Exotic particle searches at beam-dumps
— A small handbook —

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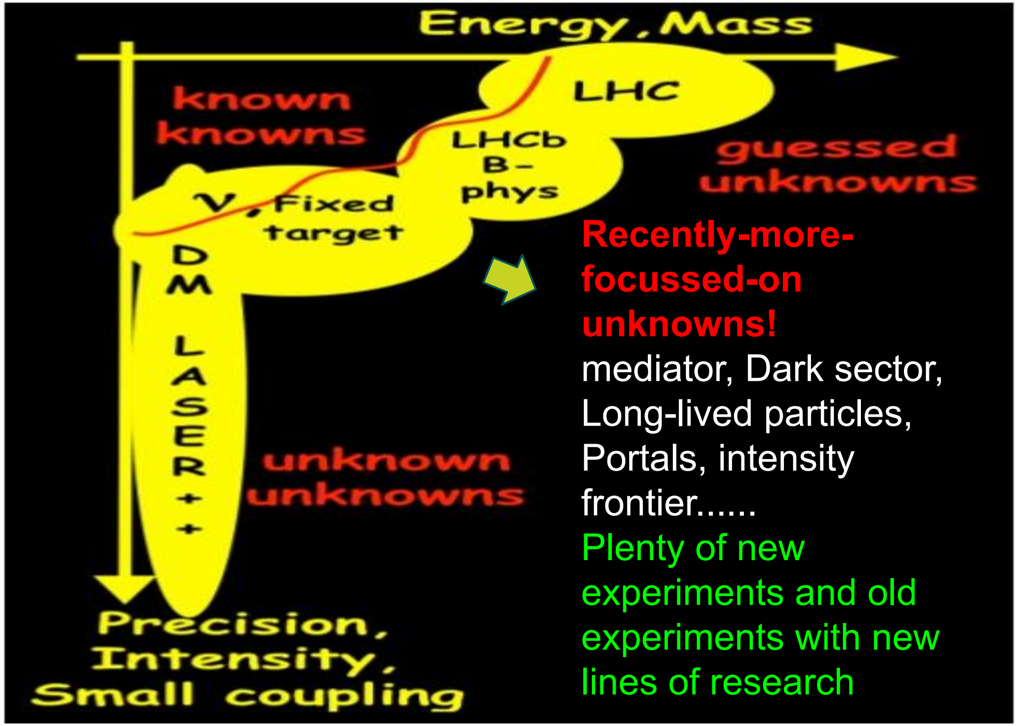
The case for weakly coupled particles at the MeV-GeV scale

E.g. SUSY, heavy Dark Matter protected from decay by symmetry

Light-weight Dark Matter: e.g. QCD axion, inherently stable, cannot decay into SM particles



Recently-more-focussed-on unknowns!
mediator, Dark sector, Long-lived particles, Portals, intensity frontier......
Plenty of new experiments and old experiments with new lines of research

