Latest dark sector results from e^+e^- colliders

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Alpine Particle Physics Symposium 2023

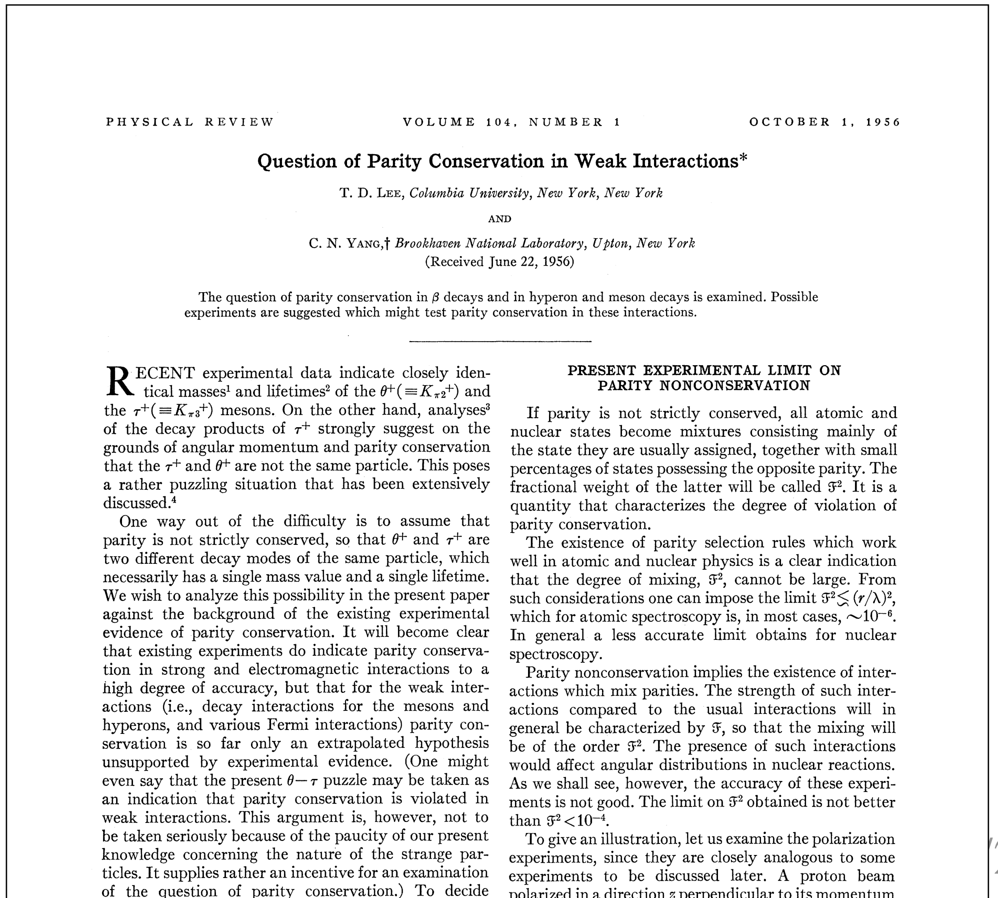
Outline

- Introduction - what is Dark Sector.
- The previous results of search for Dark Photon A'
- Search for Dark Photon via $D^{*0} \to D^0 A'$ decay
- The recent results of searches for Dark Sector Particles
    - Dark Photon
    - Dark Z boson
    - Dark Higgs

Introduction - Dark Sector

- "Dark sector" is an "allowed" theoretical hypothesis in the SM (Standard Model), but recently it attracts interest in relation with the Dark Matter.
- The origin of idea is the existence of left-handed and right-handed protons (p_L and p_R) in the parity symmetry breaking.
  - The Dark Sector is a collection of particles similar to Standard Model.
  - They has their own symmetries independent of Standard Model.
- They are predicted to be in MeV-GeV mass region. Therefore, the low background environment and high luminosity of lepton colliders suit the search.

T. D. Lee and C. N. Yang,
"Question of Parity Conservation in Weak Interactions
Phys. Rev. 104, 254 (1956);


PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

T. D. LEE, *Columbia University, New York, New York*
AND
C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*
(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

RECENT experimental data indicate closely identical masses[1] and lifetimes[2] of the $\theta^+(\equiv K_{\pi 2}^+)$ and the $\tau^+(\equiv K_{\pi 3}^+)$ mesons. On the other hand, analyses[3] of the decay products of τ^+ strongly suggest on the grounds of angular momentum and parity conservation that the τ^+ and θ^+ are not the same particle. This poses a rather puzzling situation that has been extensively discussed.[4]

One way out of the difficulty is to assume that parity is not strictly conserved, so that θ^+ and τ^+ are two different decay modes of the same particle, which necessarily has a single mass value and a single lifetime. We wish to analyze this possibility in the present paper against the background of the existing experimental evidence of parity conservation. It will become clear that existing experiments do indicate parity conservation in strong and electromagnetic interactions to a high degree of accuracy, but that for the weak interactions (i.e., decay interactions for the mesons and hyperons, and various Fermi interactions) parity conservation is so far only an extrapolated hypothesis unsupported by experimental evidence. (One might even say that the present $\theta-\tau$ puzzle may be taken as an indication that parity conservation is violated in weak interactions. This argument is, however, not to be taken seriously because of the paucity of our present knowledge concerning the nature of the strange particles. It supplies rather an incentive for an examination of the question of parity conservation.) To decide

PRESENT EXPERIMENTAL LIMIT ON PARITY NONCONSERVATION

If parity is not strictly conserved, all atomic and nuclear states become mixtures consisting mainly of the state they are usually assigned, together with small percentages of states possessing the opposite parity. The fractional weight of the latter will be called $\mathfrak{F}^2$. It is a quantity that characterizes the degree of violation of parity conservation.

The existence of parity selection rules which work well in atomic and nuclear physics is a clear indication that the degree of mixing, $\mathfrak{F}^2$, cannot be large. From such considerations one can impose the limit $\mathfrak{F}^2 \lesssim (r/\lambda)^2$, which for atomic spectroscopy is, in most cases, $\sim 10^{-6}$. In general a less accurate limit obtains for nuclear spectroscopy.

Parity nonconservation implies the existence of interactions which mix parities. The strength of such interactions compared to the usual interactions will in general be characterized by $\mathfrak{F}$, so that the mixing will be of the order $\mathfrak{F}^2$. The presence of such interactions would affect angular distributions in nuclear reactions. As we shall see, however, the accuracy of these experiments is not good. The limit on $\mathfrak{F}^2$ obtained is not better than $\mathfrak{F}^2 < 10^{-4}$.

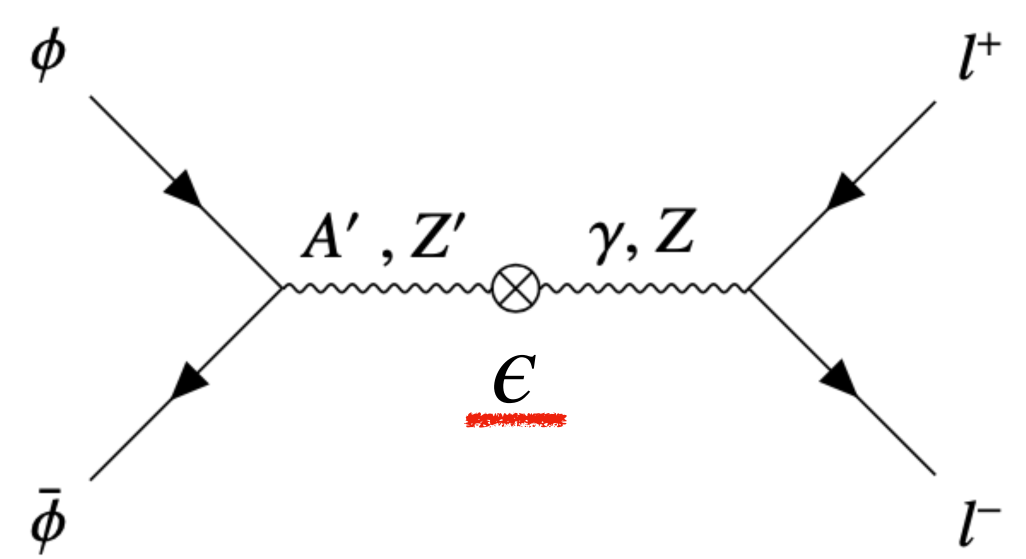
To give an illustration, let us examine the polarization experiments, since they are closely analogous to some experiments to be discussed later. A proton beam polarized in a direction z perpendicular to its momentum

Introduction - Dark Sector

- The particles in the hidden sector do not interact with Standard Model particles directly, but there are "portals" acting as indirect interaction.

- In direct search for Dark particles by collider experiments, they search for a missing momentum and energy or a pair of SM particles into which Dark particle decays.
  - The hottest topic is the vector portal, Dark photon and Dark Z boson.
  - Searching for the decays like $A'/Z' \to l^+l^-$ or invisible.

Portals	SM particle	DS particle
Scalar	Higgs h	Dark Higgs h'
Neutrino	Neutrino ν	Sterile neutrino ν_d
Vector	Photon / Z γ / Z	Dark photon / Z A' / Z'



The annihilation of Dark Sector particle ϕ

Introduction - Dark Photon and Dark Z

- Dark Photon A' and Dark Z boson Z' are Dark particles corresponding photon and Z.

  - There are models in which those dark bosons explain the anomaly of $(g-2)_\mu$.

- Dark photon is a new neutral vector particle couples to EM current.

  - Extension of SM in which a new $U(1)$ symmetry is introduced, so-called "kinetic mixing model".

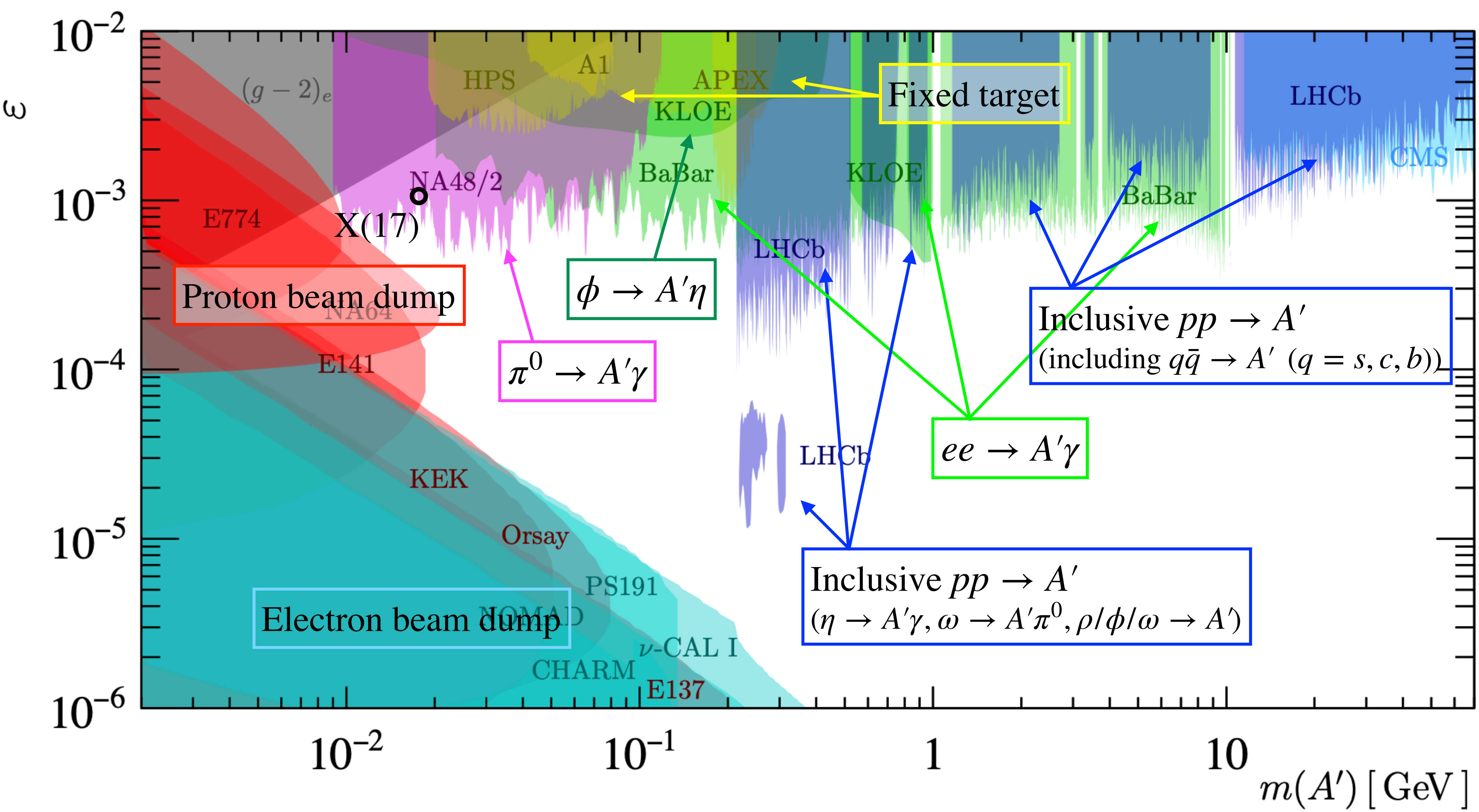
  - It mirrors the hypercharge interactions in the SM and A' can mix with the SM photon.

