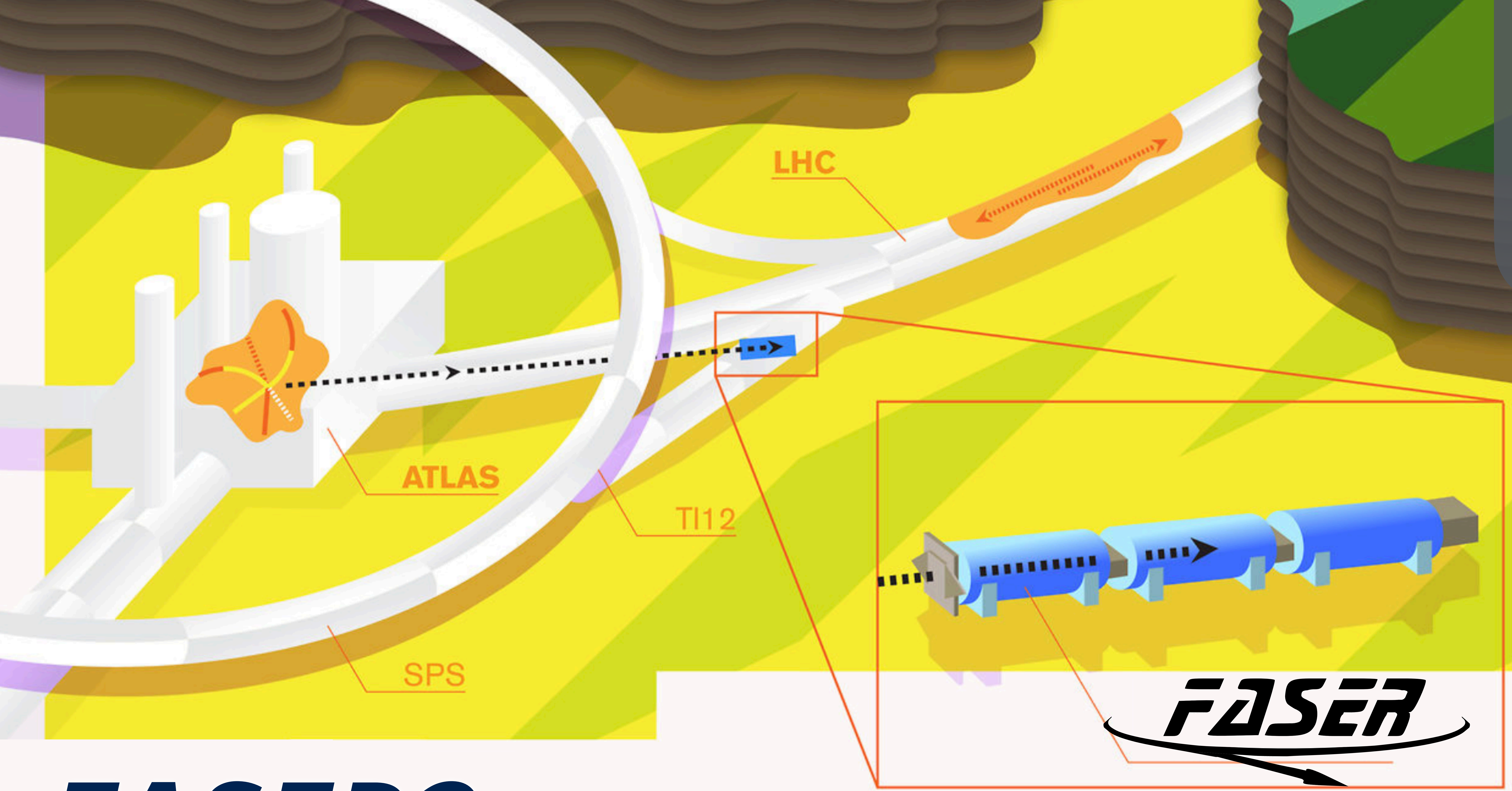

FASER2

FPF Workshop #4

31/1/2022

Alan Barr (Oxford), Jamie Boyd (CERN),
Jonathan Feng (UCI), Felix Kling (DESY),
Josh McFayden (Sussex)

UNIVERSITY OF SUSSEX

THE ROYAL SOCIETY

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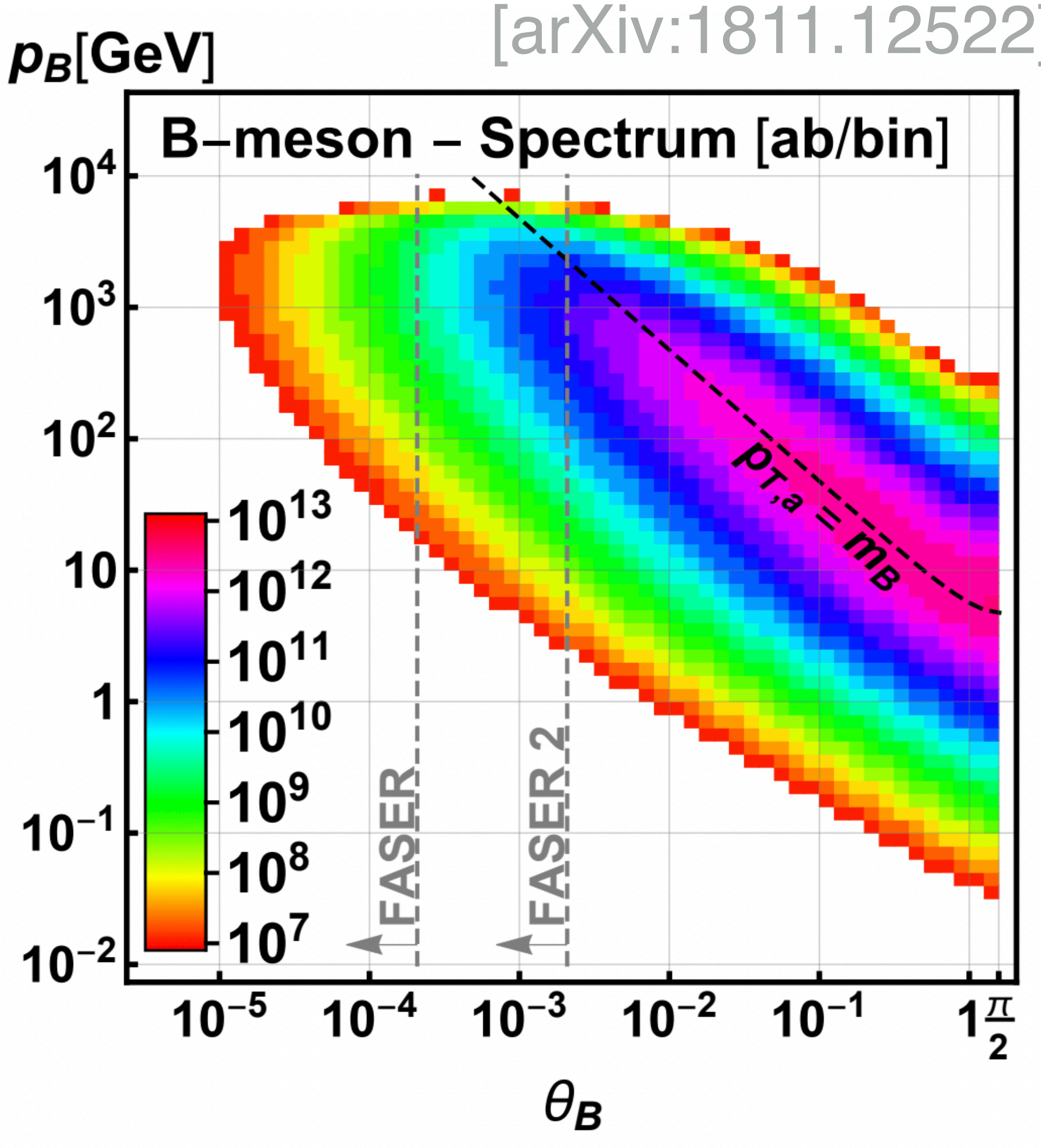
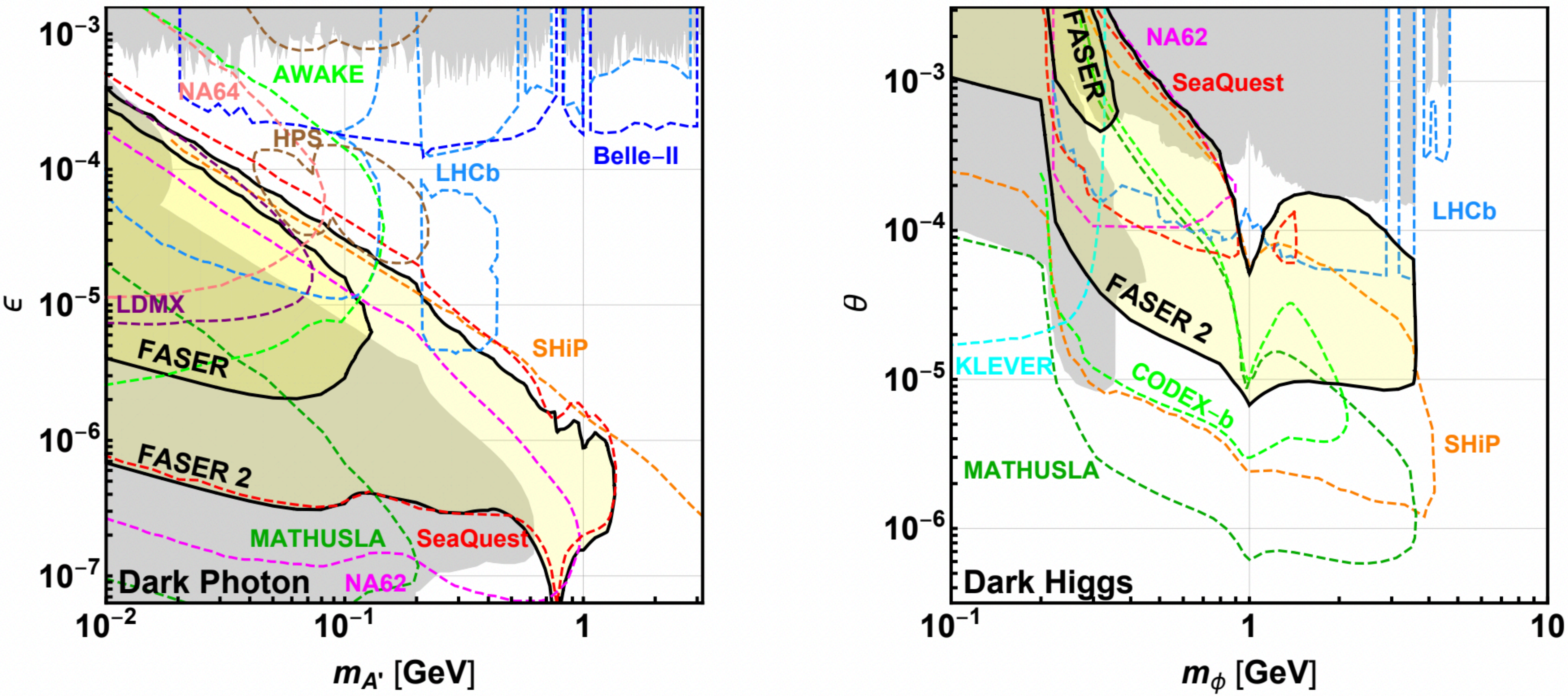
FASER Upgrade for HL-LHC

- The existing FASER experiment is already set to probe new phase space.
- But FASER's size is heavily constrained by the available space underground
- The potential reach with an enlarged detector "FASER2" is under study
  - Decay Volume: Length=5m, Diameter=2m
- 4 orders of magnitude improvement in Reach
  - Angular acceptance of of all neutral pions:
    - 0.6% in FASER
    - 10% in FASER2
  - Improves sensitivities to LLPs produced in decays of heavy mesons
  - Improves sensitivity to larger LLP masses
- FASER already starting to give prood-of-principle of detector design and philosophy!

[arXiv:1811.12522]

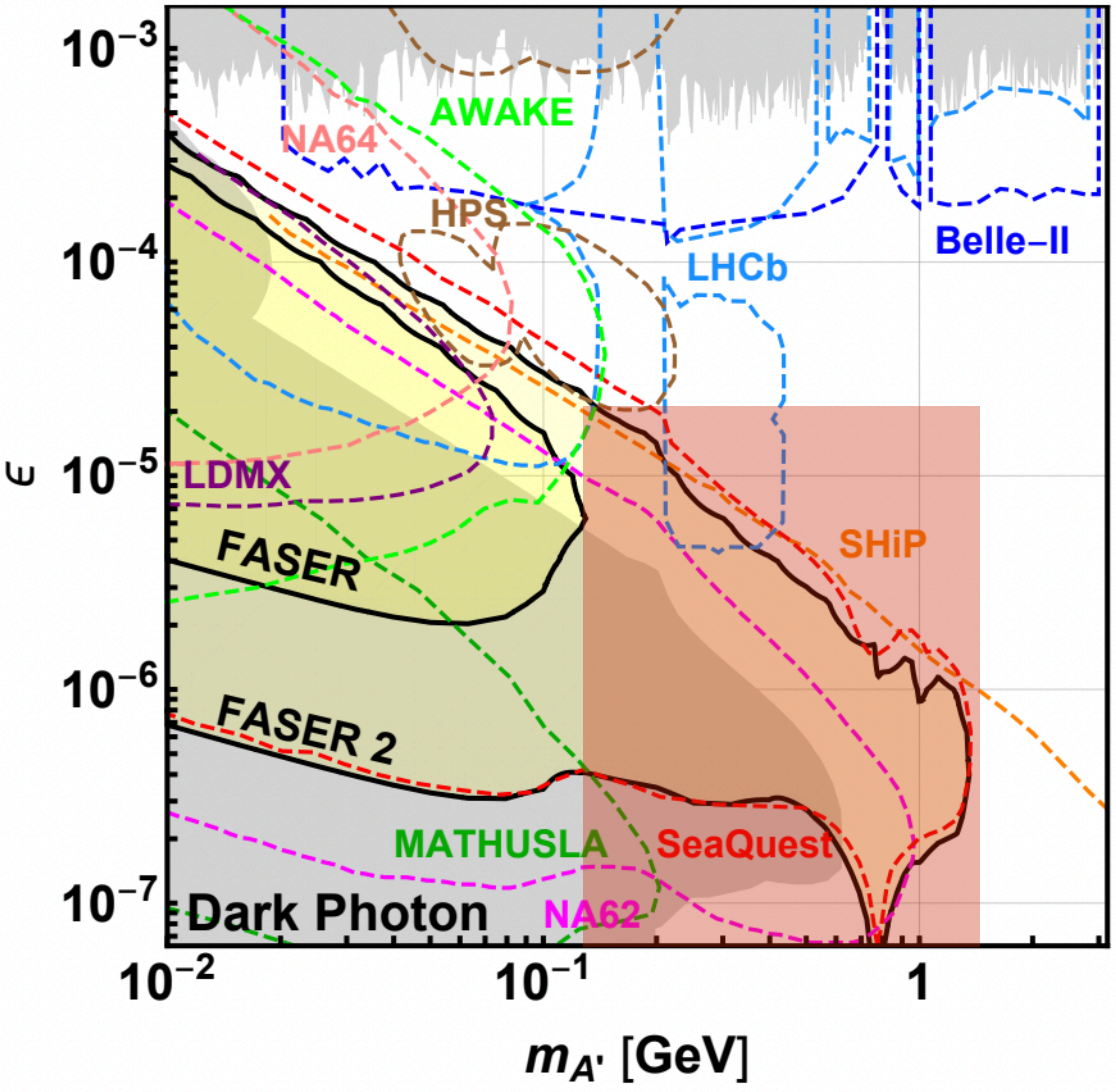


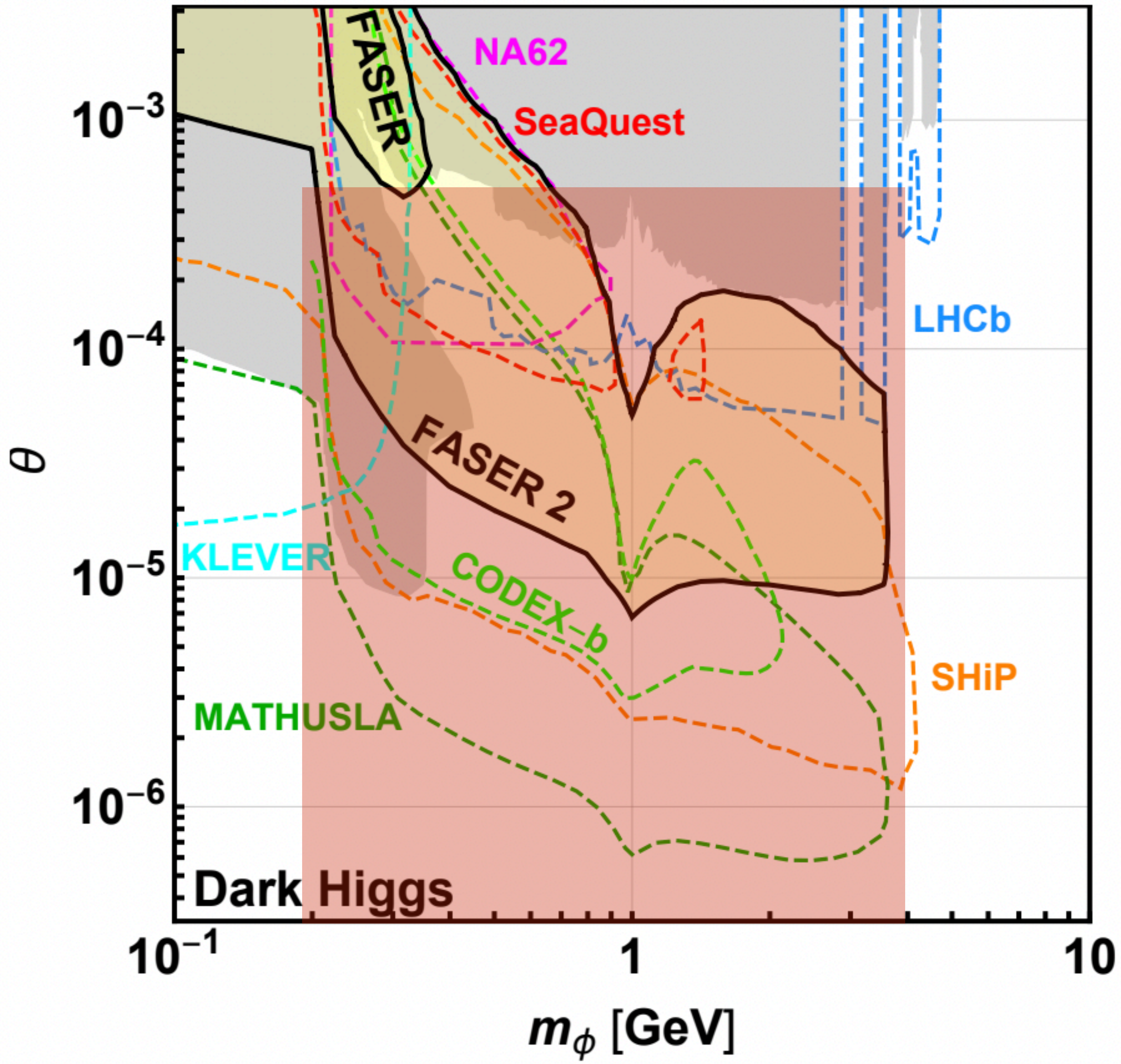
FASER2 Reach



[arXiv:1811.12522]

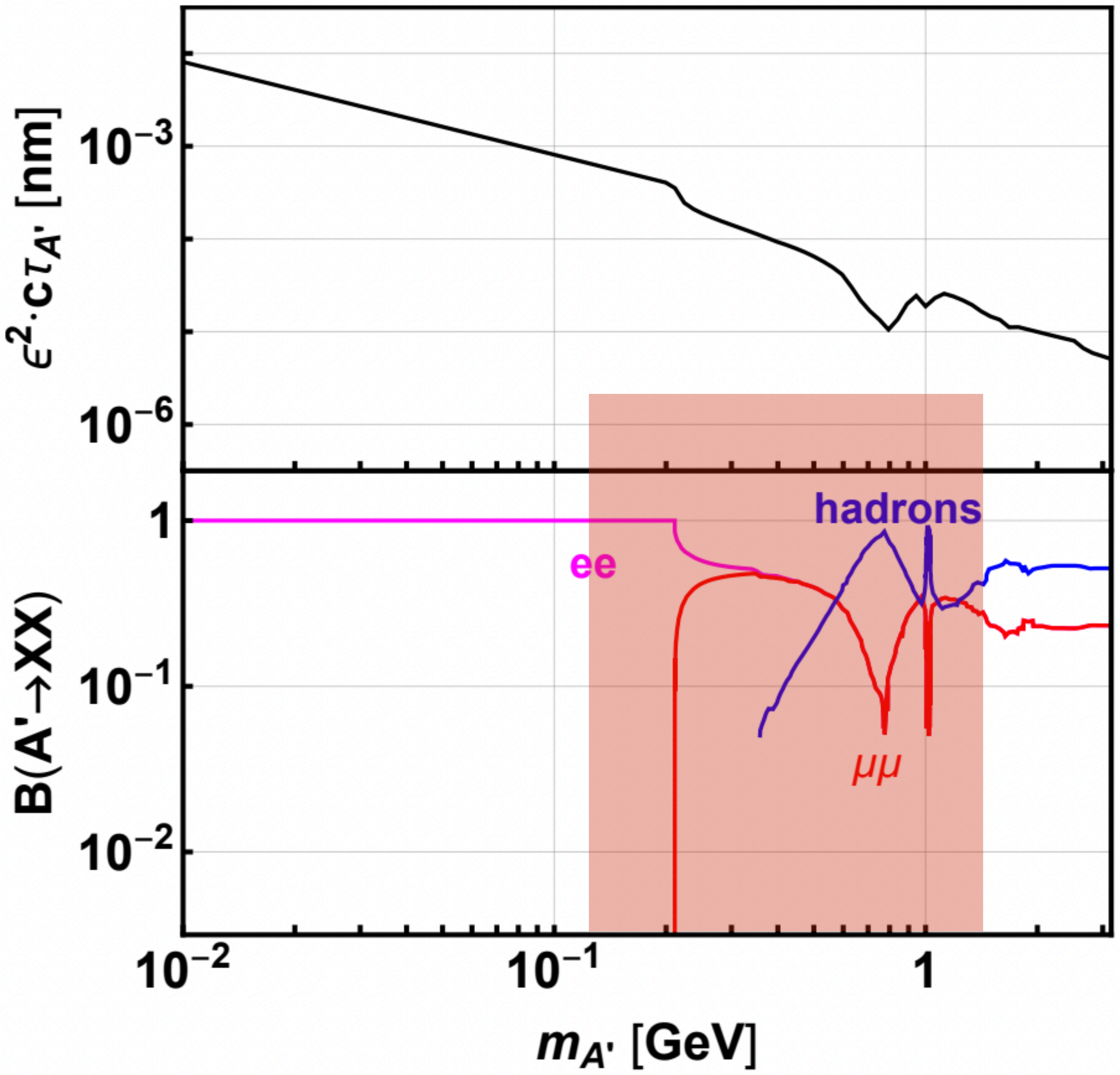
FASER2 Reach

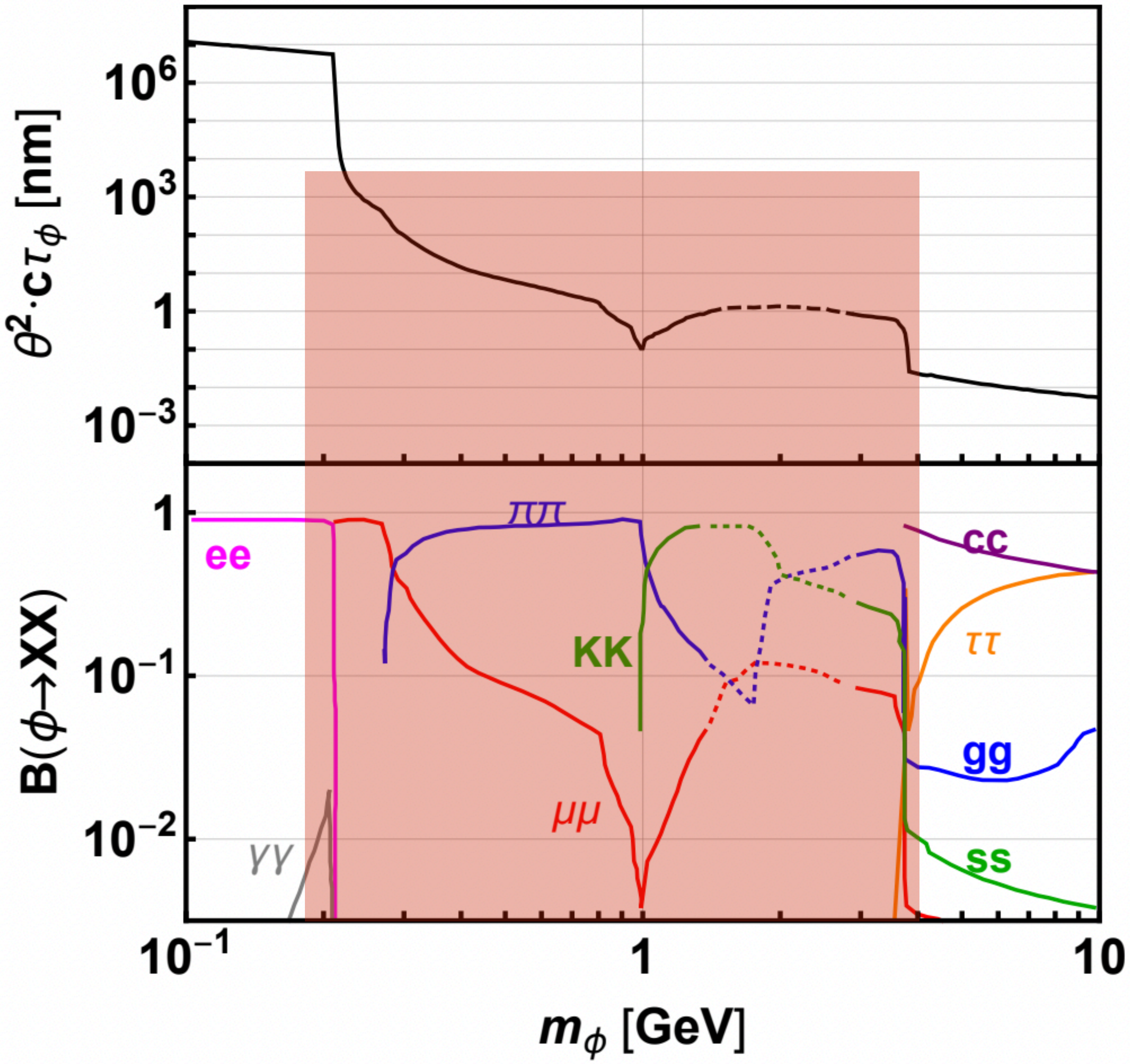




[arXiv:1811.12522]

FASER2 Reach



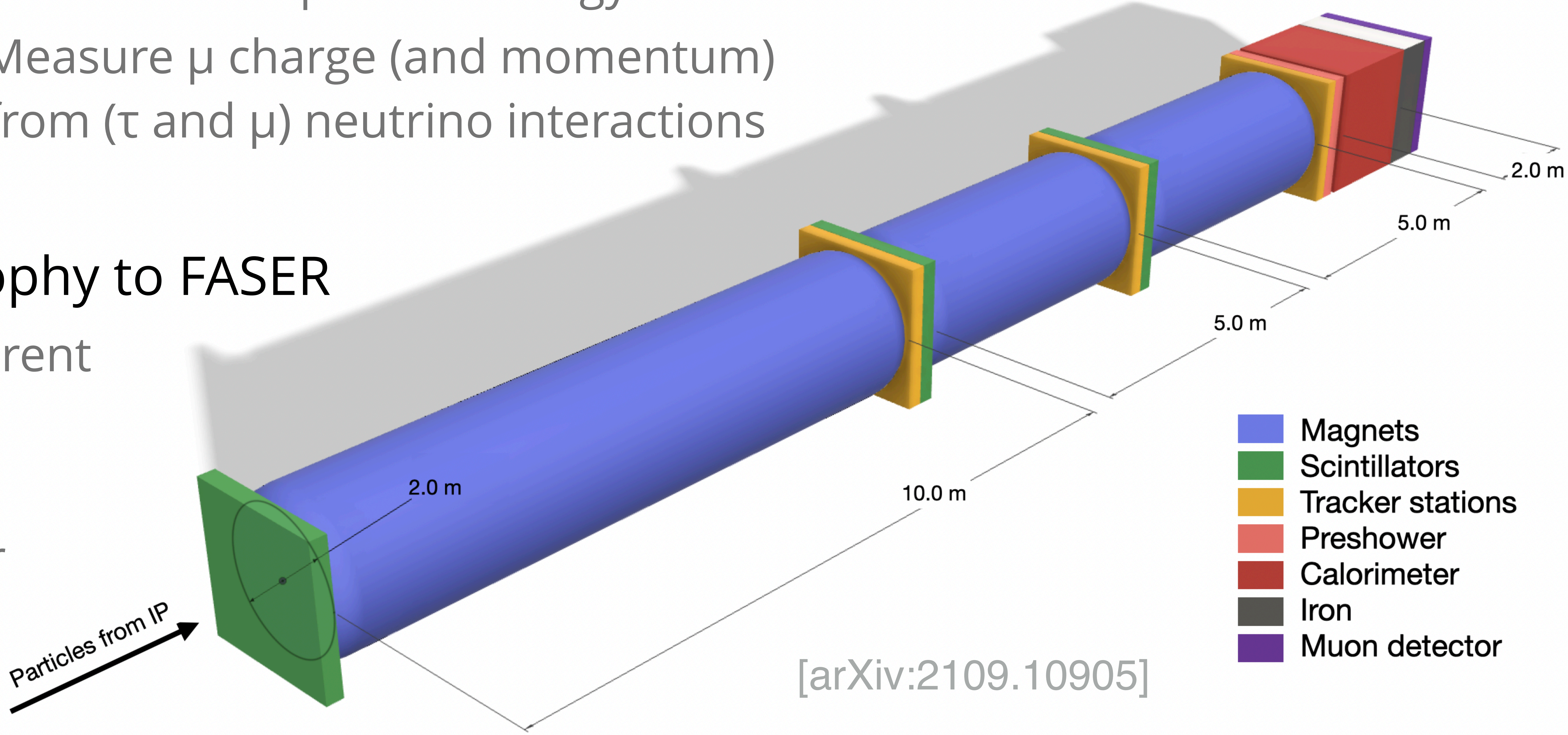


[arXiv:1811.12522]

FASER2 Design

- Design considerations for FASER2
  - Larger radius → Being on-axis less important
  - More decay channels → Need for particle ID
  - Larger detector → Larger background rate
    → Different/cheaper technology
  - Link to FASERν2 → Measure μ charge (and momentum) from (τ and μ) neutrino interactions

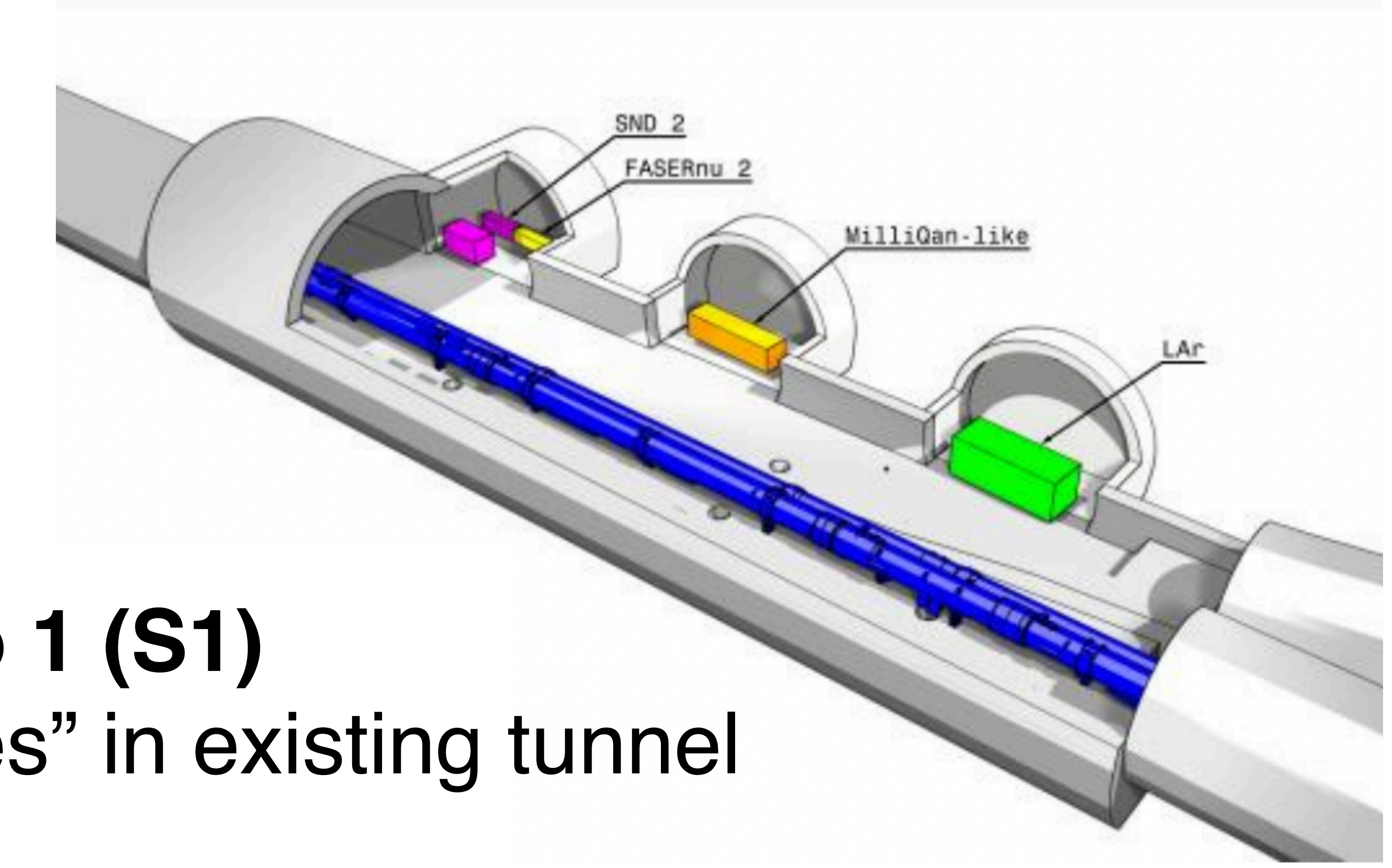
- Will be similar in philosophy to FASER
  - Can be optimised for different FPF scenarios
  - Still much to be studied in terms of possible detector configurations and technologies.



