正负电子对撞机上的新物理和暗物质研究
searching for new light dark particles

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南京大学

味物理前沿研讨会暨味物理讲座100期特别活动

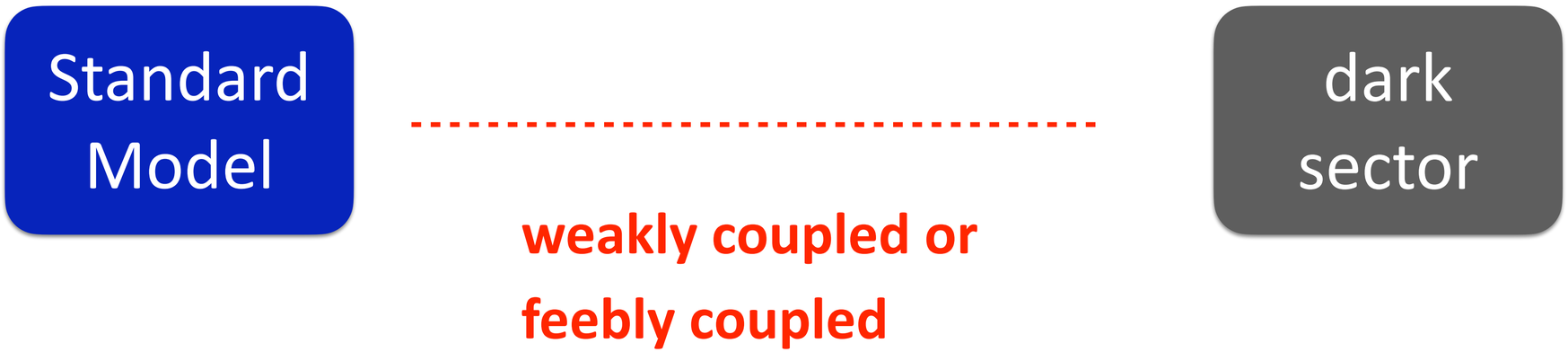
2026年1月30日 - 2月4日

dark sector

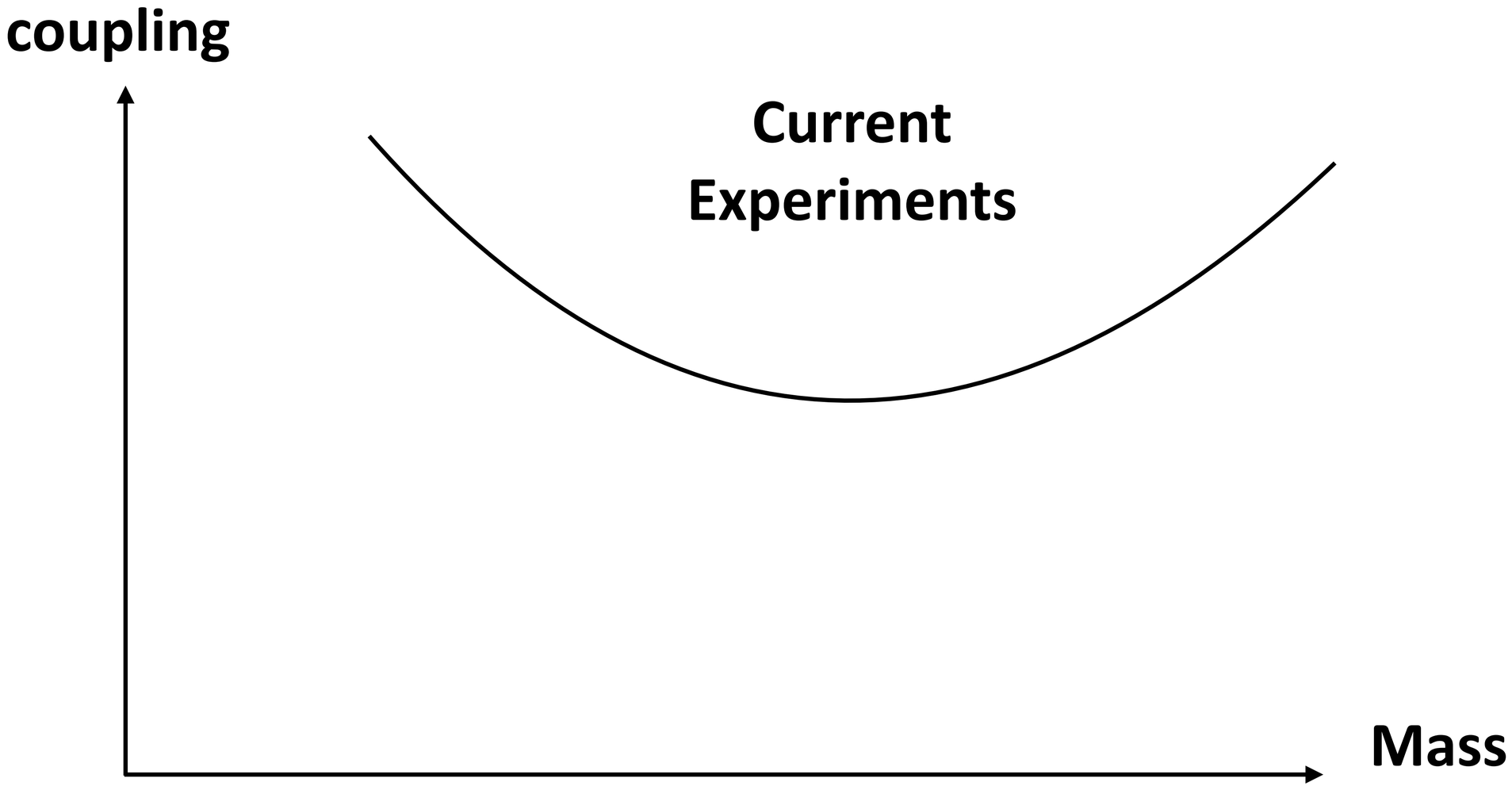
Standard Model

dark sector

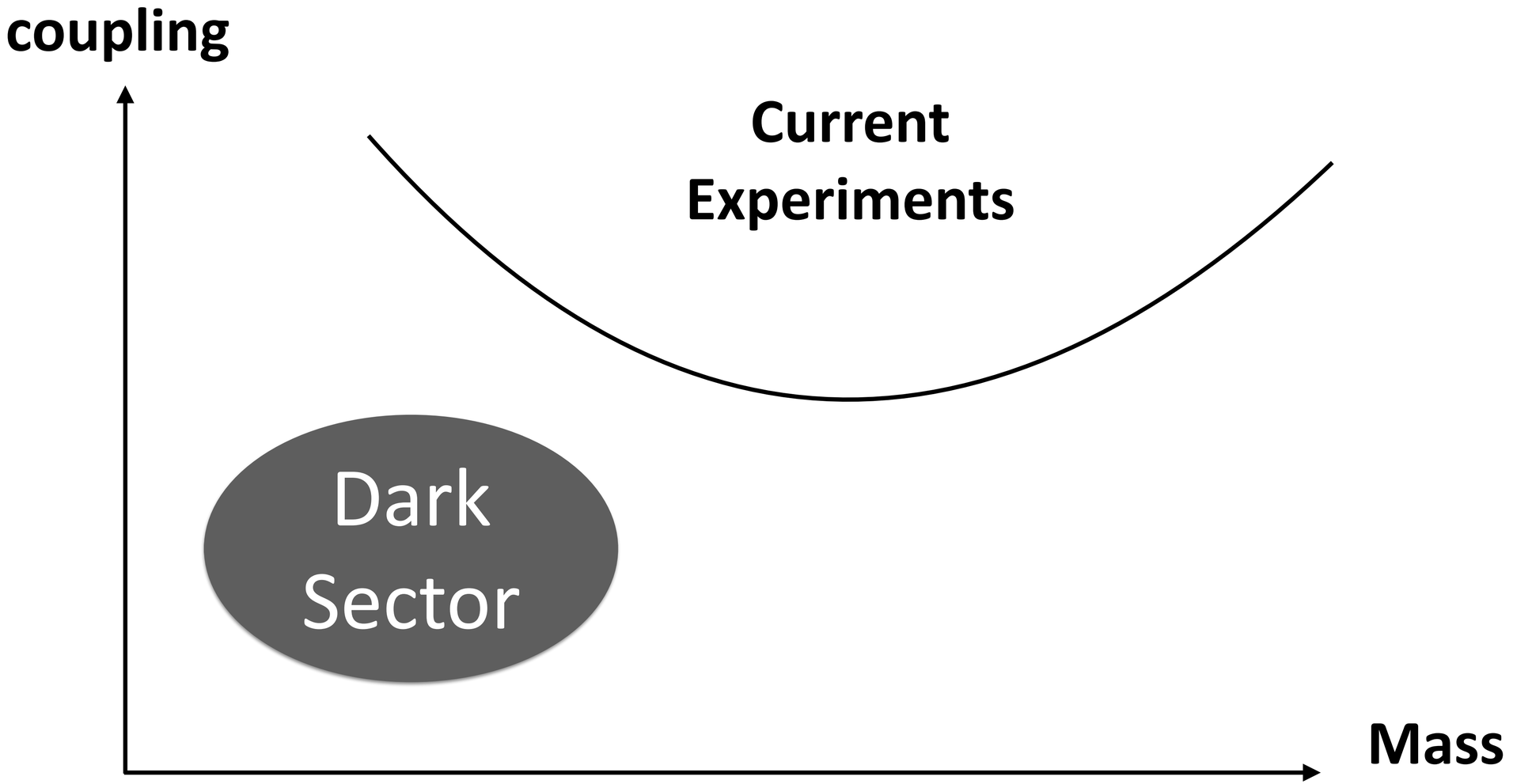
dark sector


Standard Model
weakly coupled or
feebly coupled
dark sector

parameter space of interest for electron colliders

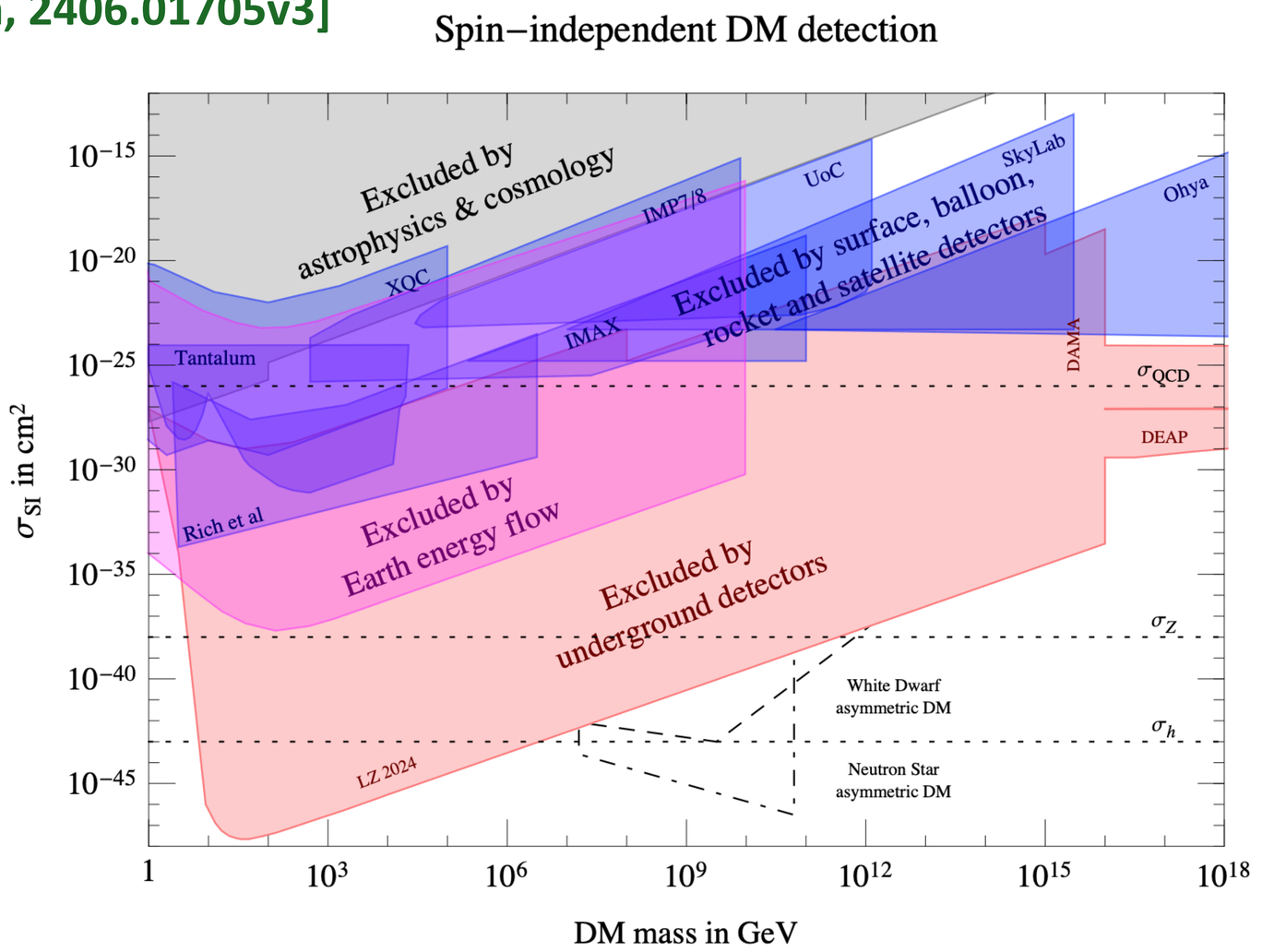


parameter space of interest for electron colliders



dark matter detection

[Cirelli, Strumia, Zupan, 2406.01705v3]



see also

2507.11930 (PandaX-4T)

2510.21458 (CDEX)

Outline

1. dark photon & millicharged particles
2. dark matter
3. leptophilic gauge boson
4. axion & axion-like particles (ALPs)

1 dark photon & millicharged particles

Hypercharge portal models

Hypercharge portal model for dark photon & millicharged particles

$SU(3)_c \times SU(2)_L \times U(1)_Y$

SM sector

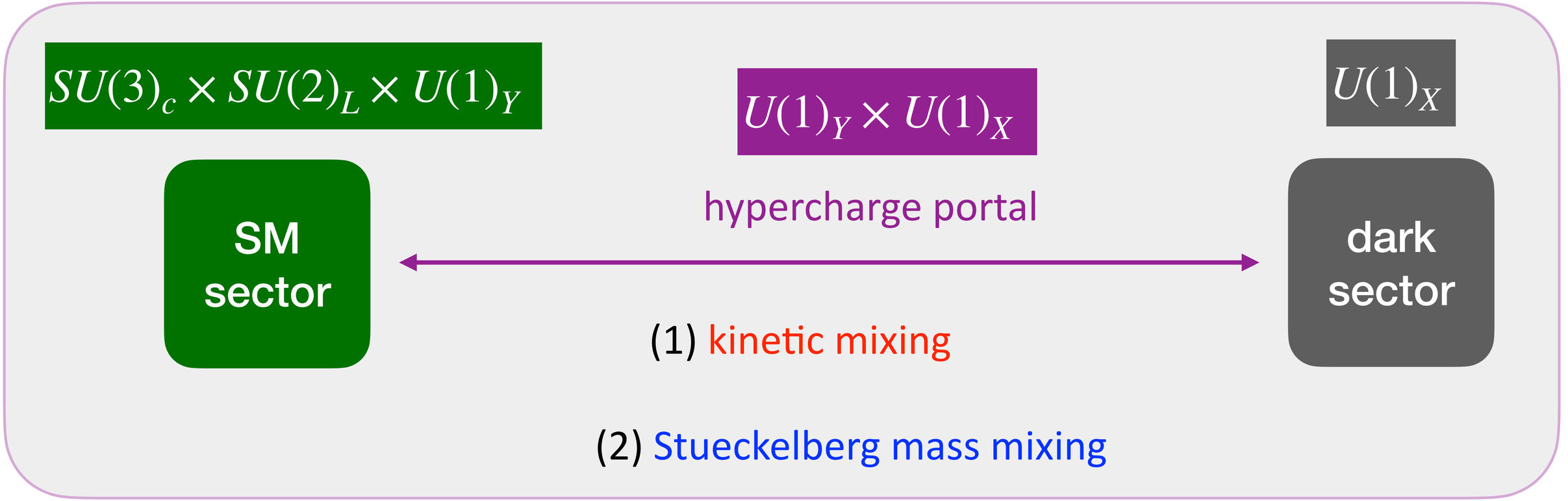
$U(1)_X$

dark sector

[Holdom 1986; Foot & He 1991; Cheung & Yuan 2007; Feldman, ZL, Nath 2007]

Hypercharge portal models

Hypercharge portal model for dark photon & millicharged particles



[Holdom 1986; Foot & He 1991; Cheung & Yuan 2007; Feldman, ZL, Nath 2007]

Kinetic mixing & mass mixing

$$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X$$

$$\mathscr{L} = -\frac{1}{4}A_{\mu\nu}A^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + g_D X_\mu \bar{\chi}\gamma^\mu \chi - \frac{\tilde{\epsilon}_1}{2} A_{\mu\nu} X^{\mu\nu} - \frac{M_1^2}{2}(\partial_\mu \sigma + X_\mu + \tilde{\epsilon}_2 A_\mu)^2$$

[Feldman, ZL, Nath, hep-ph/0702123, 437 cites]

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kinetic mixing

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kinetic mixing

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[Feldman, ZL, Nath, hep-ph/0702123, 437 cites]

dark photon & millicharged particles

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[see also Fabbrichesi+, 2005.01515, Dark Photon Review]

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- X_μ is hypercharge-like if $M_1 \gg M_Z$ (better probed at LHC)
- If dark photon is massive, hidden fermion χ is millicharged only when $\tilde{\epsilon}_2 \neq 0$
- Millicharged particle χ interacts with photon via $\epsilon e A_\mu \bar{\chi}\gamma^\mu \chi$

[Feldman, ZL, Nath, hep-ph/0702123, 437 cites]

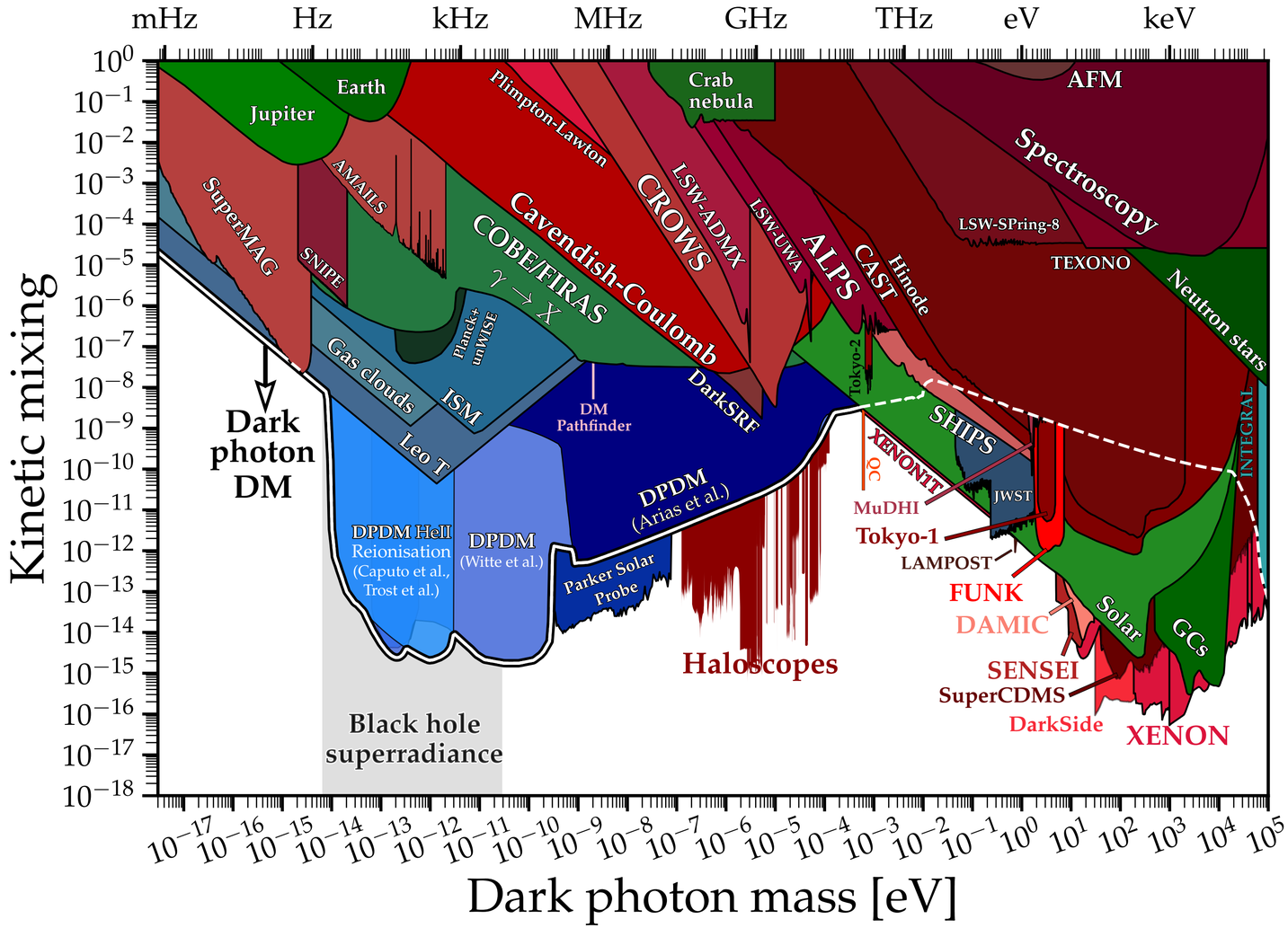
[see also Fabbrichesi+, 2005.01515, Dark Photon Review]

dark photon

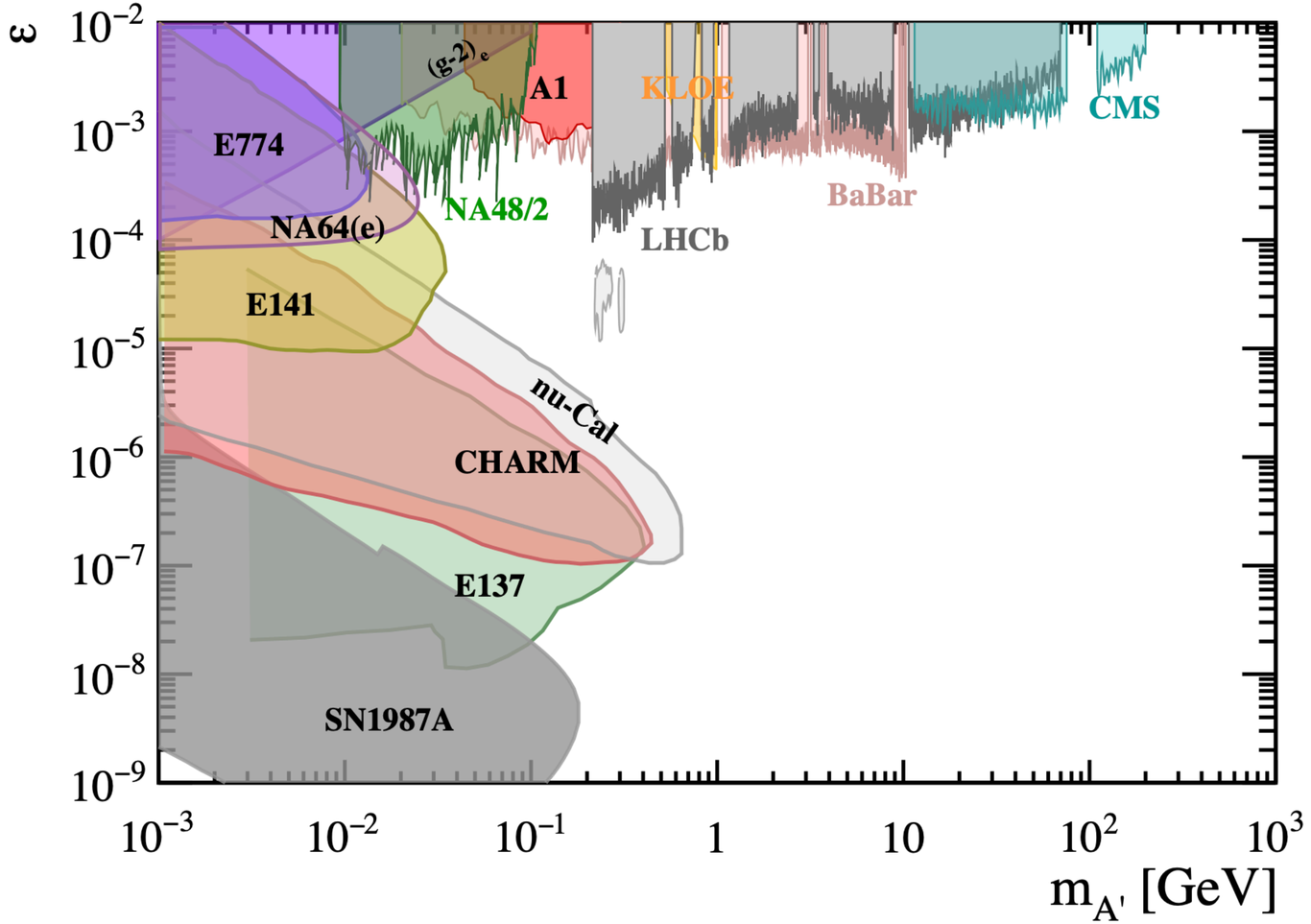
Limits on dark photon with mass below 1 MeV

[https://cajohare.github.io/AxionLimits/]

ultralight dark photons
are DM candidates



Limits on dark photon with mass above 1 MeV



[Fabbrichesi+, 2005.01515, Dark Photon Review]