- Dark Z is a new neutral vector particle, similar to A', but couples to neutral weak current as well as EM current. (In $\epsilon \to 0$ limit, coupling is neutral only.)

  - Z' can, unlike A', couples to each lepton differently.

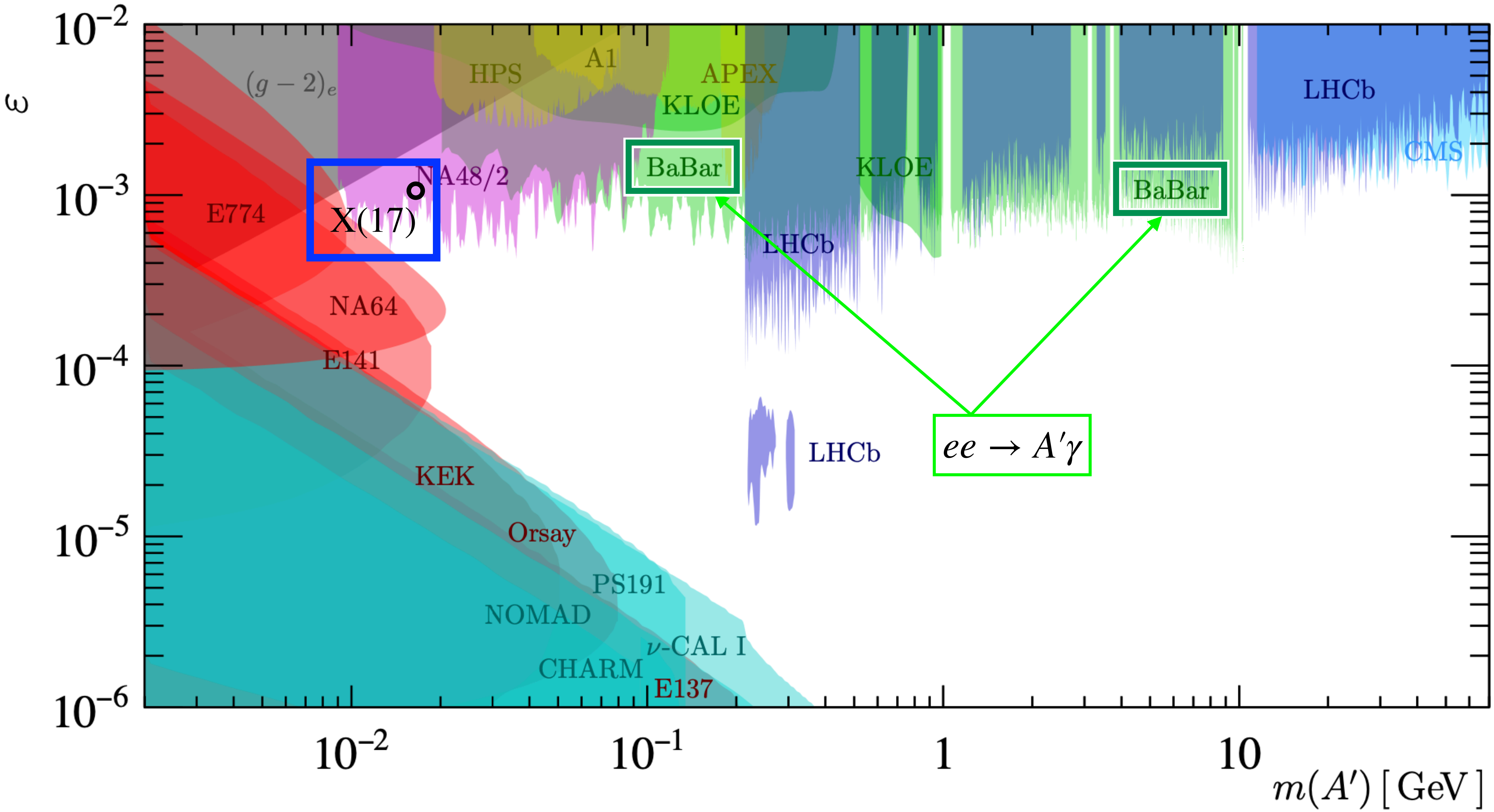
  - Z' couples to electrically neutral particles such as neutrinos. There are many neutrino scattering experiments and low mass region is already excluded.

Previous results of search for A'



Phys. Rev. Lett. 124, 041801 (2020)

Previous results of search for A'



There are two major e^+e^- collider experiment; BaBar and Belle II.

Phys. Rev. Lett. 124, 041801 (2020)

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Search for A' in $D^{*0} \to D^0 A'$ at Belle

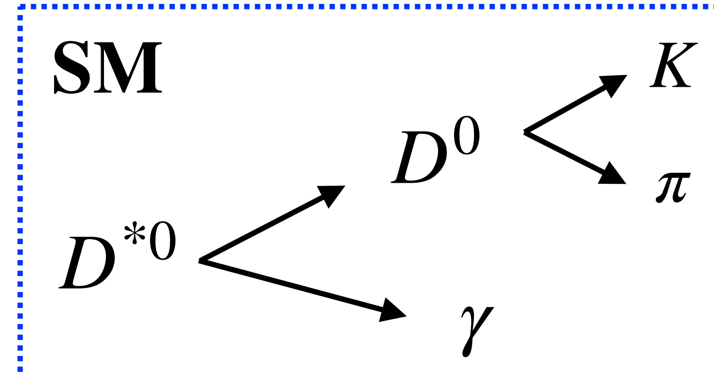
The target: $D^{*0} \to D^0 A'(\to e^+e^-)$

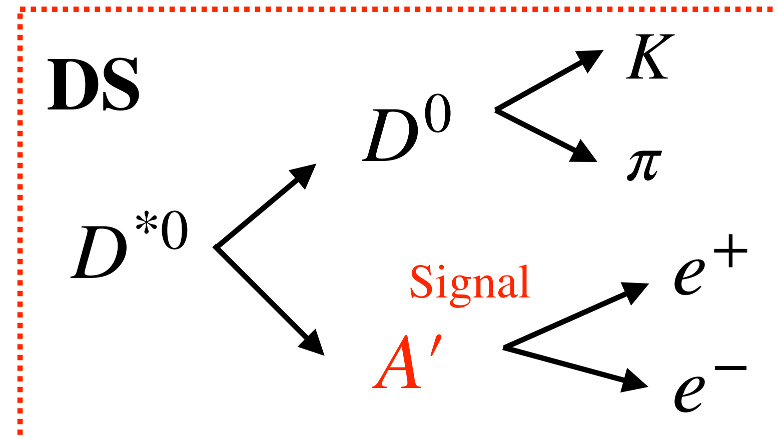
- The first search for Dark Photon in charm-related decay.

- SM decay $D^{*0} \to D^0\gamma$ where $\Delta m = 142$ MeV mixing of γ to A'. The dataset is 1 ab^{-1} of Belle experiment including 4.0×10^9 $e^+e^- \to c\bar{c}$ events, i.e. $\sim 1.0 \times 10^8$ of D^{*0} events.

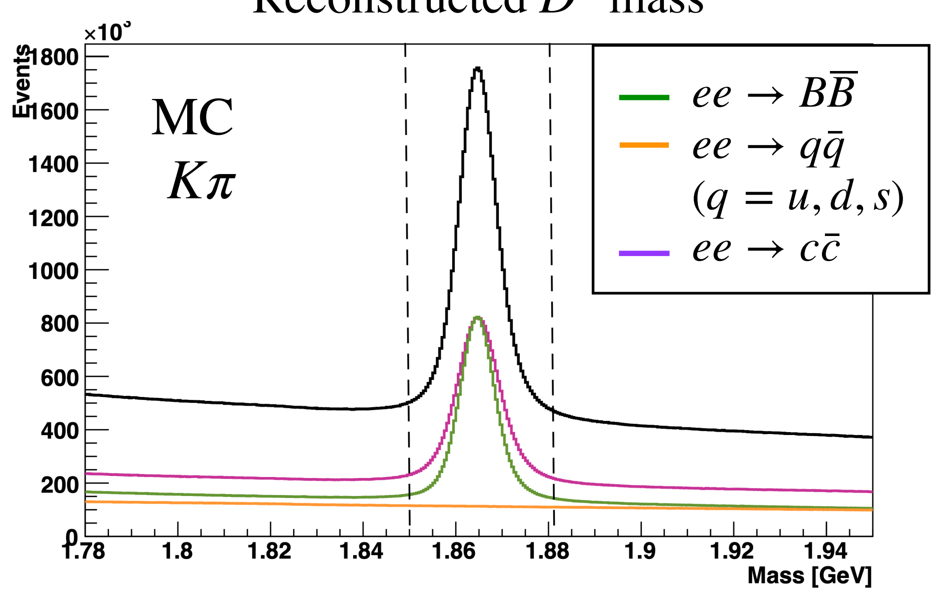
- D^0 is reconstructed by $K^-\pi^+$ (4%), $K^-\pi^+\pi^0$ (14%), and $K^-\pi^+\pi^-\pi^+$ (8%). A' is reconstructed from a pair of an electron and a positron. D^{*0} is reconstructed from D^0 and the pair.

- Selections are based on kinematics.





