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Unitarity constraints and collider searches for dark photons

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Overview

Introduction

- One of the directions to search for physics beyond the Standard Model is search for **Hidden sectors**.
- The hunt for hidden sector degrees of freedom is one of physics program at LHC, HL-LHC and future colliders.
- Physics of dark sector characterized by *dark sector particle content* and *mediators* (fermion, vector, scalar, or pseudoscalar) that connect the dark states to the SM fields.
- Dark photon (Z_D) is the gauge boson of a new $U(1)_D$ group of the Hidden sector.
- Hidden sector coupling to SM fields can be through:
  - *Hypercharge portal*, via kinetic mixing coupling ϵ:

$$\mathcal{L} \supset -\frac{1}{4}\hat{Z}_{D\mu\nu}\hat{Z}_D^{\mu\nu} - \frac{1}{4}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu} + \frac{1}{2}\frac{\epsilon}{\cos\theta_W}\hat{Z}_D^{\mu\nu}\hat{B}_{\mu\nu},$$

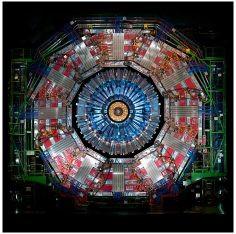
  - *Higgs portal*, via higgs mixing κ:

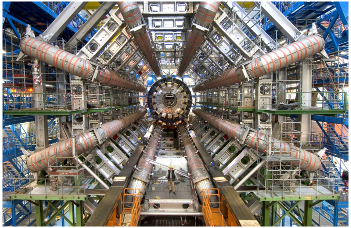
$$V(H,S) = -\mu^2|H|^2 + \lambda|H|^4 - \mu_S^2|S|^2 + \lambda_S|S|^4 + \kappa_{HS}|H|^2|S|^2.$$

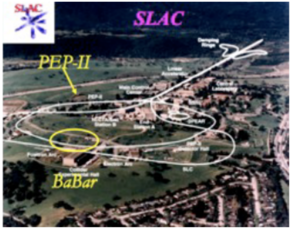
  - In this work the concentration is on values of ϵ and m_{Z_D} above $\sim$ 20 GeV that Z_D decays promptly.

Introduction

- Substantial study has been performed to search for dark photon:
  - $Z_D \to \mu^+\mu^-$, CMS Collaboration, arXiv:1912.04776
  - $e^+e^- \to Z_D\gamma$, $Z_D \to \ell^+\ell^-$, BABAR, arXiv:1406.2980
  - $Z_D \to \mu^+\mu^-$, LHCb, arXiv:1603.08926
  - $H \to ZZ_D \to 4\ell$, $H \to Z_DZ_D \to 4\ell$, ATLAS, arXiv:1505.07645
  - $pp \to Z(\to 2\ell)H(\to Z_D\gamma)$, CMS, arXiv:1908.02699







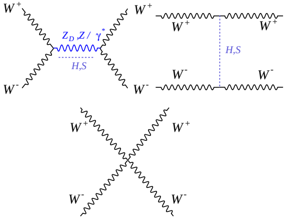
Unitarity constraints

- Unitarity requirement imposes consistency conditions on the theory parameters to be valid up to a given energy scale.

$$|Re(a_0)| \leq \frac{1}{2}, \quad a_0 = \frac{1}{32\pi}\int_{-1}^{+1} \mathcal{M}(\cos\theta)d\cos\theta.$$

$$VV \longrightarrow VV$$

- $W^+W^- \to W^+W^-$

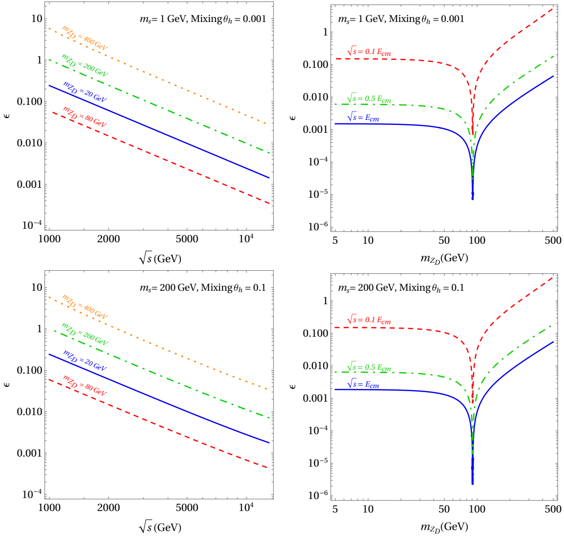


$g_{SW^+W^-} \sim \dfrac{m_W^2 sin\theta_h}{v}$

$m_S \lesssim 10$ GeV, θ_h above 10^{-4} has been excluded

$\left(\dfrac{m_W^2 sin\theta_h}{v}\right)^2 \lesssim \mathcal{O}(10^{-6})$

Unitarity constraints



- $Z^+Z^- \to Z^+Z^-$: limits are two orders of magnitude looser
- $Z_D^+Z_D^- \to Z_D^+Z_D^-$: no dependence on ϵ

