Search for the dark gauge vector and scalar bosons, the axion-like pseudo-scalar, and the dark matter at lepton colliders

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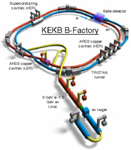

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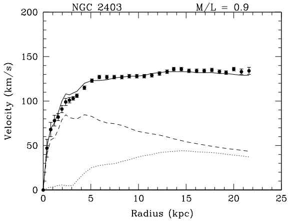
The Universe missing mass "problem"?

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).

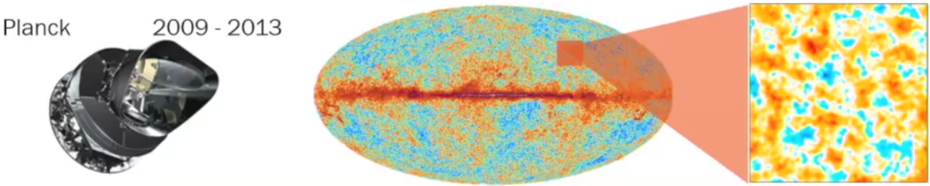
There are different ways to solve this relation problem between mass and gravity:

- 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

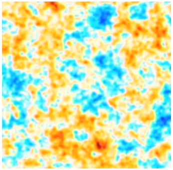
Mass and/or Gravity "problem"?

Universe missing mass "problem" at different ages

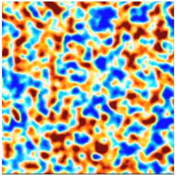
Cosmic Microwave Background (CMB) observed by Planck (arXiv:1807.06205) cannot be explained by MOND (so far).



- CMB MC simulation with DM and visible matter



- CMB MC simulation with visible matter only



Difference between data and model is 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

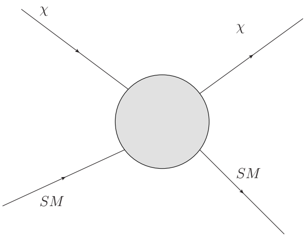
The Weakly Interacting Massive Particle (WIMP)

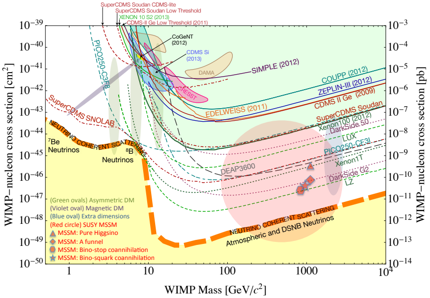
Can be naturally explained by a minimal Supersymmetry extension of the Standard Model

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





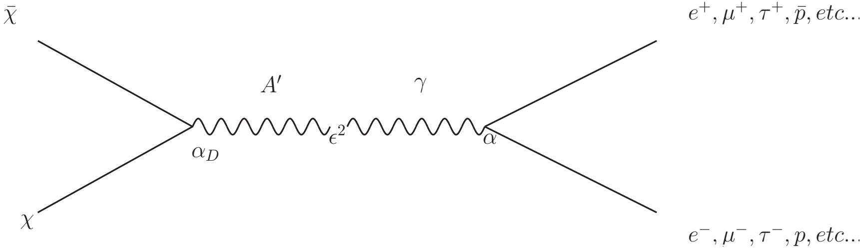
arXiv:1401.6085, Planning the Future of U.S. Particle Physics (Snowmass 2013)

- 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)



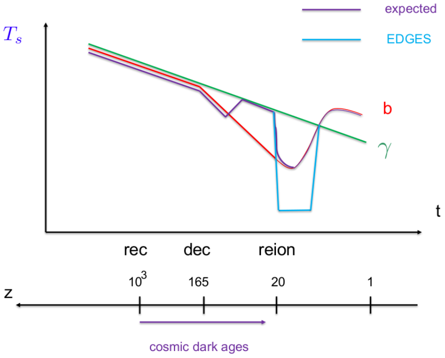
- α_D: dark matter, χ, coupling to dark photon, A' ($m_{A'} \neq 0$ GeV/c^2)
- $m_{A'}$ between 1.022 MeV/c^2 and 10's of GeV/c^2
- $\epsilon = \sqrt{\alpha'/\alpha}$: kinetic mixing between A' and Standard Model γ ($m = 0$ GeV/c^2)
  - $\alpha = 1\ /\ 137$: SM electromagnetic coupling constant
  - α':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

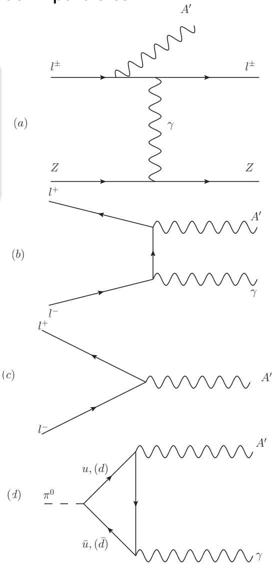
Most accelerator based experiments are looking for sub-GeV to GeV dark particles

