Contributions to inelastic proton bremsstrahlung related to Dirac and Pauli form factors

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Dark photons

Portal framework

$$\mathcal{L}_{\text{portal}} = \sum \mathcal{O}_{\text{SM}} \mathcal{O}_{\text{DS}}$$

The lowest dimensional portals

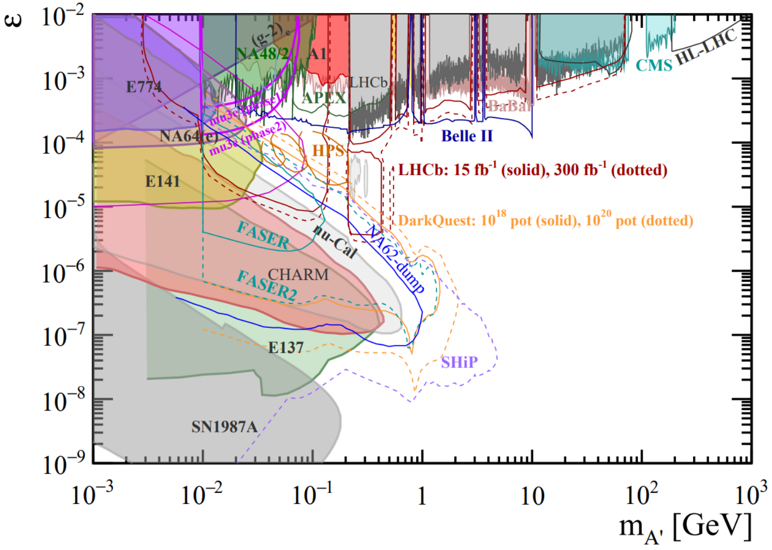
- **Vector:** dark photon A'_μ, $-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
- **Scalar:** dark Higgs S, $(\mu S + \lambda S^2) H^\dagger H$
- **Fermion:** heavy neutral lepton N, $Y_N L \tilde{H} N$
- **Pseudoscalar:** axion-like particle a, $\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$

The Lagrangian of the **minimal dark photon model**

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{4} \tilde{F}'_{\mu\nu} \tilde{F}'^{\mu\nu} - \frac{\epsilon}{2\cos\theta_W} \tilde{F}'_{\mu\nu} B^{\mu\nu} + \frac{m^2_{\gamma'}}{2} \tilde{A}'_\mu \tilde{A}'^\mu,$$

Simultaneous rotation of $(W^3_\mu, B_\mu, \tilde{A}'_\mu) \to$ interaction $-\epsilon e J^\mu_{\text{em}} A'_\mu$

Searches for visible decays of γ'

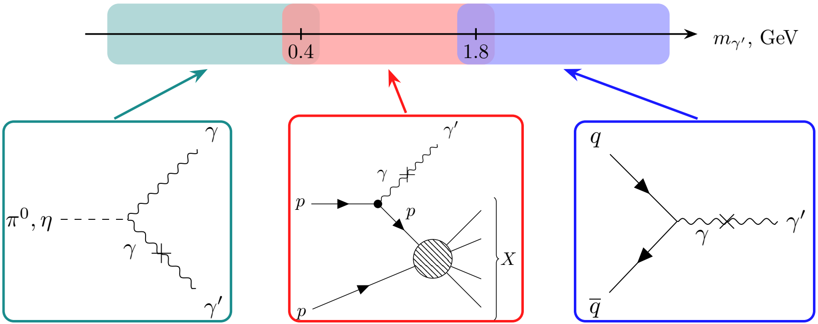


G. Lanfranchi, M. Pospelov and P. Schuster, Ann. Rev. Nucl. Part. Sci. **71** (2021), 279-313

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** $q\bar{q} \to \gamma'$.



