PROCEEDINGS OF SCIENCE

Exotic particle searches at beam-dumps – dos and don’ts

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The search for long-lived and feebly interacting particles at proton fixed target facilities is enjoying renewed interest, and it is a high time for the release of white papers and/or reports with parameter space regions that contain projections for the reach of numerous existing and proposed experiments. As the physics case for such searches is very compelling, we want to highlight a few selected aspects that may be useful when interpreting such projections, or producing new ones.

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1. Scrutinizing Dark Sector Projections

In contrast to the very highest energy direct new physics searches, which are currently possible only at the LHC, somewhat lower mass-scales (MeV-GeV) are accessible to a number of current and proposed experiments. The attractiveness of this physics case arises, among other reasons, because "light" Dark Matter (DM) interactions with Standard Model fields could proceed via new light mediators in order to reproduce the observed DM relic abundance. There is a number of models (and benchmark cases) that can be defined that are motivated by minimal extensions of Standard Model (SM) [1, 2]. An example of the parameter space of such a benchmark scenario is shown in Figure 1, displaying the status of current exclusions for a Heavy Neutral Lepton (HNL) with predominant muon-coupling (so-called BC7 scenario in the CERN-PBC benchmark cases, see for example [3] and references therein.).

For the unsuspecting reader, a few thoughts may cross her/his mind, when studying Fig 1:

1. Clearly there is some interest/competition! But what is funded and if so, when?
2. Do some curves stand-out with respect to the others?
3. Is some parameter region more relevant than others?
4. Is the plot done in a consistent fashion? I.e.: are the underlying assumptions comparable?

One has to mention that various attempts have been made to make such projections more readable: For example, introducing different line-styles to indicate time-line, level of "maturity/readiness". Still, for a non-expert, trying to judge figures such as the one displayed here can be somewhat up-setting. This proceedings is thus aimed at presenting a selection of a few basic aspects that address particularly worry number 4 of the unsuspecting reader.

What we'll detail on is the specific case in which the exotic decay is detected far away from their production point, even more specifically, projections from *proton dumps* (such as NA62-dump/HIKE-dump, SHADOWs, SHiP, SeaQuest, re-interpretations of CHARM and others...).

Our presentation should help the reader consider some background information when attempting to read such a plot (or produce a new one).

Specifically we want to point at the the impact of:

1. Comprehensiveness of input processes, influence/options of different input shapes (Sec 2)
2. Transparency of assumptions (Sec 3)
3. Model-dependence and complementarity (Sec 4)

A disclaimer has to be given though: This presentation draws from the authors' own experience in working on the issues above, and is thus intended purely to give an an idea of the aspects arising, with no attempt for completeness!

Also it should be said that the benchmark scenario displayed in Fig. 1 is selected somewhat arbitrarily. The points mentioned above are relevant to all portal scenarios and we will also refer to those when appropriate.

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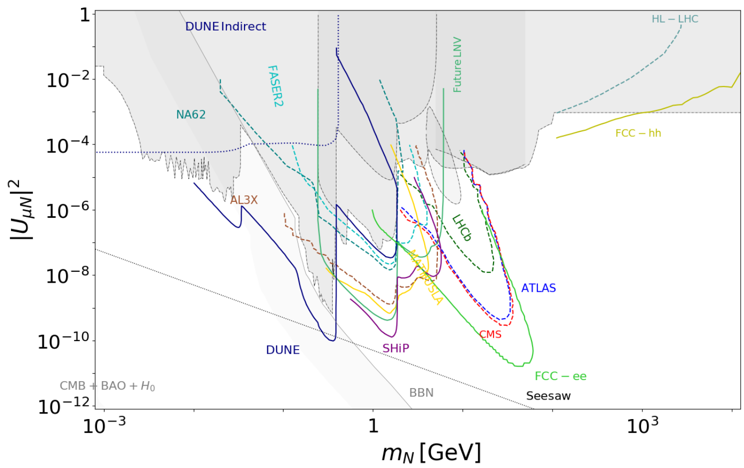

Figure 1: Projection of future sensitivites (colored lines) and existing constraints (gray areas) for the scenario of a Heavy Neutral Lepton coupled predominantly to muons (adapted from [4]).

2. Input processes and shapes

The very first deliberation concerns the input processes, i.e. the processes that can lead to the production of a BSM particle. In many cases, relevant contributions can be easily overlooked before a full computation/simulation is performed. For example, in [5] it was shown, that a factor of at least 2 in mass range could be gained in the search of Axion-like particles when a certain production mechanism was accounted for that previously hadn't been considered (in this example photo-production from decaying π^0s instead of photo-production from the photon cloud of the primary proton only). Another more recent example is a much extended parameter range for Dark Photons from pion-bremsstrahlung [6] in proton dumps (instead of Bremsstrahlung from primary protons only).

But even if one is diligent in considering all possible production modes, another possible pitfall has to be considered. A predominant production process of exotics in many scenarios is in the decay of secondary mesons from the primary proton shower. In proton beam dumps, it is often the most forward component of those mesons which is almost exclusively relevant in the computation of the exotics yield. A standard choice in generating those mesons is then PYTHIA [7]. In the case of lighter mesons, an attempt [5] has been made to validate existing experimental literature against PYTHIA. In this way, uncertainties in shape and yield can be accounted for when producing BSM projections.