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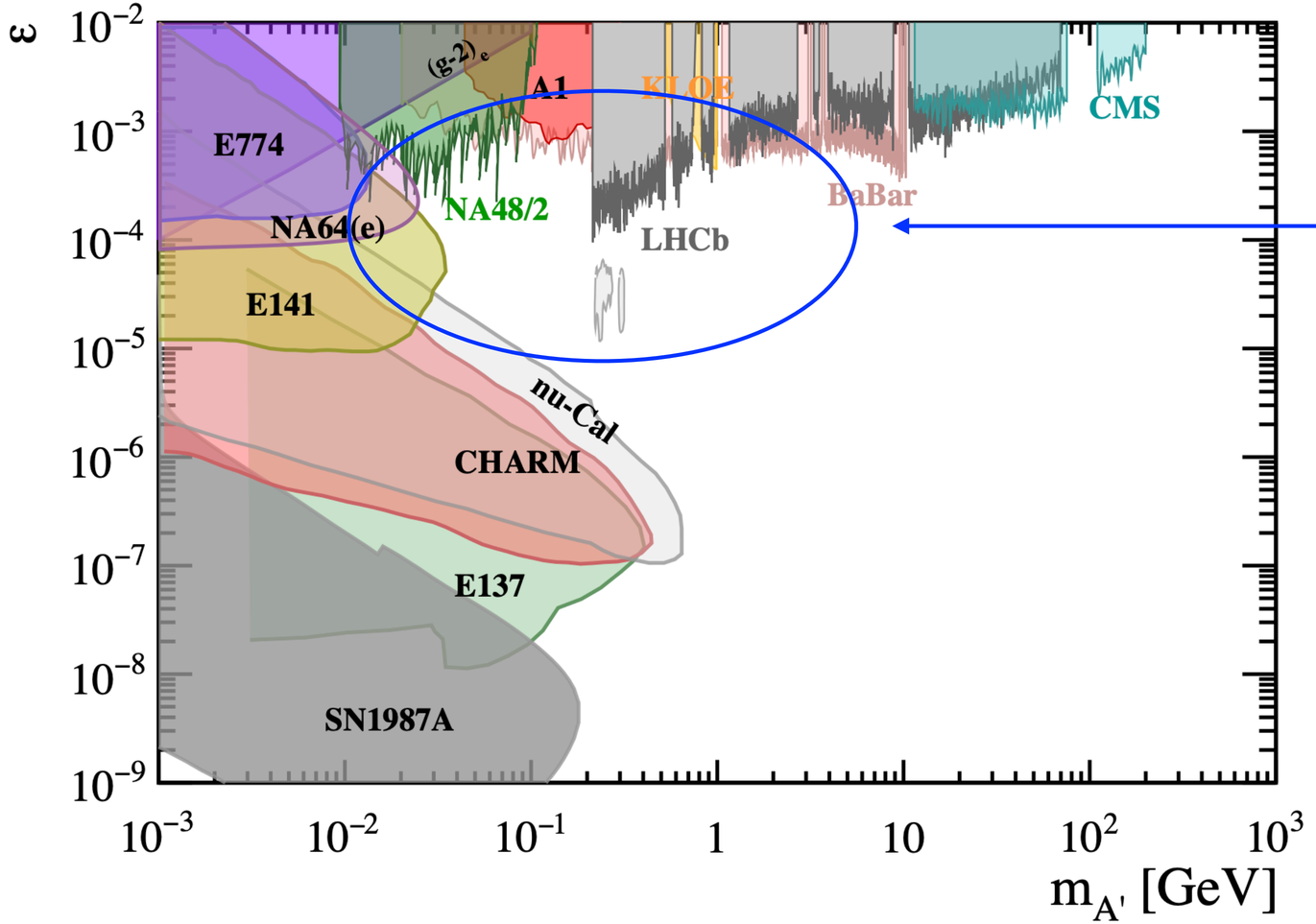


probed by e^+e^- colliders

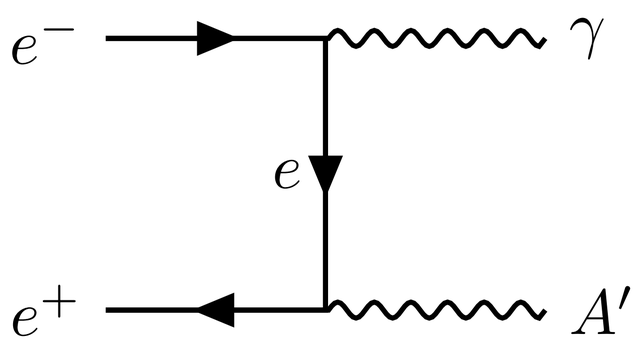
[Fabbrichesi+, 2005.01515, Dark Photon Review]

Dark photon production @ electron colliders

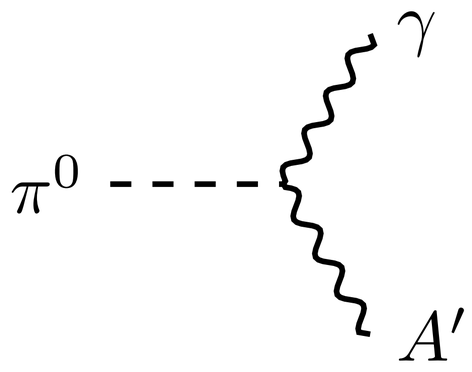
Dark photon A'_μ interactions: $\epsilon e Q_f A'_\mu \bar{f} \gamma^\mu f$ (visible) and $g_D A'_\mu \bar{\chi} \gamma^\mu \chi$ (invisible)

Production channel

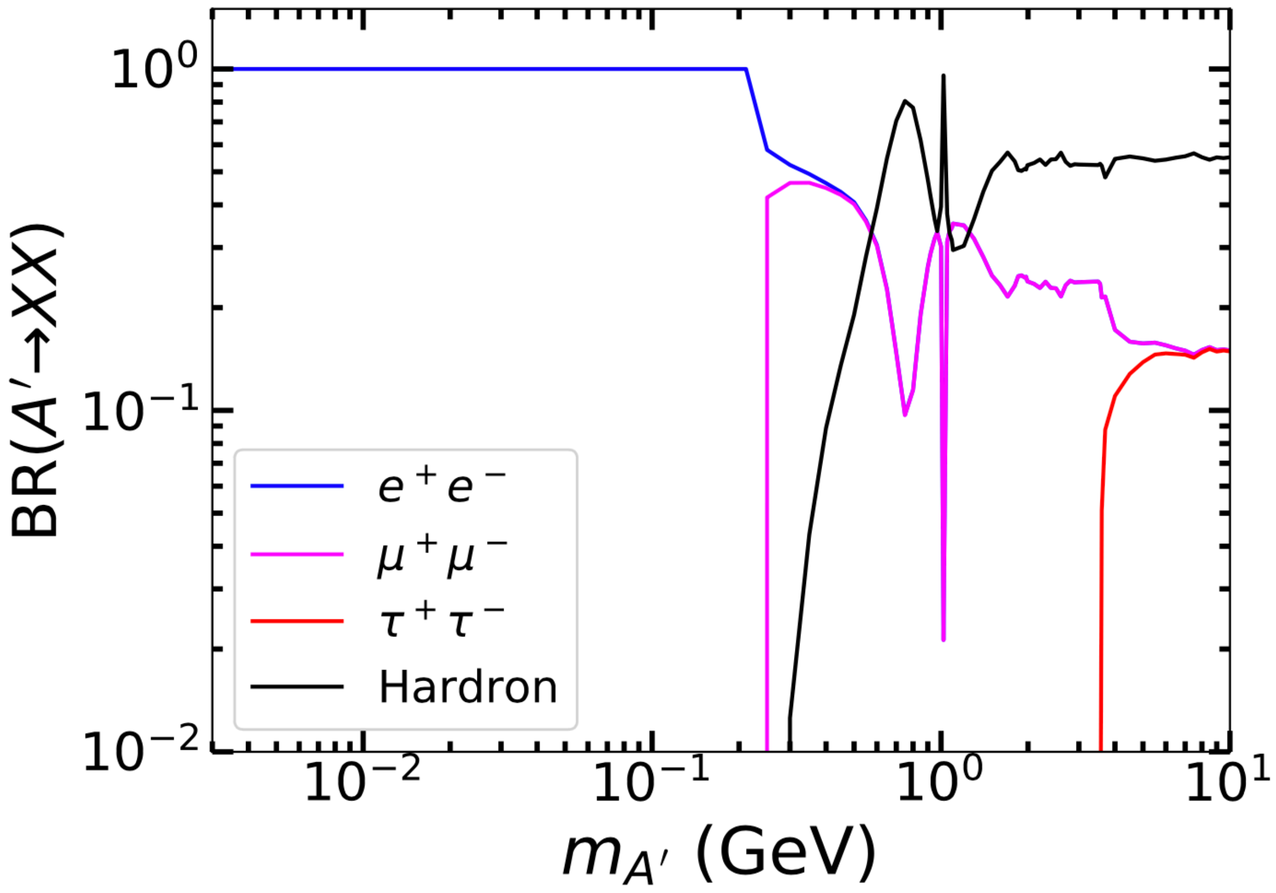
(1) radiative return



(2) hadron decays



Dark photon visible decay branching ratio



only visible channels here

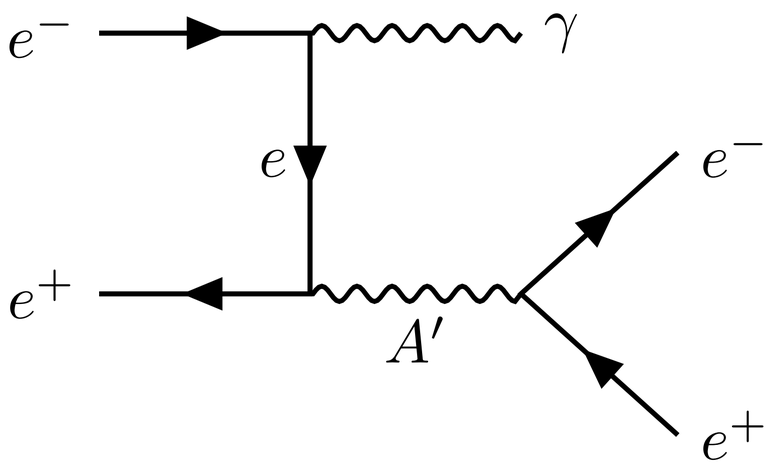
invisible ones can dominate over the visible ones

[Mingxuan Du, ZL, Van Que Tran, 1912.00422]

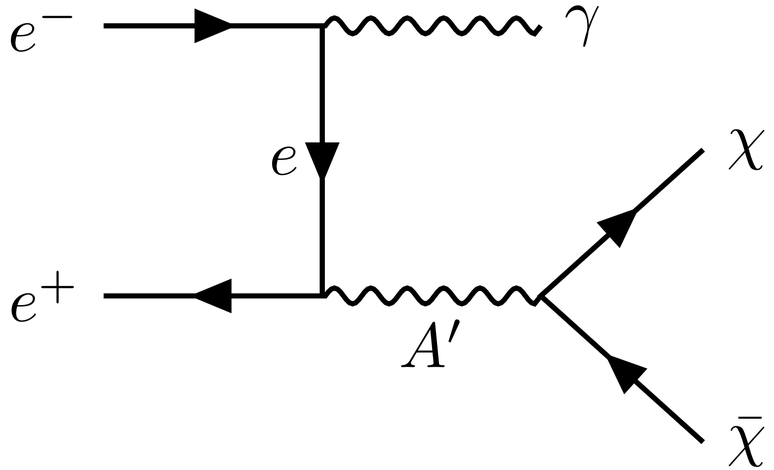
Dark photon signatures @ electron colliders

Two different collider signatures for dark photon

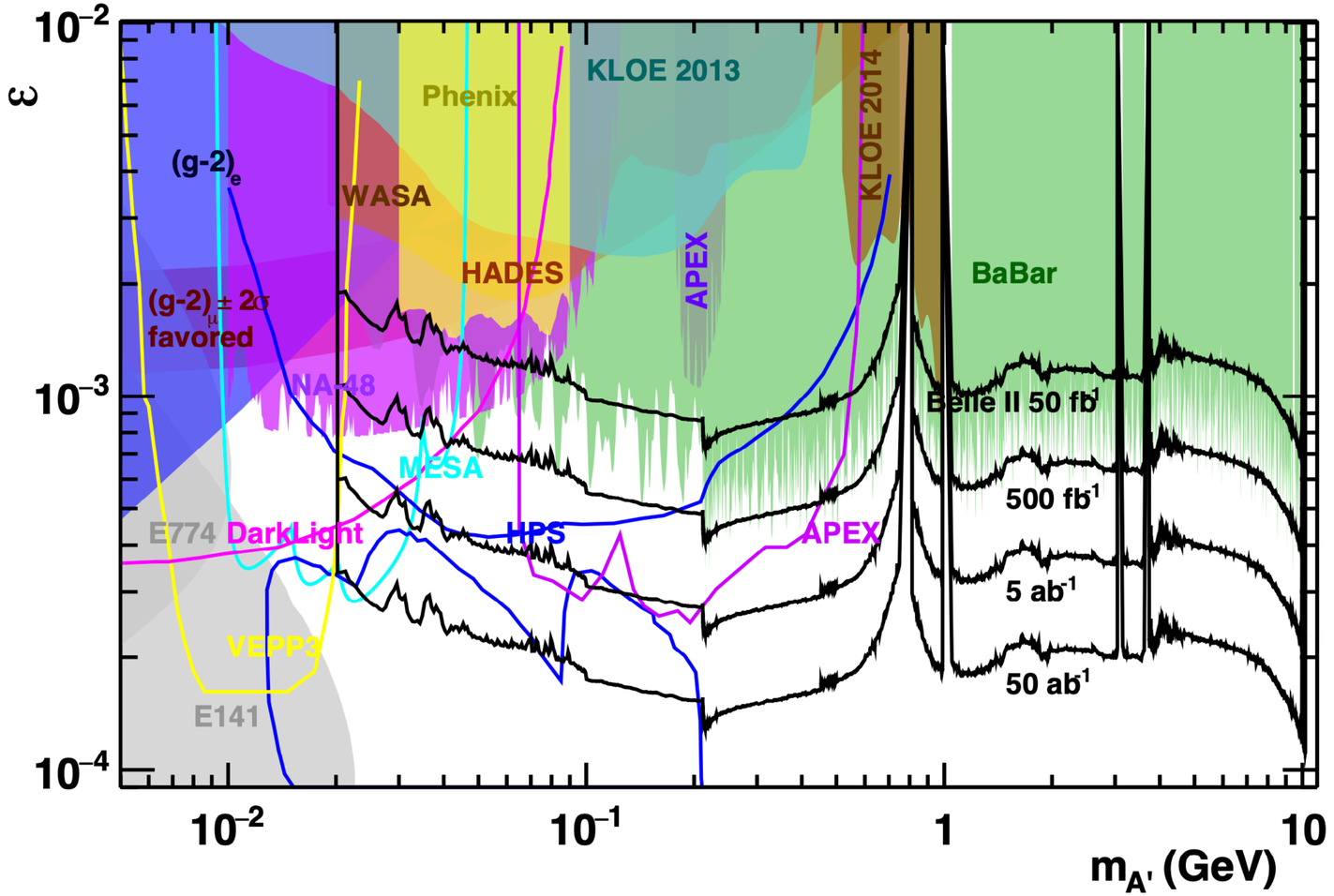
visible decay ($ee/\mu\mu$)
(1) prompt
(2) long-lived

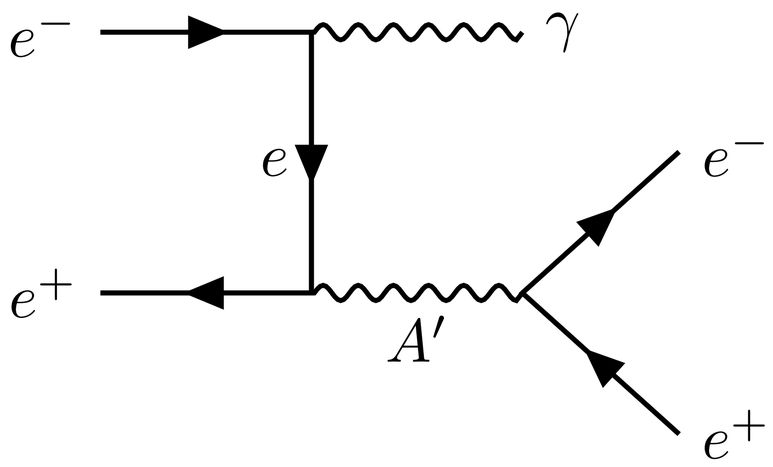


invisible decay: mono-photon



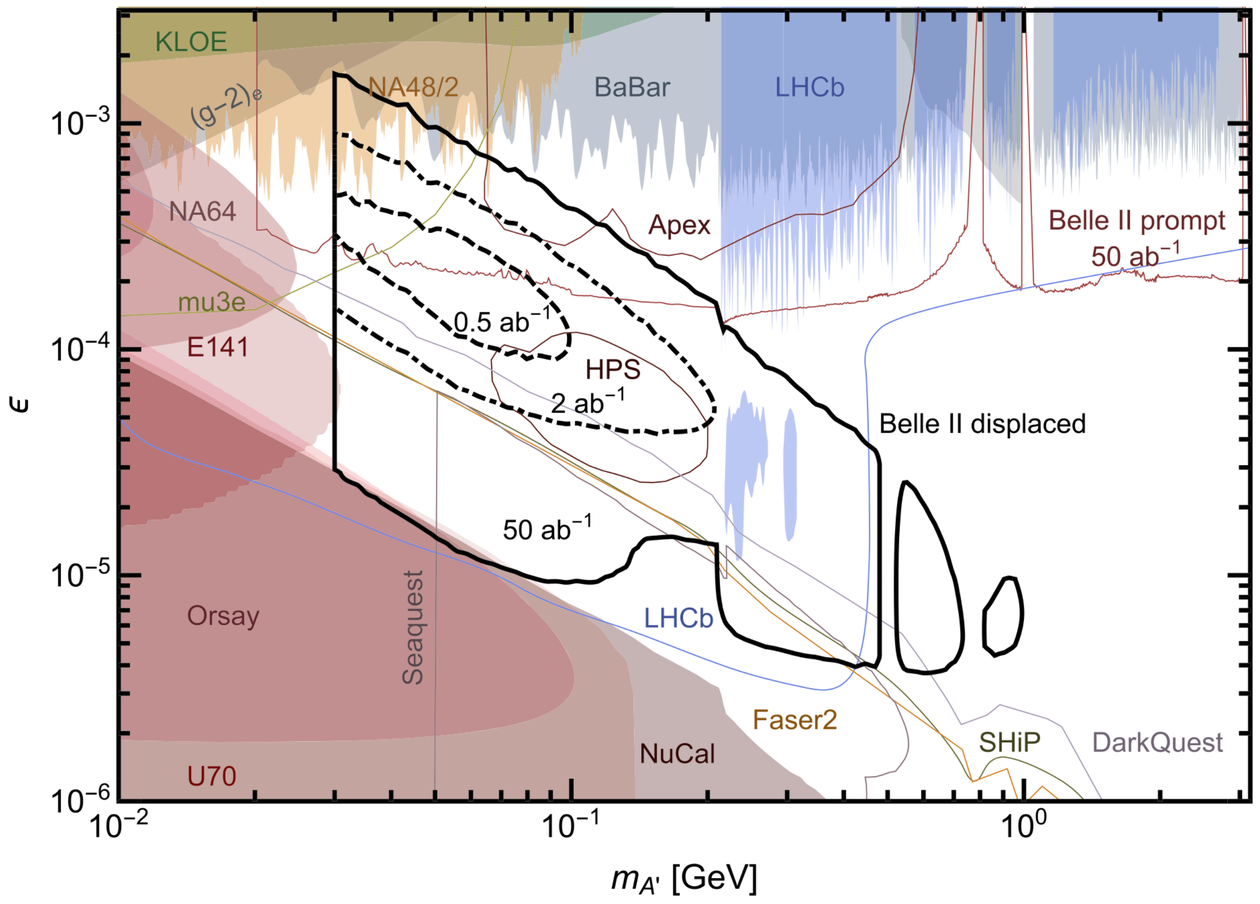
Belle II sensitivity on prompt dark photon visible decay



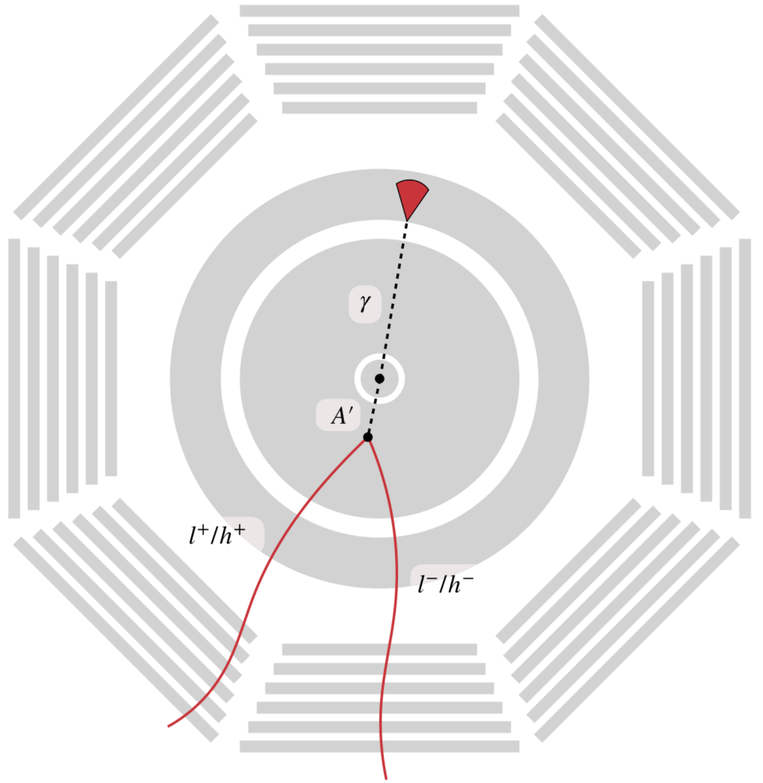


Belle-II, 2207.06307, Snowmass

Belle II sensitivity on long-lived dark photon



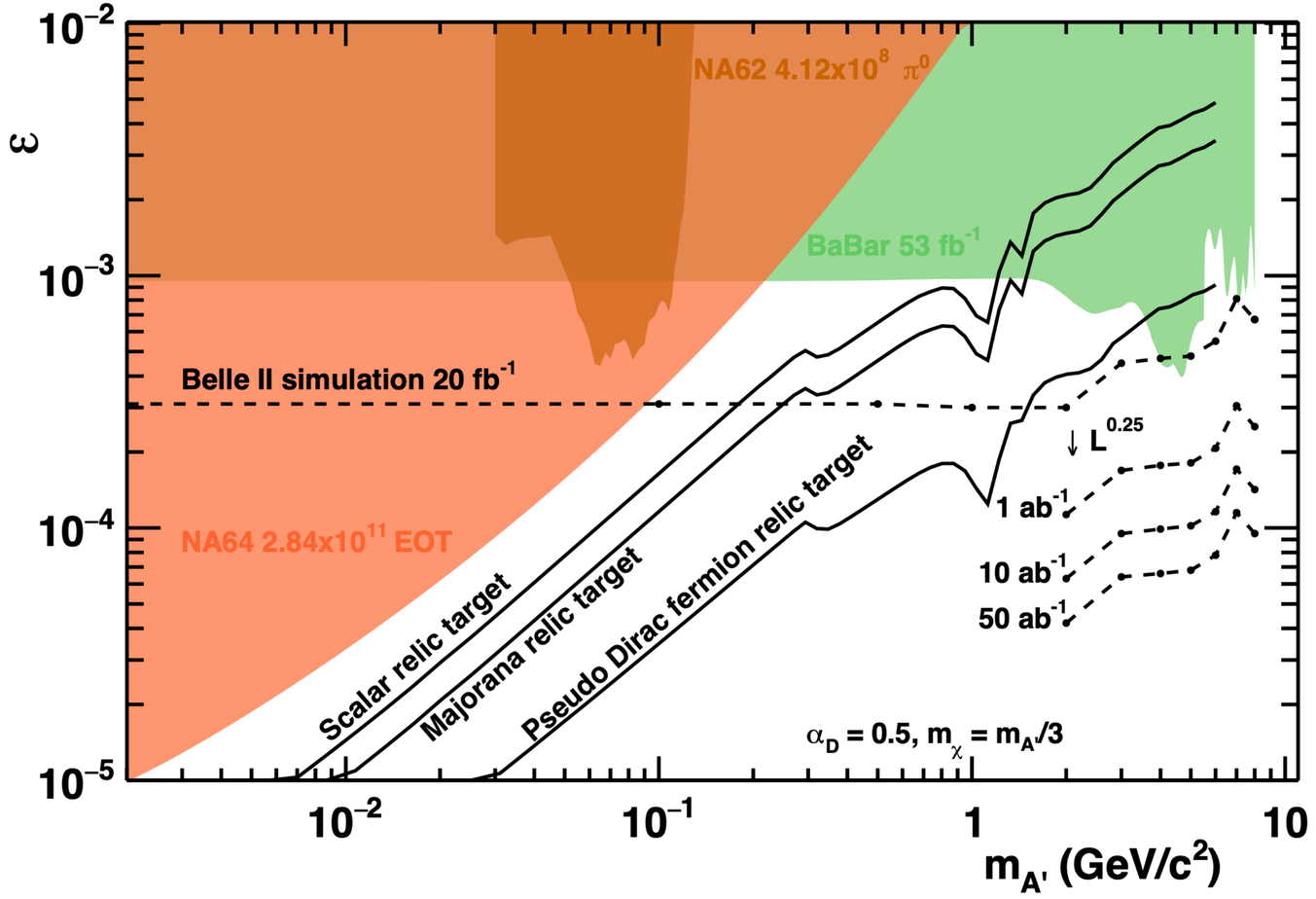
[Ferber, Garcia-Cely, Schmidt-Hoberg, 2202.03452]



photon + displaced vertex

e & non-e final states

Belle II sensitivity on dark photon invisible decay



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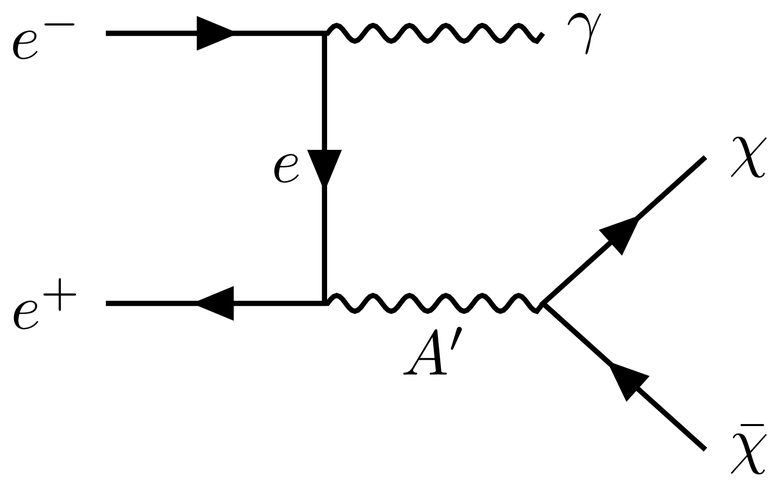
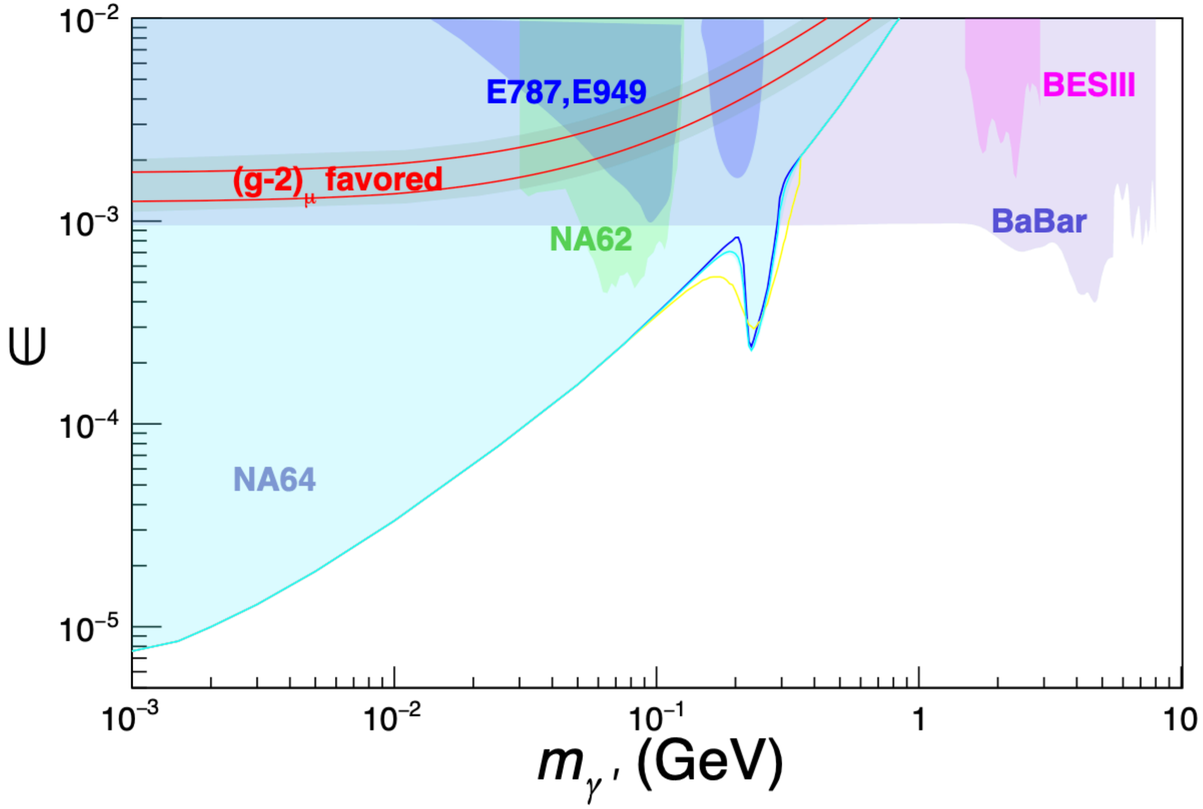


monochromatic photon for on-shell dark photon

challenge: reducible BG (see later slides)

