FASER-2 :
Status of current FASER2 designs and performance studies

Olivier SALIN
Visit for study with Alan Barr
24/05/2022

Introduction

I am Olivier SALIN, master student at ENS Paris-Saclay on a visit for study with Alan Barr at University of Oxford working on the FASER-2 project

Involvement in FASER-2 project

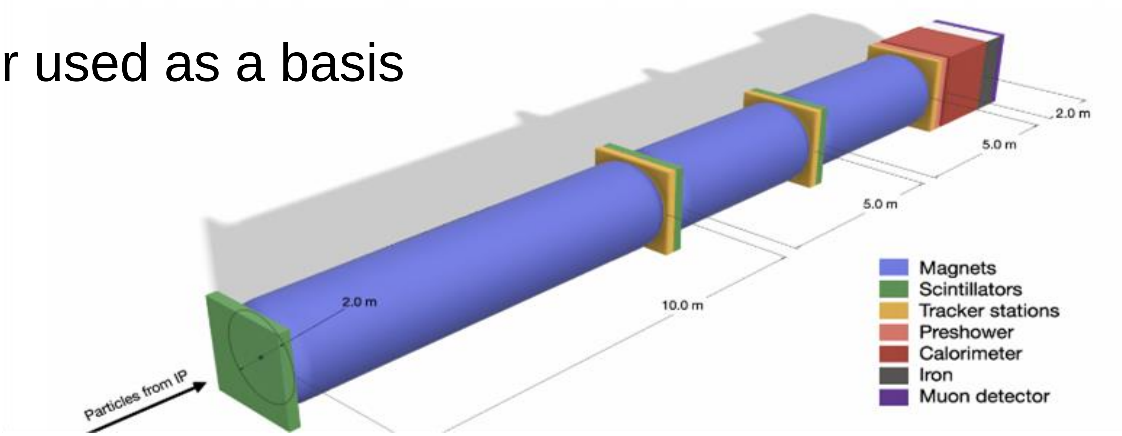
- Started working on FASER-2 in **April 2022**
- Work on FASER-2 until **June 2023**

Outlines of this talk

1. Vertical separation for different geometries
2. Exploring the decay modes of the Dark Higgs and Dark Photon
3. Preliminary new layout with a thin magnet
4. Tracking software with 2D Helix fit and smearing

Detector Layout and software

Detector Layout for used as a basis



LLP decay and spectra handled by FORESEE as input for Geant4

FORESEE: FORward Experiment SEnsitivity Estimator

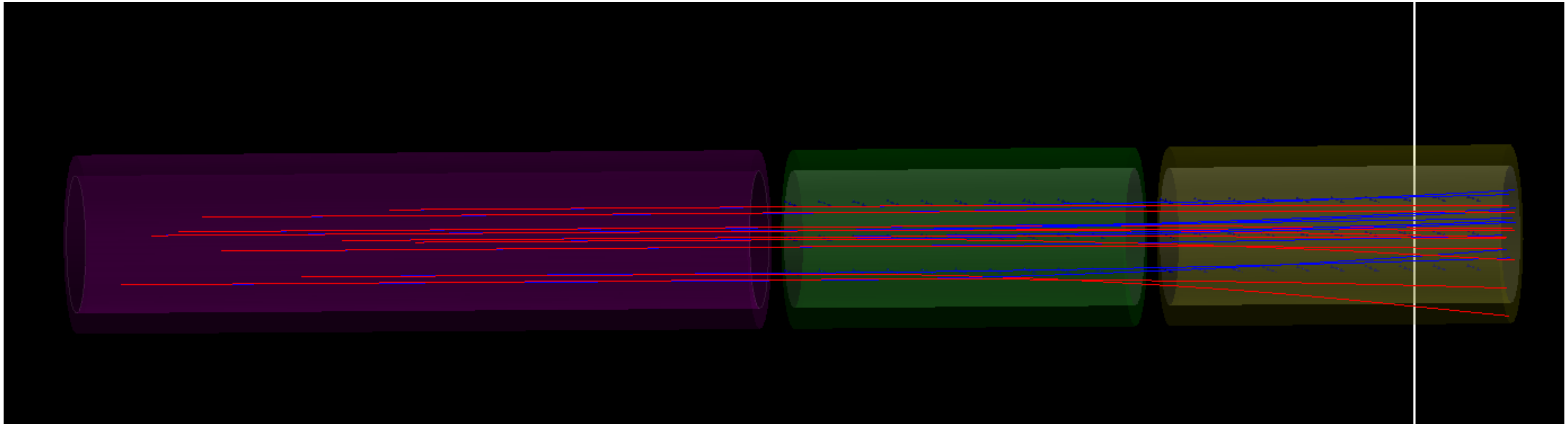
By Felix Kling and Sebastian Trojanowski

arXiv 2105.07077

Detector Layout and software

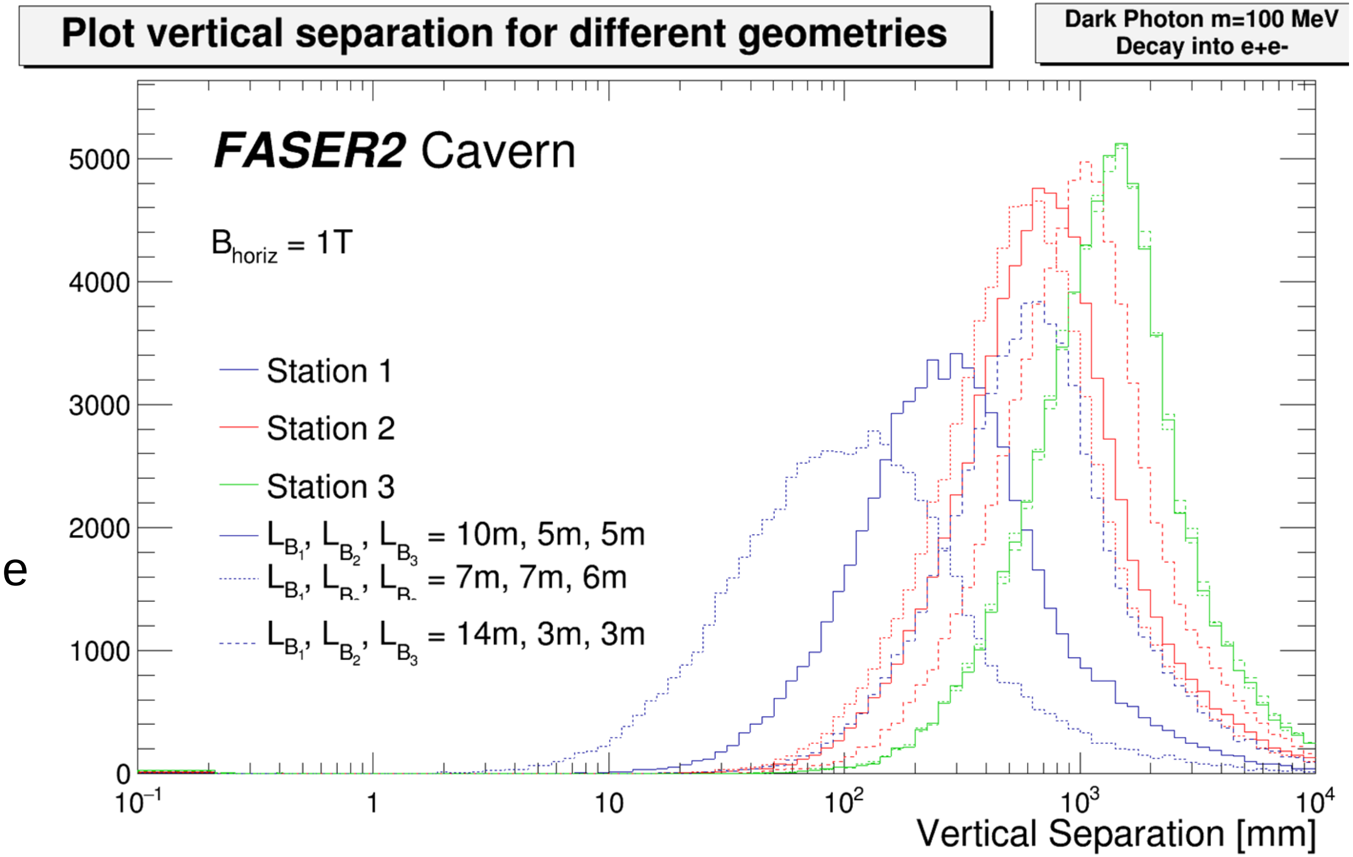
Geant4 simulations for FASER-2 design created by Josh McFayden