Reconstructed D^0 mass



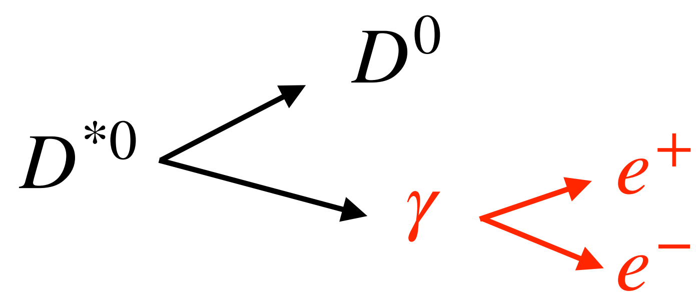
Selection for $K\pi$ mode
$1.857 < m_{D^0} < 1.878$ GeV
$134.6 < \Delta m < 150.9$ MeV
$2.5 < p_{D^{*0}}$ GeV
$dr_{ee} < 0.44$ cm

Search for A' in $D^{*0} \to D^0 A'$

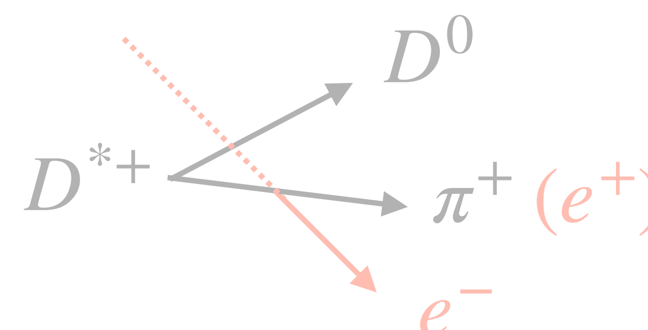
Backgrounds

- Two major backgrounds;

(1) (Displaced) γ conversion. (2) D^{*+} background.

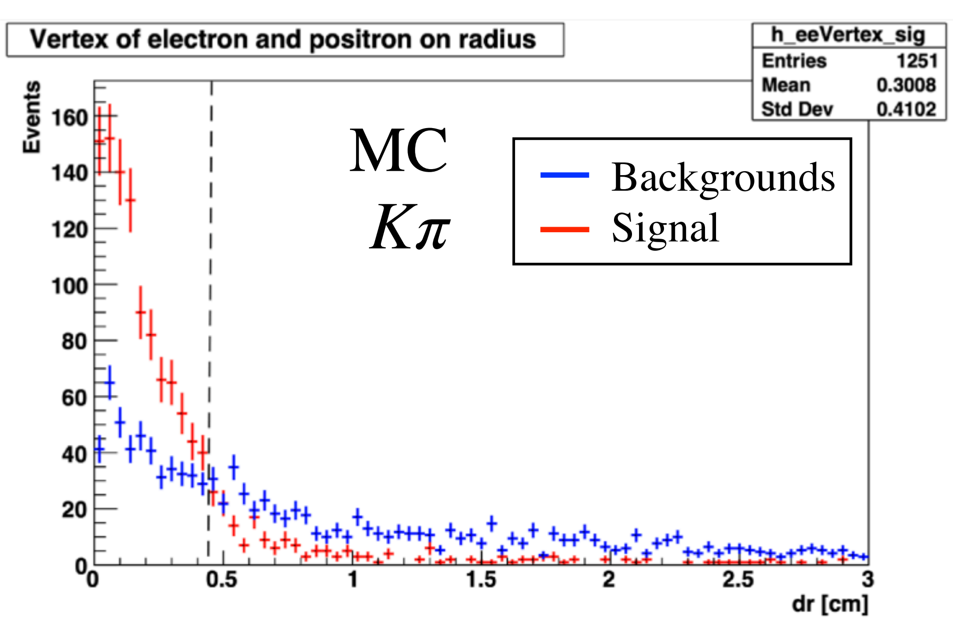


- For background (1), apply selection on dr that excludes larger radial distance from the interaction point.

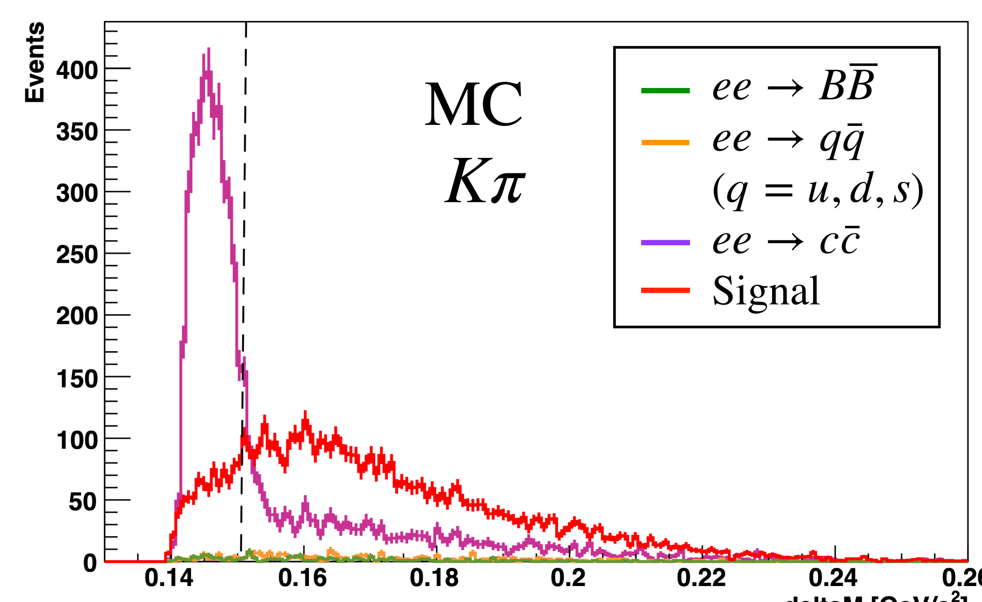


- For background (2), the mass difference Δm is calculated assuming "e^+" is π^+ and ignoring e^-. Then, a selection is applied.

dr distribution of $K\pi$



Δm distribution of $K\pi$

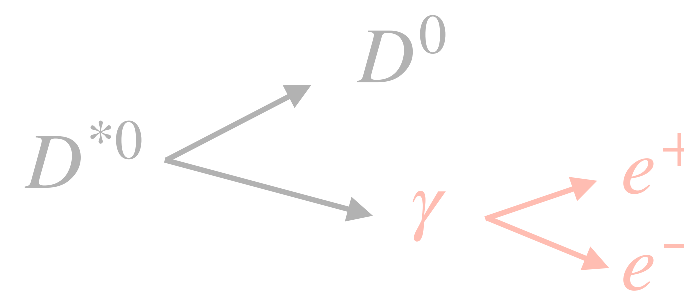


Search for A' in $D^{*0} \to D^0 A'$

Backgrounds

- Two major backgrounds;

  (1) (Displaced) γ conversion. **(2) D^{*+} background.**



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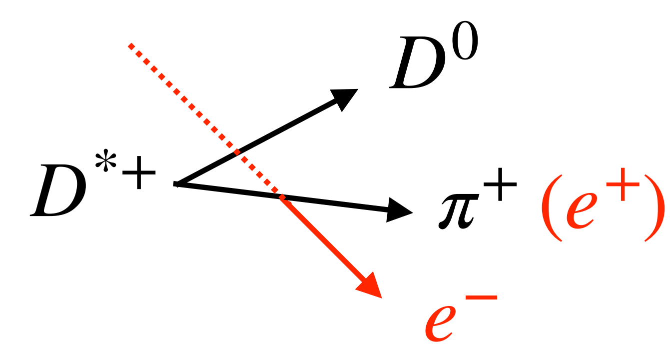

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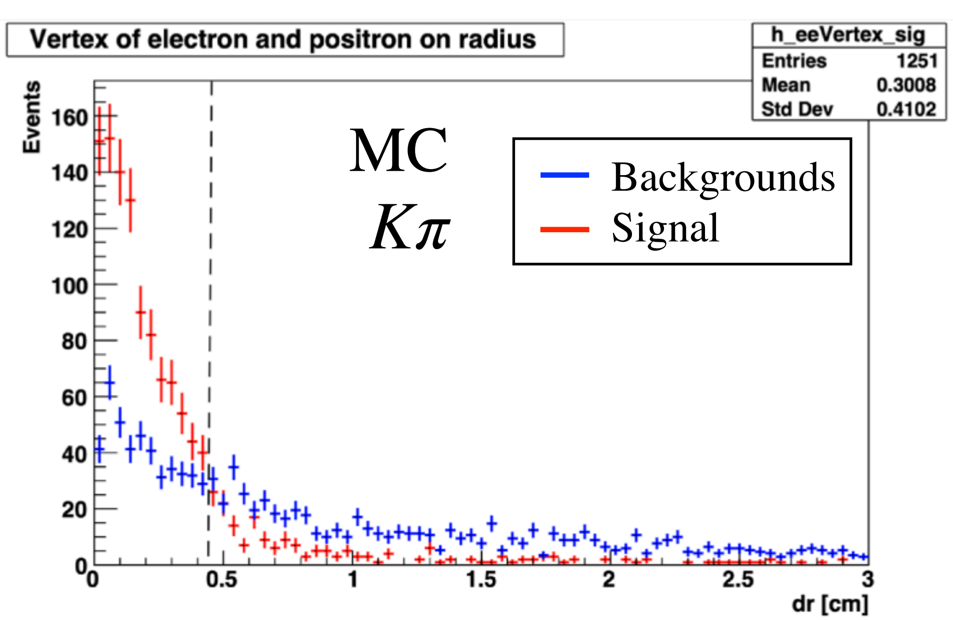
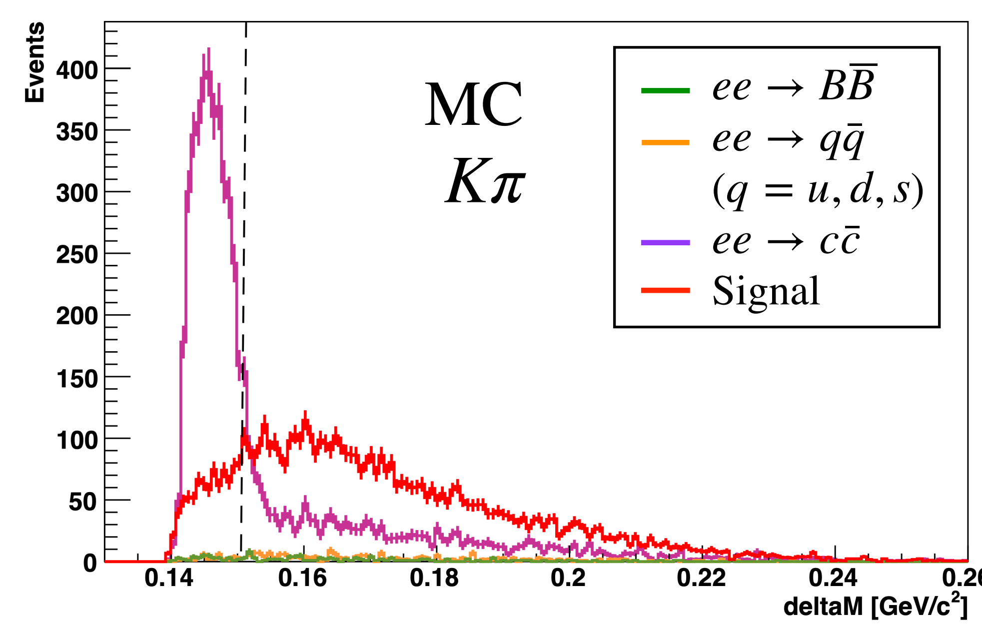
dr distribution of $K\pi$