BESIII limits on dark photon invisible decay

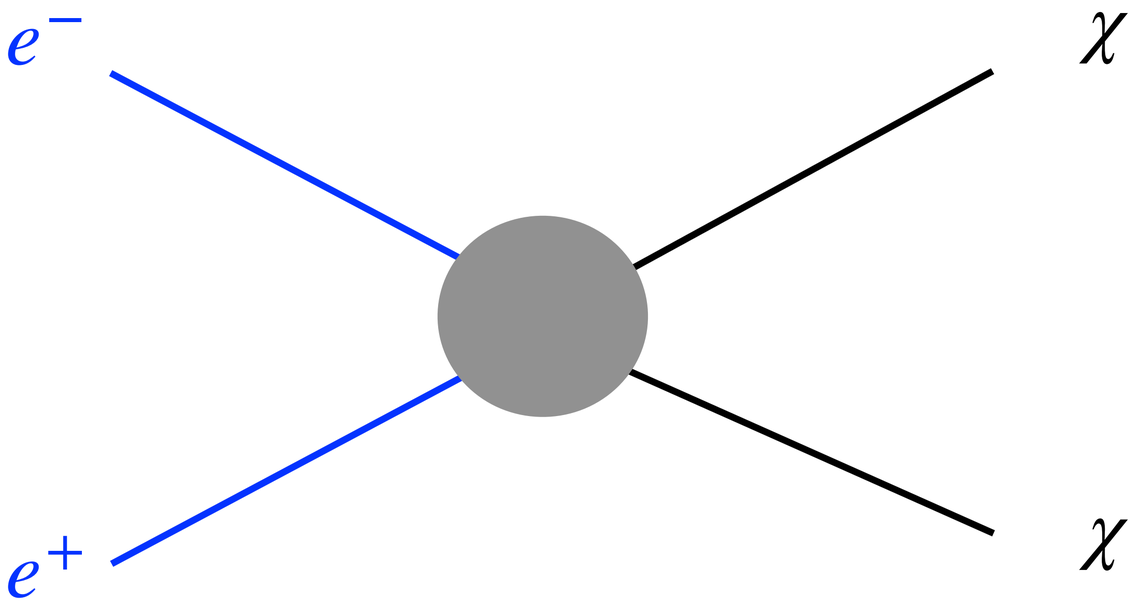


BESIII, 2209.13893

14.9/fb at 4.13-4.60 GeV

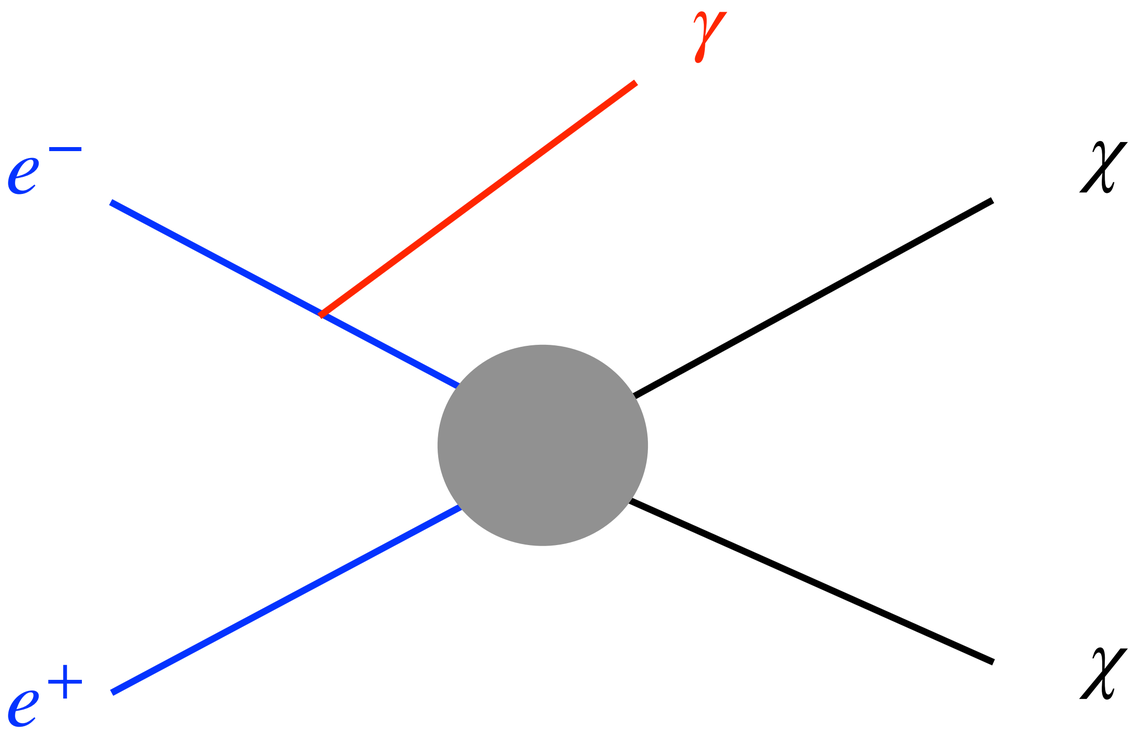
2 dark matter & millicharged particles

Mono-photon signature at electron colliders



Mono-photon signature at electron colliders

mono-photon



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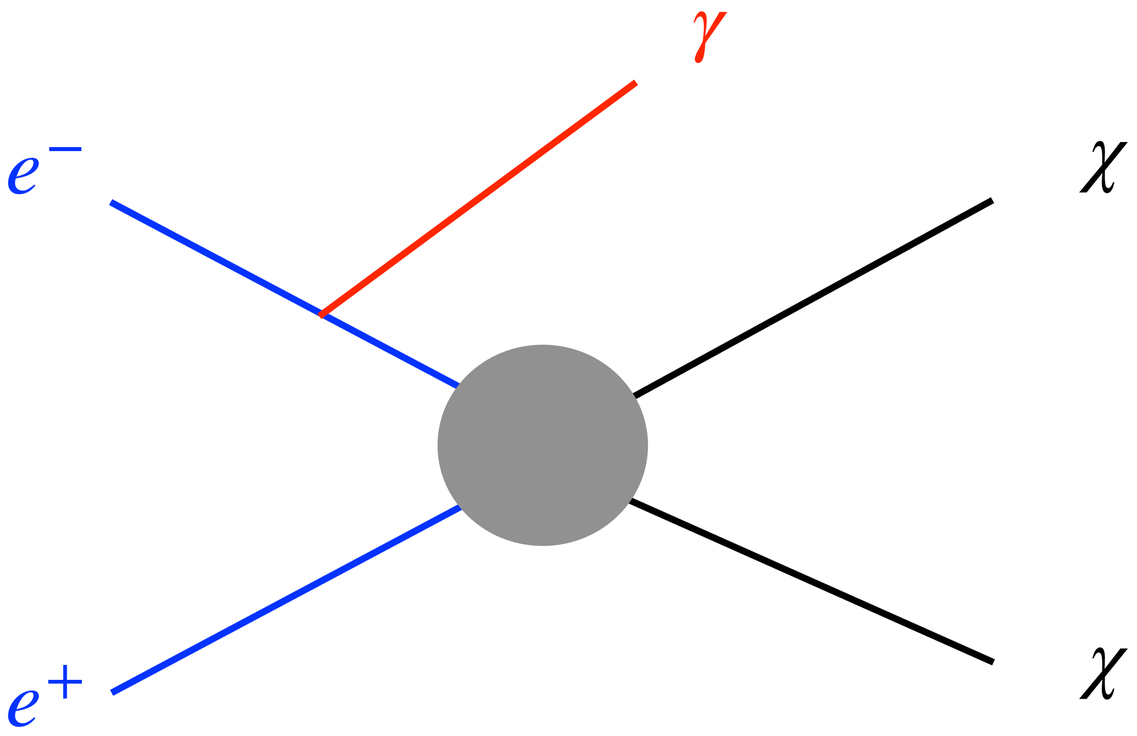


probe a variety of models:

- EFT DM
- light mediator DM
- millicharged particles (undetectable ionization)
- invisible dark photon

Different sub-GeV DM models (diff mediator mass)

EFT DM	$\frac{1}{\Lambda_V^2}\bar{\chi}\gamma_\mu\chi\bar{\ell}\gamma^\mu\ell$	$\frac{1}{\Lambda_A^2}\bar{\chi}\gamma_\mu\gamma_5\chi\bar{\ell}\gamma^\mu\gamma_5\ell$	$\frac{1}{\Lambda_s^2}\bar{\chi}\chi\bar{\ell}\ell$	$\frac{1}{\Lambda_t^2}\bar{\chi}\ell\bar{\ell}\chi$

[ZL, Zhang, 1808.00983] [Liang, ZL, Ma, Zhang, 1909.06847] [Liang, ZL, Yang, 2111.15533]

Different sub-GeV DM models (diff mediator mass)

EFT DM

$$\frac{1}{\Lambda_V^2}\bar{\chi}\gamma_\mu\chi\bar{\ell}\gamma^\mu\ell \qquad \frac{1}{\Lambda_A^2}\bar{\chi}\gamma_\mu\gamma_5\chi\bar{\ell}\gamma^\mu\gamma_5\ell \qquad \frac{1}{\Lambda_s^2}\bar{\chi}\chi\bar{\ell}\ell \qquad \frac{1}{\Lambda_t^2}\bar{\chi}\ell\bar{\ell}\chi$$

Light mediator DM

$$Z'_\mu\bar{\chi}\gamma^\mu\left(g_v^\chi - g_a^\chi\gamma_5\right)\chi + Z'_\mu\bar{\ell}\gamma^\mu\left(g_v^\ell - g_a^\ell\gamma_5\right)\ell$$

[ZL, Zhang, 1808.00983] [Liang, ZL, Ma, Zhang, 1909.06847] [Liang, ZL, Yang, 2111.15533]

Different sub-GeV DM models (diff mediator mass)

EFT DM $\frac{1}{\Lambda_V^2}\bar{\chi}\gamma_\mu\chi\bar{\ell}\gamma^\mu\ell$ $\frac{1}{\Lambda_A^2}\bar{\chi}\gamma_\mu\gamma_5\chi\bar{\ell}\gamma^\mu\gamma_5\ell$ $\frac{1}{\Lambda_s^2}\bar{\chi}\chi\bar{\ell}\ell$ $\frac{1}{\Lambda_t^2}\bar{\chi}\ell\bar{\ell}\chi$

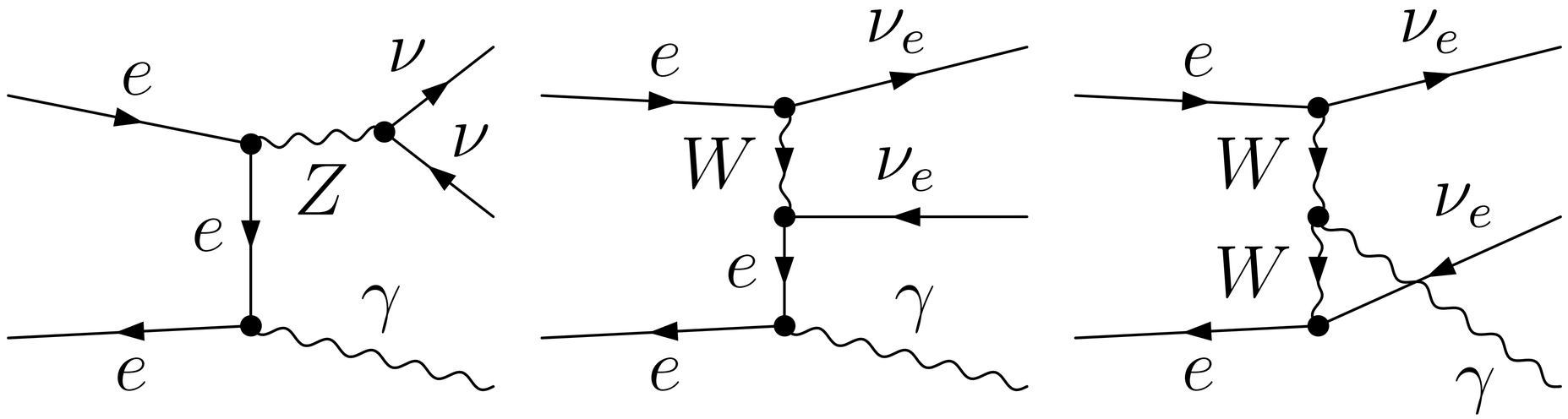
Light mediator DM $Z'_\mu\bar{\chi}\gamma^\mu\left(g_v^\chi - g_a^\chi\gamma_5\right)\chi + Z'_\mu\bar{\ell}\gamma^\mu\left(g_v^\ell - g_a^\ell\gamma_5\right)\ell$

Millicharged particles $\epsilon e A_\mu\bar{\chi}\gamma^\mu\chi$

[ZL, Zhang, 1808.00983] [Liang, ZL, Ma, Zhang, 1909.06847] [Liang, ZL, Yang, 2111.15533]

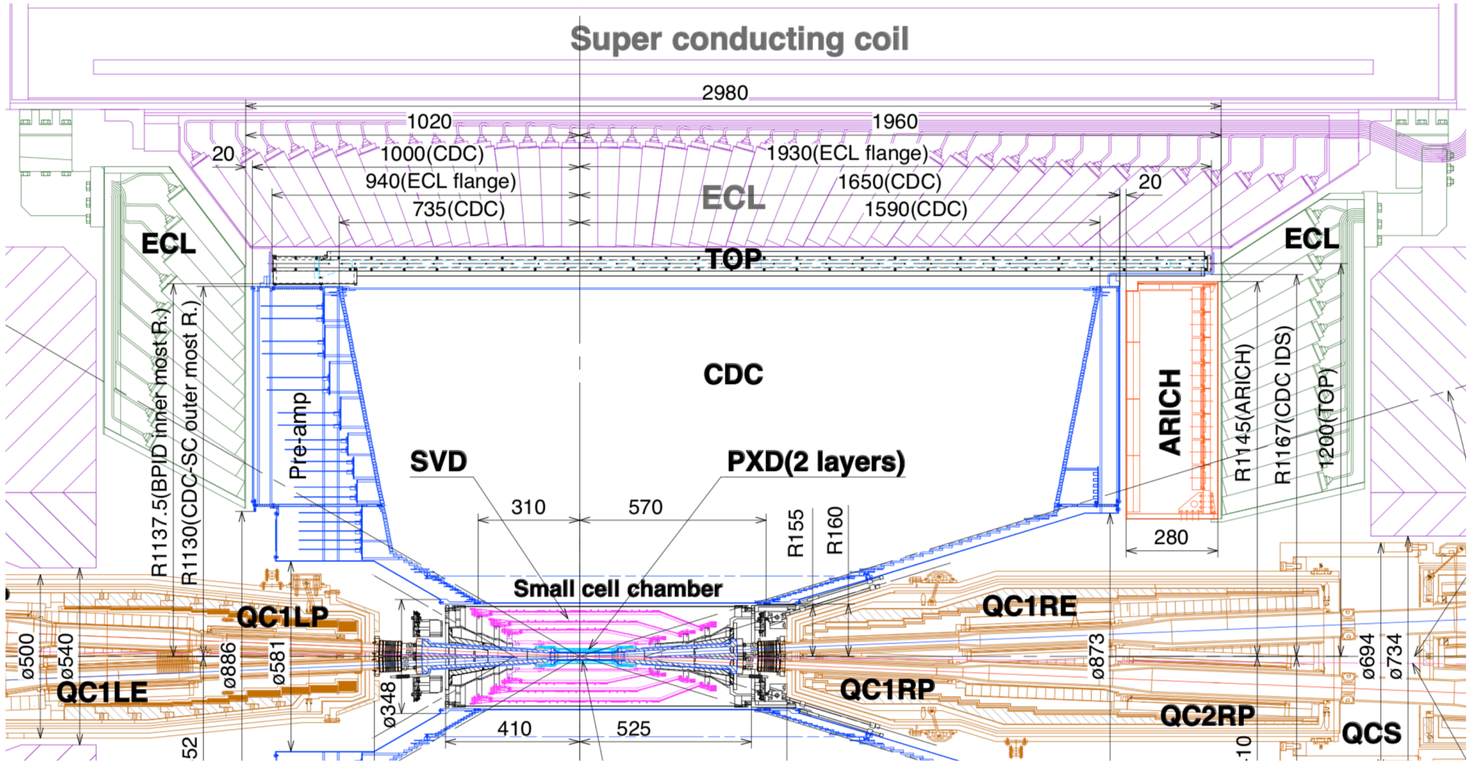
Irreducible background for mono-photon

Irreducible BG: $e^+e^- \to \gamma\nu\nu$

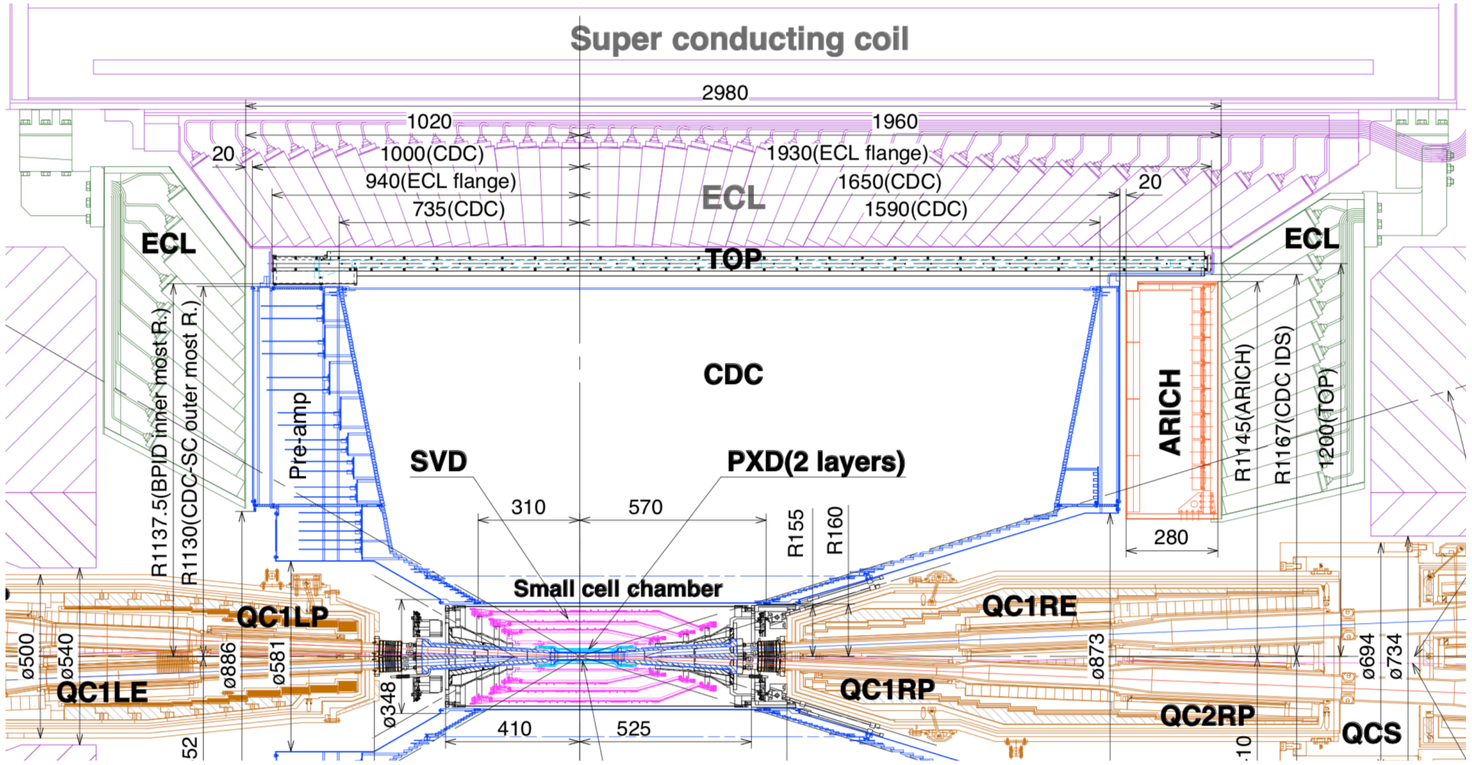


more challenging: reducible BG (due to limitations of the detectors)

Reducible background @ Belle II



Reducible background @ Belle II



ECL angles

(lab frame)

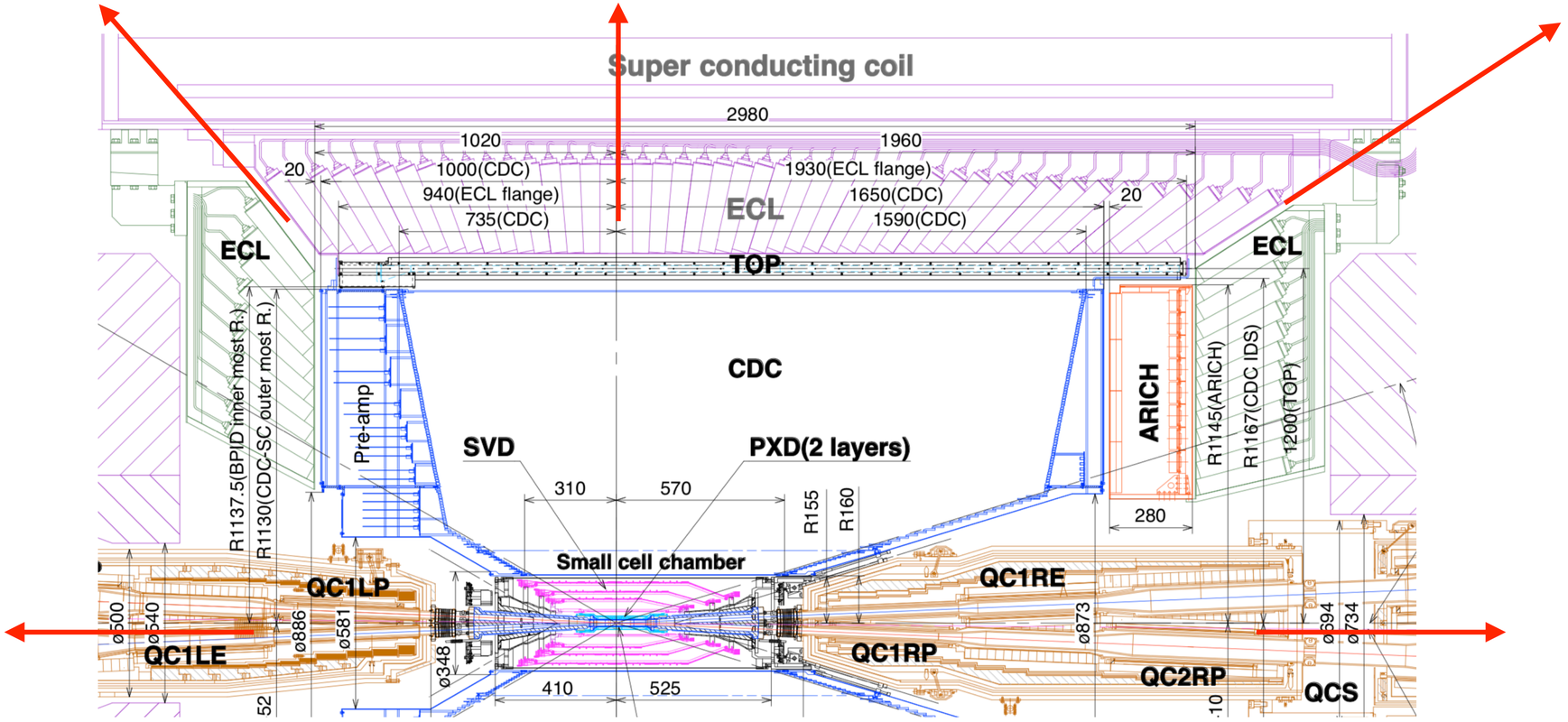
$12.4^\circ < \theta < 31.4^\circ$

$32.2^\circ < \theta < 128.7^\circ$

$130.7^\circ < \theta < 155.1^\circ$

[Belle II 1808.10567]

