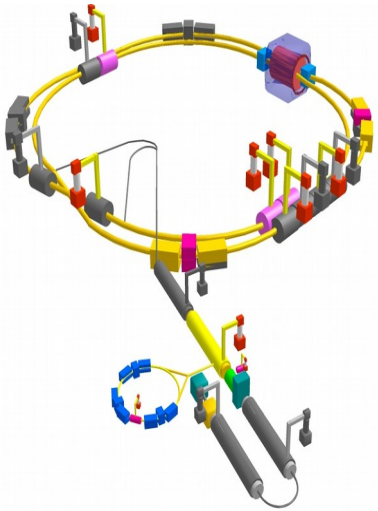
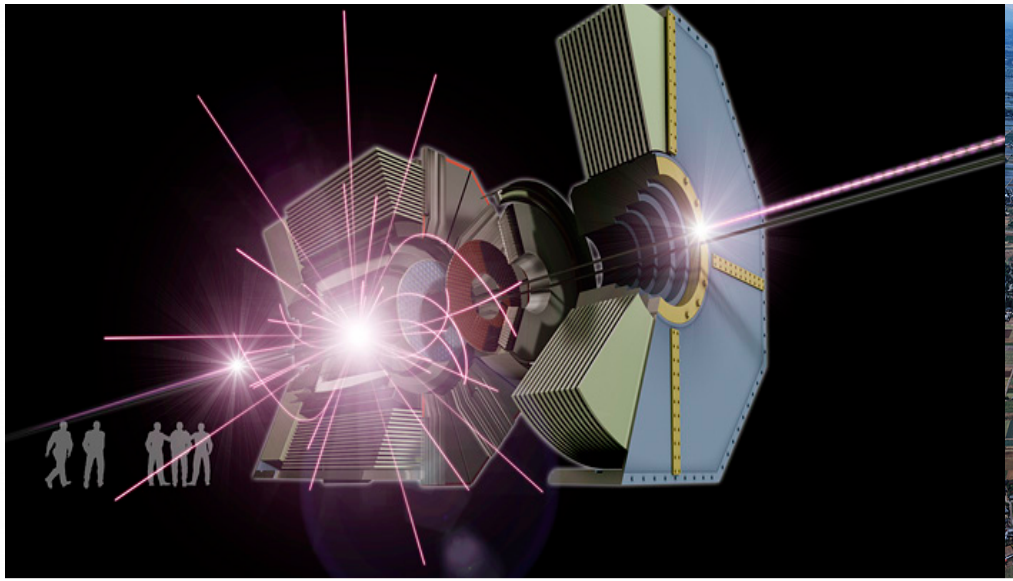
Dark sector searches at Belle (II)





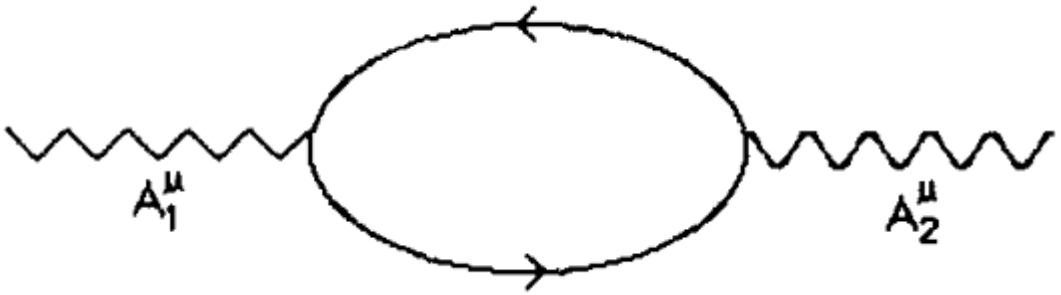
Gianluca Inguglia- DESY

20/04/2017

Dark photon: The general idea of kinetic mixing γ-A'

Dark photon first proposed in P. Fayet, Phys. Lett. B **95**, 285 (1980),
P. Fayet Nucl. Phys. B **187**, 184 (1981).

- (Holdom, 1986) A boson belonging to an additional U(1)' symmetry would mix kinetically with the photon:

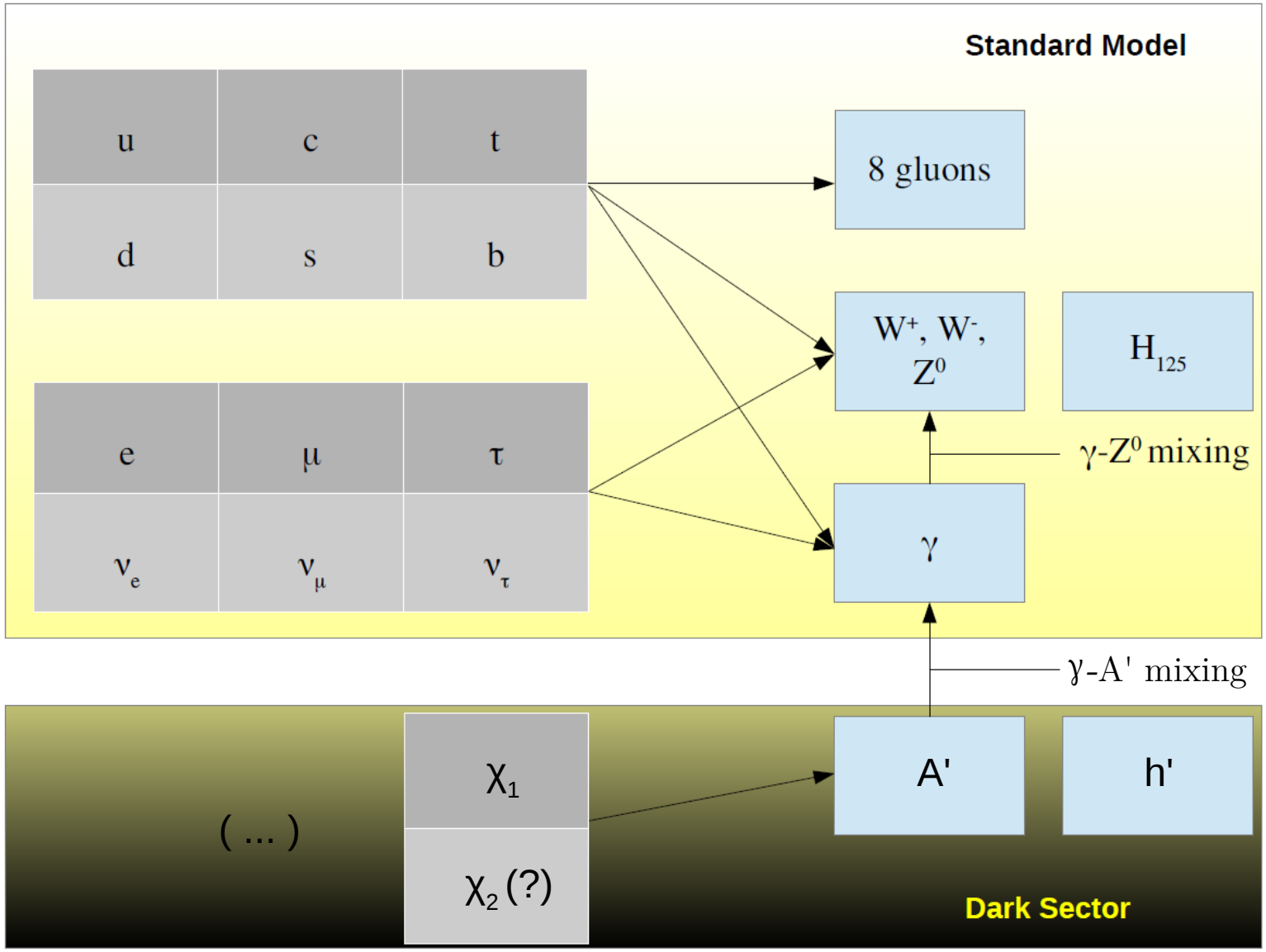


- The kinetic mixing is a term in the Lagrangian expressed by $\frac{1}{2}\epsilon F^{Y}_{\mu\nu} F'^{\mu\nu}$
- For the dark photon to acquire mass an extended Higgs sector might be required to break the new U(1)' symmetry

