Status of benchmark models

Problems, solutions, open questions

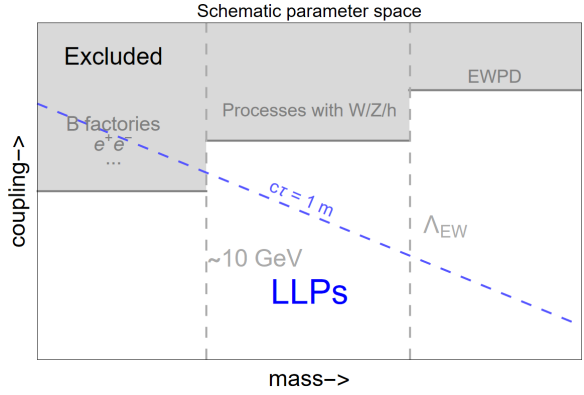
Maksym Ovchynnikov

FIPs Physics Centre meeting

September 11, 2024

Long-lived particles I

- Consider a new unstable particle with mass m and coupling g
- Masses $m \ll \Lambda_{\mathrm{EW}}$: past experiments excluded large g
- $c\tau \propto g^{-2} \Rightarrow$ unexplored parameter space corresponds to **Long-Lived Particles** (LLPs)



Long-lived particles II

"Portals" – lowest-dimensional gauge-invariant operators with LLPs. Some examples: *(potentially connecting to dark sectors)*

Model	(Effective) Lagrangian	What it looks like
HNL N	$Y\bar{L}\tilde{H}N + \text{h.c.}$	Heavy neutrino with interaction suppressed by $U \sim Yv_h/m_N \ll 1$
Higgs-like scalar S	$c_1 H^\dagger H S^2 + c_2 H^\dagger H S$	A light Higgs boson with interaction suppressed by $\theta \sim c_2 v_h/m_h$
Dark photon V	$-\frac{\epsilon}{2} F_{\mu\nu} V^{\mu\nu}$	A massive photon with interaction suppressed by ϵ
Axion a	$a g_a G^{\mu\nu}\tilde{G}_{\mu\nu} + \ldots$	A pion-like particle with the interaction suppressed by $f_\pi g_a$

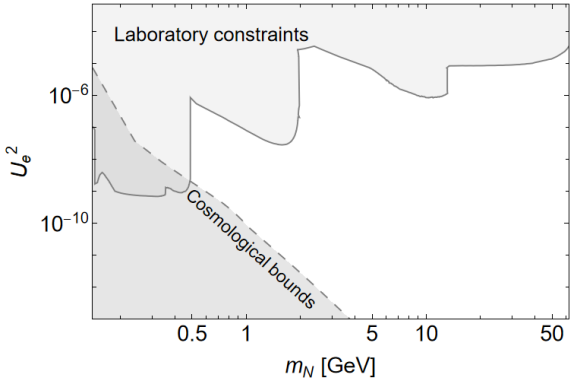
Other less explored portals with LLPs exist

See also 1504.04855, 1901.09966

Parameter space of LLPs I

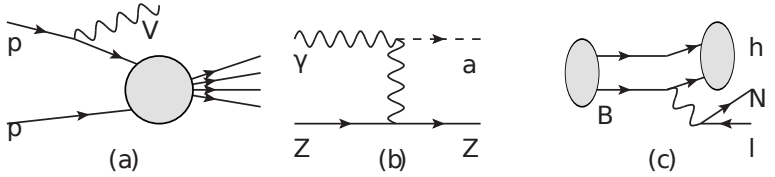
parameter space:

- **Small lifetimes**: ruled by past experiments
- **Large lifetimes**: ruled out by cosmological observations



Cosmological and laboratory constraints work in synergy

Phenomenology of LLPs I



- To find the reach of any experiment looking for decaying LLPs, we need to know their phenomenology: how they are produced and how decay (and in particular $c\tau_{\rm LLP}(m, g)$)
- 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

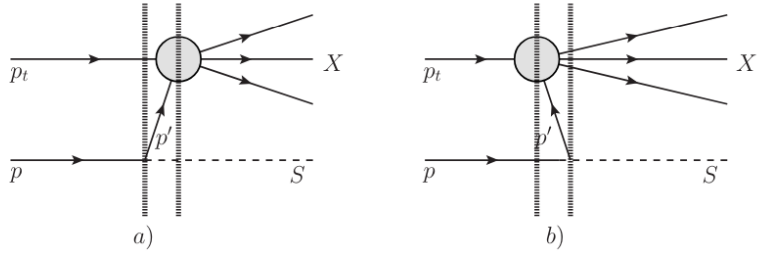
Phenomenology of LLPs II

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

Reasons:

- **Lack of data: we do not have many "LLP-like" events**
  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**
  Toy descriptions coming from old studies but being used nowadays; missing production channels etc.

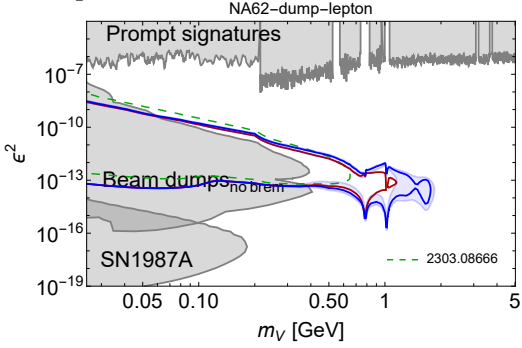
Example 1: proton bremsstrahlung I

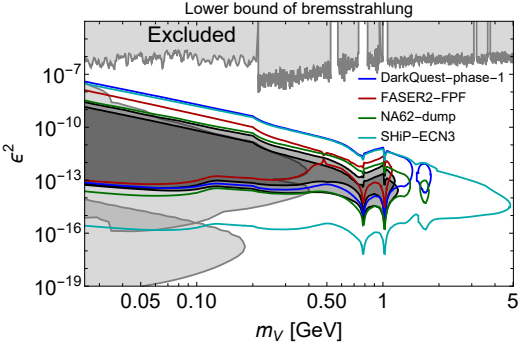


- Proton bremsstrahlung: ISR emission of a LLP X by Xpp vertex
- Description: approximate the total cross-section with the cross-section $\sigma_{pp,\text{inel}}$ (known from experiment) times the splitting function ω_{spl} for a sub-process $p \to p' + X$
- Approach adopted by the community [1311.3870]: ω_{spl} calculated by extrapolating the WW approximation for quasi-elastic scattering $\Rightarrow$ theoretical uncertainty undefined

