Magnetic contribution to inelastic proton bremsstrahlung

Ekaterina Kriukova, Dmitry Gorbunov

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

XXII International Seminar "Quarks 2024",
24 May 2024

Dark photons

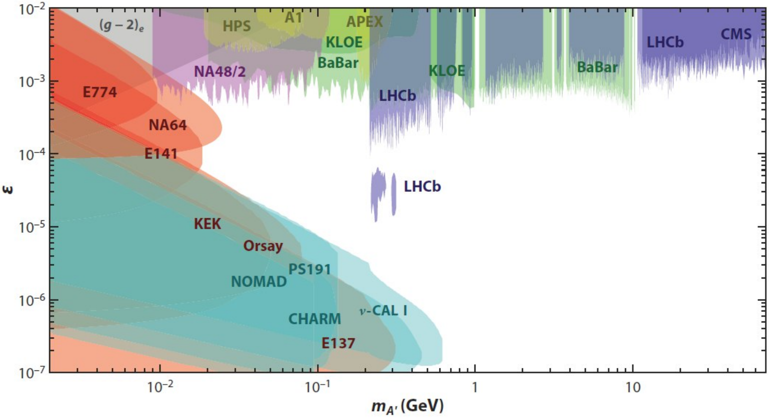
Portals — three ways to write down the renormalizable interaction of the SM fields with the hidden sector

- **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, $\mathcal{L} \supset Y_N L \tilde{H} N$

The Lagrangian of the minimal dark photon model

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

Searches for γ' at accelerators



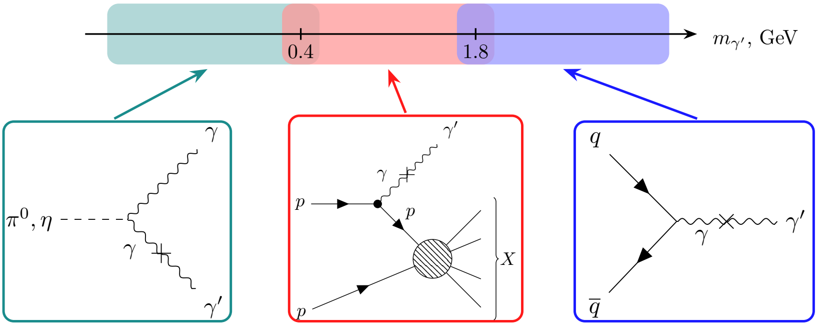
To **estimate the sensitivity** of the DUNE, T2K and SHiP experiments, one needs to study the phenomenology of $\mathcal{O}(1)$ GeV dark photon, in particular its **production modes**.

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 $j_\mu^{em} \equiv \bar{q} Q \gamma_\mu q$

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

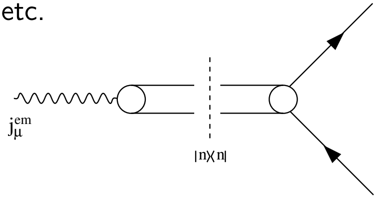
can be parametrized using **Dirac** F_1^N and **Pauli** F_2^N form factors

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

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

How to measure nucleon electromagnetic form factors

Spacelike region

$$Q^2 \equiv -t > 0$$

$eN \to eN$ scattering
PRad, Jefferson Lab, MAMI
measure Sachs form factors

$$G_E(t) \equiv F_1(t) + \frac{t}{4M^2} F_2(t),$$
$$G_M(t) \equiv F_1(t) + F_2(t)$$

Timelike region

$$q^2 \equiv t > 0$$

$e^+e^- \to N\bar{N}$ annihilation
threshold $t = (2M)^2$
BABAR, BESIII, CMD-3, SND
measure $|G_E/G_M|$ and effective form factors

$$|G_{\rm eff}| \equiv \sqrt{\frac{|G_E|^2 + t/2M^2 |G_M|^2}{1 + t/2M^2}}$$

Estimate for spacelike Dirac and Pauli form factors

Proton EM form factors at low $Q^2 \equiv -t > 0$ can be approximated using **dipole form factor** $G_D(t)$

