Dark photon search and the Higgs-strahlung channel at Belle for $0.25 < m_A < 3.5$ GeV/c^2 and $0.5 < m_{h'} < 10.5$ GeV/c^2

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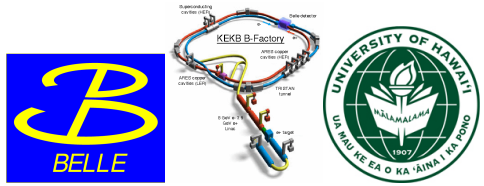
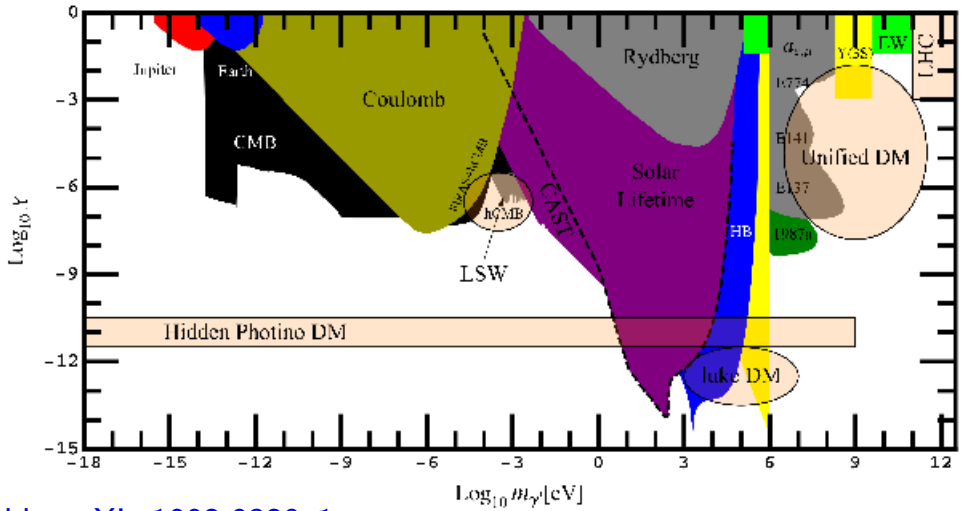


Table of contents

Previous and new search

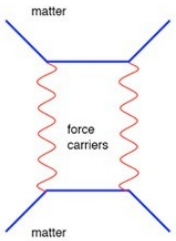
- search for $U(1)$ boson coupling to SM fermions via EM current started in the late 80's
- recently strong interest in dark sector models (Unified DM)
- introduce a vector boson A, and often a dark Higgs h' by a Higgs mechanism
- fixed target experiments have been approved/commissioned at JLAB and MAMI
  - plot below shows astrophysical and cosmological, constraints and experimental limits: kinetic mixing vs. $U(1)$ boson mass
    - ★ $U(1)$ boson/dark photon: $\gamma'/A/U/A'/A_D$
    - ★ kinetic mixing: χ/ϵ

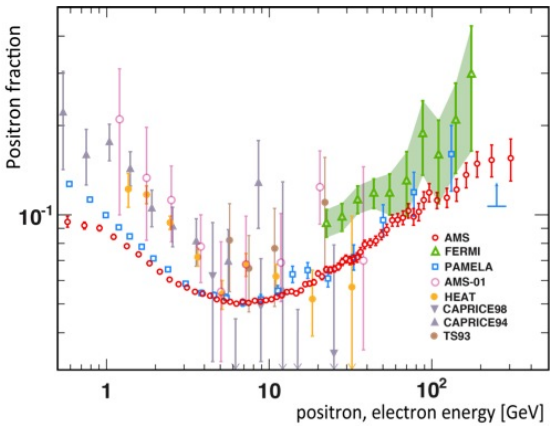


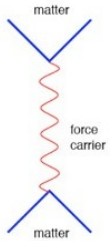
J. Jaeckel and A. Ringwald - arXiv:1002.0329v1

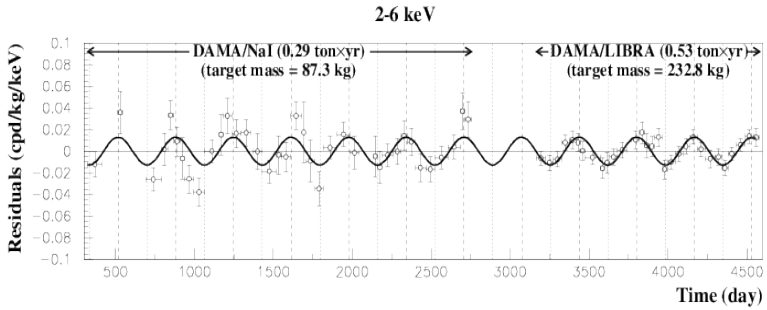
Experimental anomalies

- DM can explain observed anomalies in astrophysical data and dark matter experiments
  - positron excess but no $\bar{p}$ excess due to dark matter annihilation into dark photons that decay into e^+e^-? AMS2 PRL 110, 141102 (2013)
  - annual modulation due to the Earth's orbit around the Sun as the Sun orbits the galactic centre ? DAMA/LIBRA, Eur. Phys. J. C 56: 333-355 (2008)





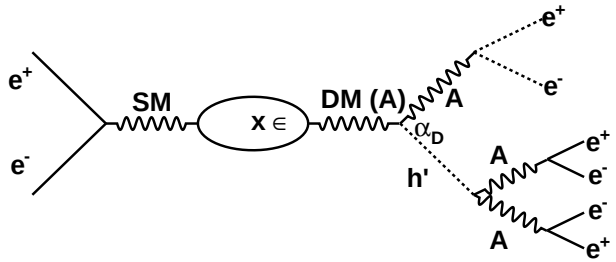




- no $\bar{p}$ excess implies $\Rightarrow$ $m_A < 2\ GeV/c^2$
- scattering cross section $\sigma \propto \frac{1}{(q^2 - M_*^2)^2}$ with q: momentum transfer ($q^2 = 2m_{nucleus}E_{recoil}^{nucleus}$) and M_*: carrier particle = A or W, Z
  - $M_* \to 0$ then $\sigma \propto \frac{1}{q^4}$, long range interaction $\Rightarrow$ $\frac{d\sigma}{dE_{recoil}^{nucleus}} \propto \frac{1}{(m_{nucleus}E_{recoil}^{nucleus})^2}$
  - $M_* \gg q$ then $\sigma \propto \frac{1}{M_*^4}$, contact term interaction
- modulation amplitude enhanced if long range interaction
- in this interpretation $\Rightarrow$ $m_A \ll 1\ GeV/c^2$

