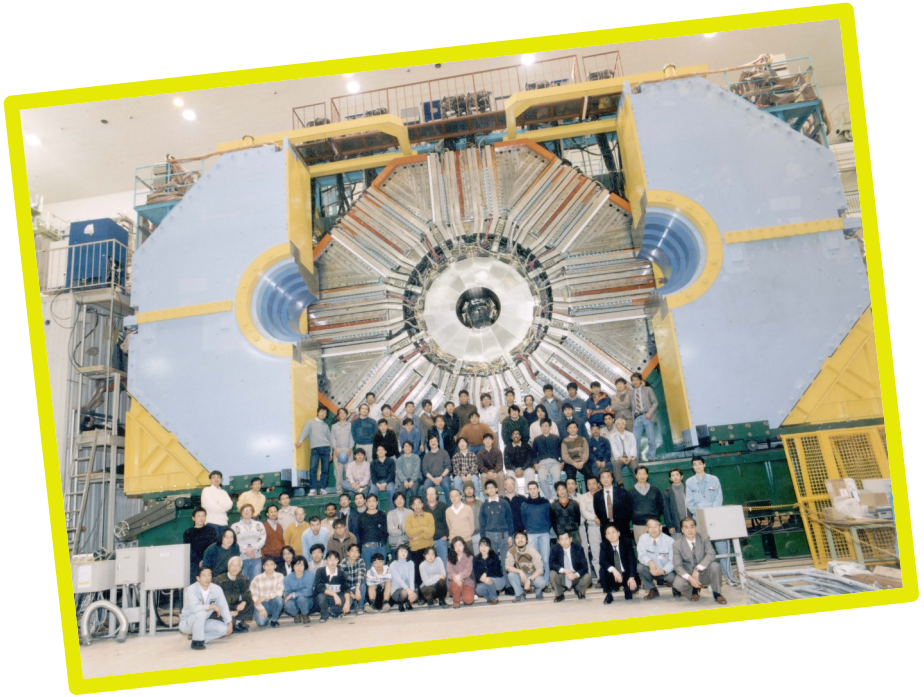
Search for Dark Sector at Belle



Giacomo De Pietro

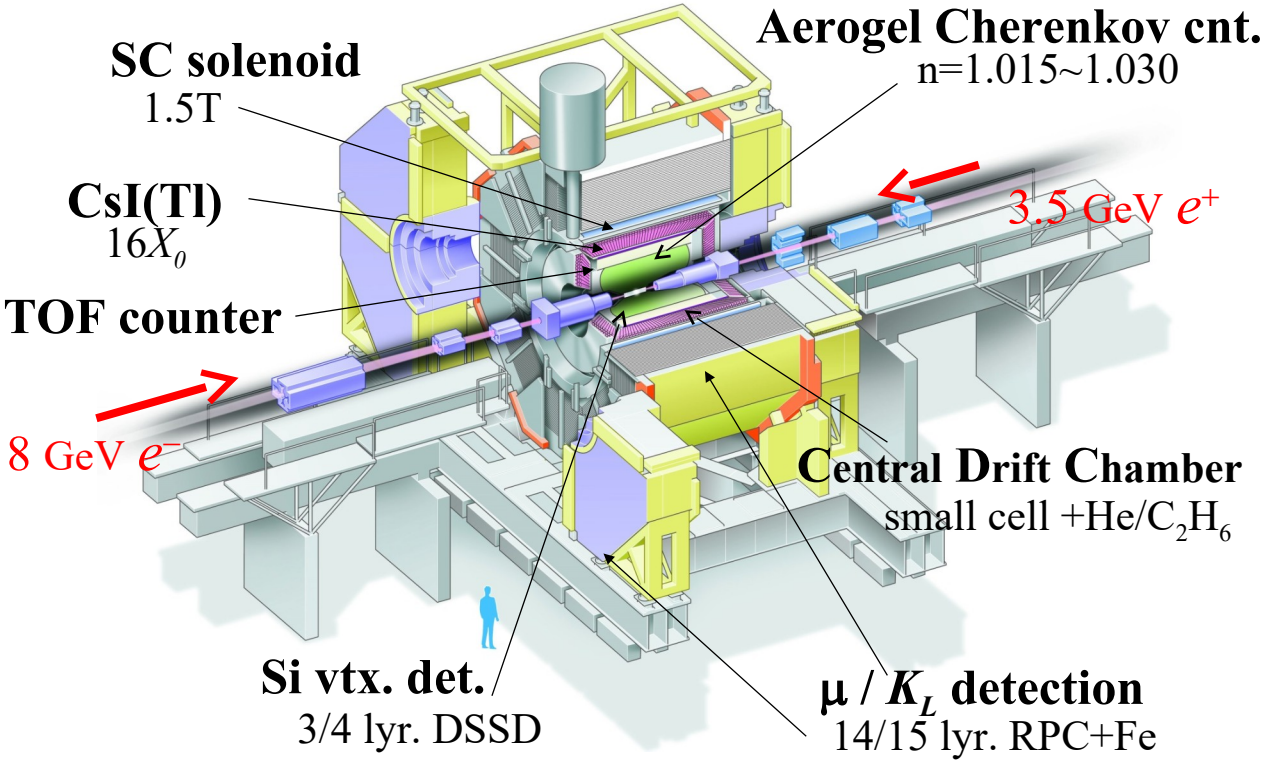
INFN Roma Tre

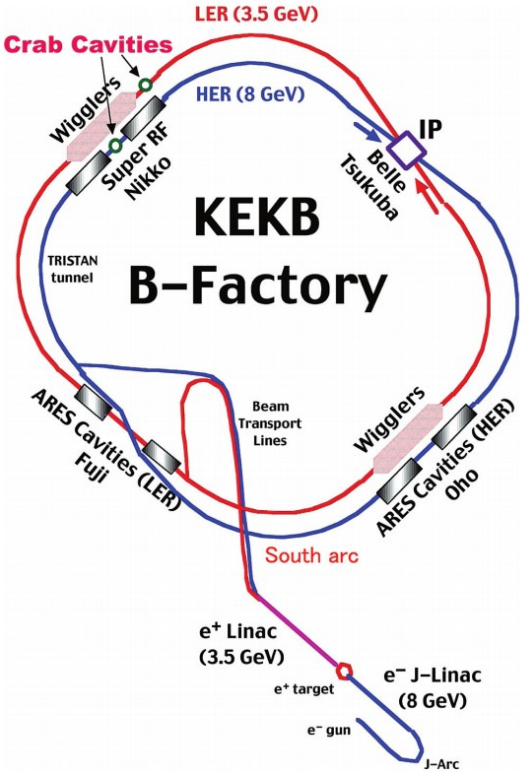
The XXVIII International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY 2021)

Belle @ KEKB

Belle collected 1040 fb^{-1} of data from 1999 to 2010

- 710 fb^{-1} collected at the $\Upsilon(4S)$ mass $\rightarrow 772 \cdot 10^6$ $B\overline{B}$ pairs





Dark Matter

It is “dark”.

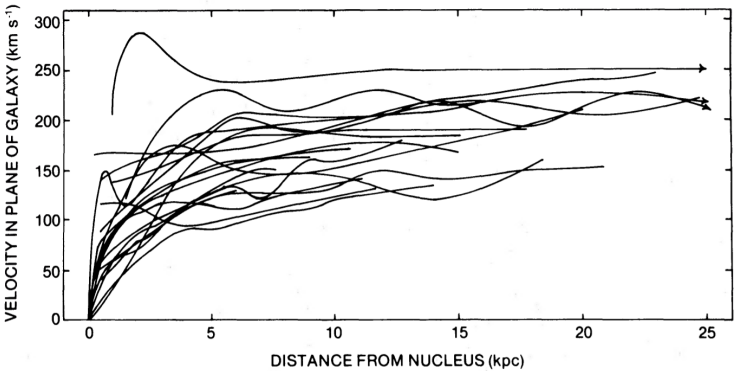
It exists...

