Searches for long-lived particles at hadron colliders and beyond

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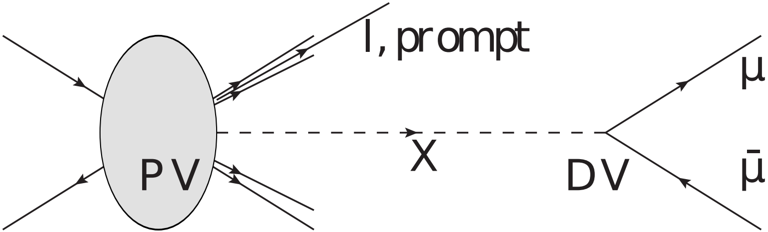
Long-lived particles

- Mass scale of new physics particles is unknown
- One of the possibilities: $m_{\text{new physics}} \ll m_{\text{EW}} \Rightarrow$ may be copiously produced at accelerators
- Large couplings ($\equiv$ small lifetimes) of such particles are often excluded by past experiments $\Rightarrow$ **L**ong-**L**ived **P**articles (LLPs)

LLP	**Dark photons** V	**Dark scalars** S	**HNLs** N	**ALPs** a
$\mathcal{L}$	$-\epsilon F_{\mu\nu}V^{\mu\nu}$	$H^{\dagger}HS$	$Y_{l}\bar{L}H^{c}N$	$\frac{a}{f}F_{\mu\nu}\tilde{F}^{\mu\nu}+\dots$

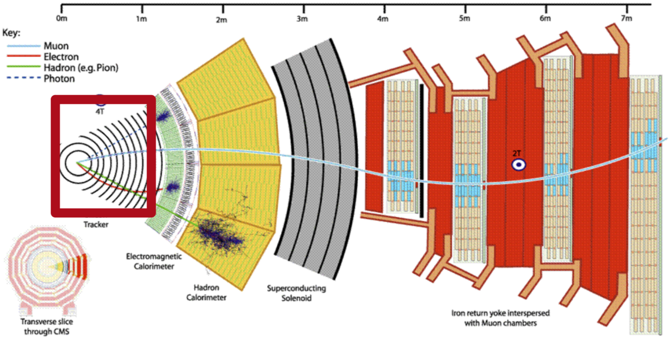
Current LHC reach for LLPs I



- FIPs are unstable ⇒ searches for displaced vertices
- Ongoing searches for $\mathcal{O}(1\text{ GeV})$ LLPs at the LHC:
  1. **Tag over production vertex** (associated high-p_T particles)
  2. Decay vertex within inner trackers

[2201.05578], [2204.11988]

Current LHC reach for LLPs II

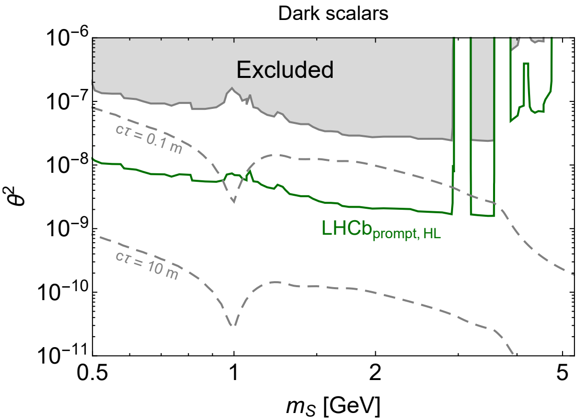


- FIPs are unstable ⇒ searches for displaced vertices
- Ongoing displaced vertex searches for $\mathcal{O}(1\text{ GeV})$ LLPs at the LHC:
  1. Tag over production vertex (associated high-p_T particles)
  2. **Decay vertex within inner trackers**

[2201.05578], [2204.11988]

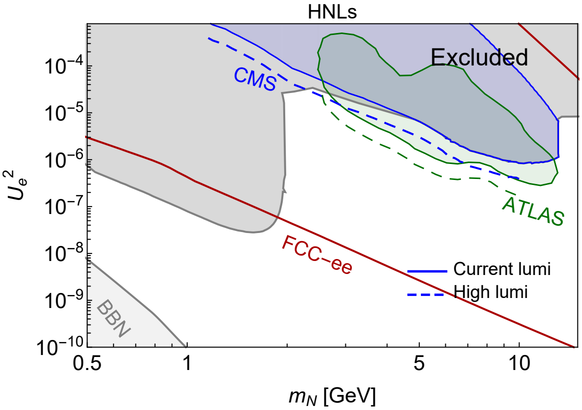
Current LHC reach for LLPs III

- Problems of these searches:
  1. **High-p_T associated primary particle(s): uncommon for light LLPs**
  2. Small size of inner trackers $\Rightarrow$ small P_{decay} ($c\tau_{\text{LLP}} \propto m_{\text{LLP}}^{-n}$)
  3. Numerous background $\Rightarrow$ severe selection