Search for the dark photon and dark Higgs at Belle

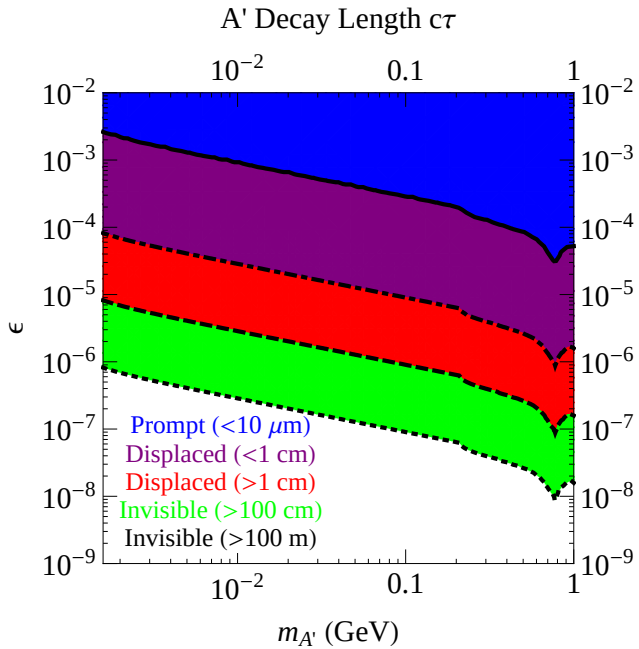
$e^+e^- \to Ah' \to AAA$ with $A \to l^+l^-$ (l=e or μ) or hadrons, A and h' prompt and $m_{h'} > 2m_A$
B. Batell, M. Pospelov, and A. Ritz arXiv:0903.0363 (2009)



α_D: dark sector constant
ϵ^2: kinetic mixing

- channels presented today
  - $e^+e^- \to 3e^+3e^-$
  - $e^+e^- \to 3\mu^+3\mu^-$
  - $e^+e^- \to 2\mu^+2\mu^-e^+e^-$
  - $e^+e^- \to 2\pi^+2\pi^-e^+e^-$
- if A coupling to h' unity
- Higgs-strahlung channel most sensitive to A since QED background low
- than other decays e.g.: $e^+e^- \to A\gamma$ with huge QED background

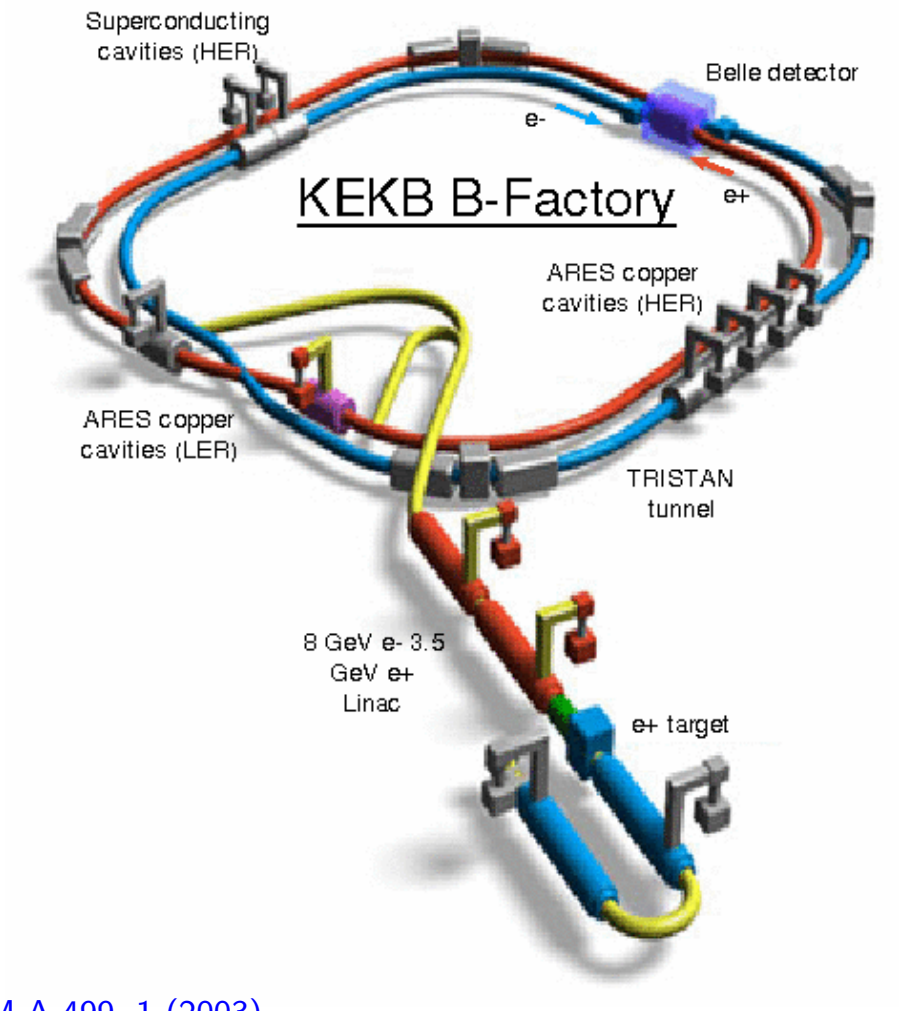
- plot shows lifetime of A as a function of its mass m_A and ϵ
  R. Essig et al, arXiv:0903.3941



- $m_{h'} < m_A$: $h' \to$ invisible
- $m_A < m_{h'} < 2m_A$: $h' \to l^+l^-$ or hadrons
- $m_{h'} > 2m_A$: $h' \to AA$
- A and h' not necessarily prompt