A lot of experimental techniques

to probe the Dark Matter existence:

- production at colliders;
- production in fixed target experiments;
- indirect astronomic searches;
- direct underground searches.

Rotational curves of the galaxies



Bullet clusters

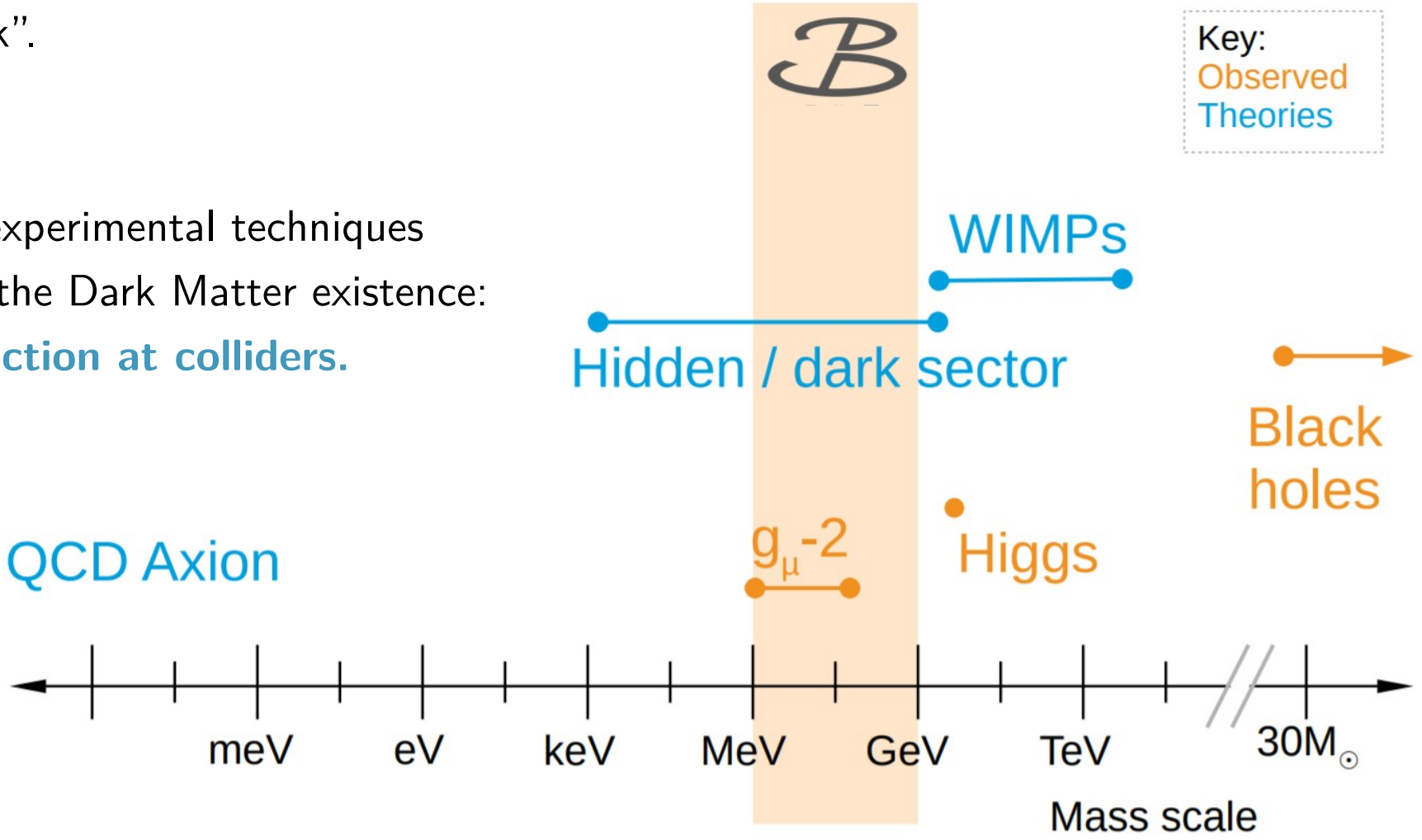
Dark Matter

It is “dark”.

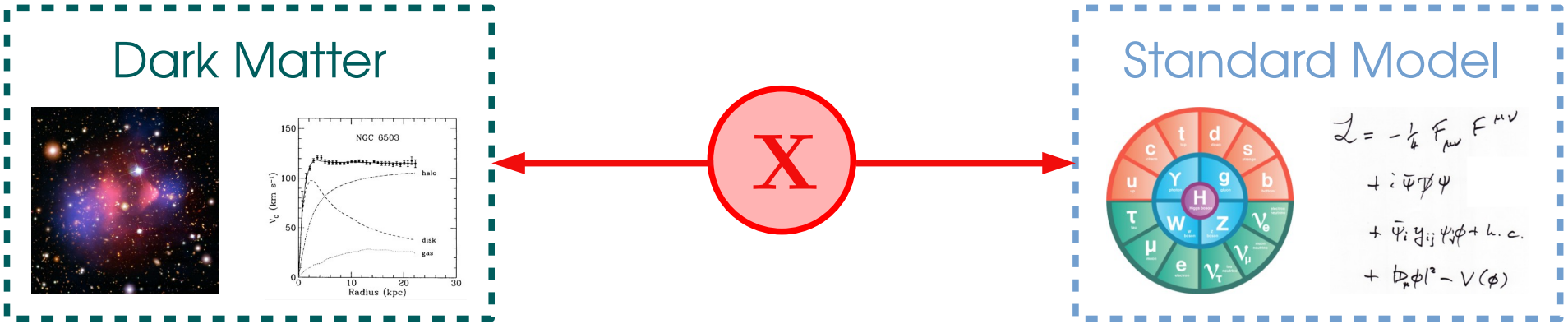
It exists...

A lot of experimental techniques
to probe the Dark Matter existence:

- **production at colliders.**



Dark Matter coupling to SM



Different possible portals between **Dark Matter** and **Standard Model** depending on the **dark mediator X**:

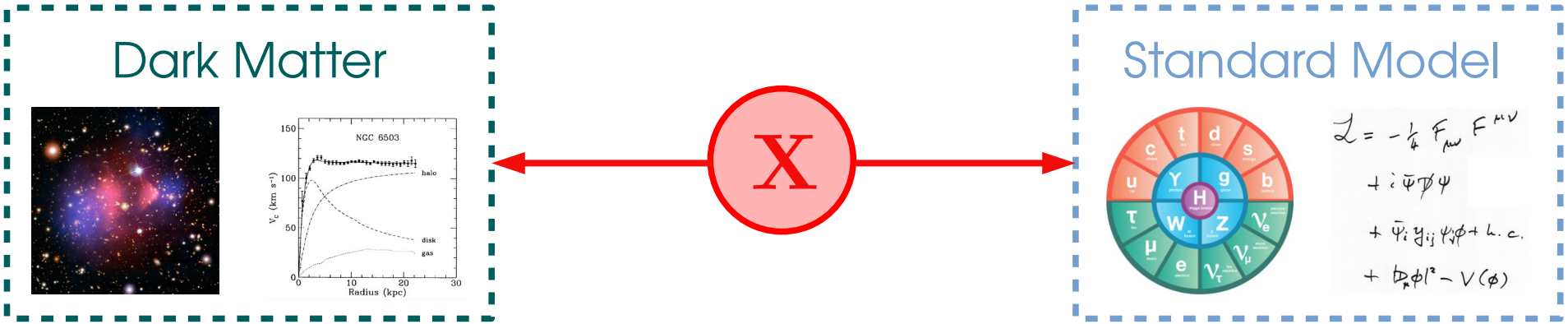
Vector portal $\rightarrow$ Dark Photon / Z'