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

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

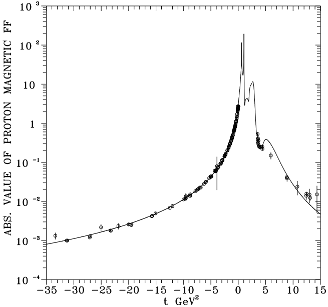
$$G_D(t) \equiv \left(1 - \frac{t}{m_D^2}\right)^{-2}, \quad m_D^2 = 0.71 \text{ GeV}^2.$$

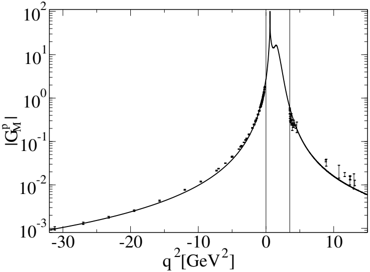
At $t = 0$ these FFs can be connected to proton **charge** and **anomalous magnetic moment** by fixing

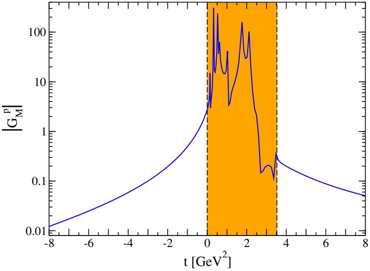
$$\mu_N = \frac{e}{2M}, \quad \frac{\mu_p}{\mu_N} = 2.79.$$

Electromagnetic form factors in unphysical region

$$G_M^p(t) = F_1^p(t) + F_2^p(t)$$







[1] S. Dubnicka, A. Z. Dubnickova and P. Weisenpacher, J. Phys. G **29** (2003), 405-430

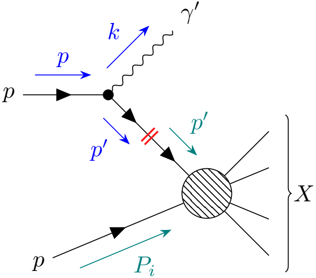
[2] A. Faessler, M. I. Krivoruchenko and B. V. Martemyanov, Phys. Rev. C **82** (2010), 038201

[3] H. W. Hammer, U. G. Meissner and D. Drechsel, Phys. Lett. B **385** (1996), 343-347

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

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

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

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

Splitting functions

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

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

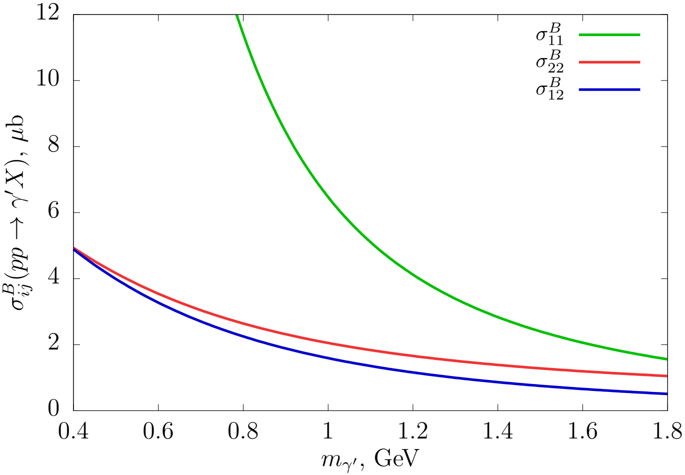
$$w_{12}(z, k_\perp^2) \equiv \frac{\epsilon^2 \alpha_{em}}{2\pi H(z, k_\perp^2)} \left(\frac{3z}{4} - \frac{3m_{\gamma'}^2 z(1-z)}{2H(z, k_\perp^2)} \right),$$

