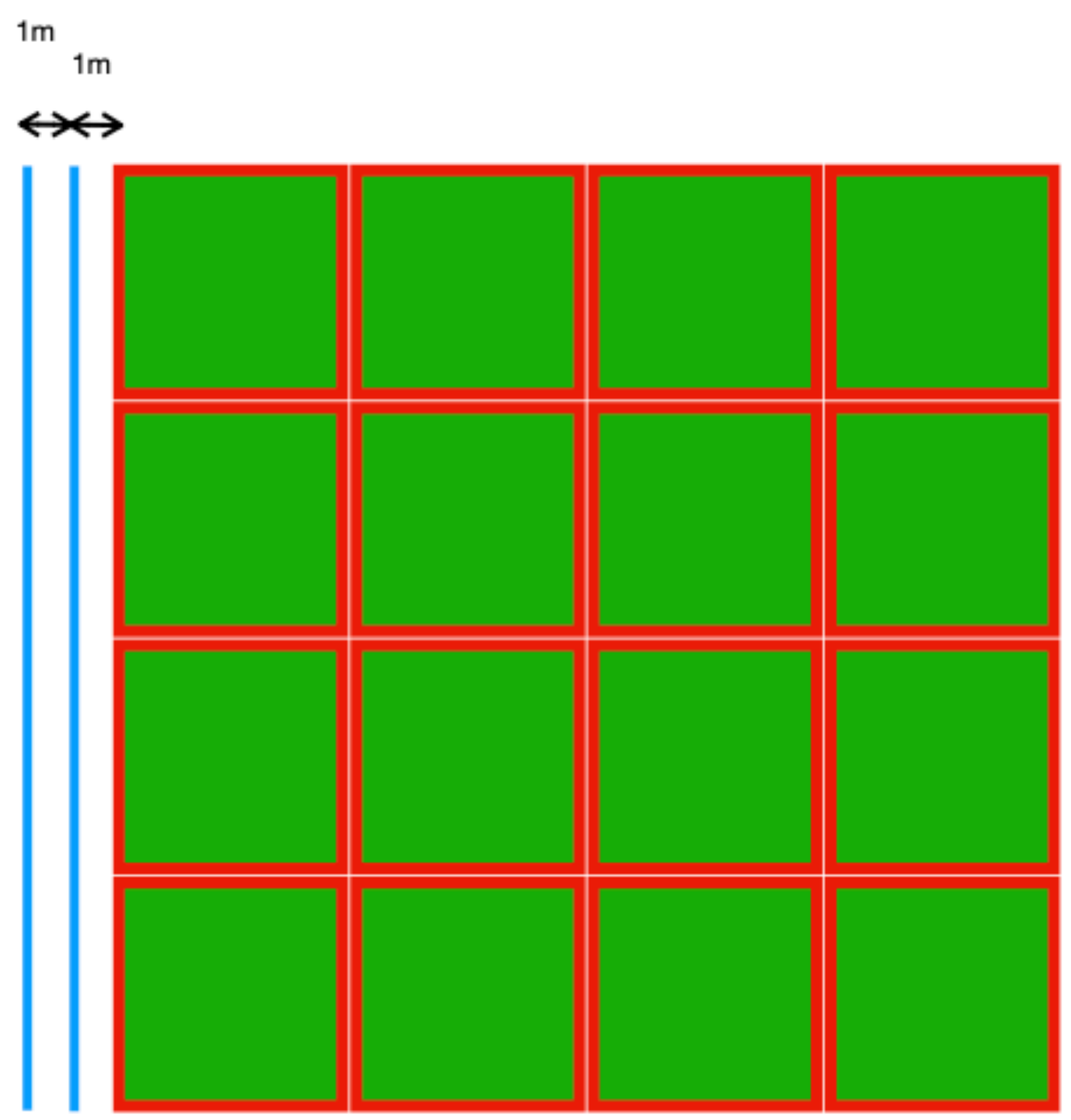
1. MATHUSLA benchmark Geometry (100m x 100m)

- Floor layer: 10m x10m modules, no gap
- Other layers: 9m x 9m modules, 1m gap
- Front layers (vertical): span the entire height, no gaps