Scalar portal $\rightarrow$ Dark Higgs / Dark Scalar

Pseudoscalar portal $\rightarrow$ Axion-Like Particles

Neutrino portal $\rightarrow$ Sterile Neutrinos

Dark Matter coupling to SM



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Vector portal $\rightarrow$ **Dark Photon** / **Z′**

Scalar portal $\rightarrow$ **Dark Higgs** / Dark Scalar

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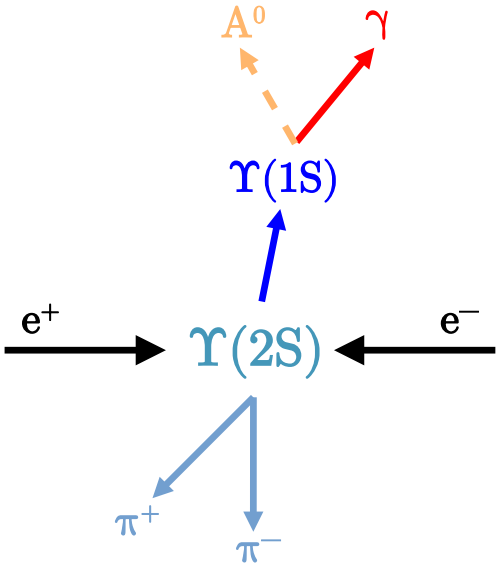
Light CP-odd Higgs boson

Belle searched for a light CP-odd Higgs boson decaying into dark matter particles: $\Upsilon(2S) \to \pi^+\pi^- \Upsilon(1S)$; $\Upsilon(1S) \to \gamma A^0$; $A^0 \to \chi\chi$

PRD 74 054034
PRD 80 115019

- Considered both A^0 on-shell and off-shell decays
- Used a data sample of 24.9 fb^{-1} collected at the $\Upsilon(2S)$ resonance



Events reconstructed by requiring two opposite-charged tracks identified as pions and by taking the most energetic photon in the event

- recoil mass w.r.t. dipion system tags the $\Upsilon(1S)$
- the presence of an on-shell A^0 contributes with a peak in the E^{CM} distribution of the photon

Largest background contributions from $\Upsilon(2S) \to \tau^+\tau^-$ and $\Upsilon(1S) \to \ell^+\ell^-$

Belle, PRL 122 011801 (2019)

Light CP-odd Higgs boson

No statistically significant signal excess is observed: largest local significance is 2.1σ

Upper limits on the BF of the process $\Upsilon(1S) \to \gamma A^0$ (both on-shell and off-shell cases) are thus set

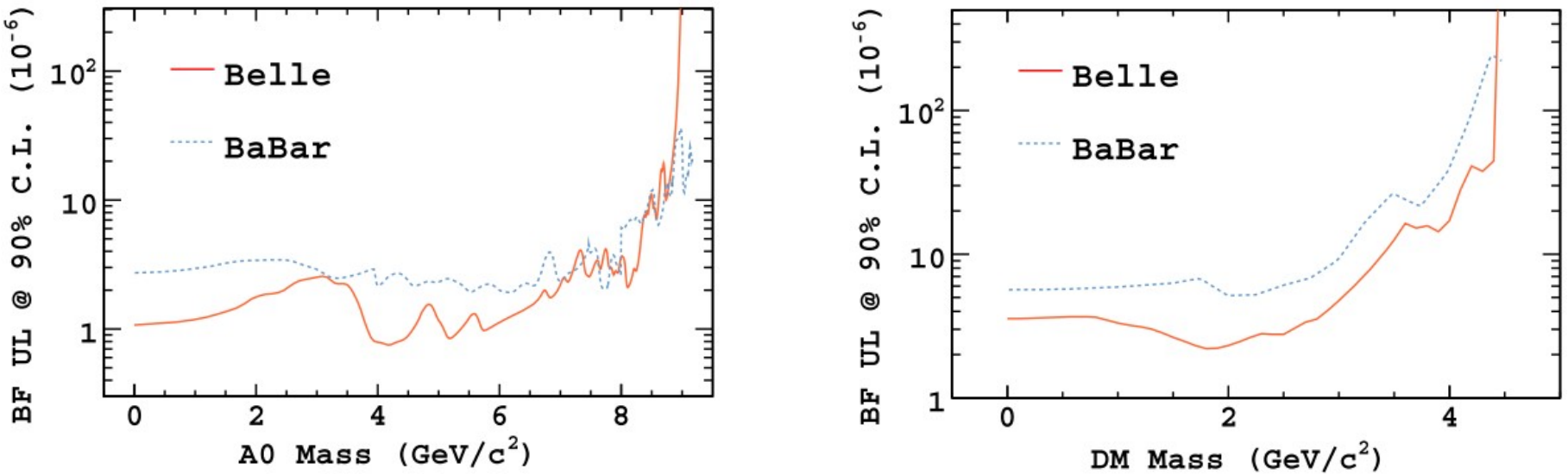


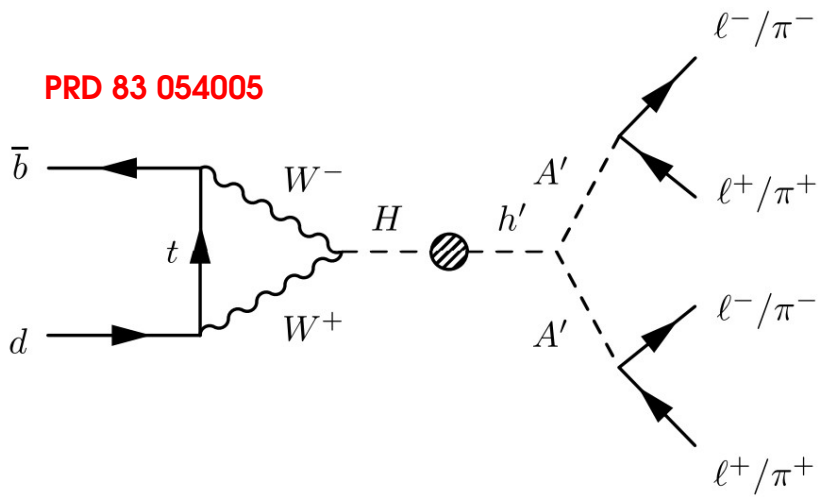
FIG. 2. 90% C.L. upper limits on the BFs of the on-shell process $\Upsilon(1S) \to \gamma A^0$ with $A^0 \to \chi\chi$ (top) and the off-shell process $\Upsilon(1S) \to \gamma\chi\chi$ (bottom). The orange solid curves are the Belle limits and the blue dashed curves are the *BABAR* limits.

Belle, PRL 122 011801 (2019)

$B^0 \to A'A'$: introduction

In this search, short-lived and 100% visible dark photon is assumed.

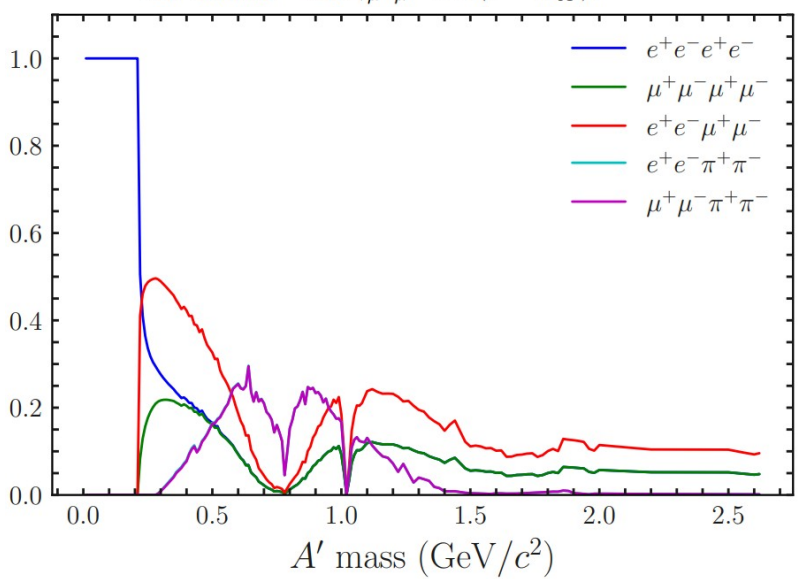
- 5 different final states ($4e$, 4μ, $2e2\mu$, $2e2\pi$, $2\mu2\pi$) as target decay modes.
- Kinematically allowed A' mass region: 10 – 2620 MeV.