For heavier mesons, this endeavour is much more difficult [8], and this fact has thankfully stimulated projects to overcome this problem [9, 10]. To illustrate the effect, the hypothetical reach of a forward beam-dump experiment at a 400GeV proton beam-line is illustrated in Fig. 2 using an upgraded version of the ALPINIST MC [11, 12]. Curves are drawn for different levels of 'forwardness' of the initial D-meson distributions. In terms of the Feynman x variable $x_f = p_{\parallel,CM}/p_{\parallel,max,CM}$, the differential cross section is $d\sigma \sim (1-x_F)^n * \exp(-bp_T^2)$ with free parameters n and b. Omitting[1]. the influence of b in this instance, we show that the actual reach in this toy

[1]To simplify this discussion we are also neglecting discussions about the impact of the exact target material in the

example can vastly differ depending on the choice of n (for a fixed common initial crosssection $\sigma_{c\bar{c}}$). While 'vanilla' PYTHIA 8.3. suggests to use around $n = 5$ (depending on the meson), the measured NA27 distribution is closer to $n = 3.1$ [13]. Other intermediate n are shown for comparison. As can be seen, the correct choice of n would be crucial to decide the statistics needed to probe a novel region in BC7. Another subtle point (not discussed here), is how to handle the fact that the most forward parts of the meson spectra are typically least populated in terms of statistics [11].

To summarize: When expectations such as the one in Fig. 1 are presented, it has to be assured that comparable total crosssections for secondary mesons, their multiplicity, as well as the same kinematic shape of those mesons is used in order to achieve a fair prediction.

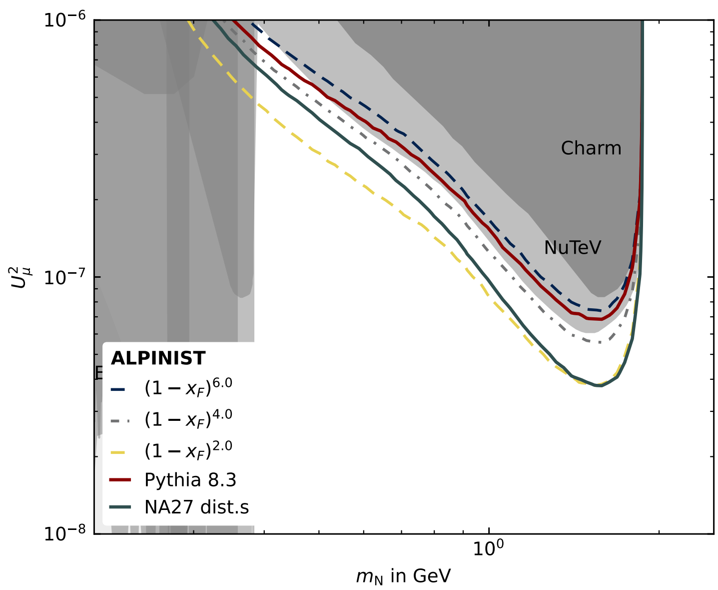

Figure 2: Schematic sensitivity dependence in BC7. For fixed geometry parameters of a forward 'model experiment' at given number of protons on target, the exponent n parameterizing the "forwardness" of the heavy mesons that produce the HNLs is varied. For various well-motivated choices, a significantly different reach is projected (see text for details).

3. Transparency/Model-dependence

The above example illustrates that a transparency in the assumptions used in preparing a sensitivity projection is crucial in assessing their validity. A good practice are therefore toy-MCs[2] that are *publicly available* and have a common set of inputs for a number of different experiment geometries.

proton dump and we are also neglecting discussions about the fact that different D-mesons can have significantly different parameterization in n.

[2]It is clear that a toy MC can never replace the actual predictions from an experiment MC which knows about possible inefficiencies or subtelties in geometric features. Good public toys are however also indispensible to phenomenologists as a first rough check for new models.

A number of such tools are currently on the 'market' that are able to make projections for proton beam-dumps:

- ALPINIST [12] (only Axion-like particles implemented publicly at the time of writing, public meson distributions)
- SENSCALC [14] (a number of models are implemented, however the meson input file has to be requested from the authors)
- MADDUMP [15] (derived from the popular MadGraph MC generator but difficulty of handling certain decay modes in detail, such as 3-body decays via Dalitz plot)
- DDC (Displaced Decay Counter) [16] (mainly for far detectors at the LHC, can be used in association with MadGraph5 and PYTHIA8)

From these (and probably many more), users are able to test new models and experiments, where the choice of the best public MC depends on the specific use-case.

4. Model-dependence and 'going life'

It is understandable that benchmark cases need to be defined to compare facilities, in this way one can understand the specific reach in different scenarios as is the case for Fig. 1. One has to bear in mind though that if one wants to remain more open/agnostic about the new physics, plotting a reach in coupling vs lifetime (for a fixed mass) is more powerful. In this way, it becomes also clearer that each facility has often a unique range in which it is most sensitive as the decay-length of the exotic 'matches' the geometry of the set-up. This is examplified in recent results [17, 18] in the search of axion-like particles coupled predominantly to fermions. A complementary reach of parameter space can searched even with comparably 'low' statistics if the geometry of the detector permits it (and backgrounds are under control).

5. Conclusions

The MeV/GeV mass scale weakly-coupled physics is compelling, vibrant field with many proposals and experiments. In this talk, we presented a selection of considerations to have in mind when attempting to interpret or add to a "busy" plot that addresses the future sensitivities of these searches.

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