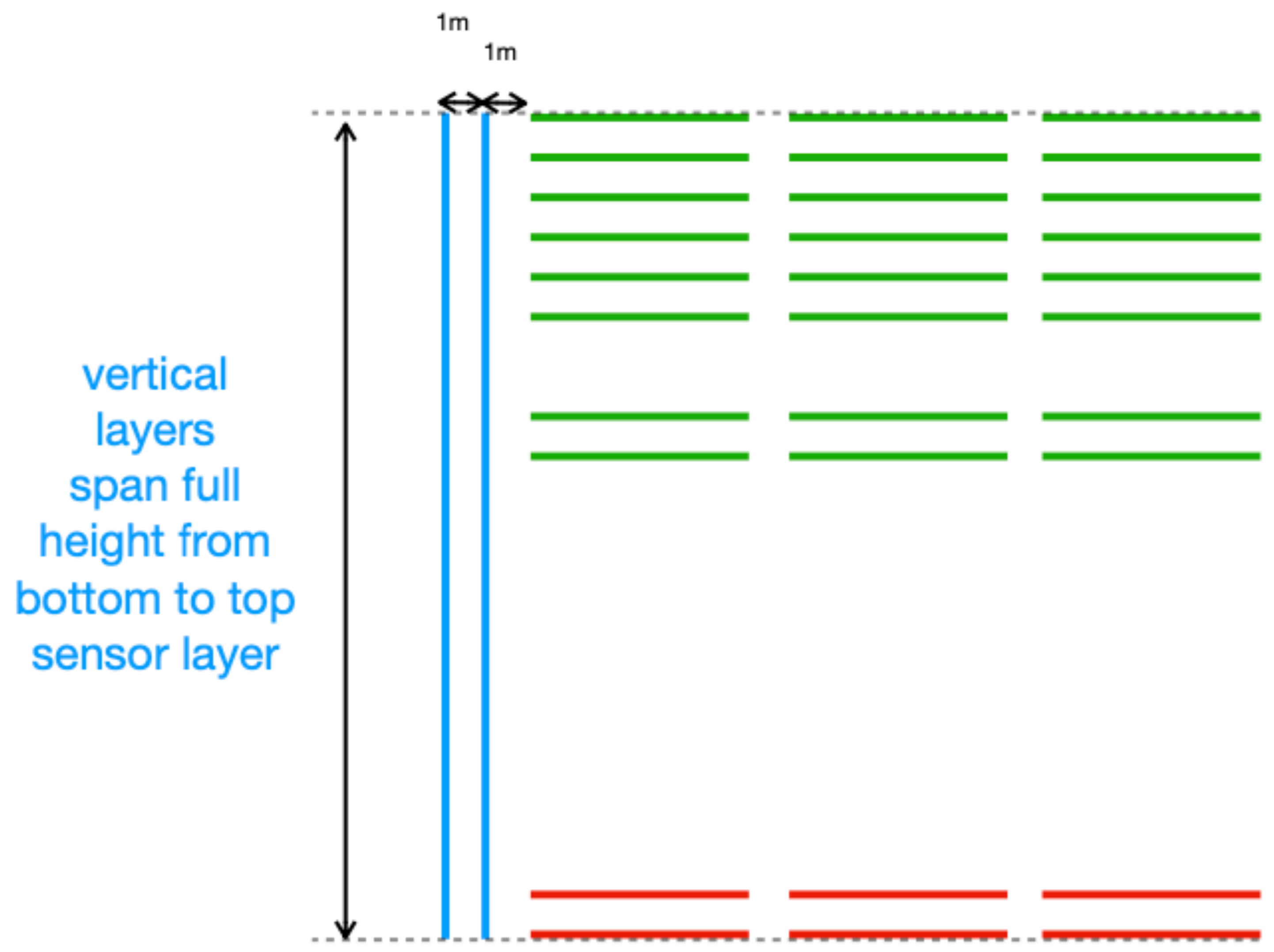
2. Reconstruction Criteria **“DV2 (DV3)”**

