Search for Dark Particles at Belle

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on behalf of the Belle Collaboration
Korea Univ.

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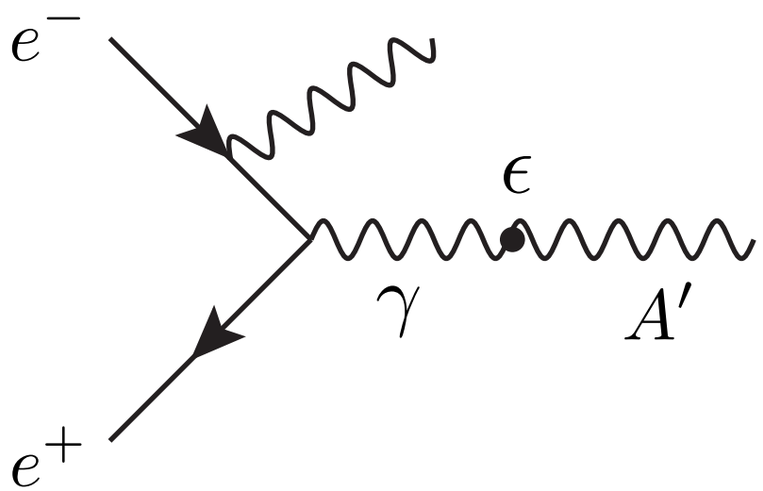
Jeju Islands, Korea

Motivation

- Dark particles: originally considered as a new spin-1 boson for new physics beyond SM.
  - P. Fayet, Phys. Lett. B 95, 285 (1980)
- This proposed “dark (hidden) sector” can be a part of dark matter.
- It would mix kinetically with the photon.

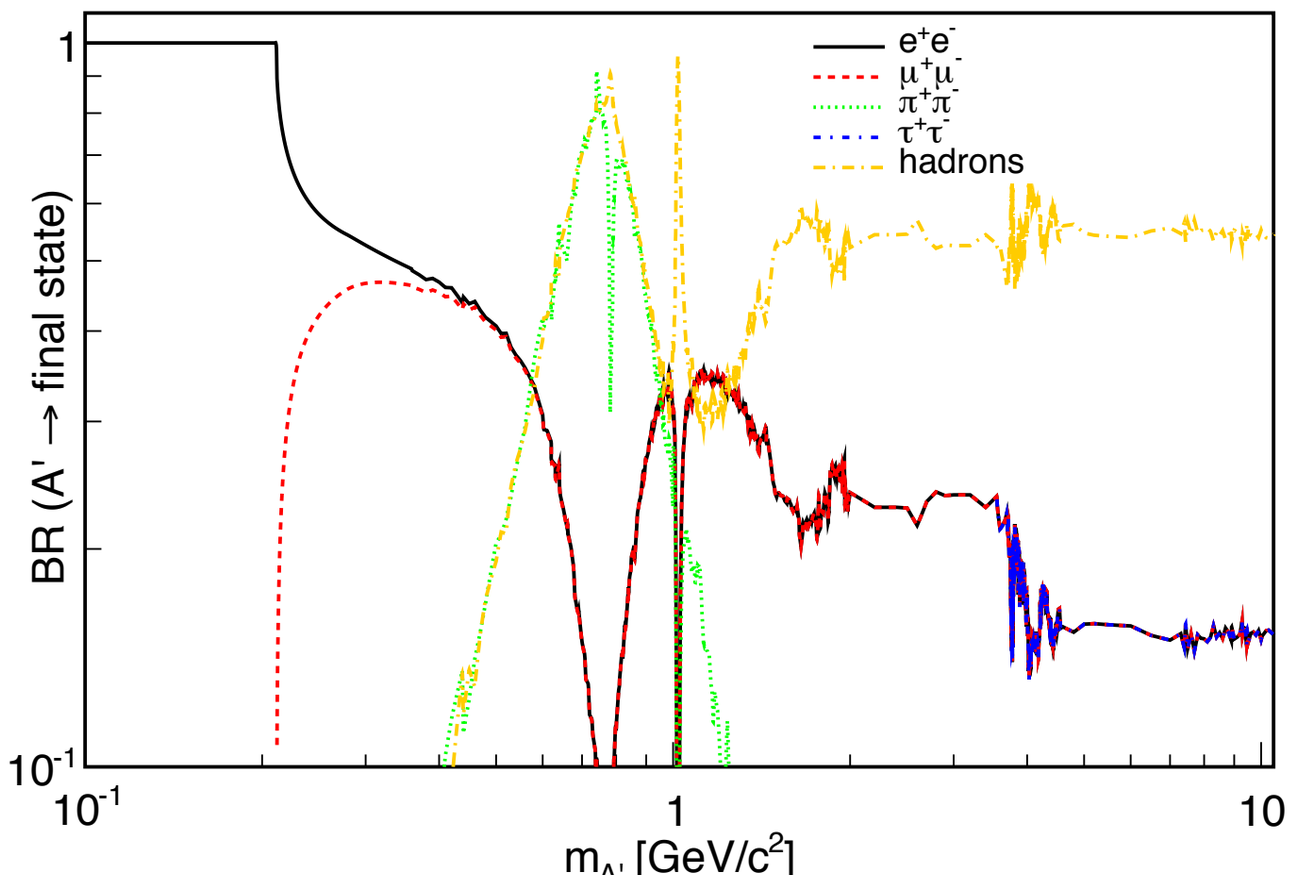
$$\mathcal{L} = -\frac{1}{2}\epsilon F^{\mu\nu} F'_{\mu\nu} \qquad \epsilon : \text{kinetic mixing parameter}$$



- A’ is created on-shell in radiative e^+e^- collisions.

A' can be short or long lived.

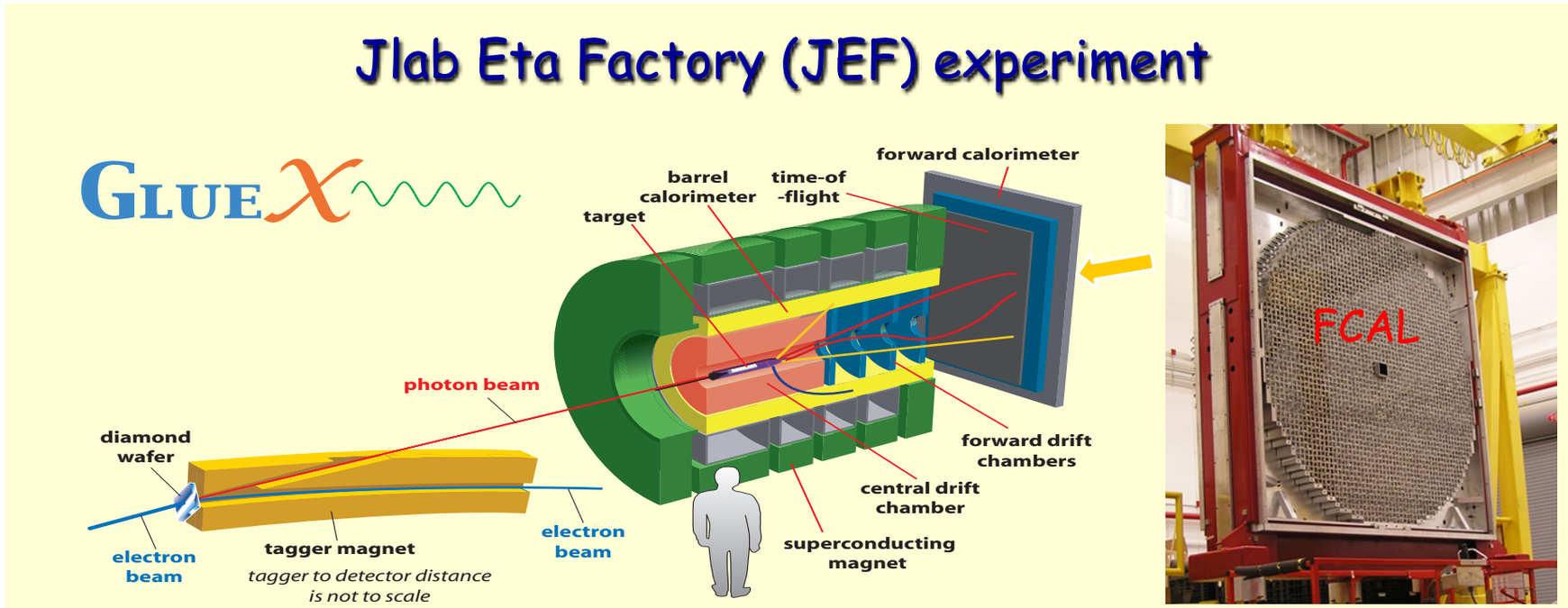
PRD 79 115008 (2008)



Motivation

The 11th Patras Workshop on Axions, WIMPs and WISPs: Gan Liping, JLab proposal: https://indico.desy.de/conferenceTimeTable.py?confId=11832#all (last talk)

Liping Gan



Simultaneously measure η decays: $\eta\to\pi^0\gamma\gamma$, $\eta\to3\gamma$, and …

- η produced on LH_2 target with **9-11.7 GeV tagged photon beam:**
  $\gamma+p \rightarrow \eta+p$
- Reduce non-coplanar backgrounds by **detecting recoil p's** with GlueX detector (ε~75%)
- Upgraded Forward Calorimeter with **High resolution, high granularity** $PbWO_4$ insertion (**FCAL-II**) to detect multi-photons from rare η decays

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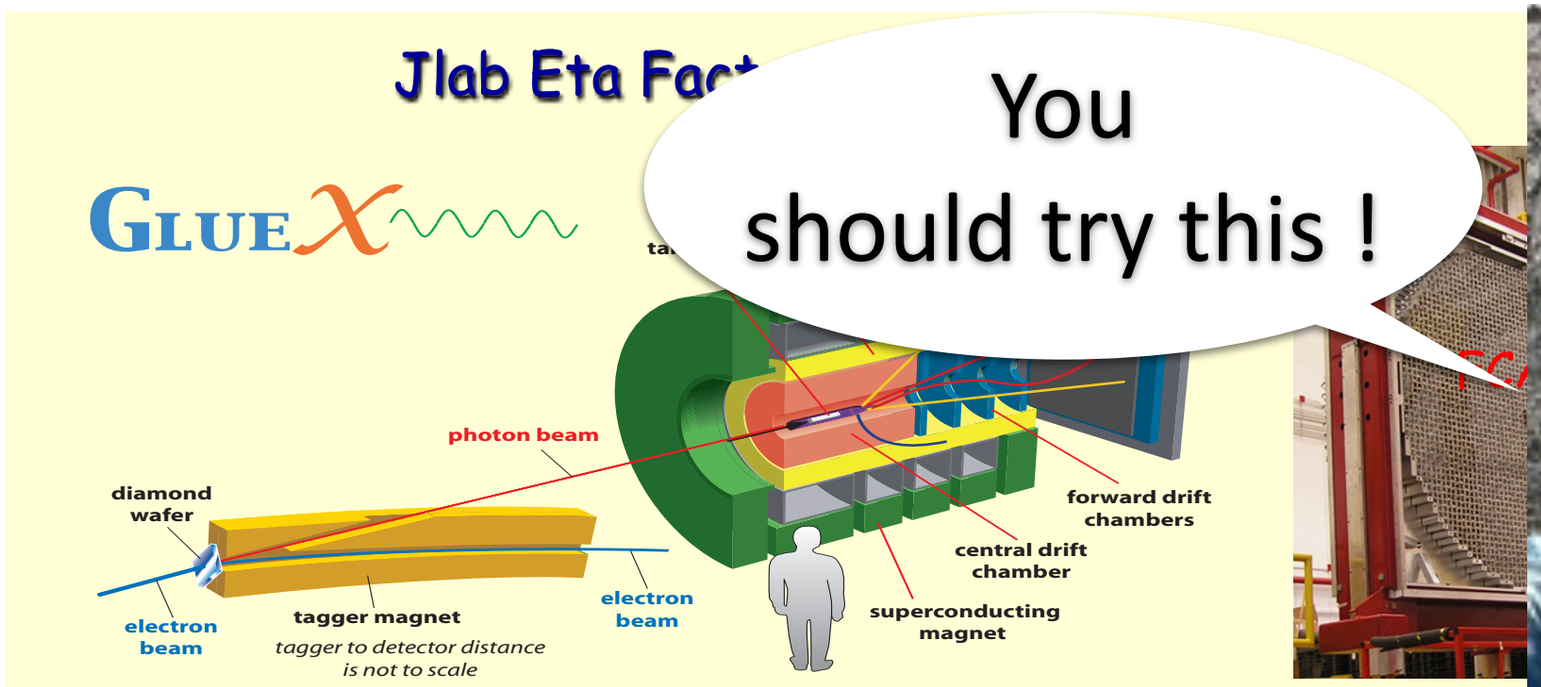

