Dark photon search status in tau charm energy region

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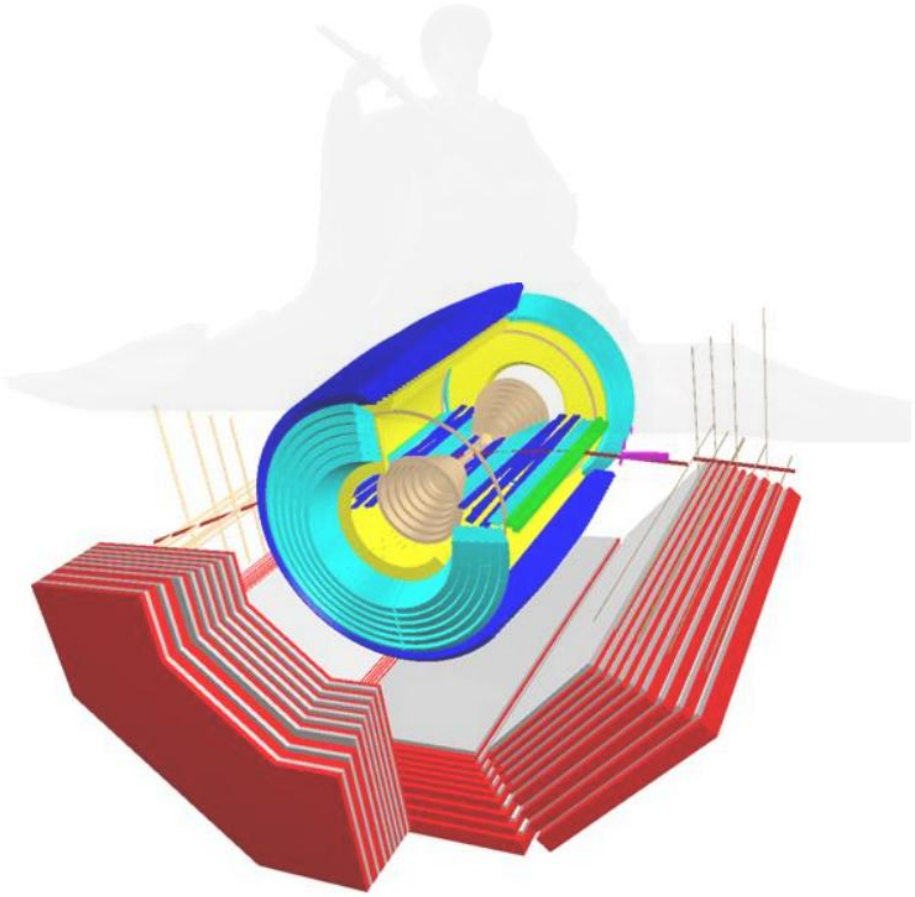
OUTLINE

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



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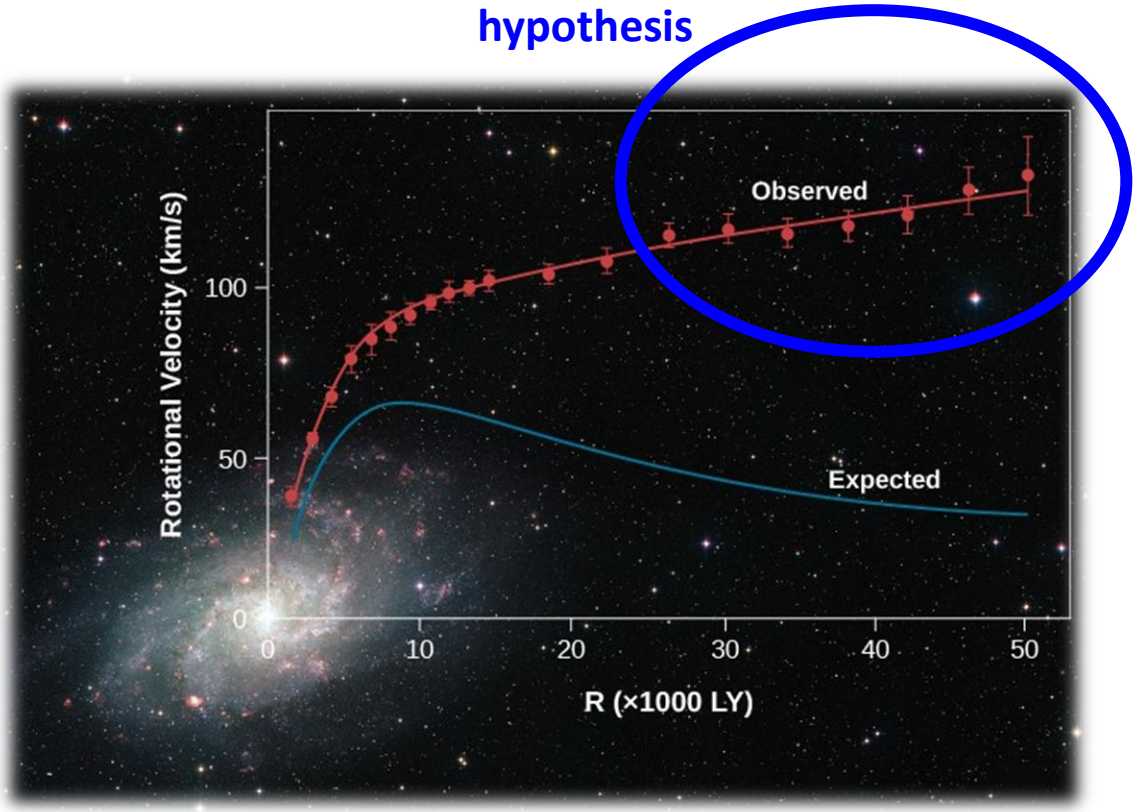
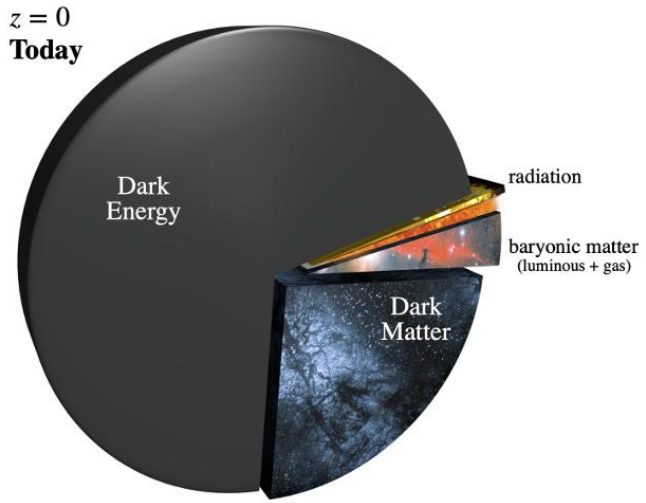
Dark matter

Dark matter (DM) hypothesis





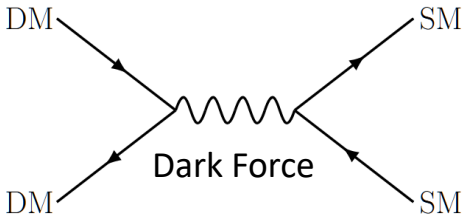
- DM constitutes about 84% of the total matter
- **The most precise nature of DM:**
  $\Omega_{\mathrm{DM}} h^2 = 0.12 \pm 0.0012$ (stands for DM density)

- Other nature: only the gravitational interaction is known
- **Particle type, mass or other interactions: unknown**

Freeze-out mechanism

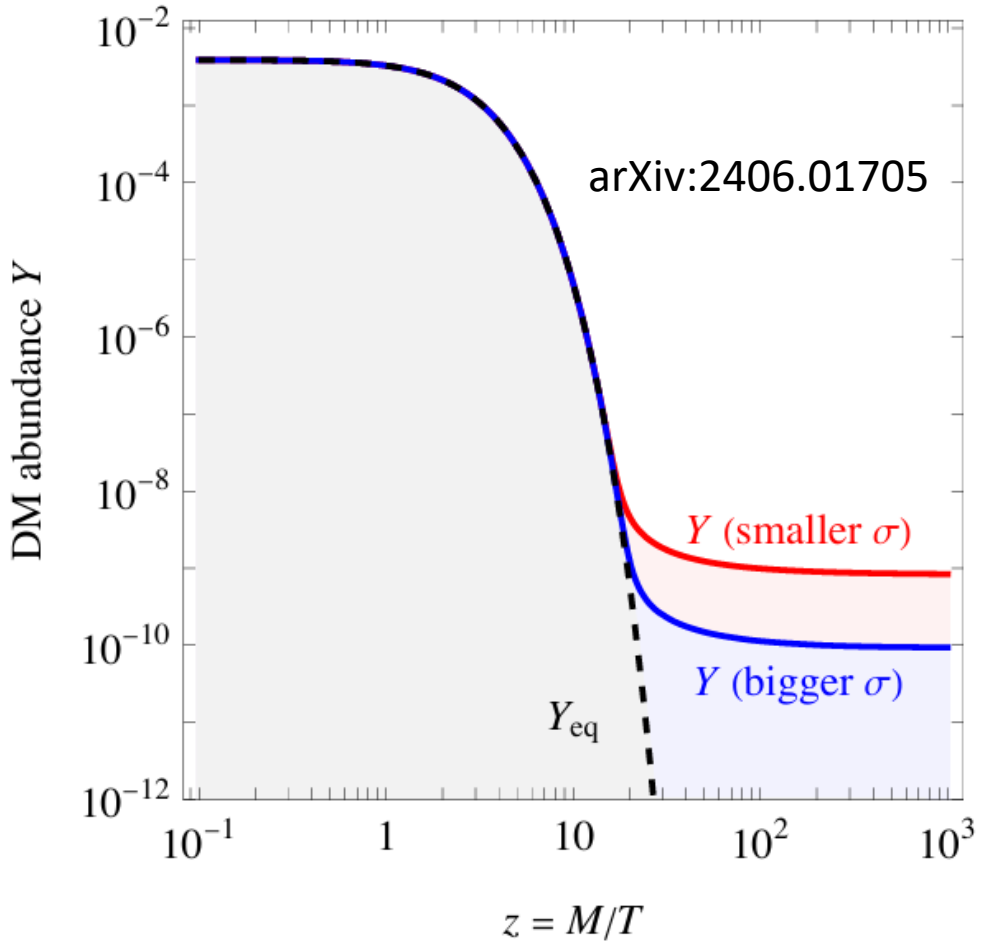
The most popular theory of current DM:

thermal relic by freeze-out

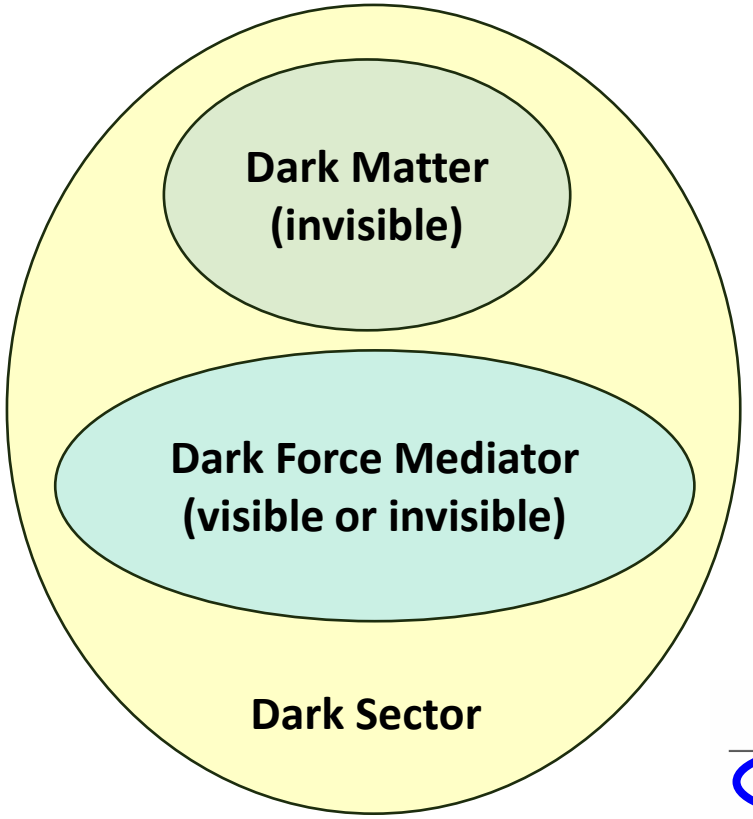


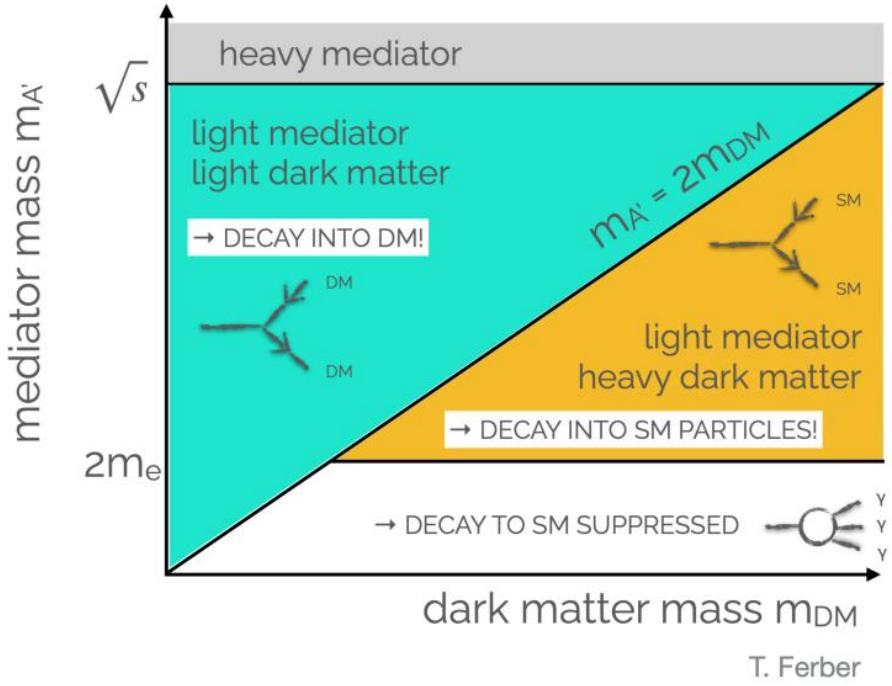
- If only **gravitational interaction: too weak**, the DM abundance must be much larger than the observed value
- Requiring **other interactions from dark sector**:
- To generate the current DM abundance, usually
  - For DS≫GeV, coupling~$\mathcal{O}(1)$, eg. WIMP
  - **For DS≲GeV, coupling $\ll 1$**

