



Dark photon search status in tau charm energy region

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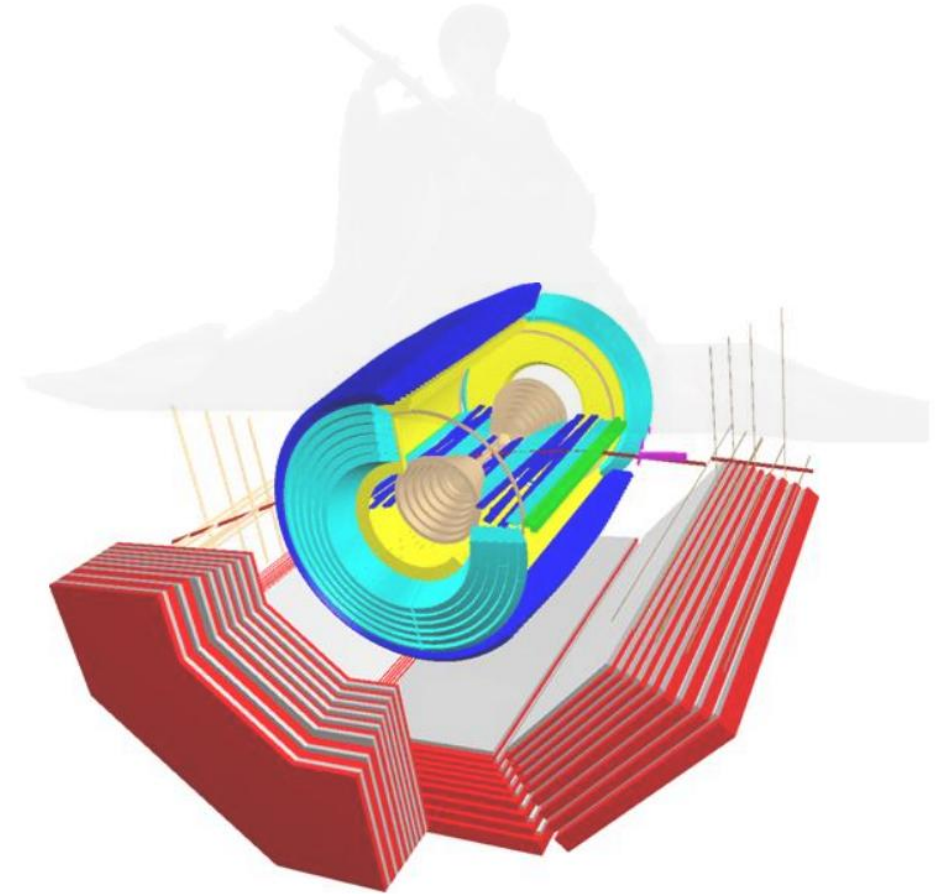
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OUTLINE

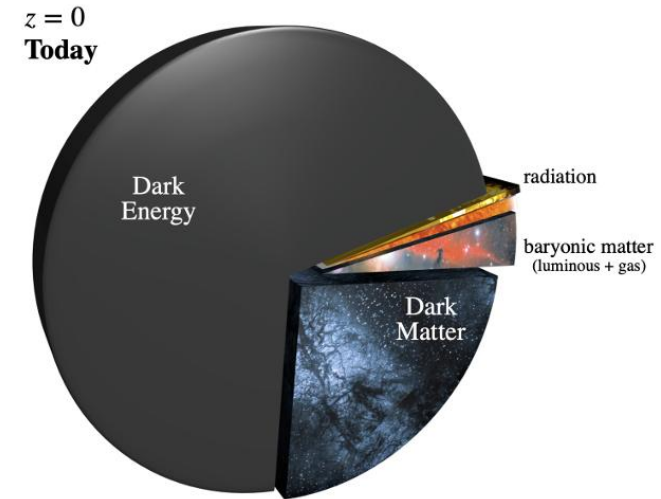
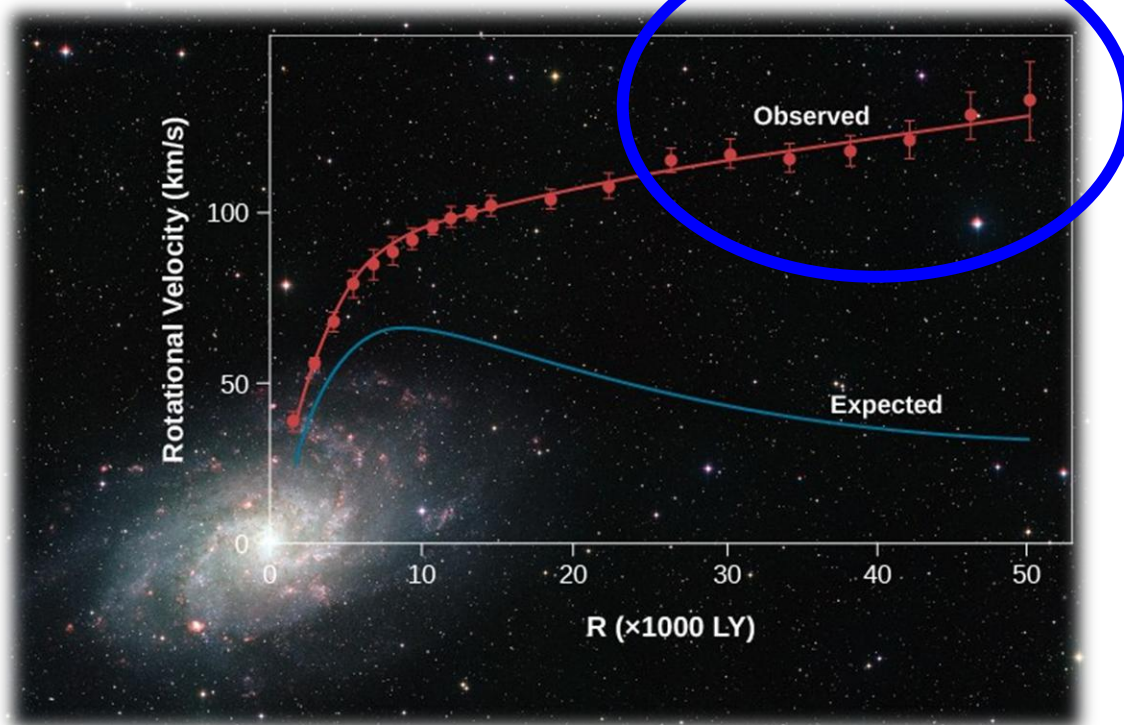
- **Introduction**
- Massive dark photon
- Muon-philic particle
- Massless dark photon
- Summary



Dark matter



Dark matter (DM)
hypothesis

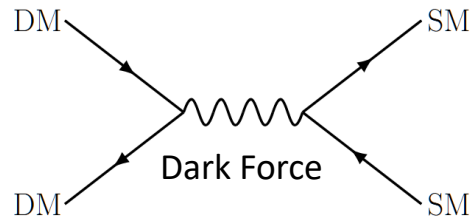


- DM constitutes about 84% of the total matter
- **The most precise nature of DM:**
 $\Omega_{\text{DM}} h^2 = 0.12 \pm 0.0012$ (stands for DM density)
- Other nature: only the gravitational interaction is known
- **Particle type, mass or other interactions: unknown**

Freeze-out mechanism

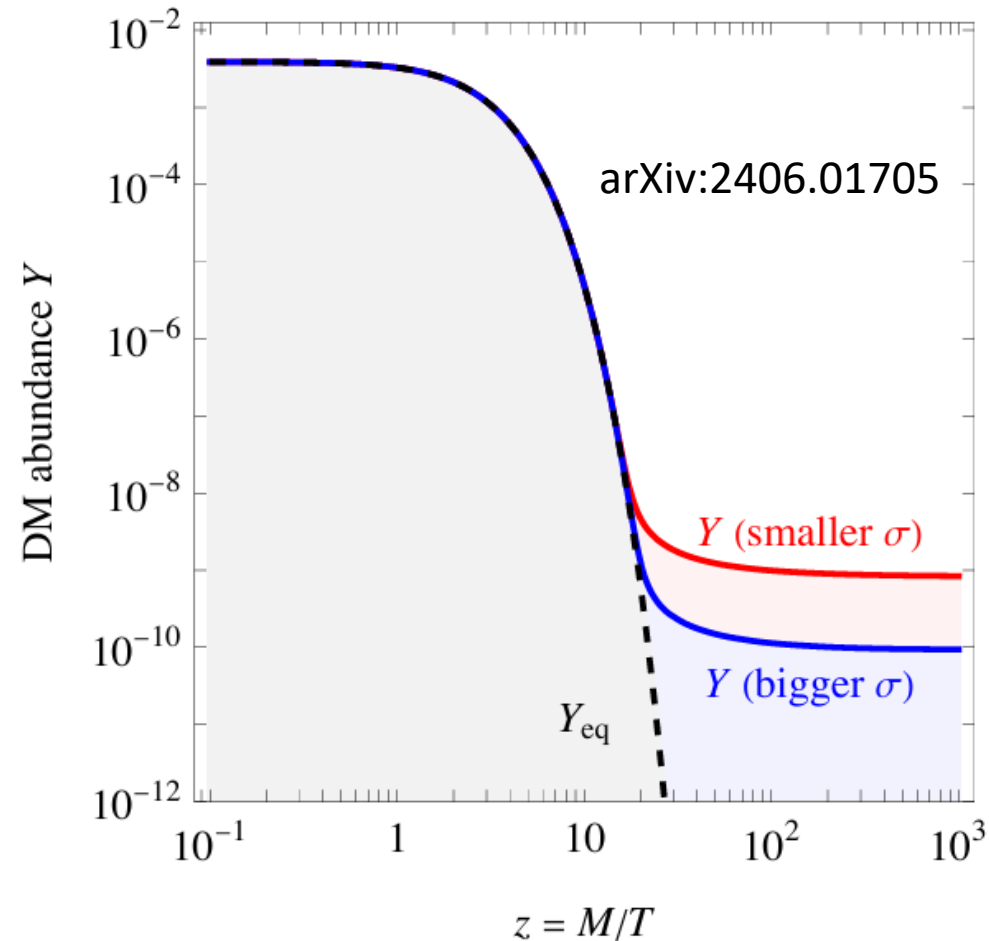
The most popular theory of current DM:

thermal relic by freeze-out

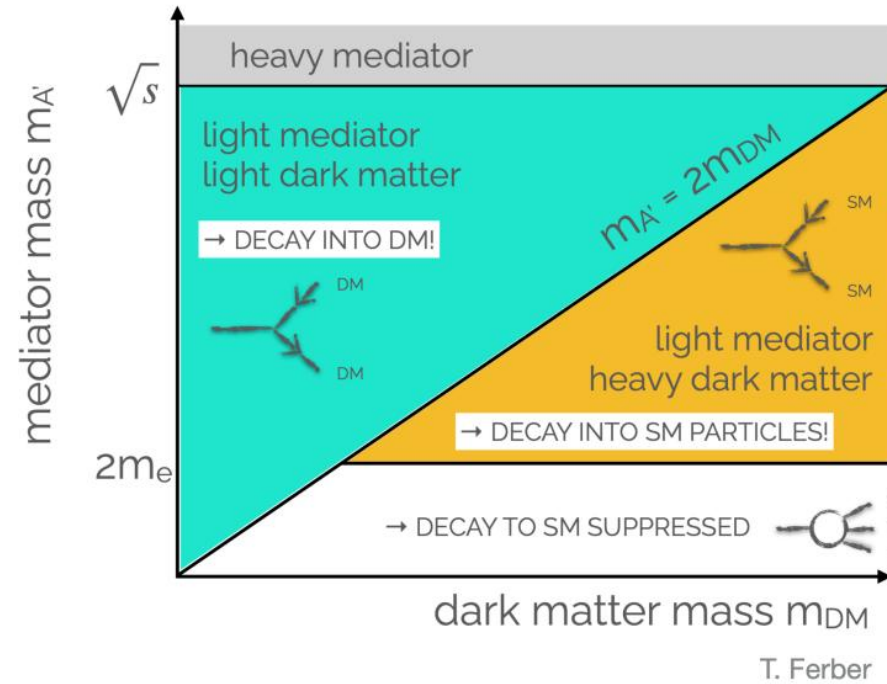
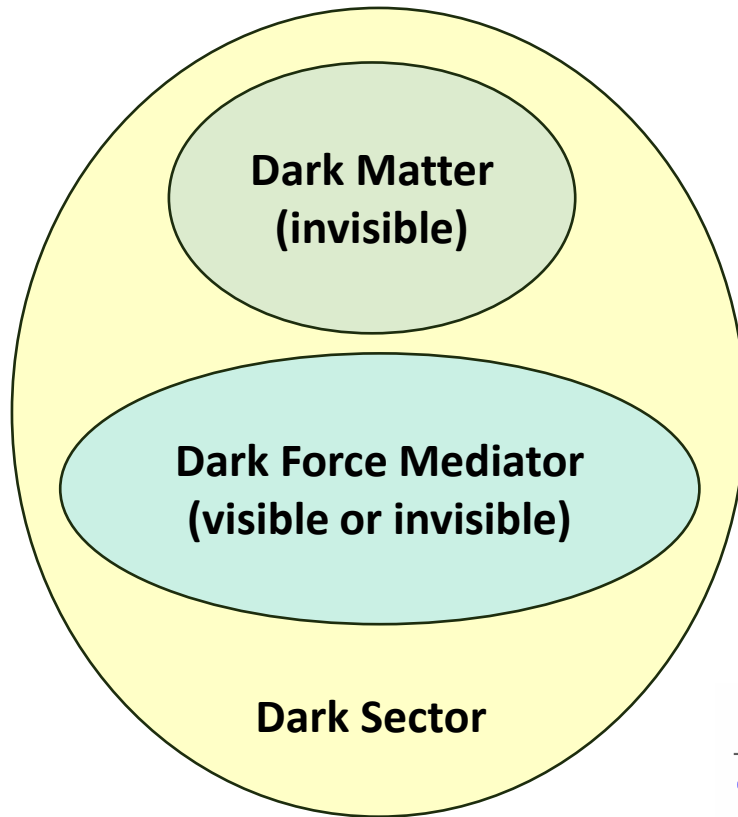


