Pion bremsstrahlung as a new source for dark photons

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Dark photons

Portal formalism

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

The lowest dimension portals

- **Vector:** dark photon A'_μ, $-\frac{\epsilon}{2\cos\theta_W} \tilde{F}'_{\mu\nu} B^{\mu\nu}$
- **Scalar:** dark scalar 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, $\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$

Minimal dark photon model Lagrangian

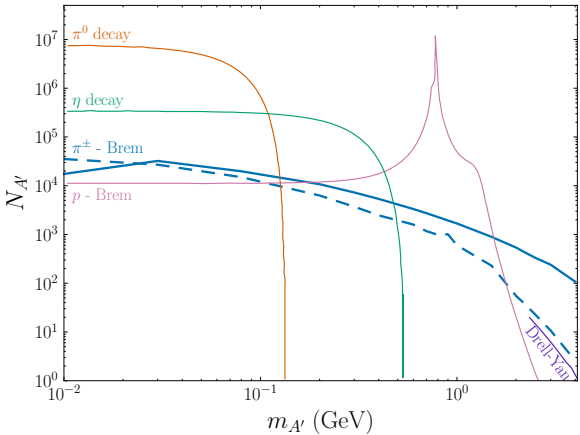
$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{4} \tilde{F}'_{\mu\nu} \tilde{F}'^{\mu\nu} - \frac{\epsilon}{2\cos\theta_W} \tilde{F}'_{\mu\nu} B^{\mu\nu} + \frac{m^2_{\gamma'}}{2} \tilde{A}'_\mu \tilde{A}'^\mu,$$

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

γ' production in fixed-target experiments

Production mechanisms

1. **meson decays** $m \to \gamma'\gamma$ (m: π^0, η)
2. **proton bremsstrahlung** $pp \to \gamma' X$
3. **Drell–Yan-like process** $q\bar{q} \to \gamma'$
4. **NEW pion bremsstrahlung** $\pi p \to \gamma' X$

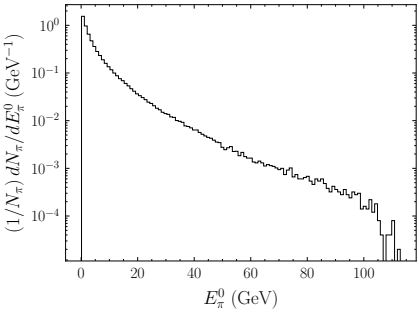


for $P = 120$ GeV, SpinQuest, Fermilab

D. Curtin, Y. Kahn, R. Nguyen Phys.Rev.D 108 (2023) 9, 095039

Pion bremsstrahlung

Secondary pions in the fixed-target experiments with proton beam: T2K, DUNE, SHiP et al.



for $P = 120$ GeV, SpinQuest, Fermilab

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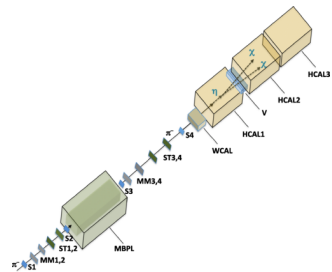
NA64h experiment: π^--beam with $P = 50$ GeV from CERN SPS. Dark photon searches in meson decays are planned



NA64 Collaboration Phys.Rev.Lett. 133 (2024) 12, 121803,

S. N. Gninenko, D. V. Kirpichnikov et al. Phys.Rev.D 109 (2024) 7, 075021

Half-off-shell pion electromagnetic form factor

When both pions are **on-shell**,

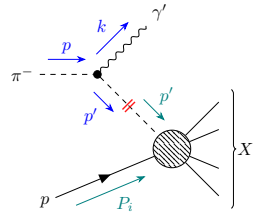
$$\left\langle \pi^-(p')\right| J^\mu_{\rm em}(0) \left|\pi^-(p)\right\rangle = \\ = -eF^\pi_{\rm em}((p'-p)^2)(p+p')^\mu \equiv -e\Gamma^\mu_0$$

Vertex function for **half-off-shell** case

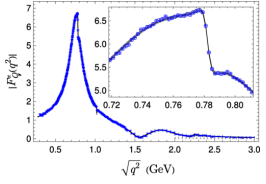
$$\Gamma^\mu_{1/2} = (p+p')^\mu F_1(-k^2, p'^2) - \\ - k^\mu \frac{(p'^2 - m_\pi^2)}{k^2}\left(F_1\left(0, p'^2\right) - F_1\left(-k^2, p'^2\right)\right)$$

Approximation using hadronic off-shell FF

$$F_1(-k^2, p'^2) \simeq F^\pi_{\rm em}((p'-p)^2) F_{\rm virt}(z, k^2_\perp)$$



$F^\pi_{\rm em}$ from BaBar data, $e^+e^- \to \pi^+\pi^-$



E. R. Arriola, P. Sanchez-Puertas
Phys.Rev.D 110 (2024) 5, 054003

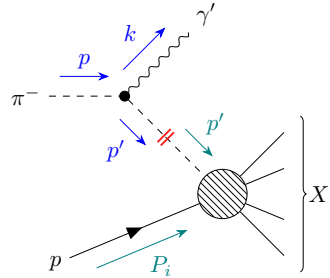
Splitting function for pion bremsstrahlung