- **2+ (3+) charged tracks passing 4+ layers - “recon”**

top-down view

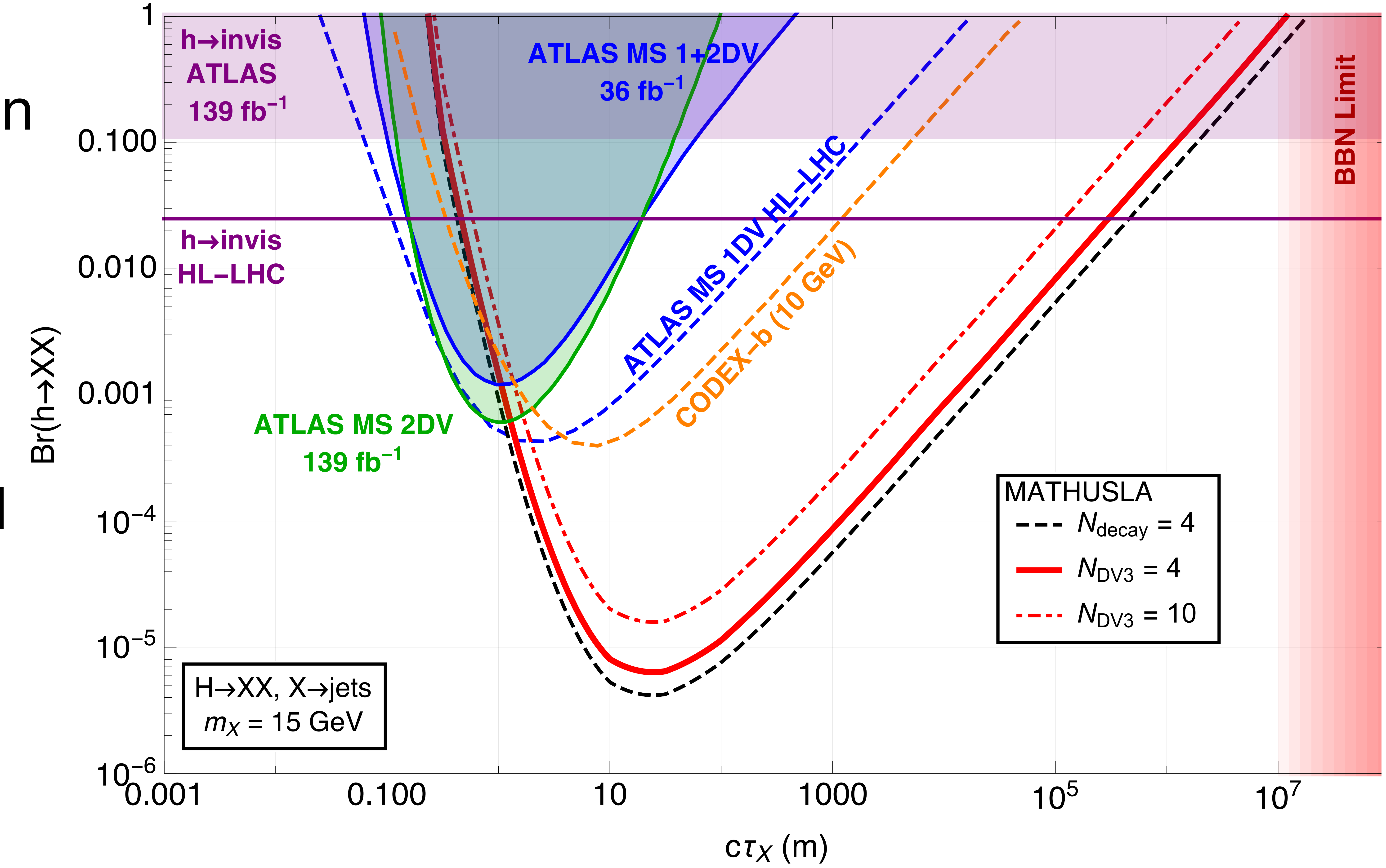


side view



Primary Physics Case: $h \to XX, X \to jj$

- Simulate LLP production and decay in MadGraph5 + Pythia8 + Delphes
- Obtained expected ξ^{geo}_{decay} **~ 70-80+%** (increases with LLP mass)
- Doesn't vary much between DV2 and DV3 given high multiplicity - so we show DV3 data, which is highly BG resilient



Secondary Physics Case: SM + singlet scalar S

- Consider SM + long-lived light scalar mixing with Higgs

$$\mathcal{L}_{scalar} = \mathcal{L}_{kin} - \frac{1}{2}\epsilon S^2 H^\dagger H + \frac{1}{2}\mu_S S^2 - \frac{\lambda_s}{4!}S^4 + \mu_H^2 H^\dagger H - \lambda_H \left(H^\dagger H\right)^2$$

