



Dark Photons in the Dalitz-like decay of a scalar

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DP: what do we know

New Physics:, Dark matter/ Dark photons, Monophotons

Search through: Cosmological observations or lab's experiments

Accelerator exp's: - CERN SPS

$$e^- Z \rightarrow e^- Z \bar{\gamma} \rightarrow e^- Z e^+ e^-$$

$$10^{-5} < \varepsilon_{\gamma-\bar{\gamma}} < 10^{-3}$$

NA64

S. Gninenko PRD 89 (2014) 075008

- SINDRUM, PSI

$$\pi^- p \rightarrow \pi^0 n \rightarrow \gamma \bar{\gamma} n \rightarrow \gamma e^+ e^- n$$

$$\varepsilon_{\gamma-\bar{\gamma}} > 10^{-3}$$

S. Gninenko PRD 87 (2013) 035030

Colliders @ high energies (LHC/.../FCC...)

$$S \rightarrow \gamma \bar{\gamma} \rightarrow \gamma \bar{\nu} \nu, S = H, \dots$$

$$\varepsilon_{\gamma-\bar{\gamma}} < 3 \cdot 10^{-2}$$

$$\mathcal{O}_{SM} \mathcal{O}_{IR} \sim \varepsilon \bar{q} \gamma_{\mu} q S B_{\mu} M^{-1}$$

G Kozlov ICHEP2016 BSM

G.K. arXiv:1604.04599(2016)

In the absence of an **explicit sector that breaks gauge invariance**, the interactions of SM gauge bosons with fermions are **approximately conformal** down to QCD scale $\Lambda_{QCD} \sim O(1\text{GeV})$.

- Could we see something else – not in terms of **SM**?
 - Should one expect new stuff?
Great!
 - **Scale invariant hidden world?**
- ✓ The question of **triggering gauge symmetry breaking** in the SM is tied to the dynamical breaking of scale invariance.



Hidden world

At high enough energies $Q \sim O(M)$ (**UV**, Cosmology)

the nearly conformal (matter) sector couples in the UV to the HIDDEN world through the exchange of heavy state(s), the messenger(s)

Mediators in terms of ATLAS – CMS LHC Forum, arxiv:1507.00966

Stage I

$$\left[\begin{array}{l} \textit{Nearly} \\ \textit{conformal} \end{array} \right] \overset{\textit{heavy}}{\underset{\textit{messenger}(s)}{\leftrightarrow}} \left[\begin{array}{l} \textit{Hidden} \\ \textit{world} \end{array} \right]$$

$$\textit{Below UV } M : \frac{1}{M^{d-4}} O_{SM} \frac{1}{M^{d_{UV}}} O_{UV} \quad \text{No masses allowed}$$

All masses can be generated dynamically in **IR**.

Conformal symmetry is spont. broken – low energy eff. theory contains a dilaton field

$$x_\mu \rightarrow x'_\mu = e^{-\lambda} x_\mu, \quad \mathcal{S} = \bar{\sigma}, \quad \bar{\sigma}(x) \rightarrow \bar{\sigma}'(x') = \bar{\sigma}(x) + \lambda f, \quad f \geq v = 246 \text{ GeV}$$

Below breaking scale the symmetry is realized non-linearly

$$L \sim \sum_i g_i(\mu) \mathcal{O}_i(x), \quad g_i(\mu) \rightarrow g_i(\mu \bar{\sigma} / f) (\bar{\sigma} / f)^{4-d_i}$$

Stage II (coupling of dilaton to **DP** sector in **UV**)

- **In UV:** $\frac{1}{M^{d_{UV}-2}} |\bar{\sigma}^2| \mathcal{O}_{UV}, \quad \bar{\sigma}(x) = \sqrt{H^+ H}(x), \quad m_\sigma^2 \sim x_\sigma f^2$

- **in IR** \Downarrow flows to couplings of H to **DP** operator \mathcal{O}_{IR}

$$\text{const} \frac{\Lambda^{d_{UV}-d_{IR}}}{M^{d_{UV}-2}} |H^2| \mathcal{O}_{IR} \quad \text{Scale invariance is almost breaking}$$

DM particle is the only DP within the reach of the LHC energy

Kinetic term $\sim \varepsilon F_{\mu\nu} B^{\mu\nu}$ $SU_L(2) \times U_Y(1) \times U_B(1) \Leftarrow$ **DP origin**

Triangle anomaly coupling $L_{S\gamma\bar{\gamma}} = \varepsilon g_{S\gamma\bar{\gamma}} F_{\mu\nu} B^{\mu\nu} S$, $B^{\mu\nu} = \partial^\mu B^\nu - \partial^\nu B^\mu$

