Interpreting the LHC Run 2 Data and Beyond

Massless dark photons from Z boson decays at LHC and CEPC

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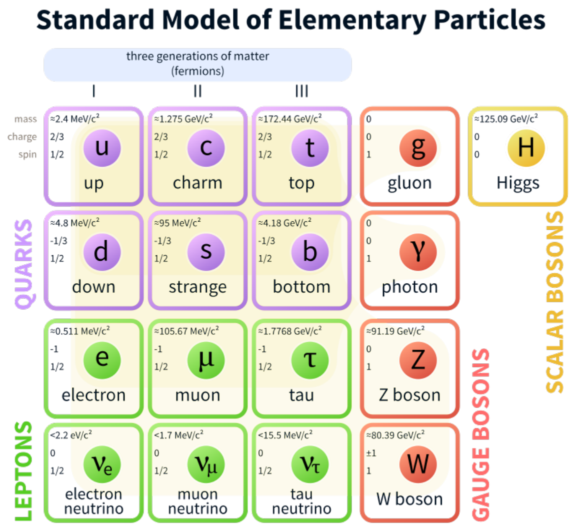
Outline

- Introduction to Dark Matter & dark photon
- Previous results from LEP (Large Electron Positron collider)
- Dark photon at LHC (Large Hadron Collider)
- Dark photon at CEPC (Circular Electron-Positron Collider)
- Conclusions

Dark Matter

The Standard Model is the best existing description of the sub-atomic world



https://it.wikipedia.org/wiki/Modello_standard#/media/File:Standard_Model_of_Elementary_Particles.svg

Dark Matter

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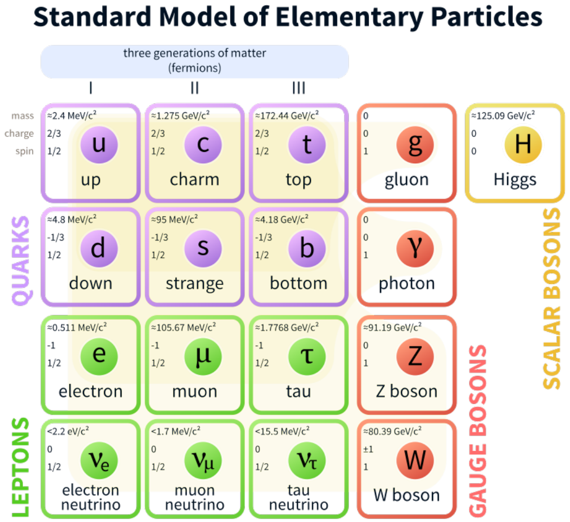


But…

The SM does not explain some important physical phenomena, in particular the existence of the Dark Matter.

Dark Matter:

- has (only) gravitational interaction with matter
- is “dark” (e.g. invisible to traditional collider experiment)
- is very stable (**τ**~Universe)
- is non-relativistic
- is collisionless

https://it.wikipedia.org/wiki/Modello_standard#/media/File:Standard_Model_of_Elementary_Particles.svg

Dark Matter search strategies

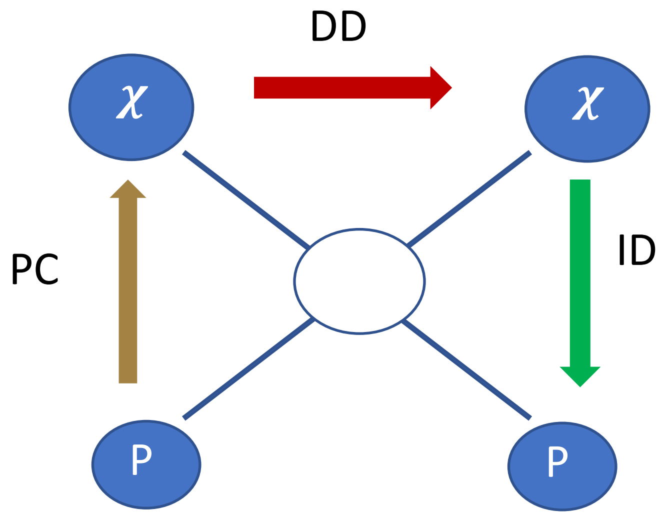
- Direct detection:

  galactic DM (like WIMPs) colliding with underground targets made of ordinary matter