Reducible background @ Belle II



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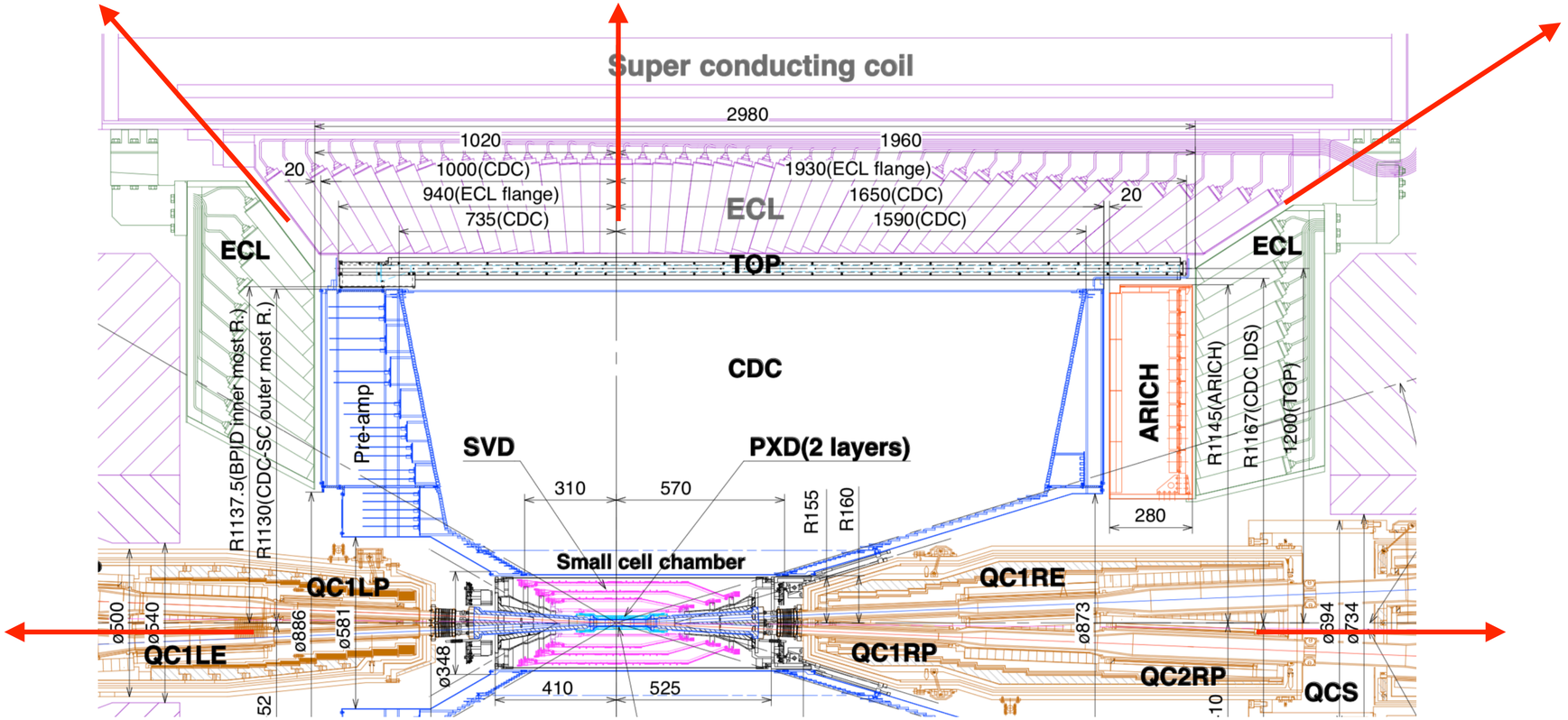
Reducible background @ Belle II



ECL angles

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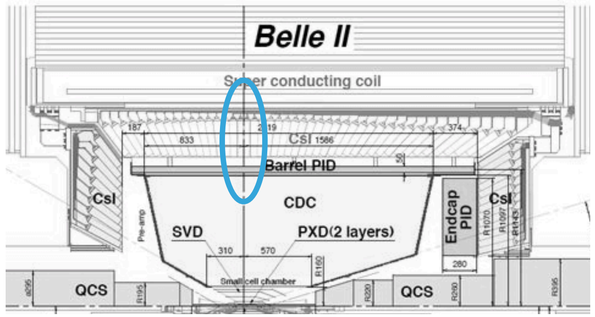
[Belle II 1808.10567]

reducible BG

- BG due to ECL gaps (gBG)
- BG due to beam (bBG)

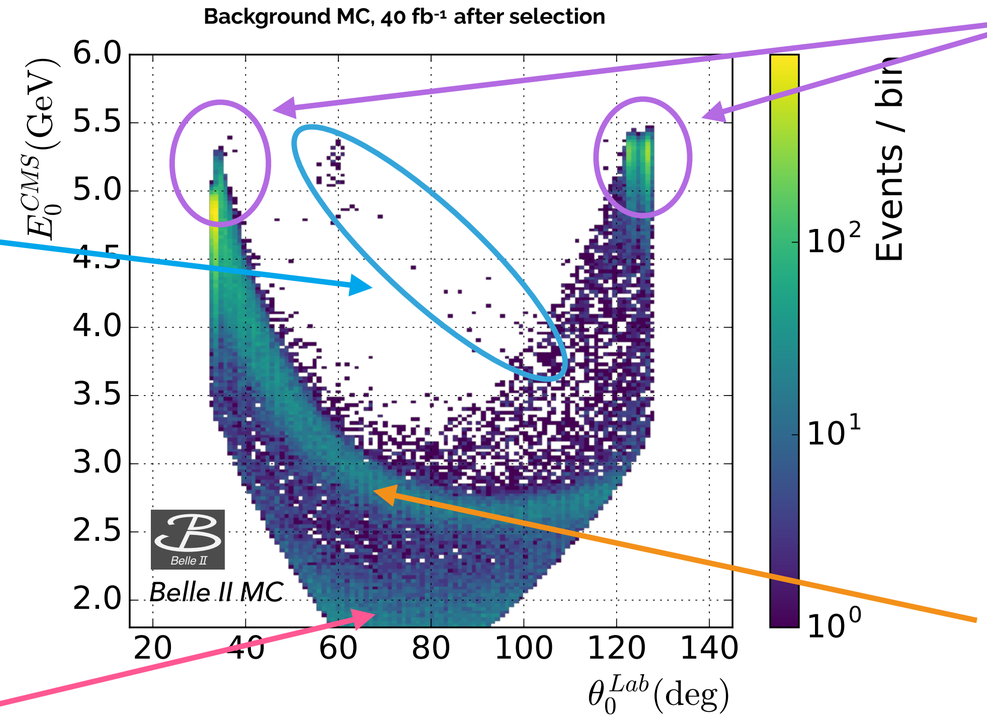
[from Ferber's talk]

B: Invisible Dark Photon searches

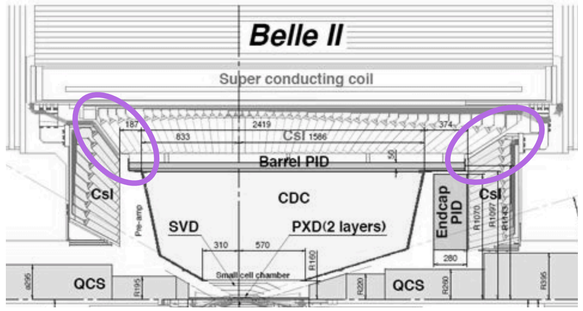


ee→2γ and 3γ
1γ in ECL 90° gap
1γ out of ECL acceptance

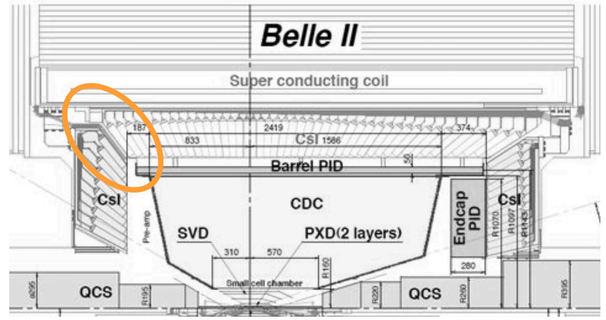
$$E_\gamma = \frac{s - M_{A'}^2}{2\sqrt{s}}$$



ee→eeγ
both electrons
out of tracking acceptance



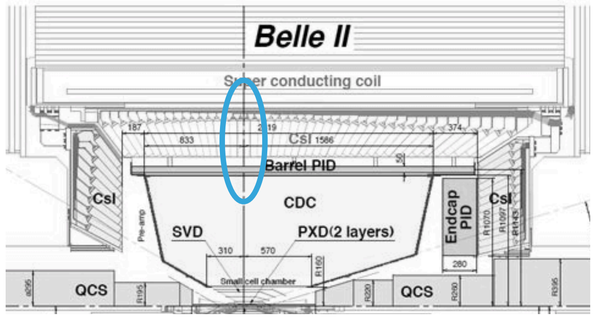
ee→2γ
1γ in ECL BWD or FWD gap



ee→3γ
1γ in ECL BWD gap
1γ out of ECL acceptance

[from Ferber's talk]

B: Invisible Dark Photon searches



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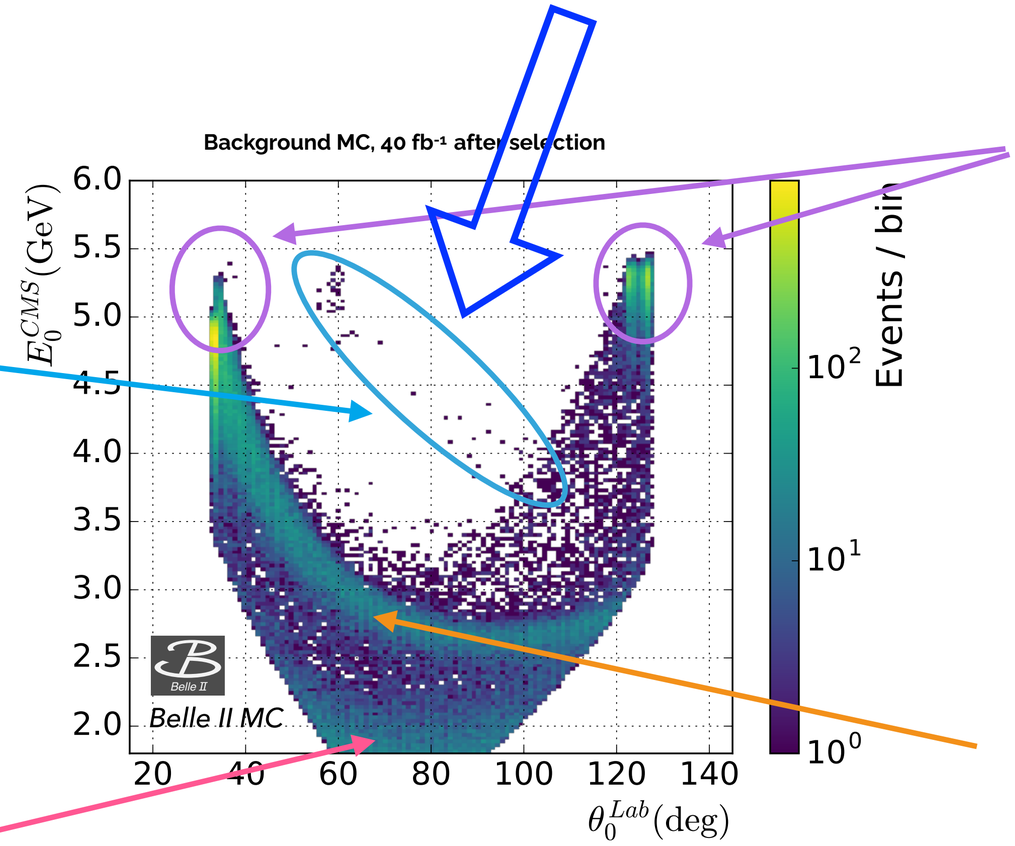
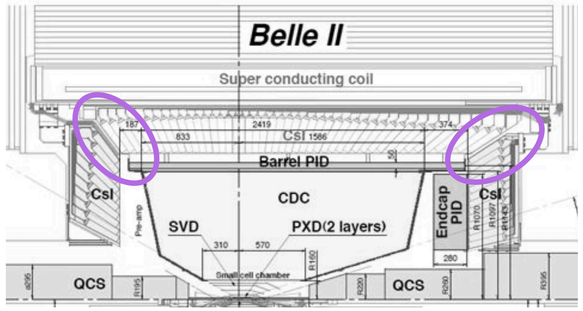
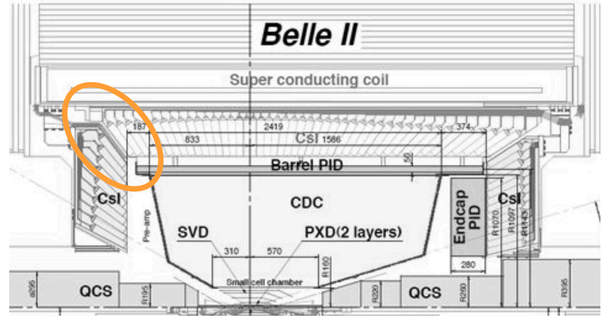
$$E_\gamma = \frac{s - M_{A'}^2}{2\sqrt{s}}$$





ee→2γ
1γ in ECL BWD or FWD gap



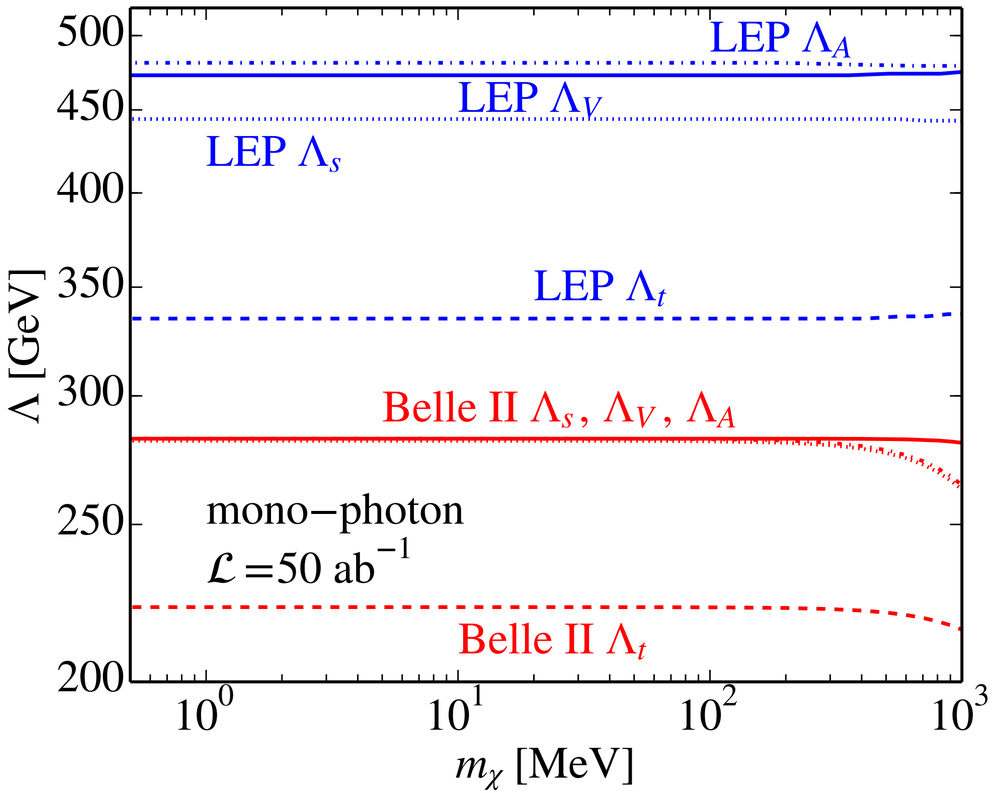
ee→3γ
1γ in ECL BWD gap
1γ out of ECL acceptance

ee→eeγ
both electrons
out of tracking acceptance

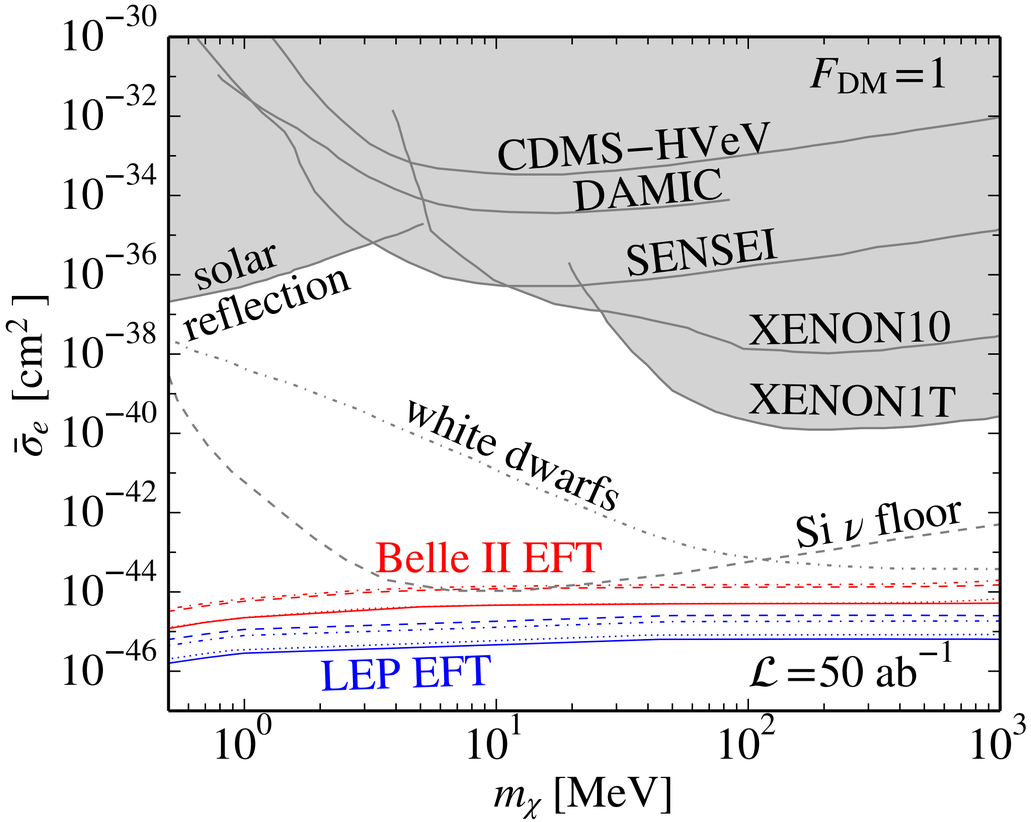
EFT DM probed by Belle II (50/ab)

[Liang, ZL, Yang, 2111.15533]

LEP is better than Belle II for EFT-DM



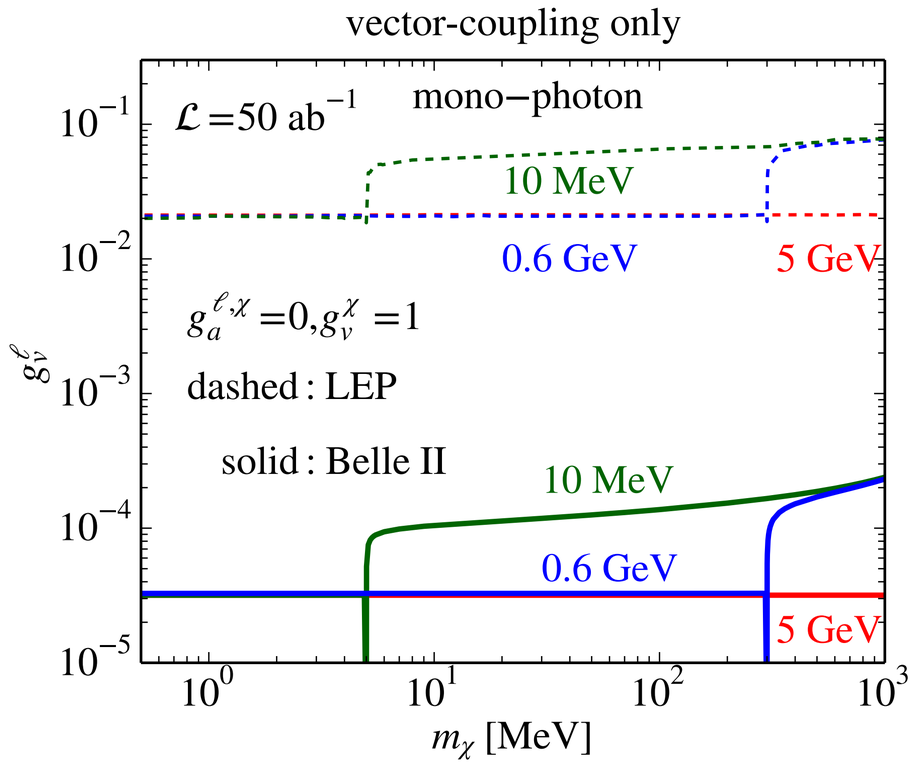
Electron colliders are better than DMDD



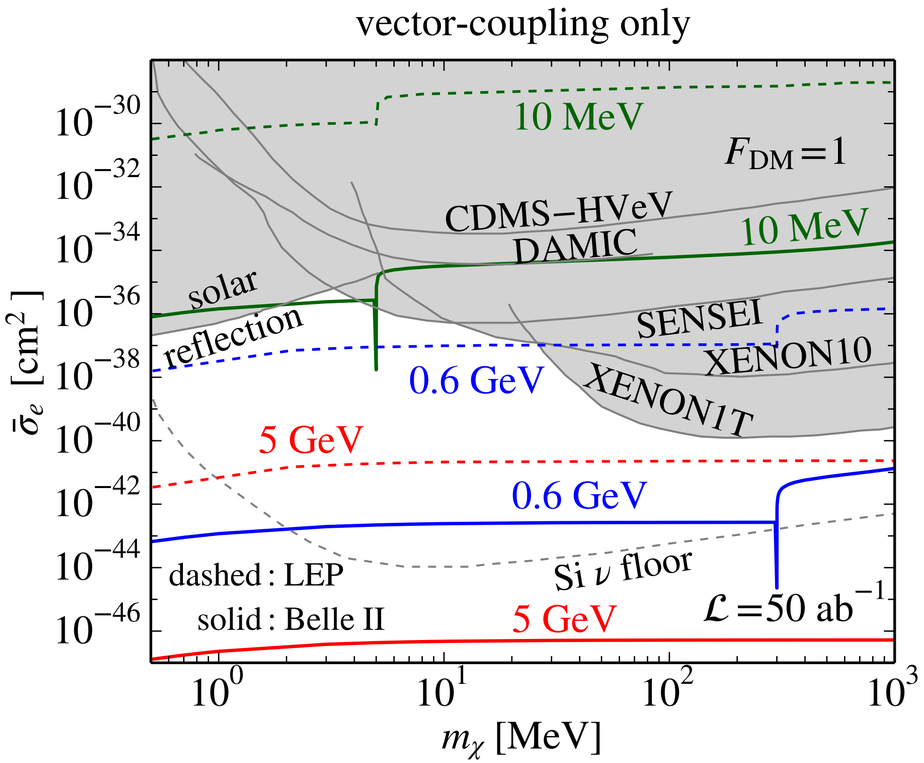
$$\frac{1}{\Lambda_V^2}\bar{\chi}\gamma_\mu\chi\bar{\ell}\gamma^\mu\ell$$

Light mediator DM probed by Belle II (50/ab) [2111.15533]

Belle II is better than LEP for light mediator DM



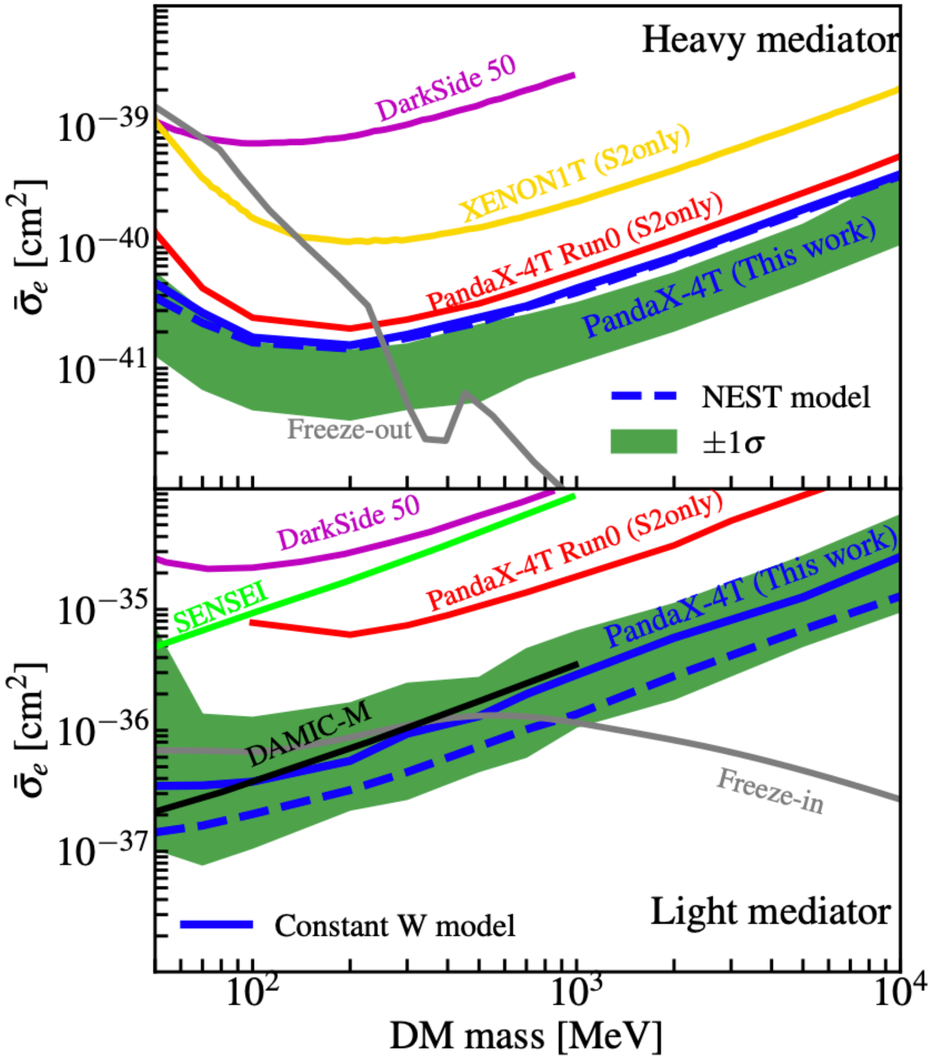
Electron colliders can be better than DMDD



$$Z'_\mu \bar{\chi}\gamma^\mu \left(g_v^\chi - g_a^\chi \gamma_5\right)\chi + Z'_\mu \bar{\ell}\gamma^\mu \left(g_v^\ell - g_a^\ell \gamma_5\right)\ell$$