- If only **gravitational interaction: too weak**, the DM abundance must be much larger than the observed value
- Requiring **other interactions from dark sector**:
- To generate the current DM abundance, usually
 - For $DS \gg \text{GeV}$, coupling $\sim \mathcal{O}(1)$, eg. WIMP
 - **For $DS \lesssim \text{GeV}$, coupling $\ll 1$**

This talk



Dark sector

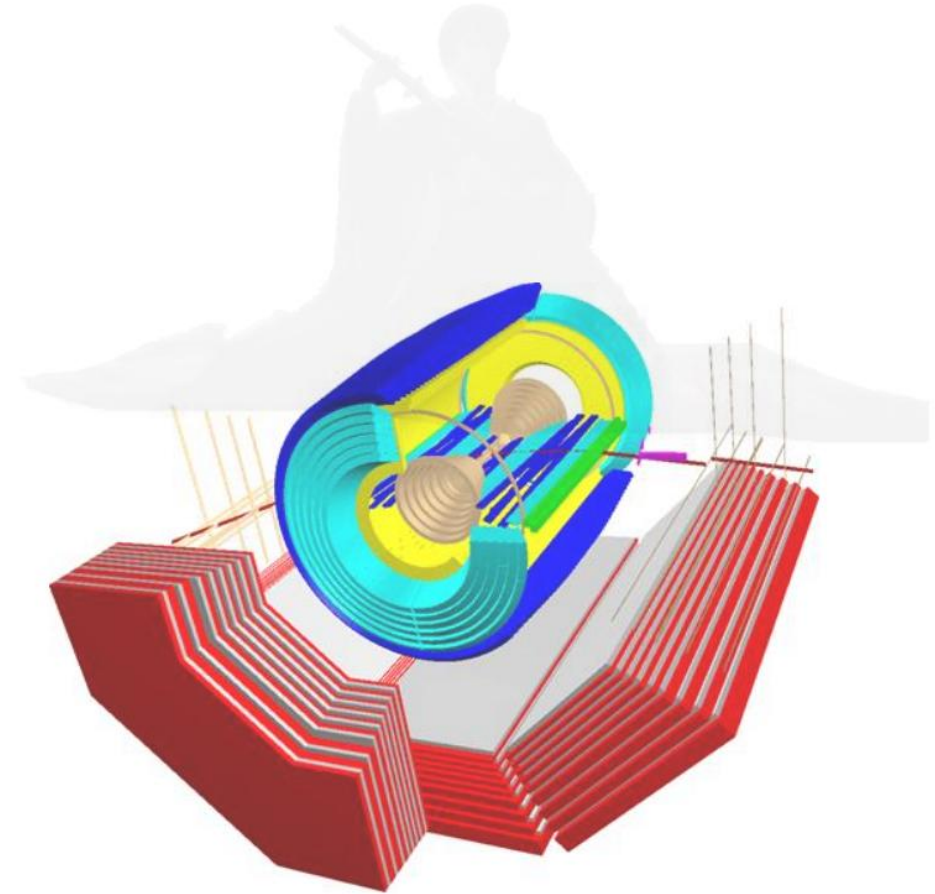


Portal	Particles	Operator(s)
"Vector"	Dark photons	$-\frac{\epsilon}{2 \cos \theta_W} B_{\mu\nu} F'^{\mu\nu}$
"Axion"	Pseudoscalars	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}, \frac{a}{f_a} G_{i\mu\nu} \tilde{G}_i^{\mu\nu}, \frac{\partial_\mu a}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$
"Higgs"	Dark scalars	$(\mu S + \lambda S^2) H^\dagger H$
"Neutrino"	Sterile neutrinos	$y_N L H N$

An (experimental) overview of Dark photon in this talk

OUTLINE

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- Massless dark photon
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Dark photon



SM
photon



Dark
photon

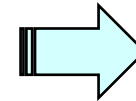
The most popular vector portal

Kinetic mixing: $\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$

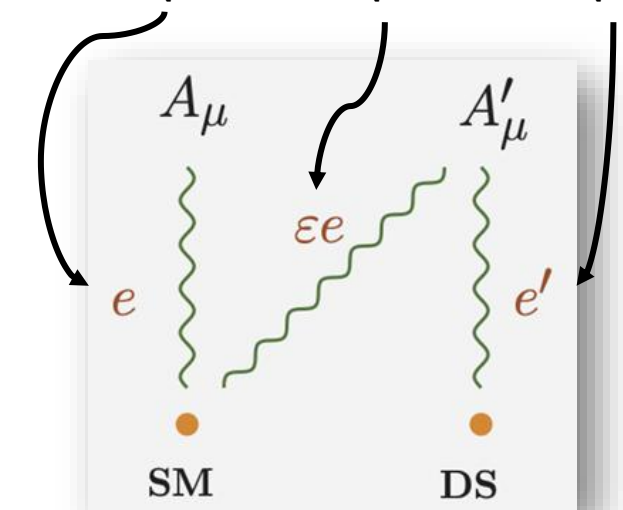
$$A^\mu \rightarrow A^\mu + \epsilon A'^\mu$$

ϵ : mixing strength

PLB 166, 196 (1986)

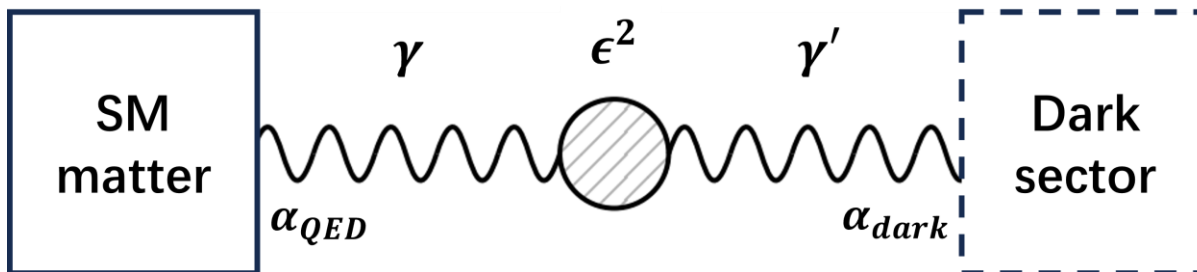


$$\mathcal{L} = eJ_\mu A^\mu + e\epsilon J_\mu A'^\mu + e'J'_\mu A'^\mu$$



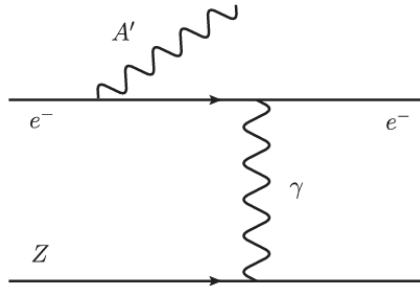
arXiv:2005.01515

(Symmetry broken spontaneously, massive kind)

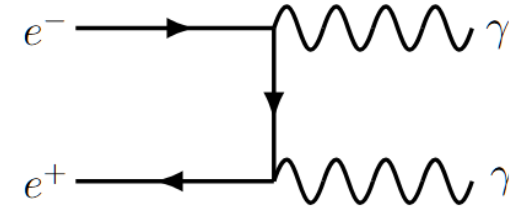


A portal to connect the SM
matter and the dark sector

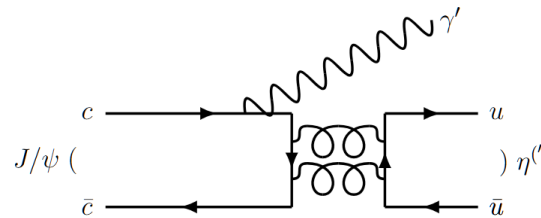
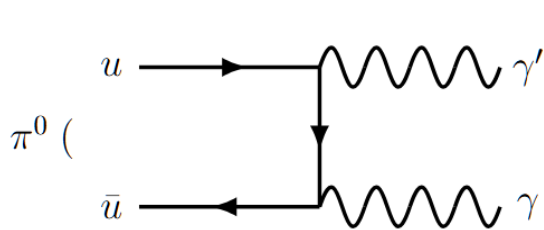
The production of dark photon



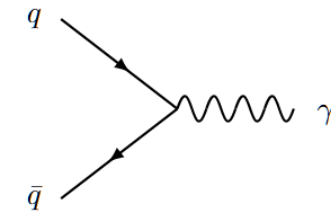
- **Bremsstrahlung:** $e^- Z \rightarrow e^- Z \gamma'$, $p Z \rightarrow p Z \gamma'$,
- Fixed target experiment: NA64, NA62...



- **Annihilation:** $e^+ e^- \rightarrow \gamma \gamma'$
- $e^+ e^-$ collider: BaBar, BESIII, KLOE, Belle...



- **Meson decay:** $\pi^0 / \eta / \eta' \rightarrow \gamma \gamma'$, $\phi \rightarrow \eta \gamma'$, $J/\psi \rightarrow \gamma' \eta / \eta'$
- $e^+ e^-$ collider, LHC...



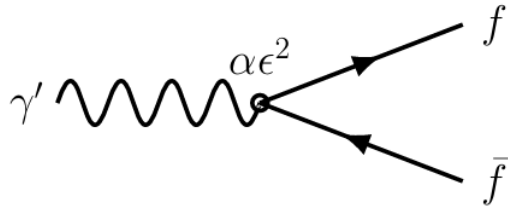
- **Drell-Yan:** $q \bar{q} \rightarrow \gamma'$
- LHC...

➤ Dark photon can be produced in any process by replacing SM photon

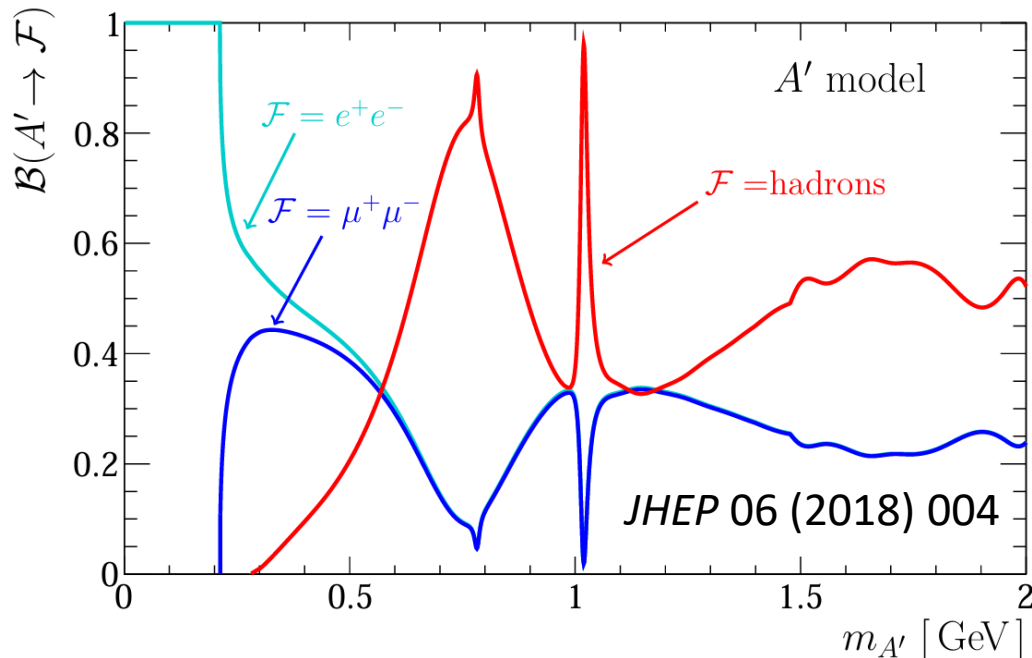
$$\mathcal{P}(\blacksquare \rightarrow \blacksquare \gamma') \sim \epsilon^2 \times \mathcal{P}(\blacksquare \rightarrow \blacksquare \gamma)$$

The decay of dark photon

Case I Visible



- $m_\chi > \frac{m_{\gamma'}}{2}$
- $m_{\gamma'} > 1 \text{ MeV}$

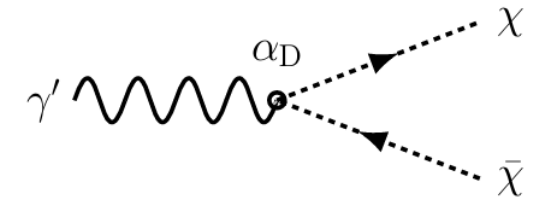


$$\Gamma(\gamma' \rightarrow l^+ l^-) = \frac{1}{3} \alpha \epsilon^2 m_{\gamma'} \sqrt{1 - \frac{4m_l^2}{m_{\gamma'}^2}} \left(1 + \frac{2m_l^2}{m_{\gamma'}^2}\right)$$

$$\Gamma(\gamma' \rightarrow \text{hadrons}) = \Gamma(\gamma' \rightarrow \mu^+ \mu^-) R(s = m_{\gamma'}^2)$$

Usually Detecting lepton final state

Case II Invisible



- $m_\chi < \frac{m_{\gamma'}}{2}$
- $\alpha_D \gg \alpha \epsilon^2$

$$\Gamma(\gamma' \rightarrow \chi \bar{\chi}) = \frac{1}{3} \alpha_D m_{\gamma'} \sqrt{1 - \frac{4m_\chi^2}{m_{\gamma'}^2}} \left(1 + \frac{2m_\chi^2}{m_{\gamma'}^2}\right)$$

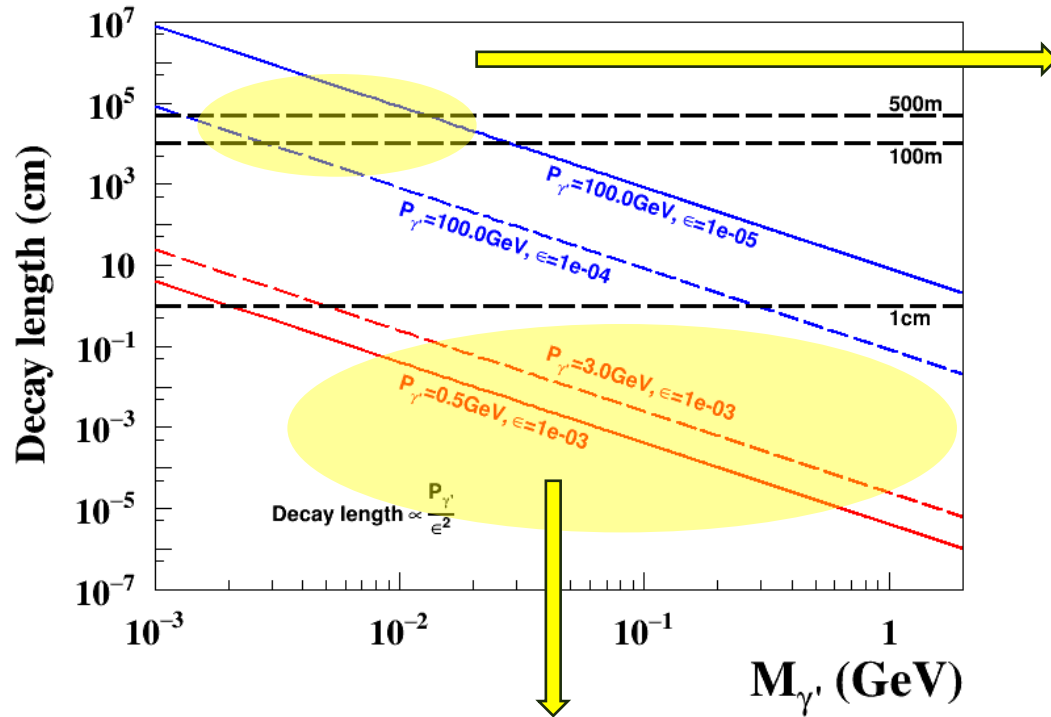
$$\mathcal{B}(\gamma' \rightarrow \chi \bar{\chi}) \sim 100\%$$

Missing energy,
Missing mass ...



