Dark photon emission in elastic proton bremsstrahlung

(based on arXiv:2306.15800)

Dmitry Gorbunov, **Ekaterina Kriukova**

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

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Dark photons

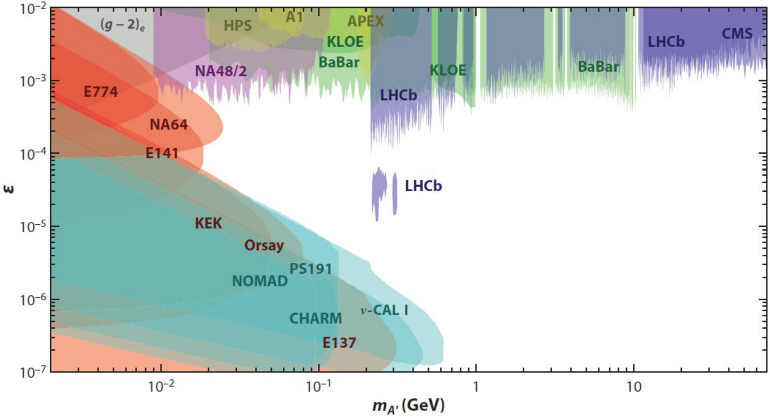
Portals — three ways to write down the renormalizable interaction of the SM fields with the hidden sector

- **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

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

Searches for γ' at accelerators



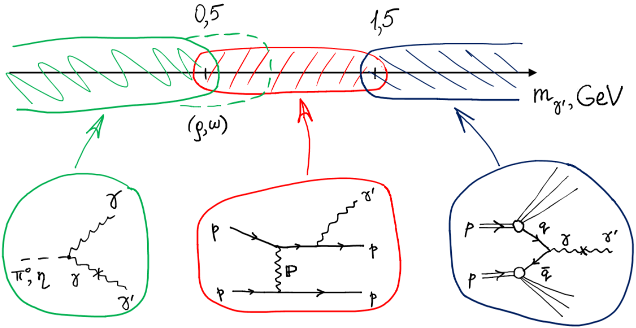
To **estimate the sensitivity** of the DUNE, T2K and SHiP experiments, one needs to study the phenomenology of $\mathcal{O}(1)$ GeV dark photon, in particular its **production modes**.

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

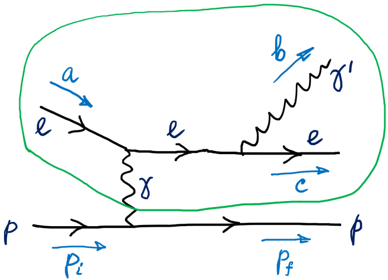
Mechanisms of γ' production

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

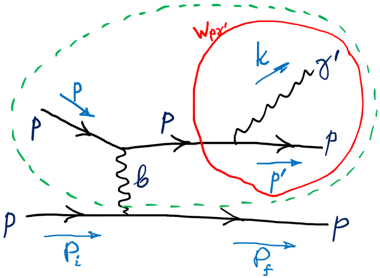
1. $m_{\gamma'} < 0.4$ GeV: **meson decays** $m \to \gamma'\gamma$ (m: π^0, η) due to mixing with the SM γ.
2. 0.4 GeV $< m_{\gamma'} < 1.8$ GeV: **proton bremsstrahlung**.
3. $m_{\gamma'} > 1.8$ GeV: **Drell-Yan process** $q\bar{q} \to \gamma'$.



Previously suggested methods



(a) Weizsäcker, Williams



(b) Blümlein, Brunner

K. J. Kim and Y. S. Tsai, Phys. Rev. D **8** (1973), 3109
J. Blümlein and J. Brunner, Phys. Lett. B **731** (2014), 320-326

Bremsstrahlung in *ep*-collisions

Generalized **Weizsacker-Williams approximation** for the process $e(a)p(P_i) \to \gamma'(b)e(c)p(P_f)$ with one γ-exchange

- photon propagator $\to \frac{1}{t^2}$
- the largest contribution is at $t_{\min}^{1/2} = \frac{(a \cdot b) - m_{\gamma'}^2/2}{a_0 - b_0}$, when $\vec{a} - \vec{b} \parallel \vec{c}$ in the lab frame
- in $2 \to 2$ subprocess γ is taken on-shell $(t = 0)$

