Searching for Beyond the Standard Model particles decaying to muon pairs in SND@LHC

Henrique Santos

June 2024

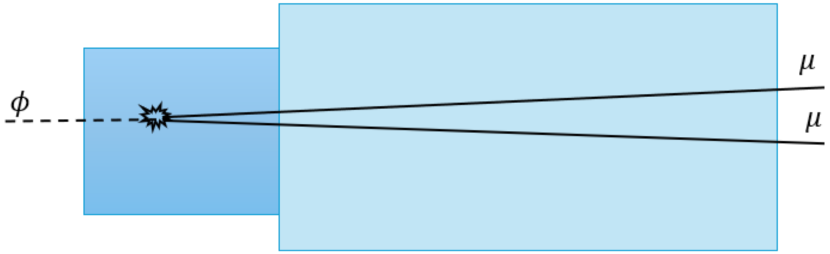
LHC

Scattering and Neutrino Detector at the LHC

FIP decays to dimuon

An introduction

- This project's aim is to study the FIP to dimuon decay channel in a model independent way.
- SND@LHC low background and great muon detection system are both major assets for this study.
- This is the first FIP study to use the full detector simulation.
- We decided to used the Dark Higgs as a benchmark particle.



FIP decay to dimuon at SND@LHC

Scattering and Neutrino Detector at the LHC

The Dark Higgs

- Discovery of the Higgs Boson sparked the search for additional scalar/pseudo-scalar particles.
- Singlet states lead to the required weak couplings
- Dark Higgs Portal: quartic scalar interaction resultant from adding a real scalar field h'

$$\mathcal{L} = \mu_H^2|H|^2 - \frac{1}{4}\lambda_H|H|^4 + \mu'^2h'^2 - \mu_3'h'^3 - \frac{1}{4}\lambda'h'^4 - \mu_{12}'h'|H|^2 - \epsilon h'^2|H|^2$$

Higgs sector Lagrangian

$$\mathcal{L} = -\frac{1}{2}m_\phi^2\phi^2 - \sin\theta\frac{m_f}{v}\overline{f}f - \lambda vh\phi\phi + \ldots$$

Dark Higgs Lagrangian after potential minimization and mass diagonalization

ϕ-dark Higgs field
m_ϕ-dark Higgs mass
θ-mixing angle
λ –trilinear coupling

FIP decay event generation with Foresee

- Forward Experiment Sensitivity Estimator (FORESEE) is a useful tool for “FIP event simulation at experiments in the far-forward direction” (like SND@LHC)
- Customizable with production modes, decay modes, detector geometry and FIP mass and spectrum

- FORESEE output:
  - Particle PDG code (32 for FIP, $\pm$13 for muons)
  - Particle 3-momenta
  - Particle mass and charge
  - Vertex spacetime coordinates

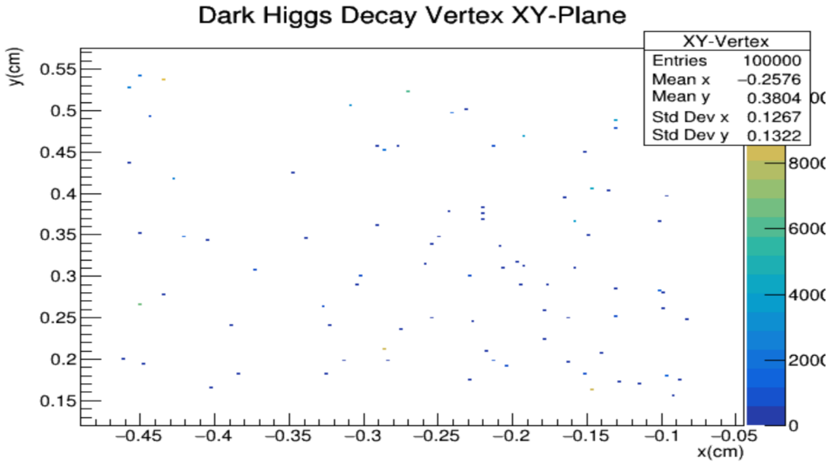
- FORESEE paper: https://arxiv.org/abs/2105.07077
- FORESEE GitHub: https://github.com/KlingFelix/FORESEE (release 1.1.7)

