Search for axion-like and dark particles at Belle II

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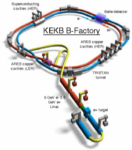
New Physics with Exotic and Long-Lived Particles:
A Joint ICISE-CBPF Workshop
1 - 6 July 2019
ICISE Conference Center, Quy Nhon, Vietnam



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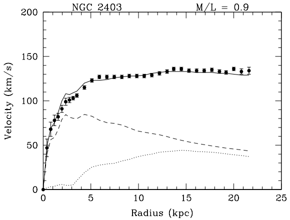
The Universe missing mass "problem"?

First observed by Fritz Zwicky in 1933 and reported in Helvetica physica acta, vol. 6, p. 110

- Missing mass problem, gravitational mass of galaxies in Coma galaxy cluster is much higher than expected
- Dunkle Materie or dark matter?

Validated by Vera Rubin and Kent Jr. W. Ford in 1970 and reported in Astrophysical Journal, vol. 159, p.379

- Measure rotation curves of spiral galaxies
- Observe: outermost components of the galaxy move as quickly as those close to the center



Rotation curve of NGC 2403. The points are the observed rotation curve, the dashed and dotted curves are the Newtonian rotation curves of the baryonic components (stars and gas respectively), and the solid curve is the MOND rotation curve, R. H. Sanders CJP 93 2 (2015).

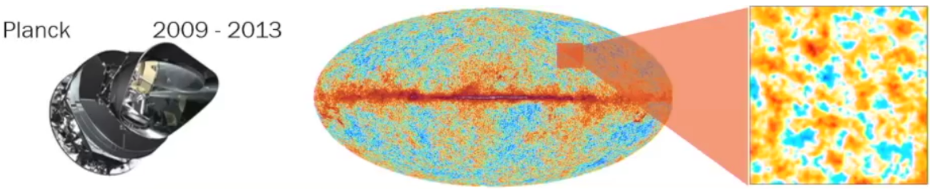
There are different ways to solve this relation problem between mass and gravity:

- Add an extra mass (most popular solution) which is not
  - Baryonic (Standard Model of Particles does not apply)
  - Interacting with known electromagnetic force (missing force(s))
- Modify the theories of gravity, eg MOdified Newton Dynamics (MOND) theories
- Combination of the above
- None of the above

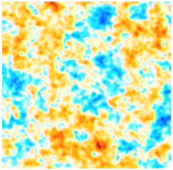
Mass and/or Gravity "problem"?

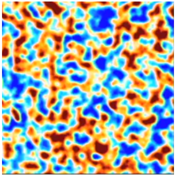
Universe missing mass “problem” at different ages

Cosmic Microwave Background (CMB) observed by Planck (arXiv:1807.06205) cannot be explained by MOND (so far).



- CMB MC simulation with DM and visible matter
- CMB MC simulation with visible matter only





Difference between data and model is interpreted as an indication of the proportion of:

- Visible (luminous) matter ($\sim$5 %)
- Non-luminous (dark) matter ($\sim$25 %) to bind cosmic structures: Galaxies & clusters of Galaxies
- Dark energy ($\sim$70 %) to drive cosmic acceleration: now and at primordial inflation

Criteria and list of candidates

There is so far no proof that dark matter exists but if it exists:

Dark matter criteria:

- Slowly moving particle
- Does not emit light
- Produced during the Big Bang
- Does not decay

List of candidates:

- Massive AstrophysiCal Halo Object (MAHO)
- Weakly Interacting Massive Particle (WIMP)
- Dark Sector Light Dark Matter
- Sterile neutrino
- (QCD) Axion(-like)
- Something else
- A combination of the above