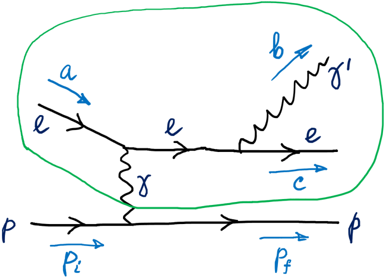
$$\left[\frac{\mathrm{d}^2\sigma(ep \to \gamma' ep)}{\mathrm{d}(a \cdot b)\,\mathrm{d}(b \cdot P_i)}\right]_{WW} = \left[\frac{\mathrm{d}\sigma(e\gamma \to \gamma' e)}{\mathrm{d}(a \cdot b)}\right]_{t=t_{min}} \frac{\alpha}{\pi}\frac{\chi}{(c \cdot P_i)},$$

- flux of photons emitted by the target

$$\chi = \int_{t_{\min}}^{t_{\max}} \frac{t - t_{\min}}{t^2} G_2(t)\mathrm{d}t$$

K. J. Kim and Y. S. Tsai, Phys. Rev. D **8** (1973), 3109

Previously suggested methods



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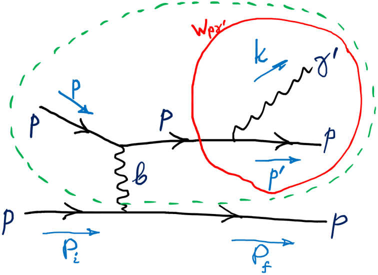

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J. Blümlein and J. Brunner, Phys. Lett. B **731** (2014), 320-326

Proton bremsstrahlung by Blumlein & Brunner

Now we compute the cross section of $pp \to \gamma' pp$

- consider pp interaction as the exchange of hypothetical massless **vector** particles b
- **in WW approximation** relate $\mathcal{M}(pp \to \gamma' pp)$ with the amplitude of $2 \to 2$ process $pb \to \gamma' p$
- set b momentum $q^\mu \equiv 0$ and extract the probability of subprocess $p \to \gamma' p$

$$\left[\frac{\mathrm{d}^2\sigma(pp \to \gamma' pp)}{\mathrm{d}z\mathrm{d}k_\perp^2}\right]_{BB} = w_{\gamma' p}(z, k_\perp^2)\sigma_{pp}(\bar{s}),$$

here **splitting function** for $p \to \gamma' p$ depends on $z \equiv k_z/p_z$ and $k_\perp^2$

$$w_{\gamma' p}(z, k_\perp^2) = \frac{\epsilon^2\alpha}{2\pi H}\left[\frac{1+(1-z)^2}{z} - 2z(1-z)\left(\frac{2M^2+m_{\gamma'}^2}{H} - z^2\frac{2M^4}{H^2}\right) + \right.$$
$$\left. +2z(1-z)(1+(1-z)^2)\frac{M^2 m_{\gamma'}^2}{H^2} + 2z(1-z)^2\frac{m_{\gamma'}^4}{H^2}\right],$$

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

Expected experimental constraints in γ' parameter space for invisible (left) and visible (right) decays

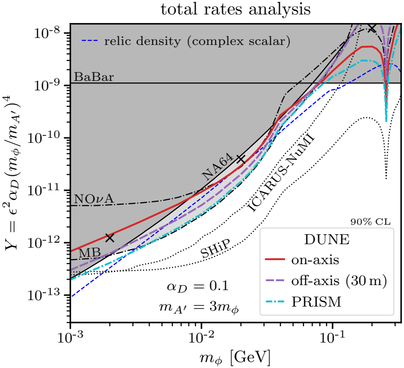


Figure: DUNE near detector (Fermilab), M. Breitbach et al., JHEP **01** (2022), 048

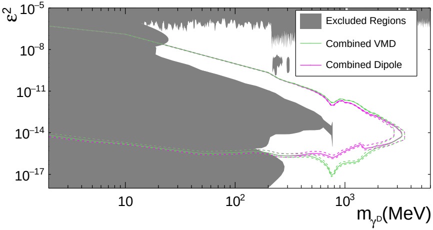
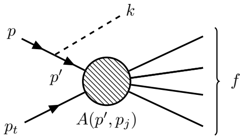