Dilepton production through dark photon at the LHC

- To probe the dark photon, we investigate the potential of :
  - HL-LHC ($\sqrt{S} = 13$ TeV, $\mathcal{L} = 3000$ fb^{-1}),
  - multi-TeV future muon collider.
- The potential of the HL-LHC to probe the dark photon is investigated using:
  - Drell-Yan,

$$pp \to Z_D \to \ell^+\ell^-$$

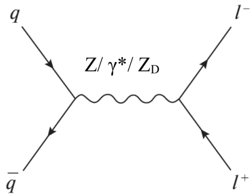
  - Drell-Yan associated with a photon.

$$pp \to Z_D\gamma \to \ell^+\ell^-\gamma$$

- Why leptonic decay?
  - Although the hadronic decay mode is the major decay channel, it has large multijet background,
  - The leptonic decay is cleaner,
  - The lepton reconstruction and identification efficiency is better than those for jets.

Dilepton production through dark photon at the LHC

- The dominant SM backgrounds:
  - SM Drell-Yan: $pp \to Z/\gamma^* \to \ell^+\ell^-$,
  - VV (V = Z, W),
  - Drell-Yan production of $\tau^+\tau^-$ and $\tau \to \ell\nu_\ell(\ell = e/\mu)$,
  - $t\bar{t}$ (particularly dileptonic decay),
  - single top in tW-channel,
  - jets misidentified as leptons.



- The $|\Delta\eta| = |\eta_{\ell^+} - \eta_{\ell^-}|$ distribution is a sensitive variable.
- The cross section of dilepton production:

$$\frac{d\sigma(pp \to \ell^+\ell^-)}{dm_{\ell\ell}} = \frac{d\sigma_{\gamma\gamma}}{dm_{\ell\ell}} + \frac{d\sigma_{ZZ}}{dm_{\ell\ell}} + \frac{d\sigma_{Z_D Z_D}}{dm_{\ell\ell}} + 2\frac{d\sigma_{\gamma Z}}{dm_{\ell\ell}} + 2\frac{d\sigma_{\gamma Z_D}}{dm_{\ell\ell}} + 2\frac{d\sigma_{Z Z_D}}{dm_{\ell\ell}}$$

- The differential cross sections can be factorized as:

$$\frac{d\sigma(pp \to \ell^+\ell^-)}{dm_{\ell\ell}} = \sum_{q,\bar{q}} \int dx_1 dx_2 f_q(x_1, Q) f_{\bar{q}}(x_2, Q) \times \frac{d\hat{\sigma}(q\bar{q} \to \ell^+\ell^-)}{dm_{\ell\ell}}$$

Dilepton production through dark photon at the LHC

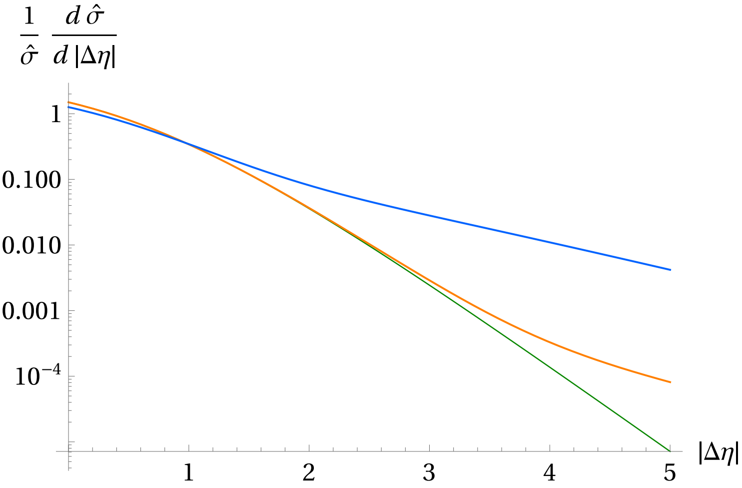


Figure: SM(Green), $m_{Z_D} = 50$ (orange) and 1200 (blue) GeV assuming $\epsilon = 0.05$.