$M_{Z'} =$ 5 GeV, 0.6 GeV, 10 MeV

PandaX-4T limits on light DM

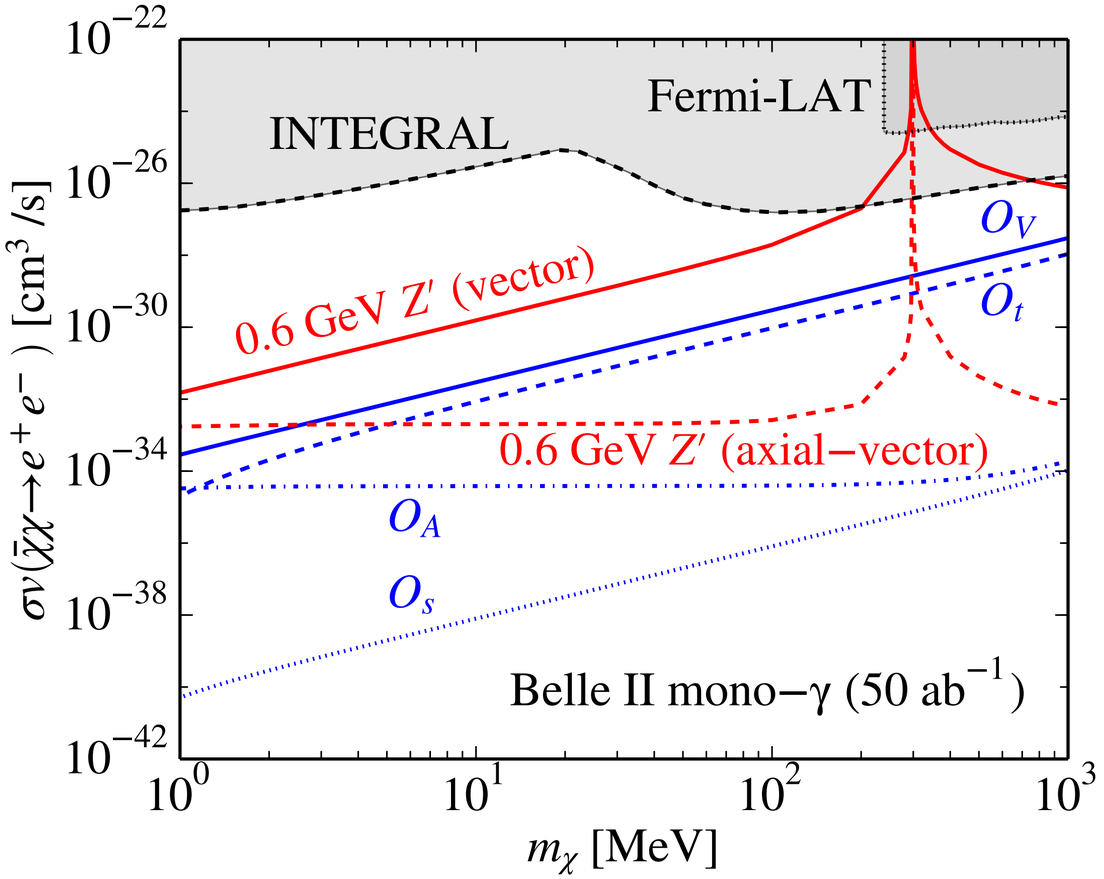


Search for Light Dark Matter with 259 Days of Data in PandaX-4T

[PandaX-4T, 2507.11930]

Belle II vs dark matter indirect detection experiments

Electron colliders can be better than DMID



Photons from DM annihilation

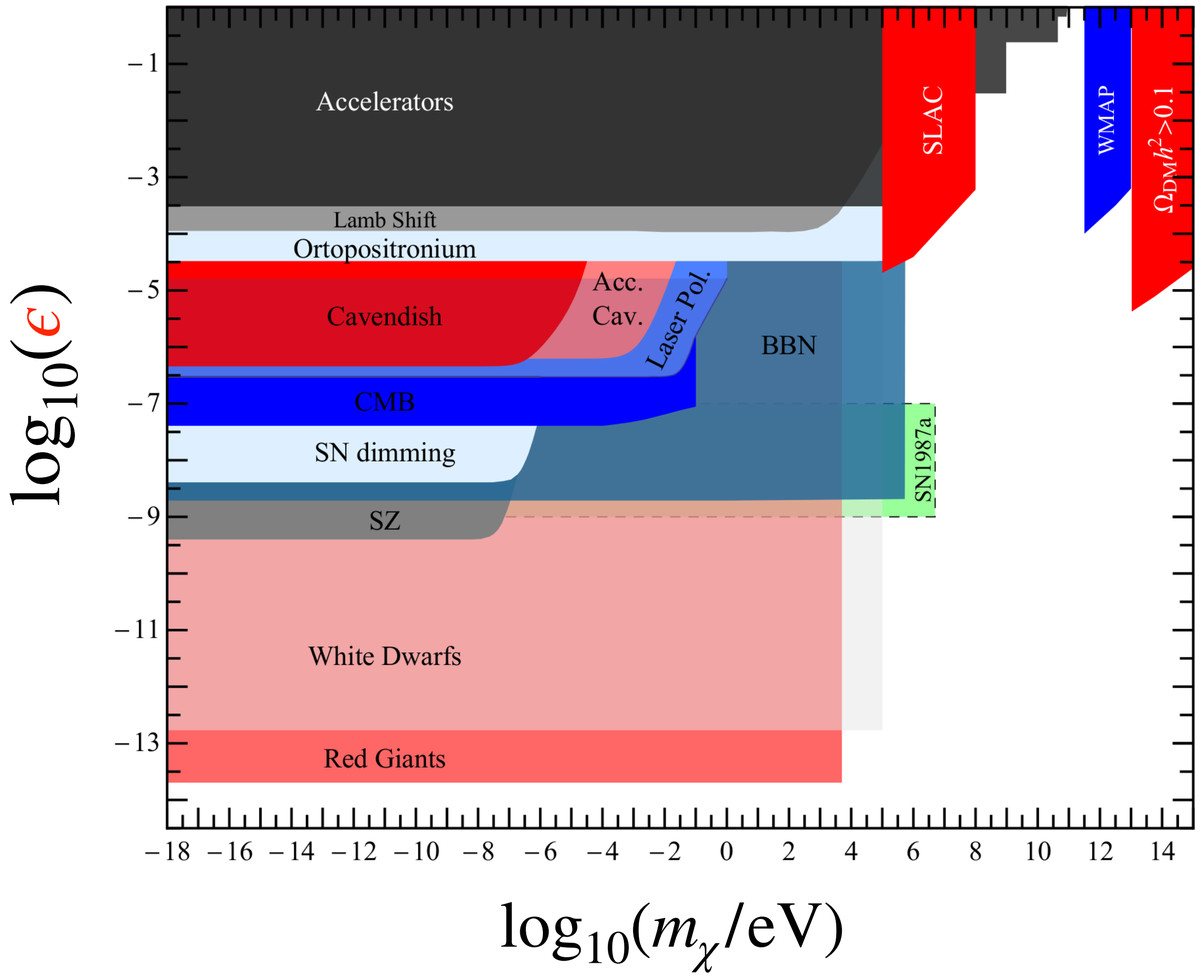
INTEGRAL

Fermi-LAT

[Liang, ZL, Yang, 2111.15533]

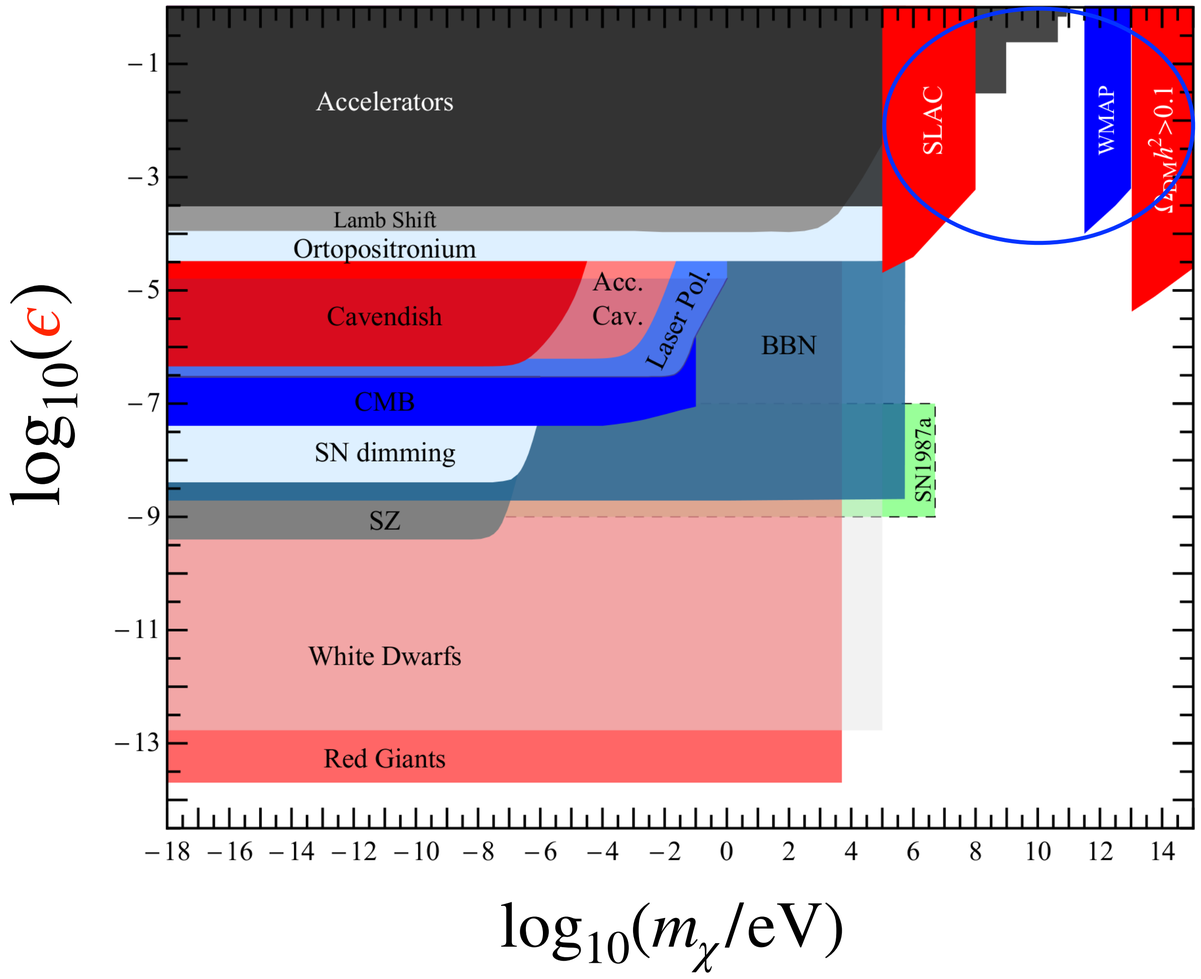
millicharged particles

Millicharge in BSM can be quite “large”



[Jaeckel, Ringwald, 1002.0329]

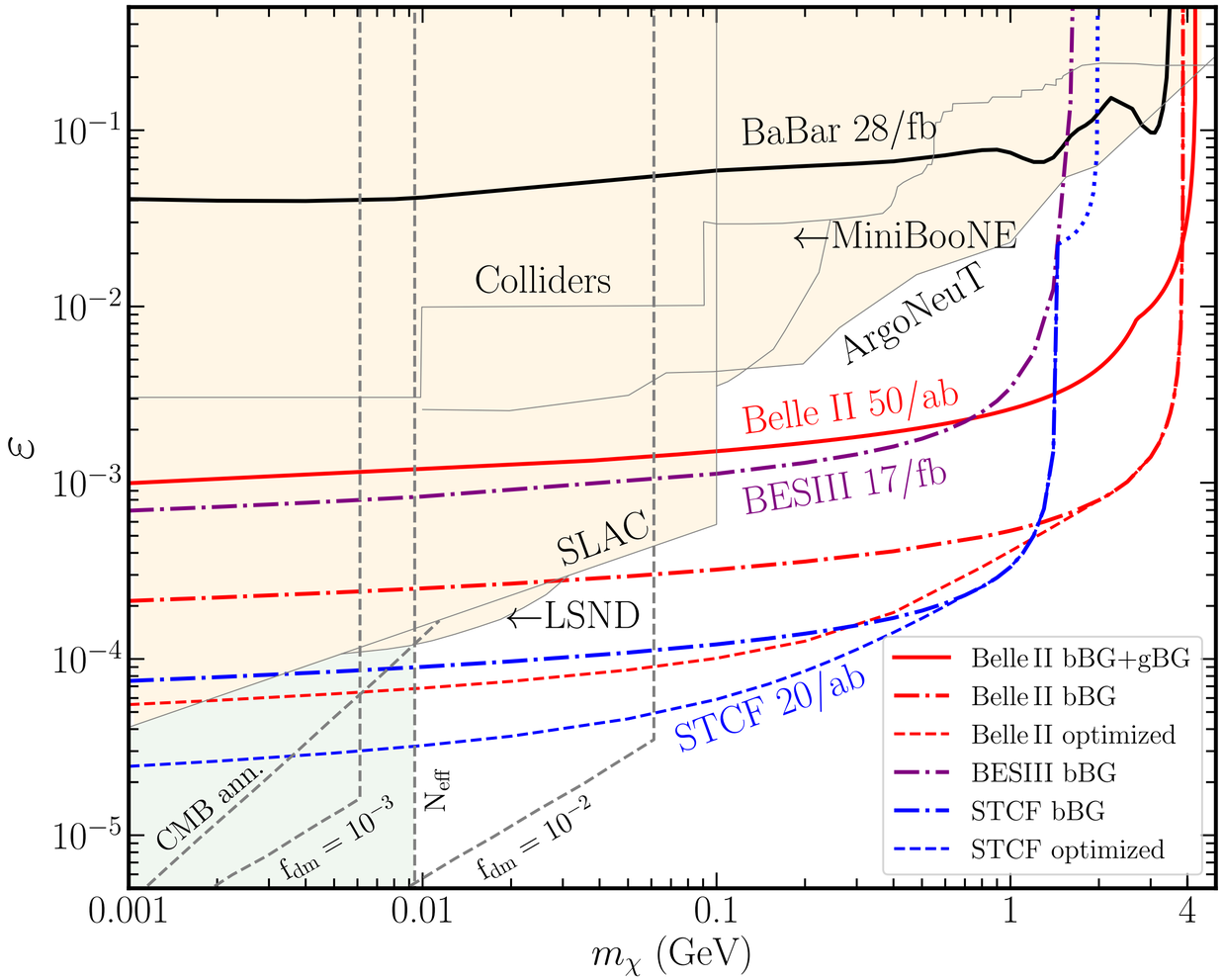
Millicharge in BSM can be quite “large”



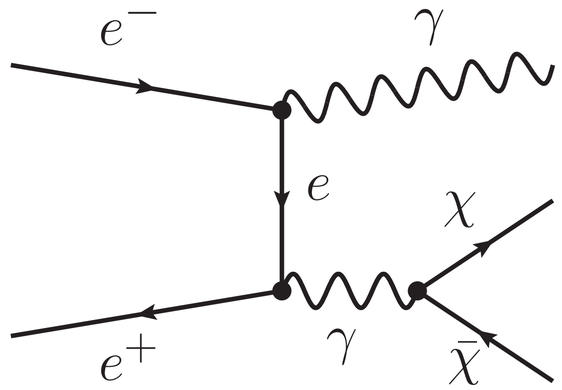
probed by e^+e^- colliders

[Jaeckel, Ringwald, 1002.0329]

Millicharged particles probed by electron colliders



mono-photon

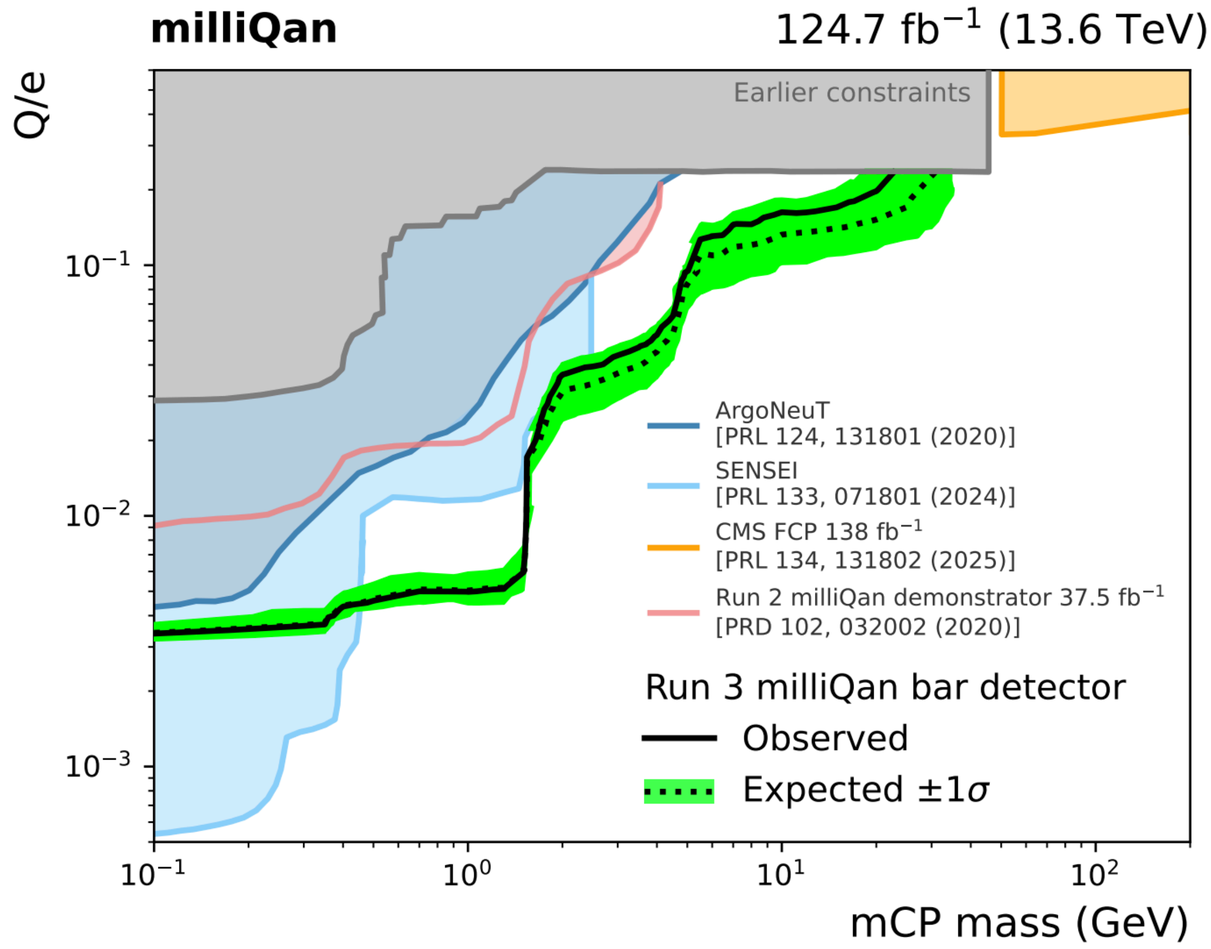


electron collider can probe new parameter space

[ZL, Zhang, 1808.00983]

[Liang, ZL, Ma, Zhang, 1909.06847]

Run 3 milliQan bar detector

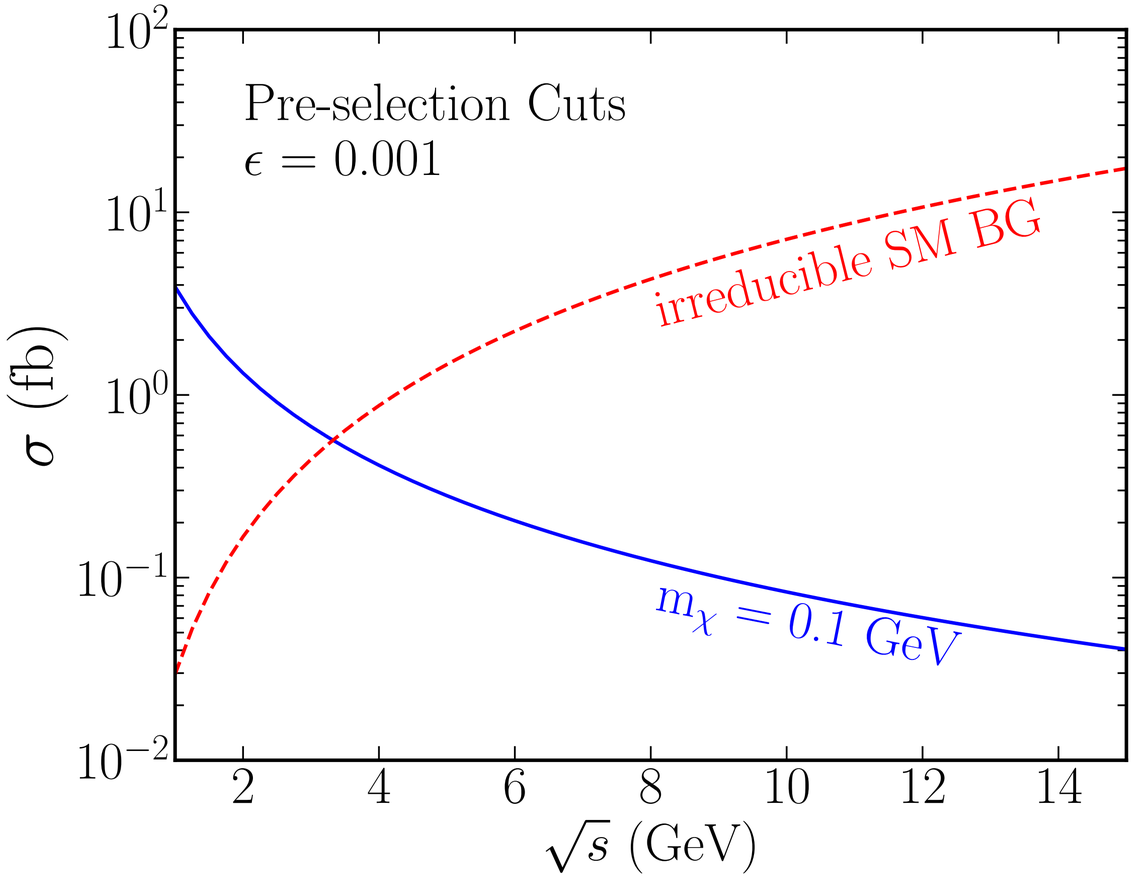


[2506.02251]