Figure: SHiP experiment (CERN), C. Ahdida et al., Eur. Phys. J. C **81** (2021) no.5, 451

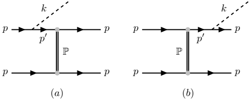
Proton bremsstrahlung is estimated using BB answer

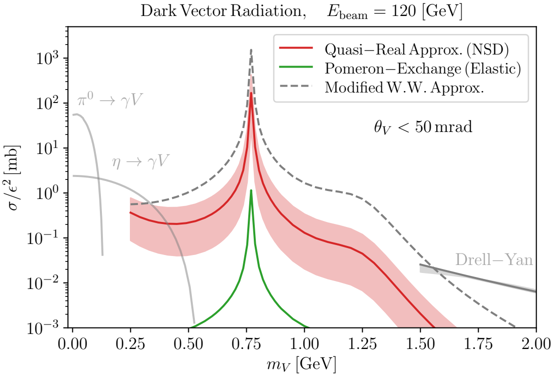
Proton bremsstrahlung by Foroughi-Abari & Ritz

- **Inelastic process:** initial state radiation



- **Elastic process:** vector pomeron exchange in WW approximation





Does NOT agree with BB

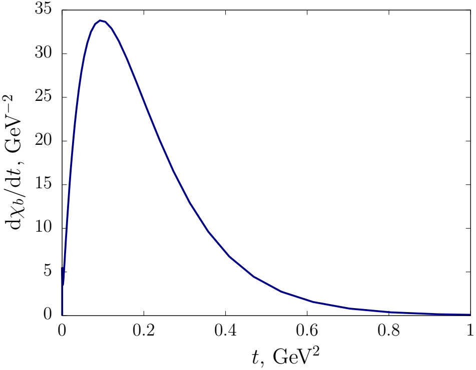
S. Foroughi-Abari and A. Ritz, Phys. Rev. D **105** (2022) no.9, 095045

Proton bremsstrahlung with $q \neq 0$

For the elastic process in the WW approximation ($t \equiv -q^2$) the differential flux of hypothetical bosons b

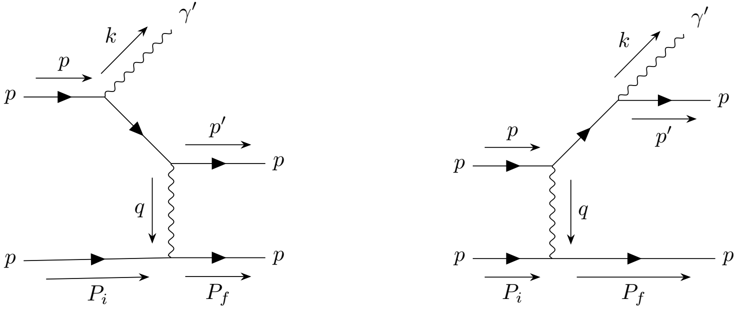
$$\frac{\mathrm{d}\chi_b}{\mathrm{d}t} = (t - t_{\mathrm{min}})\,|\mathcal{M}_{pp}|^2,$$

$|\mathcal{M}_{pp}|^2$ can be obtained from the data on elastic proton scattering



Max flux is at $\sqrt{t} \sim \Lambda_{\mathrm{QCD}} \Rightarrow$ we should consider the case $q \neq 0$

Bremsstrahlung with non-zero momentum transfer q, p.1



Particles momenta

$$P_i^\mu = \{M, 0, 0, 0\}, \quad p^\mu = \{P + \frac{M^2}{2P}, 0, 0, P\},$$

$$k^\mu = \{zP + \frac{m_{\gamma'}^2 + k_\perp^2}{2zP}, k_x, k_y, zP\},$$

$$p'^\mu = \{p'_0, -k_x - q_x, -k_y - q_y, P(1-z) - q_z\},$$

$$q^\mu = \{q_0, q_x, q_y, q_z\}.$$

Bremsstrahlung with non-zero momentum transfer q, p.2

Matrix element

$$i\mathcal{M} = -i\epsilon e Q_b^2 L^\nu \frac{-ig_{\nu\lambda}}{q^2} J^\lambda$$