Accelerator

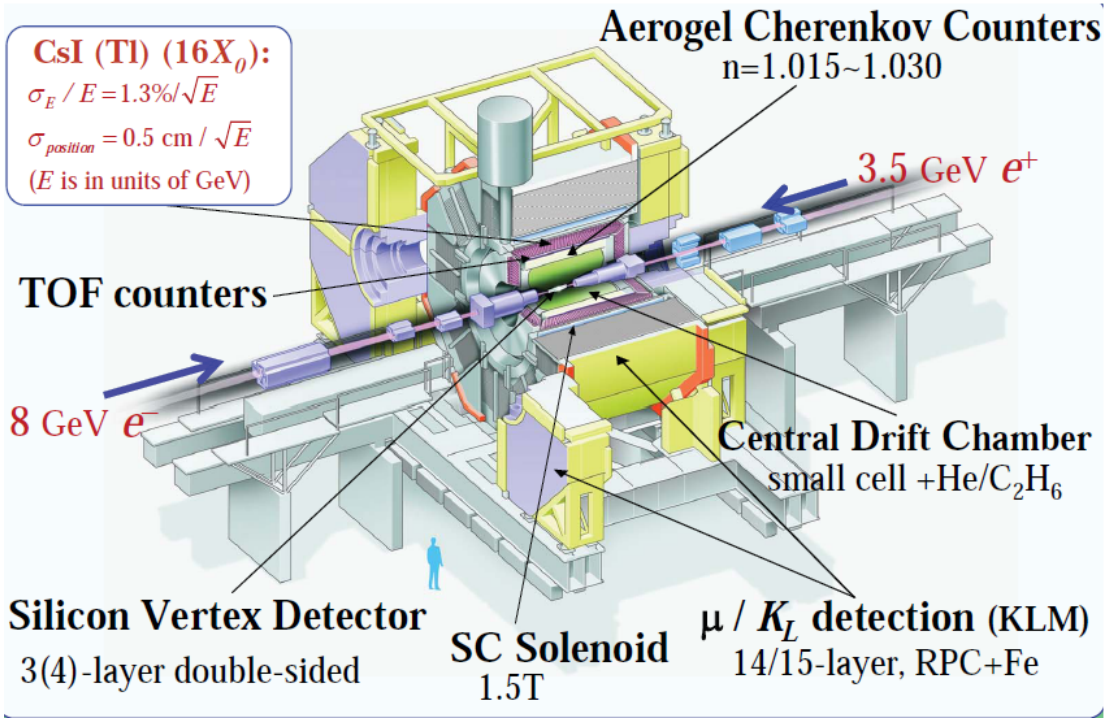
- Belle experiment at KEK B-factory in Tsukuba, Japan
- $E_{e^-} \sim 8$ GeV/c^2 and $E_{e^+} \sim 3.5$ GeV/c^2
- L $= 977$ fb^{-1} at $\Upsilon(1S, 2S, 3S, 4S, 5S)$ and continua



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

Belle setup

- plot shows Belle setup



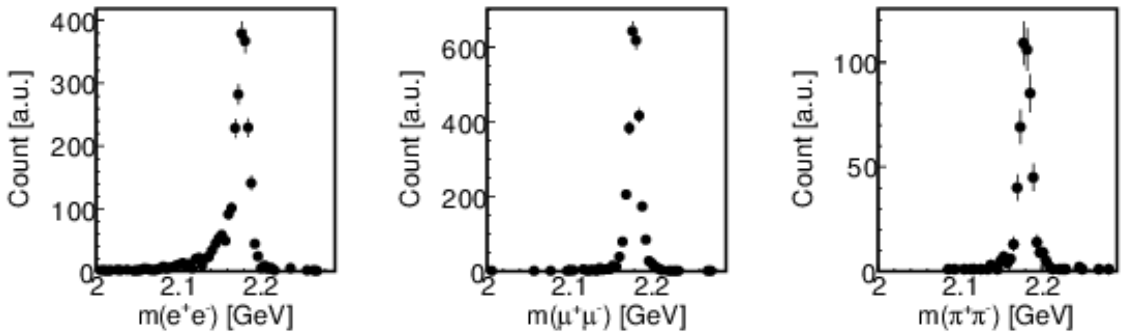
- particle identification
  - electron ID: E-ECL/p-CDC
  - μ ID: μ/K$_L$ measurements of penetration depth and charged track muon cluster matching

K. Hanagaki et al, NIM A 485, 490 (2002)
A. Abashian et al, NIM A 491, 69 (2002)
Belle Collaboration, NIM A 479, 117 (2002)

Analysis strategy

Full reconstruction of exclusive six-lepton/hadron final states from $e^+e^- \to Ah' \to AAA$

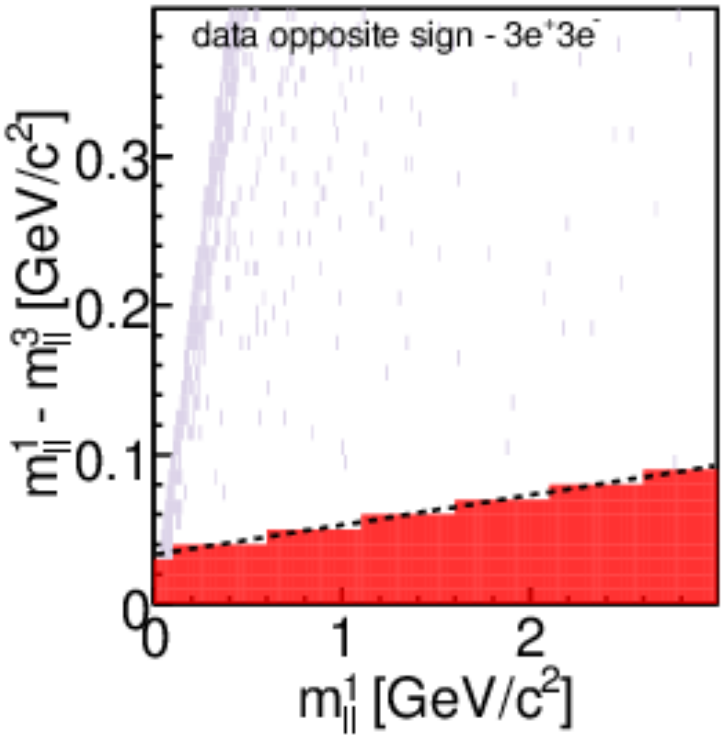
- final state identification
  - 6 charged tracks
  - 3 pairs of opposite charge
- signal reconstruction
  - impact parameters and χ^2 vertex fit cuts
  - require energy conservation
  - calculate invariant mass for each combinations of leptons/hadrons consistent with three distinct $A \to l^+l^-$ or hadrons
  - keep combinations with three masses "equal"
  - plots below show signal Monte Carlo simulation events surviving selection with $m_{h'} = 5$ GeV/c^2 and $m_A = 2.19$ GeV/c^2