Scattering and Neutrino Detector at the LHC

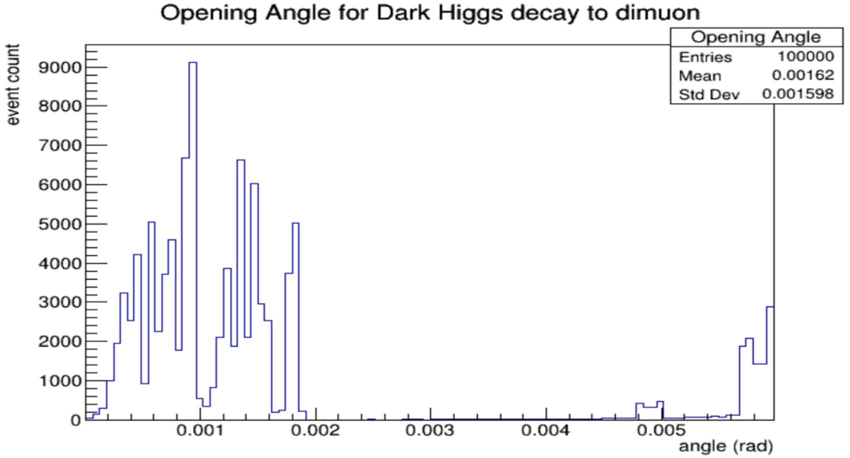
FIP decay event generation with Foresee

Early data analysis

- For starters, the simulation was checked for biases in the decay vertex position.
- The Opening angle of the DH decay to a muon pair was also calculated (track separation requires a minimum of 0.01 rad)
- Unfortunately, the opening angle is not large enough



Dark Higgs decay vertex XY-distribution for a DH mass of 354.8 MeV



Dark Higgs opening angle distribution for a DH mass of 354.8 MeV

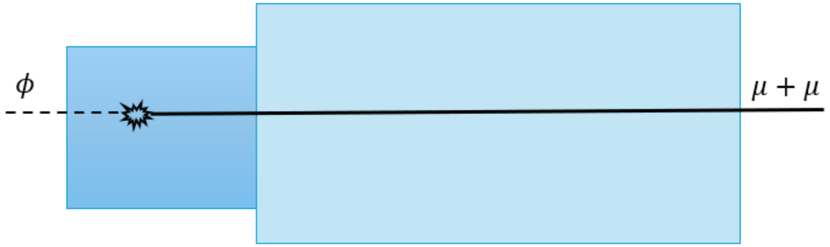


Diagram of DH decaying inside the detector

Simulating Events in the SND@LHC detector with SNDSW

- The next step was to develop a script to convert FORESEE output to a SNDSW-friendly format (Genie gst).
- SNDSW takes as input a ROOT TTree.
- FORESEE output is a csv file.

Since SNDSW event simulation was made for neutrino events, the following changes were implemented:

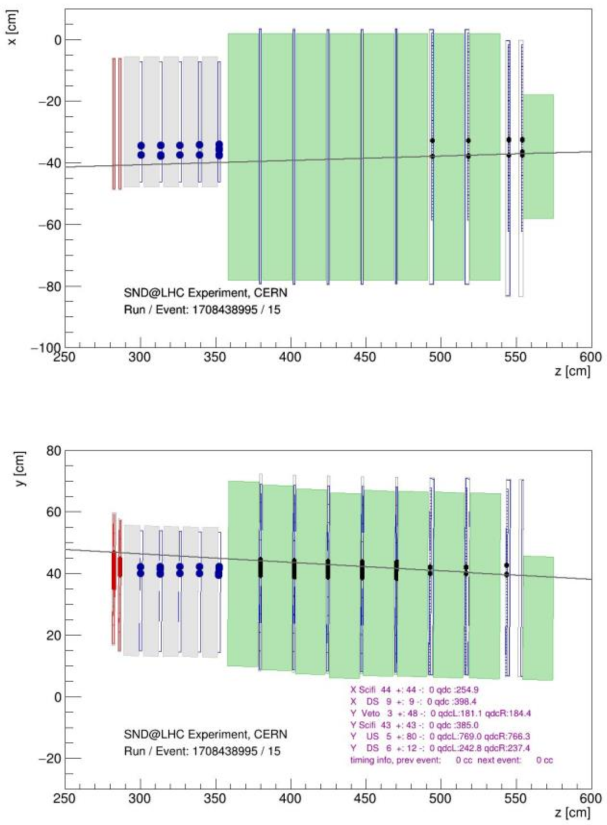
- Incoming neutrino variables → FIP variables
- Outgoing hadronic variables → outgoing muon variables
- CC and NUEL flags → False
- Outgoing lepton variables→ remain unused, but were filled with FIP variables to prevent errors

```
fTree->SetBranchAddress("Ev",&Ev);    // incoming neutrino energy
fTree->SetBranchAddress("pxv",&pxv);
fTree->SetBranchAddress("pyv",&pyv);
fTree->SetBranchAddress("pzv",&pzv);
fTree->SetBranchAddress("neu",&neu);    // incoming neutrino PDG code
fTree->SetBranchAddress("cc",&cc);      // Is it a CC event?
fTree->SetBranchAddress("nuel",&nuel);  // Is it a NUEEL event?
fTree->SetBranchAddress("vtxx",&vtxx);  // vertex  in SI units
fTree->SetBranchAddress("vtxy",&vtxy);
fTree->SetBranchAddress("vtxz",&vtxz);
fTree->SetBranchAddress("vtxt",&vtxt);
fTree->SetBranchAddress("El",&El);      // outgoing lepton momentum
fTree->SetBranchAddress("pxl",&pxl);
fTree->SetBranchAddress("pyl",&pyl);
fTree->SetBranchAddress("pzl",&pzl);
fTree->SetBranchAddress("Ef",&Ef);   // outgoing hadronic momenta
fTree->SetBranchAddress("pxf",&pxf);
fTree->SetBranchAddress("pyf",&pyf);
fTree->SetBranchAddress("pzf",&pzf);
fTree->SetBranchAddress("nf",&nf);     // nr of outgoing hadrons
fTree->SetBranchAddress("pdgf",&pdgf);     // pdg code of hadron
```