Incident proton current

$$L_\nu = \epsilon^{*\mu}_{\gamma'}(k)\bar{u}(p')\left(\gamma_\nu \frac{\hat{p}-\hat{k}+M}{(p-k)^2-M^2}\gamma_\mu + \gamma_\mu \frac{\hat{k}+\hat{p}'+M}{(k+p')^2-M^2}\gamma_\nu\right)u(p)$$

makes **hadronic tensor #1**, $L_{\mu\nu} \equiv L_\mu L_\nu^*$
Hadronic tensor #2, $W^{\mu\nu} \equiv J^\mu J^{*\nu}$, is made of target proton current

$$W^{\mu\nu} = \left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right)W_1 + \frac{1}{M^2}\left(P_i^\mu - \frac{q_\lambda P_i^\lambda}{q^2}q^\mu\right)\left(P_i^\nu - \frac{q_\rho P_i^\rho}{q^2}q^\nu\right)W_2$$

Averaged square of the matrix element

$$\overline{|\mathcal{M}|^2} = \frac{1}{4}\epsilon^2 e^2 Q_b^4 \frac{L_{\mu\nu}W^{\mu\nu}}{(q^2)^2} \simeq \frac{1}{4}\epsilon^2 e^2 Q_b^4 \frac{L_{00}W_2}{(q^2)^2}$$

Final result: diff. cross section for $pp \to pp\gamma'$ if $q \neq 0$

$$\frac{\mathrm{d}^2\sigma\left(pp \to pp\gamma'\right)}{\mathrm{d}k_\perp^2\,\mathrm{d}z} = \frac{\epsilon^2 \alpha I}{32\left(2\pi\right)^2 zP\tilde{S}^2\sqrt{P^2(1-z)^2+k_\perp^2}},$$

where we integrate over $t \equiv -q^2$

$$I \equiv \int_{t_{\text{min}}}^{t_{\text{max}}} \mathrm{d}t \left| T_+ + T_+^c \right|^2 B(t)$$

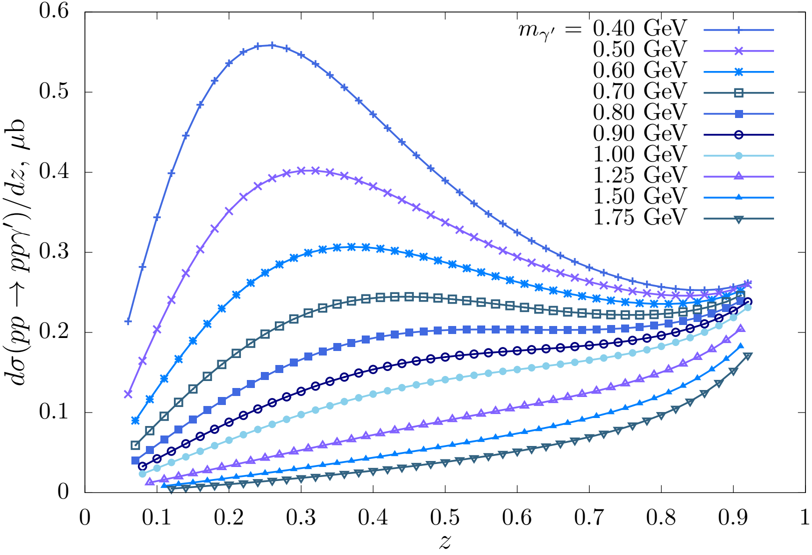
and the integrand now **explicitly** depends on t

$$B(t) \equiv -b_0 - \frac{b_1 t}{2M} + b_4 t + \left(b_2 + \frac{b_5 t}{2M}\right)\frac{k_\perp^2 |\vec{q}| \cos\hat{\theta}_q}{\sqrt{P^2(1-z)^2+k_\perp^2}} -$$