Low colliding energy is better to probe MCPs

if irreducible BG is the only important BG

BESIII/STCF vs Belle II



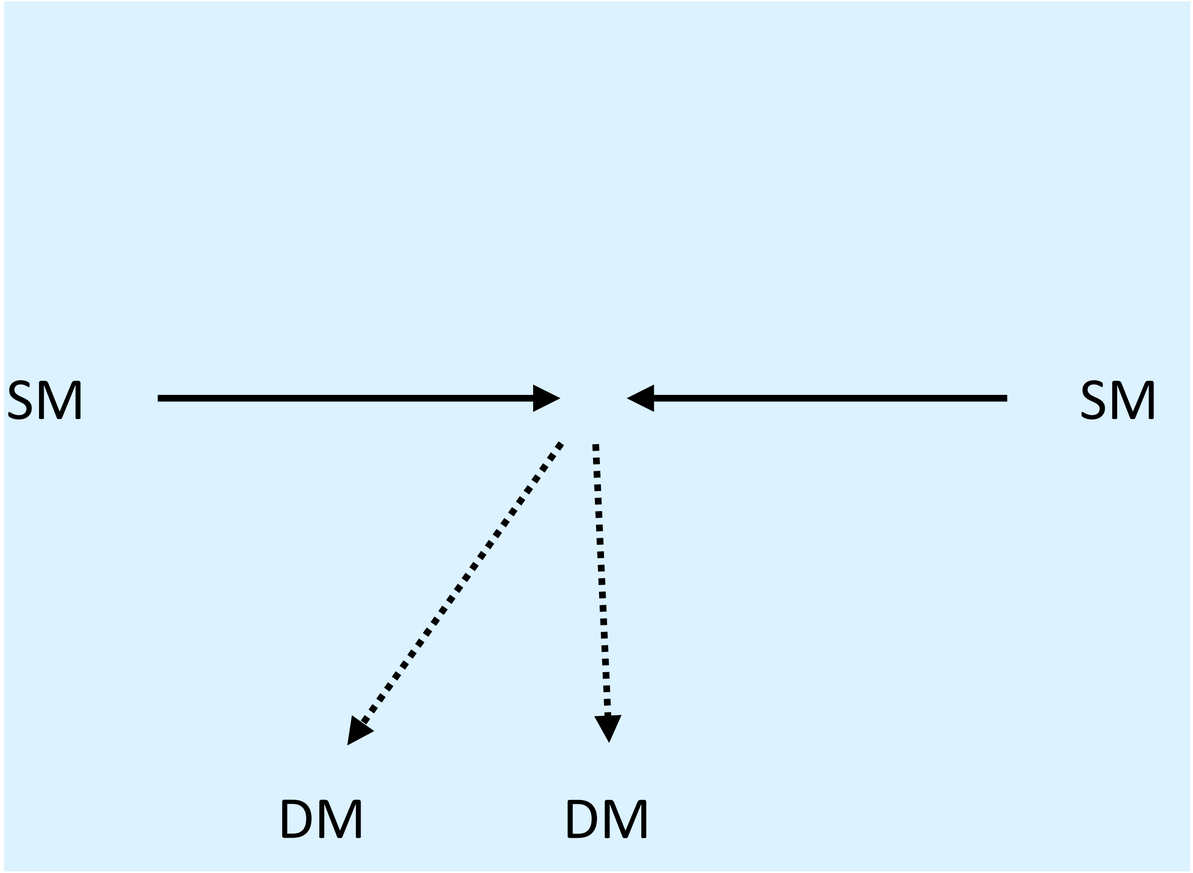
$e^+e^- \to \gamma\bar{\nu}\nu$

$e^+e^- \to \gamma\bar{\chi}\chi$

new dark matter detection channel at electron colliders

Previous dark matter detection channels at colliders

Most studies focus on mono-X channel with SM X produced at the primary vertex



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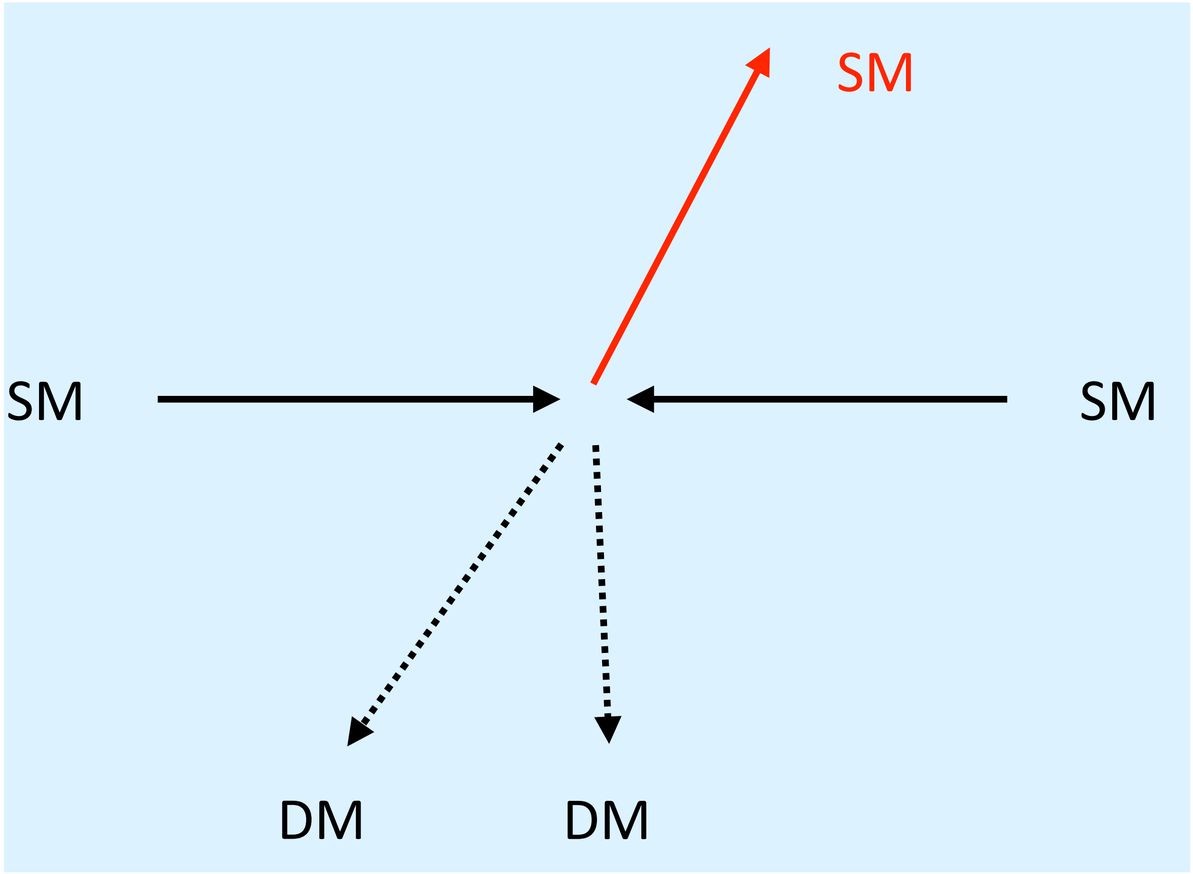
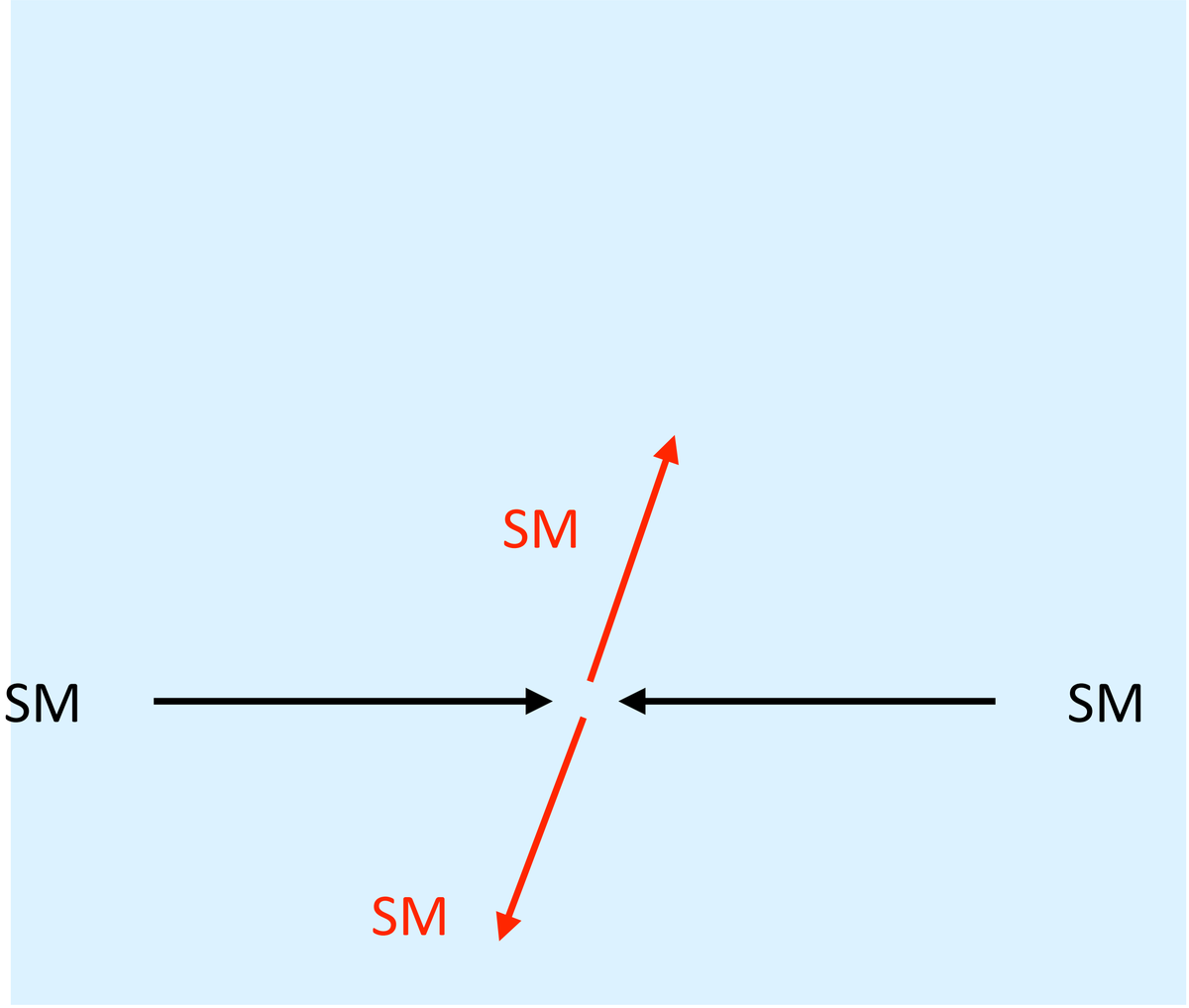
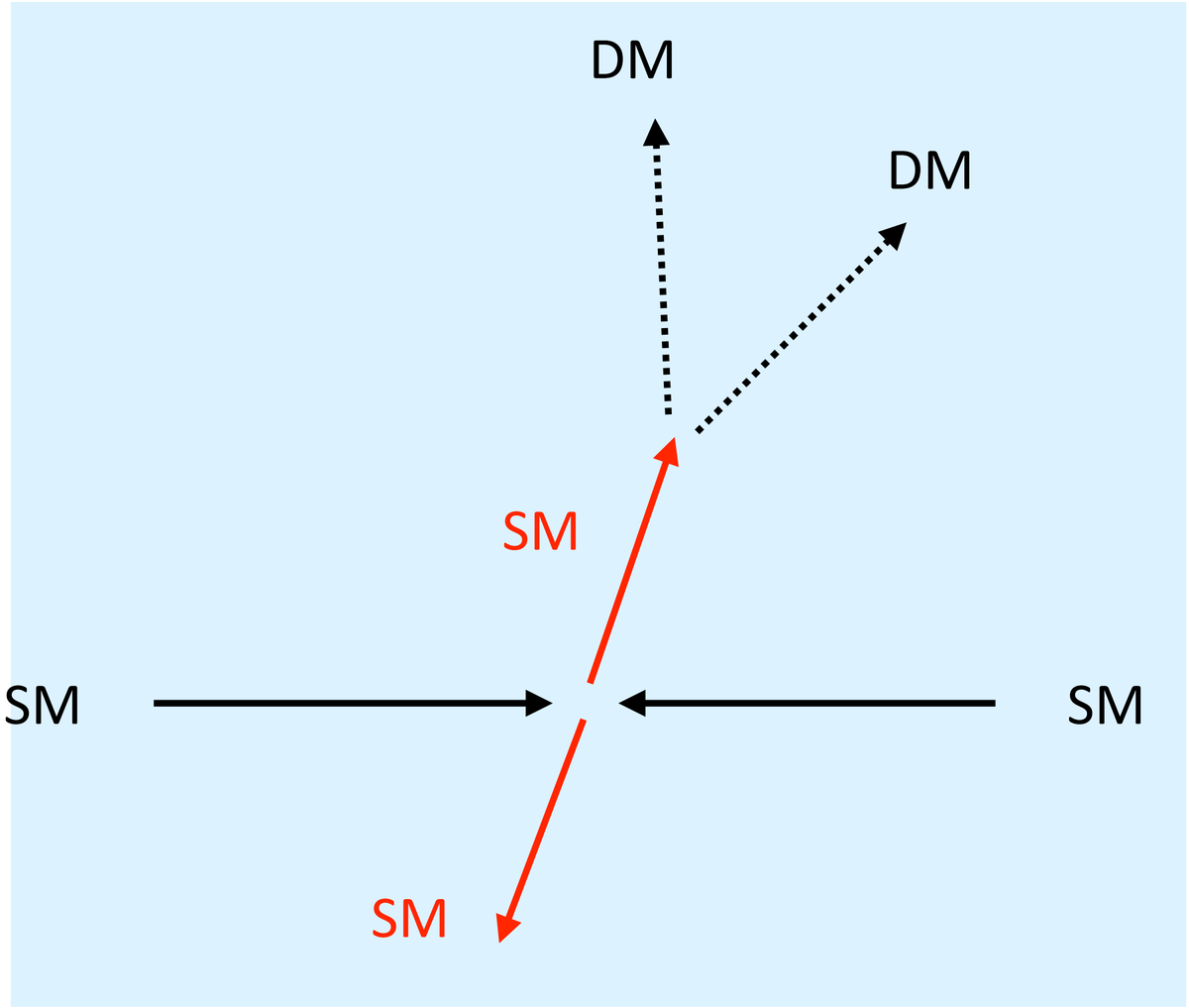


New dark matter channel at colliders



A pair of SM particles
produced at the primary vertex

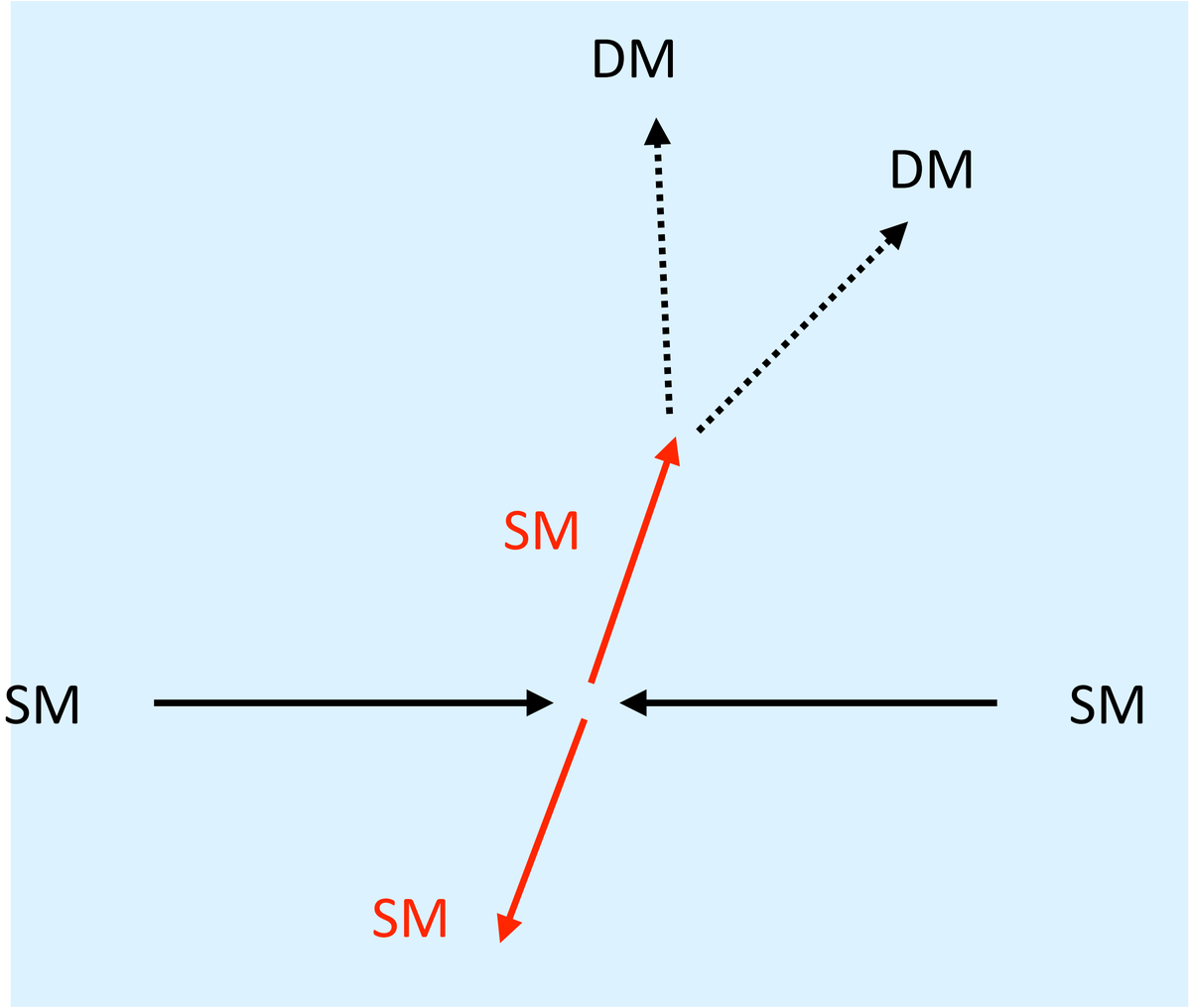
New dark matter channel at colliders



One SM particle interacts with the detector to produce a pair of DM particles

A pair of SM particles produced at the primary vertex

New dark matter channel at colliders

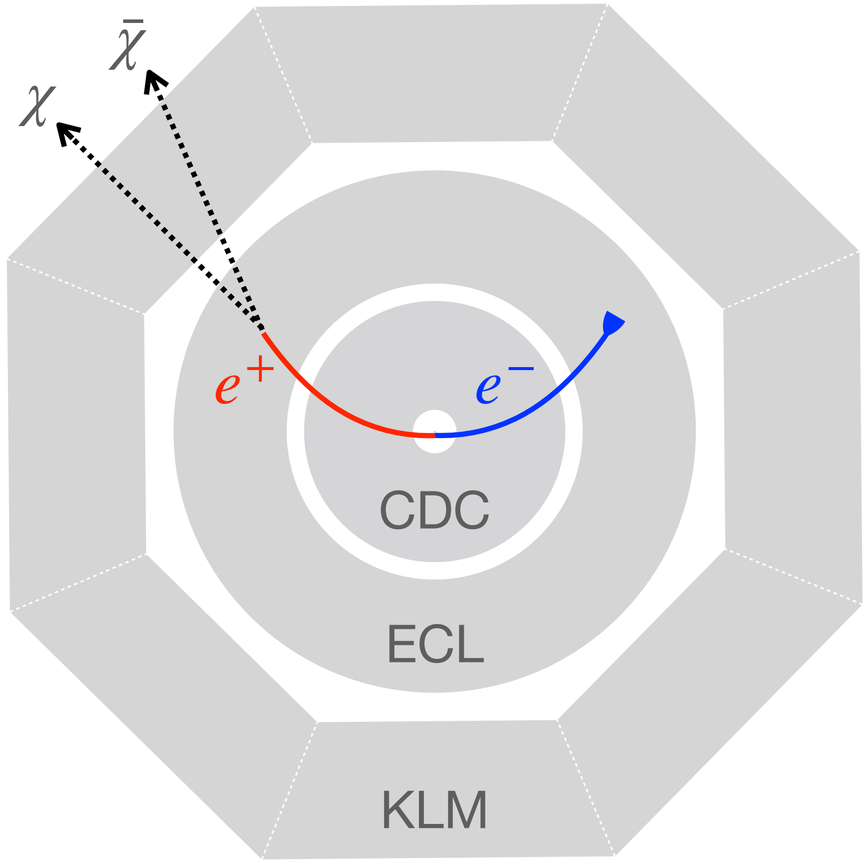


One SM particle interacts with the detector to produce a pair of DM particles

A pair of SM particles produced at the primary vertex

fixed target in collider

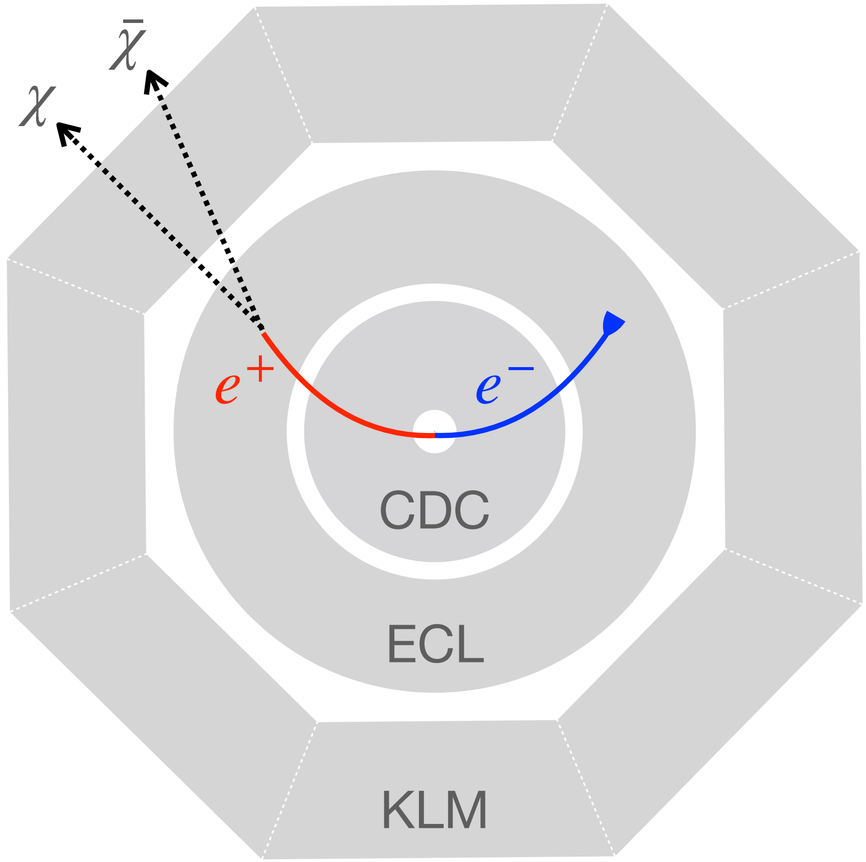
New dark matter channel @ electron colliders



[Liang, ZL, Yang, 2212.04252]

- $e^+e^- \to e^+e^-$
- e^- deposit energy in ECL
- e^+ interact with ECL to produce DM
- signature: e^-, e^+, and missing energy (<5% e^+ energy deposited in ECL)

New dark matter channel @ electron colliders

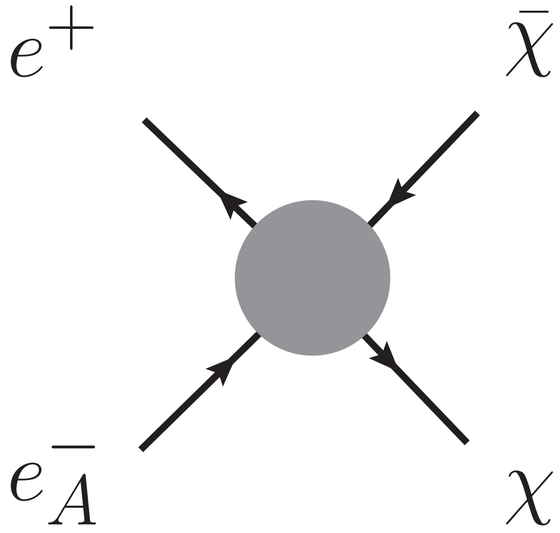


[Liang, ZL, Yang, 2212.04252]

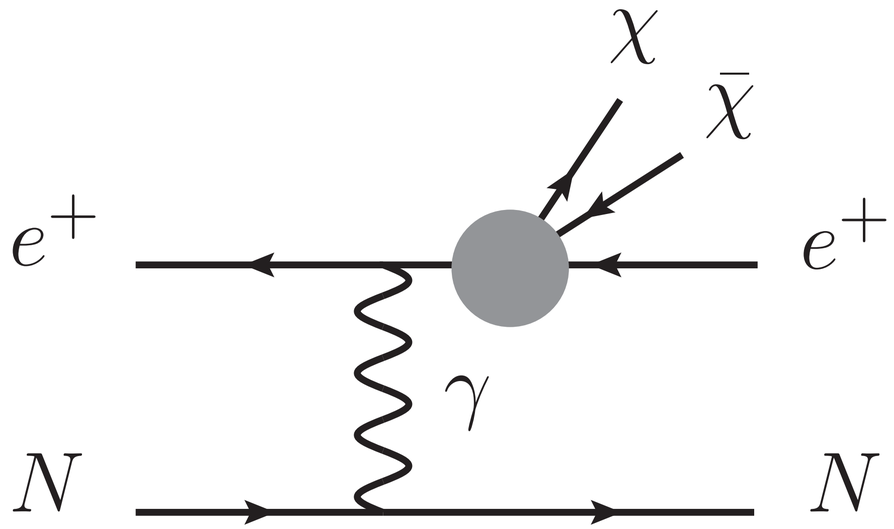
- $e^+e^- \to e^+e^-$
- e^- deposit energy in ECL
- e^+ interact with ECL to produce DM
- signature: e^-, e^+, and missing energy (<5% e^+ energy deposited in ECL)

disappearing positron track

Positron interaction with ECL



annihilation w/
atomic electron



bremsstrahlung w/
target nucleus

[Liang, ZL, Yang, 2212.04252]

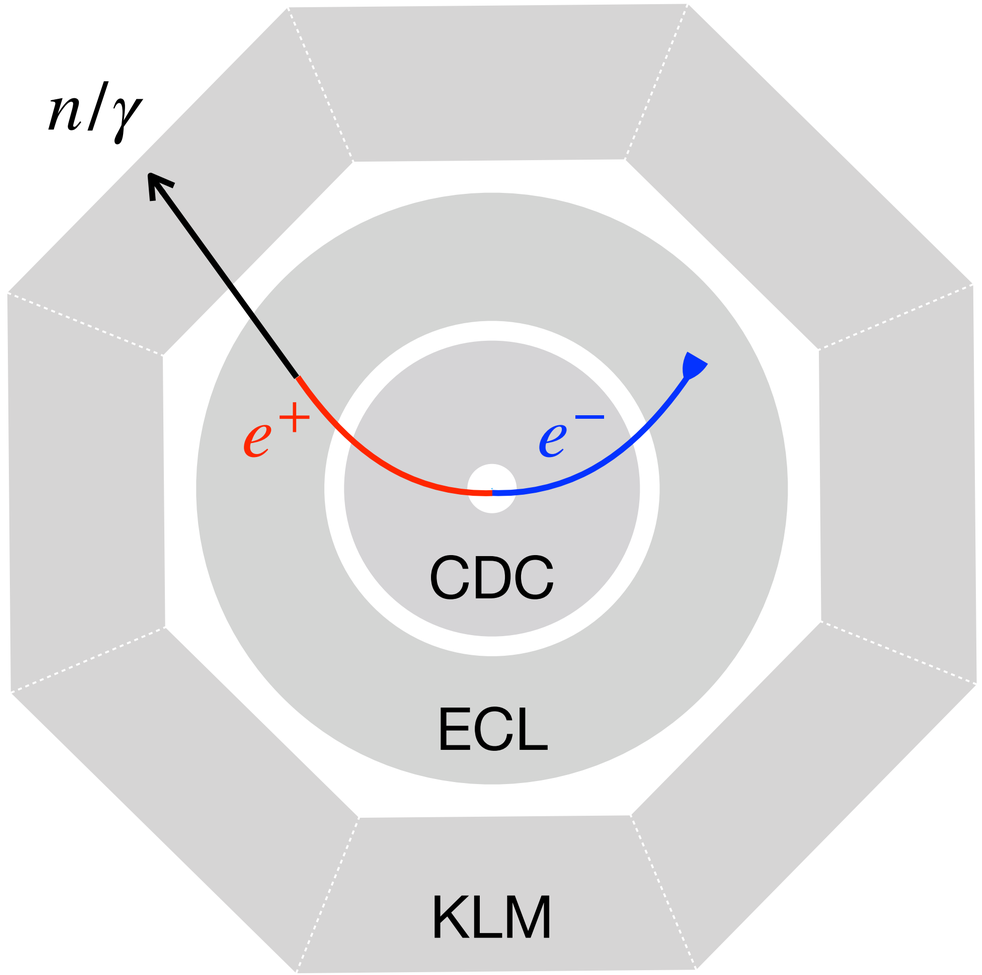
Background estimation

BG: e^+ + ECL $\rightarrow \gamma/n$ which escape detection

Use KLM to veto such BG

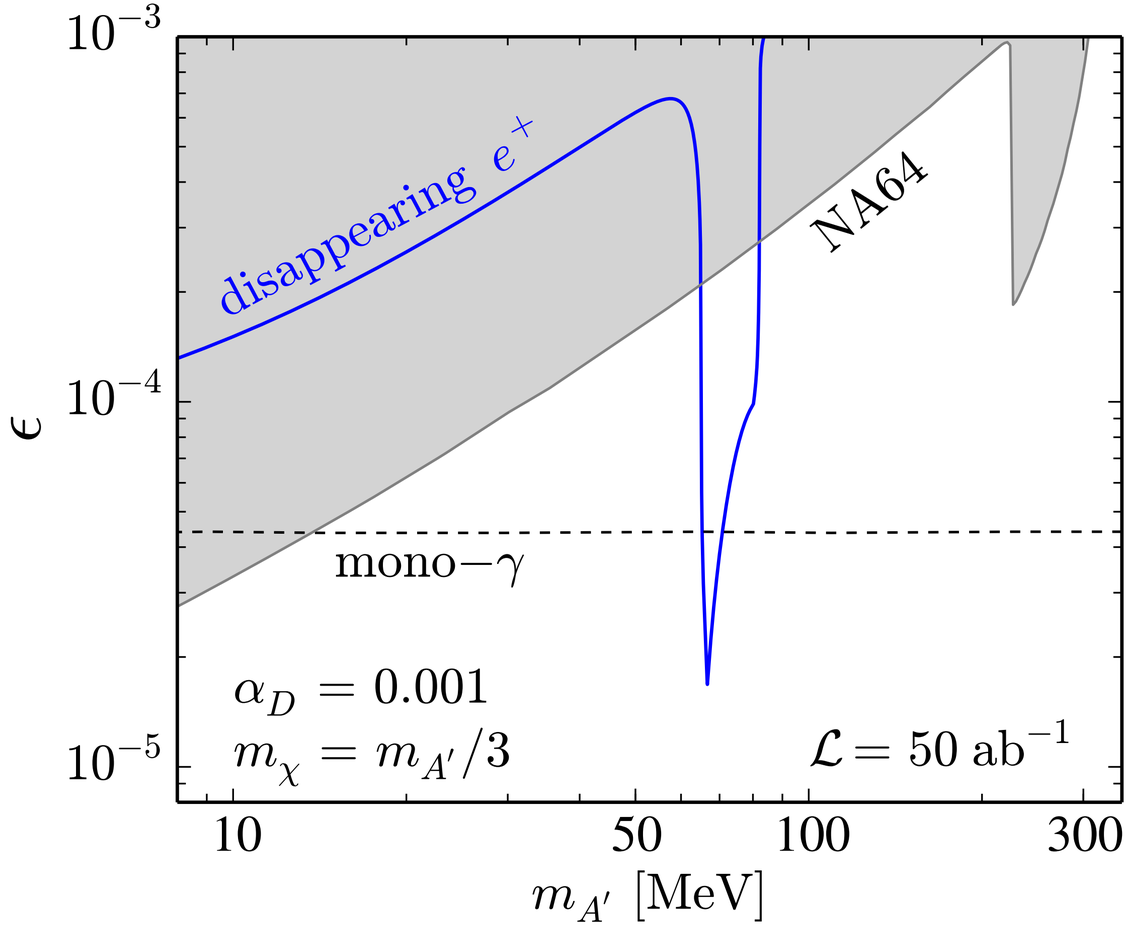
- photon BG events: ~ 13
- neutron BG events: ~ 81