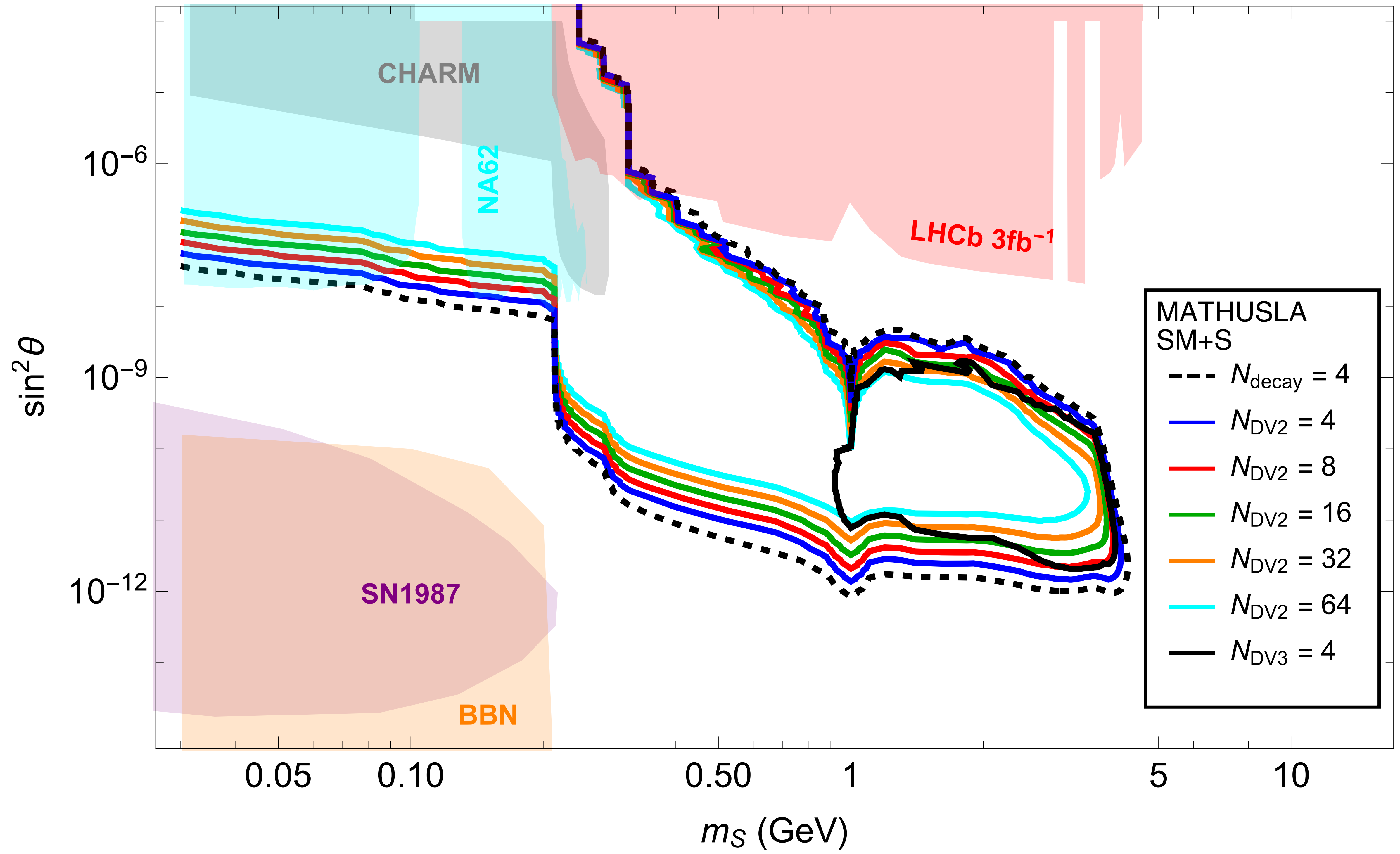
- In the $\epsilon \to 1$ limit, obtain mixing between two scalars, $\sin\theta = \frac{\epsilon v_h v_s}{m_h^2 - m_s^2} + \mathcal{O}(\epsilon^3)$