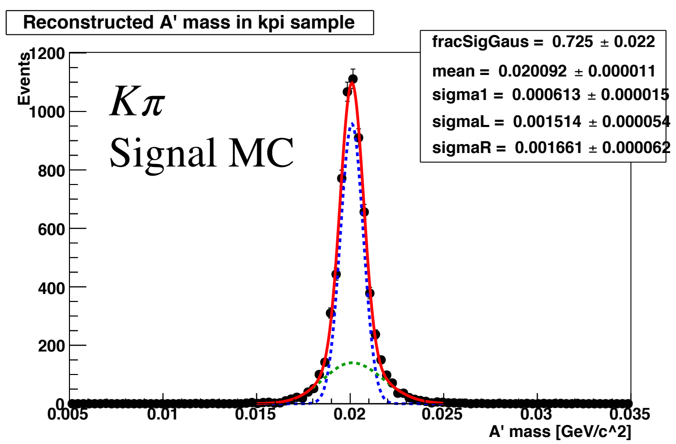


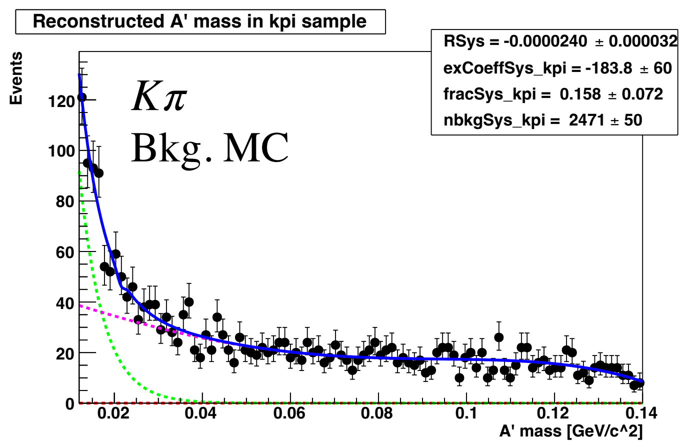
Δm distribution of $K\pi$

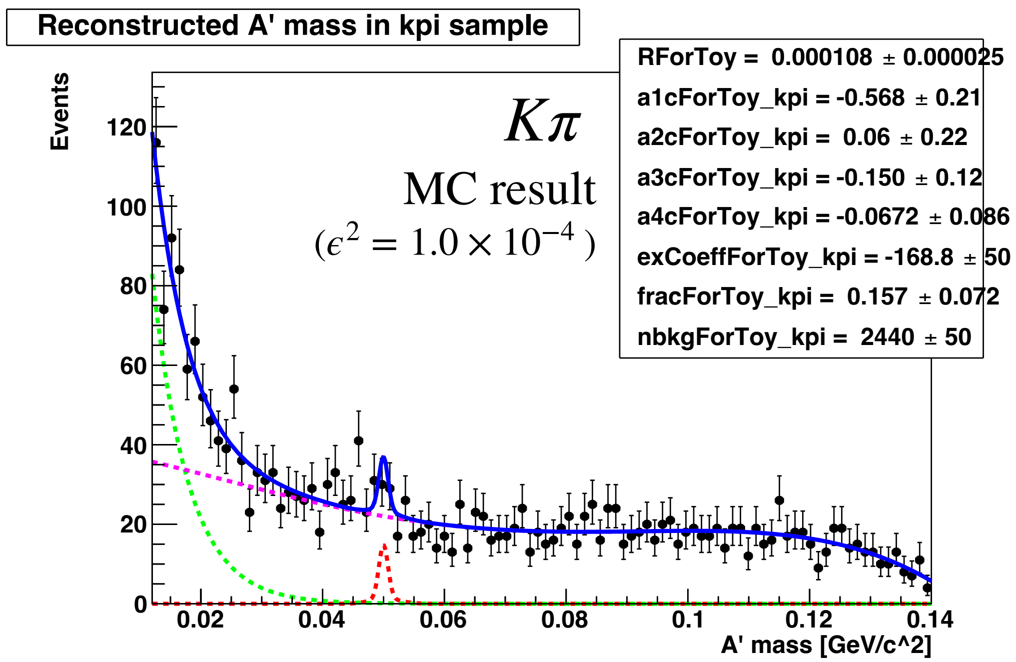


Search for A' in $D^{*0} \to D^0 A'$

- Fit $m_{A'}$ distribution simultaneously to the three D^0modes.





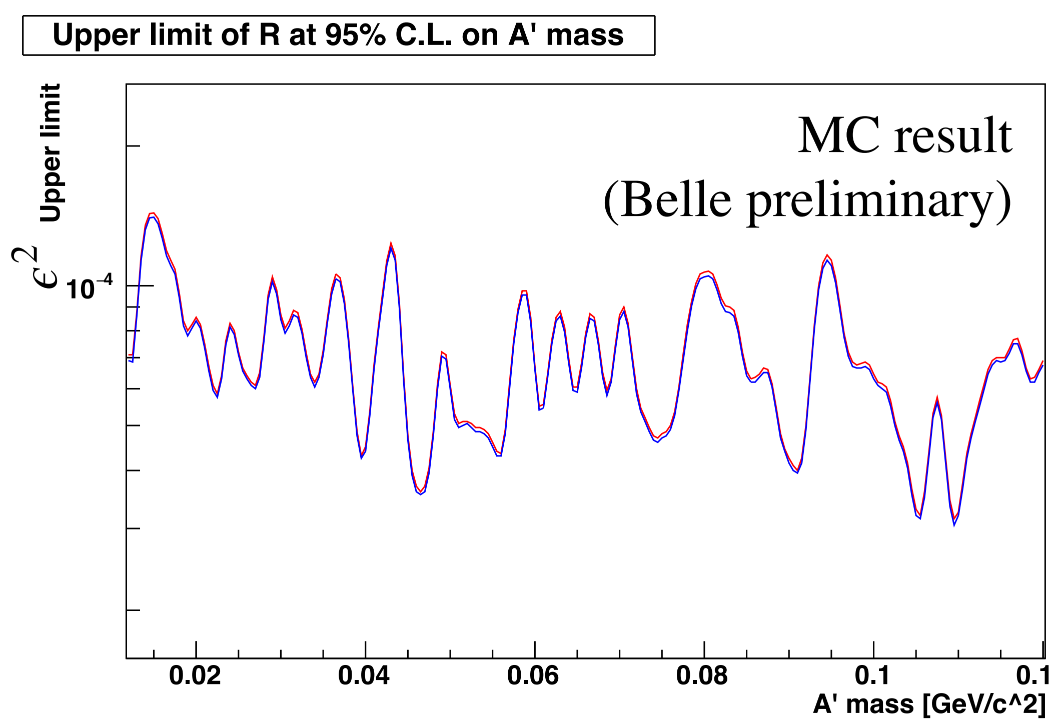


- To reduce the systematics uncertainty, the SM process $D^{*0} \to D^0\gamma$ is used as the normalization mode.
  The mixing parameter ϵ is calculated by

$$\frac{BR(D^{*0} \to D^0 A')}{BR(D^{*0} \to D^0\gamma)} = \epsilon^2\left(1 - \frac{m_{A'}^2}{\Delta m^2}\right)$$

- With full dataset of Belle, the upper limit of ϵ^2 reaches order of 10^{-4}.

- Data unblinding is expected soon.



Upper limit of ϵ at 90% C.L. in MC simulation. Without and With systematics.

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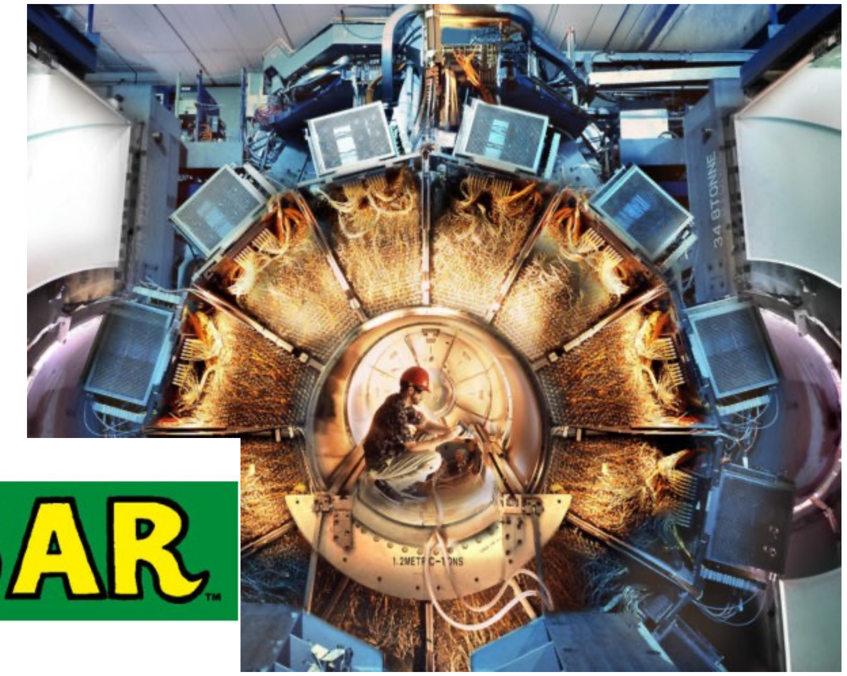
  - **- Dark Z boson**
  - **- Dark Higgs**

BaBar and Belle experiment

- BaBar experiment (1999 - 2008, SLAC)

An electron-positron collider experiment with PEP-II accelerator operating at $E_{c.m.} = 10.58$ GeV ($\Upsilon(4S)$ resonance).

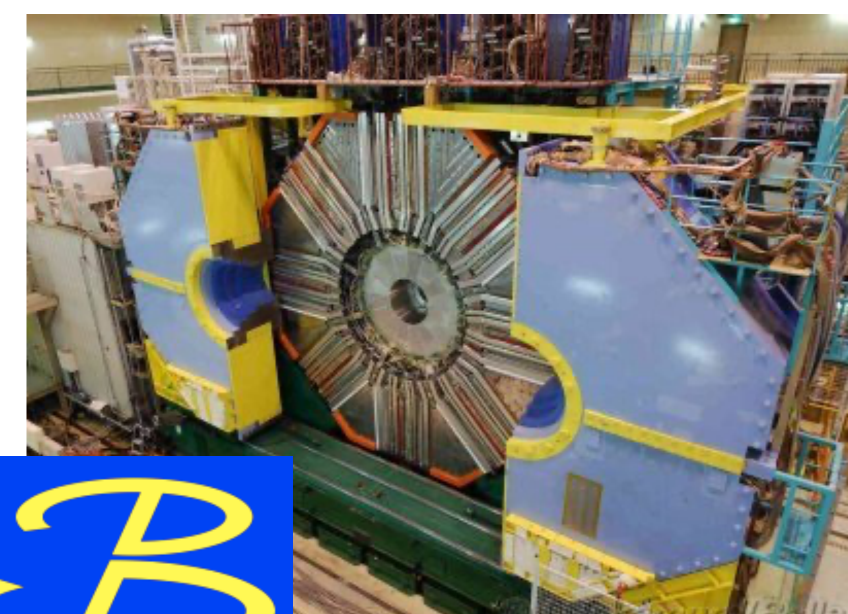


Integrated luminosity: $514\ \mathrm{fb}^{-1}$

- Belle experiment (1999 - 2010, KEK)

Belle II experiments (2018 - present, KEK)

Electron-positron collider experiments with KEKB / SuperKEKB accelerator operating at $E_{c.m.} = 10.58$ GeV ($\Upsilon(4S)$ resonance).



