Revising laboratory searches for long-lived vector mediators

Based on 2409.11096 and on studies to appear

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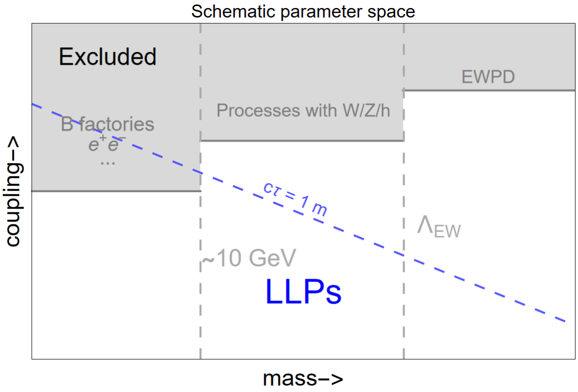
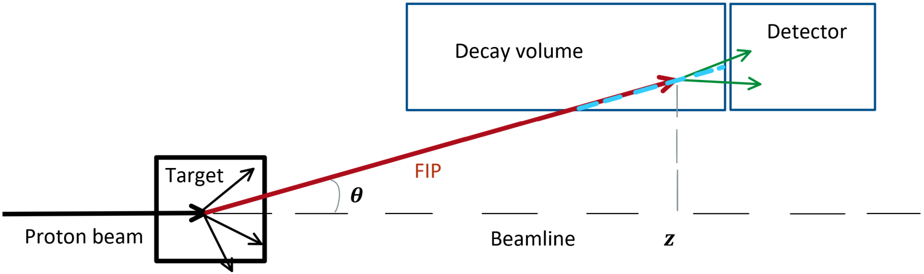
Introduction: GeV-scale LLPs I

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



Introduction: GeV-scale LLPs II



Typical experiment to search for LLPs – reconstructing their decays:

- High intensity
- System of background-suppressing elements: absorbers, muon shields, veto systems
- Large displaced decay volume
- Detector downward the decay volume

CHARM, NuCal, NA62-dump, FASER, Downstream@LHCb, SHiP, DarkQuest, FASER2, MATHUSLA, ...

Introduction: GeV-scale LLPs III

"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 $\theta \sim c_2 v_h/m_h$
Vector V	$-\frac{\epsilon}{2}F_{\mu\nu}V^{\mu\nu} + \epsilon_2 J^{\mu}_{B}V^{\nu} + \dots$	A massive photon with interaction suppressed by ϵ or ϕ-like particle, etc.
ALP a	$a g_a G^{\mu\nu}\tilde{G}_{\mu\nu} + \dots$	A $\pi^0/\eta/\eta'$-like particle with the interaction suppressed by $f_\pi g_a$

Focus of this talk: GeV-scale vector mediators

– Highlighting the role of uncertainties in phenomenology
– Revising laboratory reach of these particles

Dark photons I

- Dark photons (DP) $\boldsymbol{V}$: massive vector particles having kinetic mixing with SM photons

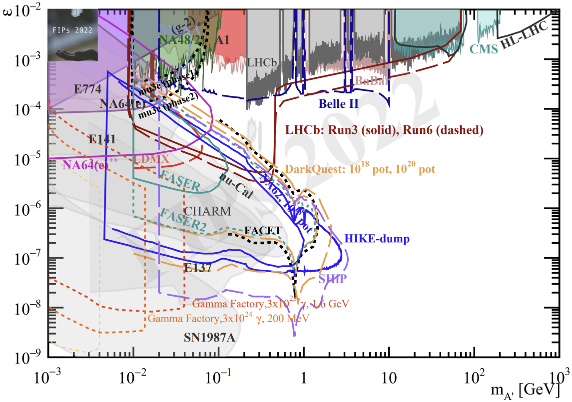
$$\mathcal{L} = -\frac{\epsilon}{2} F_{\mu\nu} V^{\mu\nu} \tag{1}$$

- Various models adding DPs [1901.09966]:
  - Minimal model with $\boldsymbol{V}$ only
  - Model with elastic dark matter (DM) coupled via $\boldsymbol{V}$
  - Inelastic DM model
- To search for $\boldsymbol{V}$s at laboratory experiments, we need to understand its phenomenology and uncertainties