- Focus on vertical separation
- Change in the magnetic field and geometries



Impact of different geometries

Same magnetic field
Same sample of Dark Photon

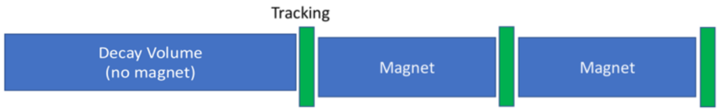


- The vertical separation is the same for each geometries

- Vertical separation >1 m

Tracker is similar to infinite plane

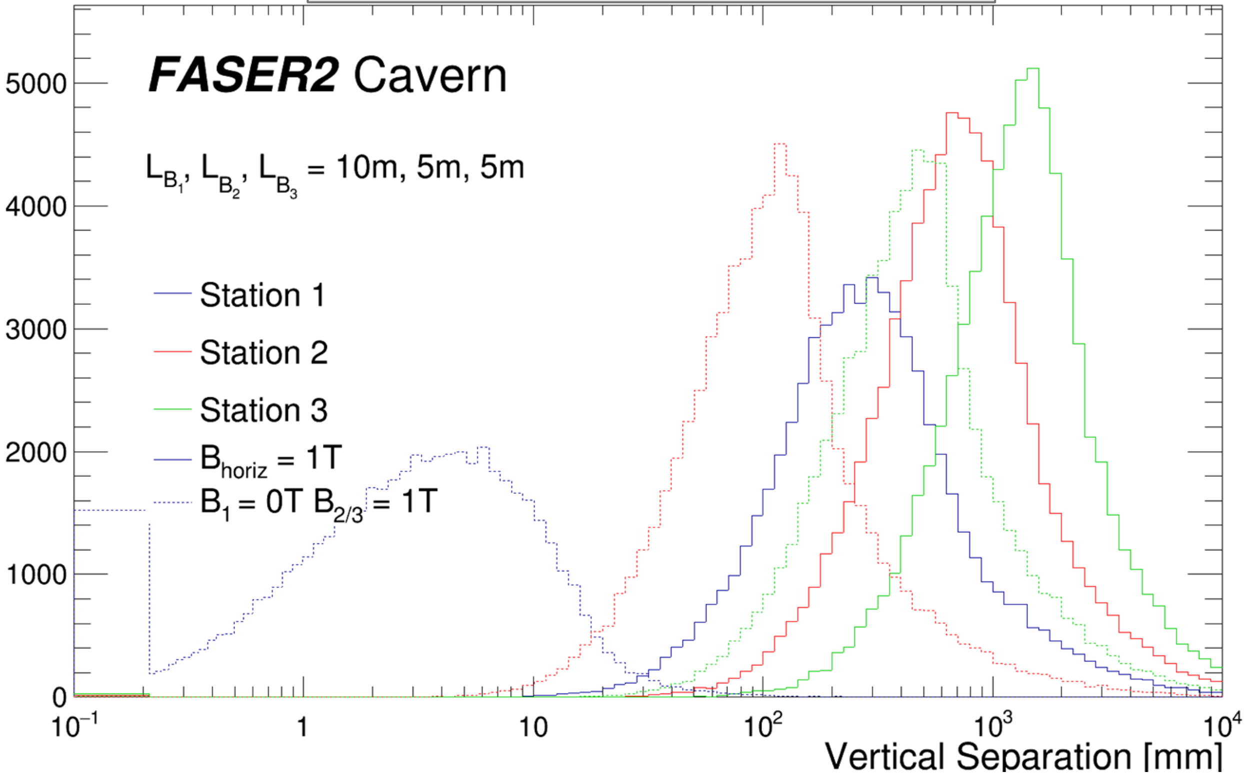
Decay volume with no magnet



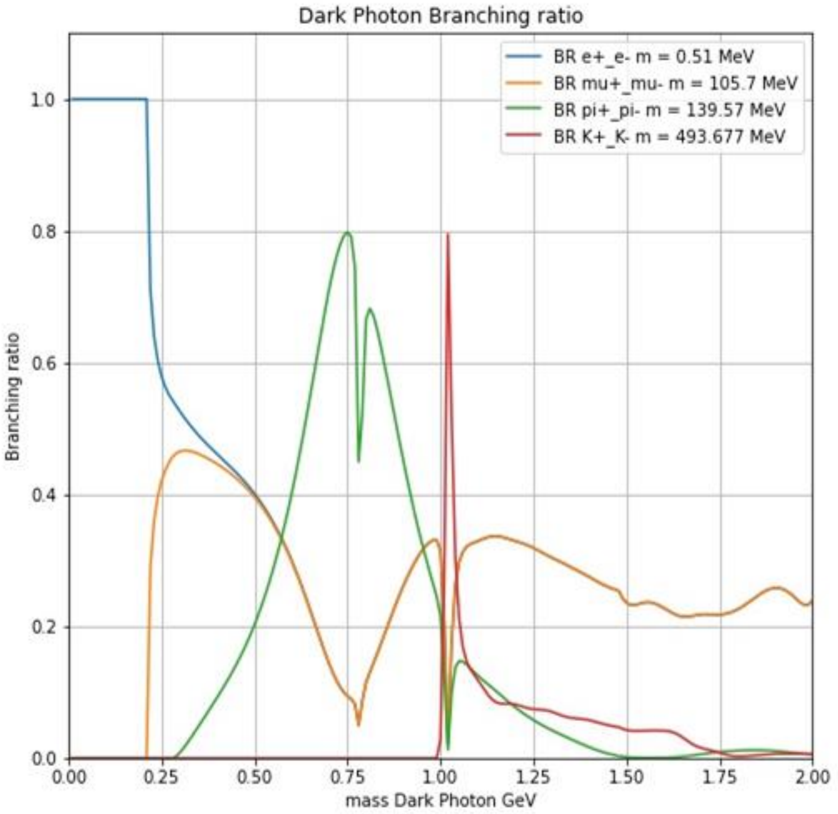
- Vertical separation on the 3rd Tracker still very good and stay within the detector

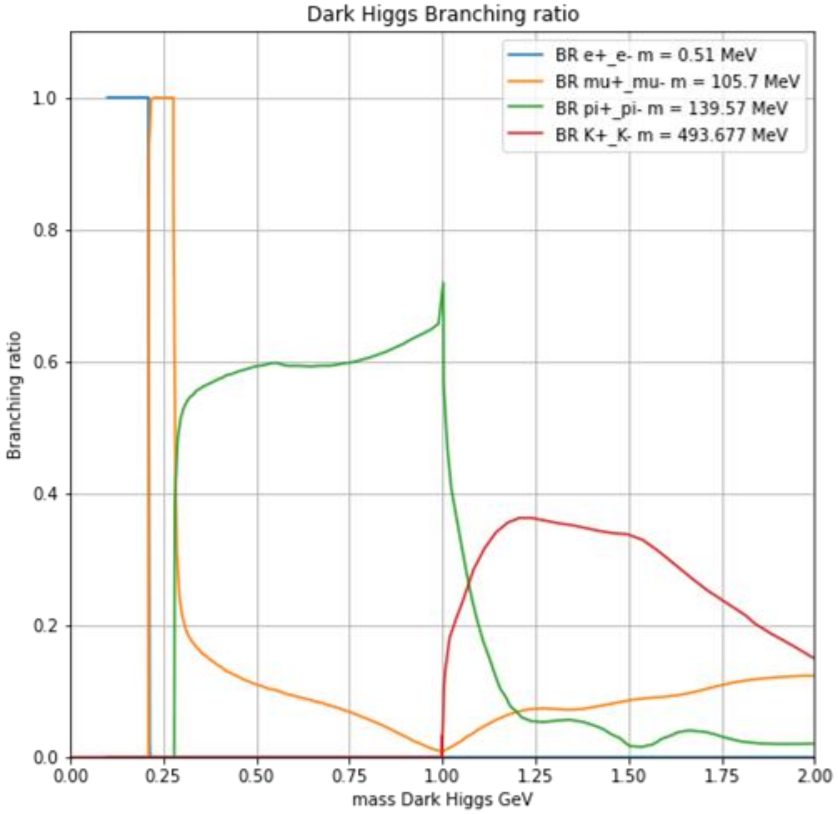
- Vertical separation :
  1st Tracker >100 um
  compatible with SciFi Tracker

Dark Photon m= 100 MeV decay e^+e^-



Exploring other decays of LLP





Exploring other decays of LLP

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To create input of Geant4 in FORESEE
Particle are limited to one decay mode (e+e-)

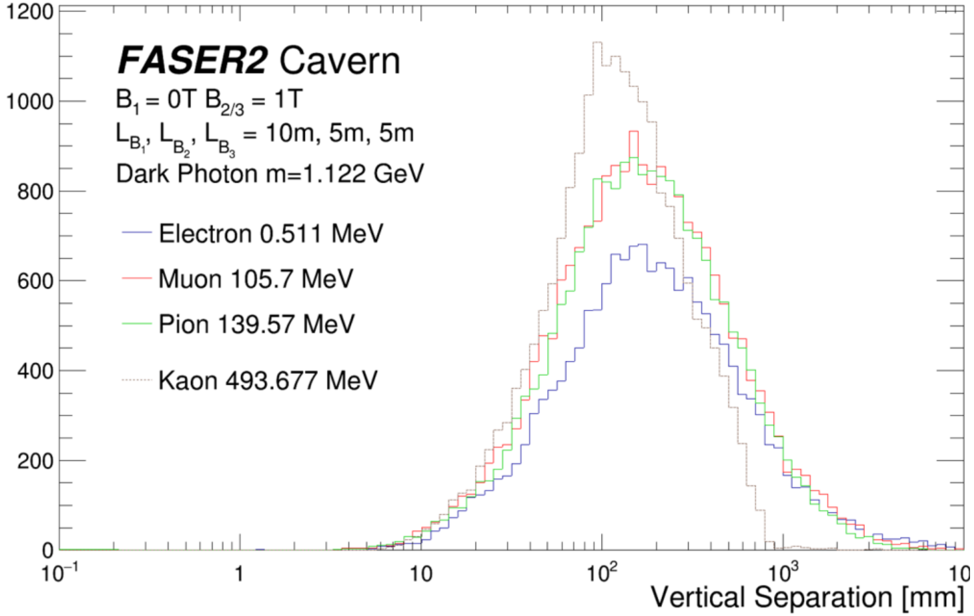
```python
    #particles
    particles = foresee.decay_llp(mass=0.1, energy=energy)
    for n,particle in enumerate(particles):
        if n == 0 :
            f.write("P "+str(n+1)+" 11 ")
        else:
            f.write("P "+str(n+1)+" -11 ")
        f.write(str(particle.px)+" ")
        f.write(str(particle.py)+" ")
        f.write(str(particle.pz)+" ")
        f.write(str(particle.e)+" ")
        f.write("0 1 0 0 0 0\n")
f.write('HepMC::IO_GenEvent-END_EVENT_LISTING\n')
f.close()
```

