LHCb as a Lifetime Frontier experiment

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Positioning of the talk

This talk is not on behalf of the LHCb collaboration

However:

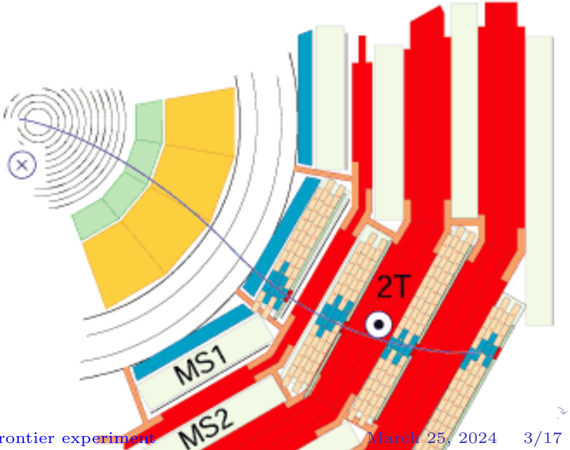
- It is based on the work 2312.14016 made with people from LHCb
- The search algorithm that will be discussed is already in the LHCb system and will start taking the data this year

Important in the context of PBC

Main LHC detectors as lifetime frontier? I

- LHC: high luminosity+ large energies ⇒ natural lifetime frontier experiment
- Past searches at the LHC are inefficient for GeV scale LLPs:
  1. Triggering the events by their production vertex and/or huge $p_{T,\mathrm{miss}}/E_{\mathrm{miss}}$
  2. Limiting the decay volume by the inner trackers
  3. Because of this, a large backgrounds

- Search schemes that partially omit the problem:
  - Search with muon chambers at ATLAS, CMS, LHCb
  - Missing mass searches at LHCb
- **Need more to explore longer lifetimes**



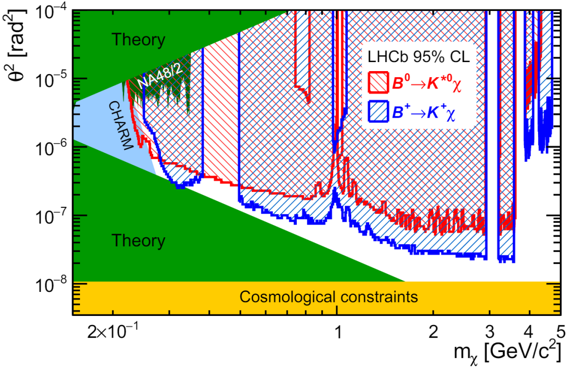
Downstream algorithm at LHCb I

– **Example of past searches**: searching for

$$B \to K^{(*)} + \text{LLP} \to K^{(*)} + \mu\mu \qquad (1)$$

Limitations:

- Misses other (dominant) production channels
- Restricted by a rare decay LLP $\to \mu\mu$
- Restricted by the inner tracker (VELO)



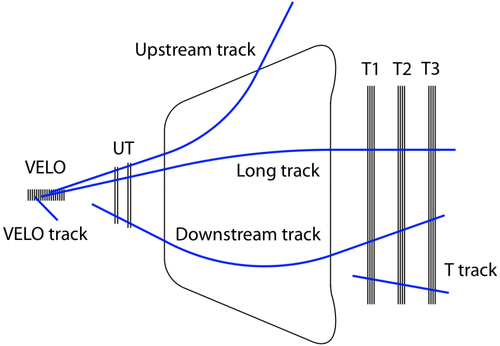
1612.07818

Downstream algorithm at LHCb II

Types of tracks based on the occurrence of the vertex

- Long (in VELO)
- Downstream (between VELO and UT)
- *T* (after UT)

