Synchrotron Loss due to Dark Photons

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Project 6

9th August, 2018

Project 6 Dark Photon -

Electrons in a circular accelerator will emit a substantial amount of electromagnetic radiation (as Jackson tells us). Consider an extension of electrodynamics where a new particle, the **dark photon**, exists with a **mass of 10 MeV** which couples to charged particles the **same way as a photon** does but with a strength **reduced by** **$=10^{-3}$**. In a circular accelerator, such as the proposed FCC-ee or CEPC, with a **center of mass energy of 250 GeV**, **determine the power loss due to the emission of dark photons**.

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Dark Sector

Standard Model has (almost) been well established.

Dark sector is well motivated (Problems in Standard Model per se; Dark matter; Muon g-2 anomaly, etc)!

Portal to dark sector

1. Scalar portal; e.g. a new scalar couples to Higgs
2. Pseudoscalar portal; e.g. axion
3. Neutrino portal; e.g. right-handed neutrino
4. **Vector portal; e.g. Dark photon!**
5. etc.

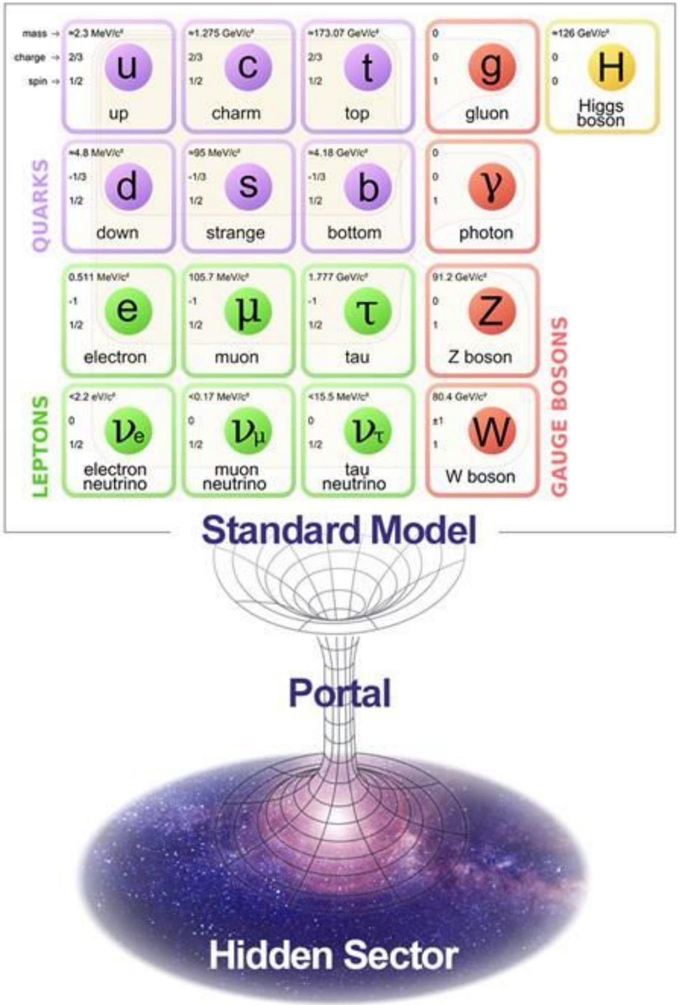
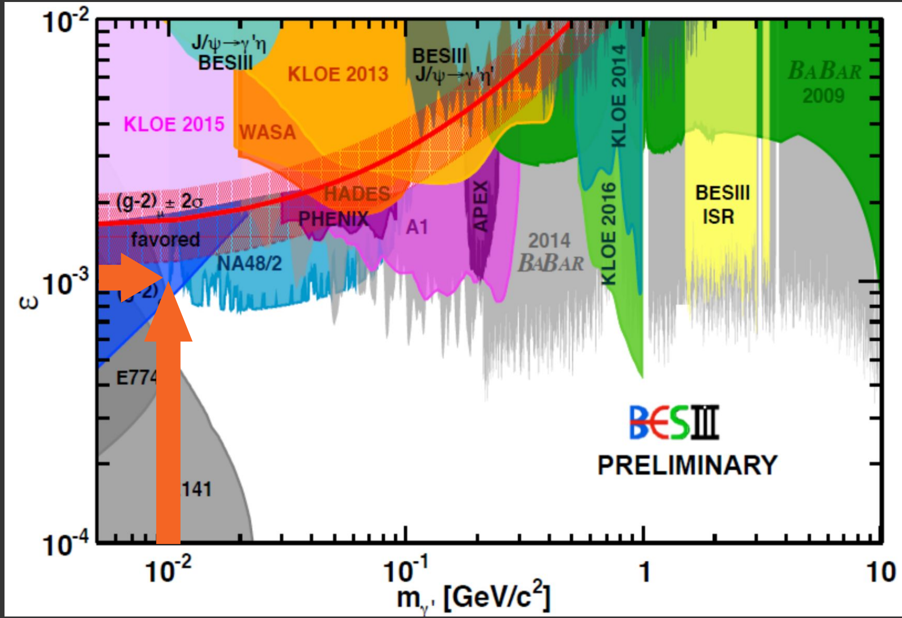