[arXiv:2109.10905]

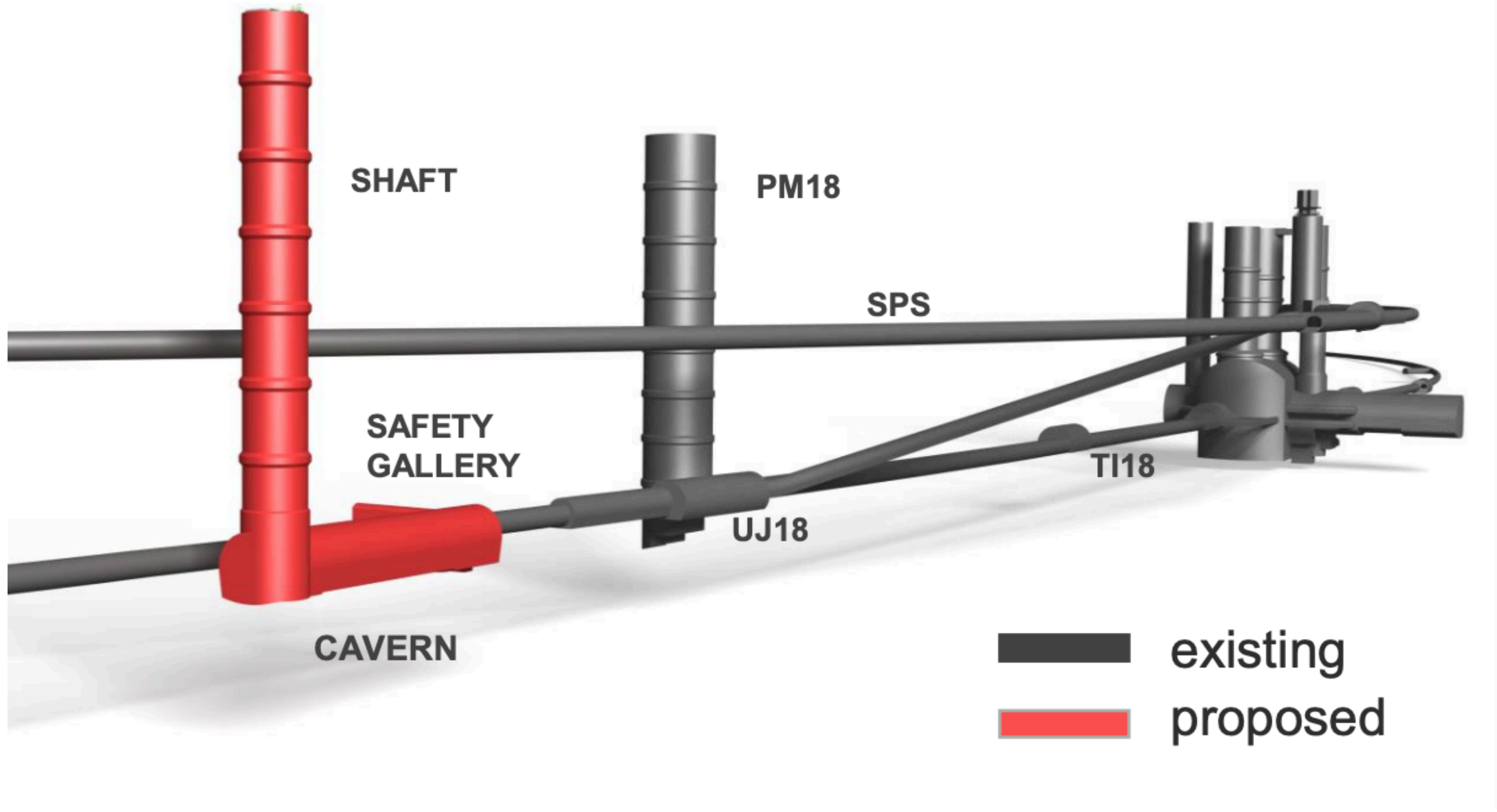
FASER2 Design | Parameters

- Available space for FASER2 based on different facility scenarios:



Scenario 1 (S1)
- "Alcoves" in existing tunnel

Scenario 2 (S2)
- New dedicated cavern



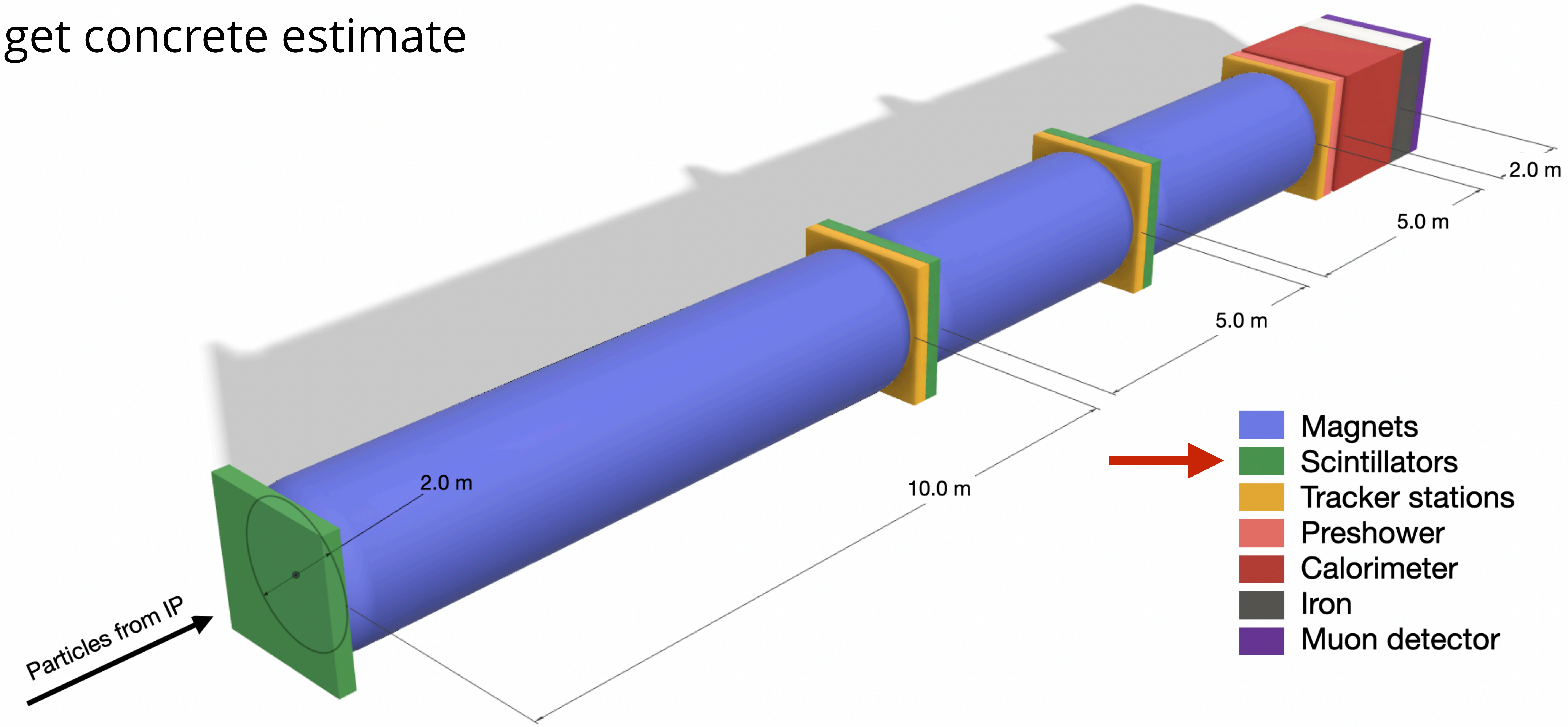
- Possible detector configurations:

Scenario	Distance to IP [m]	Available Length [m]	Decay Volume Length [m]	Available Diameter [m]	Decay Volume Diameter [m]
Original FASER2	480	15	5	2	2 (/ 1 / 0.5)
Alcove (S1)	500	5	1.5 (/ 2)	1.5 (/ 2)	2 / 1 (/ 0.5)
New cavern (S2)	620	25	10 (/ 15 / 20)	2	2 / 1 (/ 0.5)

[arXiv:2109.10905]

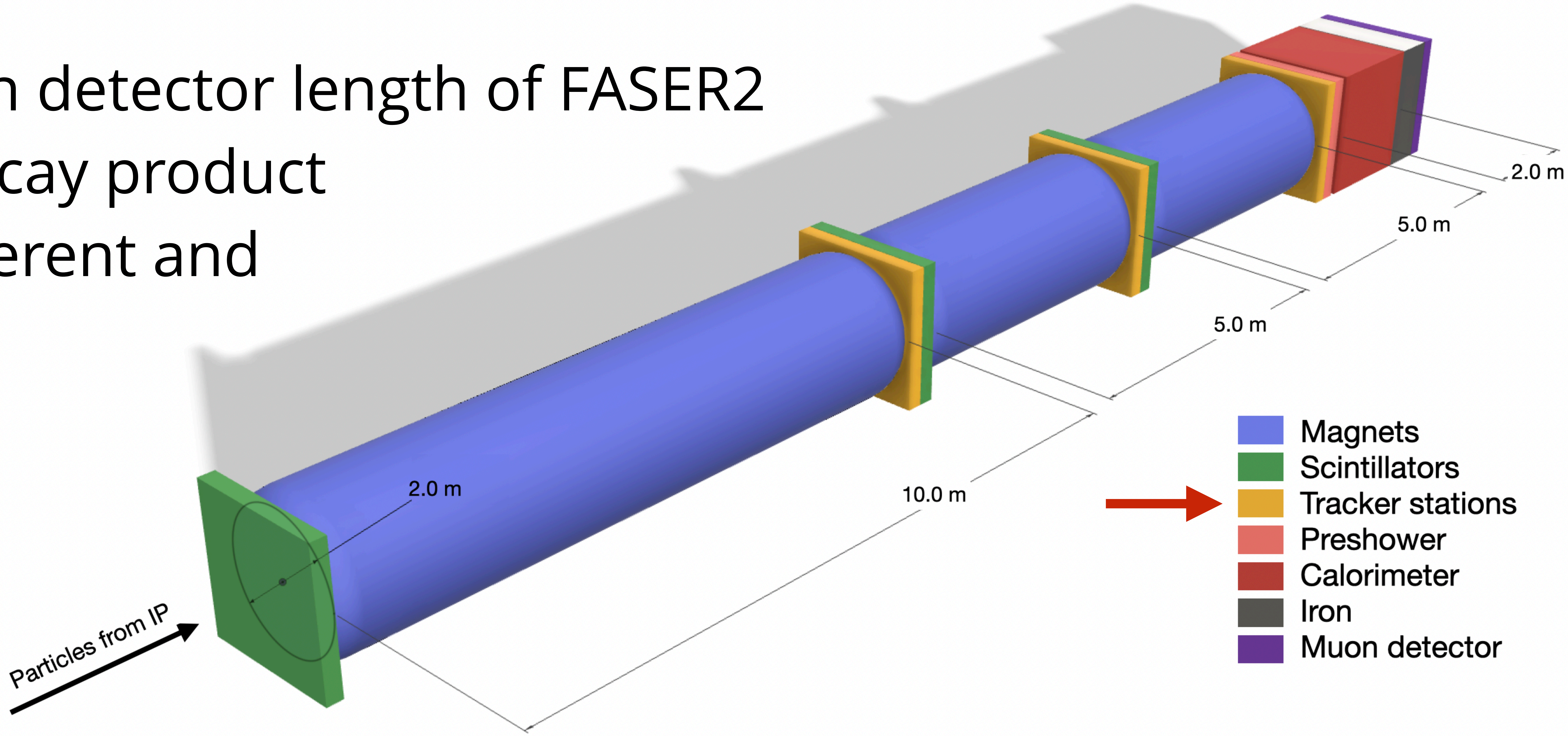
FASER2 Design | Veto

- The veto system will be similar to FASER.
  - Reasonably simple to extend scintillator-based technology to cope with higher muons rates at HL-LHC.
    - Planning to use Fluka to get concrete estimate for muon rate.



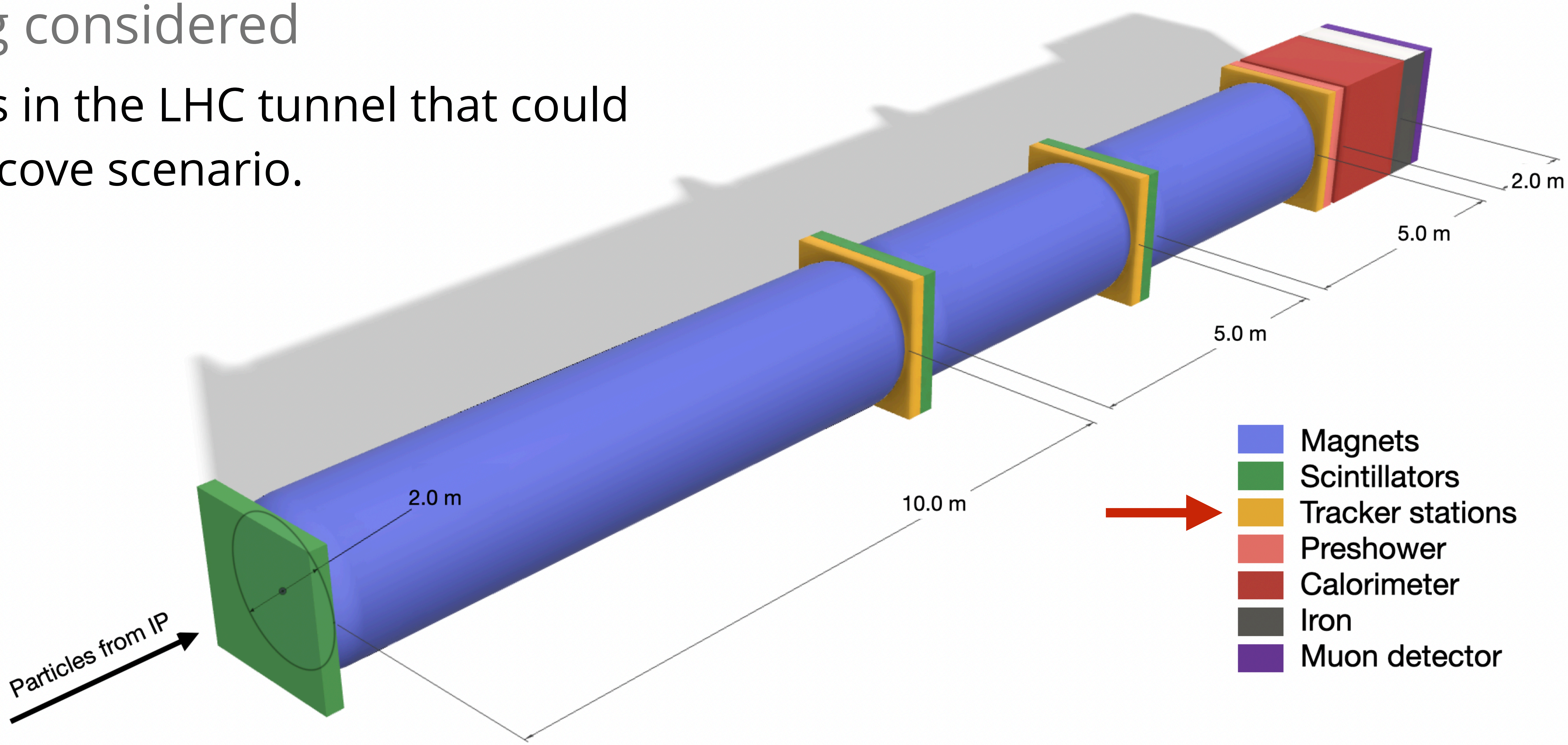
FASER2 Design | Tracking

- Factor 10 increase in radius → 100x increase in area to be instrumented.
- Much more challenging to accommodate extended version of ATLAS SCT tracker module configuration, due to cost and services considerations.
- Significant increase in detector length of FASER2 could allow larger decay product separations with different and possibly cheaper technology.



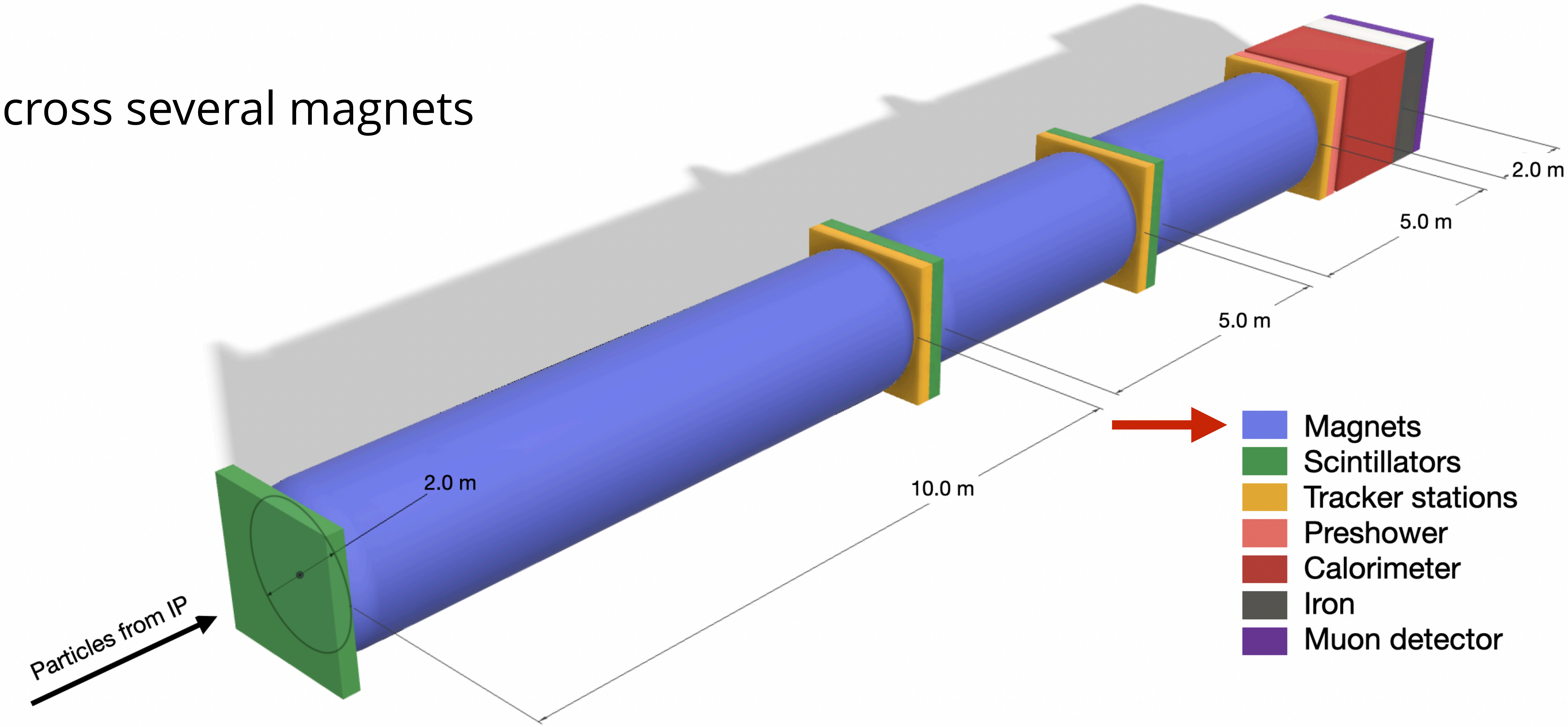
FASER2 Design | Tracker technologies

- There are two current main tracker technology candidates:
  - A SiPM and scintillating fibre tracker technology, such as LHCb's SciFi detector is a strong candidate
  - Monitored Drift Tube (MDT) technology, similar to ATLAS New Small Wheel also being considered
    - Requires the use of gases in the LHC tunnel that could be problematic for the Alcove scenario.



FASER2 Design | Magnets

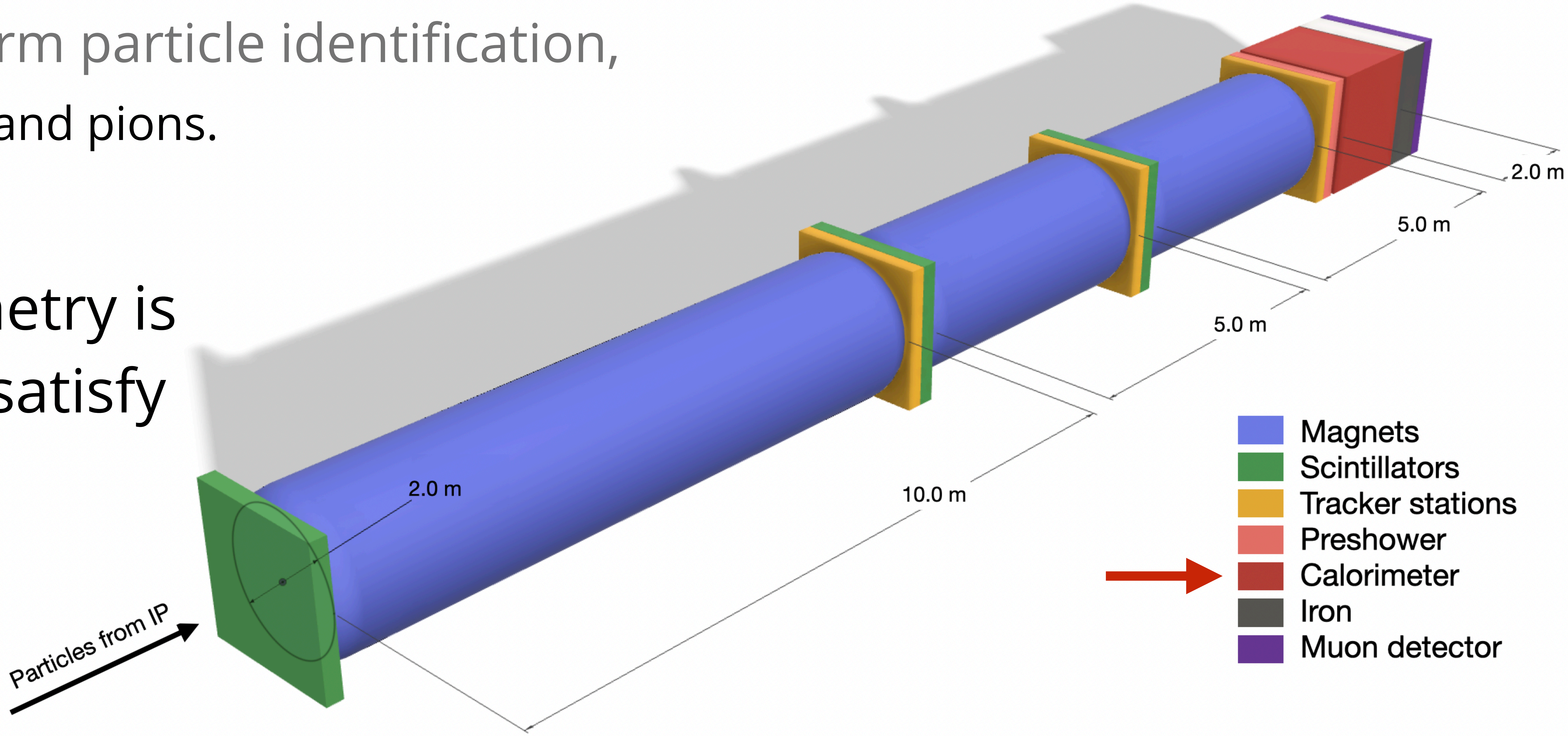
- To maintain sufficient field strength across the much larger aperture superconducting magnet technology is likely to be required
  - Suitable technology for this already exists and can be built for FASER2.
  - Cooling is one of the main obstacles but several possibilities:
    - Use of cryocoolers
    - Share a single cryostat across several magnets



FASER2 Design | Calorimeter

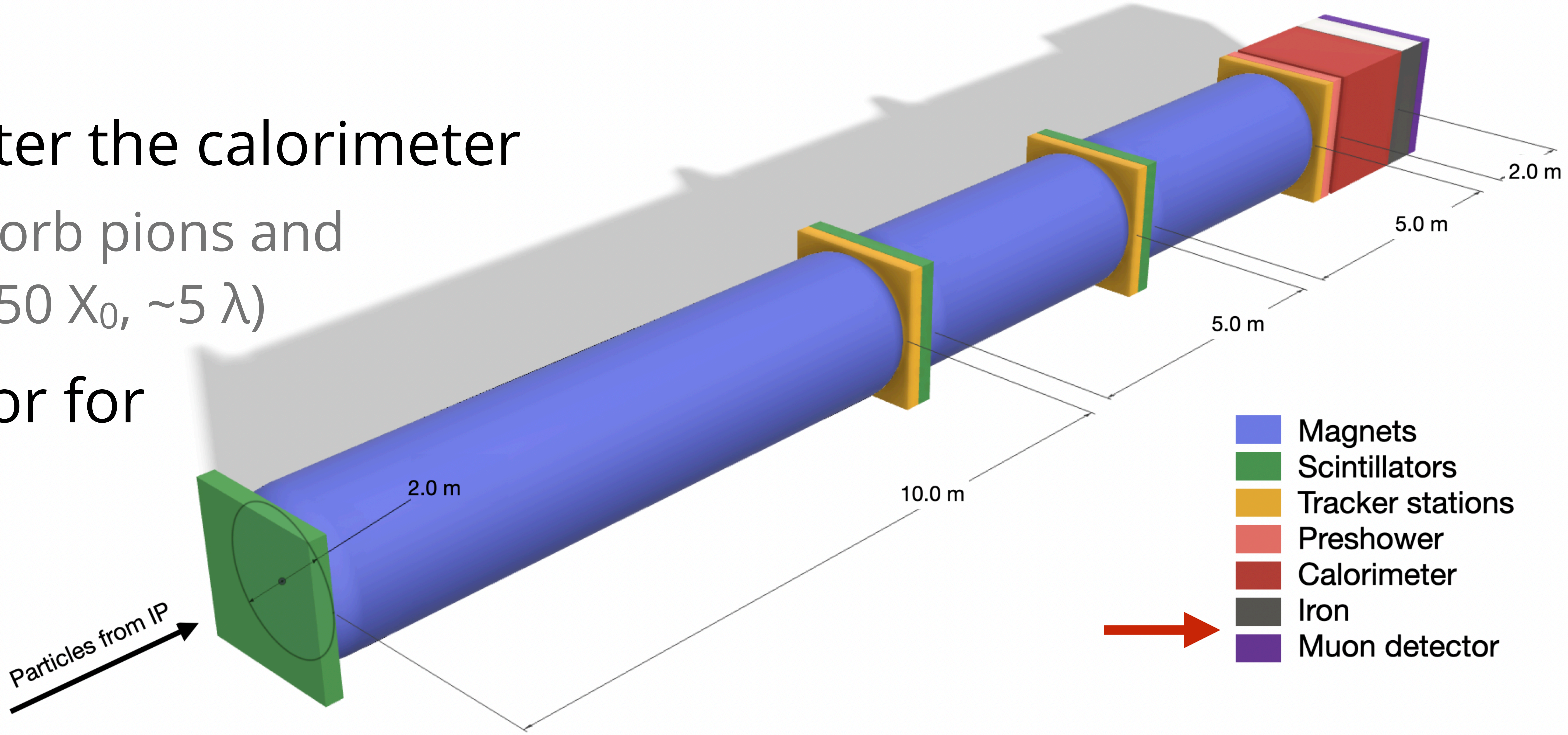
- The calorimeter needs to have:
  - Sufficient spatial resolution to be able to identify particles ~mm-cm separation;
  - Good energy resolution
  - Improved longitudinal separation with respect to FASER
  - The capability to perform particle identification,
    - Separating e.g. electron and pions.

- Dual readout calorimetry is a good candidate to satisfy these requirements.



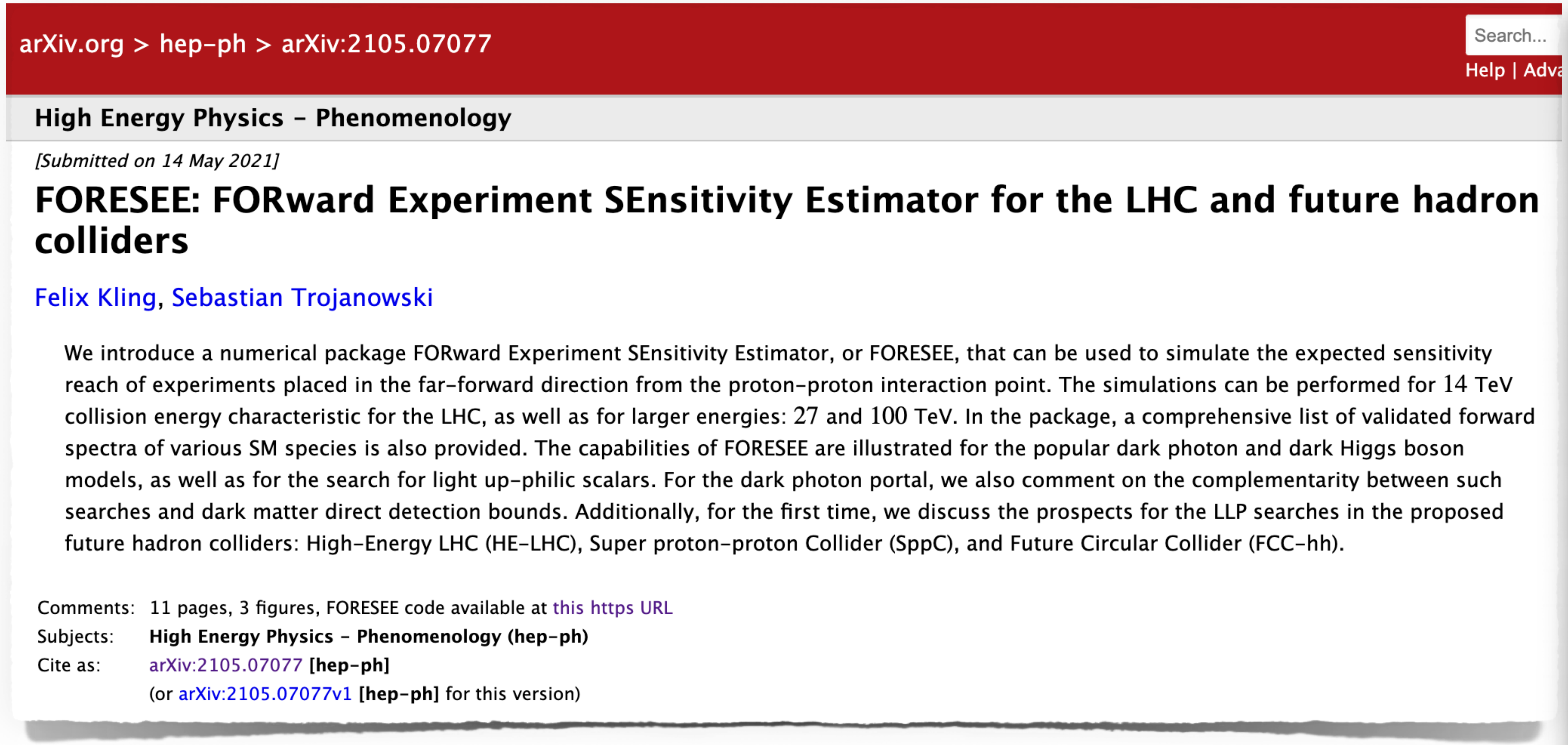
FASER2 Design | Muon ID

- The ability to identify electrons and muons would be important for:
  - Signal characterisation
  - Background suppression
  - The interface with FASERν2
- Iron will be placed after the calorimeter
  - Sufficient depth to absorb pions and other hadrons (~1m ≃ 50 X_0, ~5 λ)
- Followed by a detector for muon identification



FORESEE

- Projections created with the FORSEE tool:
  - Phys. Rev. D 104, 035012
  - https://github.com/KlingFelix/FORESEE



arXiv.org > hep-ph > arXiv:2105.07077

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High Energy Physics – Phenomenology

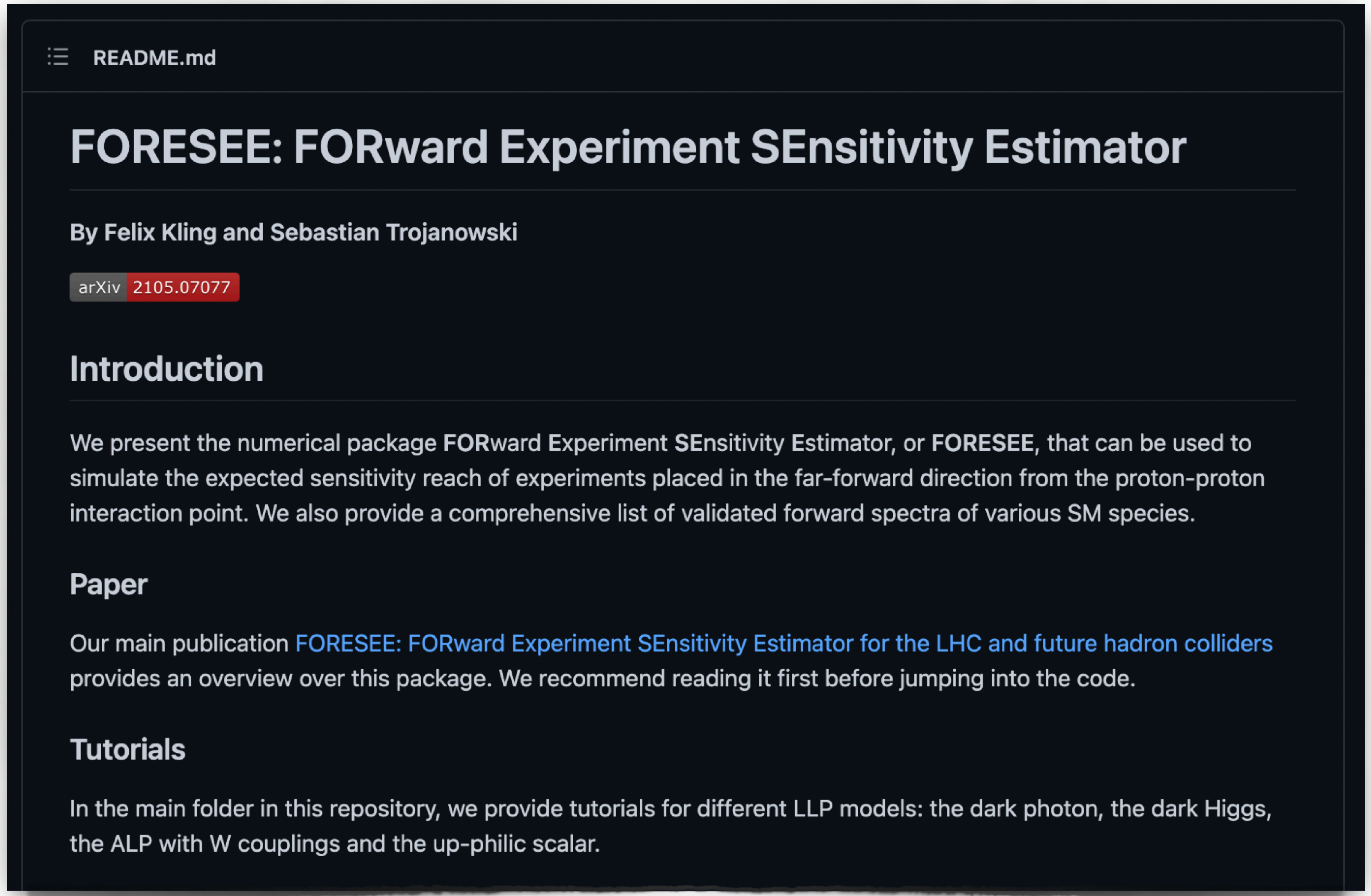
[Submitted on 14 May 2021]

FORESEE: FORward Experiment SEnsitivity Estimator for the LHC and future hadron colliders

Felix Kling, Sebastian Trojanowski

We introduce a numerical package FORward Experiment SEnsitivity Estimator, or FORESEE, that can be used to simulate the expected sensitivity reach of experiments placed in the far-forward direction from the proton-proton interaction point. The simulations can be performed for 14 TeV collision energy characteristic for the LHC, as well as for larger energies: 27 and 100 TeV. In the package, a comprehensive list of validated forward spectra of various SM species is also provided. The capabilities of FORESEE are illustrated for the popular dark photon and dark Higgs boson models, as well as for the search for light up-philic scalars. For the dark photon portal, we also comment on the complementarity between such searches and dark matter direct detection bounds. Additionally, for the first time, we discuss the prospects for the LLP searches in the proposed future hadron colliders: High-Energy LHC (HE-LHC), Super proton-proton Collider (SppC), and Future Circular Collider (FCC-hh).

Comments: 11 pages, 3 figures, FORESEE code available at this https URL
Subjects: **High Energy Physics – Phenomenology (hep-ph)**
Cite as: arXiv:2105.07077 **[hep-ph]**
(or arXiv:2105.07077v1 **[hep-ph]** for this version)



README.md

FORESEE: FORward Experiment SEnsitivity Estimator

By Felix Kling and Sebastian Trojanowski

arXiv 2105.07077

Introduction

We present the numerical package **FOR**ward Experiment **SE**nsitivity Estimator, or **FORESEE**, that can be used to simulate the expected sensitivity reach of experiments placed in the far-forward direction from the proton-proton interaction point. We also provide a comprehensive list of validated forward spectra of various SM species.

Paper

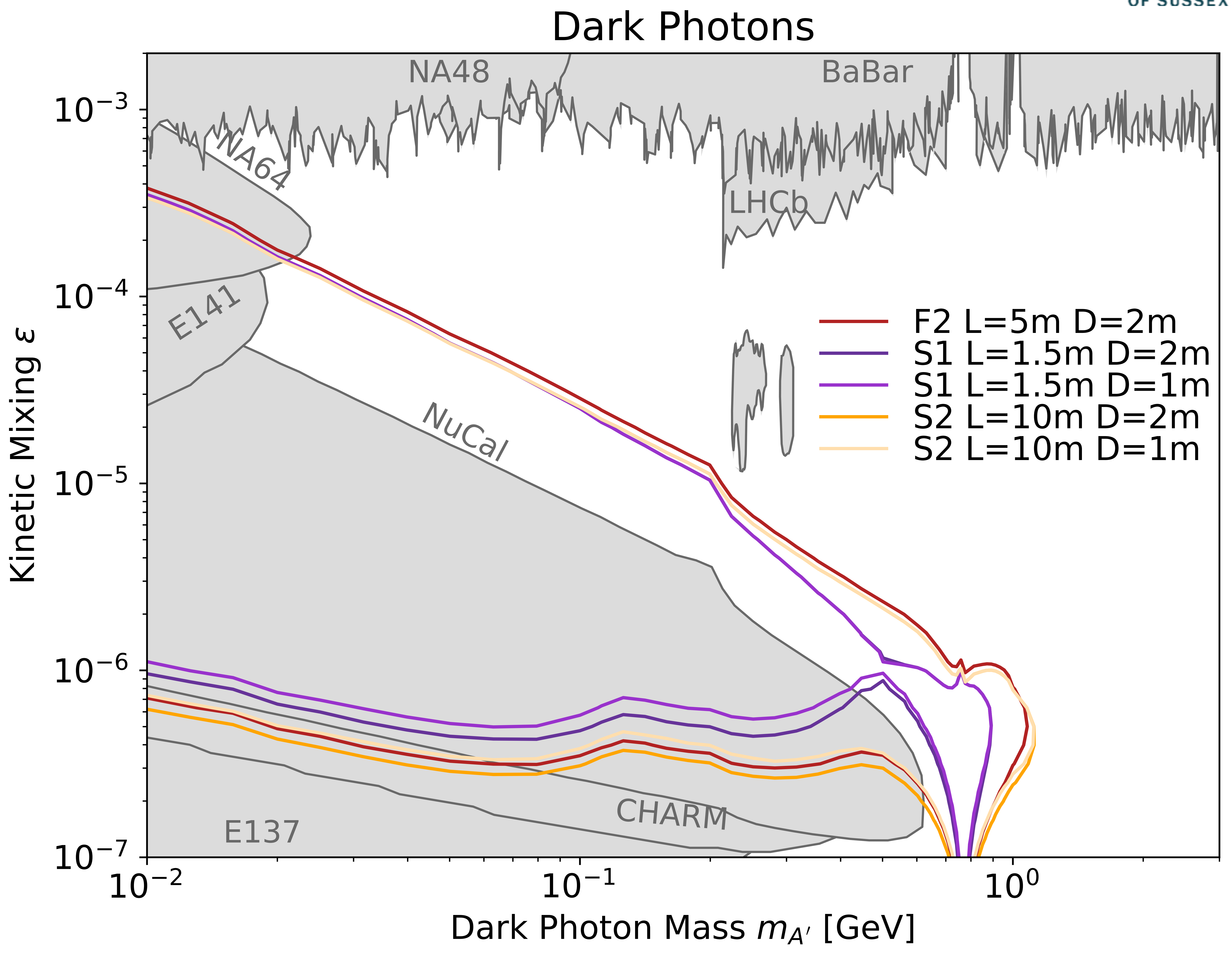
Our main publication FORESEE: FORward Experiment SEnsitivity Estimator for the LHC and future hadron colliders provides an overview over this package. We recommend reading it first before jumping into the code.

Tutorials

In the main folder in this repository, we provide tutorials for different LLP models: the dark photon, the dark Higgs, the ALP with W couplings and the up-philic scalar.

FPF Scenarios | Dark photons

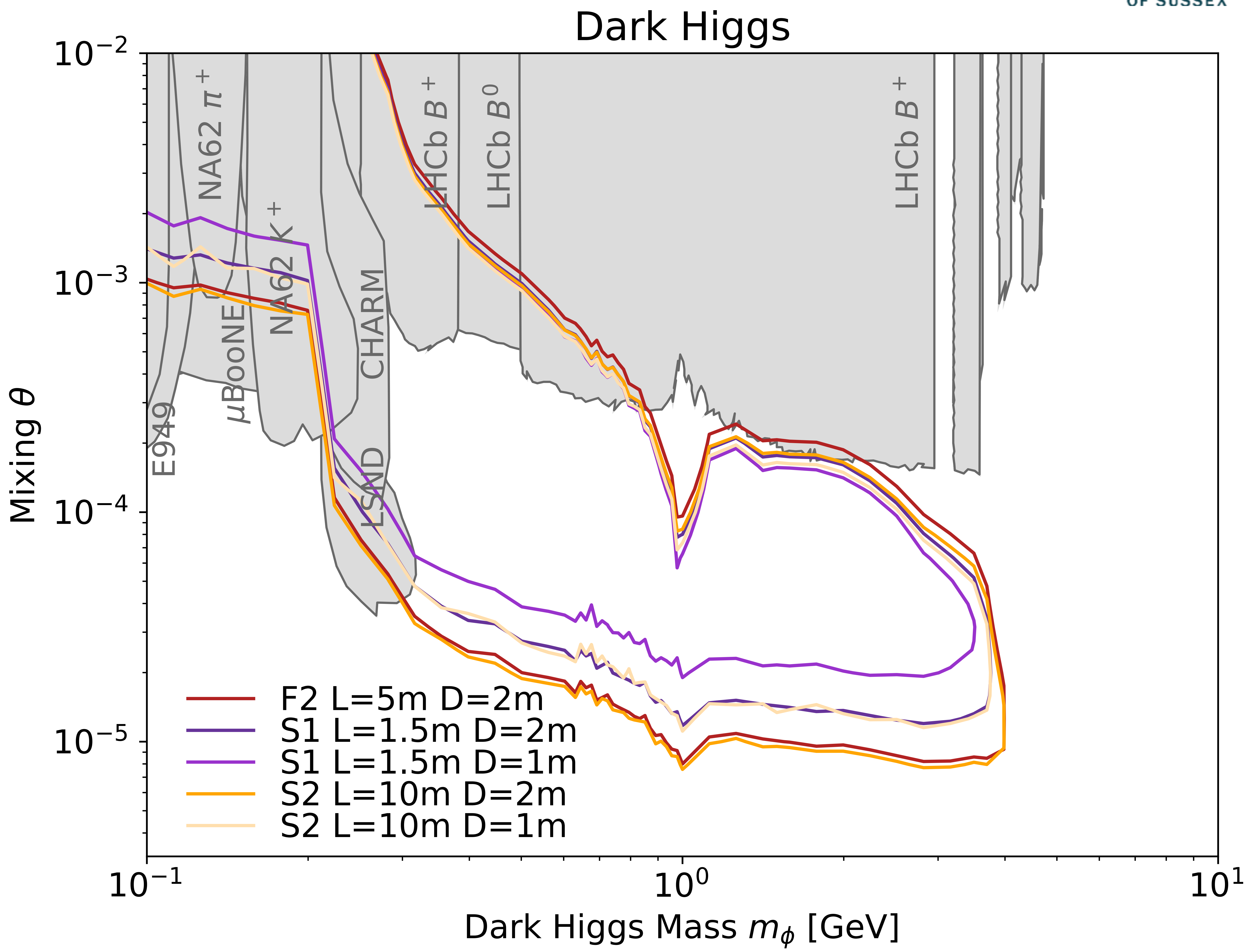
- **FASER2-default**
- **Scenario 1:**
  - Significantly degraded sensitivity due to reduced decay volume length
- **Scenario 2:**
  - Comparable sensitivity to FASER2-default, but somewhat improved due to larger decay volume length.
  - Very small degradation in diagonal due to increased distance from IP.