Currently, triggering only by long tracks

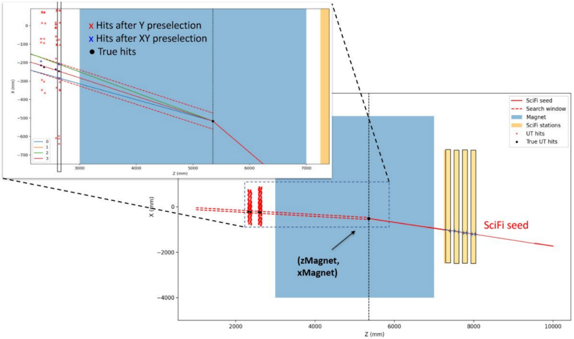


- An algorithm allowing to filter and write data with *downstream*- or *T-tracks* on-flight is in need

Downstream algorithm at LHCb III

Downstream algorithm:
trigger decision requiring at least two downstream tracks on the common vertex (hits in SciFi+UT). To match between UT and SciFi hits:

- Take SciFi output and filter out the used seeds
- Extrapolate them to the UT through the magnetized region



To reduce the rate of fake tracks (improper SciFi-UT connections), a neural network is used; the rate of correctly reconstructed tracks is 70%

B. Jashal, V. Kholoimov, A. Oyanguren, V. Svintozelskyi, J. Zhuo

Backgrounds

Background sources (and how to suppress them in general):

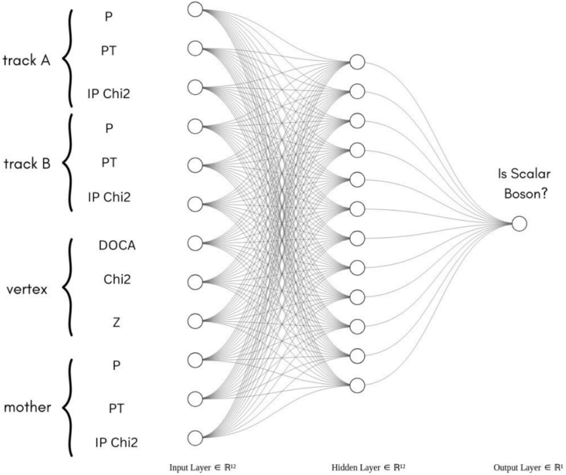
- Long-lived resonances K_S^0, Λ: vetoing by kinematics (domain in m_{inv}, ratio between the momenta of daughters)
- Material interaction – beam pipe, boundaries of the effective decay volume: suppressed by using control data samples and vetoing specific regions of the detector. May be reduced down to a negligible level [1803.07466]
- Combinatorial background: vetoed by kinematics (χ^2, DOCA), hits only in UT+SciFi, IP/number of coinciding tracks, neural network and PID

To be studied later this year on real data

Signal selection/background reduction I

Signal selection for post-processing: based on a neural network

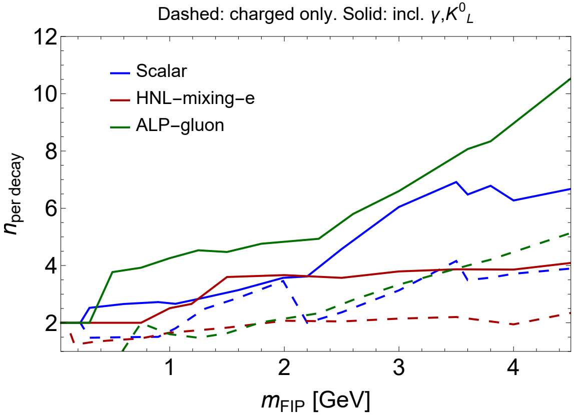
- For LLPs decaying into two particles:
  - Takes track and vertex quality + IP as an input
  - Trained with simulated signal events and background MinBias
  - Excellent background rejection and tracking efficiencies



B. Jashal, V. Kholoimov, A. Oyanguren, V. Svintozelskyi, J. Zhuo, to appear soon

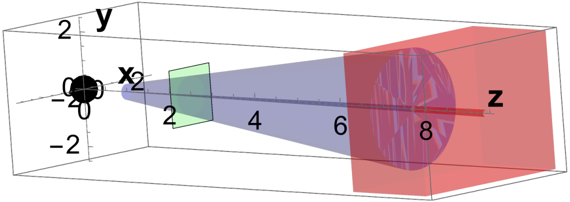
Signal selection/background reduction II

- For many-body decays: different input - number of tracks
- Reduce background even more (study in preparation)