Example 1: proton bremsstrahlung II

- Study [2108.05900] by S. Foroughi-Abari and A. Ritz: quasi-real description for $\omega_{\rm spl} \Rightarrow$ uncertainty in terms of the virtuality of p' in $p \to p' + X$. Improved revision by the same people to appear soon
- In preparation: use their results to revise the reach of past and future experiments to dark photons





Example 1: proton bremsstrahlung III

(Some of) **open questions**:

- ISR/FSR interference?
- Application to other particles:
  - ALPs
  - $B - L$ mediators (in preparation)
  - Elastic/inelastic DM coupled to these mediators
  - ...

Example 2: mixing with mesons

– Mixing with mesons:

$$\text{meson}_{\text{int}} = \text{meson}_{\text{mass}} + \boldsymbol{\theta}_{\text{meson-LLP}}\text{LLP} \tag{1}$$

ALPs mix with π^0, η, η' (and their excitations), vector mediators mix with ρ^0, ω, ϕ, scalars mix with f_0, ...

– State-of-the-art approach (see, e.g., [2201.05170]):

$$\boldsymbol{\sigma}_{\boldsymbol{pp}\to\text{LLP}} \approx |\boldsymbol{\theta}_{\text{meson-LLP}}|^{\boldsymbol{2}}\boldsymbol{\sigma}_{\boldsymbol{pp}\to\text{meson}} \tag{2}$$

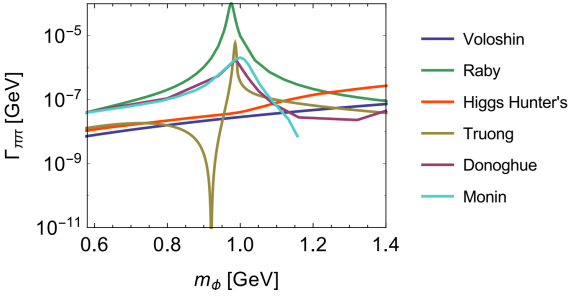
Wrong kinematics, no effects of LLP mass on the yield (other than via $\theta_{\text{meson-LLP}}$)

– To appear soon: implementation of the production via mixing in the fragmentation chain using `pythia`

– **Open questions:** treating the mixing with higher excitations of mesons (that are not properly implemented in `pythia`)

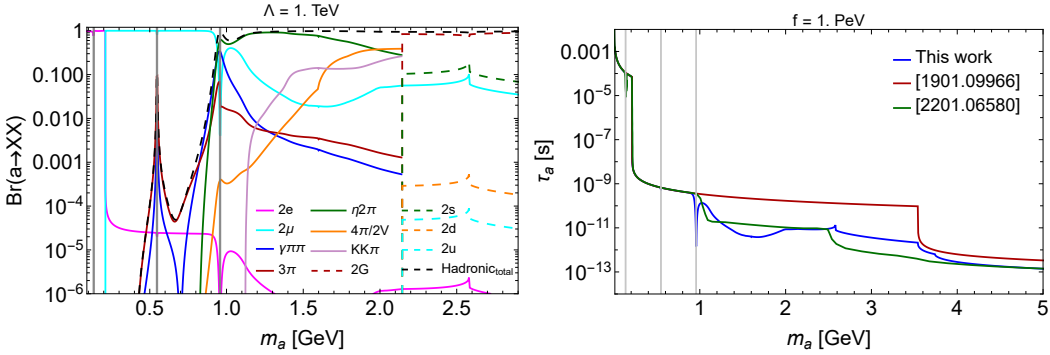
Example 3: hadronic width of Higgs-like scalars

- Huge uncertainties in hadronic decays of Higgs-like scalars in the mass range $m \lesssim 2$ GeV: $S \to \pi\pi, KK$, multi-meson, etc. 1809.01876, 1904.10447, 2303.12847
- Requires knowing gravitational $\pi\pi, KK$ form-factor



- **Open questions:** properly define the uncertainty and/or improve theoretical calculations, show uncertainties in the parameter space

Example 4: ALPs coupled to fermions



- The widely adopted phenomenology [1901.09966] missed hadronic ALP decays and various production channels (decays of Bs, mixing with neutral mesons)
- Phenomenology has been partially revised in 2310.03524
- **Open questions:** update mixing description, recalculate all constraints/sensitivities

Other questions (in one-line)

- `pythia` tunes for SPS and Fermilab facilities (to understand uncertainties in fluxes of mesons producing LLPs)
- Coherent implementation of the LLPs phenomenology in existing event generators (`SensCalc`, `FORESEE`, `ALPINIST`, ...), as well as cross-checks
- Detailed studies of matching between different descriptions of hadronic decay widths (pQCD, ChPT, dispersion relation method, data-driven) for GeV-scale LLPs

Conclusions

- Studies of the phenomenology of PBC benchmark models require a significant improvement:
  - Developing missing theoretical description
  - Highlighting uncertainties
  - Push them to the community to show the resulting parameter space
- Any help is welcome!