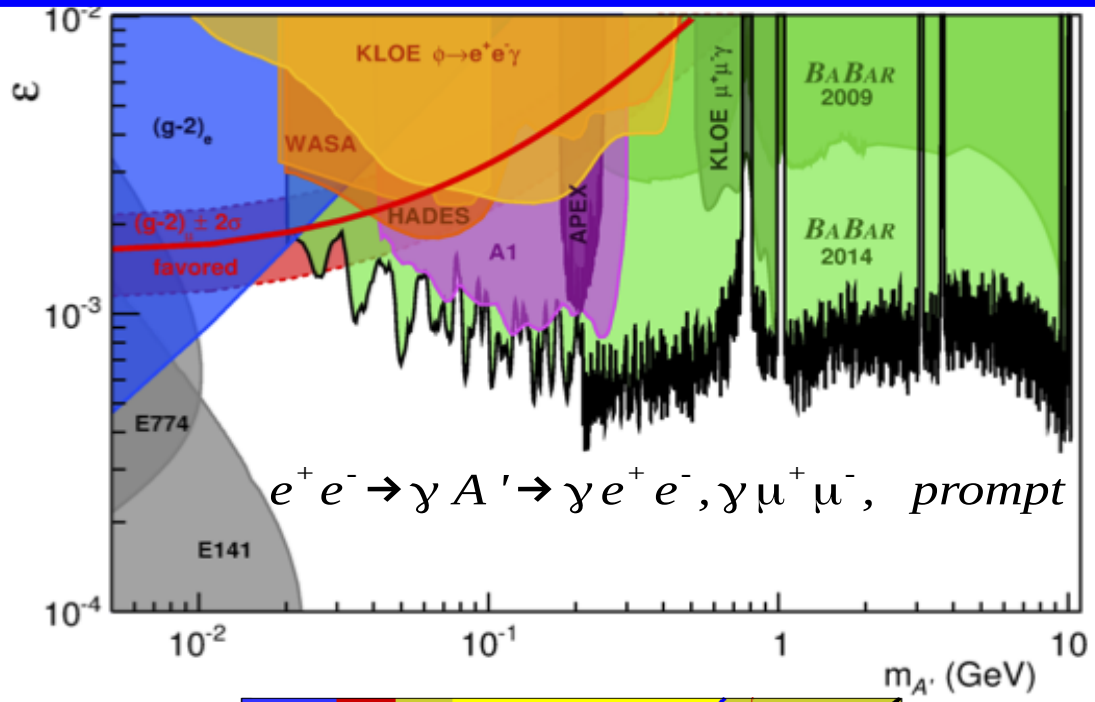
Note: ϵ is the strength of the kinetic mixing and it is supposed to be small, 10^{-5}-10^{-2}, **the smaller the value of ϵ the longer A' lifetime** (i.e. **long lived**).

The Mass of the new boson should be in the range few MeV to few Gev allowing for the Sommerfeld enhancement that would also explain anomalies observed in astrophysical data (Nima Arkani-Hamed et al. Phys. Rev. D **79,** 015014, 2009).

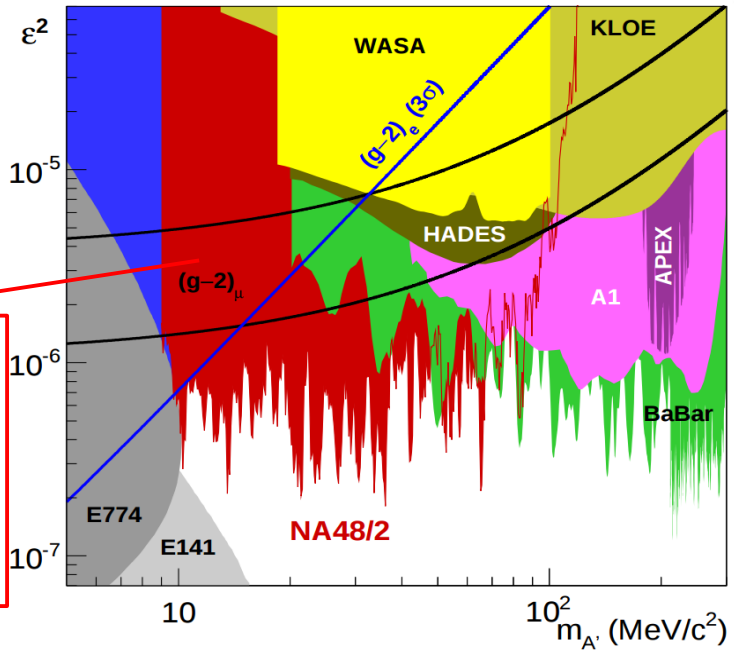
Dask sector: how does it look like?



Dark photon: current limits

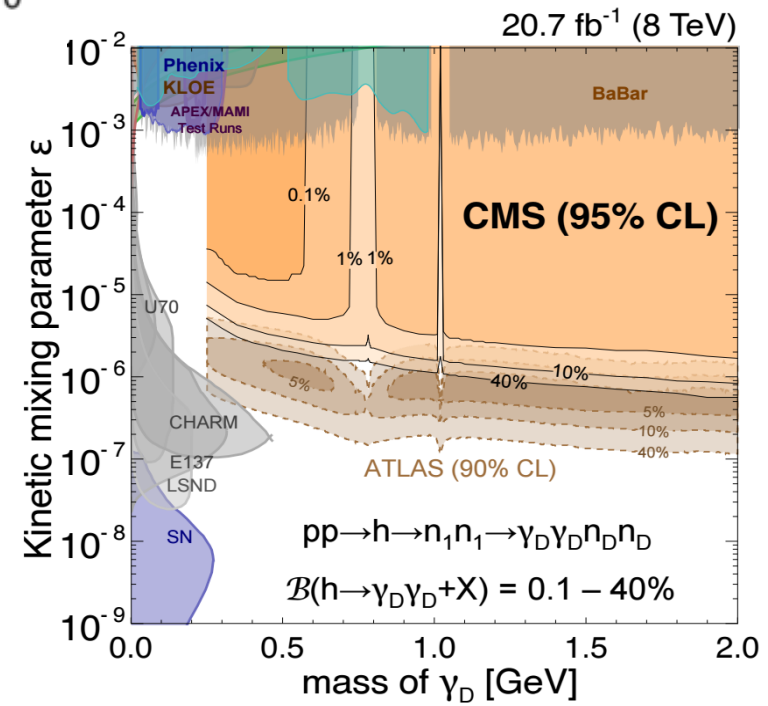


Many constraints for different region of the parameter space from different experiments.
Shown here:
-top left: BaBar ,
-bottom left NA48,
-bottom right CMS (containing ATLAS) [highly model dependent] ⚠