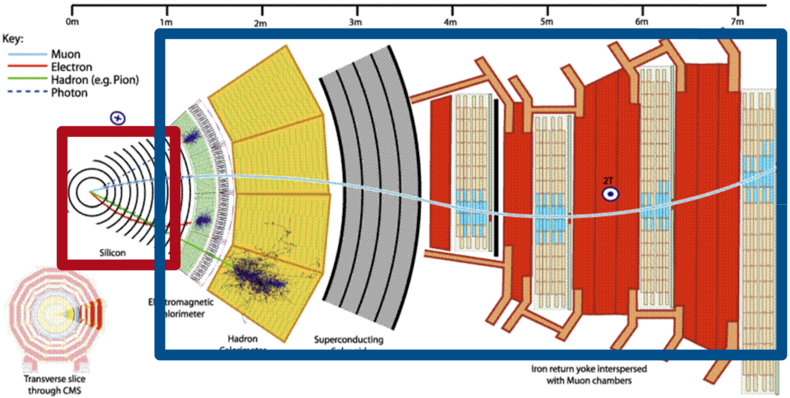
Current LHC reach for LLPs IV

- Problems of these searches:
  1. High-p_T associated primary particle: uncommon for light LLPs
  2. **Small size of inner trackers ⇒ small $P_{\mathbf{decay}}$ ($c\tau_{\mathbf{LLP}} \propto m_{\mathbf{LLP}}^{-n}$)**
  3. **Numerous background ⇒ severe selection**



We need to go beyond the current searches

Improving the reach of colliders I



1. Going beyond inner trackers
2. Triggering without tagging over production vertex
   (ATLAS/CMS: since 2029. LHCb: currently)

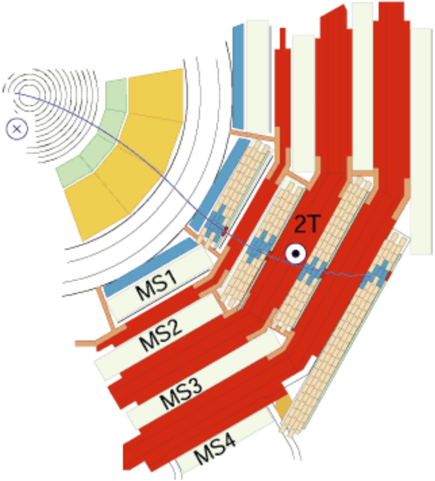
Improving the reach of colliders II

Method 1

Muons from outer space at muon stations

- Decay volume: all space $|\eta| < 2.5$ between the IP and muon stations
- **Limitations**: no full kinematics reconstruction, only $\mu\mu$ final state

1903.11918

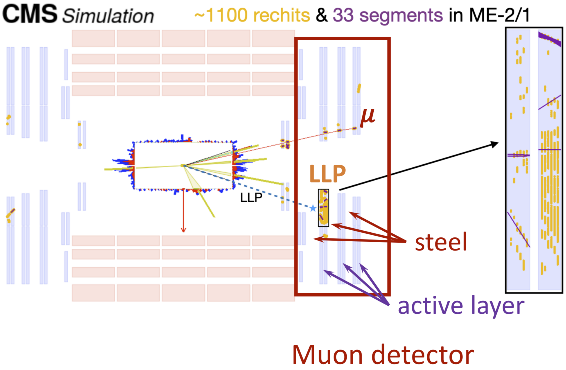


Improving the reach of colliders III

Method 2

Non-muonic showers in muon chambers

- Current CMS analysis: triggering over high-p_T prompt leptons
  Study of the potential of track-triggers: in preparation
- **Limitations**: no full kinematics reconstruction