Virtual dark Higgs h' coming from kinetic mixing with H and then decaying into a A' pair

$$\Gamma_{A'\to\ell^+\ell^-} = \frac{1}{3}\alpha\varepsilon^2_{\rm mix} m_{A'}\sqrt{1-4m^2_\ell/m^2_{A'}}(1+2m^2_\ell/m^2_{A'})$$

$$\Gamma_{A'\to\rm hadrons} = \Gamma_{A'\to\mu^+\mu^-} \times R(s=m^2_{A'}),$$



Relative B^0 branching fraction for each target final state

Belle, JHEP 04 (2021) 191

$B^0 \to A'A'$: analysis strategy

Require at least 4 charged tracks,

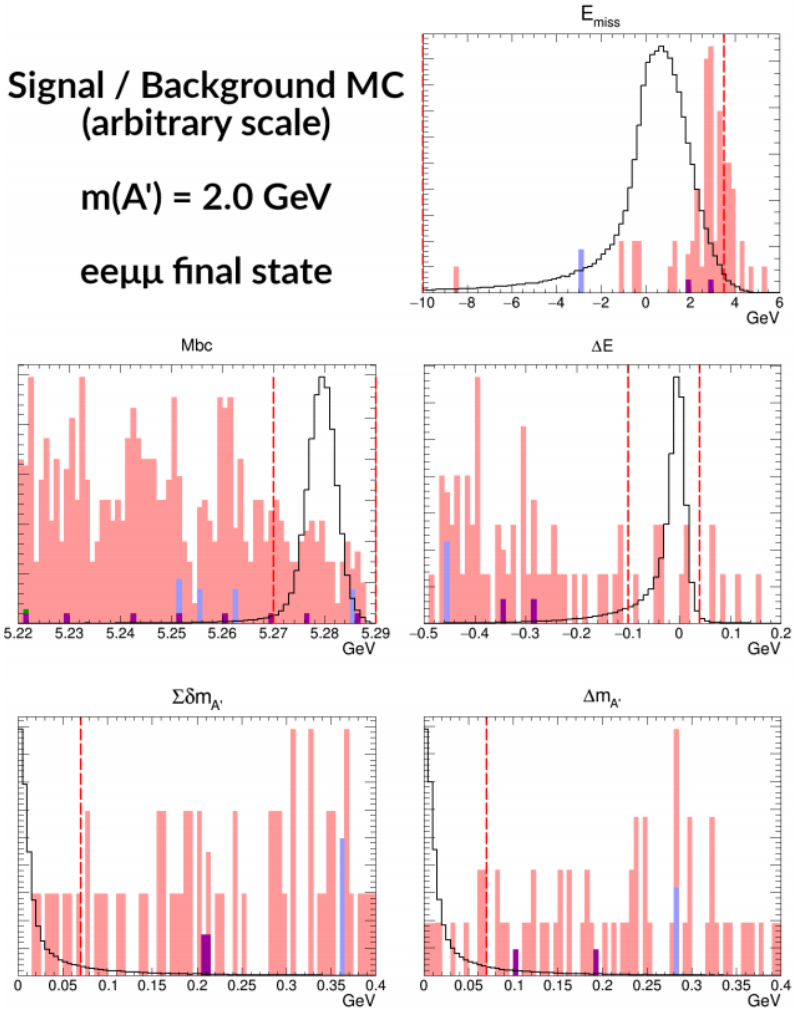
including at least one e^+e^- or $\mu^+\mu^-$ pair

- Each track should appear near the interaction point with good track fitting

Possible SM resonances to be identified by A' are rejected

- J/ψ, $\psi(2S) \to \ell^+\ell^-$
- $D^0 \to \pi^+\pi^-$, including $K^-\pi^+$ with misidentified $K^\pm$
- Light mesons (K_S, ρ^0, φ, etc.)

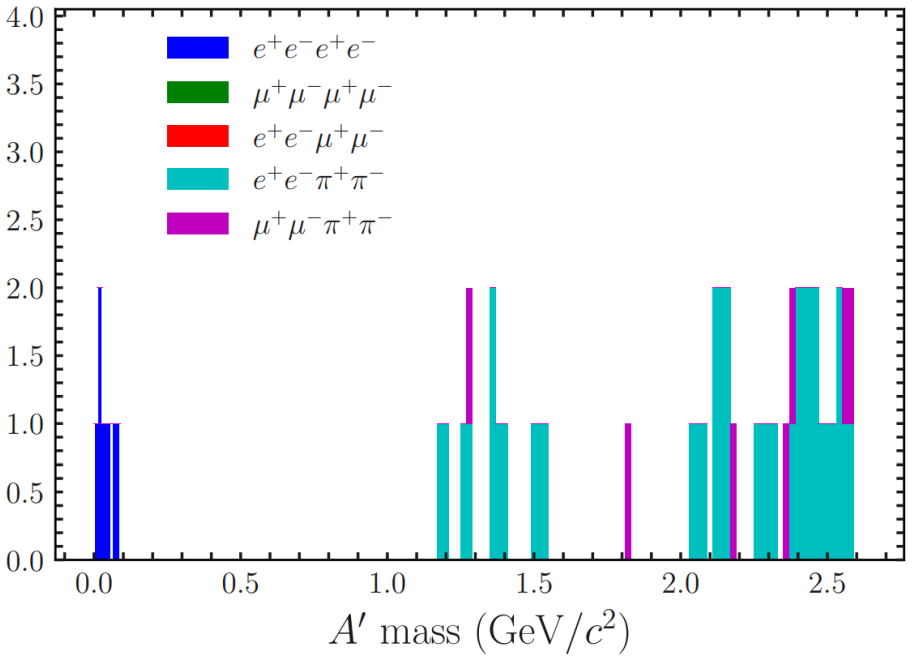
Used several variables for discriminating signal from background candidates



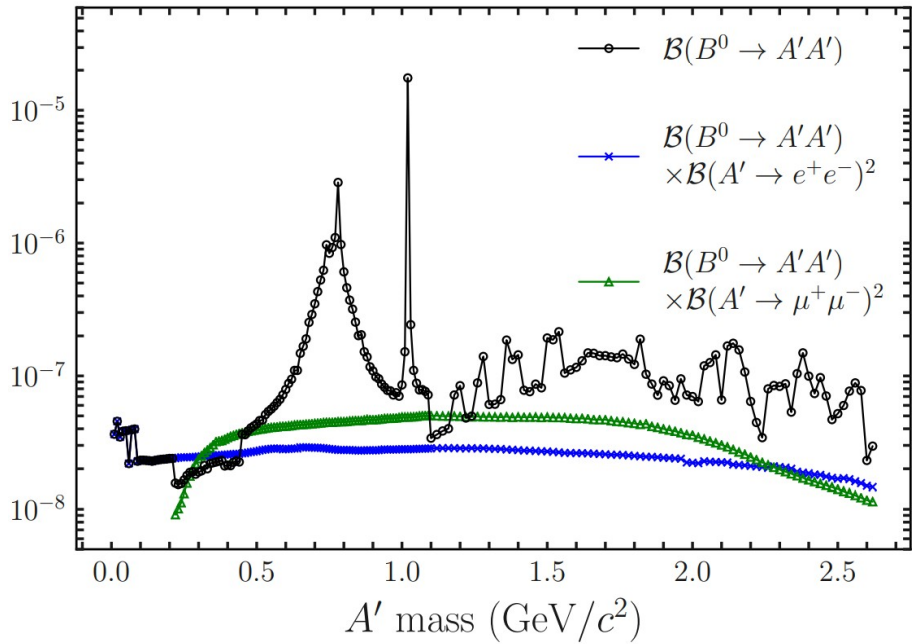
$B^0 \to A'A'$: results

No significant signal excess is observed, so upper limits are computed

- Mostly $O(10^{-8}$ - $10^{-7})$ of upper limits
- Near the light meson rejection region, up to $O(10^{-5})$ of upper limits