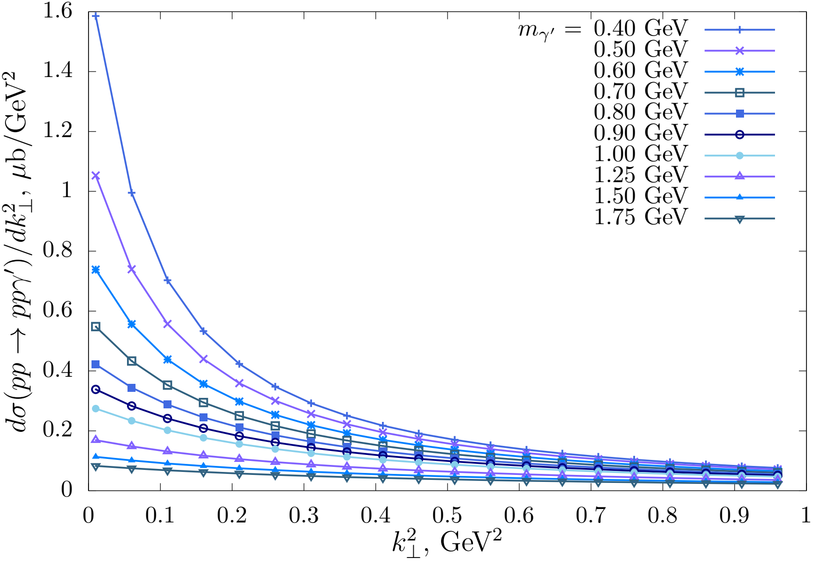
$$-\frac{b_3 k_\perp^2}{P^2(1-z)^2+k_\perp^2}\left[\frac{t}{2}\left(\frac{t}{4M^2}+1\right)P^2(1-z)^2 + \right.$$

$$\left. + |\vec{q}|^2 \cos^2\hat{\theta}_q \left(k_\perp^2 - \frac{P^2}{2}(1-z)^2\right)\right].$$

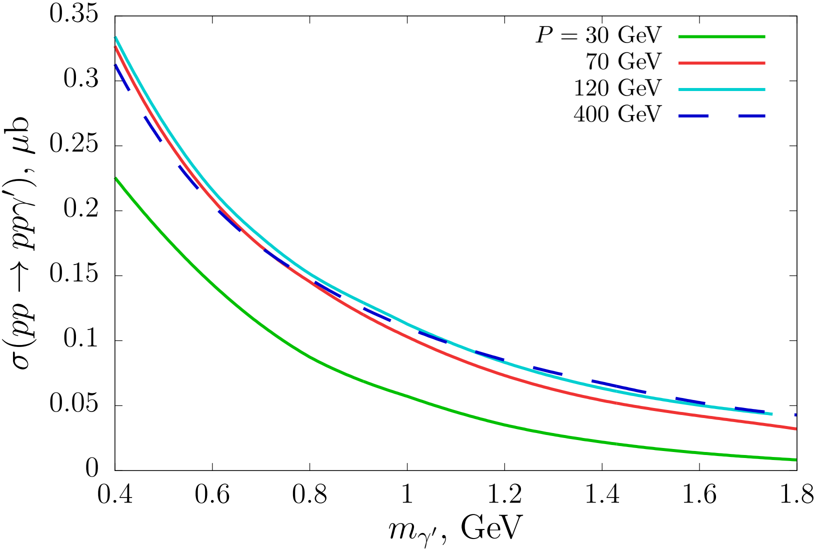
Differential cross section depending on the ratio $z \equiv k_z/p_z$



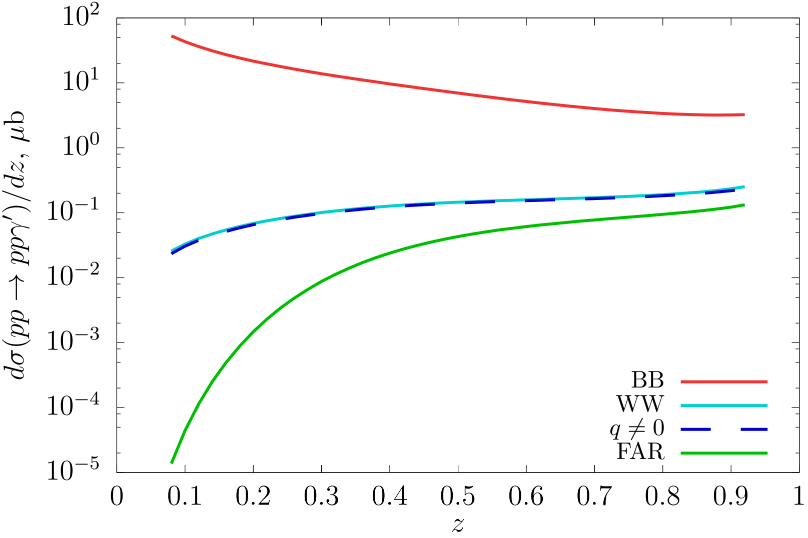
Differential cross section depending on the $k_\perp^2$