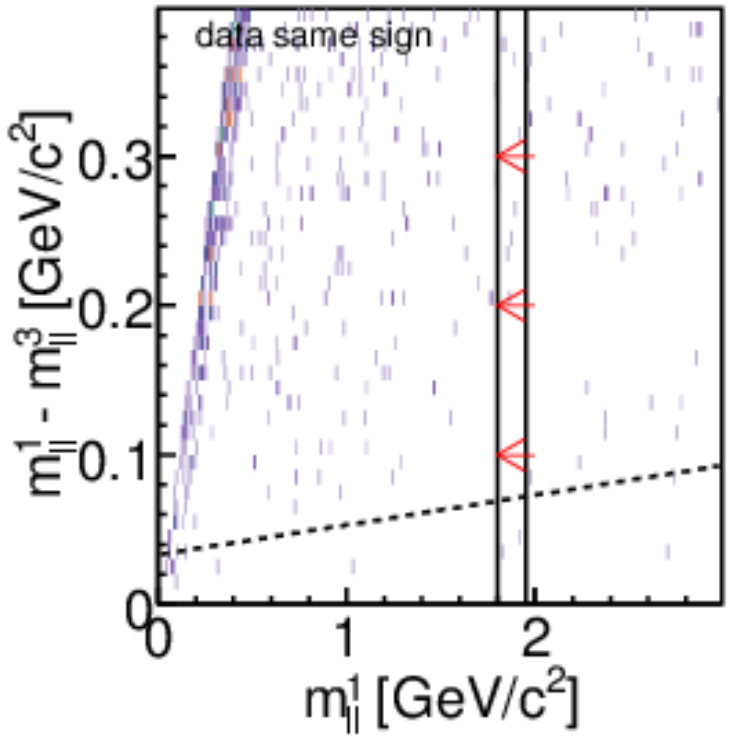


Background estimation with signal box blinded - part I

Data driven background estimation

- estimate background using "same sign" events $e^+e^- \to Ah' \to A(l^+l^+)A(l^+l^+)A(l^-l^-)$
- order masses of lepton pairs $m^1_{ll} > m^2_{ll} > m^3_{ll}$ and plot $m^1_{ll} - m^3_{ll}$ vs. m^1_{ll}
- select region in m_{ll} and predict background there using same sign
  - $e^+e^- \to 3e^+3e^-$

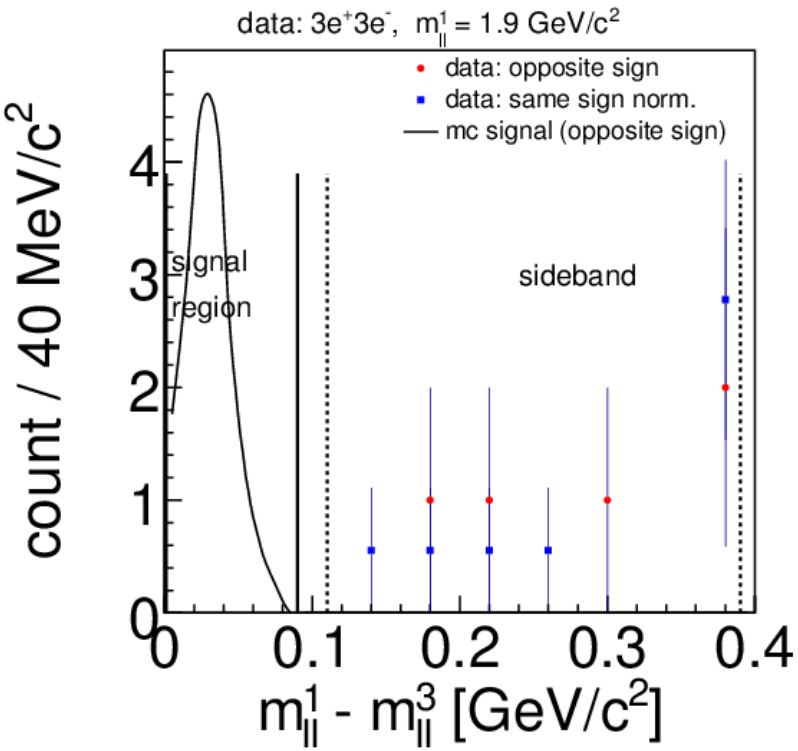




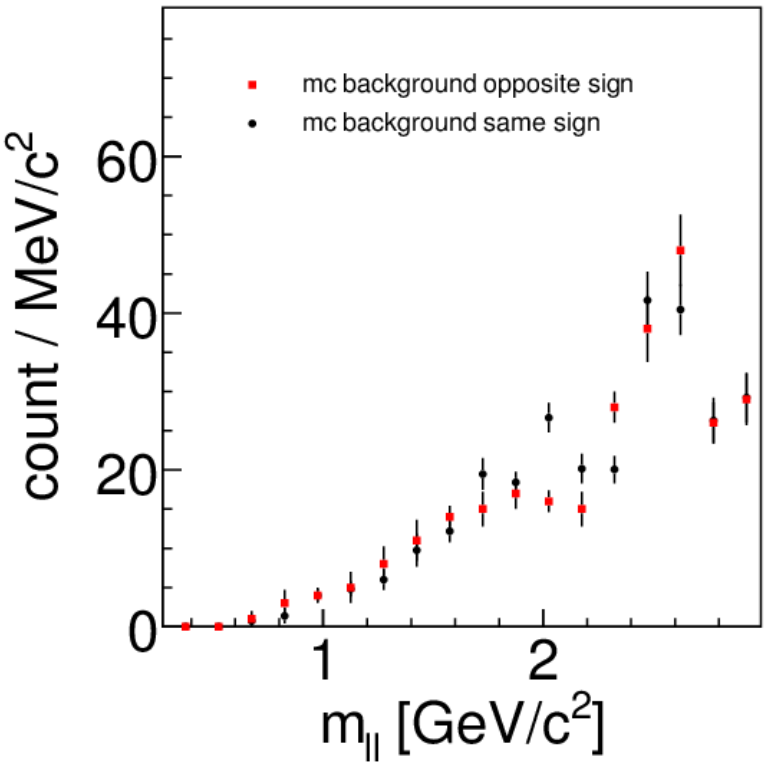
Background estimation with signal box blinded - part II

- sideband used to normalize same sign to opposite sign
- background estimated from the number of counts in the signal region of the same sign distributions
- background estimation method verified successfully with MC