Observed events in Belle data



90% C.L. upper limits of $B^0 \to A'A'$ branching fraction

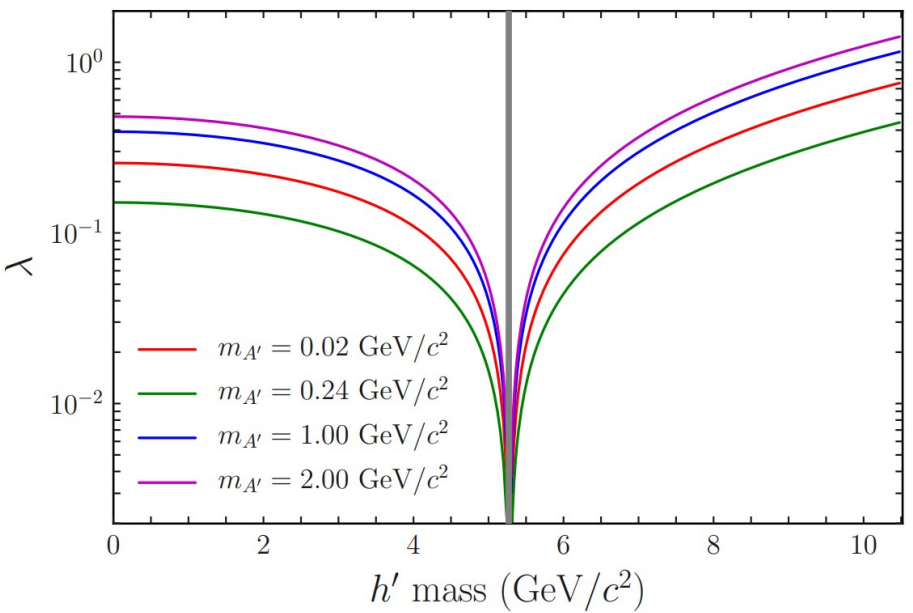
Belle, JHEP 04 (2021) 191

$B^0 \to A'A'$: results

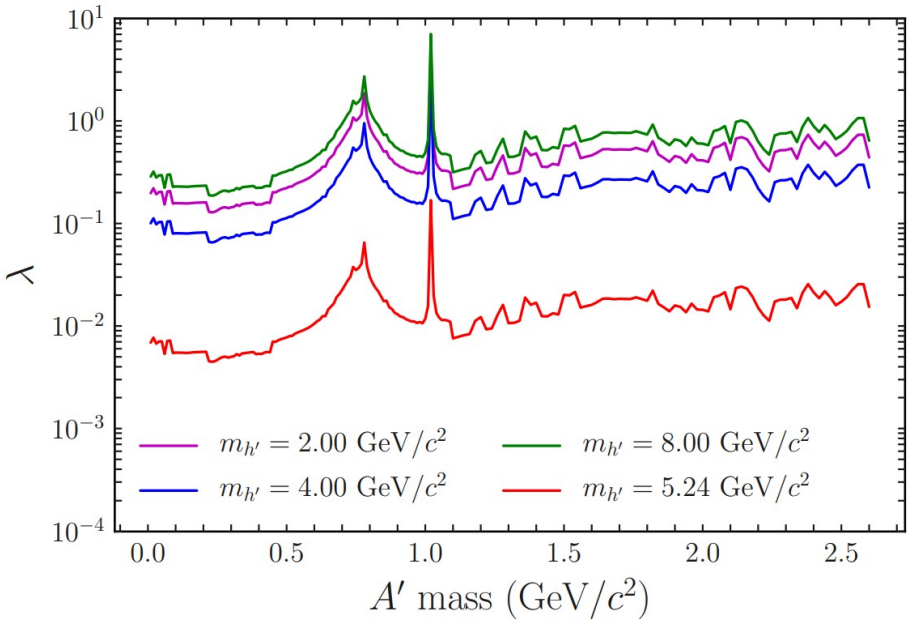
Higgs portal coupling λ is derived using the following equation:

$$\mathcal{B}(B^0 \to A'A') \simeq 7 \times 10^{-7} \times \lambda^2 \times V_{A'A'}^{1/2} \times \frac{V_{A'A'} + 12 m_{A'}^4 / m_{B^0}^4}{(1 - m_{h'}^2 / m_{B^0}^2)^2}, \; V_{A'A'} = 1 - 4 m_{A'}^2 / m_{B^0}^2$$

PRD 83 054005



90% C.L. limits of λ versus h' mass for some A' masses



90% C.L. limits of λ versus A' mass for some h' masses

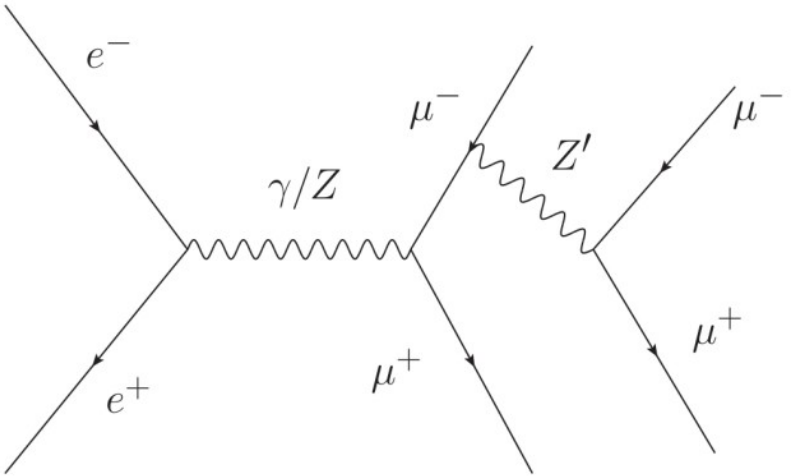
Belle, JHEP 04 (2021) 191

$L_\mu - L_\tau$ model: $Z' \to \mu^+\mu^-$

New light gauge boson Z′ coupling only to **2nd and 3rd** generation of leptons (**Lμ – Lτ model**):

$$\mathcal{L} = \sum_{\ell = \mu, \tau, \nu_{\mu,L}, \nu_{\tau,L}} \theta g' \bar{\ell} \gamma^\mu Z'_\mu \ell$$

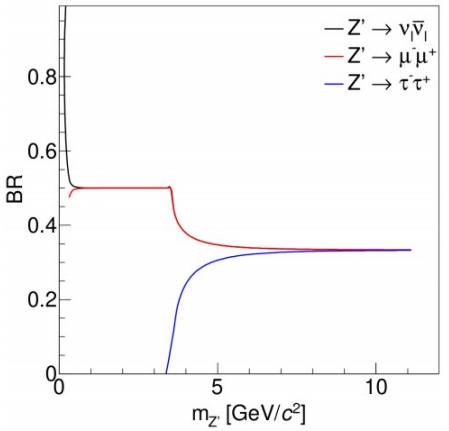
PRD 89 113004



It may explain:

- DM puzzle;
- $(g\text{-}2)_\mu$ anomaly;
- R(K) and R(K*) anomalies.