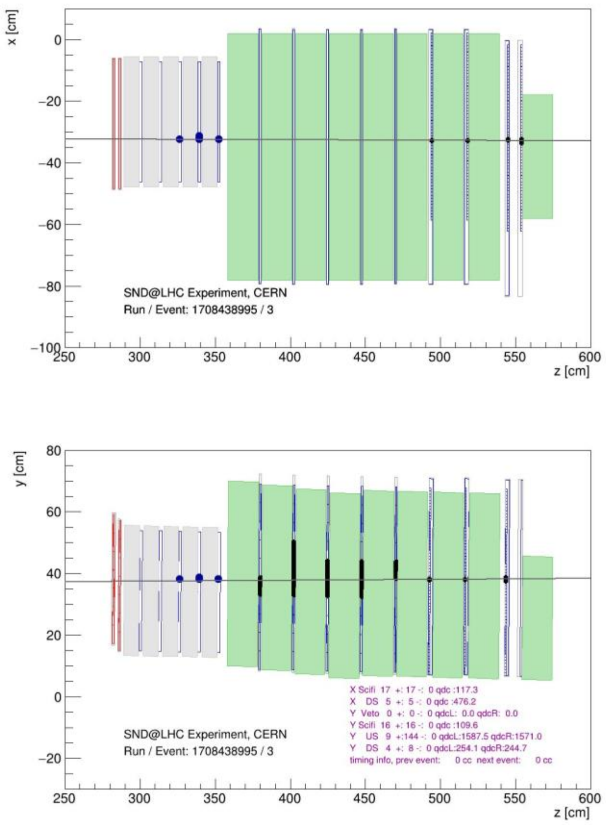
SNDSW simulation input variables

Script GitHub link: https://github.com/henrytheweeb/SNDthesis/blob/main/scripts/csv_to_sndsw.py

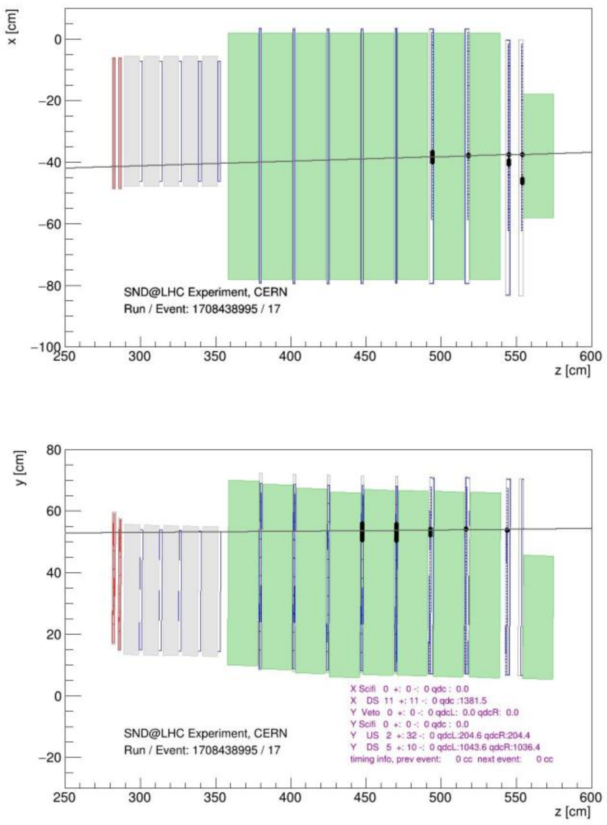
Event Displays (DH with $m = 354.8$ MeV)