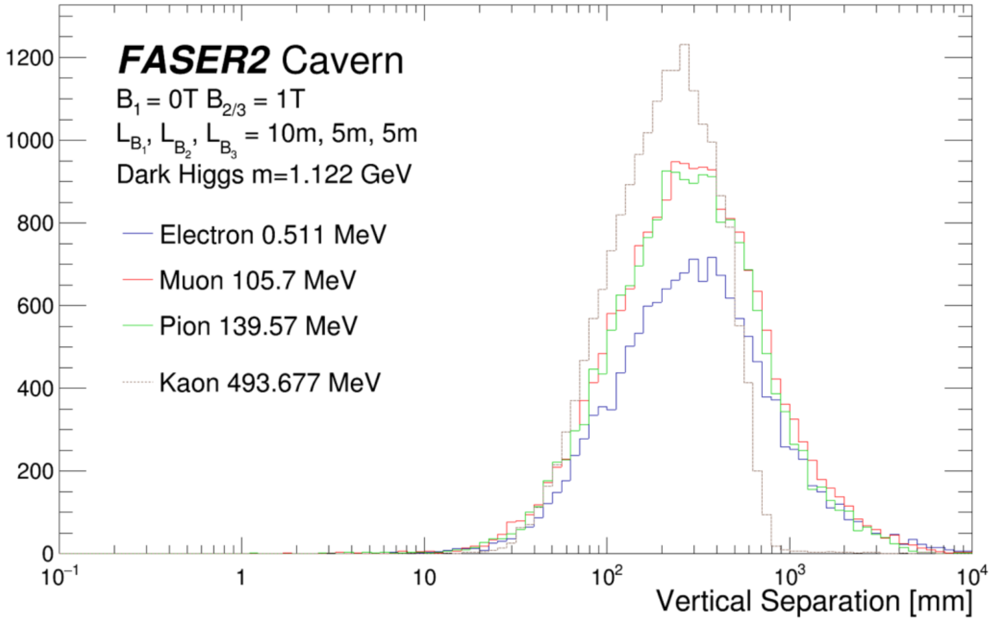
- Modification on the FORESEE function by adding the mass of decayed particles

```python
def decay_llp(self, mass,energy):

    #randomly choose angles
    costh = random.uniform(-1.,1.)
    phi = random.uniform(-math.pi,math.pi)

    #4-momentum of p1 and p2 in ALP rest frame
    pz = mass/2. * costh
    py = mass/2. * math.sqrt(1.-costh*costh) * np.sin(phi)
    px = mass/2. * math.sqrt(1.-costh*costh) * np.cos(phi)
    p1 = LorentzVector( px, py, pz,mass/2.)
    p2 = LorentzVector(-px,-py,-pz,mass/2.)

    #boost decay products in lab restframe
    xxx=math.sqrt(energy**2-mass**2)
    p0 = LorentzVector(0,0,math.sqrt(energy**2-mass**2),energy)
    p1_=p1.boost(-1.*p0.boostvector)
    p2_=p2.boost(-1.*p0.boostvector)

    return p1_, p2_

def decay_llp_massive(self, mass,energy,m_decay):

    if mass > 2*m_decay :

        p_decay = 0.5*math.sqrt(mass**2-4*m_decay**2)
        #randomly choose angles
        costh = random.uniform(-1.,1.)
        phi = random.uniform(-math.pi,math.pi)

        #4-momentum of p1 and p2 in ALP rest frame
        pz = p_decay * costh
        py = p_decay * math.sqrt(1.-costh*costh) * np.sin(phi)
        px = p_decay * math.sqrt(1.-costh*costh) * np.cos(phi)
        p1 = LorentzVector( px, py, pz,mass/2.)
        p2 = LorentzVector(-px,-py,-pz,mass/2.)

        #boost decay products in lab restframe
        xxx=math.sqrt(energy**2-mass**2)
        p0 = LorentzVector(0,0,math.sqrt(energy**2-mass**2),energy)
        p1_=p1.boost(-1.*p0.boostvector)
        p2_=p2.boost(-1.*p0.boostvector)
```

Exploring other decays of LLP

Plot of the vertical separation for each decay for the Dark Higgs and Dark Photon



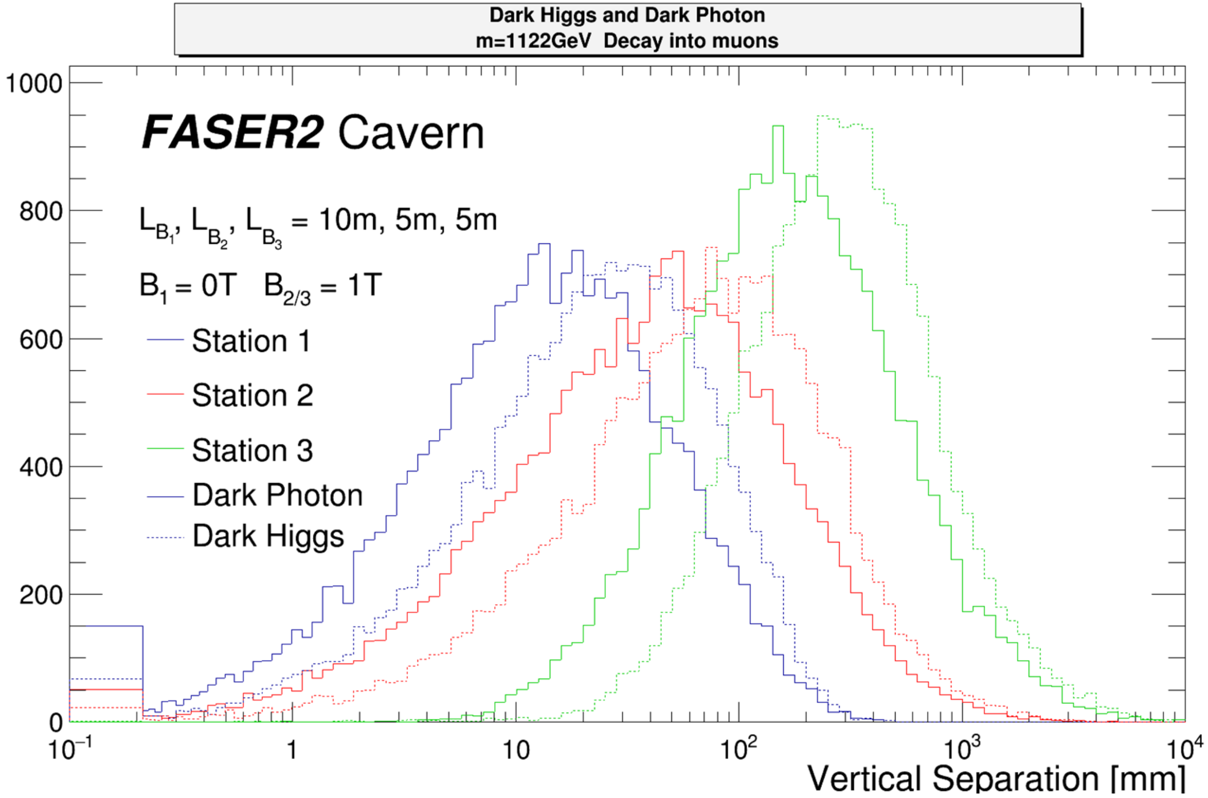


- For each decayed particle the main differences is the upper tail of the vertical separation
- The higher the mass of the decayed particle the more narrow the upper tail is
- Studies focussing on the decay into e^+e^- are still a very good approximation