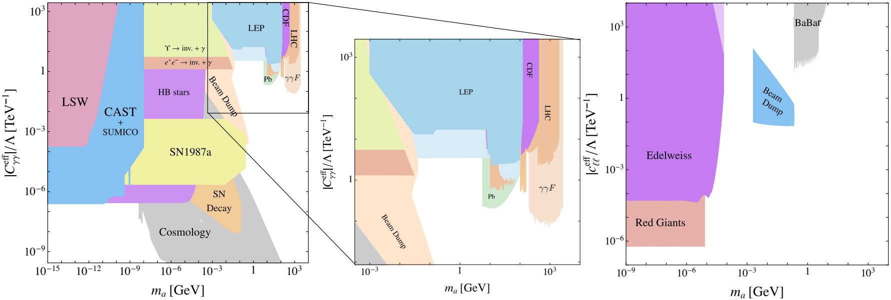
The (QCD) axion(-like)

To solve the neutron's electric spin or the strong-CP violation problem

- Peccei and Quinn proposed a pseudo-particle in 1977 ("CP Conservation in the Presence of Pseudoparticles") which
- Weinberg and Wilczek (the same year) formely introduced as the (QCD) axion ("A New Light Boson" and "Problem of Strong P and T Invariance in the Presence of Instantons")
- Sikivie in 1984 defined the experimental principals needed to observe this hypotetical ultra-light particle: (QCD) axion can convert into photon while crossing a magnetic field perpendicular to its direction

More generally, Axion-Like pseudo-scalar Particles (ALP) appear in any theory with a spontaneously broken global symmetry and possible ALP masses and couplings to SM particles range over many orders of magnitude.

- (QCD) axion (below eV) could represent up to 30 % of dark matter
- MeV range ALPs could represent only a fraction of dark matter

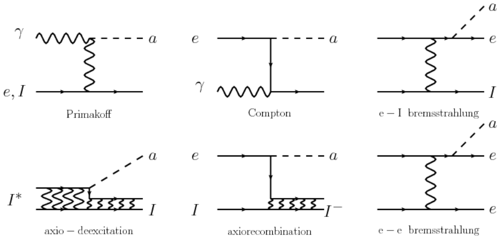


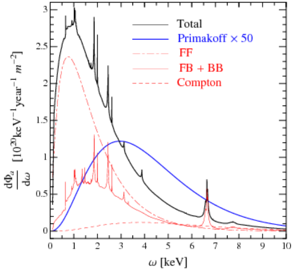
$\Lambda/|C^{\rm eff}| = 32\pi^2 f_a$ where f_a and $C^{\rm eff}$ axion decay constant and effective coupling, respectively

Last detour in the (QCD) axion world

First axion helioscope proposed by P. Sikivie

- P. Sikivie, Experimental Tests of the "Invisible" Axion, PRL 51, 1415; Erratum PRL **52**, 695 (1984)
- Idea refined by K. van Bibber et al. by using buffer gas to restore coherence over long magnetic field, K. van Bibber et al., Design for a practical laboratory detector for solar axions, PRD **39**, 2089 (1989)
- J. Redondo, Solar axion flux from the axion-electron coupling, JCAP 1312 008 (2013)





- ABC reactions responsible for the solar axion flux in non-hadronic axion models.

- Flux of solar axions due to ABC reactions driven by the axion-electron coupling (for $g_{ae} = 10^{-13}$). The different contributions are shown as red lines: Atomic recombination and deexcitation (FB+BB, solid), Bremsstrahlung (FF, dot-dashed) and Compton (dashed). The Primakoff flux from the axion-photon coupling is shown for comparison using $g_{a\gamma} = 10^{-12}$, a typical value for meV axions having $g_{ae} = 10^{-13}$. Note that has been scaled up by a factor 50 to make it visible

One can learn a lot from these searches that are in their third decade

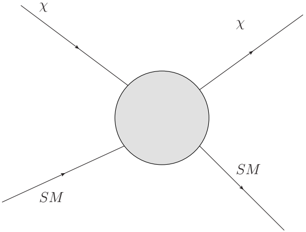
The Weakly Interacting Massive Particle (WIMP)