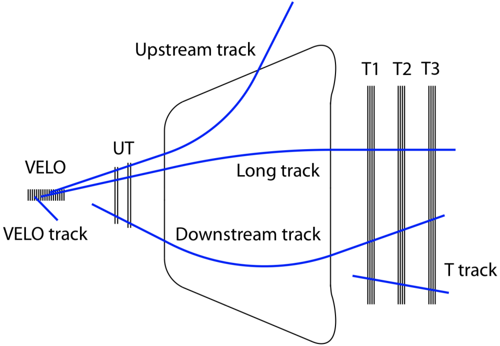


Improving the reach of colliders IV

Method 3

T tracks at LHCb

- Decay volume: LHCb detector
  $2 < \eta < 5$ until SciFi
- **Limitations**: low luminosity

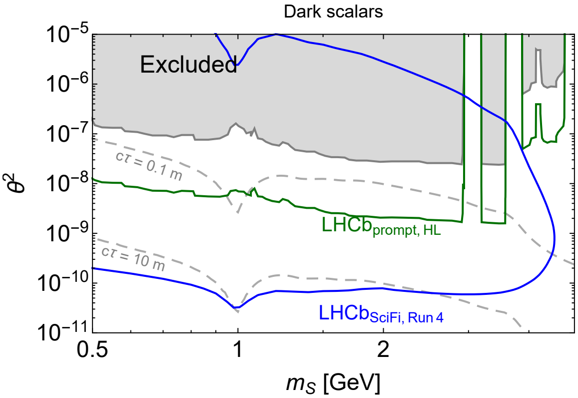


In preparation

Improving the reach of colliders V

– Preliminary studies: good potential to explore light LLPs with $m_{\mathrm{LLP}} \lesssim m_B$

In preparation



Limitations are still there

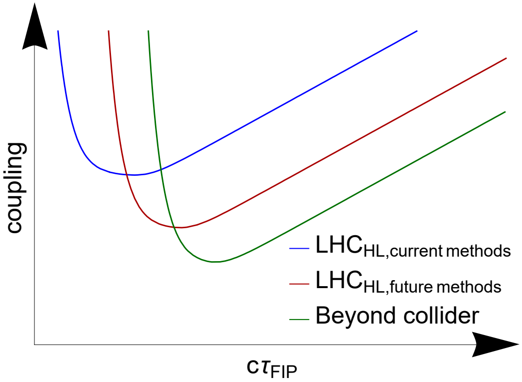
Dealing with background, finite reconstruction efficiency, . . .

Going beyond main LHC experiments I

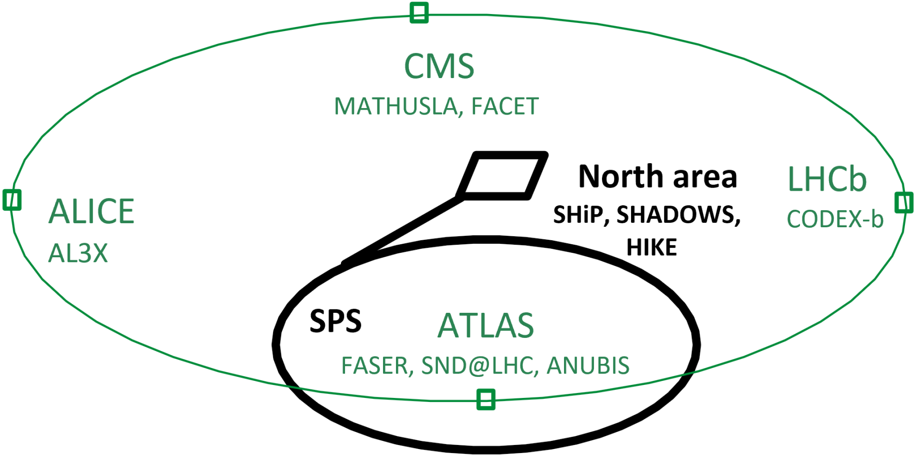
Workaround

Going beyond ATLAS/CMS/LHCb

- A displaced decay volume
  1. **Collider-based**
  2. Dedicated (**beam dump**)
- Advantages:
  - Far from IP ⇒ low (zero) background without selection
  - Long decay volume



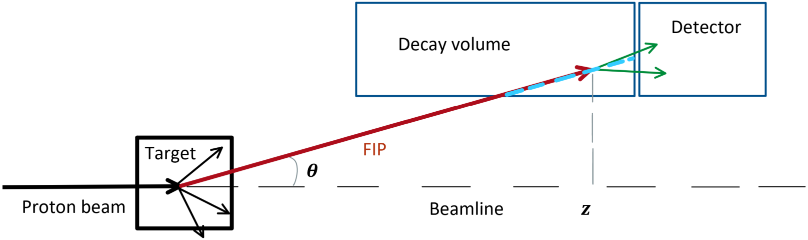
Comparison of the BC experiments in nutshell I



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

[1901.09966]

Comparison of the BC experiments in nutshell II



Experiments differ in:

- Placement relative to the beam axis
- Detector equipment
- Decay volume geometry

Need to choose among them (budget limitations!!)