[arXiv:2109.10905]

FPF Scenarios | Dark Higgs

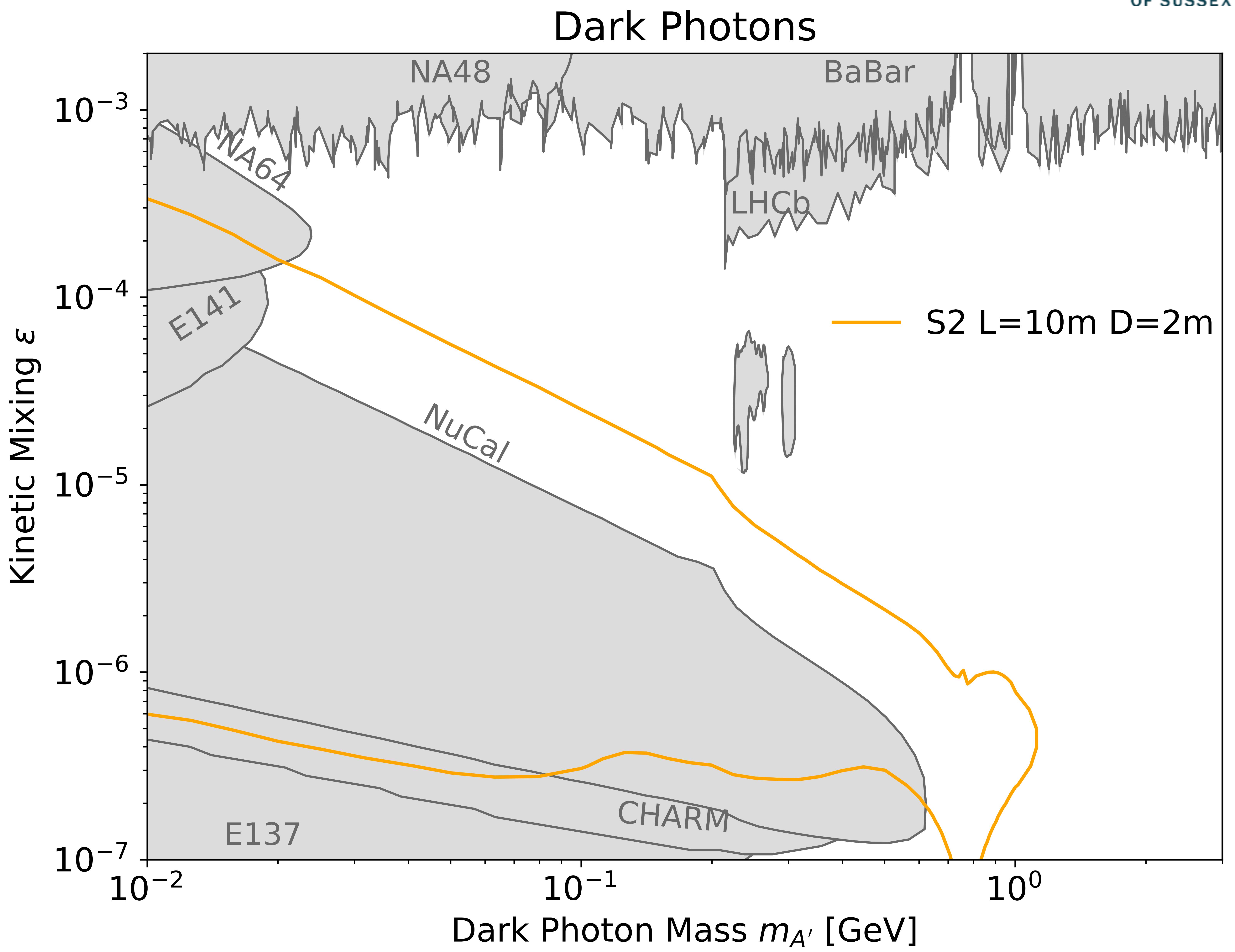
- **FASER2-default**
- **Scenario 1:**
  - Significantly degraded sensitivity due to reduced decay volume length
- **Scenario 2:**
  - Diameter of detector much more important here. Due to larger angle emission from B-hadrons of LLP.



[arXiv:2109.10905]

FPF Scenarios | Dark photons

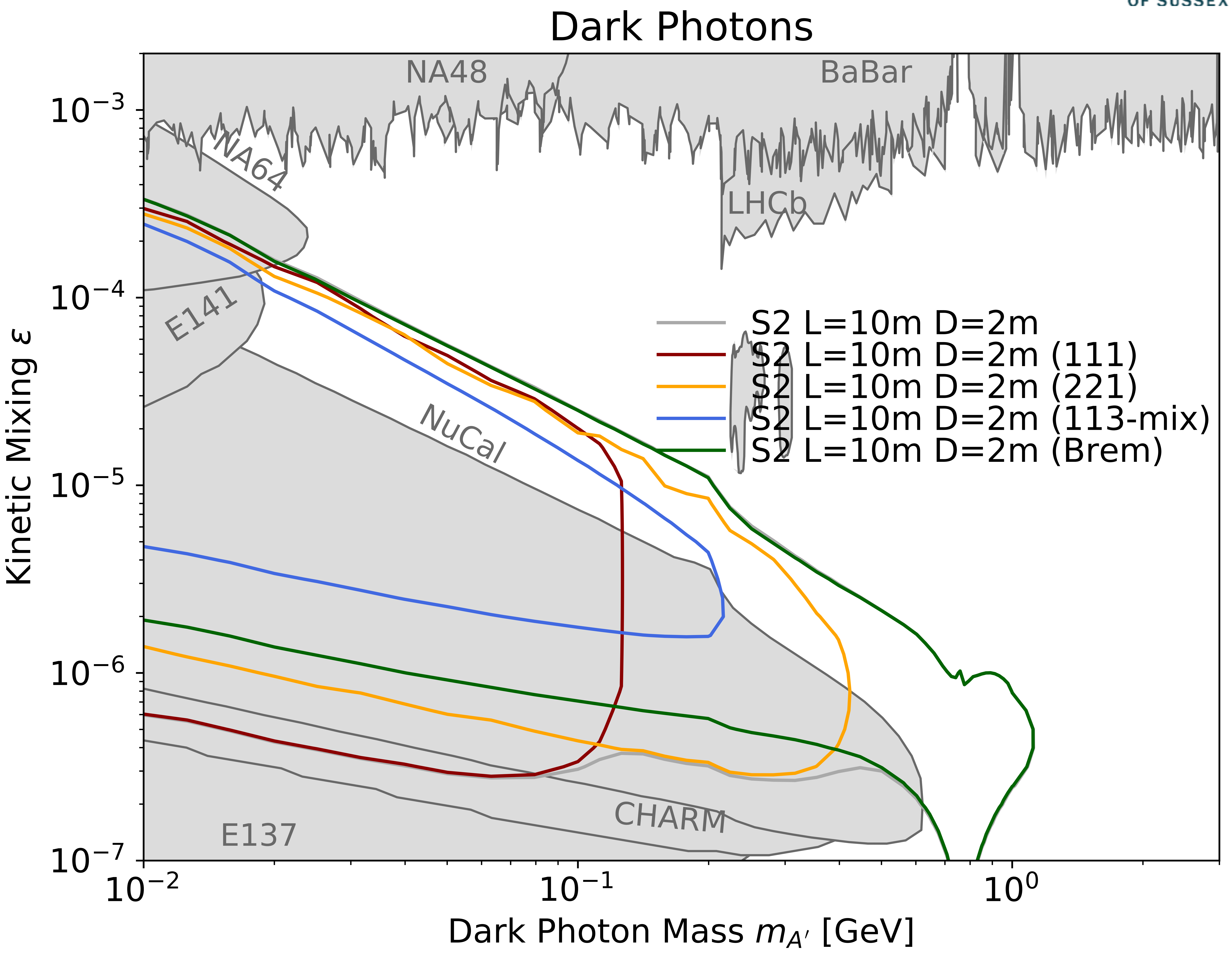
- **Scenario 2**:
  - Check effect of different production and decay modes



[arXiv:2109.10905]

FPF Scenarios | Dark photons

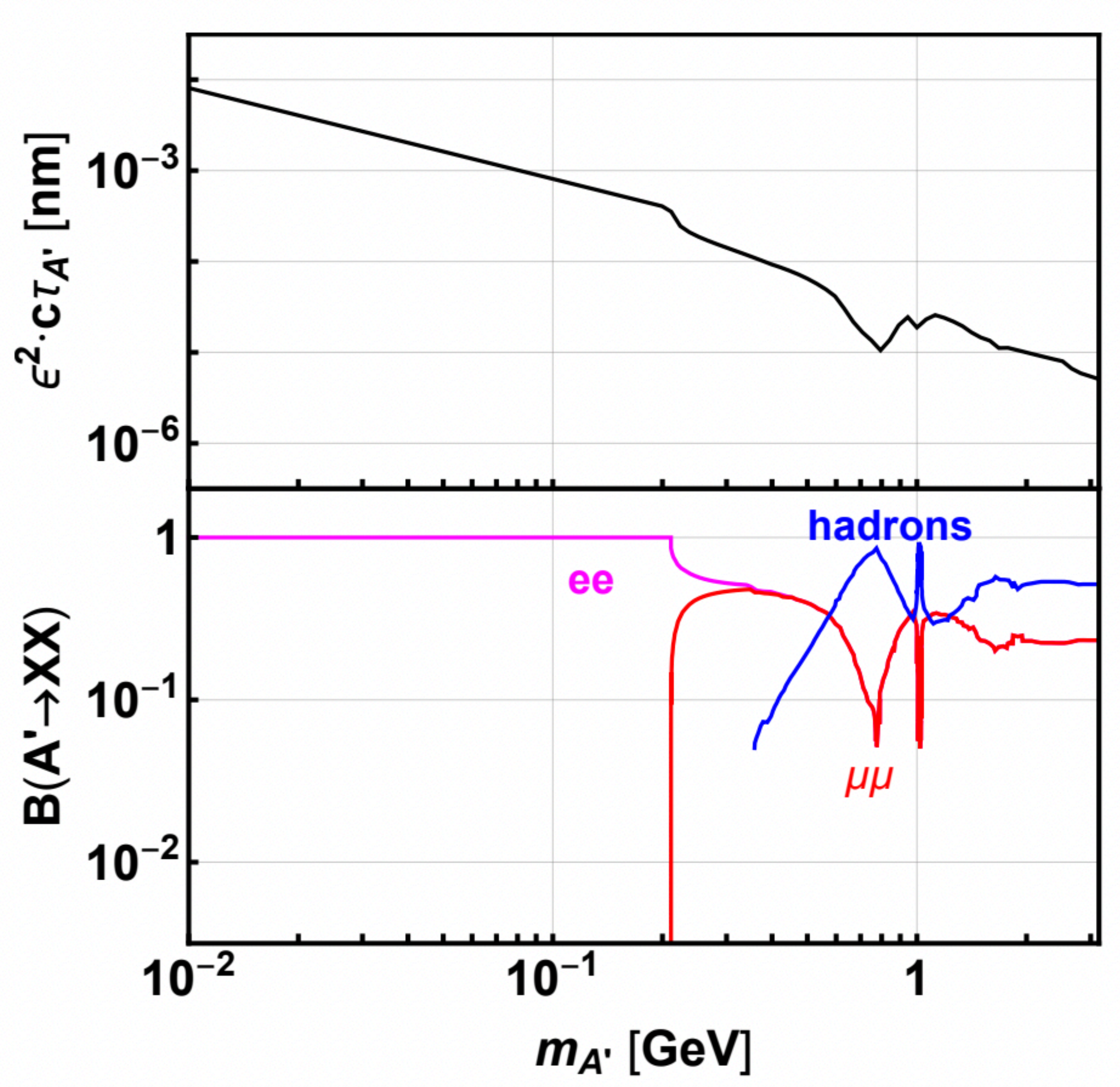
- **Scenario 2**:
  - **Production modes** rather different than for FASER
    - Pion decay at low mass
    - Then eta decay
    - Then Dark Bremsstrahlung

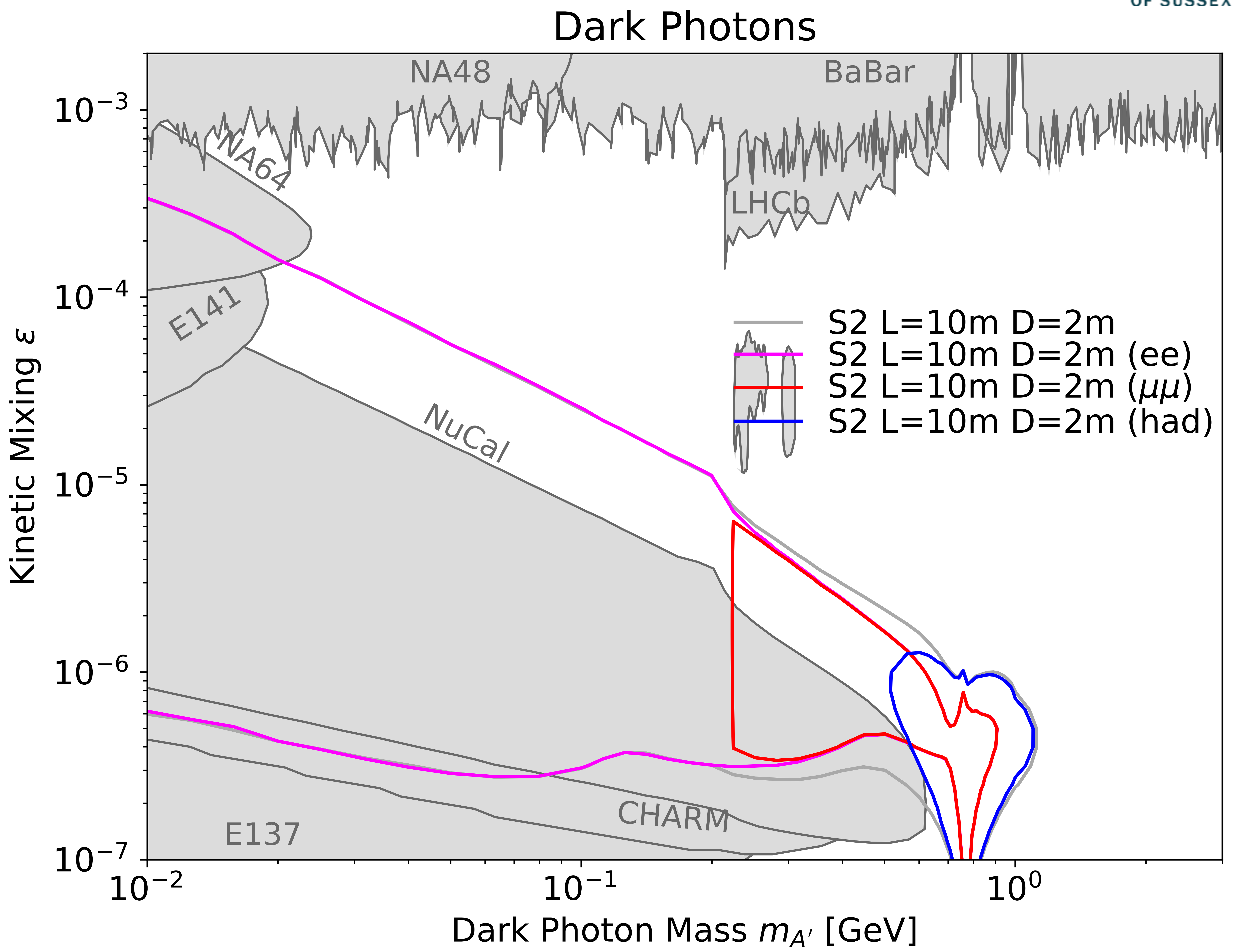


[arXiv:2109.10905]

FPF Scenarios | Dark photons

- **Scenario 2:**
  - **Decay modes** also very different to FASER
    - Electron decay at low mass
    - Muon decay
    - Hadrons

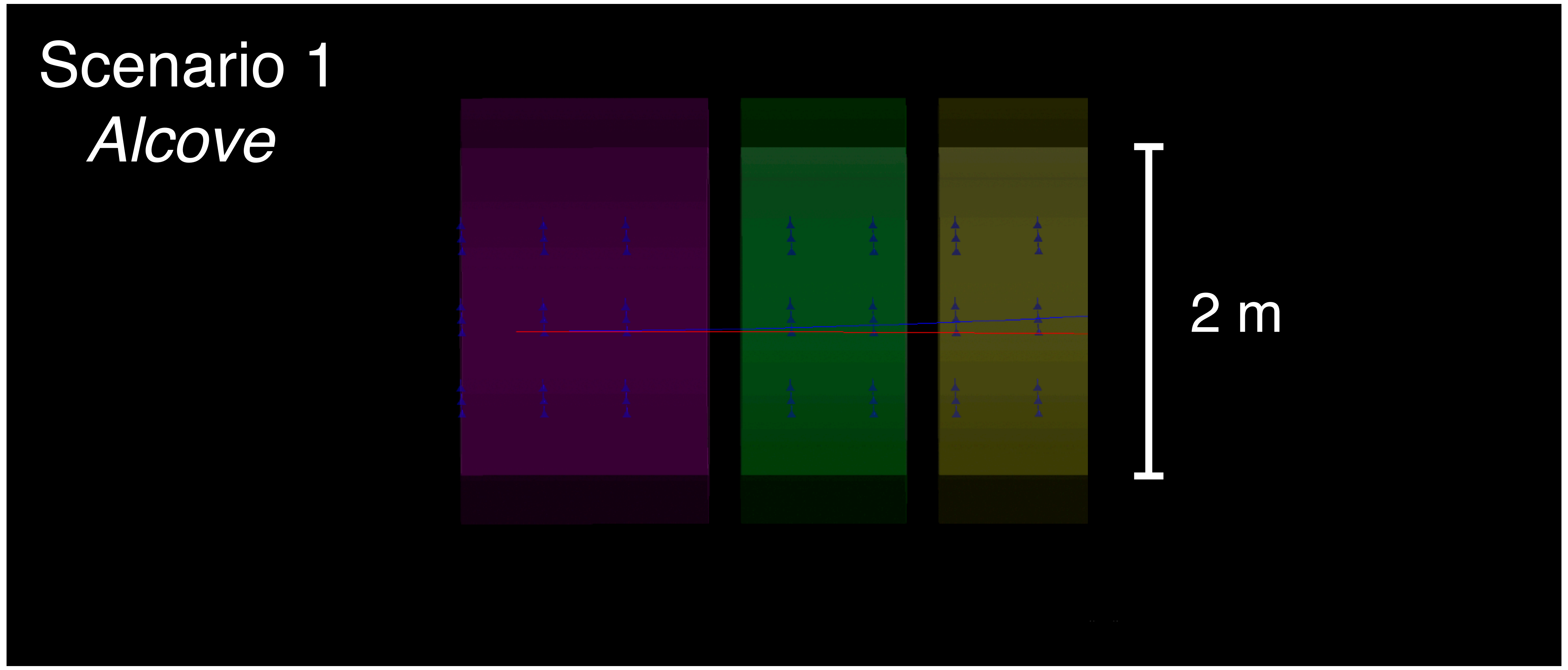


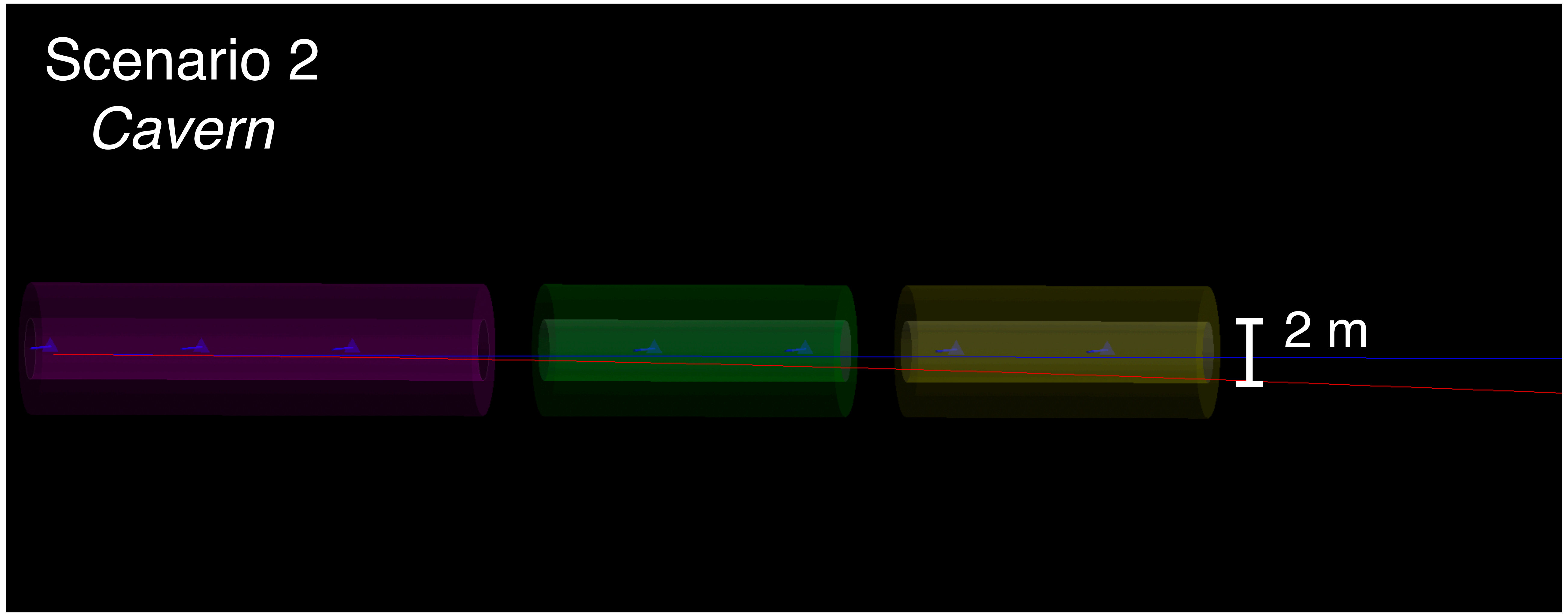


[arXiv:2109.10905]

Simulation studies

- Started Geant4 simulations of possible FASER2 designs
  - Focussing on magnets and particle separations
  - Impacts tracker and calorimeter design considerations
- Using events generated with FORESEE as input to G4
  - LLP spectra and decays handled by FORESEE
  - Currently only looking at Dark Photon decay to e+ e-.





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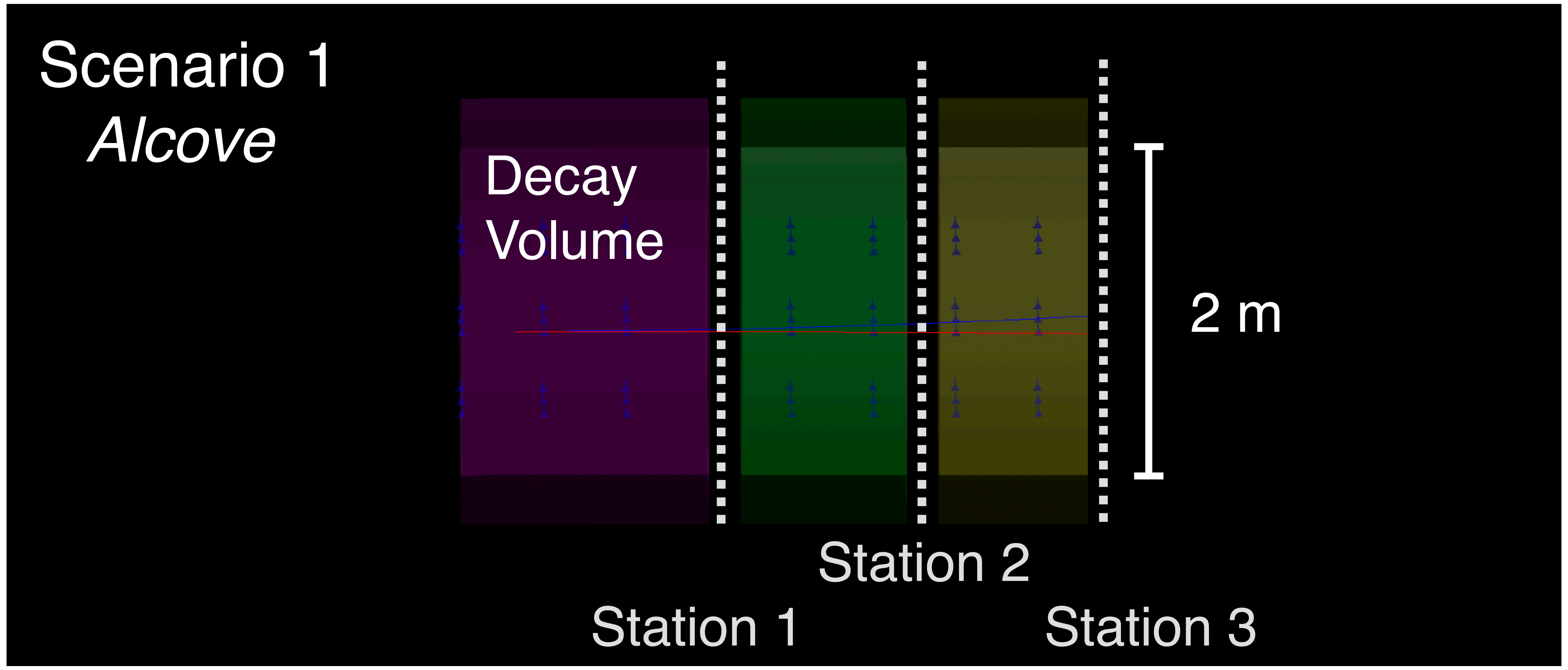
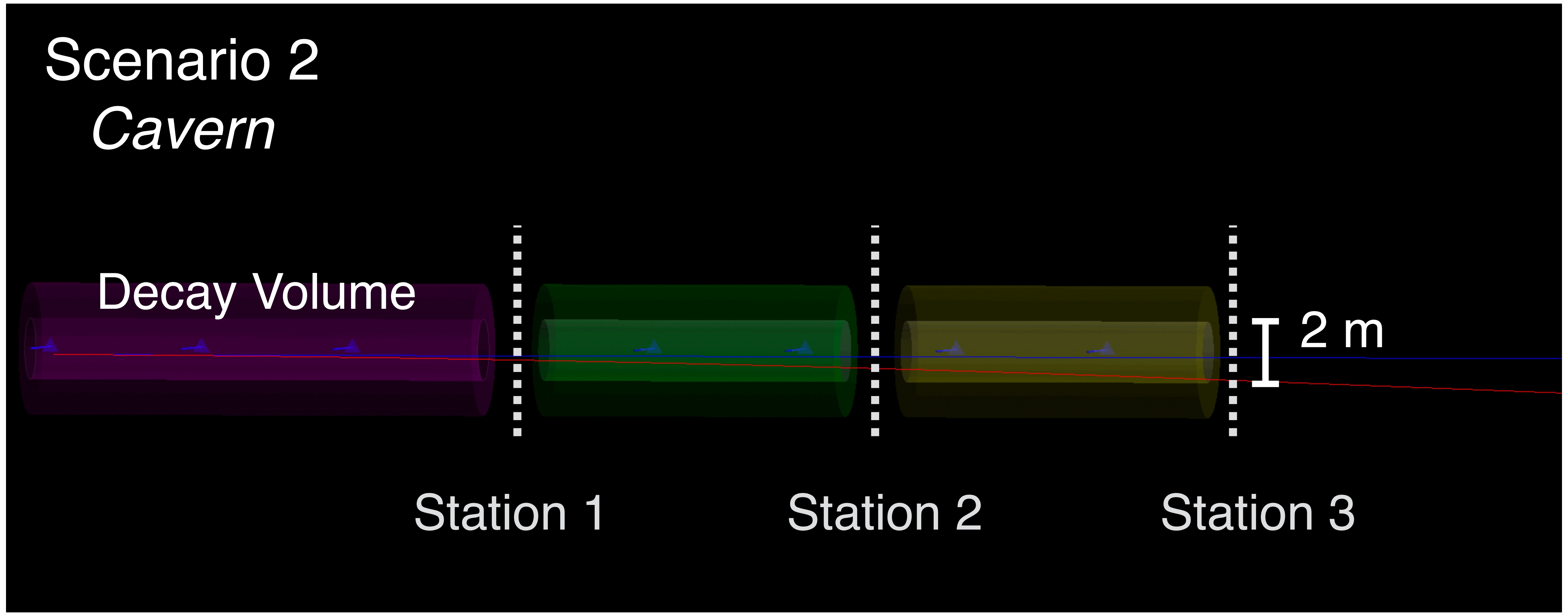
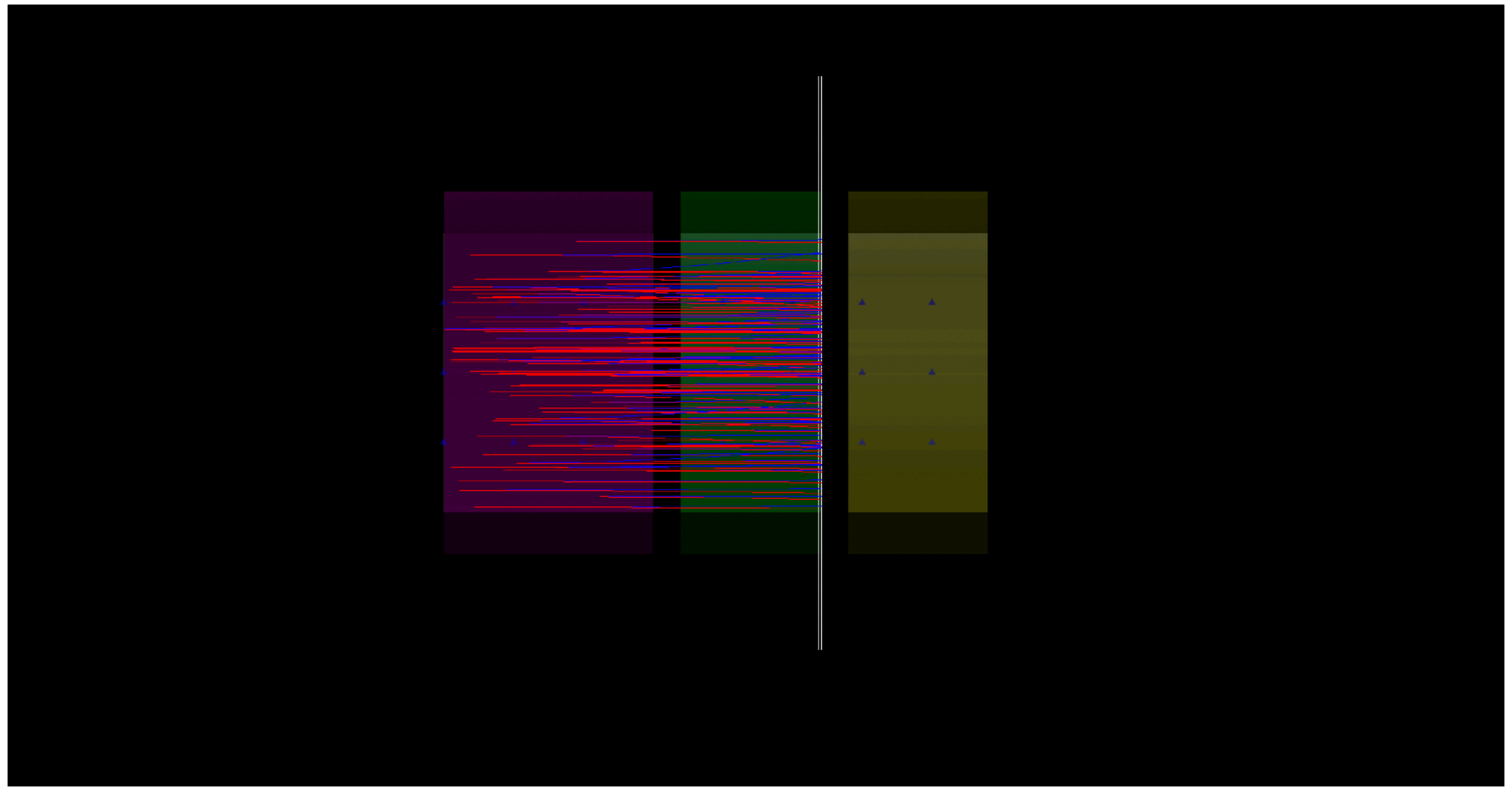
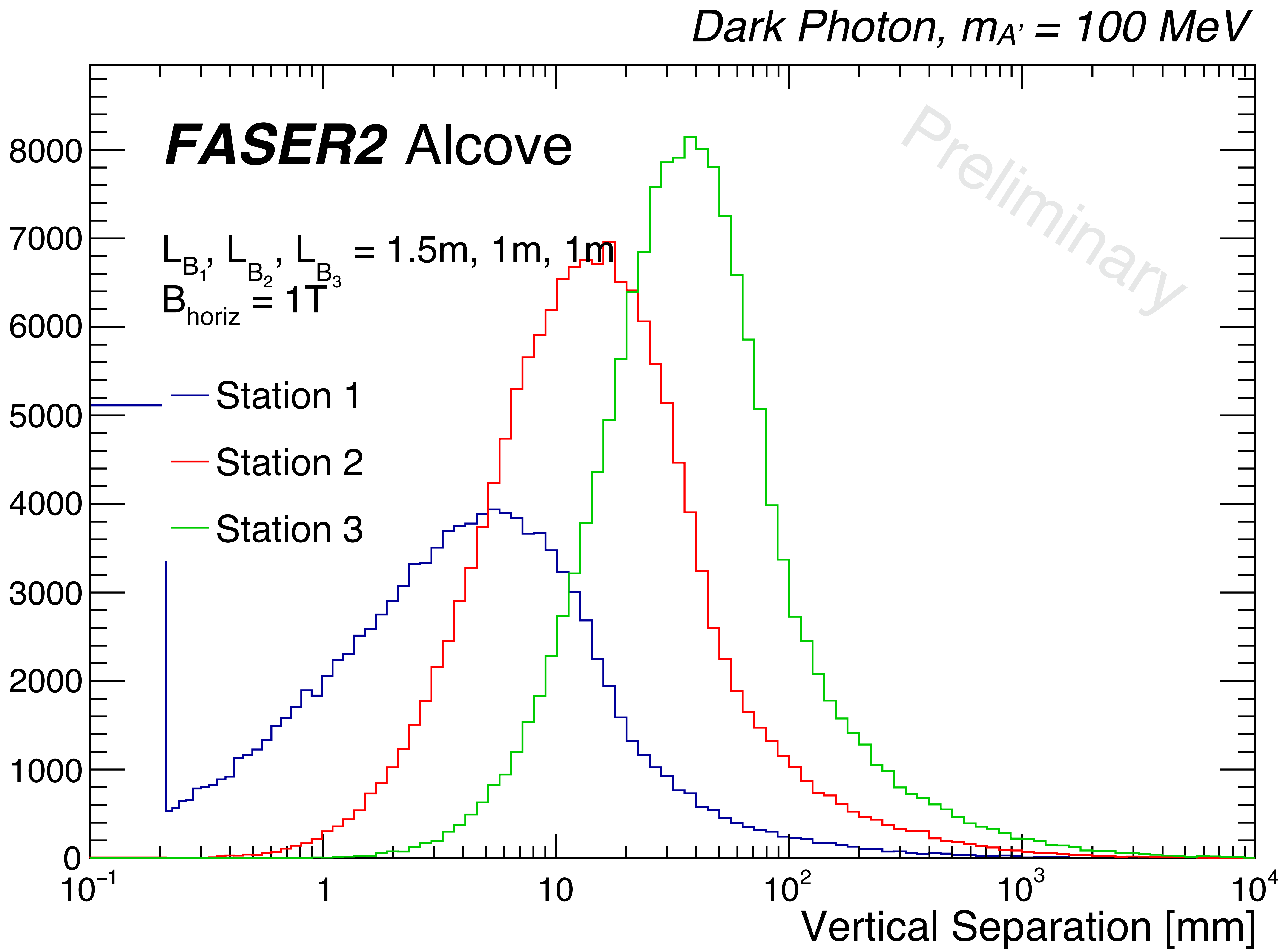




Simulation studies | Scenario 1

- **Scenario 1:**
  - 1T field gives ~5mm separation at Station 1 with 1.5m DV.
  - At Station 3/Calo need ~20 mm resolution for good separation.