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	$\frac{a}{f_a} F_{\mu\nu}\widetilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i\mu\nu}\widetilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
"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

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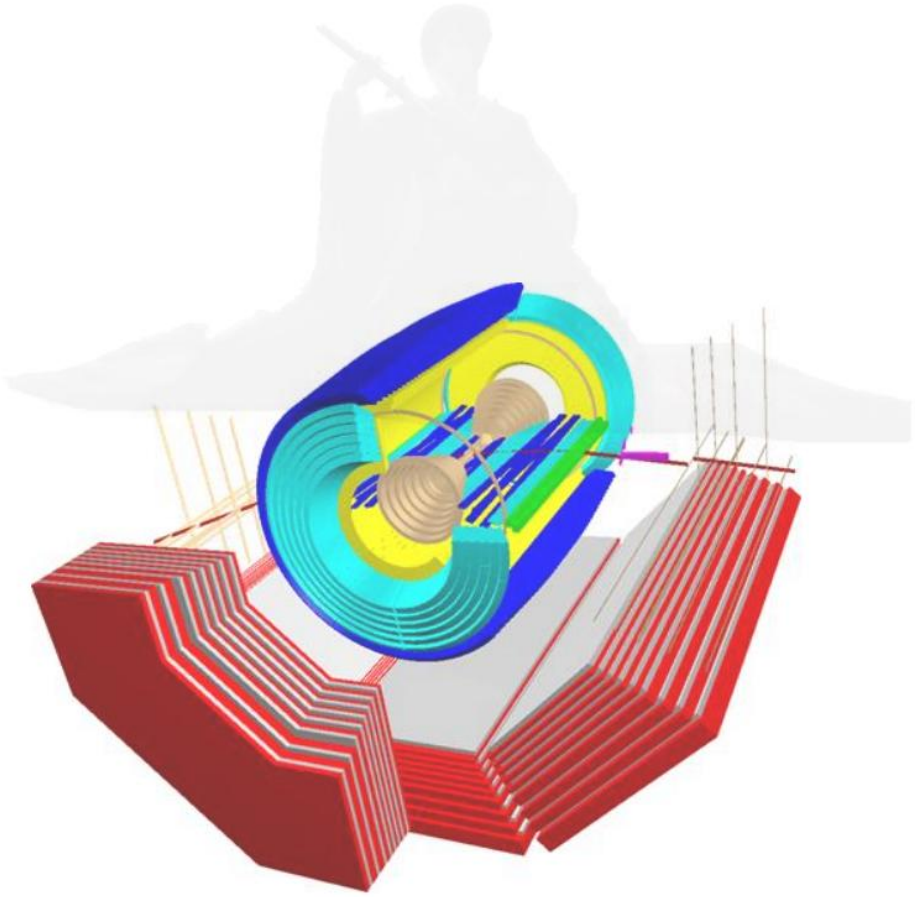

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Dark photon

SM photon

Dark photon

(Symmetry broken spontaneously, massive kind)

The most popular vector portal

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

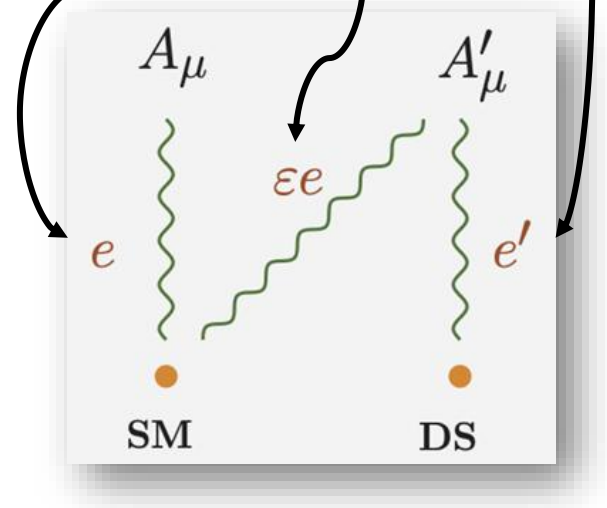
$A^\mu \rightarrow A^\mu + \epsilon A'^\mu$

ϵ: mixing strength

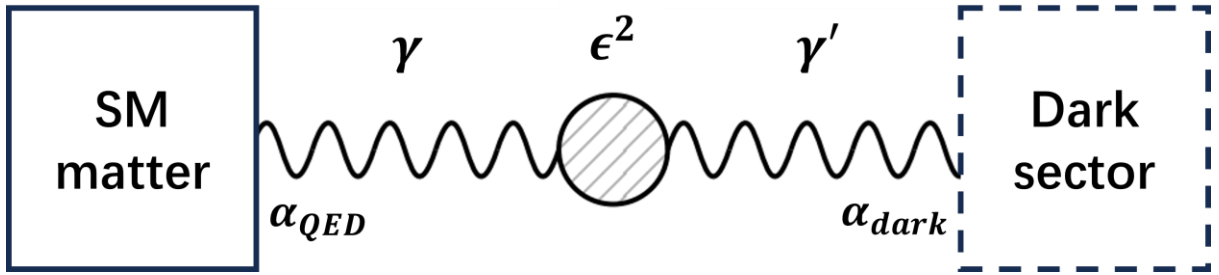
PLB 166, 196 (1986)

$(J^\mu = q_f \bar{\psi} \gamma^\mu \psi)$

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

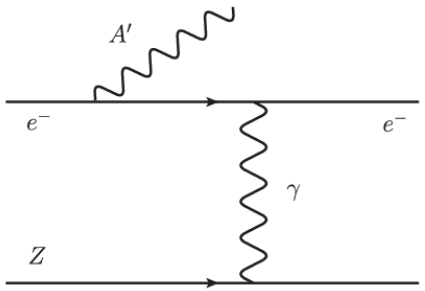


arXiv:2005.01515

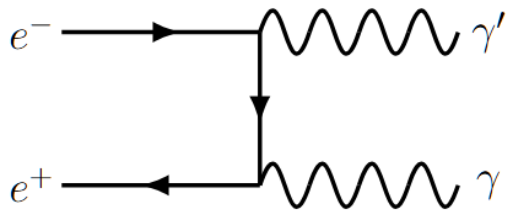


A portal to connect the SM matter and the dark sector

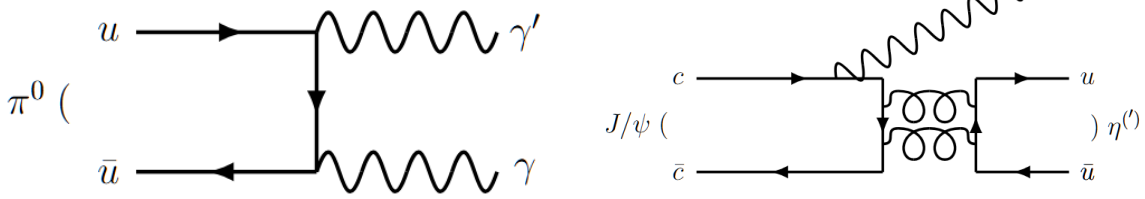
The production of dark photon



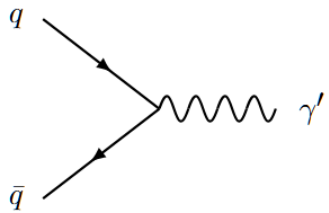
- **Bremsstrahlung:** $e^-Z \to e^-Z\gamma'$, $pZ \to pZ\gamma'$,
- Fixed target experiment: NA64, NA62…



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



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



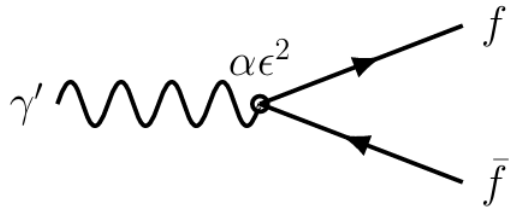
- **Drell-Yan**: $q\bar{q} \to \gamma'$
- LHC…

➢ **Dark photon can be produced in any process by replacing SM photon**

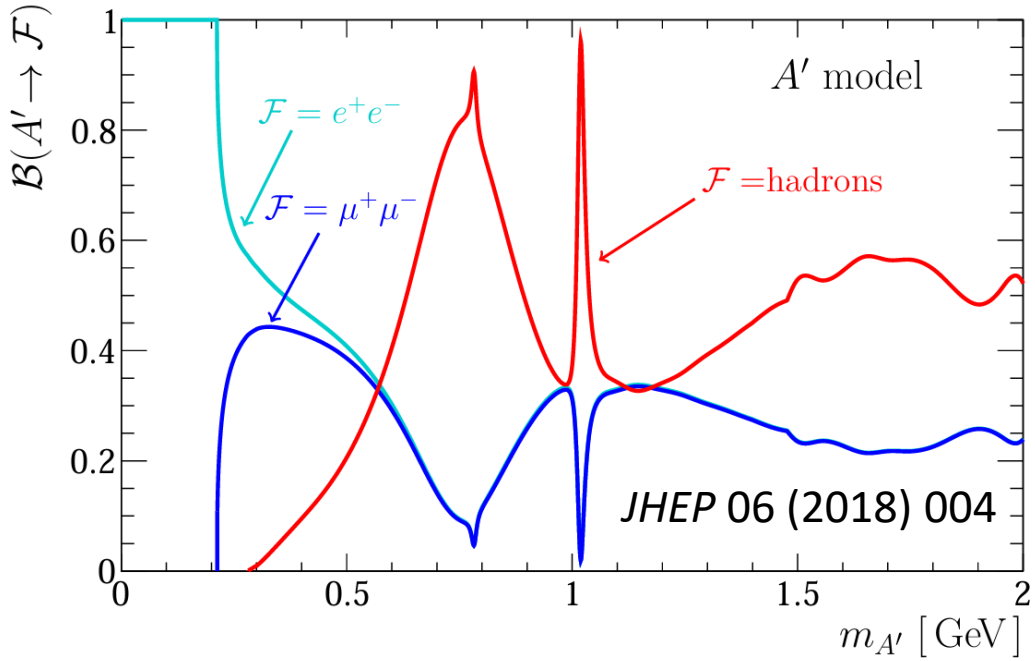
$$\mathcal{P}(\blacksquare \to \blacksquare\boldsymbol{\gamma'}) \sim \boldsymbol{\epsilon^2} \times \mathcal{P}(\blacksquare \to \blacksquare\boldsymbol{\gamma})$$

The decay of dark photon

Case I
Visible



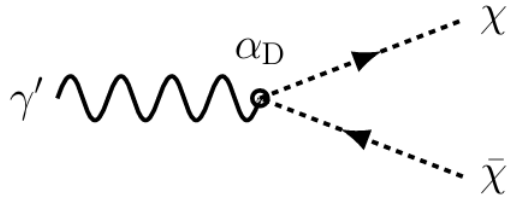
- $m_\chi > \frac{m_{\gamma'}}{2}$
- $m_{\gamma'} > 1\ MeV$