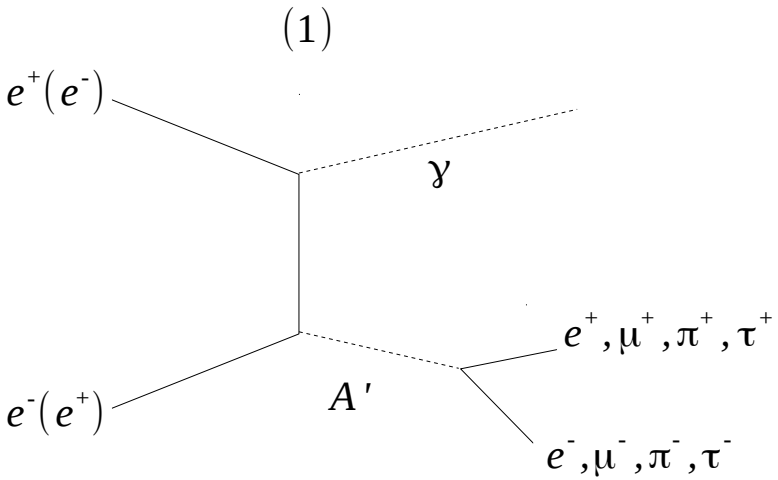
dark photon explanation of $(g-2)_\mu$ ruled out for $A' \to e^+e^-$

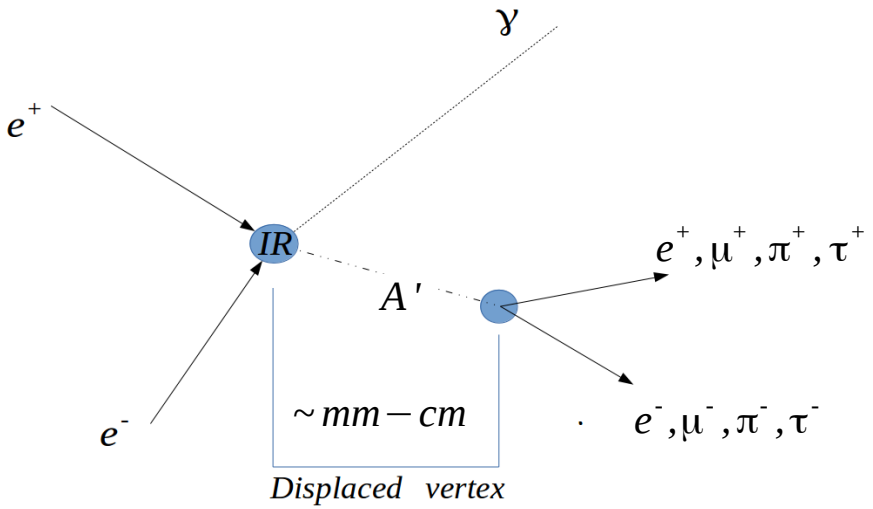
NA48 arXiv:1504.00607
π^0 decays



arXiv:1506.00424 [hep-ex]
Long lived, decays to leptons

Dark photon searches @ BELLE II



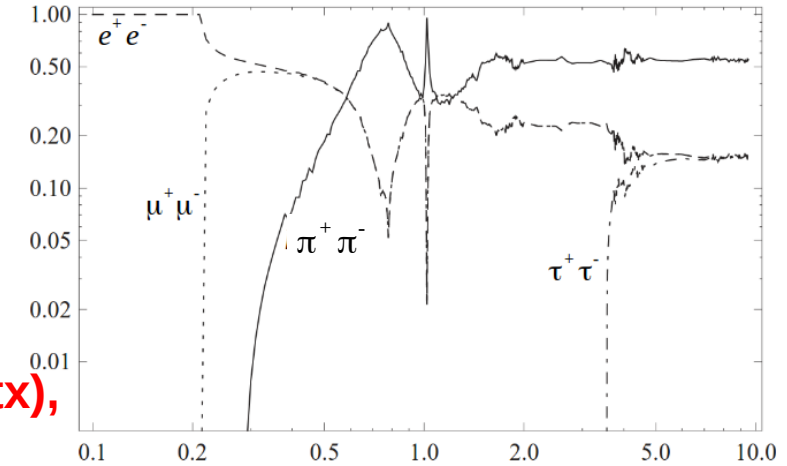


A'= dark photon.
A' decays to SM final states through kinetic mixing (if allowed by kinematics). Low multiplicity final states. 2 charged tracks and 1 photon, prompt or displaced vertex. Require dedicated trigger to increase efficiencies, especially for the displaced vertex case.

"*A'* " decays depend on $M_{A'}$:

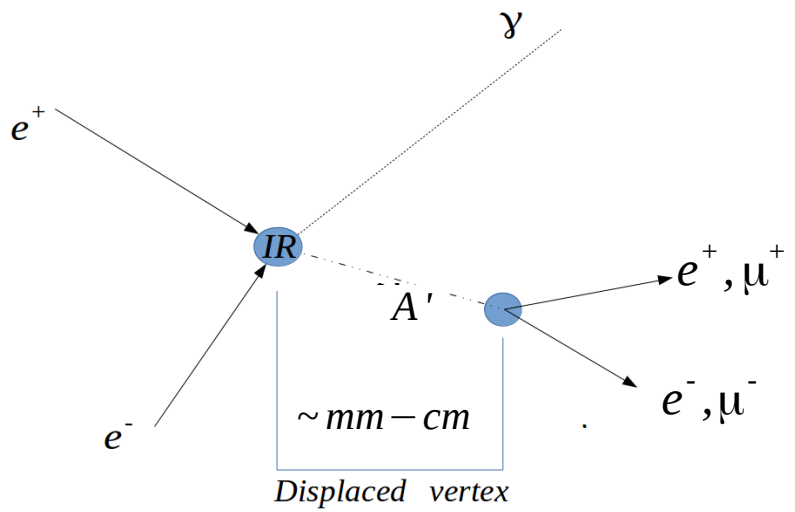
-Decays to leptons require $M_{A'}>1.02$ MeV/c^2
-Decays to hadrons require $M_{A'}>0.36$ GeV/c^2