- Indirect detection:

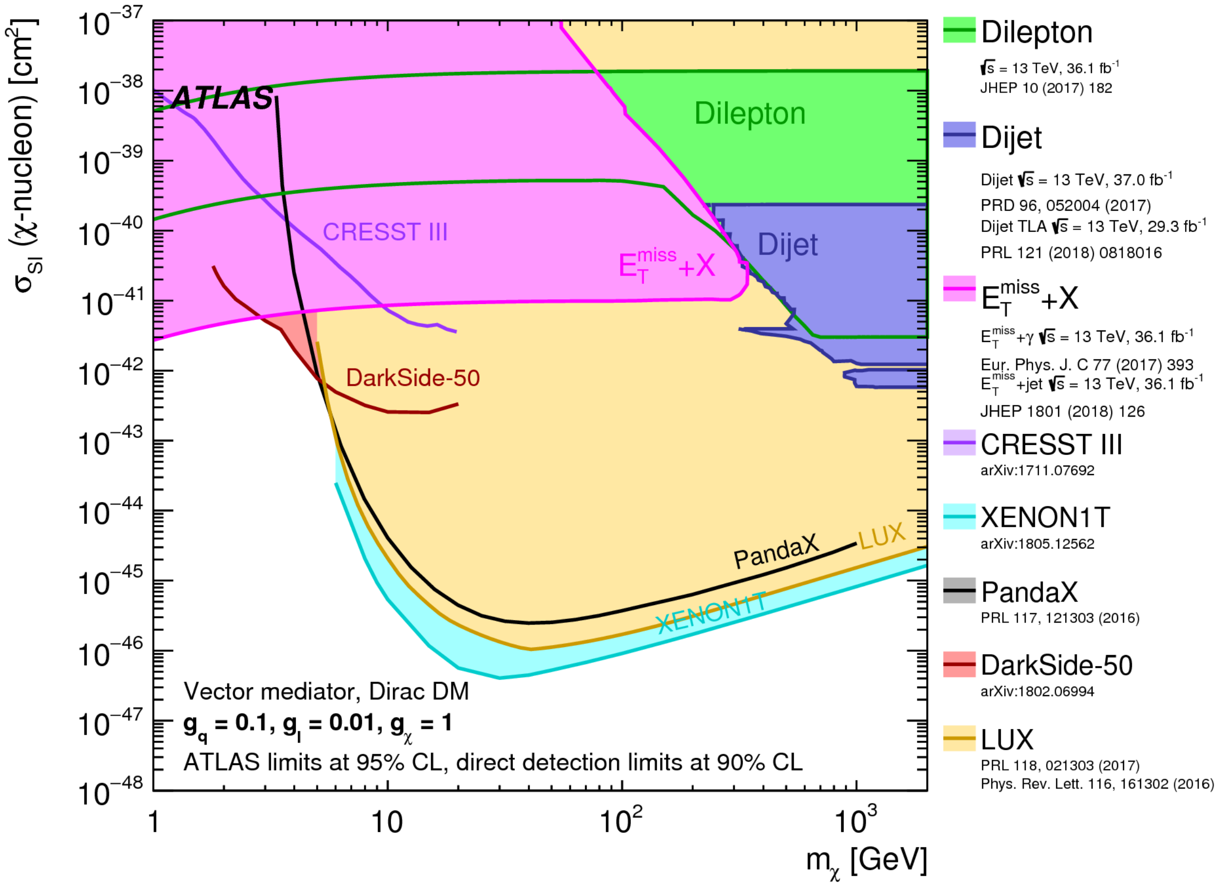
  search for the products of annihilating DM