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

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

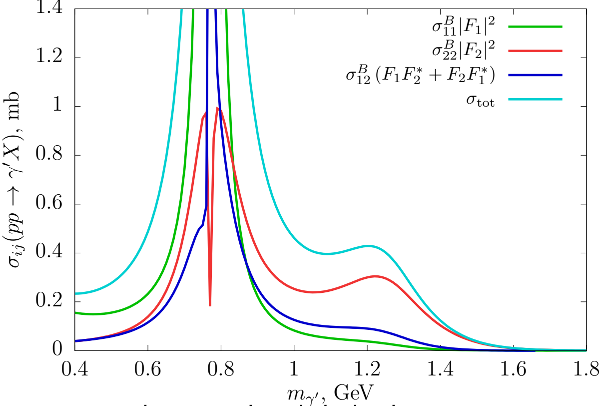
$$\sigma^B_{ij}(pp \to \gamma' X) \equiv \int w_{ij}(z, k_\perp^2)\sigma(pp \to X)\mathrm{d}z\mathrm{d}k_\perp^2$$



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

Final inputs to cross section including EM form factors

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

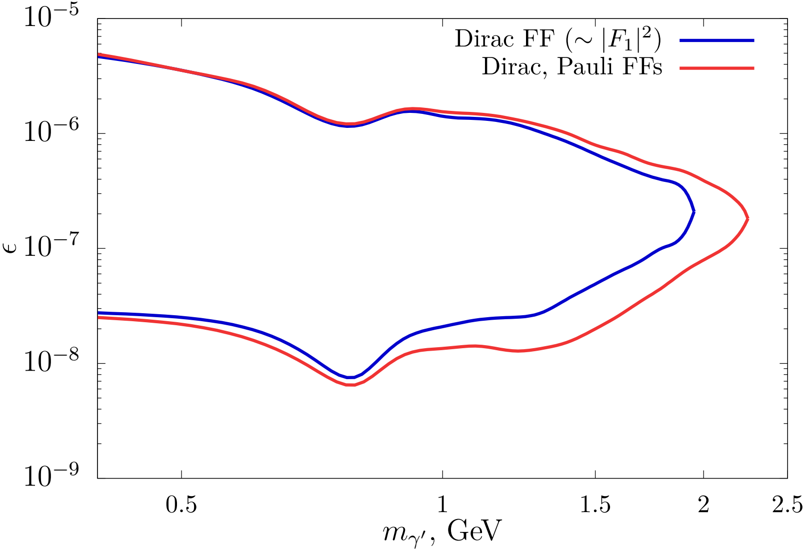


On the contrary, in the considered dark photon mass region it is also possible to have the hierarchy

$$\sigma_{22}^B |F_2|^2 > \sigma_{12}^B \left(F_1 F_2^* + F_2 F_1^*\right) > \sigma_{11}^B |F_1|^2$$

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

Expected sensitivity of the SHiP experiment to dark photons decaying to two charged particles, 95% CL

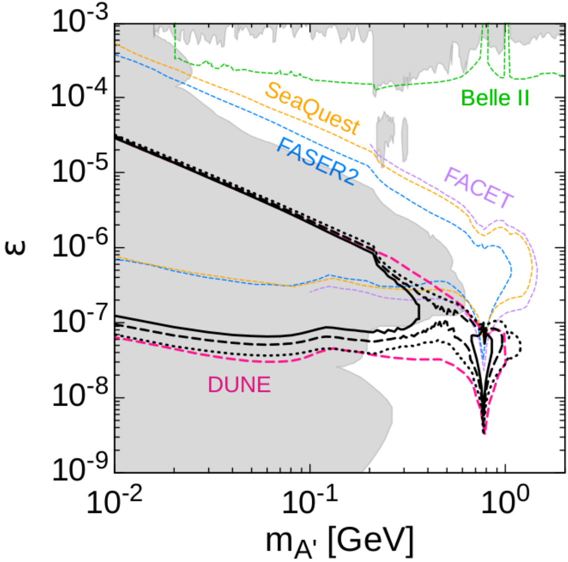


Conclusions and future plans

- 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 **other recent fits** of experimental data on proton EM form factors
- Obtain the **sensitivity curves** for future dark photon searches at T2K and DUNE taking into account both Dirac $F_1(m^2_{\gamma'})$ and Pauli $F_2(m^2_{\gamma'})$ form factors

Sensitivity of T2K (unupdated estimates)



T. Araki, K. Asai, T. Iizawa, et al., JHEP **11** (2023), 056