Based on figure from Joerg Jaeckel, ITP Heidelberg

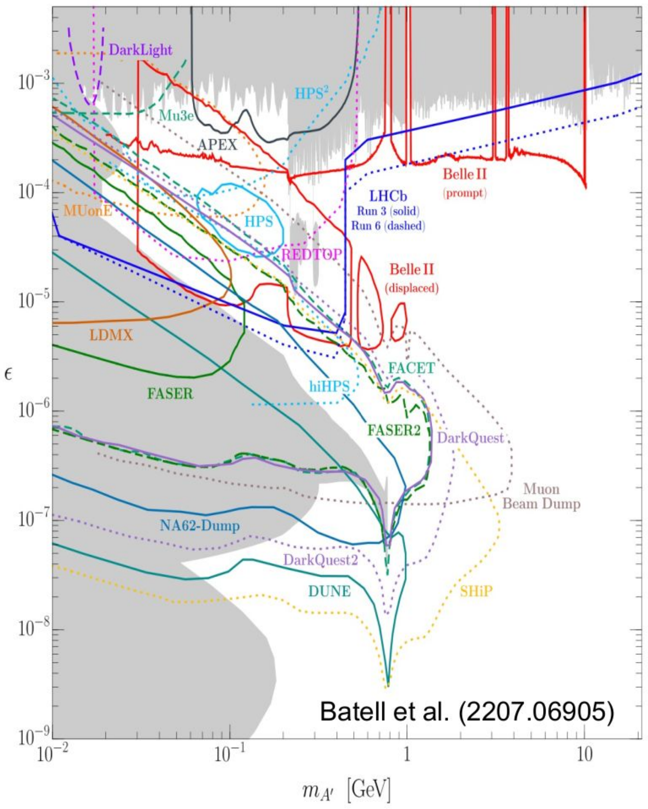
Example: The Dark Photon

- "light" DM interactions with SM fields must proceed via new light mediators in order to reproduce the observed DM relic abundance, and thus result in a dark sector at (sub)-GeV scales
- portal benchmarks motivated by minimal extensions of SM that can give rise to thermal relic DM at the MeV-GeV scale without violating cosmological, astrophysical, or terrestrial bounds
- Example: Dark Photons $m_{A'} < 2m_\chi$ and thermal freeze

$$\chi\chi \leftrightarrow A' \leftrightarrow f\bar{f}$$

MeV-GeV & $\epsilon \sim 10^{-6} - 10^{-3}$ preferred for significant DM fraction

- See, e.g. summary report of FIPS 2022



Example: The Dark Photon

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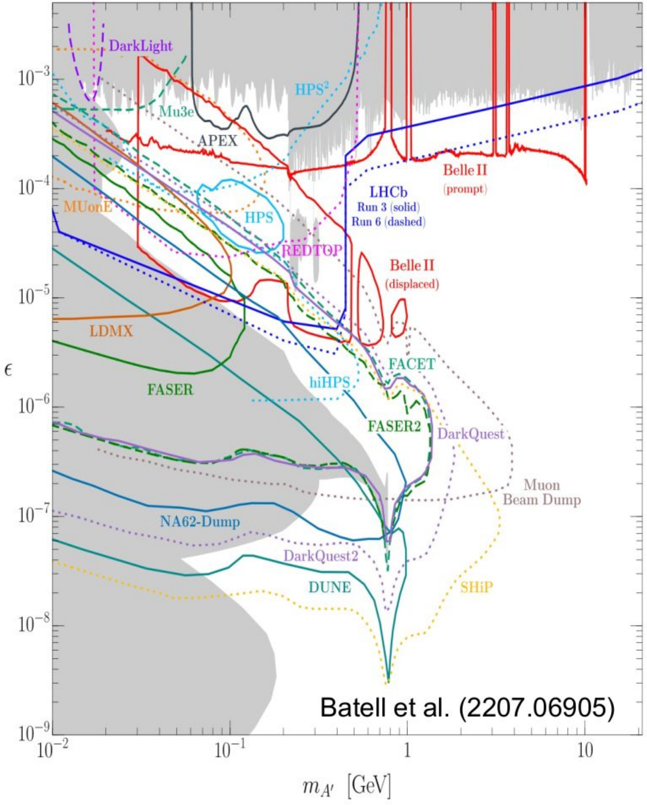
Some observations/remarks regarding plot on the r.h.s.:

1. **Clearly there is some interest/competition**
2. **Attempts have been made to make this more readable: different line-styles to indicate time-line, level of “maturity/readiness”**
3. **Still, for a non-expert, this can be somewhat up-setting:**

- **What’s a relevant parameter region?**
- **Do some curves stand-out with respect to the others?**
- **Is the plot done in a consistent fashion? I.e.: are the underlying assumptions comparable?**