Simulation studies | Scenario 1

- **Scenario 1:**
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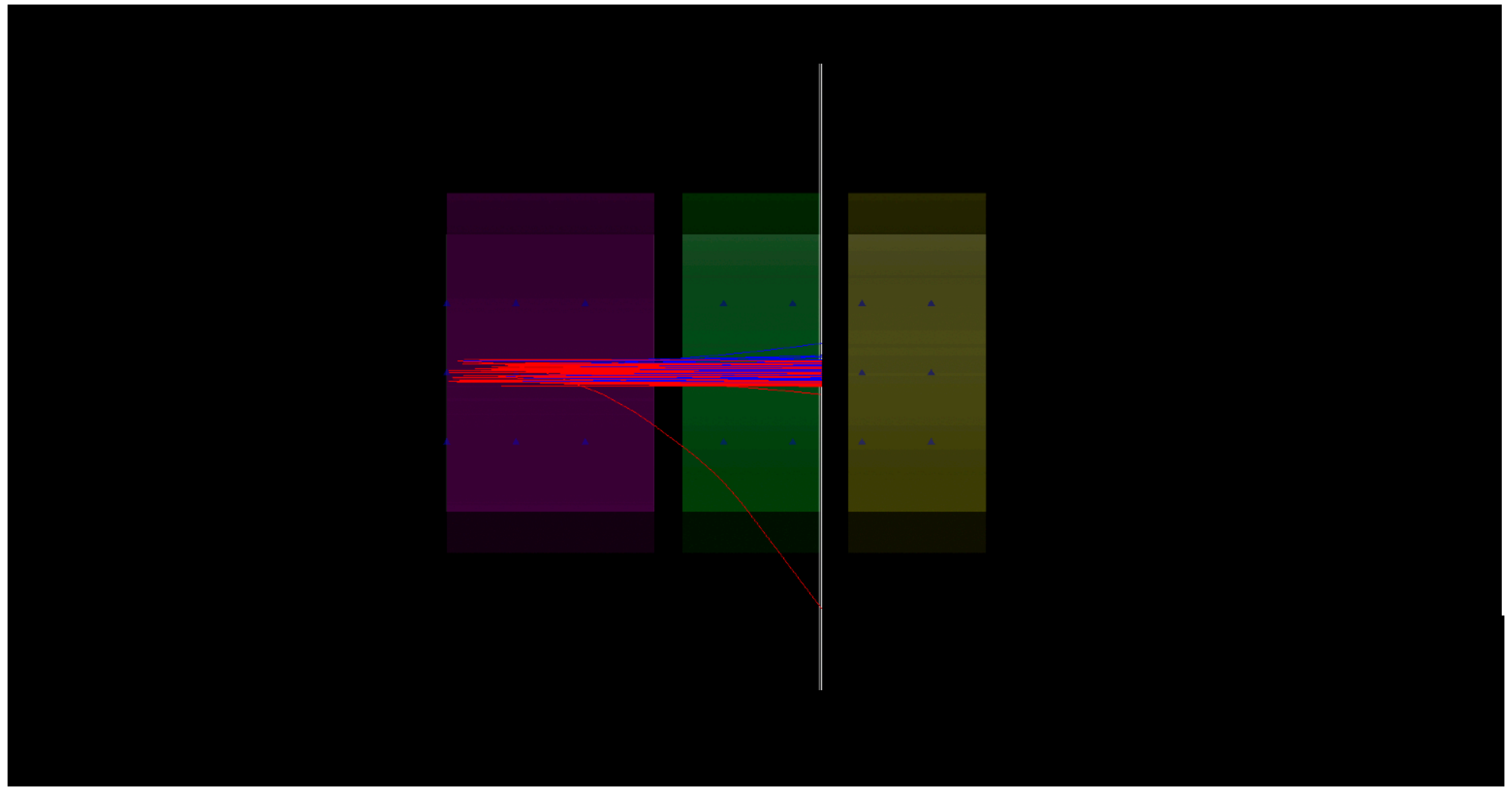
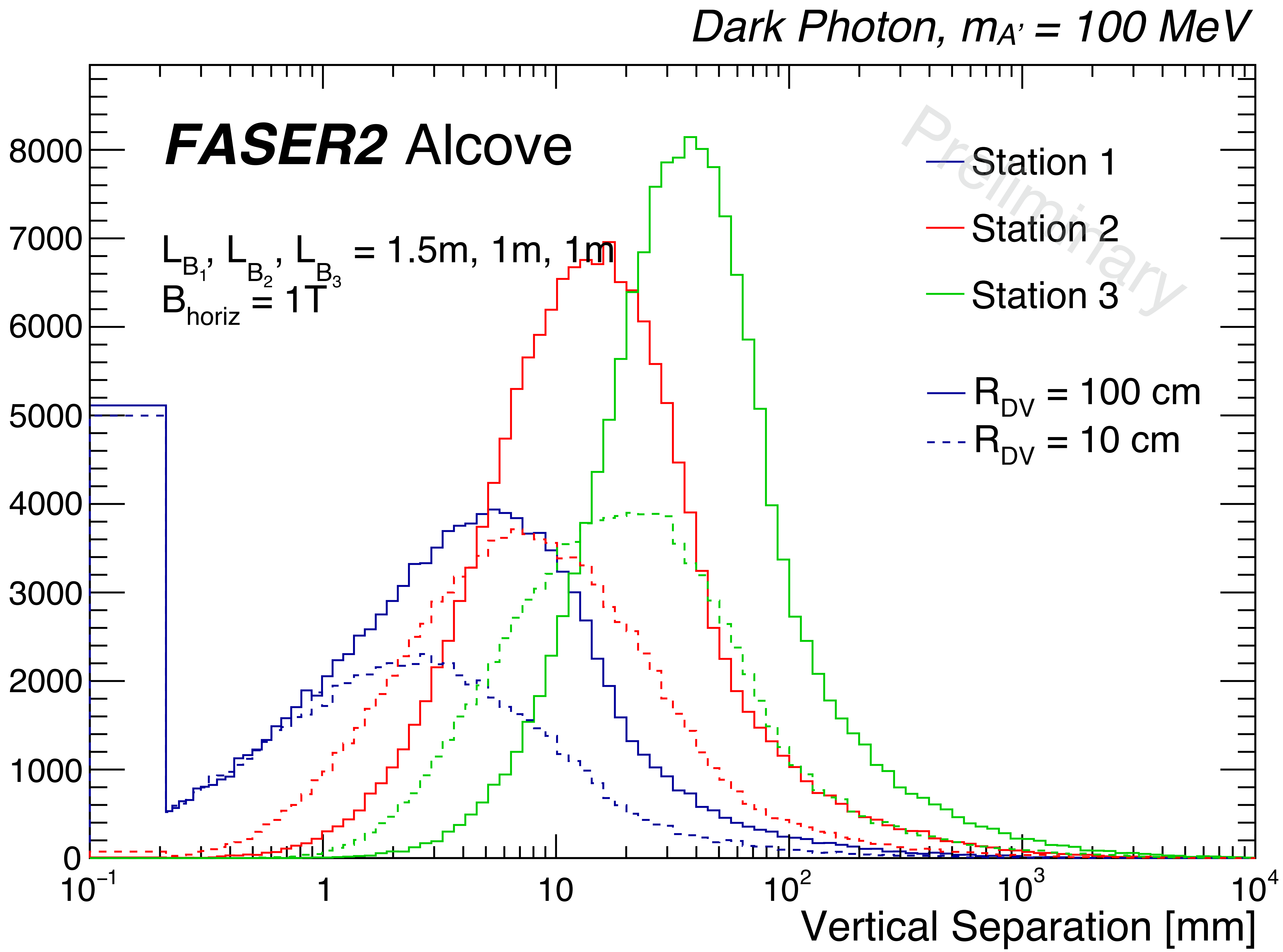
  - Larger radius = softer LLPs





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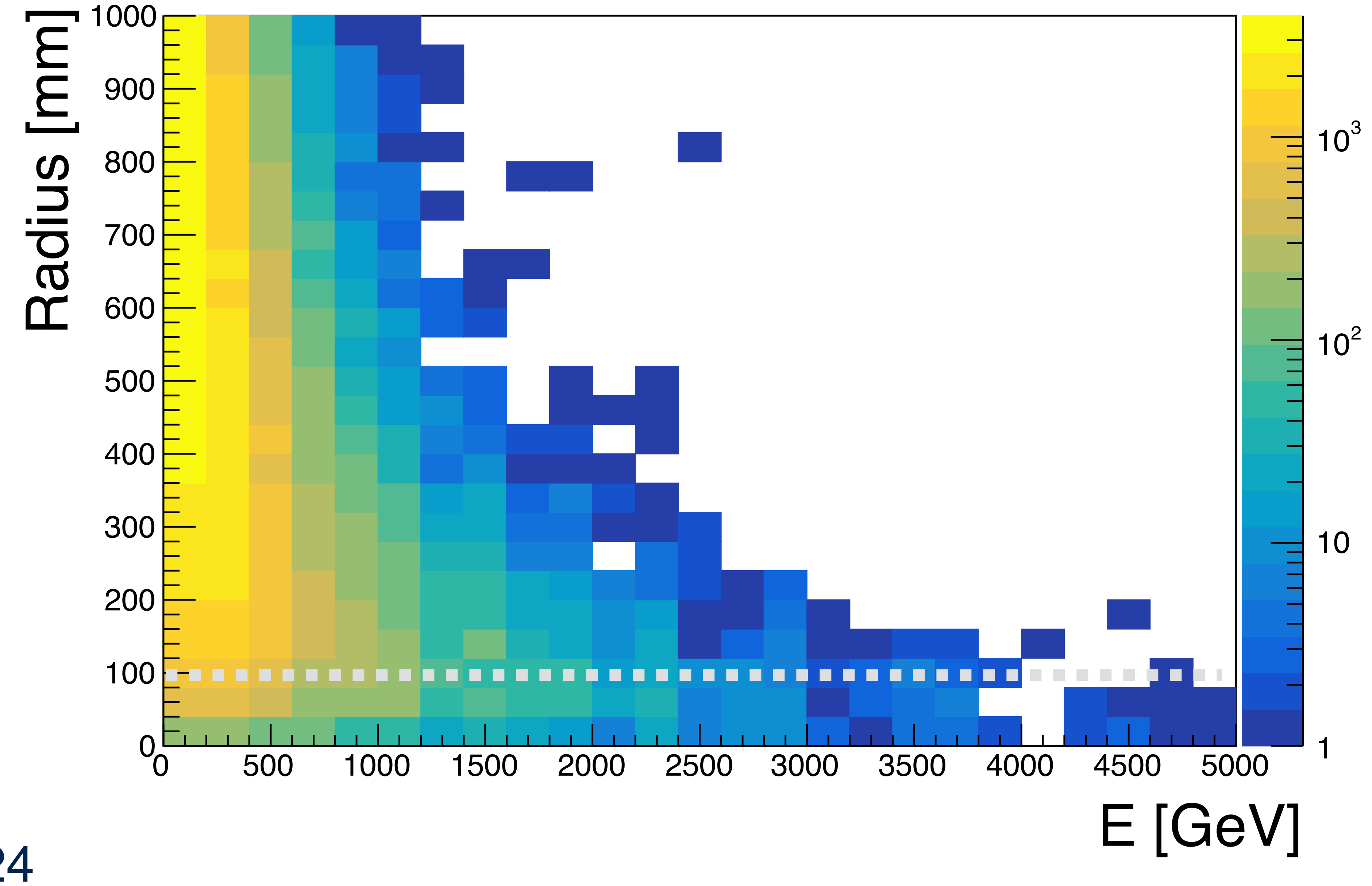
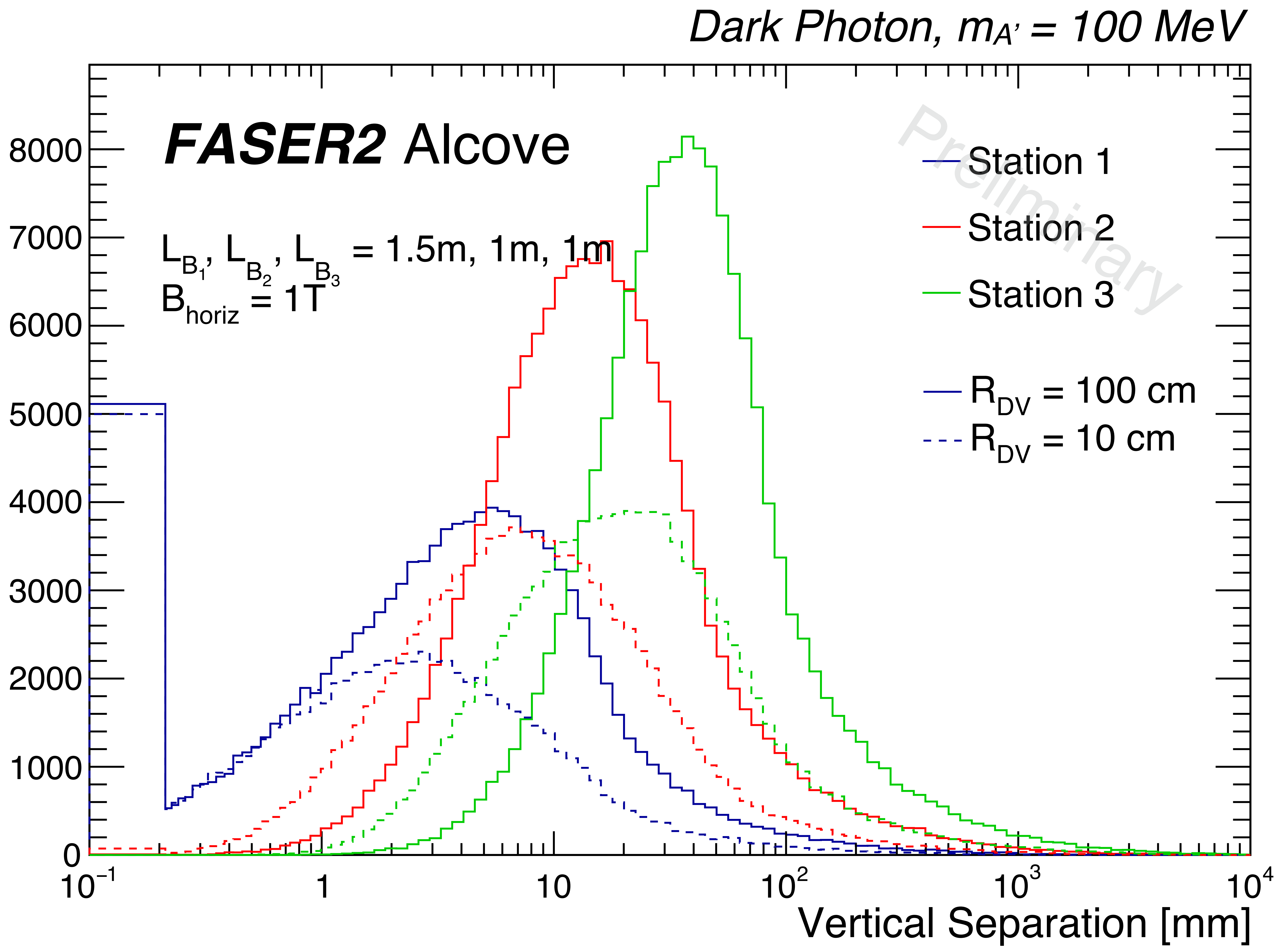
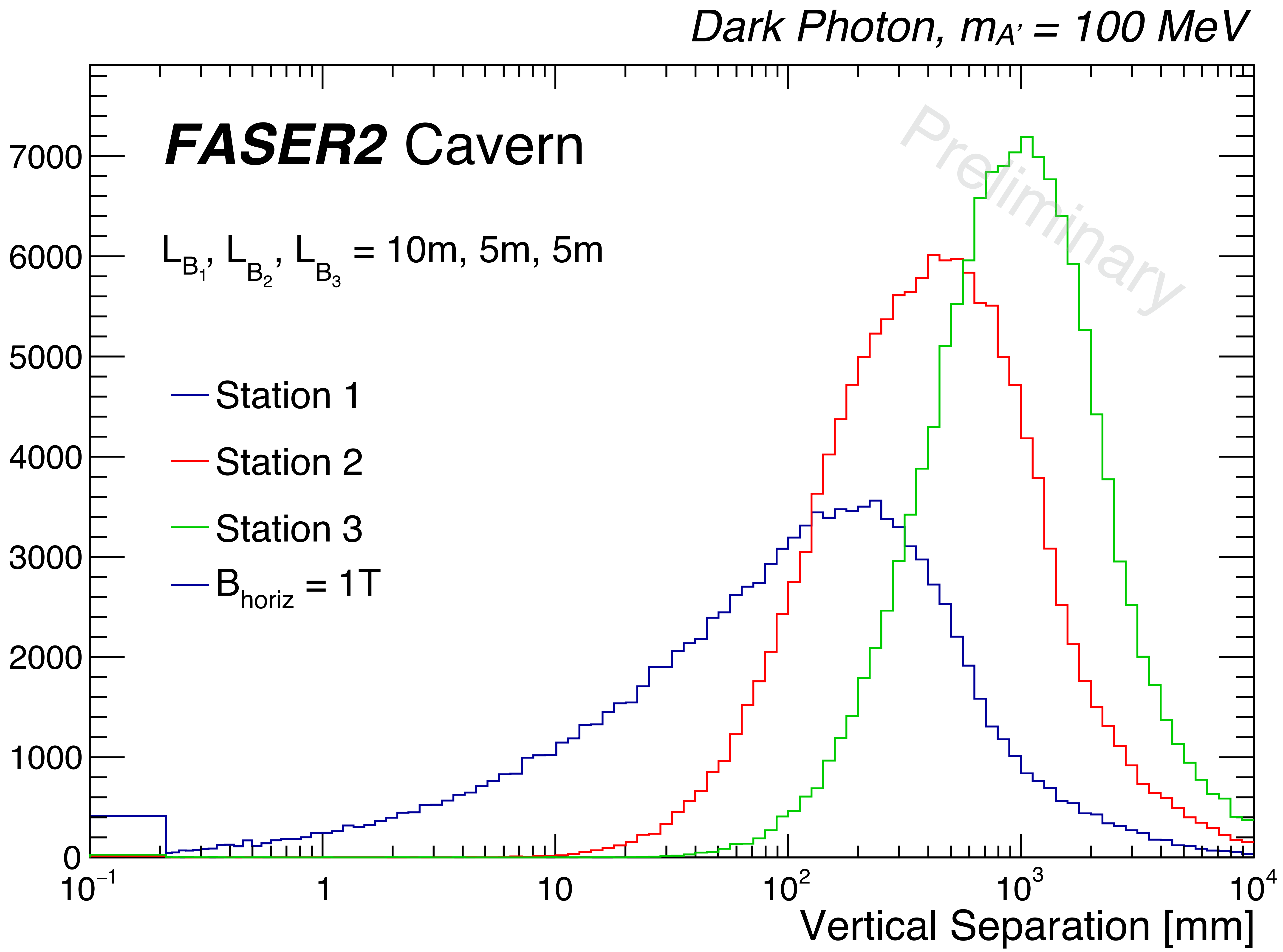




Simulation studies | Scenario 2

- **Scenario 2:**
  - Significantly increased detector/magnet lengths results in large separations even at first station.



Simulation studies | Scenario 2 no B-field

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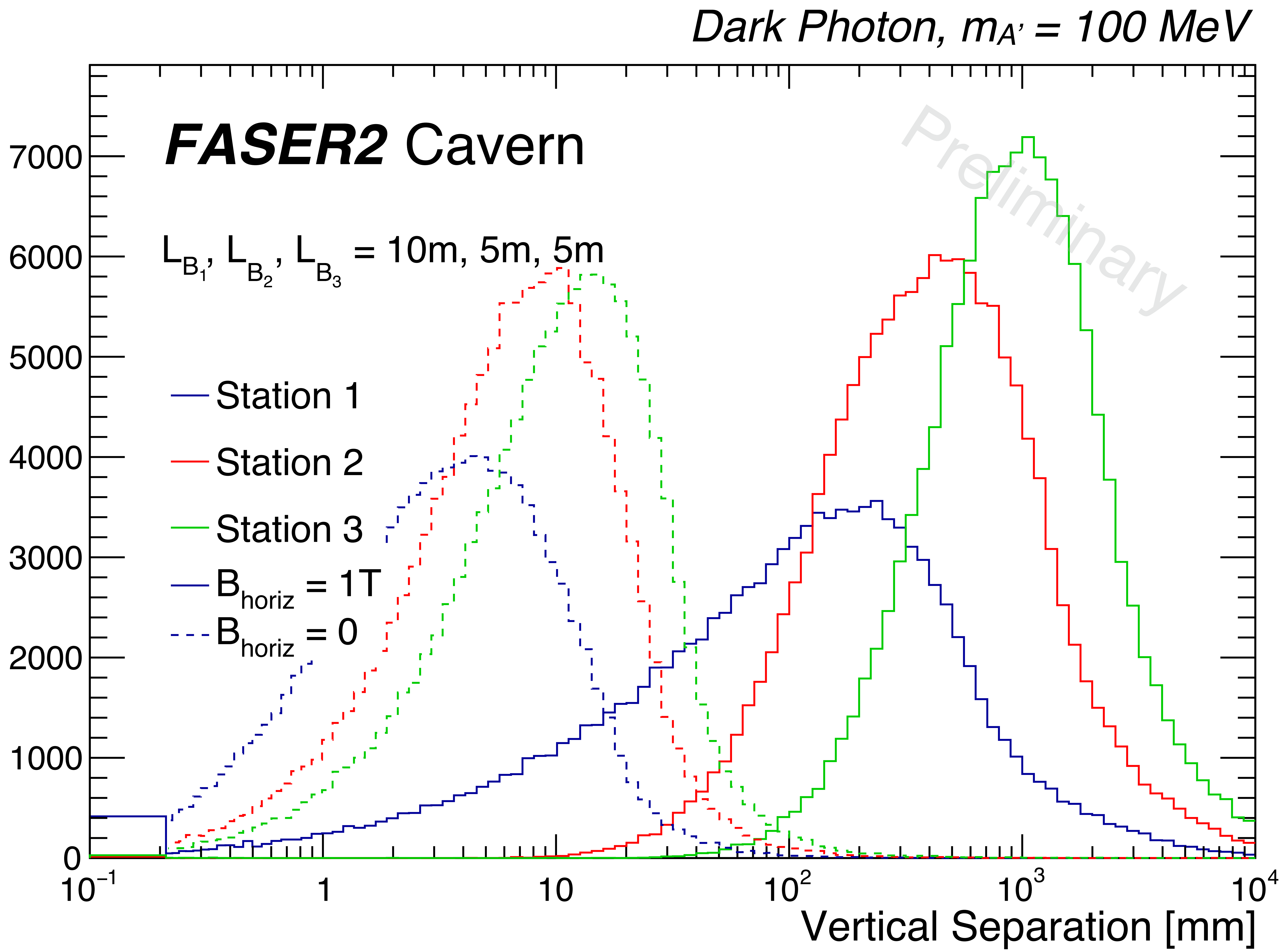
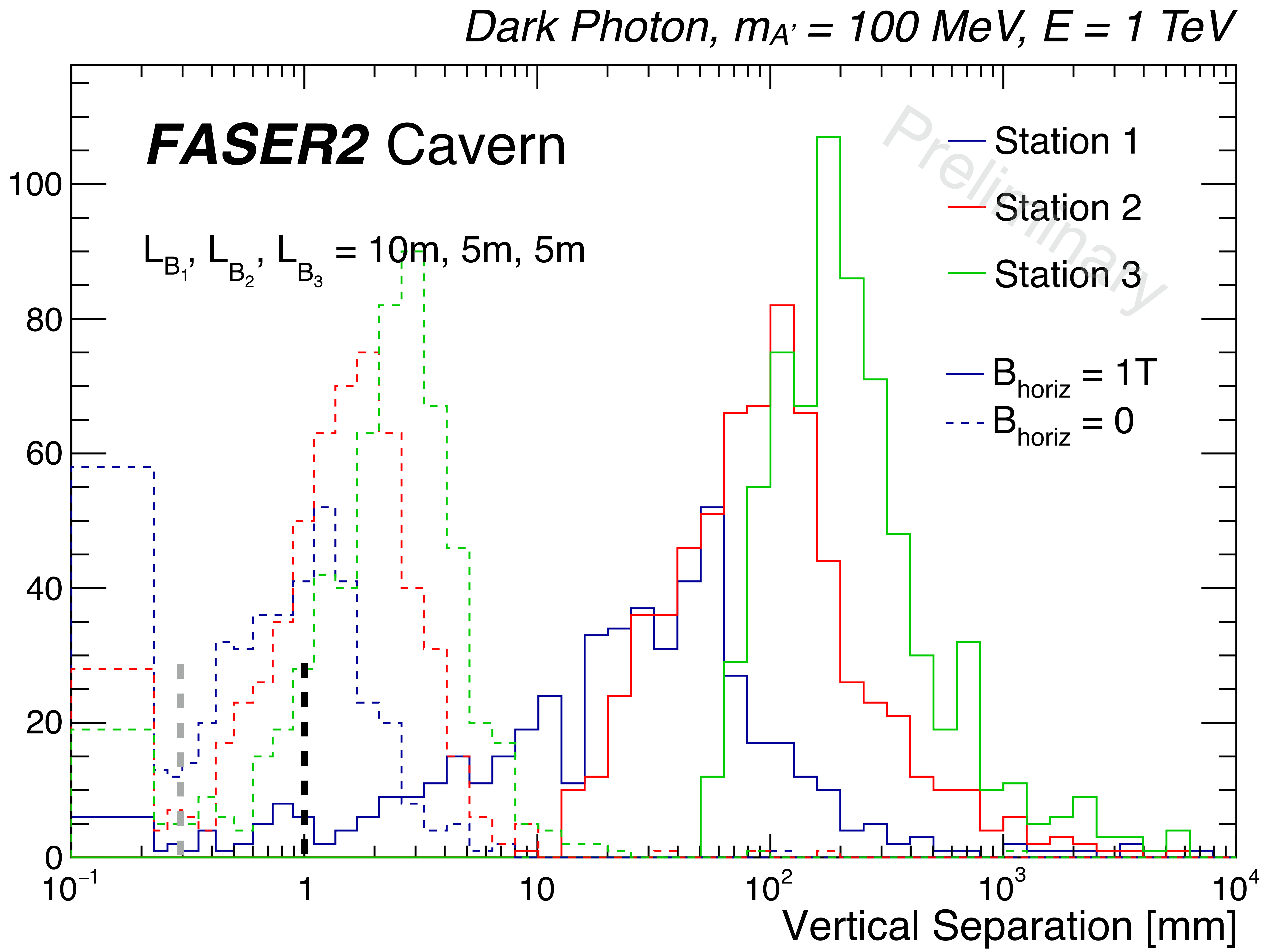
- **Scenario 2:**
  - Significantly increased detector/magnet lengths results in large separations even at first station.
  - Even without any magnetic field separations are comparable to Scenario 1.



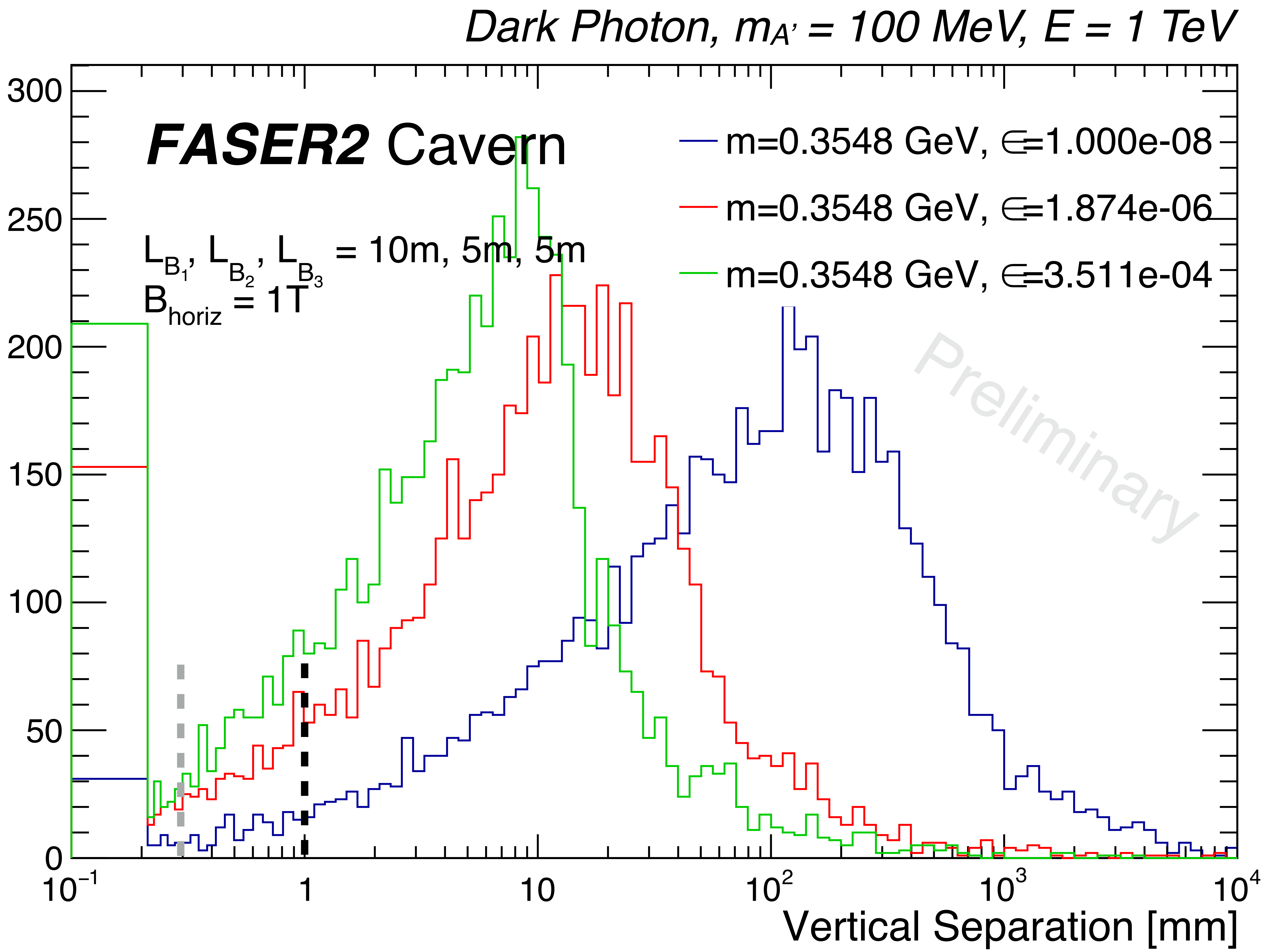
Simulation studies | Scenario 2 E = 1 TeV

- **Scenario 2:**
  - Significantly increased detector/magnet lengths results in large separations even at first station.
  - Even without any magnetic field separations are comparable to Scenario 1.
  - But need to consider the effect on the reach of high momentum LLPs
    - E.g. much smaller separations at high energy



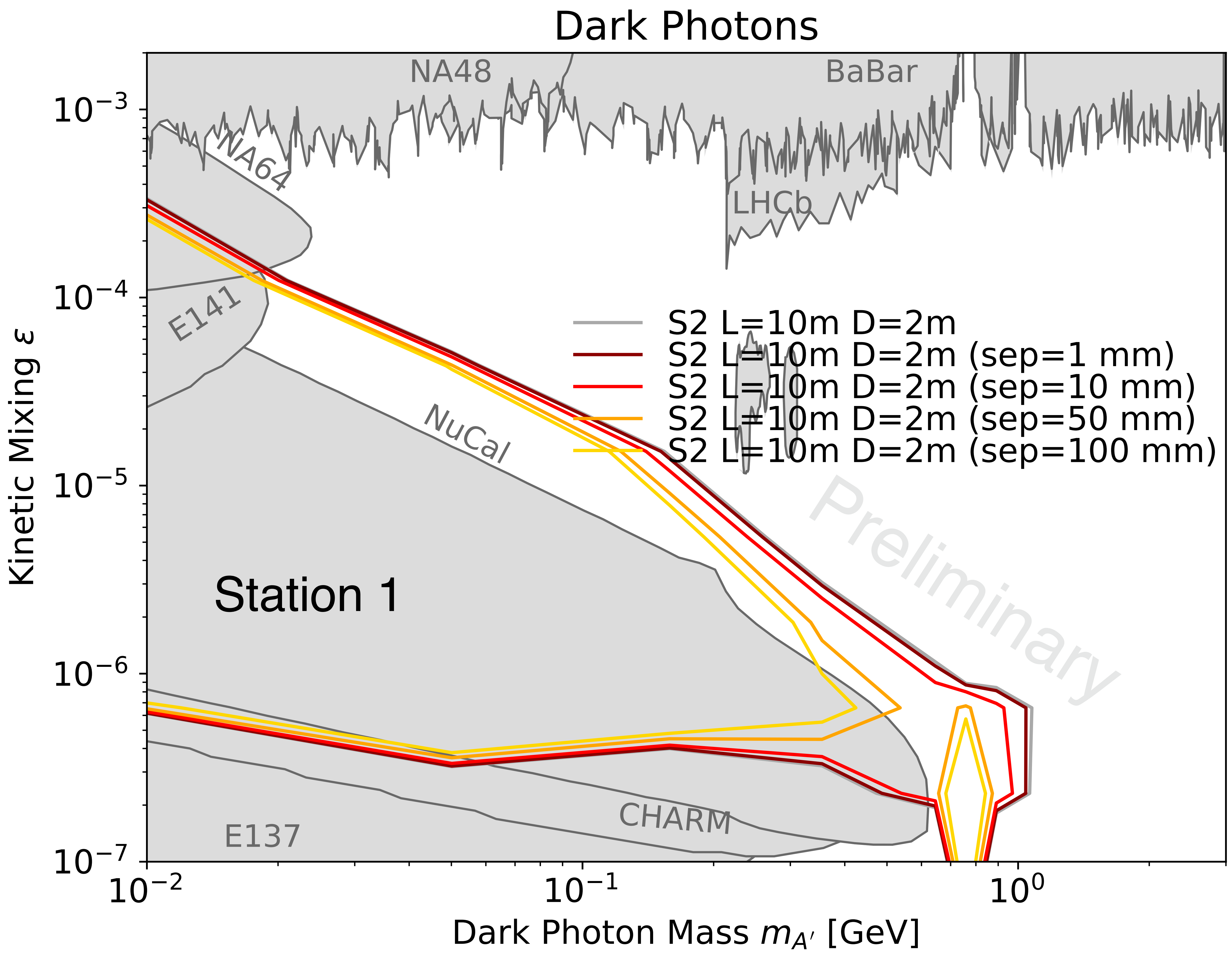
Simulation studies | Scenario 2 coupling

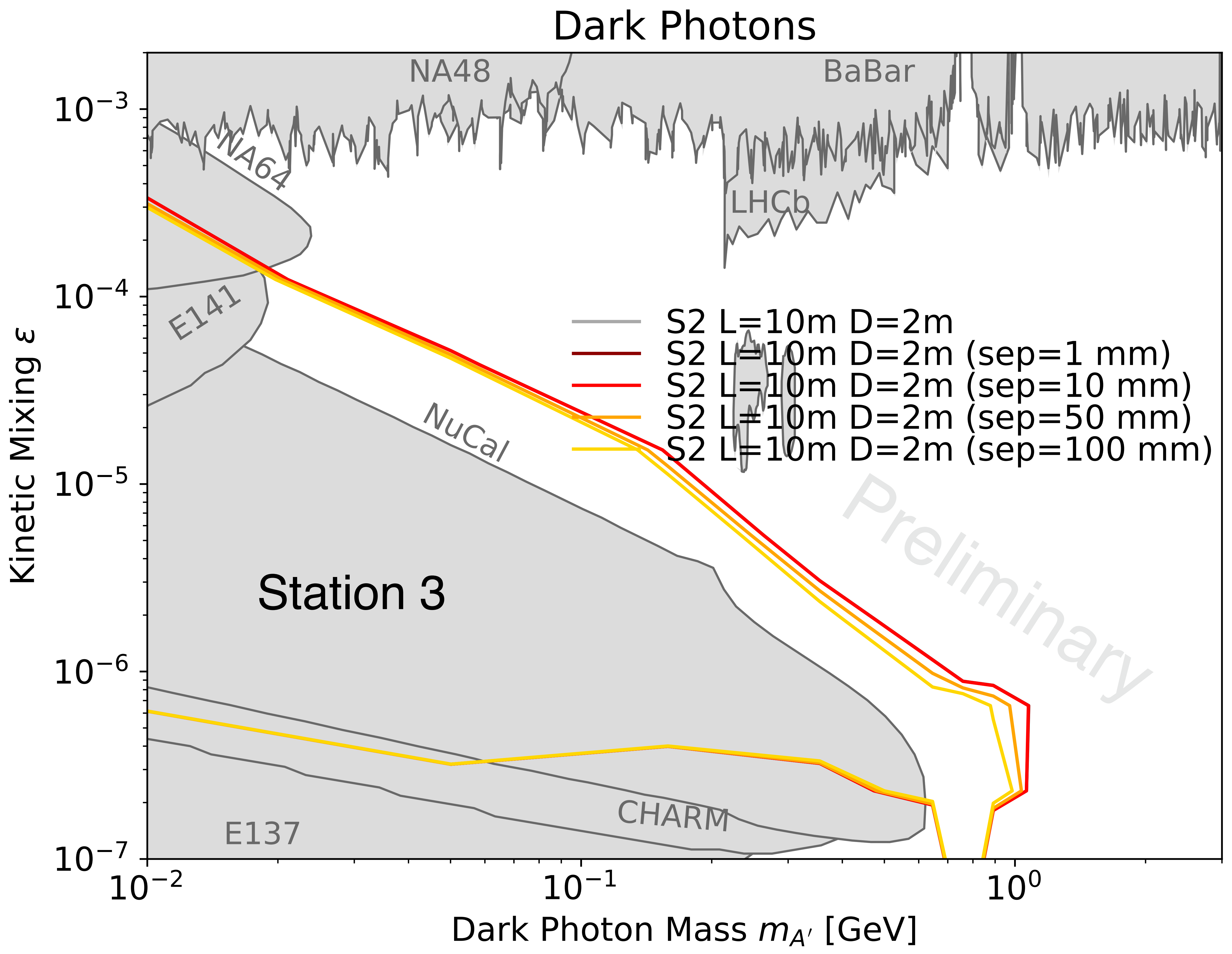
- **Scenario 2:**
  - Significantly increased detector/magnet lengths results in large separations even at first station.
  - Even without any magnetic field separations are comparable to Scenario 1.
  - But need to consider the effect on the reach of high momentum LLPs
    - E.g. much smaller separations at high energy
    - Lower couplings require larger boost to reach decay volume
    - **Need to see full effect on reach!**



Simulation studies | Scenario 2 Reach

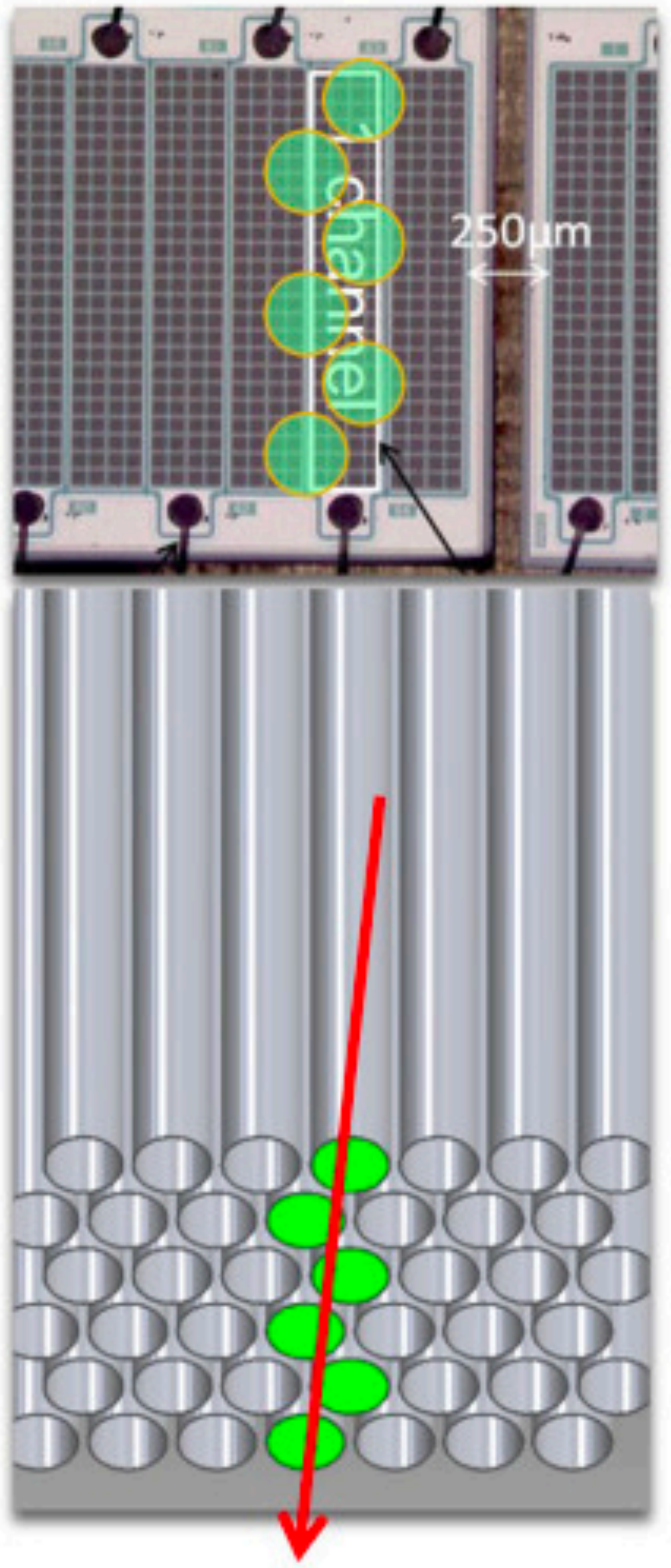
- **Scenario 2:**
  - At 1st tracker station loss of sensitivity comes between 1 and 10 mm separations.
  - At 3rd tracker station/calorimeter loss comes between 10 and 50 mm separations.

