Testing Dark Photon Scenarios @ LHCb

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Implications of LHCb measurements and future prospects
CERN 23-25 Oct. 2024

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based on: EPJC 84 (2024) 5,460; 2402.05901 [hep-ph]

Motivations

- Belle II collaboration has recently observed the rare decay

$B^+ \to K^+ \nu\bar{\nu}$ with **3.5σ** significance

Belle II Coll.
PRD 109, 112006 (2024)

$$\mathrm{BR}(B^+ \to K^+ \nu\bar{\nu})_{\mathrm{had}} = \left(1.1^{+0.9+0.8}_{-0.8-0.5}\right) \times 10^{-5},$$

$$\mathrm{BR}(B^+ \to K^+ \nu\bar{\nu})_{\mathrm{incl}} = (2.7 \pm 0.5 \pm 0.5) \times 10^{-5}$$

- An excess with respect to the SM predictions has been observed

$$\mathrm{BR}(B^+ \to K^+ \nu\bar{\nu})_{\mathrm{exp}} = (2.3 \pm 0.7) \times 10^{-5}$$ → average

$$\mathrm{BR}(B^+ \to K^+ \nu\bar{\nu})_{\mathrm{SM}} = (4.29 \pm 0.23) \times 10^{-6}$$ ⇨ pure FCNC

W. Parrot, et al, PRD 107, 014511 (2023)

⇩

long distance contributions from $B^+ \to \tau^+(\to K^+\bar{\nu})\nu$ subtracted

⇨ **2.7σ** discrepancy (mainly given by inclusive-tag result, had-tag result is consistent with SM)

- If this excess is due to New Physics (NP) beyond the SM, then

$$\mathrm{BR}(B^+ \to K^+ \nu\bar{\nu})_{\mathrm{NP}} = (1.9 \pm 0.7) \times 10^{-5}$$

- Two potential NP scenarios considered :

Indirect-NP effects → related to the presence of **heavy NP particles** affecting FCNC operators b → s + neutrinos (SMEFT)

Direct-NP effects → related to the presence of invisible **light NP particles** X produced along B+ → K+ transitions that can mimic neutrinos missing energy (dark sector origin)

↓ considered here

$$B^+ \to K^+ X$$

⇩ Favored X mass of order of few GeV

resonant missing energy (Emiss)

$$B^+ \to K^+ X \bar{X}$$

⇩

continuum missing energy

- We focus on the possibility that this excess is due to a dark X emission

$$B^+ \to K^+ X \bar{X}$$

  and analyze its phenomenological implications for LHCb searches

- We assume existence of X as (light) Dark Fermions, SM singlets, charged under an unbroken $U(1)_D$ gauge interaction in the dark sector, predicting a massless Dark Photon mediating long range forces between dark particles

- massless DP scenarios might help to solve several phenomenological problems in astroparticle and cosmology (small-scale structure formation problems, dark discs of galaxies, etc.), as well as the SM flavor hierarchy problem

- Intense searches for DP are carried out by various experiments, mainly massive DP scenario which is strongly constrained for DP masses below GeV

  2005.01515 [hep-ph]

- massless DP scenario is mainly unconstrained due to the fact that it does not interact at tree-level with SM sector → dedicated searches in lab experiments are required

- Large U(1) couplings in dark sector are viable for a massless DP

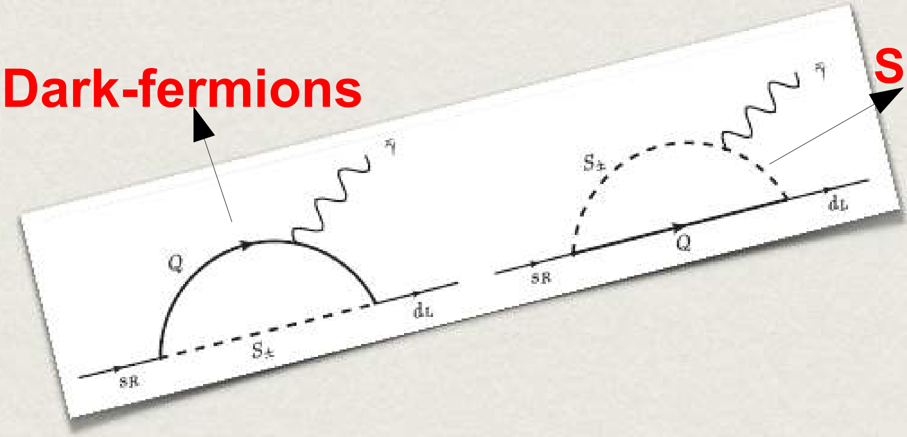
massless dark photon (invisible)

the **massless** dark photon is not
the massless limit of the **massive** dark photon