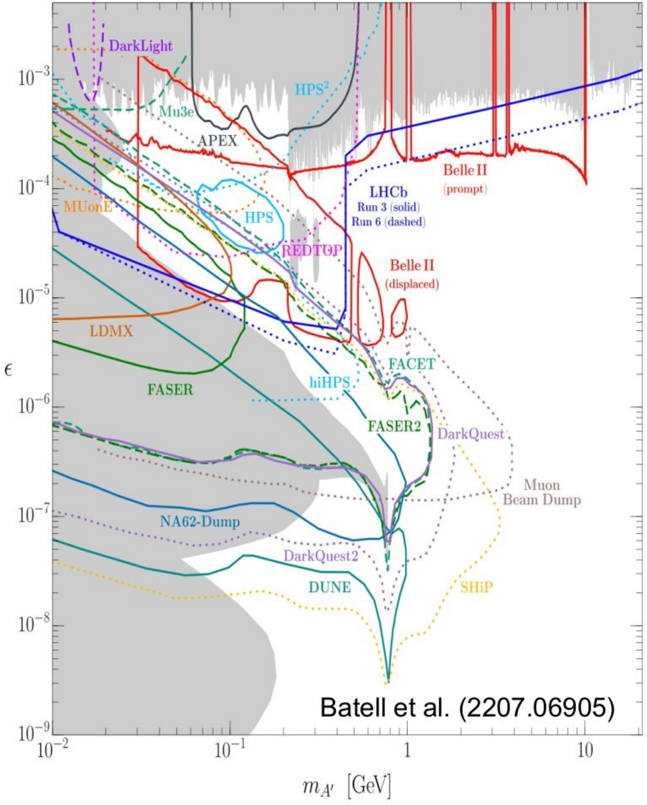


Scrutinizing Dark Sector Projections

This talk is meant to present a selection of aspects that is important to address when attempting to read such a plot (or produce one yourself), not only for Dark Photons

Specifically I'll talk about the impact of:

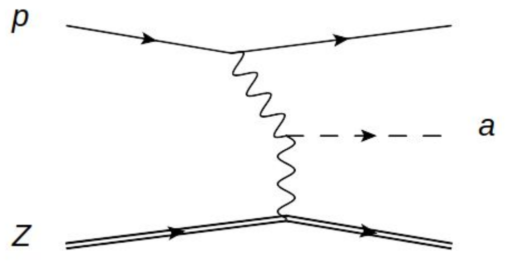
1. **Comprehensiveness of input processes**
2. **Influence/options of different input shapes**
3. **Transparency of assumptions**
4. **Theoretical limitations (model-dependence)**
5. **Practical limitations**

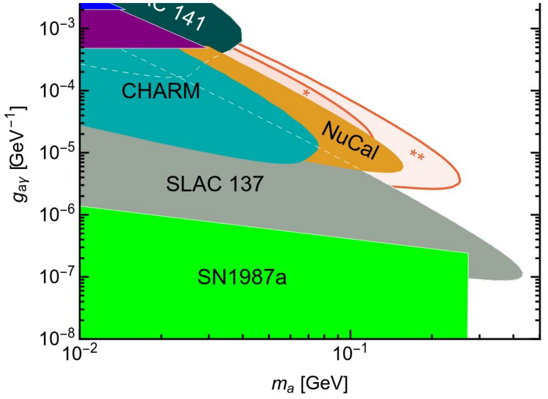


Disclaimer: Presentation focuses somewhat on work I've been involved in, and is purely an idea of <u>exemplifying</u> such issues, with <u>no attempt for completeness</u>!

Comprehensiveness of input processes I

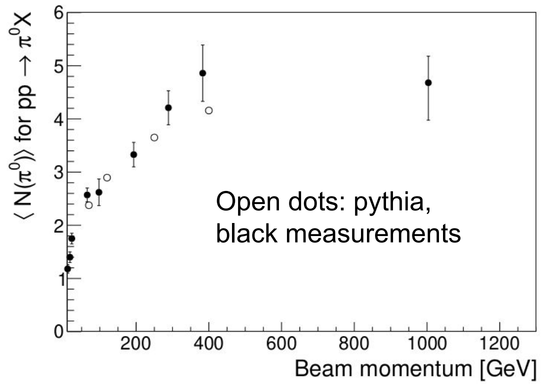
- Example: Axion-like particle coupled to photons
- Evaluated potential for NA62 in beam-dump mode (see later) in 2016 (BD et al. JHEP 1602 (2016) 018): dominant production process assumed to be ``photon-from-proton mechanism" (PFP) -> orange region on r.h.s.
- Implement past experiments in same (toy) set-up to assess what could be achieved: here CHARM and NuCal
- Found Reach beyond past experiments even with 1 day (*) (assuming 0 background, see later) or 1 month (**) of data -> highly motivating!