[Liang, ZL, Yang, 2212.04252]



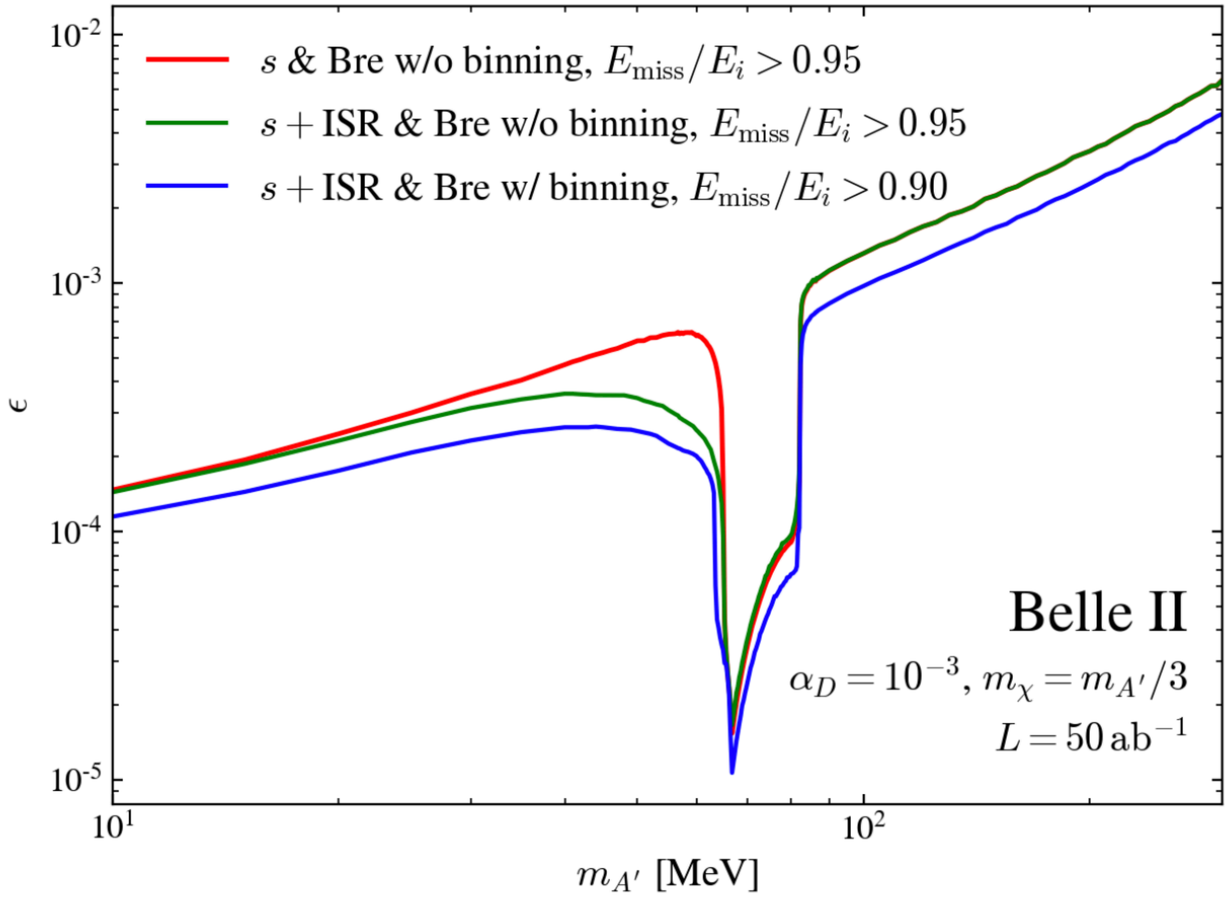
Belle II sensitivity on invisible dark photon

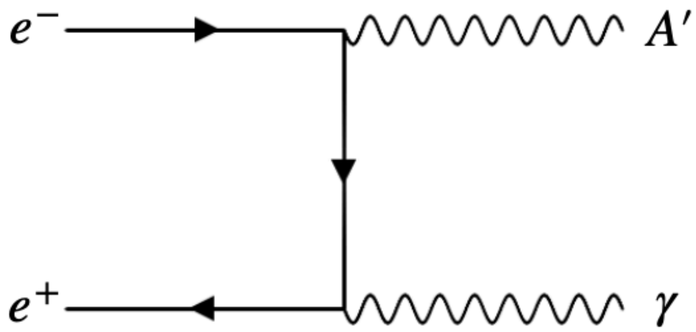
[Liang, ZL, Yang, 2212.04252]



Belle II sensitivity with ISR included

[Shao-Feng Ge, Jinhan Liang, ZL, Ui Min, 2505.10302]





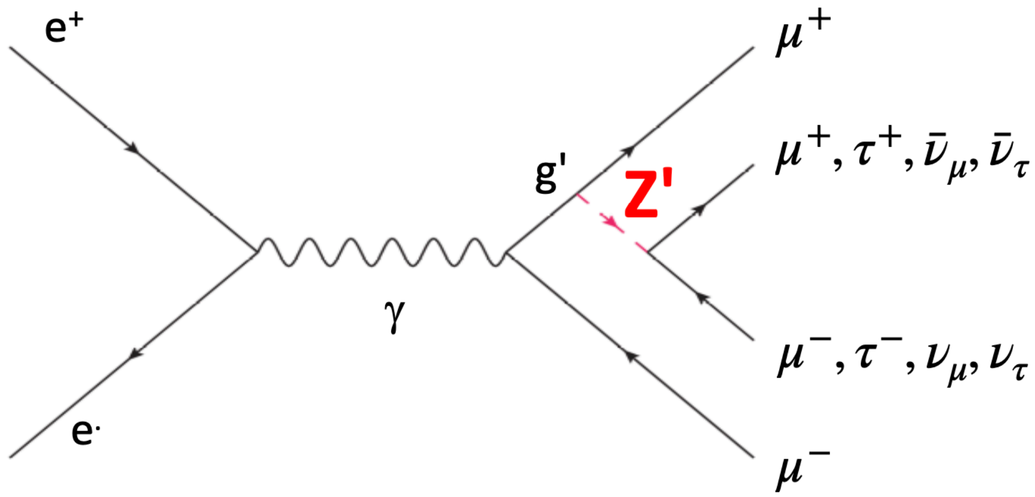
3 Leptophilic gauge boson

Anomaly free extension to the standard model

Gauged lepton flavor $L_i - L_j$ are anomaly free extensions of the standard model

[Xiao-Gang He, Girish C. Joshi, H. Lew, R.R. Volkas, Phys.Rev.D 44 (1991) 2118-2132]

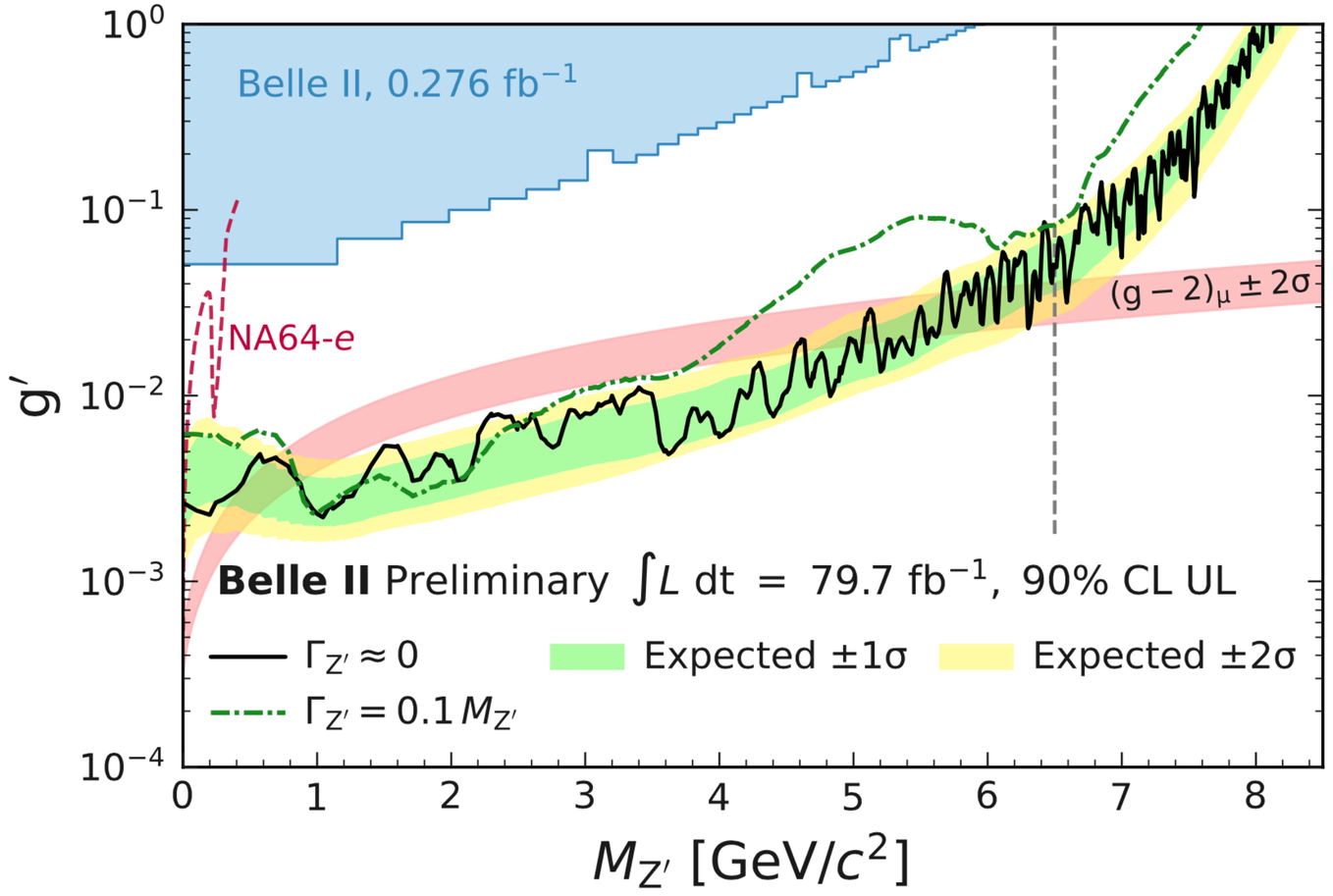
signature @ electron colliders



from Hearty's talk

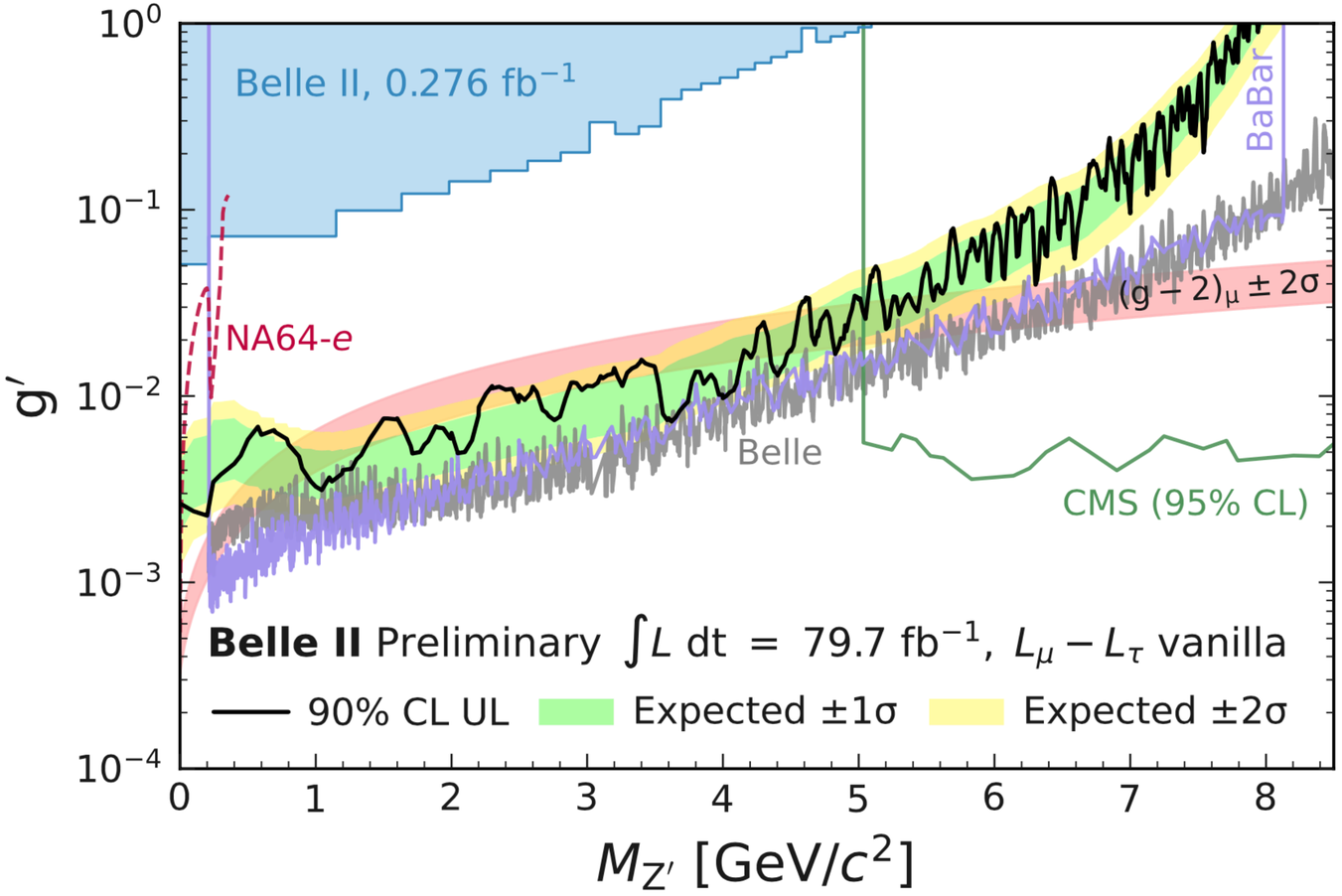
Belle II constraints on fully-invisible $L_\mu - L_\tau$ boson Z'

$\mu\mu$ + miss



Belle-II, 2212.03066

Belle II constraints on vanilla $L_\mu - L_\tau$ boson Z'



Belle-II, 2212.03066

$\mu\mu$ + miss

vanilla: only couple to SM fermions

invisible decay:
- Belle II
- NA64-e

decay to muons:
- Belle
- BaBar
- CMS

4 axion & axion-like particles

Axion & axion-like particles

Axion is proposed as a solution to the strong CP problem (QCD axion)

[Peccei & Quinn 1977]

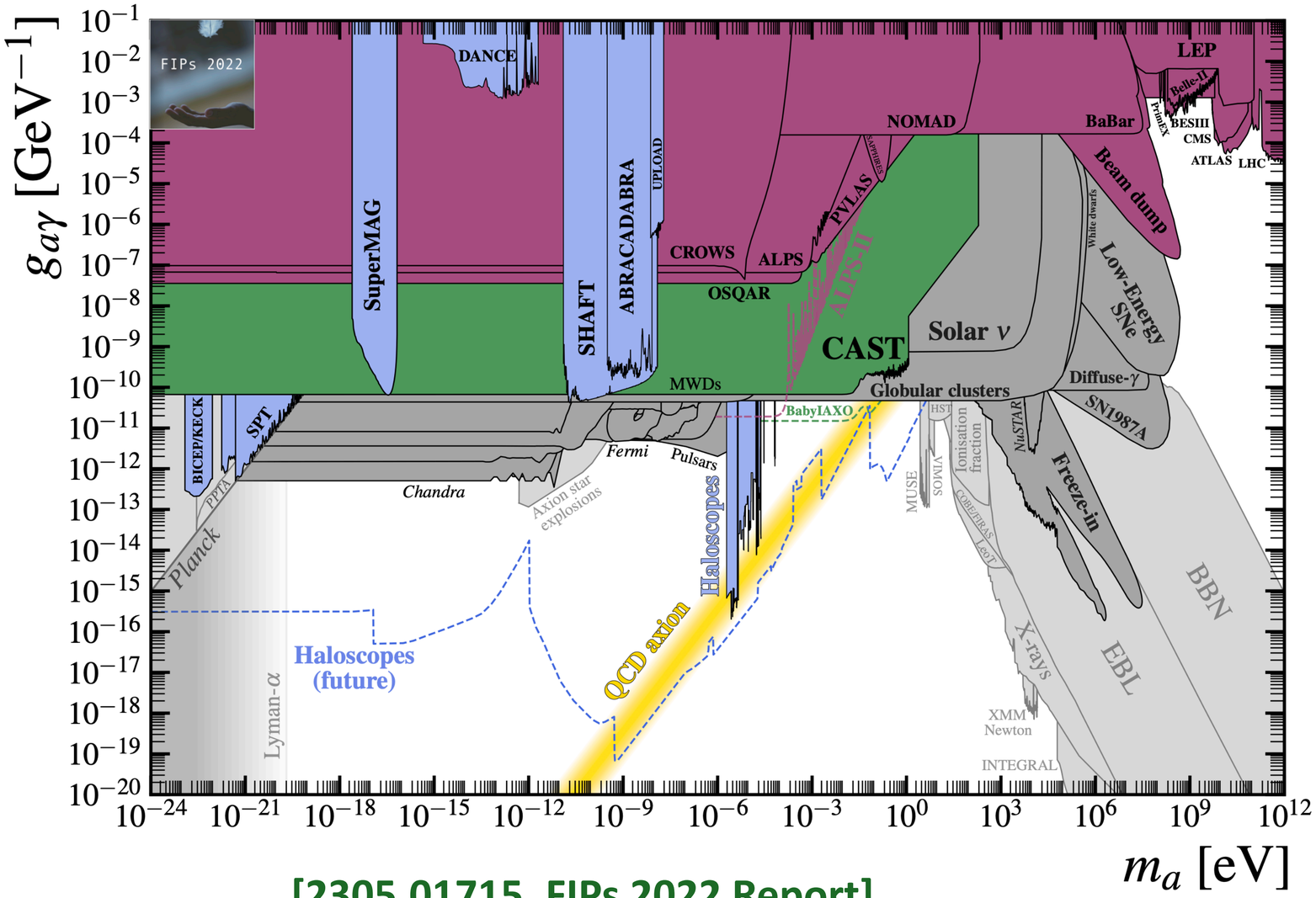
Axion-like particles (ALPs) appears in many beyond-the-standard-model theories.

[see e.g. Ringwald 1210.5081]

$$\mathscr{L}_{\text{int}} = -\frac{1}{4} g_{a\gamma\gamma} F^{\mu\nu} \tilde{F}_{\mu\nu}\, a = g_{a\gamma\gamma} \mathbf{E} \cdot \mathbf{B}\, a$$

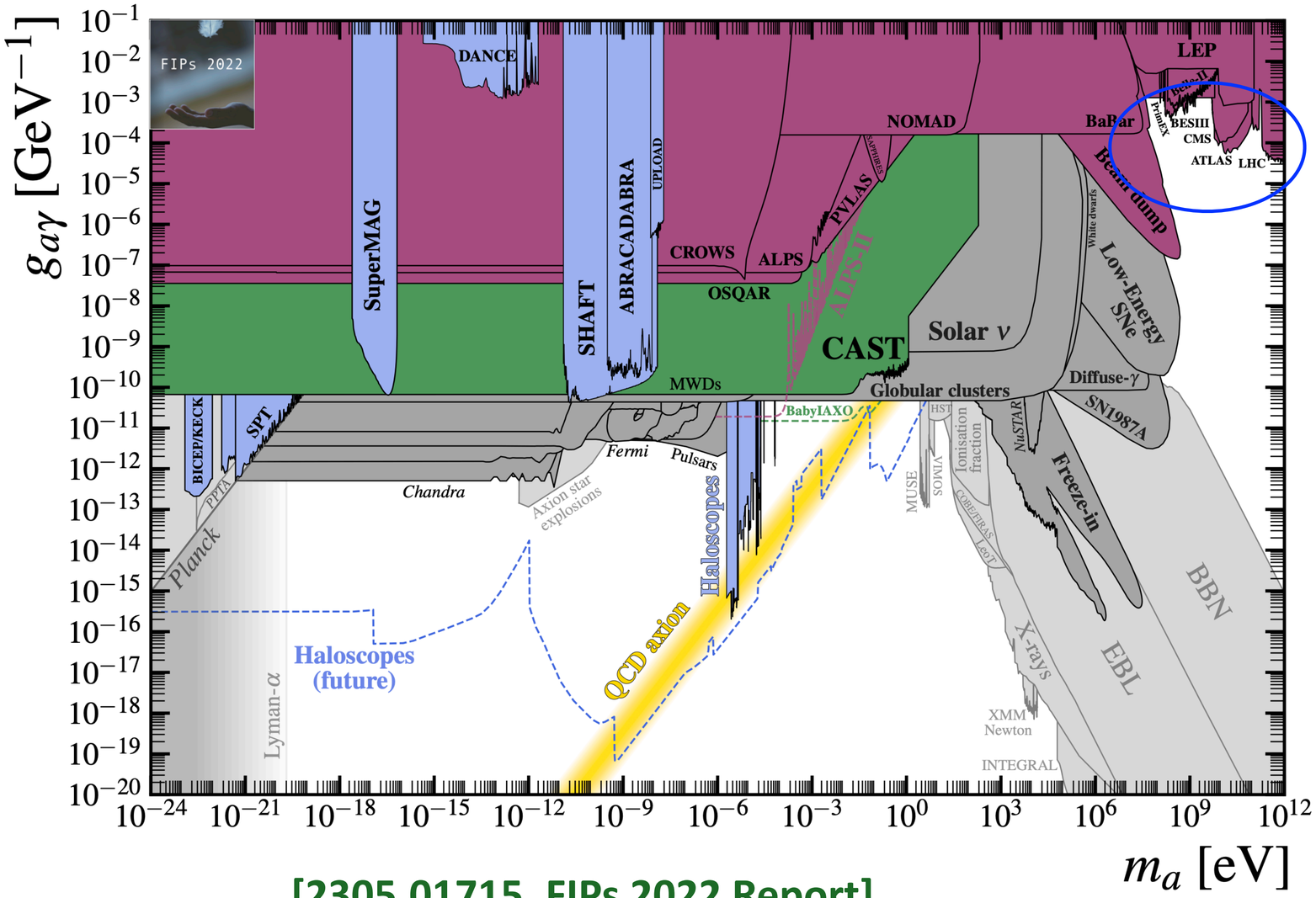
axion-photon couplings

Constraints on axion-photon coupling



[2305.01715, FIPs 2022 Report]

Constraints on axion-photon coupling

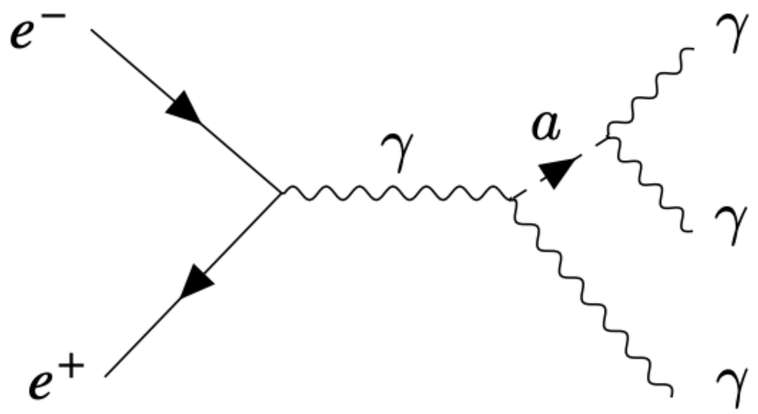


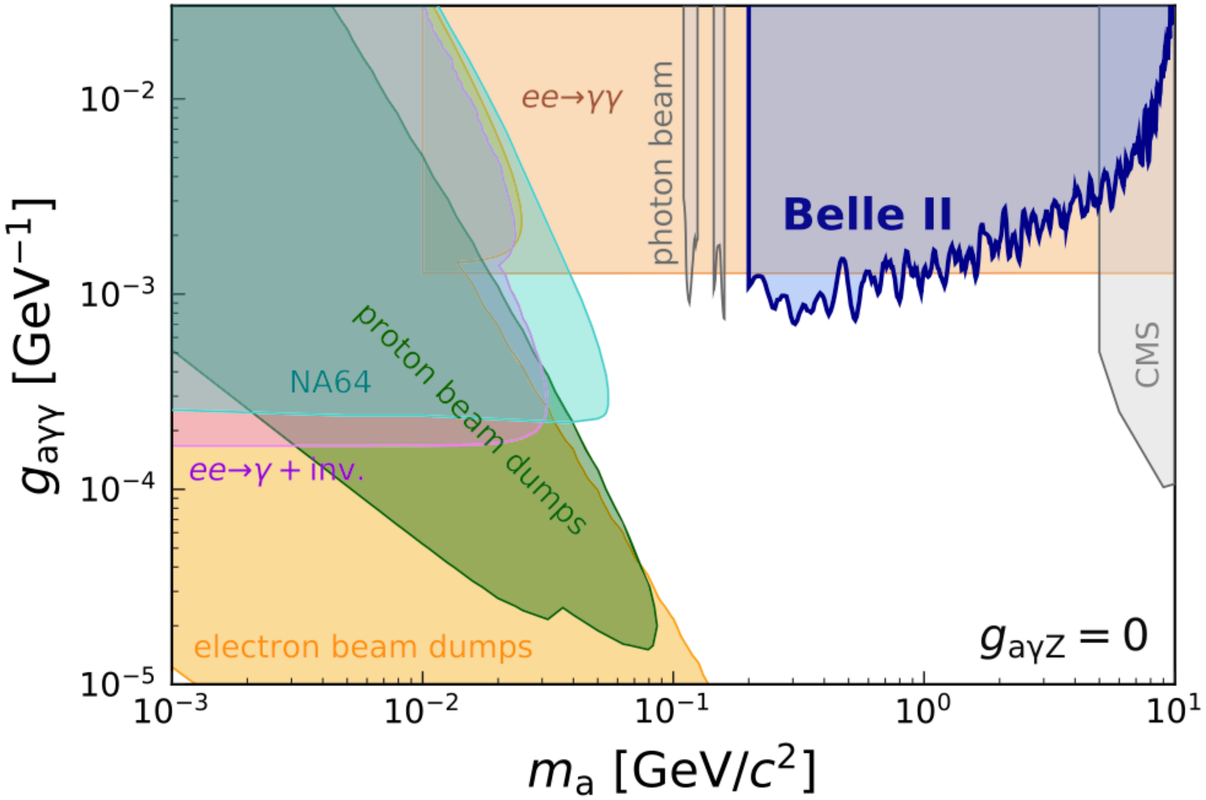
probed by e^+e^- colliders

[2305.01715, FIPs 2022 Report]