Basic object $S \rightarrow \gamma\bar{\gamma} \rightarrow \gamma\bar{\nu}\nu$, $\mathcal{S} = \begin{cases} higgs \\ dilaton \end{cases}$

LO: $\sigma(pp \rightarrow SX) = \sigma^{exp}(pp \rightarrow HX) \times \frac{\Gamma^{th}(S \rightarrow gg)}{\Gamma^{SM}(H \rightarrow gg)}$

QCD radiative corrections $gg \rightarrow Higgs \stackrel{equal}{\Leftrightarrow} gg \rightarrow dilaton$

Increasing of $\sqrt{s} \Rightarrow$ **Approx. conformal invariance** $\frac{\partial g(\mu)}{\partial \mu} \cong 0$

Breaking @ $\sim f > v = \langle H \rangle_0$ by $\mu \approx M_{UV} \mathbf{exp}[-8\pi^2 / (b_0 g_0^2)]$

CA: $\partial_\mu K^\mu = \theta_\mu^\mu = \frac{\beta(g)}{2g} G_{\mu\nu}^a G^{\mu\nu a} + \sum m_q [1 + \gamma_m(g)] \bar{q}q \neq 0$

Why LHC13 instead of LHC7 ?

$$S \sim m_S \sim f \sim S^{\alpha/2}$$

Strong coupling theory.

At \sqrt{s} below Λ , $\beta(g_i) \neq 0$ conformal breaking

$$L \sim \sum_i g_i(\mu) \mathcal{O}_i(x), \quad \theta_\mu^\mu = \sum_i g_i(\mu) (d_i - 4) \mathcal{O}_i(x) + \sum_i \beta_i(g) \frac{\partial}{\partial g_i} L$$

Scale invariance exact if $\beta(g_i) = 0, d_i = 4$

$$L_{trace} = \frac{\chi}{f} \theta_\mu^\mu(SM), \quad \theta_\mu^\mu \neq 0, \quad \theta_\mu^\mu(SM) = \theta_\mu^\mu(SM)^{tree} + \theta_\mu^\mu(SM)^{anom}$$

Collider physics importance: $\theta_\mu^\mu(SM)^{anom} = -\frac{\alpha_s}{8\pi} b_o \sum G_{\mu\nu}^a G^{\mu\nu,a} - \frac{\alpha}{8\pi} b_{EM} F_{\mu\nu} F^{\mu\nu}$

Higgs has not such a coupling, only triangle-loop with heavy quarks

If QCD \in Conformal sector: $\sum_{light} b_0 + \sum_{heavy} b_0 = 0 \Rightarrow b_0 = -11 + \frac{2}{3} n_{light}$ compared to Higgs

Important: The sum is splitting over all colored particles in mass scale separated by dilaton mass m_S

- Dilaton serves as the conformal compensator up to $f = v$.
- The σ contribution to $S \rightarrow \gamma\bar{\gamma}$ decays corresponds to including states lighter than σ .

Effect of DP sector on observable(s)

Mixing strength ε is bounded by $\varepsilon < \frac{s^d}{(v^2 M^{d-2})^2}$

- **Important:** no dependence on d_{UV} , d_{IR} , Λ
- NP signals with DP increase with \sqrt{s} , d

Assume $\varepsilon \sim O(3\%)$, DP visible @ LHC for $M < 10^3$ TeV, $d=4$

For $S \rightarrow \gamma\bar{\gamma}$: $L \sim O_{SM} O_{IR} \sim \varepsilon \bar{\psi} \gamma_\mu \psi \mathcal{S} B^\mu M^{-1}$