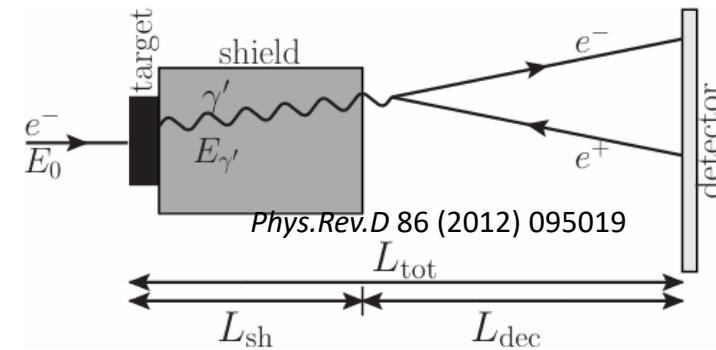
The decay length of **visible** dark photon

- Depend on both of the **new physics (ϵ and $m_{\gamma'}$)** and the **experiment setup ($P_{\gamma'}$)**



➤ Long lived

- Low ϵ , low $m_{\gamma'}$, large $P_{\gamma'}$
- Detector far away from the DP production point
- Low $\epsilon \Rightarrow$ **need high luminosity**
- Fixed target experiment NA62, Faser...

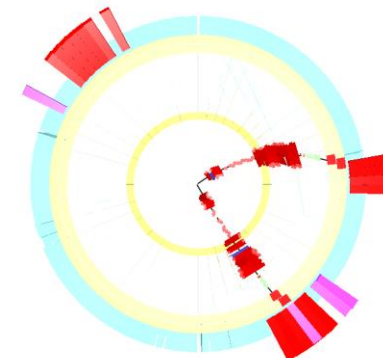


Background clean search

(But no sensitivity for short lived dark photon)

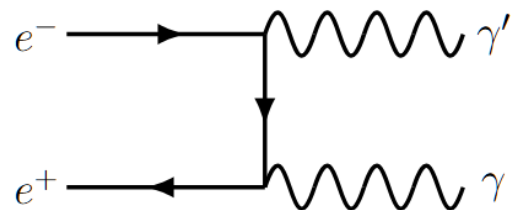
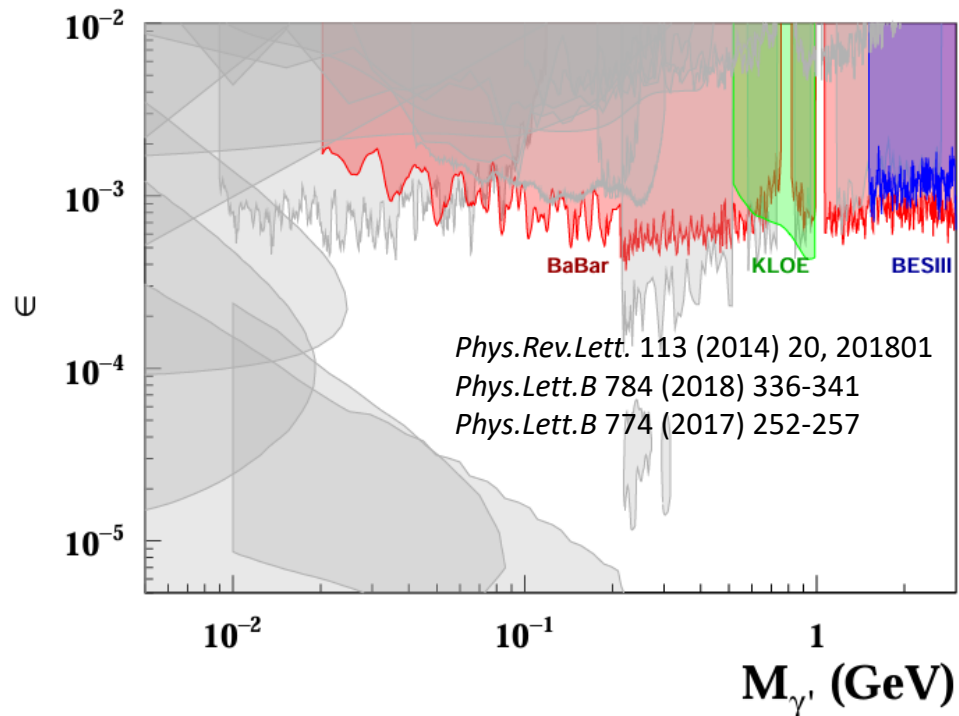
➤ Short lived

- large ϵ , large $m_{\gamma'}$, low $P_{\gamma'}$
- Detector cover the DP production point
- BaBar, BESIII, KLOE, Belle...



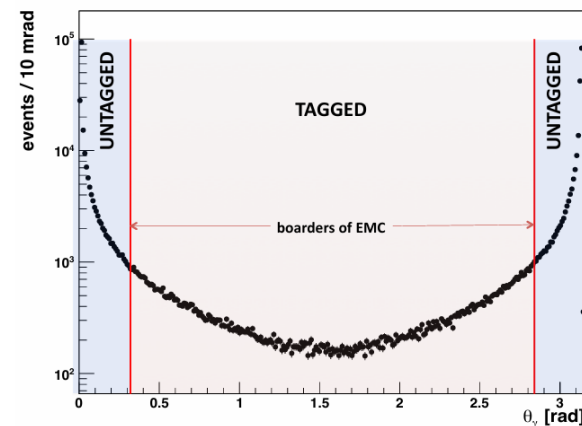
Irreducible background from $\gamma^* \rightarrow e^+ e^-$ (QED)

Visible case: Annihilation $e^+ e^- \rightarrow \gamma \gamma'$

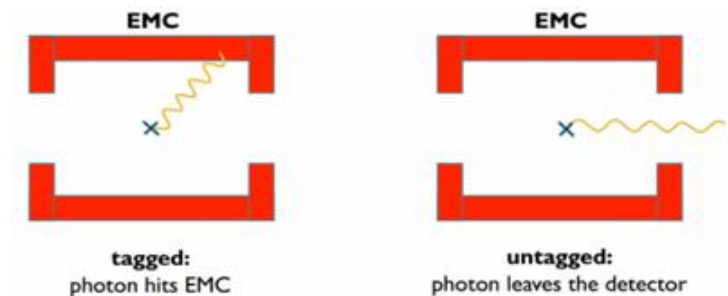


Irreducible background
from $e^+ e^- \rightarrow \gamma e^+ e^-$

Exp.	$\sqrt{s}$	$\mathcal{L}$	γ' rec.	Method
BaBar	10.6 GeV	514 fb ⁻¹	$e^+ e^-, \mu^+ \mu^-$	Tagged
KLOE	1.0 GeV	1.93 fb ⁻¹	$\mu^+ \mu^-, \pi^+ \pi^-$	Untagged
BESIII	3.8 GeV	2.93 fb ⁻¹	$e^+ e^-, \mu^+ \mu^-$	Untagged

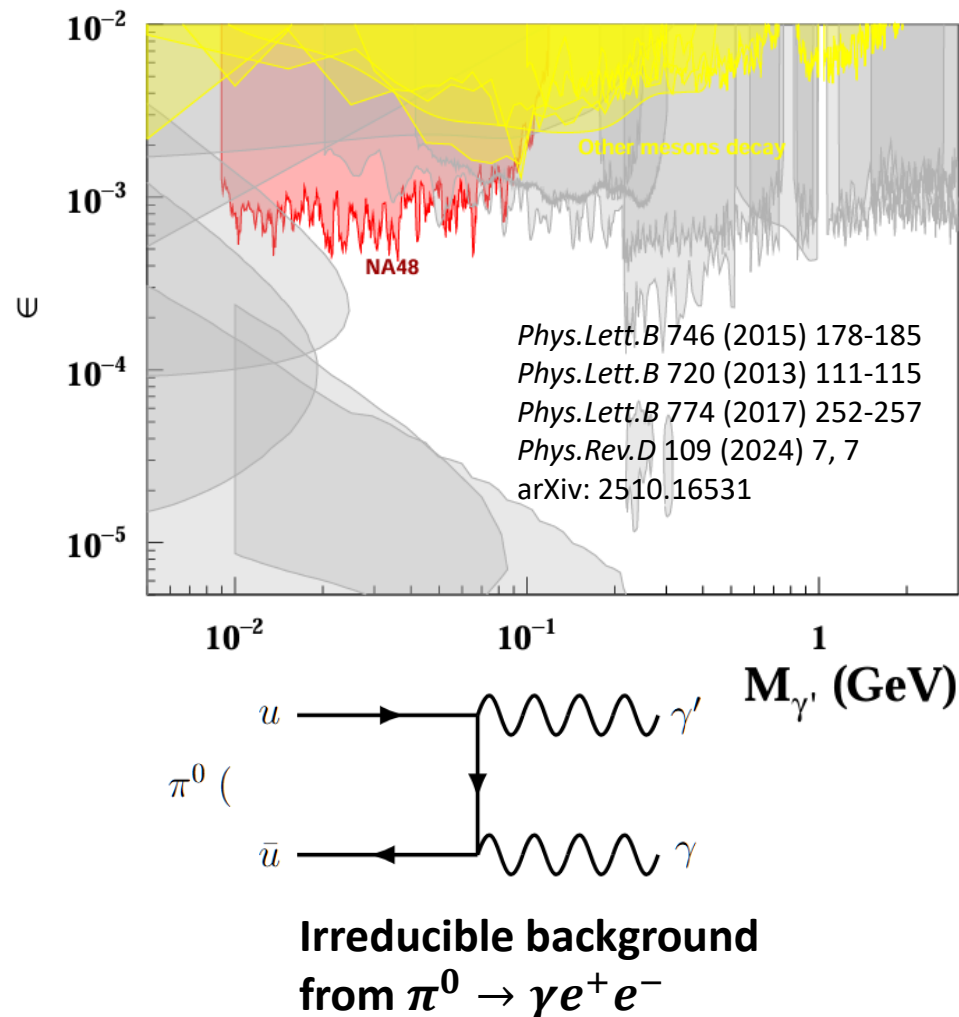


20.3 fb⁻¹ now, and 100 × in FCTF



- 2 order lower $\mathcal{L}$ of KLOE and BESIII, but competitive limit, benefit from the **untagged method**
- Better limit from KLOE, benefit from low $\sqrt{s}$ ($\sigma \sim \frac{1}{\sqrt{s}}$) and **$\pi^+ \pi^-$ rec. (larger BF in ρ region)**

Visible case: Meson decay



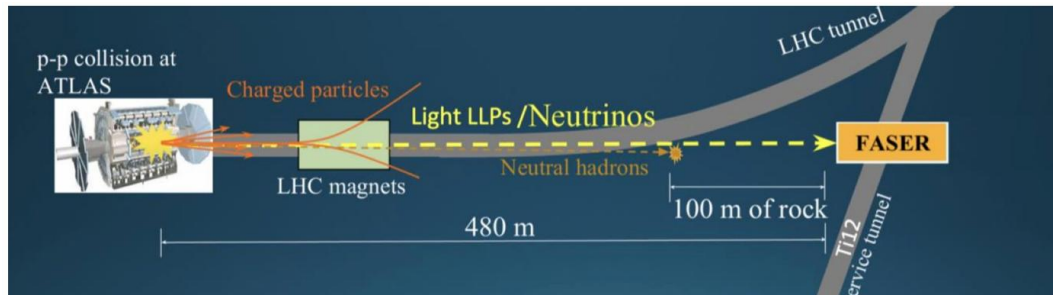
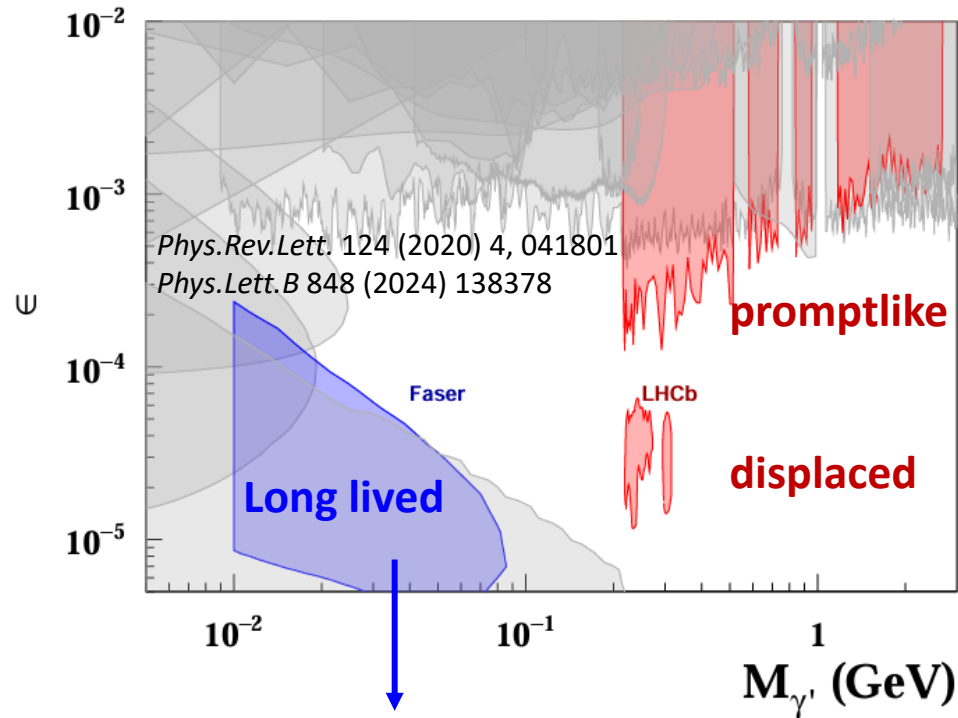
➤ NA48