Electromagnetic proton form factors

Matrix elements of the electromagnetic current $j^{\mu}_{\text{em}} \equiv \sum_i Q_i \bar{q}_i \gamma^{\mu} q_i$ can be expressed through the **Dirac** $F_1(t)$ and **Pauli** $F_2(t)$ electromagnetic proton form factors

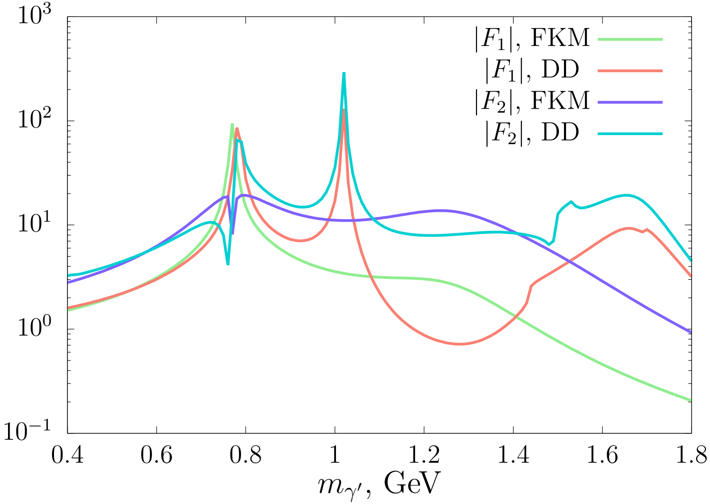
$$\langle p(p_2)|\, j^{\mu}_{\text{em}}\, |p(p_1)\rangle \equiv \overline{u}(p_2) \left[F_1(t)\gamma^{\mu} + i\frac{F_2(t)}{2M}\sigma^{\mu\nu}(p_2 - p_1)_{\nu} \right] u(p_1),$$

$\sigma_{\mu\nu} \equiv i\left[\gamma_{\mu}, \gamma_{\nu}\right]/2$, $t \equiv (p_2 - p_1)^2$

Electromagnetic proton form factors measurements

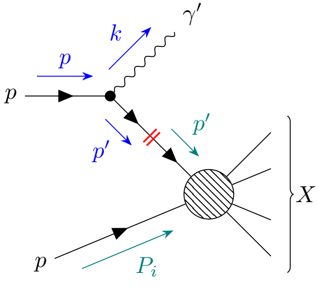
- spacelike region, $t < 0$: $ep \to ep$
- timelike region, $t > 4M^2$: $e^+e^- \to p\bar{p}$
- *unphysical* region, $0 < t < 4M^2$: interpolation

Absolute values of Dirac and Pauli form factors



F_1, F_2 from A. Faessler, M. I. Krivoruchenko and B. V. Martemyanov, Phys. Rev. C **82** (2010), 038201,
A. Z. Dubnickova and S. Dubnicka, arXiv:2010.15872 [hep-ph].

Inelastic proton bremsstrahlung: idea of calculation



Particles momenta in the lab frame

$$p = \{E_p, 0, 0, P\},$$
$$k = \{E_k, k_\perp \cos\varphi, k_\perp \sin\varphi, zP\},$$
$$p' = p - k.$$

We would like to **factorize** *inelastic* bremsstrahlung cross section with the help of **master splitting function** $w_{\text{mas}}(z, k_\perp^2)$ and off-shell form factor

$$F_{\text{virt}}(z, k_\perp^2) \equiv \frac{\Lambda^4}{\Lambda^4 + H^2(z, k_\perp^2)/z^2},$$
$$H(z, k_\perp^2) \equiv k_\perp^2 + (1-z)m_{\gamma'}^2 + z^2 M^2,$$

$$\frac{\mathrm{d}^2\sigma(pp \to \gamma' X)}{\mathrm{d}z\mathrm{d}k_\perp^2} \simeq w_{\text{mas}}(z, k_\perp^2) F_{\text{virt}}^2(z, k_\perp^2) \sigma(pp \to X).$$