Dark photons II

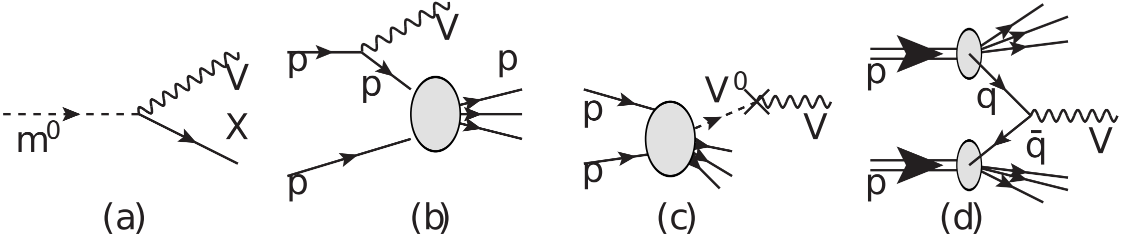
All-inclusive parameter space plots from the past (e.g., [2305.01715]):

- Took "standard" descriptions of the DP phenomenology that are either wrong or do not include theoretical uncertainty
- Even within this, non-coherent descriptions were used



Systematic revision of the parameter space is needed

Dark photon production I



Main **production modes** at proton beam experiments:

- Decays of mesons ***(a)***
- ISR production – proton bremsstrahlung ***(b)***
- FSR production via
  - Mixing with vector resonances $\boldsymbol{\rho^0, \omega, \phi}$, ... ***(c)***
  - Drell-Yan process ***(d)***

Dark photon production II

FSR production via mixing:

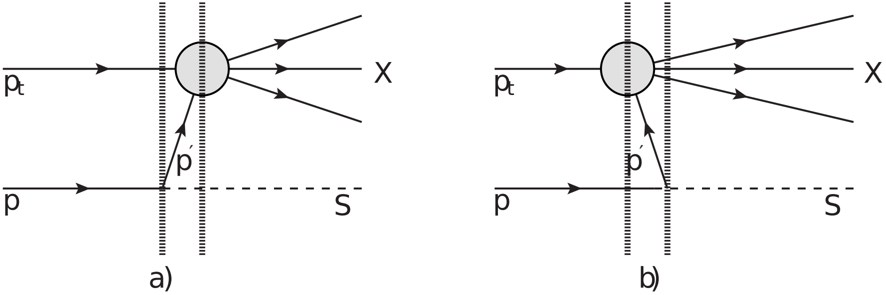
- Idea: similarly to γ, DP mixes with $V^0 = \rho^0, \phi, \omega \Rightarrow$ may be produced in any process where these particles are produced
- Widely used approach: simply

$$\sigma^{\text{mixing}}_{pp\to V} = \sigma_{pp\to V^0} \times |\theta_{VV^0}|^2, \qquad (2)$$

  where $\theta_{VV^0} \propto \epsilon$ is the mixing angle
- **This leads to wrong yield and kinematics of DPs**
- Revision: intermediate V^0 at the last stage of the fragmentation is replaced by V with the probability given by ϵ

To appear soon, results are already in use

Dark photon production III



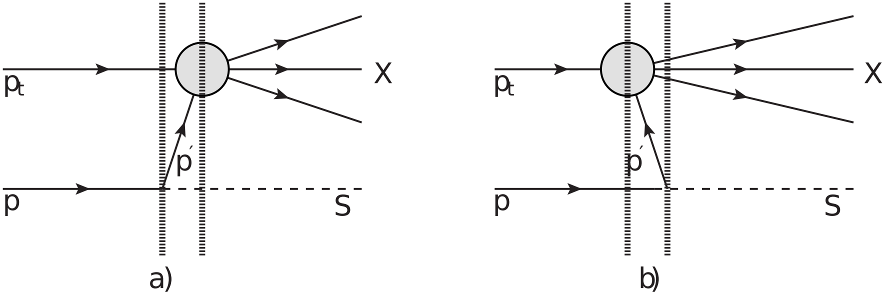
Proton bremsstrahlung:

– Idea – making use of OFPT [1904.10447]:

$$\boldsymbol{\sigma_{p+p_t\to V+X} \approx \omega_{p\to p'+V}\cdot\sigma_{p'+p\to X}} \tag{3}$$

– Widely adopted approach [1311.3870]: extrapolated quasi-elastic description onto the full inelastic process, without any uncertainties description

Dark photon production IV



- Recent bremsstrahlung study [2409.09123]:
  - Introduced phenomenological virtuality form-factor parametrized by the hard scale Λ_p
  - Revised the calculation of the elastic EM form-factor (entering the vertex ppV)

Dark photon production V

Summary production plot:

- The uncertainty is sizeable only for bremsstrahlung
  Varied $\boldsymbol{\Lambda_p = 0.5 - 2\ GeV}$, *masses and widths of* $\boldsymbol{V^0}$*s*
- It reaches 2-3 orders of magnitude, almost independently of the facility