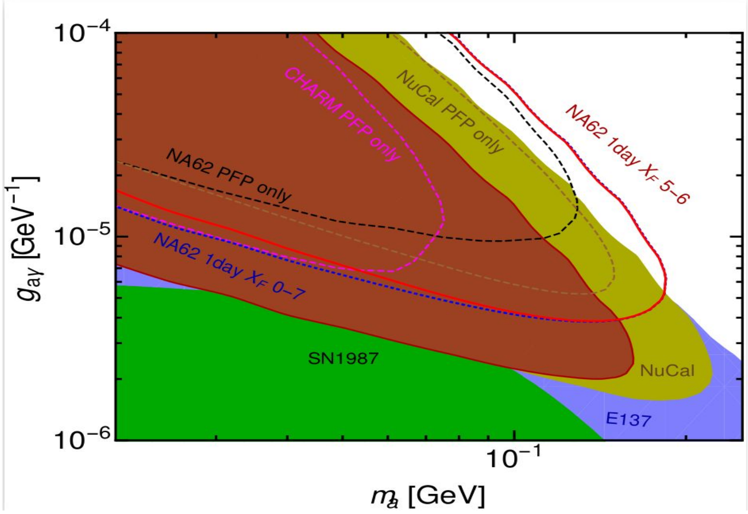




Comprehensiveness of input processes II

- Are the photons from protons really the dominant source to produce ALPs?
- No! Consider photons from (basically instantaneous) pi0 decay
- Process can be more efficient by orders of magnitude, see e.g. black vs red line **(BD et al** *JHEP* 05 (2019) 213, *JHEP* 10 (2020) 046 (erratum))
- Message above oversimplified: results depend on detailed kinematics (see next slide) and thus for example on “how forward” or “how offset” your experiment is w.r.t. the incoming beam
- <u>TAKE AWAY (somewhat trivial but huge effects possible): look closely at the production processes accounted for in projections!</u>

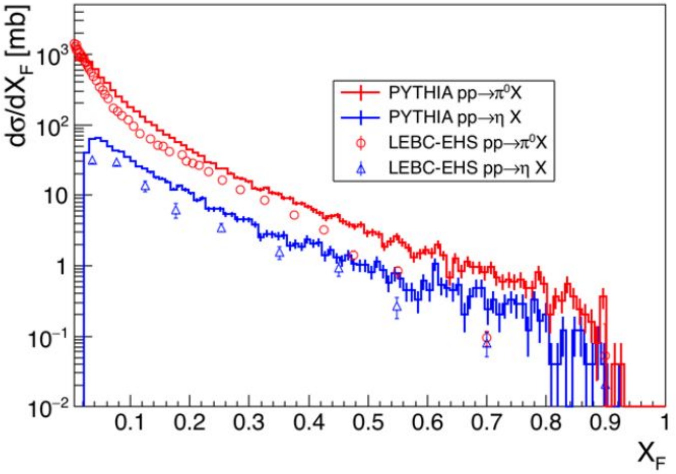




Influence of different input shapes I

- **For the previous scenario, validation of the input kinematics of light mesons is feasible, data available for a number of input proton momenta** **(BD et al** *JHEP* 05 (2019) 213, *JHEP* 10 (2020) 046 (erratum))
- **Possible to some degree to assess uncertainty due to difference in input spectra from generators such as PYTHIA and measurements, see example LEBC-EHS at 400GeV. More difficult for heavy mesons!**
- **Typically, the (least well known) forward component matters:** $x_f = P_{\|,CM}/P_{\|,max,CM}$
- **Fit parameters n and b**

$$d\sigma \sim (1 - x_F)^n * \exp(-bp_T^2)$$



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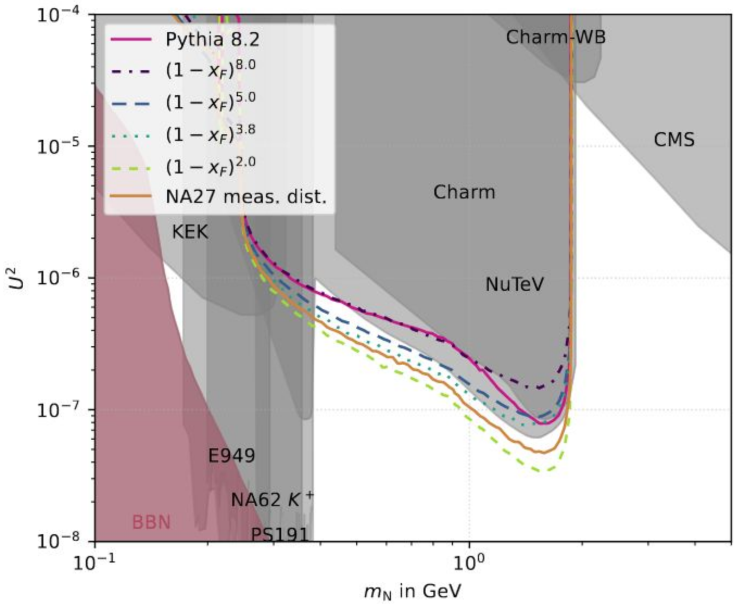
Influence of different input shapes II