Implementation of setup in SensCalc I

- Sensitivity studies must be as transparent as possible and reproducible
- The LHCb setup for `Downstream algorithm` has been implemented in `SensCalc`

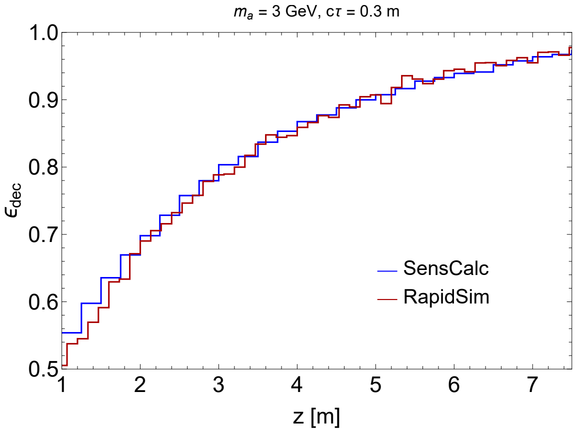


- **`SensCalc`: public and unified sensitivity calculator**
  - A variety of experiments at FermilabBD, SPS, LHC, FCC-hh, etc. is implemented
  - Validated across several simulation frameworks and light-weight MC codes
  - HNLs, ALPs coupled to photons, fermions, gluons, dark scalars, dark photons, $B-L$ mediators are implemented
  - Supports many production channels, 2-,3-,4-body decays, flexible selection criteria
  - Exists in private: inelastic LDM, HNL dipole portal

Implementation of setup in `SensCalc` II

Event selection and efficiency assumptions:

- Decay vertex within $z_{\text{VELO}} < z < z_{\text{UT}}$ and $2 < \eta < 5$;
- At least two charged tracks with energies $E > 5$ GeV, $p_T > 0.5$ GeV within the last SciFi layer;
- $\epsilon_{\text{reco}} \approx 0.4$
- $N_{\text{events}} \geq 2.3$ (assume absence of backgrounds)

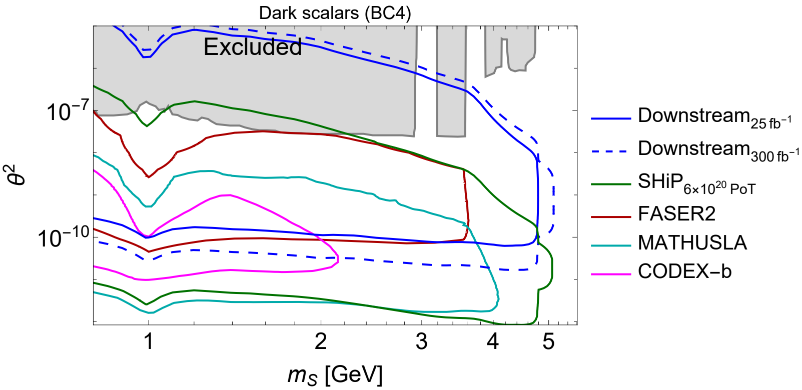


- Predictions of `SensCalc` agree with full LHCb simulation framework and `RapidSim`
  Small discrepancy at $z \lesssim 2$ m: tighter cut due to the beam pipe used in `RapidSim`

Downstream algorithm over landscape of experiments

Tricky comparison between the experiments:

- Different running times
- Approved or not?
- Full detector equipment?



[2305.01715]+[2308.05860]+SensCalc

Two experiments to compare:

- Downstream algorithm (2024+)
- Recently approved SHiP (2030+)

Sensitivities: comparison with SHiP I

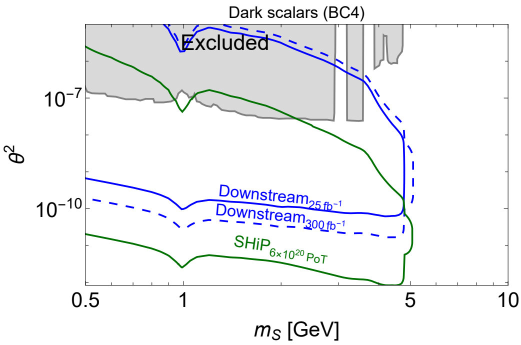
Complementarity between the `Downstream` algorithm and SHiP