- projection on $m^1_{ll} - m^3_{ll}$ for $m^1_{ll} = 1.9$ GeV/c^2



- MC test



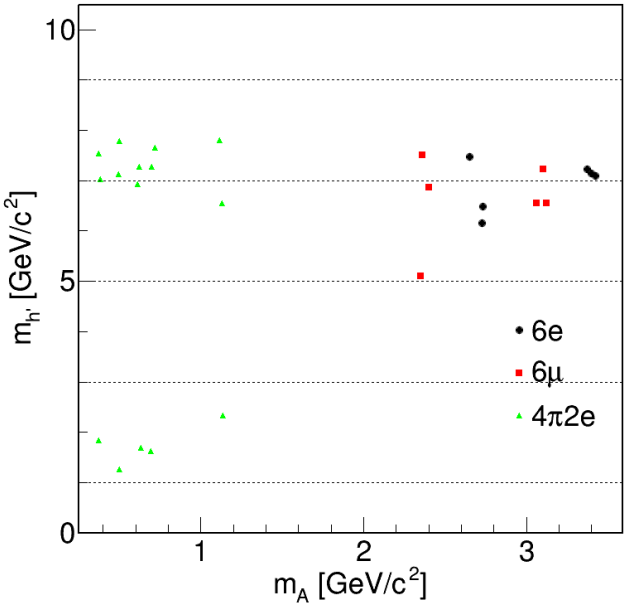
Background estimation with signal box opened

Comparison between predicted Belle background, Belle number of events measured and BaBar number of events measured

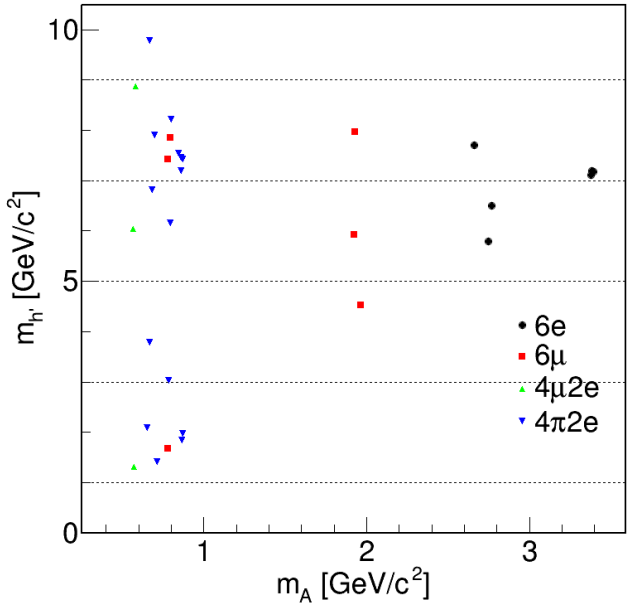
Final state	6e	6μ	$4\mu 2e$	$4\pi 2e$
Belle expected	3.60 ± 1.31	1.64 ± 1.12	0	6.81 ± 3.64
Belle measured	2	2	1	5
BaBar measured	0	0	0	2

=> Number of events measured consistent with background expectation

- same sign (predicted)



- opposite sign (measured)

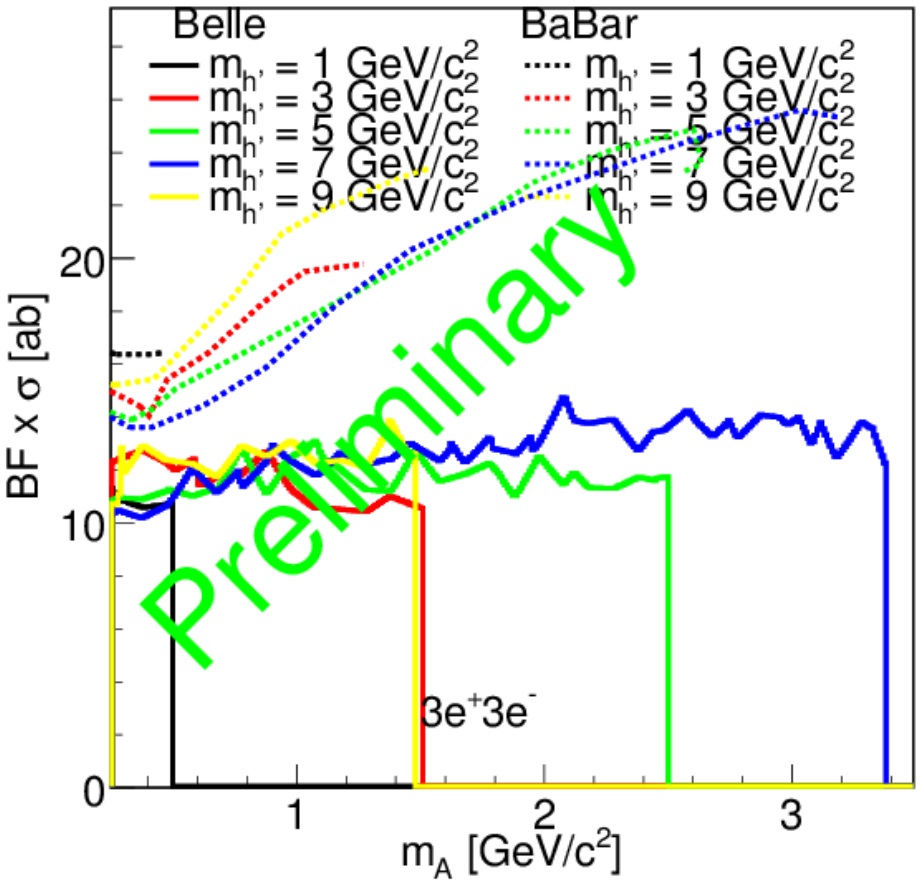


contribution of $\rho \to \pi^+\pi^-$ or $\omega \to \pi^+\pi^-$ decays for $0.7 < m_A < 0.9$ GeV/c^2