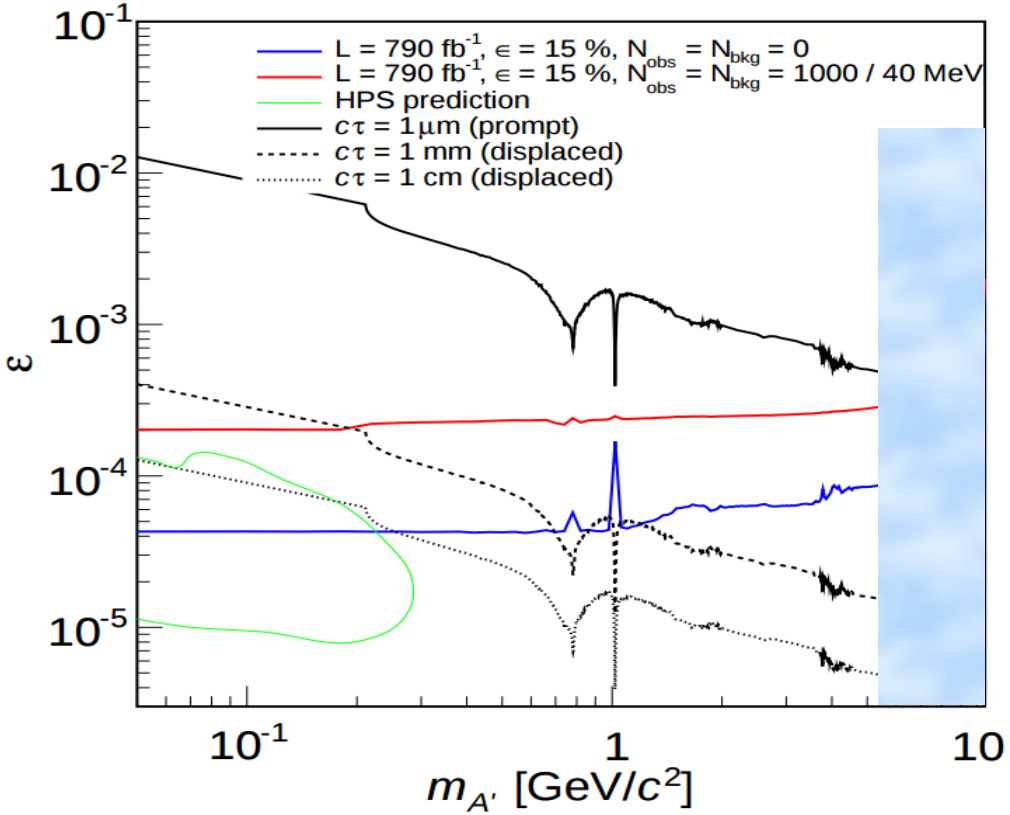
Currently ongoing analyses at Belle for e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^-$ final sates (including displaced vtx), results expected this year.



Dark photon searches @ BELLE II

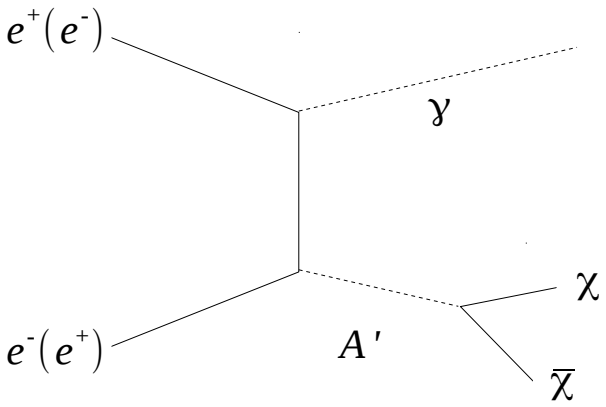
$$A' \rightarrow l^+ l^- \quad (l = e, \mu)$$
$$M_{A'} = 0.01 - 0.3\, GeV/c^2$$
$$W_{A'} = 1\, KeV/c^2$$
$$c\tau = 1\, cm$$

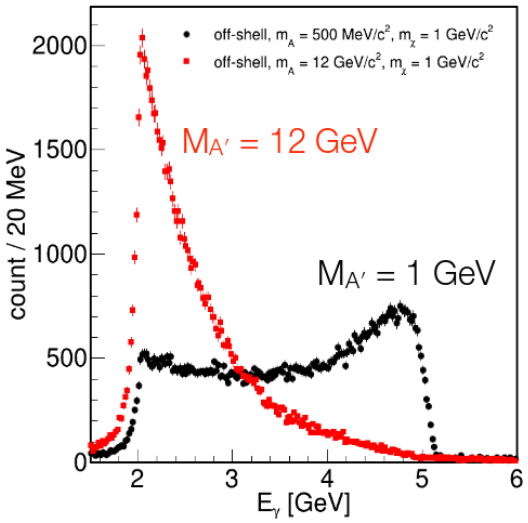


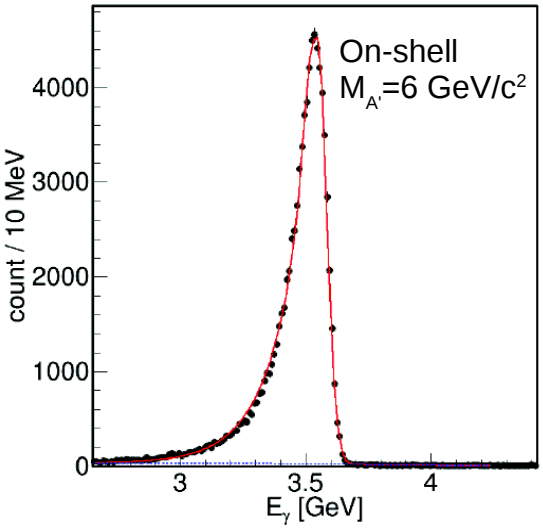


Dark photon searches @ BELLE II

See *R. Essig et al. JHEP11 (2013) 167.*





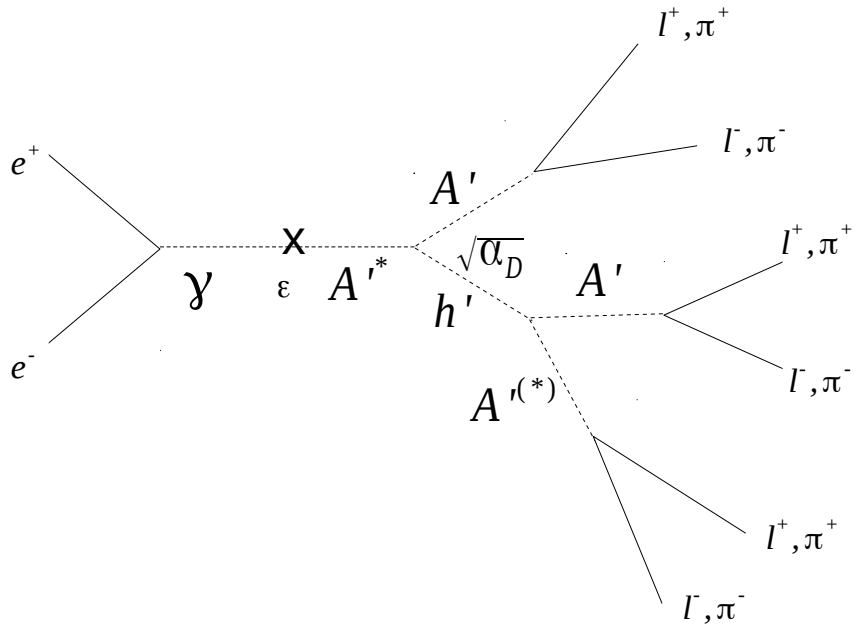


A'= dark photon, χ= dark matter particle (neutral under SU(3)xSU(2)xU(1))
A' decays to dark matter. On-shell or off-shell with different gamma spectrum .

radiative production in e+e- collisions
only one photon in the final state with $E^*_\gamma = (s - M^2_{A'})/2\sqrt{s}\,(on-shell)$
No existing limits

- Requires high rate single photon trigger, not available in Belle. The BaBar Collaboration implemented a single photon trigger (arXiv:0808.0017 [hep-ex]). Single photon trigger will be implemented at Belle II.
- Plans to study e+e- $\rightarrow \mu^+\mu^- A'$, followed by $A' \rightarrow \chi\chi$ (no special trigger required).