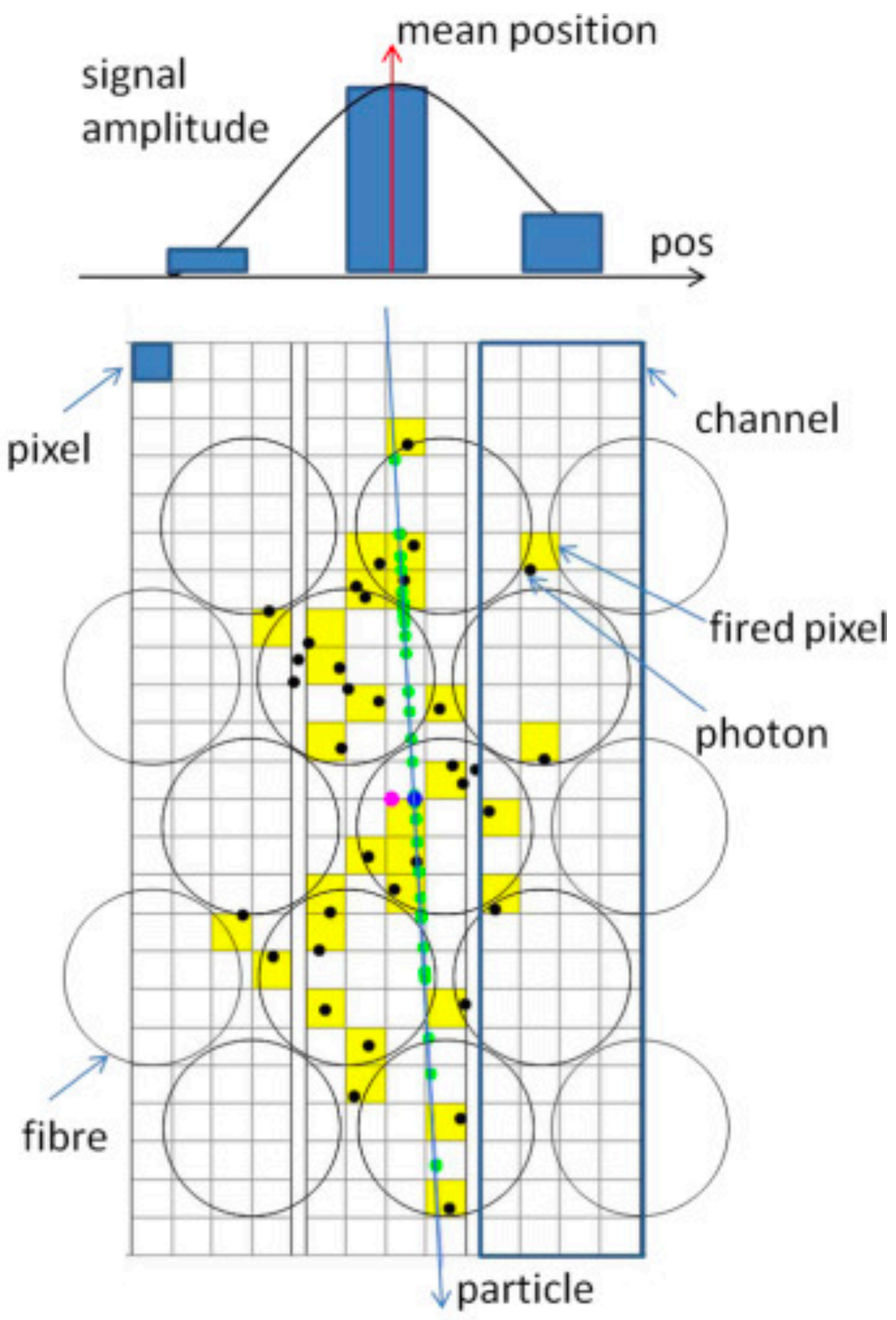


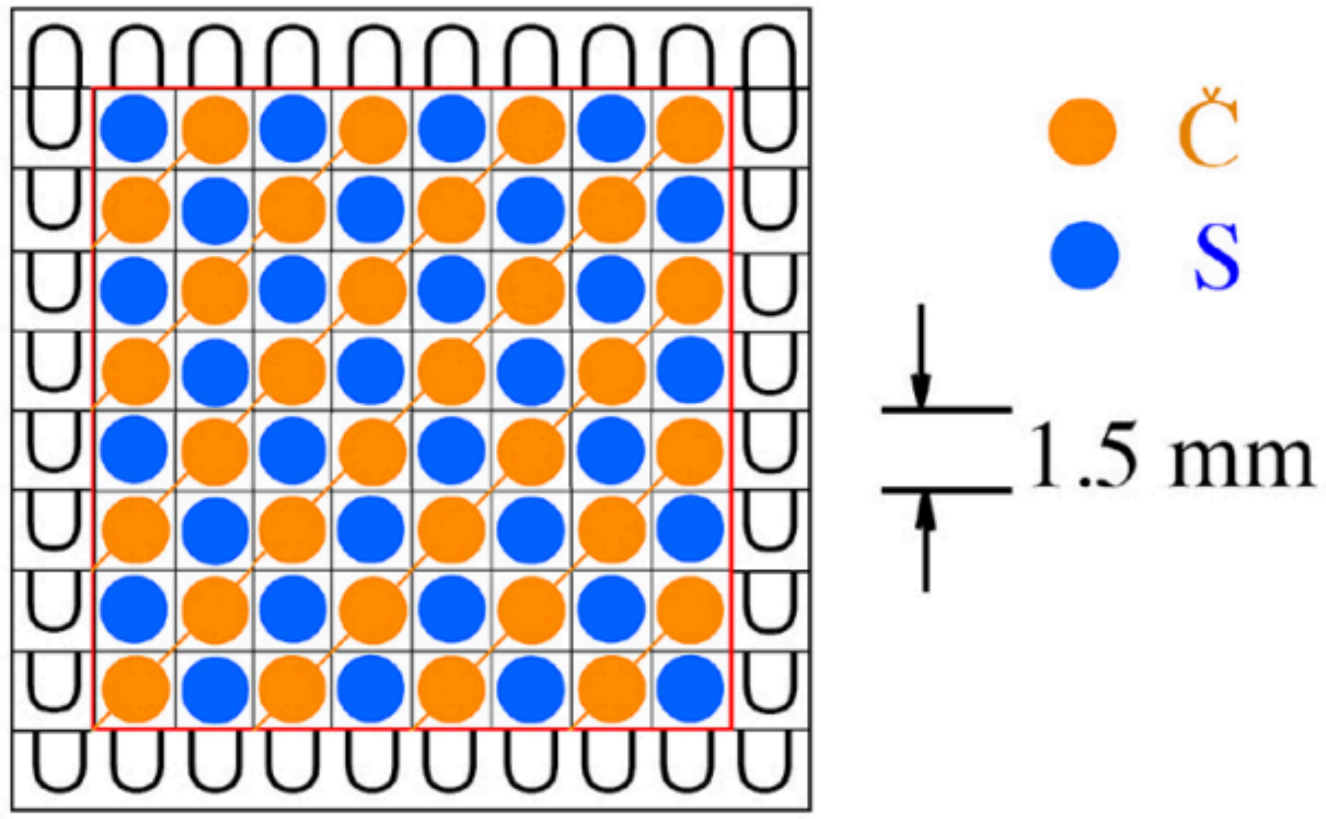


Simulation studies

- Possible detector technologies
  - Tracker
    - SCT:
      - Pitch = 80 um, resolution = 17 um
      - Naive hit cluster ~300 um
    - SciFi:
      - Pitch = 250 um, Resolution = 100 um
      - Naive hit cluster: ~1 mm?
    - Reduced resolution of SciFi detector seems acceptable even in 1
  - Calorimeter
    - Dual readout
      - Resolution: <10 mm? (Tested with fibre diameter of 1mm)
    - Dual readout calorimeter resolution sufficient at 3rd tracker station







- Also need to extend studies to include LLP mass reconstruction
  - Not possible without magnet
  - Want to understand what is possible with a magnet.

Other considerations

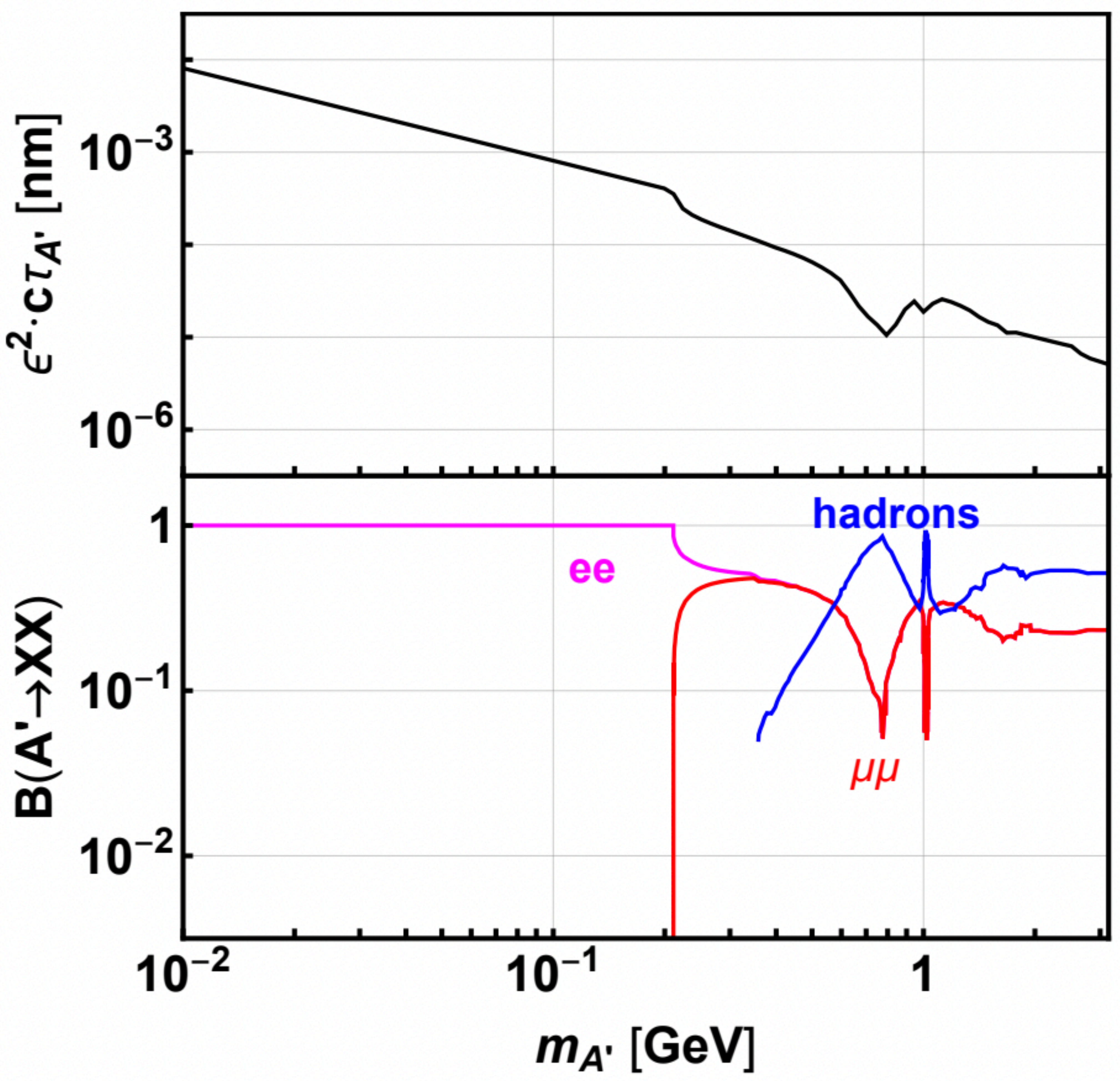
- Separations of up to >1m
  - Could actually be too much - particles may be bent out of the detector and miss the last tracking station and also the calorimeter
- For high energy particle momentum measurements alignment of the tracker planes becomes very important
  - (and will likely dominate the momentum resolution over the hit resolution).
  - With an electromagnet alignment can be constrained with field off data
    - Need to know detector movements when magnet is ramped up - may require (optical?) alignment system.
- There are models where π_0s are important - may want to reconstruct these from calorimeter
  - As the π_0 will be high energy this can be challenging as 2 photons will be very collimated and the decay position of the π_0 will be unknown.

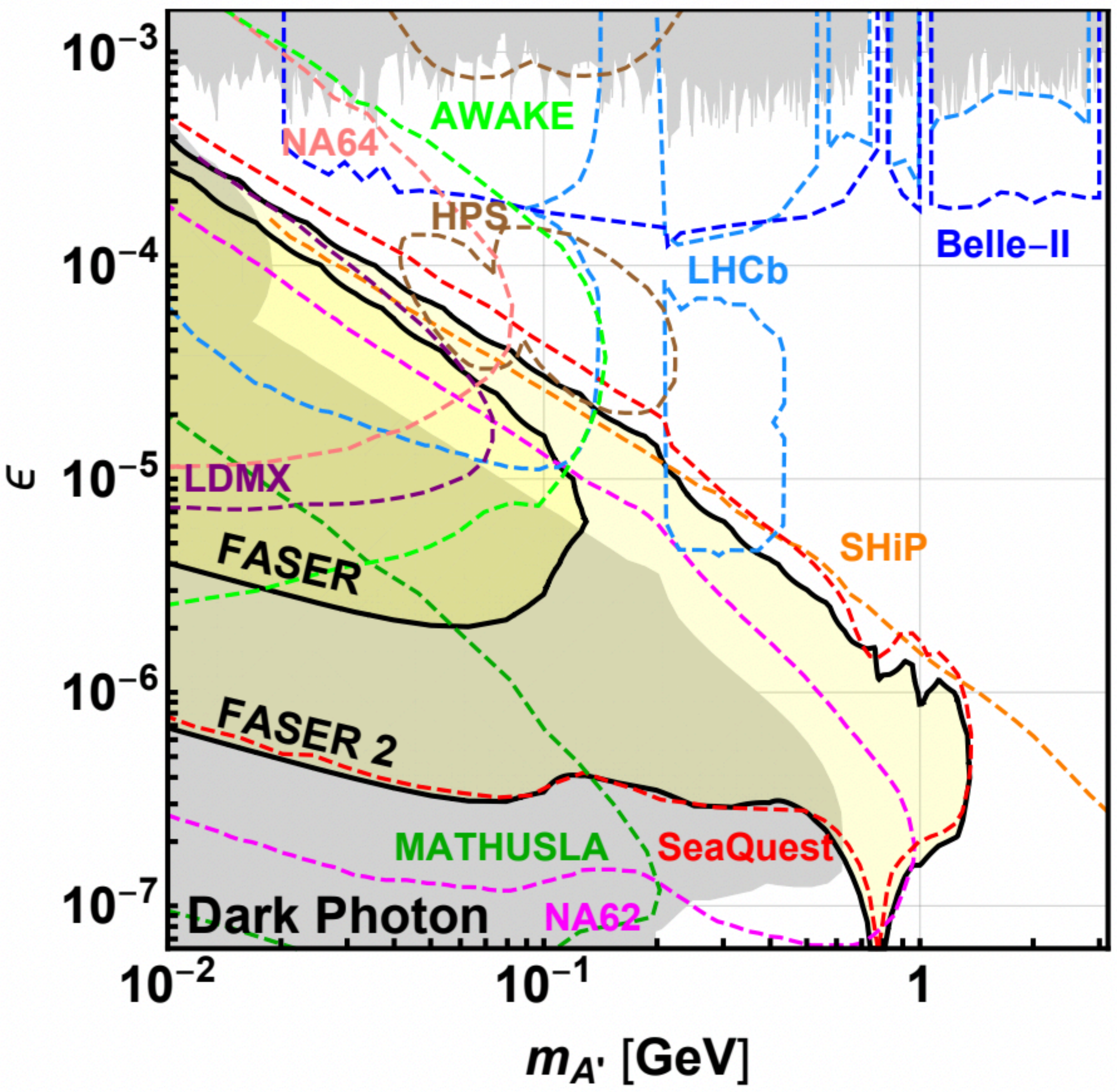
Conclusions

- The physics potential of a larger scale successor to FASER is clear.
- Possible scenarios for this larger detector are being explored and initial reach studies strongly indicate a preference for a FPF with a dedicated new cavern.
- Possible detector technologies already being identified.
- Design simulations in Geant4 started
  - Refining understanding of detector technology needs and optimal layouts.
  - Machinery used for simply signature so far
  - Several important studies still to perform:
    - Determine possible mass reconstruction performance (also including material in simulation)
    - Extend reach studies to other Dark Higgs and other more complicated decay channels