Dark Higgs and Dark Photon

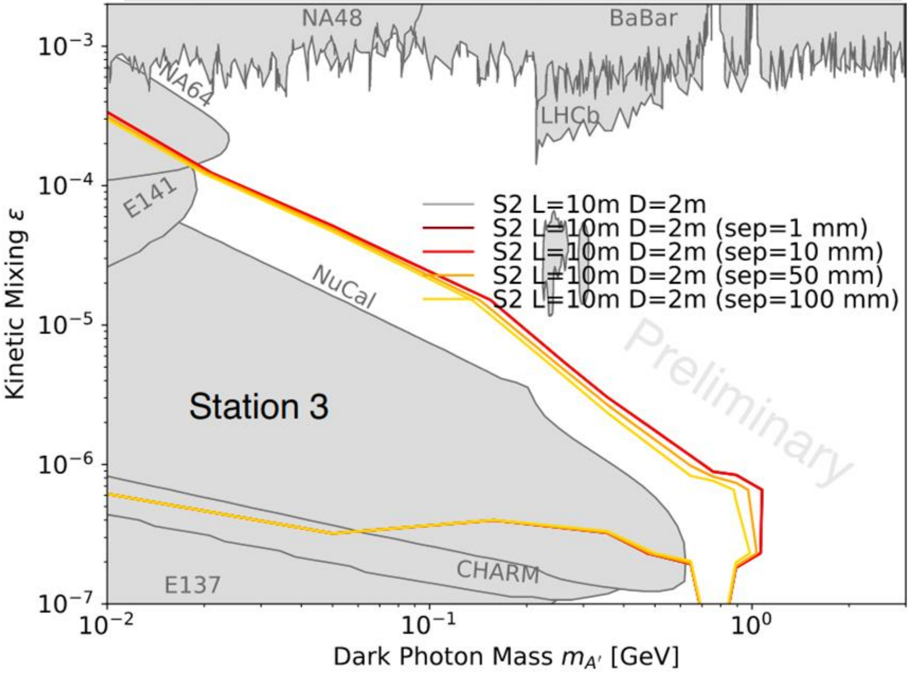
- For a same mass differences in vertical separation between Dark Higgs and Dark electron

- Investigation needed to explain this difference

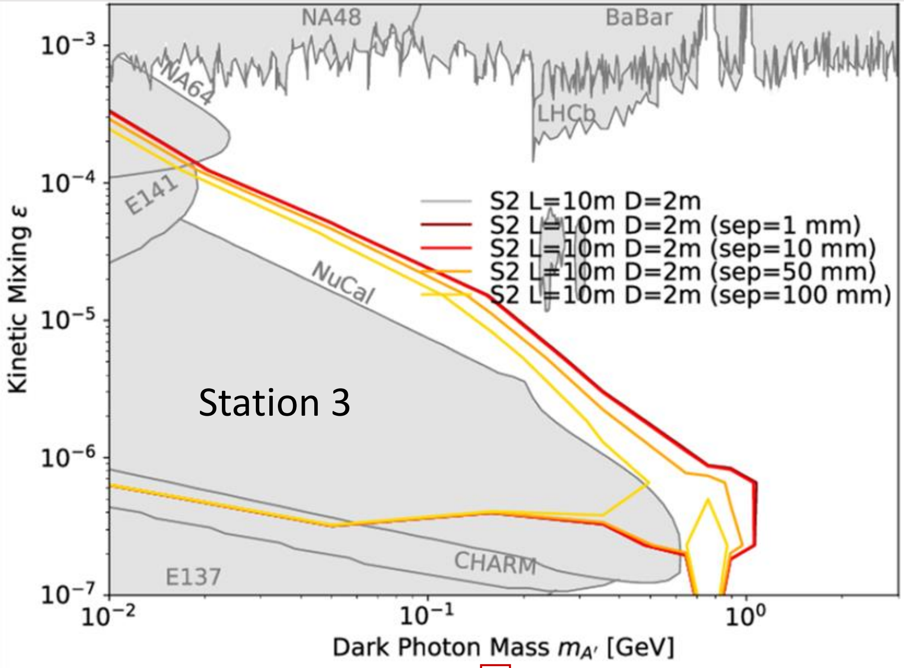


Separation Scans

Separation Scan Dark Photon B=1T by Josh



Separation Scan Dark Photon no magnet in decay volume



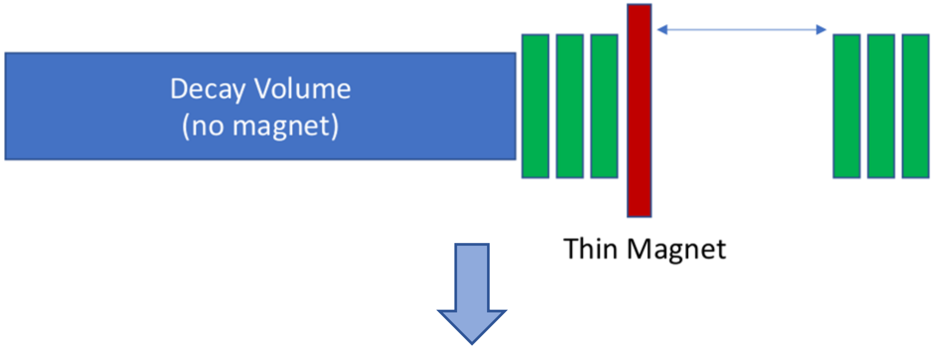
- Calorimeter loss comes between 10 and 50 mm

Compatible with Calorimeter Dual Readout (10 mm)

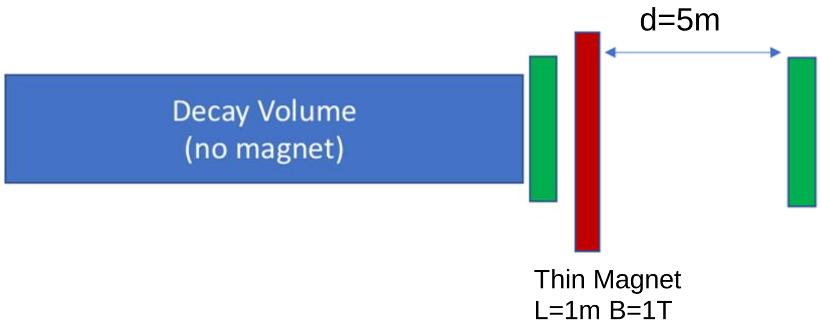
Loss in reach resolution >10 mm
more significatif for no magnet decay volume