Decay before detector



Decay in Target

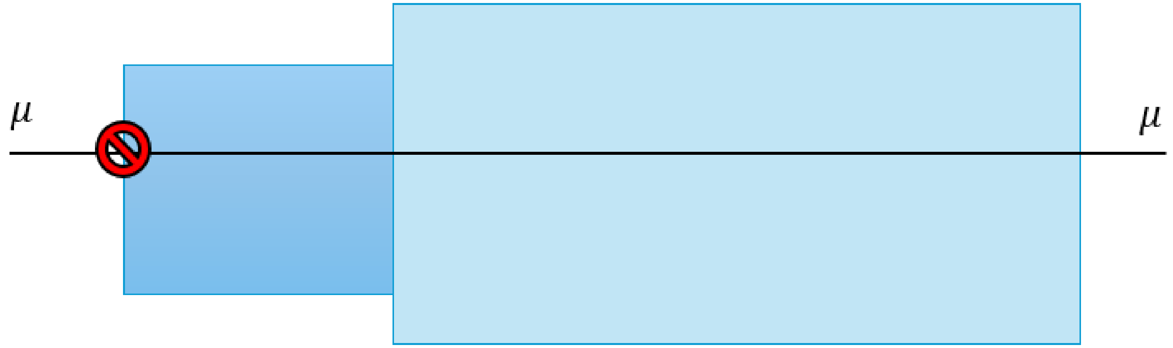


Decay in MS

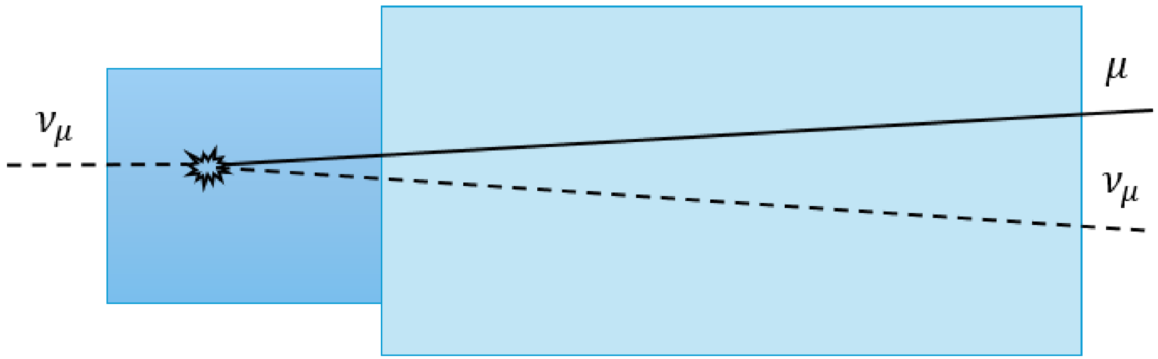
LHC
Scattering and Neutrino Detector
at the LHC

Backgrounds

- We are considering background from:
  - Single muons



  - Neutrino interactions



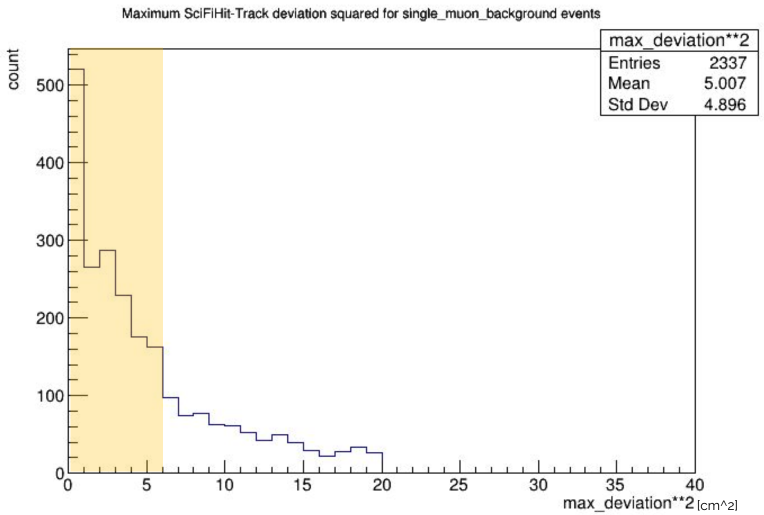
Selection cuts

Single Muon Background

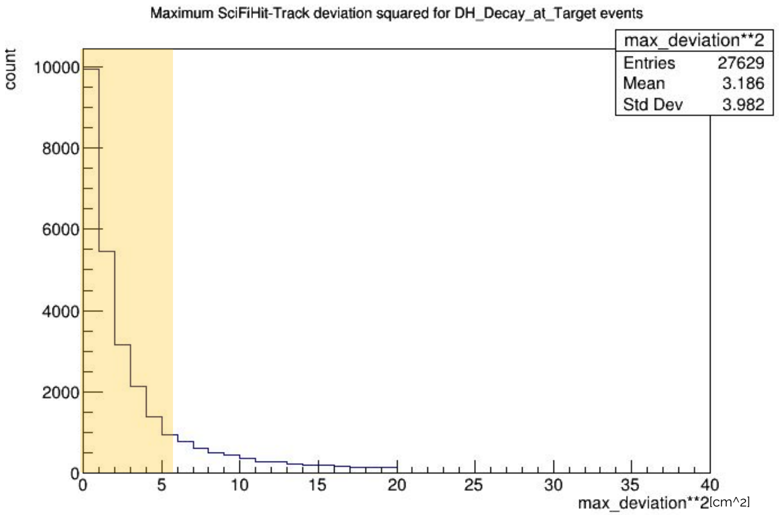
From visualization of surviving single muon events after previous cuts, combined with histogram analysis.