Figure Credit: IBS

Dark photon & the Dark Sector

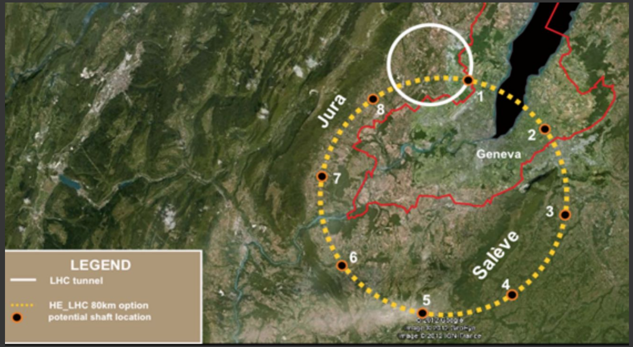
$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}MA'_{\mu}A'^{\mu} + \epsilon e\bar{\psi}\gamma^{\mu}\psi A'_{\mu}$$

- Two Parameters:
  Kinetic mixing ε vs. dark photon mass *M*
- Popular model for experiments
- The given parameters (ε=1e-3, *M*=10 MeV) favored by μ(g-2) experiment



https://conference-indico.kek.jp/indico/event/40/session/22/contribution/72/material/slides/1.pdf

Future Accelerators –



Two proposals for Higgs factories:

- **Future Circular Collider (FCC-ee)** -
  Proposed by CERN
  Location: in Geneva area

- **Circular Electron-Positron Collider (CEPC) -**
  Proposed by IHEP et al.
  Location: China

Both accelerators are slated to run in 2 phases:
Phase 1: electron/positron collider
Phase 2: ~100 TeV proton/proton machine

Accelerator	**FCC-ee**	**CEPC**
Circumference [km]	100	100
Bending radius [km]	11	10.9
Magnetic field [mT]	13 - 54	37
Energy loss [GeV/turn]	1.67	1.73
Beam energy [GeV]	120	120
SR power / beam [MW]	50	50

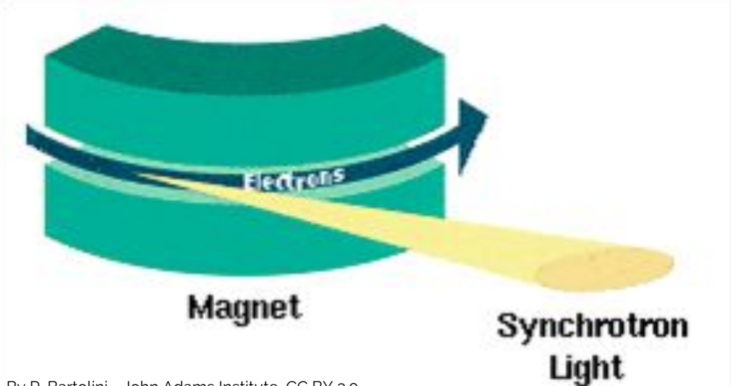
SM Synchrotron Radiation (SR) –

- Electromagnetic radiation emitted by all accelerated charged particles.

- Predicted in 1944 and first observed in 1946.