Particles momenta in the lab frame

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

Differential cross section can be **factorized** as

$$\frac{\mathrm{d}^2\sigma_{\pi p\to\gamma' X}}{\mathrm{d}z\mathrm{d}k_\perp^2} = w_\pi(z, k_\perp^2)|F_{\mathrm{em}}^\pi(m_{\gamma'}^2)|^2 F_{\mathrm{virt}}^2(z, k_\perp^2)\sigma_{\pi p\to X}(\bar{s}),$$

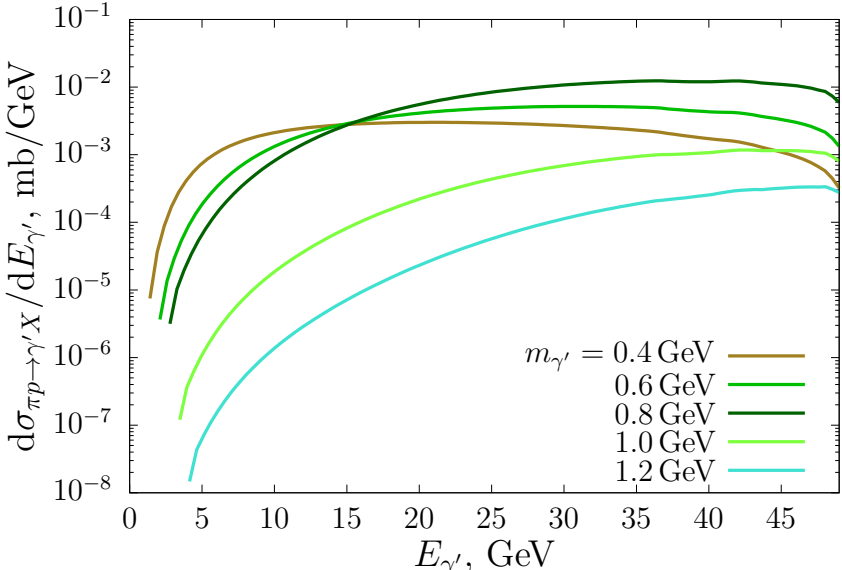


where **pion splitting function**

$$w_\pi(z, k_\perp^2) = \frac{\epsilon^2\alpha_{\mathrm{em}}(1-z)}{4\pi H_\pi}\left(\frac{H_\pi}{z m_{\gamma'}^2} + \frac{z}{H_\pi}\left(m_{\gamma'}^2 - 4m_\pi^2\right) + 2\right),$$

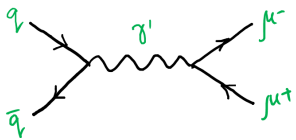
$$H_\pi \equiv m_\pi^2 z^2 + m_{\gamma'}^2(1-z) + k_\perp^2$$

Dark photons from pion bremsstrahlung in NA64h, $P = 50\,\mathrm{GeV}$



Drell–Yan-like process at LO and NLO

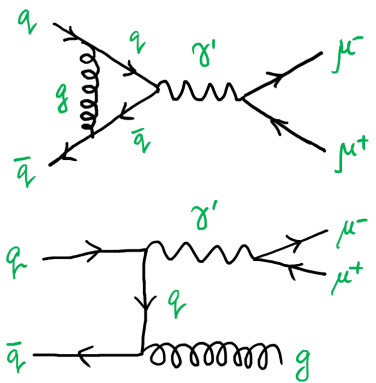
LO

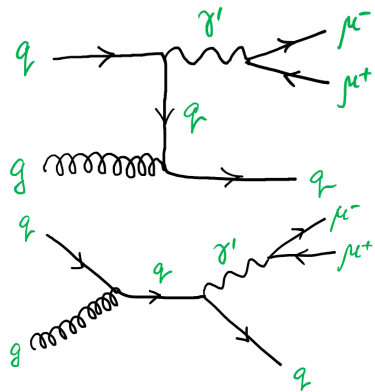


In **narrow width** approximation

$$\sigma(q\bar{q} \to \gamma') = \sigma(q\bar{q} \to \mu^+\mu^-)\frac{\Gamma_{\text{tot}}}{\Gamma(\gamma' \to \mu^+\mu^-)}$$