Integrated luminosity: $1\ \mathrm{ab}^{-1} + 362\ \mathrm{fb}^{-1}$

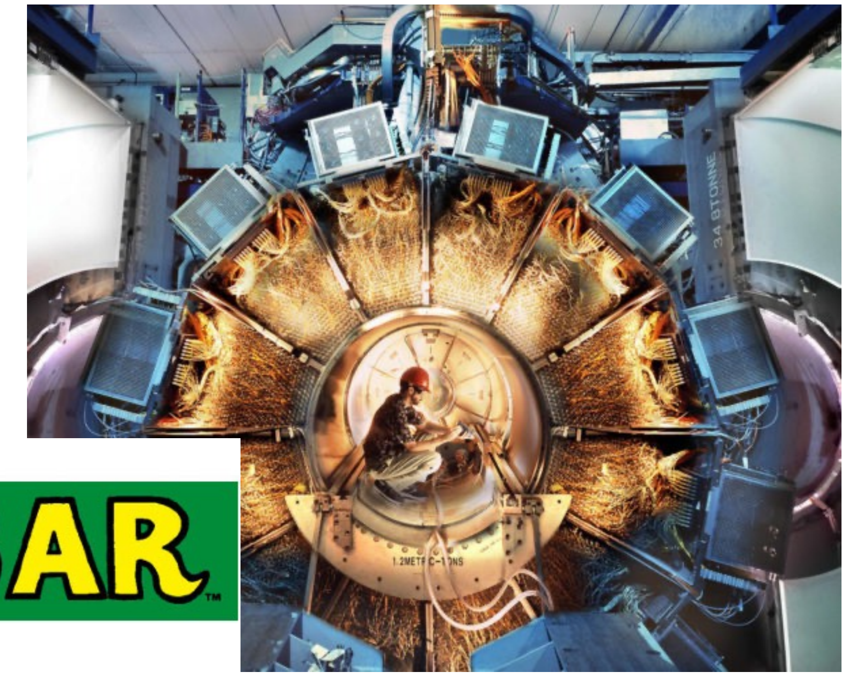
Current limit on A' by BaBar experiment

- BaBar experiment (1999 - 2008, SLAC)

  An electron-positron collider experiment with PEP-II accelerator operating at $E_{c.m.} = 10.58$ GeV ($\Upsilon(4S)$ resonance).

  Integrated luminosity: 514 fb^{-1}

  Target: $e^+e^- \to \gamma A'(\to l^+l^-)\ \ (l = e, \mu)$



BABAR

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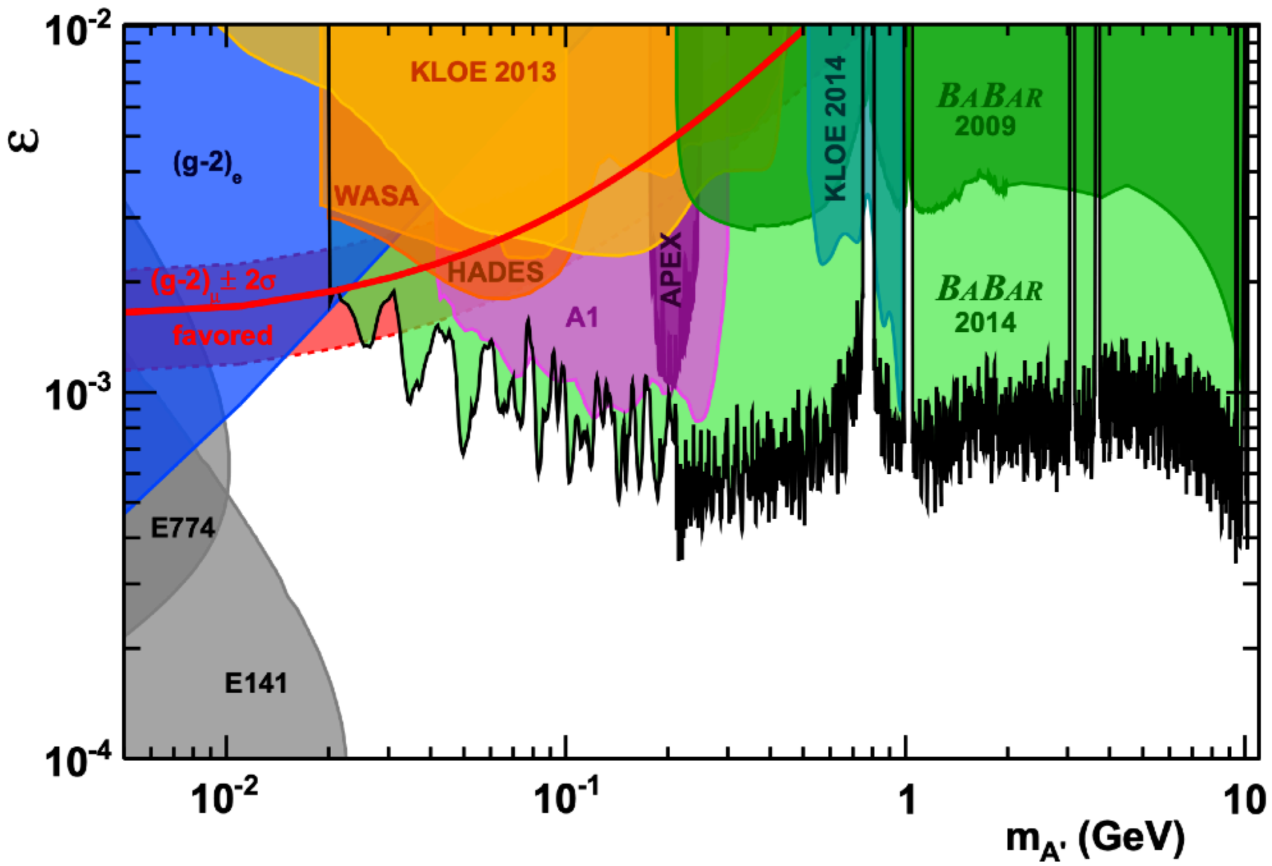
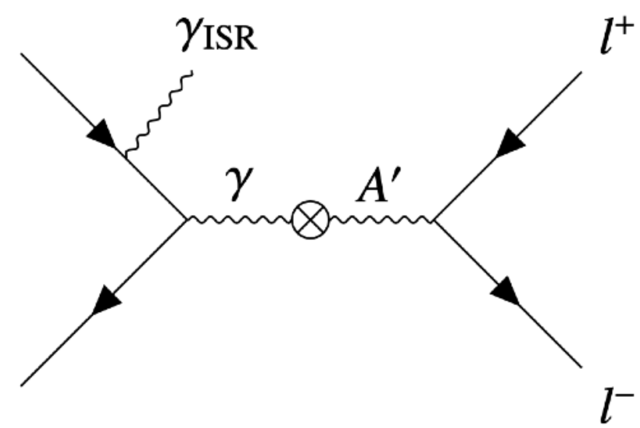


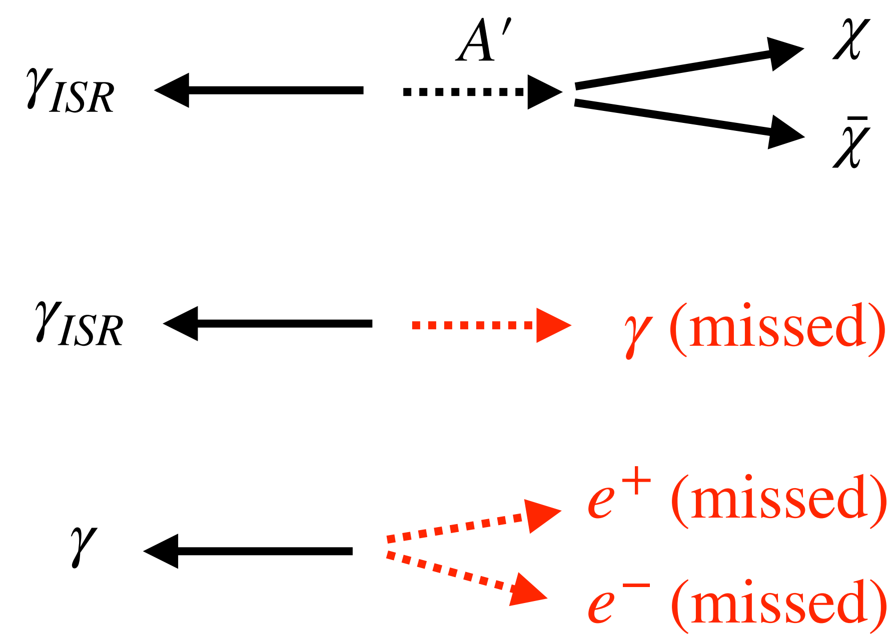


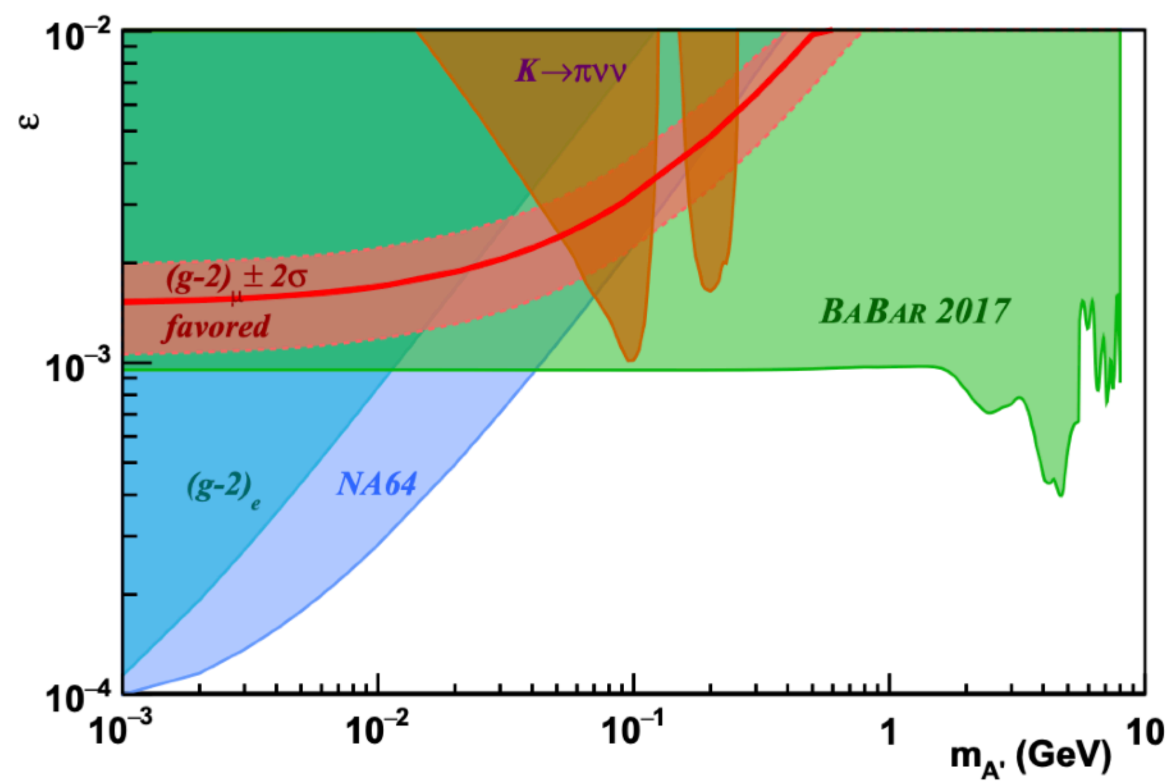
The final result of $e^+e^- \to \gamma A'(\to l^+l^-)\ \ (l = e, \mu)$.
Exclusion plot at 90% C.L. for the parameter ϵ.
(Phys. Rev. Lett., vol. 113, p. 201 801, 2014.)

Latest searches for Dark Photon A'

$e^+e^- \to \gamma A'(\to \text{Invisible})$

- Another attempt to search for A' with ISR.
- Complementary search to the previous one and allows to reach $\epsilon = 10^{-3}$ only with 53 fb^{-1} data.
- Signal is extracted by a high energy photon with significant missing energy and momentum.
  - $E_\gamma > 2$ GeV and no tracks originating from the interaction point.
  - No cluster on the calorie meter at the opposite side.
  - Select $|\cos\theta_\gamma| < 0.6$ events.
- Exclude muon g-2 favored region.