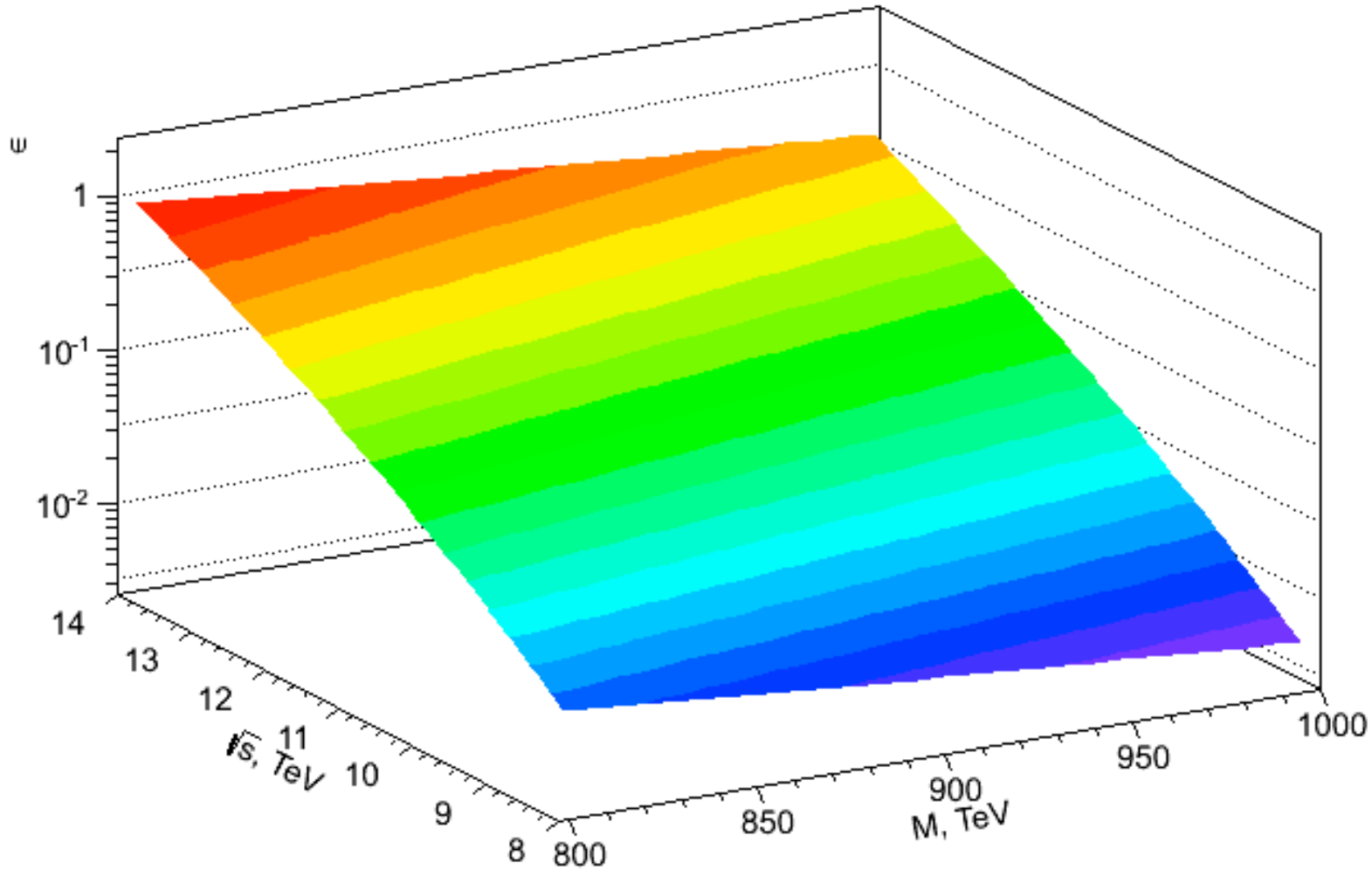
Relevant energy scale $Q \sim m_q$, $q: top, \dots$

Result: $\varepsilon < 3 \cdot 10^{-2}$, $q: top$, $d = 4; M > v$

LHC is a very good facility where the DM Physics can be tested well

Upper limit on $\varepsilon < \frac{s^d}{(v^2 M^{d-2})^2}$, *LHC up to $\sqrt{s} = 14$ TeV, $M = 800 - 1000$ TeV, $d = 4$*

G.K., N.P. B273-275 (2016)



Estimation of DP mass m . *Upper limit*

$$Am(\bar{\gamma} \rightarrow \nu\bar{\nu}) = \frac{1}{2} f_\nu \bar{\nu} \left(g_{V_\nu} \gamma_\beta + g_{A_\nu} \gamma_\beta \gamma_5 \right) \nu \bar{\gamma}_\beta$$

$$f_\nu^2 = 4\sqrt{2}Gm^2, \quad G \sim 10^{-5} \text{GeV}^{-2}$$

No final state interactions: (partial decay width)

$$\Gamma(\bar{\gamma} \rightarrow \nu\bar{\nu}) = \frac{1}{3} \bar{\alpha} \cdot \varepsilon^2 m,$$