How?

Comparison of the BC experiments in nutshell III

Exclusion potential argument

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

The event rate:

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

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 BC experiments in nutshell IV

Discovery potential argument

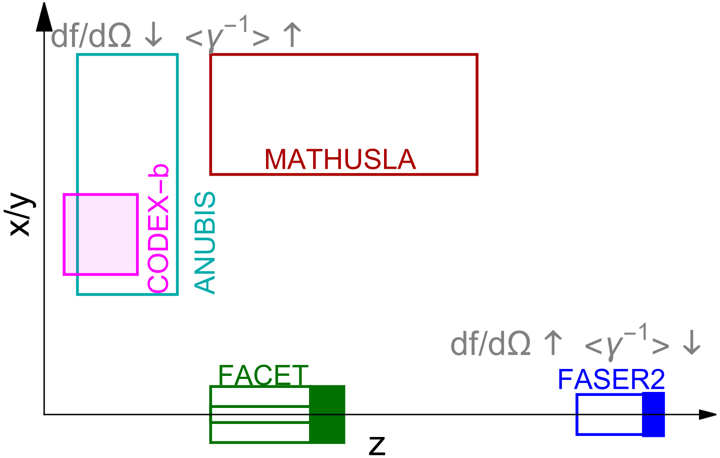
The experiment has to be equipped with a full detector system to reconstruct LLP's properties

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

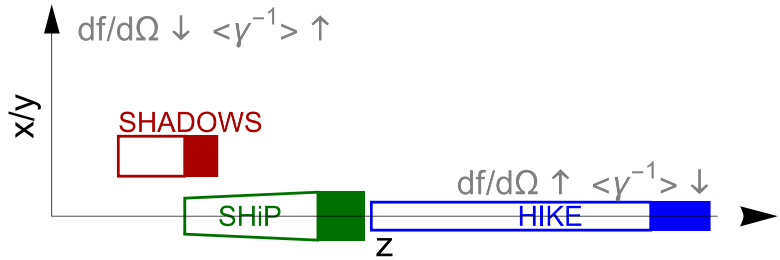
Comparison of the BC experiments in nutshell V

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 BC experiments in nutshell VI



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

Comparison of the BC experiments: a detailed study I

– A more detailed analysis: compare sensitivity curves – regions of exclusion/discovery

Sensitivities comparison in a perfect world:

1. The same LLP phenomenology input
   Phenomenology is revising continuously
2. Control over numerical artifacts
   Complicated to find errors in pure MC generators
3. Transparency and publicity of the sensitivity calculations
   Sensitivities obtained by collaborations are black-box sourced

Comparison of the BC experiments: a detailed study II

– **Semi-analytic estimates**:

$$\boldsymbol{N_{\rm ev} \approx N_{\rm prod} \times \epsilon_{\rm LLP} \times \langle P_{\rm dec}\rangle \times \epsilon_{\rm dec}} \quad (2)$$

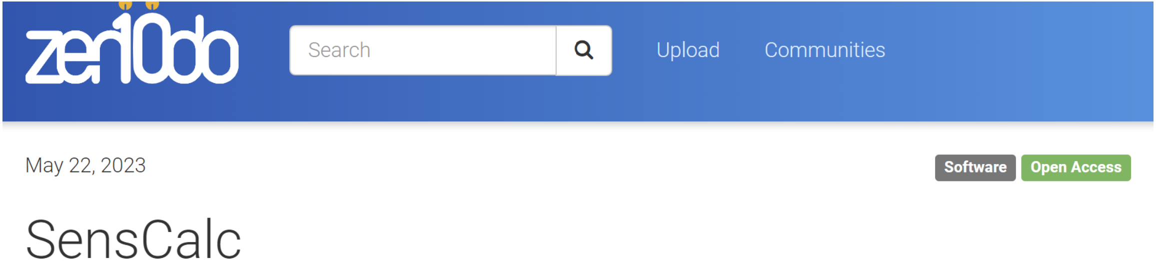
Each factor may be qualitatively estimated [1902.06240]