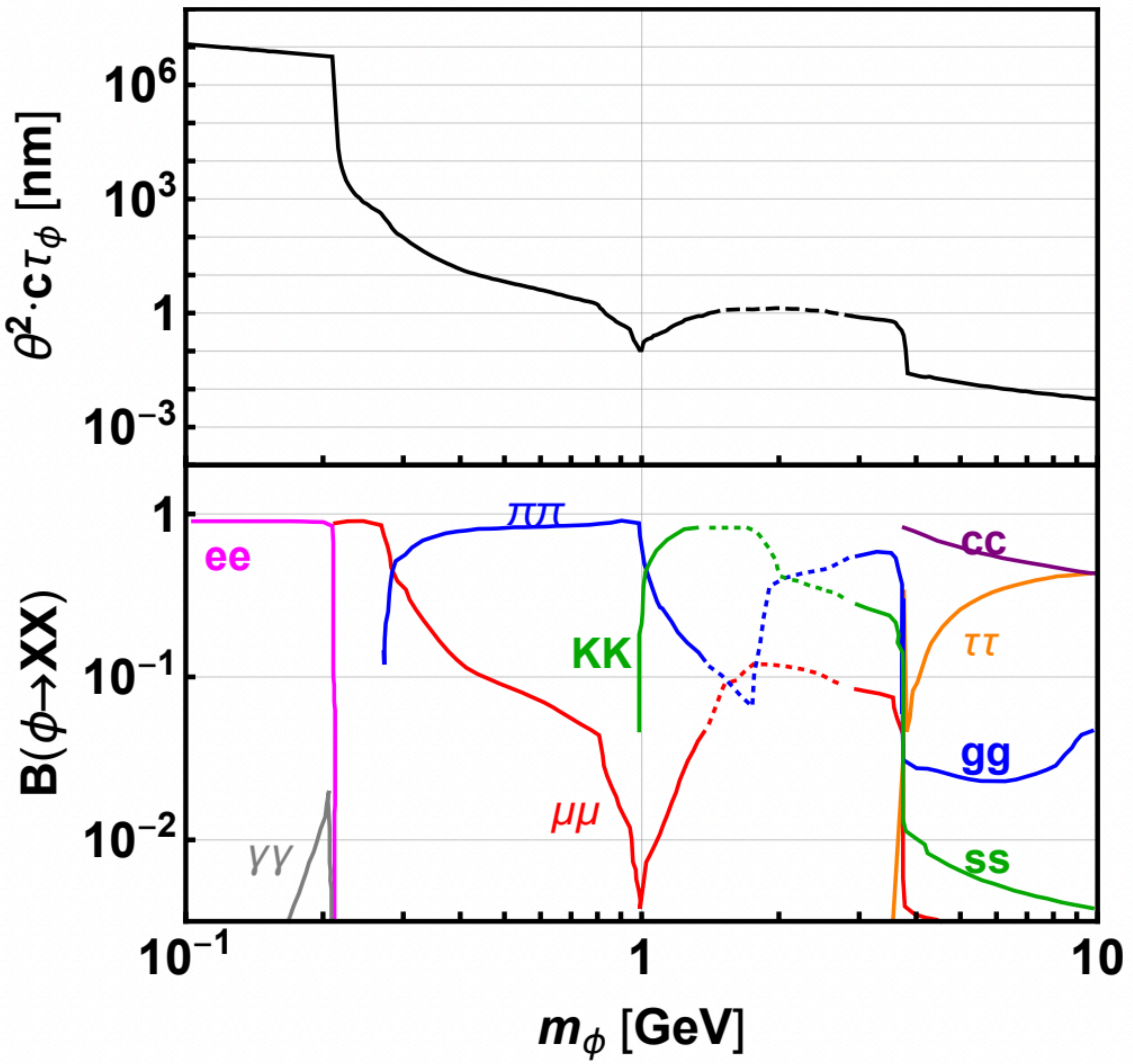
Back-ups

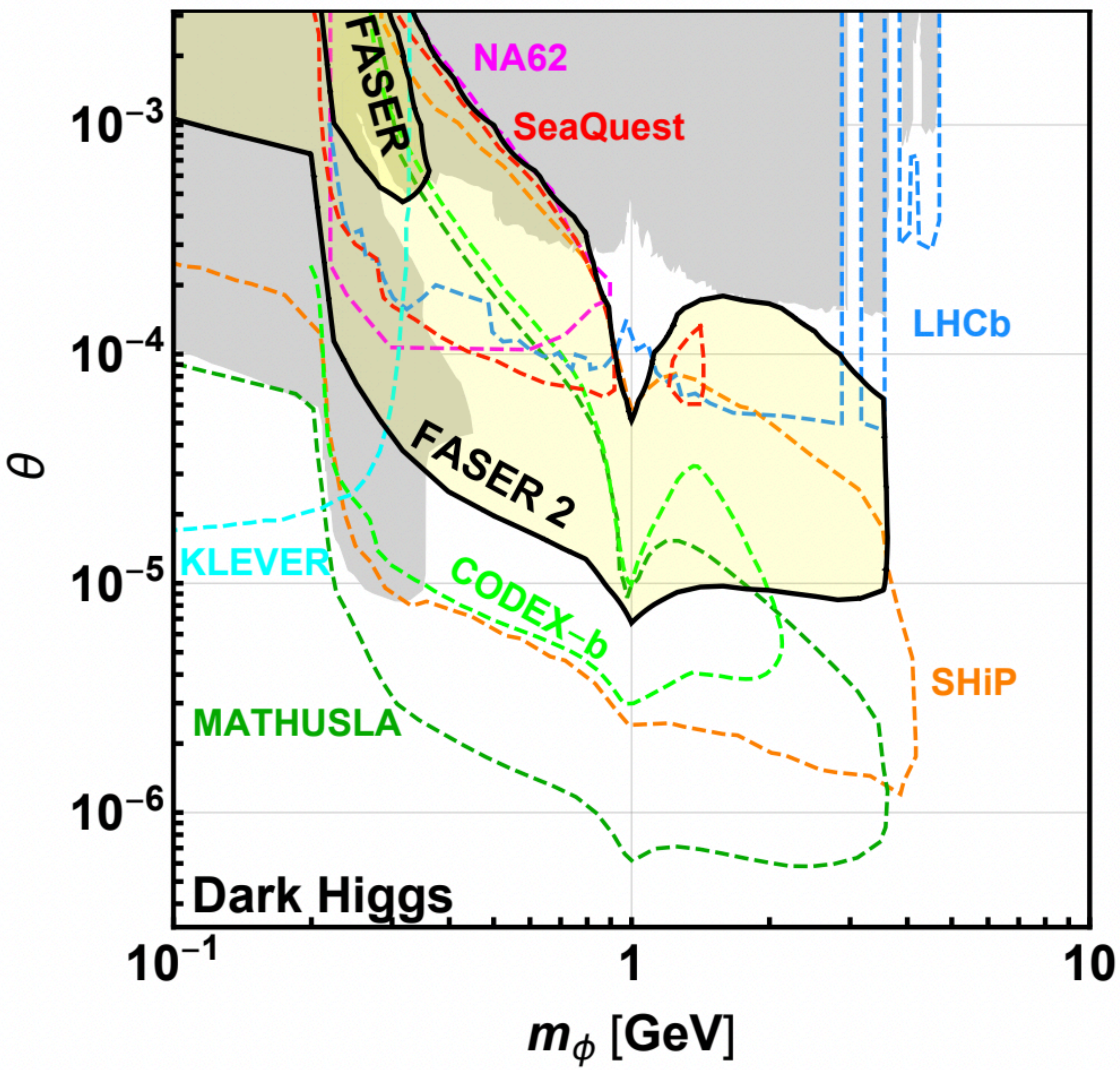
Target scenarios | Dark Photon



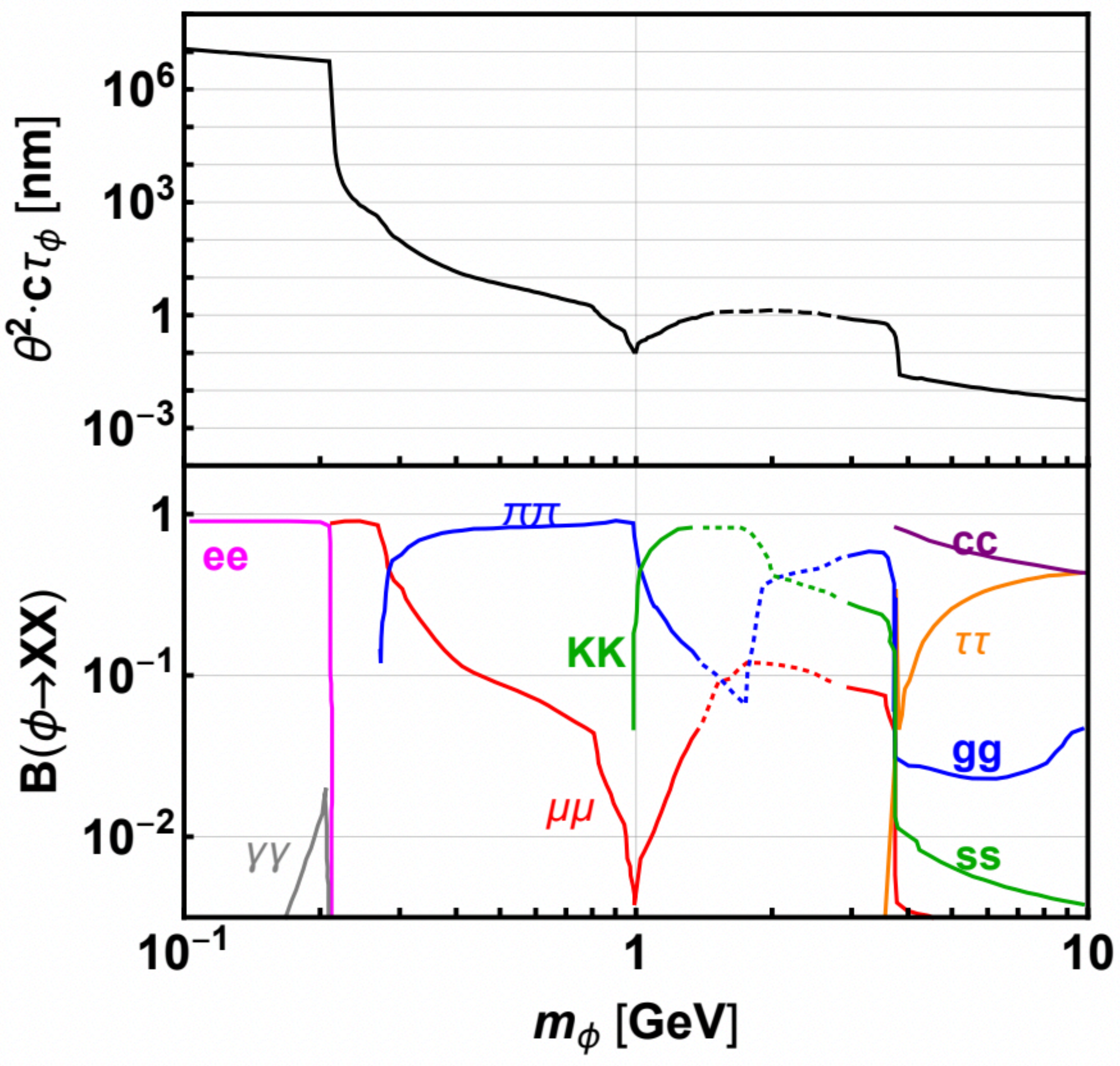


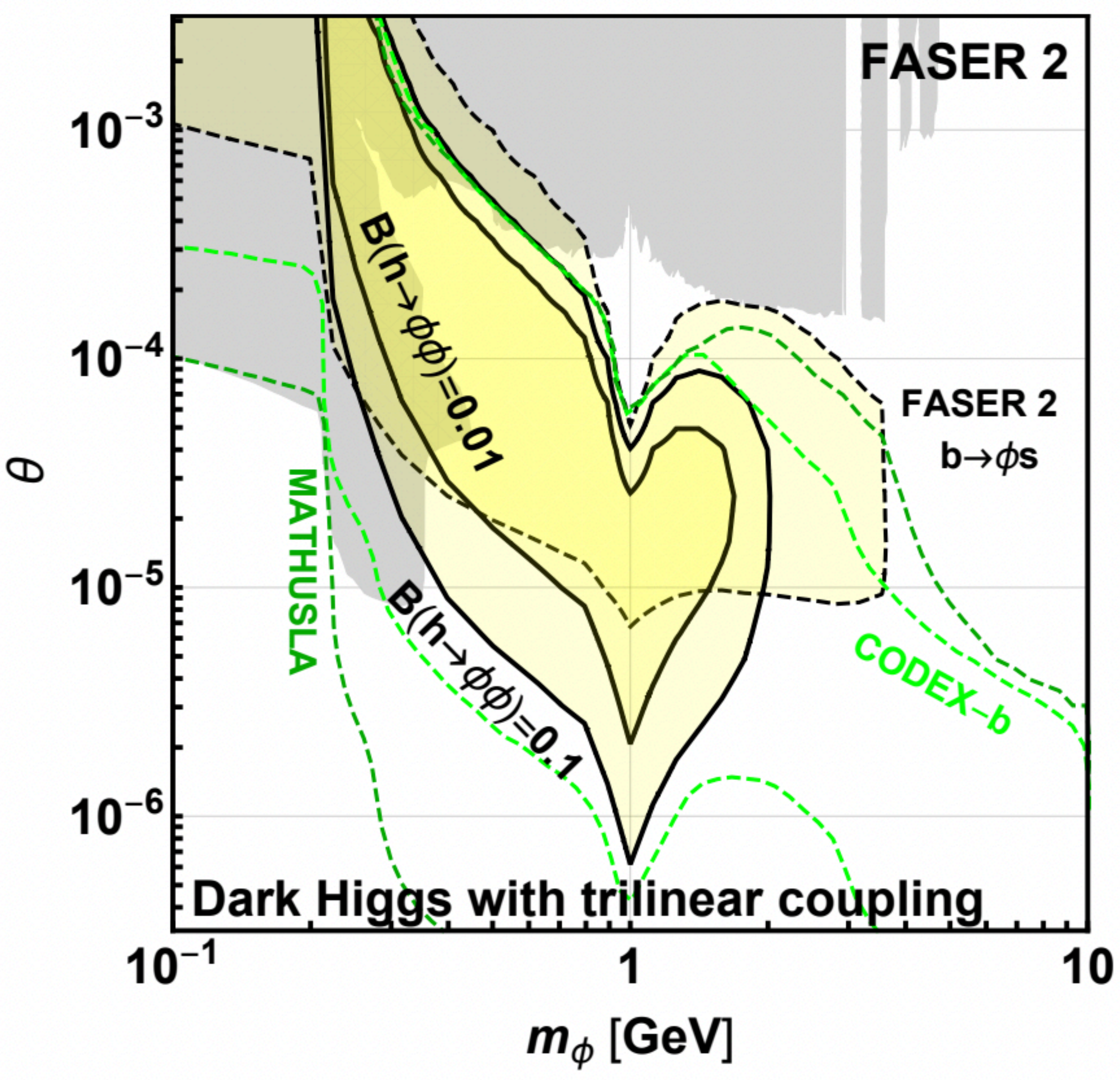
Target scenarios | Dark Higgs



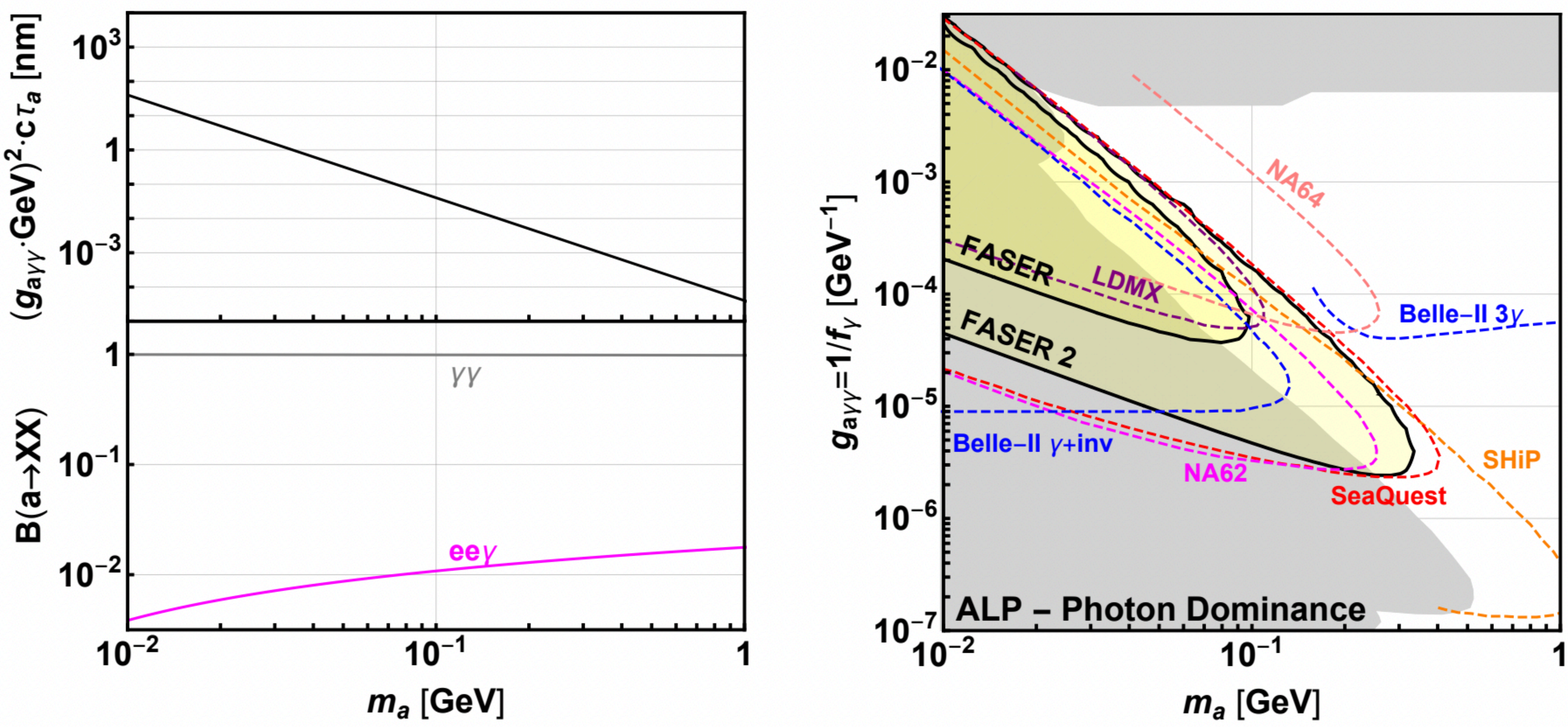


Target scenarios | Dark Higgs

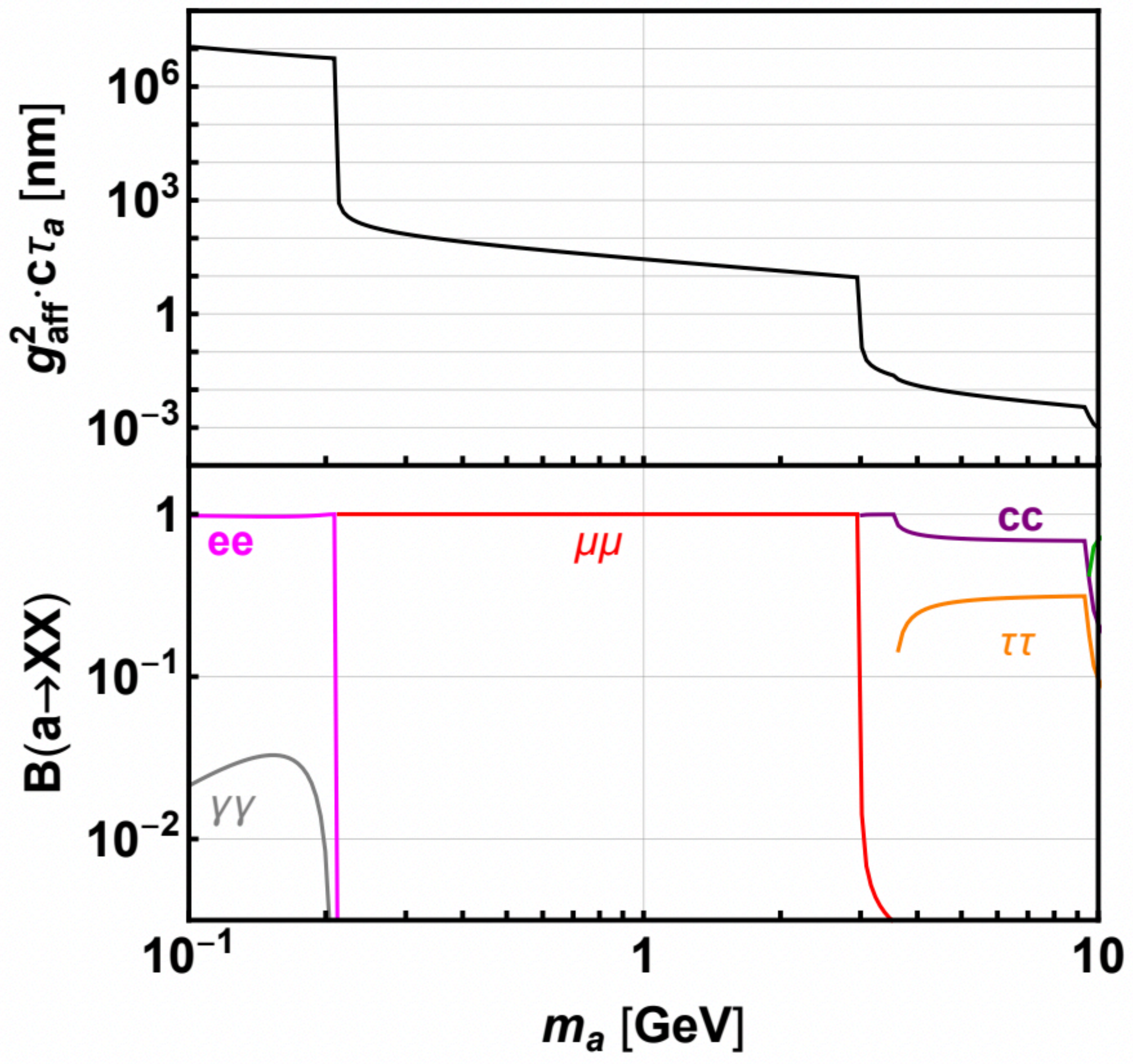


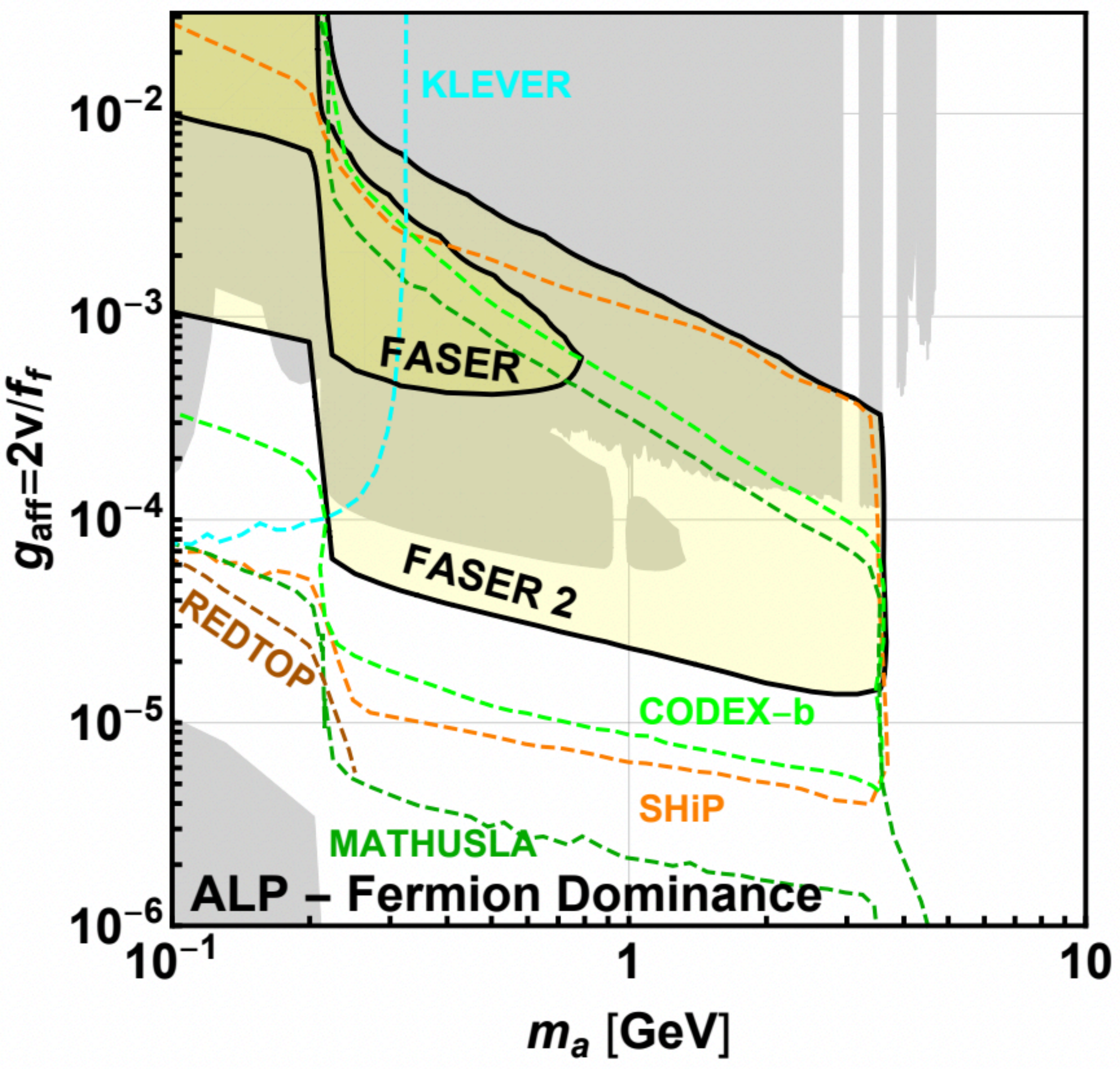


Target scenarios | ALP

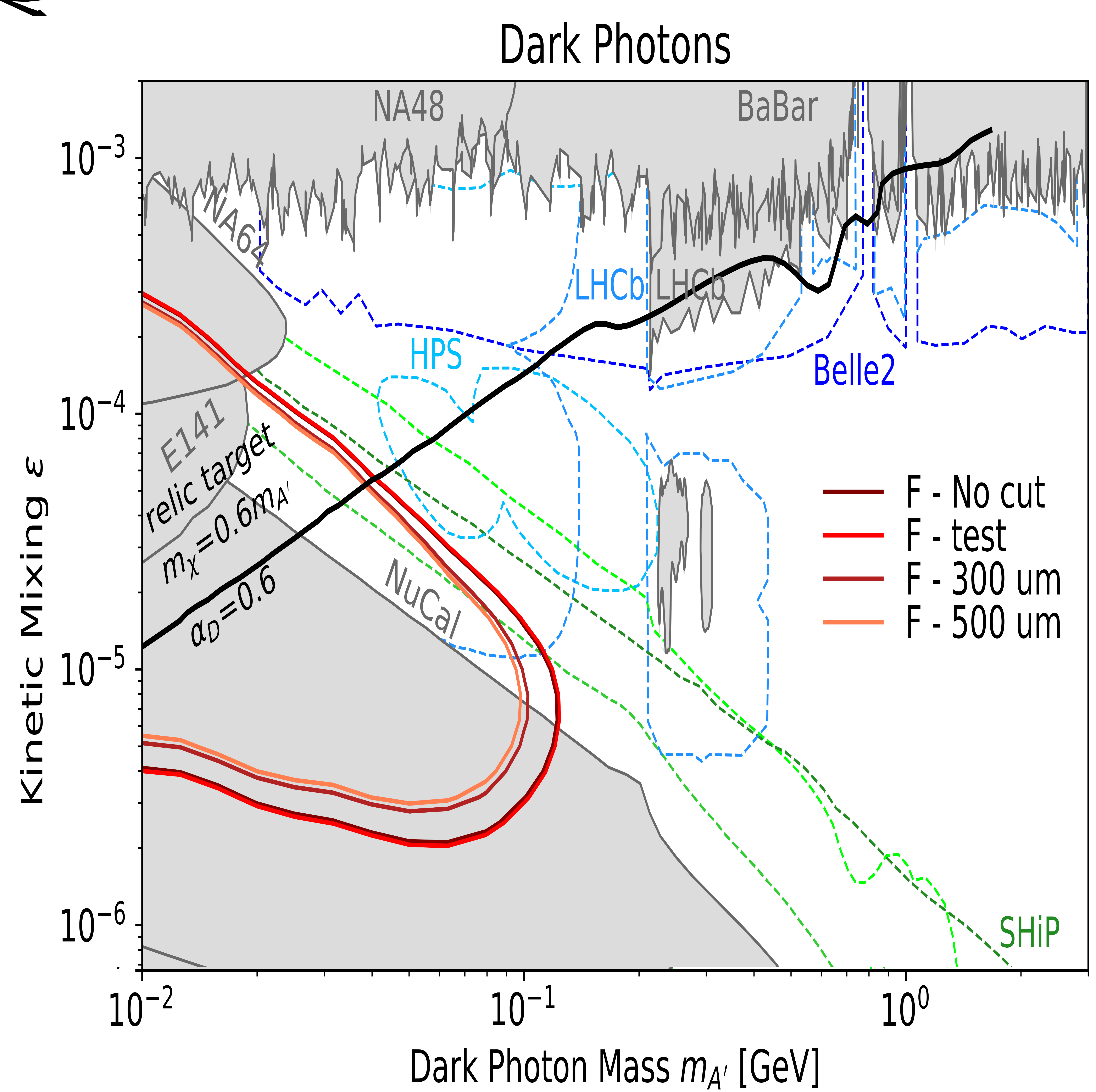


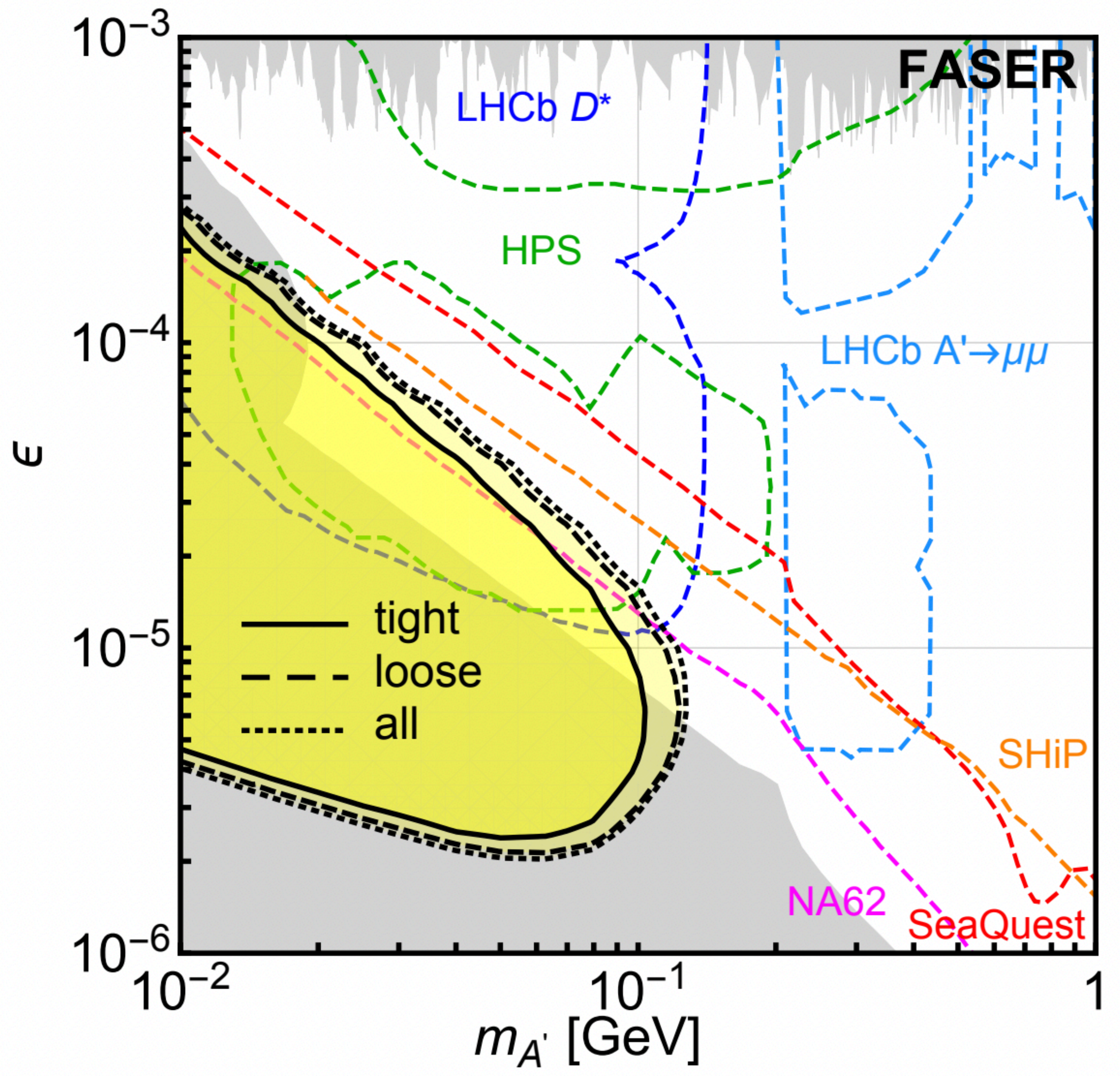
Target scenarios | ALP



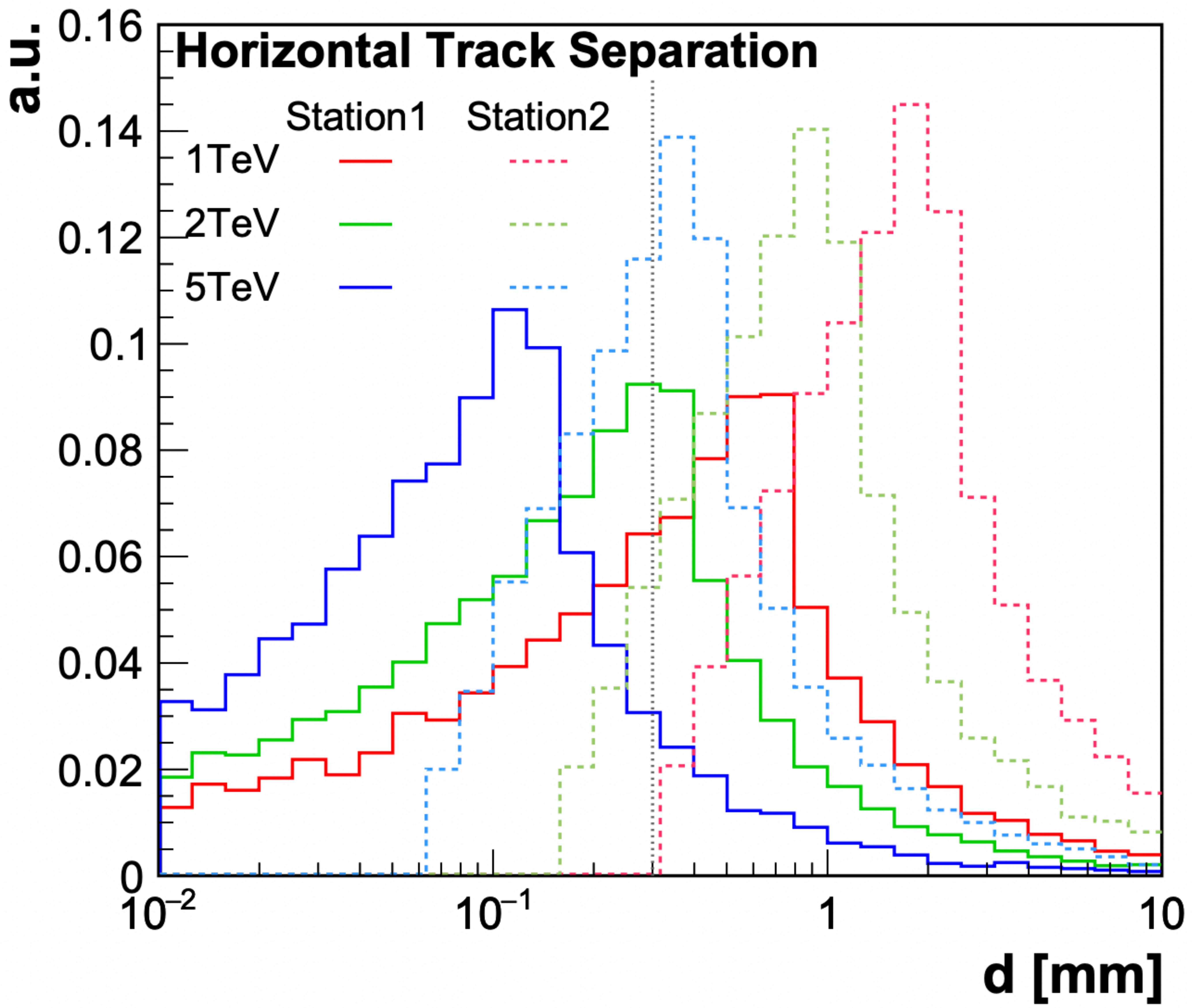


Distance from LOS



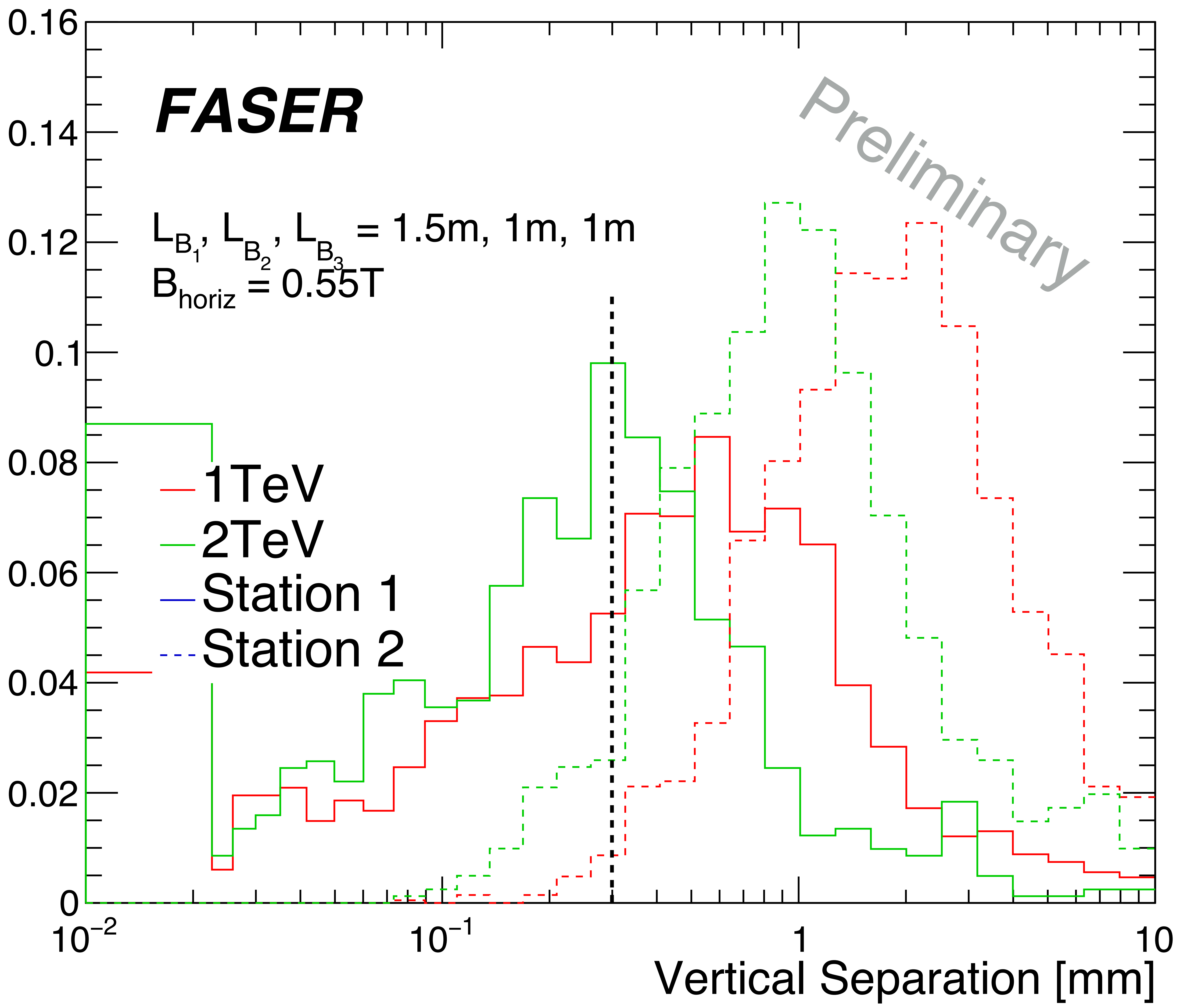


Validation



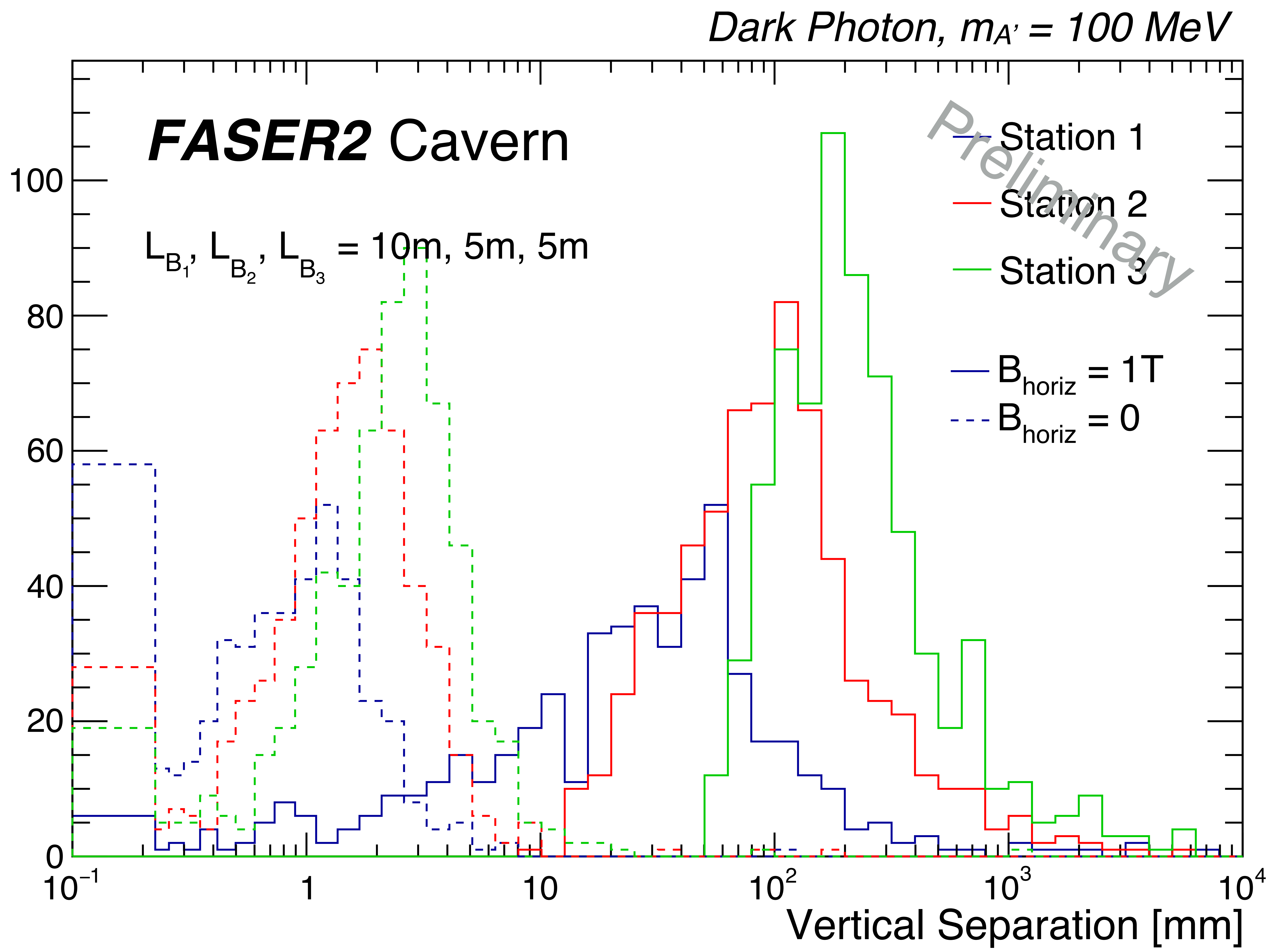
Horizontal Track Separation
Station1
Station2
1TeV
2TeV
5TeV
a.u.
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
10^{-2}
10^{-1}
1
10
d [mm]

Validation

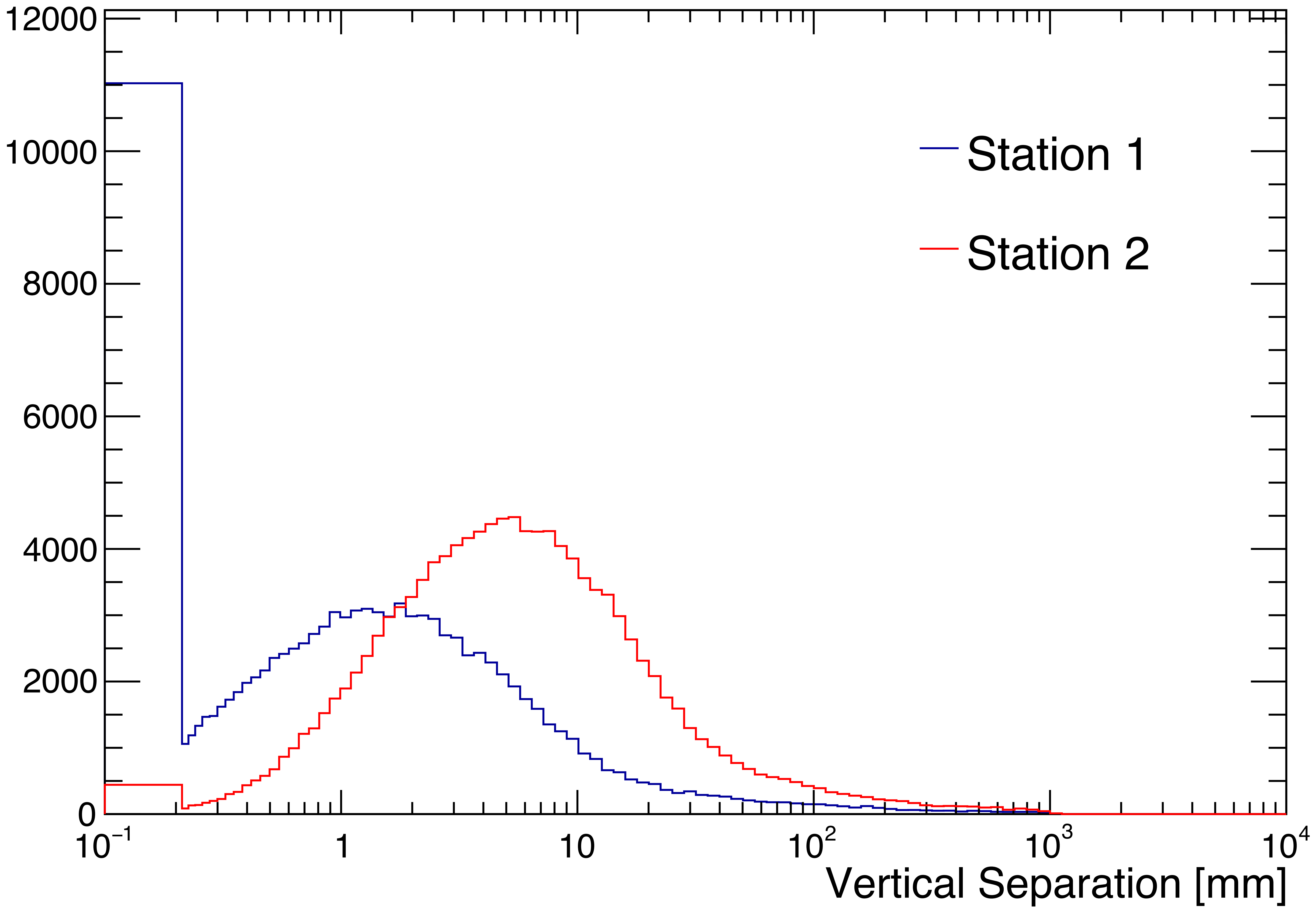


FASER
Preliminary
L_{B_1}, L_{B_2}, L_{B_3} = 1.5m, 1m, 1m
B_{horiz} = 0.55T
1TeV
2TeV
Station 1
Station 2
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
10^{-2}
10^{-1}
1
10
Vertical Separation [mm]