- Proton $\rightarrow$ target $\rightarrow K^+ \rightarrow \pi^0 X$
- $\pi^0 \rightarrow \gamma\gamma', \gamma' \rightarrow e^+e^-$
- **1.69×10^7 reconstructed $\pi^0 \rightarrow \gamma e^+ e^-$ candidates**

➤ Other mesons decay, looser constraint (limited by statistic)

- $\phi \rightarrow \gamma'\eta$: KLOE, 1.7 fb^{-1} @ $\sqrt{s} \sim 1 \text{ GeV}$
- $J/\psi \rightarrow \gamma'\eta'$: BESIII, using $10^9 J/\psi$
- $\eta^{(\prime)} \rightarrow \gamma\gamma'$: BESIII, using $10^{10} J/\psi$ (with $J/\psi \rightarrow \gamma\eta^{(\prime)}$)
- $\chi_{cJ} \rightarrow \gamma' J/\psi$: BESIII, using $2.7 \times 10^9 \psi(2S)$ (with $\psi(2S) \rightarrow \gamma\chi_{cJ}$)

Visible case: Inclusive production at LHC



➤ Dark photon source in LHC

- Meson decay $\pi^0 \rightarrow \gamma\gamma'$, $\eta \rightarrow \gamma\gamma'$
- Bremsstrahlung: $pp \rightarrow pp\gamma'$
- DrellYan: $q\bar{q} \rightarrow \gamma'$ (dominated when $m_{\gamma'} \gtrsim 1\text{GeV}$)

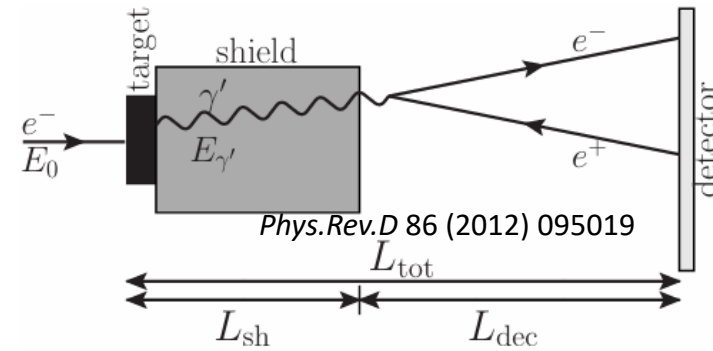
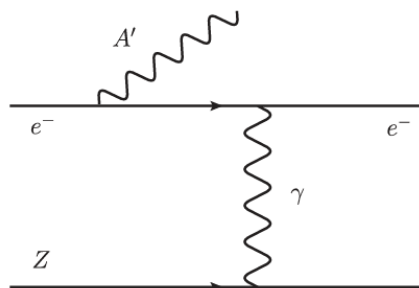
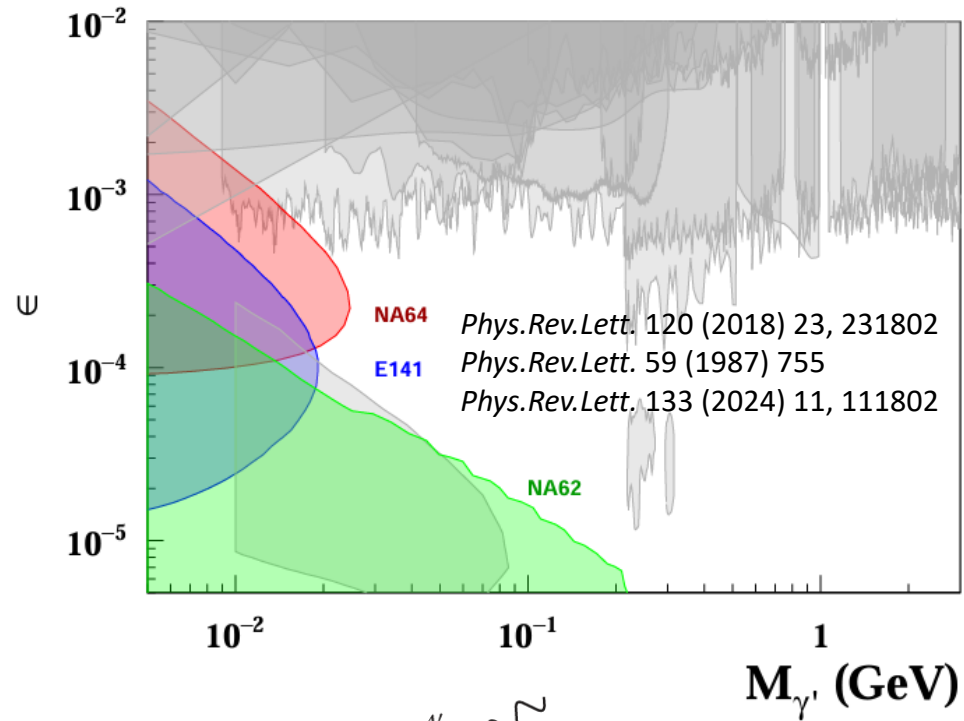
➤ **LHCb**: 5.5 fb^{-1} data, $\gamma' \rightarrow \mu^+\mu^-$

- **Promptlike search**: irreducible background from $\gamma^* \rightarrow \mu^+\mu^-$
- **Displaced search**: less background with displaced info $\Rightarrow$ better sensitivity $\Rightarrow$ lower ϵ

➤ **Faser**: 27.0 fb^{-1} data, $\gamma' \rightarrow e^+e^-$

- Decay length $\propto \frac{P_{\gamma'}}{m_{\gamma'}^2 \epsilon_{\gamma'}^2}$
- Small $m_{\gamma'} \Rightarrow$ **Longlived** dark photon
- Background free search, zero observed event in signal region

Visible case: Fixed target



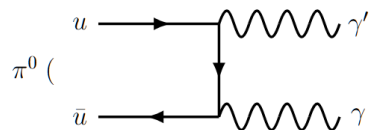
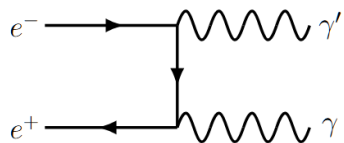
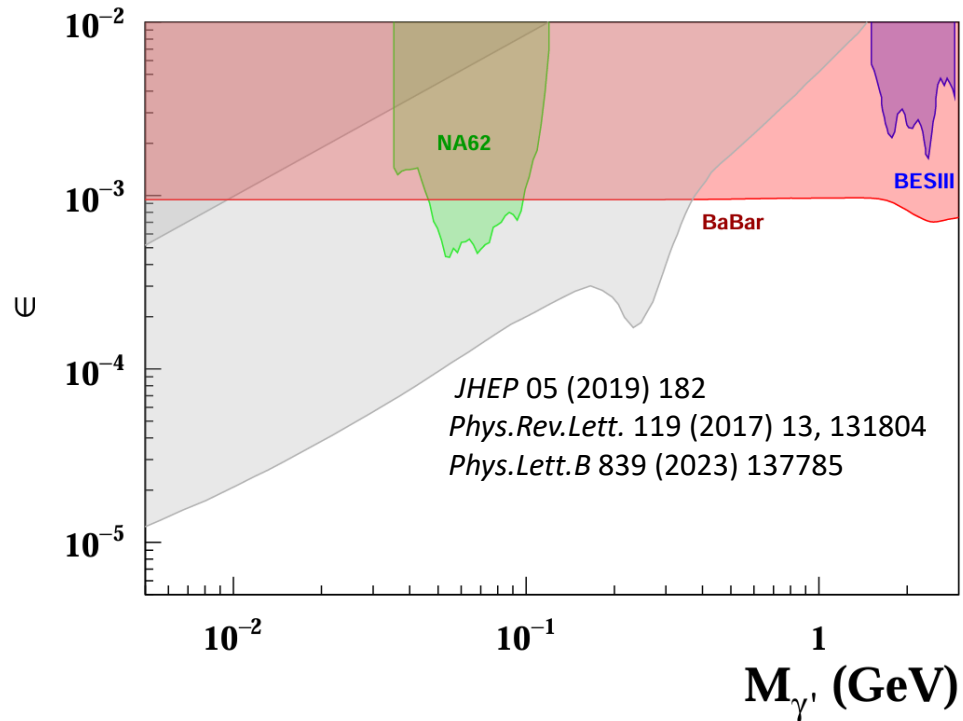
Background clean search
 (But no sensitivity for short lived dark photon)

Exp.	beam	Beam E	$N_{e^-/p}$	L_{sh}	L_{dec}	N_{obs}
NA64	e^-	100 GeV	5.4×10^{10}	short	3.5 m	0
E141	e^-	9 GeV	2×10^{15}	0.12 m	35 m	1126^{+1312}_{-1126}
NA62	p	400 GeV	2×10^{17}	100 m	120 m	0

➤ **Upper bound: limited by the detector position**

➤ **Lower bound: limited by the luminosity**

Invisible case: Annihilation and Meson decay



■ Using the missing mass to identify the invisible DP signal

➤ **BaBar**: 53 fb^{-1} of e^+e^- collision data

- Dark photon from $e^+e^- \rightarrow \gamma\gamma'$
- Leading the constraint for $m_{\gamma'} \gtrsim 300 \text{ MeV}$

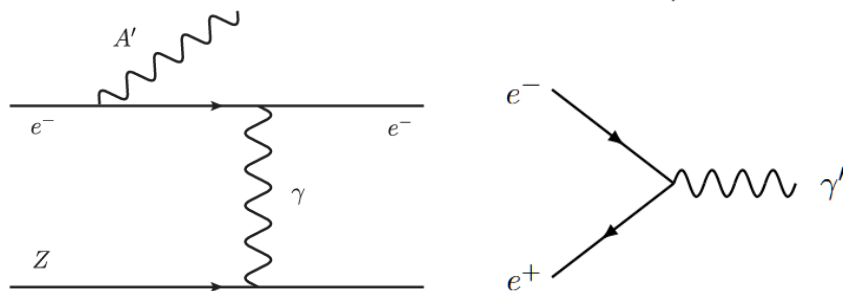
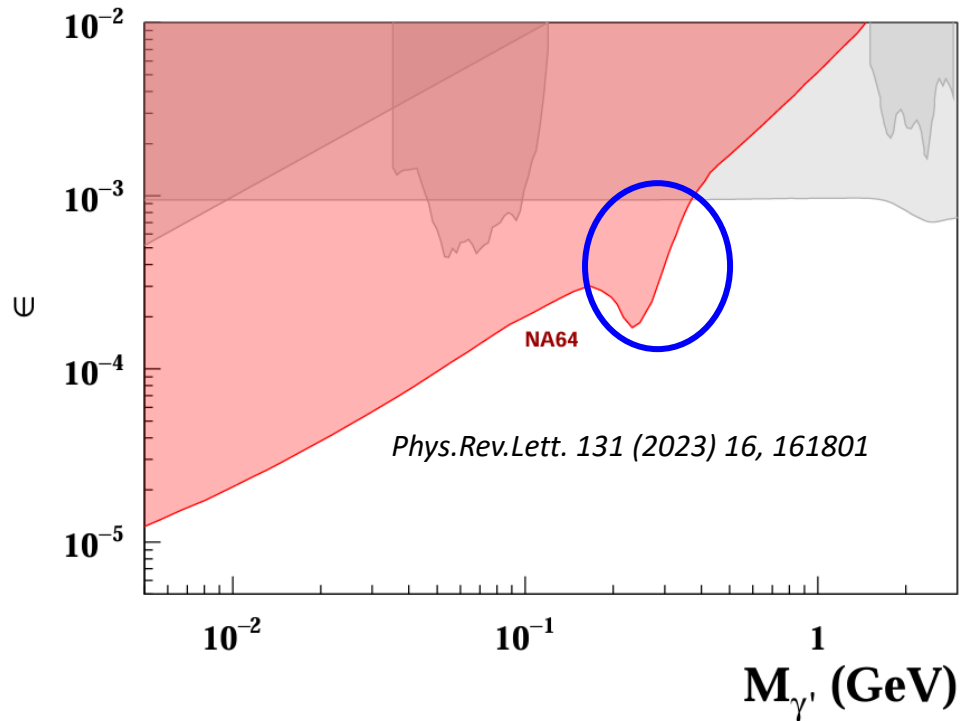
➤ **BESIII**: 14.9 fb^{-1} of e^+e^- collision data

- Limited by statistic
- Dark photon from $e^+e^- \rightarrow \gamma\gamma'$
- For photon with $E_\gamma > 2 \text{ GeV}$, saturate the EMC, shower loss

