Dark photon production via inelastic proton bremsstrahlung

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Dark photons

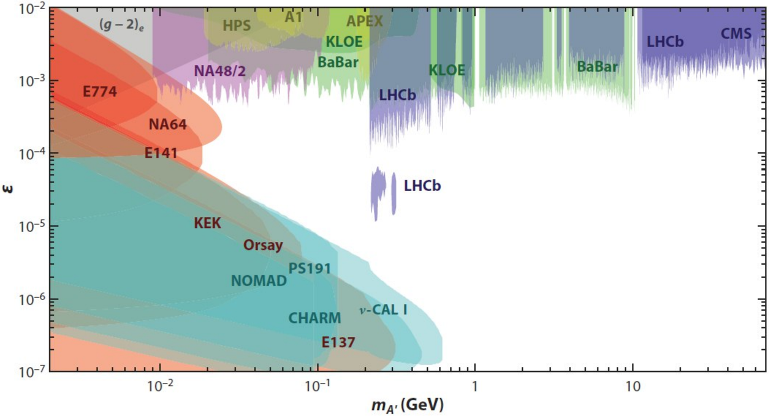
Portals — three ways to write down the renormalizable interaction of the SM fields with the hidden sector

- **Scalar:** dark scalar S, $\mathcal{L} \supset (AS + \lambda S^2)H^\dagger H$
- **Vector:** dark photon A'_μ, $\mathcal{L} \supset \frac{\epsilon}{2} F'_{\mu\nu} B^{\mu\nu}$
- **Fermion:** heavy neutral lepton N, $\mathcal{L} \supset Y_N L \tilde{H} N$

Part of the Lagrangian relevant for our study

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{\epsilon}{2} F'_{\mu\nu} B^{\mu\nu} + \frac{m^2_{\gamma'}}{2} A'_\mu A'^\mu.$$

Searches for γ' at accelerators



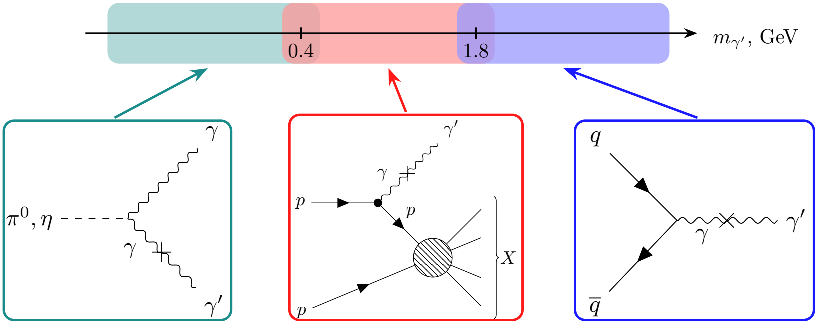
To **estimate the sensitivity** of the DUNE, T2K and SHiP experiments, one needs to study the phenomenology of $\mathcal{O}(1)$ GeV dark photon, in particular its **production modes**.

M. Graham, C. Hearty and M. Williams Ann. Rev. Nucl. Part. Sci. **71** (2021), 37-58

Mechanisms of γ' production

$m_{\gamma'}$ determines the dominant mechanism

1. $m_{\gamma'} < 0.4$ GeV: **meson decays** $m \to \gamma'\gamma$ (m: π^0, η) due to mixing with the SM γ.
2. 0.4 GeV $< m_{\gamma'} < 1.8$ GeV: **proton bremsstrahlung**.
3. $m_{\gamma'} > 1.8$ GeV: **Drell-Yan process** $q\bar{q} \to \gamma'$.



Nucleon electromagnetic form factors

Matrix element of EM current $j_\mu^{em} \equiv \bar{q} Q \gamma_\mu q$

$$J_\mu \equiv \left\langle N(p_1)\bar{N}(p_2) \right| j_\mu^{em}(0) \left|0\right\rangle$$

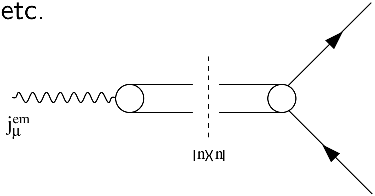
can be parametrized using **Dirac** F_1^N and **Pauli** F_2^N form factors

$$J^\mu = \overline{u}(p_1)\left[F_1^N(t)\gamma_\mu + i\frac{F_2^N(t)}{2m}\sigma_{\mu\nu}(p_1^\nu + p_2^\nu)\right]v(p_2), \quad t \equiv (p_1+p_2)^2$$

and expressed via **intermediate asymptotic states** with $J^{PC} = 1^{--}$ like 2π, $K\bar{K}$, $\rho\pi$, ω, ϕ, ρ, etc.