– Improved version ($\boldsymbol{z}$ - LLP long. displacement, θ - LLP polar angle, ϕ - az. angle):

$$\boldsymbol{N_{\rm ev} = \sum_i N^{(i)}_{\rm prod} \int dE d\theta dz\ f^{(i)}(\theta, E) \cdot \epsilon_{\rm az}(\theta, z) \cdot \frac{dP_{\rm dec}}{dz} \cdot \epsilon_{\rm dec}(m, \theta, E, z) \cdot \epsilon_{\rm rec}} \quad (3)$$

- $N^{(i)}_{\rm prod}$, $f^{(i)}(\theta, E)$ are the total number of produced LLPs and the angle-energy distribution for the given channel i
- $\epsilon_{\rm az}$ is the azimuthal acceptance for the LLP to decay inside the decay volume
- $\frac{dP_{\rm dec}}{dz} = \frac{\exp[-z/(\cos(\theta) c\tau\sqrt{\gamma^2-1})]}{\cos(\theta)c\tau\sqrt{\gamma^2-1}}$ is the differential decay probability for the LLP to decay
- $\epsilon_{\rm dec}$ is the decay products acceptance
- $\epsilon_{\rm rec}$ (may be computed externally) is the reconstruction efficiency

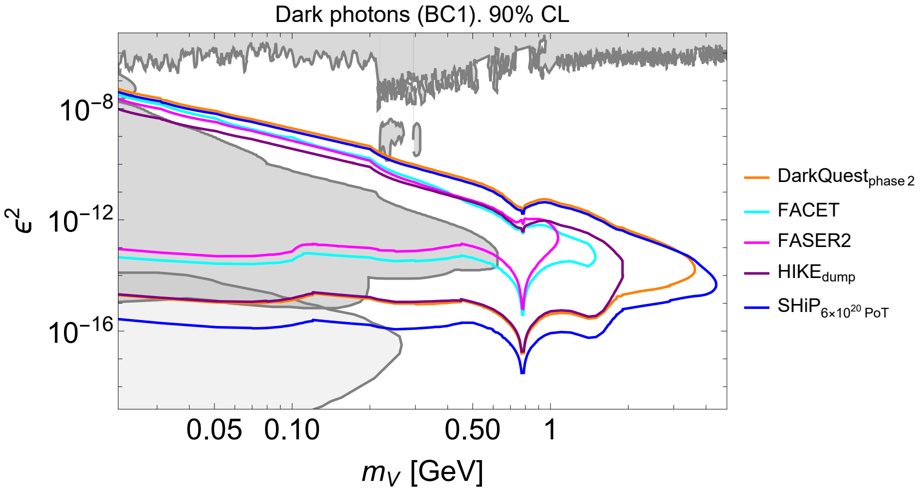
Comparison of the BC experiments: a detailed study III



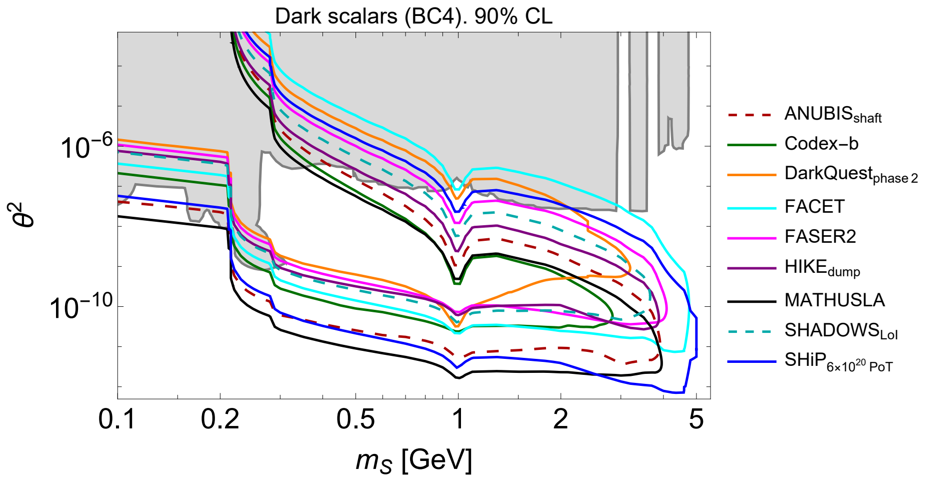
- SensCalc – a Mathematica-based sensitivity evaluator
- **Input**: model description (production, decays), experimental setup (geometry, selection cuts), the tabulated distributions of mother particles
- **Output**: tabulated number of events $N_{\text{events}}(\mathrm{m}_{\text{LLP}}, g_{\text{LLP-SM}})$ that may be converted into exclusion/discovery limits