- Even at fixed input total cross-section, fit parameter can have drastic consequences
- Exemplified r.h.s. Here HNLs produced by D-meson decay, at fixed production cross-section
- (pt influence omitted from example!)
- Vanilla pythia 8.2: n=7.1 compared to choices suggested by

1. NA27 measured $n \approx 3.1$
2. <u>Tuned pythia, including secondaries</u> $n \approx 3.8$
3. Intermediate choices

<u>Take away: Take special care of compatible input crosssections and kinematic shapes</u>

Schubert et al, in preparation



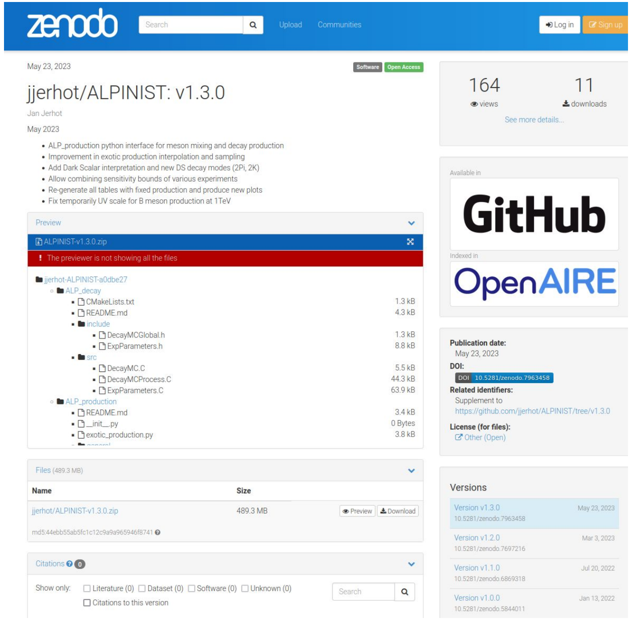
$$x_f = P_{\|,CM} / P_{\|,max,CM}$$

$$d\sigma \sim (1-x_F)^n * \exp(-bp_T^2)$$

Transparency/crosscheck

- Given a fixed input (e.g. 400GeV protons on dump), the rough sensitivity projections can be grasped using primarily the experiment geometry and main selection conditions.
- Obviously proper projections require an experiment MC (efficiencies, backgrounds, details of geometry)
- Useful to have public toys, that guarantee the same basic generators when comparing projections
- Two main such tools on the "market", particularly useful to quickly compare new ideas
- ALPINIST: created for ALPs originally, toy for a number of benchmarks, decouple production and decay
- SENSCALC: allows also HNL with arbitrary mixing, more facilities implementable

Jerhot et al, JHEP 07, 094 (2022), 2201.05170



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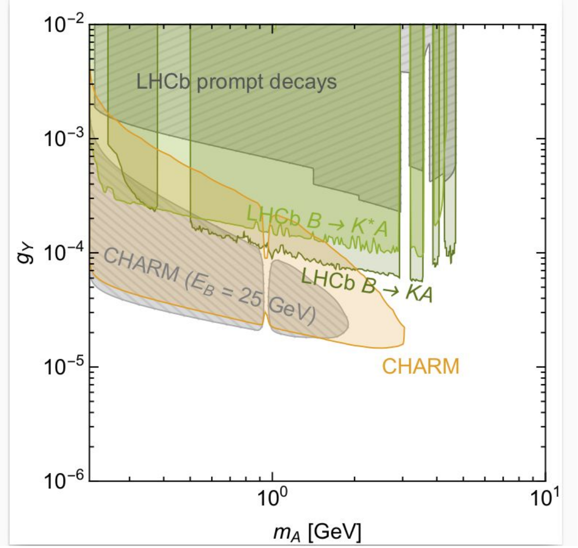
Beware of model-dependencies, introduction