Belle looked for $e^+e^- \to \mu^+\mu^- Z'$, $Z' \to \mu^+\mu^-$ events using the full dataset ($\sim 1\ ab^{-1}$)



Sizeable branching fraction into muons

$L_\mu - L_\tau$ model: $Z' \to \mu^+\mu^-$

New light gauge boson Z' coupling only to **2nd and 3rd** generation of leptons (**$L\mu - L\tau$ model**):

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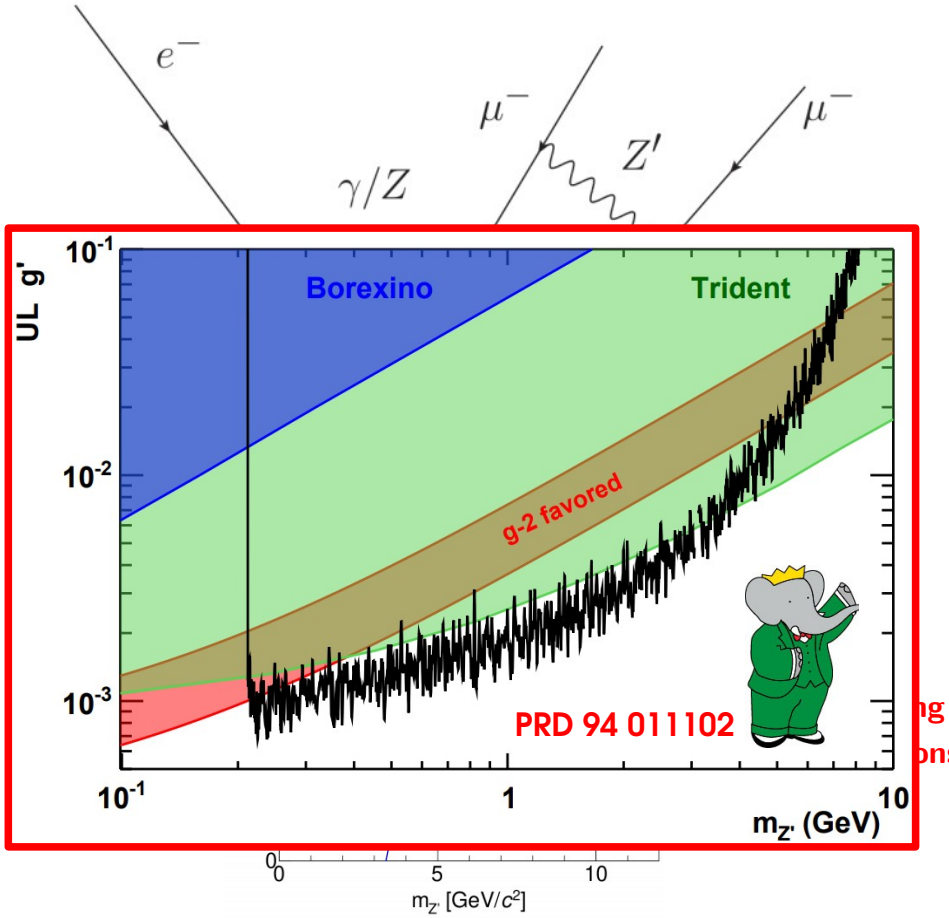
PRD 89 113004



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- competitive result w.r.t. **BaBar**

$L_\mu - L_\tau$ model: $Z' \to \mu^+\mu^-$

Belle, preliminary results

Require 4 charged tracks and sum of charges equal to 0

- At least, 2 same-signed tracks are identified as muons

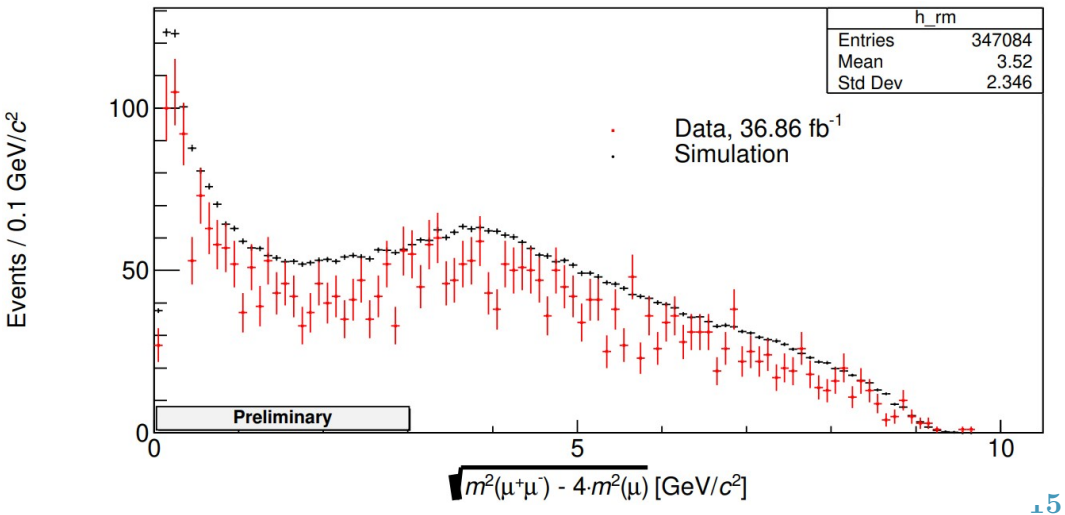
Selection creteria

- Energy remaining in ECL without track association < 200 MeV
- $m_{J/\psi}$ ± 30 MeV, $m_{\Upsilon(1S)}$ ± 100 MeV rejection from dimuon invariant mass
- 4-muon invariant mass within initial beam energy ± 500 MeV

Validation check with partial Belle dataset

Backgrounds in Belle data

- $e^+e^- \to 4\mu$
- $e^+e^- \to 4\pi$
- $e^+e^- \to 2e2\mu$
- $e^+e^- \to 2\mu 2\tau$
- $e^+e^- \to 2\mu J/\psi$ or $2\pi J/\psi$
- $e^+e^- \to 2\mu$
- $e^+e^- \to 2\tau$
- $e^+e^- \to q\bar{q}$
- $e^+e^- \to p\bar{p}$ or $n\bar{n}$
- etc.