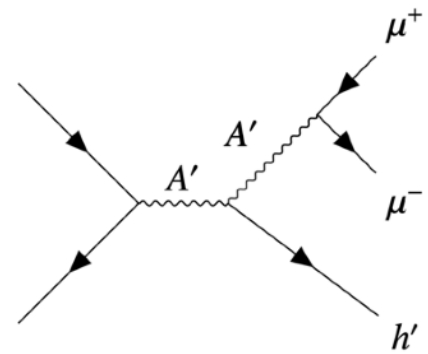




Phys. Rev. Lett. 119, 131804 (2017)

Latest searches for Dark Photon A'

$e^+e^- \to h'A'(\to \mu^+\mu^-)$ 8.3 fb^{-1}



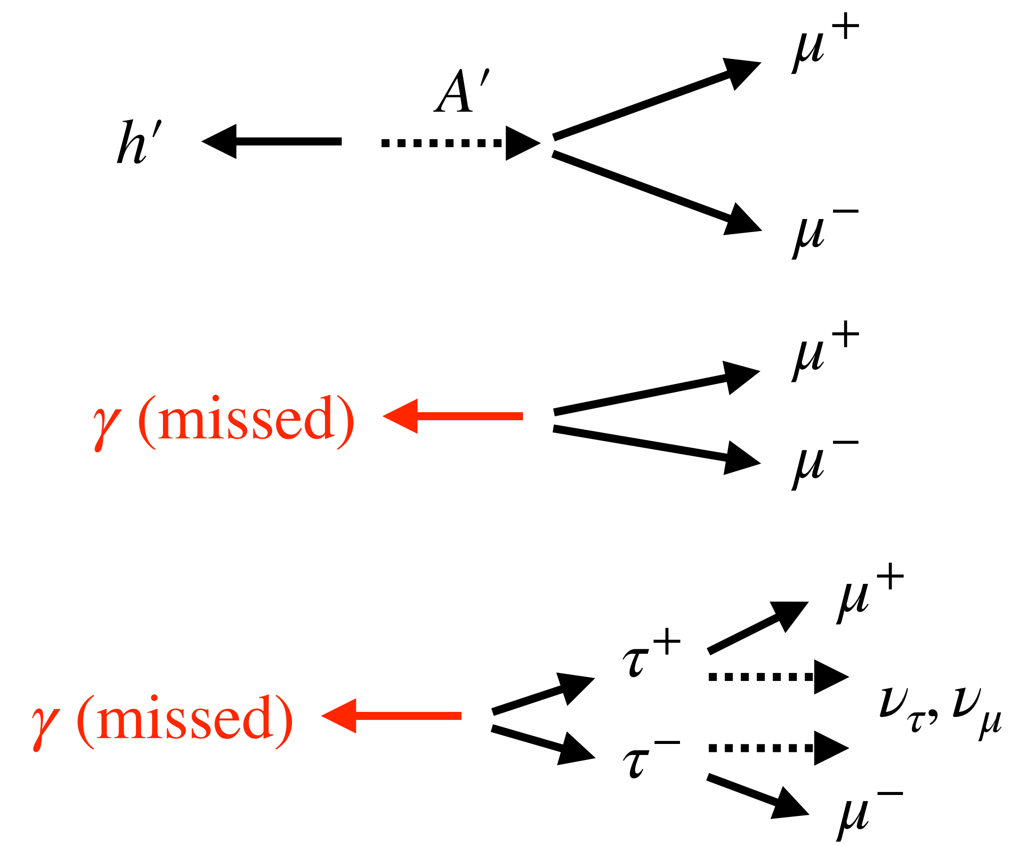
- The search for Dark Higgsstrahlung process, not kinetic mixing, assuming $m_{h'} < m_{A'}$ up to 10 GeV.

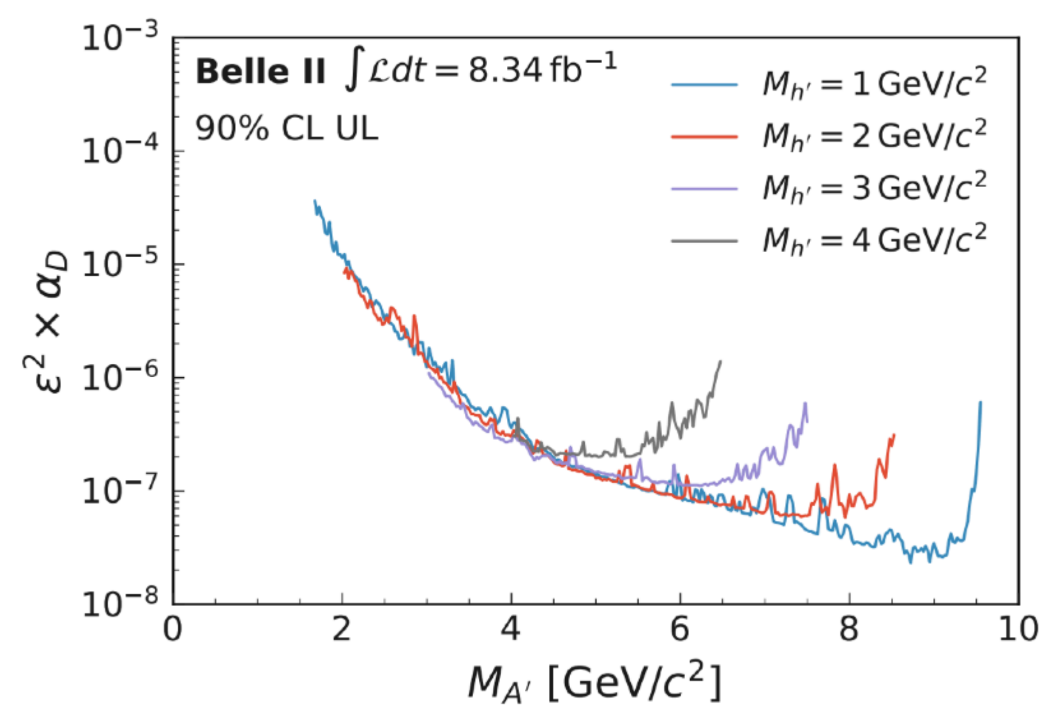
- The dataset is 8.3 fb^{-1}.

- Select events with only two muons from IP.
  - The opening angle > 90°.
  - Veto Bhabha events with specified criteria.
  - No cluster on the calorie meter at the opposite side.

- Limits are set on $\epsilon^2\alpha_D$ where α_D is coupling between A' and h'.

- It gives the most stringent limit if $\alpha_D = 1$. Even $\alpha_D = 0.1$, it is partially the most stringent.



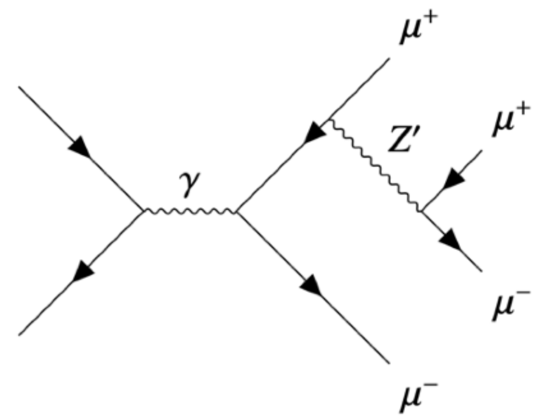


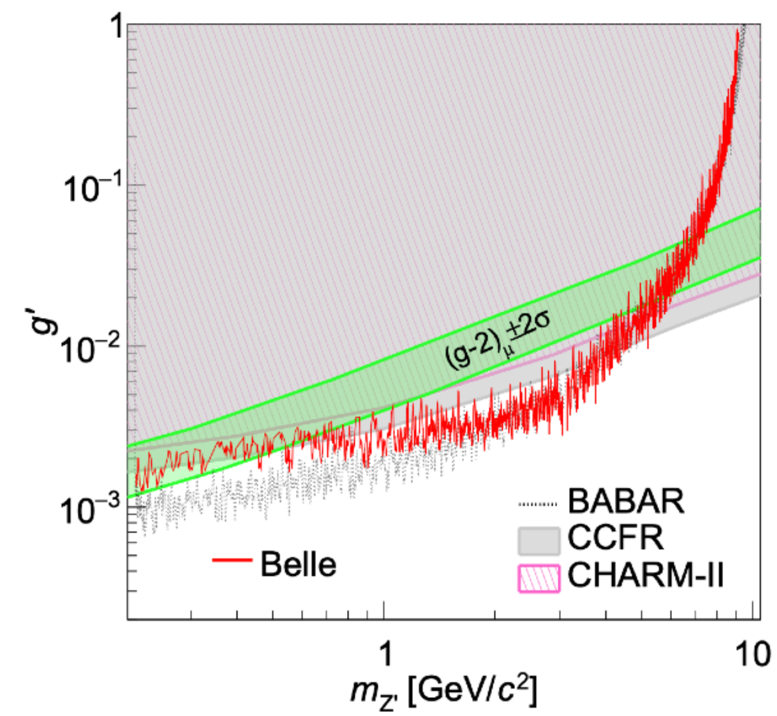
Phys. Rev. Lett. 130, 071804 (2023)

Latest search for Dark Z boson Z'

$e^+e^- \rightarrow \mu^+\mu^- Z'(\rightarrow \mu^+\mu^-)$

- Search for Z' in $L_\mu - L_\tau$ gauge-symmetric model that couples only μ, τ, and their neutrinos.
- The dataset is 643 fb^{-1}.
- Exclude most of $(g-2)_\mu$ favored region.

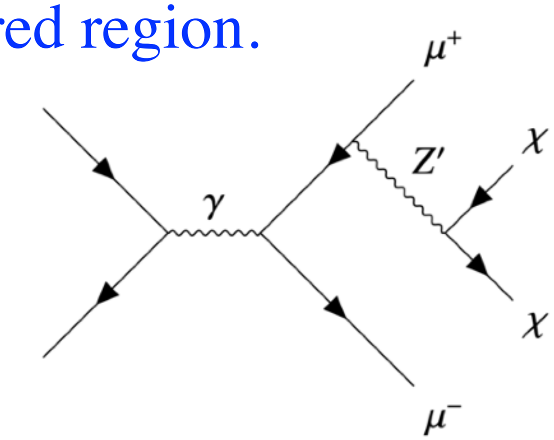


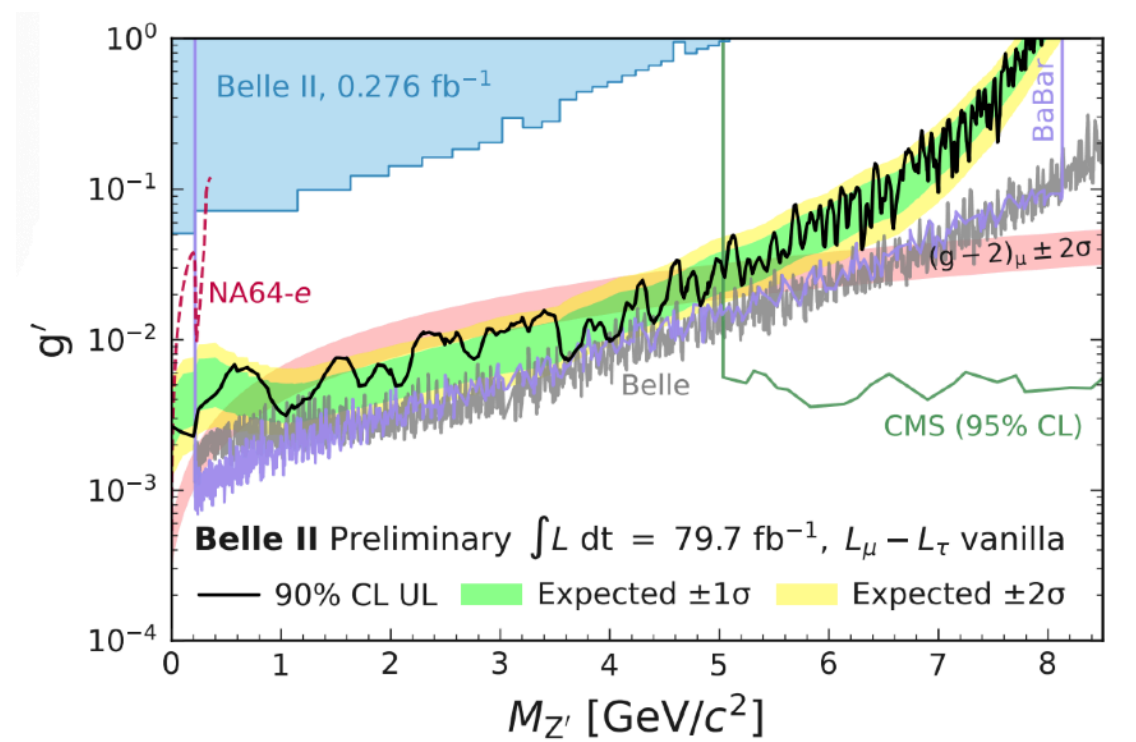


Belle Preprint 2021-20 KEK Preprint 2021-24, arXiv:2109.08596

$e^+e^- \rightarrow \mu^+\mu^- Z'(\rightarrow \text{Invisible})$

- The first direct search for invisible-Z' in high mass with 79.7 fb^{-1} data.
- Similar search for $e^+e^- \rightarrow h'A'(\rightarrow \mu^+\mu^-)$.
- Exclude most of muon g-2 favored region.