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

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

Case II
Invisible



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

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

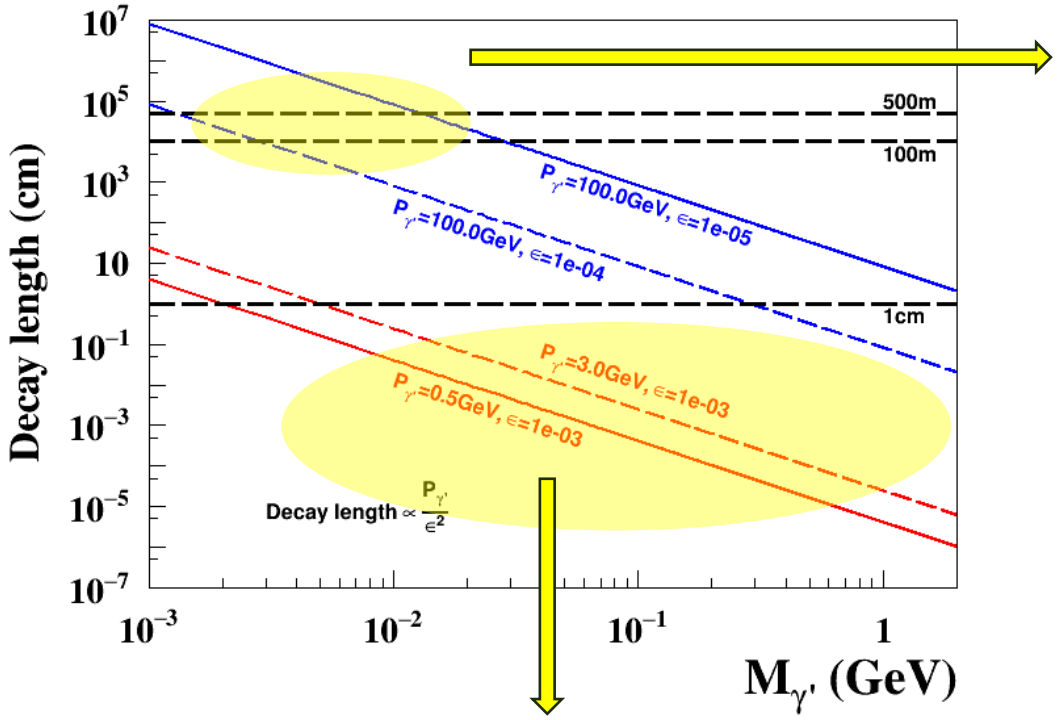
$\mathcal{B}(\gamma' \to \chi\bar{\chi}) \sim 100\%$

Missing energy,
Missing mass …

Usually Detecting lepton final state

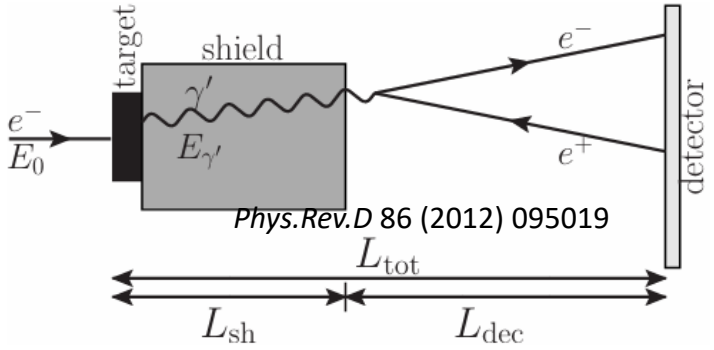
The decay length of visible dark photon

- 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 $\epsilon \Longrightarrow$ **need high luminosity**
- Fixed target experiment NA62, Faser…

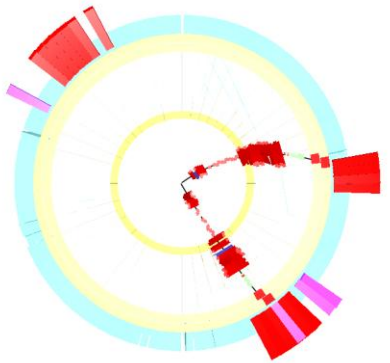


Phys.Rev.D 86 (2012) 095019

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

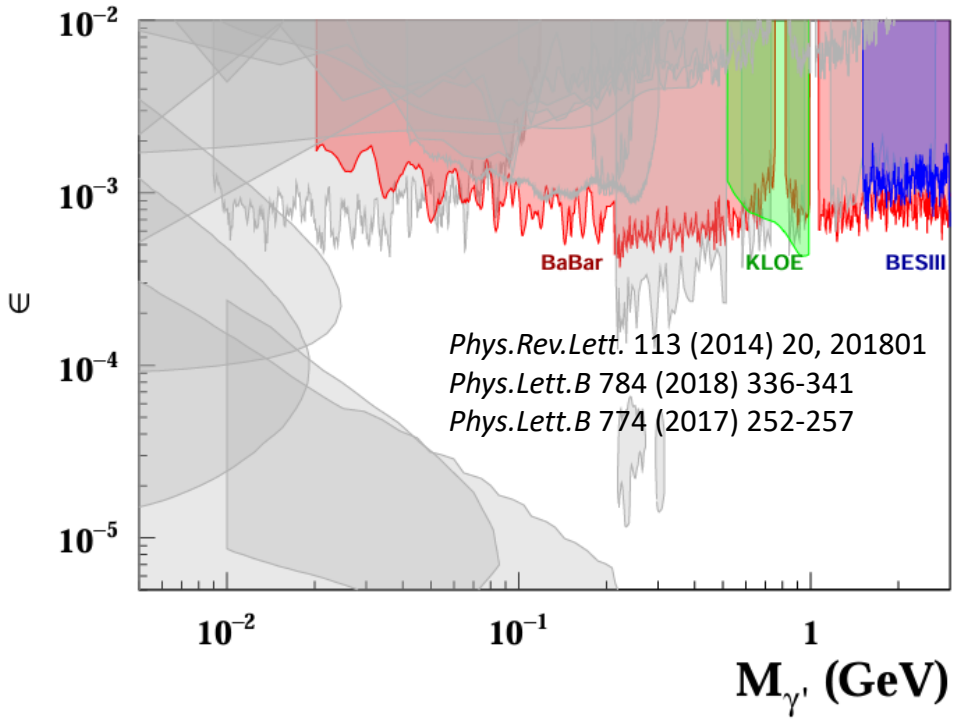
➢ **Short lived**

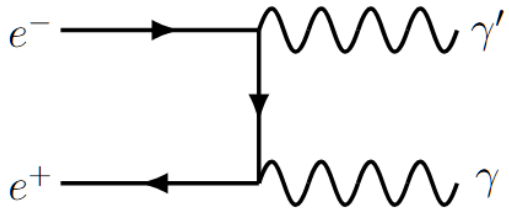
- large ϵ, large $m_{\gamma'}$, low $P_{\gamma'}$,
- Detector cover the DP production point
- BaBar, BESIII, KLOE, Belle…



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

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

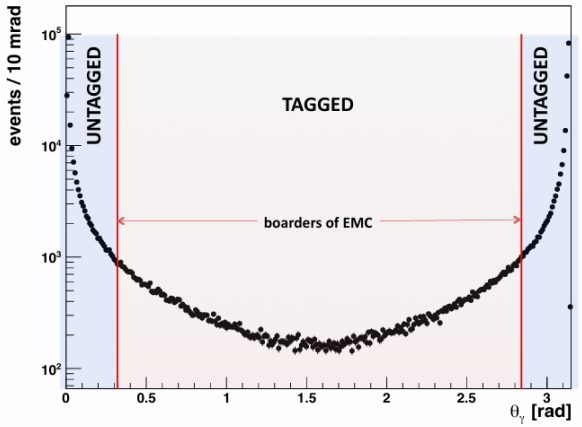


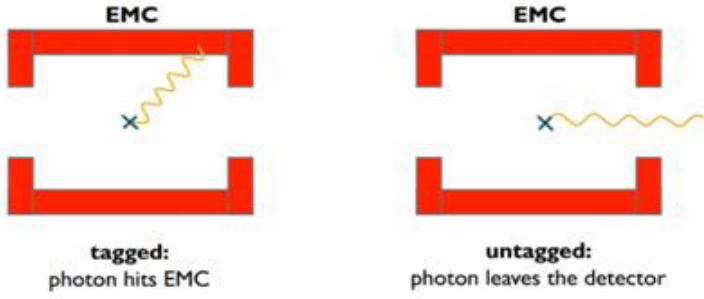


Irreducible background from $e^+e^- \to \gamma e^+e^-$

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

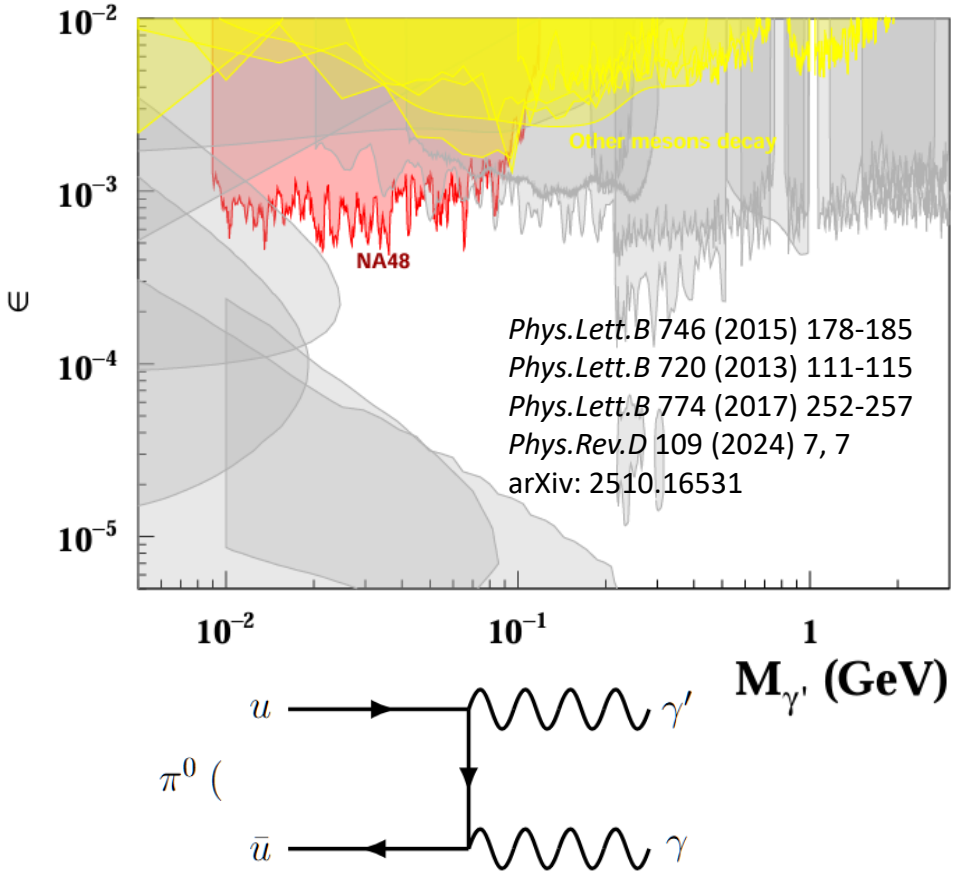
20.3 fb^{-1} now, and 100 × in FCTF





- 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

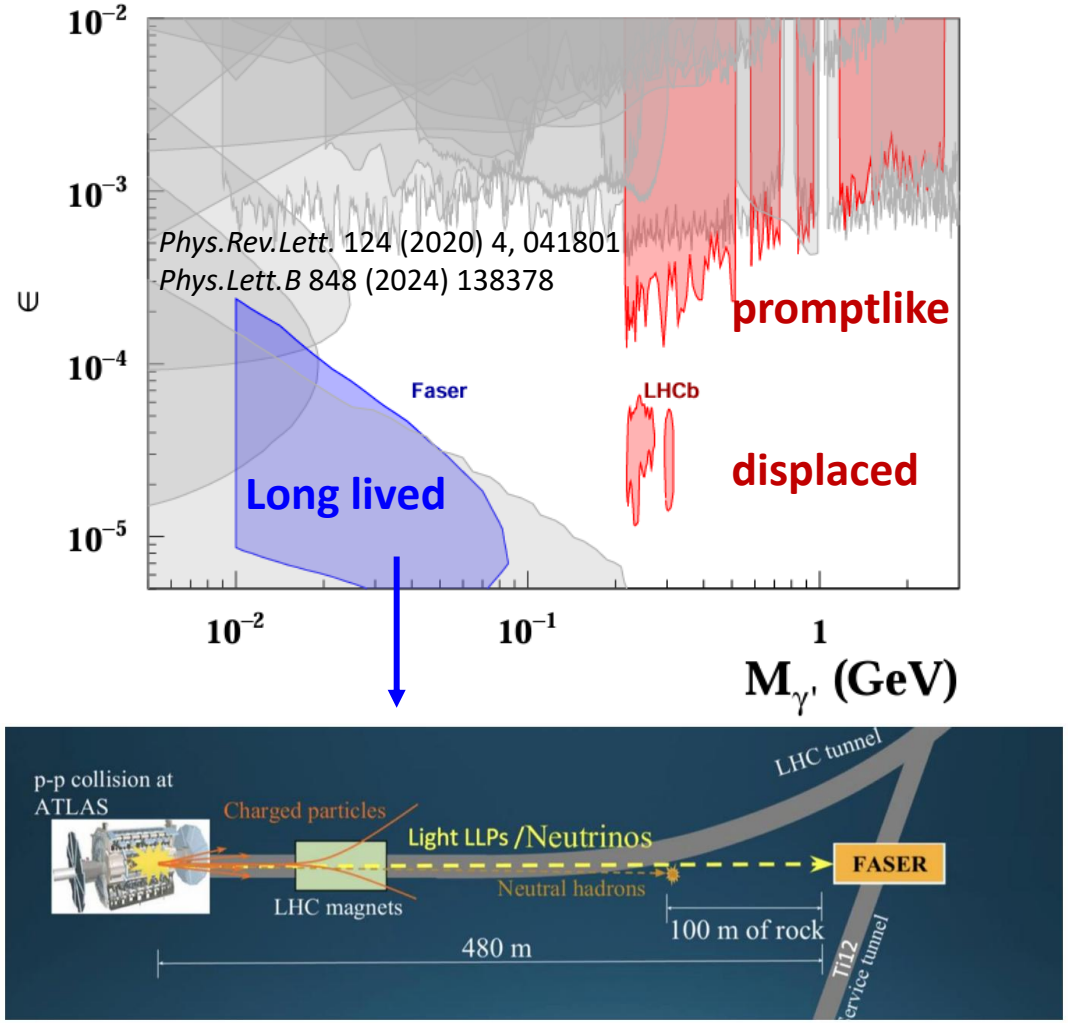


Irreducible background from $\pi^0 \to \gamma e^+ e^-$

- **NA48**
- Proton ⟶ target ⟶ $K^+ \to \pi^0 X$
- $\pi^0 \to \gamma\gamma'$, $\gamma' \to e^+e^-$
- **1.69×10^7 reconstructed $\pi^0 \to \gamma e^+ e^-$ candidates**