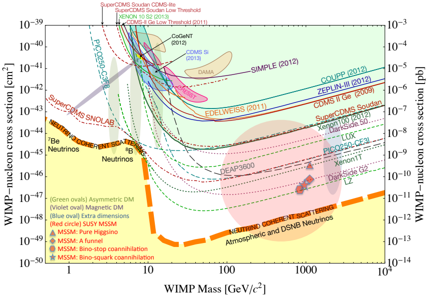
Can be naturally explained by Supersymmetry (Minimal Supersymmetric Standard Model)

WIMP with a mass of 100's of GeV/c^2 can explain

$\sim$80% of all matter is dark
Dark matter density at different ages of the Universe

If true, in this room there is 1 WIMP every 10 cm with a velocity of $\sim$ 200 km/s





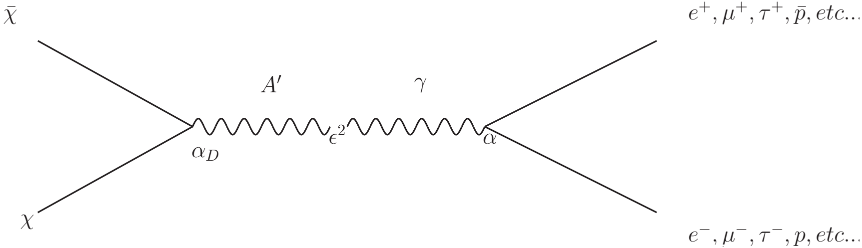
arXiv:1401.6085, Planning the Future of U.S. Particle Physics (Snowmass 2013)

- WIMP was not detected so far at underground laboratory
- Supersymmetry particles were not detected so far at LHC

The dark sector hypothesis

Introduction of a new force mediated by a Dark Gauge vector Boson

- Formulated first by P. Fayet and B. Holdom in the 80's
- Reformulated 30 years later by M. Pospelov, H. Arkani-Hamed, R. Essig, P. Shuster, N. Toro, et al. in light of the different anomalies observed
  - Anomalous magnetic dipole moment of a muon, E821 Collaboration PRL 92 1618102 (2004)
  - e^+ flux excess, AMS-02 Collaboration PRL 113, 221102 (2014)



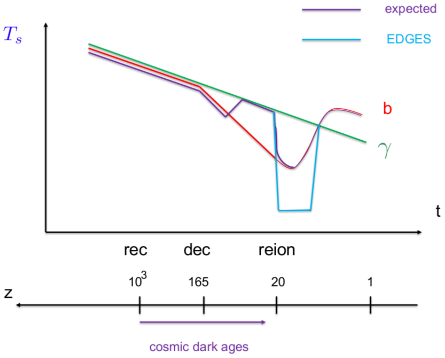
- α_D: dark matter, χ, coupling to dark photon, A' ($m_{A'} \neq 0$ GeV/c^2)
- $m_{A'}$ between 1.022 MeV/c^2 and 10's of GeV/c^2
- $\epsilon = \sqrt{\alpha'/\alpha}$: kinetic mixing between A' and Standard Model γ ($m = 0$ GeV/c^2)
  - $\alpha = 1 / 137$: SM electromagnetic coupling constant
  - α': A' coupling to SM fermions

Mediator can also be a scalar (ie Higgs-like), axion-like, or neutrino ie α' replaced by y_e, $g_{a\gamma}$, ...

EDGES 21-cm hydrogen signal at cosmic dawn

Experiment to Detect the Global Epoch of Reionization Signature (EDGES), Nature volume 555, pages 6770 (2018)

- Baryon temperature cooler than expected, 3.8σ discrepancy, and not confirmed yet by another collaboration
  - More 21-cm radiation at cosmic dawn than expected (generally considered unlikely)
  - Baryon cooling by dark matter, R. Barkana Nature volume 555, pages 7174 (2018)

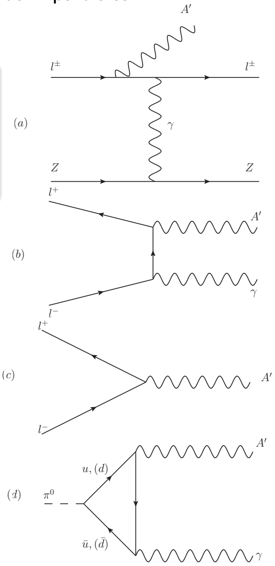


Artistic view of the Hydrogen spin temperature vs. Universe age by Pierre Sikivie.