- Energy loss per turn scales with
    - **E^4** : accelerator needs to invest a lot more power for higher energies;
    - **m^{-4}** : no problem for heavier particles (as e.g. in muon or proton colliders);
    - **R^{-1}** : larger bending radii lead to lower power loss.

$$\Delta E = \frac{(Ze)^2 \cdot E^4}{\varepsilon_0 \cdot 3R \cdot (mc^2)^4}$$



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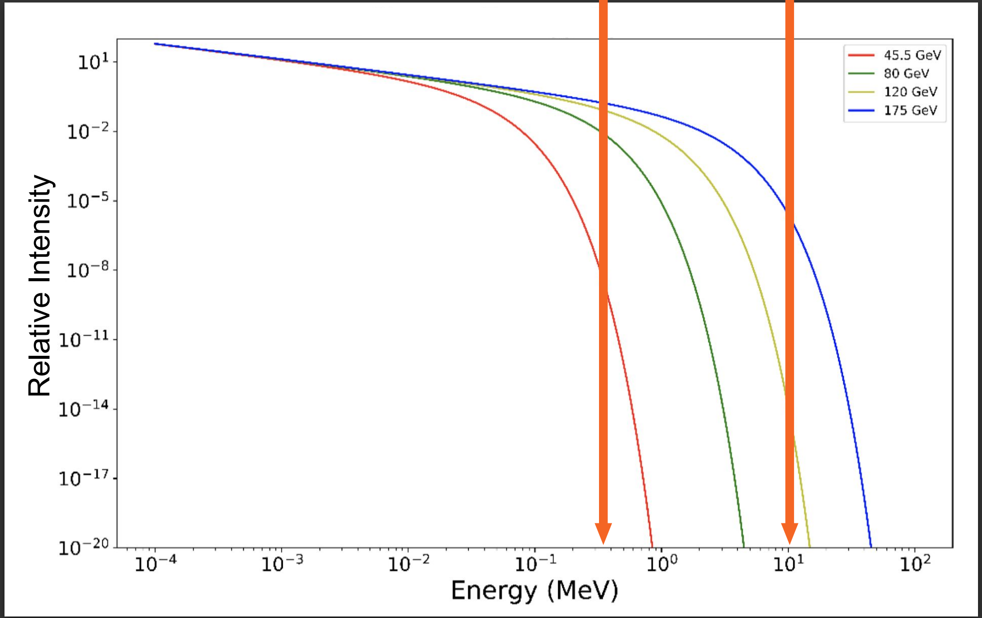
SM Energy Spectrum –