BD et al. PLB 2019

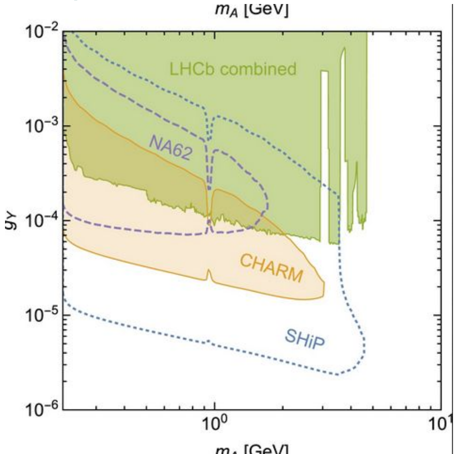
- **Example: light pseudoscalar with fermion coupling:**
- $$\mathcal{L} = i\, g_Y \sum_{f=q,\ell} \frac{m_f}{v} A\, \bar{f}\gamma^5 f\,,$$

Past literature (re-cast) bound based on monochromatic (sic!) spectrum of B-meson decays (see previous discussion)



- **Re-evaluation:**

  Seemingly no good prospect For NA62 to compete ,
- **BUT**



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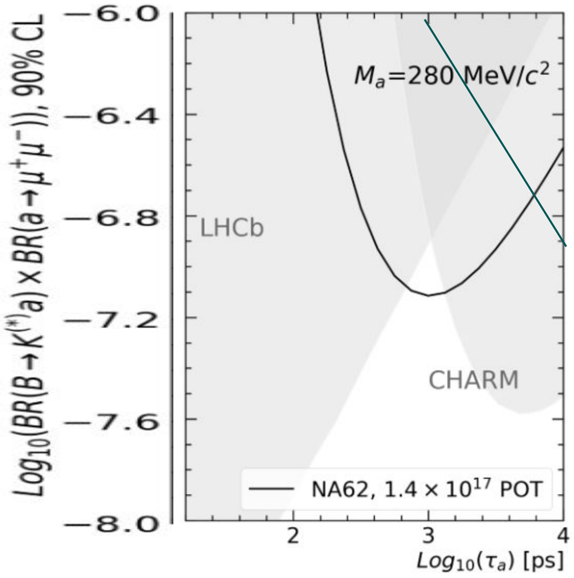
Beware of model-dependencies

- **Benchmark choices are a (maybe) unavoidable tool in order to have a comparative measure**
- **However such choices don't grasp the wealth of possibilities -> <u>most parameter spaces are not 2-dimensional</u>**
- **Example: light pseudoscalar with fermion coupling:**

$$\mathcal{L} = i\, g_Y \sum_{f=q,\ell} \frac{m_f}{v} A\, \bar{f} \gamma^5 f \ ,$$

Effective theory -> divergent loop diagrams, parameterization with `new physics scale' Λ

NA62 collaboration, JHEP09, 35 (2023)



Line at $\Lambda \approx 1$ TeV

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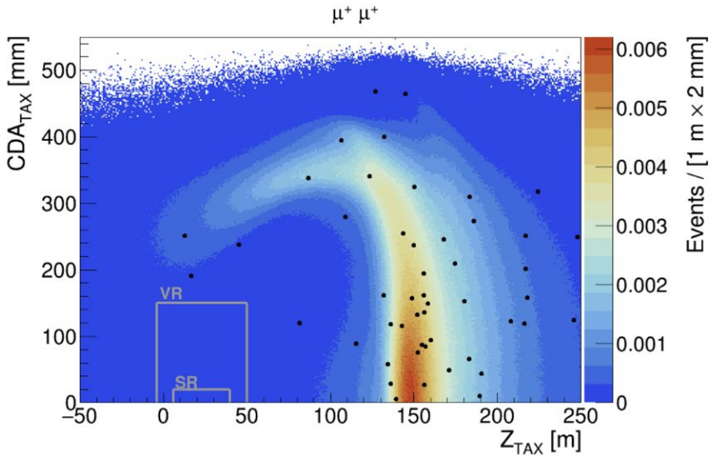
Going live, backgrounds and other nuisances