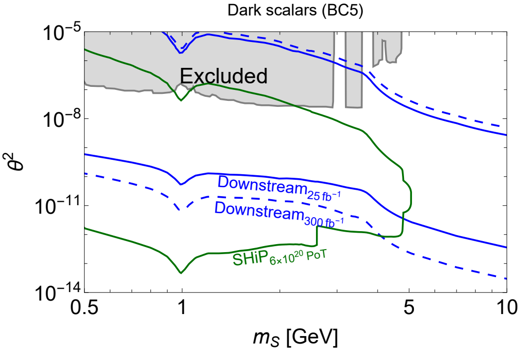
Parameter	Ratio $\frac{\texttt{Downstream}}{\text{SHiP}}$	Meaning
$\gamma_{\text{max}}/z_{\text{to decay volume}}$	$\frac{5000/1}{400/32} \gg 1$	At the upper bound of the sensitivity, `Downstream` is much better
$\sqrt{s}$	$\approx \frac{13000}{28} \gg 1$	`Downstream` may probe particles from decays of W, h, Z while SHiP can't
$N_{\text{meson}} \cdot \Delta z_{\text{DV}} \cdot \langle \gamma^{-1} \rangle$	$\ll 1$	At the lower bound of the sensitivity, SHiP is much better
η	$\frac{5}{\infty}$	SHiP is additionally better for particles produced in far-forward direction

"Grain of salt"

Huge uncertainties in LLPs' phenomenology may heavily affect the results

Sensitivities: comparison with SHiP II

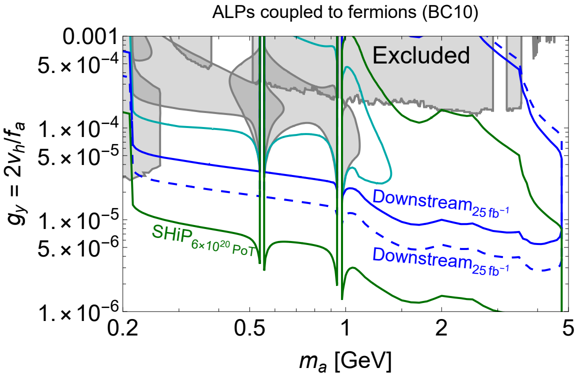


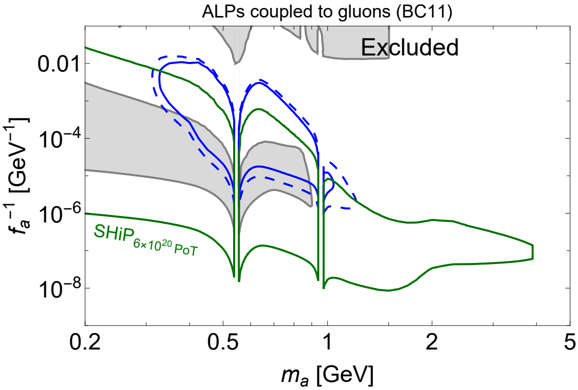


Dark scalars:

- Goes beyond $B \to K\mu\mu$ search at LHCb by many orders of magnitude
- hSS coupling: access to the whole mass range $m_S < m_h/2$