- **Other mesons decay, looser constraint (limited by statistic)**
- $\phi \to \gamma'\eta$: KLOE, 1.7 fb^{-1} @$\sqrt{s}$~1 GeV
- $J/\psi \to \gamma'\eta'$: BESIII, using 10^9 J/ψ
- $\eta^{(\prime)} \to \gamma\gamma'$: BESIII, using 10^{10} J/ψ (with $J/\psi \to \gamma\eta^{(\prime)}$)
- $\chi_{cJ} \to \gamma' J/\psi$: BESIIII, using 2.7×10^9 $\psi(2S)$ (with $\psi(2S) \to \gamma\chi_{cJ}$)

Visible case: Inclusive production at LHC

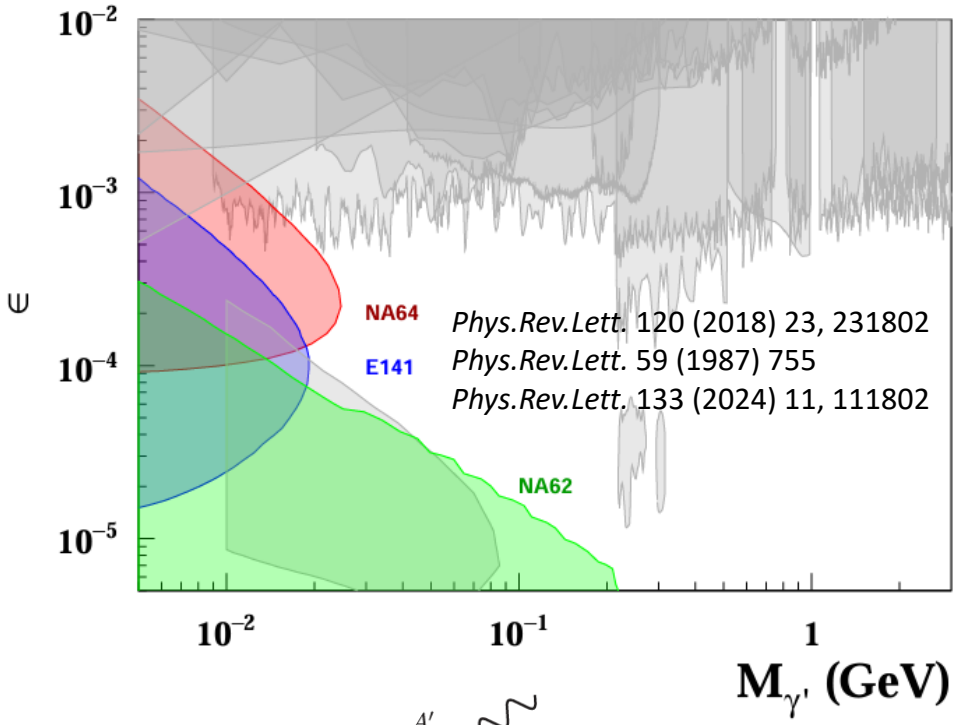


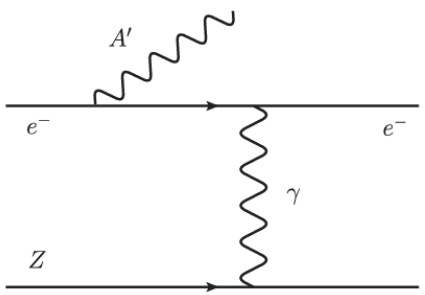
- **Dark photon source in LHC**
- Meson decay $\pi^0 \to \gamma\gamma', \eta \to \gamma\gamma'$
- Bremsstrahlung: $pp \to pp\gamma'$
- DrellYan: $q\bar{q} \to \gamma'$ (dominated when $m_{\gamma'} \gtrsim 1GeV$)

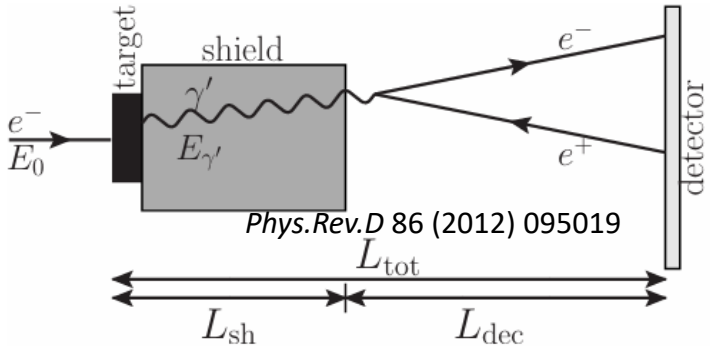
- **LHCb**: 5.5 fb^{-1} data, $\gamma' \to \mu^+\mu^-$
- **Promptlike search**: irreducible background from $\gamma^* \to \mu^+\mu^-$
- **Displaced search**: less background with displaced info $\Longrightarrow$ better sensitivity $\Longrightarrow$ lower ϵ

- **Faser:** 27.0 fb^{-1} data, $\gamma' \to e^+e^-$
- Decay length $\propto \frac{P_{\gamma'}}{m_{\gamma'}^2 \epsilon_{\gamma'}^2}$
- Small $m_{\gamma'} \Longrightarrow$ **Longlived** dark photon
- Background free search, zero observed event in signal region

Visible case: Fixed target





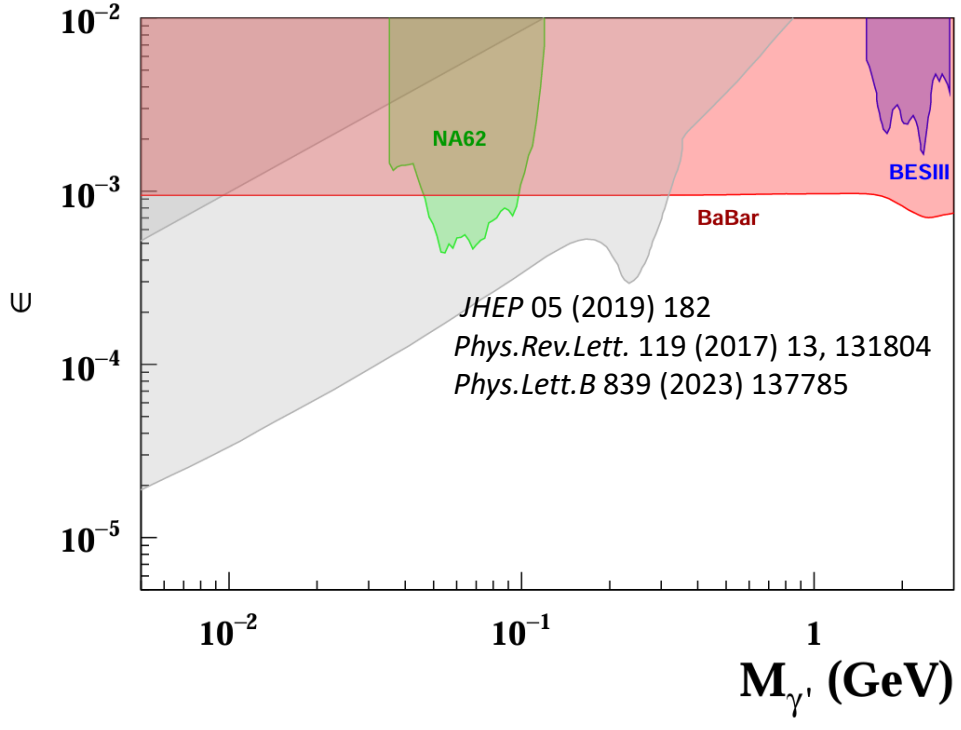


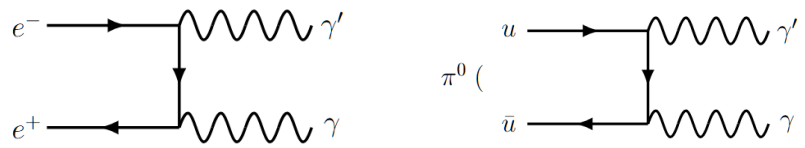
Background clean search
(But no sensitivity for short lived dark photon)

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





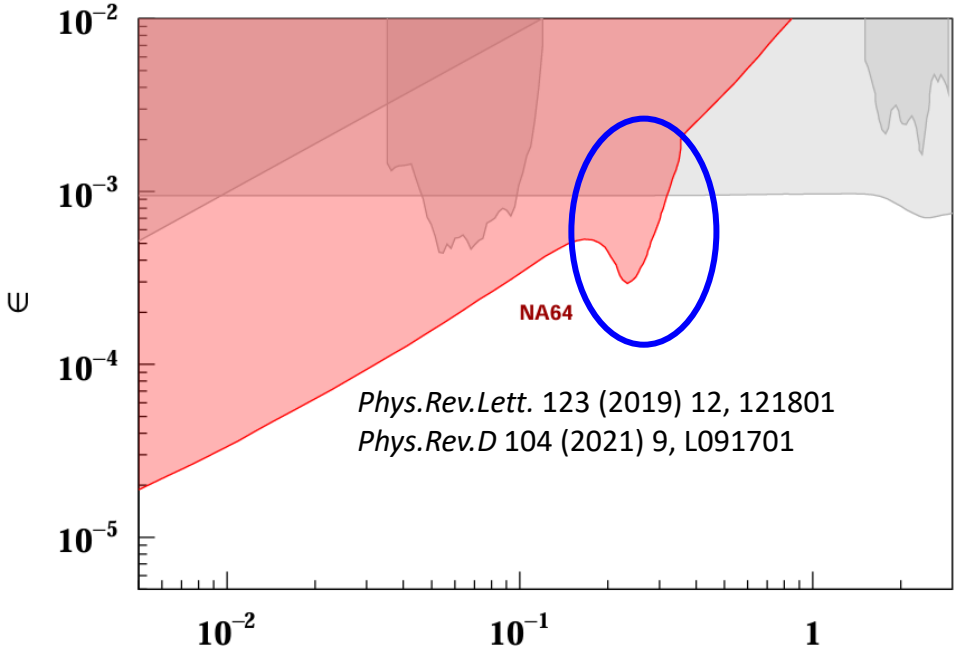
- **Using the missing mass** to identify the invisible DP signal

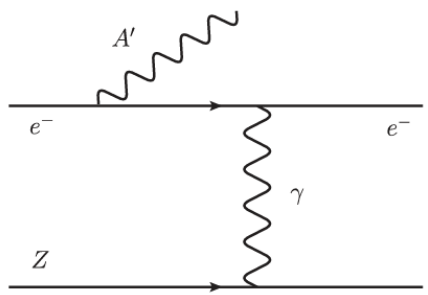
➢ **BaBar**: 53 fb^{-1} of e^+e^- collision data
- Dark photon from $e^+e^- \to \gamma\gamma'$
- Leading the constraint for $m_{\gamma'} \gtrsim 300\ MeV$

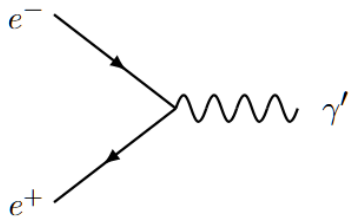
➢ **BESIII**: 14.9 fb^{-1} of e^+e^- collision data
- Limited by statistic
- Dark photon from $e^+e^- \to \gamma\gamma'$
- For photon with $E_\gamma > 2\ GeV$, saturate the EMC, shower loss