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Standard Model & Dark Sector

$$\begin{pmatrix} u \\ d \end{pmatrix}$$

$$\begin{pmatrix} c \\ s \end{pmatrix}$$

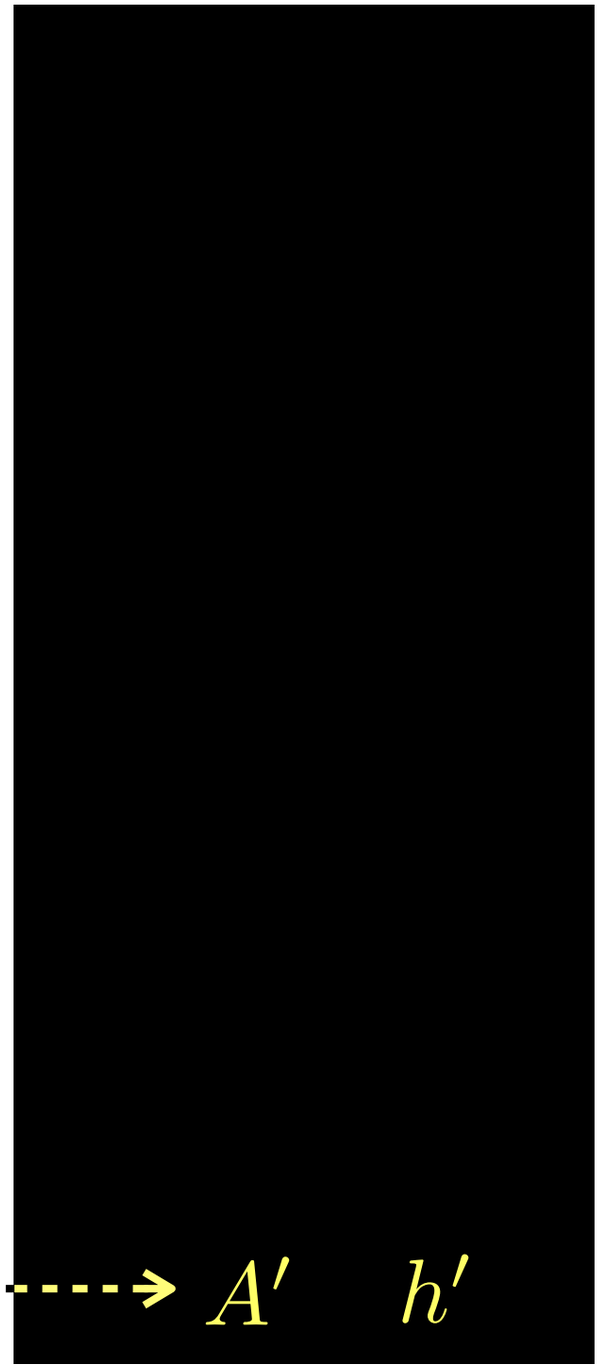
$$\begin{pmatrix} t \\ b \end{pmatrix}$$

$g, W^{\pm}, Z^0, H^0$

γ/Z^0 mixing

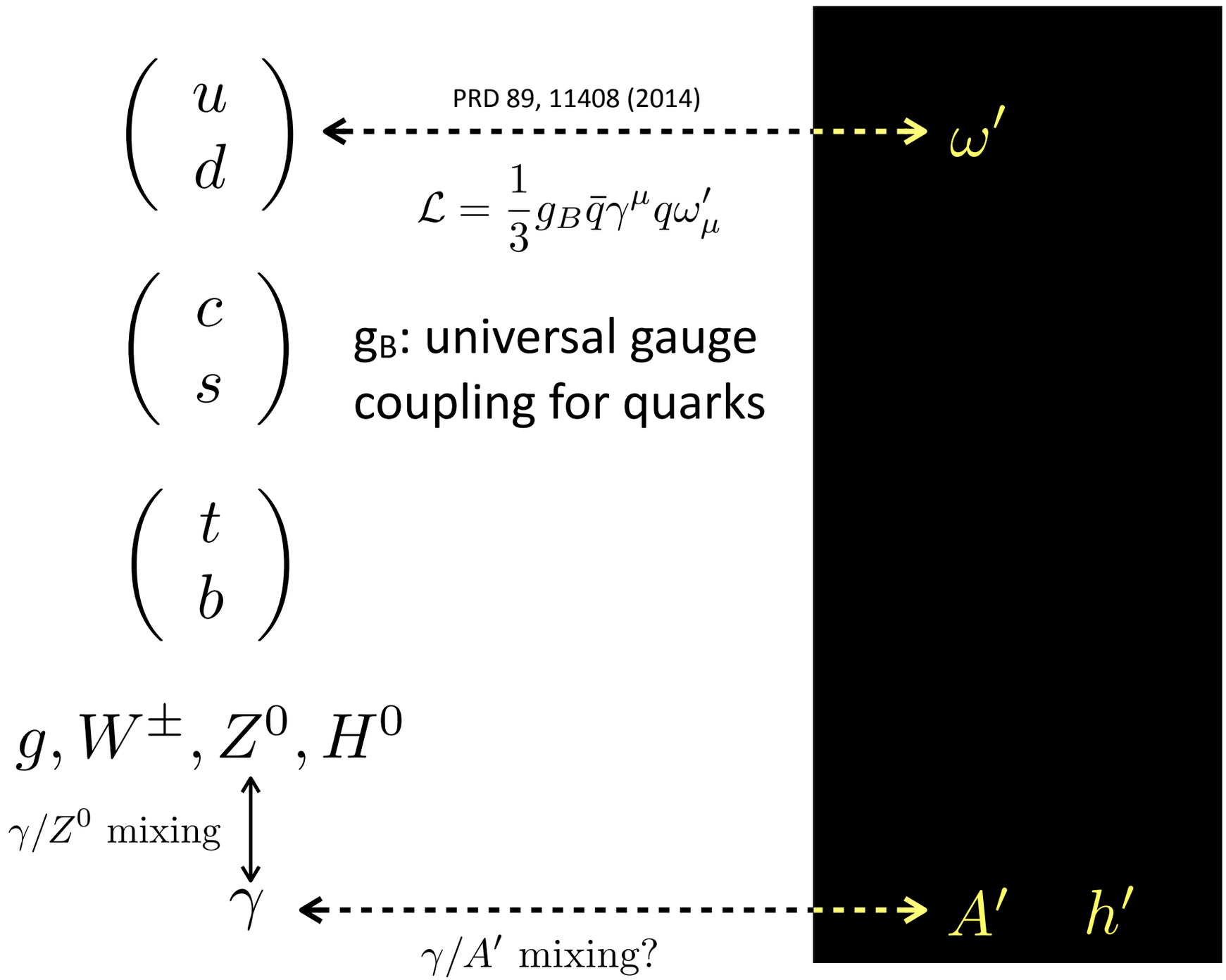
γ

γ/A' mixing?



Standard Model & Dark Sector

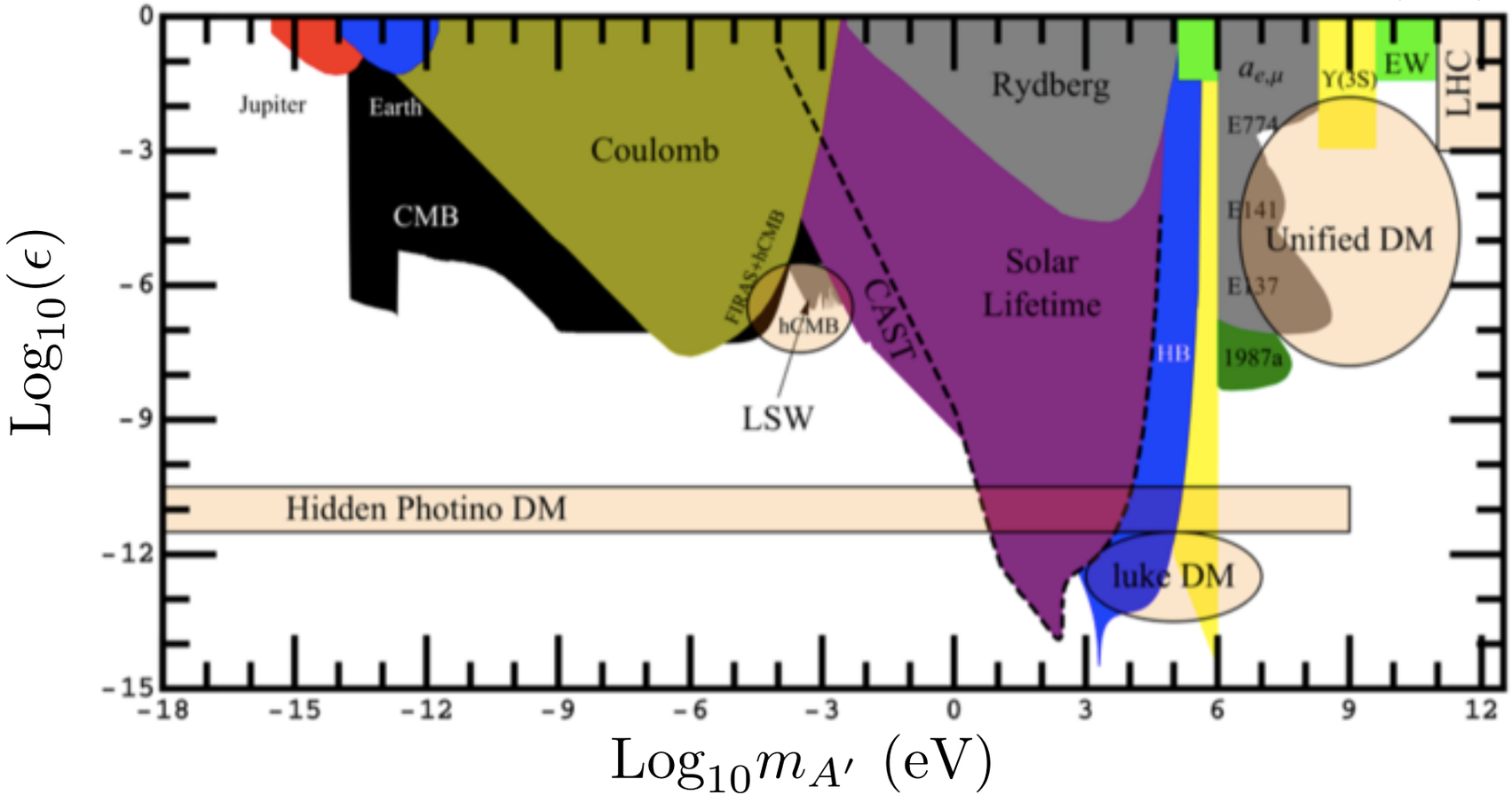
- One can also think a new boson couples to light quarks