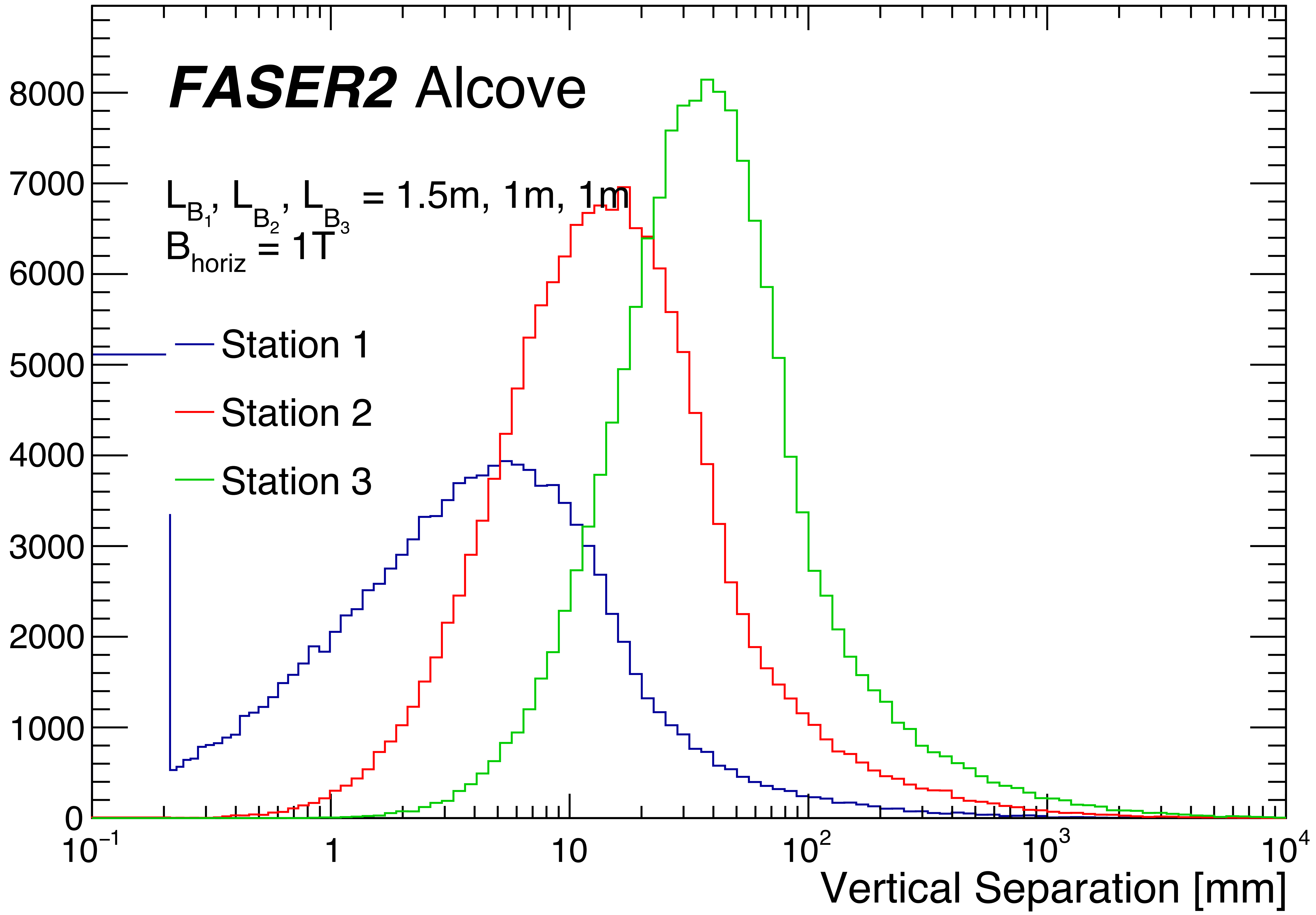
Validation | 1 TeV



Simulation studies | FASER

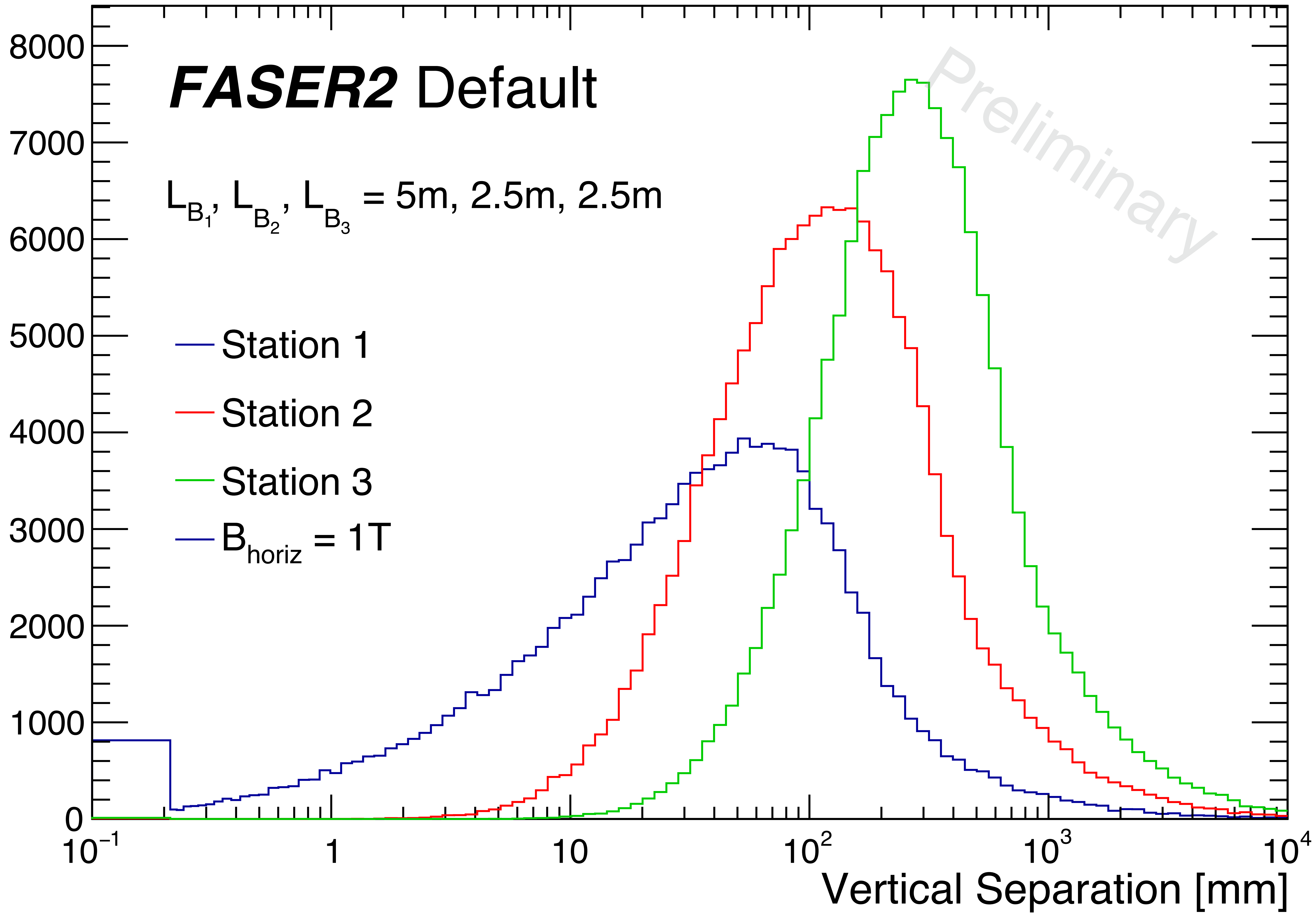


Simulation studies | Scenario 1

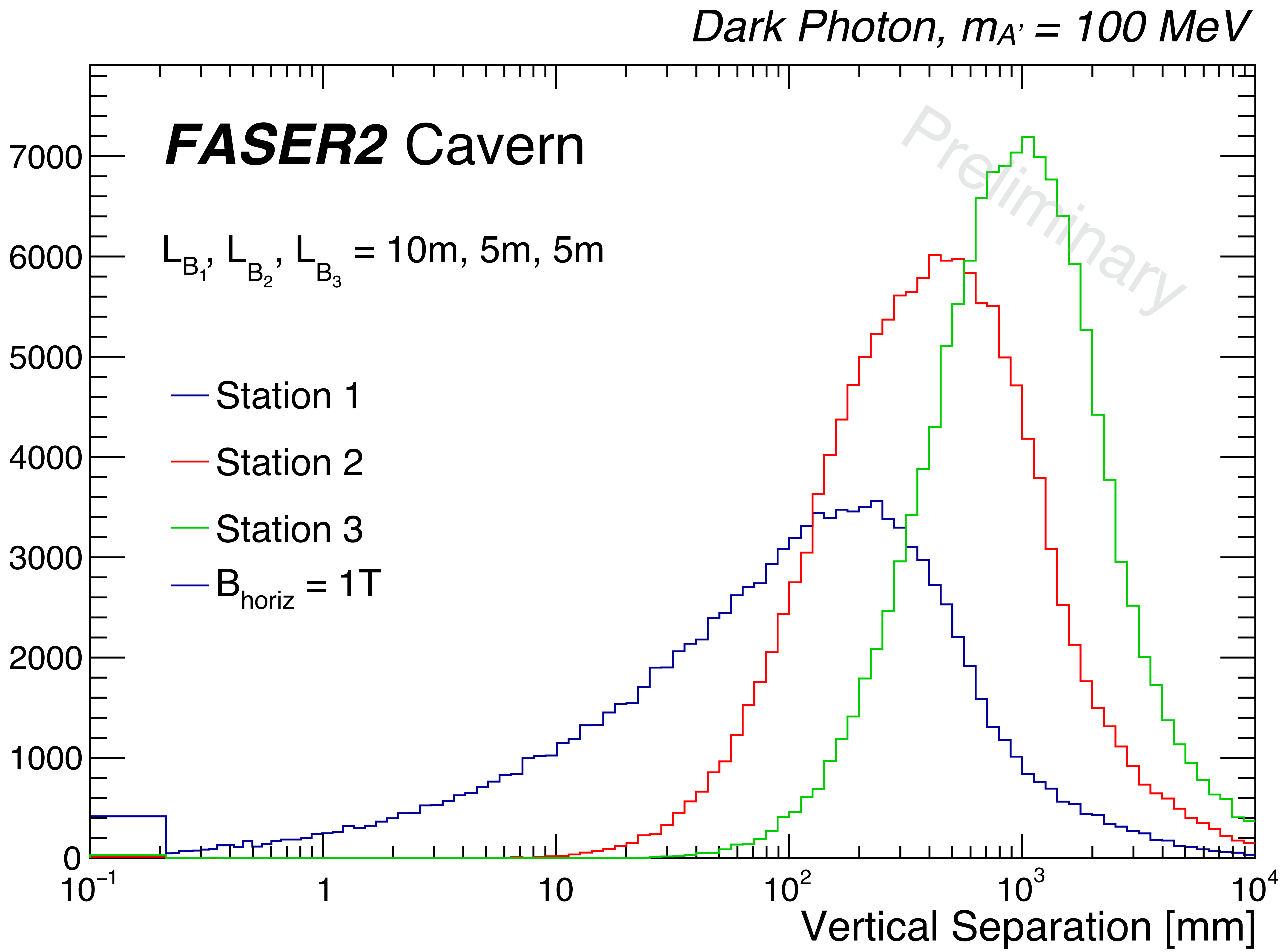


Simulation studies | Default FASER2

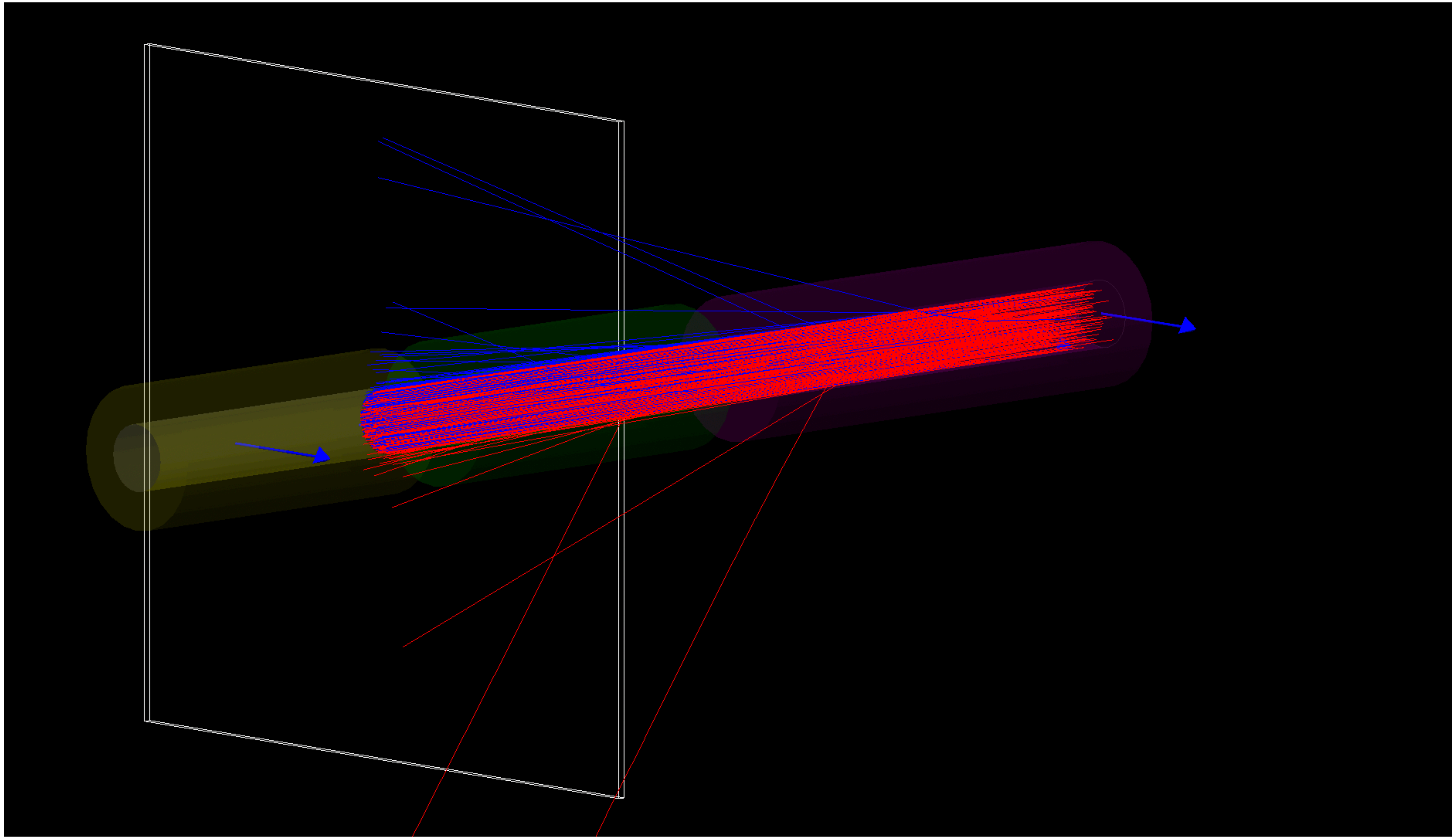
Dark Photon, $m_{A'}$ = 100 MeV



Simulation studies | Scenario 2



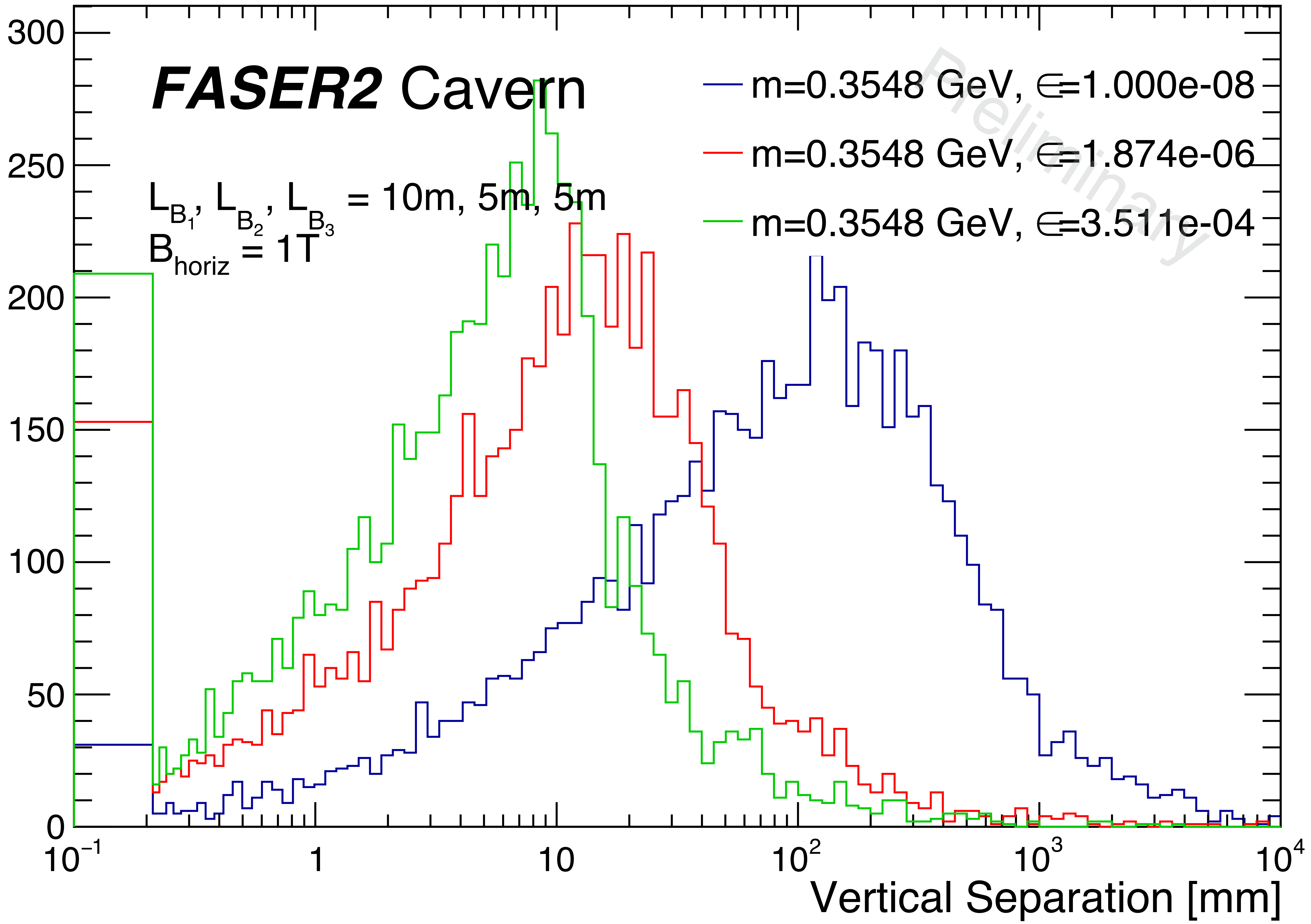
Simulation studies



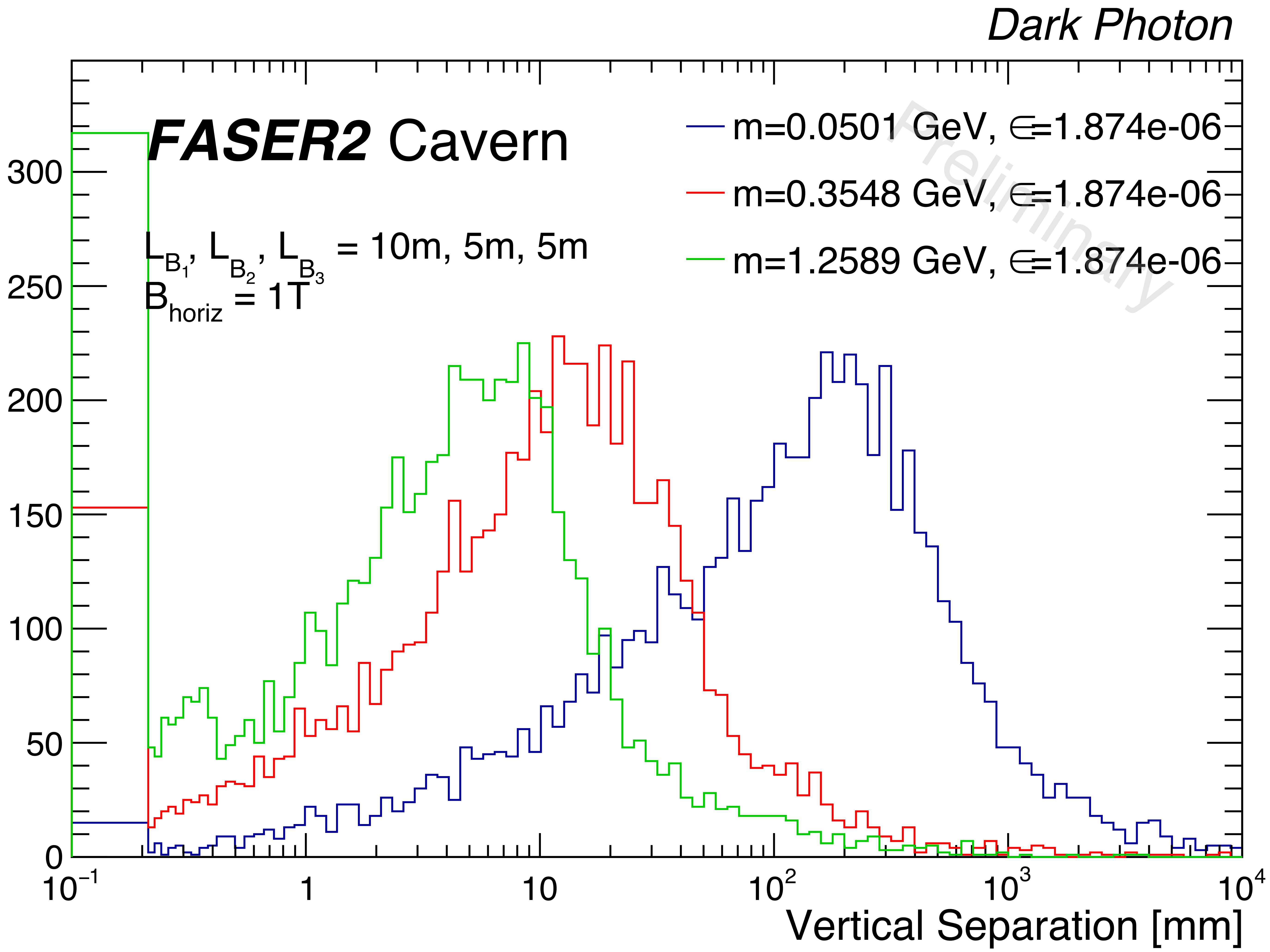
Simulation studies | Coupling

- **Scenario 2:**
  -

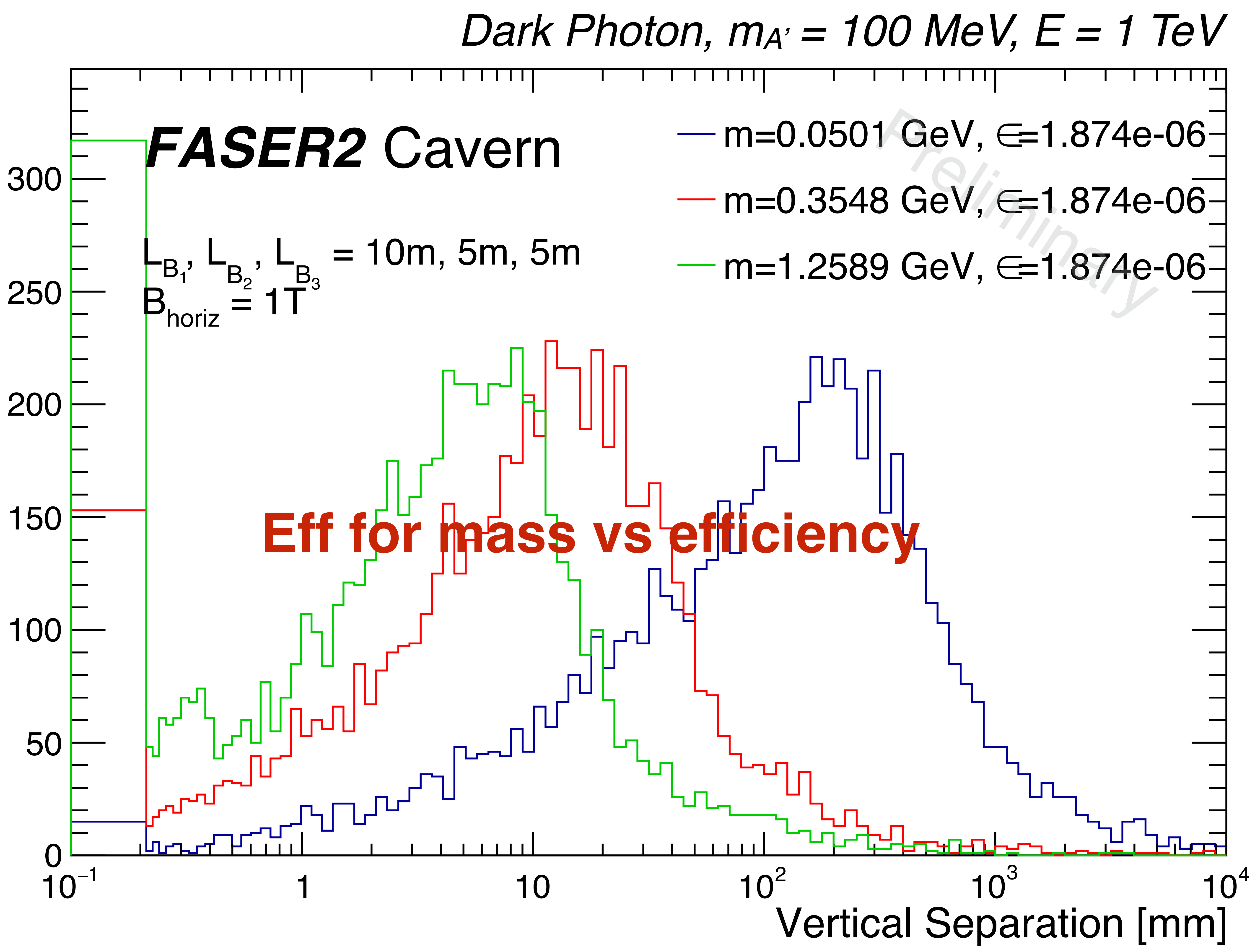
Dark Photon



Simulation studies | Mass



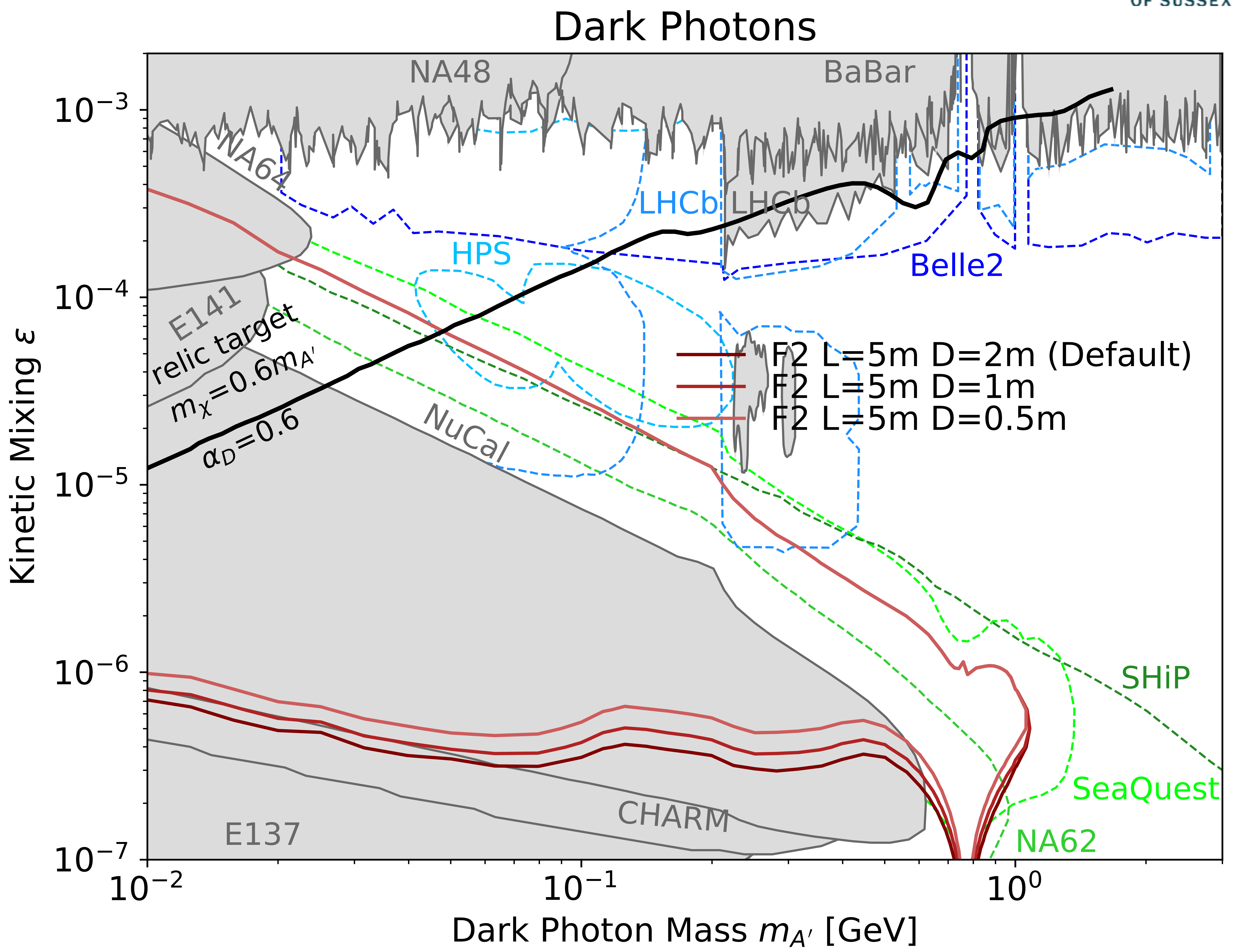
Simulation studies | Scenario 2 E = 1 TeV



Dual readout calo

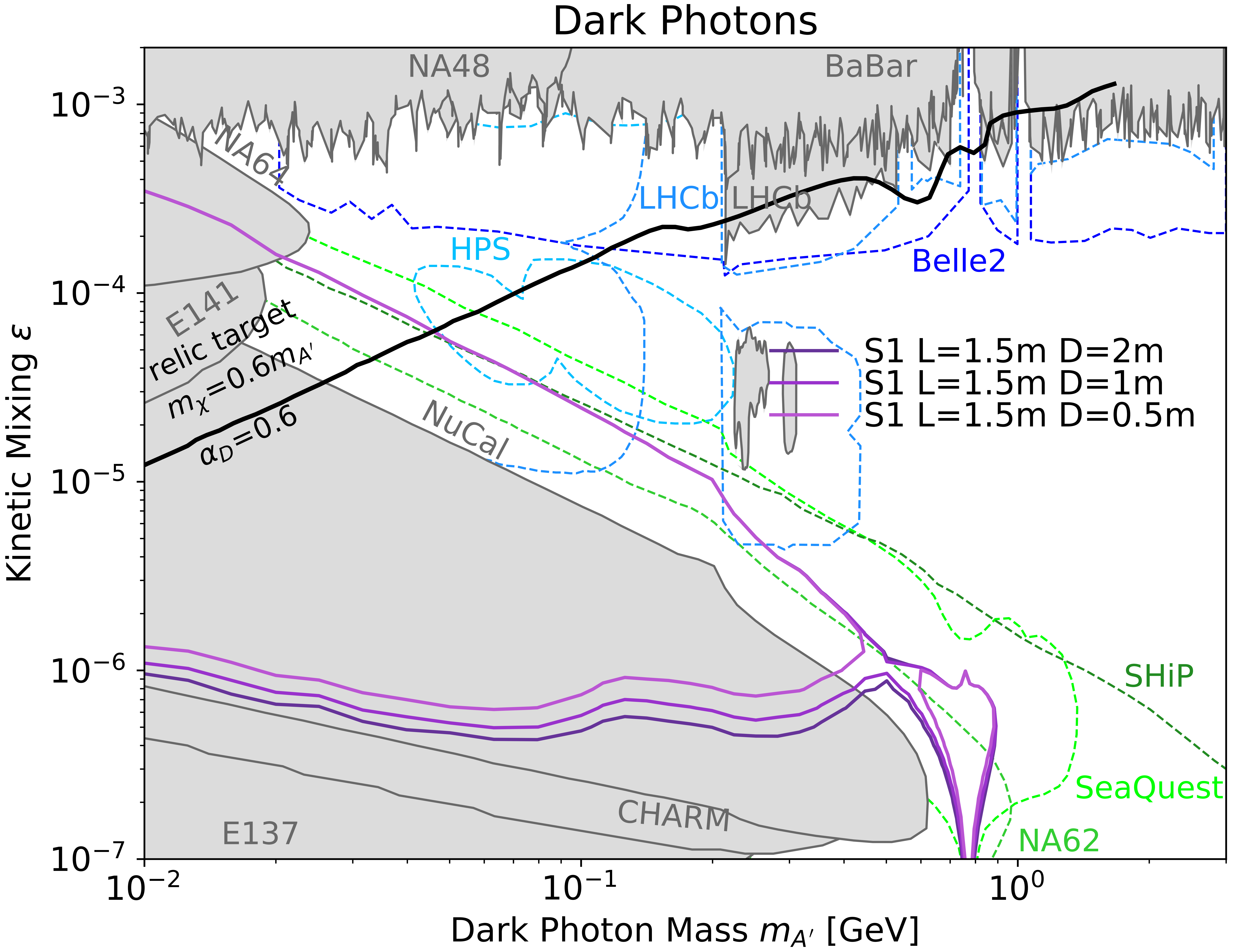
FPF Scenarios | Dark photons

- **FASER2** (incl default)



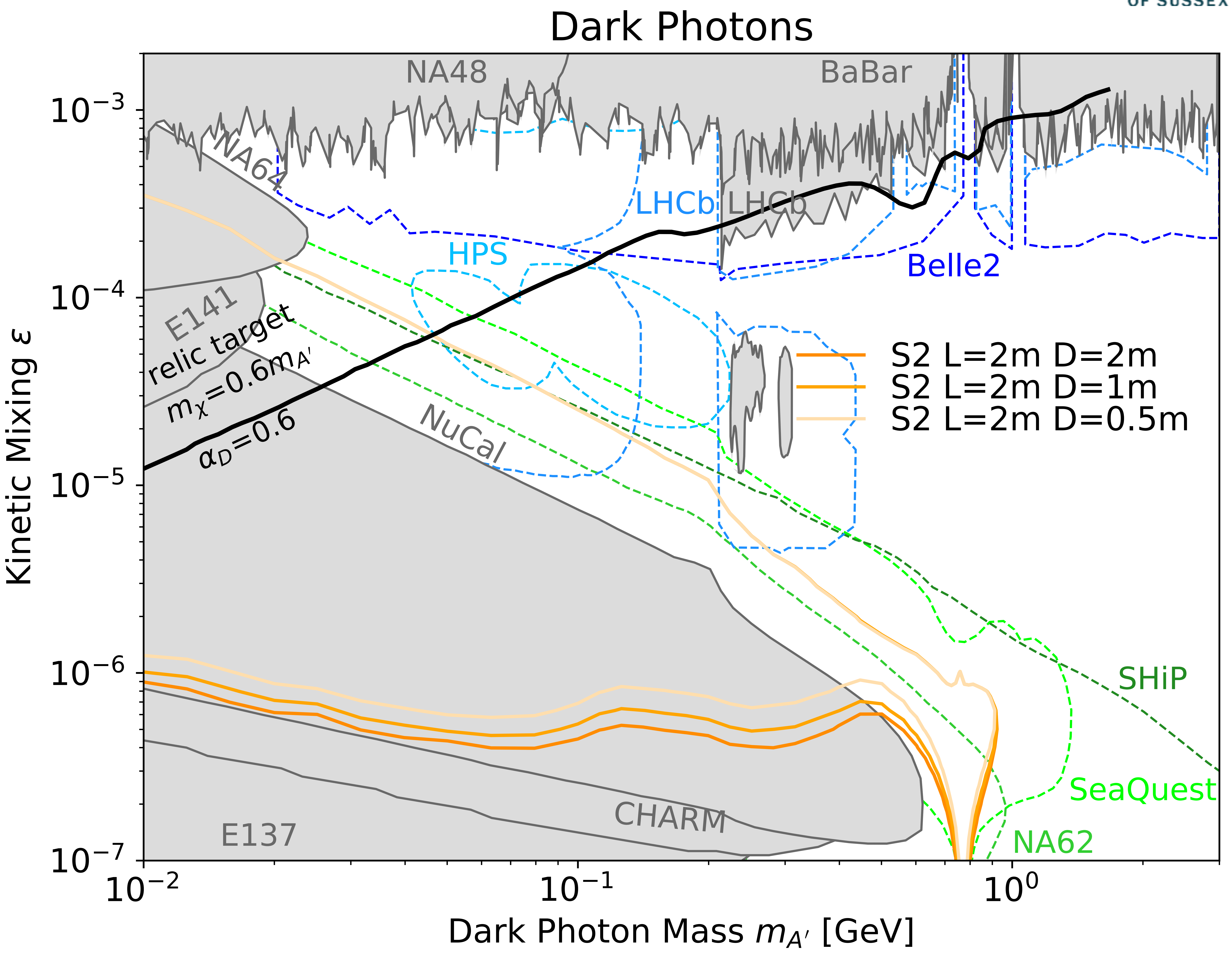
FPF Scenarios | Dark photons

- **FASER2** (incl default)
- **S1 (alcove)**
  - Worse than very narrow F2



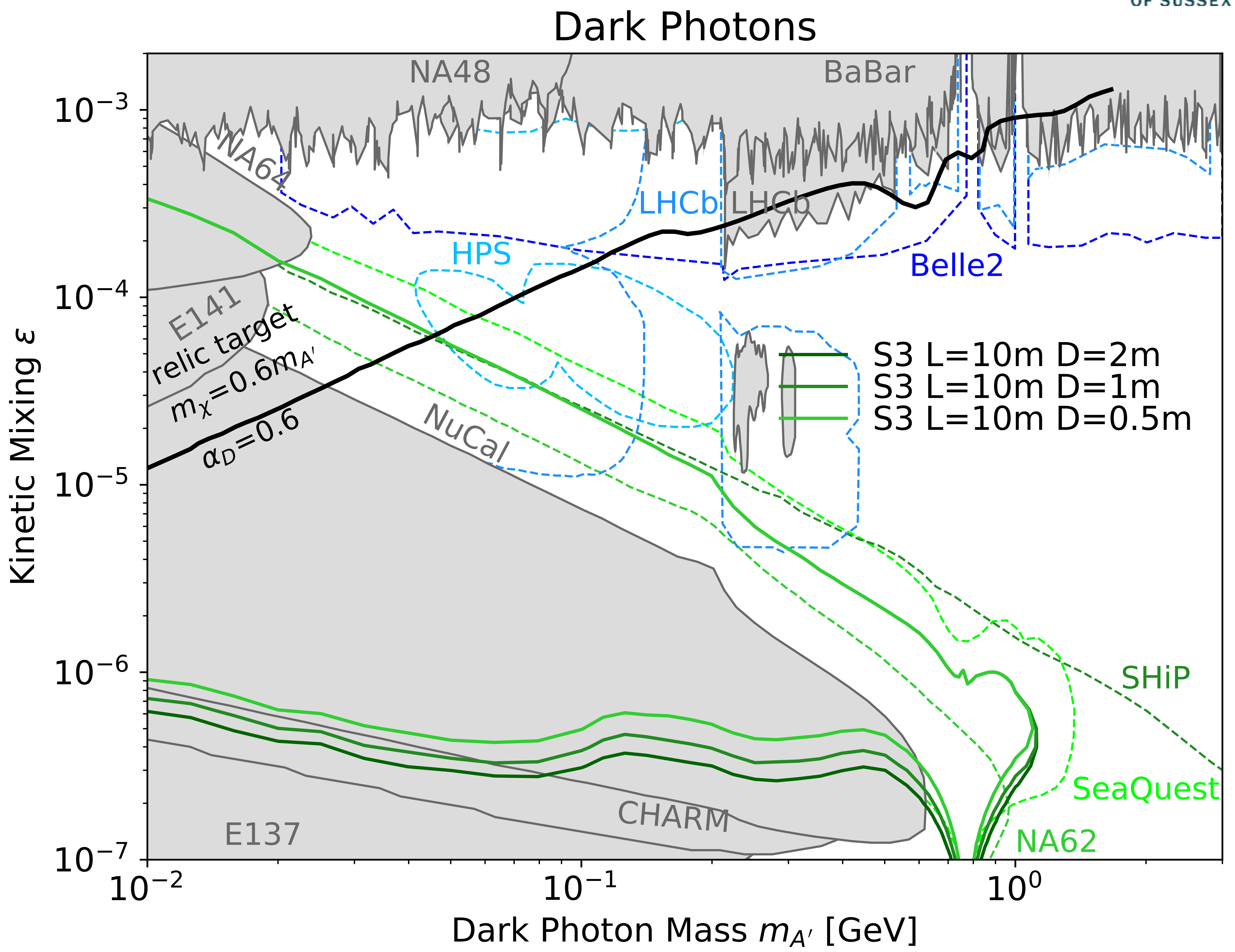
FPF Scenarios | Dark photons

- **FASER2** (incl default)
- **S1 (alcove)**
  - Worse than very narrow F2
- **S2 (enlarged UJ12)**
  - Worse than very narrow F2



FPF Scenarios | Dark photons

- **FASER2** (incl default)
- **S1 (alcove)**
  - Worse than very narrow F2
- **S2 (enlarged UJ12)**
  - Worse than very narrow F2
- **S3 (new cavern)**
  - Better than but comparable to F2
  - Slight shift in diagonal due to increased distance from IP.



FPF Scenarios | Dark photons

- **FASER2** (incl default)
- **S1 (alcove)**
  - Worse than very narrow F2
- **S2 (enlarged UJ12)**
  - Worse than very narrow F2
- **S3 (new cavern)**
  - Better than but comparable to F2
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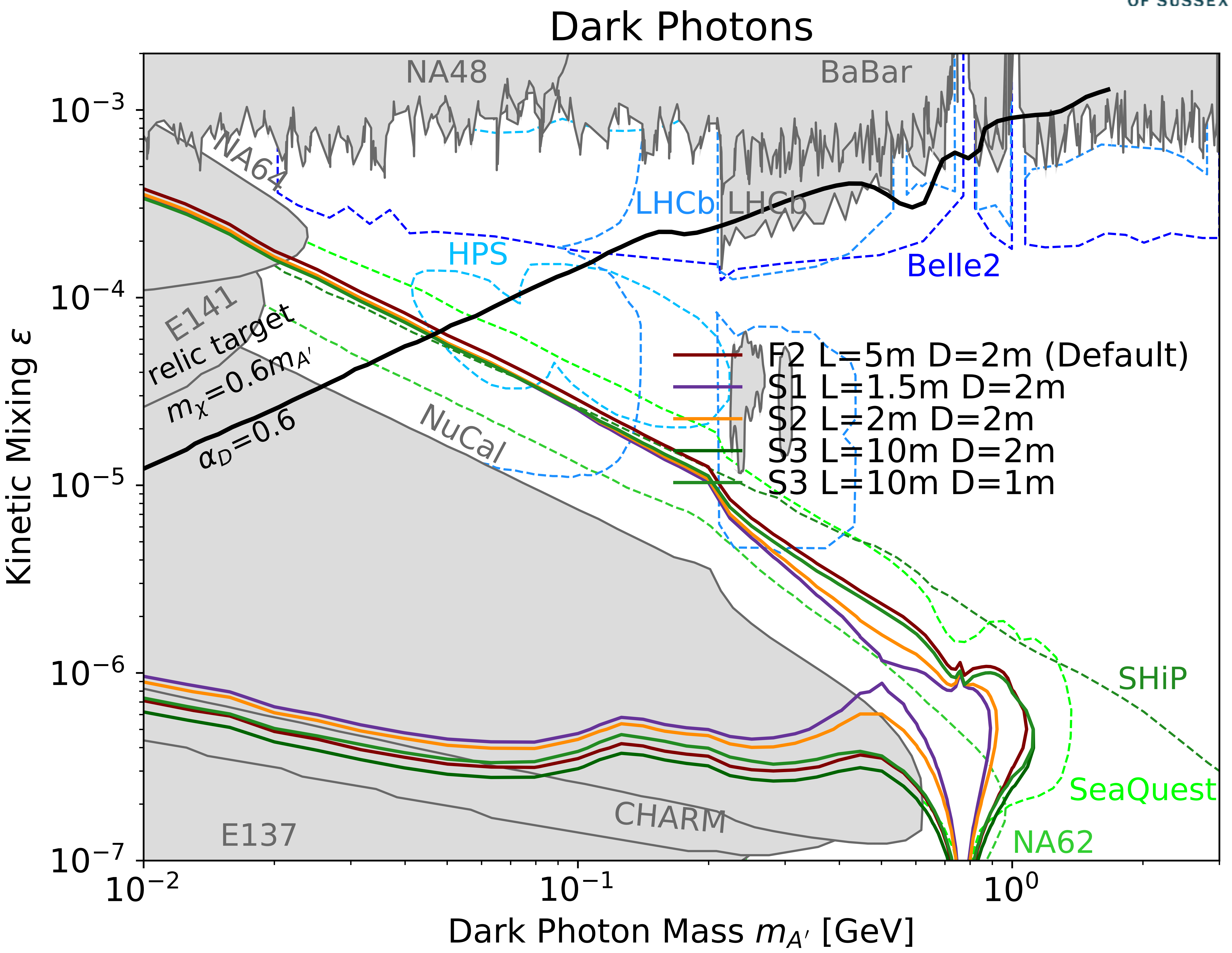
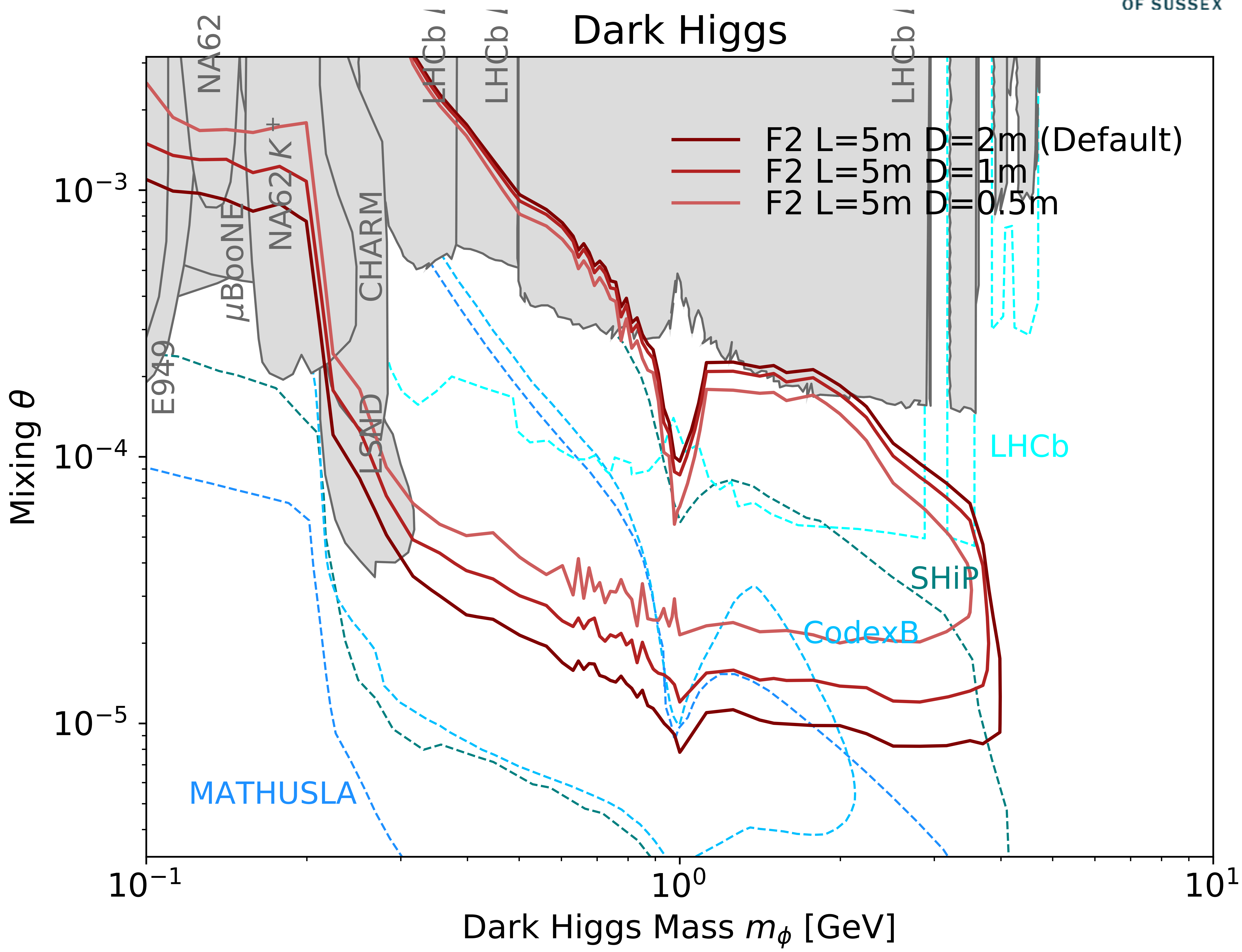


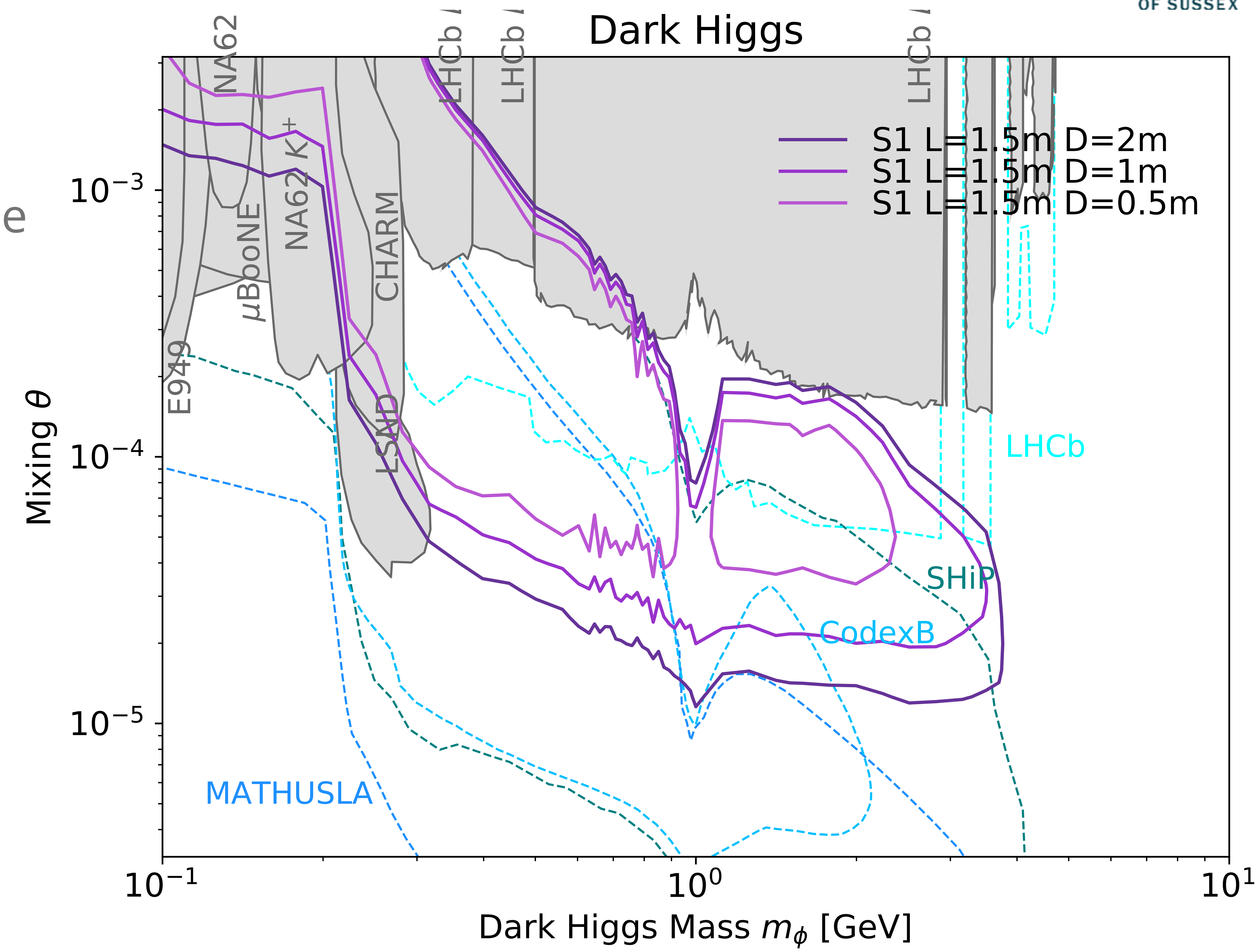
FPF Scenarios | Dark Higgs

- **FASER2** (incl default)



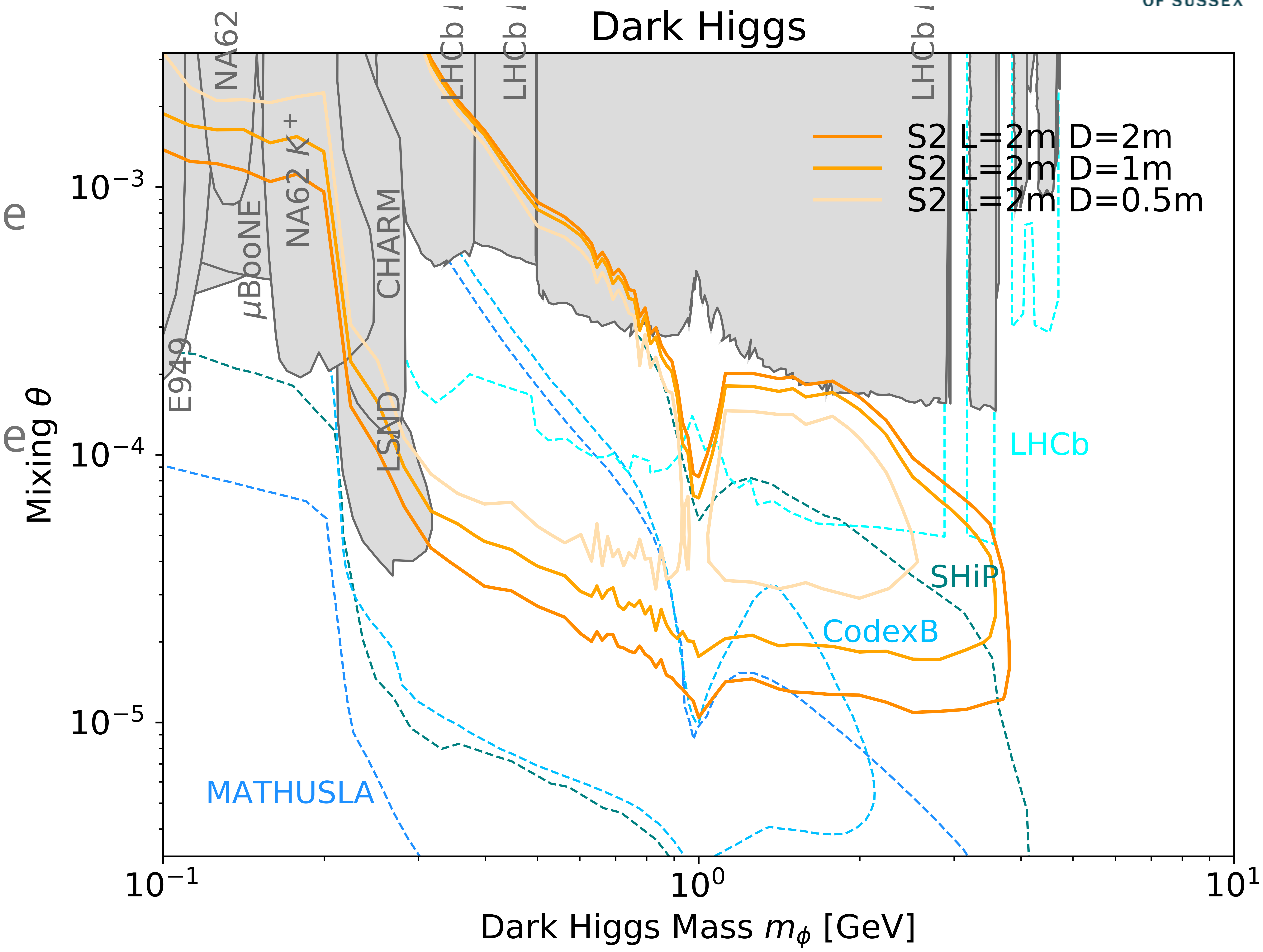
FPF Scenarios | Dark Higgs

- **FASER2** (incl default)
- **S1 (alcove)**
  - Widest S1 design comparable to D=1m F2.