Dilepton production through dark photon at the LHC

Signal & Background generation → MadGraph5_aMC@NLO.
Showering, hadronization and decays of unstable particles → Pythia8.
Detector Impacts simulation → Delphes 3.5.0.

- Event Selection:
  - two opposite-sign charged lepton,
  - leading lepton $p_T > 25$ GeV and sub-leading lepton $p_T > 20$ GeV,
  - $|\eta| < 2.4$,
  - leptons are required be isolated,
  - $\Delta R(\ell^+,\ell^-) > 0.3$,
  - invariant mass of dilepton > 10 GeV,
  - $p_T^{\ell\ell} > 30$ GeV (reduce background contributions from non-prompt leptons),
  - events with a third, loosely-identified charged lepton with $p_T > 10$ GeV are discarded (reduce VZ),
  - missing transverse momentum < 20 GeV,
  - events containing any b-jet with $p_T > 30$ GeV and $|\eta| < 2.4$ are discarded (reduce $t\bar{t}$, tW channel).

Dilepton production through dark photon at the LHC

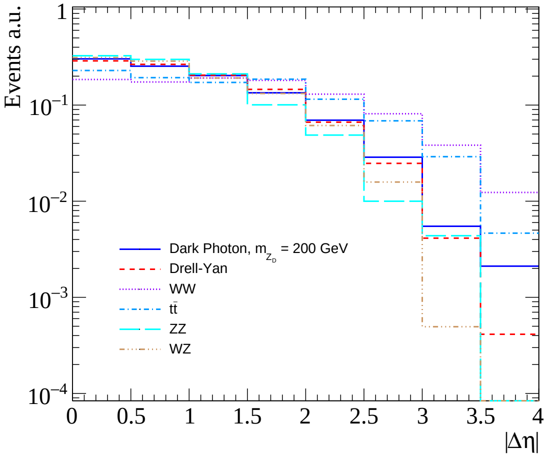


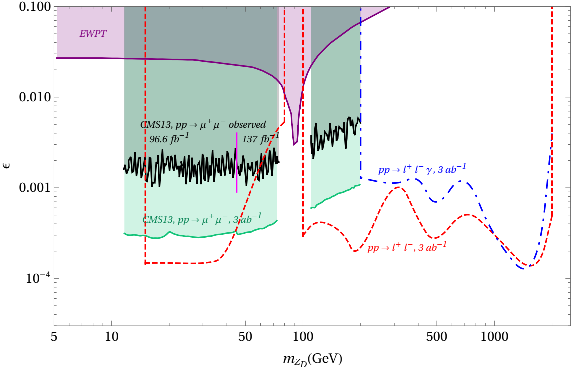
Figure: $m_{Z_D} = 200$ GeV, $\epsilon = 0.01$.

Dilepton production through dark photon at the LHC

- In order to obtain the projected sensitivity for the dark photon parameters, χ^2 is defined over the $|\Delta\eta|$ distribution:

$$\chi^2(\epsilon, m_{Z_D}) = \sum_{i \in bins} \frac{(N^i_{SM+DP} - N^i_{SM})}{(\delta^i)^2},$$

- The uncertainties includes statistical and systematic uncertainties.
- In order to increase the sensitivity: $\Delta_1 < |m_{\ell\ell} - m_{Z_D}| < \Delta_2$.



Dark photon production associated with a photon at the LHC

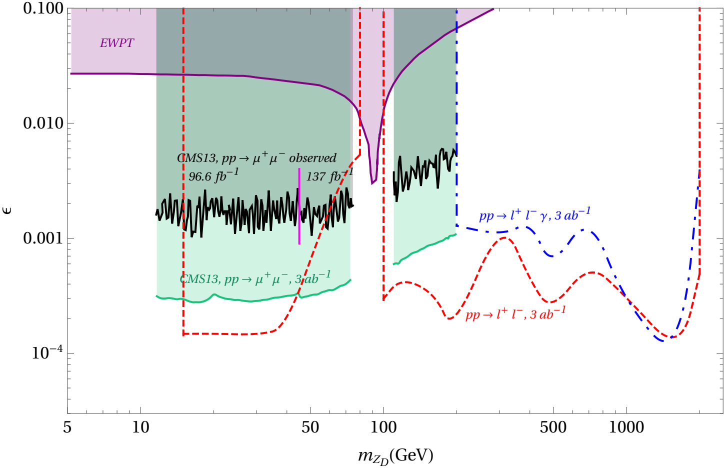
Search for dark photon through:

$$pp \longrightarrow \ell^+\ell^-\gamma \quad (\ell = e, \mu)$$

- Main SM background processes:
  - SM $\ell^+\ell^-\gamma$,
  - $t\bar{t}\gamma$ (top decays semileptonically),
  - VV, $VV\gamma$ (V = W,Z),
  - Events containing Higgs boson $H \longrightarrow Z + \gamma$.
- Event selection:
  - ✓ two oppositely charged same-flavour leptons (e or μ) + one photon,
  - ✓ photon: $p_T^{\gamma} > 20$ GeV, $|\eta| < 2.5$, isolated,
  - ✓ Events containing additional photons with $p_T^{\gamma} > 20$ GeV, $|\eta| < 2.5$ and RelIso < 0.2 are rejected.
  - ✓ ΔR $(\ell^{\pm}, \gamma) > 0.3$,
  - ✓ $p_T^{\ell,leading} > 25$ GeV, $p_T^{\ell,subleading} > 20$ GeV, $|\eta| < 2.4$, isolated,
  - ✓ ΔR $(\ell^+, \ell^-) > 0.3$,
  - ✓ missing transverse momentum < 20 GeV,
  - ✓ events with jet with $p_T > 30$ GeV and $|\eta| < 2.4$ are rejected.

Dark photon production associated with a photon at the LHC

- In order to assess the sensitivity, χ^2 is constructed over $m_{\ell\ell\gamma}$.
- The $m_{\ell\ell\gamma}$ range is optimized.

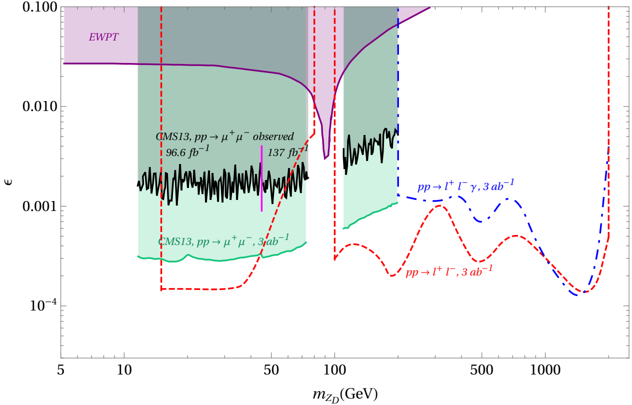


Projection of $Z_D \to \mu^+\mu^-$ measurement at HL-LHC

CMS collaboration performed a search for dark photon using data recorded at $\sqrt{S} = 13$ TeV (137 fb^{-1}) through $Z_D \to \mu^+\mu^-$.

- Mass range : 45 − 75 GeV and 110 − 200 GeV.
- An extrapolation of expected results to $\mathcal{L} = 3$ ab^{-1} is performed.
- Stronger limits from the Drell-Yan Z_D production due to using shape analysis on $\Delta\eta$ distribution.
- Considering only dimuon channel loosens constraints ∼ 15% − 25%.

arXiv : 1912.04776



Prospects for a multi-TeV muon collider

- The advantages of high-energy muon colliders:
  - The muon's full energy is available in a collision,
  - Cleaner final states,
  - Its considerable mass suppresses the synchrotron radiation.
- We perform the search for dark photon in muon colliders through **Drell-Yan**.

$$\mu^+\mu^- \longrightarrow \ell^+\ell^- \quad (\ell = e, \mu)$$

- Photon radiation effect, modified the lowest order cross section:

$$\left(\frac{\Gamma_{Z_D}}{m_{Z_D}}\right)^{\frac{4\alpha}{\pi}\log(\sqrt{s}/m_\mu)}$$

- For $m_{Z_D} > m_Z$, $\epsilon \ll 1$: $\left(\frac{\Gamma_{Z_D}}{m_{Z_D}}\right) < \left(\frac{\Gamma_Z}{m_Z}\right) \Rightarrow$ more photon radiations for SM Drell-Yan. This effect shows up in $|\vec{p}_T^{\,\ell\ell}|$ distribution.

Prospects for a multi-TeV muon collider

Main SM background processes:

- SM $\ell^+\ell^-$ production,
- W^+W^- (both $W^\pm \to \ell^\pm\nu$),
- ZZ (at least one $Z \to \ell^+\ell^-$),
- HZ ($Z \to \ell^+\ell^-$).