Present experimental sensitivity

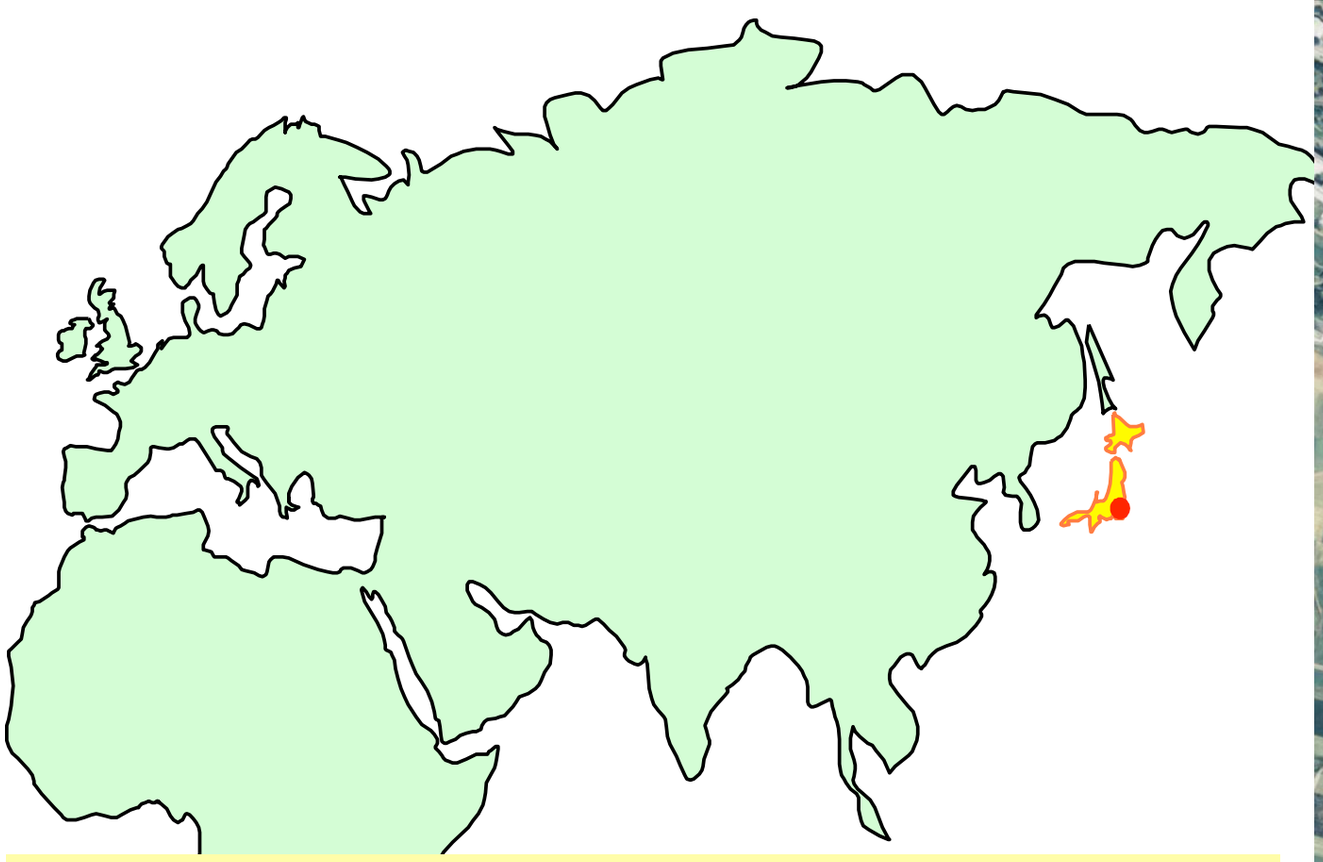
- Dark gauge boson (dark photon): $A' = \gamma' = A = U$
- Expected to have small coupling to SM particles.
- Low mass of order MeV to GeV.

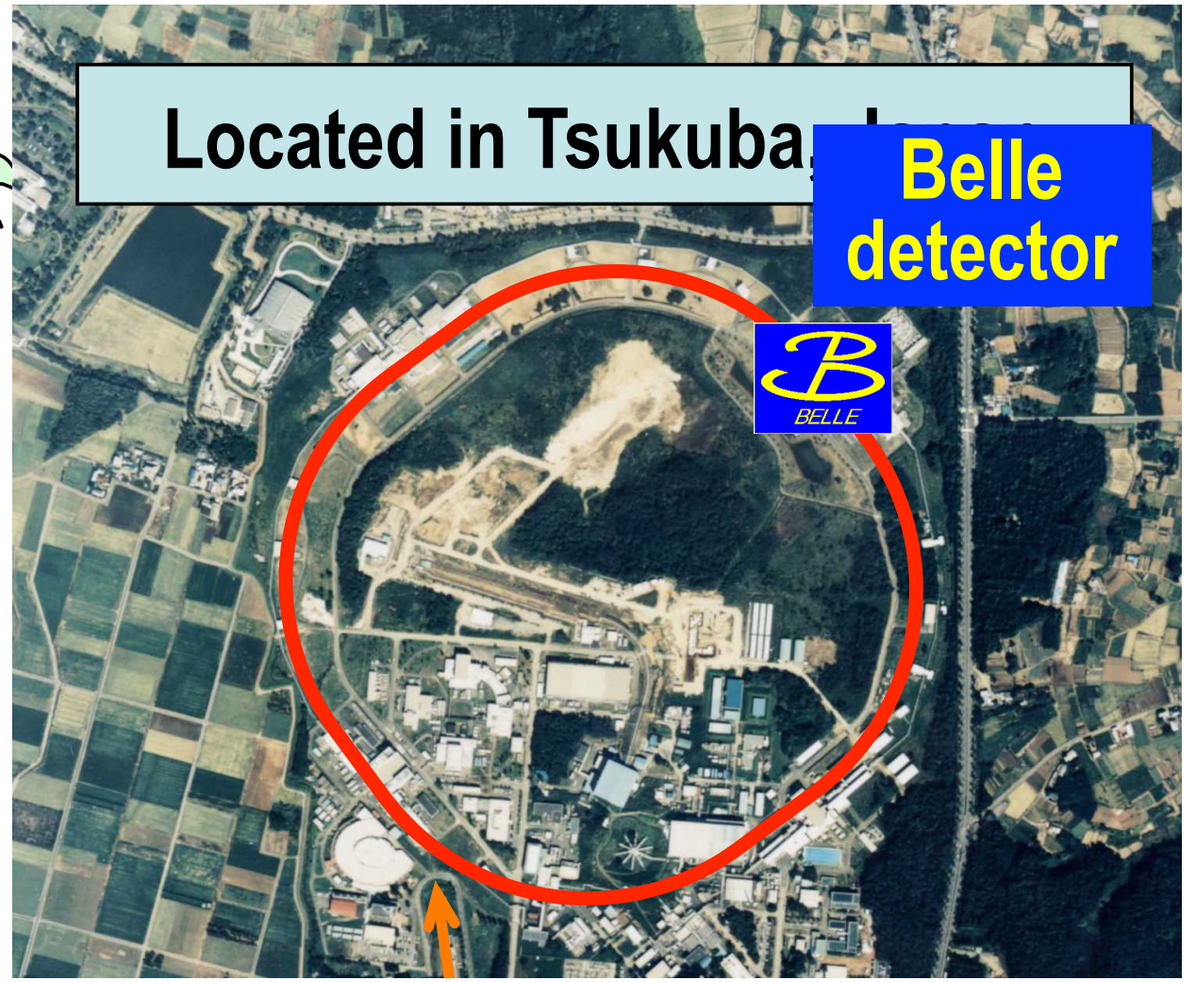
Annual Review of Nuclear and Particle Science 60 405 (2010)



- An extended Higgs sector is required to break the new U(1)' symmetry (dark Higgs: h').

KEKB e^+e^- Collider





3.5 GeV e^+ × 8.0 GeV e^-

$e^+e^- \rightarrow \Upsilon(4S)$

with $\beta\gamma = 0.425$

22 mrad crossing angle

$L_{peak} = 2.1 \times 10^{34}/cm^2/sec$

> 1 M BB pairs/day

Integrated L = 1 ab^{-1}

Experiment: 1999 - 2010

Belle Detector

γ, π^0 reconstruction
e^{+-}, K_L identification

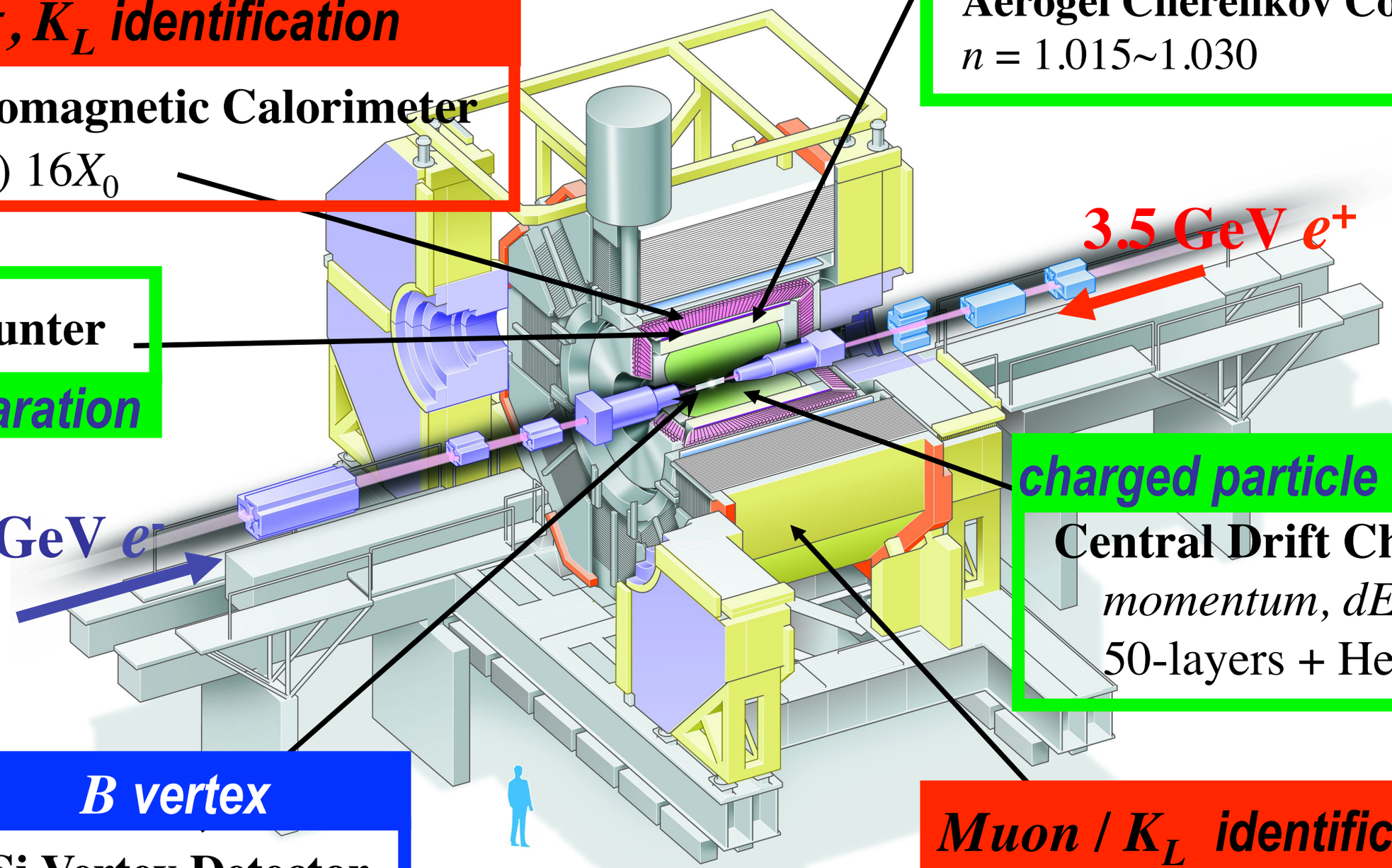
Electromagnetic Calorimeter
CsI(Tl) $16X_0$