- Production at colliders:
  - search for invisible particles at colliders
  - indirect search for DM through the presence of mediators



Dark photon

No evidences of WIMPs ⇒ investigate other models: <u>hidden dark sector</u>

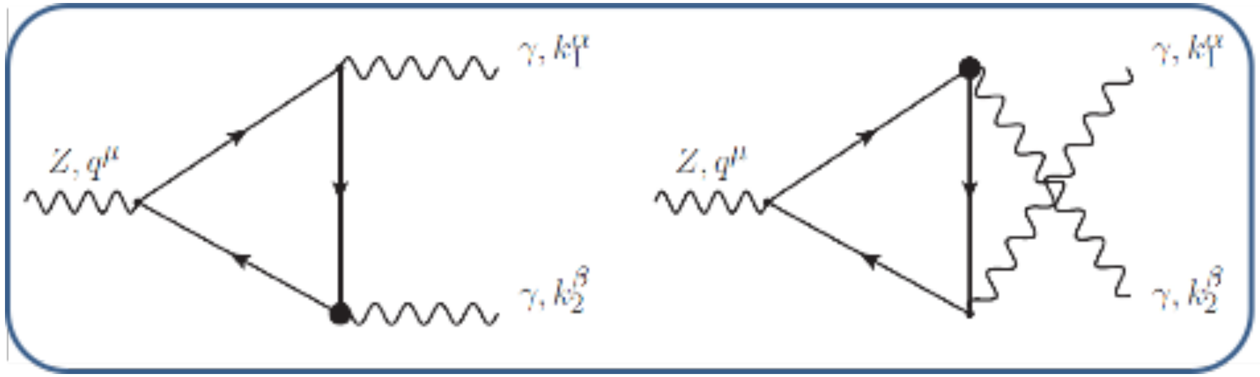


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/

Dark photon

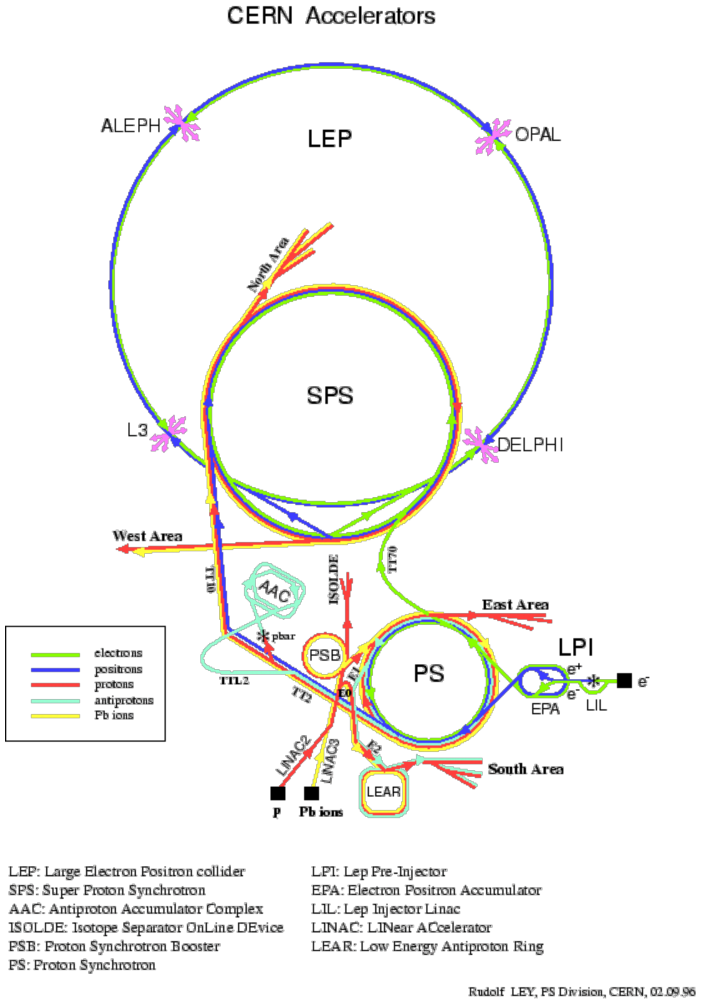
No evidences of WIMPs ⇒ investigate other models: hidden dark sector