↓

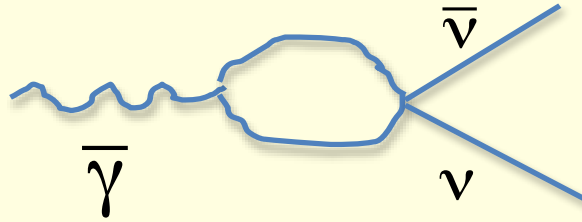
$$\frac{Gg_\nu^2 m^2}{\sqrt{2\pi\bar{\alpha}}}, \quad g_{V_\nu}^2 = g_{A_\nu}^2 = g_\nu^2 = \frac{1}{4}$$

$$\text{For } \varepsilon < 3 \cdot 10^{-2} \Rightarrow m < 3.3 \text{GeV}$$

DP mass m in $S \rightarrow \gamma \bar{\gamma} \rightarrow \gamma \nu \bar{\nu}$

more detailed calculation are needed

E.g., EM ν F



$$\Gamma(\bar{\gamma} \rightarrow \nu \bar{\nu}) \sim \alpha^2 m^5 G^2 \left(\ln \frac{\Lambda_\nu^2}{m_l^2} - \frac{1}{6} \right)^2$$

DP mass: Combined calculations give

$$m \cong m_\mu \left[\frac{3\sqrt{2}\pi}{\bar{\alpha} \sum_{l:e,\mu} \left(\ln \frac{\Lambda_\nu^2}{m_l^2} - \frac{1}{6} \right)} \right]^{1/2} \Rightarrow 0.83 \text{ GeV}, \Lambda_\nu \sim O(m_Z), e^+e^- \text{ \& } \mu^+\mu^- \text{ loops}$$

Mixing strength result $\varepsilon = 7.6 \cdot 10^{-3}$

Agree with excl. region by BaBar (2015), E787+E949 (2014), as well as (g-2) (2014)

Model (Higgs-Dilaton Abelian gauge theory).

- TPWF, $\delta'(p^2, M^2)$ singularities/ $\sigma(x)$ virtual state – dilaton

$A_\mu - B_\mu$ mixing $H - \bar{\sigma}$ LD

$$L_\varepsilon = -\frac{1}{2}\varepsilon F_{\mu\nu} B^{\mu\nu} - \xi(\partial A)(\partial B) + \bar{q}\left(i\hat{\partial} - m_q - g\hat{A}\right)q - I^\mu\left(B_\mu - \partial_\mu\sigma\right)$$

Gauge inv. $A_\mu \rightarrow A_\mu + \partial_\mu\alpha$, $B_\mu \rightarrow B_\mu + \partial_\mu\alpha$, $\sigma \rightarrow \sigma + \alpha$, $q \rightarrow qe^{ig\alpha}$, $I_\mu \rightarrow I_\mu$, $\partial^2\alpha(x) = 0$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \quad B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu, \quad \xi = \varepsilon\bar{\xi}$$

Sub-canonical scalar operator $\sigma(x) = f^{-1}\bar{\sigma}(x) \left\{ \begin{array}{l} \text{primary operator} \\ \text{grandfather potential} \end{array} \right.$

(primary means not a derivative of another operator)

$d \geq j_1 + j_2 + 2 - \delta_{j_1 j_2, 0}$ Dim. of the gauge inv. primary operator

$\sigma(x)$ provides the control over UV & IR divergences

LD & equations of motion

GK, arXiv:1604.04599 (2016)

$$L = L_\varepsilon + L_\sigma - \frac{1}{2} m^2 B_\mu^2 + L_{H\sigma}, \quad L_H \rightarrow L_\sigma = -\frac{\sigma}{\sqrt{2}} \sum_{q'} (m_{q'} + x_\sigma y_{q'} \nu) q' \bar{q}', \quad x_\sigma = \frac{m_\sigma^2}{f^2} < 1$$

$$L_{H\sigma} = \frac{1}{2} \left[(\partial_\mu H)^2 + (\partial_\mu \bar{\sigma})^2 \right] - \frac{\lambda}{4} (H^2 - \beta^2 \bar{\sigma}^2)^2 - \frac{\eta}{4} (\bar{\sigma}^2 - f^2)^2, \quad \beta = \frac{\langle H \rangle}{\langle \bar{\sigma} \rangle} = \frac{v}{f}$$

$$\partial^2 B_\mu = \frac{1}{\varepsilon} Y_\mu + (1 - \bar{\xi}) \partial_\mu \partial^\nu B_\nu, \quad Y_\mu = g \bar{q} \gamma_\mu q \quad (*)$$

$$B_\mu = \frac{\varepsilon}{m^2} \left[\partial^2 A_\mu - \frac{1}{\varepsilon} I_\mu - (1 - \bar{\xi}) \partial_\mu \partial^\nu A_\nu \right]$$

$$Eq. (*) + Eq. B_\mu(x) = \partial_\mu \sigma(x) \Rightarrow \quad (\partial^2)^2 \bar{\sigma}(x) \approx 0, \quad f \neq 0$$

Dipole eq. for virtual field $\bar{\sigma}(x)$

What is the feature the dilaton field is characterized by?