K/π separation

Aerogel Cherenkov Counter
n = 1.015~1.030

TOF counter

K/π separation



charged particle tracking

Central Drift Chamber
momentum, *dE/dx*
50-layers + He/C_2H_6

B vertex

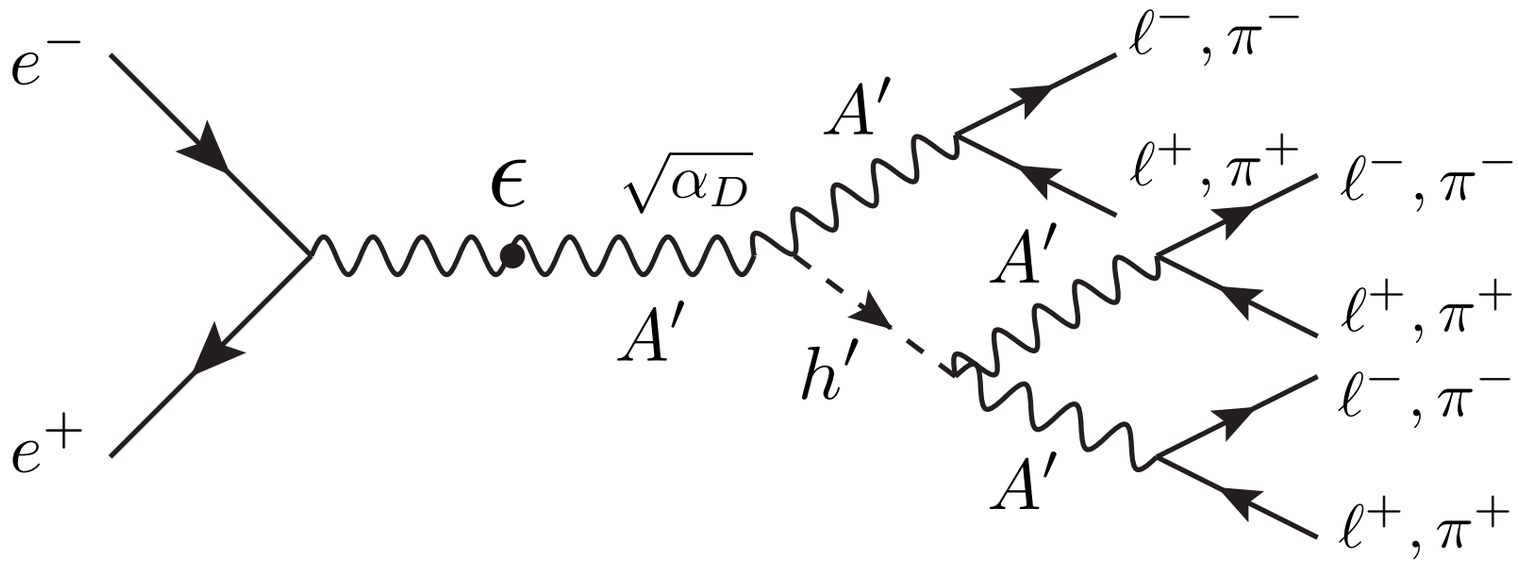
Si Vertex Detector
4-layer DSSD

Muon / K_L identification

K_L μ detector
14/15 layer RPC+Fe

Search for A’ and h’ @ Belle

- Higgs-strahlung process (PRD 79 111508 (2008))
- $M_{h'} > 2M_{A'}$ and QED background is suppressed in this channel.



α_D : dark sector coupling constant

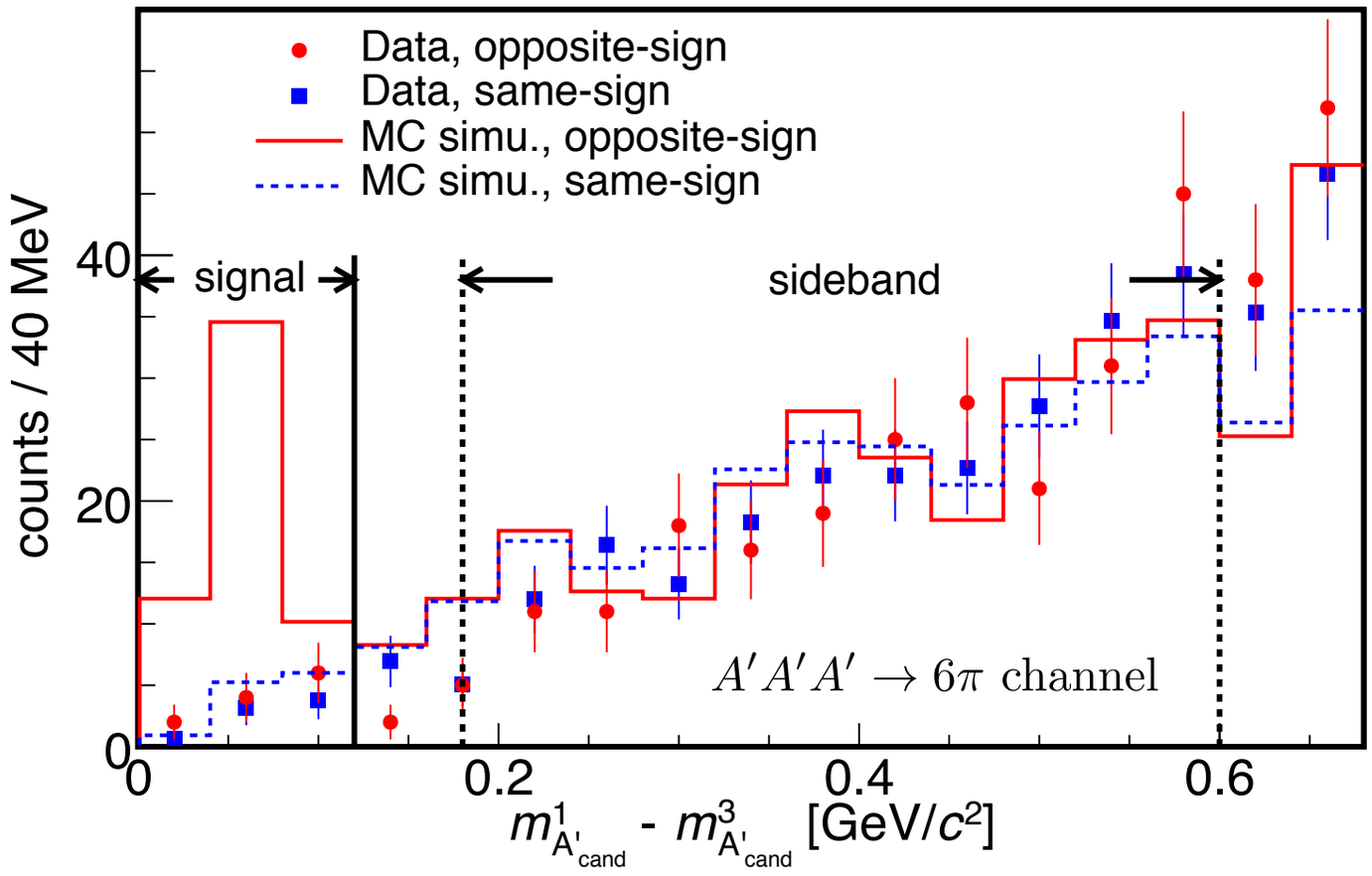
ϵ : kinetic mixing parameter

- 10 exclusive channels: $3(\ell^+\ell^-), 2(\ell^+\ell^-)(\pi^+\pi^-), (\ell^+\ell^-)2(\pi^+\pi^-),$ and $3(\pi^+\pi^-)$
- 3 inclusive channels for $m_{A'} > 1.1$ GeV: $2(\ell^+\ell^-)X$

(X: missing mass from dark photon cand.)

Background Estimation

- Use same sign events: $e^+e^- \to (\ell^+\ell^+)(\ell^-\ell^-)(\ell^+\ell^-)$
- Order masses of lepton (hadron) pairs as $m^1_{\ell\ell} > m^2_{\ell\ell} > m^3_{\ell\ell}$
- Plot $m^1_{\ell\ell} - m^3_{\ell\ell}$ vs. $m^1_{\ell\ell}$
- Select the region in invariant mass and predict the background using the same sign events



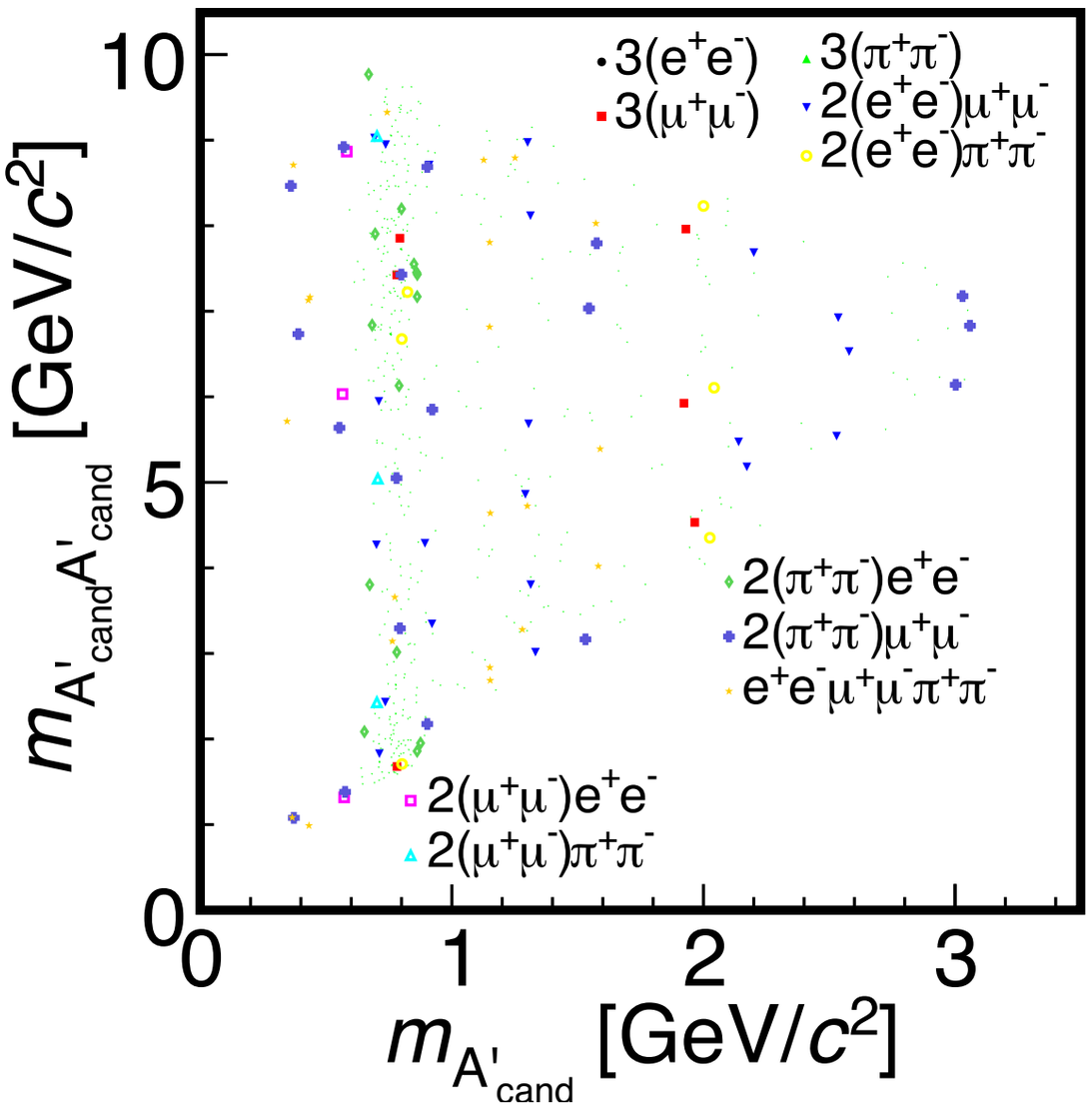
(I. Jaegle et al., (PRL 114, 211801 (2015))