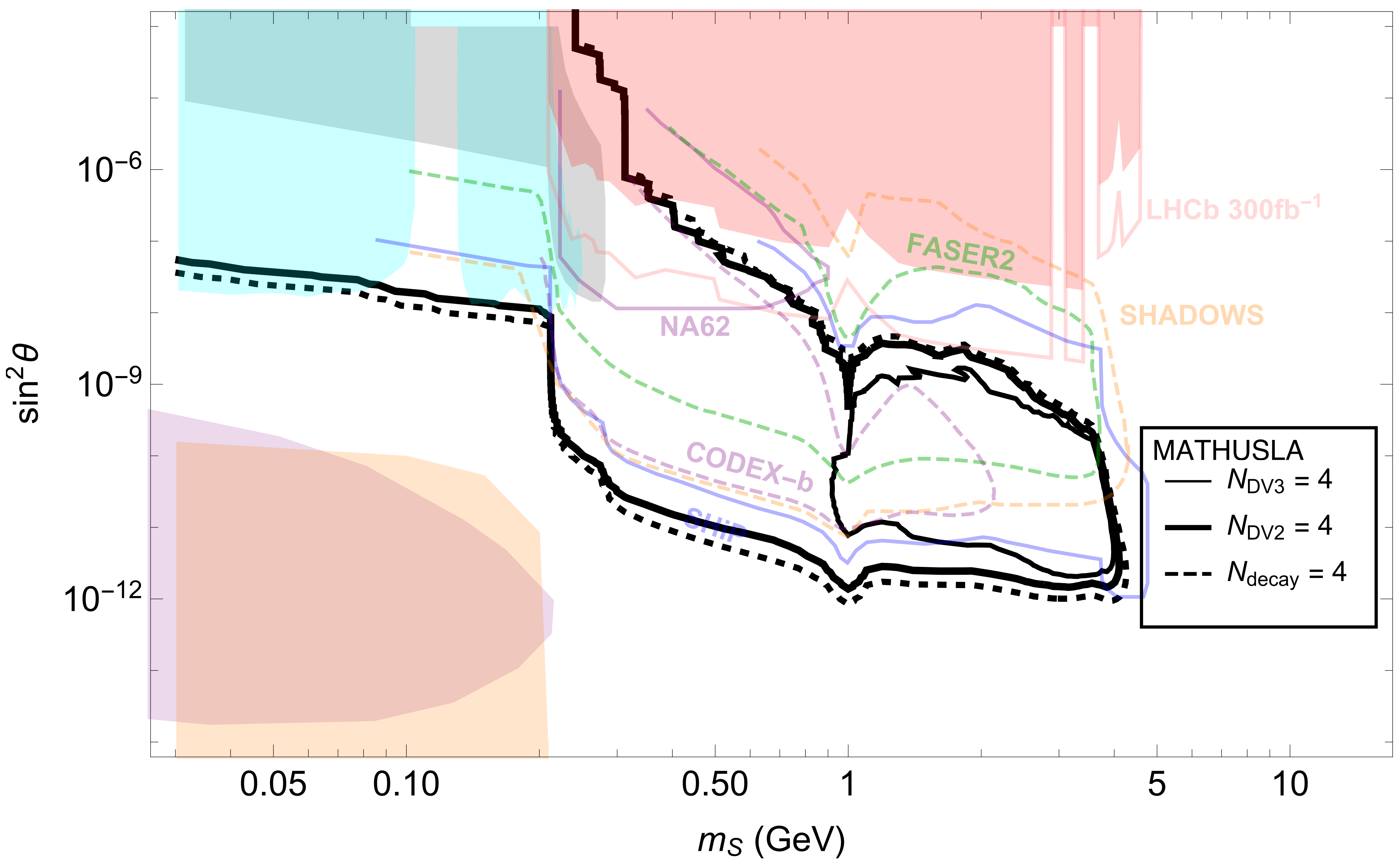
Simulating LLP production and decay for FastSIM

- Produced in B-decays, used FONLL differential meson cross sections as B meson Monte Carlo generator, then decayed to LLP.

- S decays are tricky - used Boiarska et al. (1904.10447) to get possible branching ratios to weigh different decay processes for S obtained via 2-body decays or MadGraph + Pythia (for masses above 0.7 GeV)

Secondary Physics Case: SM + singlet scalar S





- Obtained ξ_{DV2}^{geo} **~ 50%** (for low masses due to high collimation of the 2 final states; above 1 GeV due to hadronic decays turning on) and **max** ξ_{DV3}^{geo} **~ 40%** (once hadronic multi-body decays turn on)

Key-point: MATHUSLA + FASER2 gives good coverage for mixing angles below projected LHCb sensitivity.