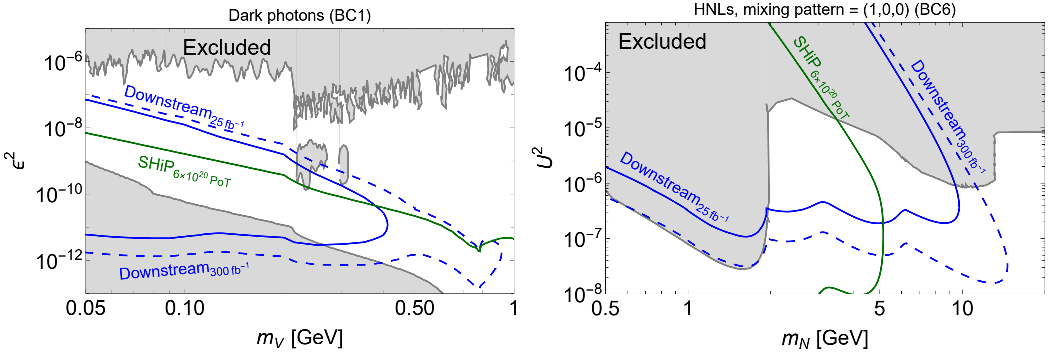
Sensitivities: comparison with SHiP III





- ALPs coupled to fermions (BC10): situation similar to dark scalars
- ALPs coupled to gluons (BC11): situation similar to dark photons

Sensitivities: comparison with SHiP IV



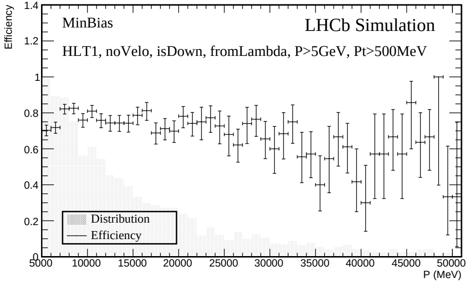
- Dark photons: most DPs fly in the far-forward direction, while LHCb covers $\eta < 5$. However, there is good sensitivity at the upper bound due to the much higher ratio $\gamma_{\max}/z_{\min}$
- HNLs: conclusions similar to dark scalars + access to the HNLs produced by decays of W

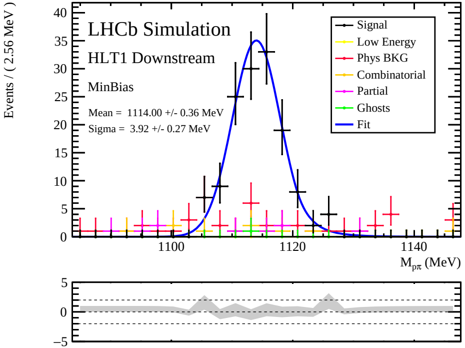
Conclusions

- The `Downstream` algorithm at LHCb: powerful intensity frontier experiment **already this year**
- Room for future improvements: upgrade of the detector, adding the possibility to pass the trigger using T-tracks only
- The search is complementary to the future SHiP experiment

Backup slides

Downstream algorithm: Λ/K_S study case



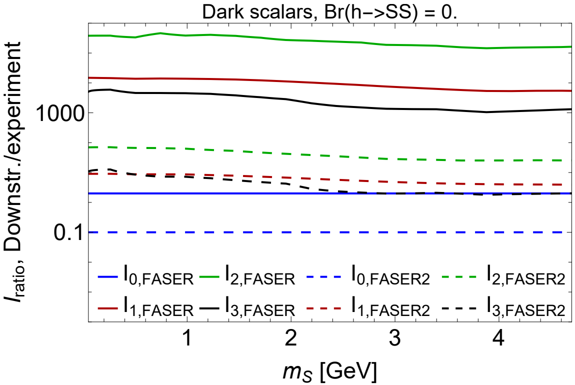


- The downstream algorithm has been studied in details for Λ/K_S^0 decays
- The reconstruction efficiency comes mainly from the efficiency of making the correspondence of hits in SciFi and in UT, and is equal to 0.7 per track on average