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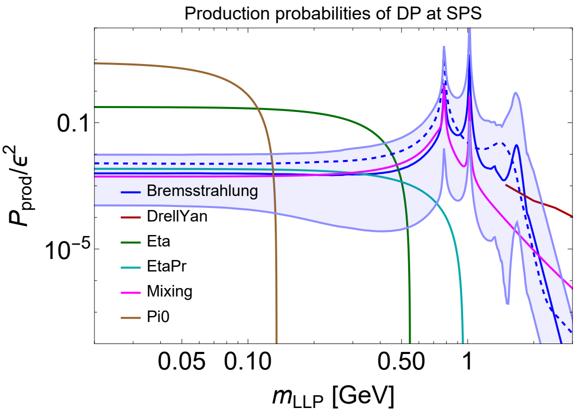
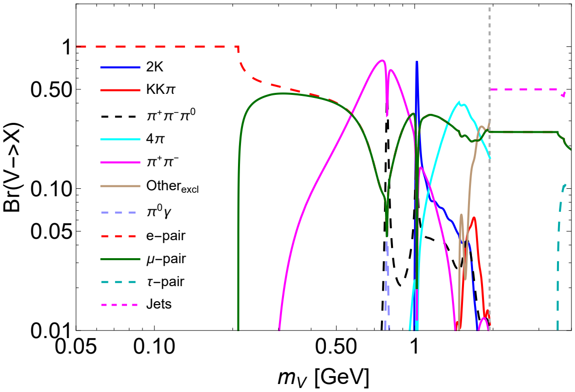
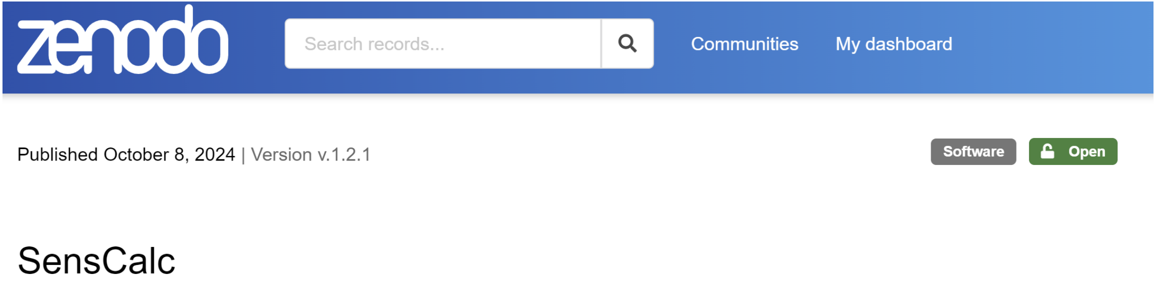


Dark photon decays



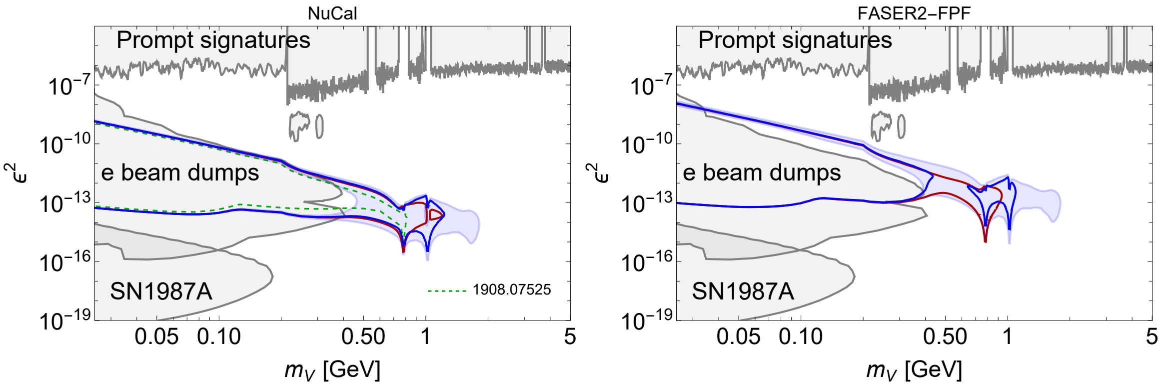
– Dark photon decay modes: may be understood using VMD+HLS approach [1801.04847]
Mixing with $\boldsymbol{\rho^0} \Rightarrow$ *decay* $\boldsymbol{V \to \pi^+\pi^-}$, *etc.*