- Millicharged dark matter possible if very small fraction (< 1 %) of total dark matter, mass m_χ between 0.5 and 35 MeV/c^2, and ϵ between 10^{-6} and 10^{-4}, E. D. Kovetz et al. arXiv:1807.11482
  NB: millicharged dark matter <=> slide 6 dark matter if off-shell mediator
- Dark matter is axions (QCD axion and/or axion-like), P. Sikivie arXiv:1805.0557
- Composite dark matter?
- Or something else?

Meanwhile on Earth

Most accelerator based experiments are looking for sub-GeV to GeV dark particles



Produced in the processes:

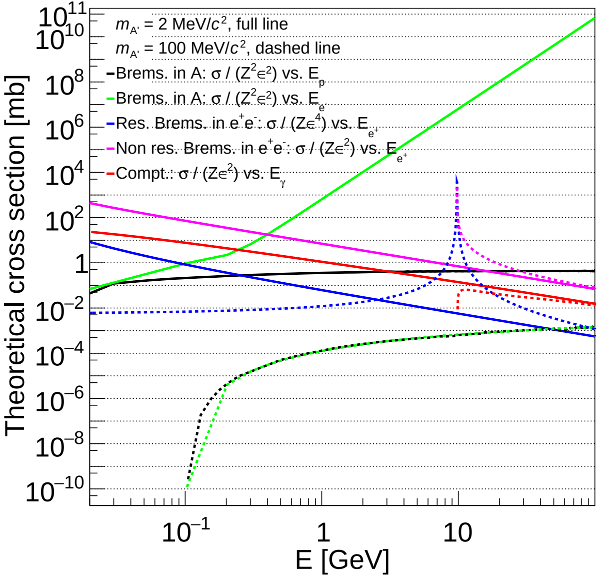
(a) "Dark" Bremsstrahlung in nucleus scattering
(b) "Dark" Bremsstrahlung in l^+l^- or pp annihilation
(c) "Dark" resonance in l^+l^- or pp annihilation
(d) "Dark" meson decay
(e) "Dark" atomic deexcitation

With:

- Lepton or hadron beam on a thin or thick fixed target
  E137, E141, E774, KEK, Orsay, A1, APEX, BDX, DarkLight, (Super-)HPS, LDMX, PADME, VEPP-3, NA48, NA64, MAGIX, MMAPS, Mu3a, SeaQuest, SHIP, ATOMKI
- Lepton or hadron colliders
  KLOE, KLOE II, BABAR, Belle, Belle II, BESI/II/II, LHCb, CMS, and ATLAS
  Much less SM backgrounds than fixed target experiments
- Photon beam on a fixed target
  GlueX ("Dark" meson decay)

Colliders are mostly using (b), (c), and (d)

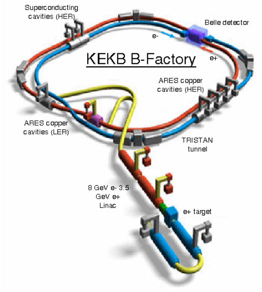
Theoretical cross-sections



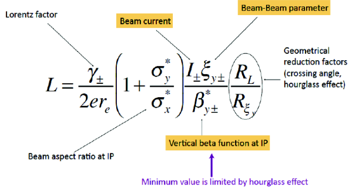
KEKB and SuperKEKB

KEKB/SuperKEKB collider, located in Japan, Tsukuba, is the world's highest-luminosity electron-position collider