LHCb-FIGURE-2023-028

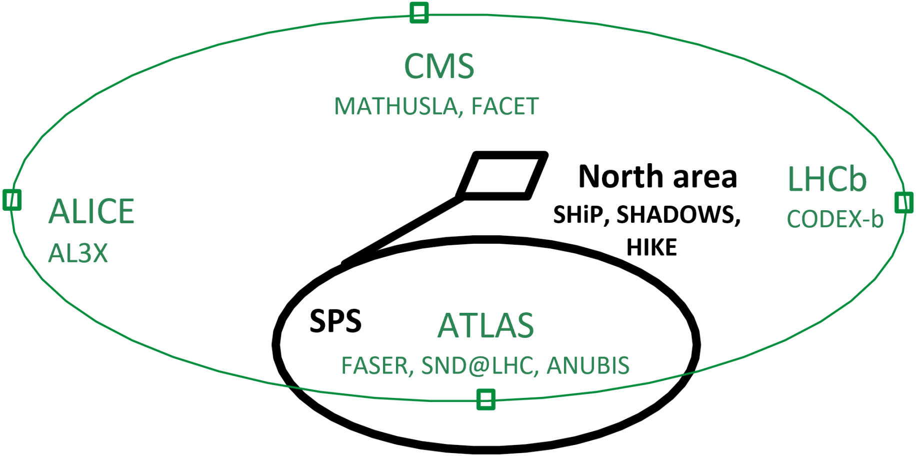
Downstream algorithm: qualitative comparison with FASER/FASER2

- Two Downstream setups: $\mathcal{L} = 25\ \text{fb}^{-1}$ (for comparison with FASER) and $300\ \text{fb}^{-1}$ (with FASER2)
- Comparison is made for the regime $c\tau\langle\gamma\rangle \gg 500$ m
- I_0 – total number of produced LLPs, I_1 – the amount of those intersecting the decay volume, I_2 – the amount decayed inside, I_3 – the amount passed decay products acceptance



In the regime of large lifetimes, the potential of the Downstream algorithm is comparable with FASER2

Comparison of the LF experiments in nutshell I



– Many possible locations and configurations ⇒ a huge number of proposed experiments

[1901.09966]

Comparison of the LF experiments in nutshell II

Exclusion potential argument

The event rate should be as large as possible to exclude the parameter space

The event rate:

$$N_{\text{events}} \propto N_{\text{prod}} \times P_{\text{decay}} \propto N_{\text{pp}} \cdot \chi_{\text{mother}}(s_{\text{pp}}) \cdot \epsilon_{\text{geom}} \times \Delta z_{\text{fid}} \langle \gamma_{\text{LLP}}^{-1} \rangle \tag{2}$$

N_{pp}: number of protons. χ_{mother}: rate of mother process per pp. ϵ_{geom}: fraction of LLPs pointing to the detector. Δz_{fid}: length of the decay volume

Two LLP categories (the spread of $df/d\Omega_{\text{LLP}}$):

- LLPs produced from heavy flavors (B, D)
- LLPs produced in EM processes, mixing with/decays of light mesons, bremsstrahlung

Comparison of the LF experiments in nutshell III

Discovery potential argument

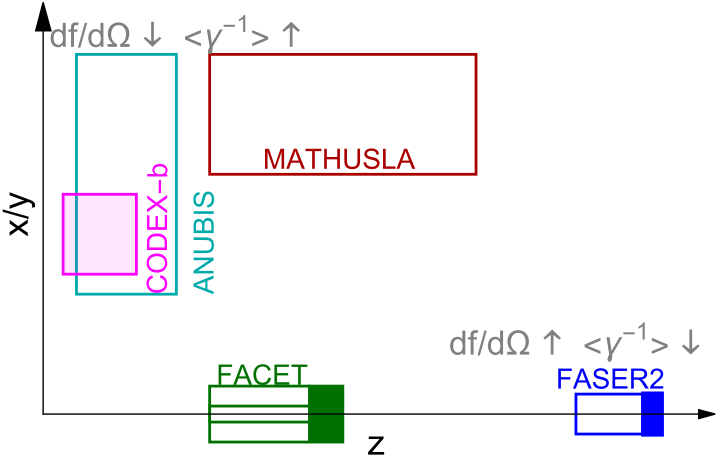
The experiment has to be equipped with a full detector system to reconstruct LLP's properties

- Measuring LLP's mass and spin
- Measuring its decay modes
- Establishing LLP's relation to the resolution of the BSM problems