- interacts predominantly via gravity
- extra unbroken $U(1)_D$ gauge group [1]
  - mirror electromagnetism
  - massless dark photon $\bar{\gamma}$
- interactions SM-$\bar{\gamma}$ are suppressed
  - one possibility is $Z \to \gamma\bar{\gamma}$



[1] M. Fabbrichesi, E. Gabrielli, and B. Mele, Phys. Rev. Lett. 120, 171803 (2018), arXiv:1712.05412 [hep-ph]

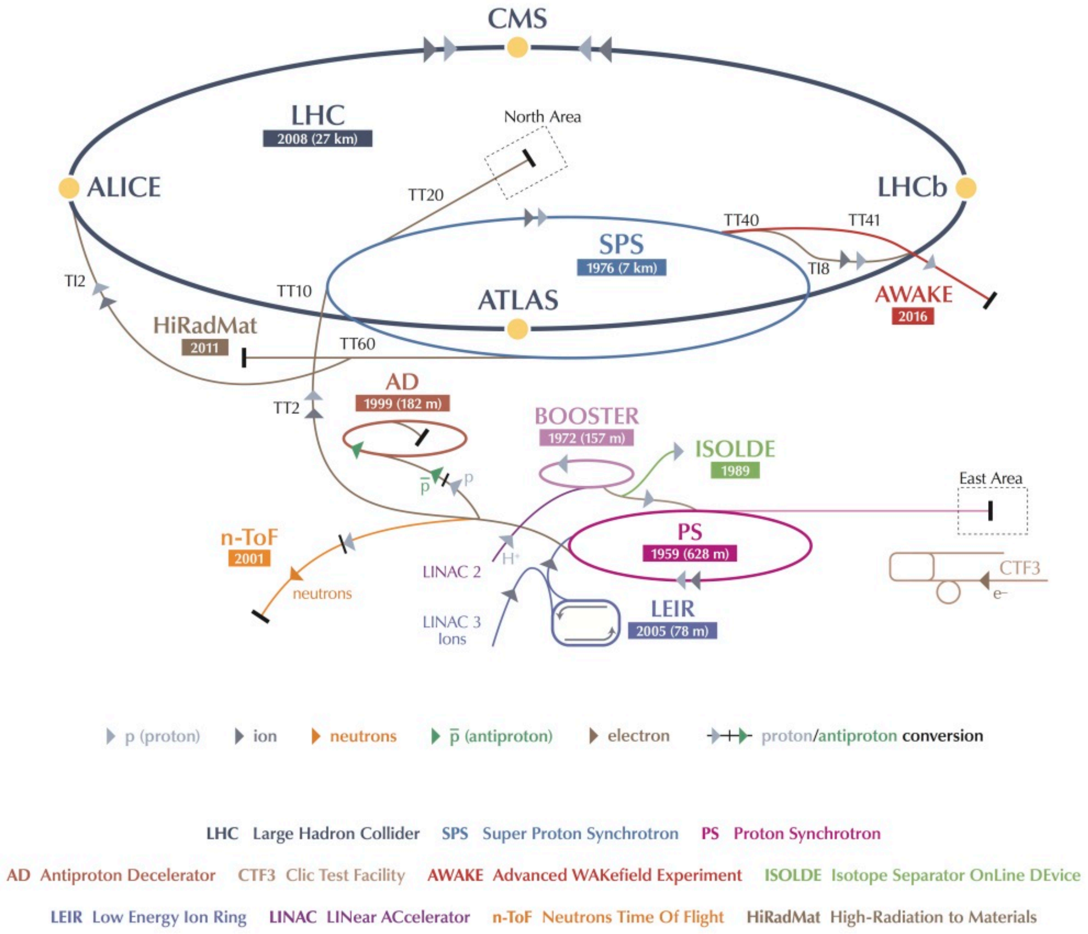
Dark photon at LEP (already published)