[2305.13383]

Comparison of the BC experiments: a detailed study IV

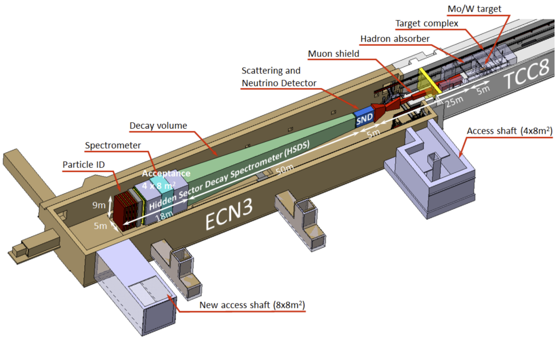


Comparison of the BC experiments: a detailed study V



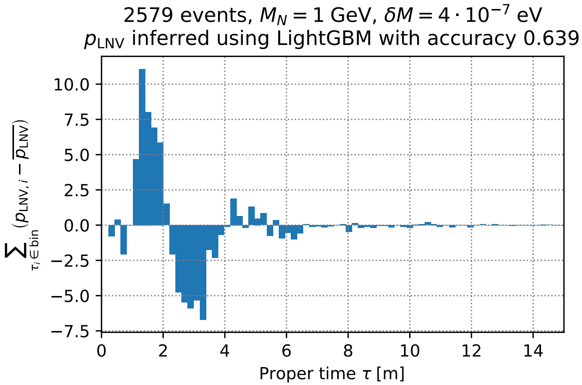
SHiP: a perfect balance between exclusion and discovery potentials

Reconstructing LLPs at SHiP: HNL example I



- SHiP experiment: despite limitations of the ECN3 hall, already has the optimal placement [2305.13383]
- Decision about SHiP: will be made by the end of this year

Reconstructing LLPs at SHiP: HNL example II



[1912.05520]

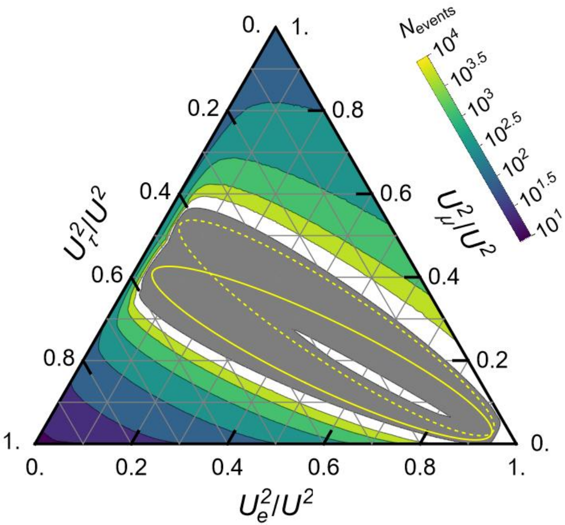
- Standard properties: mass, decay modes, spin
- By measuring the angular distribution of decay products, it is possible to check the nature of HNLs and resolve $N - \bar{N}$ oscillations