➢ **NA62**: 4×10^8 tagged π^0 from $K^+ \to \pi^+\pi^0$
- The sole result from meson decay: $\pi^0 \to \gamma\gamma'$
- BESIII now has similar statistic: 10^{10} J/ψ, $\mathcal{B}(J/\psi \to \pi^+\pi^-\pi^0)$~2%
- FTCF is expected providing better constraint

Invisible case: Fixed target







- **Using the missing energy** to identify the invisible DP signal
- **NA64:** 2.84×10^{11} 100 GeV e^- on target

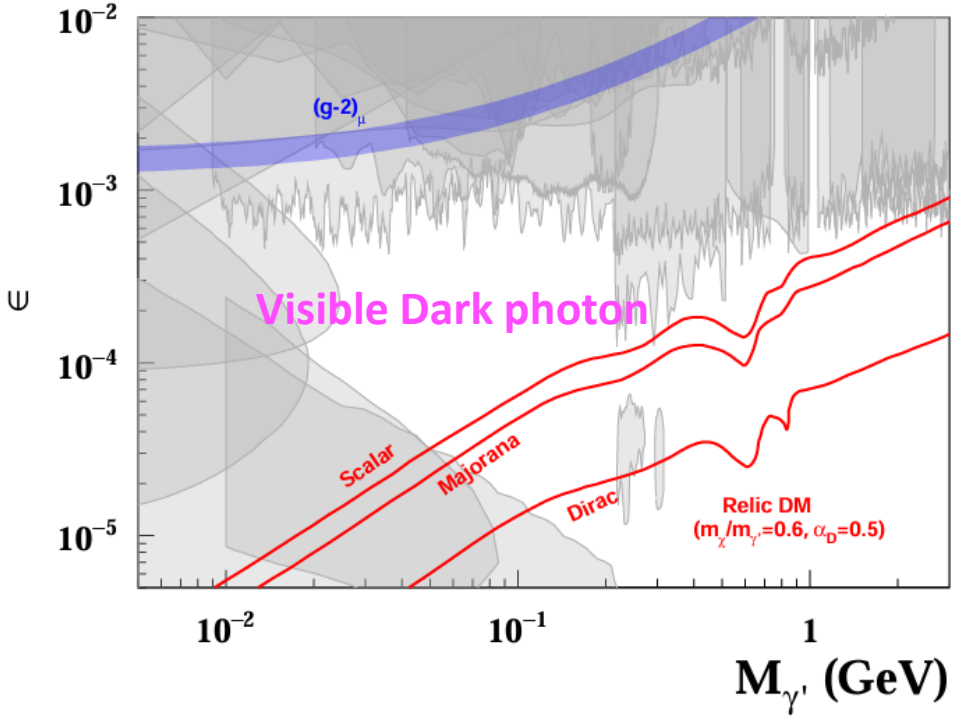
➢ **Bremsstrahlung search:** $e^- Z \rightarrow e^- Z \gamma'$

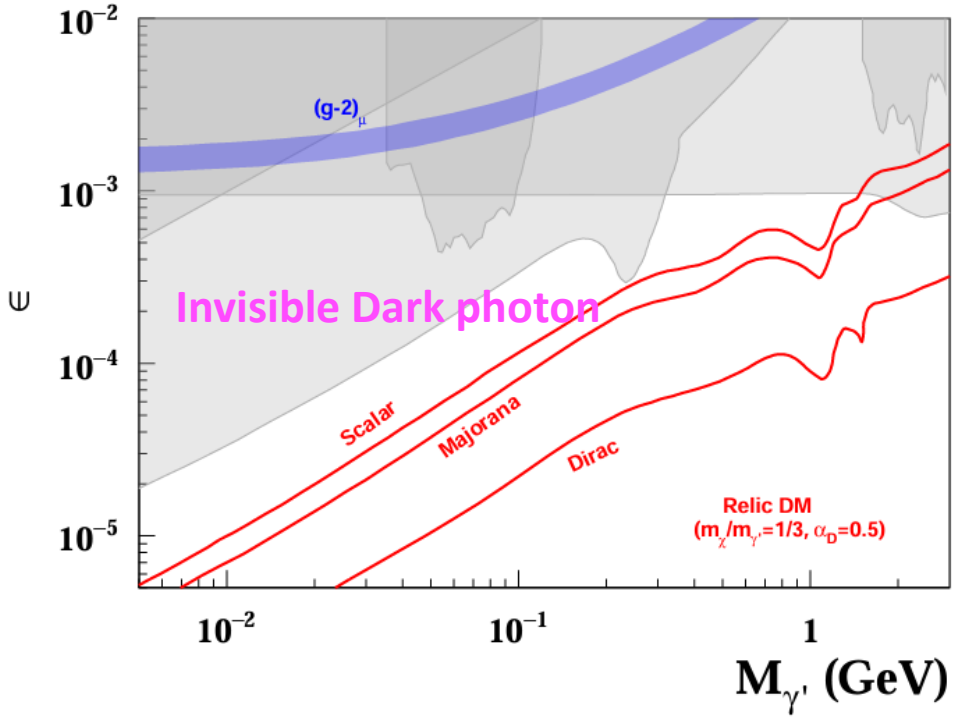
- Leading the constraint for low mass region

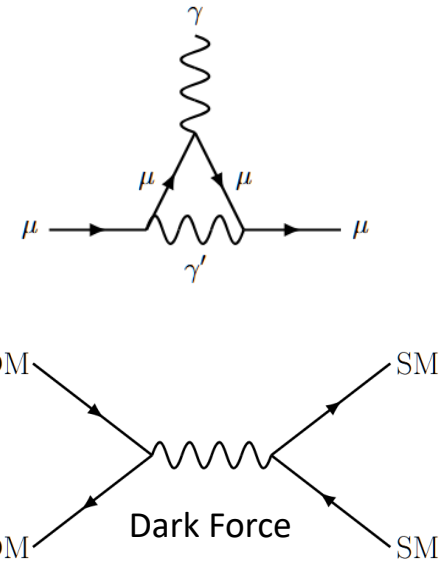
➢ **Annihilation search:** $e^+ e^- \rightarrow \gamma'$

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

Summary of massive dark photon







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

- ➢ **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 $\chi\bar{\chi} \to \gamma'\gamma'$

Still a significant opportunity for Relic DM target in FCTF

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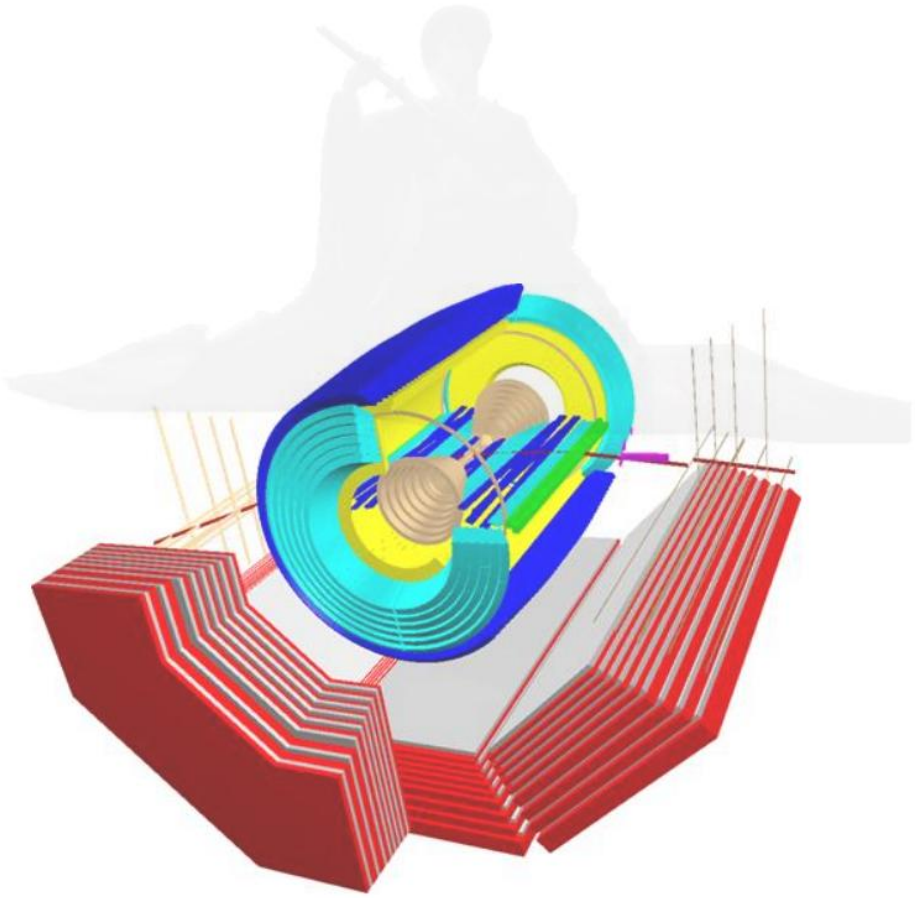

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Other models of vector portal

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

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

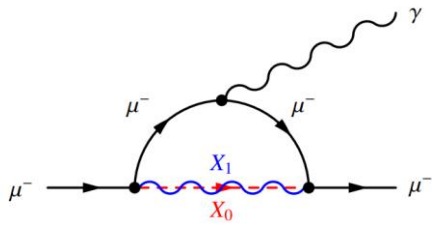
Coupling/model	Dark photon	$B-L$	B	Protophobic	$L_\mu - L_\tau$
g	ϵe	g_{B-L}	g_B	$g_{\not p}$	g'
$x_{u,c,t}$	2/3	1/3	1/3	-1/3	0
$x_{d,s,b}$	-1/3	1/3	1/3	2/3	0
x_e	-1	-1	$-e^2/(4\pi)^2$	-1	0
x_μ	-1	-1	$-e^2/(4\pi)^2$	-1	1
x_τ	-1	-1	$-e^2/(4\pi)^2$	-1	-1
x_{ν_e}	0	-1	0	0	0
x_{ν_μ}	0	-1	0	0	1
x_{ν_τ}	0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

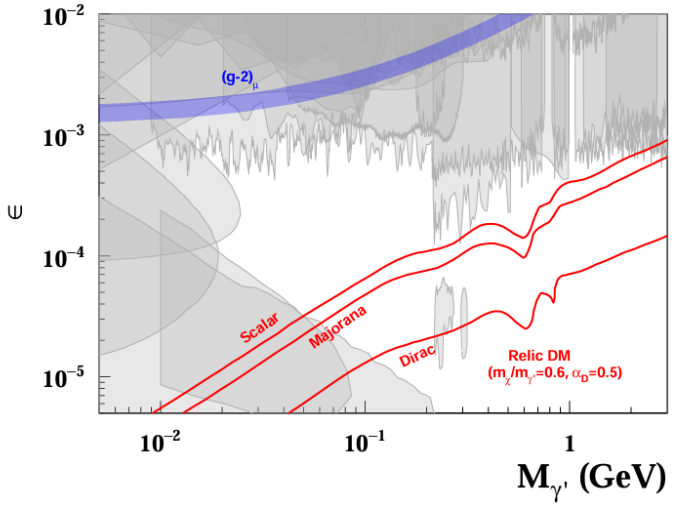
→ Talk something more later, **γ' only coupling to $\mu, \tau, \upsilon \Longrightarrow$ muonphilic particle**

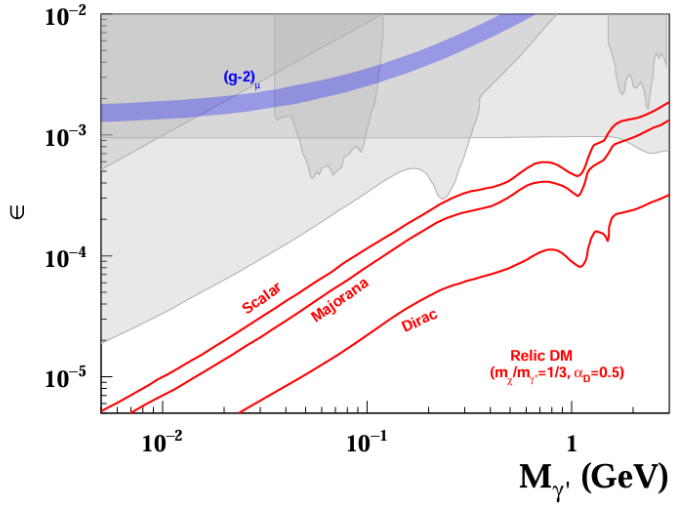
Previous talk, the leading constraint are mostly based on $e - \gamma'$ coupling

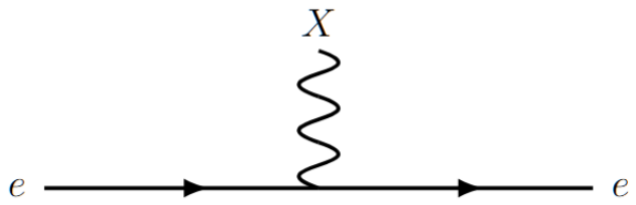
Meson decay will dominate the constraint for some models