Cut introduced:

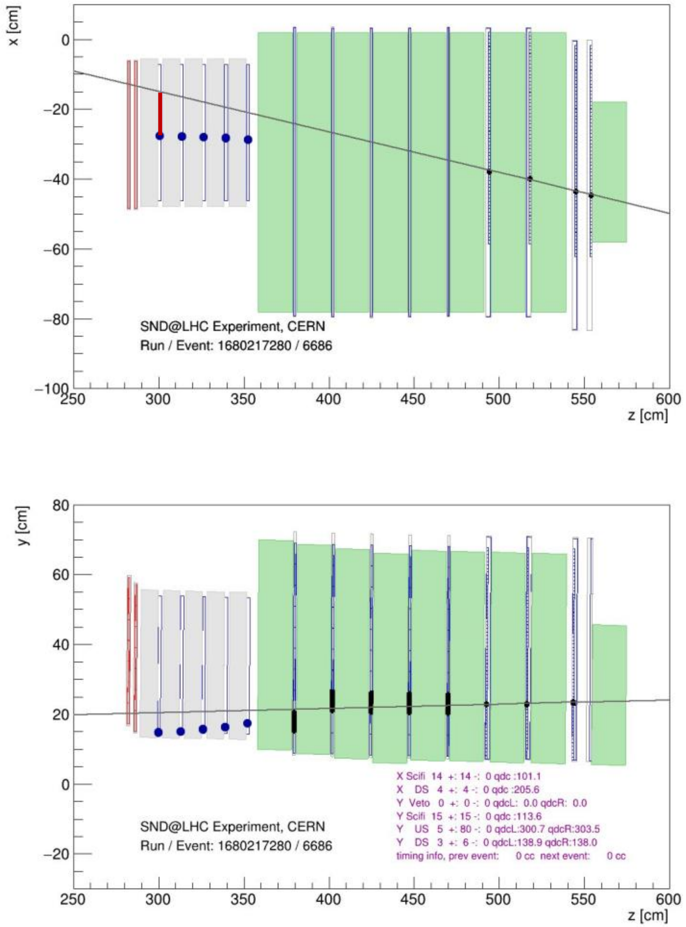
- The SciFi Hit furthest away from track extrapolation must have a deviation not exceeding $\sqrt{5}$ cm.