Holdom, PLB 166, 196 (1986)

no tree-level couplings with SM fermions (can be rotated away)

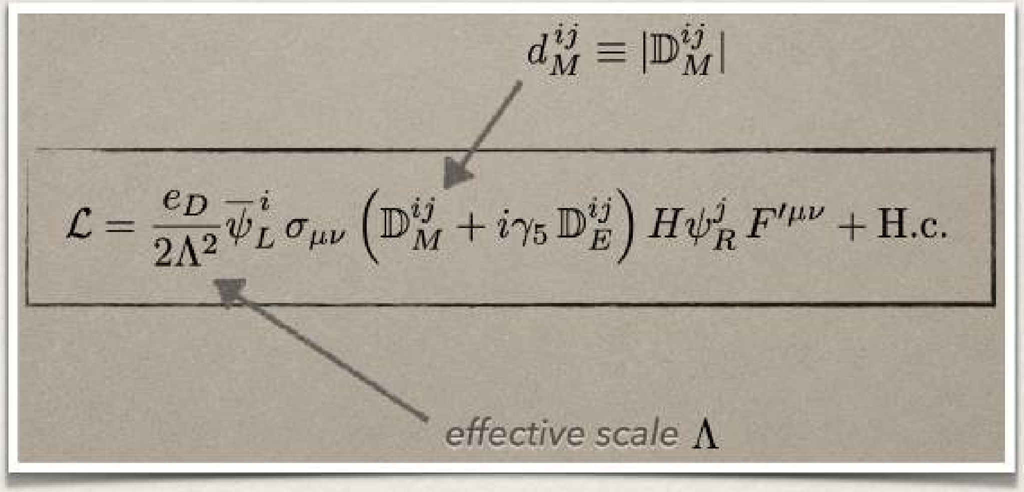
we need a specific benchmark



Dark-fermions

Scalar-messengers

coupling to SM particles induced at 1-loop



$$d_M^{ij} \equiv |\mathbb{D}_M^{ij}|$$

$$\mathcal{L} = \frac{e_D}{2\Lambda^2} \bar{\psi}_L^i \, \sigma_{\mu\nu} \left(\mathbb{D}_M^{ij} + i\gamma_5 \, \mathbb{D}_E^{ij} \right) H \psi_R^j \, F'^{\mu\nu} + \text{H.c.}$$

effective scale Λ

B.A. Dobrescu [hep-ph/0411004]

EG et al, PRD 94 (2016);
1607.05928 [hep-ph]

only **massive** dark-photon can have tree-level couplings with SM fermions via kinetic mixing

- Same loop-induced couplings holds also for massive DP

Simplified theoretical framework

- Assume existence of N light Dark Fermions (Q_i) in the DS
- charged under an unbroken $U(1)_D$ (analogy with QED interactions)

- massless Dark Photon (A_D) in the spectrum

$$\mathcal{L}_{dark} = e_D \sum_i q_i \left[\bar{Q}_i \gamma_\mu Q_i\right] A^\mu_D$$

→ Tree-level DP couplings with its own dark sector

$$\mathcal{L}_{eff} = \frac{1}{2\Lambda} \left[\bar{s}\sigma_{\mu\nu} b\right] F^{\mu\nu}_D + h.c.$$

→ Dark-magnetic-dipole operator for FCNC b → s transitions

(possible also for massive DP)