$(g-2)_\mu$ favor

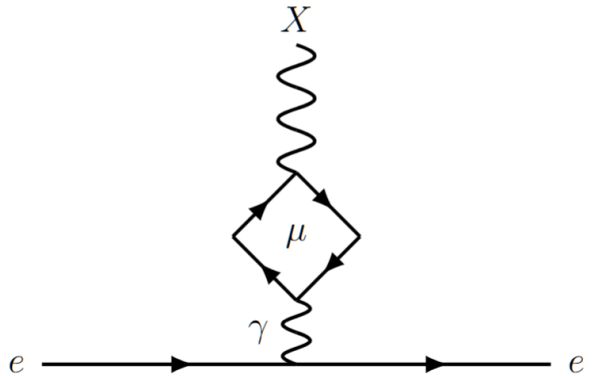








Forbidden in muonphilic



$e-X$ effective coupling in Muonphilic (Suppressed)

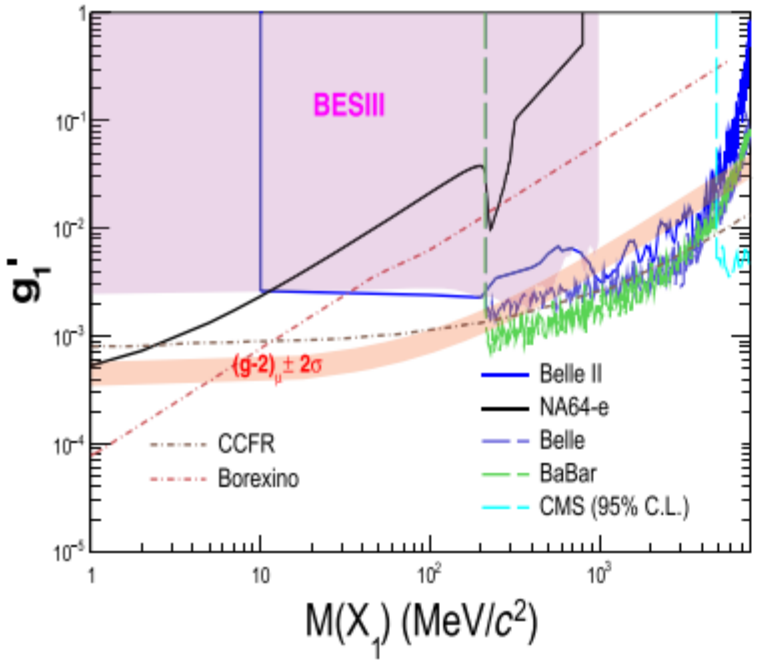
- The $(g-2)_\mu$ favor region (before 2025) **has been excluded** in the dark photon
- Most of the dark photon experiments are based on **electron or light quark coupling**

- If the new particle is muonphilic, the previous experiment will have less constraint due to the loop diagram

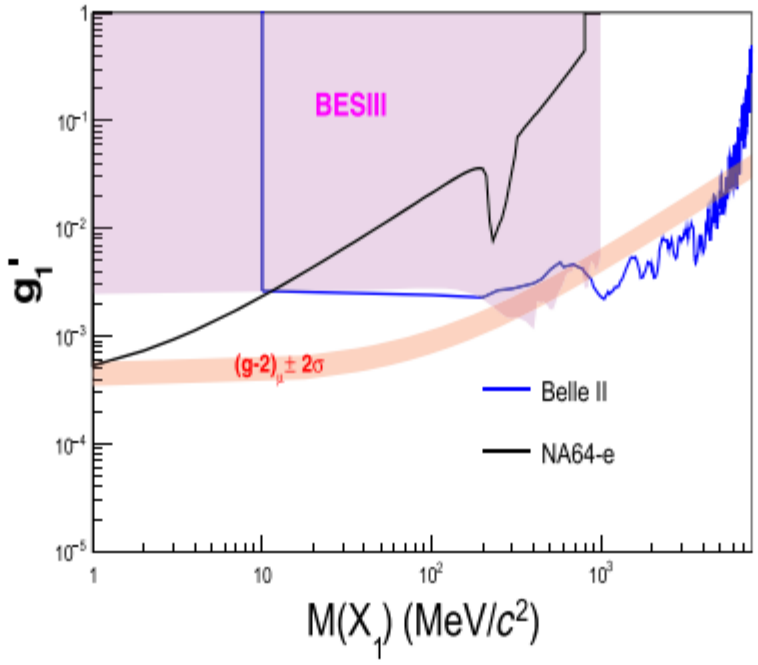
- **The $(g-2)_\mu$ favor region may be revived in the muonphilic model**

Current status of muonphilic vector

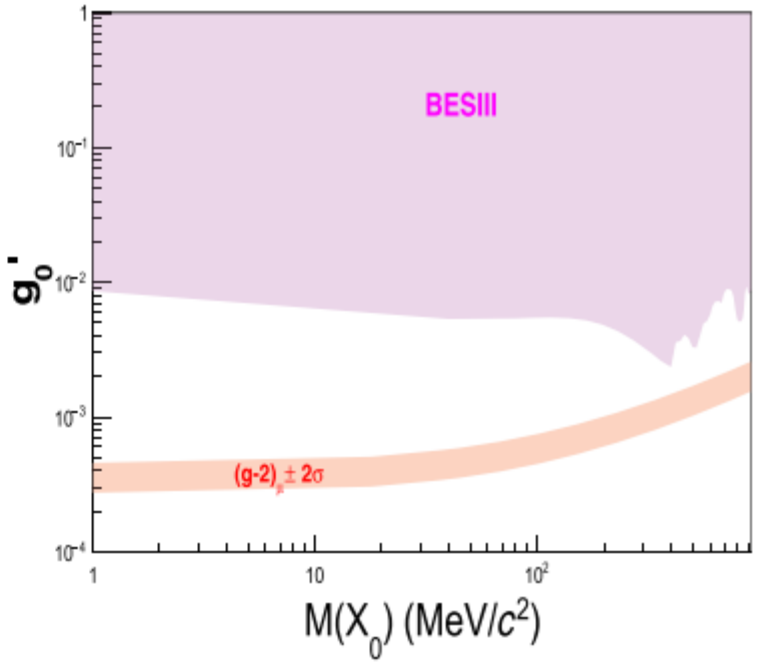
$X \to$ SM $(m_\chi > m_X/2)$

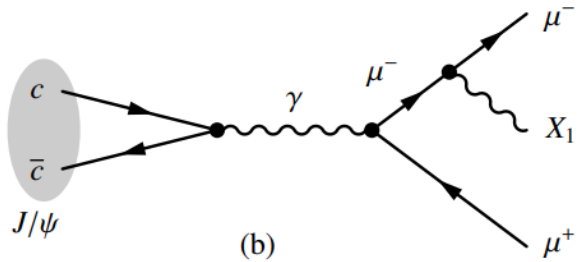


$X \to$ DM $(m_\chi < m_X/2)$



Muon-philic scalar



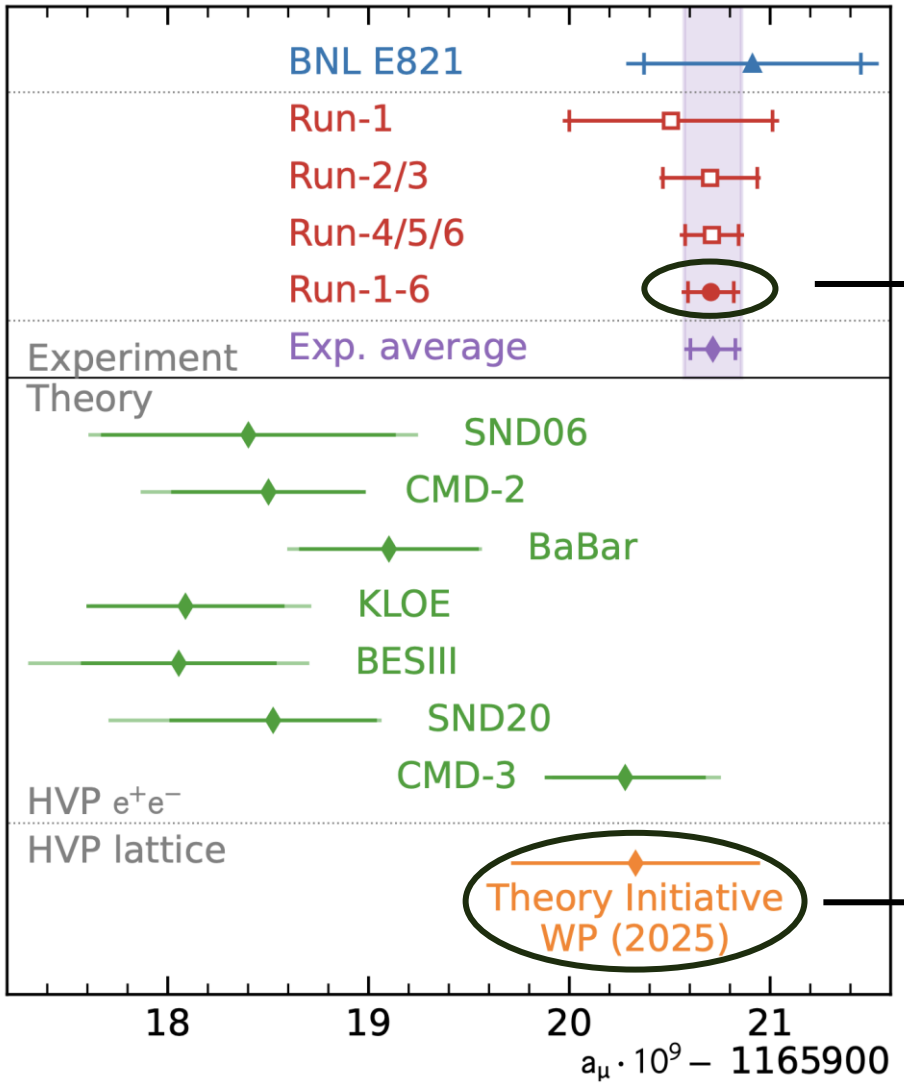


- **Muonphilic particle generated from muon radiation,** eg. $J/\psi \to \mu^+\mu^- X$ at BESIII
- X decaying to $\mu^+\mu^-$ (BarBar, CMS, Belle) , $\nu\bar{\nu}$ or $\chi\bar{\chi}$ (Belle II, BESIII)

- **Significant Room Remaining for $(g-2)_\mu$ Anomaly**

Phys.Rev.D 109 (2024) 3, L031102

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



New exp. value
arXiv:2506.03069

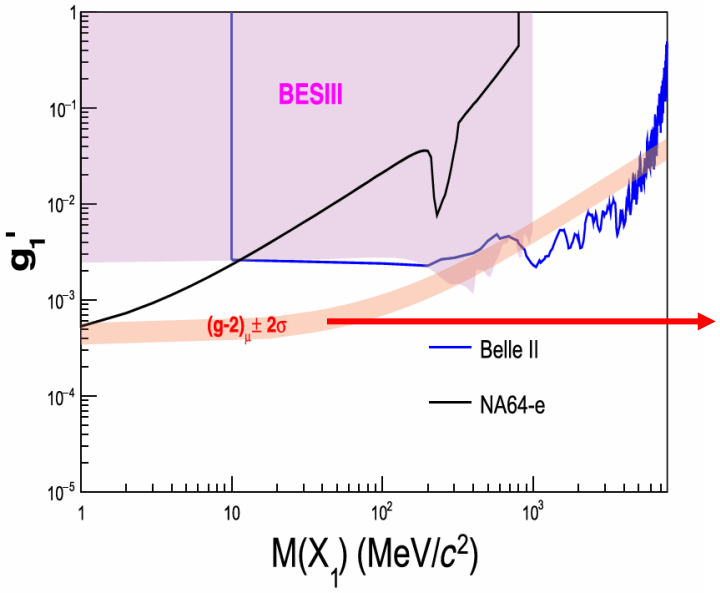
New Lattice value
arXiv: 2505.21476

Before 2025.5:

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

After 2025.5:

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



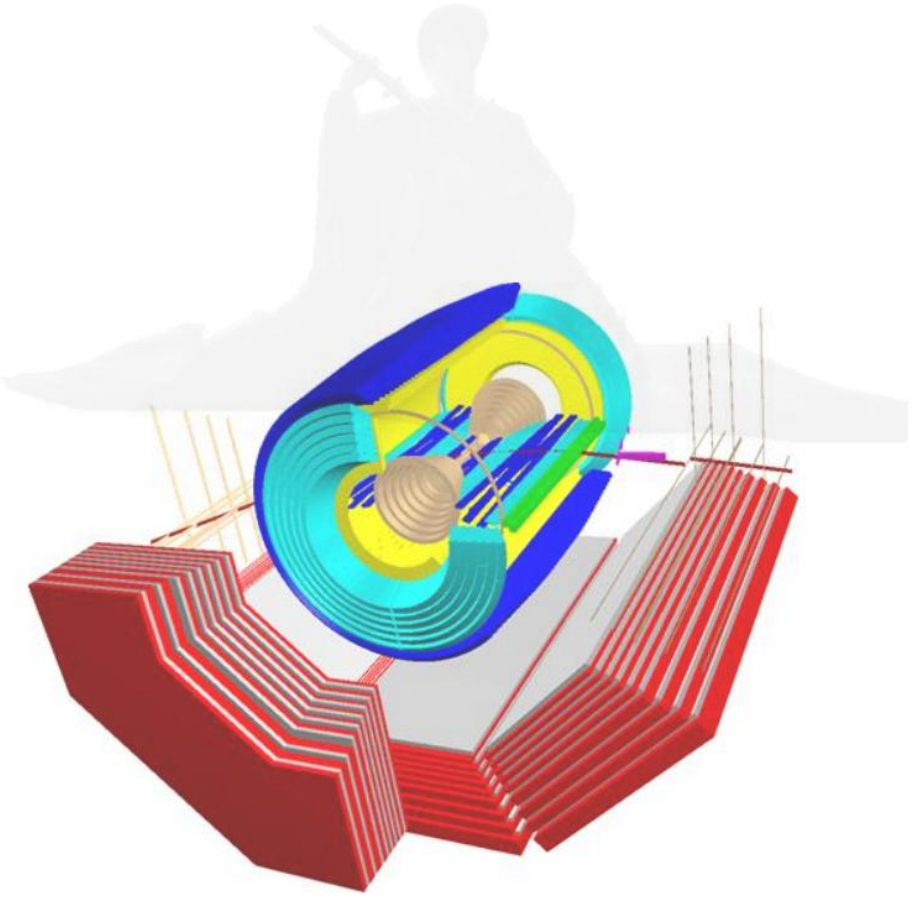
Before 2025.5:
Favor region

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



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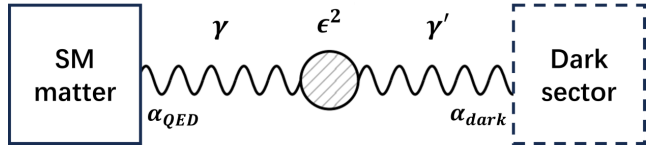
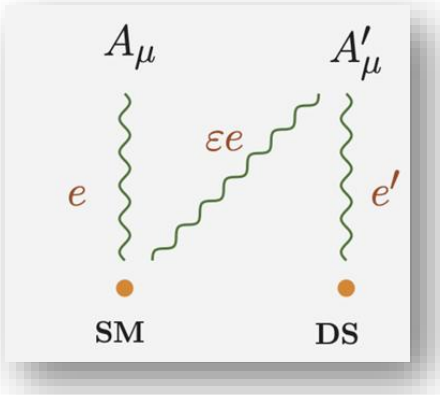
Massless dark photon

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



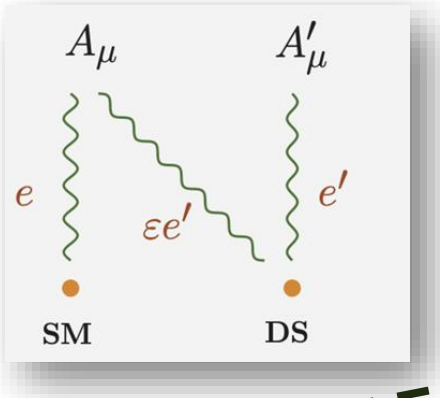


➢ **Massive dark photon**

- Symmetry broken spontaneously

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

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



➢ **Massless dark photon**

- Symmetry remains unbroken

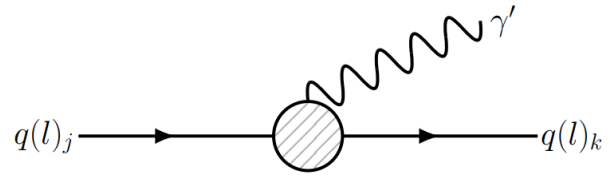
$$A'^\mu \rightarrow A'^\mu + \epsilon A^\mu$$

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

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

PRL 94, 151802 (2005)

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



➢ **Naturally allow the FCNC coupling**

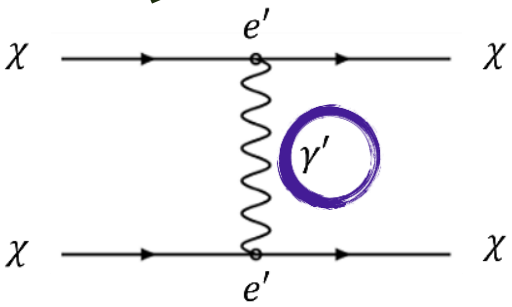
- **Less background and higher sensitivity**

Λ_{NP}: New physics energy scale

C_{jk}^i: Dimensionless coefficient

Role of the massless dark photon

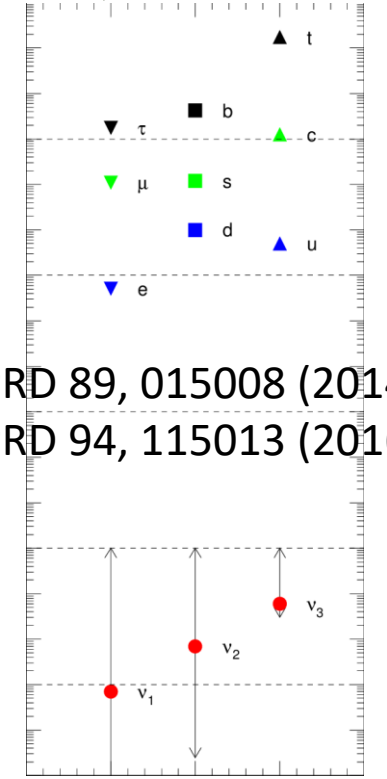
Provide a new long-range force of the DM



⟼ Explain the galaxy formation and dynamics

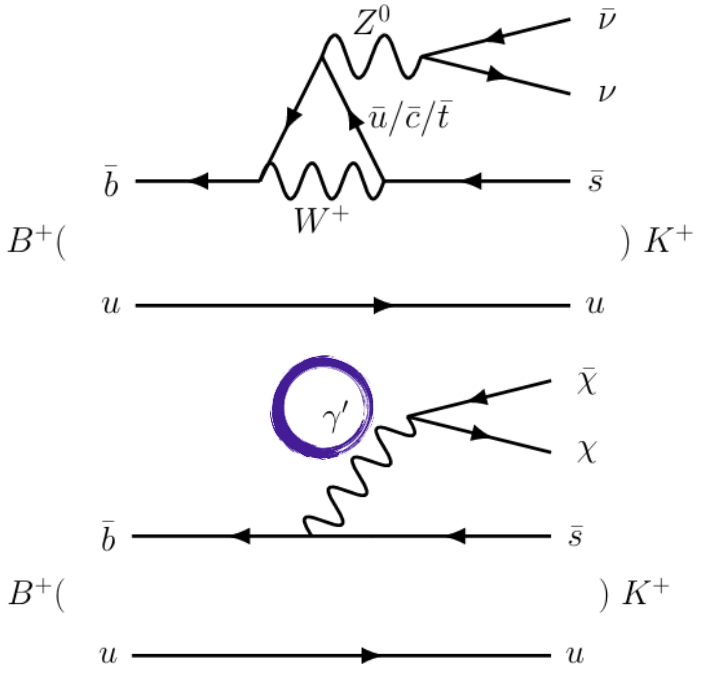
Phys.Rev.D 79 (2009) 023519
Phys.Rev.D 91 (2015) 023512
Phys.Lett.B 749 (2015) 236-241
JCAP 05, 022 (2017)
Phys.Rev.D 102 (2020) 8, 083009

Solution to the Fermion mass hierarchy



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

Explain excess of $B^+ \to K^+ \nu\bar{\nu}$ 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

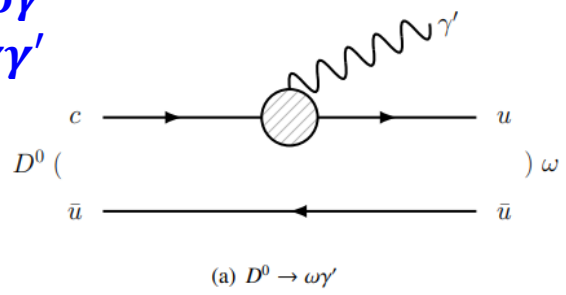
- **BESIII: large charm sample for invisible search**

- $4.5\ fb^{-1}\ e^+e^-$ collision data for Λ_c ($\sim 10^5\ \Lambda_c$)

- $7.9\ fb^{-1}\ e^+e^-$ collision data for D ($\sim 6.3 \times 10^6\ D^0$)

- Using **missing mass** to identify the massless dark photon

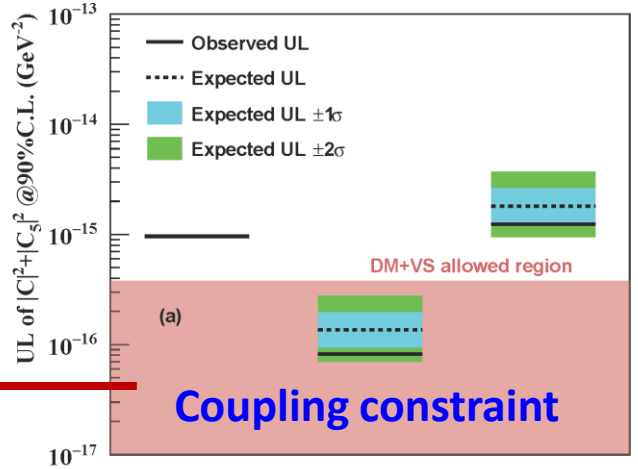
- $\Lambda_c \to p\gamma'$
- $D^0 \to \omega\gamma'$
- $D^0 \to \gamma\gamma'$