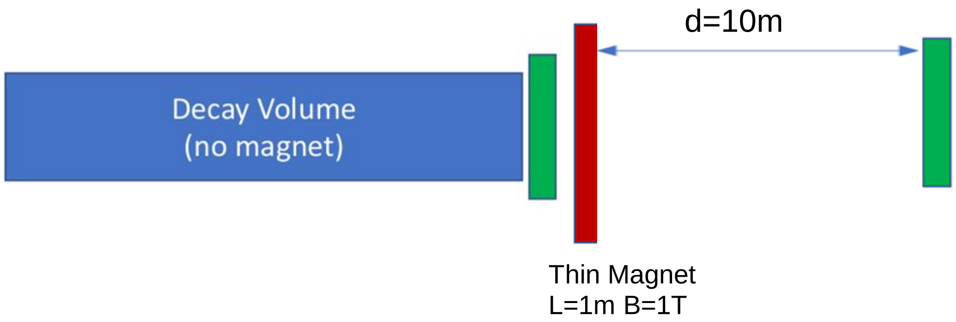
Detector Layout Thin magnet

- Proposed layout by Jamie

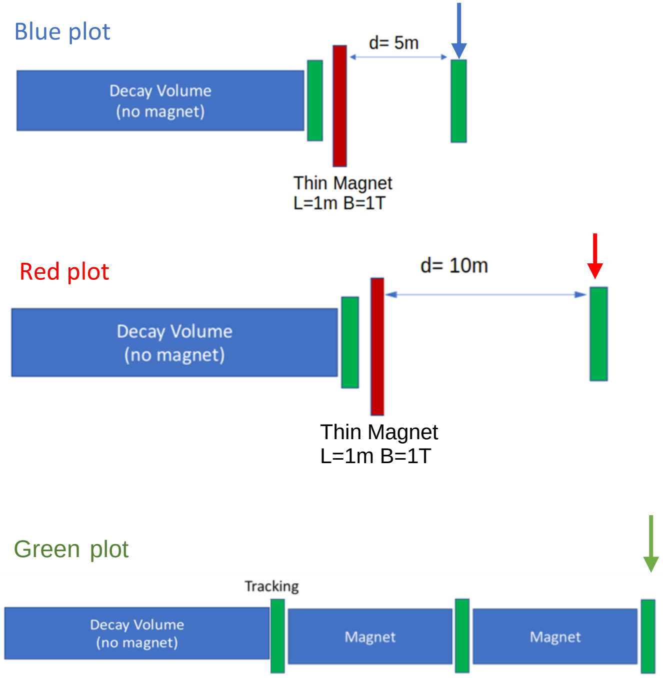


- Approximation for Geant4 of the new configuration



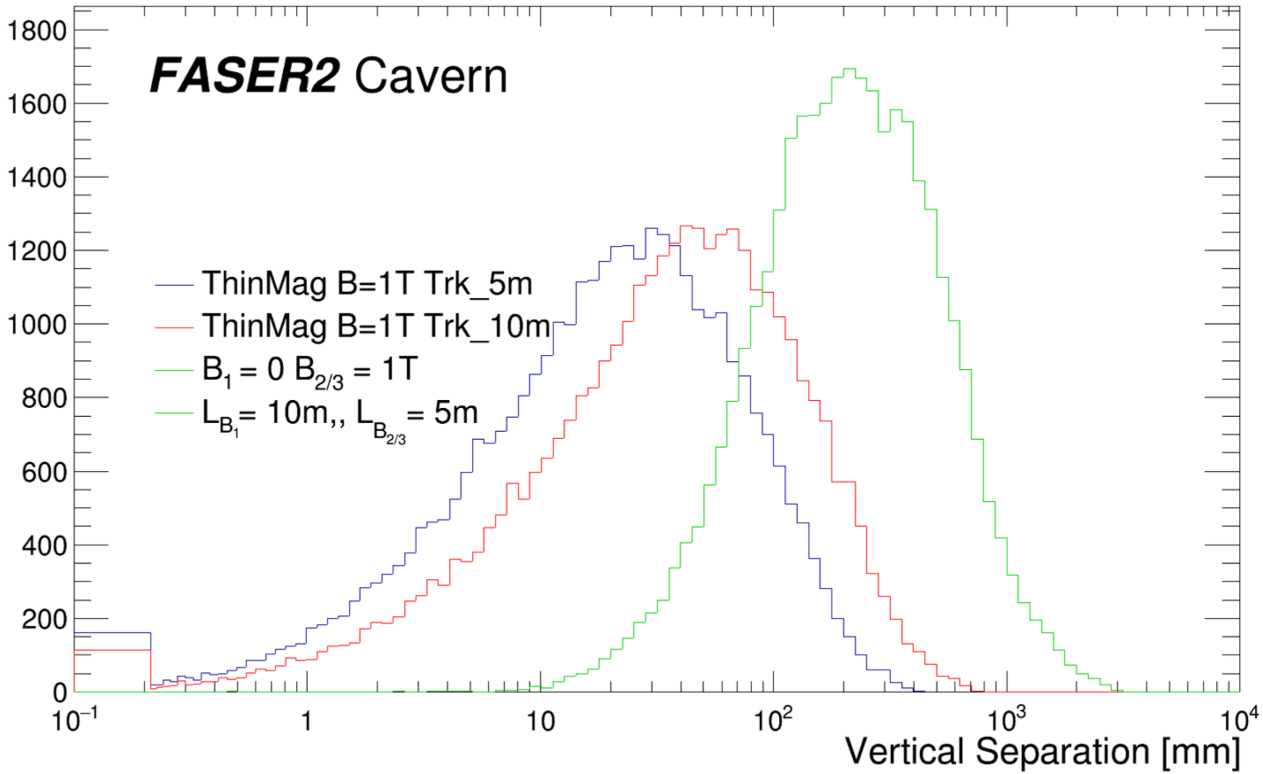


Detector Layout Thin magnet

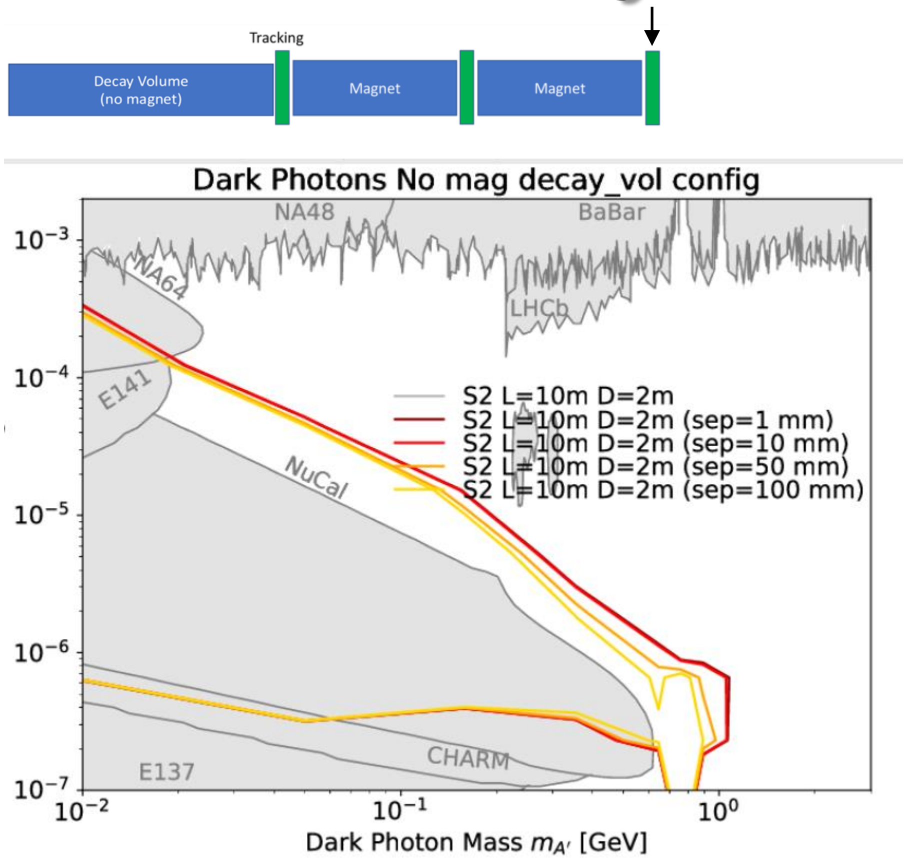


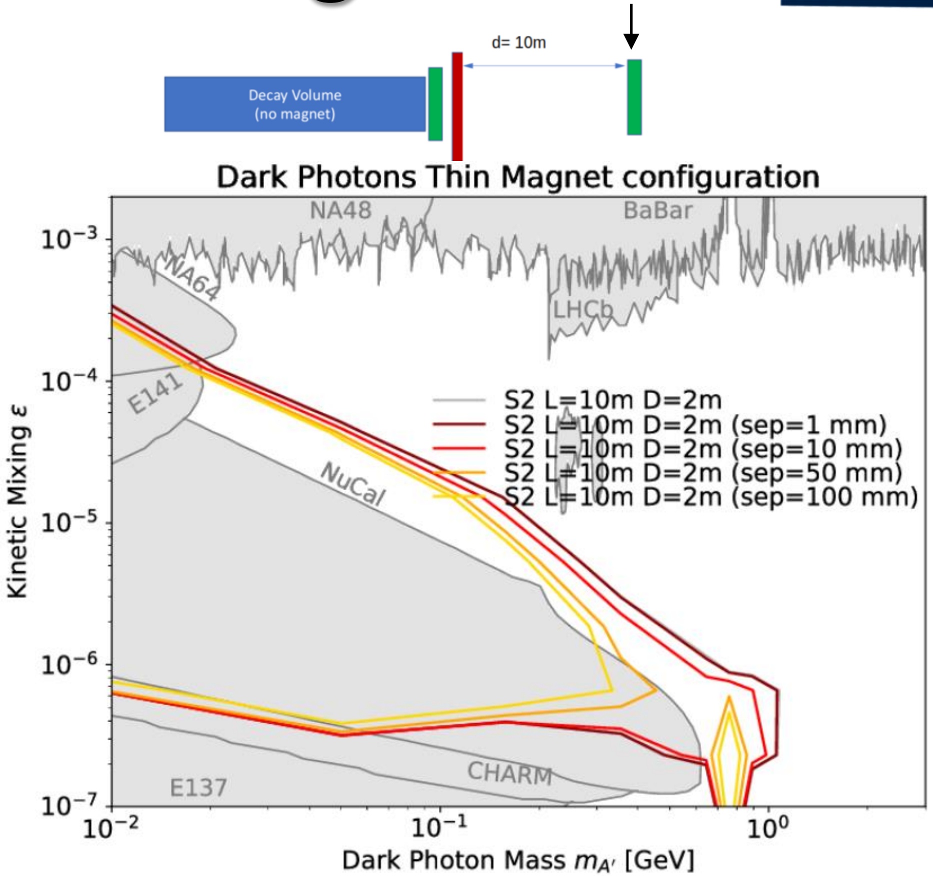
Plot Vertical separation ThinMag new config

Dark Photon m = 501 MeV
decay into muons



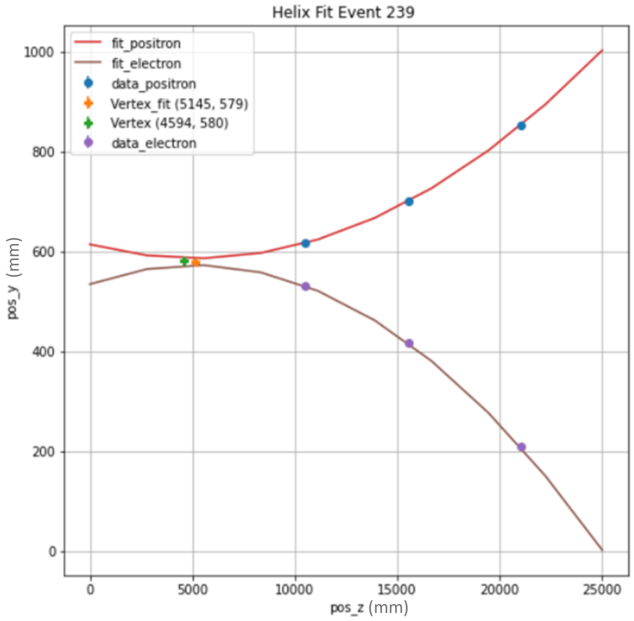
Detector Layout Thin magnet

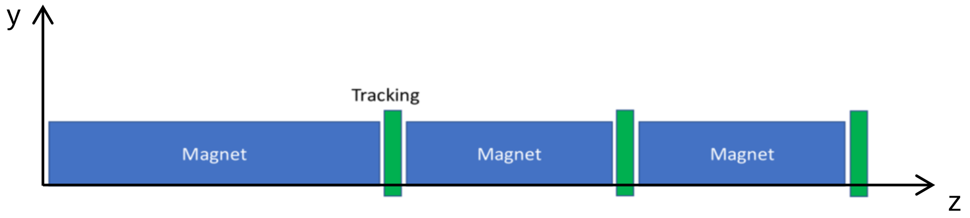




Tracking software with 2D helix fit

Code written in Python who takes for parameters : Position of each tracking station
Position of the Vertex from FORESEE for checking
Momentum of the particles from FORESEE for checking