Dark Higgs-strahlung at Belle



h'= dark Higgs,

Higgs-strahlung: h' decays depending on $M_{h'}$ and M_A. Measures the coupling constant of the dark photon to the dark Higgs, α_D.

$M_{h'}>2M_{A'}$: h' → A'A', Very low background.

Exclusive: 3 charged tracks pairs with same invariant mass and total energy of the event.

Inclusive: 2 charged tracks pairs, same invariant mass, third A from 4-mom. of e^+e^- system

$M_{A'}<M_{h'}<2M_{A'}$: h' → A'A'*

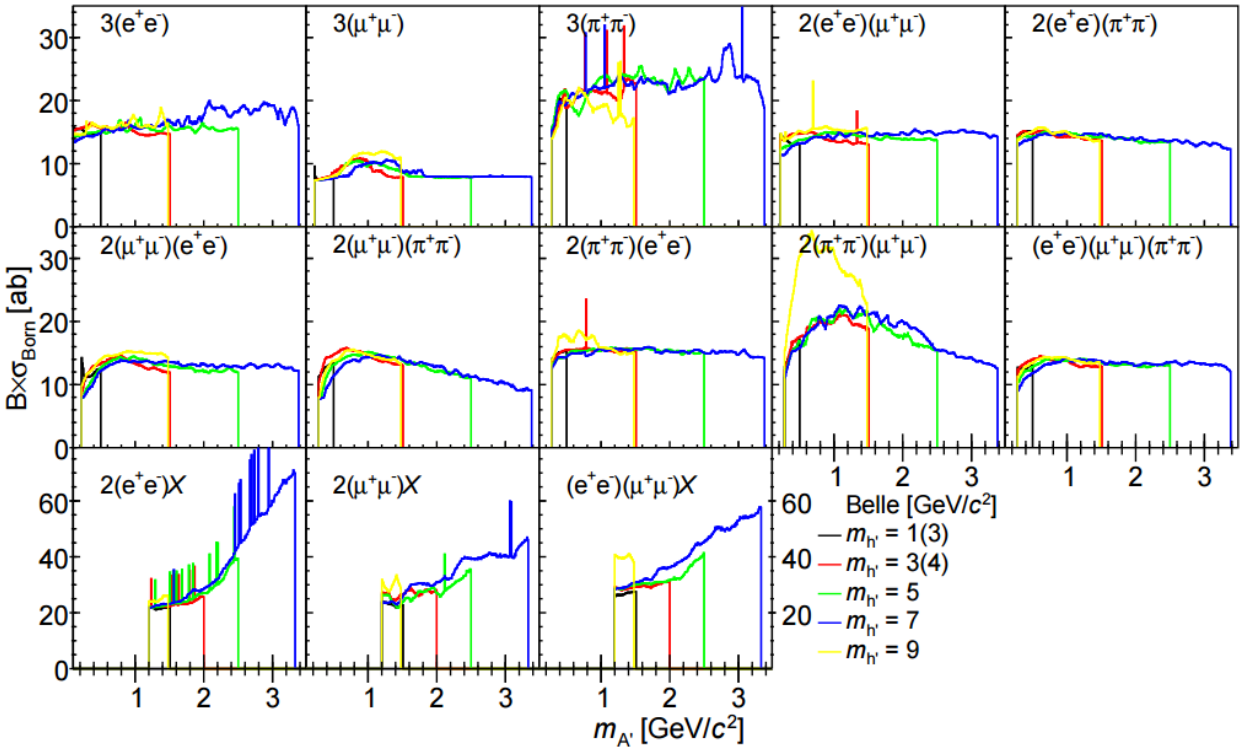
$M_{h'}<M_{A'}$: h' **long lived** and h' → $l^+l^-,\pi^+\pi^-$.

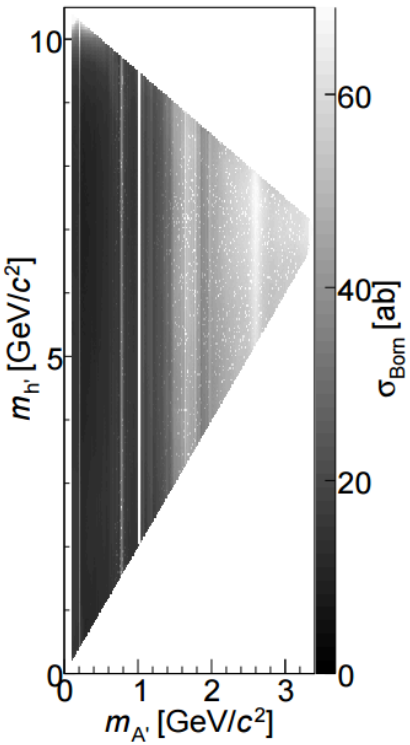
Dark Higgs-strahlung at Belle

$$e^+e^- \to A'h', \quad h' \to A'A'$$
$$A' \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-$$
$$2(e^+e^-)A', \quad 2(\mu^+\mu^-)A', \quad A' \to \textit{invisible}$$

Phys. Rev. Lett. **114**, 211801 (2015)

- Belle limits for $\mathcal{L} = 977$ fb^{-1} on $\mathcal{B} \times \sigma_{\mathrm{Born}}$ and σ_{Born}
  - 90% CL upper limit for each of the 13 final states
  - 90% CL upper limit on the combined Born cross section





- 90 % Credibility Level (CL) upper limit determined by Bayesian inference method with the use of Markov Chain Monte Carlo *A′*. Caldwell et al., CPC 180 (2009) 2197-2209

Limits from $3(\pi^+\pi^-)$ and $2(e^+e^-)X$ are the first placed by any experiment