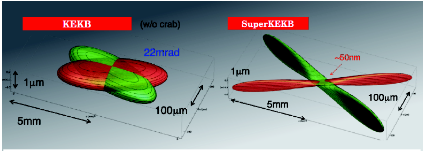
- 1999-2010: Belle collected $\mathcal{L}_{int} = 1050$ fb^{-1} at $\Upsilon(1S, 2S, 3S, 4S, 5S)$ and continuum
- 2016-2029: Belle II (upgrade version of Belle) expects to collect $\mathcal{L}_{int} = 50\ ab^{-1}$



Schematic view of KEKB



$$L = \frac{\gamma_\pm}{2er_e}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\left(\frac{R_L}{R_{\xi_y}}\right)$$



	E (GeV) LER/HER	β*y (mm) LER/HER	β*x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L (cm^{-2}s^{-1})
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1 x 10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80 x 10^{34}

S. Kurokawa and E. Kikutani, NIM A 499, 1 (2003)

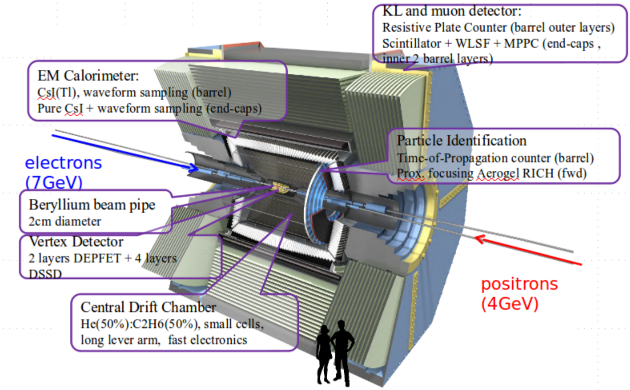
KEKB beam vs. SuperKEKB nano-beam

Belle II $\mathcal{L}_{peak} = 8 \times 10^{35} cm^{-2} s^{-1}$

Belle and Belle II experiments

CP violation measurement in the B-meson system with Belle and *BABAR*, established the Kobayashi Maskawa mechanism as a valid description of CP violation in the Standard Model.

- Main motivations
  - Study of CP violation (i.e. matter-antimatter asymmetry)
  - Study of heavy flavor
  - Search for physics beyond the Standard Model
- Complementary to efforts at energy frontier



Add PID in endcaps

Add μ ID in endcaps

Increase K_S efficiency

Improve IP and secondary vertex resolution

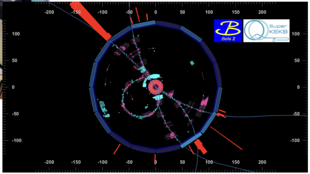
Improve π/K separation

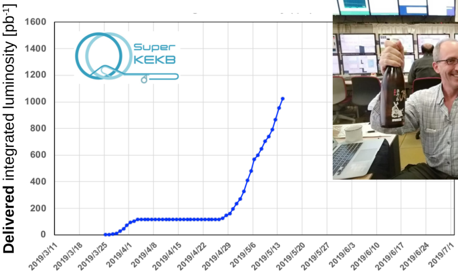
Improve π^0 efficiency

Belle II is an upgrade of Belle

Belle II current status

First (physics) collisions in March 2019, by March 2029, we plan to collect 50 ab^{-1}

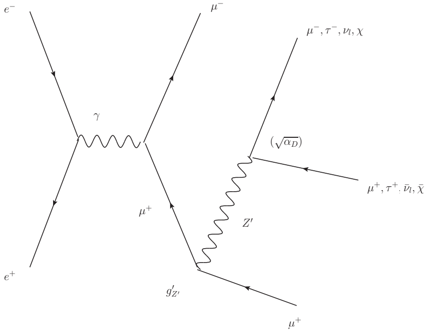




Search for the dark vector gauge boson

There are two broad categories of theory:

- Gauging the difference of baryon-number and leton-number, $(B - L)$ A' or dark photon, R. Essig et al. PRD 80 015003 (2009)
- Gauging the difference of muon-number and tau-number, $(L_\mu - L_\tau)$ Z', X. G. He et al. PRD 43 22 (1991) and PRD 44 2118 (1991)