Variation of x position for each tracking station

1st Tracker 2nd Tracker 3rd Tracker

```
[ 914.85612171  913.7003417   911.99266557]
[ 390.45289714  386.77009765  381.54536374]
[ 479.45019197  481.36084666  484.20824341]
[-444.4862556  -444.93631005 -445.31178648]
[-455.77010911 -457.99041885 -460.22705775]
```

Variation in x direction is negligible compared to y or z direction → 2D

Distance between the Vertex in FORESEE and reconstructed Vertex : 550 mm

Radius e+ : r_{fit}=472.87 m $r_{FORESEE}$ = 467.32 m | **Relative error on momentum e+ : 1,18 %**

Radius e- : r_{fit}=345.36 m $r_{FORESEE}$ = 340.52 m | **Relative error on momentum e- : 1,42 %**

Tracking software with 2D helix fit

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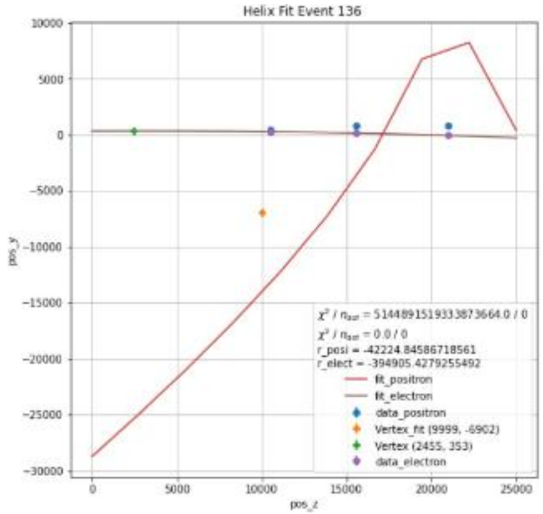
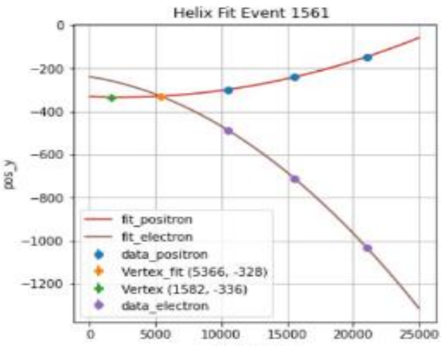
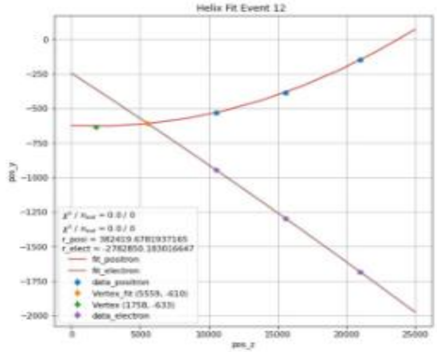
- Many fits are not good or have a high relative error on momentum
    - Cuts needed



$\chi^2 < 0,1$





Trajectorie of e+ > trajectory e-

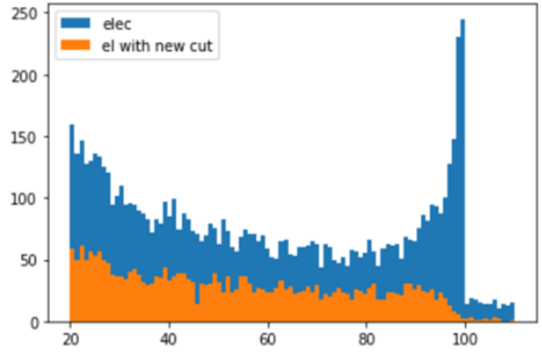
Those tracks would have been kept in the true tracking
For this study, prority of having a clean tracking software

	Electron
Relative error on momentum > 20 %	67.84 %
Relative error on momentum > 20 % with new cuts	32.55 %

Tracking software with 2D helix fit

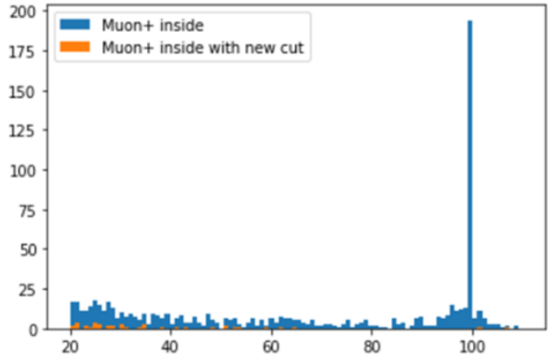
	Electron	Muon	Muon inside	Muon inside with no gap
Relative error on momentum > 20 %	67.84 %	33.99 %	20.51 %	19.85 %
Relative error on momentum > 20 % with new cuts	32.55 %	0.57 %	0.3 %	0.03 %
Relative error on momentum > 10 %	75.34 %	37.3 %	22.81 %	21.04 %
Relative error on momentum > 10 % with new cuts	43.18 %	3.34 %	1.81 %	0.1 %

```
Nombre total d'evenement Elec 34367
Nombre total d'evenement Elec with new cut 14707
```



Relative error on momentum in %

```
Nombre total d'evenement Muon inside 28008
Nombre total d'evenement Muon inside with new cut 15216
```

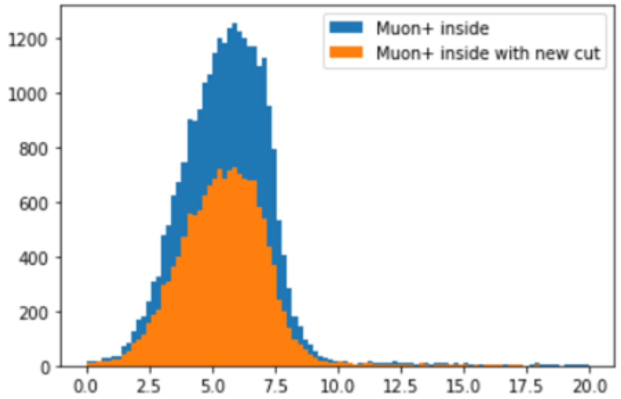


Relative error on momentum in %

- With Muon inside and with the cuts the mass reconstruction is more reliable

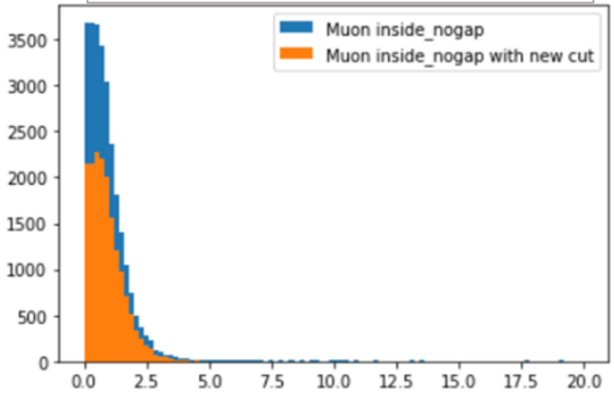
The gap in the fitting

- The detector layout has gap inbetween the magnets
  - Fitting with a helix has an intrinsic error with the gap



Relative error on momentum in %

Gap was removed from the Geant4

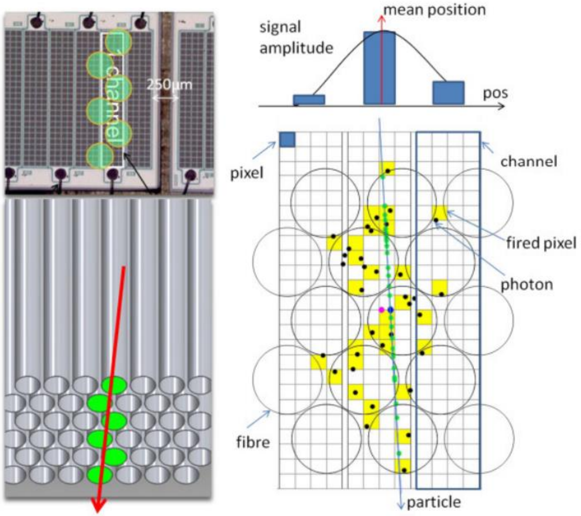



```
Nombre total d'evenement Muon inside 28008
Nombre total d'evenement Muon inside with new cut 15216
```