- BR($e^+e^- \rightarrow Z \rightarrow \gamma + X$) studied and analysed in [2]
- LEP:
  - $\sqrt{s}$=89.48-91.26-93.08 GeV
  - $\mathcal{L}$=7.5-52-7.6 pb^{-1}
- Background sources:
  - $e^+e^- \rightarrow \gamma\nu\bar{\nu}$ (main)
  - $e^+e^- \rightarrow \gamma e^+e^-$
- BR excluded (at 95% CL): <10^{-6}

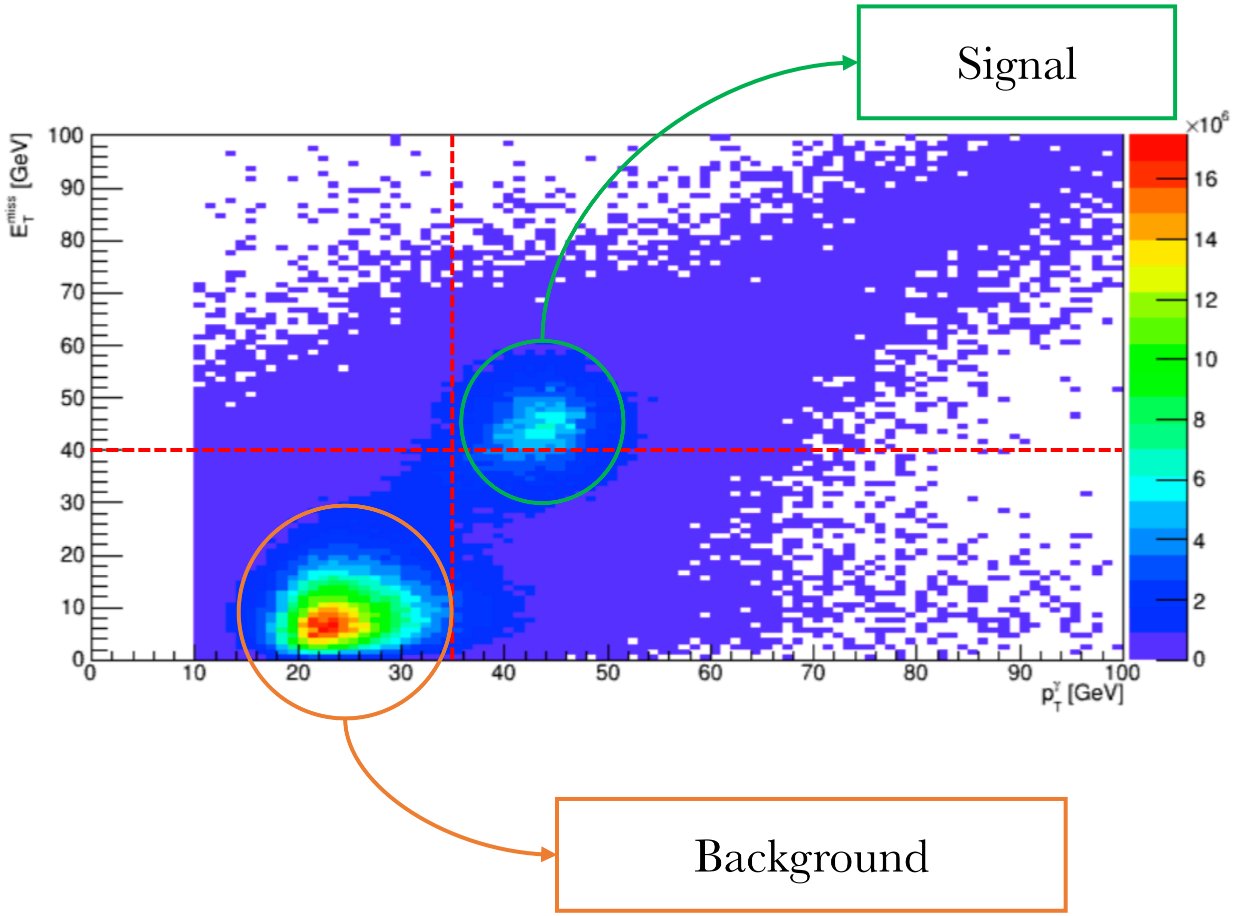
[2]P. Abreu et al. (DELPHI), Z. Phys. C74, 577 (1997)