Λ → Effective scale

$$F^{\mu\nu}_D = \partial^\mu A^\nu_D - \partial^\nu A^\mu_D$$

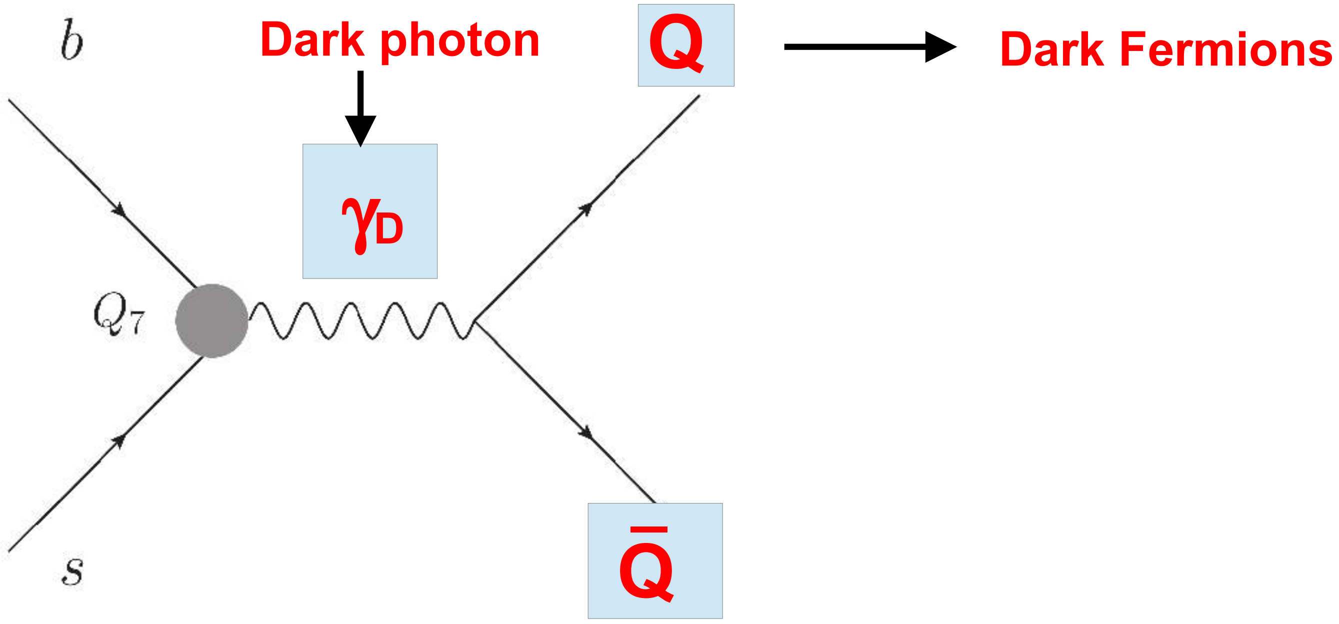
$$\alpha_D = e^2_D / 4\pi$$

q_i → U(1) quantum charges

$B^+ \to K^+ \, Q\bar{Q}$

at quark level

$$Q_7 = [\bar{s}\sigma_{\mu\nu} b] \, F_D^{\mu\nu}$$



Due to angular momentum conservation

$B^+ \to K^+ \, \gamma_D$ ⇨ **FORBIDDEN for a "massless" Dark Photon**

→ avoid constraints from $B^+ \to K^+$ + resonant missing Energy

$B^0 \to K^* \, \gamma_D$ ⇨ **ALLOWED also for a "massless" Dark Photon**

$B^+ \to K^+ \, Q\bar{Q}$

Quantum amplitude

$$\mathcal{M} = \frac{-ie_D}{\Lambda} \boxed{\langle K|[\bar{s}\sigma_{\mu\nu}b]|B\rangle \frac{q^\nu}{s}} [\bar{Q}\gamma^\mu Q]$$

$$\boxed{\langle K(p_K)|\,[\bar{s}\sigma_{\mu\nu}q^\nu b]\,|B(p_B)\rangle} = i\Big[(p_B+p_K)_\mu s - q_\mu(m_B^2-m_K^2)\Big]\frac{f_T(s)}{m_B+m_K}$$

$f_T(s)$ → Form factor estimated using Light-Cone sum rules approach

C.Bobbet, et al. JHEP 01, (2012) 107

s $\longrightarrow$ $Q\bar{Q}$ invariant mass square

Tree-level result for the total BR (1 dark fermion with unit charge)

$$\boxed{\mathrm{BR}(B^+ \to K^+ Q\bar{Q}) \simeq 5.43 \times 10^{-6}\left(\frac{10^5\,\mathrm{TeV}}{\Lambda}\right)^2 \times \alpha_D}$$

Relevant radiative corrections included:

- **Sommerfeld-Fermi** corrections induced by $U(1)_D$ interactions

$$d\Gamma^K_{\rm SF} = \Omega(\beta_{12})\, d\Gamma^K\,,$$

SF correction factorizes

$$\boxed{\Omega(\beta_{12}) = \frac{2\pi\alpha_D q_i^2}{\beta_{12}}\,\frac{1}{1-\exp\left[-\frac{2\pi\alpha_D q_i^2}{\beta_{12}}\right]}}$$