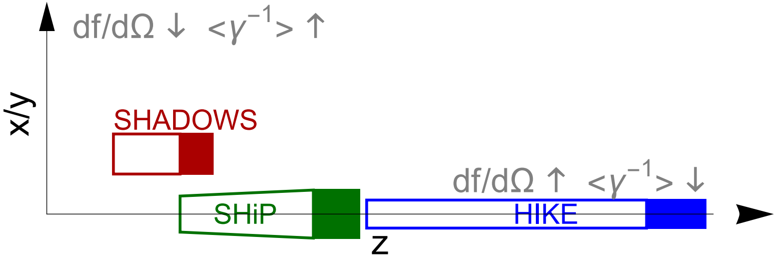
Comparison of the LF experiments in nutshell IV

LHC-based

- **On-axis**: very small $\langle\gamma^{-1}\rangle$, full detector, large ϵ_{geom}
- **Off-axis**: very large $\langle\gamma^{-1}\rangle$, large $\epsilon_{\text{geom}}^{\text{heavy}}$, but...
- Tiny $\epsilon_{\text{geom}}^{\text{light}}$, no full detector



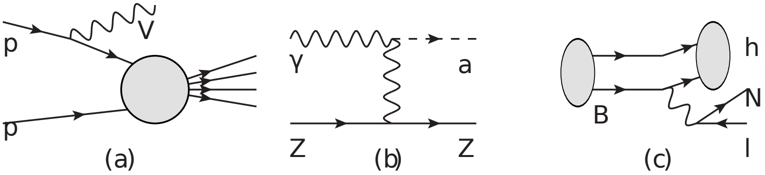
Comparison of the LF experiments in nutshell V



Beam dump:

- **SHiP**: very large ϵ_{geom}, medium $\langle\gamma^{-1}\rangle$, full detector
- Smaller χ_{mother} for heavy flavors is compensated by a very large N_{PoT}
- **SHADOWS/HIKE**: smaller N_{PoT}+geometric limitations

Phenomenology of LLPs I



- To search for LLPs in the lab, we need to know their phenomenology: how they are produced and how decay (and in particular $c\tau_{\text{LLP}}(m,g)$)
- Examples of production mechanisms:
  - Proton bremsstrahlung (a), Drell-Yan process (dark photons, $B-L$)
  - Primakov process (b), photon fusion (ALPs)
  - Decays of light and heavy mesons (c), $W/Z/h$ bosons (dark photons, HNLs, ALPs, scalars)
  - Mixing with neutral mesons (dark photons, ALPs, scalars)
- Decay modes: 2-, 3-, 4-body decays

Phenomenology of LLPs II

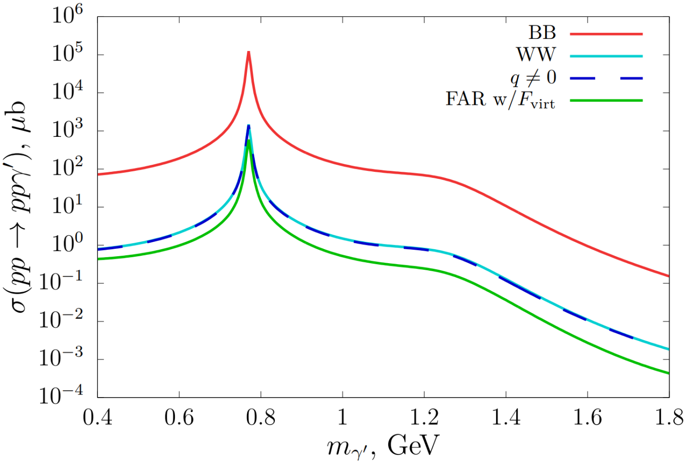
Do we understand LLPs' phenomenology well enough? Not at all

Reasons:

- **Lack of data: we do not have LLP-like SM particles**
  We may extract DP's decay width from EM scattering $\sigma_{ee\to hadrons}$*, but we can't do the same for Higgs-like scalars*
- **GeV scale LLPs: where perturbative QCD meets ChPT**
  Hadronic decays of a GeV scale LLP: contribution of resonances. Mixing with neutral mesons
- **Artifacts from the past**
  Completely wrong descriptions coming from old studies but being used nowadays

Example 1: proton bremsstrahlung

- Dominant production channels of dark photons (DPs) in the mass range $m_\pi \lesssim m_{\mathrm{DP}} \lesssim 2$ GeV
- 2 orders difference in the DP flux comparing commonly used approach and recent calculations (e.g., [2306.15800])