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

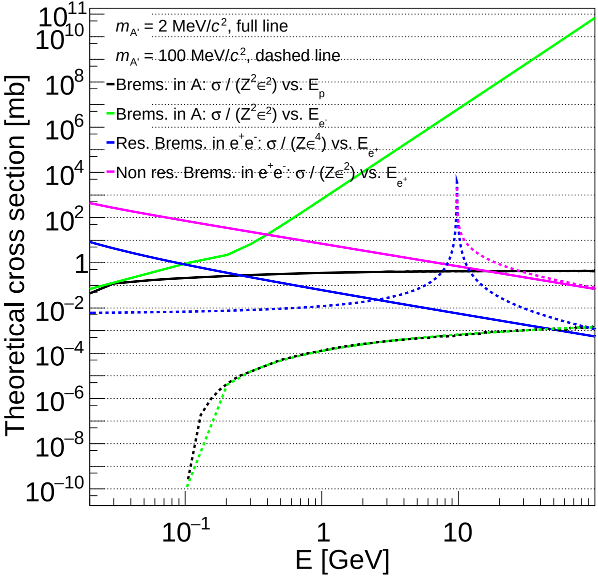
With:

- 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)

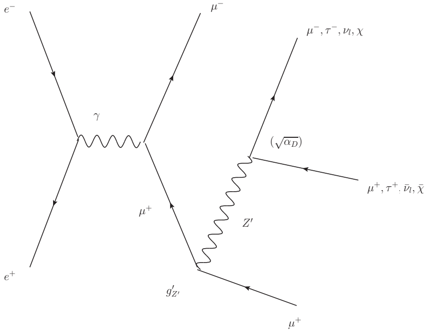
Theoretical cross-sections



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)

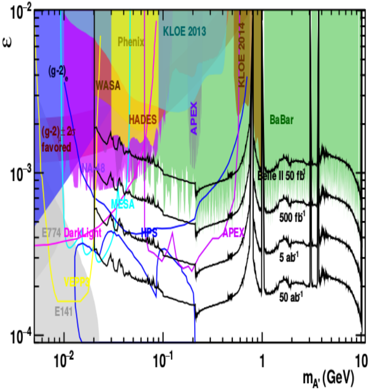


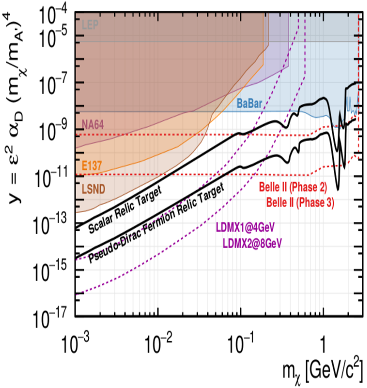
Possible production mode of Z'. For the light dark matter decay mode, there is two coupling: $g'_{Z'}$ and α_D.

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

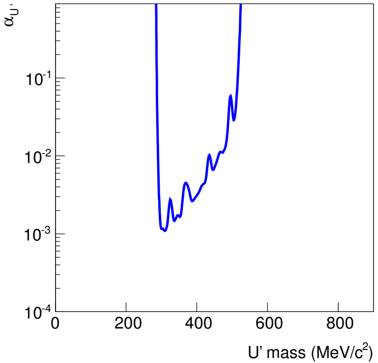




Search for the visible U'

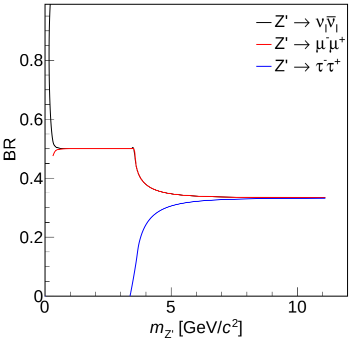
Belle results PRD 94 092006 (2016)

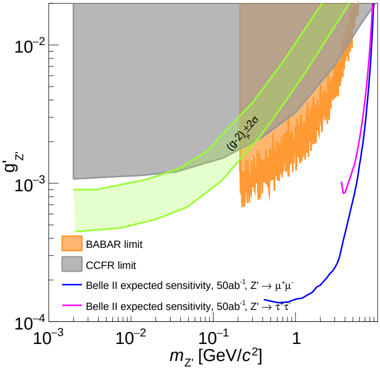
- U', dark vector gauge boson $(B-L)$ coupling preferentially to quarks
- Search for $U' \to \pi^+\pi^-$ in $D^0 \to K_S^0\eta$, $\eta \to U'\gamma$ using $977 fb^{-1}$ of Belle data
- Exclusive charm meson decays to reduce background
- 95% CL limit on the baryonic fine structure constant
- Better limit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



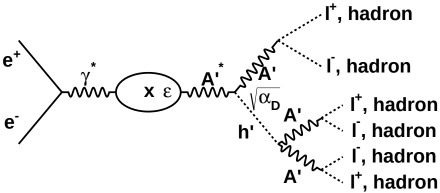


Left: branching ratio versus $m_{Z'}$. Right: current limits and Belle II expected sensitivity.