$$\beta_{12} = \sqrt{1-\frac{m_Q^4}{(s-2m_Q^2)^2}}$$

gives large contribution for large α_D , especially at threshold

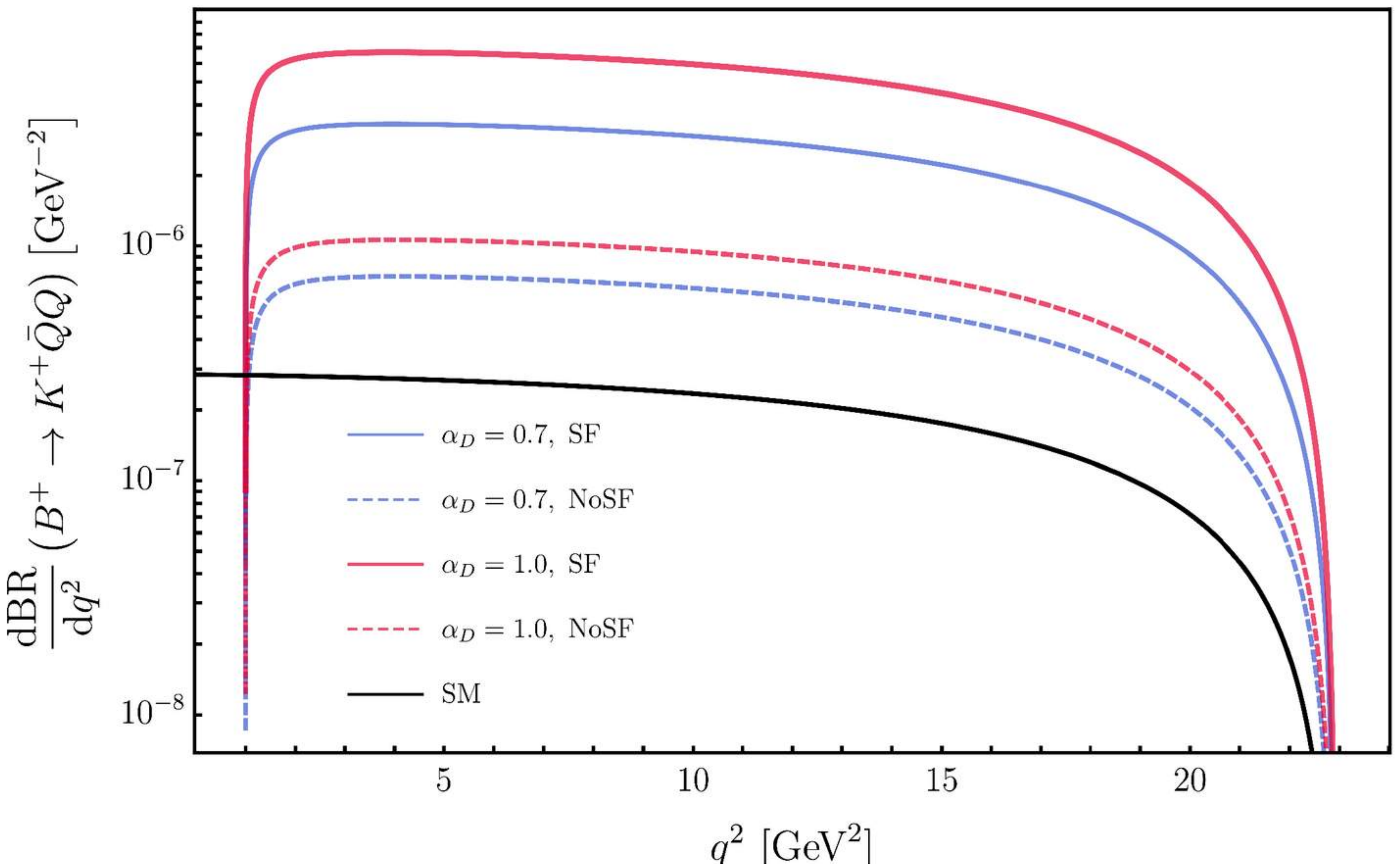
- Dark dipole corrections (give small contributions)

$$\lambda(\hat s) \to \lambda(\hat s)\left[1+\Delta_M(\hat s)\right]$$

$$F_2(\hat s) = \frac{\alpha_D}{2\pi}\frac{\hat m_Q}{\sqrt{\hat s(\hat s-4\hat m_Q^2)}}\log\left[\frac{2\hat m_Q^2-\hat s+\sqrt{\hat s(\hat s-4\hat m_Q^2)}}{2\hat m_Q^2}\right]$$

$$\boxed{\Delta_M(\hat s) = 4\hat m_Q\,{\rm Re}\left[F_2(\hat s)\right]+\frac{1}{3}\left|F_2(\hat s)\right|^2\left(\hat s+8\hat m_Q^2\right)}$$

Sommerfeld-Fermi corrections



Tree-level result for the total BR (1 dark fermion with unit charge)

$$\mathrm{BR}(B^0 \to K^* \gamma_D) = 2.47 \times 10^{-5} \left(\frac{10^5\,\mathrm{TeV}}{\Lambda} \right)^2$$

Form factor estimated using Light-Cone sum rules approach

C.Bobbet, et al. JHEP 01, (2012) 107

- Expected signature → resonant monochromatic missing energy peaked at

$$E_{\gamma_D} = E_{\mathrm{miss}} = 2.56\,\mathrm{GeV}$$

dedicated analysis for such a signature are required, not available at moment.
BR in the ballpark of sensitivity of future LHCb experiments