Maximum deviation squared for single muon background events

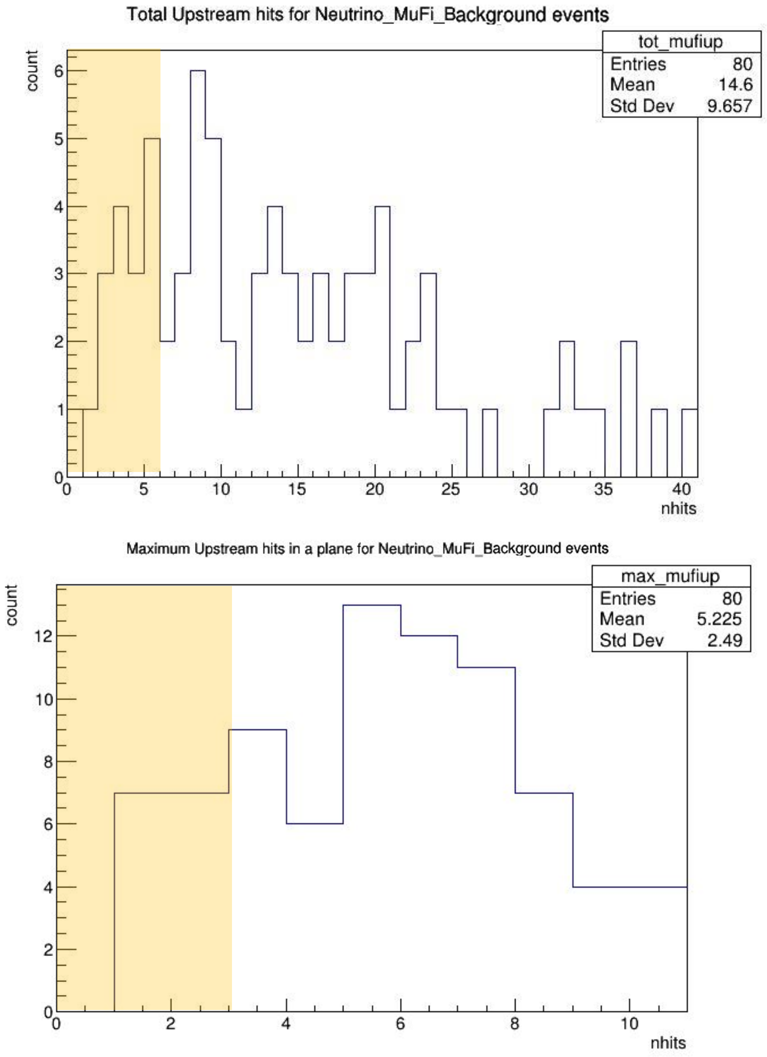


Maximum deviation squared for Dark Higgs signal events



Single muon background event showcasing the need for this cut

Selection cuts
Neutrino Background

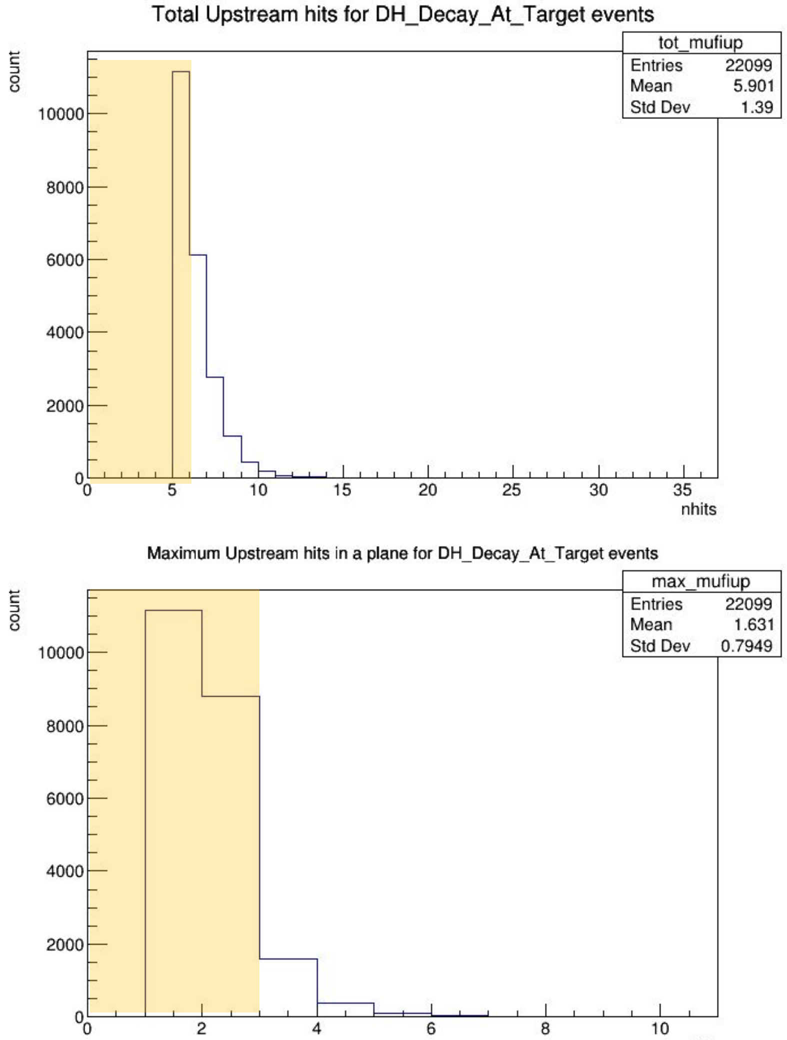


Total US bar hits and Max bar hits in a single plane for neutrino background

From comparing US hits in signal and neutrino background.

Cut introduced:

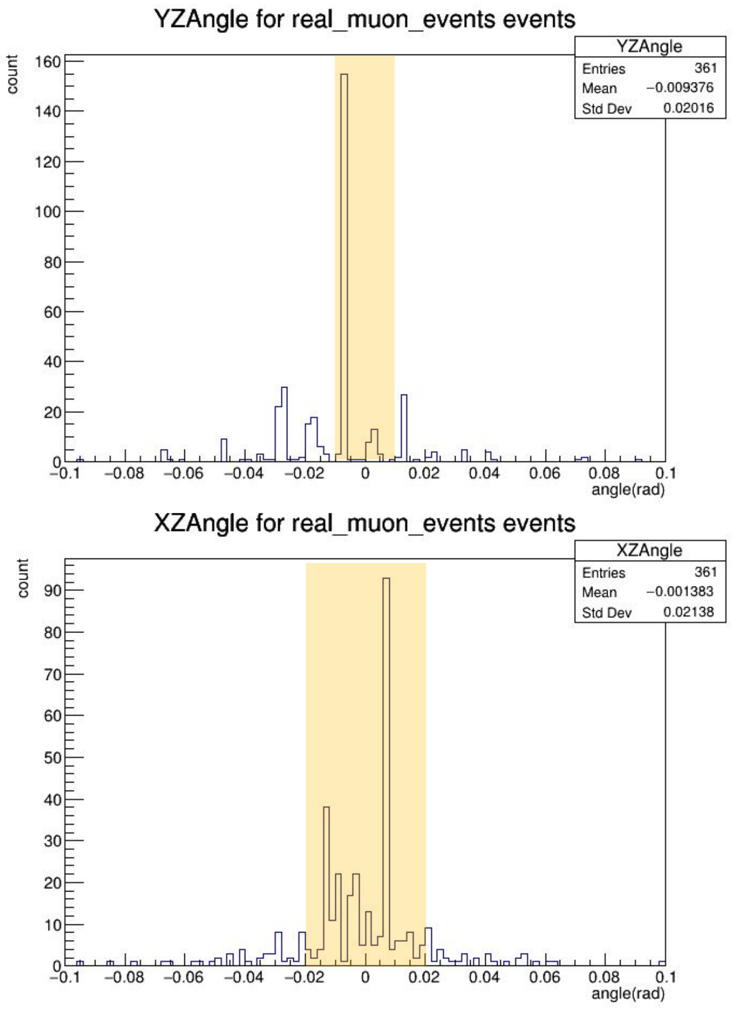
- Total hits ≤ 5
- Max hits in a single plane ≤ 2