In preparation

Example 2: mixing with mesons

– Mixing with mesons:

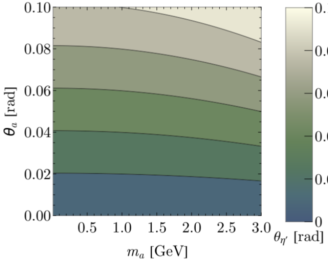
$$\text{meson}_{\text{int}} = \text{meson}_{\text{mass}} + \boldsymbol{\theta}_{\text{meson-LLP}}\text{LLP} \qquad (3)$$

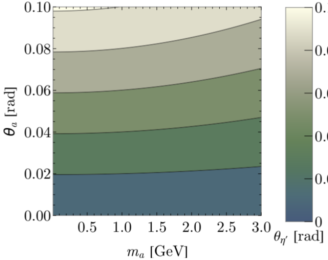
– The most naive approach (commonly used):

$$\boldsymbol{\sigma}_{\boldsymbol{pp}\to\text{LLP}} \approx |\boldsymbol{\theta}_{\text{meson-LLP}}|^{2}\boldsymbol{\sigma}_{\boldsymbol{pp}\to\text{meson}} \qquad (4)$$

Wrong kinematics, no effects of LLP mass on the flux

– Going beyond: convert meson kinematics to LLP kinematics (by relating, e.g., $\mathbf{p}_{\text{meson,CM}} = \mathbf{p}_{\text{LLP,CM}}$). Still no impact from LLP mass on the overall flux, ambiguous kinematics correspondence

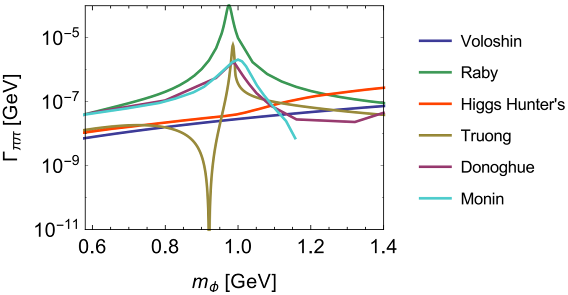




In preparation

Example 3: hadronic width of Higgs-like scalars

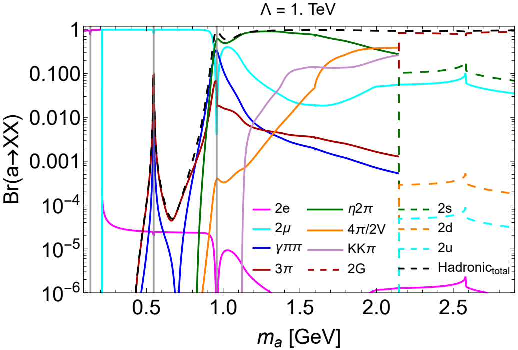
- Huge uncertainties in hadronic decays of Higgs-like scalars $S \to \pi\pi, KK$
- May be partially resolved by experimental observations of gravitational $\pi\pi$ form-factor

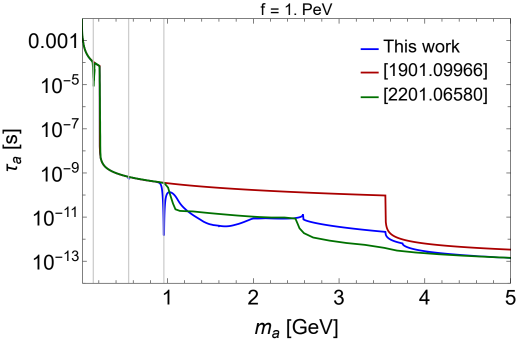


Uncertainties may easily reach 1-2 orders of magnitude

1809.01876, 1904.10447, 2303.12847

Example 4: ALPs coupled to fermions





– ALPs with universal fermion coupling: the widely adopted phenomenology [1901.09966] missed all hadronic ALP decays and various production channels (decays of Bs, mixing with neutral mesons)

2310.03524