- So, we use limits on BR(B → K* + Emiss) from Belle II to set bounds on Λ

$$\mathrm{BR}(B^0 \to K^* \nu \bar{\nu}) < 2.7 \times 10^{-5} \text{ at } 90\% \text{ C.L.}$$

$$\Lambda \geq 9.56 \times 10^4\,\mathrm{TeV}$$

32 times stronger than from

$$\mathrm{BR}(b \to s X_{\mathrm{inv}}) < \mathcal{O}(10\%)$$

Fitting the $B^+ \to K^+ \nu\bar{\nu}$ excess

We assume the inclusive production of N_Q number of dark fermions

Dependece from the scale Λ
cancels out in the ratio

$$\frac{\mathrm{BR}(B^0 \to K^* \gamma_D)}{\mathrm{BR}(B^+ \to K^+ Q_X \bar{Q}_X)_{\mathrm{SF}}} \simeq \frac{0.72}{N_Q}$$

for $\alpha_D \sim \mathcal{O}(1)$

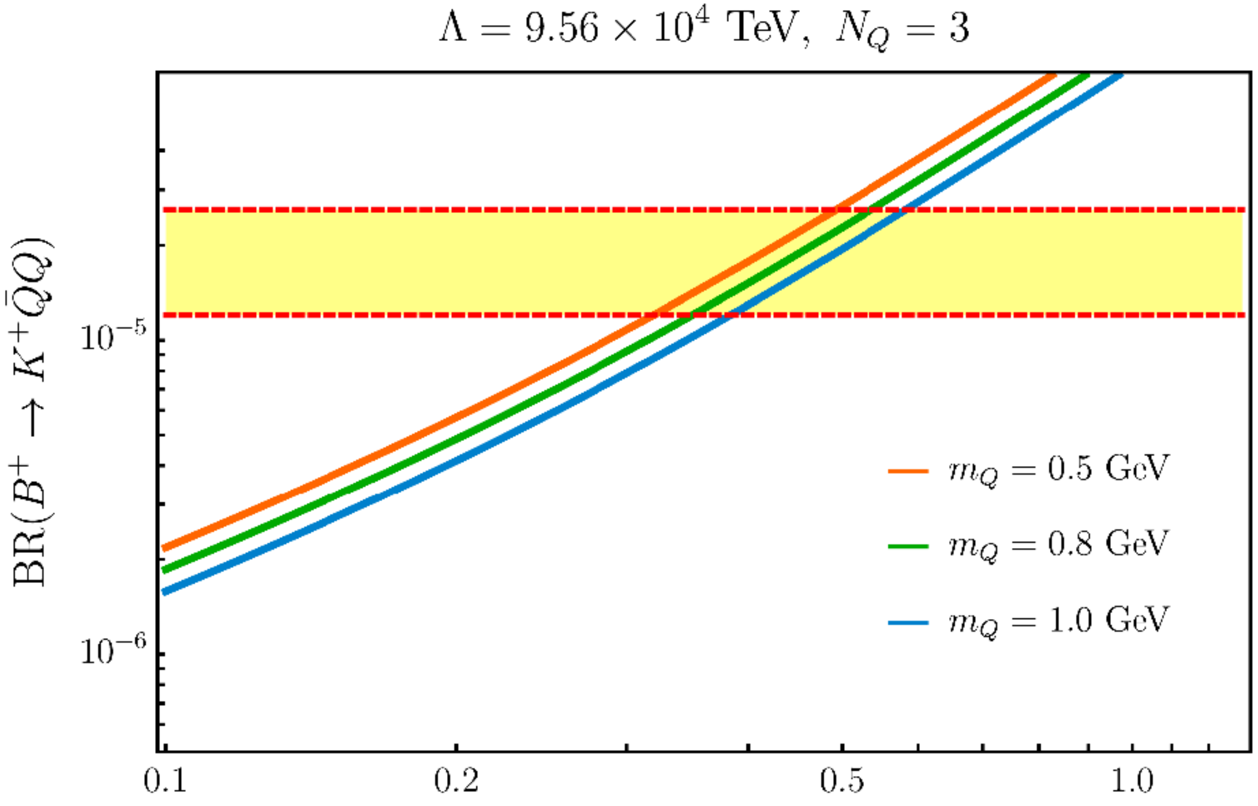
assuming $B^+ \to K^+ Q_X Q_X$ as full source of NP required to explain the excess

$$\mathrm{BR}(B^+ \to K^+ Q_X \bar{Q}_X) = \mathrm{BR}(B^+ \to K^+ + \mathrm{inv})_{\mathrm{NP}} \sim 1.9 \times 10^{-5}$$

$$\mathrm{BR}(B^0 \to K^* \gamma_D) \simeq \frac{1.37}{N_Q} \times 10^{-5}$$

then imposing $\mathrm{BR}(B^0 \to K^* \nu\bar{\nu}) < 2.7 \times 10^{-5}$ → $N_Q \geq 1$

- the larger the number of dark fermions the smaller the α_D required to explain the excess, compatible with perturbation theory!