- Normalisation is from the side band same sign events
- Background estimated from counting same sign events

Belle results

(I. Jaegle et al., (PRL 114, 211801 (2015))

Exclusive modes



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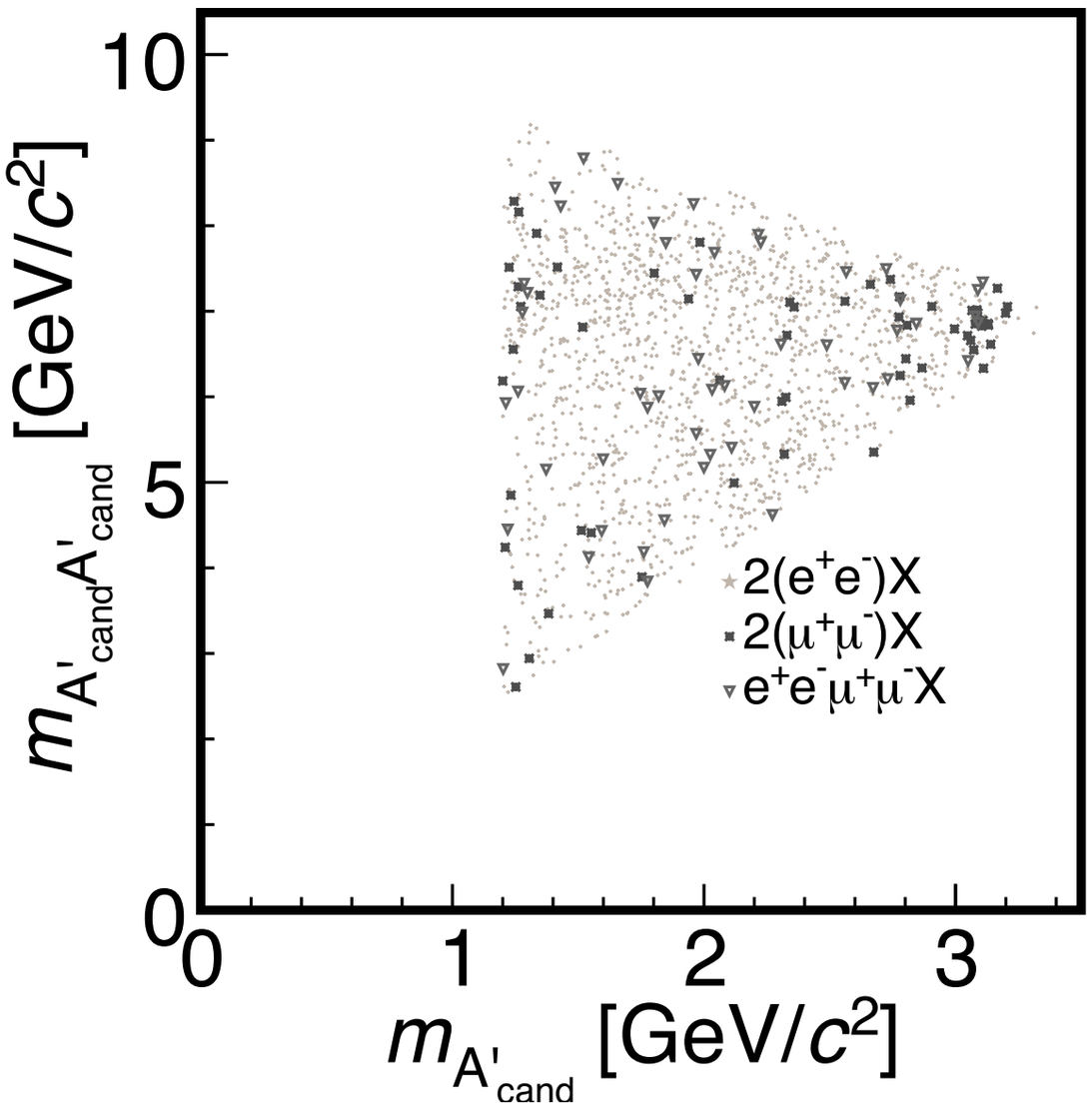
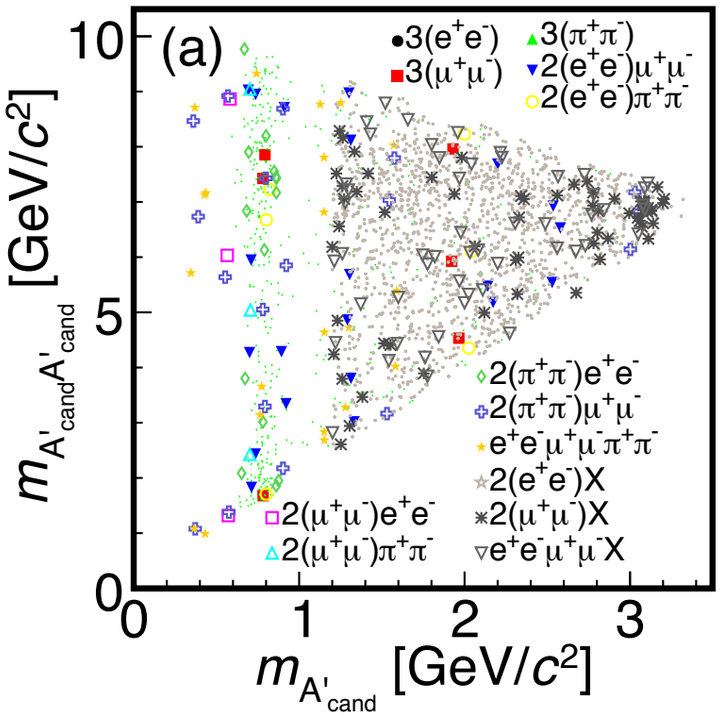
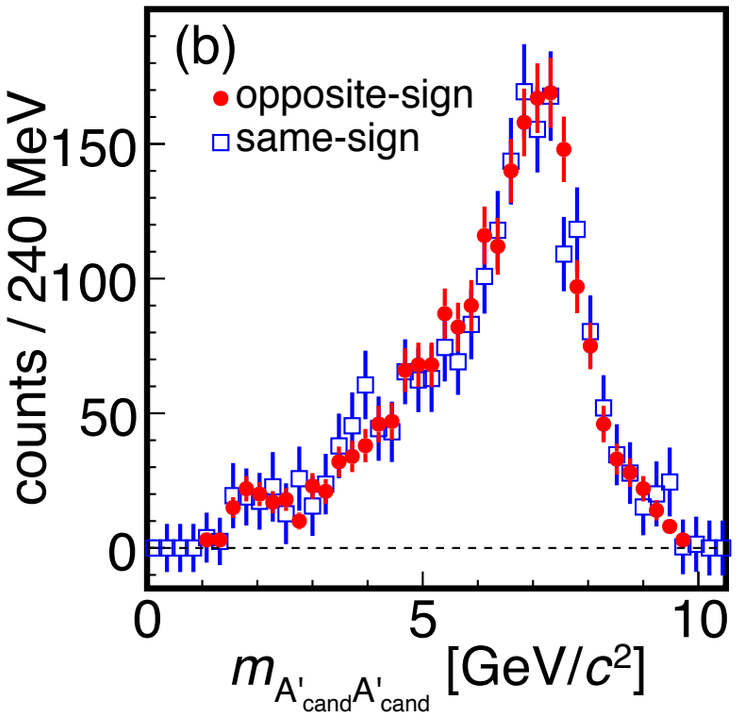
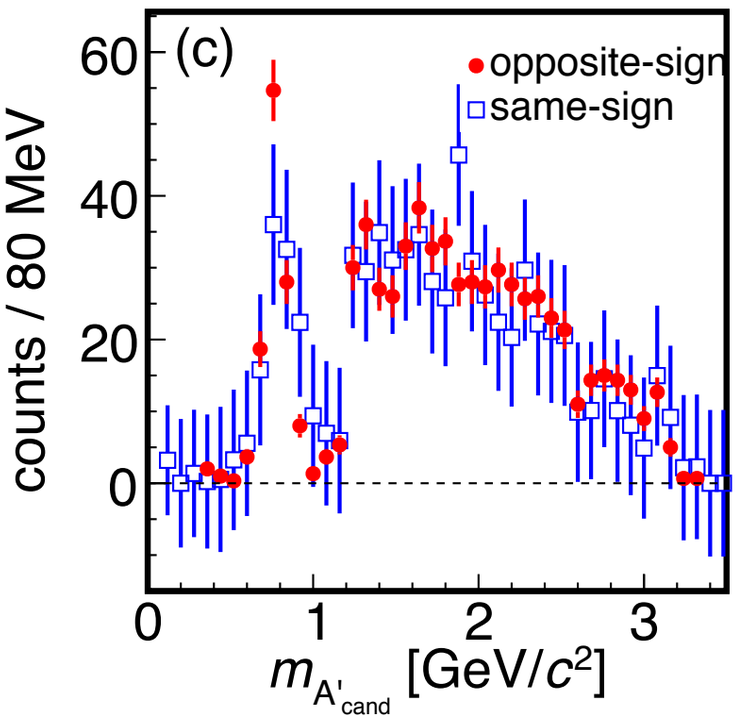


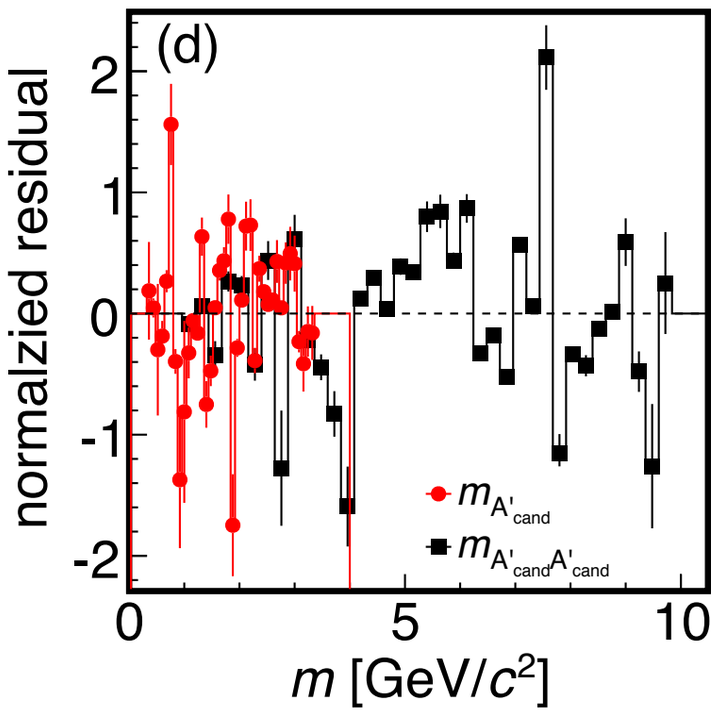
- 19% of events due to $3(\pi^+\pi^-)$
- 74% of events due to $2(l^+l^-)X$