$$\mathrm{Im}\, J_\mu \propto \sum_n \left\langle N(p_1)\bar{N}(p_2) \right| n \rangle \times$$

$$\times \langle n| j_\mu^{em}(0) \left|0\right\rangle \delta^{(4)}(p_1 + p_2 - p_n)$$

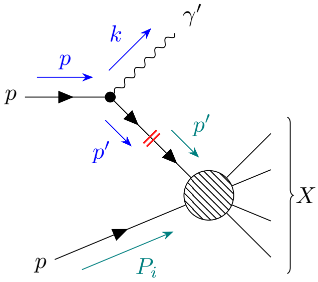


Y. H. Lin, H. W. Hammer and U. G. Meißner, Phys. Rev. Lett. **128** (2022) no.5, 052002

Inelastic proton bremsstrahlung: idea of calculation

We aim to **factorize** *inelastic* bremsstrahlung cross section

$$\frac{\mathrm{d}^2\sigma(pp \to \gamma' X)}{\mathrm{d}z\mathrm{d}k_\perp^2} \simeq w(z, k_\perp^2)\sigma(pp \to X)$$



Propagator numerator → polarization sum

$$\hat{p} - \hat{k} + M = \sum_{r'} u^{r'}(p-k)\overline{u}^{r'}(p-k)$$

Introduce **vertex functions**

$$V_1^{r'r\lambda} \equiv \overline{u}^{r'}(p-k)\widehat{(\epsilon^\lambda)^*}u^r(p),$$

$$V_2^{r'r\lambda} \equiv \frac{1}{2M}\overline{u}^{r'}(p-k)\frac{i}{2}\left[\widehat{(\epsilon^\lambda)^*}, \hat{k}\right]u^r(p)$$

Extract the input of **subprocess** to the amplitude

$$\mathcal{M}^{r\lambda}_{pp\to\gamma' X} = \sum_{r'} \mathcal{M}^{r'}_{pp\to X}\frac{\epsilon e z}{H}\left(-V_1^{r'r\lambda}F_1\left(m_{\gamma'}^2\right) + iV_2^{r'r\lambda}F_2\left(m_{\gamma'}^2\right)\right)$$

Part with F_1: S. Foroughi-Abari and A. Ritz, Phys. Rev. D **105** (2022) no.9, 095045

Inelastic proton bremsstrahlung: splitting functions

Finally, the *inelastic* bremsstrahlung cross section **factorizes** as

$$\frac{\mathrm{d}^2\sigma(pp\to\gamma' X)}{\mathrm{d}z\mathrm{d}k_\perp^2} \simeq \left(w_{11}|F_1|^2 + w_{22}|F_2|^2 + w_{12}\left(F_1F_2^* + F_2F_1^*\right)\right)\sigma(pp\to X).$$

Splitting functions

$$w_{11}(z,k_\perp^2) \equiv \frac{\epsilon^2\alpha_{em}}{2\pi H(z,k_\perp^2)}\left(z - \frac{z\,(1-z)}{H(z,k_\perp^2)}\left(2M^2+m_{\gamma'}^2\right) + \frac{H(z,k_\perp^2)}{2zm_{\gamma'}^2}\right),$$

$$w_{22}(z,k_\perp^2) \equiv \frac{\epsilon^2\alpha_{em}}{2\pi H}\frac{m_{\gamma'}^2}{8M^2}\left(z - \frac{z\,(1-z)}{H(z,k_\perp^2)}\left(8M^2+m_{\gamma'}^2\right) + \frac{2H(z,k_\perp^2)}{zm_{\gamma'}^2}\right),$$