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

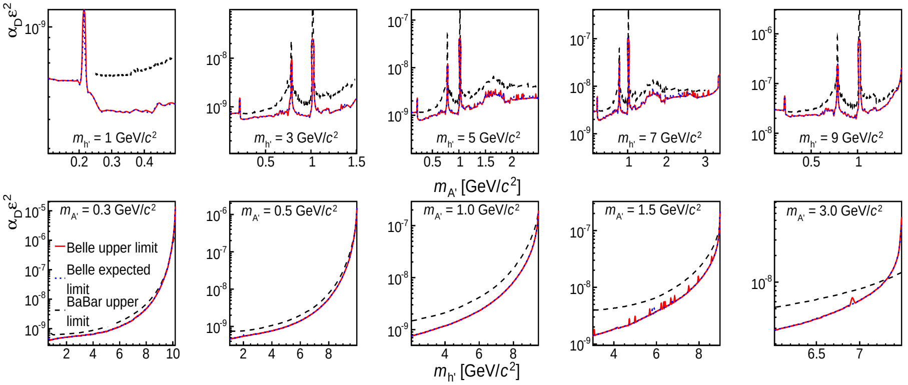
- 10 exclusive channels: $3(l^+l^-)$, $2(l^+l^-)(\pi^+\pi^-)$, $2(\pi^+\pi^-)(l^+l^-)$, and $3(\pi^+\pi^-)$, where l^+l^- is an electron or muon pair
- 3 inclusive channels for $m_{A'} > 1.1$ GeV$/c^2$: $2(l^+l^-)X$, where X is a dark photon candidate detected via missing mass

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)

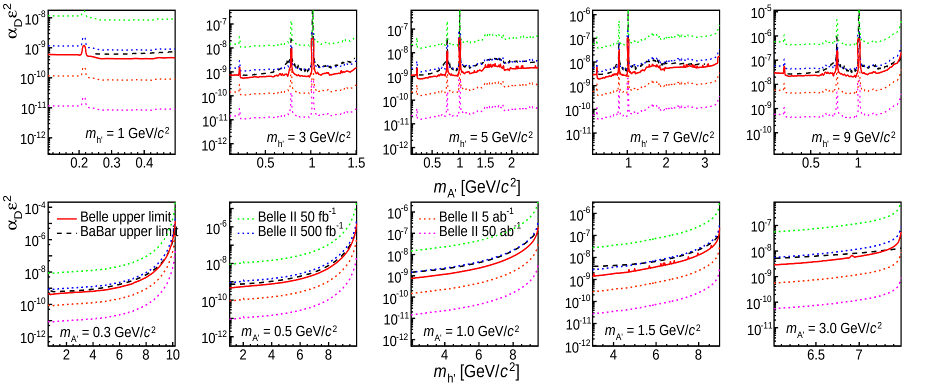
Results scale nearly linearly with integrated luminosity.This bodes well for future searches with Belle II.

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:

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

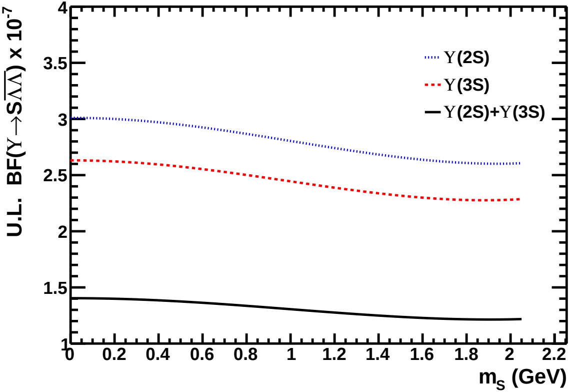
where the superscript 0 corresponds to Belle values. $\mathcal{L}$ is integrated luminosity. The scaling uses both statistical and systematic uncertainties.



Search for a stable Six-Quark State, S

BABAR results PRL 122 072002 (2019) for the process: $\Upsilon(2S, 3S) \to S\bar{\Lambda}\bar{\Lambda}$

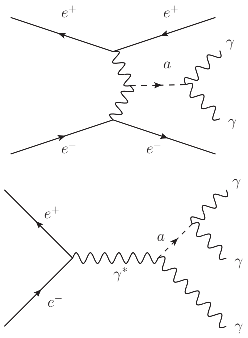
- *uuddss* state: stable system and deeply bound, could be a candidate for dark matter G. R. Farrar arXiv:1708.08951
- Similar state predicted by Jaffe in the 80's: H-dibaryon(2150) searched but not found so far

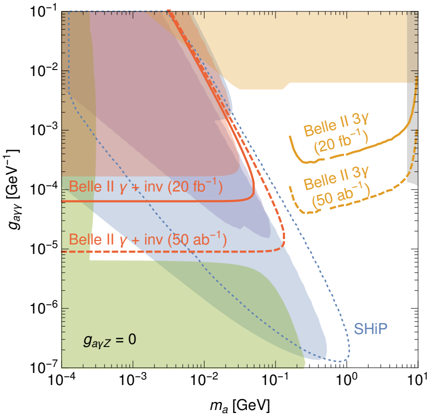


Search for the axion-like pseudo-scaler

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





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

Thanks for your attention