Reconstructing LLPs at SHiP: HNL example III

- By measuring the decay modes, it is possible to recover the mixing pattern

$$U_e^2 : U_\mu^2 : U_\tau^2 \tag{4}$$

- This allows us to check whether HNLs are consistent with IH/NH hypothesis

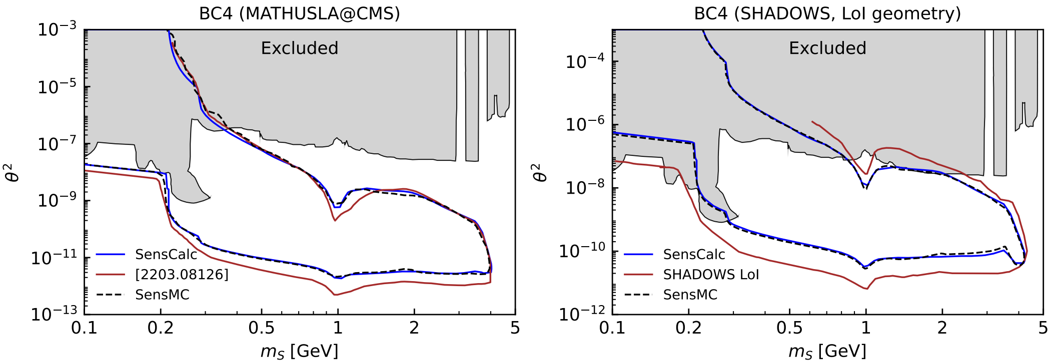


Summary

- We need to go beyond LHC to explore light LLPs
- Comparison of these beyond-collider experiments: unified way was missing, `SensCalc` provides it
- Detailed study: SHiP is optimal for probing LLPs with $m \lesssim 5$ GeV

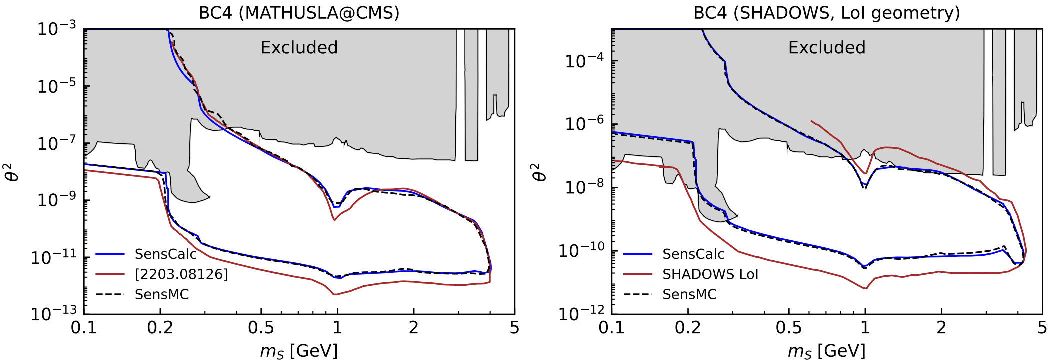
Backup slides

Validation: dark scalars at MATHUSLA and SHADOWS I



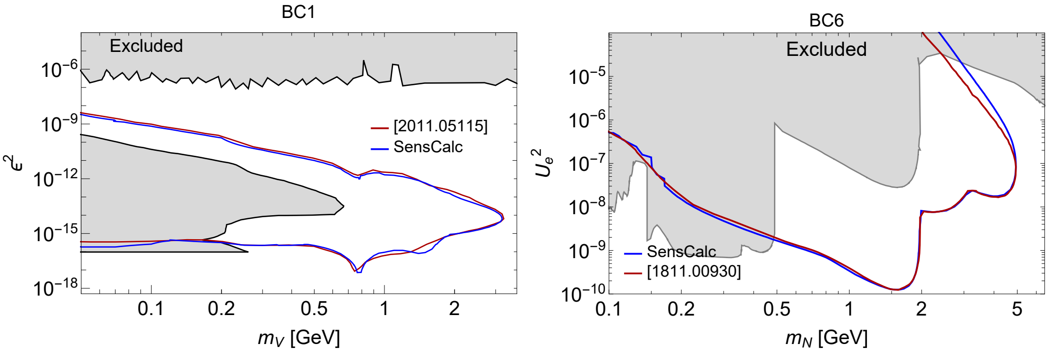
- Setups: taken from the SHADOWS LoI and MATHUSLA Snowmass paper
- Minimal event requirements: scalars must decay inside the decay volume, decay products have to point to the end of the detector
- `SensCalc` predictions cross-checked with a dedicated simulation under the same input

Validation: dark scalars at MATHUSLA and SHADOWS II



- The sensitivities obtained by SHADOWS and MATHUSLA people: a huge difference
- **Reason 1**: the setups used in the collab. estimates do not match the setups described publicly: $\epsilon_{\text{dec}} = 1$ for MATHUSLA, a larger decay volume (without clearly studied background status) for SHADOWS
- **Reason 2**: different description of the scalar production