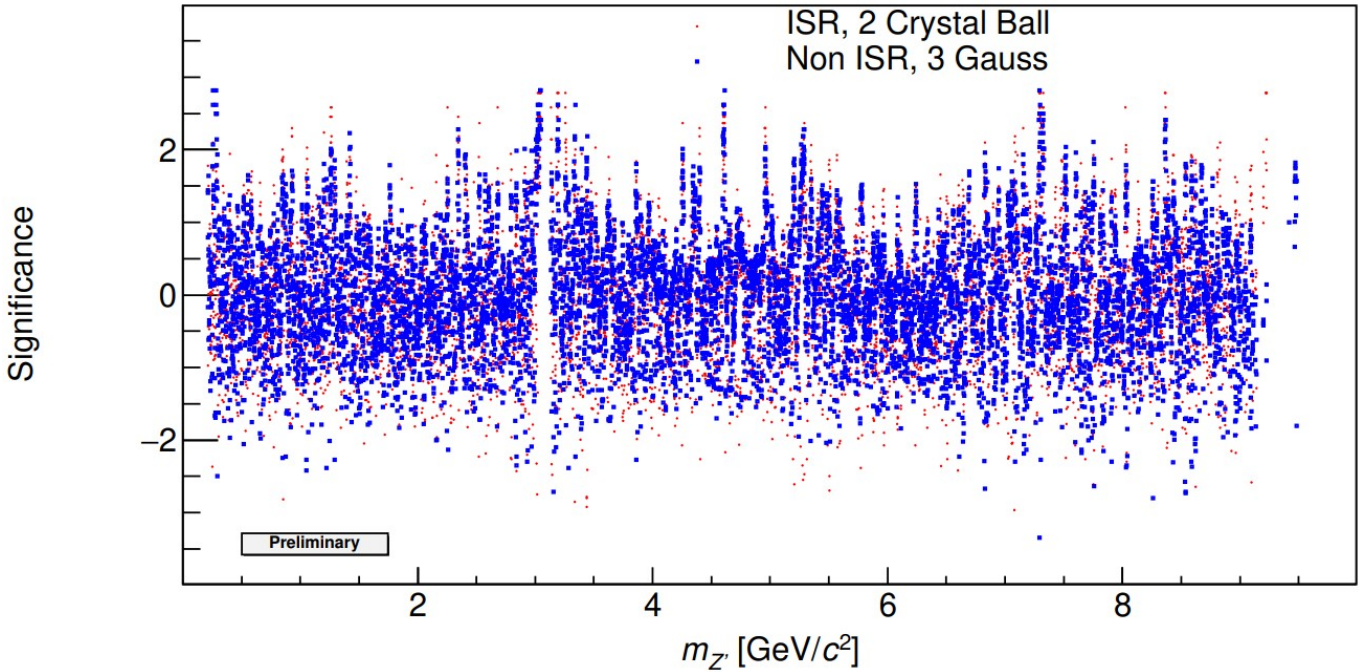


$L_\mu - L_\tau$ model: $Z' \to \mu^+\mu^-$

The coupling constant g' is obtained by the Born cross section: $\sigma_{\rm Born} = N_{\rm obs}/(\mathcal{L} \times \mathcal{B} \times \epsilon_{\rm rec})$

- $N_{\rm obs}$ is extracted by $M_{Z'}$ fitting

No siginficant signal events are observed



Belle, preliminary results

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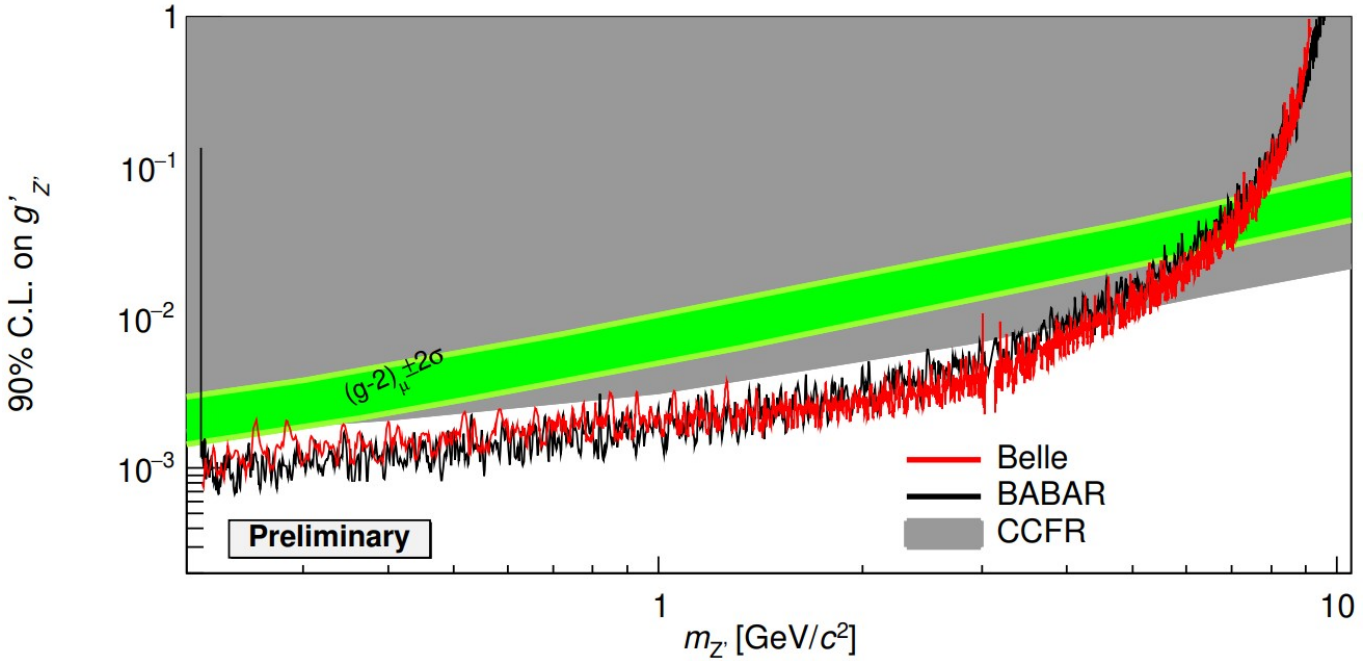
- $N_{\rm obs}$ is extracted by $M_{Z'}$ fitting

No siginficant signal events are observed → **upper limits on g' are thus set**



Belle, preliminary results

Summary

- Belle is (still) a major player for searching Dark Sector signals
- Three searches presented here:
  - - light CP-odds Higgs boson (PRL 122 011801 (2019))
    - best upper limits on BF of $\Upsilon(1S) \to \gamma A^0$ / $\Upsilon(1S) \to \gamma\chi\chi$
  - $B^0 \to A'A'$ (JHEP 04 (2021) 191)
    - mostly $O(10^{-8}$ - $10^{-7})$ of upper limits on BF of $B^0 \to A'A'$
  - $Z' \to \mu^+\mu^-$ (preliminary results)
    - best upper limits on g' for $1 < M_{Z'} < 5$ GeV
- Many other dark sector searches from Belle (and Belle II) will arrive soon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JTAG
Phi AXIS
Thank you for your attention