➤ **NA62**: 4×10^8 tagged π^0 from $K^+ \rightarrow \pi^+\pi^0$

- The sole result from meson decay: $\pi^0 \rightarrow \gamma\gamma'$
- BESIII now has similar statistic: $10^{10} \text{ J}/\psi$, $\mathcal{B}(\text{J}/\psi \rightarrow \pi^+\pi^-\pi^0) \sim 2\%$
- FTCTF is expected providing better constraint

Invisible case: Fixed target



■ Using the missing energy to identify the invisible DP signal

■ **NA64:** 9.37×10^{11} 100 GeV e^- on target

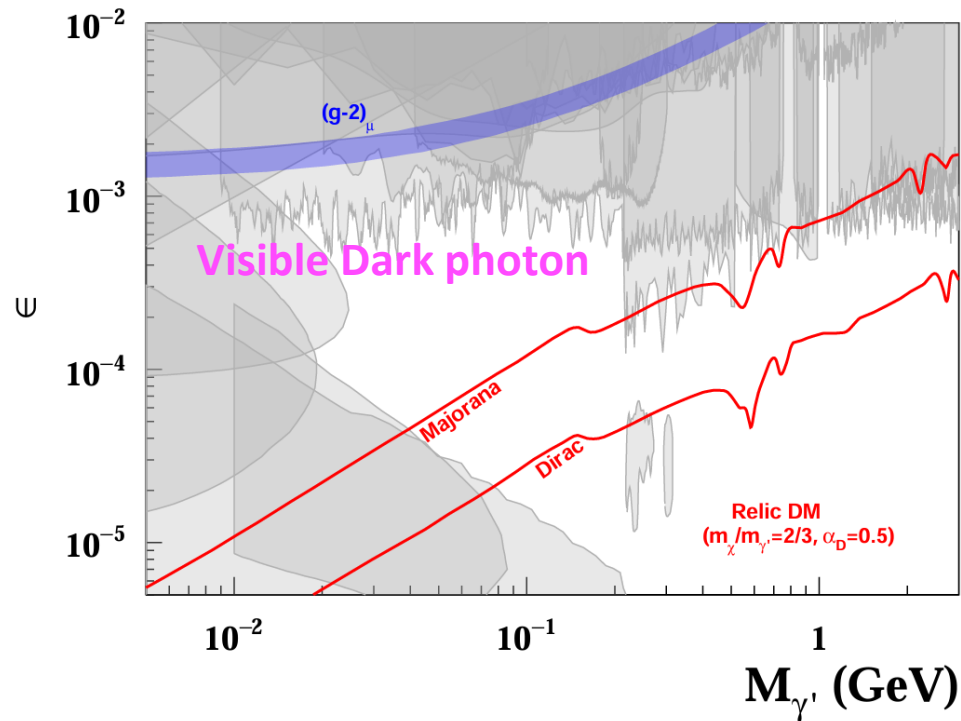
➤ **Bremsstrahlung search:** $e^- Z \rightarrow e^- Z \gamma'$

- Leading the constraint for low mass region

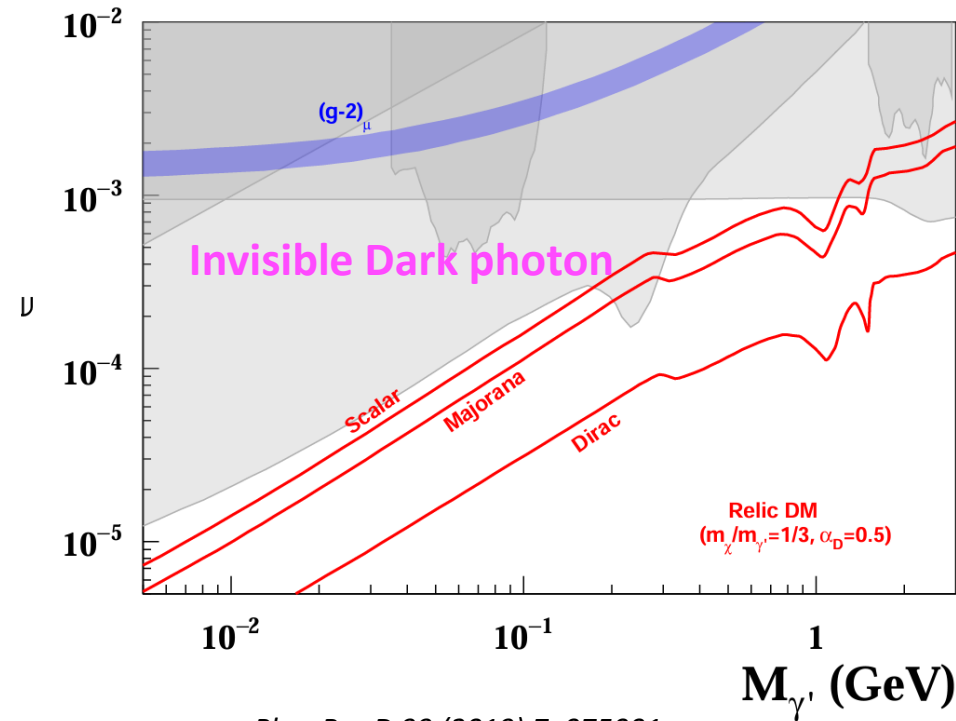
➤ **Annihilation search:** $e^+ e^- \rightarrow \gamma'$

- Secondary positron in target annihilation with atomic electrons
- Benefits from the resonance enhancement
- Further constraint around $m_{\gamma'} \sim \sqrt{2E_e + m_e}$

Summary of massive dark photon

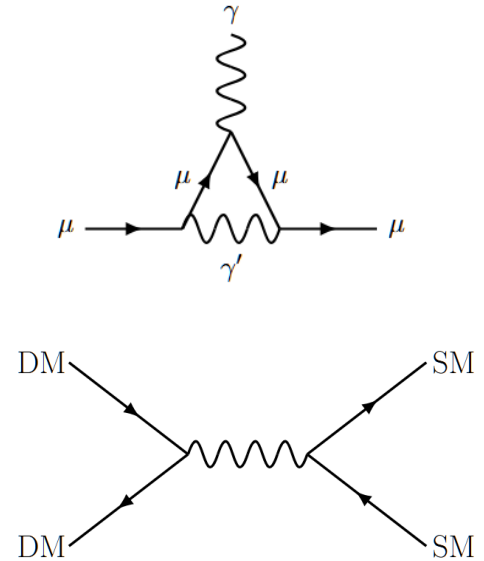


- $(g - 2)_\mu$ favor target
- Favor region before 2025
- **Have been excluded** for both visible and invisible DP case



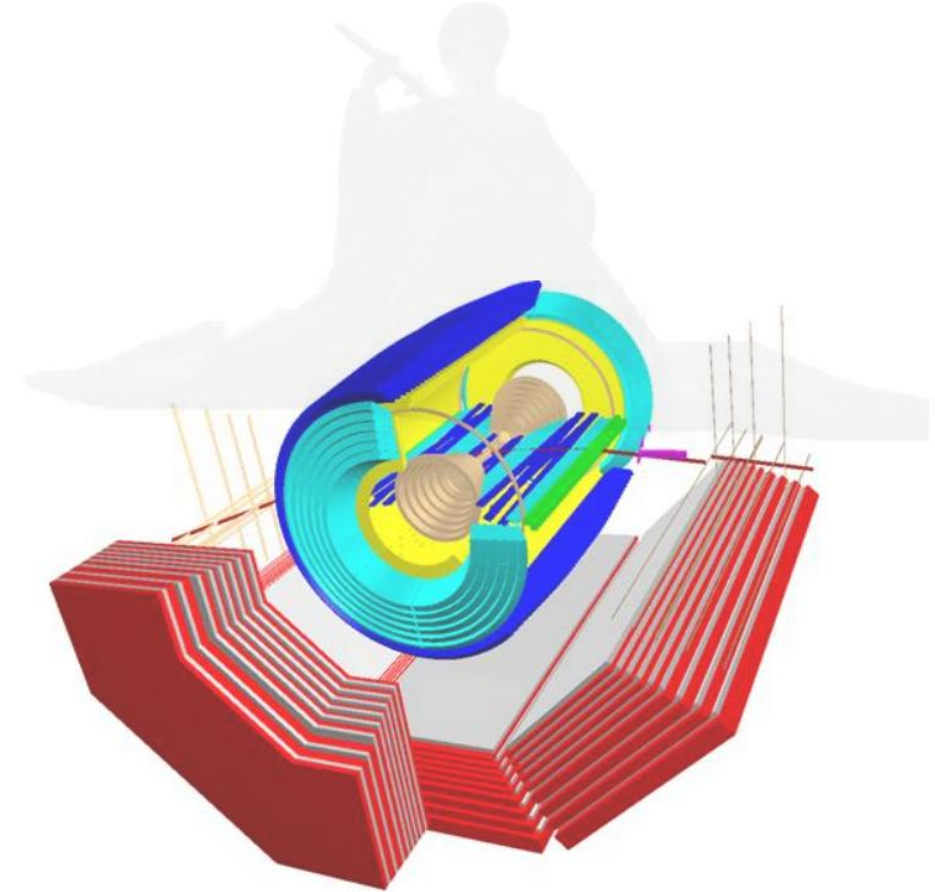
Phys.Rev.D 99 (2019) 7, 075001

- **Relic DM target** (to obtain $\Omega_{DM} h^2 = 0.12$ in Freeze-out)
- Dark matter parameter: $y = \epsilon^2 \alpha_D (m_\chi / m_{\gamma'})^4$
- Given a DM mass m_χ , y is a constant value
- $\frac{m_\chi}{m_{\gamma'}} \neq 0.5$, avoid resonance effect; $\frac{m_\chi}{m_{\gamma'}} < 1$, avoid $\chi \bar{\chi} \rightarrow \gamma' \gamma'$



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- Massless dark photon
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Other models of vector portal

$$\mathcal{L} \subset g \sum_f \mathbf{x}_f \bar{f} \gamma^\mu f A'_\mu$$

For dark photon transform to the other models,
please refer to DarkCast *JHEP* 06 (2018) 004

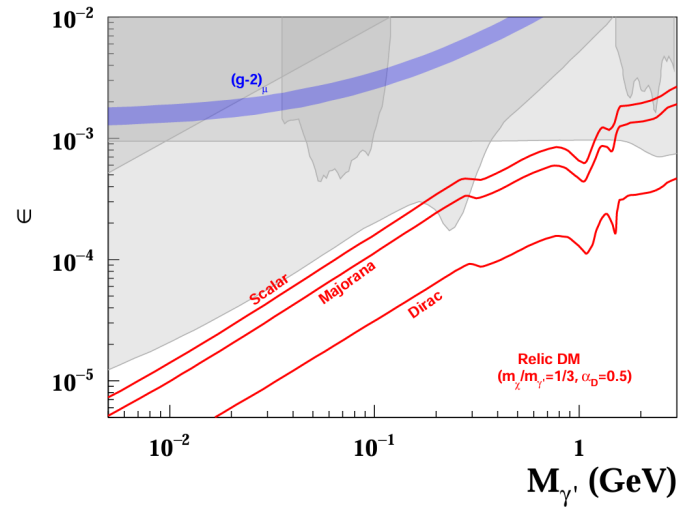
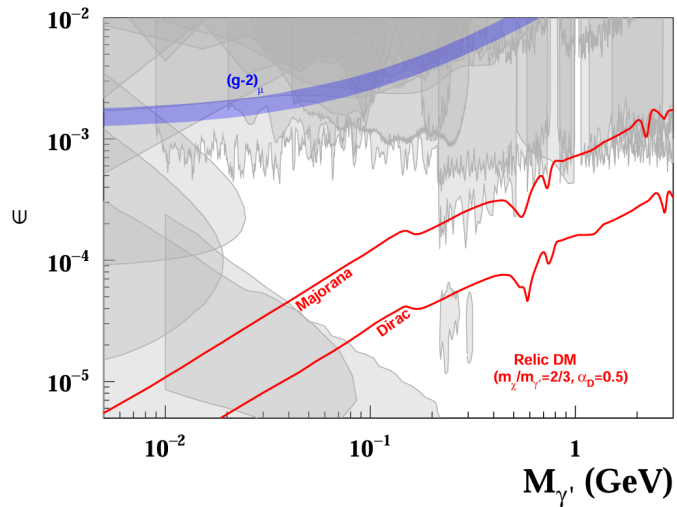
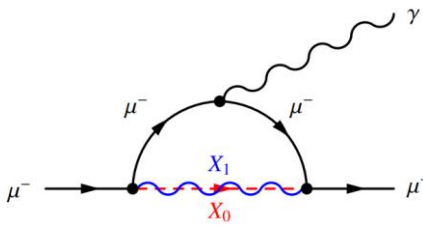
Coupling/model	Dark photon	$B - L$	B	Protophobic	$L_\mu - L_\tau$
g	ϵe	g_{B-L}	g_B	g_p	g'
$x_{u,c,t}$	2/3	1/3	1/3	-1/3	0
$x_{d,s,b}$	-1/3	1/3	1/3	2/3	0
x_e	-1	-1	$-e^2/(4\pi)^2$	-1	0
x_μ	-1	-1	$-e^2/(4\pi)^2$	-1	1
x_τ	-1	-1	$-e^2/(4\pi)^2$	-1	-1
x_{ν_e}	0	-1	0	0	0
x_{ν_μ}	0	-1	0	0	1
x_{ν_τ}	0	-1	0	0	-1

→ Talk something
more later,
 **γ' only coupling to
 $\mu, \tau, \nu \Rightarrow$
muonphilic particle**