Total US bar hits and Max bar hits in a single plane for DH signal

Selection cuts

Run data (run 5396,files 20-24)

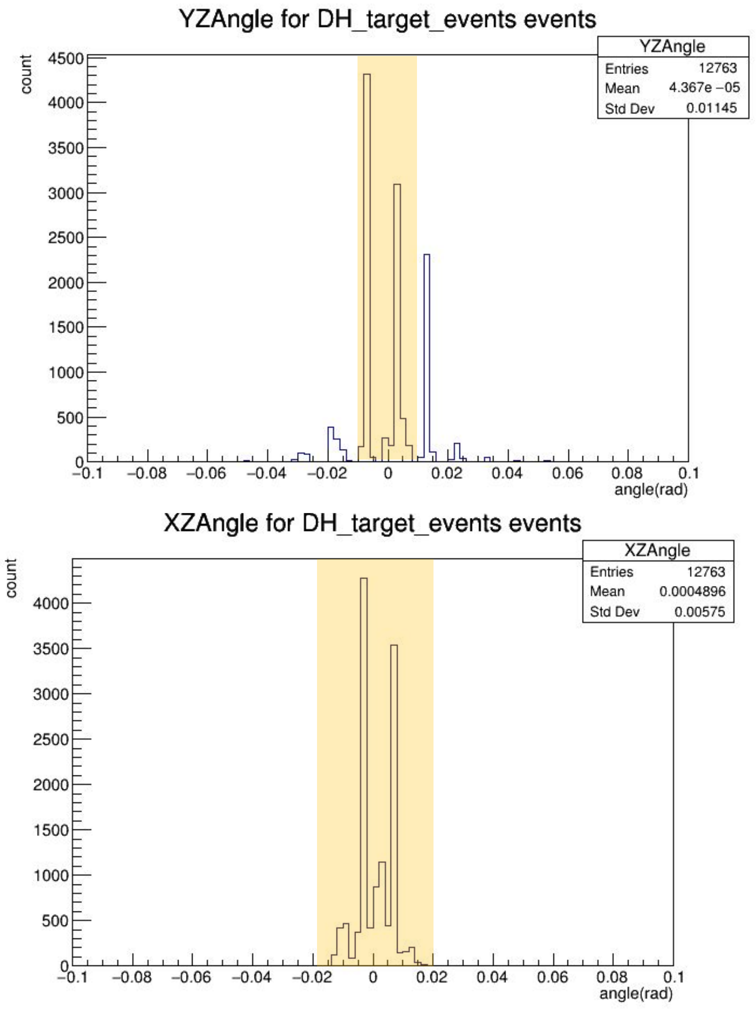


Track angles for run data events

From comparing track angles between signal and run data.

Cut introduced:

- Abs(YZAngle ≤ 0.01 rad)
- Abs(XZAngle ≤ 0.02 rad)



Track angles for DH signal events

Complete criteria list

- No Veto Hits.
- Track recognized by muon reconstruction of DS hits.
- Track within a tightened XY veto region at z=280cm and z=500cm.
  - $x \in [-44, -10]$cm and $y \in [18{,}52.5]$cm
- Max SciFi hit deviation from track $\leq \sqrt{5}$cm.
- Total US bars hit ≤ 5 and Max US bars hit per plane ≤ 2.
- Track XZ-Angle $\leq \mathbf{0.02\ rad}$ and YZ-Angle $\leq \mathbf{0.01\ rad.}$
- At least one SciFi hit (lets us focus on DH target decays and prevents surviving background from side-entering muons and extrapolation errors).

Soon to be implemented:

- Reject events where the first 2 US planes only have hits on the top or bottom bars (similar cut to neutrino selection) .
- We also plan to explore the possibility of QDC-based selection.

Selection Results

Signal			
Event type	**Total sample**	**Surviving events**	**Selection efficiency**
DH Target	100 000	11 160	11.16%
Background			
Event type	**Total sample**	**Surviving events**	**Surviving events adjusted to 70 fb^{-1}**
Neutrino MuFilter	9 171	0	-
Neutrino Target	5 439	6	0.42
Single Muon	1 100 000	0	-
Run data			
Event type	**Total sample**	**Surviving events**	**Surviving events adjusted to 70 fb^{-1}**
Run data (run 5396 files 20-24)	5 000 000	131	$\approx 400\,000$

- There is clearly still a need for further selection cuts (we would expect around 13 run data surviving events from veto inefficiency).