Full cross section depending on the dark photon's mass

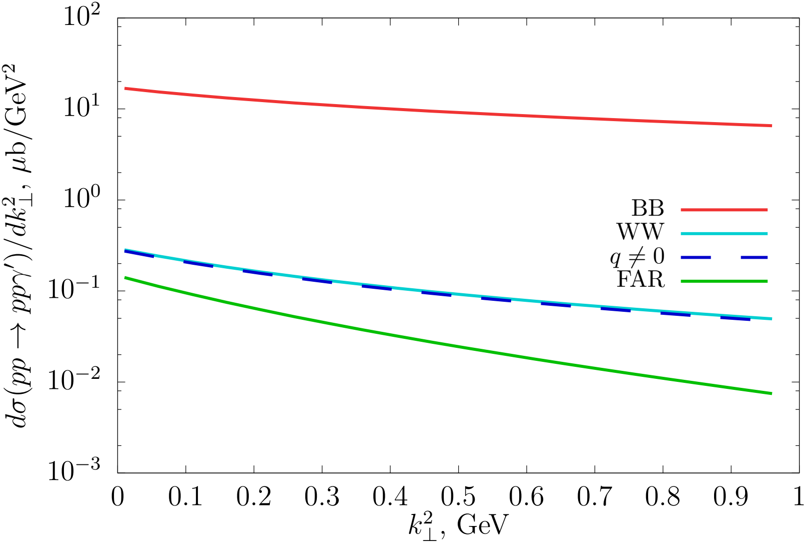


Comparison with other works: differential cross section p.1



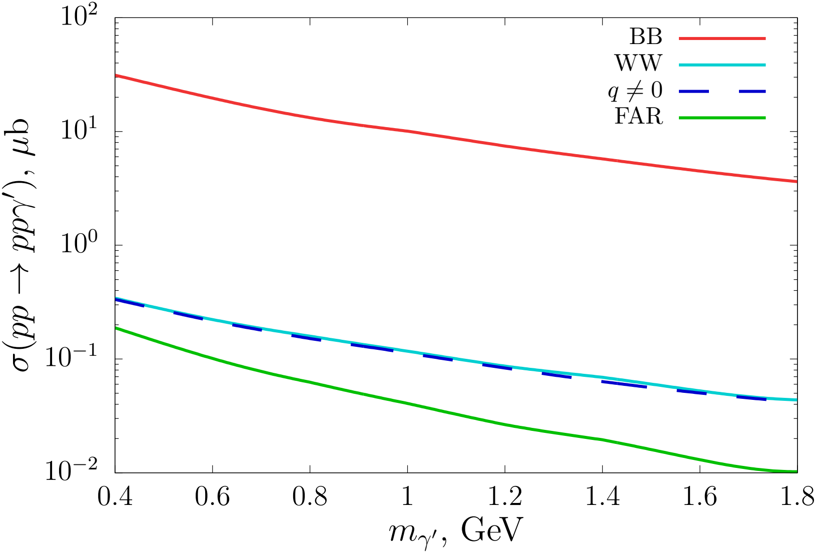
for dark photon mass $m_{\gamma'} = 1$ GeV and incident proton momentum $P = 120$ GeV

Comparison with other works: differential cross section p.2



for dark photon mass $m_{\gamma'} = 1$ GeV and incident proton momentum $P = 120$ GeV