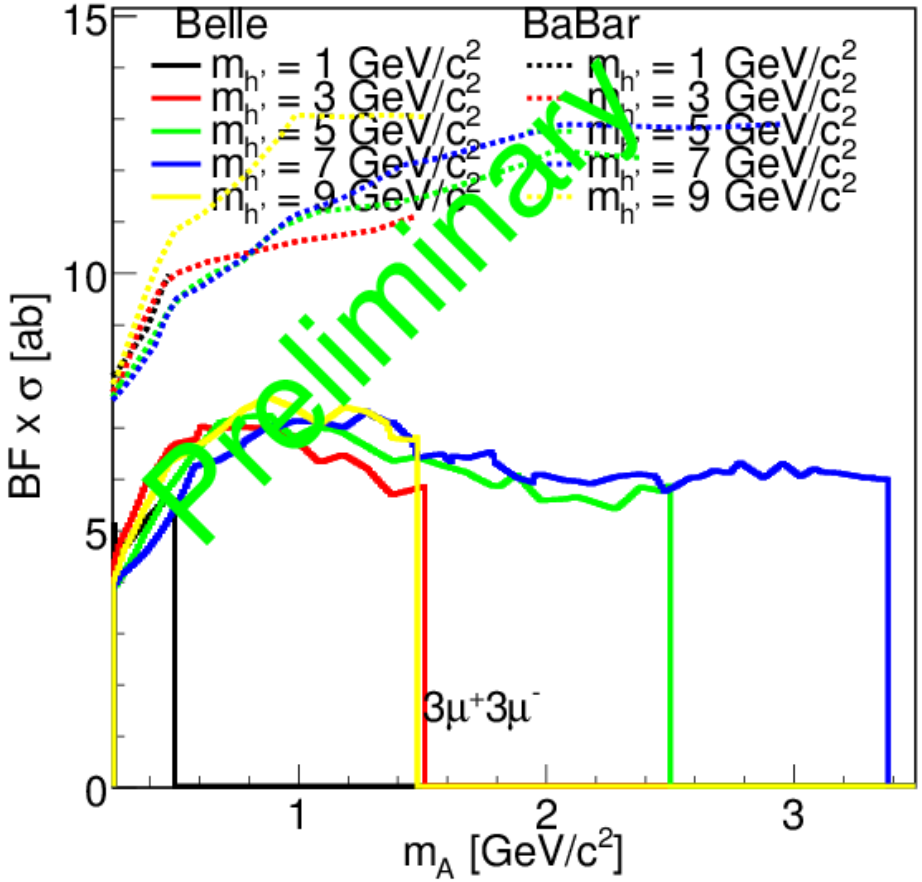
Preliminary limit

Compare to BaBar limits BaBar Collaboration - arXiv:1202.1313

- $e^+e^- \to 3e^+3e^-$



- $e^+e^- \to 3\mu^+3\mu^-$



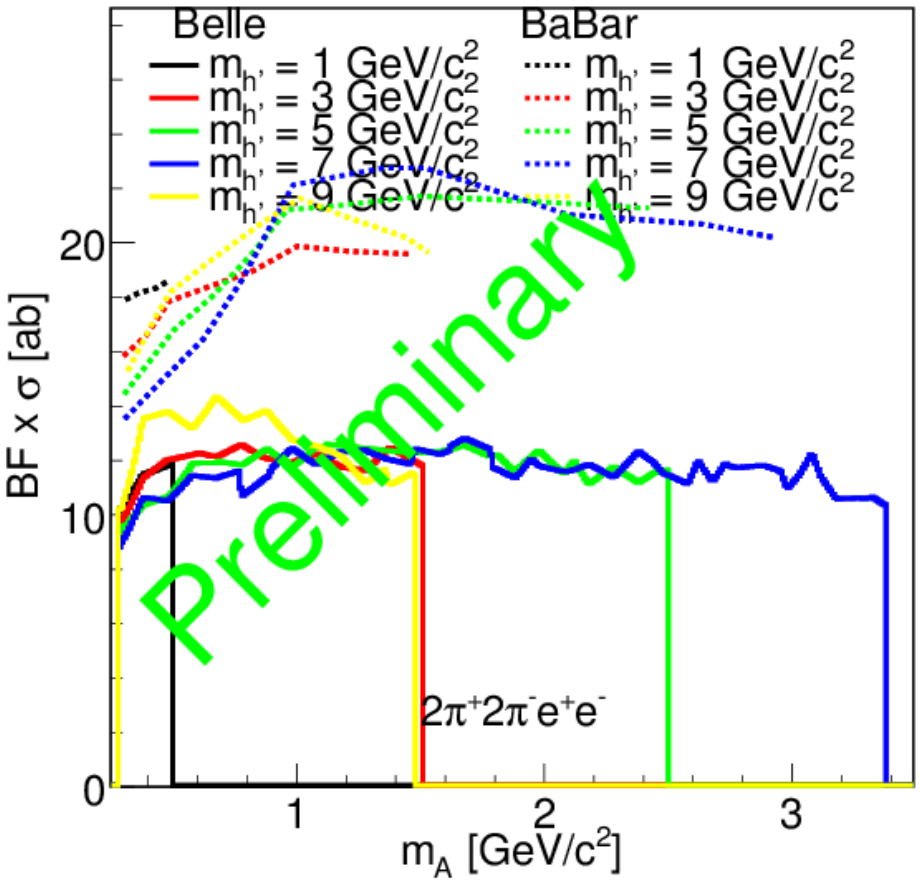
- assume error on background in one bin = background estimation error for all bins
- upper limit (90 % CL) determined by Bayesian inference method with the use of Markov Chain Monte Carlo

A. Caldwell et al., CPC 180 (2009) 2197-2209

Preliminary limit

Compare to BaBar limits BaBar Collaboration - arXiv:1202.1313

- $e^+e^- \to 2\pi^+2\pi^- e^+e^-$



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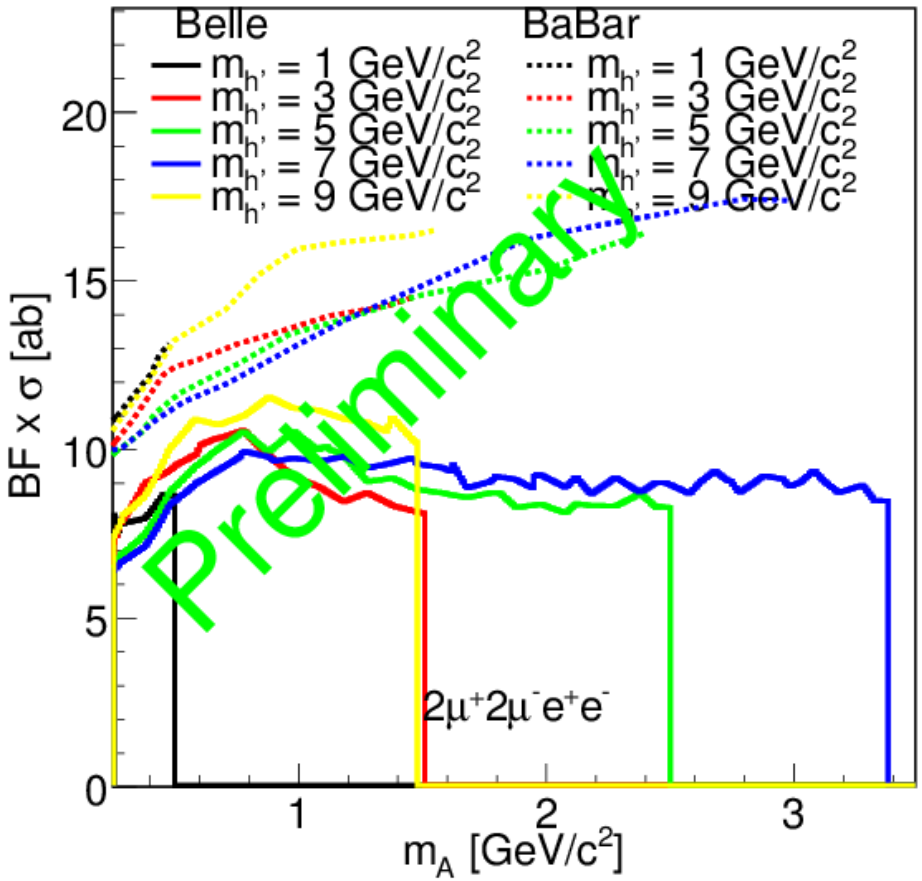