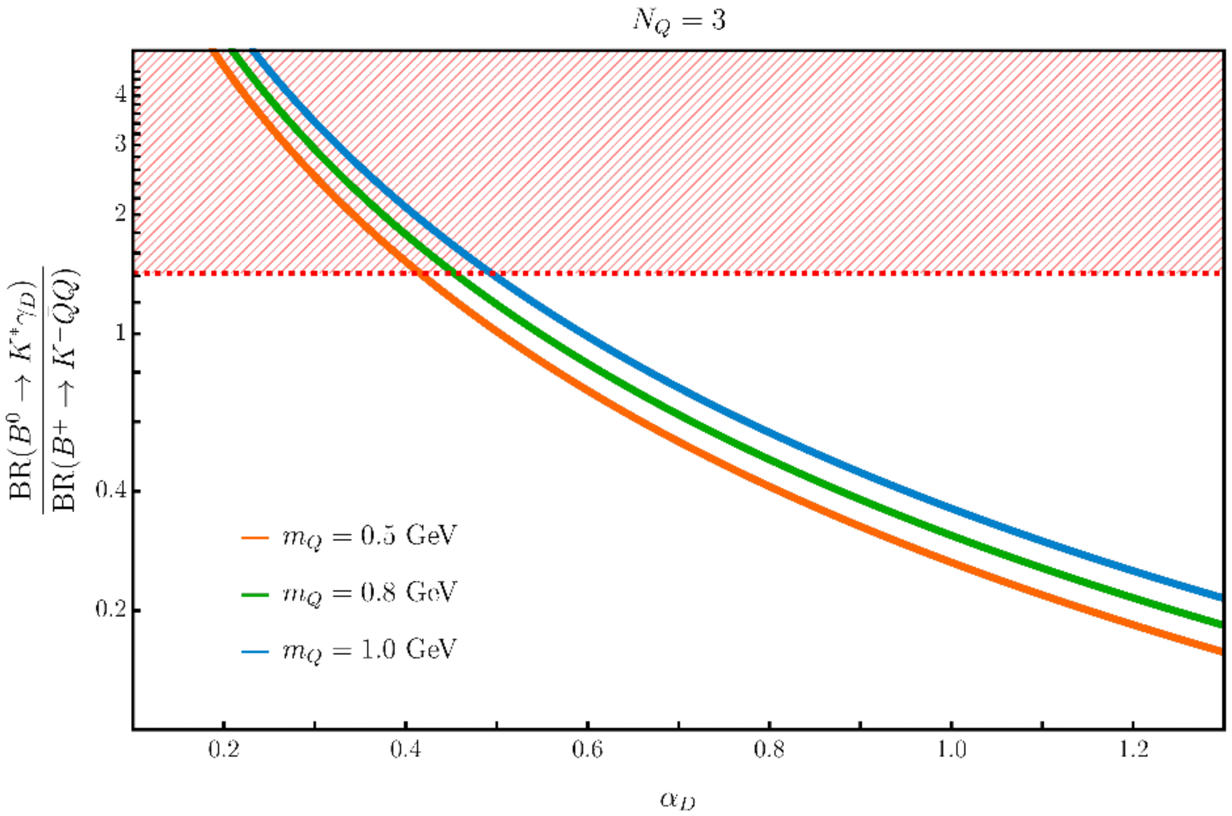


Yellow band stands for NP contribution fitting the Belle II excess at 95%CL

- Massless Dark Photon scenario can fit Belle II excess for dark fermion masses

  $M_Q \sim 0.5$ - 1 GeV and $\alpha_D \sim 0.3$-0.5

- A strongly coupled but still perturbative $U(1)_D$ sector is required



scale Λ cancel out in the ratios of Brs

- Dashed line corresponds to central value of BR(B+ → K+ QQ) for NP interpretation of Belle II excess