Inelastic proton bremsstrahlung: details

The matrix element of the **inelastic** subprocess $p(p-k)p(P_i) \to X$

$$\mathcal{M}^{r'} \equiv A(p-k, P_i) u^{r'}(p-k)$$

can be extracted from the full **bremsstrahlung** matrix element

$$\mathcal{M}^{r\lambda} = A(p-k, P_i)\frac{i(\hat{p}-\hat{k}+M)}{(p-k)^2-M^2}(-i\epsilon e)\times$$
$$\times\left(\gamma_\mu F_1\left(m^2_{\gamma'}\right) + \frac{i}{2M}\sigma_{\mu\nu}(-k^\nu)F_2\left(m^2_{\gamma'}\right)\right)(\epsilon^\lambda)^{*,\mu}(k)u^r(p)$$

by replacing propagator numerator with **polarization sum**

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

and simplifying propagator denominator

$$(p-k)^2 - M^2 = -H/z.$$

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

Inelastic proton bremsstrahlung: vertex functions

For simplicity, we introduce the **vertex functions**

$$V_1^{r'r\lambda} \equiv \overline{u}^{r'}(p-k)\widehat{(\epsilon^\lambda)^*}u^r(p),$$
$$V_2^{r'r\lambda} \equiv \frac{1}{4M}\overline{u}^{r'}(p-k)\left[\widehat{(\epsilon^\lambda)^*},\hat{k}\right]u^r(p)$$

and finally extract the input of **subprocess** to the amplitude

$$\mathcal{M}^{r\lambda} = -\sum_{r'}\mathcal{M}^{r'}\frac{\epsilon e z}{H}\left(V_1^{r'r\lambda}F_1\left(m_{\gamma'}^2\right)+V_2^{r'r\lambda}F_2\left(m_{\gamma'}^2\right)\right).$$

The square of full matrix element

$$\sum_{r,\lambda}|\mathcal{M}^{r\lambda}|^2 = \left(\frac{\epsilon e z}{H}\right)^2\left(N\sum_{r'}|\mathcal{M}^{r'}|^2 + A\sum_{r'}\mathcal{M}^{r'}\left(\mathcal{M}^*\right)^{-r'}\right)$$

contains the **normal** and **anomalous spin-flip** parts

$$N \equiv |F_1|^2\left(I'_{11}+I''_{11}\right)+|F_2|^2\left(I'_{22}+I''_{22}\right)+\left(F_1F_2^*+F_2F_1^*\right)\left(I'_{12}+I''_{12}\right),$$
$$A \equiv \left(F_1F_2^*-F_2F_1^*\right)\left(J'_{12}+J''_{12}\right).$$

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

Inelastic proton bremsstrahlung: splitting functions

Master splitting function

$$w_{\text{mas}}(z, k_\perp^2) \equiv w_{11}(z, k_\perp^2)|F_1|^2 + \\ + w_{22}(z, k_\perp^2)|F_2|^2 + w_{12}(z, k_\perp^2)\left(F_1 F_2^* + F_2 F_1^*\right)$$

and three **auxiliary splitting functions**

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

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

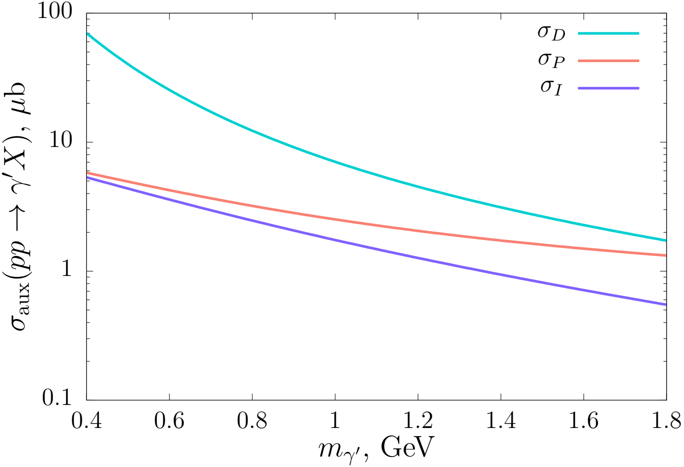
$$w_{12}(z, k_\perp^2) \equiv \frac{\epsilon^2 \alpha_{\text{em}}}{2\pi H}\left(\frac{3z}{4} - \frac{3m_{\gamma'}^2 z(1-z)}{2H}\right).$$