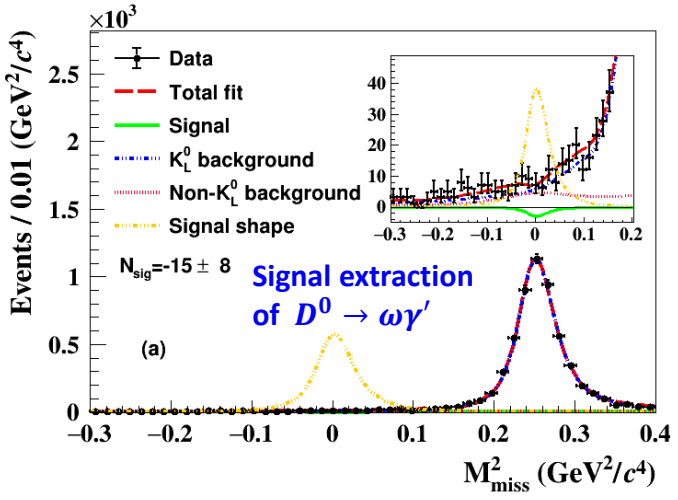


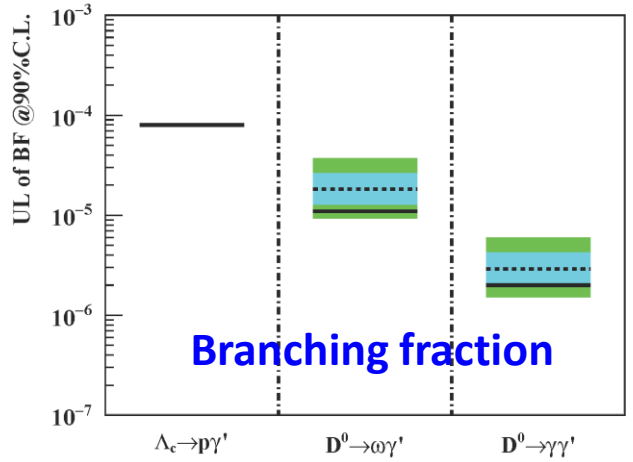
(a) $D^0 \to \omega\gamma'$

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

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

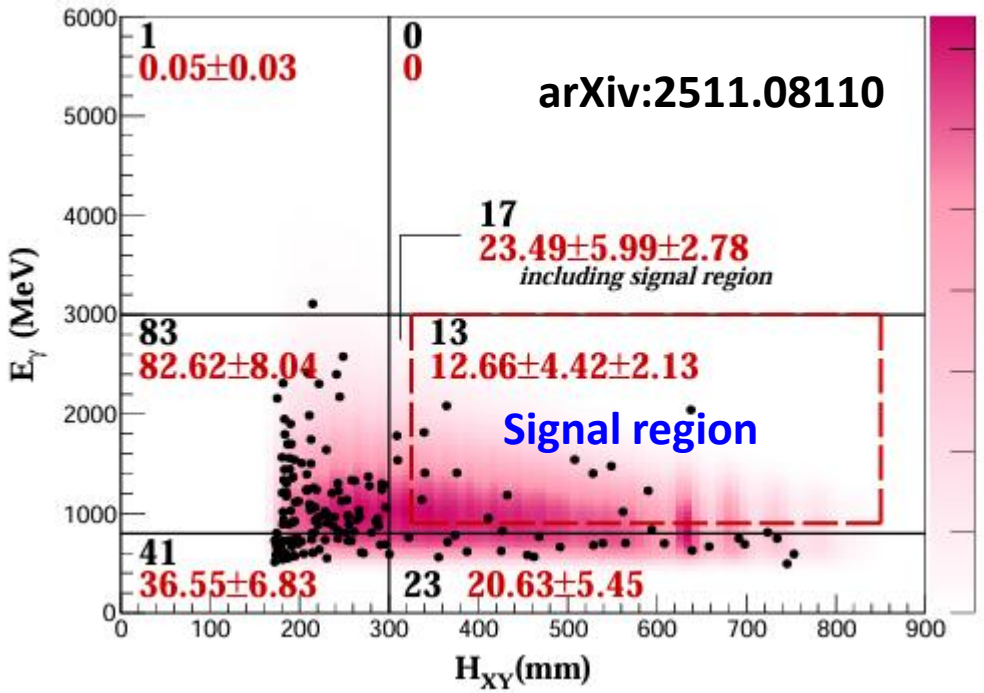


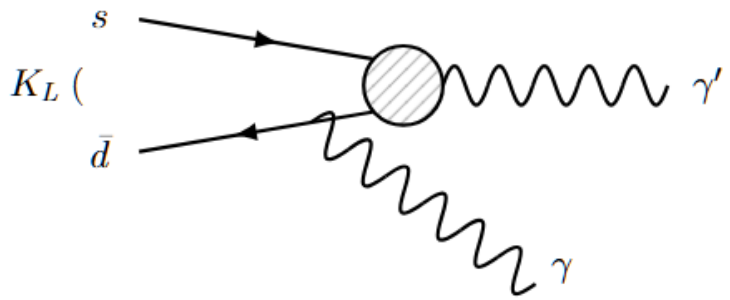




Phys.Rev.D 106 (2022) 7, 072008
Phys.Rev.D 111 (2025) 1, L011103

Massless γ' in strange quark decay





- **KOTO**: 1.29×10^{10} K_L from 5×10^{16} protons on target
- $K_L^0 \to \gamma\gamma'$, 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
- $\mathcal{B}(K_L^0 \to \gamma\gamma') < \mathbf{3.4 \times 10^{-7}}$
- $|\mathbb{C}|^2 + |\mathbb{C}_5|^2 < \mathbf{6.0 \times 10^{-20}}\ \boldsymbol{GeV^{-2}}$,
  Compared to charm sector $|\mathbb{C}|^2 + |\mathbb{C}_5|^2 < \mathbf{8.2 \times 10^{-17}}\ \boldsymbol{GeV^{-2}}$
- But no specific prediction for coupling in different flavor

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

Charm sector　　Strange sector

Other search: $H \to \gamma\gamma'$ — JHEP 03 (2021) 011; JHEP 07 (2023) 133; JHEP 08 (2024) 153

OUTLINE

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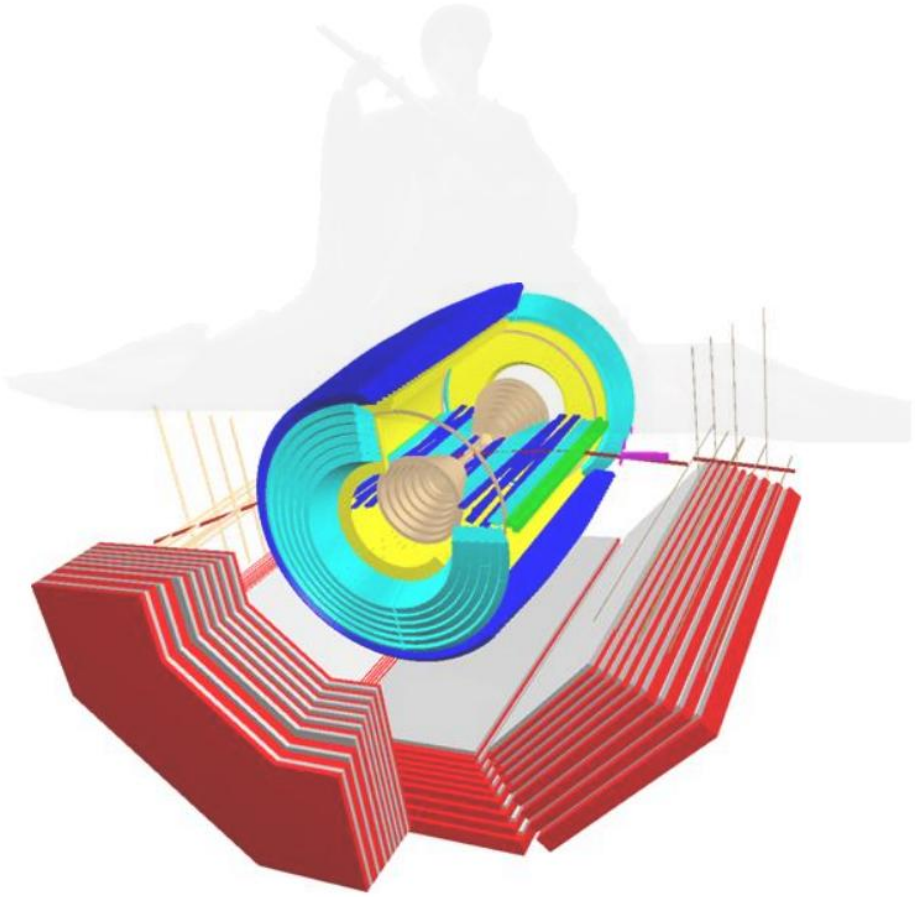
- **Summary**



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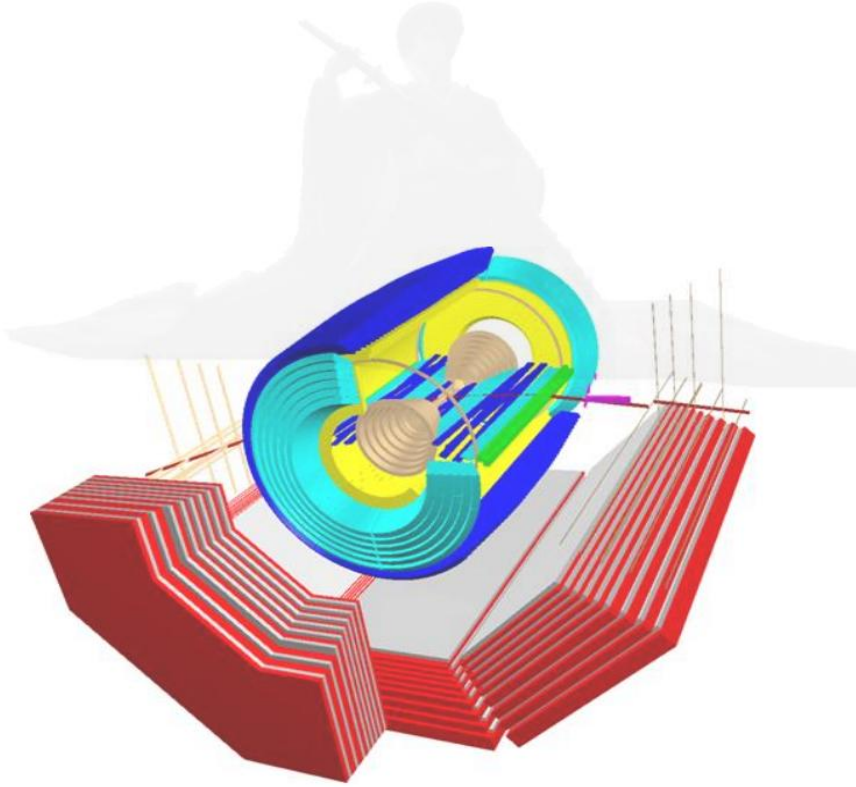
Summary

➢ **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 !

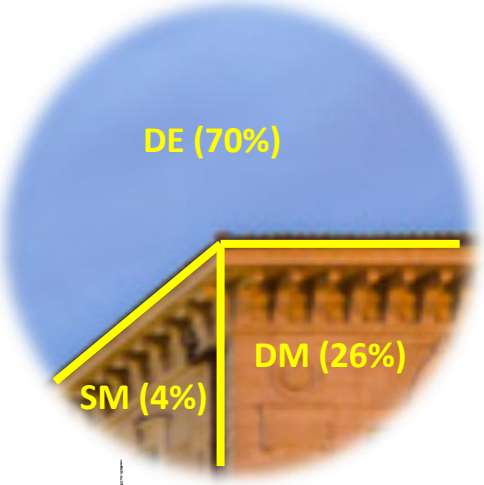
THANK YOU

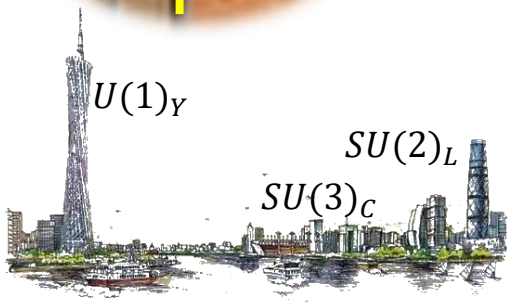
Appendix

Standard model and Puzzles

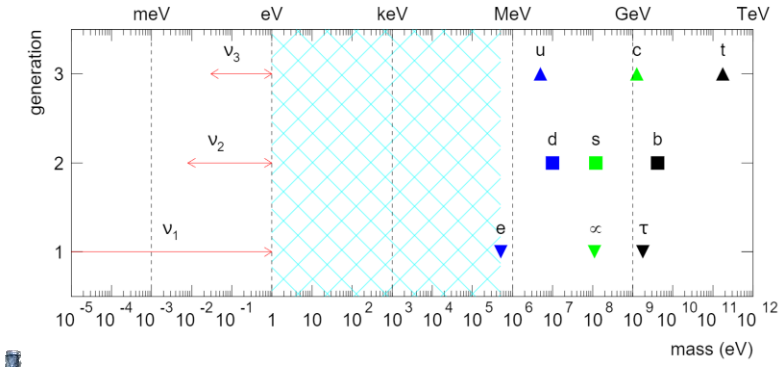
Dark Matter

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

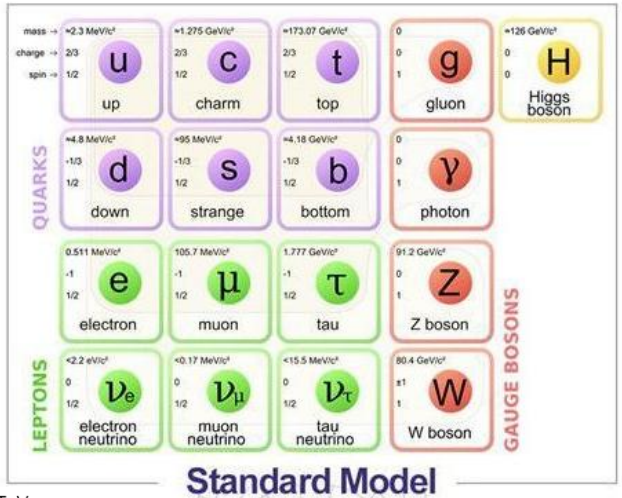


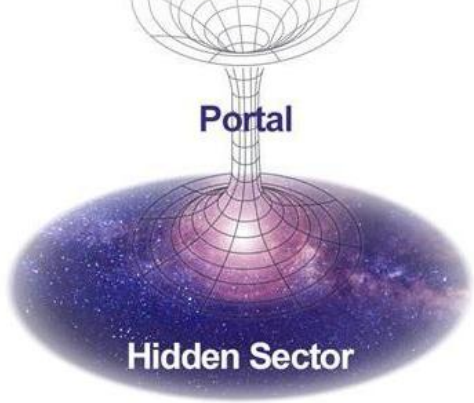


Fermion Mass Hierarchy



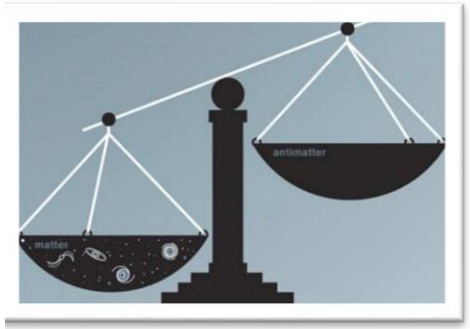
More . . .



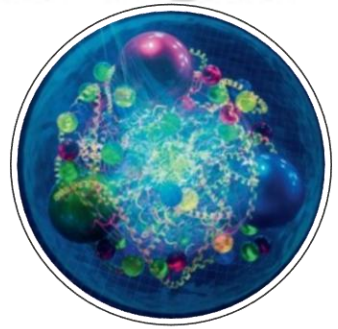


Potentials to find new physics

Matter Anti-matter Asymmetry



Strong CP Problem



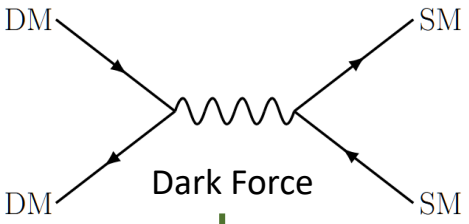
Role of dark photon

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

$m_{\gamma'} < 1\ MeV$