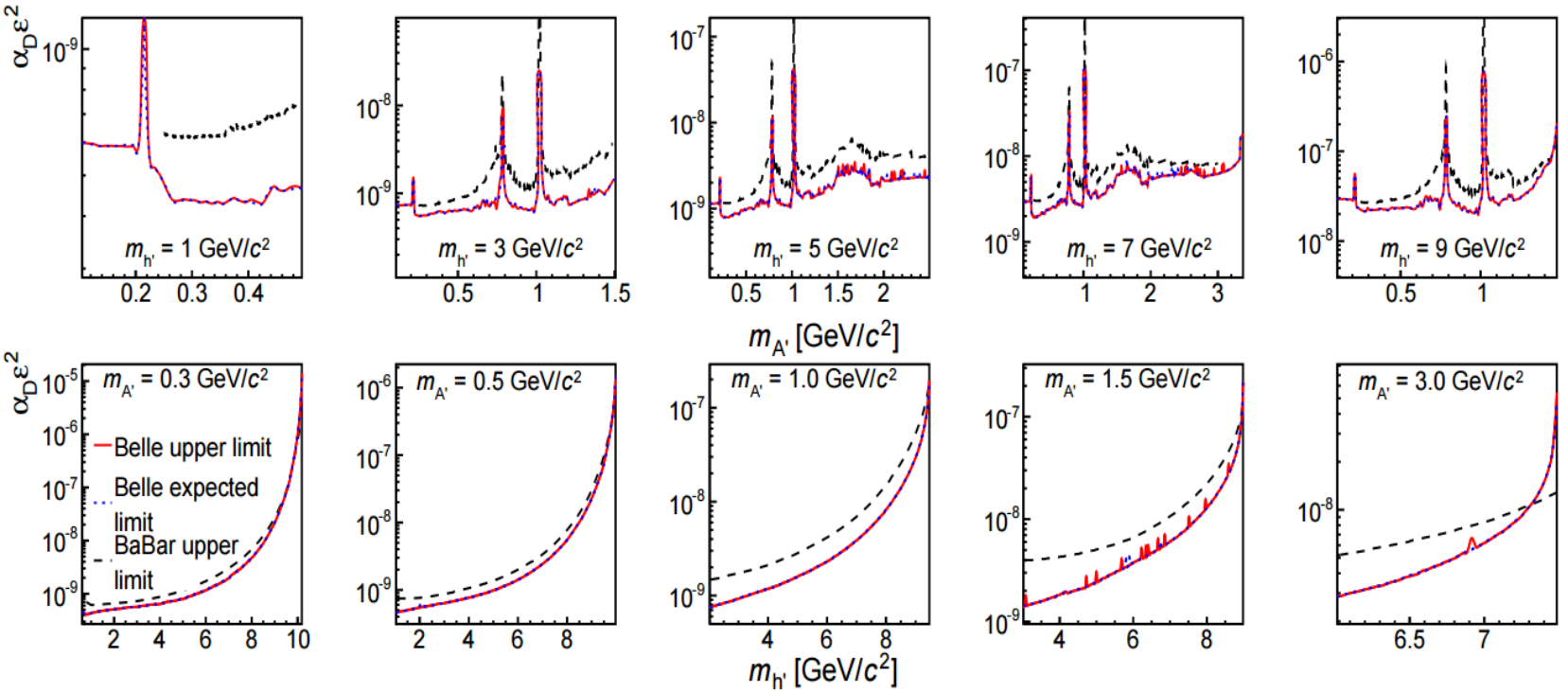
Dark Higgs-strahlung at Belle

$$e^+e^- \to A'h', \quad h' \to A'A'$$
$$A' \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-$$
$$2(e^+e^-)A', \quad 2(\mu^+\mu^-)A', \quad A' \to invisible$$

Phys. Rev. Lett. **114**, 211801 (2015)

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
- BaBar limits for $\mathcal{L} = 520$ fb^{-1} based on the visible cross section PRL 108 211801 (2012)

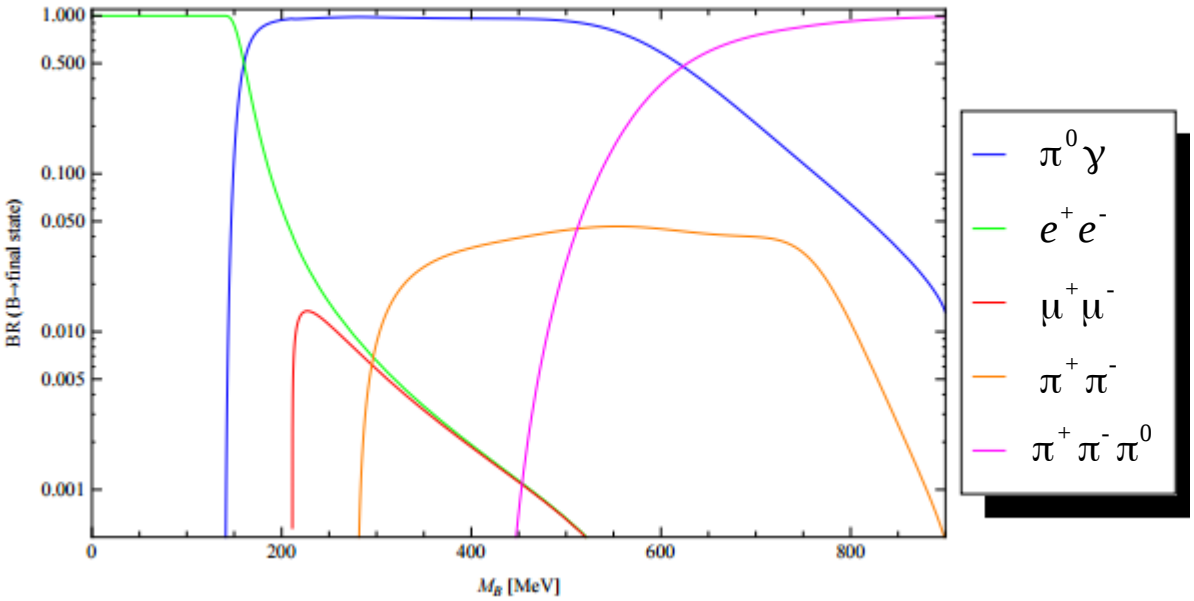


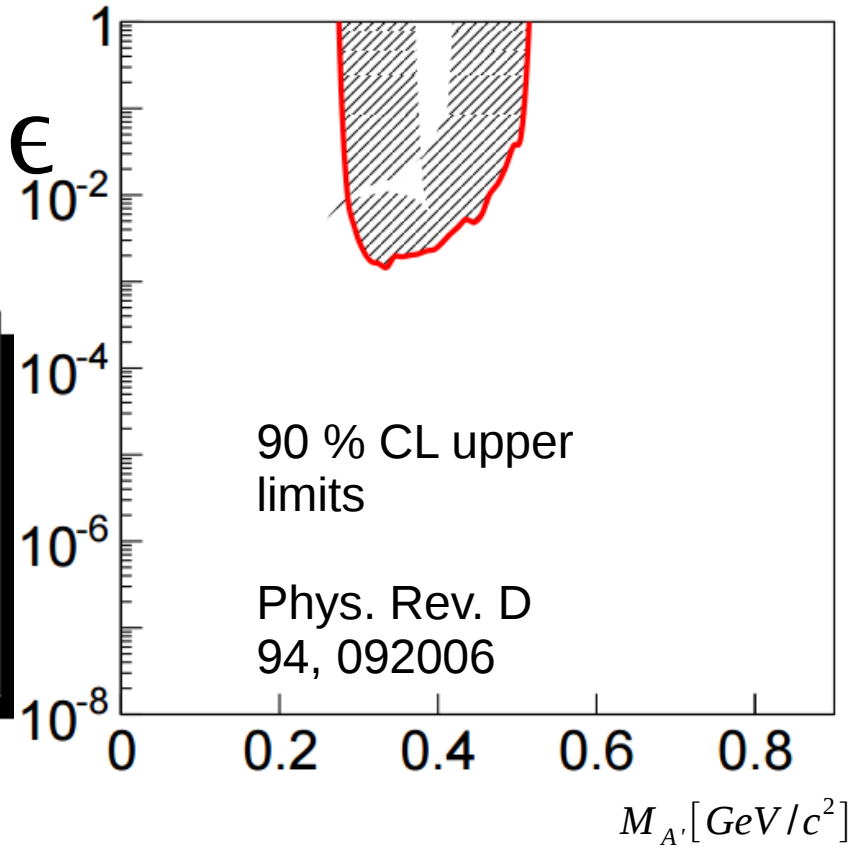
90% CL upper limit on the product $\alpha_D \times \varepsilon^2$ versus dark photon mass (top row) and dark Higgs boson mass (bottom row)

- Assuming branching fractions and couplings versus cross section from B. Batell et al. PRD 79 (2009) 115008