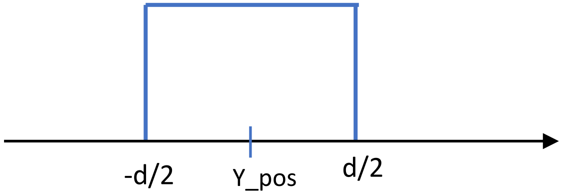
```
Nombre total d'evenement Muon inside_nogap 28466
Nombre total d'evenement Muon inside with new cut 16975
```

- The analysis of the smearing of muons will be done without the gap

Smearing of the muons



- Tophat smearing applied tracking position :



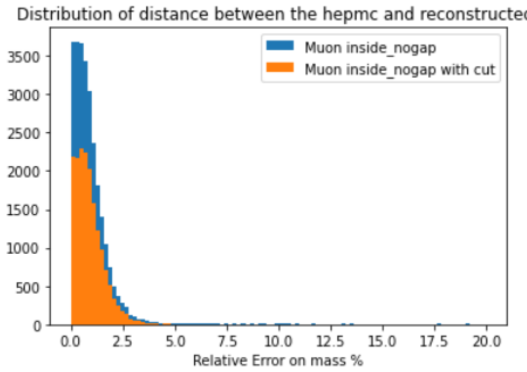
d = distance between strip

- SciFi:
  - Pitch = 250 um, Resolution = 100 um
  - Naive hit cluster: ~1 mm?
- Reduced resolution of SciFi detector seems acceptable even in 1

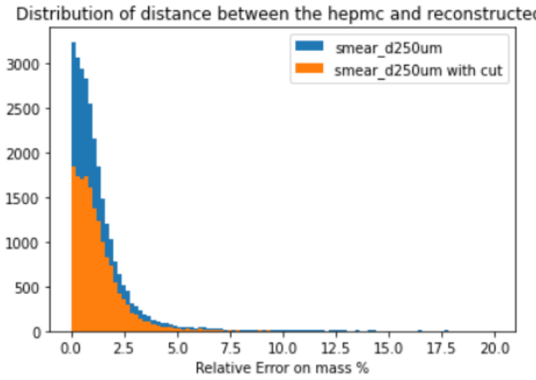
Smearing the muons

	Muon inside with no gap	Smeared d = 100 um	Smeared V2 d = 100 um	Smeared d = 250 um	Smeared d = 500 um	Smeared d = 750 um
Relative error on momentum > 20 % with cuts	0,18%	0,09%	0,59%	0,57%	0,73%	1,30%
Relative error on momentum > 10 % with cuts	0,34%	0,24%	0,76%	0,92%	2,53%	5,28%
Relative error on momentum > 5 % with cuts	0,63%	0,64%	1,21%	3,30%	10,92%	20,24%

```
Nombre total d'evenement Muon inside_nogap 28466
Nombre total d'evenement Muon inside with cut 17114
```




```
Nombre total d'evenement smear_d250um 28466
Nombre total d'evenement smear_d250um with cut 16707
```

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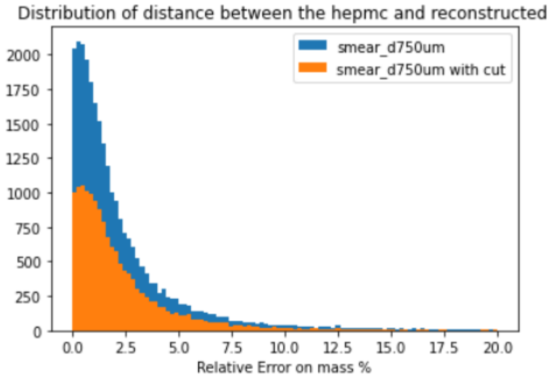
Nombre total d'evenement smear_d750um 28466
Nombre total d'evenement smear_d750um with cut 15006
```

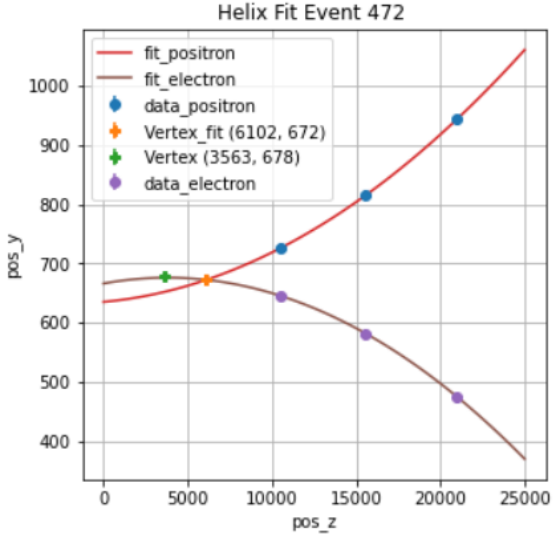


- SciFi Tracker Pitch strip < 250 mm → Low impact on mass reconstruction

Prospects

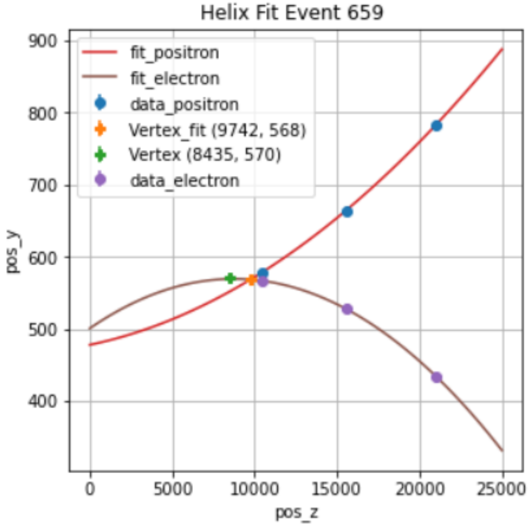
- Study differents possible geometries for the thin magnet configuration
  - Reducing the length of the decay volume
- Propagate the error from the fit on the momuntum to reconstruct the mass of the LLP
- Adding the effect of the alignement of the trackers to the smearing
- The background for FASER-2

Backup




```
Distance between the Vertex of the fit and reconstructed Vertex : 2538 mm

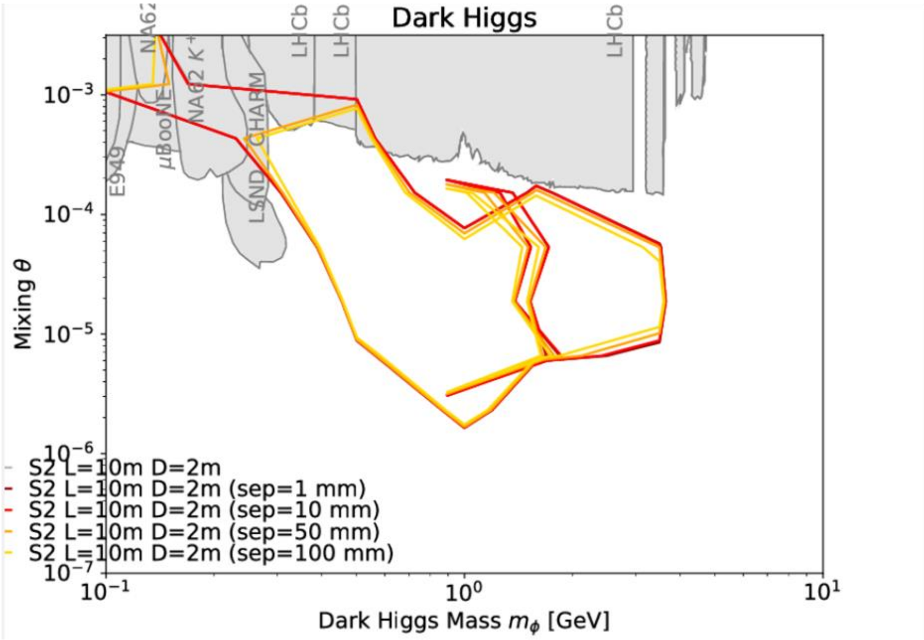
Value of the radius (r_fit,r_hepmc)=[864.7759349544502, 501.77569109964224]
Relative error on mass for e+ : 72.34313066447925 %
Value of the radius (rfit,r_hepmc)=[733.6910032529358, 702.9539985969353]
Relative error on mass for e- : 4.372548519156332 %
```