Largest power emission at **352 keV** for 120 GeV

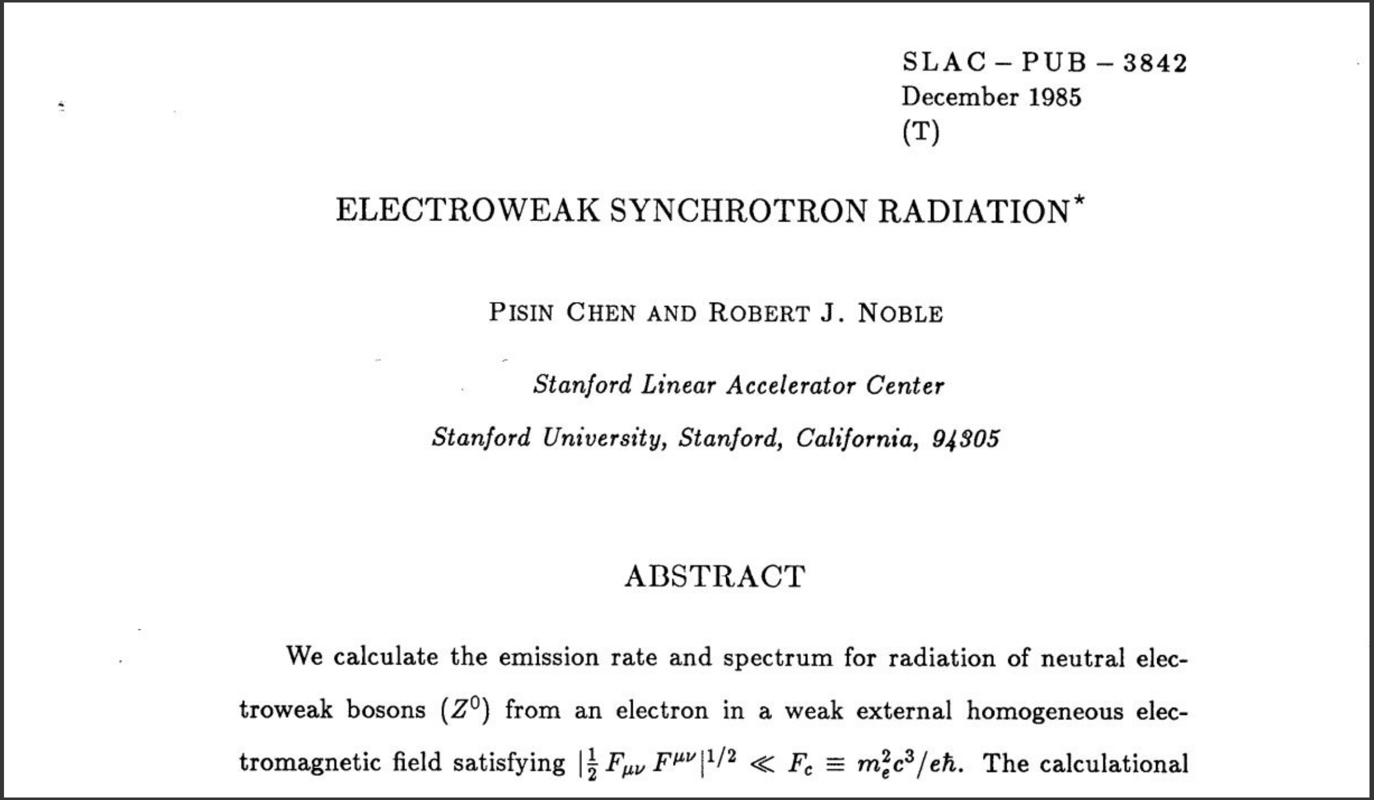
Dark Photon mass: 10 MeV

- Number of photons emitted as a function of energy
- Strong decrease at high energies
- Up to 120 GeV beam energy essentially **no photons above 10 MeV**
- At 175 GeV (top resonance) very few higher energetic photons

Energy of Radiated Synchrotron Photon



SR of a Massive Boson (Z^0) –



SLAC – PUB – 3842
December 1985
(T)

ELECTROWEAK SYNCHROTRON RADIATION*

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Stanford Linear Accelerator Center

Stanford University, Stanford, California, 94305

ABSTRACT

We calculate the emission rate and spectrum for radiation of neutral electroweak bosons (Z^0) from an electron in a weak external homogeneous electromagnetic field satisfying $|\frac{1}{2} F_{\mu\nu} F^{\mu\nu}|^{1/2} \ll F_c \equiv m_e^2 c^3/e\hbar$. The calculational

Dark Photon Power Spectrum –

$$x = \frac{E}{E_e}$$

$$P(x) = \alpha x \left\{ F_0 \left(\int_{-\xi}^{\infty} d\eta K_{5/3}(\eta) \right) + F_1(x) K_{2/3}(\xi) + F_2(x) K_{1/3}(\xi) \right\}$$

$$\boxed{\alpha \propto \varepsilon^2 = 10^{-6}}$$

Cross Check: with $\varepsilon = 1$ & $M = 0$ we recover the SM value for the photon

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$$\xi = \frac{2x\left(1 + \left(\frac{M}{m}\right)^2 x^{-2}(1-x)\right)^{3/2}}{3\Upsilon(1-x)}$$

—

Dark Photon Power Spectrum –

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$$\Upsilon = \frac{eE_e B}{m^3}$$

$$\boxed{\approx 2.9 \times 10^{-6}}$$

Kinematic Constraint:

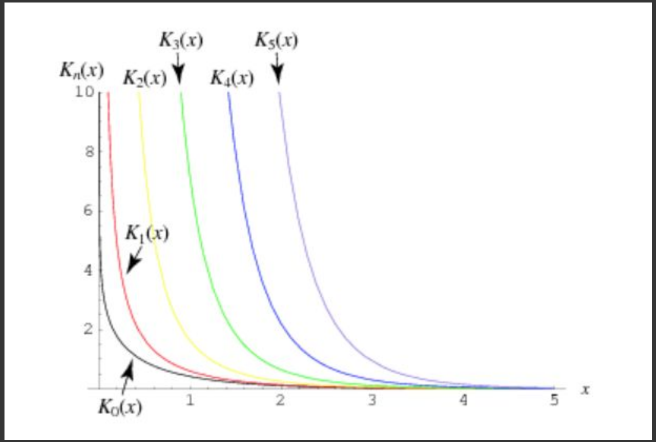
$$E \in [M, E_e)$$

$$\xi \gtrsim 10^8$$

Dark Photon Power Spectrum –

$$P(x) = \alpha x \left\{ F_0 \left(\int_{-\xi}^{\infty} d\eta K_{5/3}(\eta) \right) + F_1(x) K_{2/3}(\xi) + F_2(x) K_{1/3}(\xi) \right\}$$

