Muon DIS: recent updates

Maksym Ovchynnikov

October 3, 2024

Outline

Covered by this talk:

- Effects of the recent changes in the SHiP setup:
  - Helium decay vessel
  - Thinner walls
  - Absence of the entrance lid

  on the muon DIS events rate
- Only baseline selection (so outdated vetoing)
- Preliminary ideas about the signal sample to generate when

  Directly connected to Martina's talk

Report on past signal/background studies

Signal and background studies for ECN3

Iaroslava Bezshyiko, Oliver Lantwin, Maksym Ovchynnikov, Anupama Reghunath

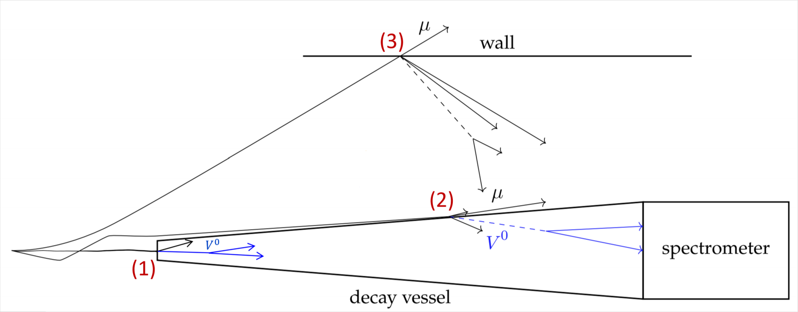
October 1, 2024

Abstract

In this report, we summarize physics studies performed for the SHiP experiment: neutrino deep-inelastic scattering background, muon deep-inelastic scattering background, and sensitivity to new physics particles. The report contains research work carried out up to summer 2024. Namely, we recapitulate the main steps of the analysis that appeared in the SHiP LoI to make them reproducible. We also highlight features to be improved in future studies.

– **Report on past signal and background studies is available here**

Muon DIS events



Muon DIS events may occur in scatterings with:

- The decay vessel
- Cavern's wall
- Medium inside the decay volume

Algorithm and event selection I

Algorithm (Oliver's PhD thesis):

1. Start with n muons after leaving the muon shield (generated by fast muon simulation)
2. Analyze separately "front" (entering from the front of the decay volume), "side" (entering from the side), and "cavern" (seem-to-be-irrelevant) muons
3. Generate the N DIS interactions per muon (currently – externally, using `pythia6`)
4. Distribute the DIS vertices according to the material density ρl
5. Simulate event reconstruction
6. Impose simple kinematic pre-selections and veto
7. As $N_{\text{DIS,samples}} \ll N_{\text{DIS,expected}}$, impose the statistical estimate for the expected background

   If after all cuts $N_{DIS,samples} = 0$, impose 90% CL upper limit on the rejection efficiency

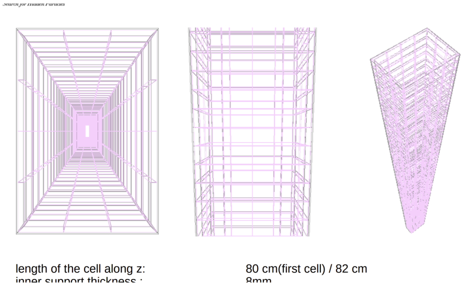
Algorithm and event selection II

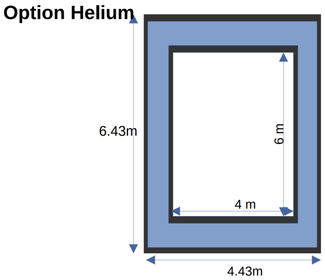
Cuts on the events:

Cut	Value
Good daughters	nDoF>25, χ^2/nDoF < 5, $p_{\text{track}} > 1$ GeV
Number of "good" candidates per event	1
DOCA	< 1 cm
Vertex distance from vessel's wall	> 5 cm (transverse), 20 cm (longitudinal)
IP (f.r.)	< 10 cm
IP (p.r.)	< 250 cm

- Only muons with trajectories intersecting the decay vessel are dangerous after imposing these cuts
- Further background rejection with veto systems: SBT and UBT
- SBT: any SBT activity per event with $E_{\text{deposit}} > 45$ MeV

Simulations I





- Two SHiP setups: **“pre-24.09”** and **“24.09”**
  - pre-24.09: optimized for the vacuum decay volume
  - 24.09: adjusted for the He/air decay volume