Dark photon in pseudoscalar decays

- Search for a dark vector boson in meson decays.
- Dark boson produced in pseudoscalar decays.
- Exclusive decay mode: $D^0 \to K_S^0 \eta \qquad \eta \to U'(\to \pi^+ \pi^-)\gamma$
- Reconstruct η.
- Search for a bump in the $M_{\pi\pi}$ distribution

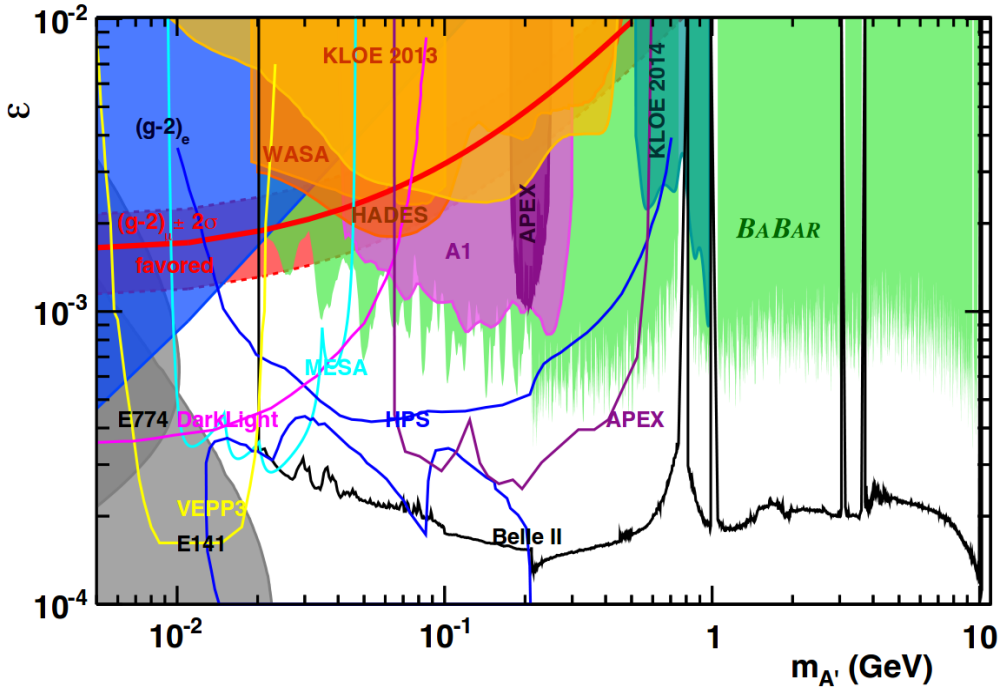




Dark photon, decays to SM particles and dark matter: expected limits at Belle II compared to other experiments

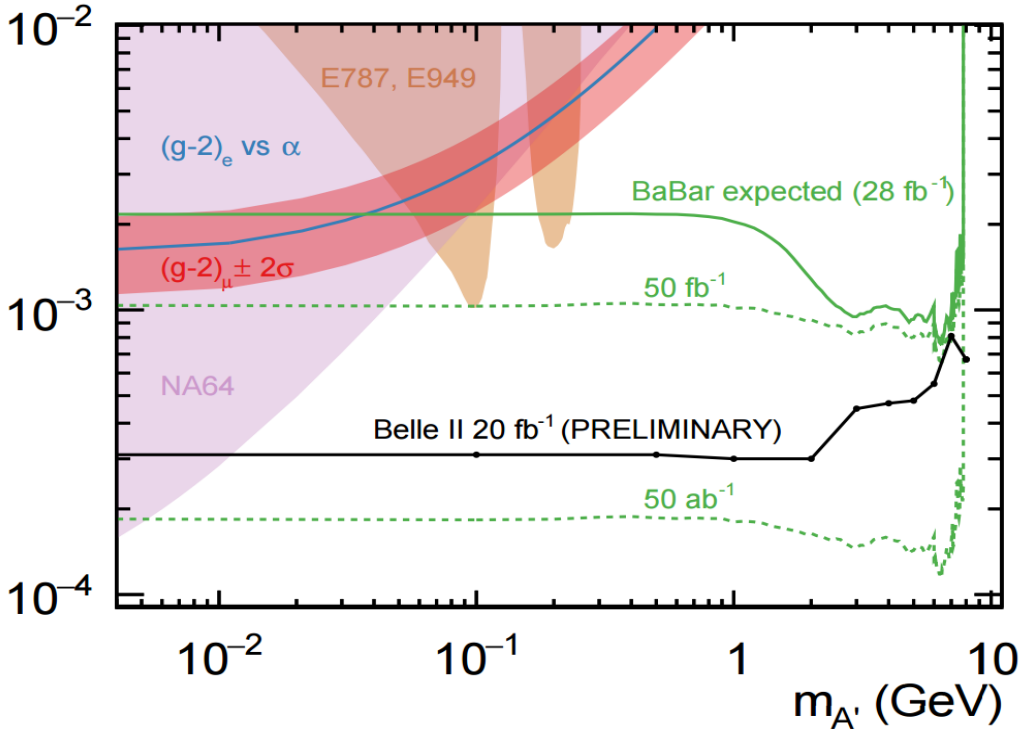
Projection from BABAR results to Belle 2 luminosity assuming same trigger/detector/reconstruction efficiencies

$e^+e^- \to \gamma A' \to \gamma e^+e^-, \gamma \mu^+\mu^-,$ *prompt*



Projection from BABAR results to Belle 2 luminosity assuming same trigger/detector/reconstruction efficiencies and Belle II MC study

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



Low mass dark matter @ Belle (II)

Y(nS): bound state of a b quark and a b antiquark

$$\frac{BR\left(Y(1S)\to \nu\bar{\nu}\right)}{BR\left(Y(1S)\to e^+e^-\right)}=\frac{27G^2M_{Y(1S)}^4}{64\pi^2\alpha^2}\left(-1+\frac{4}{3}\sin^2\theta_W\right)^2=4.14\times10^{-4}$$

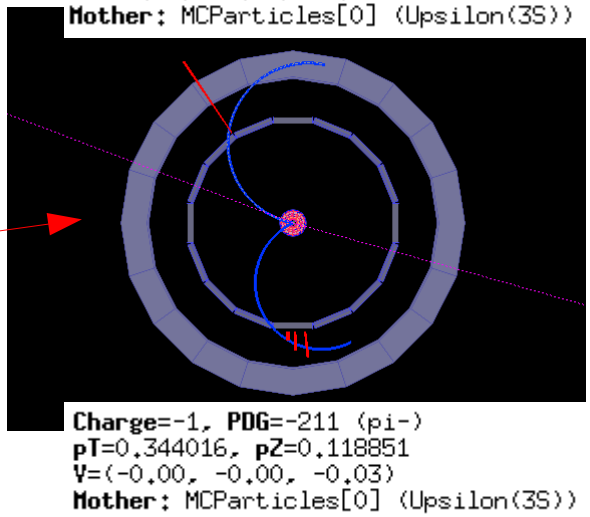
$$BR\left(Y(1S)\to \nu\bar{\nu}\right)\sim 9.9\times10^{-6}$$