- **All projections usually based on 0 (or few) background events**
- **This means not "only" suppressing background to that level (e.g. through muon sweeping), but also modelling/understanding it down to the ~20th order of magnitude (which is a really difficult job!)**
- **R.h.s.: inferring combinatorial background, here $\mu\mu$ control sample from separate, independent trigger line**
- **Prompt bkg: Many avenues explored (several years!), in practice: backward MC PUMAS**
- **Take away: Don't take the 0 background assumption for granted but ask for proof!**

NA62 collaboration, JHEP09, 35 (2023), Analysis of 1.4×10^{17} POT



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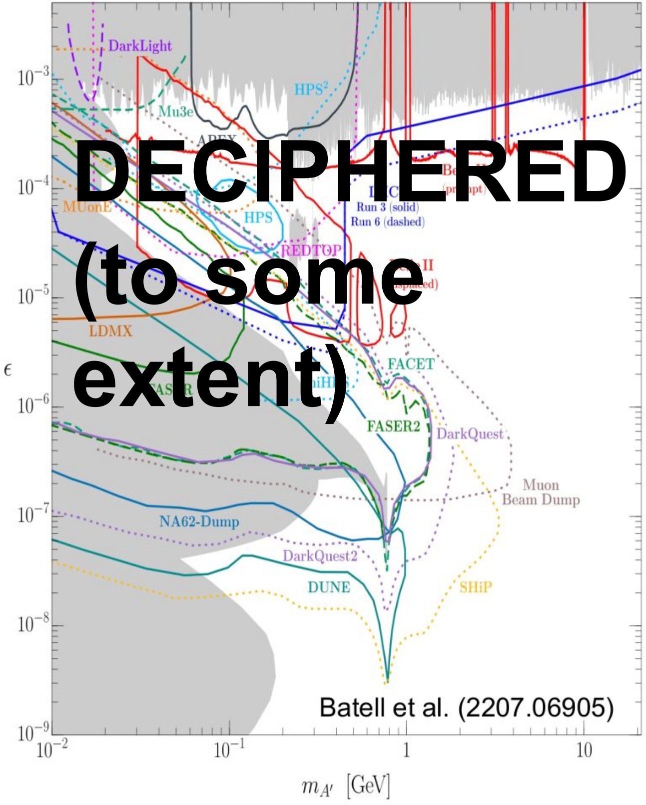
Beyond projections: ECN3

- Discussion ongoing about ECN3 Future after 2029: CERN courier article, January 2023
- First step: experiment agnostic high-intensity facility: SPSC expressed "strong support" to the facility (February 2023)
- Second Step: decision of experimental program late this year.
- Current proposals: SHiP, HIKE, SHADOWs, see report on options in ECN3 -> Decision in December?

Conclusion

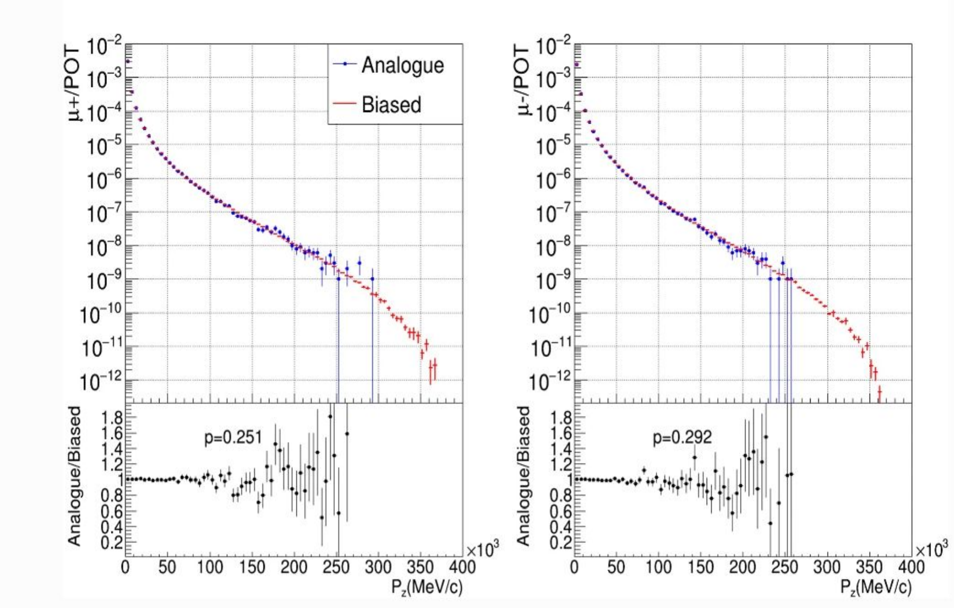
- The MeV/GeV mass scale weakly coupled physics is compelling, vibrant field with many proposals and experiments
- In this talk, I presented a selection of considerations to have in mind when attempting to interpret or add to a "busy" plot as shown e.g. on the r.h.s.
- Selected results presented drawn from joyful collaboration with numerous colleagues, here: F. Ertas, J. Jaeckel, J. Jerhot, F. Kahlhoefer, J. Schubert, T. Spadaro, and more
- MANY THANKS FOR YOUR ATTENTION! Questions? Comments?