Modified Bessel Functions of the 2nd Type



Dark Photon Power Spectrum –

Provided: $\frac{M^2}{m^2} \gg \Upsilon = 2.9 \times 10^{-6}$

$$P(x;\varepsilon, M) \sim e^{-\xi}$$

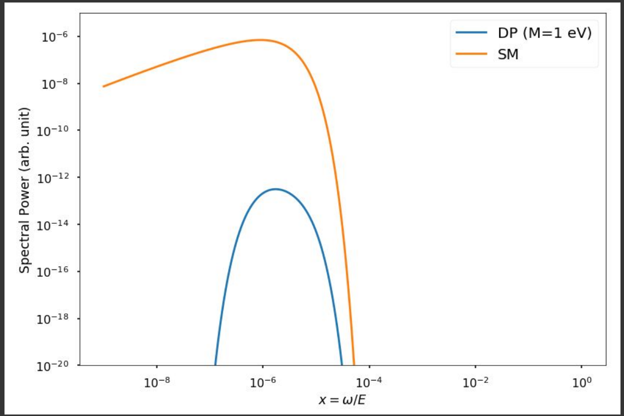
$$\xi \gtrsim 10^8 \longrightarrow P = 0W$$

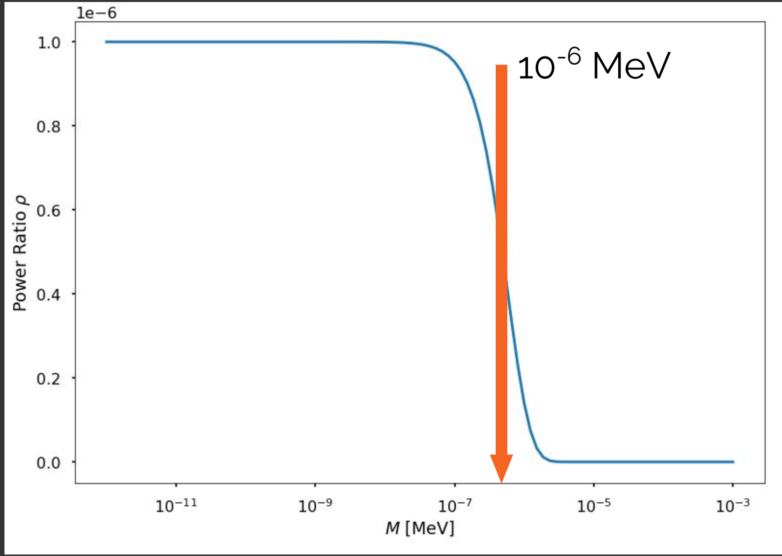
For M = 10 MeV and Υ = 2.9x10^{-8}, no power is radiated via Dark Photons

– A Light... Dark Photon –

- Let's stick to the ε = 10^{-3} (coupling)
- But change **M** to **1 eV** (instead of 10 MeV)
- Emitted power of Standard Model (SM) and Dark Photon (DP) synchrotron radiation as a function of the fraction of the beam-energy
- ϱ is ratio of emitted DP radiation to SM synchrotron radiation as a function of the DP mass

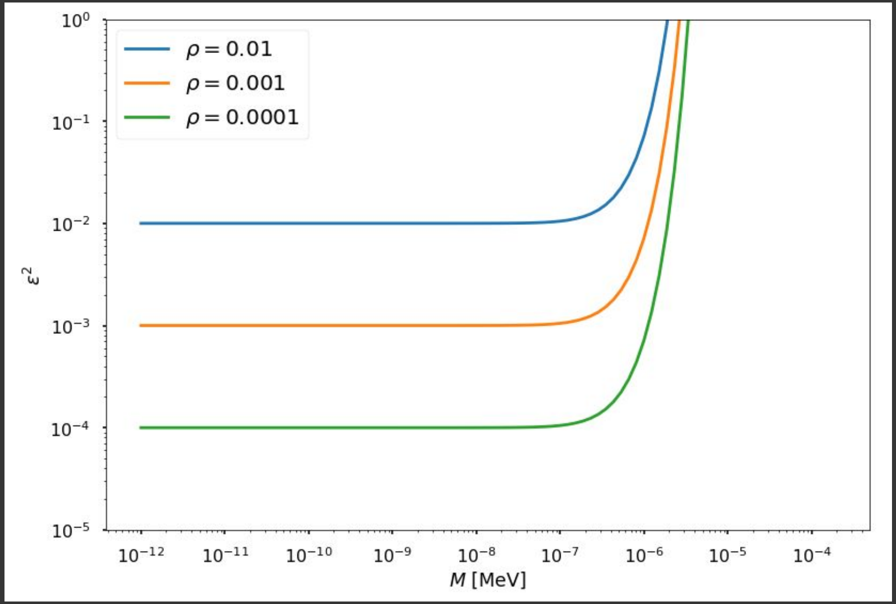
$$\rho = \frac{\int dx P(x;\epsilon, M)}{\int dx P(x;\epsilon=1, M=0)}$$