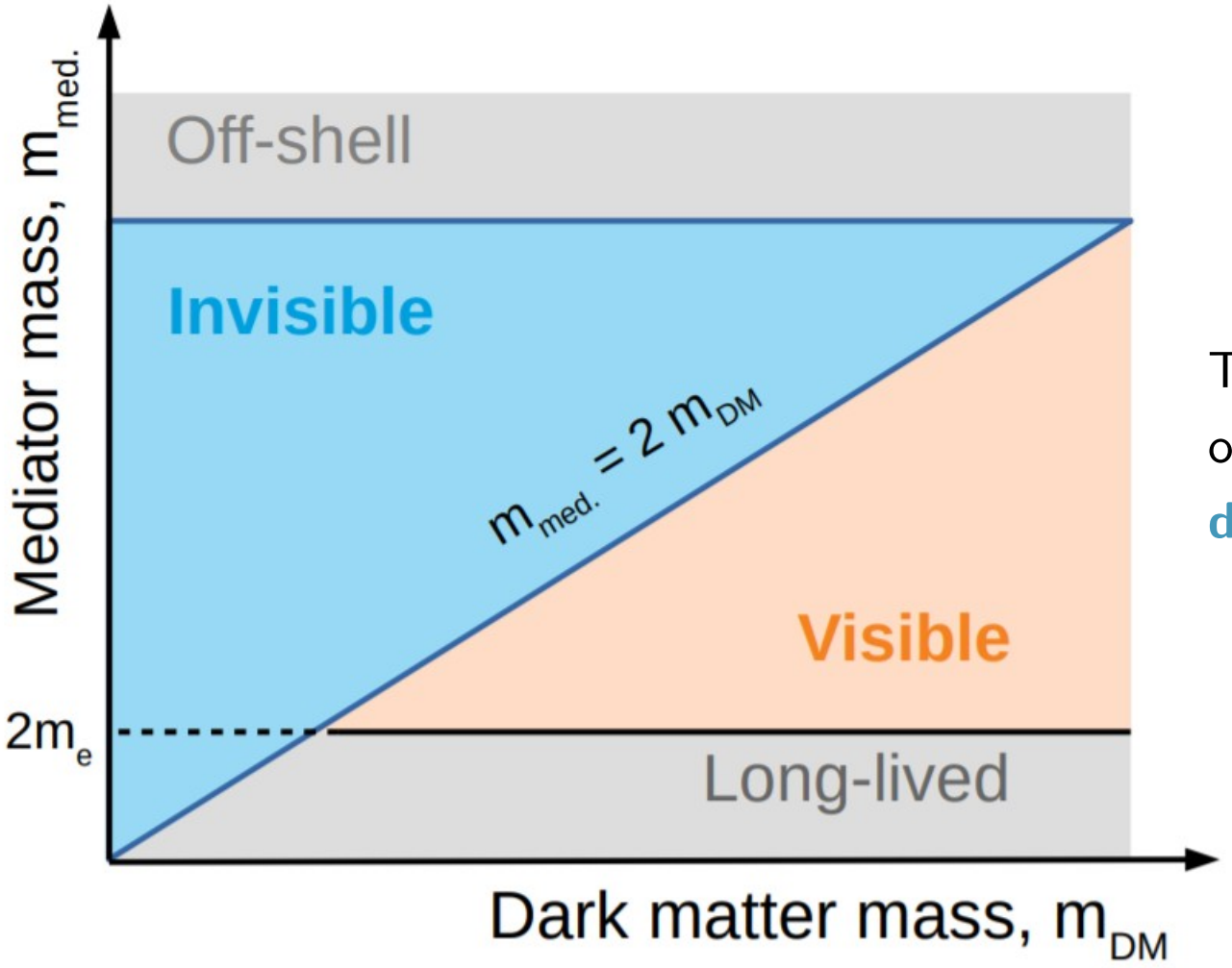
Backup slides

Cross sections at a B-factory

Physics process	Cross section [nb]	Selection Criteria	Reference
$\Upsilon(4S)$	1.110 ± 0.008	-	[2]
$u\bar{u}(\gamma)$	1.61	-	KKMC
$d\bar{d}(\gamma)$	0.40	-	KKMC
$s\bar{s}(\gamma)$	0.38	-	KKMC
$c\bar{c}(\gamma)$	1.30	-	KKMC
$e^+e^-(\gamma)$	300 ± 3 (MC stat.)	$10^\circ < \theta_e^* < 170^\circ$, $E_e^* > 0.15\,\text{GeV}$	BABAYAGA.NLO
$e^+e^-(\gamma)$	74.4	$p_e > 0.5\,\text{GeV}/c$ and e in ECL	-
$\gamma\gamma(\gamma)$	4.99 ± 0.05 (MC stat.)	$10^\circ < \theta_\gamma^* < 170^\circ$, $E_\gamma^* > 0.15\,\text{GeV}$	BABAYAGA.NLO
$\gamma\gamma(\gamma)$	3.30	$E_\gamma > 0.5\,\text{GeV}$ in ECL	-
$\mu^+\mu^-(\gamma)$	1.148	-	KKMC
$\mu^+\mu^-(\gamma)$	0.831	$p_\mu > 0.5\,\text{GeV}/c$ in CDC	-
$\mu^+\mu^-\gamma(\gamma)$	0.242	$p_\mu > 0.5\,\text{GeV}$ in CDC, $\geq 1\ \gamma\ (E_\gamma > 0.5\,\text{GeV})$ in ECL	-
$\tau^+\tau^-(\gamma)$	0.919	-	KKMC
$\nu\bar{\nu}(\gamma)$	0.25×10^{-3}	-	KKMC
$e^+e^-e^+e^-$	39.7 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5\,\text{GeV}/c^2$	AAFH
$e^+e^-\mu^+\mu^-$	18.9 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5\,\text{GeV}/c^2$	AAFH

E. Kou, P. Urquijo et al., arXiv:1808.10567

A rule of thumb...



The masses of the mediator and of the DM candidates lead to **different type of searches**.

Light CP-odd Higgs boson

No statistically significant signal excess is observed: largest local significance is 2.1σ

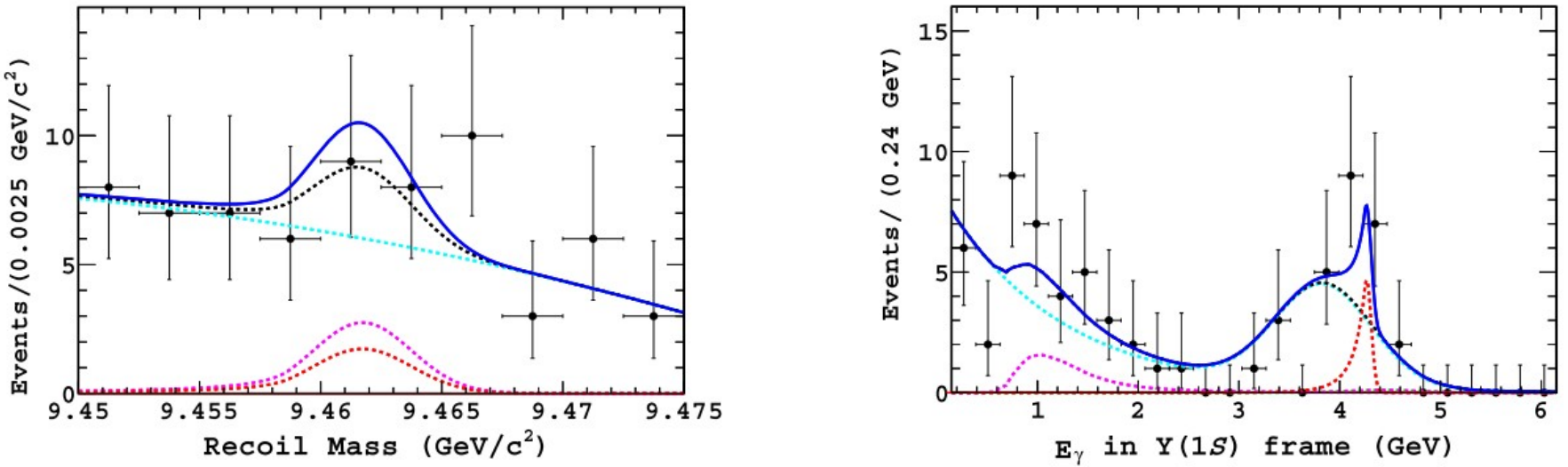


FIG. 1. Fit result for the on-shell process mass scan point with $M_{A^0} = 2.946\ \mathrm{GeV}/c^2$, which has the highest local signal significance; 2.1σ. Top: M_{recoil} distribution. Bottom: E^*_γ distribution. The fitted components are continuum background (cyan dashed curve), $\Upsilon(1S)$ decay background (magenta dashed curve), total background (black dashed curve), and the on-shell signal (red dashed curve). The blue solid curve shows the sum of all fitted components.

PRL 122 011801 (2019)

$B^0 \to A'A'$: background rejection

Possible SM resonances to be identified by A' are rejected

- J/ψ, $\psi(2S) \to \ell^+\ell^-$
- $D^0 \to \pi^+\pi^-$, including $K^-\pi^+$ with misidentified $K^\pm$
- Light mesons (K_s, ρ^0, φ, etc.)

$e^+e^- \to q\bar{q}$ suppression using 16 event shape variables

- Including B^0 cand. momentum direction, angle between trhust axis of B^0 cand. and other particles, and (modified) Fox-Wolfram moments
- Only applied for $\ell^+\ell^-\pi^+\pi^-$ final states

Small amount of combinatorial backgrounds

- Leptons are mostly from semi-leptonic decay of quarks
  $\to$ missing energy from neutrinos

Belle, JHEP 04 (2021) 191

$B^0 \to A'A'$: event reconstruction

Require at least 4 charged tracks,
including at least one e^+e^- or $\mu^+\mu^-$ pair
- Each track should appear near the interaction point with good track fitting

After combining A' and B^0, five variables are used to judge the quality of B^0
- M_{bc}: beam-constrained mass
- ΔE: energy difference b/w beam and B^0 cand.
- Missing energy of an event
- ΔM_A : $|M_{A'1} - M_{A'2}|$
- $\Sigma\delta M_{A'}$: $|M_{A'1} - m_{A'}| + |M_{A'2} - m_{A'}|$
  $M_{A'1,2}$: reconstructed $A'_{1,2}$ mass
  $m_{A'}$: target A' mass