  See Anupama’s slides
- Key aspects of 24.09: smaller inner wall’s thickness, absence of the entrance rid ⇒, a much smaller number of the DIS events from front muons is expected

Simulations II

3 simulations for comparison:

Simulation	Setup details	Simulation details	Note	Refs.
Jul #1	Pre-24.09	$(n \cdot N)_{\text{side}}$: $6.2 \cdot 10^6$ $(n \cdot N)_{\text{front}}$: $3.9 \cdot 10^6$ Dec. vessel+dec. vol.	Wrong He number density in `FairShip`	Slides Samples: 1, 2, ...
Sept #2	Pre-24.09	$(n \cdot N)_{\text{side}}$: $6.2 \cdot 10^5$ $(n \cdot N)_{\text{front}}$: $3.9 \cdot 10^5$ Dec. vol. only	Fixed He number density	Slides Samples: 1, 2
Oct #3	24.09	$(n \cdot N)_{\text{side}}$: $6.2 \cdot 10^5$ $(n \cdot N)_{\text{front}}$: $3.9 \cdot 10^5$ All	Segmentation fault during reconstruction	Samples: 1, 2

Results I

Sim.	$\boldsymbol{N}^{\text{vtx}}_{\text{DIS}}$	$N^{+\text{Fid. vol.}}_{\text{DIS}}$	$N^{\cdots+\text{DOCA}}_{\text{DIS}}$	$N^{\cdots+\text{IP250}}_{\text{DIS}}$	$N^{\cdots+\text{IP10}}_{\text{DIS}}$
#1	$3.5\cdot 10^{8}$ (all) 26550 (dec.vol.)	$6.5\cdot 10^{7}$ (all) 17441 (dec.vol.)	$5.9\cdot 10^{6}$ (all) 8429 (dec.vol.)	$4\cdot 10^{5}$ (all) 5381 (dec.vol.)	$8.1\cdot 10^{3}$ (all) 197 (dec.vol.)
#2	16233 (dec.vol.)	14008.9 (dec.vol.)	9430 (dec.vol.)	8144 (dec.vol.)	971 (dec.vol.)
#3	$2.54\cdot 10^{8}$ (all) $7.3\cdot 10^{3}$ (dec.vol.)	$4.5\cdot 10^{7}$ (all) $7.1\cdot 10^{3}$ (dec.vol.)	$3.5\cdot 10^{6}$ (all) $5.5\cdot 10^{3}$ (dec.vol.)	$2.7\cdot 10^{5}$ (all) $5.2\cdot 10^{3}$ (dec.vol.)	$4.4\cdot 10^{3}$ (all) 400 (dec.vol.)

– The table shows the number of DIS events per full timeline, under subsequent application of cuts: 1 good candidate, +fiducial+wall, +DOCA, +IP250. $N_{\text{PoT}} = 6\times 10^{20}$ is assumed

– Effect of new geometry: $\mathcal{O}(1)$ impact on the total number of events. Why?

Results II

- Effect of new geometry: $\mathcal{O}(1)$ impact on the total number of events. Why?

Sim.	$(N_{\text{DIS}}^{\text{vtx}})_{\text{side}}$	$(N_{\text{DIS}}^{\text{vtx}})_{\text{front}}$
#1	$3.51 \cdot 10^8$	$2.97 \cdot 10^5$
#3	$2.51 \cdot 10^8$	$8 \cdot 10^3$

- The amount of front muons has been reduced significantly – the effect of lid removal
- The amount of side muons has changed by $\mathcal{O}(1)$ – the effect of wall's thickness change

Results III

– Decomposition of the fiducial+wall+DOCA+IP250 events by the DIS nodes:

Node	Veto*	LiScY*	DecayVacuum*
$N_{\text{DIS,expected}}$	$\simeq 4.9 \cdot 10^4$	$\simeq 2.2 \cdot 10^5$	$\simeq 5.2 \cdot 10^3$

– DIS occurs inside the veto system and liquid scintillator

Results IV

Two ways to proceed:

1. Utilize veto systems – SBT and UBT
   Problem: false vetoing of signal events with high multiplicity
2. Discriminate signal over a background by going beyond the standard cuts:
   - $z_{\text{vtx}}, m_{\text{inv}}, \theta_{\text{vtx}}$ distributions
   - Decays topology
   - ...