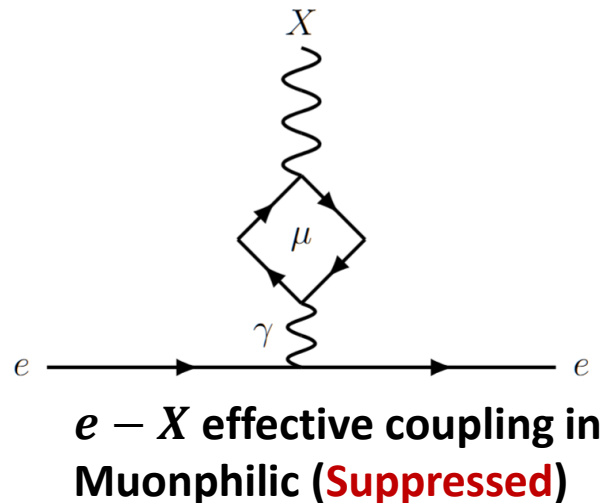
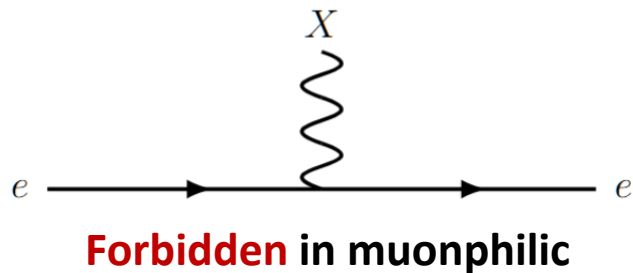
Previous talk, the leading constraint
are mostly based on $e - \gamma'$ coupling

Meson decay will dominate the
constraint for some models

$(g - 2)_\mu$ favor

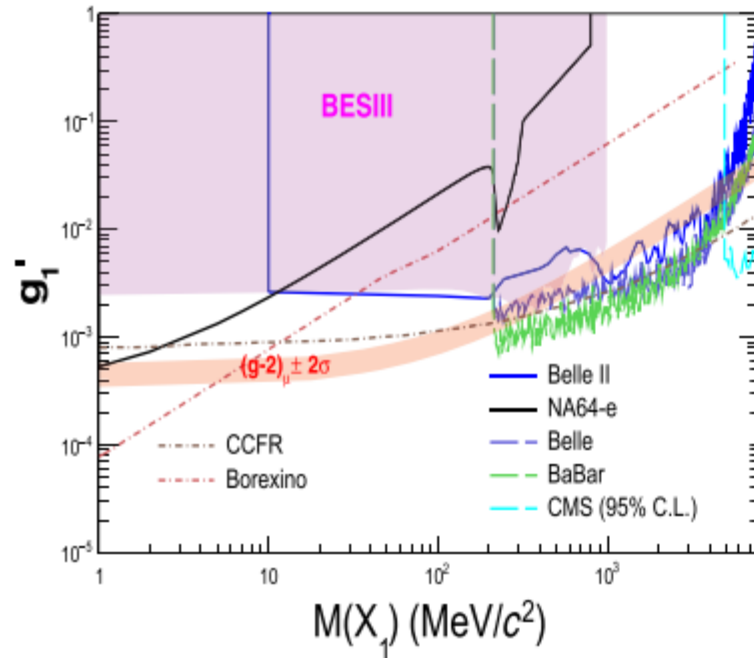


- The $(g - 2)_\mu$ favor region (before 2025) **has been excluded** in the dark photon
- Most of the dark photon experiments are based on **electron or light quark coupling**
- If the new particle is muonphilic, the previous experiment will have less constraint due to the loop diagram
- **The $(g - 2)_\mu$ favor region may be revived in the muonphilic model**

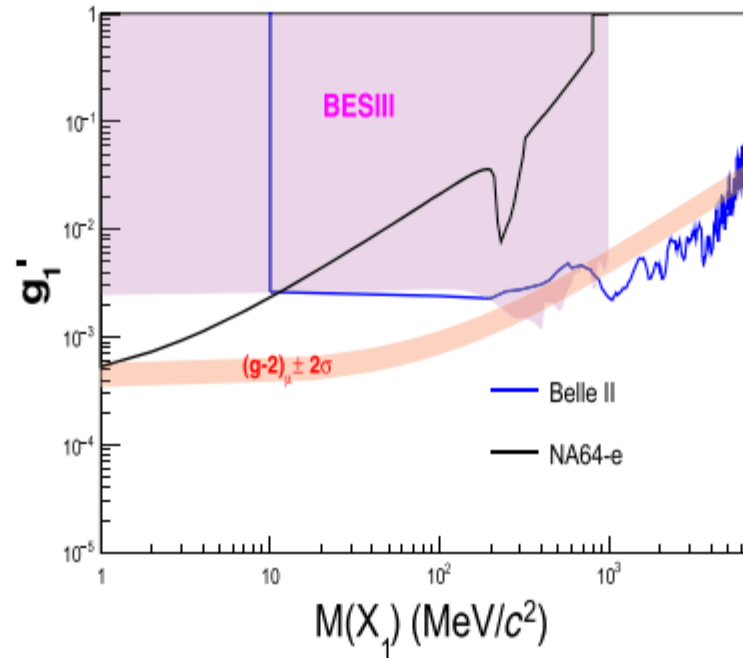


Current status of muonphilic vector

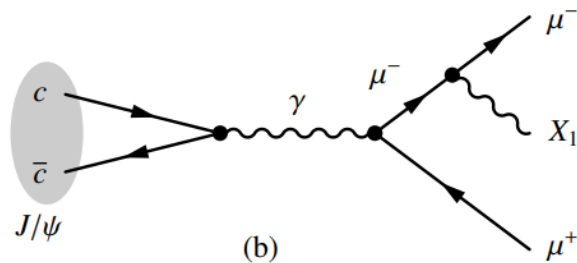
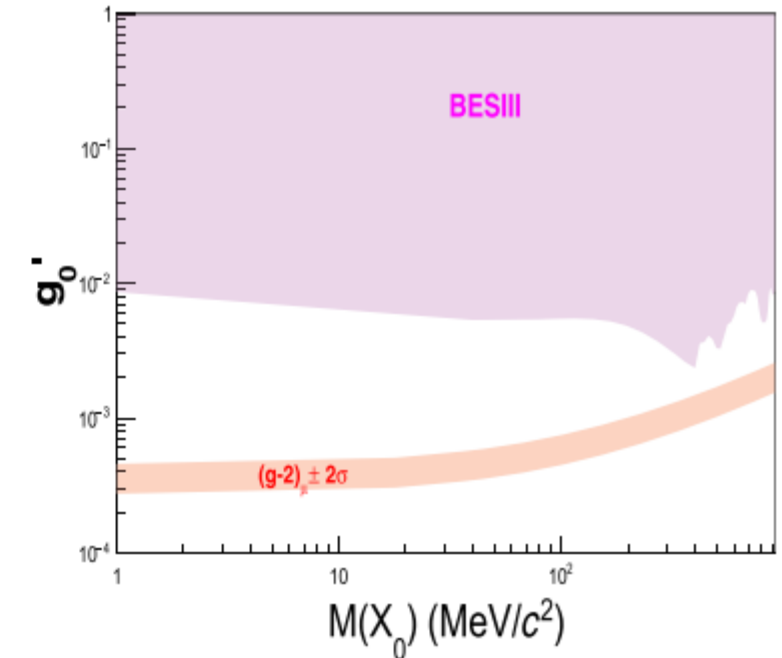
$X \rightarrow \text{SM}$ ($m_X > m_X/2$)



$X \rightarrow \text{DM}$ ($m_X < m_X/2$)

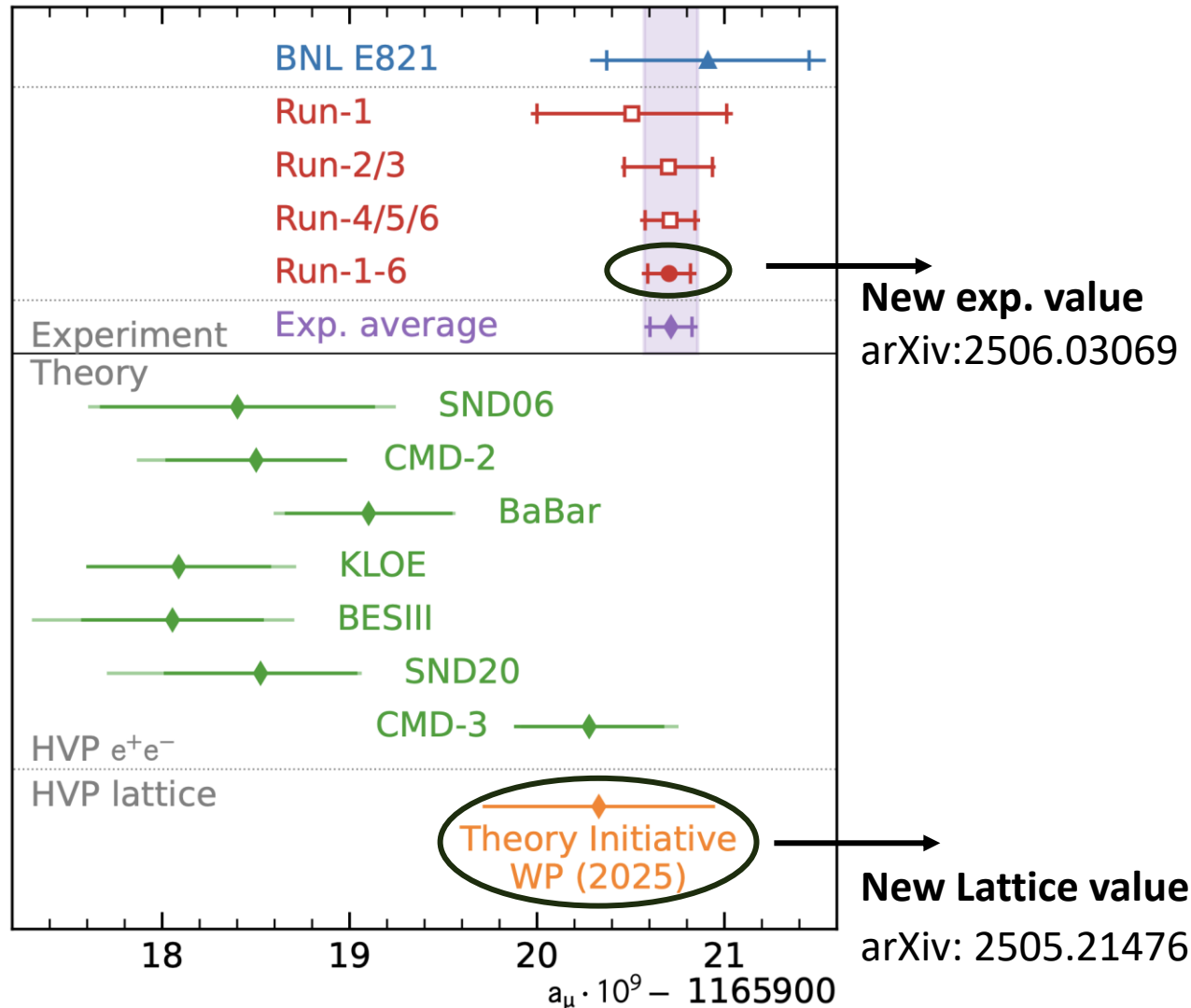


Muon-philic scalar



- Muonphilic particle generated from muon radiation, eg. $J/\psi \rightarrow \mu^+\mu^-X$ at BESIII
- X decaying to $\mu^+\mu^-$ (BarBar, CMS, Belle), $\nu\bar{\nu}$ or $\chi\bar{\chi}$ (Belle II, BESIII)
- Significant Room Remaining for $(g-2)_\mu$ Anomaly

Newest state of $(g - 2)_\mu$

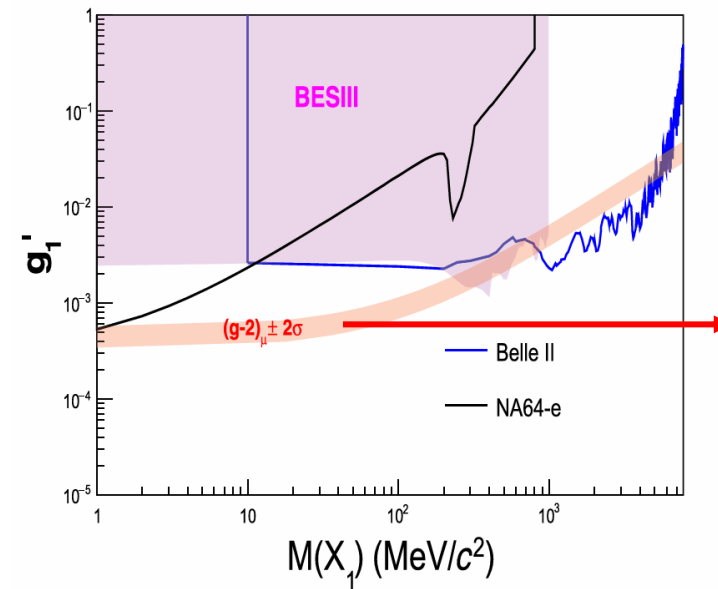


Before 2025.5:

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (249 \pm 48) \times 10^{-11}$$

After 2025.5:

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (38.5 \pm 64) \times 10^{-11}$$