Dark photon at LHC (this study)



- (HL-)LHC:
  - $\sqrt{s}$=13 TeV
  - $\mathcal{L}$=140 (3000) fb^{-1}
- Background sources:
  - $pp \to \gamma + jets$ (main)
  - $pp \to \gamma \nu \bar{\nu}$
- Simulation:
  - MadGraph5_aMC@NLO (LO generator)
  - Pythia8 (PS and hadronisation)
  - Delphes (detector)

Dark photon at LHC – selection cuts



- List of cuts that maximises the ratio between the signal and the background

$p_T^{\gamma} > 35$ GeV
$E_T^{miss} > 40$ GeV
$80 < M_T < 105$ GeV
$\lvert\Delta\phi(\gamma, E_T^{miss})\rvert > 2.8$ rad
$\lvert\eta_{\gamma,l}\rvert \leq 2.5$
No jets in the final state

Dark photon at LHC – results

The 95% CL limit on the branching ratio can be approximated as

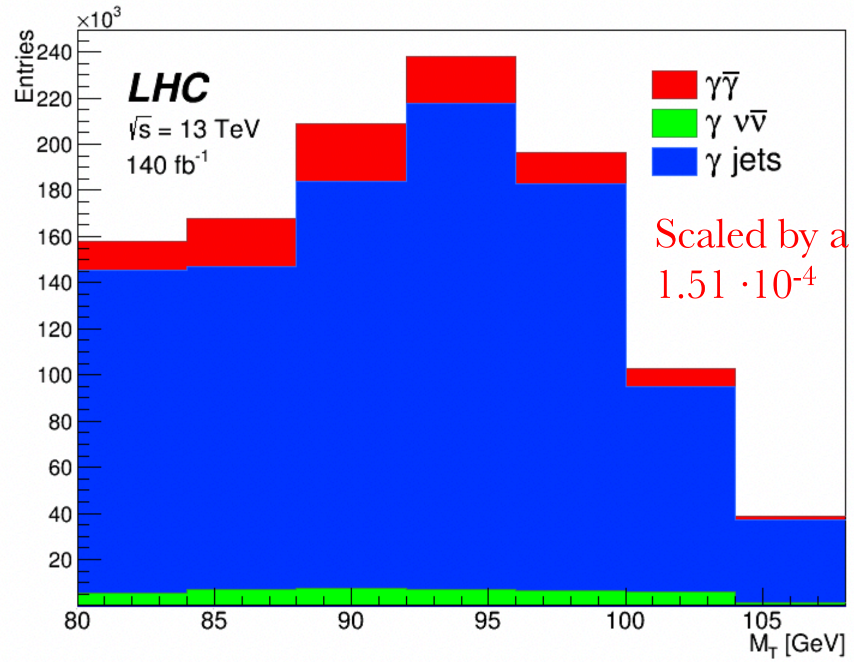
$$BR = \frac{2}{s}\sqrt{b + (c \cdot b)^2},$$