Comparison with other works: full cross section



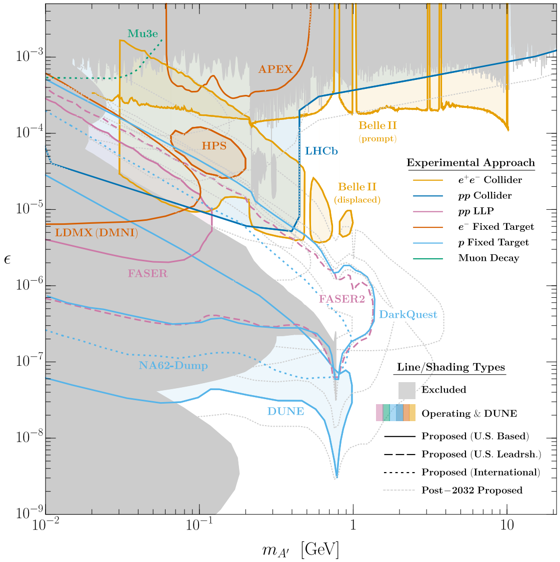
for incident proton momentum $P = 120$ GeV

Conclusions and future plans

- We have obtained the elastic bremsstrahlung cross section considering the **non-zero momentum transfer** between incident and target protons
- Our result **agrees** well with the WW approximation
- WW approximation **is applicable** to protons and can give reliable results

- Accurate consideration of **tensor Pomeron** exchange?
- Corrections due to exchange of **virtual Δ** instead of p^*?
- Initial state radiation in **inelastic** bremsstrahlung?

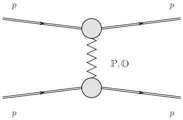
Future dark photon searches



B. Batell et al., 2022 Snowmass Summer Study, arXiv:2207.06905.

Is pomeron a vector, tensor or scalar particle?

- **Donnachie-Landshoff's pomeron**: in the high-energy limit at $pp \to pp$, $p\bar{p} \to p\bar{p}$



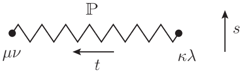
$$\left\langle p(p_1'), p(p_2') \right| \mathcal{T} \left| p(p_1), p(p_2) \right\rangle = \\ = iC(-is\alpha'_{\mathbb{P}})^{\alpha_{\mathbb{P}}(t)-1} \bar{u}(p_1')\gamma^\mu u(p_1)\bar{u}(p_2')\gamma_\mu u(p_2)$$

$$\left\langle \bar{p}(p_1'), p(p_2') \right| \mathcal{T} \left| \bar{p}(p_1), p(p_2) \right\rangle = \\ = iC(-is\alpha'_{\mathbb{P}})^{\alpha_{\mathbb{P}}(t)-1} \bar{v}(p_1')\gamma^\mu v(p_1)\bar{u}(p_2')\gamma_\mu u(p_2)$$

- The structure is $\gamma^\mu \otimes \gamma_\mu \Rightarrow$ effectively exchange of "**vector** particles" with $C = +1$. Well describes experimental data, but there are problems at high energies.
- **Tensor** pomeron model: the same coupling to p and $\bar{p}$, in the high energy limit the same behaviour as of DL-pomeron.
C. Ewerz, M. Maniatis and O. Nachtmann, Annals Phys. **342** (2014), 31-77

Effective vertex and pomeron propagator

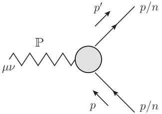
- Propagator $\mathbb{P}$



$$i\Delta^{\mathbb{P}}_{\mu\nu,\kappa\lambda} = \frac{1}{4s}\left(g_{\mu\kappa}g_{\nu\lambda} + g_{\mu\lambda}g_{\nu\kappa} - \frac{1}{2}g_{\mu\nu}g_{\kappa\lambda}\right)(-is\alpha'_{\mathbb{P}})^{\alpha_{\mathbb{P}}(t)-1}$$

$$\alpha_{\mathbb{P}}(t) = 1 + \epsilon_{\mathbb{P}} + \alpha'_{\mathbb{P}}t$$

- Vertex $\mathbb{P}NN$ (N: p, n, $\bar{p}$)

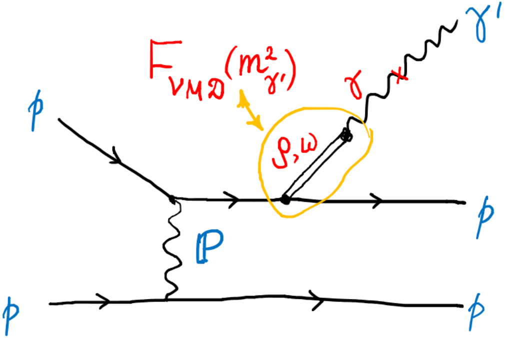


$$i\Gamma^{\mathbb{P}NN}_{\mu\nu} = -iC'\left(\gamma_\mu(p'+p)_\nu + \gamma_\nu(p'+p)_\mu - \frac{1}{2}g_{\mu\nu}(\hat{p}'+\hat{p})\right)$$