Belle II limits on ALPs

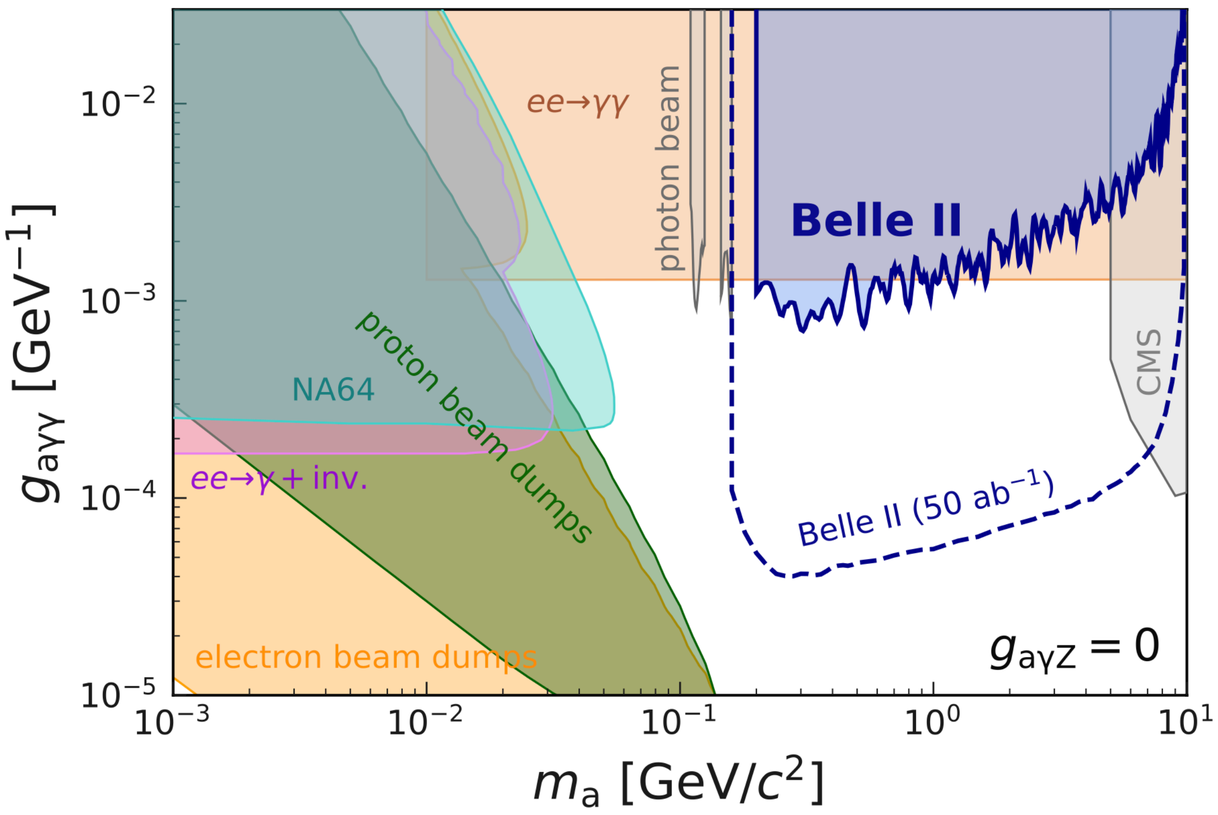
$$\mathscr{L}_{\text{int}} = -\frac{1}{4} g_{a\gamma\gamma} F^{\mu\nu} \tilde{F}_{\mu\nu} a$$





Belle-II, 2208.01101

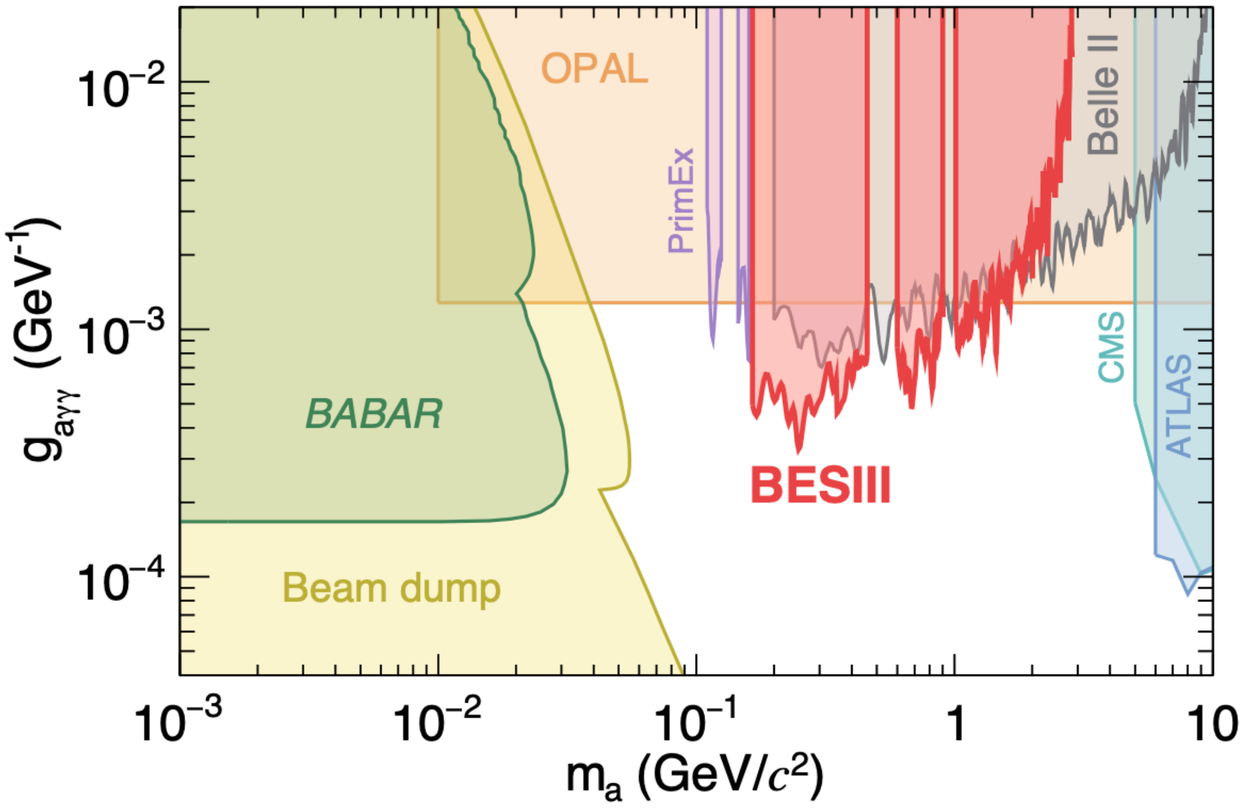
Belle II sensitivity on ALP



Belle-II, 2207.06307

BESIII limits on ALPs

$$(2.71 \pm 0.01) \times 10^9\, \psi(3683) \to \pi^+\pi^- J/\psi, J/\psi \to \gamma a, a \to \gamma\gamma$$



BESIII, 2211.12699

lepton flavor violating axions/ axion-like particles

Lepton flavor violating axion-like particles

Lepton flavor violating axion-like particles

$$\mathscr{L}_{\text{eff}} = \sum_i \frac{\partial_\mu a}{2f_a} \bar{\ell}_i C^A_{\ell_i \ell_i} \gamma^\mu \gamma_5 \ell_i + \sum_{i \neq j} \frac{\partial_\mu a}{2f_a} \bar{\ell}_i \gamma^\mu (C^V_{\ell_i \ell_j} + C^A_{\ell_i \ell_j} \gamma_5) \ell_j \,,$$

[Motoi Endo, Syuhei Iguro, Teppei Kitahara, 2002.05948]

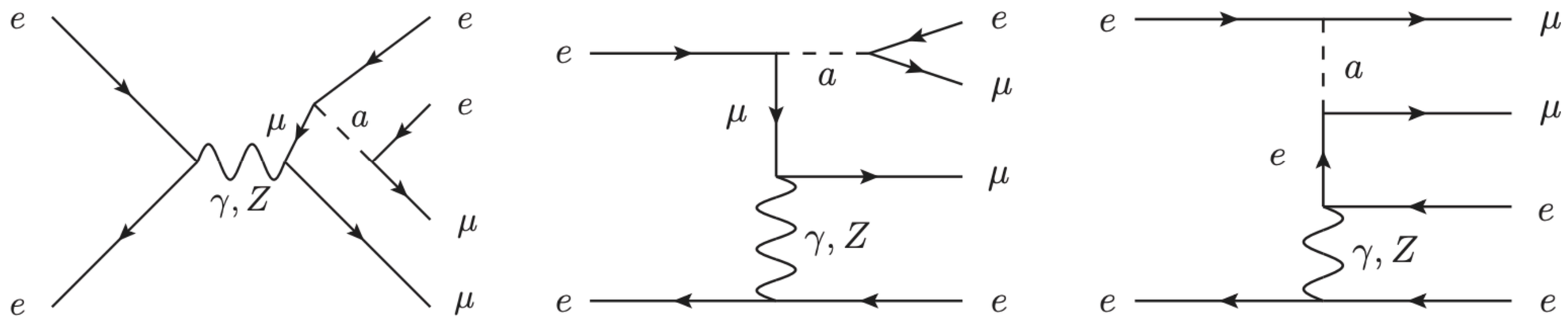
[Lorenzo Calibbi, Diego Redigolo, Robert Ziegler, Jure Zupan, 2006.04795]

[Hooman Davoudiasl, Roman Marcarelli, Ethan T. Neil, 2112.04513]

[Yonglin Li, Zuowei Liu, 2501.12075]

$e\mu$ flavor violating axion-like particles @ Belle II

$$(y_A)_{e\mu}\, a\bar{e}\gamma_5\mu$$

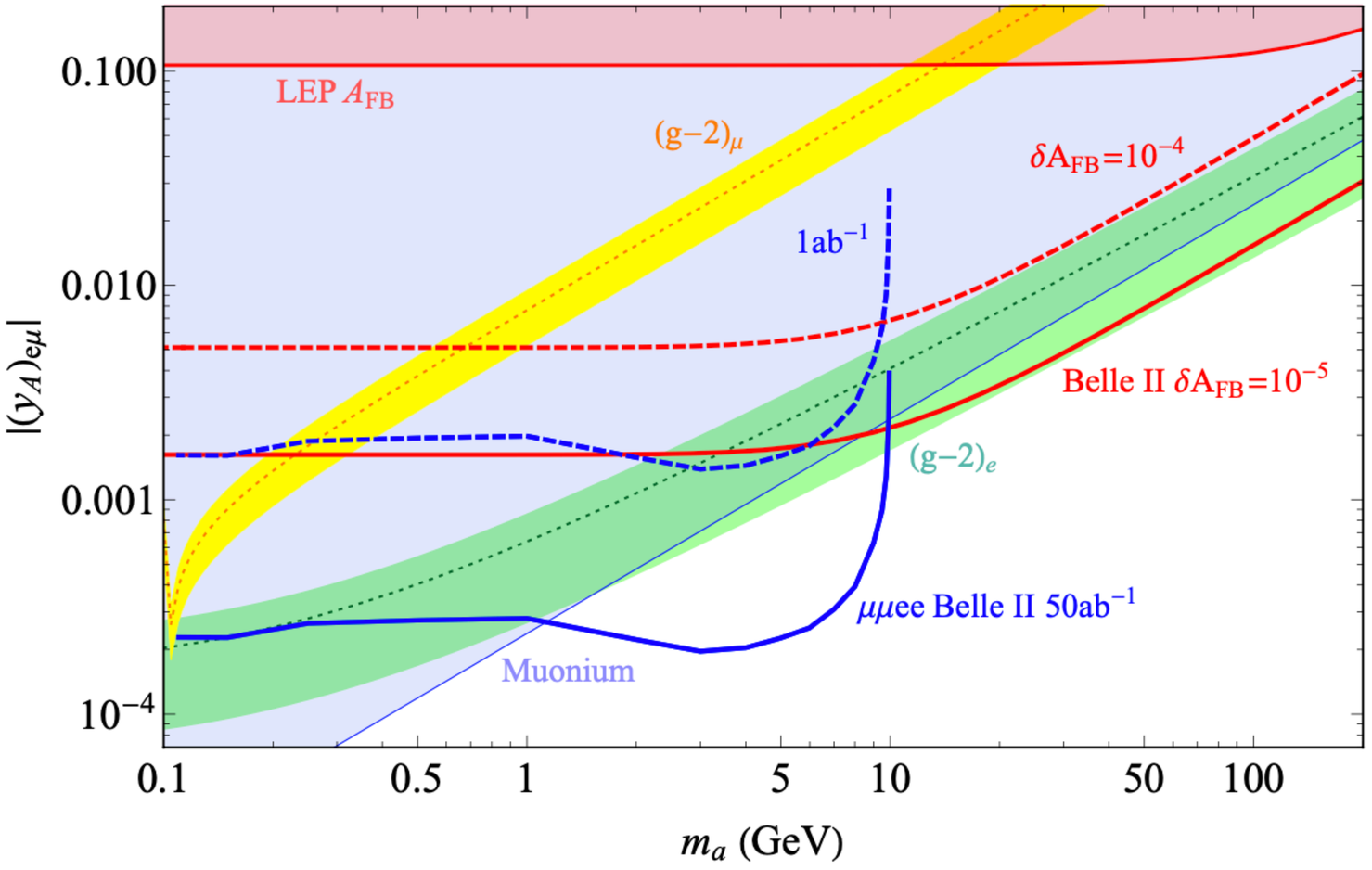


same sign & same-flavor lepton pairs via on-shell ALP: $e^+e^- \to \mu^\pm e^\mp a \to \mu^\pm\mu^\pm e^\mp e^\mp$

[Motoi Endo, Syuhei Iguro, Teppei Kitahara, 2002.05948]

$e\mu$ flavor violating axion-like particles @ Belle II

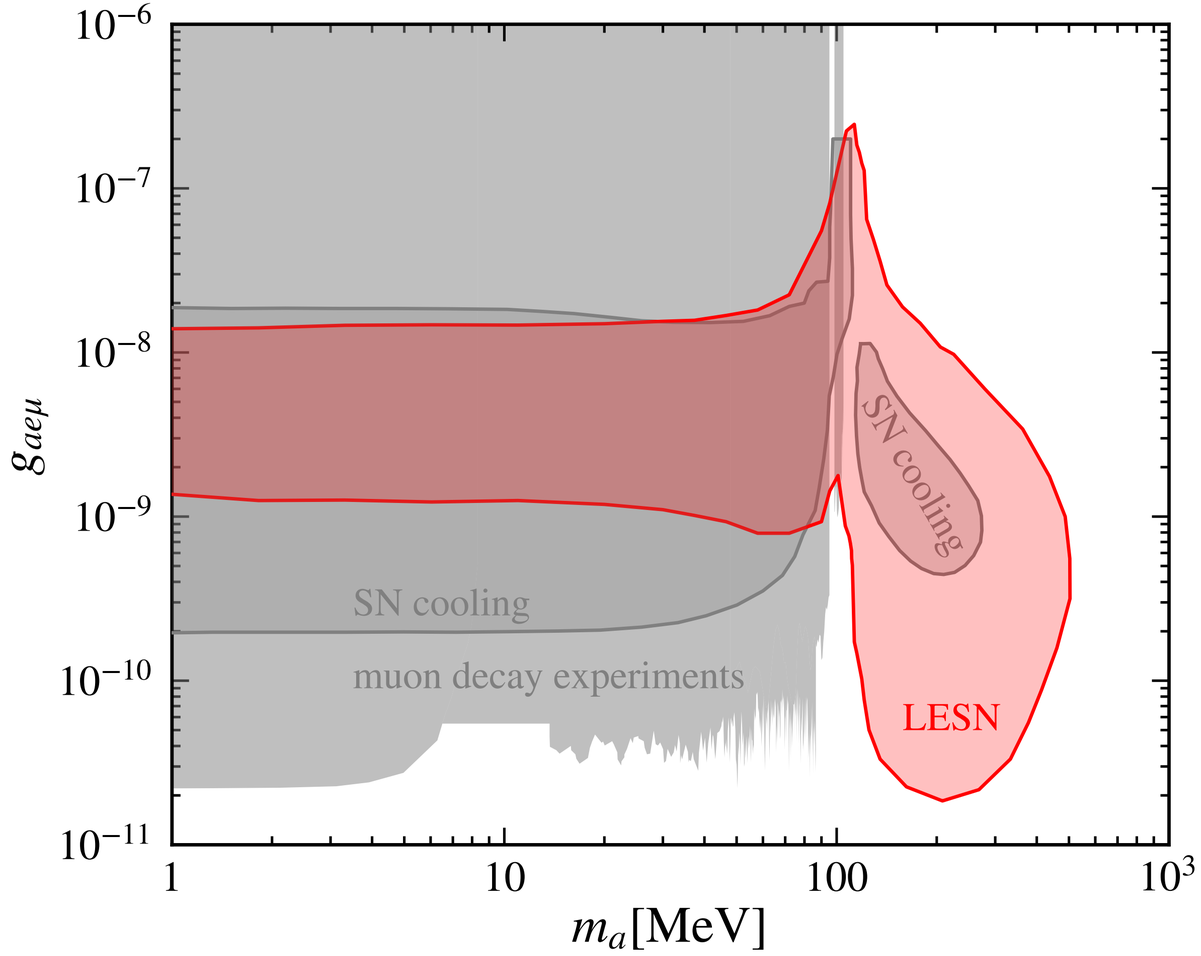
[Motoi Endo, Syuhei Iguro, Teppei Kitahara, 2002.05948]



$$(y_A)_{e\mu}\, a\bar{e}\gamma_5\mu$$

Supernova constraints on $e\mu$ flavor violating ALPs

constraints from supernova cooling & low-energy supernova explosion energy



$$\mathscr{L}_{\rm int} = -\, i g_{ae\mu}\, a\, \bar{e}\, \gamma_5\, \mu + {\rm h.c.}$$

$$e + \mu \to a$$

probes new para space for SN

[Li, ZL, 2501.12075]

[Huang, ZL, 2506.16922]

[Huang, Li, ZL, 2510.22523]

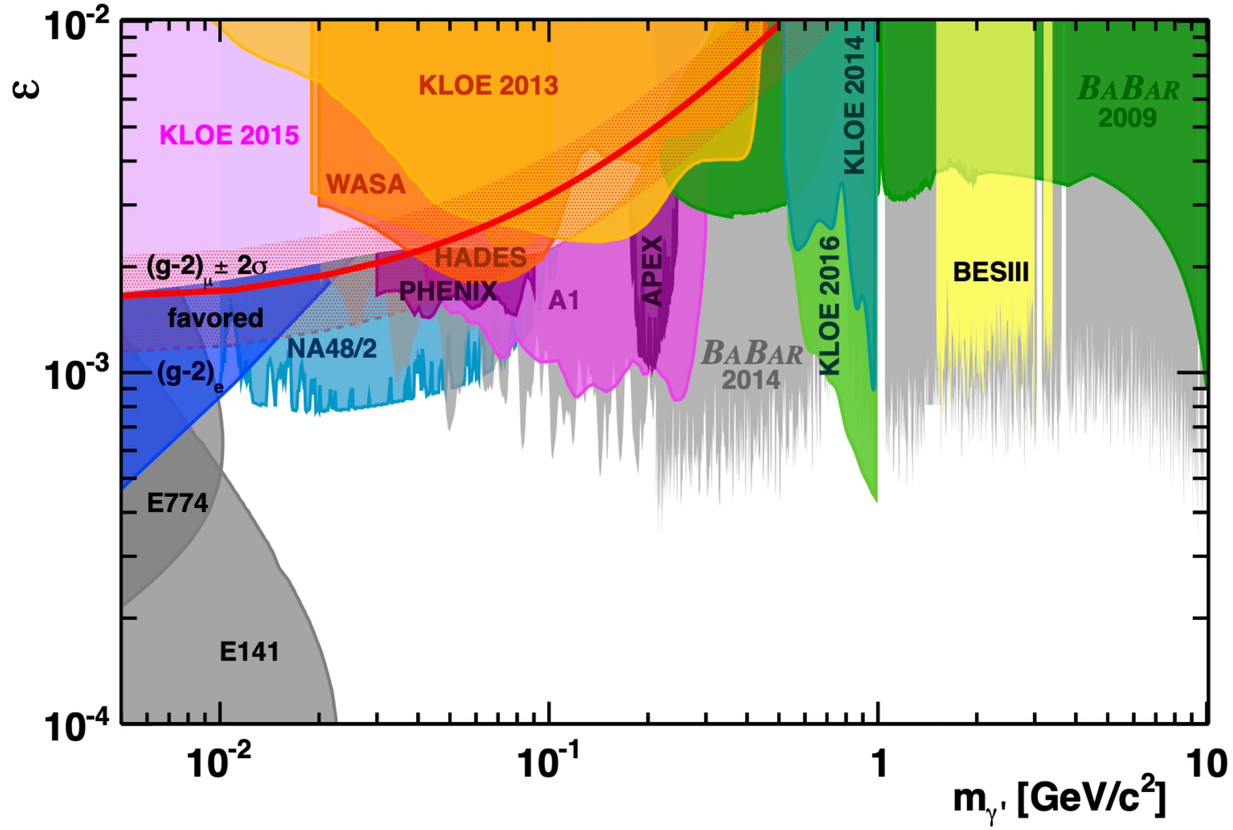
Summary

There are a variety of well-motivated new light particles that can be searched for at electron-positron colliders:

- dark photon
- millicharged particles
- dark matter
- axion and ALPS
- leptophilic boson

backup slides

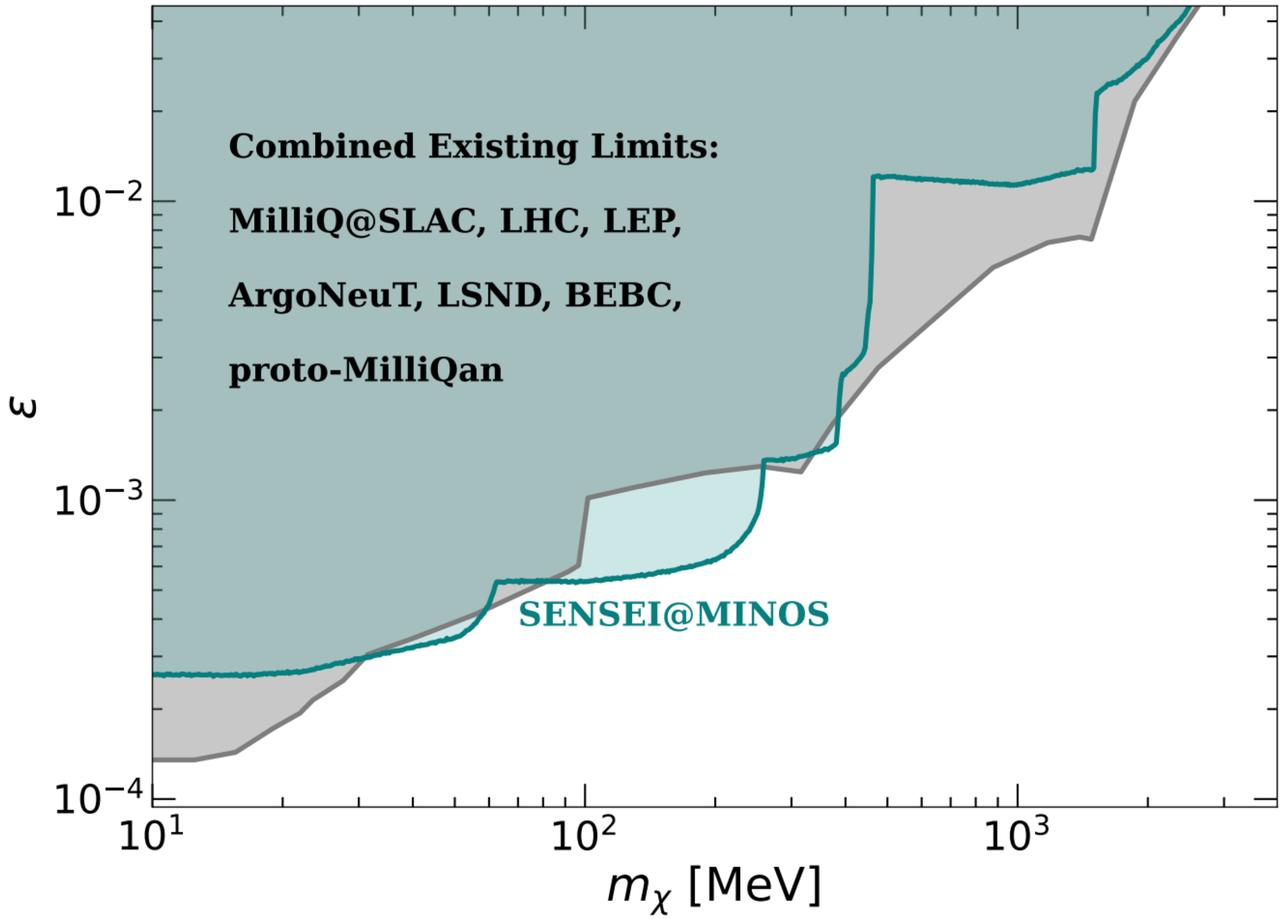
BESIII limits on prompt dark photon visible decay



BESIII, 1705.04265

2.93/fb at 3.773 GeV

SENSEI constraints on millicharged particles



SENSEI

[2305.04964]