   Problem: heavy LLP model/parameter space dependence, while only two LLP models are implemented in `FairShip`

Way 1: Veto systems I

– **Baseline SBT and UBT** (==toy) kill all the events in the sample

$N_{\text{DIS}}^{\cdots+\text{IP250}}$	+SBT	+UBT
$2.7 \cdot 10^5$	905	0

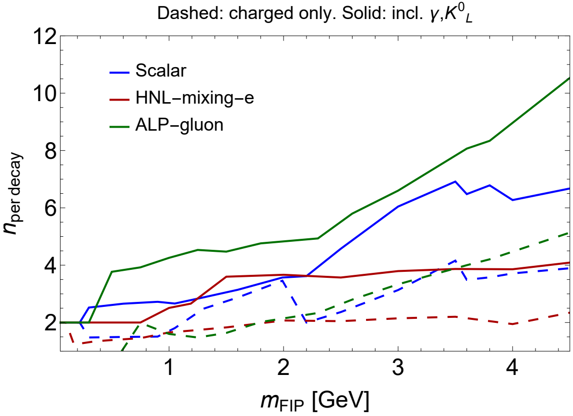
– May be used to impose upper CL on the background, < 1 event/full timeline

– **Advanced SBT** (see talk by William) may potentially deliver similar performance

– **Advanced UBT** (ongoing study by Gerardo):
  - Developing a method to calculate muon tagging efficiency using multiple detector layers
  - Determining the spatial and timing requirements

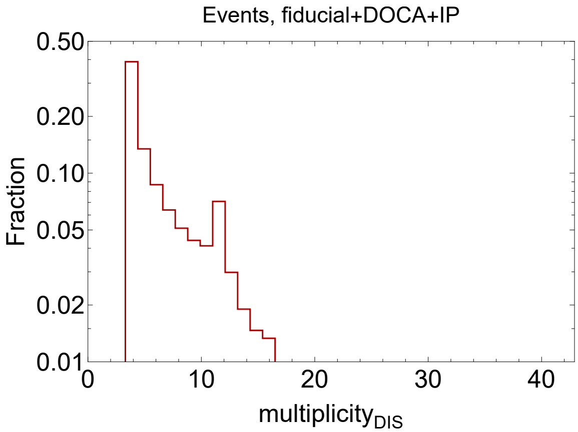
Way 1: Veto systems II

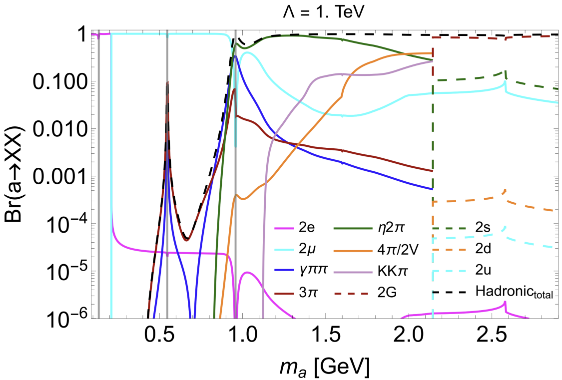
– **Problem** with any SBT: signal events often have high multiplicity (solid lines in the figure), with decay products intersecting SBT



– The problem is unstudied: the currently selected signal modes, $N \to \mu\pi$, $N \to ll'\nu$ produce only two visible particles

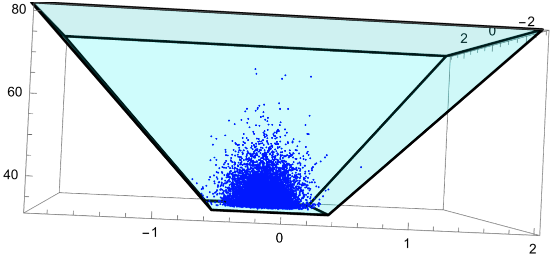
Way 2: Non-standard selection I

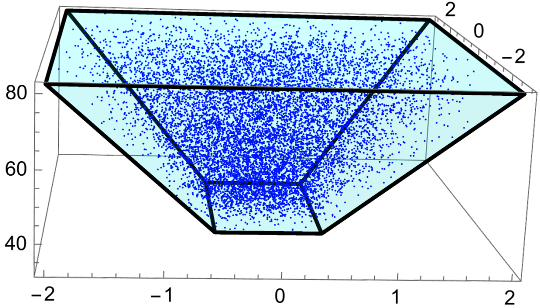




1. **Decay topology** – number and type of decay products, total electric charge, etc.
   - *Complexity*: both LLPs and backgrounds typically have many modes, various multiplicities, and event kinematics
   - What is shown: muon DIS multiplicity (left) and decay modes of ALPs coupled to fermions (right)