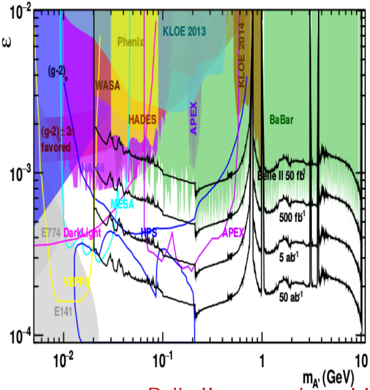


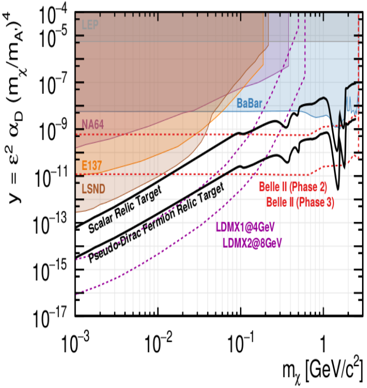
Possible production mode of Z'. For the light dark matter decay mode, there is two coupling: $g'_{Z'}$ and α_D.

Search for the dark photon and the light dark matter

Results from BABAR PRL 113 201801 (2014) & 119 131804 (2017), and Belle II expected sensitivities arXiv:1808.10567 (Phase 2 sensitivity outdated as only 0.5 fb^{-1} instead of 20 fb^{-1})

- $e^+e^- \to \gamma A'$, $A' \to l^+l^-$, with $l = e$ or μ, and $A' \to \chi\bar{\chi}$
- Improved low multiplicity trigger in Belle II for visible decays compared to Belle
- Improved track momentum resolution compared to BABAR and Belle, by 2 and 1/3, respectively
- Single photon trigger implemented in Belle II for invisible decay



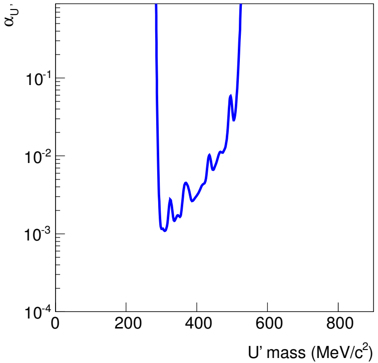


Belle II expected sensitivity in 2020, 202?, and 2029

Search for the visible U'

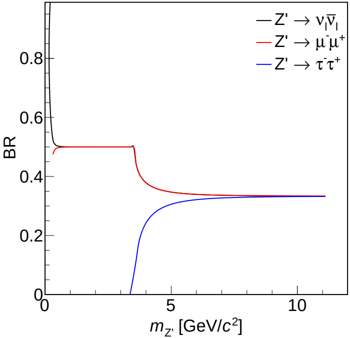
Belle results PRD 94 092006 (2016)

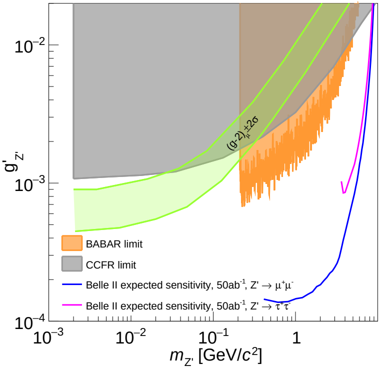
- U', dark vector gauge boson $(B - L)$ coupling preferentially to quarks
- Search for $U' \to \pi^+\pi^-$ in $D^0 \to K_S^0\eta$, $\eta \to U'\gamma$ using $977 fb^{-1}$ of Belle data
- Exclusive charm meson decays to reduce background
- 95% CL limit on the baryonic fine structure constant
- Better limit for $m_{U'} > 450$MeV/c^2 and $\phi \to e^+e^-\gamma$



Search for the dark gauge vector boson $(L_\mu - L_\tau)$ Z'