Belle II Preprint 2022-008, KEK Preprint 2022-40, arXiv:2212.03066

Latest search for Dark Higgs h'

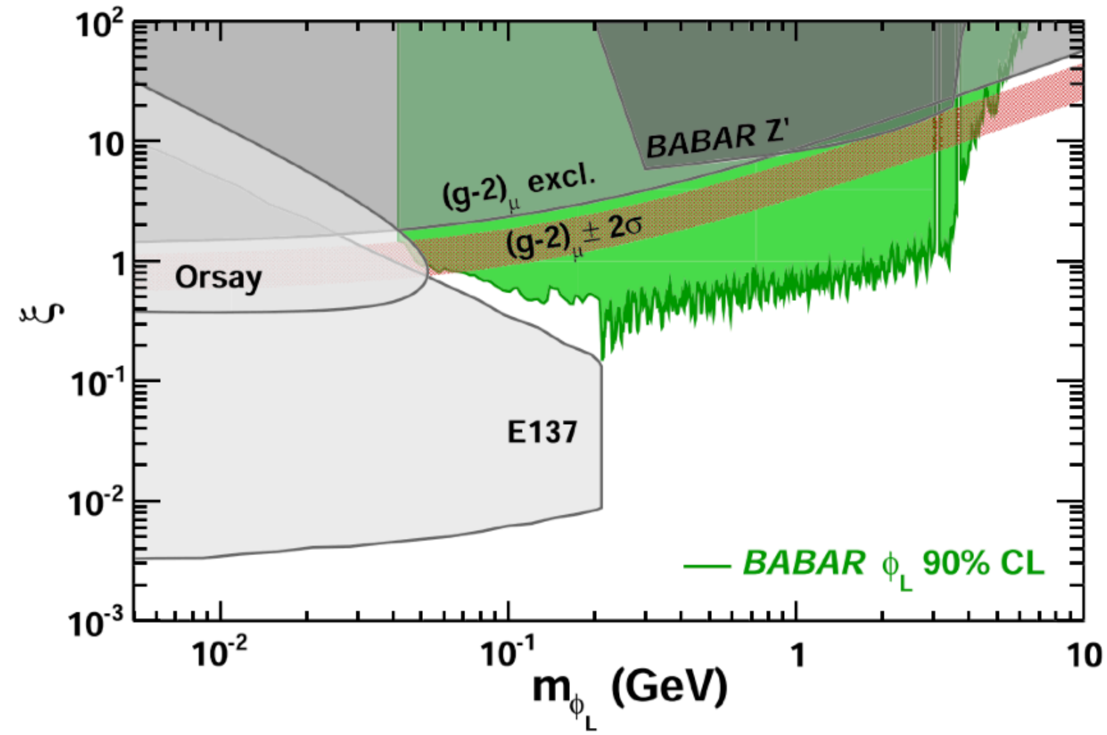
$e^+e^- \to \tau^+\tau^-\phi_L(\to l^+l^-),\ (l = e, \mu)$

- Search for leptonic scalar.

- The mixing between a new scalar and SM Higgs gives rise to couplings proportional to SM fermion masses and constrained by the searches for rare FCNC decays.

BABAR

Phys. Rev. Lett. **125**, 181801



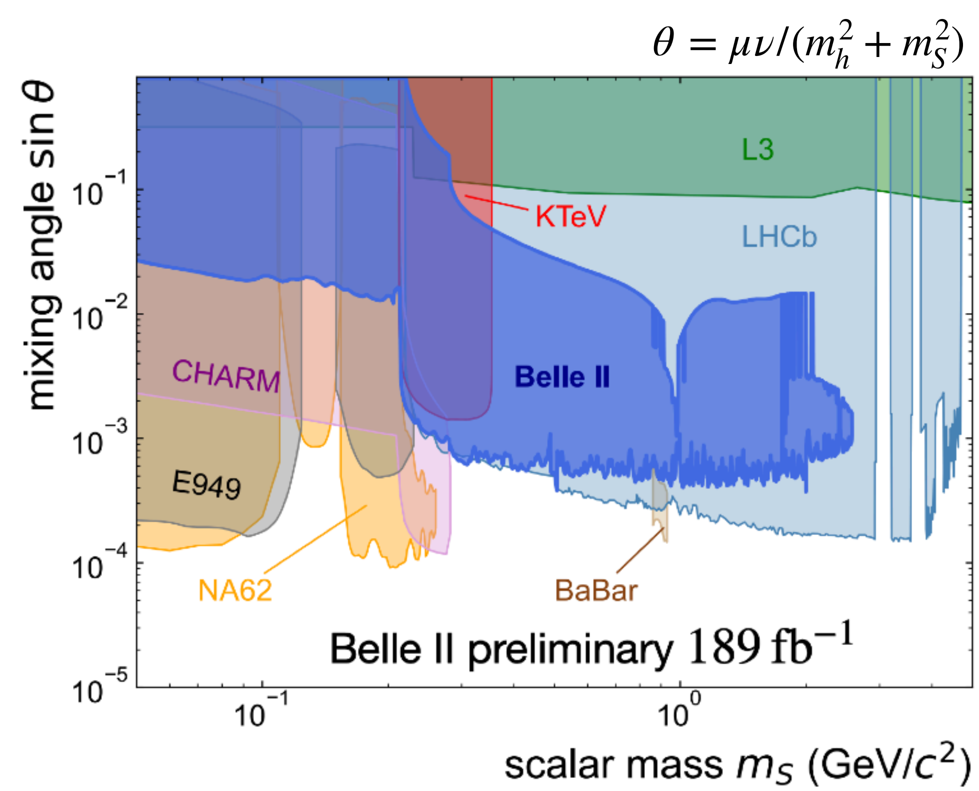
$B \to K^{(*)}S(\to x^+x^-)\ (x = e, \mu, \pi, K)$

Belle II

- Search for long-lived scalar particle like Dark Higgs in loop-induced FCNC decays.

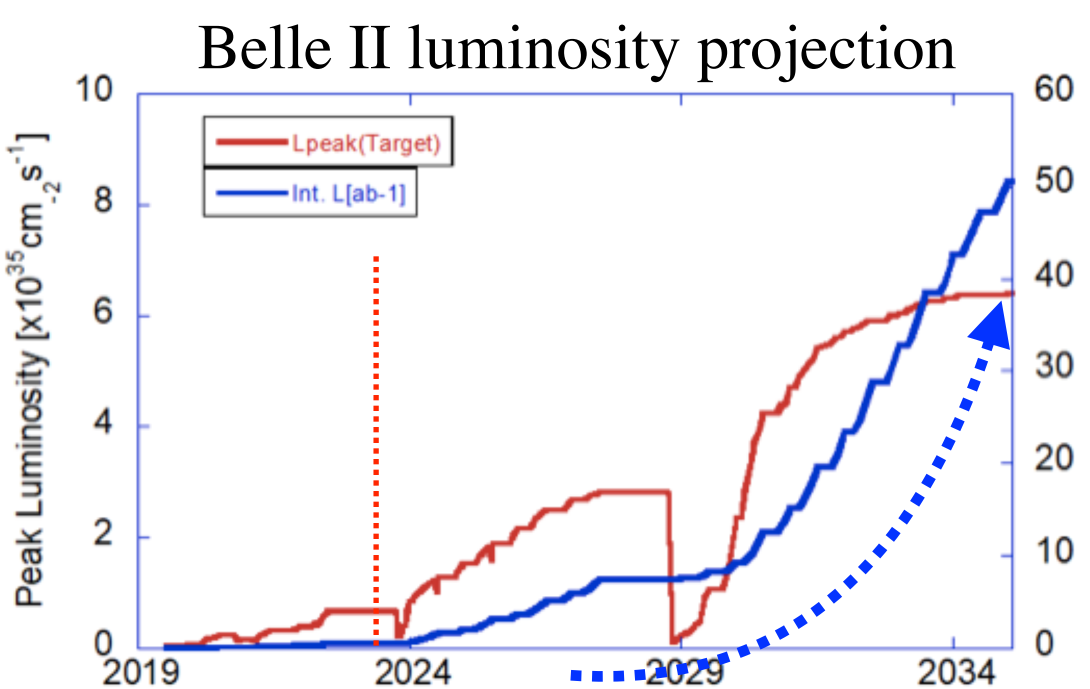
- LHCb result is based on only $x = \pi$ case. Therefore, the other decays are first or strongest results.