```
Distance between the Vertex of the fit and reconstructed Vertex : 1306 mm

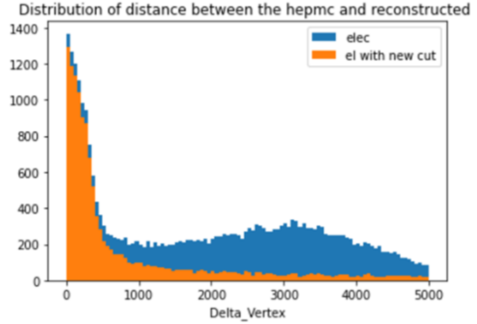
Value of the radius (r_fit,r_hepmc)=[1075.8053984061394, 216.94981342844125]
Relative error on mass for e+ : 395.87754025010173 %
Value of the radius (rfit,r_hepmc)=[556.8125997510824, 520.2722370482265]
Relative error on mass for e- : 7.023315891343394 %
```

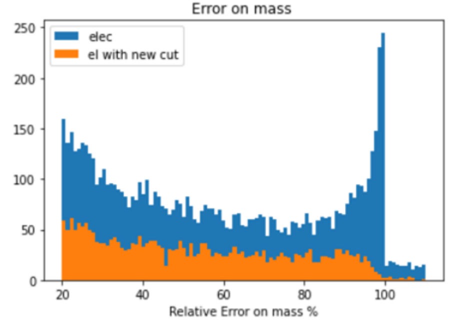
Higgs SepScan not working



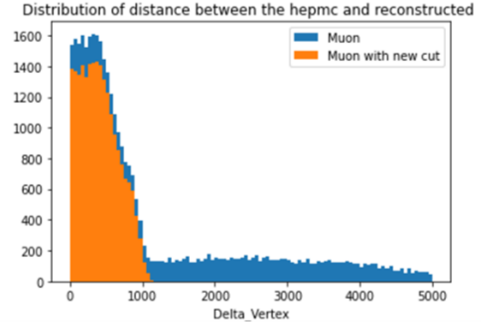
	Electron	Muon	Muon inside	Muon inside with no gap
no cut	34 367	34 995	28 008	28 466
Old cut	27 169	24634	20 311	20 936
New cut	14 707	21 487	15 216	16 975

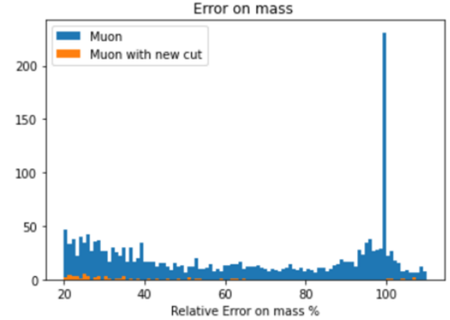
```
Nombre total d'evenement Elec 34367
Nombre total d'evenement Elec with new cut 14707
```



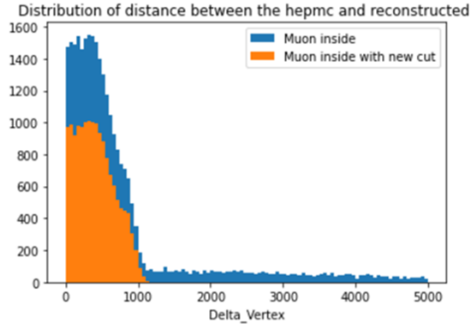


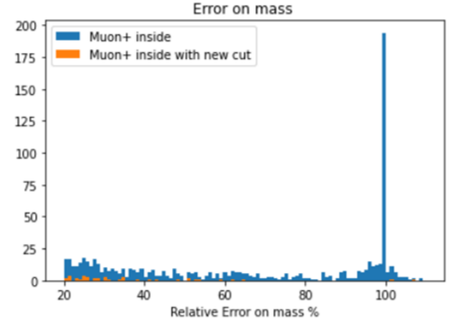

```
Nombre total d'evenement Muon 34995
Nombre total d'evenement Muon with new cut 21487
```



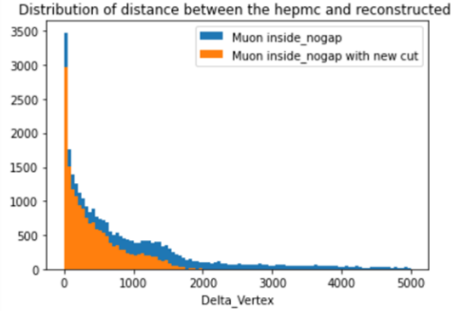


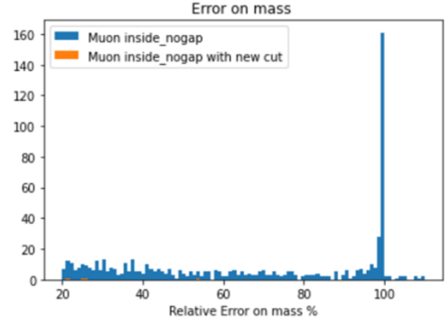

```
Nombre total d'evenement Muon inside 28008
Nombre total d'evenement Muon inside with new cut 15216
```






```
Nombre total d'evenement Muon inside_nogap 28466
Nombre total d'evenement Muon inside with new cut 16975
```

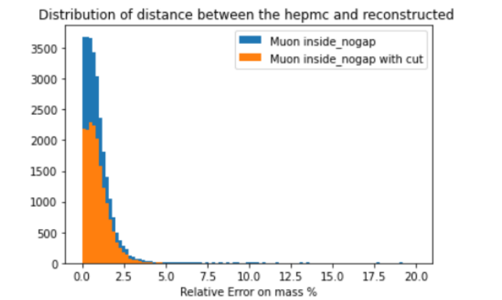




	Electron	Muon	Muon inside	Muon inside with no gap
Proportion relative error on mass > 20	67.84 %	33.99 %	20.51 %	19.85 %
Proportion relative error on mass > 20 with cuts	63.05 %	32.23 %	16.47 %	14.47 %
Proportion relative error on mass > 20 with new cuts	32.55 %	0.57 %	0.3 %	0.03 %
Proportion relative error on mass > 10	75.34 %	37.3 %	22.81 %	21.04 %
Proportion relative error on mass > 10 with new cuts	43.18 %	3.34 %	1.81 %	0.1 %

	Muon inside with no gap	Smeared d = 1 mm	Smeared V2 d = 1 mm	Smeared d = 2 mm	Smeared d = 5 mm	Smeared d = 10 mm
Proportion relative error on mass > 20 with cuts	0,18	1,46	2,29	7,13	29,22	55,81
Proportion relative error on mass > 10 with cuts	0,34	8,25	9,29	25,57	59,18	81,05
Proportion relative error on mass > 5 with cuts	0,63	28,7	29,82	54,26	83,01	94,35

```
Nombre total d'evenement Muon inside_nogap 28466
Nombre total d'evenement Muon inside with cut 17114
```




```
Nombre total d'evenement smear_d1 28466
Nombre total d'evenement smear_d1 with cut 14287
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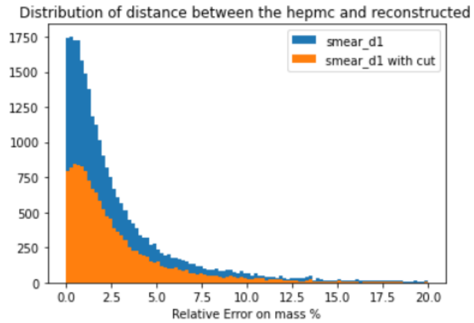
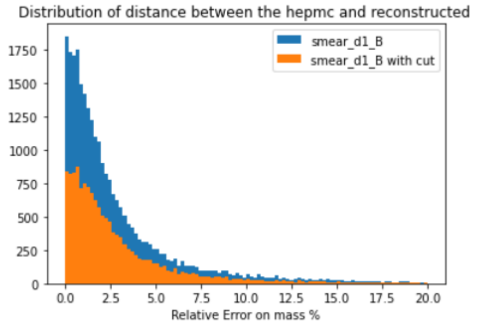
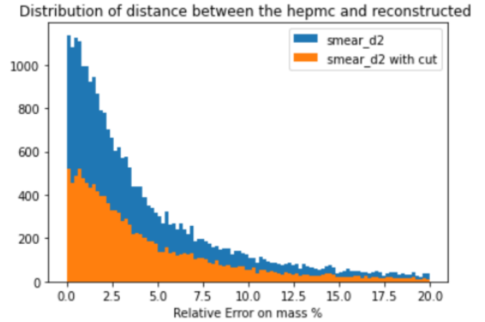


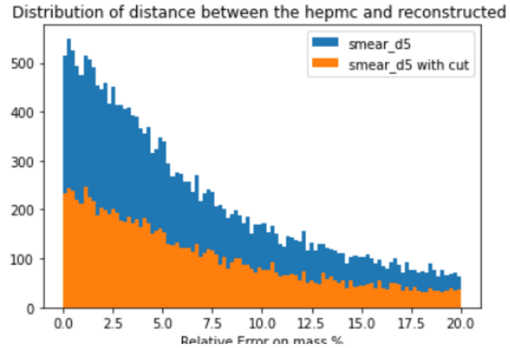

```
Nombre total d'evenement smear_d1_B 28466
Nombre total d'evenement smear_d1_B with cut 14356
```

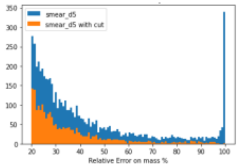



```
Nombre total d'evenement smear_d2 28466
Nombre total d'evenement smear_d2 with cut 13041
```




```
Nombre total d'evenement smear_d5 28466
Nombre total d'evenement smear_d5 with cut 12216
```






```
Nombre total d'evenement smear_d10 28466
Nombre total d'evenement smear_d10 with cut 11941
```