where

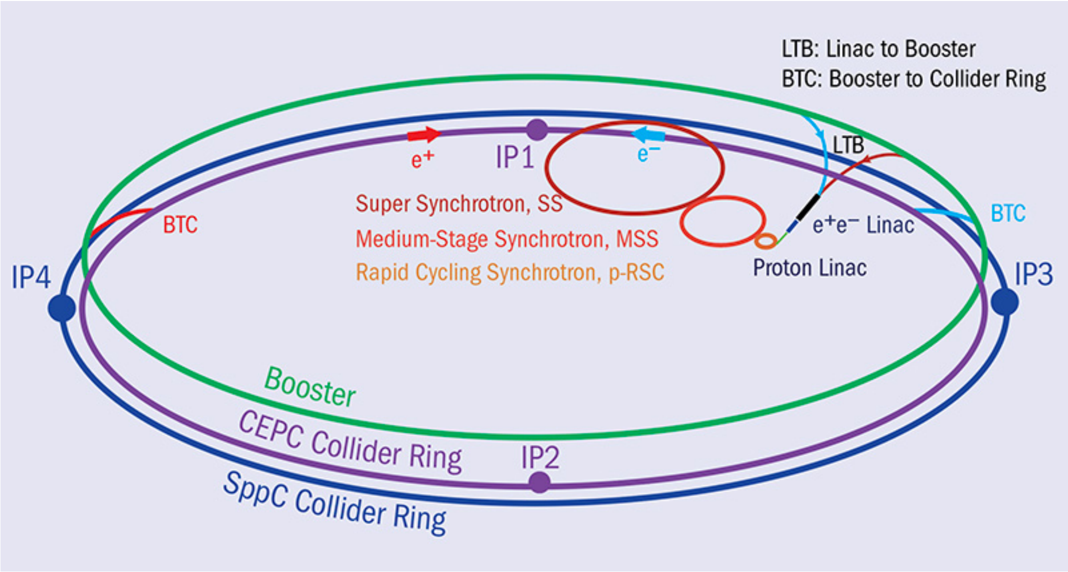
- *s* is the number of signal events
- *b* is the number of background events
- *c* is a factor introduced to parametrise the total systematic uncertainty on background $\sigma_{syst} = c \cdot b$

Assuming only statistical uncertainty (c=0), the excluded BR is ~$\underline{3 \cdot 10^{-6}}$, higher than the LEP limit.

Assuming an uncertainty on E_T^{miss}=1% and on p_T^{γ}=0.3% (c=3.7%) the upper limit on BR is found to be $\mathbf{\underline{1.51 \cdot 10^{-4}}}$ for LHC and $\mathbf{\underline{3.26 \cdot 10^{-5}}}$ for HL-LHC.



Dark photon at CEPC (this study)



https://cerncourier.com/chinas-bid-for-a-circular-electron-positron-collider/

- CEPC:
  - $\sqrt{s}$=91.2-240 GeV
  - $\mathcal{L}$=8-5.6 ab^{-1}
- Background sources:
  - $e^+e^- \to \gamma\nu\bar{\nu}$ (main)
  - $e^+e^- \to \gamma e^+e^-$
- Simulation:
  - MadGraph5_aMC@NLO (LO generator)
  - Pythia8 (PS and hadronisation)
  - Delphes (detector)

Dark photon at CEPC – selection cuts

- List of cuts that maximises the ratio between the signal and the background at $\sqrt{s}$=240 GeV

$E_\gamma > 113$ GeV
$M_T > 159$ GeV
$\lvert\eta_\gamma\rvert \leq 0.9$
No charged particles in the final state

- List of cuts that maximises the ratio between the signal and the background at $\sqrt{s}$=91.2