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

Auxiliary cross sections independent of EM FF

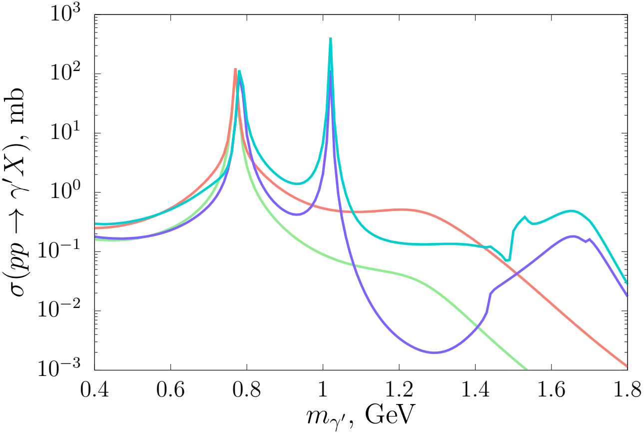
Dirac, Pauli and interference cross sections

$$\begin{pmatrix} \sigma_D \\ \sigma_P \\ \sigma_I \end{pmatrix} \equiv \int \begin{pmatrix} w_{11}(z, k_\perp^2) \\ w_{22}(z, k_\perp^2) \\ w_{12}(z, k_\perp^2) \end{pmatrix} F_{\rm virt}^2(z, k_\perp^2)\sigma(pp \to X)\mathrm{d}z\mathrm{d}k_\perp^2,$$



Full inelastic bremsstrahlung cross section

$$\sigma(pp \to \gamma' X) = |F_1|^2 \sigma_D + |F_2|^2 \sigma_P + (F_1 F_2^* + F_2 F_1^*)\, \sigma_I .$$



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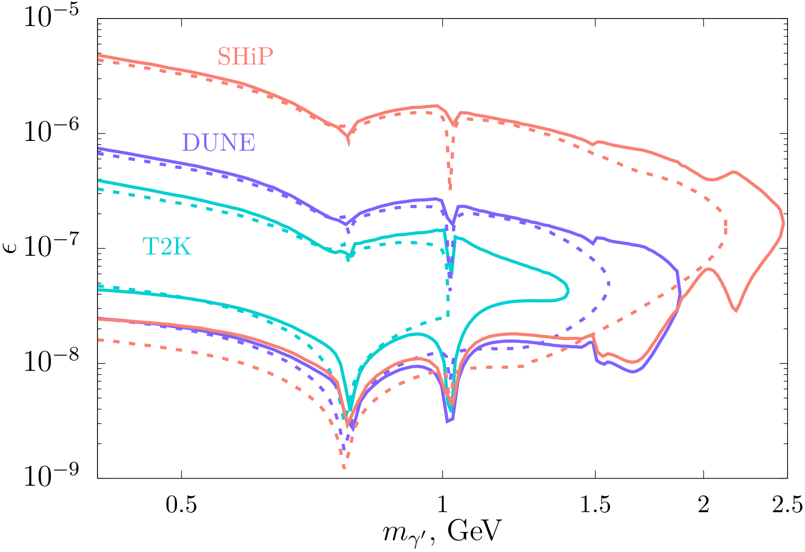
Expected sensitivity of future experiments to visible dark photons decays, 95% CL



Conclusions and future plans

- Found **new contribution** from the Pauli form factor to inelastic proton bremsstrahlung cross section
- Showed that its input is **non-negligible** and can make decisive contribution to the total cross section for certain dark photon masses
- Refined the **sensitivity curves** for future dark photon searches at T2K, DUNE and SHiP taking into account both Dirac $F_1(m_{\gamma'}^2)$ and Pauli $F_2(m_{\gamma'}^2)$ form factors

- To do: estimate the contribution of virtual **Δ^+-resonance** to the inelastic proton bremsstrahlung