Bringing altogether: revising laboratory reach I



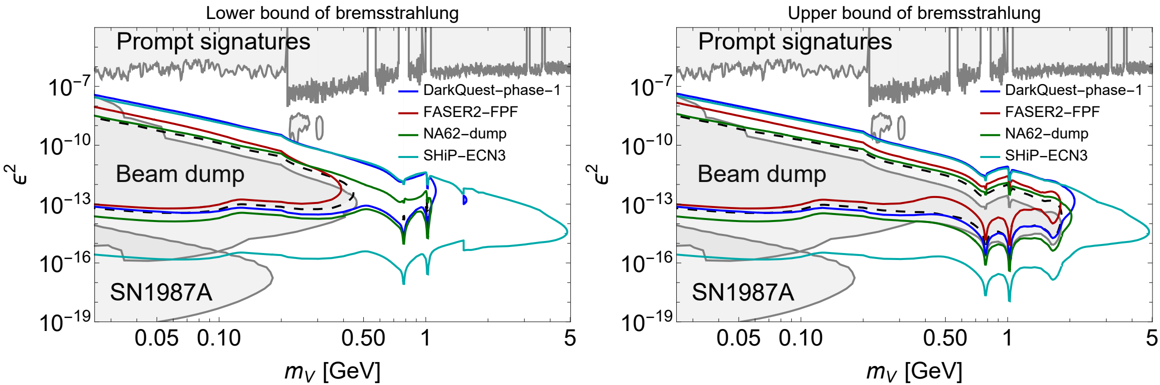
- To revise the reach of all proton beam experiments in a unified way, we used `SensCalc` [2305.13383]
- Includes:
  - Variety of experiments (based on facility, geometry of decay volume, and detector)
  - Different LLPs (HNLs with arbitrary mixing pattern, Higgs-like scalars, ALPs, vector mediators . . .)
- `SensCalc`-based event sampler has been interfaced to SHiP simulation framework, interfacing to LHCb in progress

Bringing altogether: revising laboratory reach II



- Blue domain: uncertainty band in the constraint/sensitivity. Blue line: central prediction
- The probed region heavily varies

Bringing altogether: revising laboratory reach III



– Apply this to all past and future lifetime frontier experiments
– Maximal mass reach of different experiments may change within a factor of a few

2409.11096

Generic vector mediators (to appear soon) I

- Consider a generic vector mediator V (B mediators, $B-L_{(\alpha)}$, protophobic, etc.)
- The same analysis as for dark photons can be applied to them
- Difference compared to dark photons:
  1. Different coupling pattern to vector mesons – may be understood in terms of VMD+hidden local symmetry approach [1801.04847]
  2. Absence of observations of elastic NNV form-factor
     Problem may be avoided if using HLS+VMD and relate couplings of $\boldsymbol{V}$ *to* $\boldsymbol{V^0}$ *in terms of DP couplings*
  3. Potential anomaly-driven decays of B mesons: we revised their presence for $B-L$ mediators and added new modes, such as
     $\boldsymbol{B_s \to \phi + V, B \to K_1/K_2^*/K^*(1410) + V}, \dots$
- Once analysis is done, it is straightforward to apply to various models of light dark matter (elastic, inelastic, etc.) coupled via these mediators
  Methods similar to used in [2405.08081] may be used

To appear soon

Conclusions

- GeV-scale LLPs may be viable candidates to resolve BSM problems
- Their production and decay modes at lab experiments suffer from large uncertainties
- This study
  - Revised the phenomenology of vector mediators and
  - Systematically implemented it in event generator to be used for various laboratory experiments
- Next step: perform the same for other BSM models

Backup slides

Details on generic vector mediators I

– Idea of calculating the ppV form factor:

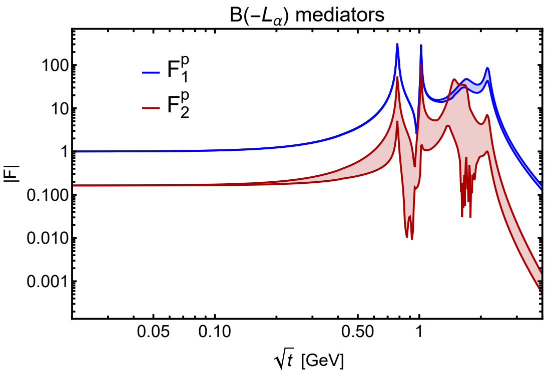
1. Represent the nucleon EM form factor in terms of pole expansion

$$F_N^{\text{EM}}(t) = \sum c_r \frac{m_r^2}{m_r^2 - t} \tag{4}$$

2. Unitarize it and find the coefficients $c_r, \ldots$ from asymptotic and data [1601.06190]
3. Apply the same expansion as (4) but for generic vector mediator V. Assumption: c_r may be expressed as

$$\frac{c_r^V}{c_r^{\text{EM}}} \equiv \frac{\frac{1}{3}\text{tr}[\mathbf{T}_V]}{\text{tr}[\mathbf{T}_V Q]} \tag{5}$$