Way 2: Non-standard selection II

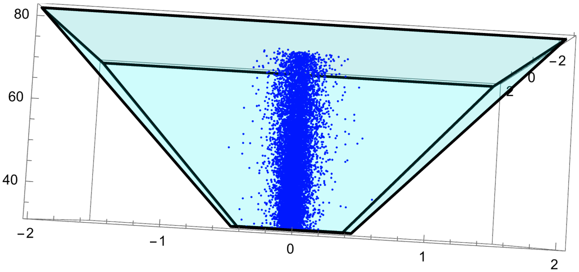


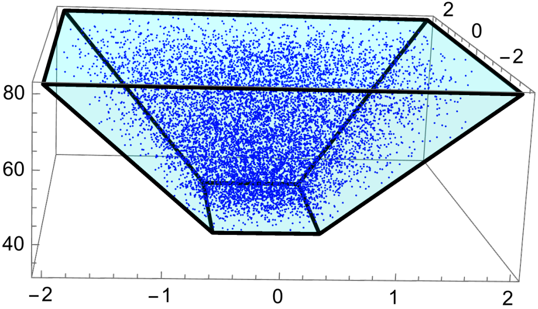


2. $z_{\mathbf{vtx}}$ **distribution -** drop the boundaries of the decay volume
   - *Complexity*: depending on $l_{\text{decay}} = c\tau\langle\gamma\rangle$, LLPs may have different z distribution
   - Distribution of dark photons with mass $m = 2.9$ GeV in $\mathbf{r}_{\text{vtx}}$ for small (left) and large (right) l_{decay}

     Produced by `EventCalc`

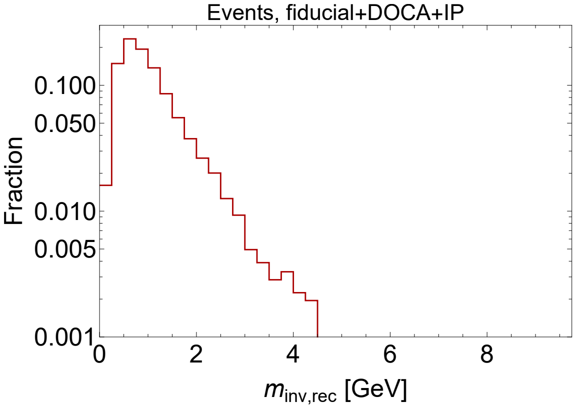
Way 2: Non-standard selection III





3. **Angular distribution** – select signal based on θ_{vtx}
   - *Complexity*: depending on the mass and particle, the distribution $df/d\cos(\theta)$ may be both isotropic and very narrow
   - What is shown: the angular distribution of dark photons with $m = 0.9$ (left) and 2.9 (right) GeV

Way 2: Non-standard selection IV



4. **Invariant mass distribution**. Remove background based on the invariant mass distribution
   - *Complexity*: both signal and background may have any invariant mass
   - What is shown: distribution of the muon DIS events in m_{inv}

Algorithm to proceed I

1. **Consider several models with LLPs:**
    1. HNLs with various coupling pattern
    2. ALPs with various coupling pattern
    3. Dark photons
    4. $B - L$ mediators
    5. Higgs-like scalars with/without quartic coupling
    6. Inelastic light dark matter
    7. ...

    "Less popular" models have to be added too

Algorithm to proceed II

2. **For each of the LLP, to cover all possibilities, consider parameters spanning the physics case:**
   - Three characteristic lifetimes: short ($l_{\text{decay}} = c\tau\langle\gamma\rangle < 32$ m), medium (e.g., $l_{\text{decay}} = 40$ m), large ($l_{\text{decay}} \gg 100$ m)
   - Three characteristic masses: $m \lesssim 0.1$ GeV (leptonic/photonic decays only), $m = 0.5 - 1$ GeV (variety of exclusive decays), $m \gtrsim 1 - 2$ GeV (decays into jets)
3. **Generate samples with these LLPs**
   - Use `EventCalc` for this (see Martina's talk)

Backup slides