NLO





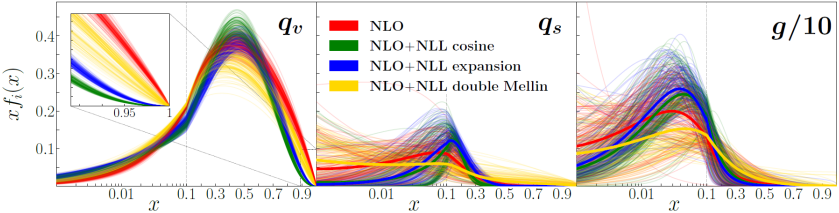
DY cross section in parton model

$$\frac{\mathrm{d}^2\sigma_{\mathrm{DY}}}{\mathrm{d}M^2\mathrm{d}x_F} = \frac{\mathrm{d}^2\sigma_{\mathrm{LO}}}{\mathrm{d}M^2\mathrm{d}x_F} + \frac{\mathrm{d}^2\sigma_{\mathrm{NLO}}}{\mathrm{d}M^2\mathrm{d}x_F},$$

$$\frac{\mathrm{d}^2\sigma_{\mathrm{LO}}}{\mathrm{d}M^2\mathrm{d}x_F} = \frac{4\pi\alpha_{\mathrm{em}}^2}{9}\frac{x_1x_2}{x_1+x_2}\frac{1}{(M^2-m_{\gamma'}^2)^2+m_{\gamma'}^2\Gamma_{\mathrm{tot}}^2}\times$$

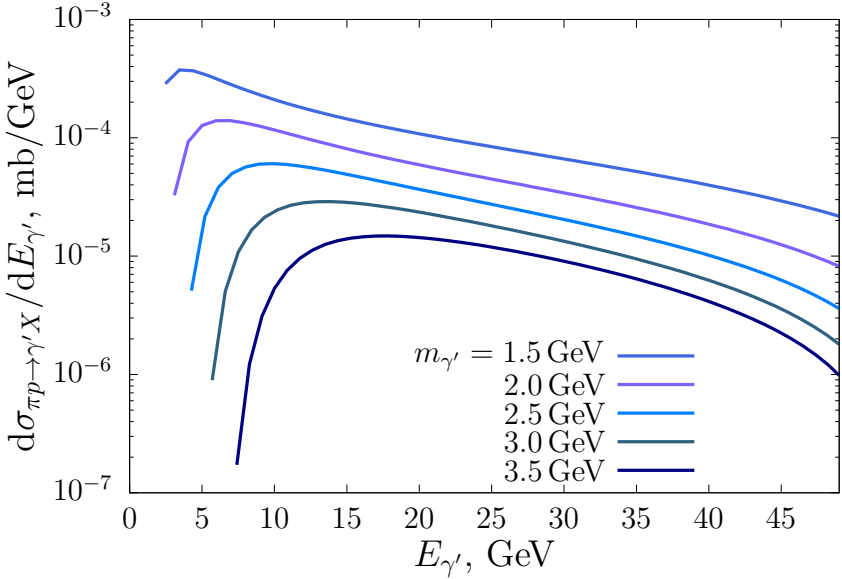
$$\times\sum_f e_f^2\left(q_f(x_1,M^2)\bar{q}_f(x_2,M^2)+\bar{q}_f(x_1,M^2)q_f(x_2,M^2)\right),$$

where M is the inv mass of $\mu^+\mu^-$, $x_F = x_1 - x_2$ is Feynman variable, $q_f(x,Q^2)$, $\bar{q}_f(x,Q^2)$ are taken from LHAPDF sets JAM21PionPDFnlo, CT14lo, CT14nlo

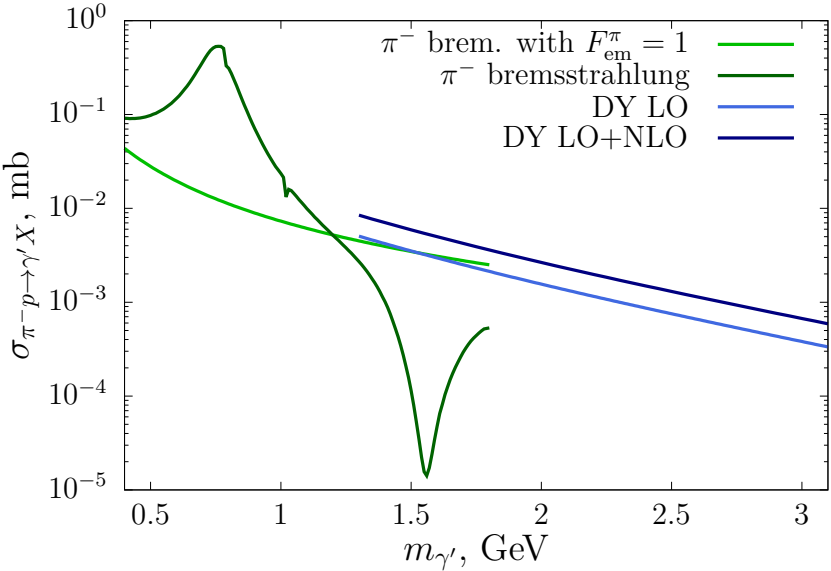


JAM Collaboration Phys.Rev.Lett. 127 (2021) 23, 232001

Dark photons from DY (LO+NLO) in NA64h, $P = 50\,\text{GeV}$



Full cross section of dark photon production



Results

- **New splitting function** for pion bremsstrahlung
- Predictions for **full cross section and spectra** of dark photons with masses $0.4-3.5$ GeV, produced in NA64h experiment
- For $m_{\gamma'} = 0.4-1.3$ GeV pion bremsstrahlung is **enhanced** by electromagnetic form factor and gives the important contribution to dark photon production