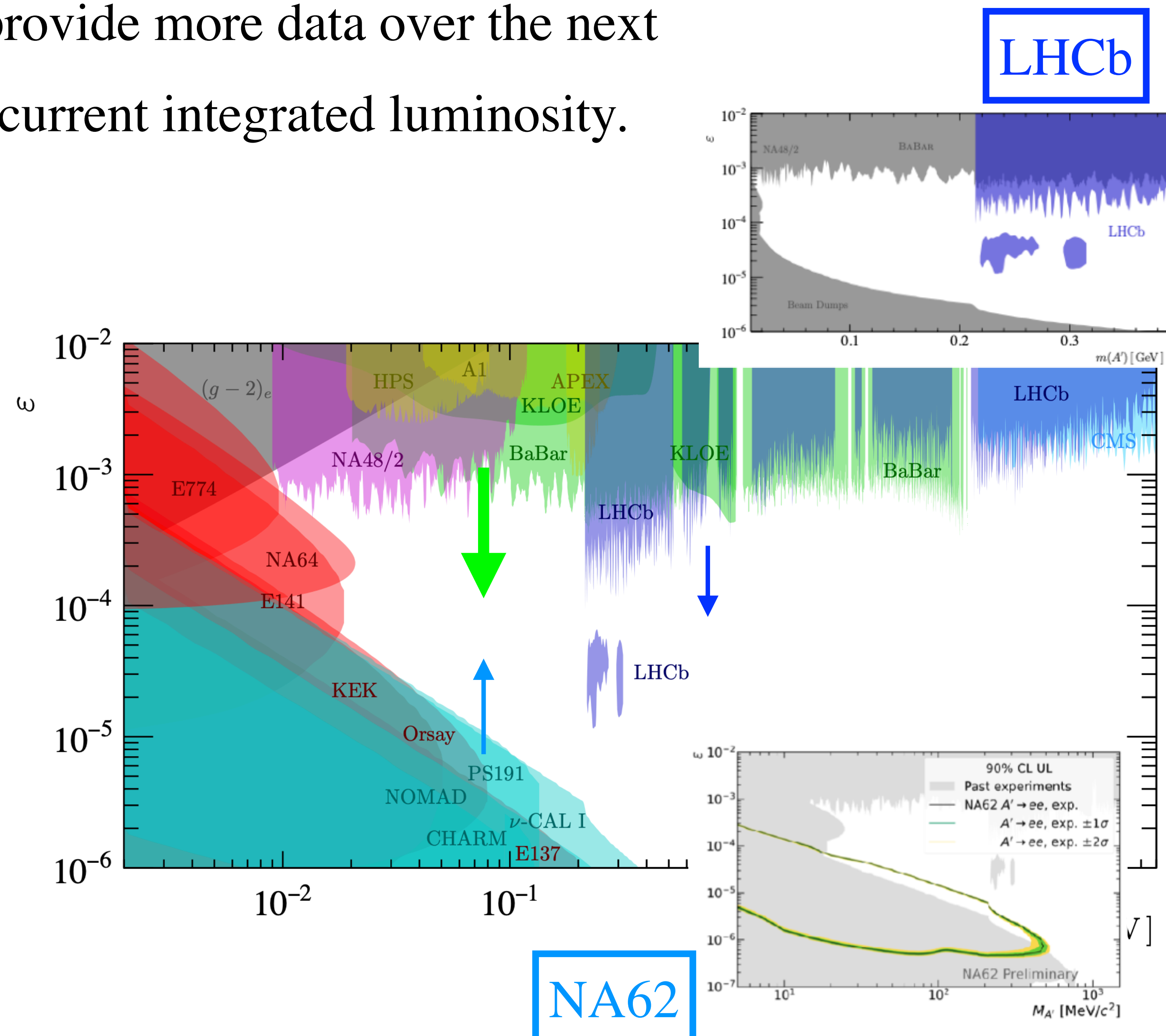
New!!



Summary & Outlook

- Search for Dark Sector particles is one of the hot topics for BSM.
- Lepton colliders are useful tools to search for DM in MeV-GeV region.
- Belle2 experiment has just started and will provide more data over the next 10 years up to 50 ab^{-1}, 10 times larger than current integrated luminosity.

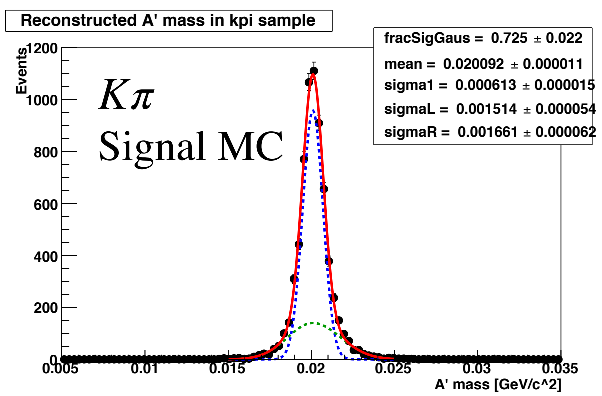


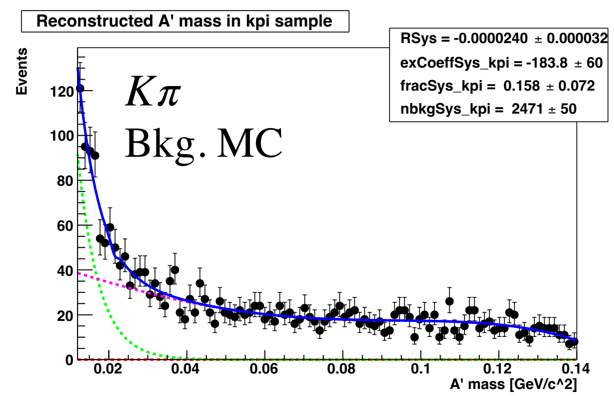


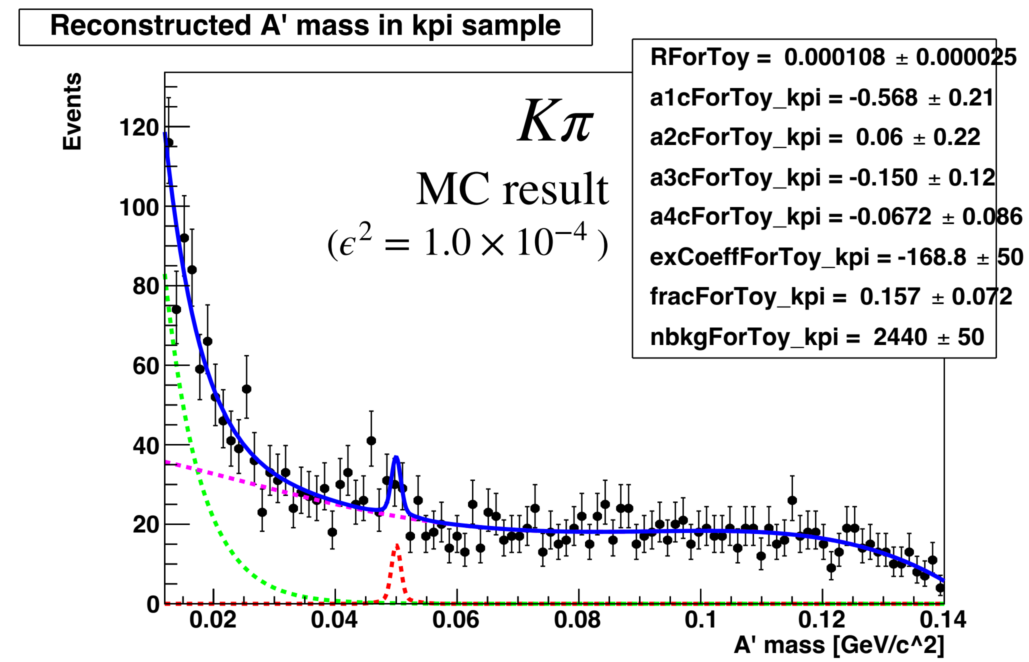
Backup

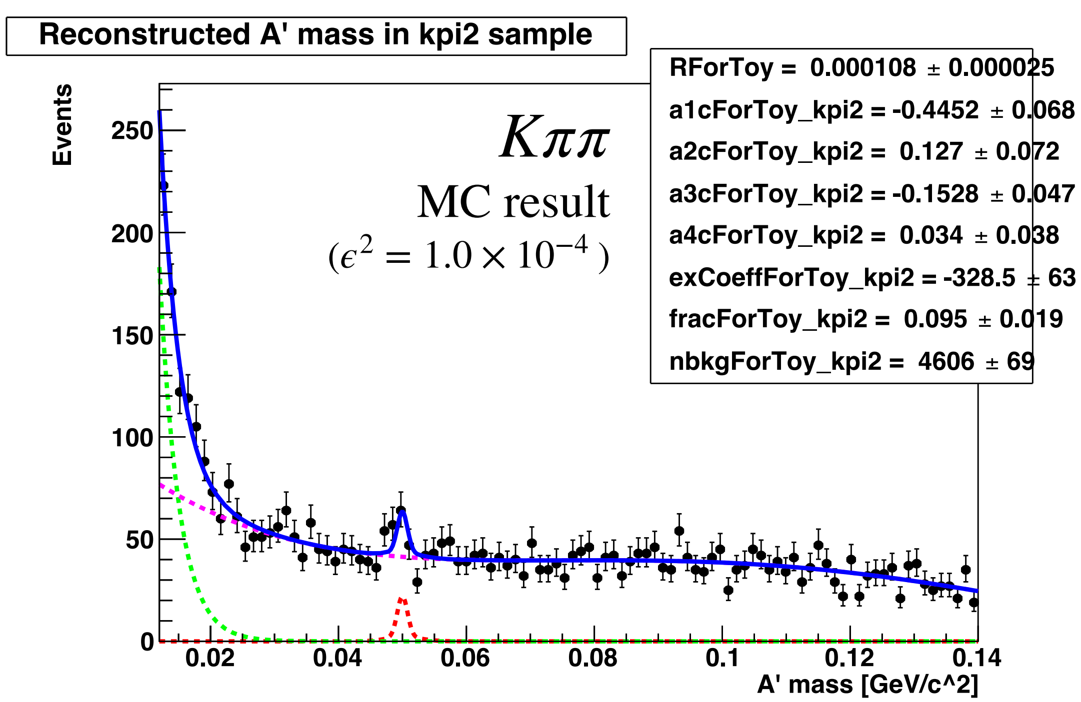
Search for A' in $D^{*0} \to D^0 A'$

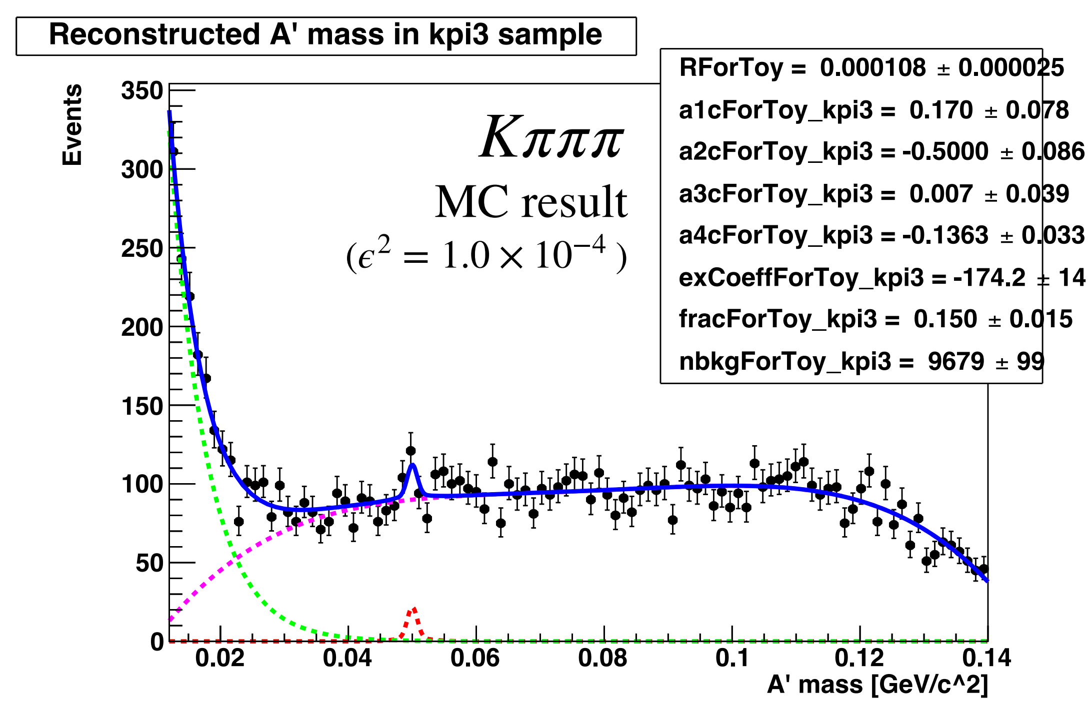
- Finally, we get $m_{A'}$ distribution. And three sub-decay modes are fit simultaneously.











Searches for Dark Photon A'

$e^+e^- \rightarrow h'(\rightarrow A'A')A', A' \rightarrow \mu^+\mu^-$

- The search for Dark Higgsstrahlung process, not kinetic mixing, assuming $m_{A'} < m_{h'}$ up to 10 GeV.