Secondary Physics Case: Right-Handed Neutrino (RHN)

- Consider SM + long-lived Right Handed Neutrino (or Heavy Neutral Lepton)

$$\mathcal{L}_{\text{vector}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} + \sum F_{\alpha I}(\bar{L}_\alpha H)N_I$$

- The neutrino mixing is parametrized by the mixing angle $U_{\alpha I} = F_{\alpha I}/\sqrt{2}v$, where v is the Higgs vev.

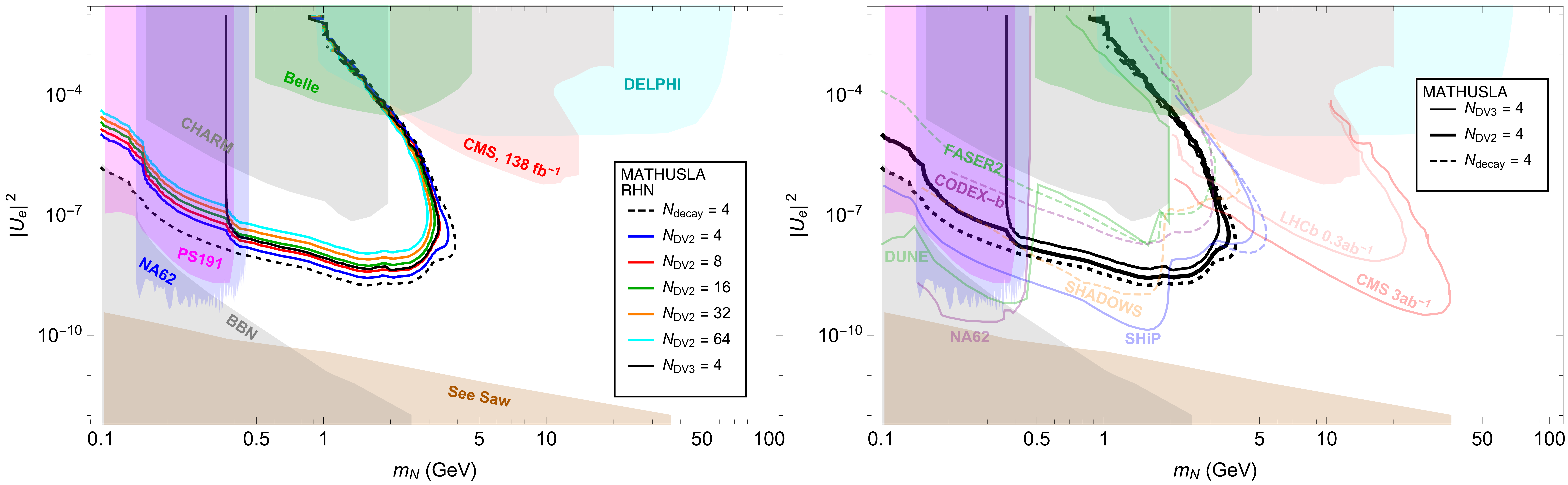
- Assume $U_e = 1, U_\mu = U_\tau = 0$ (other benchmarks in progress)

Simulating LLP production and decay for FastSIM

- Produced in B- and D-meson decays, again use FONLL as Monte Carlo generator.

- Again hadronic decays in the GeV mass range have uncertainty. Used Bondarenko et al. (1805.08567) to get possible decays and branching ratios for RHN decays via MadGraph + Pythia (similar to SM+S)

Secondary Physics Case: Right-Handed Neutrino (RHN)



- Obtained ξ^{geo}_{DV2} **~ 50% above 0.5 GeV** (once hadronic multi-body decays turned on) , **~10% for lower masses.** ξ^{geo}_{DV3} **~ 20% above 0.5 GeV** (4+ charged particle production threshold)

- Constraint is a little less sensitive than previous one in the Physics Beyond Colliders (PBC) report (1901.09966) - might be because we used more realistic RHN production simulation.

Conclusions

- Reach is **not significantly affected** by the realistic geometric acceptances of the LLP decay products
- Even a search that requires **3-pronged DV (i.e. DV3 criteria) would still give good sensitivity**
- This is welcome insurance, because while the collaboration expects zero background for 2-pronged DV search (DV2), the relevant background veto studies are still in progress, and the **DV3 search is even more robust against possible backgrounds.**