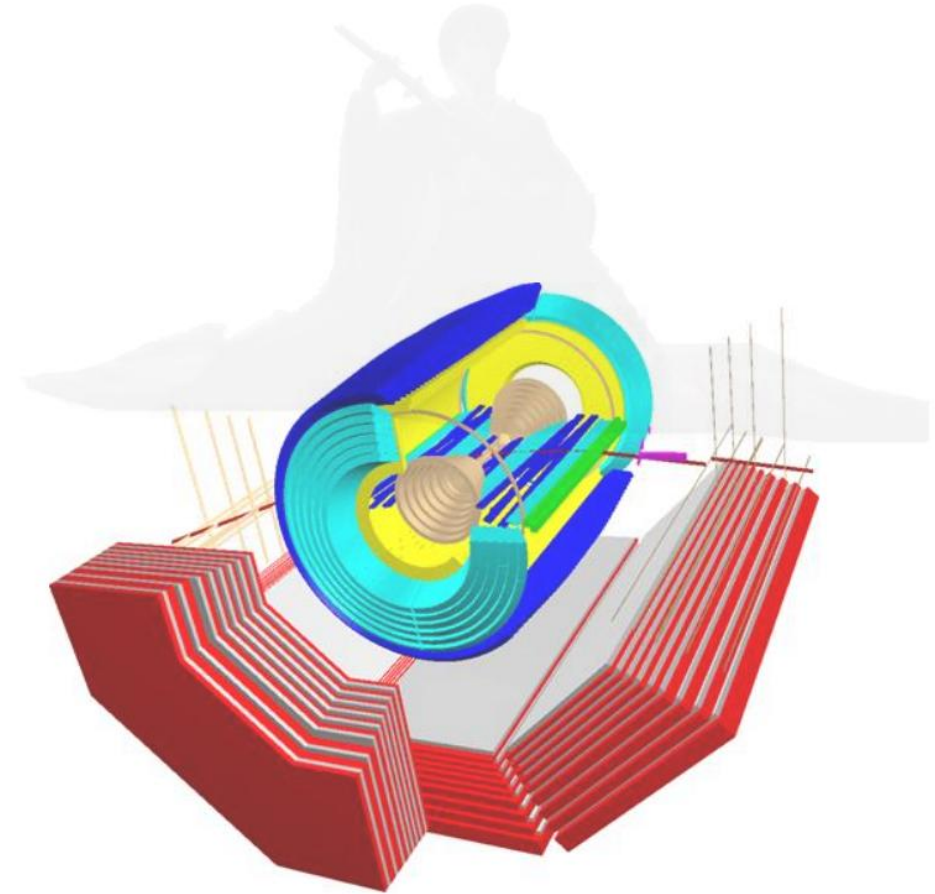
Before 2025.5:
Favor region

After 2025.5:
Upper limit

**If LQCD is correct...
Wait for further check**

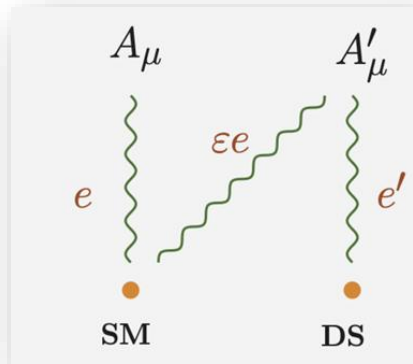
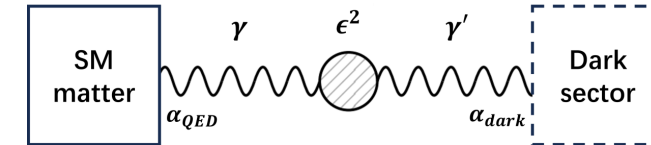
OUTLINE

- Introduction
- Massive dark photon
- Muon-philic particle
- **Massless dark photon**
- Summary



Massless dark photon

Simplest extension of the SM $\Rightarrow$ An extra Abelian gauge group, $U(1)_D \Rightarrow$ dark photon

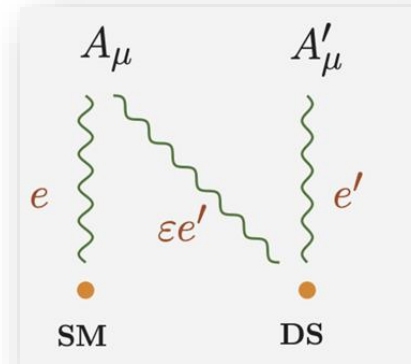


➤ Massive dark photon

- Symmetry broken spontaneously

$$A^\mu \rightarrow A^\mu + \epsilon A'^\mu$$

$$\mathcal{L} = eJ_\mu A^\mu + \underline{e\epsilon J'_\mu A'^\mu} + e'J'_\mu A'^\mu$$



➤ Massless dark photon

- Symmetry remains unbroken

$$A'^\mu \rightarrow A'^\mu + \epsilon A^\mu$$

$$\mathcal{L} = eJ_\mu A^\mu + \underline{e'\epsilon J'_\mu A'^\mu} + e'J'_\mu A'^\mu$$

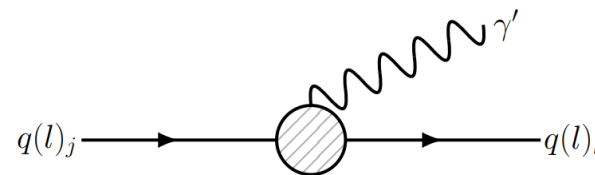
Searching for the massless case can only be in the higher dimension operator:

$$\mathcal{L}_{NP} = \frac{1}{\Lambda_{NP}^2} (C_{jk}^U \bar{q}_j \sigma^{\mu\nu} u_k \tilde{H} + C_{jk}^D \bar{q}_j \sigma^{\mu\nu} d_k H + C_{jk}^L \bar{l}_j \sigma^{\mu\nu} e_k H + h.c.) \bar{F}_{\mu\nu}$$

PRL 94, 151802 (2005)

➤ Naturally allow the FCNC coupling

- Less background and higher sensitivity

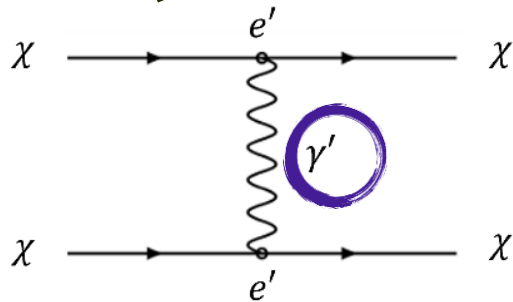


Λ_{NP} : New physics energy scale

C_{jk}^i : Dimensionless coefficient

Role of the massless dark photon

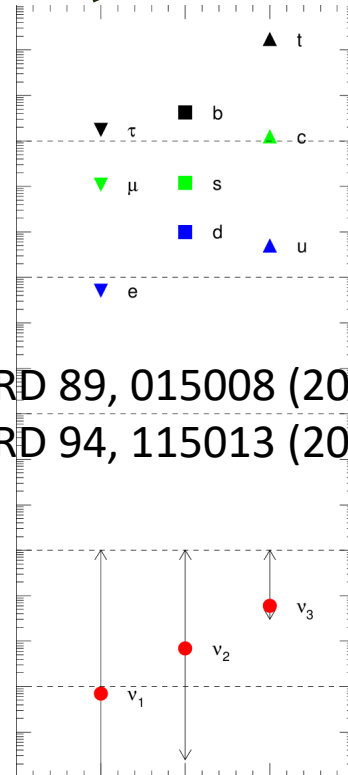
Provide a new long-range force of the DM



→ Explain the galaxy formation and dynamics

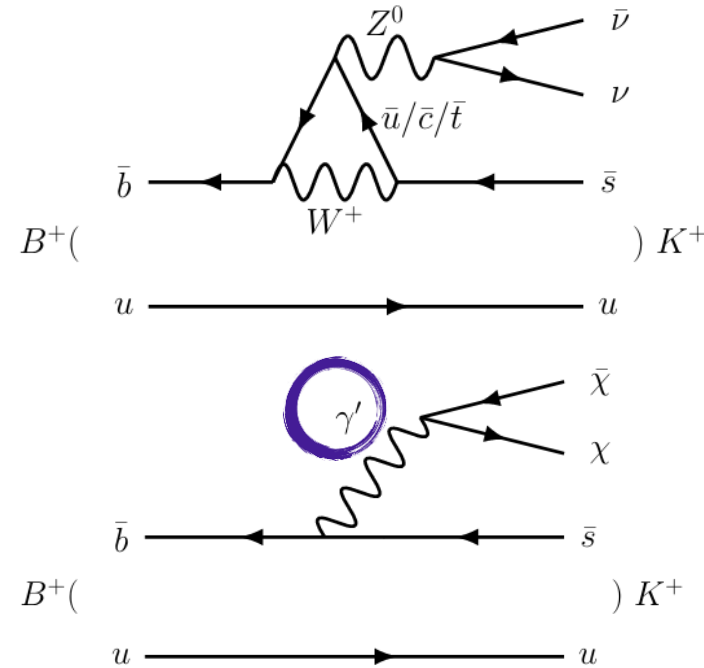
Phys.Rev.D 79 (2009) 023519
Phys.Rev.D 91 (2015) 023512
Phys.Lett.B 749 (2015) 236-241
JCAP 05, 022 (2017)
Phys.Rev.D 102 (2020) 8, 083009

Solution to the Fermion mass hierarchy



PRD 89, 015008 (2014)
PRD 94, 115013 (2016)

Explain excess of $B^+ \rightarrow K^+ \nu \bar{\nu}$ from Belle II



Phys.Rev.D 109 (2024) 11, 112006
Eur.Phys.J.C 84 (2024) 5, 460

More...

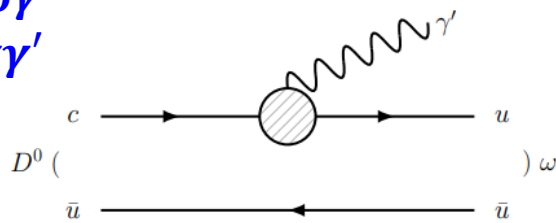
- Solution to the origin of the CKM matrix structure
 - Solution to the vacuum instability problem in SM Higgs Sector
 - ...
- PRD 101 (2020) 7, 075019
JHEP 01 (2022) 142

Massless γ' in charm decay

➤ BESIII: large charm sample for invisible search

- $4.5 \text{ fb}^{-1} e^+e^-$ collision data for Λ_c ($\sim 10^5 \Lambda_c$)
- $7.9 \text{ fb}^{-1} e^+e^-$ collision data for D ($\sim 6.3 \times 10^6 D^0$)
- Using **missing mass** to identify the massless dark photon

- $\Lambda_c \rightarrow p\gamma'$
- $D^0 \rightarrow \omega\gamma'$
- $D^0 \rightarrow \gamma\gamma'$

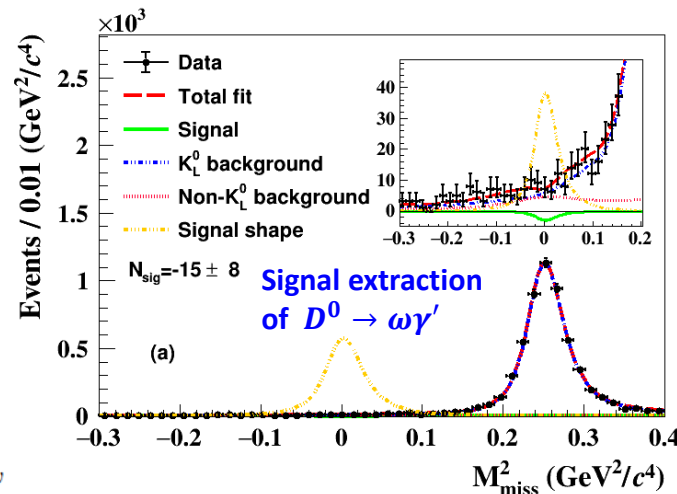


(a) $D^0 \rightarrow \omega\gamma'$

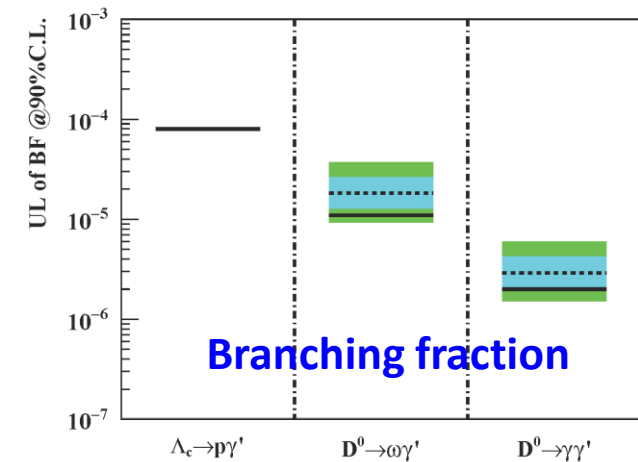
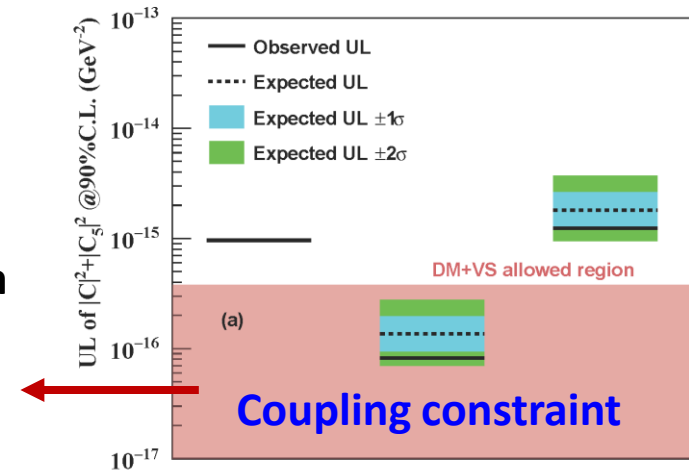
$$\mathbb{C} = \Lambda_{NP}^{-2} (C_{12}^U + C_{21}^{U*}) v / \sqrt{8}$$

$$\mathbb{C}_5 = \Lambda_{NP}^{-2} (C_{12}^U - C_{21}^{U*}) v / \sqrt{8}$$

Theoretical allowed region from dark matter (DM) and vacuum stability (VS) allowed region