$E_\gamma > 40$ GeV
$M_T > 36$ GeV
$\lvert\eta_\gamma\rvert \leq 1.5$
No charged particles in the final state

Dark photon at CEPC – results

The 95% CL limit on the branching ratio can be approximated as

$$\mathrm{BR} = \frac{2}{s}\sqrt{b},$$

where

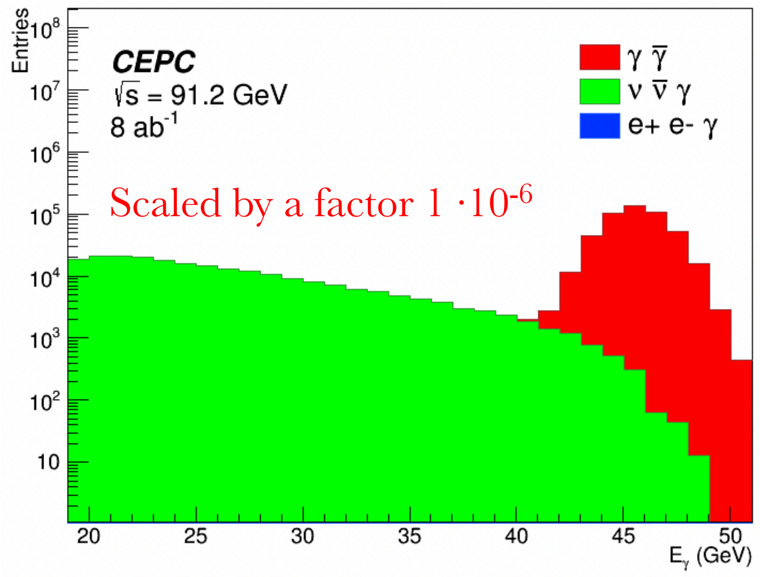
- s is the number of signal events
- b is the number of background events

At $\sqrt{s}$=240 GeV, the excluded BR is **$7.2\cdot10^{-7}$**, lower than the LEP limit.

The contribution of a possible systematic luminosity uncertainty is estimated to be ΔBR=$0.004\cdot10^{-7}$.

At $\sqrt{s}$=91.2 GeV, the excluded BR is **$3.35\cdot10^{-10}$**, lower than the LEP limit.

The contribution of a possible systematic luminosity uncertainty is estimated to be ΔBR=$0.0002\cdot10^{-10}$.



Conclusions

- Extra $U(1)_D$ gauge group mediated by a "dark photon"
- $Z \rightarrow \gamma\bar{\gamma}$ process is studied
- Excluded branching ratios are found to be:

	BR ($Z \rightarrow \gamma\bar{\gamma}$)
LEP	10^{-6}
LHC	$1.5 \cdot 10^{-4}$
HL-LHC	$3.3 \cdot 10^{-5}$
CEPC (240 GeV)	$7.2 \cdot 10^{-7}$
CEPC (91.2 GeV)	$3.4 \cdot 10^{-10}$

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Bibliography

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LEP: https://home.cern/science/accelerators/large-electron-positron-collider

LHC: https://home.cern/science/accelerators/large-hadron-collider

CEPC: https://arxiv.org/abs/1811.10545

Backup

Exclusion limits in the presence of large background

- Z: the significance for rejecting the hypothesis of $s = 0$
- In case of s+b large $Z = \frac{n_{obs} - b}{\sqrt{b}} = \frac{s}{\sqrt{b}}$
- If b has a systematic uncertainty $\sqrt{b} \rightarrow \sqrt{b + \sigma_{syst}^2}$
- $s = s_{BR=1} \cdot BR$ and $\sigma_{syst} = c \cdot b$
- The 95% CL means Z=2:

$$2 = \frac{s_{BR=1} \cdot BR}{\sqrt{b + (c \cdot b)^2}} \Longrightarrow BR = \frac{2}{s_{BR=1}} \sqrt{b + (c \cdot b)^2}$$