

New splitting functions for inelastic bremsstrahlung
from Pauli electromagnetic form factor
(based on arXiv:2409.11089, 2409.11386)

Ekaterina Kriukova, Dmitry Gorbunov

Institute for Nuclear Research of the RAS,
Lomonosov Moscow State University

7th International Conference on
Particle Physics and Astrophysics,
24 October 2024

Dark photons

Portal framework

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

The lowest dimensional portals

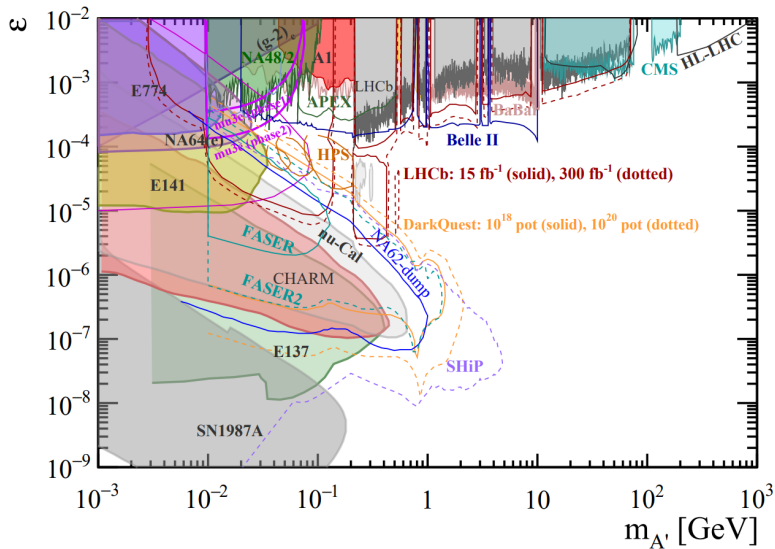
- ▶ **Vector:** dark photon A'_μ , $-\frac{\epsilon}{2 \cos \theta_W} \tilde{F}'_{\mu\nu} B^{\mu\nu}$
- ▶ **Scalar:** dark Higgs S , $(\mu S + \lambda S^2) H^\dagger H$
- ▶ **Fermion:** heavy neutral lepton N , $Y_N L \tilde{H} N$
- ▶ **Pseudoscalar:** axion-like particle a , $\frac{a}{f_a} F_{\mu\nu}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

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

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

Simultaneous rotation of $(W_\mu^3, B_\mu, \tilde{A}'_\mu) \rightarrow$ interaction $-\epsilon e J_{\text{em}}^\mu A'_\mu$

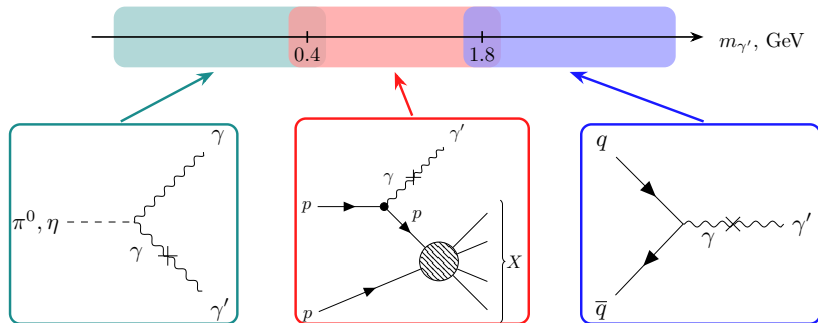
Searches for visible decays of γ'



Mechanisms of γ' production

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

1. $m_{\gamma'} < 0.4$ GeV: **meson decays** $m \rightarrow \gamma' \gamma$ ($m: \pi^0, \eta$) 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** $q\bar{q} \rightarrow \gamma'$.



Electromagnetic proton form factors

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

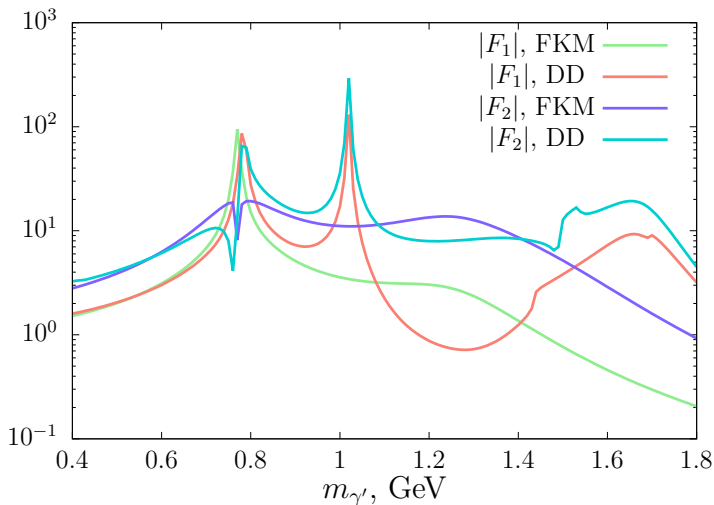
$$\langle p(p_2) | j_{\text{em}}^\mu | p(p_1) \rangle \equiv \bar{u}(p_2) \left[F_1(t) \gamma^\mu + i \frac{F_2(t)}{2M} \sigma^{\mu\nu} (p_2 - p_1)_\nu \right] u(p_1),$$