Belle results









(I. Jaegle et al., (PRL 114, 211801 (2015))

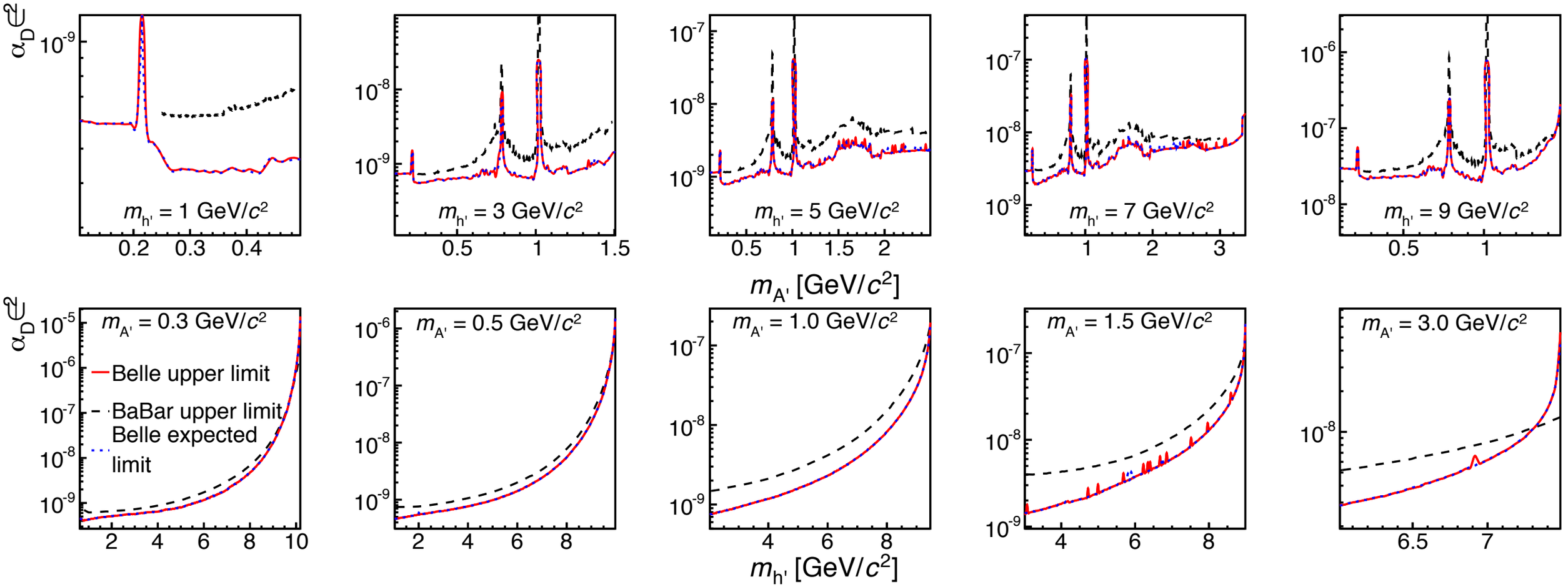
Final-state	Events	Final-state	Events
$3(e^-e^+)$	1	$2(\mu^+\mu^-)(e^+e^-)$	1
$3(\mu^+\mu^-)$	2	$2(\mu^+\mu^-)(\pi^+\pi^-)$	1
$3(\pi^+\pi^-)$	147	$2(\pi^+\pi^-)(e^+e^-)$	5
$2(e^+e^-)(\mu^+\mu^-)$	7	$2(\pi^+\pi^-)(\mu^+\mu^-)$	6
$2(e^+e^-)(\pi^+\pi^-)$	2	$(e^+e^-)(\mu^+\mu^-)(\pi^+\pi^-)$	7
$2(e^+e^-)X$	572	$(e^+e^-)(\mu^+\mu^-)X$	30
$2(\mu^+\mu^-)X$	20		

Number of events observed after all selection criteria are applied.

- Events consistent with background estimation.

Belle results - cont.

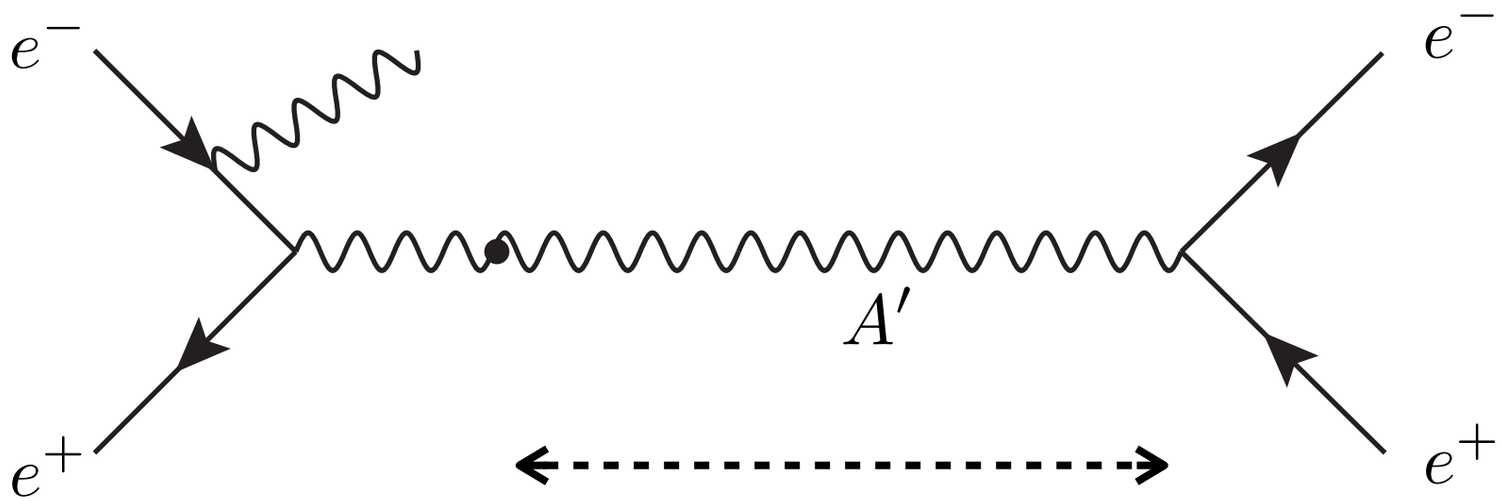
- Belle 977 fb^{-1} (PRL 114, 211801 (2015)) and BaBar 520 fb^{-1} (PRL 108 211801 (2012))



- 90% CL upper limit on the product of $\alpha_D\varepsilon^2$ vs. dark photon mass (top) and dark Higgs boson mass (below)

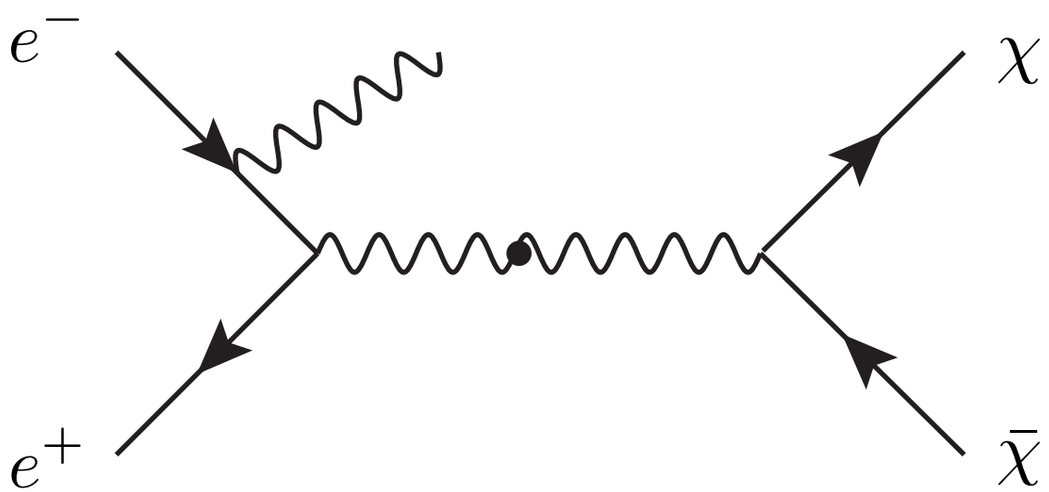
Other ongoing analyses

- Long lived dark photon search.



$c\tau$ = 1 - 10 cm

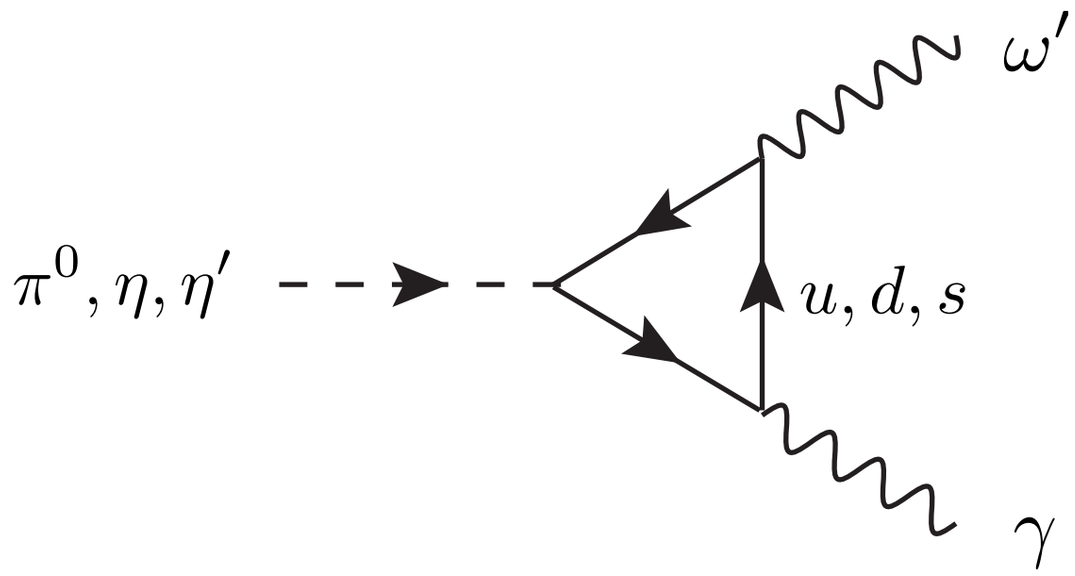
- Invisible decays with photon conversion.