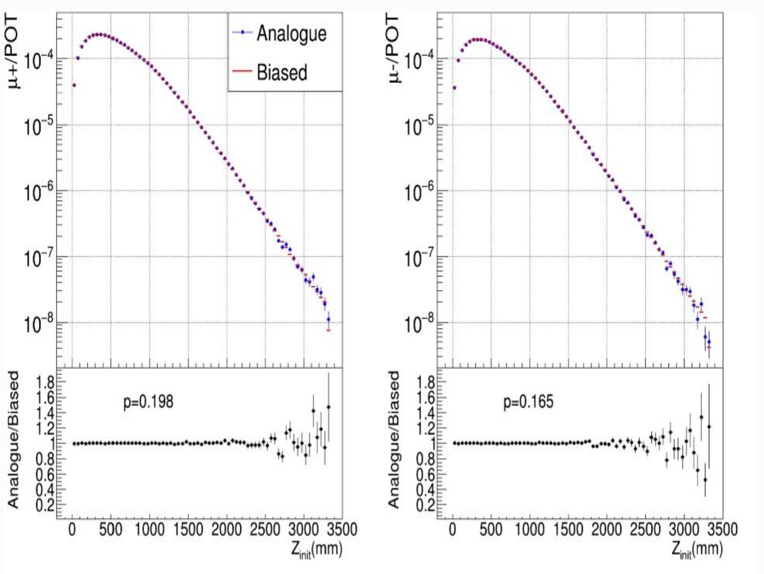


sufficient statistics in MC: several attempts…

Biasing: Clone particle that would be killed (analogue), keep propagating

- Apply appropriate weights according to interactions that could have occurred. see EPCJ 81,767 for more details





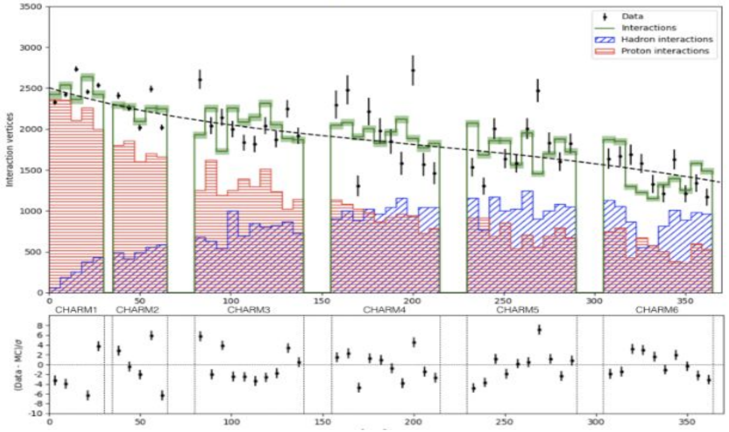
Total crosssection

DIFFERENT INPUT ASSUMPTIONS

$c\bar{c}$ CROSS SECTION

- **$c\bar{c}$ very important for HNL search with NA62BD as production mainly in D-meson decays**
- **Especially forward region is *not well constrained* which has implications on HNL momentum distributions and consequently detector acceptance**
- **SHiP-charm *project* aims at measuring $c\bar{c}$ differential cross section and already ran a *pilot measurement* to validate their cascade interaction model**

Primary and Secondary interactions MC vs data at the *SHiP-charm experiment*



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