- Search based on the theoretical works of W. Altmannshofer et al. PRL 113 091801 (2014), B. Shuve et al. PRD 89 11 113004 (2014), ...
- Z' search in the following process: $e^+e^- \to \mu^+\mu^- Z'$
- BABAR performs the first search PRD 94 1 011102 (2016)
- Belle plans to publish a similar search in the next few months
- Search also carries out by Belle II



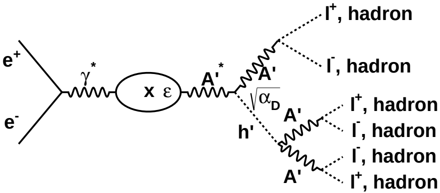


Left: branching ratio versus $m_{Z'}$. Right: current limits and Belle II expected sensitivity.

Search for the dark photon and the dark Higgs boson

Production in the so-called Higgs-strahlung channels, $e^+e^- \to A'h'$, with $h' \to A'A'$ B. Batell et al. PRD 79 (2009) 115008.

- A' and h' assuming prompt decays
- $m_{h'} > 2m_{A'}$
- $0.1 < m_{A'} < 3.5$ GeV/c^2 and $0.2 < m_{h'} < 10.5$ GeV/c^2



α_D: dark sector constant
ε: kinetic mixing

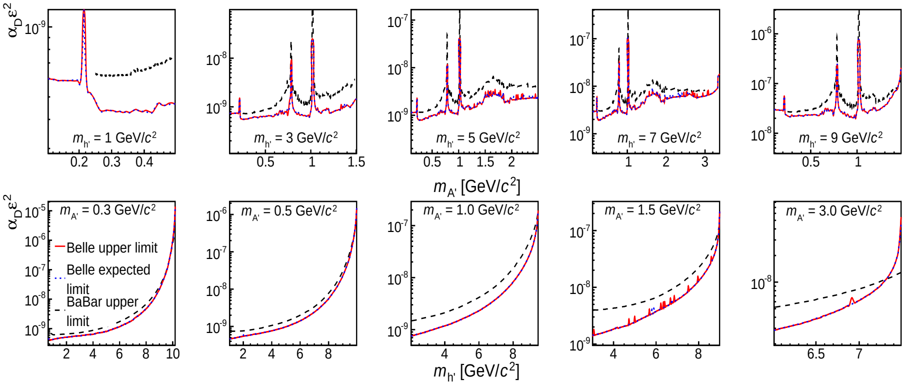
- 10 exclusive channels: $3(l^+l^-)$, $2(l^+l^-)(\pi^+\pi^-)$, $2(\pi^+\pi^-)(l^+l^-)$, and $3(\pi^+\pi^-)$, where l^+l^- is an electron or muon pair
- 3 inclusive channels for $m_{A'} > 1.1$ GeV/c^2: $2(l^+l^-)X$, where X is a dark photon candidate detected via missing mass

If $\alpha_D = 1$, Higgs-strahlung channels most sensitive to A'

Limits on the product of $\alpha_D \varepsilon^2$

Belle combined limits compared to BaBar combined limits

- Belle limits for $\mathcal{L} = 977$ fb^{-1} based on the Born cross section, ISR effect non negligible PRL 114 211801 (2015)
- BaBar limits for $\mathcal{L} = 520$ fb^{-1} based on the visible cross section PRL 108 211801 (2012)



90% CL upper limit on the product $\alpha_D \times \varepsilon^2$ versus dark photon mass (top row) and dark Higgs boson mass (bottom row)