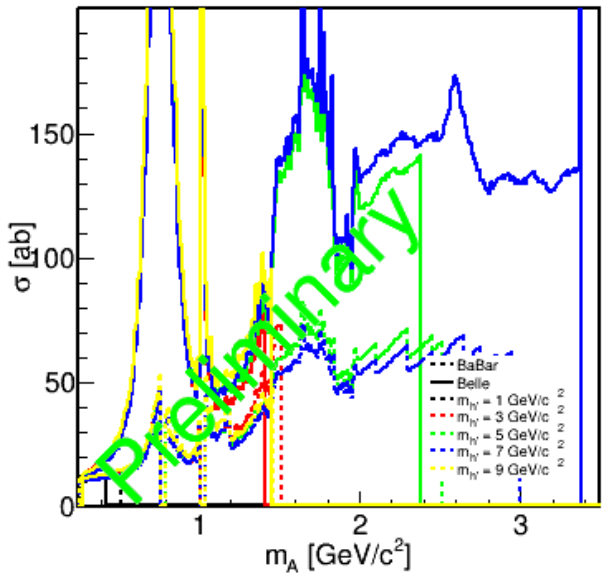
=> limit scales nearly linearly with integrated luminosity

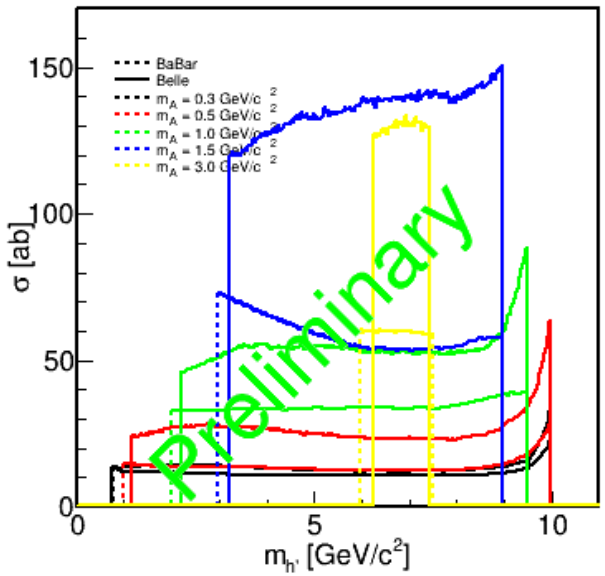
Preliminary combined limit

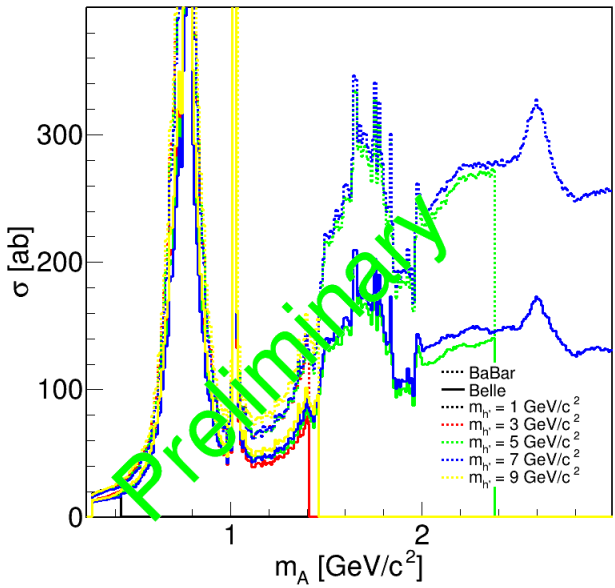
Compare to BaBar combined limit

- BaBar combined 11 channels
- this work combined 4 channels
- plot on the right comprison to BaBar with only 4 channels combined as Belle