- Low mass dark matter particles however might might play a role in the decays of Y(1S), having $Y(1S)\to\chi\chi$ if kinematic allowed. [Phys. Rev. D **80,** 115019, 2009]
- Also, new mediators (Z', A^0, h^0) or SUSY particles might enhance $Y(1S)\to\nu\nu(\gamma)$. [Phys. Rev. D **81**, 054025, 2010]
- In absence of new physics enhancement, Belle2 should be able to observe the SM $Y(1S)\to\nu\nu$

$$e^+e^-\to Y(3S)$$
$$\downarrow(4.4\%)$$
$$Y(3S)\to\pi^+\pi^-Y(1S)$$
$$\downarrow$$
$$Y(1S)\to invisible$$

$$e^+e^-\to Y(2S)$$
$$\downarrow(18.1\%)$$
$$Y(2S)\to\pi^+\pi^-Y(1S)$$
$$\downarrow$$
$$Y(1S)\to invisible$$

Belle2 Simulation
$Y(3S)\to\pi^+\pi^-Y(1S)$,
$Y(1S)\to\nu\nu$



$\sim 900\ MeV$ available for $P_{\pi\pi}$

$$M_{Y(3S)}=10.355\,GeV/c^2,\quad M_{Y(2S)}=10.023\,GeV/c^2,\quad M_{Y(1S)}=9.460\,GeV/c^2$$

$\sim 540\ MeV$ available for $P_{\pi\pi}$

Low mass dark matter @ Belle (II)

$$\frac{BR\left(Y(1S)\to\nu\bar{\nu}\right)}{BR\left(Y(1S)\to e^+e^-\right)}=\frac{27G^2M_{Y(1S)}^4}{64\pi^2\alpha^2}\left(-1+\frac{4}{3}\sin^2\theta_W\right)^2=4.14\times10^{-4}$$

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- Also, new mediators (Z', A^0, h^0) or SUSY particles might enhance Y(1S)→νν(γ). [Phys. Rev. D **81**, 054025, 2010]
- In absence of new physics enhancement, Belle2 should be able to observe the SM Y(1S)→νν

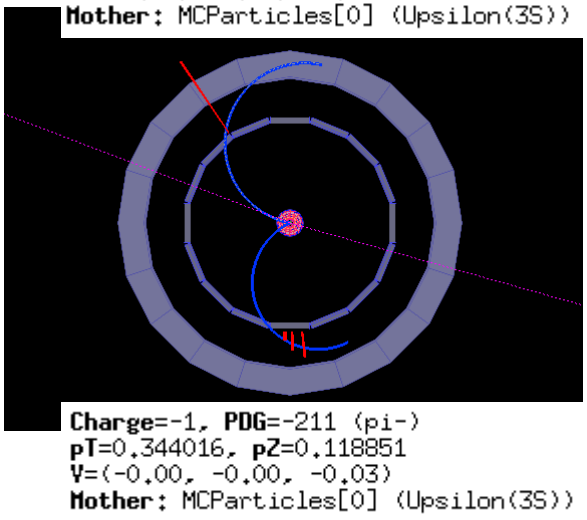
A signal of Y(1S)→*invisible* is an excess of events over the background in the M_r distribution at a mass equivalent to that of the Y(1S) (9.460 GeV/c²)

$$M_r^2=s+M_{\pi^+\pi^-}^2-2\sqrt{s}\,E_{\pi^+\pi^-}^{CMS}$$

$e^+e^-\to Y(3S)$
↓(4.4%)
$Y(3S)\to\pi^+\pi^-Y(1S)$
↓
$Y(1S)\to invisible$

$e^+e^-\to Y(2S)$
↓(18.1%)
$Y(2S)\to\pi^+\pi^-Y(1S)$
↓
$Y(1S)\to invisible$

Belle2 Simulation
Y(3S)→π⁺π⁻Y(1S),
Y(1S)→ νν



Low mass dark matter @ Belle II: Expected Yields

$$\frac{BR\left(Y(1S)\to\nu\bar{\nu}\right)}{BR\left(Y(1S)\to e^+e^-\right)}=\frac{27G^2M_{Y(1S)}^4}{64\pi^2\alpha^2}\left(-1+\frac{4}{3}\sin^2\theta_W\right)^2=4.14\times10^{-4}$$

$$BR\left(Y(1S)\to\nu\bar{\nu}\right)\sim9.9\times10^{-6}$$

$e^+e^-\to Y(3S)$
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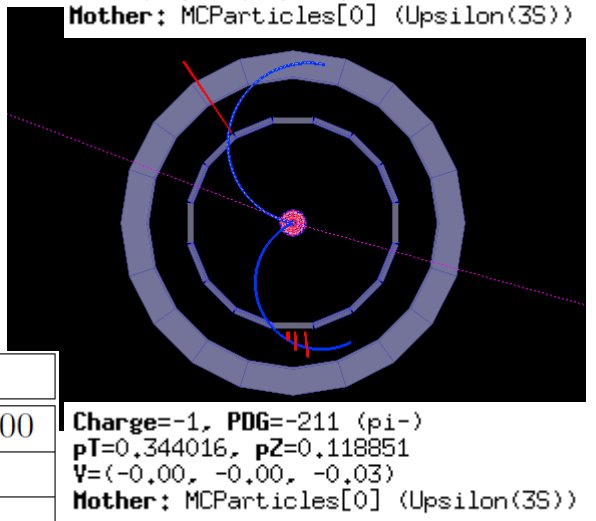
- In absence of new physics enhancement, Belle2 should be able to strongly constrain the SM Y(1S)→νν

Belle2 Simulation
Y(3S)→$\pi^+\pi^-$Y(1S),
Y(1S)→ νν



No signal was observed over the expected background and upper limits have been obtained: BR(Y→νν) < 3x10^{-4} (BaBar) and BR(Y→νν) < 3.0x10^{-3}(Belle).

Process	$L_{int}(ab^{-1})$	ϵ	$N(\Upsilon(1S))$	$N_{\Upsilon(1S)\to\nu\bar{\nu}}$	N_{NP}
$\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$	$0.2,\Upsilon(2S)$	0.1-0.2	2.3×10^8	230-460	6900-13800
$\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$	$0.2,\Upsilon(3S)$	0.1-0.2	3.2×10^7	32-64	945-1890
$\Upsilon(4S)\to\pi^+\pi^-\Upsilon(1S)$	$50.0,\Upsilon(4S)$	0.1-0.2	5.5×10^6	5.5-11	165-310
$\Upsilon(5S)\to\pi^+\pi^-\Upsilon(1S)$	$5.0,\Upsilon(5S)$	0.1-0.2	7.6×10^6	7.6-15.2	228-456
$\gamma_{ISR}\Upsilon(2S)\to(\gamma_{ISR})\pi^+\pi^-\Upsilon(1S)$	$50.0,\Upsilon(4S)$	0.1-0.2	1.5×10^8	150-300	4500-9000
$\gamma_{ISR}\Upsilon(3S)\to(\gamma_{ISR})\pi^+\pi^-\Upsilon(1S)$	$50.0,\Upsilon(4S)$	0.1-0.2	3.5×10^7	35-70	1050-2100

Conclusions

- Lack of experimental evidence for WIMPs
  - Ongoing searches of the dark photon with Belle data, results planned to be ready by the end of the year.
  - Belle II will cover additional regions of the parameter space of the dark photon mass vs. mixing parameter with high discovery potential; plan to search for decays of the dark photon to low mass dark matter.

- Search for low mass dark matter in Y(1S)→invisible (+gamma) planned at Belle II.

- Belle II will have a strong impact in the searches for new physics from 2018 for the next decade

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Thank you for your attention!

Conclusions

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