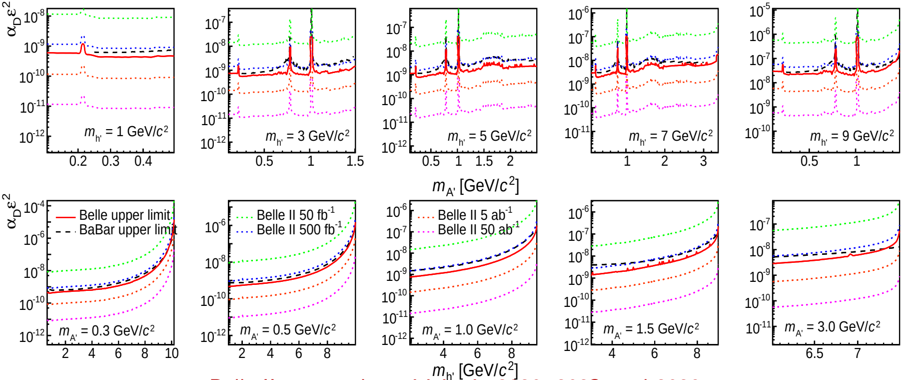
Results scale nearly linearly with integrated luminosity.This bodes well for future searches with Belle II.

Belle II prospects for the Higgs-strahlung channels

Predicted Belle II upper limits $U_{\alpha_D \varepsilon^2}$ in the $\alpha_D \varepsilon^2$ vs $m_{A'}$ vs $m_{h'}$ plane by scaling the Belle limits linearly with the integrated luminosity:

$$\frac{U_{\alpha_D \varepsilon^2}}{U^0_{\alpha_D \varepsilon^2}} = \frac{\mathcal{L}^0}{\mathcal{L}},$$

where the superscript 0 corresponds to Belle values. $\mathcal{L}$ is integrated luminosity. The scaling uses both statistical and systematic uncertainties.

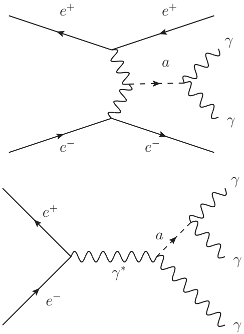


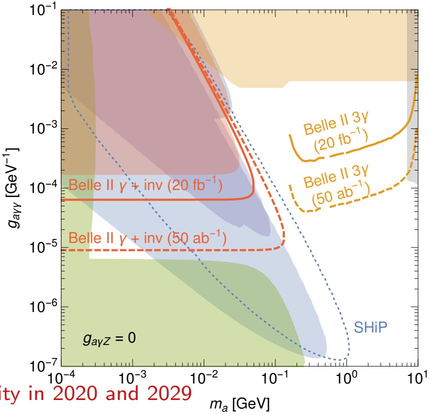
Belle II expected sensitivity in 2020, 202?, and 2029

Search for the axion-like pseudo-scalar

Proposed by M. J. Dolan et al. JHEP 1712 (2017) 094

- 2 processes: a-strahlung and resonance in e^+e^- annihilation
- a can be visible ie decays into two photons, long-lived, or invisible





Belle II expected sensitivity in 2020 and 2029

Search for the axion-like pseudo-scalar

Proposed by M. J. Dolan et al. JHEP 1712 (2017) 094

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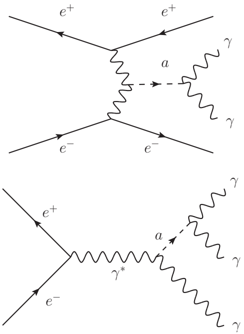

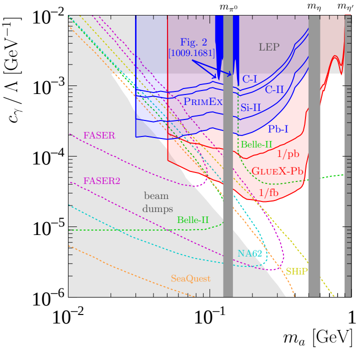

Low intensity tagged photon-beam fixed-target competitive below the η-meson mass

Conclusion

Universe has a missing mass “problem”, possibly there is a non-luminuous matter or dark matter

- Dark matter could be millicharged, axion, axion-like, ...
- Dark matter and/or its mediators can be searched by lepton colliders for mass hypothesis below 10 GeV/c^2
- Belle and Belle II published or actively searching for:
  - Dark gauge scalar and vector bosons
  - Light dark matter
  - Axion-like

Thanks for your attention