Dark Photon Sensitivity –

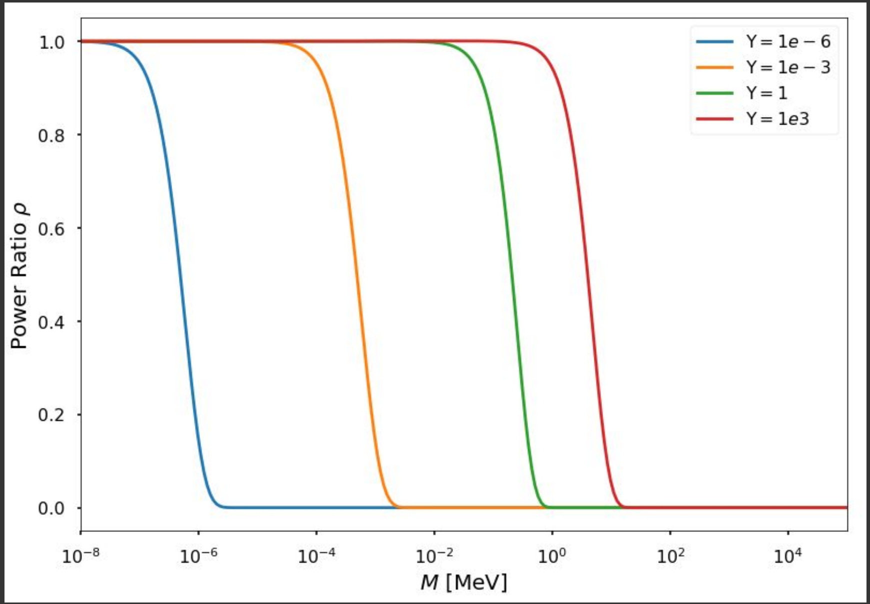
- Assume that we are able to detect a 1% (or 0.1% or 0.01%) power increase
- We could detect DP mass and coupling combinations up/left of the curves
  - very low masses (<10^{-5} MeV)
  - high mixing (>10^{-2})



Dark Photon Sensitivity –

- ϱ falls off at M/m ~ Υ

- In order to detect DP with M= 10 MeV, we need Υ ~ 400, which is **8 orders of magnitude** higher than FCC or CEPC !
  We need e.g. 1 PeV beam in 100 T B-field



Conclusion –

- Dark Photon of 10 MeV emitted as synchrotron radiation can not be detected at proposed upcoming electron/positron colliders
    - extreme suppression by high mass compared to available energy
    - power due to DP would be 0
- Lower mass dark photon might be visible
    - already excluded by former experiments for reasonable couplings
- A Dark Photon with the given mass and coupling would be visible at an electron beam-energy of 1 PeV in a tiny ring using 100 T magnets