- Another point of view: consider the amplitude of **scalar** exchange (experimentally excluded?)
  C. Ewerz, M. Maniatis and O. Nachtmann, Annals Phys. **342** (2014), 31-77
  C. Ewerz, P. Lebiedowicz, O. Nachtmann and A. Szczurek, Phys. Lett. B **763** (2016), 382-387

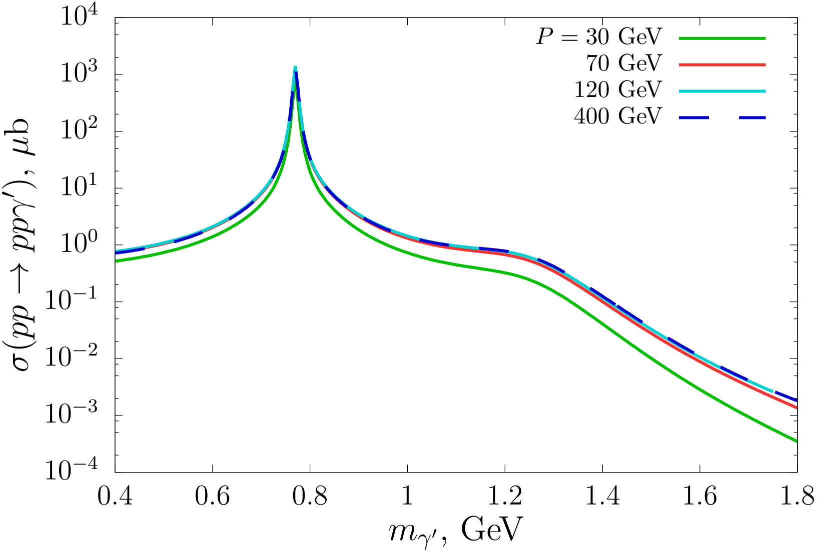
VMD (vector meson dominance) form factor

$$F_{VMD}(m^2_{\gamma'}) = \sum_i \frac{f_i m_i^2}{m_i^2 - m^2_{\gamma'} - i m_i \Gamma_i}$$

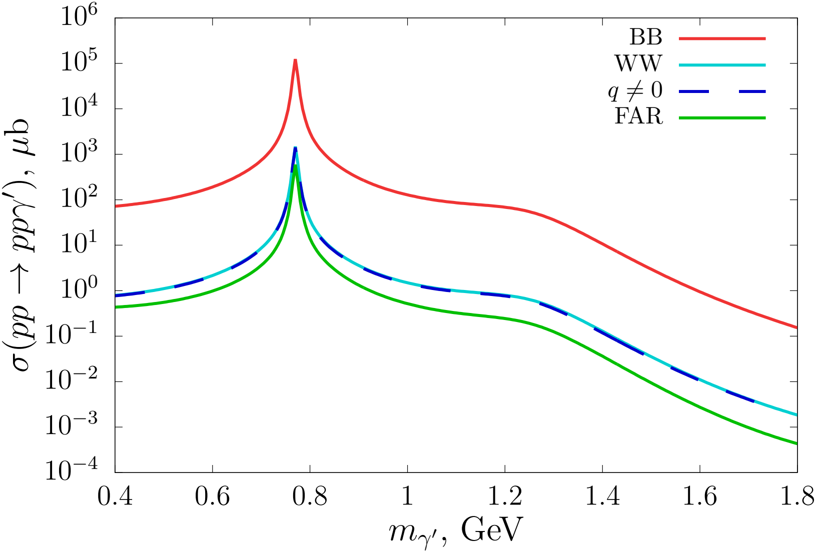


A. Faessler, M. I. Krivoruchenko and B. V. Martemyanov, Phys. Rev. C **82** (2010), 038201

Full cross section depending on the dark photon's mass with VMD form factor



Comparison with other works: full cross section with VMD form factor



for incident proton momentum $P = 120$ GeV