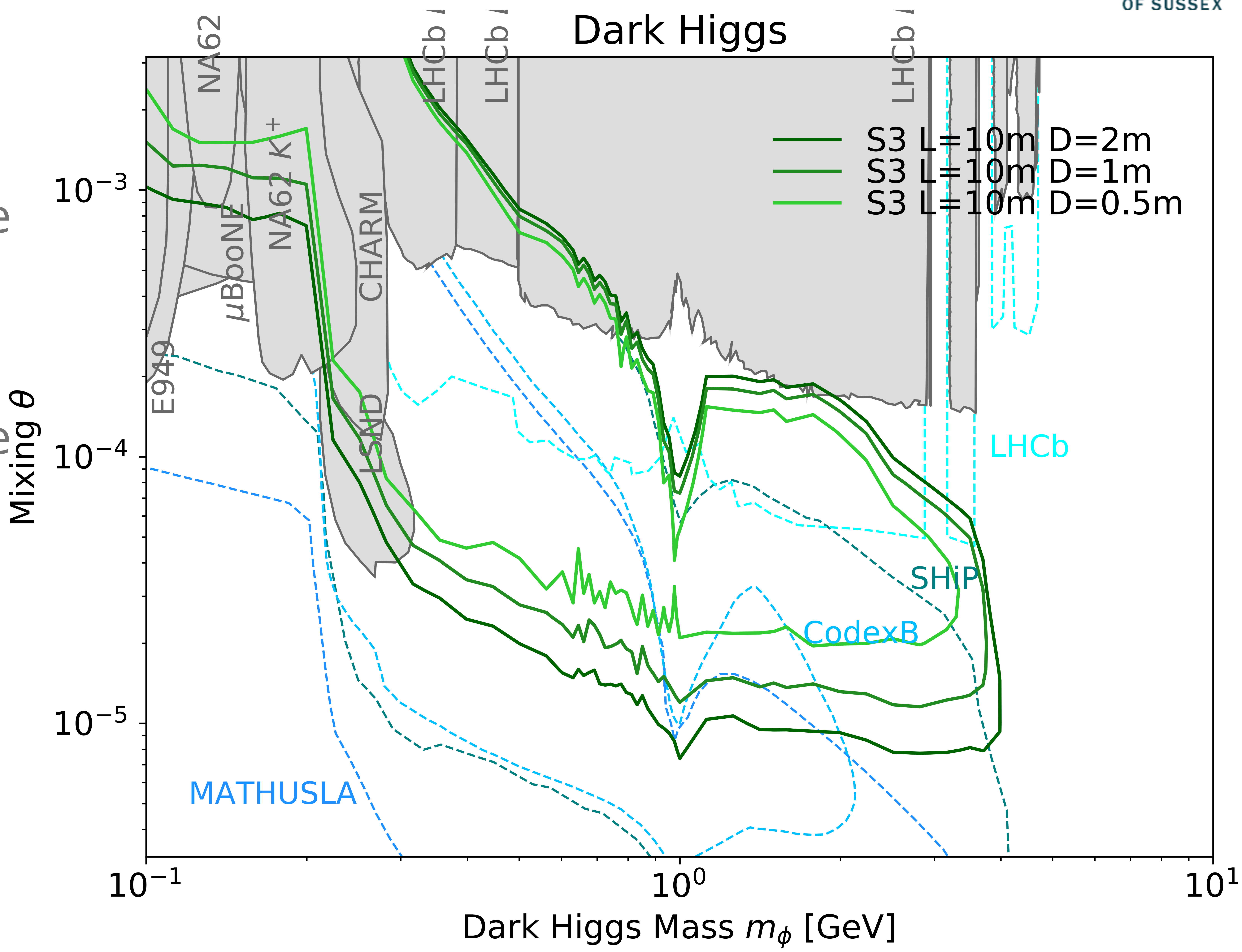
FPF Scenarios | Dark Higgs

- **FASER2** (incl default)
- **S1 (alcove)**
  - Widest S1 design comparable to D=1m F2.
- **S2 (enlarged UJ12)**
  - Widest S2 design comparable to D=1m F2.



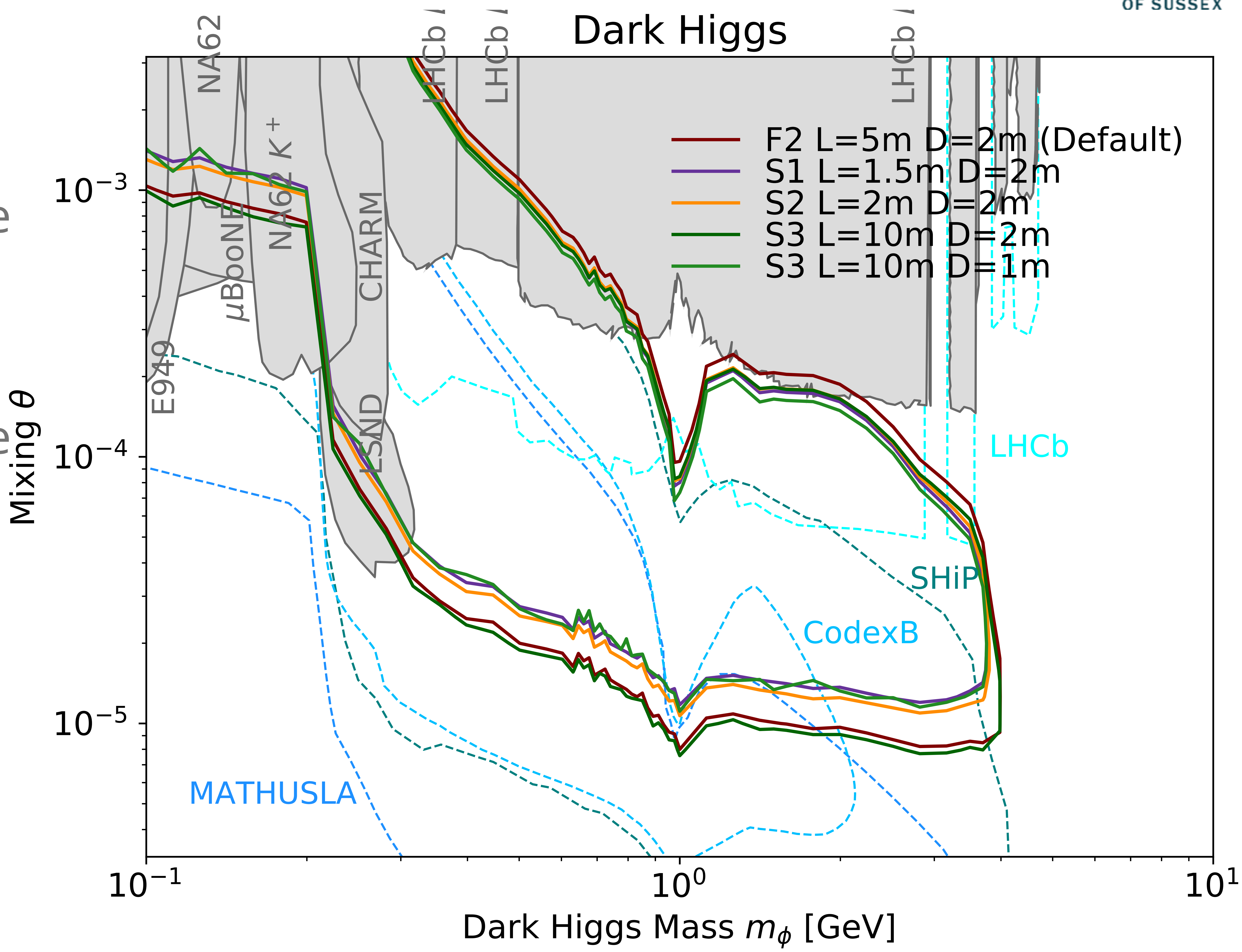
Forward Physics Facility | Dark Higgs

- **FASER2** (incl default)
- **S1 (alcove)**
  - Widest S1 design comparable to D=1m F2.
- **S2 (enlarged UJ12)**
  - Widest S2 design comparable to D=1m F2.
- **S3 (new cavern)**
  - Better than but comparable to F2
  - Slight shift in diagonal due to increased distance from IP.



FPF Scenarios | Dark Higgs

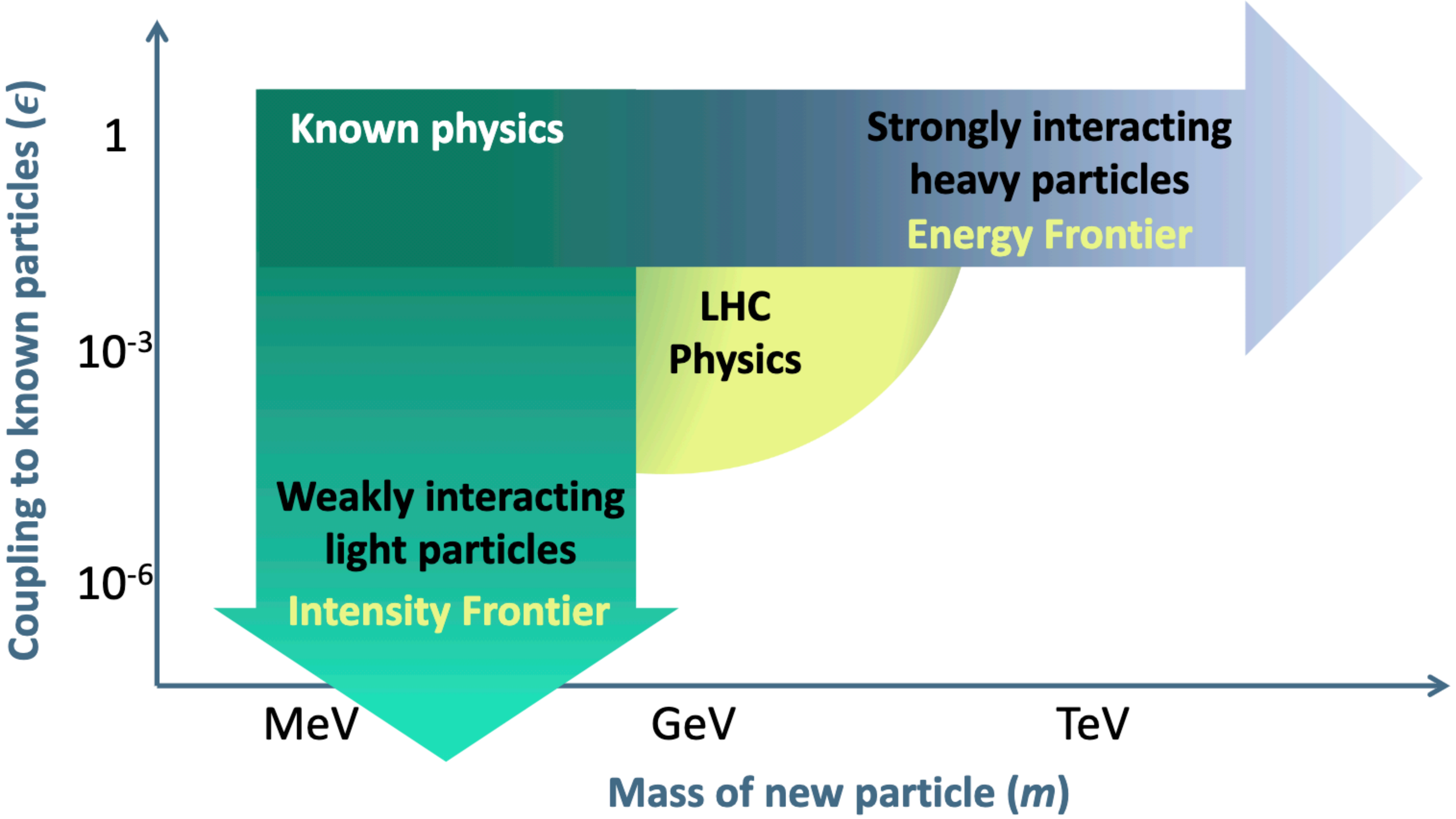
- **FASER2** (incl default)
- **S1 (alcove)**
  - Widest S1 design comparable to D=1m F2.
- **S2 (enlarged UJ12)**
  - Widest S2 design comparable to D=1m F2.
- **S3 (new cavern)**
  - Better than but comparable to F2
  - Slight shift in diagonal due to increased distance from IP.



Light Weak DM Motivation

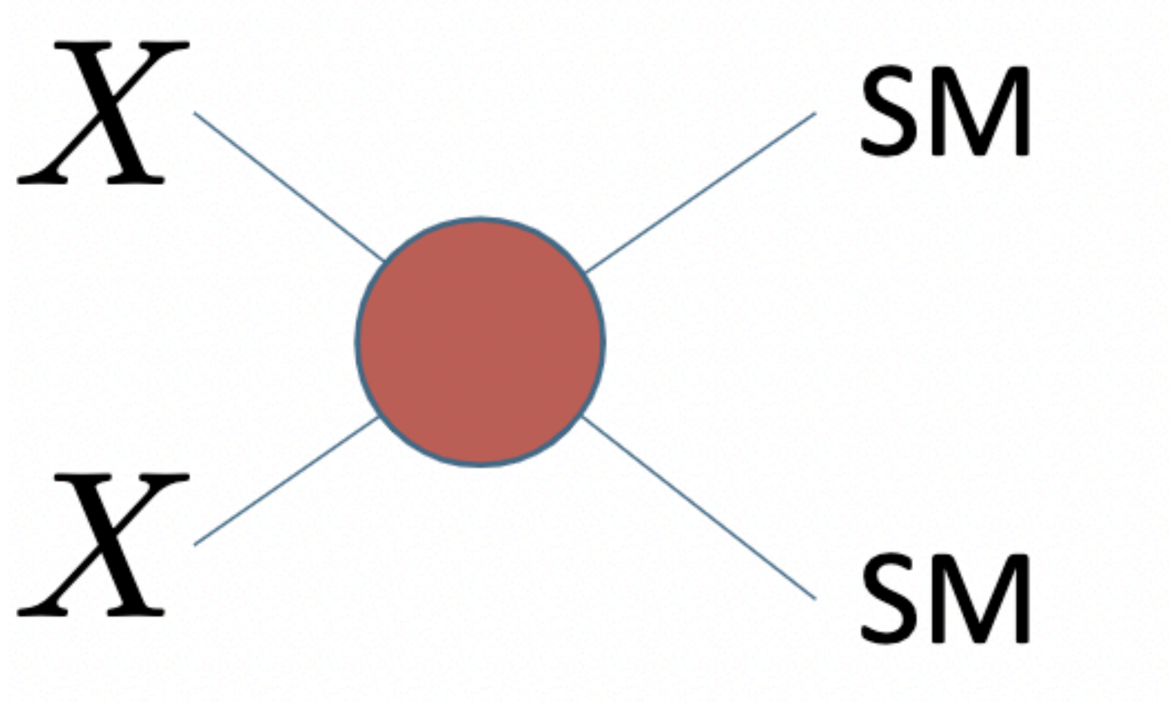
- The **LHC experiments** are producing incredible results, extending reach to more extreme phase-spaces and performing increasingly precise measurements.

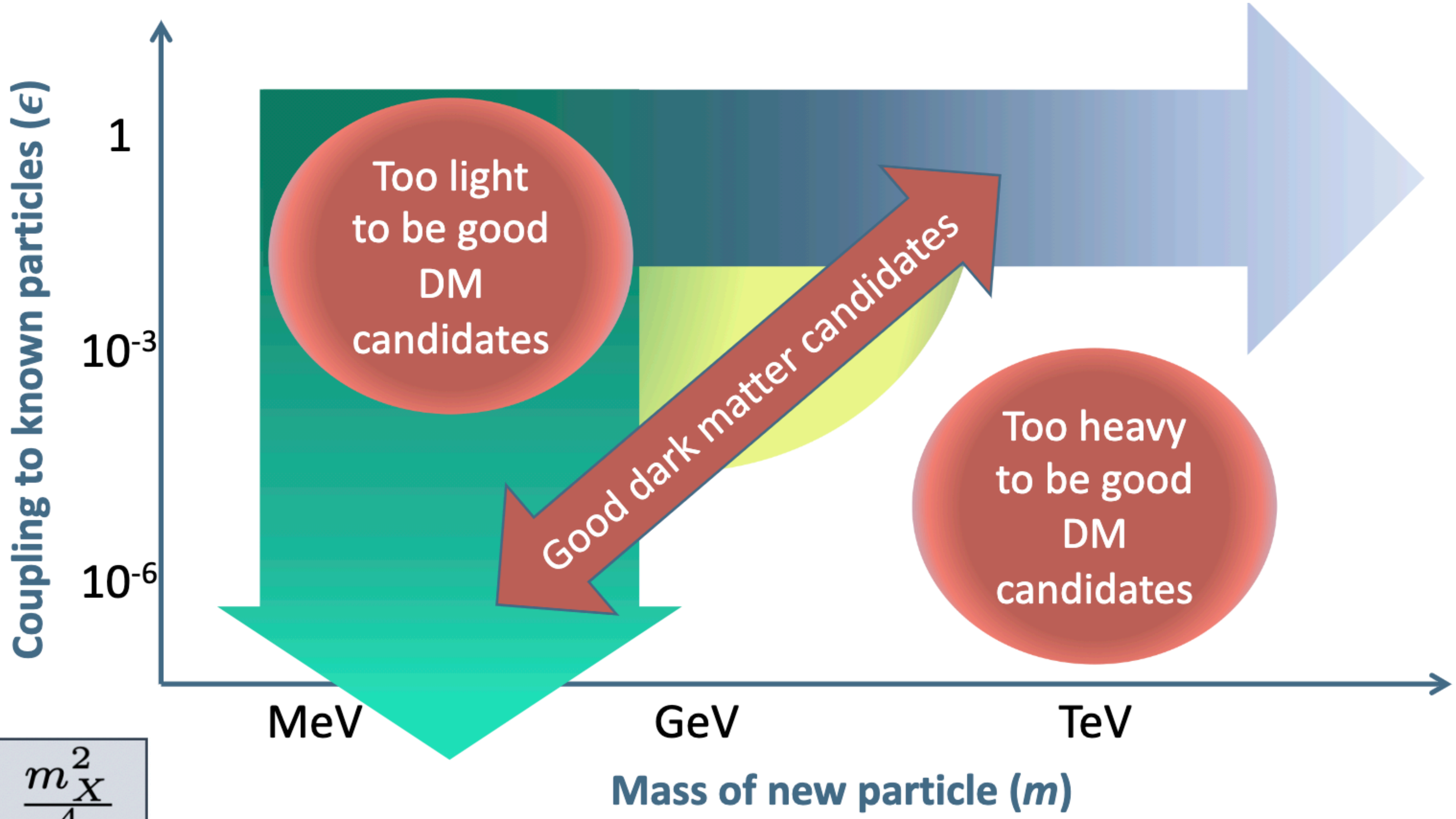
- But the lack of any observation of BSM physics motivates **looking elsewhere** too.



Light Weak DM Motivation

- Main region of interest is for new particles that satisfy DM relic density requirements.





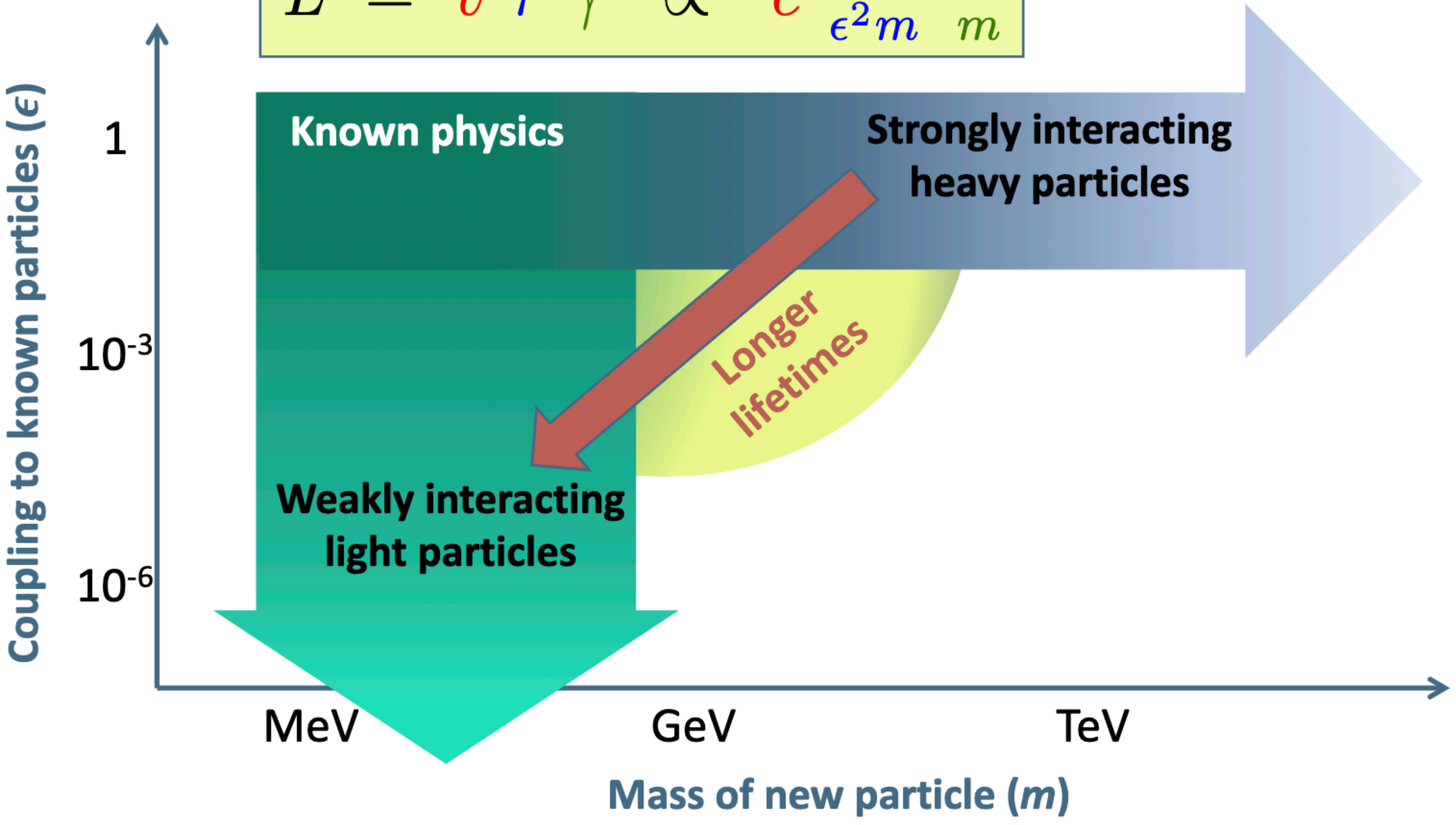
Surviving DM density: $\Omega_X \propto \frac{m_X^2}{\epsilon_X^4}$

Light Weak DM Motivation

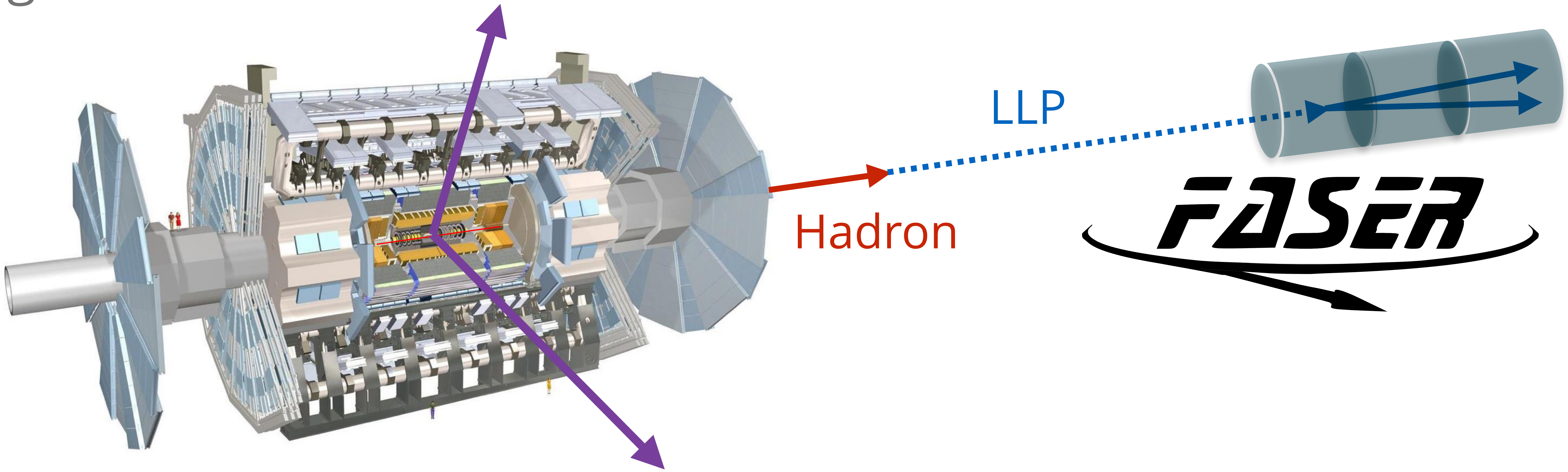
- One of the defining characteristics of weakly interacting light particles is their **long lifetime**.
- Distinct signatures
- But could still be produced in large numbers in hadron decays at ATLAS!

Distance travelled by particles:

$$L = v\,\tau\,\gamma \;\propto\; c\,\frac{1}{\epsilon^2 m}\,\frac{E}{m}$$



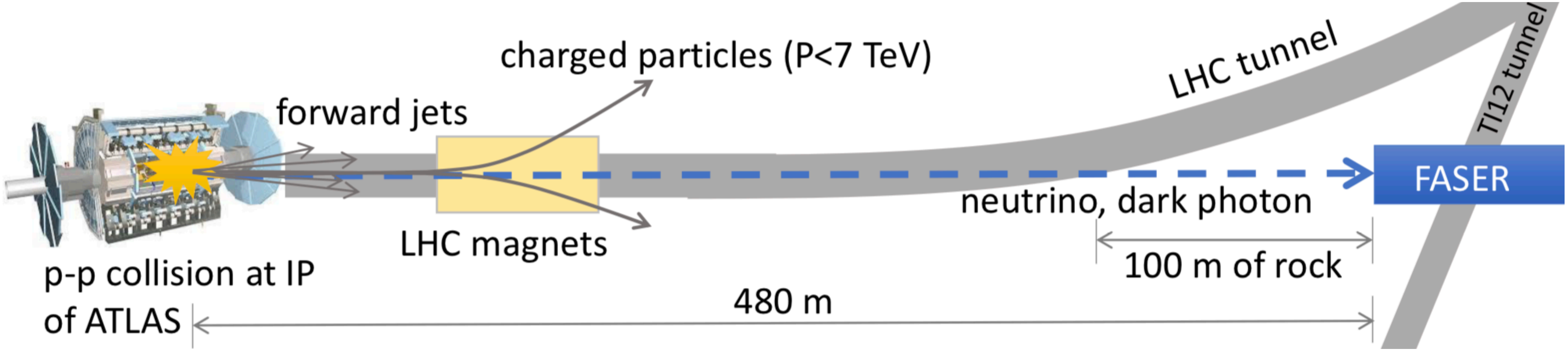
- FASER is a new experiment at CERN!
  - Data-taking starts in Run 3



- Detector is 480m from ATLAS IP1
  - Directly in line with beam collision axis.
  - Transverse radius of only 10cm covering the mrad regime (η>9.1)
- Inelastic pp cross section is huge → 10^{16} collisions in Run 3 → 10^{17} π, 10^{13} B
  - From only 10^{-8} of solid angle 1% of π_0s are in acceptance.

FASER Location

- The TI12 service tunnel just happens to be in just the right place for FASER:



- Old SPS → LEP tunnel
  - On line-of-sight (with some digging)
  - Shielded by ~100m rock/concrete
  - Low beam backgrounds
    - Charged particles bent by LHC magnets

FASER Location

- In relation to ATLAS at Point 1

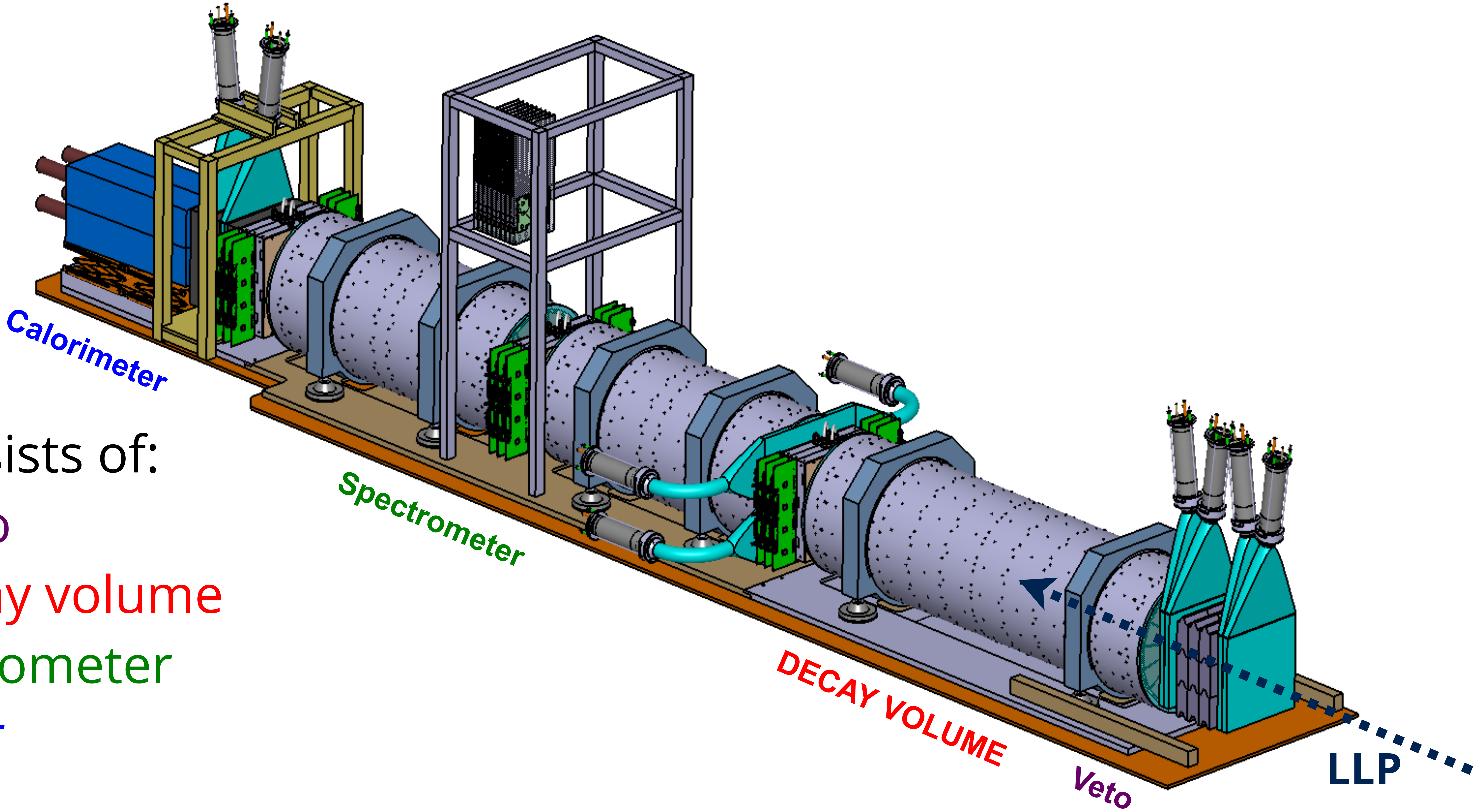
FASER Now Installed!

- From first scouting photos

FASER Now Installed!

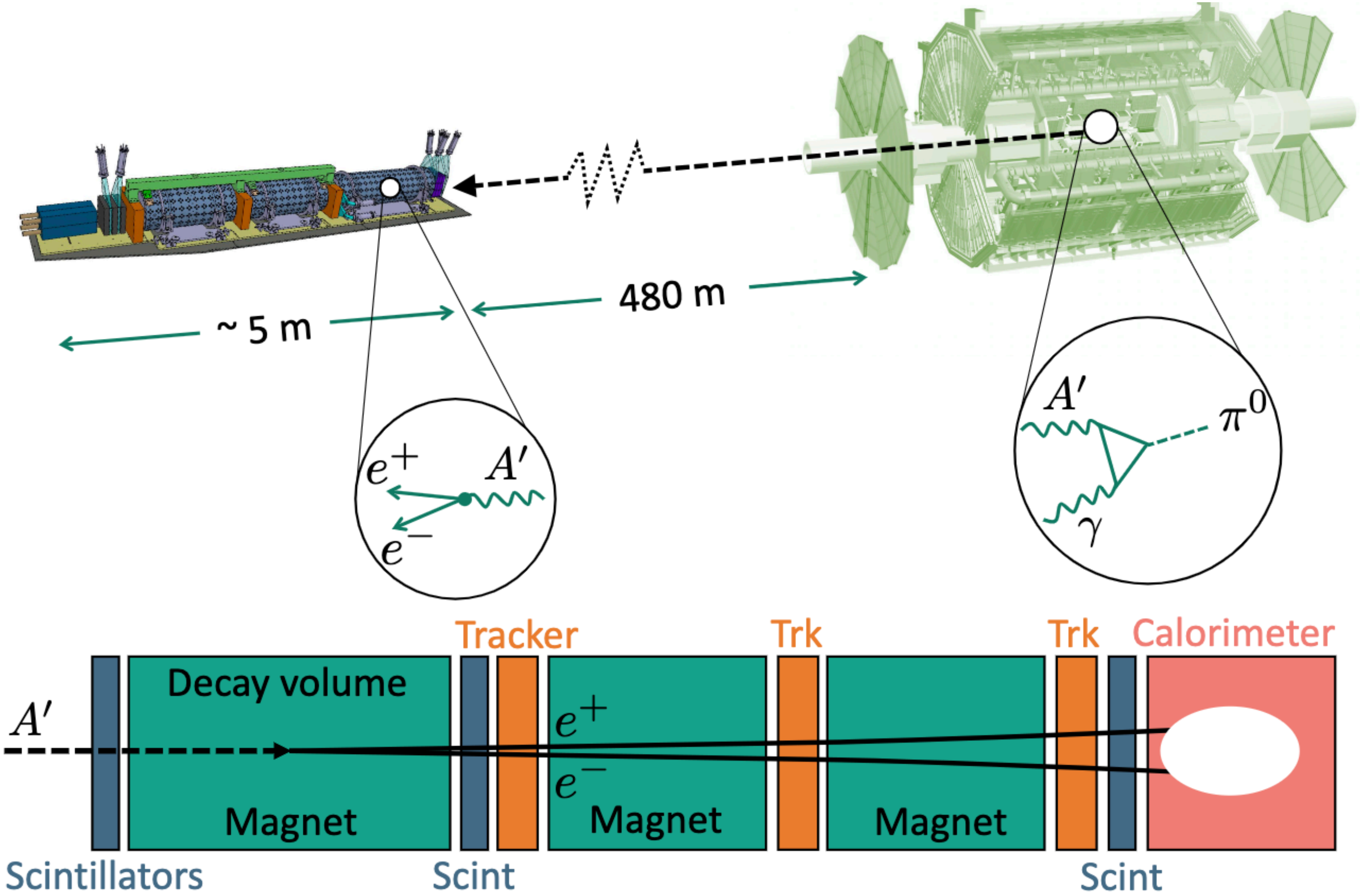
FASER Now Installed!

FASER Detector



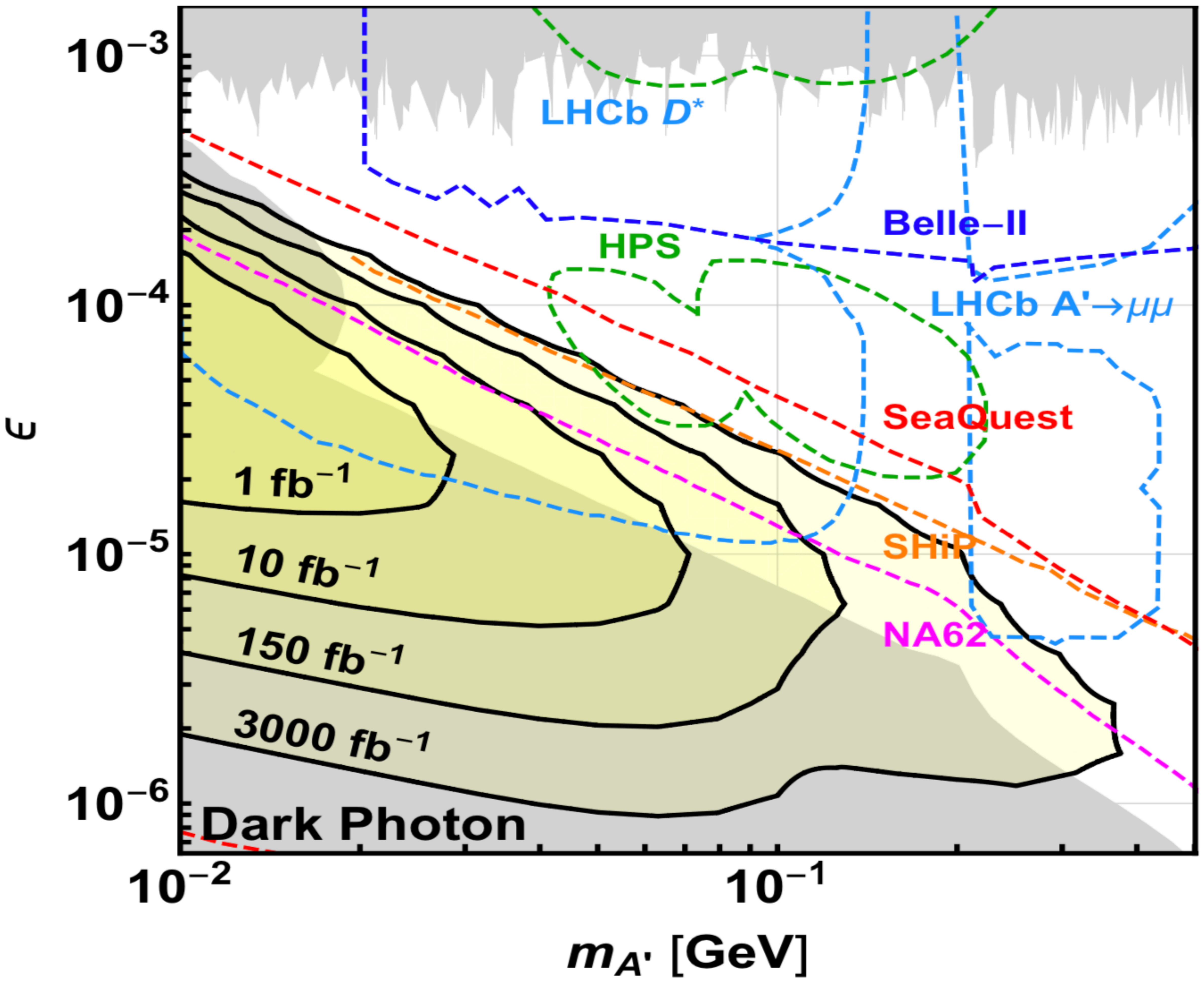
The detector consists of:
- Scintillator veto
- 1.5m long decay volume
- 2m long spectrometer
- EM calorimeter

Target scenarios | Dark photon



Target scenarios | Dark photon

- Expected sensitivity of FASER for **dark photons**
- Detector signature:
  - A' → e+e-
  - Charged tracks appearing in decay volume
  - Opposite charges separate through detecto
  - Significant energy deposit in calorimeter
- Sensitivity
  - Considers all production channels
    - Assumes no background, requires N=3 events
  - Reach limited by decay length (high ε) and production rate (low ε)



- **New parameter space probed with just 1 fb^{-1} in 2022**