TPWF (two-point Wightman function) $(\partial^2)^2 \omega(x) = 0 \iff (\partial^2)^2 \bar{\sigma}(x) = 0$

General solution (expansion),

$\omega(x) \in \mathcal{S}'(\mathbb{R}^4)$ of temperate generalized functions on \mathbb{R}^4

$$\omega(x) = b_1 \ln \frac{l^2}{-x_\mu^2 + i\epsilon x^0} + b_2 \frac{1}{x_\mu^2 - i\epsilon x^0} + b_3$$

✓ parameter l breaks the scale invariance.

(Dilatation properties: $\omega(\rho x) = \omega(x) - \frac{1}{(8\pi)^2} \ln \rho$, $\rho > 0$)

✚ Allow: est. the propagator of $\sigma(x) \Rightarrow$ propagator of DP

⊕ Commutators

$$[\bar{\sigma}(x), \bar{\sigma}(0)] = 2\pi i \operatorname{sign}(x^0) [b_1 \theta(x^2) + b_2 \delta(x^2)]$$

■ Coefficients $b_1 \leftarrow CCR [A_\mu(x), \pi_{A_\nu}(0)]_{x^0=0} = ig_{\mu\nu} \delta^3(\vec{x})$

$$b_2 \leftarrow CCR [\bar{\sigma}(x), \pi_{\bar{\sigma}}(0)]_{x^0=0} = i\delta^3(\vec{x})$$

➤ To fix both b_1 and b_2 we choose:

$$I_\mu \rightarrow I_\mu = \varepsilon m^2 (\partial_\mu \sigma - A_\mu)$$

(invariant under gauge transformations)

■ LD mixing term $\varepsilon m^2 (A_\mu - \partial_\mu \sigma)(B_\mu - \partial_\mu \sigma)$ *addit. to* $\sim \varepsilon F_{\mu\nu} B^{\mu\nu}$

Stueckelberg-like term

+ Propagator of Dark Photon

- $\tilde{\tau}_{\mu\nu}(p) = p_\mu p_\nu \tilde{\tau}(p), \quad \tilde{\tau}(p) \sim [\tilde{\tau}_1(p) + \tilde{\tau}_2(p)]$

$$\tilde{\tau}_1(p) = \frac{1}{\overline{\xi}(1+\varepsilon)} \lim_{\lambda^2 \rightarrow 0} \left[\frac{1}{(p^2 - \lambda^2 + i\varepsilon)^2} + i\pi^2 \ln(l^2 \lambda^2) \delta_4(p) \right] \text{ *mixing part*}$$

$$\tilde{\tau}_2(p) = -\frac{1}{2(f^2 - m^2)} \frac{1}{p^2 + i\varepsilon} \quad \text{conformal breaking part}$$

- ✓ The strong gauge condition $B_\mu(x) = \partial_\mu \sigma(x)$ used
- In case no mixing, $\tilde{\tau}_{\mu\nu}(p) \Rightarrow$ standard photon propagator
- Dilaton mass does not enter the final solution

Conclusion

1. Influence of Conformal Sector (DP) to SM particle sector;
 2. Upper limit for mixing strength $\varepsilon < 3 \cdot 10^{-2}$
 3. Interaction between DP & quarks is mediated by $\partial_\mu \sigma$;
 4. Dilaton is a portal to DP propagation with $\nabla^2 (\partial \cdot B) = 0$
 5. DP solutions, DP massive, $m = 0.83 \text{ GeV}$, $\Rightarrow \varepsilon = 7.6 \cdot 10^{-3}$
 6. Dilaton mass does not enter the final solution.
 7. If $\varepsilon = 0$, $\mathcal{S} \rightarrow \gamma\bar{\gamma} \Rightarrow H \rightarrow \gamma\gamma$
 8. **LHC13**: decay $\mathcal{S} \rightarrow \gamma\bar{\gamma}$ is evident through *a single photon* plus \cancel{E}_T signature, with both energies peaked at $0.5m_s$
- ! LHC: $\gamma\gamma$ channel in scalar decay is the best probe to discover DP***