Details on generic vector mediators II

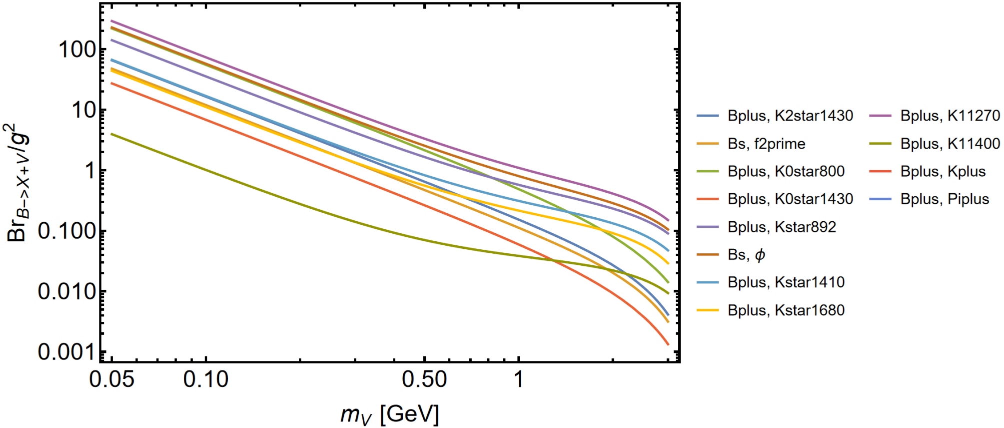


- Problem: results from [1601.06190] are not reproducible
- Preliminary result is shown
- In discussion with the authors of [2409.09123]

Details on generic vector mediators III

- Anomaly-driven decays of $\mathcal{B}$ mesons:
  - May appear in some (!) models with non-trivial anomaly cancellation
    Depends on the mechanism of the anomaly cancellation
  - $\mathcal{M}_{\mathcal{B}\to V} \propto \frac{1}{m_V}$
  - Ref. [1707.01503]: present for B mediators and absent for anomaly-free $B - L_\alpha$, discussed decays $\mathcal{B} \to V + K/K^*$
  - Recent work [2401.02483]: claimed that the $B - L$ case also has these decays, they originate from finite masses of SM fermions

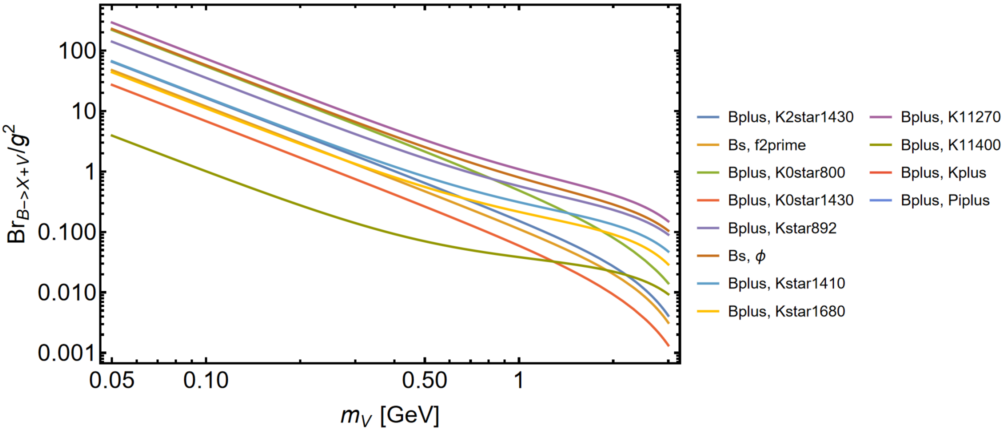
Details on generic vector mediators IV



– We use the model-independent study [1202.4940] and considered the $B - L$ case

– No anomalous vertex has been found (the situation is similar to the γZZ vertex)

Details on generic vector mediators V



– For the case of B mediators, we have included decays into higher excitations $K_0, K^*(1430), K_1, K_2^*, \ldots$ and $B_s \to \phi + V$
Some of them may be used similar to $B \to K/K^*$