- Hatched area indicates regions excluded by

$$\mathrm{BR}(B^0 \to K^* \nu \bar{\nu}) < 2.7 \times 10^{-5}$$

Predicting a possible signal in B_s^0 decays

- The same b → s dark-magnetic-dipole operator can contribute to other processes

$$B_s^0 \to \phi\,\gamma_D$$

providing NP contribution to $B_s^0 \to \phi \nu \bar{\nu}$

$$\mathrm{BR}(B_s^0 \to \phi \nu \bar{\nu})_{\mathrm{SM}} = (1.4 \pm 0.4) \times 10^{-5}$$

continuum Emiss

P. Colangelo et. al.
PRD 77 (2008) 055019

$$B_s^0 \to \phi + \mathrm{E}_{\mathrm{miss}}$$

with a resonant $E_{\mathrm{miss}} = 2.59\ \mathrm{GeV}$ in the B meson rest frame

$$\mathrm{BR}(B_s^0 \to \phi \nu \bar{\nu})_{\mathrm{exp}} < 5.4 \times 10^{-3}$$

actual limit is from LEP experiments

DELPHI Coll. , Z Phys C 72 (1996) 207

Using the measured ratio at LHCb

$$R_{K^*\phi} = \frac{\mathrm{BR}(B^0 \to K^*\gamma)}{\mathrm{BR}(B^0_s \to \phi\gamma)} = 1.23\ (6)_{\mathrm{stat}}\ (4)_{\mathrm{syst}}\ (10)_{f_s/f_d}$$

one can extract the relevant form factors for predicting the BR($B^0_s \to \phi\,\gamma_D$)

EW corrections

$\delta_{WA} \simeq 0.02$

$$r_{K^*\phi} = \frac{T_1^{B^0\to K^*}}{T_1^{B^0_s\to\phi}}$$

⇒

$$R_{K^*\phi} = |r_{K^*\phi}|^2 C_{K^*\phi}\,(1+\delta_{WA})$$

$$C_{K^*\phi} = \frac{\tau_{B^0}}{\tau_{B^0_s}}\left(\frac{m_B}{m_{B_s}}\right)^3\left(\frac{1-m^2_{K^*}/m^2_B}{1-m^2_\phi/m^2_{B_s}}\right)^3 = 1.01$$

$$\mathrm{BR}(B^0_s \to \phi\gamma_D) = 4.02\times 10^{-5}\left(\frac{10^5\,\mathrm{TeV}}{\Lambda}\right)^2$$

for Λ value saturating limits on B→ K* νν ⇒

$$\mathrm{BR}(B^0_s \to \phi\gamma_D) \lesssim 2\times 10^{-5}$$

a BR which is in the ballpark of LHCb sensitivity

Summary

- Belle II excess in B+ → K+ νν can be explained by invisible dark fermions production via B+ → K+ QQ mediated by an off-shell dark photon (DP)
- We consider benchmark mass values of dark fermions of order 500 MeV that can also avoid cosmological and astrophysical constraints
- Large but still perturbative dark photon couplings in the dark sector are required
- If this mechanism is responsible for the Belle II excess two NP signals expected: **Bs → φ + DP** and **B → K* + DP** → corresponding BRs are correlated ~ $O(10^{-5})$
- The expected signature in both channels has a monochromatic missing energy centered resp. at **Emiss = 2.59 GeV** and **Emiss = 2.56 GeV** in B rest frame
- these BRs are in the ballpark of sensitivity of future LHCb experiments
- we encourage LHCb collaboration to scrutinize these two rare decays

Backup slides

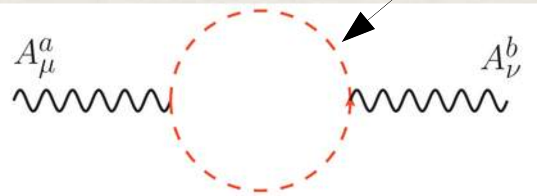
Dark Photon scenario

the vector portal

$U(1)_a \times U(1)_b$

$$\mathcal{L}_0 = -\frac{1}{4} F_{a\mu\nu} F_a^{\mu\nu} - \frac{1}{4} F_{b\mu\nu} F_b^{\mu\nu} - \frac{\varepsilon}{2} F_{a\mu\nu} F_b^{\mu\nu}$$

kinetic mixing always induced by renormalization effects, if messenger fields are present