Summary

- This is the first FIP study using the full detector simulation and is focusing on the FIP decay to dimuon channel.
- This project aims to be model independent and is currently using the Dark Higgs as a benchmark.
- Due to low opening angle, the two muon tracks will appear as one, leading to relevant single muon and neutrino interaction background.
- Although the cuts implemented so far have successfully reduced the background, there is still work to be done before reaching the veto inefficiency limit.

Searching for Beyond the Standard Model particles decaying to muon pairs in SND@LHC

Henrique Santos

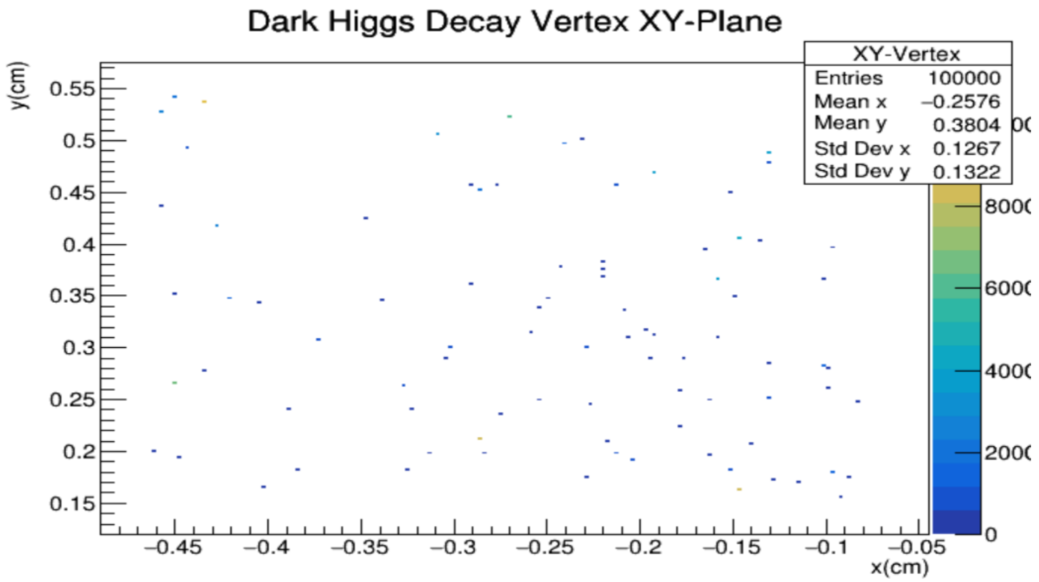
June 2024

Thank you for your attention!

LHC

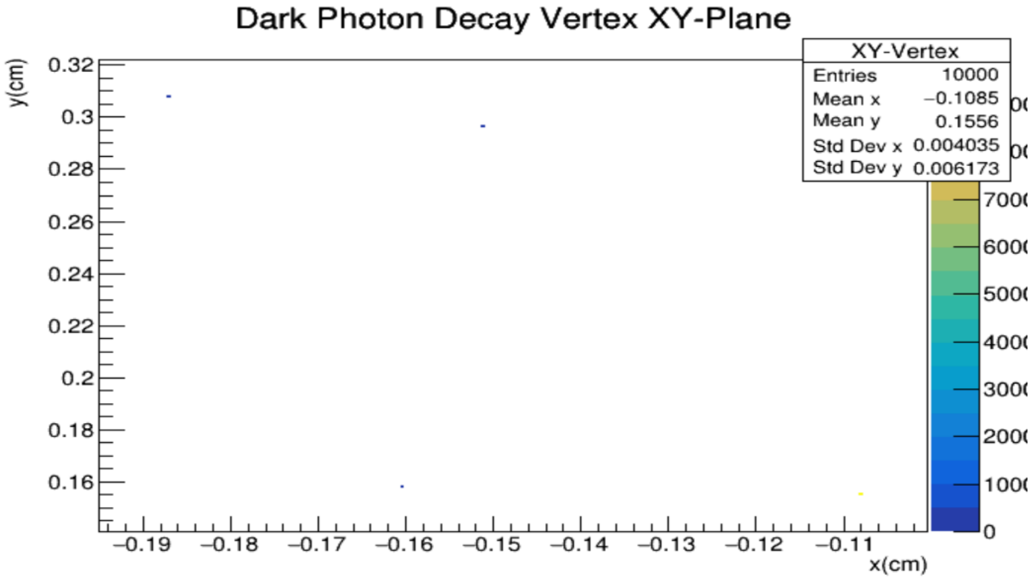
Scattering and Neutrino Detector at the LHC

Backup: Dark Photon vs Dark Higgs



Dark Higgs Decay Vertex

XY distribution



Dark Photon Decay Vertex

XY distribution

As we can see, the Dark Higgs vertex position distribution is much more promising for an unbiased analysis