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

Electromagnetic proton form factors measurements

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

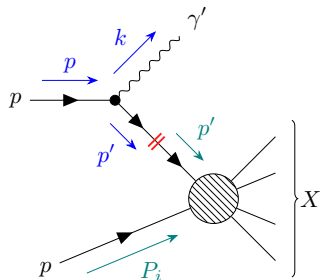
Particles momenta in the lab frame

$$p = \{E_p, 0, 0, P\},$$

$$k = \{E_k, k_{\perp} \cos \varphi, k_{\perp} \sin \varphi, zP\},$$

$$p' = p - k.$$

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



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

Inelastic proton bremsstrahlung: details

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

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

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

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

by replacing propagator numerator with **polarization sum**

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

and simplifying propagator denominator

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

Inelastic proton bremsstrahlung: vertex functions

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

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

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

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

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

The square of full matrix element

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

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

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

Inelastic proton bremsstrahlung: splitting functions

Master splitting function

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

and three **auxiliary splitting functions**

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

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

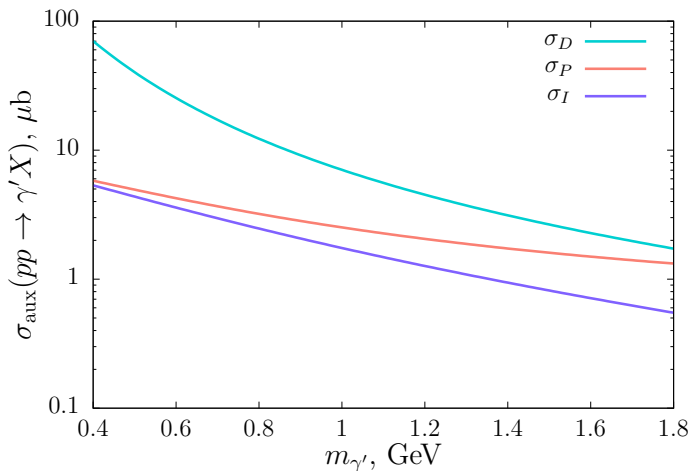
$$w_{12}(z, k_{\perp}^2) \equiv \frac{\epsilon^2 \alpha_{\text{em}}}{2\pi H} \left(\frac{3z}{4} - \frac{3m_{\gamma'}^2 z(1-z)}{2H} \right).$$

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

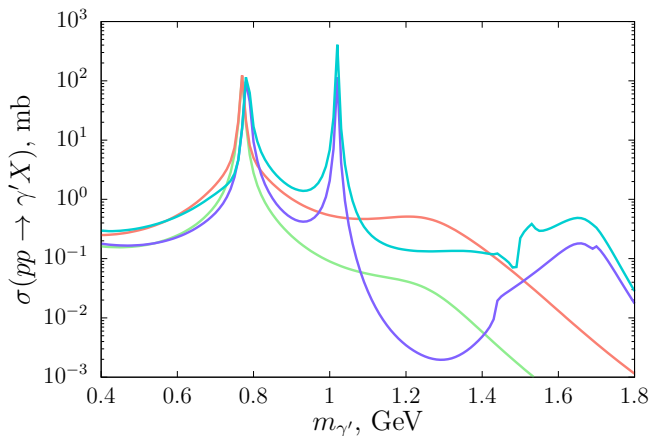
Dirac, Pauli and interference cross sections

$$\begin{pmatrix} \sigma_D \\ \sigma_P \\ \sigma_I \end{pmatrix} \equiv \int \begin{pmatrix} w_{11}(z, k_{\perp}^2) \\ w_{22}(z, k_{\perp}^2) \\ w_{12}(z, k_{\perp}^2) \end{pmatrix} F_{\text{virt}}^2(z, k_{\perp}^2) \sigma(pp \rightarrow X) dz dk_{\perp}^2,$$



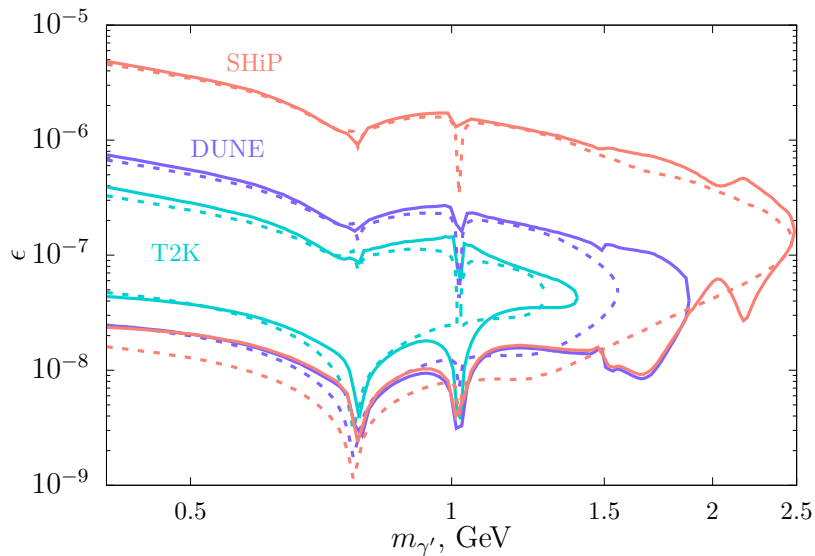
Full inelastic bremsstrahlung cross section

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



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].

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
- ▶ study the limit of **negligible** dark photon masses $m_{\gamma'} \ll M$, what happens to splitting functions?