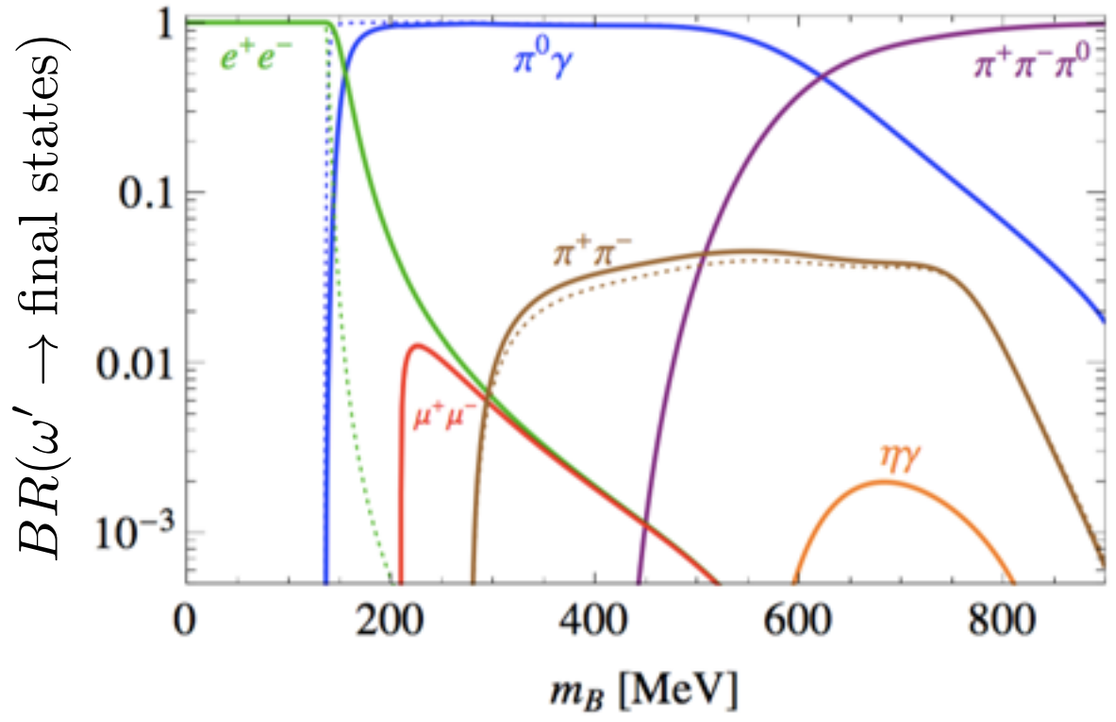


Single photon in the final state
- No such trigger in Belle.
- Photon conversion is under consideration.

Other ongoing analyses

- A new boson (ω') coupling to light quarks: S. Tulin, PRD 89, 11408 (2014)



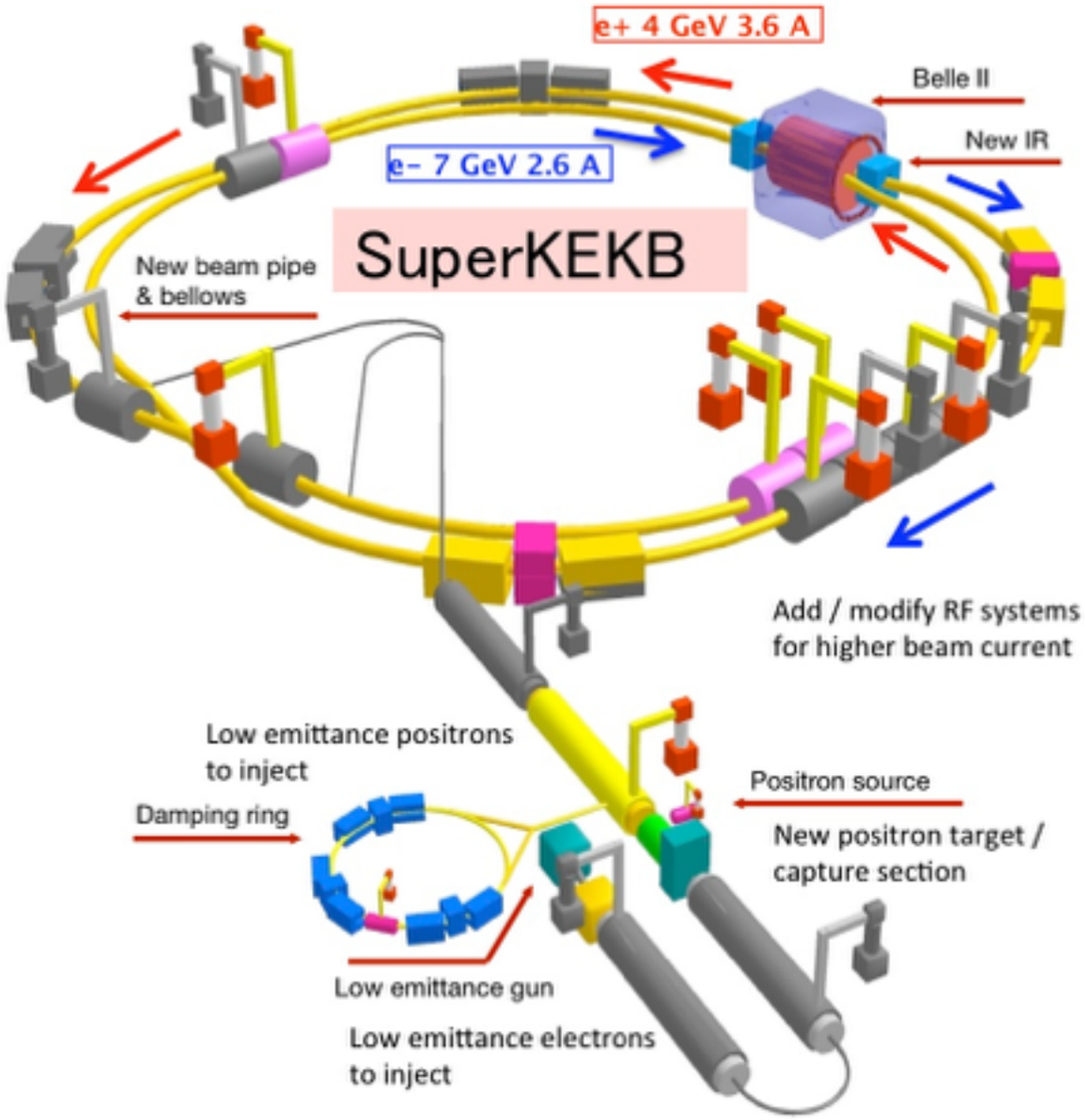


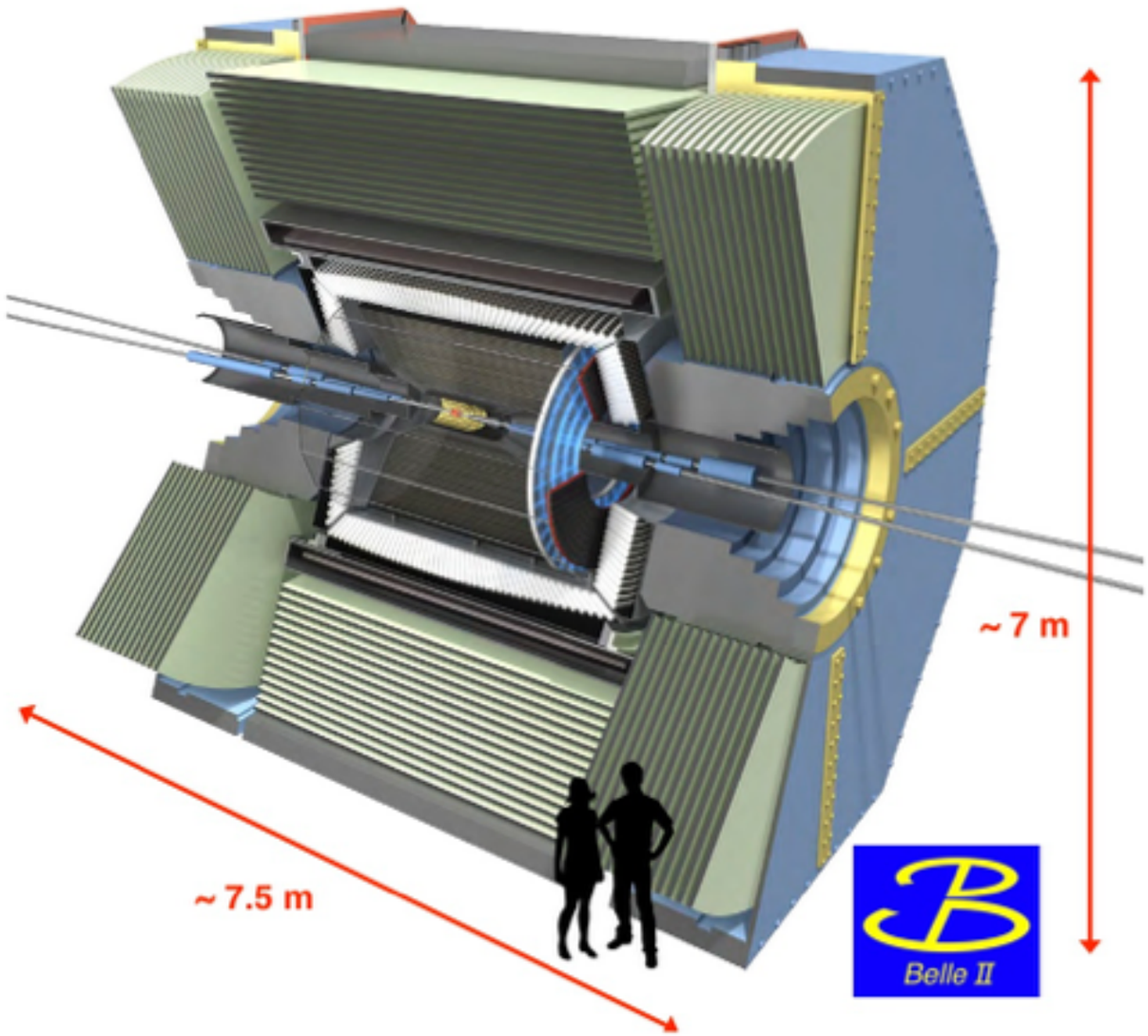
The produced π^0, η, η' from e^+e^- collision can decay to a new boson and photon pair.

- Usually reconstructed light mesons suffer from combinatorial background.
- Suppress of such background is now under consideration.

Stay tune for next Patras workshop in 2017 !

SuperKEKB & Belle II





- 40 time higher luminosity with new damping ring, new lattice, crab cavities, and nano beam.
- New detectors: pixel sensor, silicon strip, PID with quartz bar, and upgraded readout for all.