- dark photon 90 % CL limit
- dark Higgs 90 % CL limit
- same channels combined





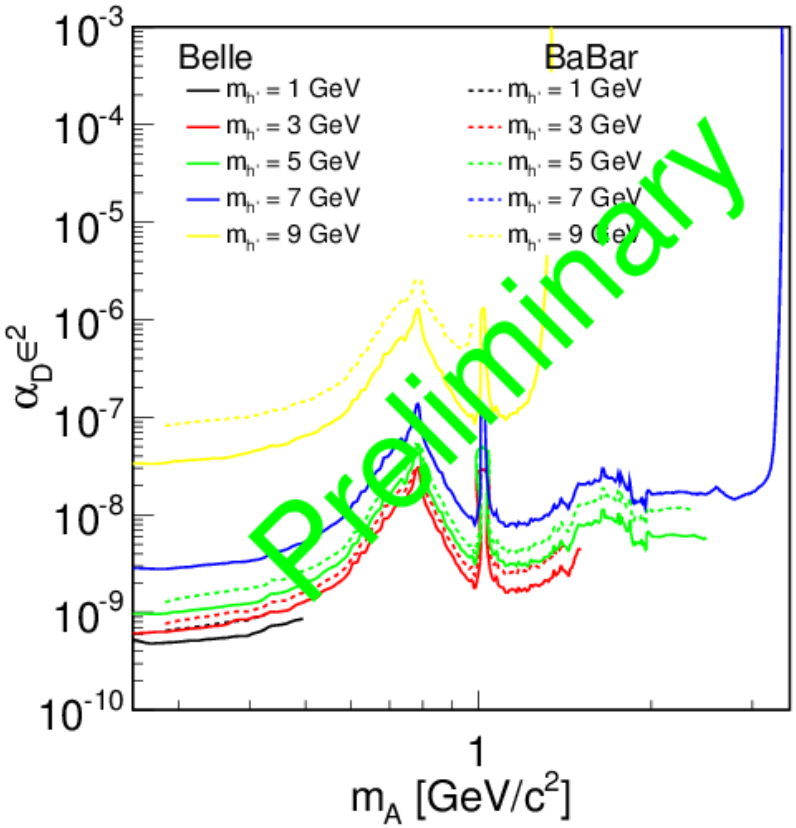


=> limit scales nearly linearly with integrated luminosity

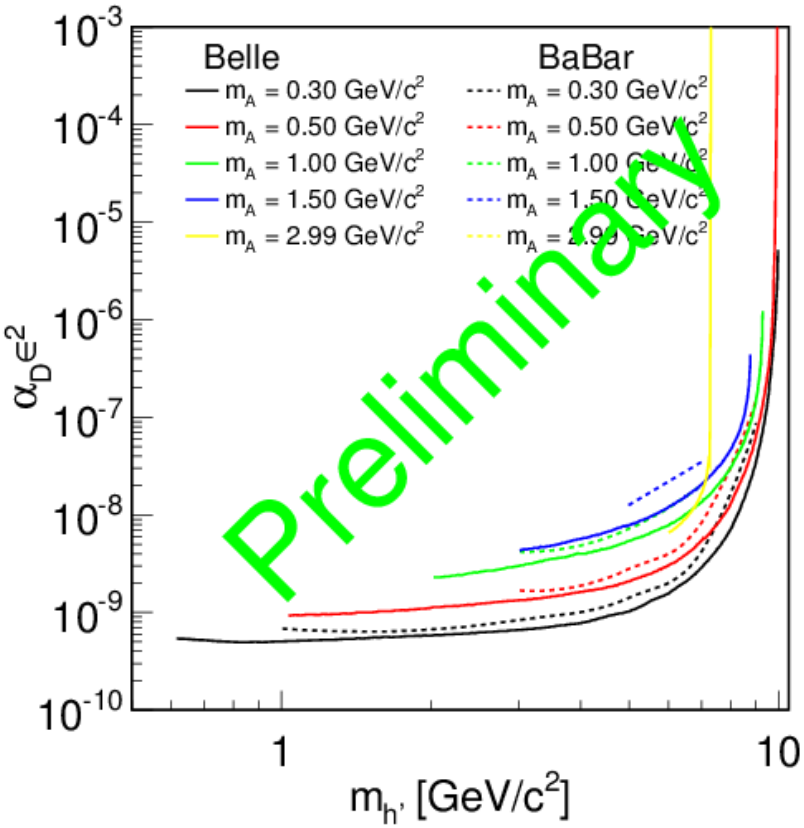
Preliminary combined limit as the product of $\alpha_D \epsilon^2$

Compare to BaBar combined limit with only 4 channels combined as Belle

- dark photon 90 % CL limit



- dark Higgs 90 % CL limit



Conclusion

Search for dark photon and dark Higgs in the mass ranges:

- $0.25 < m_A < 3.5$ GeV/c^2
- $0.5 < m_{h'} < 10.5$ GeV/c^2

We found that:

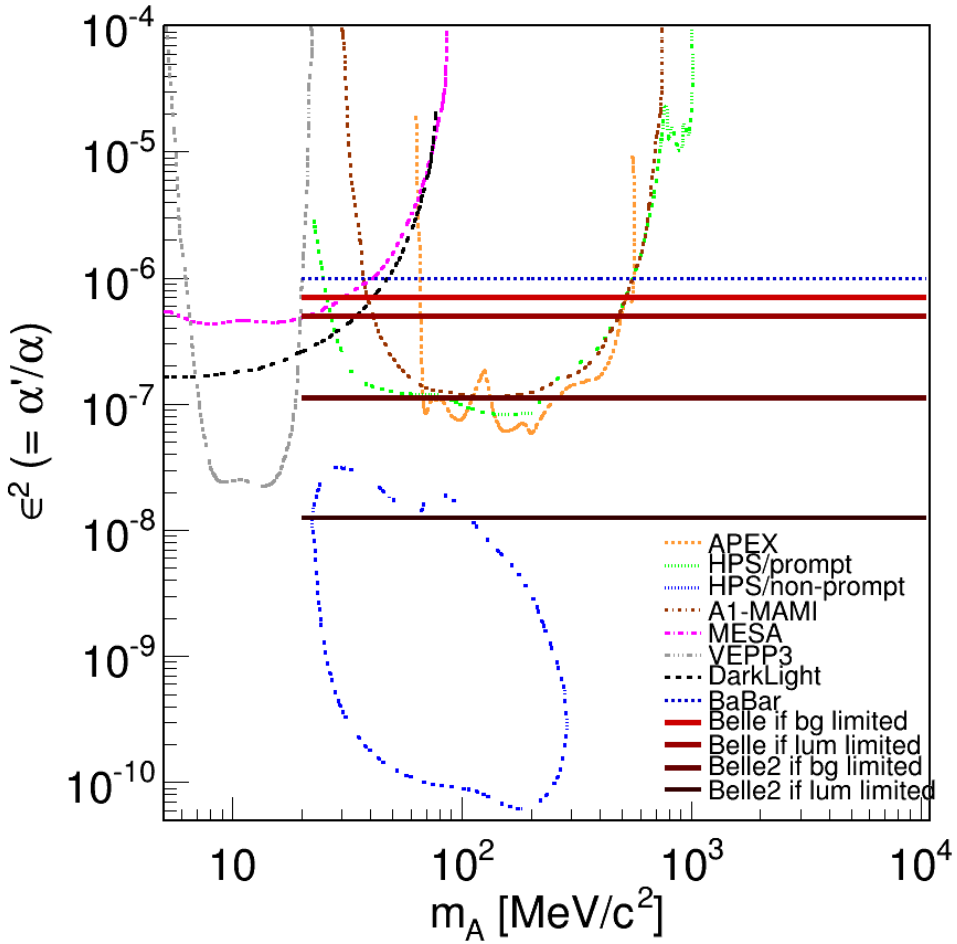
- background is small, implying
- limit scales nearly linearly with integrated luminosity

We plan in the near future to include the other possible decays in the combined limit

Outlook

Belle2 will take 40 times more statistics

- expected sensitivities for $A\gamma$ channel
  - Belle2 (and Belle/BaBar)
  - fixed target experiments



- Belle2 instantaneous luminosity $\ll$ fixed target exp. instantaneous luminosity
- Belle2 can cross-check with no extra cost any fixed target results avobe 20 MeV/c^2
- Belle2 can extract limit up to 10 GeV/c^2

Thanks for your attention