Conclusion

- Dark Photo | at proposed
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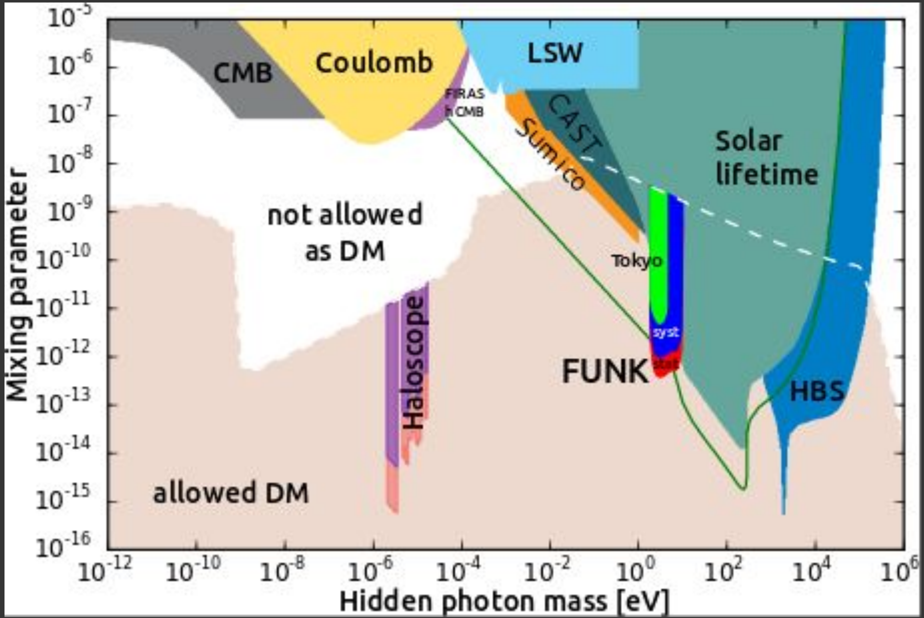
Backup Slides

Dark Photon Current Limits–



Power of Synchrotron Radiated Z^o

$$P(\omega) = \frac{2m^2}{\sqrt{3}(4\pi)^2\mathcal{E}}\,\frac{\omega}{\mathcal{E}}\left\{\left[(g_R^2+g_L^2)\left(\frac{M_Z^2}{2m^2}-1\right)+4g_Rg_L\right]\int_{\xi'}^{\infty}K_{5/3}(\eta)\,d\eta\right.$$

$$+\left[(g_R^2+g_L^2)\left(4+\left(\frac{\omega}{\mathcal{E}}\right)^2\left(1-\frac{\omega}{\mathcal{E}}\right)^{-1}+2\left(\frac{\omega}{\mathcal{E}}\right)^{-2}\left(1-\frac{\omega}{\mathcal{E}}\right)\frac{M_Z^2}{m^2}\right)-8g_Rg_L\right]$$

$$\times K_{2/3}(\xi')+\varsigma'\left[(g_R^2+g_L^2)\left(\frac{\omega}{\mathcal{E}}-2\right)+4g_Rg_L\right]$$

$$\left.\times\left[1+\left(\frac{\omega}{\mathcal{E}}\right)^{-2}\left(1-\frac{\omega}{\mathcal{E}}\right)\frac{M_Z^2}{m^2}\right]^{1/2}K_{1/3}(\xi')\right\}\quad, \tag{9}$$

where $\xi' = 2(\omega/\mathcal{E})[1+(M_Z/m)^2(\omega/\mathcal{E})^{-2}(1-(\omega/\mathcal{E}))]^{3/2}/[3\Upsilon(1-(\omega/\mathcal{E}))]$. Again by setting $M_Z = 0$ and $g_R = g_L = e$ in Eq. (9), the correct power spectrum for photon emission in a weak magnetic field is recovered. The same formula applies in a weak electric field, E, with the replacement $\Upsilon = (p_\perp/m)(eE/m^2)$.

Power of SR Z^0 weak field limit –

$$P(\omega) = \frac{2m^2}{\sqrt{3}(4\pi)^2\mathcal{E}} \frac{\omega}{\mathcal{E}} \Bigg\{ (g_R^2 + g_L^2) \\ \times \left[3 + \frac{M_Z^2}{2m^2} + \left(\frac{\omega}{\mathcal{E}}\right)^2 \left(1 - \frac{\omega}{\mathcal{E}}\right)^{-1} + 2\left(\frac{\omega}{\mathcal{E}}\right)^{-2} \left(1 - \frac{\omega}{\mathcal{E}}\right) \frac{M_Z^2}{m^2} \right] \\ - 4g_R g_L + \varsigma' \left[(g_R^2 + g_L^2)\left(\frac{\omega}{\mathcal{E}} - 2\right) + 4g_R g_L \right] \\ \times \left[1 + \left(\frac{\omega}{\mathcal{E}}\right)^{-2} \left(1 - \frac{\omega}{\mathcal{E}}\right) \frac{M_Z^2}{m^2} \right]^{1/2} \Bigg\} \left(\frac{\pi}{2\xi'}\right)^{1/2} e^{-\xi'} \quad . \tag{10}$$