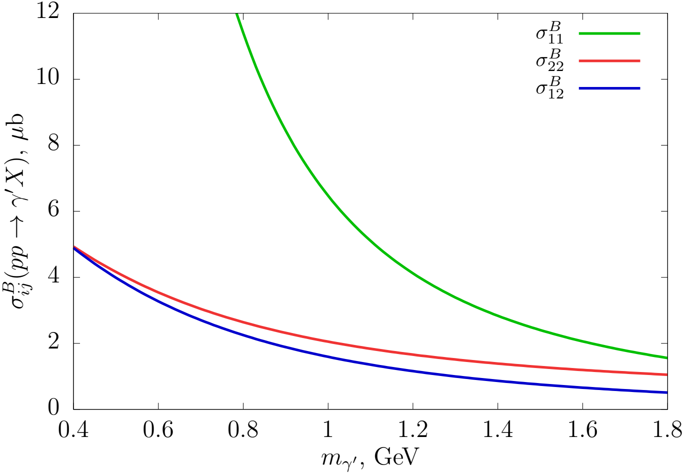
$$w_{12}(z,k_\perp^2) \equiv \frac{\epsilon^2\alpha_{em}}{2\pi H(z,k_\perp^2)}\left(\frac{3z}{4} - \frac{3m_{\gamma'}^2 z\,(1-z)}{2H(z,k_\perp^2)}\right),$$

where $H(z,k_\perp^2) \equiv k_\perp^2 + (1-z)m_{\gamma'}^2 + z^2M^2$

Part with $|F_1|^2$: S. Foroughi-Abari and A. Ritz, Phys. Rev. D **105** (2022) no.9, 095045

“Bare” cross sections without EM form factors

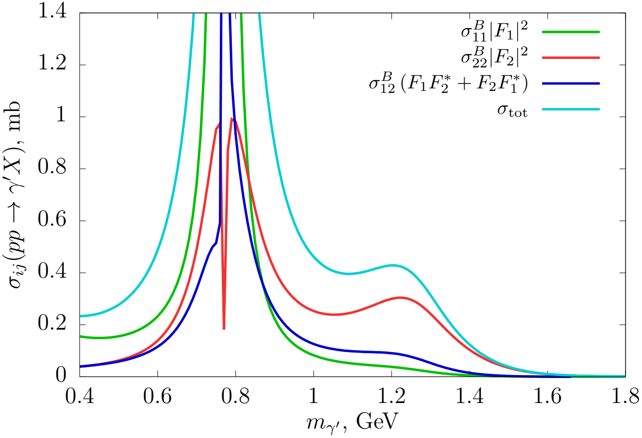
$$\sigma_{ij}^{B}(pp \to \gamma' X) \equiv \int w_{ij}(z, k_\perp^2)\sigma(pp \to X)\mathrm{d}z\mathrm{d}k_\perp^2$$



Since $\sigma_{11}^B > \sigma_{22}^B > \sigma_{12}^B$, one can naively think that the same hierarchy holds for corresponding terms with form factors

Final inputs to cross section including EM form factors

$$\sigma(pp \to \gamma' X) \simeq \sigma_{11}^B |F_1|^2 + \sigma_{22}^B |F_2|^2 + \sigma_{12}^B \left(F_1 F_2^* + F_2 F_1^*\right)$$



On the contrary, in the considered dark photon mass region the hierarchy $\sigma_{22} > \sigma_{12} > \sigma_{11}$ is also possible

F_1, F_2 from A. Faessler, M. I. Krivoruchenko and B. V. Martemyanov, Phys. Rev. C **82** (2010), 038201

Conclusions and future plans

- Found **new contribution** from the Pauli form factor to inelastic proton bremsstrahlung cross section
- Shown that its input is **non-negligible** and can make decisive contribution to the total cross section for certain dark photon masses

- Update the result using **recent fits** of experimental data on proton EM form factors
- Obtain the **sensitivity curves** for future dark photon searches taking into account both Dirac $F_1(m_{\gamma'}^2)$ and Pauli $F_2(m_{\gamma'}^2)$ form factors

Rough estimate for Dirac and Pauli form factors

Proton EM form factors

$$F_1(t) = \left(1 - \frac{t}{4M^2}\frac{\mu_p}{\mu_N}\right)\left(1 - \frac{t}{4M^2}\right)^{-1} G_D(t),$$

$$F_2(t) = \left(\frac{\mu_p}{\mu_N} - 1\right)\left(1 - \frac{t}{4M^2}\right)^{-1} G_D(t)$$

are frequently expressed via dipole form factor

$$G_D(t) \equiv \left(1 - \frac{t}{m_D^2}\right)^{-2}, \quad m_D^2 = 0.71 \text{ GeV}^2.$$

At $t = 0$ these FFs are connected to proton charge and anomalous magnetic moment by fixing

$$\mu_N = \frac{e}{2M}, \quad \frac{\mu_p}{\mu_N} = 2.79.$$