no direct interaction with visible sector

J’ → Dark current
A’ → dark-photon

J → SM current
A → photon

massless

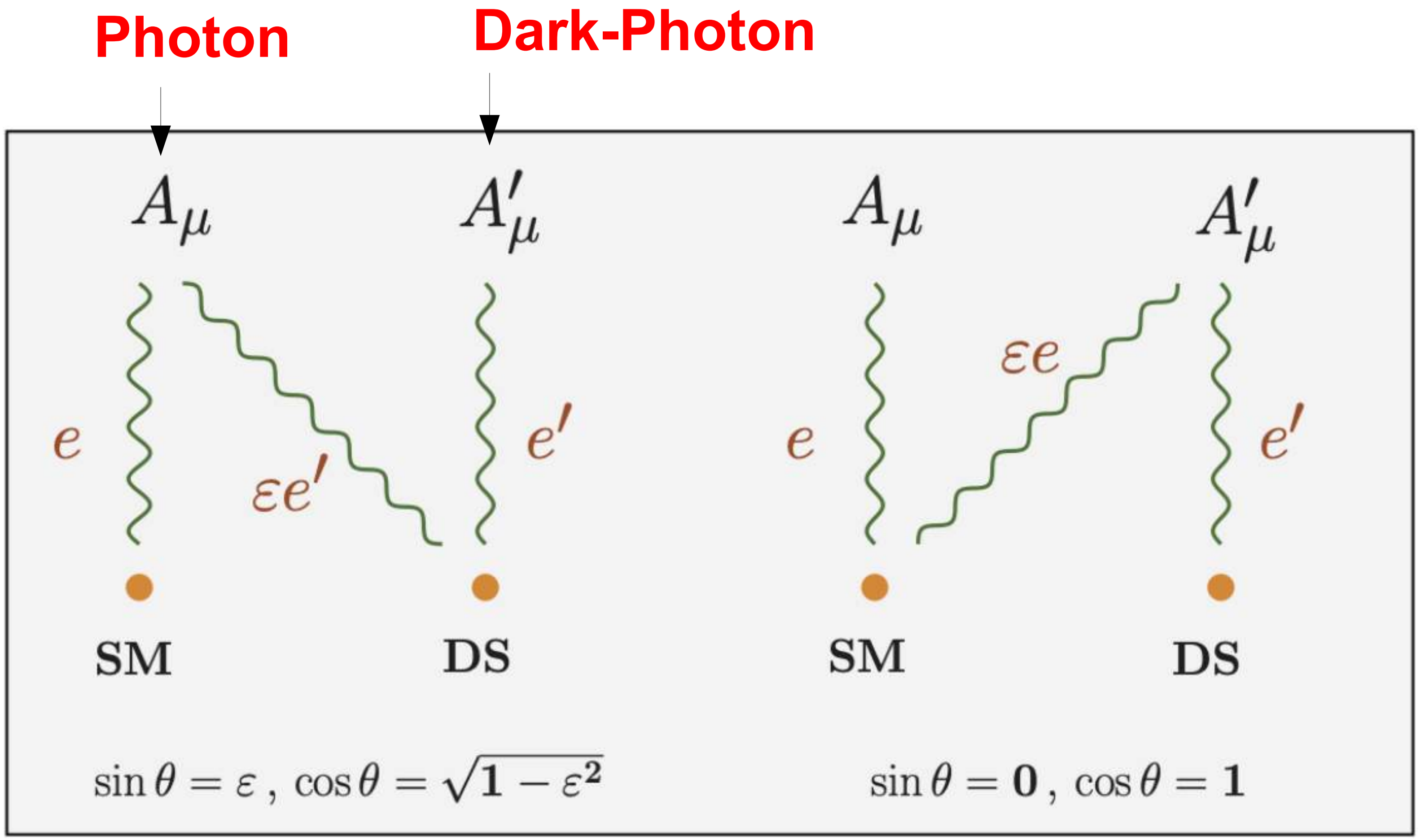
$$\mathcal{L}' = e' J'_\mu A'^\mu + \left[-\frac{e'\varepsilon}{\sqrt{1-\varepsilon^2}} J'_\mu + \frac{e}{\sqrt{1-\varepsilon^2}} J_\mu \right] A^\mu$$

$$\mathcal{L} \supset -\frac{e\varepsilon}{\sqrt{1-\varepsilon^2}} J_\mu A'^\mu \simeq -e\,\varepsilon\, J_\mu A'^\mu$$

massive

- B.Holdom, PLB 166B, 196 (1986)
- B.A. Dobreascu, PRL 94 151802 (2005); [hep-ph/0411004]
- EG, M. Fabbrichesi, G. Lanfranchi, “The dark photon” SpringerBriefs in Physics 2020; arXiv:2005.01515]

Summary of tree-level DP interactions



$$\sin\theta = \varepsilon\,,\ \cos\theta = \sqrt{\mathbf{1} - \varepsilon^{\mathbf{2}}}$$

$$\sin\theta = \mathbf{0}\,,\ \cos\theta = \mathbf{1}$$

Massless Dark-Photon

less explored scenario

Massive Dark-Photon

most of experimental searches focus on massive DP scenario (tree-level couplings)

Other constraints

- Limits from NP contributions to BR($B \to X_s\gamma$) are satisfied once bounds on Λ from BR(B → K* + missing) are imposed, even for large values of α_D

- Limits from BR($B_s^0 \to \mathrm{invisible}$) do not apply

$B_s^0 \to Q_i\bar{Q}_i$ due to dark-magnetic dipole interaction, BR vanishes

$$\langle 0|[\bar{s}\sigma_{\mu\nu}q^{\nu}b]|B_s^0(q)\rangle = 0$$