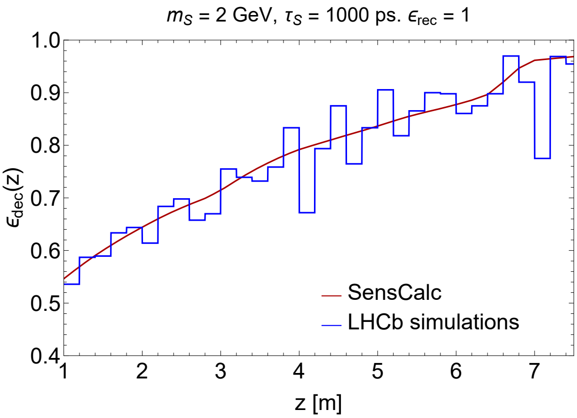
Validation: SHiP sensitivity I



– `SensCalc` predictions agree with FairShip simulations for the ECN4 setup from [1811.00930], [2011.05115]

– Differences: different phenomenology, simplification for the upper bound calculation in [1811.00930]

Validation: LHCb simulations



– New physics searches at LHCb using new downstream tracking algorithm (paper in preparation): acceptances perfectly agree with full LHCb simulations

Problems with LLP phenomenology used as input

LLPs 2022 proceedings, LLPs models BCXX:

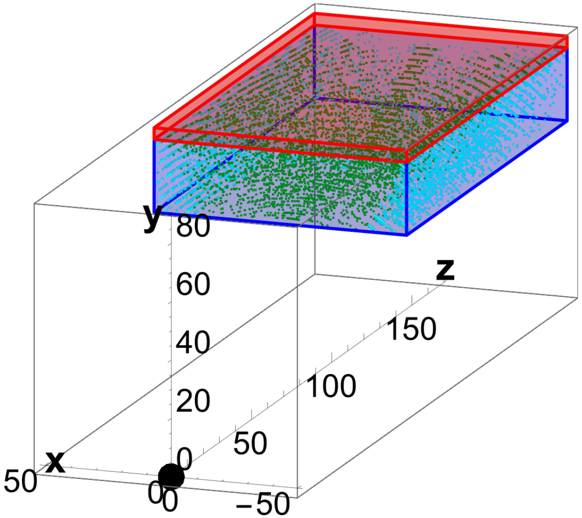
- **BC4, BC5** (Higgs-like scalars): some (most) of the experiments use inclusive description of the scalar production, which is wrong at large masses $m_S \gtrsim 3$ GeV
- **BC10** (ALPs coupled to fermions): most of the experiments use a completely wrong phenomenology (missing important production and decay channels)[1]; some of them include hadronic width, while most of them don't
- **BC11** (ALPs coupled to gluons): different definition of the coupling to SM particles is used by different experiments

[1] M. Ovchynnikov et al., in progress

Calculating acceptances I

1. Provide geometry input (decay volume, detector)
2. Find a grid $\theta_{\rm LLP}(z_{\rm LLP}), \phi_{\rm LLP}(z_{\rm LLP})$ for which the LLP is inside the decay volume $\Rightarrow \epsilon_{\rm az}(\theta_{\rm LLP}, z_{\rm LLP})$

   Simple verifications:
   - *checking $\theta_{min/max}$ belonging to the decay volume*
   - *visualization of the points $\{z_{LLP}, \theta_{LLP}, \phi_{LLP}\}$ – they must belong to the decay volume*
   - *the integral of ϵ_{az} gives the total volume of the decay volume*



Calculating acceptances II

3. Consider a grid $m_{\mathrm{LLP}}, E_{\mathrm{LLP}}, \theta_{\mathrm{LLP}}, z_{\mathrm{LLP}}, \phi_{\mathrm{LLP}}$, where $\{\theta, \phi\}$ belong to the decay volume
4. Generate phase space of the decay products at rest and boost them given $E_{\mathrm{LLP}}, \theta_{\mathrm{LLP}}, \phi_{\mathrm{LLP}}$
   - Exclusive decay channels (where analytic expression for the matrix element exists): simulating phase space with the weight given by squared matrix element
   - Inclusive decays (into jets/jets+leptons): either simulating decay into jets in `Mathematica`, or using pre-computed phase space of a typical hadronized final state obtained using `pythia`
5. Require at least two decay products with zero total charge to point to the end of the detector (may be changed to requiring all the decay products to be within the acceptance). Additionally, require some other cuts if needed (the energy cut, the p_T cut, etc.). This gives ϵ_{dec}

Averaging ϵ_{dec} over ϕ: reasonable since other quantities (such as dP_{dec}/dz, f_{LLP}) are ϕ-independent