Signal & Background generation ($\sqrt{s} = 1.5$, 6 TeV) $\longrightarrow$ MadGraph5_aMC@NLO.
Showering, hadronization and decays of unstable particles $\longrightarrow$ Pythia8.
Detector Impacts simulation $\longrightarrow$ Delphes 3.5.0.

Event selection:

- ✓ two oppositely charged same-flavour leptons (e or μ),
- ✓ $p_T^\ell > 15$ GeV,
- ✓ electron: $|\eta| < 2.5$, muon: $|\eta| < 3$,
- ✓ Both electrons and muons have to be isolated,
- ✓ $\Delta R\ (\ell^+, \ell^-) > 0.3$,
- ✓ missing transverse momentum < 20 GeV,

Prospects for a multi-TeV muon collider

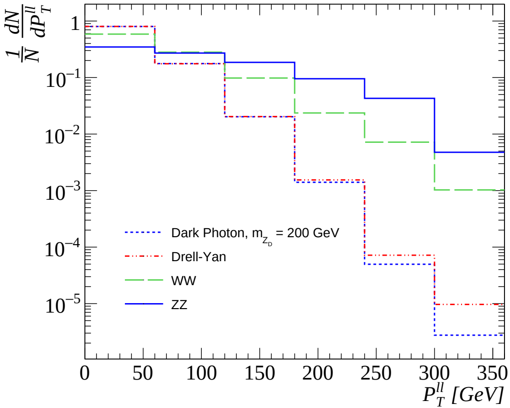
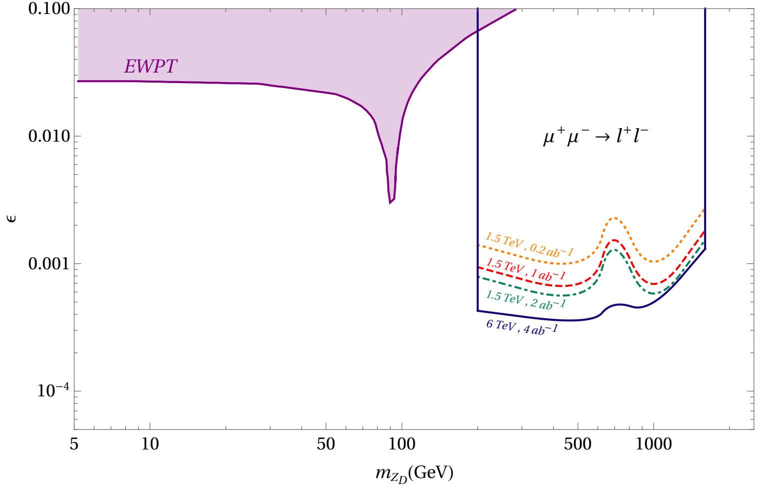


Figure: $\epsilon = 0.01$, $\sqrt{s} = 1.5$ TeV.

	efficiency
signal ($m_{Z_D} = 200$ GeV, $\epsilon = 0.01$, $\sqrt{s} = 1.5$ TeV)	72.4 %
SM Drell-Yan	72 %
WW	0.5 %
ZZ	0.02 %
$t\bar{t}$	$\lesssim 10^{-4}$ %

Prospects for a multi-TeV muon collider

- The χ^2 statistics on $|\vec{p}_T^{\ell\ell}|$ is used to scan $(\epsilon,\, m_{Z_D})$ parameter space.
- $\sqrt{s} = 1.5$ TeV, $\mathcal{L} = 0.2,\, 1,\, 2$ ab^1 and $\sqrt{s} = 6$ TeV, $\mathcal{L} = 4$ ab^1.



Summary

- Dark sector states show up in many extensions of the Standard Model.
- Firstly we obtained bounds on dark photon parameters from partial wave unitarity, examining $WW \to WW$ scattering.
- The limits depends on the center-of-mass energy and dark photon mass ($\epsilon < 0.001$ for $m_{Z_D} \leq 50$ GeV and $\sqrt{s} = 13$ TeV).
- The second part of the paper presented collider searches for dark photon.
- Scans were performed to constrain the dark photon parameter space using $pp \to Z_D \to \ell^+\ell^-$ and $pp \to \ell^+\ell^- + \gamma$.
- ϵ could be excluded down to (1.4 - 10) $\times\, 10^{-4}$.
- Finally, we showed that multi-TeV muon colliders with the clean environment have excellent sensitivity to dark photons.
- To improve the search strategy and boost the sensitivity: extending the final state to the hadronic decays of the dark photon, Exploiting multivariate techniques such as BDTs or NNs to distinguish the dark photon signal from the dominant background sources.

Thanks for your attention