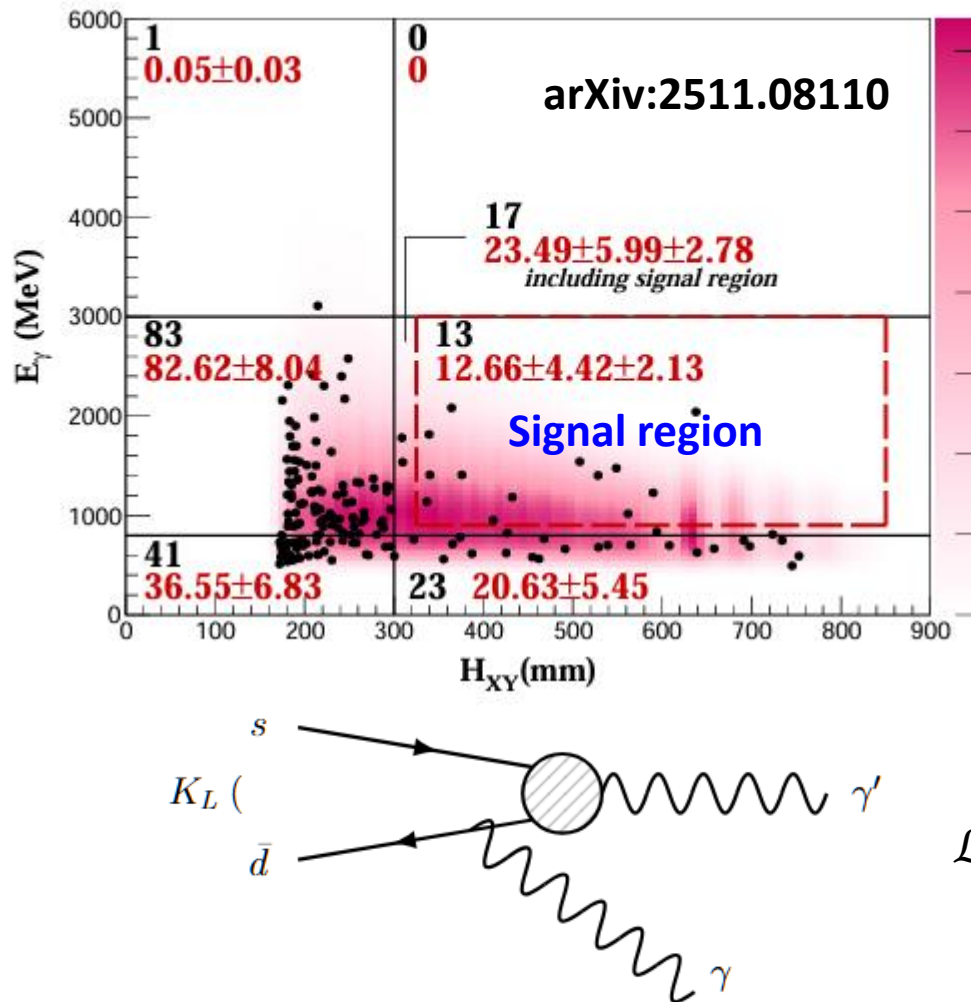
Signal extraction of $D^0 \rightarrow \omega\gamma'$



Phys.Rev.D 106 (2022) 7, 072008

Phys.Rev.D 111 (2025) 1, L011103

Massless γ' in strange quark decay



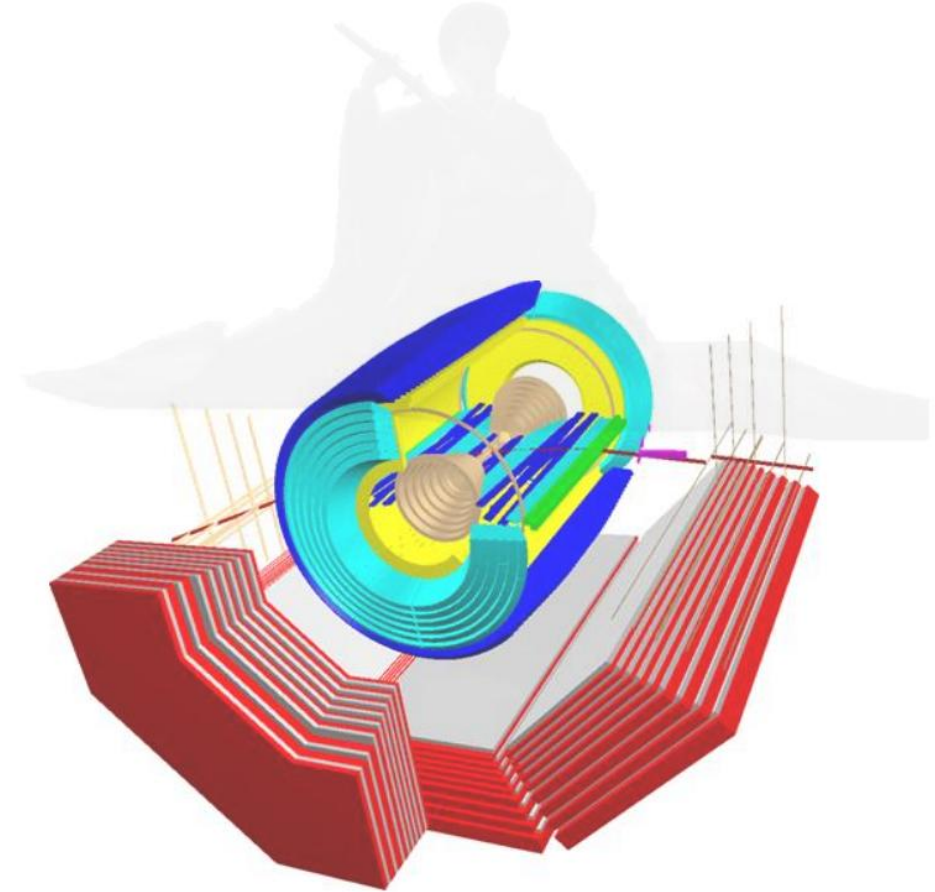
➤ **KOTO**: $1.29 \times 10^{10} K_L$ from 5×10^{16} protons on target

- $K_L^0 \rightarrow \gamma\gamma'$, Very recent result on arXiv
- Search for **single photon candidates** with no coincident activity in any veto detector
- 13 observed events compared to ~ 13 expected background
- $\mathcal{B}(K_L^0 \rightarrow \gamma\gamma') < 3.4 \times 10^{-7}$
- $|\mathbb{C}|^2 + |\mathbb{C}_5|^2 < 6.0 \times 10^{-20} \text{ GeV}^{-2}$,
Compared to charm sector $|\mathbb{C}|^2 + |\mathbb{C}_5|^2 < 8.2 \times 10^{-17} \text{ GeV}^{-2}$
- But no specific prediction for coupling in different flavor

$$\mathcal{L}_{NP} = \frac{1}{\Lambda_{NP}^2} \left(\underbrace{C_{jk}^U \bar{q}_j \sigma^{\mu\nu} u_k \tilde{H}}_{\text{Charm sector}} + \underbrace{C_{jk}^D \bar{q}_j \sigma^{\mu\nu} d_k H}_{\text{Strange sector}} + C_{jk}^L \bar{l}_j \sigma^{\mu\nu} e_k H + h.c. \right) \bar{F}_{\mu\nu}$$

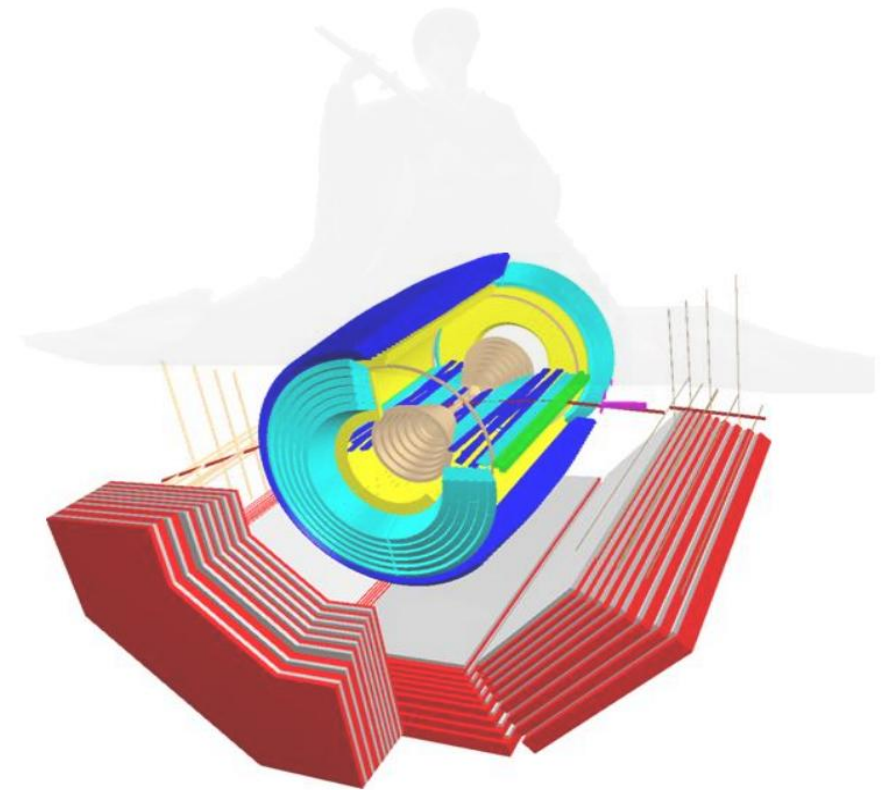
OUTLINE

- Introduction
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- Muon-philic particle
- Massless dark photon
- **Summary**



Summary

- An experimental overview of dark photon
 - **Massive dark photon:**
 - Significant opportunity for Relic DM target
 - **Muon-philic particle:**
 - Still (potential) room for $(g - 2)_\mu$ Anomaly
 - **Massless dark photon:**
 - Can't be ignored; continue working



The future of **Dark Photon** is **Bright** !

THANK YOU



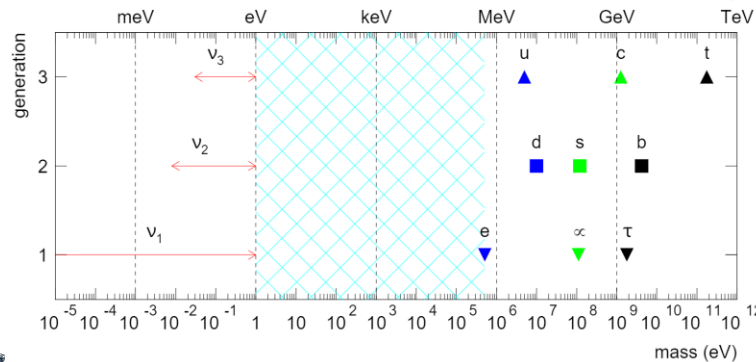
Appendix

Standard model and Puzzles

Dark Matter

- SM explains most facts but not all
- More than two **dark** clouds

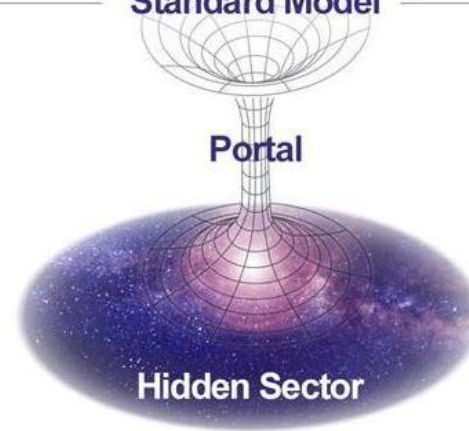
Fermion Mass Hierarchy



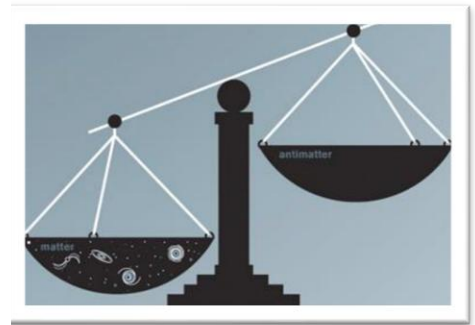
More ...

mass →	~2.3 MeV/c ²	~1.275 GeV/c ²	~173.07 GeV/c ²	0	~126 GeV/c ²
charge →	2/3	2/3	2/3	0	0
spin →	1/2	1/2	1/2	1	0
	u	c	t	g	H
	up	charm	top	gluon	Higgs boson
	d	s	b	γ	
	down	strange	bottom	photon	
	e	μ	τ	Z	
	electron	muon	tau	Z boson	
	ν_e	ν_μ	ν_τ	W	
	electron neutrino	muon neutrino	tau neutrino	W boson	

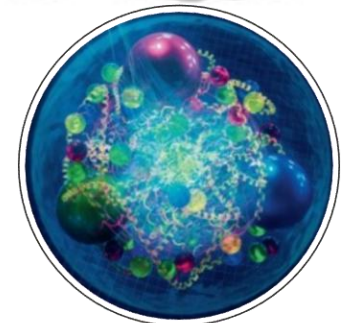
Standard Model



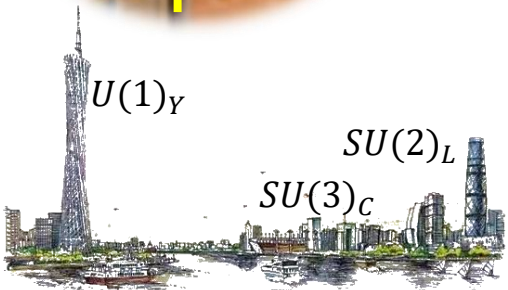
Matter Anti-matter Asymmetry



Strong CP Problem



Potentials to find new physics



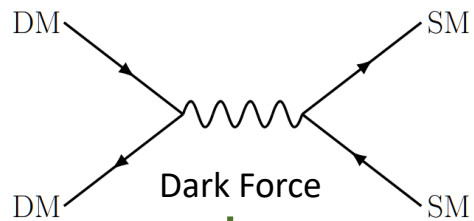
Role of dark photon

Portal to the dark sector

Dark matter candidate

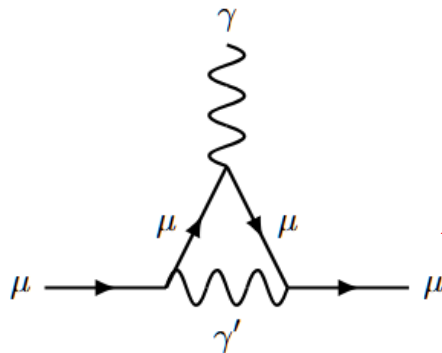
Resolve the $g_\mu - 2$ anomaly

X17 candidate



Freeze-out

$$\Omega_{DM} h = 0.12$$



Only when $m_{\gamma'} < 1 \text{ MeV}$