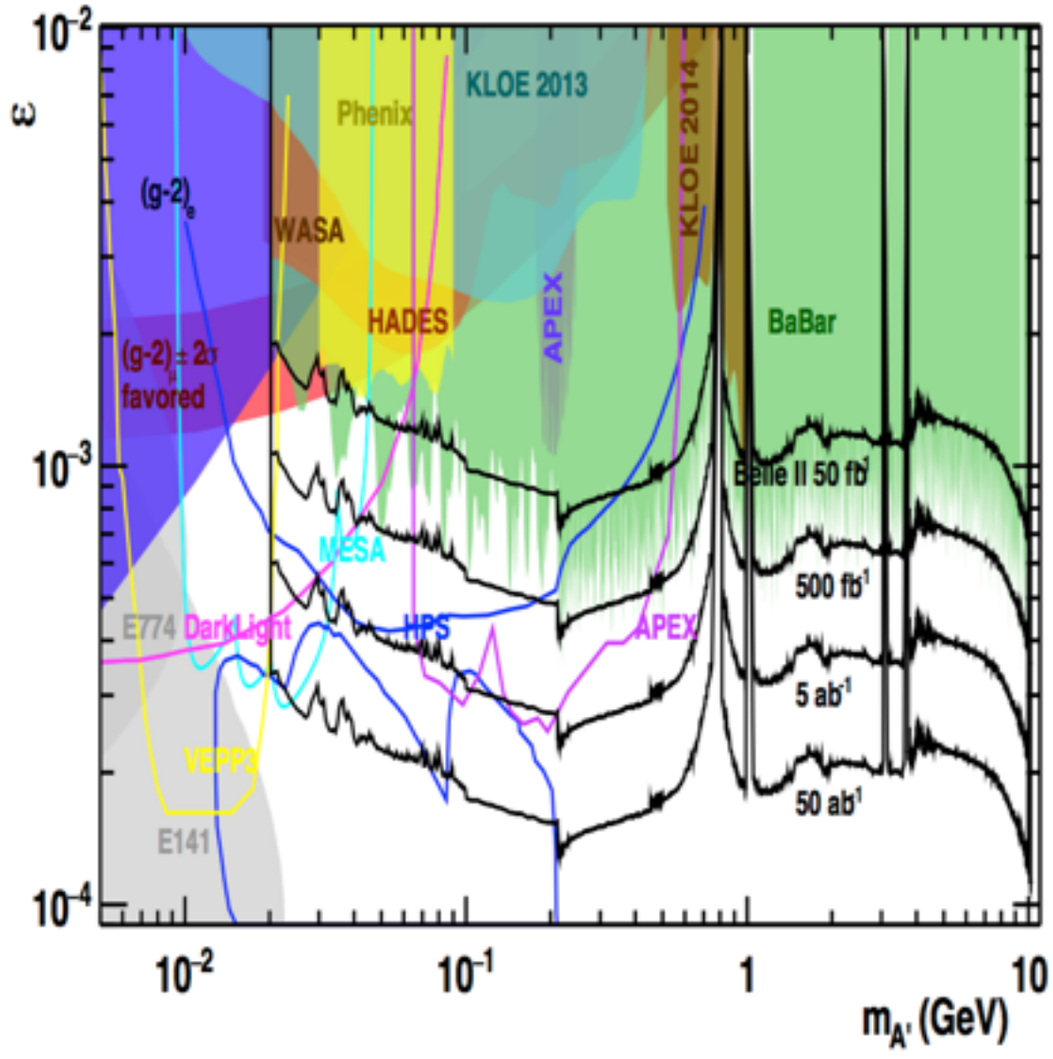
Belle II Schedule

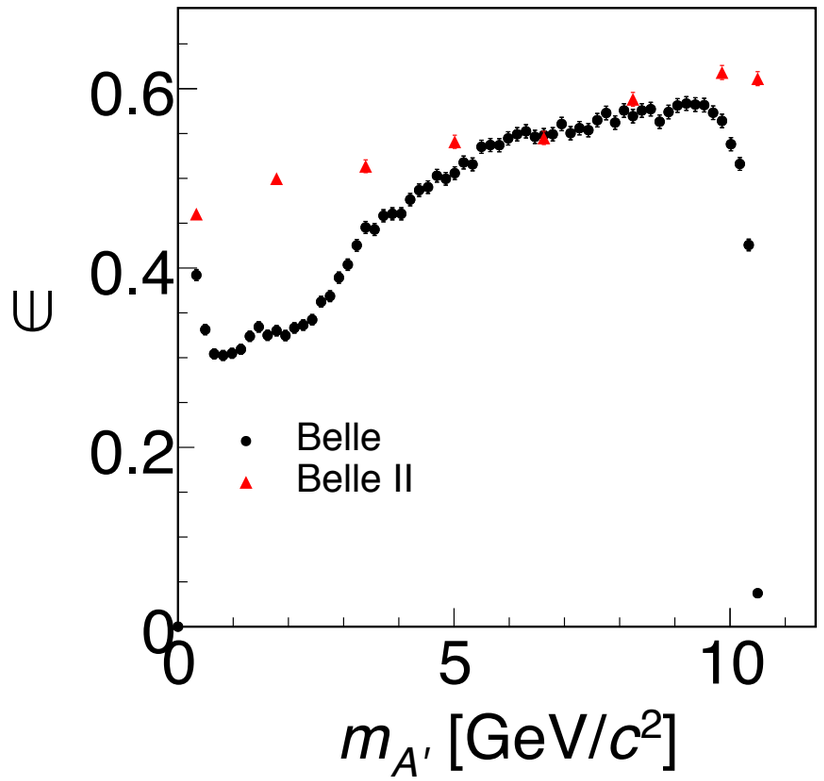
- Commissioning (phase 1) of the main ring (without final quads) started Feb. 1, 2016, with a commissioning detector (not the real Belle II detector).
- Add final quads in summer 2016.
- Belle II: installation of the outer detector: spring/early summer 2016.
- Belle II (w/o the vertex detector) roll in autumn 2016, cosmic rays.

- Phase 2 commissioning autumn 2017 - spring 2018

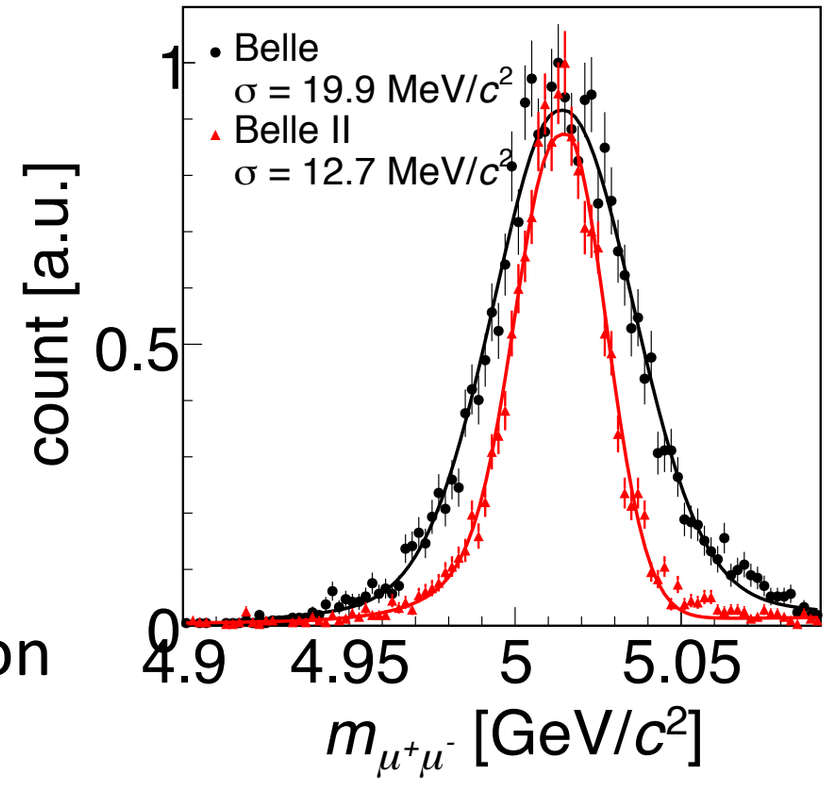
- Install vertex detector summer 2018
- **Full detector operation autumn 2018 (phase 3)**

Sensitivity @ Belle II





- $e^+e^- \to \gamma A', A' \to \ell^+\ell^- (\ell = e \text{ or } \mu)$
- Predicted Belle II limits extrapolated from BaBar PRL 113, 201801 (2014) (C. Hearty B2TIP2014)
- Improved low multiplicity trigger and better dimuon invariant mass resolution.



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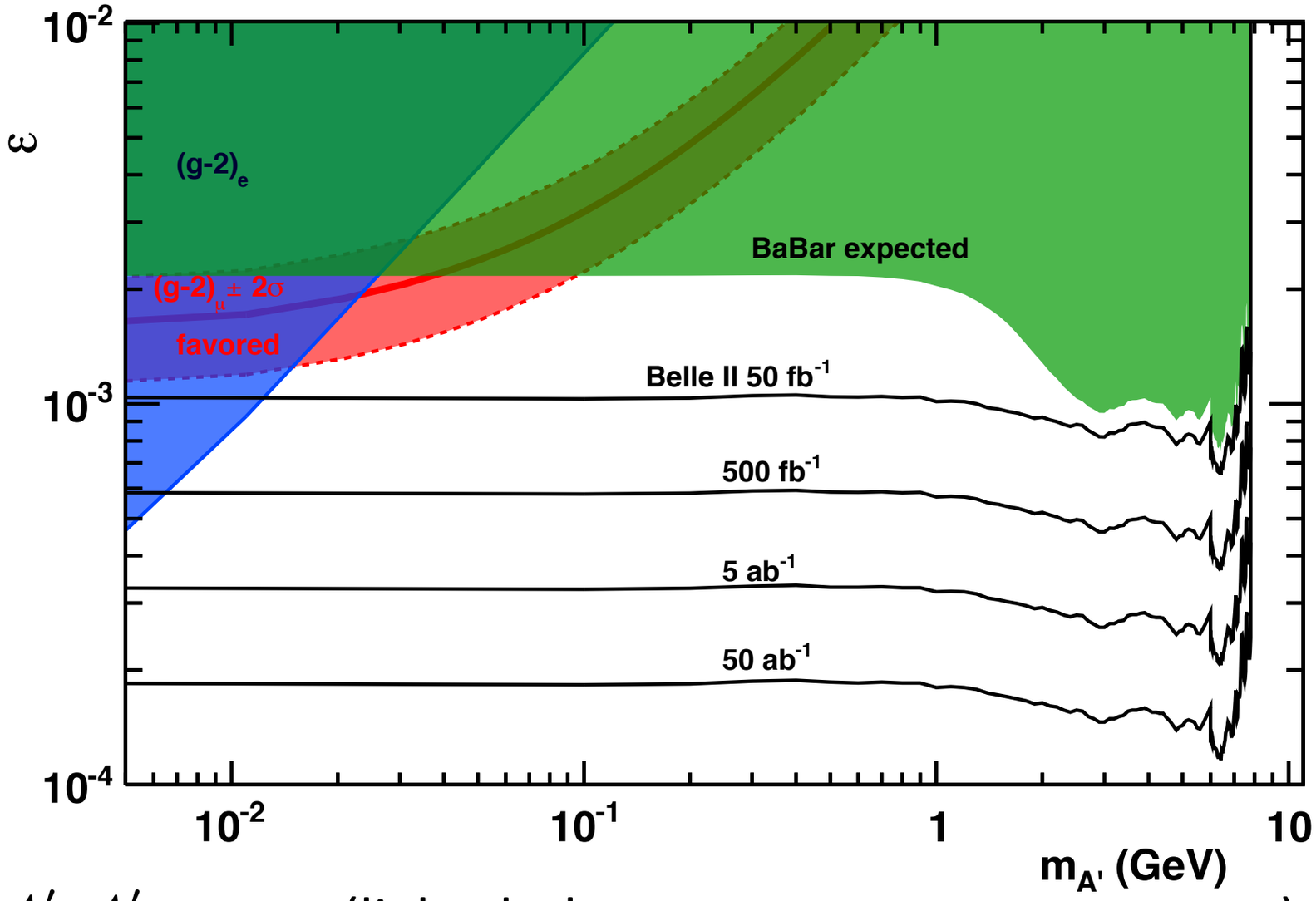

- $e^+e^- \to \gamma A', A' \to \chi\bar{\chi}$ (light dark matter R. Essig et al.arXiv:1309.5084)

- Predicted Belle II limits extrapolated from BaBar PRL 113, 201801 (2014) (C. Hearty B2TIP2014)
- Assuming a single photon trigger in Belle II.

Summary

- Studies on the dark sector represents an alternative to SM dark matter search.

- e^+e^- collider detector environment is sensitive to MeV - GeV ranges for proposed new dark particles: complementary to fixed-target experiment.

- We showed analyses at Belle for dark photon with decay to leptons or pions.

- Prospects with Belle II data are shown and we expect Belle II data taking in 2018.